OBSIDIAN STUDIES IN OREGON:

AN INTRODUCTION TO OBSIDIAN
and
AN INVESTIGATION OF SELECTED METHODS OF OBSIDIAN CHARACTERIZATION UTILIZING OBSIDIAN COLLECTED AT PREHISTORIC QUARRY SITES IN OREGON

A TERMINAL PROJECT

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Craig Skinner
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Garbage in, garbage out

Anonymous - Computer programmer's maxim.

Coming one day in sight of a magnificent elk, he [Jim Bridger] took quick aim and fired. To his amazement the elk remained immobile, not even flicking an ear. He drew cautiously nearer and took a careful bead and again pressed the trigger. The same result met his effort. A third and fourth shot produced like results. Exasperated, he clubbed his rifle and rushed for the elk, but was brought up cold by a seemingly solid wall, which he discovered to be a mountain of perfectly transparent glass, on the other side of which the elk still grazed, undisturbed. On further investigation the mountain proved to be not only perfectly transparent, but was a veritable telescopic lens, and the elk was in fact twenty miles beyond the glass wall.

V. Bright (1951) on the discovery of Obsidian
Cliff in Yellowstone Park by Jim Bridger.

It has been said that archaeology is anthropology or it is nothing... I beg to differ with this view. Archaeology and cultural anthropology do, or at least should, enjoy a close symbiotic relationship, and archaeology is indeed critically dependent on stimuli and models grounded in social, ecological, and evolutionary anthropology. But archaeology has been equally dependent on geology, biology, and geography at various times in its own right... But, like geography, archaeology is heavily dependent on both the empirical methods and models of the natural sciences, qualifying as a social science mainly by virtue of its objectives. The specific methodologies of other disciplines, including cultural anthropology and biology, cannot simply be transferred; they must be transformed, according to a new paradigm rather than a secondary paradigm, if they are to have productive input.

K. Butzer (1982) on context in archaeology.

The arrangement of the parts of the universe has always been a source of amazement to men. But this disposition proves itself more and more astonishing as, every day, our science is able to make a more precise and penetrating study of the facts. The farther and more deeply we penetrate into matter, by means of increasingly powerful methods, the more we are confounded by the interdependence of its parts. Each element of the cosmos is positively interwoven from all the others...

It is impossible to cut into this network, to isolate a portion without it becoming frayed and unravelled at all its edges.

All around us, as far as the eye can see, the universe holds together, and only one way of considering it is really possible, that is, to take it as a whole, in one piece.

Teilhard de Chardin (1959)

On the Warm Springs Indian Reservation in Central Oregon, some people tell a story about a wandering anthropologist who came across a coyote caught in a trap.

'Please let me out of this trap; if you do, I'll give you lots of money,' the coyote said.

'Well, I'm not sure; will you tell me a story, too? asked the professor.

'Sure I will; I'll tell you a real, true story, a real one for one of your books.'

So the anthropologist sprung the trap, collected a big handful of bills from the coyote, and then set up his tape machine. The coyote sat, rubbing his sore legs, and told a long story that lasted until the tape ran off. Then he ran off.

The anthropologist went home and told his wife about what had happened, but she wouldn't believe him. When he reached into his pocket to show her the money, all he came out with was a handful of fur and dirt.

And when he went to play his tape machine for the other professors, all that was in the machine was a pile of coyote droppings.

B. Lopez (1977)

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2. *Part One Cover:* This diagram is a hypothetical representation of a modified Critical Path Method (CPM) of planning, the method that was used to organize the research described in this project.

3. *Part Two Cover:* A view of the unusually well-developed obsidian columns at Obsidian Cliffs, Yellowstone National Park. This flow was a well-known source of archaeological obsidian for prehistoric peoples throughout the Midwest. This picture originally appeared in an early U.S. Geological Survey Monograph by J.P. Iddings (1899: Plate XXXIX).

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1 Introduction

Obsidian is one of the most widely-known and recognized lithic materials and has, for more than a century, been of great interest to both geologists and archaeologists. The name alone, obsidian, may be the most ancient of the rock names still in use today.

Obsidian, a naturally-occurring volcanic glass, has been used for many thousands of years as a preferred raw material for the manufacture of tools and decorative objects. The glassy consistency, the predictable fracture characteristics and the ability of the glass to gain a very sharp working edge all contributed to its popularity as a sought-after artifactual material. Obsidian was valuable enough to have been transported and traded over great distances from its original sources. Prehistoric, pre-metal cultures or groups that lived close to natural sources of obsidian invariably used it as a major component of their lithic assemblage. Only with the advent of metal-working in some regions of the world or the introduction of metal objects did obsidian lose its value as a material for tool manufacture.

Prior to a few decades ago, most archaeological interest in obsidian artifacts was centered on their culturally-ascribed characteristics. Stylistic variations, particularly in projectile points, were classified into hopefully-related groups, or types, which appeared time-sensitive and whose presence could be used to infer chronologies or changes in cultural traditions.

In the late 1950's and particularly in the 1960's, the study of archaeological obsidian began to expand rapidly along three major new lines - use-wear analysis, obsidian hydration geochronology and obsidian characterization/source correlation. It is the last of these trends, the characterization of obsidian or the search for qualities that can be used to distinguish among different obsidian sources, that will be examined in considerable detail in the following project. Also considered, though in less depth, will be the principles and problems of obsidian hydration geochronology and the relationship of hydration geochronology to obsidian characterization through the concept of "source-specific obsidian hydration dating.

Geological interest in obsidian began in the 1880's when several researchers became interested in the perplexing presence of spherulites and lithophysae in obsidian and rhyolite. Later, in the 1920's, N.L. Bowen used the supposed pristine composition of the glassy volcanic rocks, including obsidian, to make a case for a liquid line of descent in volcanic rocks, i.e. Bowen's Reaction Series (Bowen, 1928:125-132). Geologists no longer believe that obsidian represents the original and unaltered composition of magmas, for later research showed that low-temperature post-eruptive alteration of obsidian does occur. Unaltered obsidian still provides, however, the best evidence for the composition and types of early crystalline phases in magmas (Carmichael, 1979:233-234). Research in the 1950's identifying perlite as hydrated obsidian (Ross and Smith, 1955; Friedman and Smith, 1958a) led to the development of obsidian hydration geochronology shortly thereafter (Friedman and Smith, 1958b and 1960).

This geochronologic method, based on the principle that obsidian hydrates at a predictable rate, has been used, with various degrees of success, to estimate ages of many geological and archaeological events. Obsidian source identification methods, now widely used by archaeologists, have yet to be used by geologists. Obsidian characterization studies have the potential in geology, though, for correlating separate units in which obsidian is present (such as in ash-flows or sediments), for determining the sources of these units and, when combined with characterized and dated obsidian artifacts of known ages, for suggesting the age ceilings of recent obsidian flows.

THE STRUCTURE OF THIS PROJECT

The research that is reported in this project deals primarily with obsidian characterization. I have gone beyond this topic, though, in presenting an overview of the many other geological, geomorphological and archaeological properties of this natural glass. The project, as a result, is divided into five distinct, but interrelated parts, in addition to an extensive bibliography and a number of appendices.

This part, the *first* one, is an introduction to the rest of the project. It will give the reader a general idea of the structure that I used to organize this paper and of what I intended to achieve through the research that is reported. Topics touched on here will be discussed in greater detail in later sections.

Part *Two* of this project is concerned with providing an overview of the many geological and geomorphological characteristics and properties of obsidian. This includes its geographic distribution, the forms in which it occurs, how it is transported after extrusion, its macroscopic and microscopic properties and its chemical composition. An understanding of these characteristics provides a step towards comprehending how the physical and geochemical properties of obsidian may be studied and how the results can be utilized in archaeological problem-solving.

Part *Three* describes the ways in which analysis of the petrographic, optical and geochemical properties of obsidian can be applied to archaeological studies. Specifically, I will discuss obsidian characterization methods, the ways in which characterized obsidian can be used to infer prehistoric contact networks and obsidian geochronologic techniques.

Part *Four* comprises the main body of the project, a systematic investigation of some of the attributes of obsidian that may be used to characterize, or distinguish, a particular geologic source of glass. In Part Four, I will describe the ten Oregon sources that were sampled for this research and the different ways in which they were successfully and unsuccessfully "fingerprinted" or characterized. All of the sampled obsidian sources were known or suspected to be prehistoric quarry sites.

Part *Five* offers a summary and conclusions of the material presented in the project as well as suggestions for further research.

The *Bibliography* is quite comprehensive. It was my intention to review rather thoroughly the literature related to obsidian. This bibliography includes much of the available English-language research and information about obsidian.

The *Appendices* are a collection of addenda that , while being tangential to the main objectives, definitely enhance the primary thrust of the research reported here. The appendices illustrate some of the applications of obsidian characterization methods in several limited archaeological and geological problems. Also provided in the appendices is a preliminary listing of obsidian sources that are reported to exist in Oregon. In addition, a glossary and geologic time scale are included to make the information more accessible to the non-professional archaeologist or geologist. A preliminary computerized obsidian identification that can enhance the discriminatory powers of previously unsatisfactory characterization methods is also outlined.

THE RESEARCH PROBLEMS AND AN ASSESSMENT OF NEED

Several authors have suggested that a number of different steps are necessary in the development of a reliable scheme for artifactual obsidian characterization and source correlation (Dixon, 1976:288-289; Earle and Ericson, 1977:5; Leach, 1977a:10; Ward, 1974a:58; Ward, 1974b:41-42). Though the concepts of the stages of development vary somewhat among different authors, a seven-step ideal sequence is inferred:

1. A raw material (for our purposes, obsidian) and a region (culturally or physiographically delineated) are selected for further research.
2. A thorough survey is made of the selected region for possible sources of obsidian or obsidian-like rocks.
3. The areal extent of the obsidian sources are determined. This must include not only the primary geologic source of the obsidian (such as a flow) but also must include sites of secondary deposition by fluvial, glacial or other processes.
4. Each identified obsidian source is sampled at several locations so that a representative sample is obtained. Several samples are needed to determine the extent or range of intraunit variation for any single attribute that is being used to characterize the source.
5. The regional obsidian sources are then characterized through the determination of an attribute or attributes that will discriminate among different obsidian sources or source groups. In recent years, for instance, the trace-element composition of obsidian has been the most popular and successful of the methods of characterization in use. For an attribute to be useful in the characterization of a source, it must be exhibit a low (and known) degree of intraunit variability as well as enough interunit variation to distinguish it from other sources. Based on these criteria, one or more attributes (these are discussed in detail in Part Three) are chosen to characterize or "fingerprint" the source.
6. Artifactual or geologic obsidian from an unknown source is then characterized through the measurement of the attributes which are known to best discriminate regional geologic sources.
7. A method is chosen which can reliably correlate the data collected from samples of an unknown provenience with a geologic known source. This is typically statistical in nature if four or more variables are employed (for instance, four trace-elements) or visual (ternary or binary diagrams) if three or less are used.

In actual practice, this sequence of events, often requiring a sizeable expenditure of time and an abundance of funding, is rarely followed. Research projects carried out in New Zealand, California and the Middle East have come the closest to approaching the ideal.

A survey of much of the published archaeological literature using obsidian characterization methods revealed a number of consistent methodological weaknesses that jeopardized the validity of the reported research. These are often directly related to the omission of one or more of the seven steps just described. A number of the problems of archaeological obsidian characterization research, as they pertain to trace-element studies, have also been discussed by Ives (1975). Generally, the problems of obsidian characterization research fall into the following categories:

1. A *thorough* survey of all available obsidian sources, especially of the areal secondary extent of those sources, had not been made. This was especially true for areas in Mexico, Central America and the Western United States, where large numbers of sources are found. This single point may be the most prominent and consistent weakness in most characterization studies and casts doubt on the reliability of much research. This is particularly true of the earlier reported studies. My own impression is that this crucial and often very time-consuming stage of research is rather casually approached and sidestepped so that archaeologically-relevant results (the source of artifactual obsidian) can be determined.
2. Specific source sampling localities were rarely reported and it was often difficult to determine, when several sources were found in a limited geographic area, which had actually been sampled. Newberry Volcano in Central Oregon, for instance, has many discrete obsidian sources within and near the central caldera, yet several authors have referred to an obsidian specimen only as originating from Newberry Volcano. Similarly, the provenience of archaeological specimens whose source is to be determined through obsidian characterization also needs to be specifically reported.
3. The intraunit variability of the attribute used for characterization was often not adequately reported or determined. More than once, it was assumed by authors that intraunit homogeneity, particularly those of trace-elements, did exist. While this is often the case, it is not necessarily so (Bowman, et al., 1973a and 1973b).
4. The analytical method and error were often omitted from research reports, particularly for those involving trace-element studies. Occasionally, not even the method used to determine the results could be ascertained.
5. Quantitative data were sometimes lacking with the author reporting only his or her conclusions. For literature about obsidian characterization to have any comparative value, comparable results (such as trace-element abundances in parts per million) must be reported (along with the associated error).
6. Analytical methods of characterization were most often aimed at singling out the *one* measureable attribute (or group of related attributes, such as in trace-element analysis) that could be used to discriminate among all the probable obsidian sources. Methods with this much discriminative ability are often accessible to only a limited number of researchers. Not many archaeologists, for instance, have the laboratory access, the funds and the technical training to perform neutron activation analysis studies or multi-element X-ray fluorescence analyses on their collections of obsidian artifacts. As a result, only a limited number of researchers have

reported obsidian characterization studies with archaeological materials. Little research has been carried out in recent years with less powerful, but more easily-accessible discriminative attributes such as index of refraction, density, hardness, color and so on.

7. Potentially misleading results may show up when statistical methods of correlation are used to link archaeological obsidian with geologic sources. The multivariate statistical techniques that are used for this purpose (almost exclusively for trace-elements) are based on the premise that the obsidian source universe used for correlation is complete, when, in actuality it often is not. A method that has been used several times is reported by Nie et al. (1975). This multivariate technique reports sources for artifactual material that offer the *best fit* with known geological sources. The reported sources are drawn, of course, from the obsidian source universe of the researcher. It is important, in interpreting the results of statistical methods , to remember that results are probabilistic, not absolute, and that the results are only as complete as the initial geologic source data (which must include not only the available sources but their degree of intra-unit variability). As long as these inherent limitations are recognized, though, multivariate statistical methods are an excellent way of correlating several variables at once.

Examination of the still limited number of obsidian characterization studies involving Oregon sources shows that many of the previously discussed weaknesses are also extant in the literature (Bennett and D'Auria, 1974; Ericson, 1977; Ericson and Berger, 1976; Hughes, 1978; Huntley and Bailey, 1978; Nelson et al., 1975; Sappington, 1980a and 1980b; Sappington, 1981; Sappington and Toepel, 1981; Stevenson et al., 1971; Waibel, 1971; White, 1974; White, 1975; Wright et al., 1969; Sappington, 1982; Toepel and Sappington, 1982).

It was these consistent weaknesses that surfaced in the literature that led to the study of obsidian characterization that is reported in this project.

THE OBJECTIVES OF THIS PROJECT AND HOW THEY WERE MET

The major goal of this project was to investigate systematically, using carefully sampled obsidian sources, some of the attributes of obsidian that might distinguish one source from another or differentiate among a group of sources. Surprisingly, a careful search of the literature showed that few, if any, controlled experimental studies of obsidian characterization had been attempted. Obsidian characterization methods were almost always secondary to the archaeological objectives of the researcher. In short, the basic research phase had been forgotten. My only regret concerning the research reported here is that the resources were not available to allow me to use a wider range of analytical methods and a greater number of sources than those I eventually focused on.

Several other objectives were also kept in mind during the course of this investigation, as well. They were:

1. To examine and synthesize past and current research about the geological, petrographic, optical and geochemical characteristics of obsidian. This objective is addressed in Part Two of this paper.
2. To examine the processes of obsidian transport from original primary sources. This is also examined in Part Two.

3. To provide an overview of the ways that obsidian can be utilized in archaeological research. Part Three of the project considers this goal.
4. To identify different attributes of obsidian which exhibit intraunit homogeneity and interunit heterogeneity, thus making them useful candidates for the characterization of natural glass. This objective is discussed in Parts Three and Four of the paper.
5. To test the feasibility of a non-statistical, reliable and easy-to-use method of correlating obsidian artifacts with obsidian sources. Appendix Eleven, a sample computer program designed to discriminate among sources on the basis of several different attributes, is concerned with this objective.
6. To assemble a preliminary geological, geomorphological and archaeological data base about obsidian sources for the State of Oregon. The more extensive-than-expected results appear in Appendix Four.
7. To keep the information in this project intelligible to the non-specialist while keeping it useful to the specialist (this is something of a problem in interdisciplinary research). I have tried to do this by avoiding unnecesary barrages of "jargonese" and needlessly obscure intellectual meanderings while providing a glossary (Appendix Three) to fall back on when the use of specialized nomenclature was necessary.
8. To keep the methods of characterization as accessible as possible to the geologists or archaeologists that might use them. My thinking was that the simpler and more straightforward a method of characterization was, the more likely it was to be employed by someone. For archaeologists, non-destructive methods are also an important consideration and, as you will find out later in the paper, this was a major drawback of many of the analytical methods that I eventually used in this study.

With these objectives held at least tenuously in mind, I invite you to continue on to the heart of the project presented in the ensuing pages.

1 An Introduction to the Geological and Geomorphological Properties of Obsidian

During the last century, many earth science researchers have examined the properties of obsidian. Studies have focused on the relationship of obsidian and perlite (Ross and Smith, 1955; Friedman and Smith, 1958a; Friedman et al., 1966), the mobility of minor and trace elements during the weathering of obsidian (Noble, 1967; Rosholt et al., 1971; Zielinski et al., 1977; Zielinski, 1978; Jezek and Noble, 1978), the connection between obsidian and the original composition of magmas and magmatic gasses (Bowen, 1928; Eichelberger and Westrich, 1981), the similarity of tektites to obsidian (O'Keefe, 1976), the process of hydration (Friedman and Smith, 1960; Marshall, 1961; Lofgren, 1970 and 1971; Ericson et al., 1976b; Ericson, 1977; Laursen and Lanford, 1978), the use of obsidian to understand trace element behavior in magma bodies (Magaritz and Hoffman, 1977, 1978a and 1978b), and other topics.

In general, though, obsidian has been looked upon as a medium through which other phenomenon could be understood, and not often as an object of study in itself. Though geological research about obsidian has appeared in many sources, no attempt has been made to collect and synthesize the body of information that has accumulated about natural volcanic glass. In the following chapters of Part Two of this project, this is what I will attempt to do - to present, in an abridged form, what is currently known about the geologic and geomorphic properties of obsidian.

Obsidian is found in many locations throughout the world and the global distribution as well as its relationship with tectonic structures is discussed in Chapter Two.

Chapter Three focuses on the geological properties of obsidian, obsidian-like rocks and rocks closely related to obsidian, such as pumice. The geologic context that obsidian is found in, petrogenesis, post-depositional alteration through hydration, petrographical characteristics and geochemical characteristics will be examined in this chapter.

Topics directly relating to obsidian and geomorphology are rare. I have confined my discussion in Chapter Four, therefore, to the post-depositional processes of erosion and transport of obsidian.

Much of the information appearing in recent years about obsidian is the result of a renewed interest by archaeologists in the archaeological applications of this lithic material. Developments in hydration dating and obsidian characterization have shown up with increasing frequency during the last two decades in particular. An understanding of the geologic and geomorphic properties that are presented in Part Two of this project provides a needed, and often neglected, foundation for the archaeological study of this natural glass.

2 Worldwide Distribution of Obsidian

It has been almost a century since the first description of the worldwide distribution of obsidian was made by J.P. Iddings in his classic study of Yellowstone National Park (Iddings, 1888:290-294). Since that time, many other sources of obsidian have been reported in the literature and several attempts have been made to compile regional listings of obsidian sources in various parts of the world. The collection of obsidian sources reported in this chapter, though necessarily described only briefly, is drawn from these collections and from other diverse sources. They represent most of the major obsidian sources known in the world today. The sources discussed here are those with a rhyolitic or occasionally dacitic composition, the most common of the different varieties of natural glasses. Basaltic and andesitic obsidians, as well as pitchstones and other obsidian-like glasses, are ignored for the purpose of this chapter, though they are discussed in Chapter Three. Much of the information presented in this chapter was initially gathered in conjunction with archaeological studies - a more thorough search of regional geological literature would undoubtedly add other sources to the list.

THE NEAR EAST

Many obsidian sources have been documented in the area now occupied by Turkey, northern Iran and the Caucasus Region of the U.S.S.R. One group of these sources can be found in central Turkey about 100 km east of Lake Tuz. Obsidian localities in this poorly-known area are described by Renfrew et al. (1966:38-39), Wright (1969:5-21) and Dixon (1976:300-303). Farther east near the point at which Turkey, Iran and the U.S.S.R. (Caucasus Region) meet is another broad area in which abundant obsidian sources are found. These sources are largely clustered within a 200 km radius of Lake Van in eastern Turkey and are detailed by Renfrew et al. (1966:39-40), Wright (1969:20-21) and Dixon (1976:303). Dixon (1976:310-312) mentions the presence of several obscurely-known sources in northern Iran and Armenian S.S.R. References to sources in Armenian, Azerbaidzhan and Georgian S.S.R. also appear in Gorshkov et al. (1981), Golubkov (1981), Washington (1917:143,997) and Iddings (1888:294).

EUROPE

More than two dozen sources of obsidian located in central Czechoslovakia, eastern Hungary and just over the border in the Ukrainian S.S.R., are described by Williams and Nandris (1977). Only one other European source, this one at Auvergne in France, was noted in the literature (Cann and Renfrew, 1964:113).

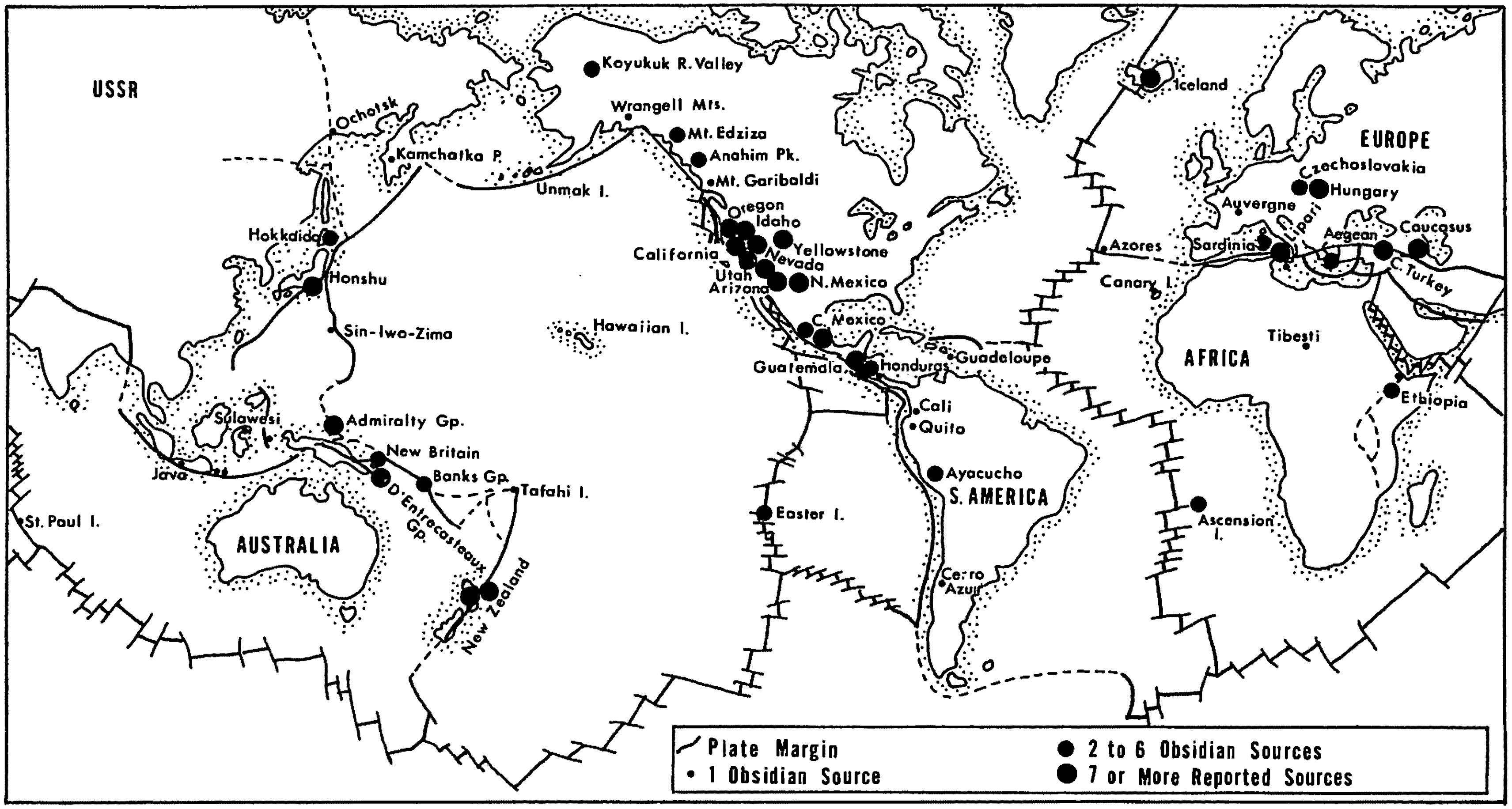


Figure 4: Worldwide distribution of geologic sources of rhyolitic and dacitic obsidian. Base map is adapted from Williams and McBirney (1979). The obsidian source locations were compiled from the many sources listed in the text of this chapter.

MEDITERRANEAN AREA ISLANDS

Obsidian is also found on many of the islands in the Mediterranean. One of the most well-known of these sources is on the island of Lipari in the Aeolian Island Group north of Sicily. The sources on Lipari and on nearby Vulcano have been described by many authors, among them Cann and Renfrew (1964:118), Bigazzi and Bonadonna (1973), Dixon (1976:293-294) and Hallam et al. (1976:94). South of Sicily on the island of Pantelleria is another source of natural glass, this one described by Dixon (1976:295-296) and Hallam et al. (1976:93-94). Off the central western coast of Italy in the Pontine Island Group, another source of obsidian has been identified on the island of Palmarola (Dixon,1976: 294-295; Hallam et al., 1976:95). Northwest of Sicily, several outcrops are found on the island of Sardinia in the Monte Arci region and on nearby Isola San Pietro (Washington, 1917:473; Dixon, 1976:289-292; Hallam et al., 1976:95-97). Farther east, in the Aegean Sea, three more island sources are found on Melos, Antiparos and Giali (Renfrew et al., 1965; Dixon, 1976:297-299).

AFRICA

Most of the known African sources of obsidian lie in the eastern portion of the continent. In central Ethopia, two sources are found, one near Addis Abeba (Muir and Hivernel, 1976) and one at Fantale Volcano (Washington, 1917: 337; Richard and van Padang, 1957:29). Obsidian is also reported in the Eritrean region of Ethiopia at Alid Volcano near the Red Sea (Washington, 1917:143; Richard and van Padang, 1957:8). Other unspecified Ethiopian sources are reported by Cann and Renfrew (1964:113). It is interesting to note that one of the Ethiopian (Abyssinian) sources was first mentioned by Pliny, the probable originator of the term *obsidian*. Across the Red Sea from Ethiopia, another unspecified source is noted by Cann and Renfrew (1964:113).

South of Ethiopia in Kenya obsidian occurs in the Great Rift Valley of East Africa. Ol Doinyo Eburru Volcano, Mount Kilamanjaro and the region near Lake Naivasha are all known to be source areas for obsidian (Richard and van Padang, 1957:57,81).

A single north-central African obsidian source in the Tibesti region of Northern Chad is also mentioned by Cann and Renfrew (1964:113).

THE ATLANTIC ISLANDS

Iceland, lying directly atop the Mid-Atlantic Ridge, is known to have many sources of obsidian, though details are lacking. The glass has been reported from Mt. Hekla, Hraftntinnuhruggur, Laugahruan, Kaldadalur, Raudhfossafjolla, Hallsheivedal ved Skriddal and Prestahnukur by several authors (Iddings, 1888: 294; Wright, 1915; Washington, 1917:93,757,969; George, 1924:36; Ross and Smith, 1955).

The island of Tenerife in the Canary Islands has also been reported as an obsidian source (Iddings, 1888:294; Washington, 1917:211; van Padang et al., 1967:76).

Ascension Island is another island source of obsidian in the Atlantic Ocean (Iddings, 1888:294; Ross and Smith, 1955).

In tha Azores Group, obsidian has been found on San Miguel Island (van Padang et al., 1967:76).

JAPAN AND THE EASTERN SOVIET UNION

A number of obsidian localities are found in the far eastern part of the Soviet Union and on the two largest Japanese Islands, Hokkaido and Honshu, as well as on several small islands off the Japanese coast.

Kamchatka Peninsula and Siberia, U.S.S.R.

References to an obsidian source in the Kamchatka Peninsula region on Unga Island and in Siberia, probably near Ochotsk, are made by Washington (1917:97, 241,975).

Japan

Several obsidian source localities are known on the island of Hokkaido, Japan, the northernmost of the main Japanese islands (Katsui and Kondo, 1976:121). The largest island of the Japanese Group, Honshu, also houses numerous sources in the central part of the island. Sources are found, as well, off the central eastern coast on the small islands of Kozujima and Ombasejima (Suzuki, 1973: 243-248). Suzuki (1973:243) also reports that a survey of Japanese obsidian sources (not examined) was published in 1950. Obsidian has additionally been found at Mount Fuji, Honshu Island, after the 1707 eruption of the volcano, but is an andesitic variety (Tsuya, 1955:374; Kuno, 1962:84).

In 1905 and 1914, obsidian was produced during an eruption of Sin-Iwo-Zima Volcano, an island cone found about 1000 km southeast of Honshu. The island, 5 km in diameter in 1905, had completely disappeared by 1916 (Kuno, 1962:265-267).

OCEANIA AND AUSTRALASIA

New Zealand

The North Island of New Zealand is one of the most thoroughly investigated areas in the world for sources of obsidian. Many sources have been located on the North Island in addition to the small neighboring islands of Mayor Island and Great Barrier Island. These sources are best described by Ward (1972 and 1973) and Reeves and Ward (1976).

Micronesia

Geologic sources of obsidian are found on many of the islands of Micronesia that stretch southeastward from New Guinea. In the Admiralty Island Group, the islands of Lou, Pam and Pam Lin are recognized as obsidian sources. Also in the Admiralty Group is Tuluman Island, another source of natural glass created by eruptions between 1953 and 1958 (Smith, 1974:20-21; Smith et al., 1977:185; Ambrose, 1976b:359). Several other sources are also reported on New Britain, a large island off the eastern coast of New Guinea (Smith, 1974:21; Bird et al., 1978; Smith et al., 1977:185). The D'Entrecasteaux Islands, found just off the southern tip of New Guinea, are another well-known source of obsidian in Melanesia. In this group, Sanaroa Island, Dobu Island and particularly Fergusson Island all harbor geologic sources of obsidian (Smith, 1974:19-20; Ambrose, 1976:369; Smith et al., 1977:186). Volcanic glass is known from the Banks Island Group in the New Hebrides archipelago (Ambrose, 1976:371; Smith et al., 1977:184). Elsewhere in the islands of Melanesia, obsidian has been reported at Tafahi Island in the Tonga Islands (Smith et al., 1977:184).

Polynesia

Natural sources of rhyolitic obsidian appear to be rare on the islands of Polynesia. Evans (1965:480) and Smith et al. (1977:179-180) report the presence of two obsidian sources on Easter Island. The only other Polynesian source of natural glass noted, though probably a pitchstone, is found on Pitcairn Island (Smith et al., 1977:180).

Indonesia

Obsidian in the Indonesian archipelago has been reported at Leles on the island of Java, on Minahasa Island, Ambon Island, Flores, Timor, Sumatra and Sulawesi (Celebes). These sources are mentioned only briefly by Iddings (1888:294), Washington (1917:89,213,975,977) and Smith et al. (1977:186-187).

CANADA

In Canada, only the province of British Columbia is known to be a source area for obsidian. Several obsidian flows are reported at Mount Edziza by Huntley and Bailey (1978) in the northern part of the province. Farther south in central British Columbia, obsidian is found in the Anahim Peak, Mount Mackenzie and Ilgachuz areas (Huntley and Bailey, 1978; Nelson et al., 1975). Obsidian has also been reported from Mount Garibaldi near Vancouver (Huntley and Bailey, 1978).

WESTERN UNITED STATES

Archaeological projects involving the identification and characterization of obsidian sources have been underway in the western United States since the early 1970's. Because of this and the large quantity of geological literature to draw on, many natural sources of obsidian have been located in the western states and Alaska.

Alaska

Although not well-described in the literature, several areas in Alaska are known to be sources of obsidian. A flow on Unman Island in the Aleutian Chain is reported by Griffin et al. (1969b:155) as is a source on Mount Drum in the Wrangell Mountains. Additional sources are located in the Koyukuk River Valley in the central part of the state (Patton and Miller, 1970; Wheeler and Clark, 1977). Ross and Smith (1955) also report obsidian from the Norwikakat River in Alaska.

Arizona

All reported Arizona sources of obsidian are found in the San Francisco volcanic field near Flagstaff. Ten sources have been reported in this area (Jack, 1971; Schreiber and Breed, 1971; Sanders et al., 1982).

California

Several lists of California obsidian sources have appeared in the preceding 40 years and this area is one of the most well-examined in the world. The first of these obsidian source "catalogs" was authored by Heizer and Treganza in 1944. They listed 24 sources, but as Jackson (1974:40) later noted: "At least twelve of the twenty-four localities which are discussed either do not exist... or they are improperly quoted from original sources." Jackson goes on to make corrections and additions to Heizer and Treganza's original list (Jackson, 1974:40-51; Jackson and Schulz, 1975). Shortly thereafter, another source compilation appeared by Ericson et al. (1976a),this one indicating a total of 32 California obsidian sources. Ericson (1977:310-314) later added more details to the list. As Jackson again writes, though (1974:34), and this seems to hold true for all areas in the world: "Despite the fact that the State of California is perhaps one of the most intensively studied geological areas in the world, the total inventory of obsidian sources is not yet known."

Colorado

Several northeast, central and south-central Colorado obsidian sources are mentioned by Zielinski (1978) and Lipman et al. (1969), though few details are available.

Idaho

Numerous sources of obsidian are reported in southwestern and southeastern Idaho, particularly in the Teton region. These sources are mentioned or briefly described by Sappington (1980a:255-256; 1982:13-15).

Nevada

Obsidian has been found in several locations in the western and southern part of the state (Ericson et al., 1976:233-234; Ericson, 1977:314-315; Zielinski, 1978; Nelson and Holmes, 1979:71; Sappington, 1981:16).

New Mexico

The Jemez Mountains of north-central New Mexico are the principal source area for obsidian in the state (Findlow and Bolognese, 1980; Boyer and Robinson, 1956; Lipman et al., 1969). Other isolated sources can also be found in the western half of New Mexico from near the Colorado border south to the Mexican border (Findlow and Bolognese, 1980:228-231). Additional source localities are reported by Iddings (1888:292) and Washington (1917:125) in the Tewan and Valles Mountains.

Oregon

About 100 discrete sources of Obsidian can be found in Oregon, likely making this state the most obsidian-rich geographic area in the world. The many domes and flows that make up the sources are found primarily in the High Cascades, the Newberry Volcano region of central Oregon and along two east-west trending series of volcanic domes in central and eastern Oregon. Obsidian sources in Oregon are described in detail in Appendix Four of this project.

Utah

Utah obsidian sources are found centered in three areas of the state, the Thomas Range, the Black Rock Desert and the Mineral Mountains (Iddings, 1888: 292; Umschler, 1975; Nelson and Holmes, 1979; Sappington, 1981:15).

Washington

A single obsidian source is reported in Washington by Weld (1962) in the Horse Heaven Hills area of the south-central part of the state.

Wyoming

The most widely-known source of obsidian in the United States is probably Yellowstone National Park's Obsidian Cliffs. This and many other lesser-known sources are located in the northwestern corner of the state in Yellowstone National Park and in the Grand Teton region to the immediate south (Iddings, 1888; Griffin et al., 1969a; Gordus et al., 1971; Frison, 1974; Sappington, 1981:15).

MEXICO AND CENTRAL AMERICA

Thanks to the many archaeological studies that have concerned themselves with obsidian source identification and geochemical characterization in Mesoamerica, many obsidian source localities in this region have been documented.

Mexico

Abundant sources of obsidian have been located in central Mexico in the states of Jalisco, Guanajuato, Michoacuan, Queretaro, Hidalgo, Mexico, Puebla, Veracruz and Guerrero. These sources have been described by several authors, principally Heizer et al. (1965), Stross et al. (1976:250-256), Ramirez (1976: 6-33), Pires-Ferreira (1975:11-18), Nelson et al. (1977), Ericson and Kimberlin (1977) and Zeitlin and Heimbuch (1978:148). Extensive geochemical studies have been carried out using obsidian from many of these Mesoamerican sources in conjunction with archaeological research.

Guatemala

The Central Highlands region of Guatemala is a well-known obsidian source area with a number of different localities described in the literature (Heizer et al., 1965; Sidrys et al., 1976; Stross et al., 1976:250-256; Hurtado de Mendoza, 1977: 10-11; Zeitlin and Heimbuch, 1978:148). As with the Mexican obsidian, the geochemical characteristics of many of the Guatemalan sources have been examined.

Other Central American Sources

Though Central American obsidian sources are found predominantly in Guatemala, a few other outcrops have been reported in nearby countries. Washington (1917:93) mentions obsidian from Corinto, Nicaragua, while Sidrys et al. (1976) names three sources in El Salvador. Two Honduran sources are briefly covered by Sidrys et al. (1976) and Zeitlin and Heimbuch (1978:148).

WEST INDIES

A single obsidian source has been mentioned in the West Indies on the island of Guadeloupe (Iddings, 1888:294; Washington, 1917:93).

SOUTH AMERICA

Although obsidian sources have not been well-documented in South America, several sources are known along the western border of the continent. Washington (1917: 127) mentions obsidian from Cali in southwestern Columbia. Iddings (1888:293) and Washington (1917:155,755,965) both mention the presence of obsidian at several locations at Ecuador's Guamani Volcano. Miller and Wagner (1981) used obsidian collected near Quito, Ecuador, for their fission-track dating research and Iddings (1888:293) mentions obsidian found at Antisano Peak, also near Quito. Miller and Wagner (1981) additionally used obsidian from Macusani, southeastern Peru, and S. Lipez, Bolivia. Several sources are also known from the southern highlands of Peru in the Ayacucho area (Burger and Asaro, 1978). In central Chile, obsidian is reported from Cerro Azul Volcano (Casertano, 1963:26).

WORLDWIDE PATTERNS OF OBSIDIAN DISTRIBUTION

The distribution of obsidian sources adjacent to tectonic features such as spreading axes and plate boundaries (see Figure 1) is a relationship that has not escaped the notice of researchers in recent years. Archaeologists looking for sources of obsidian have begun to realize that the application of the plate tectonic model can give them at least a starting place in their search. Dixon (1976:304) writes: "The application of plate-tectonic principles to the [Mediterranean and Near East] region makes it possible to identify the likely areas of outcrop of recent volcanic rocks and to predict in a very general way the chemical character of the lavas." Obsidian is a *metastable* glass, being eventually altered over time to perlite, and because of this property it is restricted to areas of relatively recent, i.e. post-Oligocene, volcanic activity. These are the areas found near the current convergent and divergent plate boundaries. Figure 1 graphically shows that obsidian is generally confined to zones bordering these plate margins.

Volcanic activity at the continental margins (examples are the Cascade and Andes mountain chains) and in island arcs (Indonesia and the New Zealand-Tonga Island Chain, for instance) both occur near convergent plate boundaries and may produce obsidian. Other source areas, such as Iceland, lie directly over active spreading centers. Recent volcanic activity is not completely limited to the plate boundaries, though, and may be found in the continental interiors such as in Hungary and at Yellowstone, both source areas for obsidian. Some of these occurrences may be attributed to the presence of "hot spots" in the mantle. The Yellowstone-Snake River volcanic chain is thought to be an example of plate movement over a stable convective plume (or "hot spot") in the mantle (Suppe et al., 1975:410-411; Williams and McBirney, 1979:303-306).

Clearly, an understanding of the plate tectonic model can help to explain and predict the worldwide distribution patterns of obsidian.

3 Geologic Properties of Obsidian

Obsidian is a naturally-occurring volcanic glass and is probably one of the most widely recognized rocks or minerals (see Plate 2). The name *obsidian* is one of the most ancient of rock names still in use today and was brought into the language by Pliny (the Elder) almost two millenia ago. Iddings (1888:261) writes that the stone was named after "...Opsius, its discoverer, in Ethiopia, according to Pliny, who says that when laid in chamber walls in the form of mirrors it reflects shadows instead of images."

The term obsidian is a *textural* one and the chemical composition of the glass can vary from basaltic to rhyolitic. Since the obsidians of varying compositions are often megascopically indistinguishable, they are all lumped into this one category. If the composition is known, however, the term obsidian should be preceded by the appropriate rock name as defined by silica content, i.e. basaltic, andesitic, dacitic or rhyolitic. Though the composition of obsidians is variable, the vast majority are rhyolitic in composition, the reason for this being related to the high viscosity of high-silica melts (discussed shortly in the explanation of obsidian petrogenesis).

Despite the fact that obsidian is a well-known rock distributed in many places over the surface of the earth, it has been subject to relatively little systematic investigation by geologists. Ericson et al. (1975:129) speculate on this when they write:

> It is a curious fact why little is known scientifically and technologically about obsidian as a naturally occurring volcanic glass. The apparent explanation is that the very nature of obsidian defines an interdisciplinary problem. On one hand, much of geology as a discipline is concerned with natural *crystalline* rocks; whereas, on the other hand, glass technology is mostly concerned with *man-made* commercial glasses.

Some of this paucity of information concerning obsidian has been remedied in the last few years, while other details about the physical properties of obsidian can be gathered from a wide variety of scattered sources. The geologic, petrographic and geochemical properties of obsidian that are the subject of the rest of this chapter have been collected from many geological and archaeological literature sources. Throughout this chapter, the obsidians that are discussed are rhyolitic in composition unless otherwise specified.

OBSIDIAN AS A "WINDOW" TO GEOLOGIC PROCESSES

> There is another source of information regarding the composition of [magmatic] liquids which gives the composition accurately, but is not as widely applicable. It is a study of the composition of glassy rocks. They are the only rocks of which we can say with complete confidence that they correspond in composition with a liquid.
>
> Bowen (1928:125)

As Bowen recognized, the composition of fresh, unaltered volcanic glass can give petrologists a look at the composition and types of early crystalline phases in silicic magmas, information that is often lost during the cooling and weathering of equivalent crystalline bodies (Carmichael, 1979). By comparing obsidian-perlite pairs, for example, it has been possible to confirm the genetic relationship of obsidian and perlite and to establish the mobility of major and trace elements during the hydration of rhyolitic glasses. It is also possible to determine the original volatile components of siliceous magmas for as the gases exsolve prior to eruption they may be trapped as bubbles in the cooled obsidian glass. Eichelberger and Westrich (1981) found that gases trapped in the vesicles of obsidian fragments were dominantly H_2O with minor CO_2 and that differences in volatile contents in successive eruptions from the same source vent indicated the sharp stratification of parent magmas. Evidence of the zonation of magma bodies, such as that provided by the volatile contents of obsidian vesicles, can help to explain the compositional variations that are sometimes found in eruptive products from volcanic centers.

In ways such as these, obsidian acts as a "window" for understanding geologic processes involving closely related rocks or the parent bodies of magma prior to their eruption.

CHEMICAL COMPOSITION OF RHYOLITIC OBSIDIANS

The rhyolitic obsidians are usually classified on the basis of their silica content with obsidians containing greater than about 68 percent silica considered rhyolitic (these obsidians rarely exceed 77 percent silica content). Rhyolitic obsidians are sometimes further divided into three broad rock types, or suites: peralkaline , calc-alkaline and alkaline (or transitional).

Peralkaline obsidians (molecular Na+K exceeds Al) are relatively uncommon and are characteristically developed in areas of non-orogenic magmatism such as in Central Africa. Calc-alkaline obsidians (molecular Al exceeds Na+K; phenocrysts, if present, are plagioclase) are very common worldwide. Alkaline obsidians (molecular Al equals Na+K) are considered transitional between the peralkaline and calc-alkaline rocks. Though Al, K and Na are usually used to delineate among the different obsidian suites, other major and trace elements also show systematic differences among the three rock types. Peralkaline obsidians, for example, contain relatively high abundances of Fe, Mn, Ti, Zr, F and Cl and comparatively low quantities of Ca, Mg and P (MacDonald and Bailey, 1973; Zielinski, 1978)(also see Table IV-4 for a sampling of major and trace element abundances for calc-alkaline obsidians).

One of these three suites will often, though not always, be represented as the predominant rock or obsidian type in a particular geographic or tectonic region. Indonesia and the Cascade Range of the western United States, for instance, are dominated by calc-alkaline obsidians. New Zealand, on the other hand, contains both peralkaline and calc-alkaline obsidians.

Compositional Variation in Individual Obsidian Sources

While the chemical composition of rhyolitic obsidian is relatively variable, the major element and particularly the trace element composition of most individual flows and domes is remarkably homogeneous. Compositional variation in

Plate 2: Obsidian from Cougar Mountain, Oregon, showing the typical conchoidal fracture.

discrete obsidian units is not uncommonly on the order of only a few percent, making it possible to distinguish individual domes or flows on the basis of their major or trace element compositions (see Part Four, Chapter Seven of this project). Numerous archaeological investigations involving the geochemical characterization of obsidian artifacts and their geologic sources have confirmed the general homogeneity of single obsidian sources. The results of these studies are summarized by Zeitlin and Heimbuch (1978:123), who write: "...in almost every case where multiple sources from an obsidian deposit have been analyzed, intra-source homogeneity has...been found adequate, relative to differences in composition between sources, for correlating artifacts with place of origin" (for individual studies, again see Part Four, Chapter Seven of this project).

It cannot be assumed, however, that all obsidian flows are compositionally homogeneous and, to ensure reliability, the compositional variability of each individual source must be empirically determined. Bowman et al. (1973a and 1973b) and Eichelberger (1981) have found marked compositional variations in two obsidian flows in Northern California. The variations, in both cases, were attributed to the mixing of two compositionally divergent magmas during the eruption of the obsidian flows. Small-scale compositional heterogeneity of obsidian has also been reported. Laidley and McKay (1971) noted a slight variation on the scale of a few centimetres at the Big Obsidian Flow in Oregon's Newberry Caldera. They ascribed this small-scale variation to the segregation of phases during the emplacement of the obsidian.

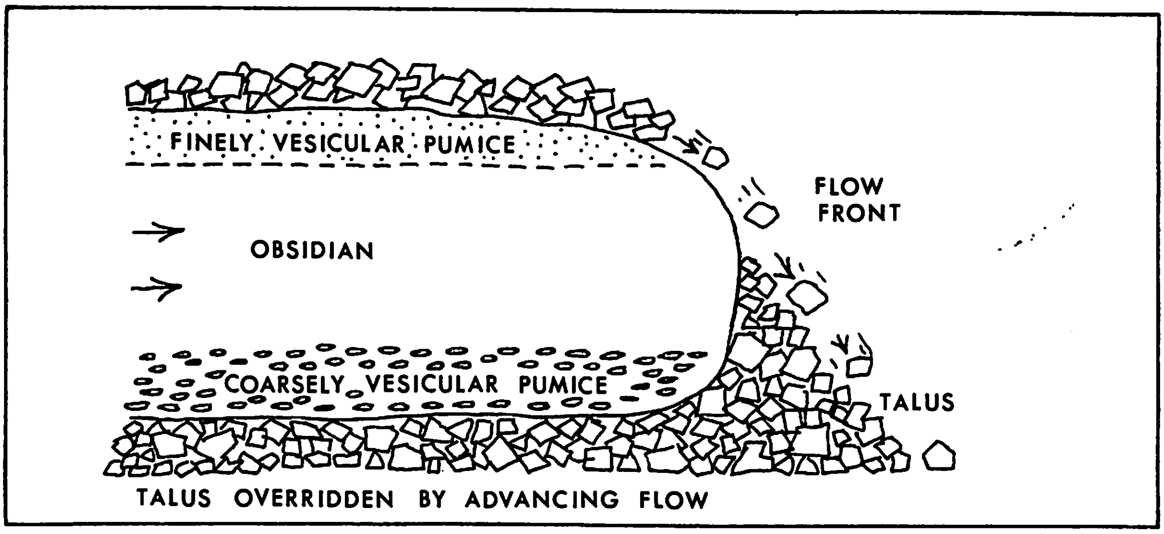


Figure 5 : Diagram of the movement and structure of an advancing obsidian Flow. Adapted from Fink (1979:3).

THE GEOLOGIC CONTEXTS OF OBSIDIAN

Rhyolitic obsidians occur in a variety of geologic contexts. These can be largely unmodified, as in the case of many obsidian flows and obsidian-rhyolite domes. Conversely, they can be highly modified by chemical and physical weathering as is the case of obsidian found associated with perlite deposits or with obsidian removed from its original context by a number of natural processes.

Obsidian Flows

The eruption of a hypothetical flow of rhyolitic obsidian is graphically described by Fink (1979:47-48):

> Consider a rising body of rhyolitic magma. As the magma nears the surface, the decreasing pressure allows dissolved volatiles to come out of solution as bubbles. Expansion of these bubbles can induce an explosion [eruption of tephra] , which is soon followed by the emplacement of lava with less volatiles. This material vesiculates as it reaches the surface, forming a pumice flow. This flow is followed by magma containing still less volatiles, which is extruded as a glassy obsidian...During this movement the obsidian continues to exsolve a small amount of bubbles at its upper surface which produces a finely vesicular cap over the whole flow. Still later, less fluid, partly crystallized lava erupts and piles over the vent. In these ways, the basic distribution of textures seen in flow fronts and on the upper surfaces can be generated.

As the viscous lava moves away from the vent and cools (Figure 5), the surface develops a number of characteristic structures such as compressional folds and extensional fractures and cracks (Fink, 1979:54-65; 1981). The vent of an obsidian flow is usually recognizable as the highest point in the flow or the point that is the focus of obsidian folds or waves that are created transverse to the flow direction as the viscous glass piles up against itself (see Plates

16, 17 and 18, Part Four of this project). Erosionally modified obsidian flows may be recognized by the steepness of the flow front, the remnants of surface folding (usually reflected as a hummocky surface) and a domal protrusion over the source vent.

The textures of an obsidian flow will typically vary from an aphyric glass to finely vesicular pumice (Figure 5). This variety of textures is easily attributable to the progressive degassing of the viscous magma as it rises to the surface (as explained in the excerpt from Fink). The mixing of glassy and crystalline phases of rhyolitic magma can also result in an obsidian-rhyolite breccia in some flows (Plate 5). Varieties of other petrographic structures also found in obsidian flows (and domes) are discussed later in this chapter.

Obsidian Domes and Obsidian-Rhyolite Domes

Sometimes, highly siliceous and viscous magmas, rather than moving as a flow away from the vent area, will simply pile up over or next to the vent, creating a steep-sided volcanic dome (Figure 6). The viscosity of the magma is reflected by the steep slopes of the flanks of the dome (Williams and McBirney, 1979:190).

Rhyolitic volcanic domes will sometimes be composed almost entirely of obsidian, but more commonly the obsidian is found in association with crystalline rhyolite. The obsidian may occur in lenses (Plate 4) or in vein-like zones in the dome. Often, glassy zones appearing as intermediate in texture between the crystalline rhyolite and the glassy obsidian can be found in obsidian-rhyolite domes. The somewhat puzzling genesis of these coexisting rocks is discussed later in this chapter.

As the surface of the dome is exposed to weathering, nodules of resistant obsidian glass are left on the surface as float (Plate 3).

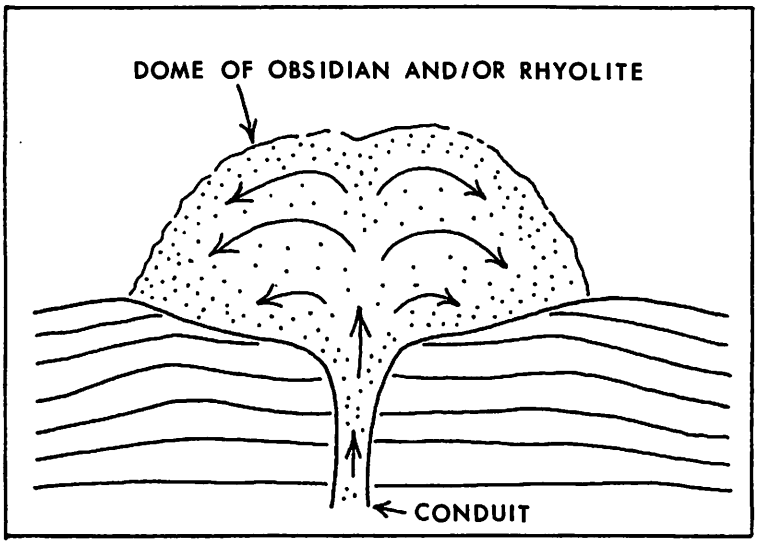


Figure 6: Emplacement and structure of an exogenous dome of viscous rhyolitic lava (after Williams and McBirney, 1979: 190).

Plate 3: A nodule of obsidian found on the surface of a rhyolite and obsidian dome (Cougar Mountain, Oregon). Weathering removes the less-resistant matrix around the obsidian lenses found in the dome, leaving it as surface float.

Plate 4: A lens of obsidian in a rhyolitic matrix near Cougar Mountain Cave No.3. The obsidian nodule pictured in Plate 3 may have originated in a lens similar to this one. This lens is about 45 cm in length.

Obsidian Selvage and Tachylyte

The formation of obsidian glass is usually dependent on the viscosity of the lavas and is generally restricted to magmas of a rhyolitic (hence, viscous) composition. The rapid chilling of the surface of a body of lava, however, will also prevent crystallization and a thin zone, or selvage, of obsidian is sometimes found on domes or flows with compositions varying from basaltic to rhyolitic. While the surface of these flows will be glassy, the texture will rapidly change to a crystalline one in the slower cooling interior of the unit.

The best-known natural glass that is not of a rhyolitic composition is basaltic obsidian or tachylyte. This dark-colored glass, occasionally known as sideromelane, is typically less than 5 millimetres in thickness and is formed by the rapid chilling of the surface of flows of basalt.

Tachlyte differs from rhyolitic obsidian in several respects:

1. The silica content of tachylyte ranges from about 40 to 55 percent as compared to 68 to 77 percent for rhyolitic obsidian.
2. Tachylyte is opaque, even in thin flakes, while rhyolitic obsidian is almost always transparent (Dietrich and Skinner, 1979:156).
3. Tachylyte displays a greasy luster, rhyolitic obsidian a vitreous luster (Dietrich and Skinner, 1979:156).
4. Crystalline inclusions are common in tachylyte; in rhyolitic obsidian the texture is usually macroscopically free of phenocrysts (Dietrich and Skinner, 1979:156).
5. The density of tachylyte is slightly greater than that of rhyolitic obsidian (Tilley, 1922; George, 1924).
6. The index of refraction of tachylyte is greater than that of rhyolitic glass (George, 1924; Ross and Smith, 1955).

Natural basaltic glass has been reported from many locations throughout the world with some of the best examples occurring in the Hawaiian Islands (Washington, 1917; George, 1924; Barrera and Kirch, 1973; Smith et al., 1977).

Tachylyte devitrifies to form palagonite and several attempts have been made to date basaltic glass artifacts from archaeological sites in the Hawaiian Islands through the determination of their devitrification (hydration) rate (Barrera and Kirch, 1973; Morganstein and Riley, 1975; Morganstein and Rosendahl, 1976; Tuggle et al., 1978). Initial results of age determinations of the basaltic glass artifacts suggest that the rate of hydration is a linear one and that the devitrification rate exceeds that of rhyolitic glass.

It should also be mentioned that the similar spellings of tachylyte (basaltic) obsidian and trachytic (microscopically flow-oriented) obsidian may have led to some confusion in the use of these terms in archaeological literature.

Obsidian Associated With Perlite Deposits

> In almost every collection of minerals there may be found specimens of the curious little glassy balls, which, from the locality of their occurrence - the great Marekanka, near Okhotsk in Siberia - have received the name of *Marekanite*. The glassy balls are more or less perfectly rounded in form, they vary in their colour, through

Plate 5: Obsidian breccia from Obsidian Cliffs, Oregon High Cascades. The fragments of obsidian are found in a rhyolite groundmass.

Plate 6: An "apache tear". These obsidian balls are found in association with perlite, the devitrified form of obsidian.

> different shades of smoke-grey to orange-brown, while in size they range from the dimensions of a pea to those of a walnut.
>
> J.W. Judd (1886:241)

The nearly spherical glass balls described above by Judd are found associated with perlite, the devitrified form of obsidian (see Plate 6). The glassy spheres, now popularly known as "Apache tears", were first recognized as obsidby Klaproth in 1812, though the first published systematic study of marekanite by Judd did not appear until 1886.

The coexistence of perlite and marekanite was long a subject of speculation but it wasn't until 1955 that Ross and Smith showed that there was a definite genetic relationship between the two. Obsidian hydrates over time to form perlite and when the devitrification of the glass is not yet complete, spheres of obsidian are found enclosed by the glassy perlite.

The marekanite balls are known to occasionally explode spontaneously and microscopic examination under crossed nichols has shown the obsidian to be in a state of intense strain (Judd, 1886; Ross and Smith, 1955; Marshall, 1961). When the marekanite cores are annealed and examined under crossed nichols, the birefringent bands characteristic of stress in the glass are found to have disappeared (Judd, 1886).

Secondary Deposits of Obsidian

Obsidian, in addition to occurring in flows,domes and deposits of perlite, is often found in a variety of secondary, post-emplacement contexts such as in river gravels, in glacial till, in welded ash-flow deposits (tuffs) and in laharic deposits. The natural and cultural processes responsible for the transport of obsidian from its primary sources to secondary contexts are discussed in detail in the next chapter, Geomorphic Properties of Obsidian.

PETROGENESIS OF OBSIDIAN

For many years, the formation of obsidian glass was generally ascribed to the rapid chilling or cooling of siliceous lavas. While this explanation may be adequate to account for the presence of obsidian selvage at the margins of lava bodies, it is clearly inadequate when applied to volcanic domes of obsidian and rhyolite or even to flows of obsidian of more than a few metres thickness. Bakken (1977:88) considers this when she writes:

> The obsidian in the [Yellowstone National Park] plateau rhyolite flows forms only an outer crust of the flow, perhaps quickly cooled, whereas obsidian cliff appears to be all obsidian. Why didn't the center of the obsidian cliff flow crystallize?

This is the crux of the problem of obsidian petrogenesis - why do some flows of lava cool and crystallize while others remain glassy? Even more enigmatic is the presence in volcanic domes of obsidian intercalated with crystalline rhyolite, an example of which is pictured in Plate 4.

The problem of obsidian formation has been typically side-stepped by most authors describing the geologic (or archaeological) properties of natural glass. Only recently has an attempt been made to consider the relationship of the composition and viscosity of the lavas and the formation of obsidian (Ericson et al., 1976b; Jack, 1976; Bakken, 1977; Carmichael, 1979).

Glasses such as obsidian are created when some physical characteristic of the magma or lava restricts the mobility of its constituent ions in the liquid to the extent that they are prevented from combining in a crystalline pattern. The lava becomes, in effect, a supercooled liquid, being unable to change from the liquid to the crystalline phase.

The physical property responsible for this is the viscosity of the lava. If the viscosity of a melt is sufficiently high to keep the ions randomly arranged on cooling, the result is the volcanic glass called obsidian.

The viscosity of the glass is affected primarily by two variables, temperature and composition (Bakken, 1977; Williams and McBirney, 1979; Carmichael, 1979). It is possible to envision at least two scenarios involving these variables in which a magma could be "trapped" in a glassy, relatively holohyaline state.

The first of these involves the rapid chilling or quenching of the margins of a lava flow, intrusive body or rhyolite/dacite dome during emplacement. This would quickly increase the viscosity of the surface of the cooling lava, serving to create a glassy selvage or envelope. Because the rapid change in temperature is the primary process operating in this case, the composition of the obsidian glass formed could be expected to vary from basaltic to rhyolitic. The typical thickness of the glassy layer has not been documented, though it is likely that it is relatively thin. Carmichael (1979) demonstrates that liquids with a low enough viscosity may be unquenchable to a glass and he concludes that the glass associated with lower viscosity lavas such as basalts will be thinner than the glass of very silicic lavas. Smith et al. (1977) corroborate this point when they note that the glassy selvage on flows of basalt seldom exceeds 5 millimetres.

The second obsidian-producing petrologic scenario considers the composition of the melt as the primary variable influencing its viscosity. The viscosities of silicate liquids are highly dependent on the amount of silica in the liquid as well as on the concentration of water. Higher proportions of silica increase the viscosity of a melt while the addition of water to a silica-rich liquid lowers its viscosity (Williams and McBirney, 1979:21-23; Carmichael, 1979). The effects of other elements and volatile gases on the viscosity of silicate liquids are not well-known, though they could also play a role in the formation of volcanic glasses. The role of composition in the formation of obsidian has also been confirmed in an experimental study by Yagi (1966), who found no crystals in a re-cooled obsidian melt. The addition of either water or a weak alkaline solution to the melt promoted the crystallization of quartz and alkali feldspars.

Obsidian contains very little water, commonly 0.3 to 0.5 percent, while crystalline rhyolites may contain up to 2 percent water. Bakken attributes the dryness of the obsidian magmas to the drying out of country rock surrounding the magma conduit and to the exsolution of volatile gases during continued eruptive activity.

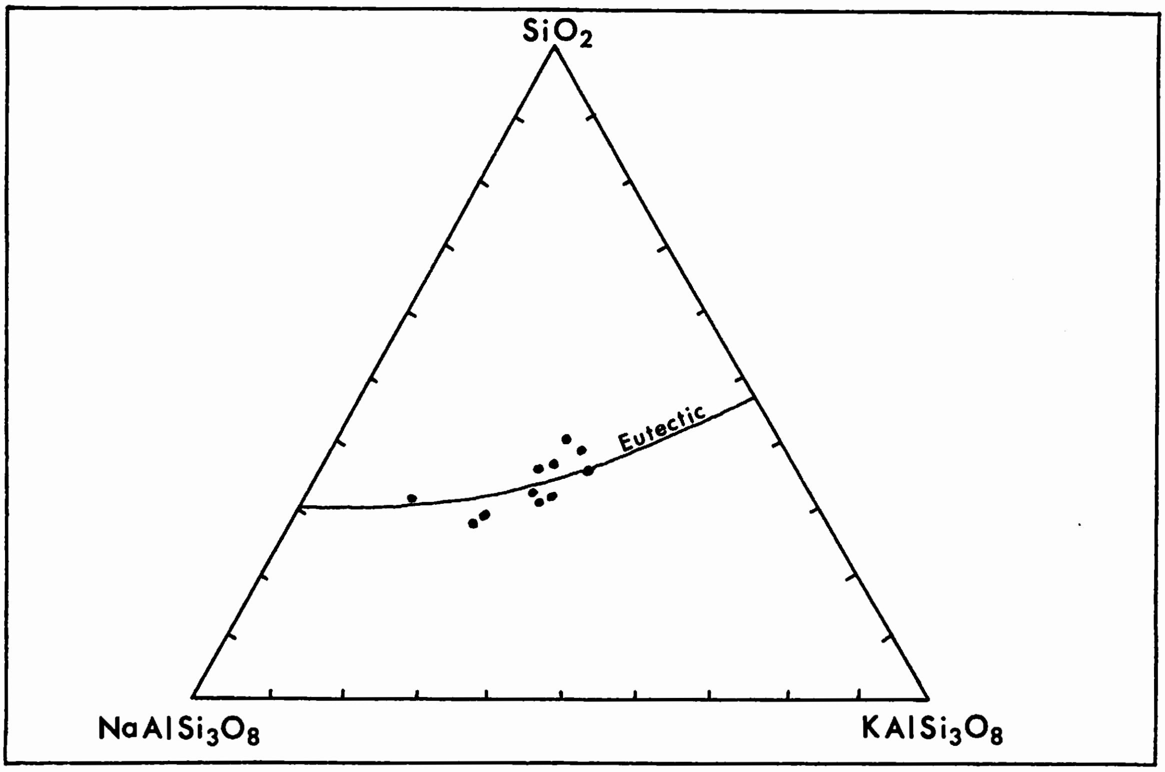


Figure 7 : Ternary system for SiO_2 (quartz), $NaAlSi_3O_8$ (albite) and $KAlSi_3O_8$ (orthoclase), the most abundant minerals that would form if obsidian lavas crystallized. The compositions of typical obsidians are plotted and all fall near the eutectic melting curve of this system. Adapted from Bakken (1977).

Most obsidians range in silica content from 68 to 77 percent and probably originate from highly differentiated bodies of magma. Obsidian flows often occur as among the last manifestations of volcanic activity at an eruptive center, commonly being preceded by the explosive eruption of gas-rich siliceous lavas in the form of ash-flows and airborne tephra. The large-scale eruption of ash-flows and tephra may empty the underlying magma chamber to the extent that it will partially collapse to form a caldera. Flows and domes of obsidian are often found associated with these calderas.

A magma must surface at a temperature near its normal crystallization temperature or eutectic melting point in order to form a glass. The formation of obsidian would then be most likely in a magma whose composition is near the eutectic melting curve (Bakken, 1977). This is illustrated in Figure 7 where the compositions of typical obsidians are plotted in a quartz-albite-orthoclase system and are found to lie near the eutectic. The composition of the glass formed by the rapid cooling of a lava (where temperature change, not composition, is the major variable operating) would not necessarily be expected to fall near the eutectic. That the obsidian-forming lavas are erupted near the liquidous temperature of the magma is further demonstrated by the presence of microlites, crystallites and occasional microphenocrysts in obsidian glass. Iron-titanium oxides such as ilmenite and magnetite often make up part of the limited crystalline assemblage of obsidian - because the total volume of these components is very small and because their composition is temperature-dependent, it can be assumed that their calculated equilibrium temperatures will be close to the liquidous temperature of the obsidian. Following this line of reasoning, it is possible to estimate the temperature of a rhyolitic obsidian on extrusion at about 900°C (Carmichael, 1979).

The final eruptive events leading to the formation of an obsidian body are summarized by Bakken (1977:92):

> As the magma rises to within three to ten kilometers of the surface, the decrease in overload pressure allows it to become more fluid thus easing its upward movement. From this depth to the surface, the effect of temperature should override that of pressure and cooling will increase viscosity. As the magma continues to rise, dissolved gases previously trapped within it escape. As these gases vaporize, the lava experiences a sharp increase in viscosity and freezing temperature. The lava has not cooled but instead the freezing point has risen. The gas loss traps the lava just below the freezing point [if the composition of the magma is close to the eutectic]. It can't crystallize.

The surface of obsidian flows often exhibit a pumiceous structure, evidence of the final loss of volatile gases.

Layers or lenses of glassy obsidian and crystalline rhyolite are often found intercalated or mixed, particularly in volcanic domes. It seems probable, in this case, that hydrothermal activity during the emplacement of the dome may enrich portions of the magma with water, differentially lowering the viscosity of the melt. The water-enriched zones or layers would crystallize on cooling, while the adjacent zone of water-poor magma would cool to a glass. An alternative hypothesis could involve the mixing of two compositionally-distinct phases of magma, one cooling to a glass, the other to a crystalline rhyolite.

The presence of obsidian, as explained by these petrologic models, may reflect the cooling history and/or the chemical composition of the magmas. Whatever the factors involved, the petrogenesis of obsidian is clearly much more complex that the simple model of "chilled lavas" that has often been used to explain the presence of natural glass.

HISTORICAL ERUPTIONS OF OBSIDIAN

> In the evening, a great fire was seen on the mountain, with black smoke repeatedly drifting to the east. Fire balls shot up into the night air and broke to pieces on falling to the ground, and flashes of lightning crossed in all directions through the clouds of black smoke. Owing to the fire, the villages to the west of the mountain were light as day in the night. Concussions accompanied with noises of rattling doors were felt almost continuously.
>
> Account of the beginning of the 1707 eruption of Mount Fuji in Japan, the site of one of the few historical accounts of the eruption of obsidian (from Tsuya, 1955:346-347).

Volcanologists have been able to learn a great deal about the behavior of prehistoric volcanic events through the observation of volcanoes currently active in many parts of the world. Very little, though, is known of activity in which the eruption of obsidian plays a part - only a handful of eruptions involving obsidian are known to have taken place in historic times and none of these events seem to have been directly observed.

Blocks of andesitic obsidian up to 1 m across were ejected at the very beginning of the 1707 eruption of Japan's Mount Fuji (Tsuya, 1955; Kuno, 1962: 80-89).

An obsidian flow (the Piette Cotte flow) was apparently extruded in 1771 from a vent on the Island of Vulcano, a volcanic cone located in the Eolian Island Group just north of Sicily (Imbo, 1965:37-38). On the nearby Island of Lipari, the Rocche Rosse and Forgia Vecchia obsidian flows were also apparently erupted in near-historic times. Fission-track and radiocarbon dating methods place the age of the two flows at about 1500 years B.P. (Bigazzi and Bonadonna, 1973; Von Jörg Keller, 1970). A local Christian legend also tells of a Liparian cenobite who chased the devil with his subterranean fire out of the craters of Lipari about 1500 years ago, corroborating the date of the obsidian eruptions (Von Jörg Keller, 1970).

On December 5, 1904, a small volcanic island cone composed of pumice and obsidian fragments, Sin-Iwo-Zima, appeared about 1000 km (600 mi) east of Japan in the Volcano Island Group (Kuno, 1962:265-267). Activity ceased in 1905, and the 1.6 km (1 mi) diameter cone disappeared into the sea after only a few years. Renewed activity at the vent in 1914 constructed another island of pumice and obsidian, this one about 1 km (.6 mi) across. The island had completely disappeared by 1916.

The most recent eruption of obsidian occurred in the D'Entrecasteaus Island Group located a few kilometres east of the southern tip of New Guinea. In 1953, a small island of pumice, ash and obsidian was formed near the Island of Lou (Ambrose, 1976b). Many other obsidian sources are known in this island group and some of them may be no more than a few hundred years old (Smith, 1974).

As I have mentioned previously, siliceous volcanic activity, because of the high viscosity of the magma, is often explosive, particularly in the early eruptive stages when the magmas tend to be richer in gas (Williams and McBirney, 1979:133). The few accounts of historical eruptions involving obsidian suggests that eruptive activity in which obsidian is a product is often, if not typically, explosive. Fragments of obsidian are commonly found in airfall tephra and ash-flow deposits, events often preceding the eruption of obsidian flows. The volume of obsidian found in coherent flows may be relatively small when compared to the amounts of fragmental obsidian that has been extruded during these explosive events.

OBSIDIAN-LIKE ROCKS AND ROCKS RELATED TO OBSIDIAN

There are, in addition to the true obsidians, several rocks that texturally or compositionally resemble obsidian. Some of these rocks, for example tektites, because of their outward similarity to obsidian, may be confused with true obsidian. Others, such as pumice, may be quite different in appearance while being compositionally similar or even genetically related to the same bodies of magma as associated obsidian flows.

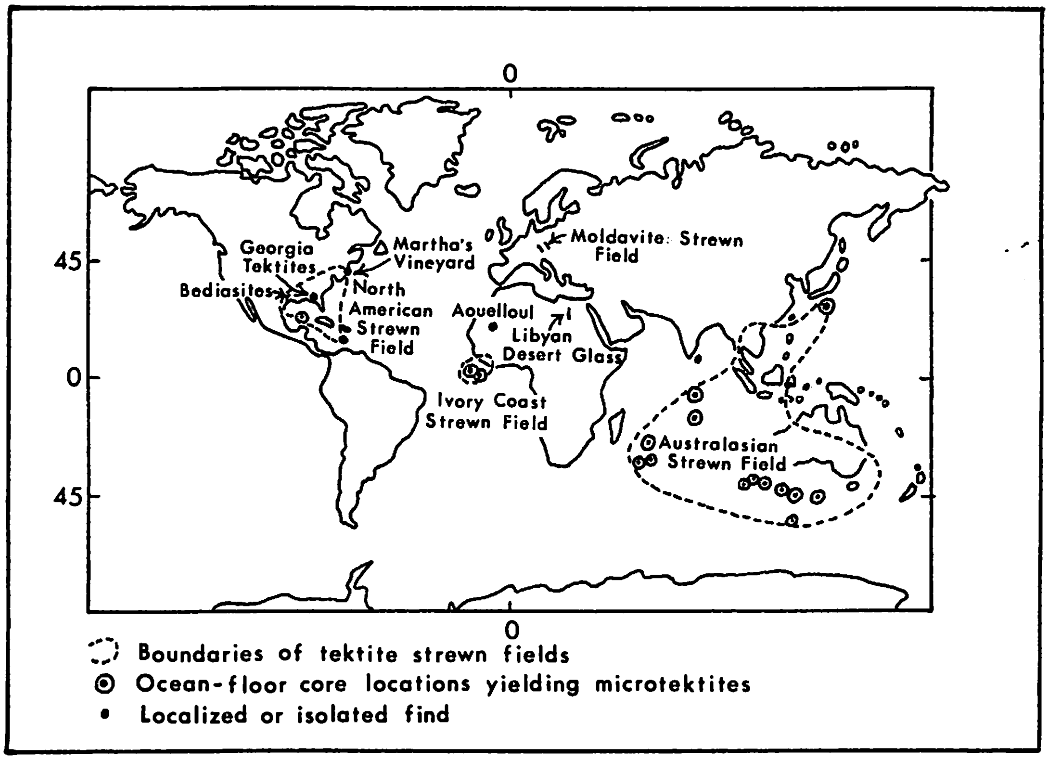


Figure 8 : Worldwide tektite distribution (adapted from O'Keefe. 1976:18).

The following descriptions of the obsidian-like rocks will serve to point out the similarities and differences of these rocks from the true obsidians as well as to point out ways in which they can be distinguished from obsidian.

Tektites

Among the most interesting of the obsidian-like rocks are tektites. Very similar in outward appearance to obsidians, tektites are found concentrated in a number of strewn fields across the earth (Figure 8). Tektites are glassy, usually black and range in size from microscopic to a few centimetres in length. The origin of tektites has puzzled scientists for many years, for tektites do not resemble, in their structure or composition, the rocks that they occur with. This has led researchers to hypothesize an extraterrrestrial origin, possibly from lunar volcanoes, for the glass, though arguments can also be made for an unusual terrestrial event as the source.

Tektites closely resemble obsidian and have often been mistaken for obsidian. There are, however, a number of distinguishing characteristics between the two:

1. Tektites tend to have greater abundances of FeO+MgO and less Na_2O+K_2O than obsidians of the same silica content (O'Keefe, 1976:7).
2. The water content of tektites is very low and most tektites contain less than 0.05 percent water (as compared to between 0.25 and 1 percent for obsidian) (Friedman, 1958).
3. Hydration rims are not found on tektites, probably because of their extremely low water content (Meighan et al., 1974:207; Lee et al., 1974; Kimberlin, 1976; Meighan and Vanderhoeven, 1978:121).

4. When heated with a blowpipe flame, tektites will melt with difficulty to a clear glass while obsidian will produce a frothy, gas-rich melt. This, again, is due to the higher water content in obsidians (LaPaz, 1948).
5. When heated, the gases given off by obsidians and tektites are very different (O'Keefe, 1976:133).
6. Tektites have been found to have gently sloping H_2O diffusion profiles rather than the steep diffusion fronts found in hydrated obsidians (Lee et al., 1974).
7. Obsidian, when seen under the microscope, usually has abundant microlites present in the glass while tektites have essentially none (O'Keefe, 1976:1).
8. The thermoluminescence profiles of tektites have been shown to lack the sharp maximum observed for obsidians (Kashkarova and Kashkarov, 1969).

For a thorough discussion of tektites (favoring a lunar origin), the reader is referred to O'Keefe (1976).

Perlite

Perlite is a brittle volcanic glass exhibiting distinctive concentric or onion-like fractures and a pearly to glassy luster. The color of perlite glass is variable and may be nearly colorless, gray, pale brown, reddish, greenish or bluish. The chemical composition of the glass is identical to that of obsidian except that the water content of perlite is greater, averaging from about 2 to 5 percent (as compared to less than 1 percent for obsidian). When rapidly heated to its softening temperature, perlite suddenly expands to a frothy, pumice-like rock also, somewhat confusingly, known as perlite. This expanded perlite is used commercially as a filler or extender (Johannsen, 1931:284-286; Ladoo and Myers, 1951:375-379; Dietrich and Skinner, 1979:159).

Deposits of perlite commonly contain small cores of obsidian known as marekanite. This association of obsidian and perlite led most early investigators to assume that obsidian-perlite occurrences represented masses of obsidian that had been partially altered, through some secondary, post-emplacement process, to perlite. Ross and Smith (1955), studying perlite-obsidian pairs, concluded that obsidian contained only pristine water derived from its parent magma while the additional water found in perlite was the result of some post-magmatic process. The presence of meteoric water in perlite was later confirmed by Friedman and Smith (1958), who considered perlite to be the result of the low-temperature secondary hydration of obsidian glass. The water in the obsidian was shown, in their study, to be primarily original magmatic water. Friedman and Smith also postulated that the shell-like fractures typical of perlite were formed by the stress created in the glass during the process of hydration. Laboratory studies by Friedman et al. (1966) of the rate of devitrification or hydration demonstrated that temperature was a critical factor governing the rate of alteration of obsidian to perlite. The low-temperature alteration of the glass proceeded at a far slower rate than for obsidian existing at an elevated temperature. Though the idea of the low-temperature origin of perlite is favored by most investigators, a high-temperature origin has been suggested by Chesterman (1954) and apparently confirmed by Slobodskoy (1977). Slobodskoy writes of the association of perlite and obsidian in an outcrop in Armenia: "It is extremely important to stress that both the perlite and the obsidian displayed plastic properties and behaved as very viscous fluids during the same interval. This suggests that they were formed at almost the same time..."

In conclusion, it appears that perlite may be formed over long periods of time as bodies of obsidian hydrate at low temperatures. Obsidians older than the early Cenezoic are uncommon, most earlier bodies having presumably been altered to perlite. The coeval high-temperature origin of perlite and obsidian is also suggested in some instances, though the process involved is not yet understood.

Pitchstone

Another volcanic glass closely resembling obsidian is pitchstone. This glass displays a greasy or dull pitch-like luster along with a conchoidal fracture. Pitchstone occurs in a variety of different colors including gray, dark brown, black, olive green and red. The chemical composition of pitchstone, like perlite, closely resembles obsidian, the major variation lying in the water content of pitchstone, which falls between 5 and 10 percent (Johannsen, 1931: 280; Ladoo and Myers, 1951:375; Dietrich and Skinner, 1979:159).

Much of the water found in pitchstone has been found to be meteoric, suggesting that it was incorporated into the glass after emplacement (Carmichael, 1979). The process of the hydration of water by pitchstone, however, is not adequately understood, though it apparently takes place under different physical conditions than does the hydration of obsidian to form perlite. A few pitchstone-perlite pairs have been found and it could be that pitchstone is somehow formed by an extension of the same hydration process that forms perlite. Alternatively,it is possible that the hydration process resulting in pitchstone occurs at higher water temperatures or that several processes operate simultaneously (Stewart, 1979). Friedman et al. (1966) also suggest that pitchstone may be formed by the hydration of glass under elevated water pressure.

Obsidian-Like Vitrophyre from Welded Ash-Flow Deposits

Many volcanic ash-flow deposits are the sources of a rock closely resembling rhyolitic obsidian, though differing in several respects from true obsidian glass. These ash-flow deposits, the result of the eruption of hot, gas-rich clouds of pyroclastic materials, are capable of travelling long distances and of covering large areas. The high heat of the ash-flow, the pressure of overlying debris or the presence of water introduced into the hot pyroclastic flow can promote the formation of an intensely-welded zone (Figure 9)(Ross and Smith, 1960; Smith, 1960; Gibson and Tazieff, 1967; McBirney, 1968a). These densely-welded zones will not uncommonly resemble porphyritic obsidian and have been referred to as fiamme, obsidian spindles, obsidian-like welded tuffs and obsidian-like vitrophyre (Ross and Smith, 1960:24; Sappington, 1980a). The latter term will be used throughout this project to describe the obsidian-like component of welded ash-flows.

Though obsidian-like vitrophyre appears megascopically similar to rhyolitic obsidian, there are several differences which serve to distinguish it from obsidian. A polished or smooth wet surface of obsidian-like vitrophyre will generally show the very fine-grained, but recognizable structure of the collapsed pyroclastic material that makes up the rock. When viewed in thin-section, the structure of the glass shards in the welded ash provides a distinctive signature of the pyroclastic origin of the rock (Plate 7). The chemical composition

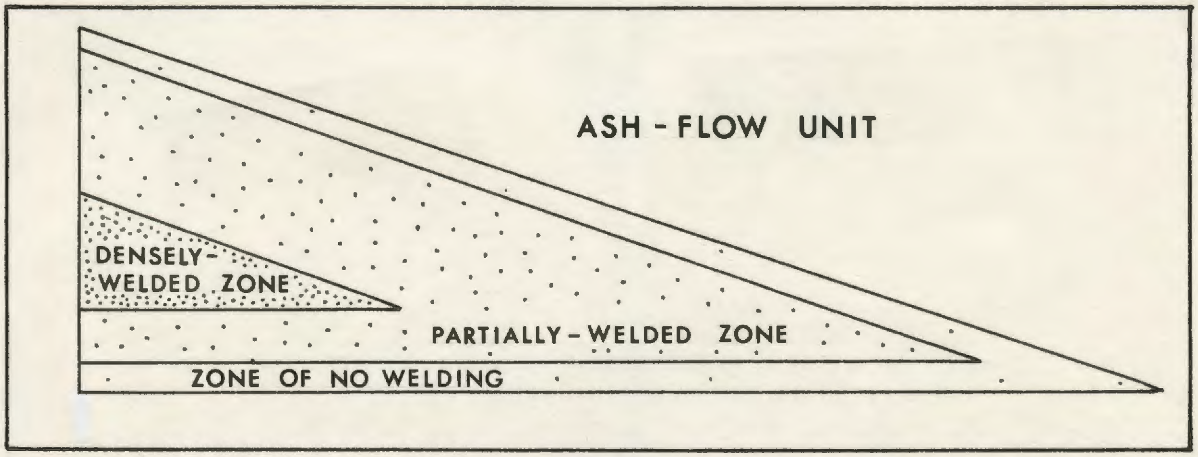


Figure 9 : Schematic illustrating different zones of welding within a single ash-flow cooling unit. The combination of high temperatures and the weight of the overlying ash-flow (sometimes exceeding 100 m in thickness) may create a densely-welded glassy zone that resembles obsidian. The rate of thinning of the ash-flow is greatly exaggerated. Adapted from Smith (1960).

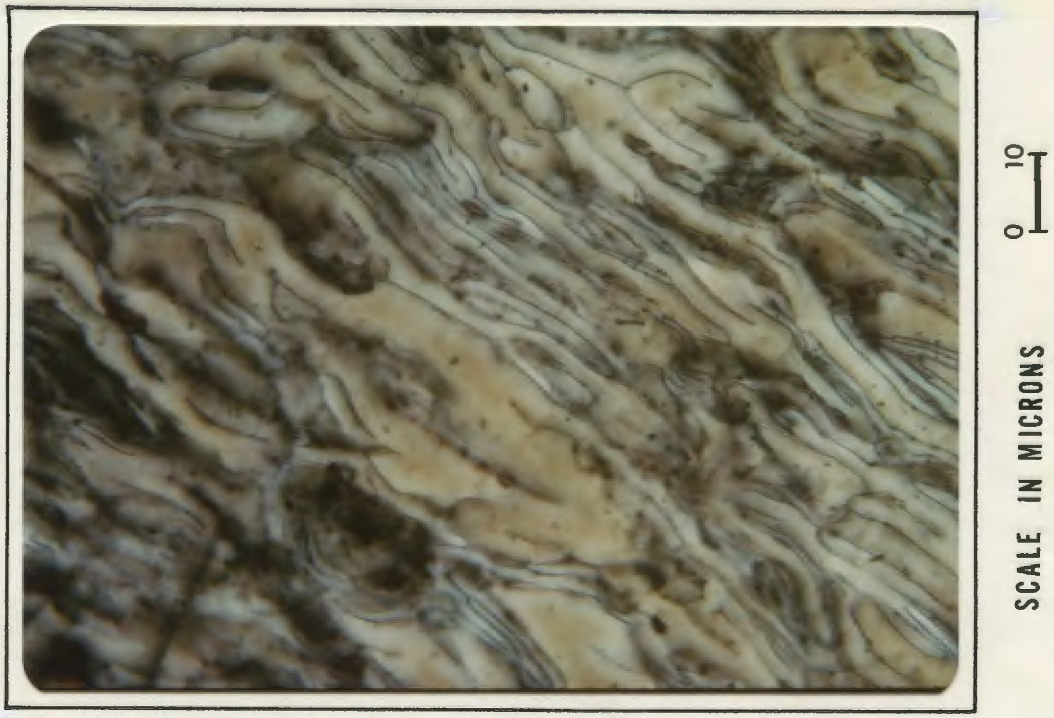


Plate 7: Photomicrograph of an obsidian-like specimen from the densely-welded zone of a rhyolitic ash-flow in western Oregon. The dark lines outline the collapsed bubbles of glass, or shards, that were welded together by the heat of the ash-flow. Nicols not crossed, x94.

of a welded ash-flow, too, is much less homogeneous than that of most obsidian sources. The presence of a large fraction (from 1 to 50 percent) of crystalline and accidental materials in ash-flows, both of which are subject to vertical and horizontal sorting, may lead to a wide compositional range in whole rock samples from a single ash-flow unit (Noble et al., 1969; Williams and McBirney, 1979:161-163; Cox et al., 1979:194-196).

The petrogenesis and characteristics of obsidian-like vitrophyre are discussed in additional detail in Part Four, Chapter Two of this project.

Obsidian-Like Products of Combustion and Contact Metamorphism

Obsidian-like rocks are not limited to rocks of a volcanic origin. In several areas, sedimentary rocks such as slate and argillite have been altered by natural processes to create rocks with a likeness to obsidian. The processes responsible for this transformation have been termed combustion metamorphism and contact metamorphism.

Bentor and Kastner (1976), in a study of a site of obsidian-like fused shale at Grimes Canyon in California, describe the process of combustion metamorphism:

> Under suitable conditions, the uppermost few hundred meters of these rocks undergo spontaneous combustion. The very high temperatures developed during this process frequently led to partial melting of the mother rocks and the formation of pseudomagmas; the latter behave in a way very similar to the behavior of ordinary magmas and form small-scale intrusions such as dikes, sills and laccoliths.

Sites of combustion metamorphic rocks have been identified in Israel, Jordan, Iran, India, Australia, Canada and at several locations in California (Bentor and Kastner, 1976). Rocks from at least one of these sources (Grimes Canyon) were quarried in prehistoric times for use in artifact construction (Ericson et al., 1976a). Frison (1974) also reports a non-volcanic glassy rock, probably the result of combustion metamorphism, in beds of coal that occur in Montana and that were utilized by the aboriginal inhabitants of the region.

Contact metamorphic rocks differ from combustion metamorphic rocks in that the source of heat responsible for their alteration originates from an external source such as an intrusive volcanic body rather than from burning internal organic matter such as coal. Keyes (1958) describes an altered argillite that is found in several locations in New Zealand and that is locally known as "blackstone". This metamorphosed sedimentary rock was widely used by prehistoric people in the construction of tools.

"High-Voltage" Obsidian

Cornwall (1978) reports the formation of an obsidian-like rock by a 38,000 volt powerline downed during a storm. Electric current from the line melted a nearby rock which recooled to form an obsidian-like glass "...which looked just like obsidian of volcanic origin."

Pumice

Pumice is the name given to glassy siliceous lavas that exhibit a frothlike, highly vesicular or filamentous texture. Due to the vesicular texture, two of the more distinguishing characteristics of pumice are its light weight and its ability to float on water, sometimes for long distances.

Pumice and obsidian are often found in direct association with each other and in many instances constitute different textural phases of a single source of magma (the explosive eruption of siliceous magmas and progressive degassing of the magma has already been discussed in this chapter). The chemical composition of the pumice and following obsidian flow from a single vent is commonly identical (Williams and McBirney, 1979:133; MacLeod et al., 1982). Flows of obsidian will also be found, as explained previously, capped by a layer of pumice created by the degassing of silica-rich lavas as the flow cools.

The highly viscous qualities of rhyolitic lavas may also prevent the escape of volatile gases that are exsolving under the lowered pressure of an obsidian flow. This can lead to the formation of zones or layers of pumice within a flow of glassy obsidian (see Figure 5)(Fink, 1979:22-34).

The relationship of obsidian and pumice was first recognized by Judd (1886:16; Anonymous, 1887), who wrote:

> I must now proceed to describe another set of remarkable phenomena - those namely which are exhibited by the Marekanite [obsidian] - nodules when they are heated.
>
> If one of these balls be subjected to a gas-jet...it will be seen that, as redness is approached, thin films of glass detach themselves...If the temperature be now raised to whiteness, the whole mass swells up in cauliflower-like excrescences, till it has attained eight or ten times its original bulk. The resulting white mass is found to be a true pumice, which floats upon water, and microscopic sections of it are indeed quite indistinguishable in appearance from many natural pumices.

The results of similar experiments are reported by Hempel (1916) and Yagi (1966).

PETROGRAPHIC PROPERTIES OF OBSIDIAN

Obsidian, far from being an amorphous, featureless, isotropic glass, contains a variety of microscopic and megascopic structures that will be described here under the general heading of petrographic properties of obsidian. The physical and optical characteristics of the natural glasses will be described as well.

Megascopic Petrographic Characteristics of Obsidian

Color. Obsidian has been found to occur in an unusually wide variety of colors, though the glass is most commonly found as black. The black color is the result of the presence of a high density of magnetite particles in the glass (see Plate 9). When a thin flake of black obsidian is examined it will usually appear as nearly transparent because an inadequate number of magnetite grains are present to color the glass (Boyer and Robinson, 1956; Senftle and Thorpe, 1959). If the magnetite becomes oxidized to hematite, it will appear as red or reddish-brown, two colors also commonly found in obsidian (Fuller, 1927; Ross, 1962). Though obsidian is also found in shades of blue, green, gray, yellow and turquoise,as well as other colors, the origins of these hues have not been examined.

Sheen and Luster. Not surprisingly, the luster of obsidian is vitreous, a characteristic that is sometimes used to megascopically distinguish it from pitchstone (which has a pitchy luster).

Occasionally, obsidian will exhibit a pearl-like sheen that has been described as iridescent, opalescent or chatoyant. This striking sheen is caused by the presence of tiny bubbles, often only a few tens of microns in diameter, in the glass (Forbes, 1934; Randolph, 1935).

Fracture. One of the most characteristic features of obsidian is its textbook conchoidal fracture (well-illustrated in Plate 2).

Hardness. The hardness of the natural glasses varies from 5½ for the basic glasses to 7 for the silicic glasses (Phillips and Griffen, 1981:329).

The Vickers hardness number for obsidian, the pressure needed to indent a polished surface, varies widely from about 500 to 900 kg/mm^2 with a mode occurring at about 700 kg/mm^2 (Ericson et al., 1975; Ericson, 1977:99-105; Ericson, 1981: 59-63).

Flow-Banding. Flow-banding, the presence of alternating layers of colored bands varying in thickness from less than a millimetre to several centimetres, is another common characteristic in obsidian. This banding is best seen in thin flakes of obsidian.

When the banding consists of layers of different shades of the color, for instance gray, the banding is usually found to be caused by the differential concentration of aligned prismatic microlites (see Plate VI-4 for an example). This alignment of microlites is generally thought to be due to laminar movement in the rhyolitic liquid during emplacement (Ross, 1962) but has also been found to take place below the melting point (under experimental conditions) when a static stress is placed on the glass (Clark, 1970).

More difficult to explain is the presence in obsidian of glassy bands of different colors, most commonly red and black. The contact of the colors is sharply delineated and accompanied by no change in texture, suggesting the incomplete mixing of different colored phases of magma while the obsidian was still in a liquid state.

Alternatively, some banding may appear as foliations - laminated structures in the obsidian flow or dome caused by a concentration of crystallites, by zones of pumiceous glass or by elongated trains of bubbles in the glass (Iddings, 1887; Jack, 1976; Fink, 1979:51). The texture of the foliations may differ significantly from the glassy portion of the obsidian. Fractures often develop along these foliations, some of which are no more than a few millimetres in thickness.

Bubbles and Vesicles. Small bubbles ranging in size from only a few microns to several centimetres in length are often found in flows of obsidian. These bubbles are generated as lowering temperature and pressure in the obsidian flow promotes the exsolution of gases. The vesicles are often stretched or elongated in the direction of flow extension and can later be used to determine the flow direction (Fink, 1979:51).

Spherulites and Lithophysae. Spherical crystalline objects known as spherulites and lithophysae are found in many lava flows and while they resemble each other in form, their origins are apparently quite different.

Spherulites, spherical-shaped masses of radiating acicular or tabular crystals of alkali feldspar, tridymite, sanidine or cristobalite, range in size from a few tenths of a millimetre to several centimetres (Iddings, 1888; Wright, 1915; Rogers, 1921; Yagi, 1966; Ewart, 1971). Spherulites often occur singly in obsidian, but often they coalesce to forms trains of spherulites in the glass. Flow-banding in the obsidian glass can be traced (when observed in thin-section) with no interruption through the spherulites (Iddings, 1888), indicating that the spherulites originated by early-stage devitrification after the glass had solidified (Phillips and Griffen, 1981). When compared to the glass that they are found in, the composition of spherulites is found to be enriched in H_2O, Na_2O, SiO_2 and Cao, and depleted in K_2O, Fe, MgO and MnO (Ewart, 1971).

The growth of spherulites in rhyolitic lavas is best described by Ewart (1971: 425):

> In the early stages of devitrification, spherulites occur mostly as isolated and nearly perfectly spherical bodies within the glass. They typically range from 1 to 5 mm in diameter, and in thin section exhibit both a radial-fibrous structure together with a concentric zoning made visible by slight changes of colour. The spherulites frequently appear to have nucleated on existing phenocrysts, especially plagioclase.
>
> With increasing devitrification, the spherulites increase in number, coalescing in groups...

Lithophysae, crystal-lined or filled cavities of quartz, tridymite or feldspar (and occasionally fayalite, garnet, topaz or tourmaline) are also common features in obsidian (Dietrich and Skinner, 1979:153)(Figure 10). The lithophysae

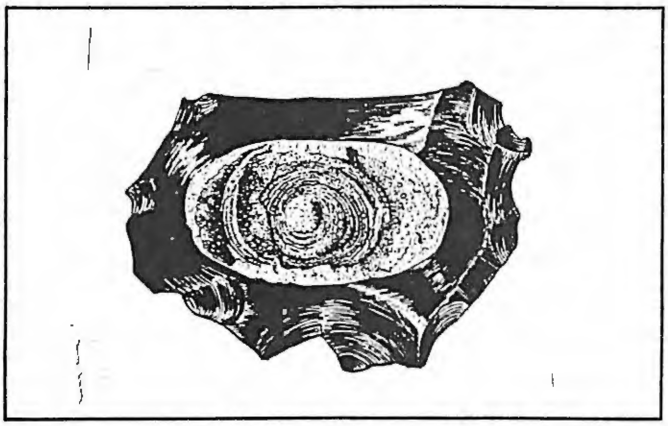


Figure 10 : Sketch of lithophysae in black obsidian from Obsidian Cliff, Yellowstone National Park, Wyoming (reproduced from Iddings, 1888: Plate XII).

may be open or filled with concentric shells of crystalline material that resembles roses when broken open (Iddings, 1887). Their origin, a subject of interest for over a hundred years, is still considered enigmatic and has been ascribed a to a variety of processes - the expansion of gas bubbles combined with secondary hydration, the alteration or decomposition of spherulites, the concentric decomposition of the glass, to crystalline nucleation around bubbles of gas and to "rhythmic crystallization" in gas-rich magmas (Iddings, 1887 and 1888; Wright, 1915; Dietrich and Skinner, 1979:153). The structure of lithophysae is described in some detail by Iddings (1888) and Wright (1915) while an early history of geologic speculation on the origin of lithophysae is provided by Iddings (1888).

Xenoliths. Flows and domes of obsidian often contain fragments of rock torn from the walls of the magma chamber or conduit that the obsidian melt has passed through. These inclusions, known as xenoliths, are termed cognate xenoliths if they are genetically related to the obsidians in which they are found and accidental xenoliths if not related.

Density. The density of rhyolitic obsidian typically falls between 2.13 and 2.46 gm/cm^3 and is affected by a variety of physical factors - the density of the glass phase, the presence of crystals and bubbles and whether or not the glass has been annealed (Ericson et al., 1975; 1977:97; 1981:58). The most important factor influencing the density of obsidian, however, is the chemical composition of the glass, particulary its silica content (Larsen, 1909; Tilley, 1922; George, 1924; Huggins, 1940a; Cann et al., 1970). When the density of

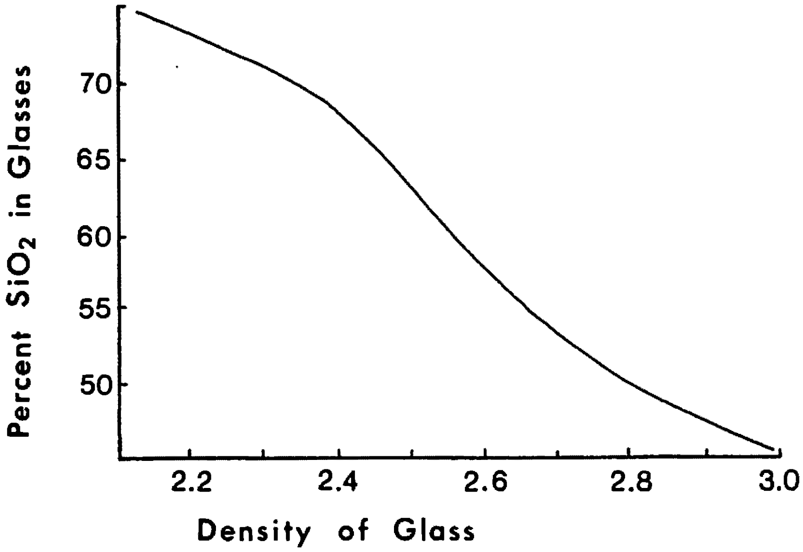


Figure 11 : Relationship of density to silica composition of natural volcanic glasses (adapted from George, 1924).

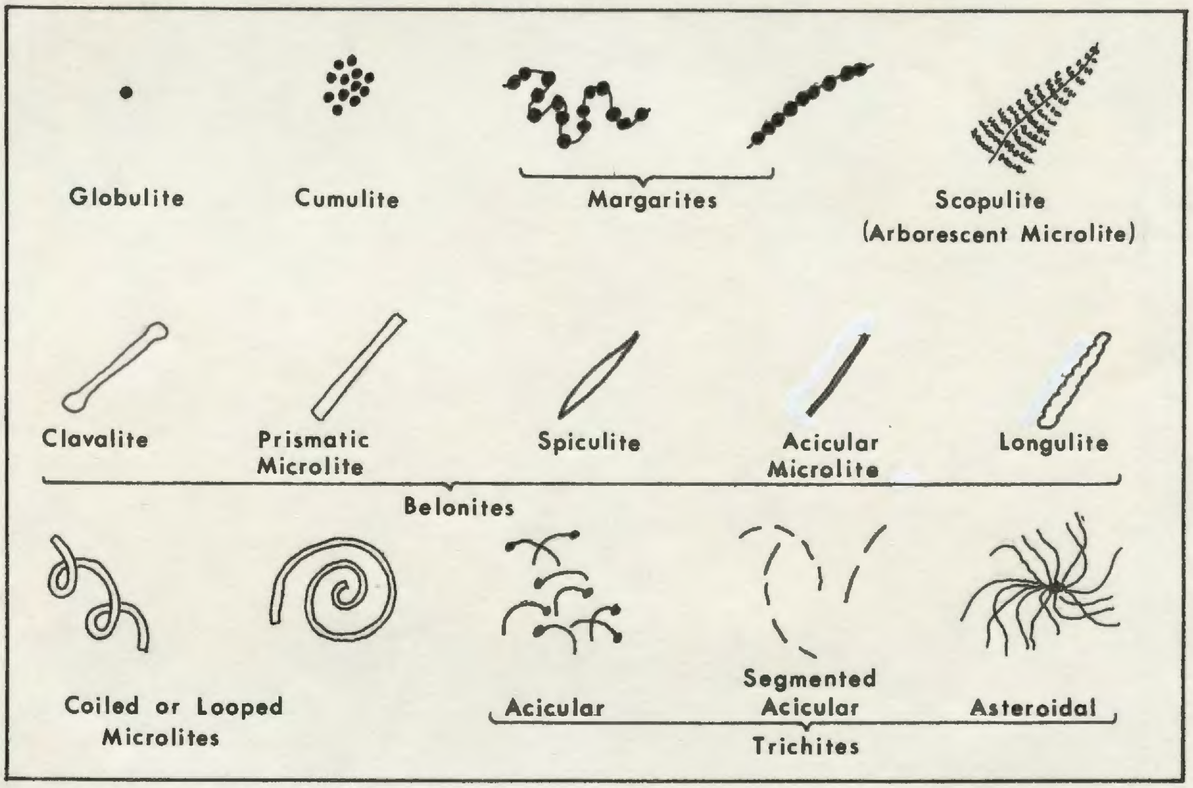


Figure 13: Assortment of microlitic structures that are commonly found in volcanic glass. Compiled from several sources (Rutley, 1891; Johannsen, 1931; Williams et al., 1954; Heinrich, 1956; Clark, 1961; Ross, 1962; Suzuki, 1973).

Plate 8: Sketch of asteroidal trichites in a thin-section of glassy rhyolite from Nevada. The magnification is unknown. The sketch photographed here appears in Ferdinand Zirkel's early work on microscopic petrography (Zirkel, 1876: Plate IX, Fig.1).

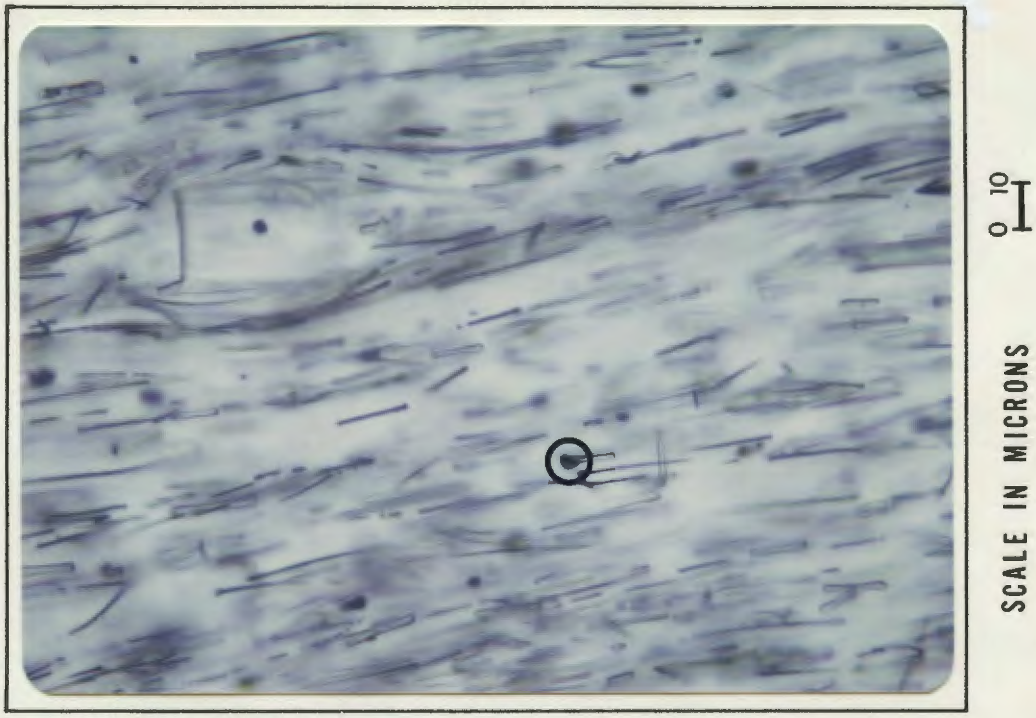


Plate 9 : Photomicrograph of strongly aligned prismatic microlites in obsidian found at Squaw Mountain, a rhyolitic dome in central Oregon. Nicols not crossed, x150. A single grain of magnetite is circled.

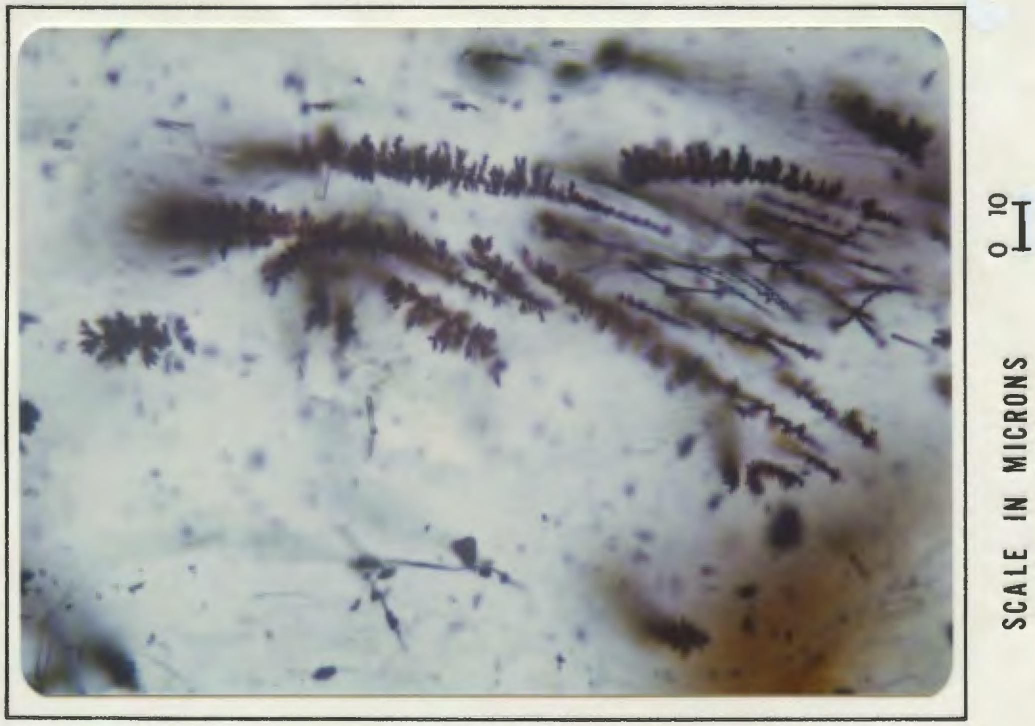


Plate 10: Photographs of scopulites in obsidian from Cougar Mountain, central Oregon. Nicols not crossed, x150.

may yield an index of refraction as high as 1.515 (Cann et al., 1970). Andesitic obsidians will give a refractive index averaging about 1.52 while basaltic obsidians (tachylite) will yield indices averaging about 1.6.

Microscopic Petrographic Characteristics of Obsidian

Microphenocrysts. Although obsidian is generally considered to be an aphyric, nearly holohyaline glass, it will almost always contain microscopic phenocrysts (microphenocrysts) and occasionally megascopic phenocrysts in the glassy groundmass. These microphenocrysts and phenocrysts, commonly plagioclase feldspars, typically make up only a very small percentage of the total volume of the obsidian in which they occur. The opaque specks (usually 1-2 microns in diameter) seen in all obsidians are tiny particles of magnetite.

Microlites and Crystallites. In addition to microphenocrysts, the natural volcanic glasses invariably contain a variety of microscopic structures known as microlites and crystallites (collectively referred to in this project as microlitic structures). Though microlite and crystallite terminology is somewhat vague, microlites are usually defined as microscopic crystals that polarize light and that have some determinable optical properties. The term crystallite is a more general one than microlite and refers to microscopic bodies of unknown mineralogic composition which do not polarize light. Crystallites and microlites are considered to represent early stages of crystallization in a magma (Johannsen, 1931:11-15; Marshall, 1961). Microlites or crystallites may be virtually nonexistent in obsidian or they occasionally may take up nearly all the volume of the glass (Ericson, 1977:114-121; 1981:66-73). These microlitic structures were first studied by Zirkel (1876) and Iddings (1888), but the most complete early study was published by Rutley in 1892. Research into the genesis and structure of crystallites and microlites has decidedly lagged behind most other areas of mineralologic study. Later contributions were made by Johannsen (1931), Clark (1961), Marshall (1961) and Ross (1962).

A number of different microlitic structures have been identified and the most common of these are reproduced in Figure 13. Globulites are small spherical or oval structures reaching a diameter of no more than about 5 microns. When found in clusters, they are known as cumulites. Chainlike lines of globulites are known as margarites. Longulites appear to be rows of coalesced globulites with only traces of their globulitic structure remaining. Fern-like bodies known as scopulites (Plate 10), often red in color, also occasionally occur and may be caused by the oxidation of other iron-rich microlitic structures in the glass. Prismatic microlites are rod-shaped structures, commonly composed of pyroxene, and are the most abundant of microlitic structures to be found in obsidian (Plate 9). Prismatic microlites usually range in length from about 5 microns to a few tens of microns. Very thin, needle-like examples of prismatic microlites are known as acicular prismatic microlites. Thin hair-like bodies also occur in some obsidians and may appear as straight, segmented or curved, singly or in groups. When observed in groups (radiating from a central point) they are called asteroidal trichites (Plate 8) - when seen singly they are known as acicular trichites. Asteroidal trichites usually radiate from a nucleau of magnetite and Clark (1961:105) speculates that trichites are not primary structures in the glass, but are microscopic cracks that have been altered (Johannsen, 1931:11-15; Rutley, 1892; Ross, 1962). Examples of several of these microlitic structures can be seen in Part Four, Chapter Six of this project.

Though the petrogenesis of microlitic structures is still not well-understood, Ericson (1981:73) offers an optimistic look at their research potential:

> Early geologists suggested that crystallites may represent a stage between the amorphous state and the crystalline...Recent technological developments of electron microscopes, electron probes, and ionic microscopes may provide the means to resolve this interesting hypothesis. If true, the states of matter, rather than being portioned into gas, liquid, and solid, would become a continuum of matter. This redefinition of a fundamental concept of the physical sciences would be quite significant.

THE WEATHERING OF OBSIDIAN AND THE PROCESS OF HYDRATION

Most *in situ* weathering of obsidian is related to the gradual hydration of the glass and its alteration to perlite, a subject briefly discussed earlier in this chapter. The process of hydration is a very gradual one, proceeding at a rate of only a few microns per thousand years, and is affected by several variables (Figure 14), most notably the composition of the obsidian and the temperature of the environment. Water vapor pressure and soil alkalinity may also affect the rate at which obsidian hydrates with water.

The Process of Hydration

The diffusion of atmospheric water vapor into rhyolitic obsidian begins when a fresh obsidian surface is exposed to the air. This exposure of a newly fractured surface of obsidian can be related to any of several different events: the emplacement of the glass and the cracks developed in the obsidian during cooling; post-emplacement faulting and cracking; glacial scouring; the cultural utilization of obsidian as an artifactual material and the spallation of a hydrated layer due to buildup of internal stresses.

The processes involved in the hydration of obsidian glass have been examined (or summarized) by a number of investigators (Friedman, 1958; Friedman and Smith, 1960; Haller, 1960; Marshall, 1961; Friedman et al., 1966; Lofgren, 1970 and 1971; Singleton, 1973; Ericson and Berger, 1976; Ericson et al., 1976b; Ambrose, 1976a; Ericson, 1977 and 1981; Laursen and Lanford, 1978; Carmichael, 1979; Michels and Tsong, 1980). No attempt will be made here to described the hydration process in great detail as this has already been accomplished by the aforementioned authors. Instead, let me only briefly describe the process of hydration and the major variables affecting it.

Obsidian, as I have mentioned previously, is a themodynamically unstable (metastable) glass and should change over time to a crystalline assemblage (Marshall, 1961). It appears, in fact, that natural glasses older than the early Cenezoic or very late Mesozoic are rare, the result of the devitrification of the metastable volcanic glasses (Lofgren, 1971). As the surface of obsidian hydrates, it incorporates meteoric water into the glass and the glassy rhyolite is eventually altered to perlite. The outer surface or rim of perlite is known as the hydration rim or band and is easily visible under the microscope because of the strain birefringence that develops in the hydrated layer. After a hydration rim of between 20 and 50 microns has developed (taking anywhere from several thousand to several hundred thousand years, depending on the rate of hydration), the internal stresses that accumulate in the rim cause it to spall off or crack

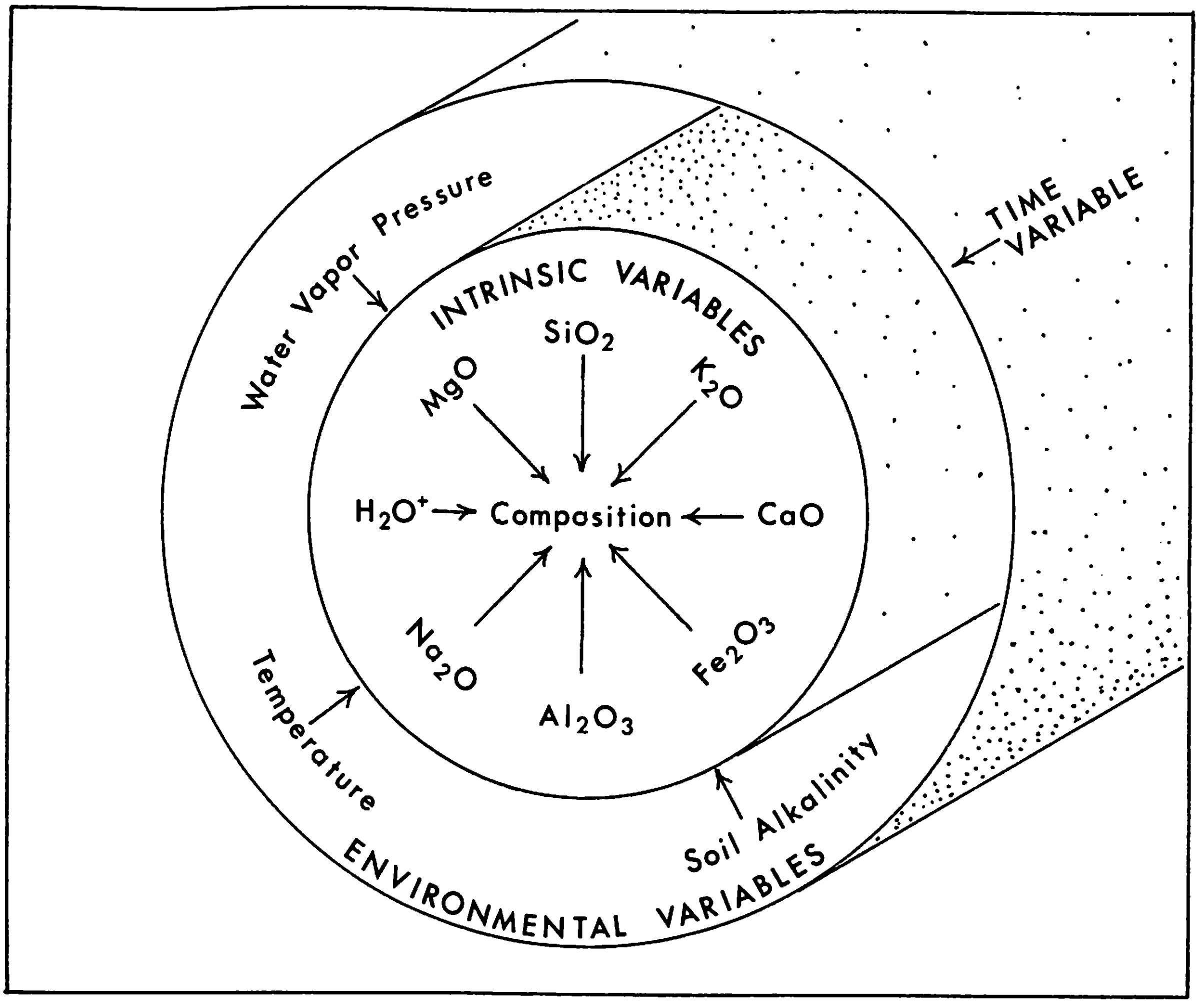


Figure 14 : The major variables that appear to effect the rate of hydration in obsidian. Environmental factors, composition of the glass and time are all factors to be reckoned with.

at the boundary of the hydrated and unhydrated glass (Friedman et al., 1966; Michels and Tsong, 1980). At this point, the formation of a new hydration rim begins again.

The Rate of Hydration

The hydration rate of obsidian is expressed as the change of hydration thickness over time. Hydration rates are dependent on a number of different interacting intrinsic and environmental variables (to be discussed shortly) and can vary greatly from one context to another. The rates are usually computed in terms of depth (in microns) per 1000 years.

When the rate of hydration and the width of the hydration rim are both known, it becomes a relatively simple matter to compute the length of time that the glass has been exposed to the atmosphere. While on the surface this appears straightforward, empirical and experimental geologic and archaeological studies have generated a variety of often conflicting hydration rates, a sample of which is shown in Table 1. While the majority of researchers have come to

Hydration Rate Formulas	Literature Source
Depth = K x Time$^{1/3}$	Kimberlin, 1971 Kimberlin, 1976
Depth = K x Time$^{1/2}$	Friedman and Smith, 1960 Friedman et al., 1966 Michels, 1967 Johnson, 1969 Suzuki, 1973 Friedman and Long, 1976 Findlow, 1977
Depth = K x Time$^{1/2}$ + K'	Findlow et al., 1975
Depth = K x Time$^{3/4}$	Clark, 1961
Depth = K x Time	Meighan et al., 1968a and 1968b Layton, 1972a and 1972b Barrera and Kirch, 1973 (for basaltic glass) Morganstein and Rosendahl, 1976 (for basaltic glass) Ericson, 1975 Russell, 1981

Table 1 : Different published hydration depth versus time formulas that have appeared since 1960. The rates are shown in rank order with slower rates on the top, faster rates toward the bottom of the list. It is details like this that have contributed to a general decline in interest in recent years in the obsidian hydration dating method. Modified from a table by Friedman and Trembour (1978).

accept the diffusion model originally proposed by Friedman and Smith (1960), a sizeable minority have relied on the linear model first used by Meighan et al. (1968). Meighan (1983) comments that the linear model may have enjoyed more popularity than it deserved simply because it is mathematically easier to deal with. It takes little mathematical skill to see that different hydration rates, when applied to the same hydration rim measurement, will produce different calculated ages. This disparity is particularly apparent when large hydration rims are examined - Meighan (1983) points out that a 15.6 micron thick hydration band would yield an age of 12,980 years using the linear model and 48,600 years using the diffusion model. Results like this have done much to undermine the confidence of some researchers in the obsidian hydration dating method.

On the basis of the considerable quantity of literature surveyed, it appears that the hydration rate of any particular obsidian source is best derived empirically using radiocarbon ages (either from carbon directly associated with the obsidian or from archaeological sites in which obsidian is found associated with the radiocarbon-dated material). There seems to be no single time and hydration band formation relationship that is applicable to all rhyolitic obsidian sources.

Obsidian Hydration Dating

As I have mentioned, when the thickness of the hydration rim and the rate of hydration are both known, it is possible to determine the length of time that has elapsed since a piece of obsidian was first exposed to the atmosphere. In principle, it becomes feasible to directly date the obsidian and therefore the geologic or cultural event that was responsible for the exposure of the fresh obsidian surface. This technique of dating, known as the obsidian hydration method, was first developed by Irving Friedman and Robert Smith (1958b; 1960), who measured the hydration rims of a large number of obsidian artifacts to see if the method could be used to directly date artifactual material. Since that time, the obsidian hydration method has been used to fix the ages of thousands of obsidian artifacts throughout the world as well as to date the eruption of obsidian flows in Oregon, California and Utah (Friedman, 1968, 1977 and 1978; Friedman and Peterson, 1971; Friedman and Long, 1976; Friedman and Trembour, 1978; Friedman and Obradovich, 1981; Wood, 1973 and 1977) and the glacial scouring of obsidian flows (Friedman et al., 1973; Pierce, 1976).

Though hydration dating is, in principle, relatively simple, in practice it has turned out to be much more difficult than was initially anticipated. The interaction of the numerous intrinsic and environmental variables affecting the rate of hydration has made obsidian hydration dating an increasingly complex method.

The more that is learned about this dating method, the more it seems that it is not likely to live up to its earlier expected reliability and ease of determination. The problems encountered with obsidian hydration dating have led to an apparent drop-off in recent years in the use of the method by many researchers (as reflected by the decreasing number of literature appearances of applications of the method). A few researchers, particularly Friedman, Michels, Meighan and their associates are still continuing optimistically with their investigations into the obsidian hydration dating method in the hopes that it can still be used as a reliable and accurate means of dating obsidian surfaces (Michels and Tsong, 1980; Meighan, 1981 and 1983; Friedman and Obradovich, 1981; Friedman and Trembour, 1983).

The pros, cons and general limitations of this dating method, particularly as they apply to archaeological problems, are discussed in more detail in Part Three, Chapter Two of this project.

Variables Affecting the Rate of Hydration

A large number of intrinsic and environmental variables affecting the rate of hydration of obsidian have been recognized (Figure 14). Though some of them have been examined in considerable depth, an understanding of how they affect the hydration of obsidian is still far from complete.

Temperature. Friedman and Smith (1960), in their original article describing the obsidian hydration dating method, recognized that temperature was a major variable affecting the hydration rate. Obsidian artifacts from tropical environments were found to hydrate at a much greater rate than artifacts recovered in the arctic. Later research by a number of investigators comparing obsidian that had been buried, recovered on the surface or exposed to heat from natural thermal areas have confirmed early findings of the significance of temperature as a factor in hydration (Friedman et al., 1966; Layton, 1973; Suzuki, 1973; Friedman, 1976; Friedman and Long, 1976; Ericson, 1977:52-61; Ericson, 1981:28-31; Friedman and Obradovich, 1981).

Most recently, Friedman and Trembour (1983:544-545) write:

> The hydration rate rises exponentially with increasing temperature and amounts to about 10% for each 1°C increase. Hence at fluctuating (diurnal and annual) temperatures the effective hydration temperature [EHT] of the range is not its arithmetic mean but some higher integrated value. It is this EHT level that was experienced by the test piece where it was found, which must be estimated closely if a reliable age interpretation of hydration depth is to be achieved.
>
> The long-term records of our national weather station network have been resorted to for mean annual air temperature (MAT) values to be used as a starting point for estimating the EHT at obsidian site locations. To use these data appropriately, a series of corrections on the MAT value is necessary, to take into account differences in elevation, the distance below surface of the findspot, the vegetational cover at the site, slope aspect in respect to insolation, and other apparent local features that combine to shape the site's microclimate.

It was originally anticipated that the study of the temperature variable would make it possible to calculate the rate of hydration at any specific locality, but this has not as yet proven feasible.

Chemical Composition of the Obsidian. That the chemical composition of obsidian was a major variable influencing the rate of hydration was suggested by Friedman and Smith in 1960. This suggestion, in spite of later supporting archaeological evidence (Clark, 1961:113; Aiello, 1969; Kimberlin, 1971; Michels, 1971a), was largely ignored until the mid-1970's when it finally became accepted that the composition of obsidian was probably *the* most important factor influencing the hydration rate. Up until this time, it had been assumed that regional rates of hydration, applicable over large areas with similar temperature and environmental conditions, were possible. Many geological and archaeological hydration studies that date from this period (and even later) must now be used with caution because of the application of a single hydration rate to obsidians of different composition. When the importance of composition was recognized, the concept of source-specific hydration dating was introduced (Ericson, 1975). This involves the identification of the geologic source (through characterization methods) of each obsidian sample that is to be dated by the hydration method.

At this point, attempts to accomodate source-specific hydration dating diverged into two directions. Friedman and his associates (Friedman and Long, 1976; Friedman and Obradovich, 1981) have attempted to construct, through experimental methods, a chemical index through which the rate of hydration could be predicted on the basis of the major element composition of the glass. Most archaeologists have, on the other hand, adopted an empirical approach to source-specific dating. Using the empirical method, artifactual obsidian samples are collected that are contextually associated with radiocarbon dated materials from archaeological sites. The obsidian is then characterized and the geologic source identified. Using the hydration rim width of the obsidian artifact and the chronometric data provided by the radiocarbon dates, it is then possible to construct a source-specific rate of hydration (Meighan, 1976).

The specific relationships of chemical composition and rate of hydration are still, in spite of a decade of research, not well understood. The state of the research is summarized by Friedman and Trembour (1983:545):

> The principal elements that constitute obsidian and are thought to include the chemical determinants of intrinsic hydration rate, are about 10 in number: O, H, Si, Fe, Al, Mg, Ca, Na, K, Ti. So far, however, no comprehensive theory has been put forth relating these elements to their specific effects on hydration. As a result of the incomplete understanding we have a body of hydration data and chemical information on a large number of individual rhyolitic glasses from many places in the world, but no accepted framework for relating them fundamentally to each other or to other hydratable glasses of adjecent chemistry such as dacitic glasses. In this situation only a few empirical efforts at quantifying the effects of chemical composition on hydration rates have been made on circumscribed sets of source material.

In an early study, Schott and Linck (1924) found that powdered obsidians high in SiO_2 hydrated slower than those low in SiO_2 and that they took up less total water. Suzuki (1973) speculated that the major element oxides Al_2O_3 and K_2O played a large role in influencing the hydration rate. Friedman and Long (1976) concluded that increased SiO_2 increased the hydration rate while elevated abundances of CaO and MgO reduced the rate. Obsidian hydration dating studies by Hughes (1982) also tended to rather vaguely support the predictions of the chemical index that Friedman and Long developed in the course of their work. Al_2O_3, FeO, Na_2O and K_2O contents were found by Friedman and Long to have little effect on the hydration rate. Ericson (1977:140-143; 1981a; 1981b:86-91) found that several elements tended to promote of retard the hydration of obsidian glass. Hydration was retarded by (in rank order, most influential first) the ratio of Na to K, Fe_2O_3, Na_2O, MgO, Al_2O_3 and TiO_2. Hydration was promoted (again in rank order) by K_2O, the initial (intrinsic) H_2O in the glass, SiO_2 and CaO. The amount of intrinsic water in the glass has also been suggested as a hydration variable by Lee et al. (1974), Kimberlin (1976) and Jambon (1979). Tektites, containing almost no intrinsic water, do not hydrate, further suggesting the importance of water content to the rate of hydration.

Though there is some agreement among investigators as to which elements influence the rate of hydration, there is, as Friedman and Trembour imply above, much to learn before the composition of obsidian can be used to predict the behavoir of the hydration rate.

Alkali-Rich Environments. Very little actual evidence exists to indicate the degree to which alkali-rich environments increase the rate of hydration of natural glass. Wilcox (1965), speaking of siliceous volcanic tephra, writes: "...the glass of an ash fall in a strongly alkaline environment, such as a playa, may alter much more rapidly than that of the same ash fall in adjacent highlands." Lofgren (1970) and Cormie (1981:47) both found that obsidian hydrated at a greatly accelerated rate when placed in strongly alkaline solutions but added that environmental conditions as severe as those that existed in their studies were not likely to be found in nature. Ambrose (1976a), though, found that the highly saline, alkaline and moist environments of some South Pacific Island archaeological sites may have been responsible for the etching and pitting of hydrated obsidian surfaces.

Water Vapor Pressure (Humidity). The water vapor pressure of the environment that obsidian is hydrating in has been thought by most investigators to have little or no effect of the rate of hydration (Friedman and Smith, 1960; Friedman and Long, 1976). Ambrose (1976a), however, cites experimental studies in which the surface adsorption of water was shown to be clearly dependent on humidity. He also adds, though, that the burial of obsidian in archaeological contexts would be likely to negate the effect of the very low water vapor pressure that is found in some very arid environments.

Effects of Weathering on the Composition of Obsidian

When obsidian is exposed to weathering, ie. when the obsidian is altered to perlite through the hydration of the glass, a number of changes take place in the composition of the altered glass.

This mobility of elements during weathering is strongly affected by environments that are strongly alkaline or acid. Cormie (1981:43-46) found that strong acid environments (such as those that siliceous glass might be exposed to in laboratory treatment) cause the preferential leaching of Ca, Mg, Ba, Fe, Pb, Cd, Mn and Zn while leaving the K concentration unaffected. Further experimental studies by Cormie (1981:47) also indicate that strong alkaline environments result in the preferential leaching of Si, Cl, B and F with a concomitant reduction in K, Ca, Li, U and V. Though most natural weathering environments would not be as extreme (in pH) as those that Cormie exposed volcanic glass to, her studies do point out trends that might exist in natural environments and compositional changes that might take place during the laboratory preparation of samples of obsidian.

In normal weathering contexts, researchers have found a number of differences between fresh and altered volcanic glass, pointing to the mobility of some elements and the addition of meteoric H_2O (during hydration). The major change in composition during hydration is in the water content which increases from a few tenths of a percent to between three and five percent (Ross and Smith, 1955; Hart, 1965; Friedman and Smith, 1958a; Jezek and Noble, 1978). Zielinski et al. (1977) report that alkalis and alkali earths are mobile during weathering but that other trace elements appear relatively stable. More specifically, a decline in Na (Hart, 1956; Noble, 1967; Jezek and Noble, 1978; Bird et al., 1978) and an increase in K (Noble, 1967; Jezek and Noble, 1978) have been documented. Tsong et al. (1978) found a depletion of the alkali metals Na, K and Li in hydrated volcanic glass in addition to the migration of the alkali earths Ca and Mg toward the outer surface of hydrated obsidian. Lee et al. (1974) found no change in Na between the weathered and unweathered portions of the obsidian, contradicting the findings of several other studies. Radiogenic Ar is also lost during hydration, rendering hydrated volcanic glass as unsuitable for K-Ar dating (Kaneoka, 1971).

Several other elements have also been found to be stable during hydration. When obsidian-perlite pairs found in direct association were compared, F (Friedman and Harris, 1961), U and Th (Rosholt et al., 1971; Zielinski, 1978) were found to be relatively stable. Bird and Russell (1976) also report no change in the F:Na ratio between weathered and unweathered obsidian. Bennett and D'Auria (1974) found that there were no significant differences in the abundances of Ti, Mn, Fe, Rb, Sr, Y, Zr and Nb between fresh obsidian glass and archaeological obsidian with the hydration rim present. Their findings suggest that small samples of obsidian (such as those that might be recovered from archaeological sites or from welded ash-flow tuffs) can be analyzed with their hydration rims left intact.

In summary, the alkali earths and alkali metals both appear to be mobile during normal weathering, while most other elements are relatively stable. H_2O is incorporated in sizeable quantities during the hydration of obsidian glass.

4 Geomorphic Properties of Obsidian

Geomorphic research directly involving obsidian is essentially *nil*, and up to now, understandably so. The mechanisms involved in the formation of obsidian-related landforms have been studied primarily by volcanologists and geologists. The study of the processes, however, that later sculp these landforms through erosion, lie largely in the province of geomorphologists and until recently, the role of earth surface processes in the distribution of obsidian has been of little interest to researchers in this profession. With the improved methods of obsidian characterization in the last few decades, though, and with an increased emphasis on interdisciplinary strategies in archaeological projects, an understanding of the weathering and natural surface transport of obsidian (as well as other lithic materials), has become essential.

As archaeologists become increasingly more interested in the reconstruction of extinct trade and exchange networks through the investigation of characterized obsidian artifacts, an understanding of the role of natural processes in the distribution of obsidian will also become increasingly important. The human transport of obsidian, as reflected by trade systems, is only one of the many different ways in which obsidian may be moved from an original, primary source or source area to a secondary location removed from the original one (Figure 15).

The natural processes that may account for the geographic distribution of natural glass have been, up to now, largely disregarded by archaeologists engaged in the study of prehistoric exchange systems. As I will show in this short chapter, however, it is essential for the validity of archaeological research involving obsidian characterization-based studies of prehistoric exchange that the geomorphic properties of obsidian, specifically those involving natural transport from a primary source locality, be considered.

PRIMARY AND SECONDARY SOURCES OF OBSIDIAN

Primary sources of obsidian are those which occur at or near the vicinity of the vent from which obsidian is extruded. Typically, these primary sources are obsidian flows, obsidian-rhyolite domes or the chilled selvage of rholitic bodies. For the purpose of this discussion, the vents from which ash-flows or tephra are issued are considered the primary source, though the entire ash-flow or tephra unit could alternatively be considered a single primary source.

Obsidian may also be recovered from *secondary* sources, that is, sources spatially removed from the original primary source. Secondary sources of obsidian can be found as stream gravels, surface float, fragmental glass, glacial till, volcanic bombs, in ash-flow tuffs, in laharic deposits, as landslide debris or conceivably, even as glacial erratics. Hurtado de Mendoza (1977:59-60) and Hurtado de Mendoza and Jester (1978) also recognized that not all obsidian sources are primary. They attributed the presence of obsidian in secondary contexts to "drift" processes, which they classified as natural and cultural (human). Their general scheme, though it was not well-developed, is followed in this chapter.

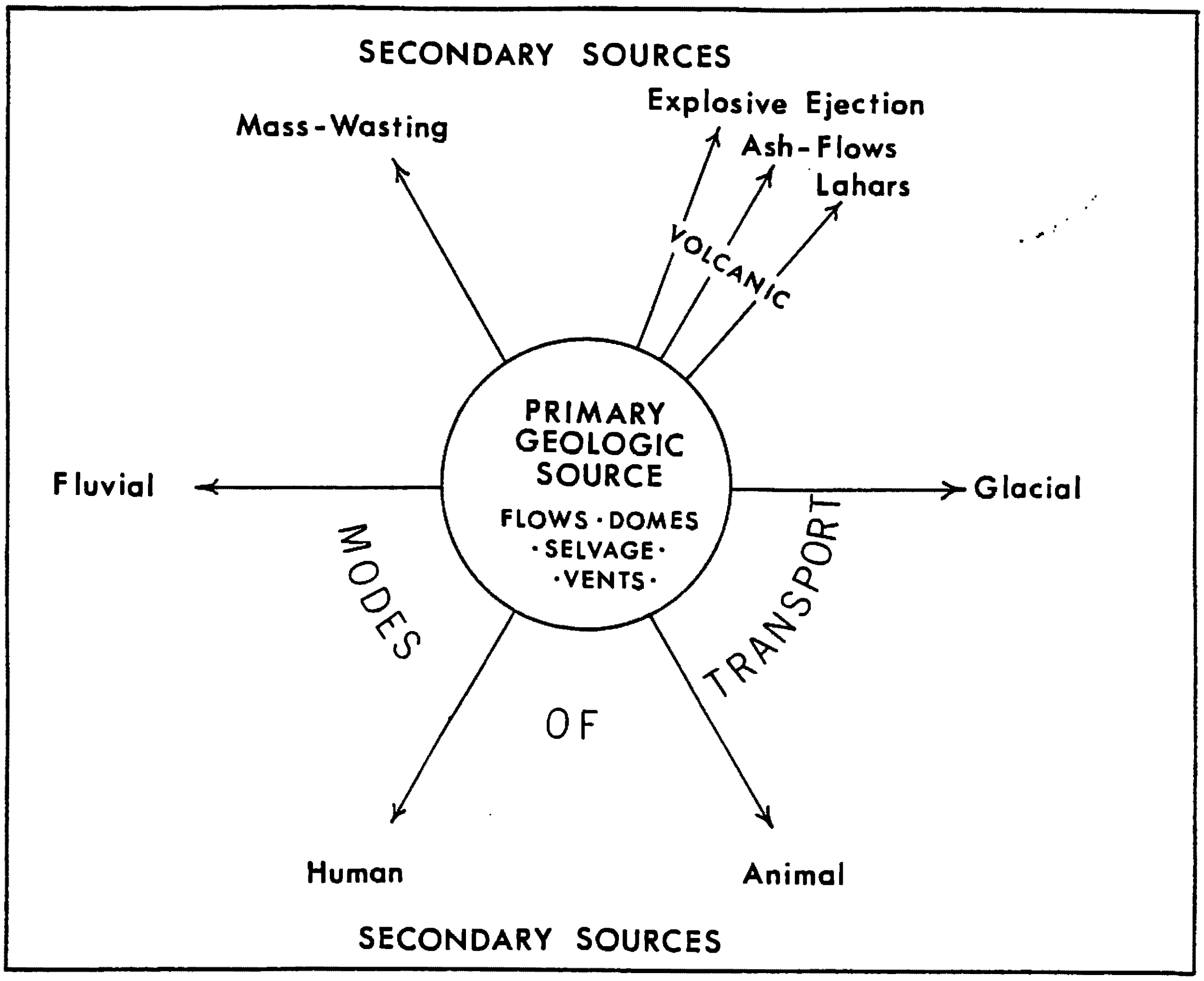


Figure 15: Simplified model of the different ways that obsidian is transported from primary geologic sources to secondary sources.

The source area, then, that must be considered as a single archaeological source (for the purpose of obsidian characterization studies only), is the combination of both the primary and secondary obsidian sources. The size of this resultant source area may be considerably larger than expected, but must be taken into account so that archaeological studies reflect cultural movement and trade and not some natural process. Just how the obsidian gets from primary to secondary sources is the subject of the rest of this chapter. The processes involved in the transport of obsidian will be illustrated by examples drawn from the literature dealing with Oregon obsidian sources.

MODES OF TRANSPORT OF OBSIDIAN FROM PRIMARY TO SECONDARY CONTEXTS

In general, the major types of processes involved in the natural movement of materials on the earth's surface are mass-wasting, fluvial, aeolian, tectonic, glacial and volcanic (Butzer, 1976). In addition to these, human or biological agents are also responsible for the movement of relatively small quantities of material, though these may be significant in their effect on human populations. In this discussion of obsidian transport processes, aeolian and large-scale tectonic events will be considered as unimportant and are omitted.

Mass-Wasting Transport

Rockfalls, debris slides, avalanches and block creep are all events that fall into the category of mass-wasting processes. While any of these events may involve primary sources of obsidian, it is unlikely that they would account for obsidian transport of more than a few kilometres at most. They are considered as only minor agents in the natural movement of obsidian.

Glacial Transport

Glaciers overriding primary obsidian sources can undermine or pluck obsidian from the source, later depositing the glass "downstream" in morainal deposits in the form of glacial till.

This process is well-documented in Oregon's Central High Cascades. Obsidian from the Obsidian Cliffs flow near the base of the Middle Sister was carried to the west at least 22 km (14 mi) where it can now be found in deposits of glacial till near the town of McKenzie Bridge (Taylor, 1968; see Part Four, Chapter Two, for more details on the secondary sources of obsidian from Obsidian Cliffs).

Glacial movement of obsidian in mountain and piedmont glaciers would be generally restricted to only a few tens of kilometres. Obsidian carried by continental ice sheets such as those that existed in the Pleistocene period in North America, however , could conceivably have been transported for long distances and spread over large areas, though no examples of this phenomenon were described in the literature.

Fluvial Transport

The movement of obsidian debris from the primary source by streams and rivers may sometimes provide an important means of transport for obsidian. Obsidian finding its way into the bed-load of a river could be carried long distances downstream. Though the potential distance that the obsidian could be moved is great, the actual distance is probably limited by the erosion of the relatively fragile glass in river and stream beds. O'Keefe (1976:29) describes a study of the destruction of artificial glass that was made by a Czechoslovakian student group. The group, studying the rate of weight loss for pieces of glass as a function of distance downstream from the glass source, found that 99% of the mass of the glass was lost in a distance of 40 km.

In Oregon, examples of the fluvial transport of obsidian can be found in the Willamette Valley of western Oregon and at the edge of the Harney Basin in eastern Oregon. Gravels of the McKenzie River near Eugene contain pebbles of obsidian that originated 110 km (65 mi) to the east at the aforementioned Obsidian Cliffs flow in the High Cascades. It is likely that the McKenzie River intersects deposits of glacial till containing obsidian from Obsidian Cliffs. Material from these tills is carried down the river to the Eugene area and eventually makes its way into the Willamette River. Mention of the possible occurrence of obsidian in the Willamette River gravels near Portland, 175 airline km (110 mi) north of Eugene, was made by Minor (1977).

Another example of fluvially-transported obsidian is located at the western margin of the Harney Basin in eastern Oregon. Beds of conglomerate at Wright's Point are known to contain pebbles of obsidian thought by Niem (1974) to have originated at either Burns Butte (25 km to the northwest) or Palamino Buttes (20 km to the west).

Volcanic Transport

Several different types of volcanic activity may contribute to the transport of obsidian from volcanic vent areas. The most important of these is the explosive ejection of pyroclastic material (tephra), lahars (mudflows) and ash-flows.

Tephra. The term tephra refers to all ejecta blown into the air by explosive volcanic activity (excluding ash-flows) and includes pyroclastic materials ranging in size from blocks and bombs to fine ash (Williams and McBirney, 1979: 127). Rhyolitic tephra has a similar composition to obsidian and instances in which eruptions of tephra have preceded the extrusion of obsidian flows (from the same vent) of identical composition are not uncommon (MacLeod et al., 1982). Rhyolitic tephra typically consists largely of glass and will sometimes contain fragments of shattered obsidian. These pieces of volcanic glass rapidly settle out of the pyroclastic cloud and it is likely that fragments of obsidian of a size suitable for archaeological utilization are carried no more than a few kilometres.

This short-distance explosive transport of obsidian can be clearly seen at the Central Pumice Cone in Newberry Caldera (see Appendix Four, this project). Chips of obsidian broken by explosive activity at this cone can be found covering the flanks of the cone and the nearby vicinity. Obsidian has also been found in tephra originating from a vent now covered by the Big Obsidian Flow in Newberry Caldera. Obsidian blocks as much as 1 m in diameter were found 2 km east of the vent (MacLeod et al., 1982).

Lahars. Lahars, sometimes called mudflows, are deposits of volcanic materials that have been mixed with water and laid down on land. They may be initiated by outpourings of hot water from volcanic vents, by water-soaked ash from a vent, by eruptions beneath crater lakes, by the melting of ice or snow by volcanic activity or by the mixing of volcanic ash with heavy rainfall (Williams and McBirney, 1979:171-178). Lahars vary widely in their volume and extent and range from very small to considerably more than 100 km in length.

Lahars may contain pieces of obsidian, as well as a variety of other volcanic debris. Green (1962:68) identified fragments of obsidian in a Miocene laharic deposit in Oregon's Malheur County, though neither the extent or the source of the deposit was determined.

Ash-Flows. Perhaps the most important (and generally unrecognized) natural process contributing to the transport of obsidian from primary sources is volcanic ash-flows. These gas-rich flows of hot pyroclastic materials, sometimes called nuées ardentes or glowing avalanches, originate from vents at volcanic domes, open craters and fissures and may cover very large areas. Many ash-flow units (ignimbrites or ash-flow tuffs) have a volume exceeding 10 km^3 while some are known to have a volume of more than 100 km^3 and are capable of covering areas of thousands of square kilometres in a relatively thin veneer. Most ash-flows are rhyolitic or dacitic in composition and may originate from the same vents or centers of silicic volcanic activity that produce rhyolitic domes, obsidian flows or tephra. It is not surprising that one of the components of ash-flow deposits may be fragmental obsidian. Obsidian, ash-flows and tephra eruptions may sometimes represent different textural phases of the same magma source and may exhibit similar or identical compositions.

Ash-flow tuffs are found in many areas of Oregon, particularly in the eastern part of the state (Walker, 1970). Obsidian has been identified in Oregon ash-flow tuffs on the slopes of Newberry Volcano (MacLeod et al., 1981), in the Paulina Basin (Davenport, 1970:17,19), in the Mitchell area of the John Day region (Fisher, 1966), in the Seneca-Silvies area (Crowley, 1960:26) and in the Danforth Formation of the Harney Basin (Piper et al., 1939:43-44; Bateman, 1961:59-72). The latter ash-flow unit has a volume in excess of 180 km^3 (45 mi^2) and covers an area of more than 10,000 km^2 (4000 mi^2). It would be quite possible for a single secondary source of ash-flow transported obsidian to be available (for archaeological purposes) in outcrops occurring in a very large area.

Animal Transport

One of the more unusual ways in which obsidian or other lithic materials could be transported to secondary sources is by migratory animals. Heizer (1968) has documented several examples of fish, waterfowl and mammals in which non-indigenous artifacts (projectile points, fish hooks, harpoons, etc.) were recovered. These animal-transported sources, though, are almost certain to be very limited in extent.

Human Transport

The last agent of transport is the human one and it is this process that most archaeologists involved in the characterization of archaeological and geological obsidian are interested in documenting. When artifactual obsidian from these human-introduced secondary sources is correlated with their primary sources, it can be possible to infer extinct patterns of movement, contact and trade. This can only be reliably achieved, though, when the primary and secondary sources are both known. People provide only one of the several means of removal and transport of obsidian from its original source and the failure to take other (natural) processes into account could lead to fallacious and unreliable archaeological models of prehistoric behavior.

CONCLUSIONS

Primary sources of obsidian are usually found in relatively restricted areas as domes, flows or selvage. A variety of natural and cultural events, though, may transport obsidian from a primary source to what is termed here a secondary source. The extent of the secondary source may only marginally exceed that of the primary source (such as in the case of mass-wasting or explosive volcanic activity) or it may extend hundreds of kilometres from the primary source (such as is possible with obsidian transported by streams and rivers or by volcanic ash-flows).

Archaeologists dealing with the reconstruction of exchange systems through the characterization of artifactual obsidian (a topic discussed in more detail in Part Three of this project) must take into account both the primary and secondary sources of obsidian when characterizing a geologic obsidian source. Human transport is only one of the many processes that can account for the movement of obsidian from its original source. For archaeological studies of characterized obsidian (or other characterized artifactual materials) to be reliable, the geomorphic processes responsible for obsidian transport must be recognized and the true geomorphic extent of the obsidian source (primary plus secondary sources) identified.

1 An Introduction to the Archaeological Utilization of Obsidian and Obsidian-Like Lithic Materials

> Flint and obsidian knives were *always* used by the Maoris at the same time that they had the well-polished tools and weapons of stone. The polished tools were used for canoe building, making paddles, spears, clubs, agricultural instruments, etc., and were exceedingly valuable. The obsidian splinters were not worth the trouble of making into a regular shape; the edge was as keen as a razor, but so brittle that it could not be used for cutting wood to any advantage. These knives were used for cutting flax, flesh, hair, and for surgical operations. The edge soon came off, when another chip would be split off the large lump of obsidian, which every family that could afford it would have lying by the house, or concealed somewhere near at hand. These blocks were usually brought from the Island of Tuhua by the Ngapuchi, when returning from southern expeditions, and were articles which fetched a considerable price in the way of barter. When I first came to the colony, in many inland villages the obsidian knife was still much used; it was merely a sharp chip, but when split off artistically, extremely sharp.
>
> F.E. Maning (1875; quoted in Ward, 1972:22-23)

For many thousands of years, obsidian has been a preferred raw material in many cultures. In areas throughout the world where obsidian was readily available, it almost inevitably became the chief lithic material used in the construction of flaked tools. The ease by which the natural glass could be shaped into a sharp-edged tool made it a very desirable material to have available, as the above excerpt from Maning suggests. The history of the exploitation of obsidian has been summarized by Zeitlin and Heimbuch (1978) and I quote from them:

> The chronicle of obsidian exploitation extends back at least a million years to Kariandusi in the Rift Valley of central Kenya where an upper Acheulian people gathered this natural, igneous glass...to produce quantities of bifacially flaked core tools. In the New World, as well, paleo-Indian immigrants were quick to make use of the locally available obsidian. Excavations at the central Mexican site of Tlapacoya have revealed a prismatic, obsidian blade in a context dated to approximately 23,000 BP. At nearby Santa Isabel Iztapan, among the stone tools found with two imperial mammoths killed by late Pleistocene hunters were several of obsidian. Other obsidian implements have been found in paleolithic sites from central Africa to Japan, North America to the Near East.

> ...where obsidian was readily available, it more often than not became the primary lithic material for flaked tools. From Preclassic times onward in the Valley of Mexico, obsidian quarried in the surrounding neovolcanic cordillera never comprised less than 80% of the total flaked stone assemblage...and despite the 16th century Spanish introduction of metallurgy, use of prismatic obsidian blades for barbering and household functions was not completely abandoned until recently. Such cultural conservatism becomes more understandable in light of the observation that even now "There is no ground or honed material or any metal tool sharper than the obsidian or glass blade replicas of prismatic blades". The ancient Maya were so impressed with its use for cutting weapons that they referred to a soldier as "The Obsidian".
>
> The workability and pleasing vitreous texture of obsidian apparently also inspired its application for other than strictly utilitarian purposes. Mesoamerican artisans painstakingly fashioned it into earspools, labarets, beads, pendants, bowls, mirrors, figurines, and other ornamental and ceremonial objects, many of startling beauty and impressive craftsmanship. Equally splendid artifacts of a similar class are found in Old World archaeological contexts. Obsidian even had ritual and mythical connotations. The Aztec word for obsidian, itzli, entered into the names of their gods (Itzpapalotl) and men (Itzcoatl) and was associated with the north, cold, the underworld, and with the deity, Black Tezcatlipoca.
>
> At a hunting and gathering level of adaptation, the means for intensive exploitation and extensive distribution of far flung resources are poorly-developed and, consequently, the presence of obsidian artifacts usually corresponds closely to the limited volcanic regions of their origin. But with the evolution of agricultural societies and the more regularized modes of exchange which almost invariably accompanied them, obsidian began to be distributed over impressive distances.

Archaeological study of the artifactual obsidian left by extinct cultures can reveal a surprising amount of information about the chronology and behavior of that culture. Archaeologists have, of course, recognized for many years the value of obsidian artifactual material in understanding and reconstructing culture histories. Over the last few decades, though, the methods available to archaeologists for obsidian study have become increasingly more sophisticated and powerful in their analytical capabilities. The major potential pathways of obsidian analysis that are now available in the archaeological study of prehistoric cultural materials are illustrated in Figure 17.

It is now possible, using the research strategies outlined in Figure 17, to use archaeological obsidian as a tool in the reconstruction of cultural chronologies, intrasite use patterns, economic and political structures, exchange and trade systems and subsistence activities and materials. In many instances, intact or finished artifacts are unnecessary for use in analysis and obsidian debitage, one of the most ubiquitous of archaeological remains, can be just as easily utilized.

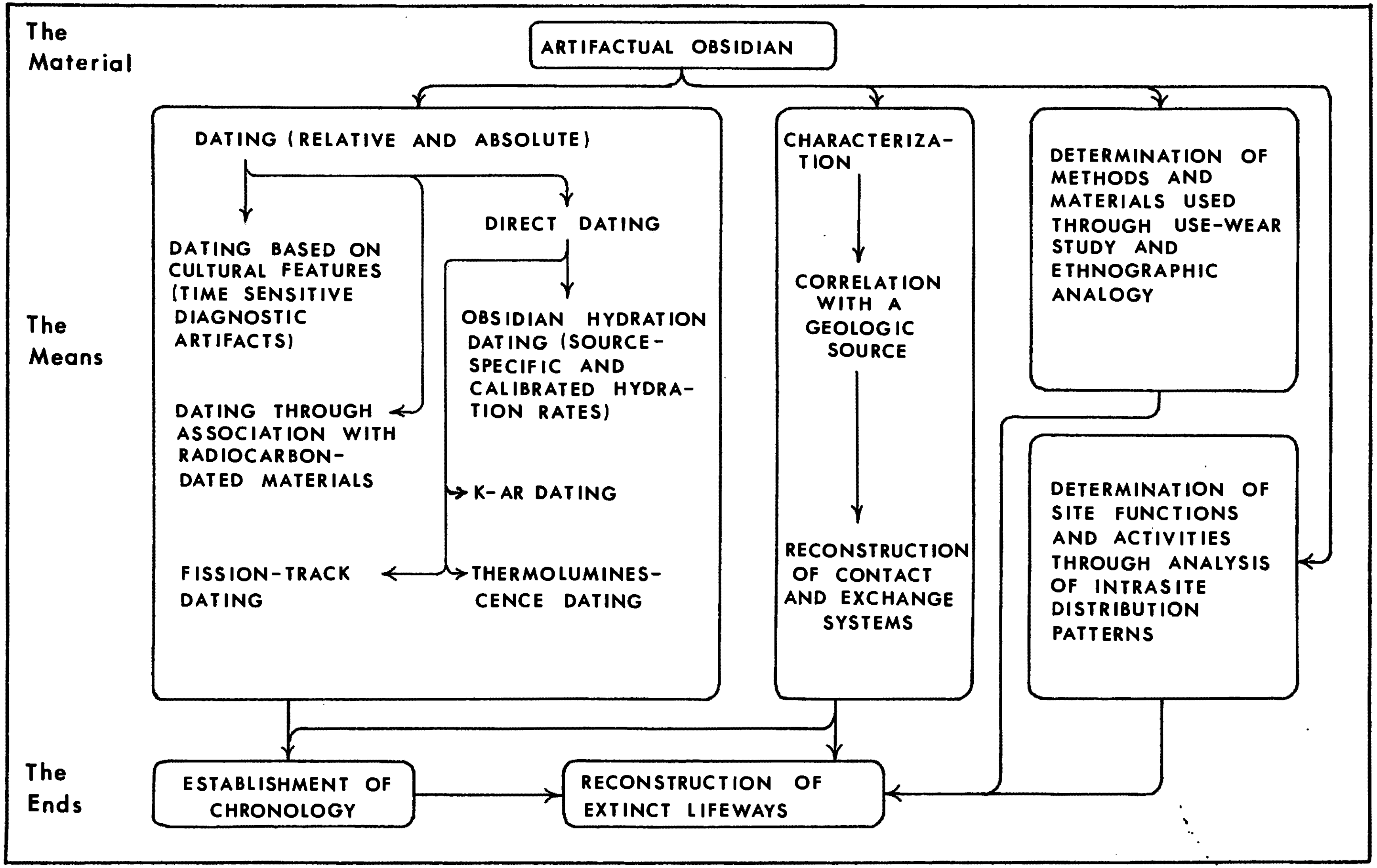


Figure 17: Some possible pathways of analysis using obsidian recovered from an archaeological context. Analysis can, in many cases, use either waste or finished forms of artifactual obsidian.

The direct and indirect use of artifactual obsidian to reconstruct chronologies will be discussed in the next chapter of this project. The characterization of obsidian and its use in reconstructing extinct contact and exchange systems will be discussed in Chapter Three.

A number of obsidian-like rocks such as pitchstone, obsidian-like vitrophyre and products of combustion and contact metamorphism (see Chapter Three, Part Two of this project) have also been occasionally found in archaeological contexts. Crabtree (1967) has described how the tool-making or flaking qualities of these obsidian-like lithic materials compares to those of obsidian and other lithic materials.

USE-WEAR ANALYSIS

Pioneering work by Semenov (1964) has led to a recent resurgence of interest in use-wear and edge-wear analysis, though the concept of using the wear patterns of archaeological implements to suggest how the tools were made and used dates to at least the 1830's (Olausson, 1980). The history and development of the method is discussed in some detail by Hayden and Kamminga (1979) and Olaussen (1980).

The keystone of use-wear analysis lies in the connection between human behavior and the patterns of wear and damage that this behavior imparts on stone tools. Use-wear analysis is, of course, not limited only to obsidian but to all lithic materials). By macroscopically or microscopically examing the working edge of artifactual tools for fracture angles, striations and polishing, it is possible, in some instances, to identify the type of contact material (bone, skin, etc.) and the motor patterns of the original user (Hayden and Kamminga, 1979). Though the examination of use-wear patterns is still in the early research stages, the edge-wear characteristics of obsidian have been recently described by a number of investigators (Hester et al., 1976; Schousboe, 1977; Greiser and Sheets, 1979; Howes, 1980; Spear, 1980; Lewenstein, 1981).

ETHNOGRAPHIC ACCOUNTS AND OBSIDIAN USE

Few ethnographic accounts of aboriginal obsidian use were examined in the course of this project. The limited number of examples that were located, though, substantiated the common belief that a great deal of cultural value was placed on obsidian and that it was a desirable material sometimes transported and traded over long distances (Maning, 1875, quoted in Ward, 1972:22-23; Iddings, 1888:261; Gould, 1966:61; Hester, 1972; Pires-Ferreira and Flannery, 1976; Clark, 1978; Ericson, 1982; see Chapter Two, Part Four of this project for an excerpt from Gould, 1966, about the long-distance movement of obsidian from the Bend, Oregon, area). Further ethnographic and ethnohistorical research into the cultural role that obsidian played, particularly as an indicator of economic structure and exchange patterns, is clearly needed in order to better understand the archaeological significance of the glass.

HEAT-TREATMENT OF OBSIDIAN

The thermal alteration of lithic materials by aboriginal artisans as a technique to improve the flaking qualities of siliceous stone has recently been recognized by archaeologists. Experimental work reported by Crabtree and Butler (1967), Purdy and Brooks (1971) and Purdy (1974) suggest that the tool-making properties of chert, flint, fine-grained siliceous rocks and other materials are significantly improved when the rocks are heated. Obsidian, however, because of its already excellent flaking qualities, seems to benefit less than most lithic materials from heat treatment. Purdy (1974) found that a 25 percent increase in compressive strength resulted from the annealing of obsidian. The use of thermal alteration of obsidian has also been ethnographically documented and several examples have been collected by Hester (1972).

Though no ethnographic examples were found, one of the best applications of obsidian heat treatment methods would have been with "apache tears" or marekanite. These nodules of obsidian are found associated with beds of perlite (devitrified obsidian). Internal strain is a characteristic feature of apache tears and when tapped with a hammer or cut on a lapidary wheel the balls may literally explode (Judd, 1886; Marshall, 1961; Crabtree, 1967). When the obsidian nodules are heated and allowed to cool (annealing), patterns of strain birefringence that were previously visible under crossed nichols (when viewed with a microscope) are found to have disappeared (Judd, 1886; Marshall, 1961). This variety of obsidian would certainly lend itself to heat treatment prior to artifact manufacture.

2 Age Determinations with Obsidian

There are a variety of methods by which the age of events in the geologic and cultural history of an obsidian artifact can be directly or indirectly determined. These techniques, when applied to obsidian artifactual materials, can be used to help reconstruct cultural chronologies at archaeological sites in which obsidian is found throughout the world. In most cases, obsidian waste material is as suitable for analysis as are finished artifacts, making possible the utilization of an often overlooked archaeological resource.

The chronometric methods described in this chapter can be used to determine the age of one or more of the following three events that have occurred in the history of an artifact:

1. The geologic age of the artifact (the length of time since the extrusion of the obsidian).
2. The thermal age of the artifact (the length of time since the obsidian was heated above normal ambient temperatures; this age usually coincides with the geologic age but is occasionally tied to a cultural event).
3. The cultural age of an artifact (the length of time since the artifact was altered or fashioned by human or cultural influences)..

The applications of the chronometric methods to these events are summarized in Figure 18.

The archaeologist is, of course , most interested in events that reflect the cultural history of an artifact. The presence of diagnostic (time-sensitive) styles of artifactual materials, of hydrated cultural surfaces and of associated materials that can be radiocarbon dated can all serve to aid in the reconstruction of

		CHRONOLOGIC METHODS					
		DIAGNOSTIC STYLISTIC FEATURES	OBSIDIAN HYDRATION DATING	FISSION TRACK DATING	THERMOLUMINESCENCE DATING	POTASSIUM ARGON DATING	C-14 AGE ASSOC.
EVENT	GEOLOGIC AGE	No	Yes	Yes	Yes	Yes	Yes[1]
	THERMAL AGE	No	Yes	Yes	Yes	Yes	No
	CULTURAL AGE	Yes	Yes	Possible[2]	Possible[2]	Possible[2]	Yes

[1] The geologic age of obsidian can be determined if the radiocarbon dated material is found in direct association with an obsidian flow.

[2] It is possible to determine the cultural age of an event using these methods if it a culturally-related thermal event.

Figure 18: Events in the history of an obsidian artifact whose ages can be determined using various chronometric methods.

the cultural history of an obsidian artifact. In more limited circumstances, thermoluminescence, fission track and potassium-argon geochronologic techniques can also be used to fix the ages of obsidian artifacts that have been intentionally or accidentally thermally altered by a culturally-related event.

The geologic age of the artifactual obsidian, while not as directly of interest to the archaeologist, can nevertheless be useful in the characterization and source determination of obsidian artifacts (see the next chapter).

TEMPORALLY DIAGNOSTIC OBSIDIAN ARTIFACTS

Though many kinds of artifactual objects are made of obsidian, the most important for the purpose of determining cultural chronologies have turned out to be projectile points. Many different styles, or types, of projectile points have been identified, and a fairly large number of them have been found to be useful as cultural time markers. Indeed, in many archaeological studies, particularly those based on surface finds, the major (or only) temporal indicators at a site may be time-sensitive, or diagnostic, projectile points.

Diagnostic projectile point styles are those which are restricted to a relatively short time period (though the period may span several thousand years). These time-sensitive artifacts have been particularly well-studied in the Great Basin of the United States (see Figure 19). Numerous point types found associated with radiocarbon dated material have been recovered from stratified sites in this region, providing an initial temporal framework in which to place the different styles of projectile points. Research dealing with chronologically significant projectile points has been most recently summarized by Layton (1970: 216-277), Hester (1973) and Heizer and Hester (1978).

The key concept related to projectile point chronologies is that of the relationship of artifact *type* to cultural reality (Krieger, 1944; Ford, 1956; Steward, 1956). Krieger (1944:270) attempted to clarify this point when he wrote:

> Thus the purpose of a type in archaeology must be to provide an organizational tool which will enable the investigator to group specimens into bodies which have *demonstrable historical meaning in terms of behavior patterns*. Any group which may be labeled a "type" must embrace material which can be shown to consist of individual variations in the execution of a definite constructional idea; likewise, the dividing lines between a series of types must be based upon demonstrable historical factors, not, as is often the case, upon the inclinations of the analyst or the niceties of descriptive orderliness.

This grouping of artifacts into types is still largely an intuitive method and it has been argued that because of this it would be difficult to produce consistent typological categories from among different researchers. While recent research by Tucker (1980) indicates that quantitatively-defined types tend to replicate intuitively-constructed tyopologies, the question of the degree of correlation between cultural behavior and artifact types is still open to question (Hantman and Plog, 1982). The use of diagnostic artifacts to reconstruct cultural chronologies is considered by most archaeologists to be a valid (and inexpensive) technique, but one that is still indirect and that should be used with care.

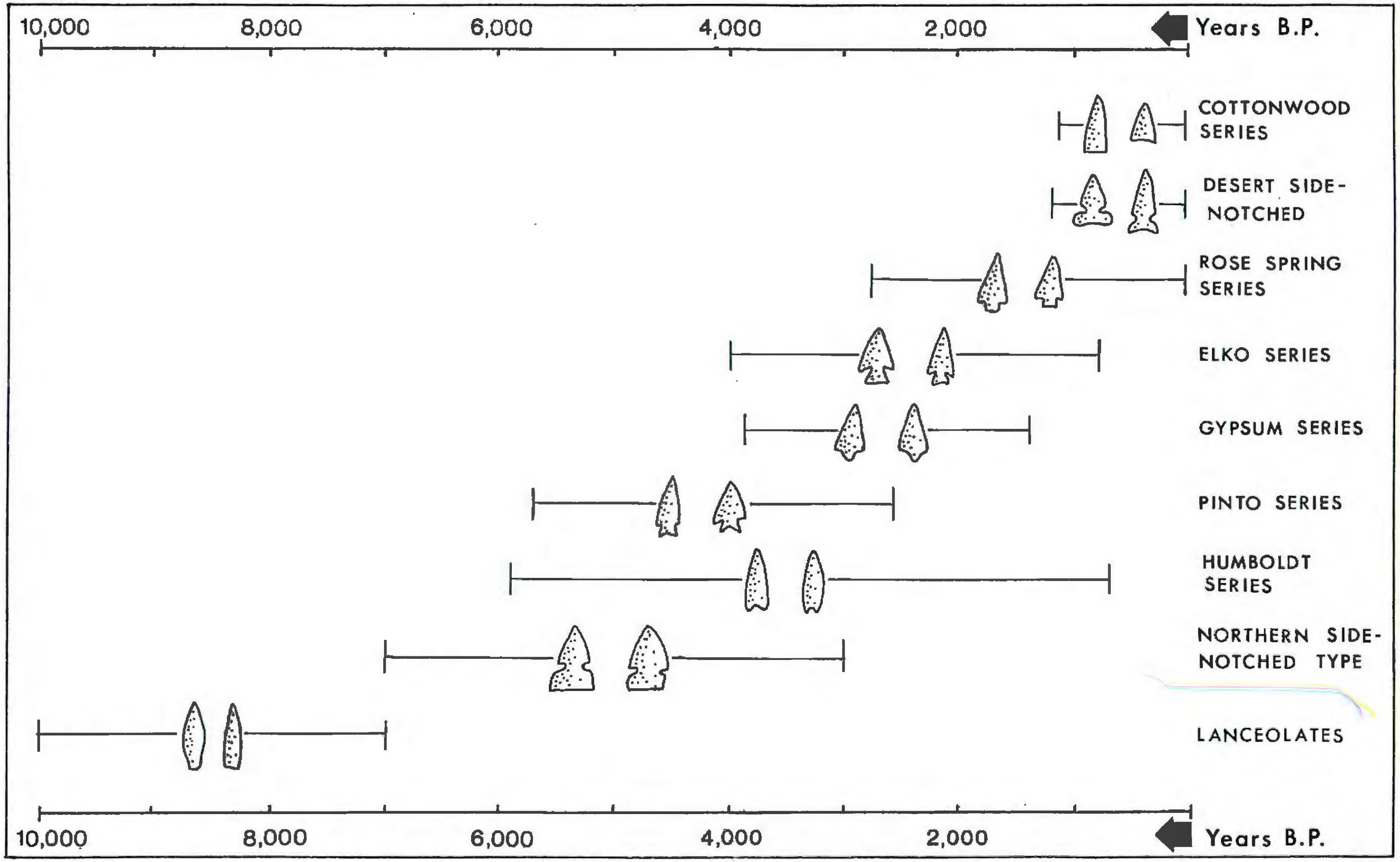


Figure 19: Examples of time-sensitive, or diagnostic, projectile point types found in the Great Basin of the United States. The projectile points pictured are drawn in various scales. Compiled from several different sources (Layton, 1972a; Bettinger, 1978; Heizer and Hester, 1978; Toepel et al., 1980; Baxter, 1981; Minor and Toepel, 1982; Hester, 1973).

OBSIDIAN HYDRATION GEOCHRONOLOGIC METHOD

The obsidian hydration geochronologic method (see Part Two, Chapter Three of this project for a discussion of the process of hydration), the outgrowth of research into the relationship between obsidian and perlite, was first utilized for the dating of archaeological materials by Friedman and Smith (1958b, 1960). The prospect of having a relatively simple technique available that could be used to *directly* date obsidian cultural surfaces quickly stimulated a great deal of archaeological interest. The archaeological possibilities of a reliable chronometric method such as this would be enormous and optimism ran high, as exemplified by this excerpt from Clark (1961):

> It is the concensus of ... workers that in the next phase of [obsidian] hydration research it will be possible to develop expressions of the hydration rate for all the major areas of the world. Ultimately, we should be able to provide a 'universal' formula for dating obsidian objects, which will contain appropriate constants for all regional variables.

During the next decade, though, it gradually became clear that the initial optimism surrounding the inception of obsidian hydration dating was premature. At first, it was conceived that "regional" hydration rates, based on temperature-defined geographic regions (temperature was known to be an important variable influencing the rate of hydration), could be used. Archaeological evidence began to indicate in the late 1960's, though, that the chemical composition of obsidian was also another major variable to be taken into account. This led to the concept of "source-specific" hydration measurements in which artifacts would be sorted into geochemically-distinct source groups. As this became accepted practice, attention was redirected on the effects of the thermal environment on the hydration of obsidian artifacts. It soon appeared that the temperature variable was even more important than was previously realized and that even quite small differences in the thermal environment that artifacts are found in could greatly influence the rate of hydration. The interacting variables influencing the rate of hydration have left the reliable application of the obsidian hydration dating method still far from a reality. This opinion is, however, not shared by all researchers, several of whom are still continuing their research in spite of difficulties.

In the two and a half decades since the inception of the obsidian hydration dating method, it has been used (and is still being used) by archaeologists in many areas of the world. The list below of published obsidian hydration dating efforts acts as a chronicle of the archaeological use of the method.

<u>Easter Island</u> - Evans, 1965.
<u>Ecuador</u> - Bell, 1977.
<u>El Salvador</u> - Meighan, 1981b.
<u>Greece</u> - Witte, 1978.
<u>Guatemala</u> - Hurtado de Mendoza, 1977 and 1981; Walters, 1978 and 1981; Michels, 1975.
<u>Japan</u> - Suzuki, 1973 and 1974; Katsui and Kondo, 1976.
<u>Mexico</u> - Dixon, 1966; Meighan et al., 1968b; Ericson and Kimberlin, 1977; Findlow and Bennett, 1978; Doolittle, 1979 and 1981; Michels, 1971.

New Zealand - Ambrose and Green, 1962; Green, 1962 and 1964.
United States
  Arizona - Findlow, 1977.
  California - Clark, 1961; Michels, 1965; Meighan and Haynes, 1970; Ericson and Berger, 1974; Michels, 1975; Ericson, 1977 and 1981; Findlow et al., 1978; Kaufman, 1978a and 1978b; Meighan, 1978a, 1978b and 1978c; Christenson and Russell, 1981; Chartkoff and Chartkoff, 1981; Sutton, 1981; Garfinkel and Schiffman, 1981; Stearns, 1980; Arnold, 1969.
  New Mexico - DeAtley and Findlow, 1979-80; Findlow et al., 1975; Russell, 1981.
  Nevada - Layton, 1970, 1972b, 1973a and 1973b; Layton and Thomas, 1979.
  Oregon - Johnson, 1969; Layton, 1972a; Heflin, 1963; Meighan et al., 1974: 65-78; Fagan, 1974 and 1975; Olsen, 1975; Minor, 1977 and 1980; Kittleman, 1977; Aikens and Minor, 1980.

As can be seen from the above collection of articles describing archaeological applications of obsidian hydration dating, most research has taken place in the Western United States and Central America. Due to the reliability problems encountered in obsidian hydration dating, the number of individuals still actively employing the method (the numbers have never been large) are centered around the hydration dating facilities at the University of California (Los Angeles), the Pennsylvania State University and the U.S. Geological Survey. Since the inception of the obsidian hydration dating technique in 1958, research has gone through a brief surge in the 1960's and 1970's, with only a few groups of researchers (represented by Michels, Friedman, Meighan and their associates) still optimistically pursuing the method in the 1980's.

The Preparation of Obsidian Artifacts for Obsidian Hydration Measurements

The preparation of obsidian artifacts prior to hydration measurement is a relatively straightformard and simple procedure, one that has been described by several authors (Friedman and Smith, 1960; Clark, 1961; Friedman et al., 1970; Friedman and Trembour, 1978; Michels and Tsong, 1980). The thin section preparation procedures are outlined below:

1. A narrowly-spaced pair of shallow parallel cuts are carefully made (with a rock saw) perpendicular to the hydrated obsidian surface that is to be measured. Katsui and Kondo (1976) suggest encasing the artifacts in epoxy resin to protect the thin hydrated surface during cutting.
2. The thin plate-like sample isolated between the two saw cuts is removed and one of the flat sides is ground (using a fine carborundum powder slurry) to a flat, smooth surface.
3. The obsidian sample is then glued to a standard petrographic slide with either cooked Canada balsam or clear epoxy cement.
4. Again using a carborundum powder slurry, the obsidian surface facing out from the slide is ground down (either by hand or on a rotating disc) to a thickness of about 0.08 mm (0.003 in).
5. Finally, the obsidian specimen is covered with cooked Canada balsam and a cover slide is affixed.

After cleaning, the thin-section of obsidian is ready for measurement. The total time investment in the preparation of each thin section will vary from about 20 to 30 minutes.

The Measurement of the Hydration Rim

Once the thin section of obsidian has been prepared, the hydrated layer is typically measured using a microscope equipped with a micrometer ocular that is calibrated using a stage micrometer. For hydration rims exceeding two microns, a magnification of x400 is adequate for most measurements, while for thinner rims, a magnification closer to x1000 may be necessary. The difference in water content and mechanical strain between the hydrated and unhydrated glass produces a well-defined boundary that is easily identifiable under either transmitted ordinary light or crossed polarized light. The measurement of the rim, however, is most easily made in plain light (Plate 11). The width of the hydration rim can be determined, using this method, to within an accuracy of ± .01 to 0.2 microns.

A variation on this method of measurement is reported by Findlow and DeAtley (1976), who compared slide projections of obsidian hydration rim photomicrographs with those of a stage micrometer to obtain rim width dimensions. They claim a greater accuracy in measurement using this method than is usually reported for the method described previously.

Plate 11: Photomicrograph of a hydration rim that has formed on the surface of an obsidian artifact. The width of the rim pictured is about 6 microns. Nicols not crossed, x150. The obsidian artifact occupies the right half of the photograph.

Recently, another quite different technique of measuring hydration rims, that of sputter-induced optical emission, has been introduced. This resonant nuclear reaction method, capable of producing high resolution hydrogen depth profile measurements, is described in detail by Leich (1974), who writes (pages 92-93):

> The reproducible profiles obtained on a variety of obsidian samples have verified the correspondence between the location of the stress birefringence line visible under the microscope, and the depth at which the H concentration gradient is a maximum, for hydration rinds up to 2μm thick. This technique appears to be particularly well-suited to the measurement of very thin ($<$0.5 mm) hydration layers where the order-of-magnitude improvement in resolution over optical techniques can be used to best advantage.

This method has also been briefly described by Tsong et al. (1978), Michels and Tsong (1980) and Bird and Russell (1976:327). Results of experimental work using the method to measure hydration profiles in obsidian have been reported by Lee et al. (1974), Leich (1974:85-91), Tsong et al. (1978) and Laursen and Lanford (1978).

Problems in the Archaeological Application of the Obsidian Hydration Geochronologic Method

The major limitations in the obsidian hydration geochronologic method lie not in its theoretical viability, but in its incorrect application by archaeologists (and geologists). The use of an easily measureable hydration rim to directly date obsidian appears deceptively simple, but unless the variables that affect the rate of hydration are carefully considered, ages derived from use of the technique are worthless. More seriously, invalid dates that find their way into the literature have a tendency to be quoted or accepted at face value and to persist even when the original investigators (hopefully) have recognized their error.

Shortcomings in the archaeological application of hydration dating tend to fall into six categories: problems in preparation and measurement; failure to adequately consider the thermal variable; failure to adequately consider the compositional variable; the application of an incorrect hydration rate; inadequate field work and the use of an inadequate sample size.

1. *Problems in preparation and measurement.* Incorrect preparation of thin sections, while probably not a major problem, could lead to the determination of misleading hydration measurements. Failure to cut the obsidian section parallel to the hydrated surface could, for example, lead to the appearance of anomalously thick hydration rims. Though a "reading error" between 0.1 and 0.2 microns is usually assumed to exist by most investigators, highly inaccurate readings have occasionally been reported (Meighan, 1981). The hydration front in obsidian, though a fairly conspicuous feature, can be confused with various optical effects by an inexperienced viewer.

2. *Failure to adequately consider the thermal variable.* The thermal environ- of obsidian artifacts, as has been pointed out, is one of the major variables affecting the rate of hydration. Specimens *must* have shared a very similar temperature environment throughout their history in order to be successfully compared with each other. This is particularly true because the effects of the thermal environment on hydration rate, though currently under study

(Friedman and Trembour, 1983), are still not well-understood. Surface collections of artifacts are particularly prone to generate erroneous results in hydration studies and should not be subjected to obsidian hydration dating (see Appendix Five, this project, for a discussion).

3. *Failure to adequately consider the compositional variable.* The chemical composition of obsidian, like the thermal environment, is a major variable influencing the hydration rate of the glass. Different geologic sources of obsidian will yield different rates of hydration, given the fact that all other variables affecting the hydration rate are the same. It follows, then, that obsidian artifacts must be separated into geochemically similar source groups prior to any attempts at hydration dating. The idea of "source-specific" hydration dating was introduced to the archaeological community by Ericson in 1975, though the effects of chemical composition on the rate of hydration had been recognized as early as 1969 by Aiello. Still, in the late 1970's, obsidian hydration studies were still appearing in which different sources of the archaeological obsidian were not taken into account. This failure to adequately consider the compositional variable is one of the major factors invalidating many earlier obsidian hydration studies. It simply *cannot* be assumed that all obsidian found at any archaeological site originates from a single source. A number of characterization techniques now exist (see the next chapter and Part Four of this project) that can be used to distinguish different obsidian sources.

4. *The application of an incorrect rate of hydration.* Numerous hydration rates have been derived by researchers working with obsidian from many different geologic sources found in many different thermal environments (see Table 1). Obsidian artifacts from different geologic sources *will* hydrate at different rates, as will artifacts from identical sources, but with different thermal histories. It is *not feasible* to apply a single rate of hydration to a group of artifacts until the artifacts have been determined to share a similar thermal history and a common geologic source. Even then, the rate should be determined empirically using obsidian artifacts from archaeological contexts that have been subjected to radiocarbon dating (Meighan, 1976). As Meighan (1983) has recently pointed out in a discussion of obsidian dating in California, though, hydration rates are being rather loosely applied. This is particularly true of the linear rate, the easiest of several rates to mathematically calculate. The inaccuracies that this can introduce into archaeological data are, needless to say, considerable. This is especially the case in sites yielding artifacts with thick hydration rims. The application of different rates to the same initial hydration measurements can generate ages which are wildly divergent. Meighan (1983), for example, figured that a 9 micron wide hydration band could result in a calculated age of from 9,280 years to 46,000 years, depending on the hydration rate utilized. Obviously, these are not the kinds of results which encourage great faith in the reliability of the obsidian hydration dating method.

5. *Inadequate field work.* Problems of association and context are well-known to archaeologists and obsidian artifacts fall prey to the same difficulties as any other artifact being excavated i.e. re-use, post-depositional disturbance, poor excavation techniques and so on. Meighan (1981) adds that a double problem with association often exists for artifacts being considered for hydration dating: "...for radiocarbon dates are applied to such things as tomb sites and stratigraphic levels, and that age is applied to associated obsidian pieces. Any mistake in interpreting these associations will obviously affect one's development of an obsidian hydration rate."

6. *Inadequate sample size.* Many obsidian hydration studies have been based on only a few measured obsidian specimens coupled with a hydration rate calibrated using a limited number of radiocarbon dates. The use of small sample sizes in hydration studies jeopardizes the validity of the results, allowing anomalous data to remain unnoticed.

In spite of the problems encountered with obsidian hydration dating, research goes on. The simplicity and potential applications of the method are still very attractive qualities and given time and more research the problems may be surmounted. The only barrier remaining then will be in attitudes. Meighan (1981:4), a long-time advocate of the method, writes of this:

> It is unfortunately true that archaeologists, like all other scholars, sometimes come to believe that they know what the answer is based on inadequate or misinterpreted evidence. Having reached a conclusion, few of us find it easy to discard our idea and accept a new conclusion based on new evidence. When obsidian-dating evidence does not conform to existing ideas of chronology, it is possible that the obsidian-dating evidence is in error. Archaeology went through this for years with arguments that the whole radiocarbon method was no good because it yielded dates not in conformity with someone's interpretation of the chronology. It took a long time for some scholars to accept the notion that it was possible to get erroneous dates on occasion without invalidating the whole theory and method of radiocarbon dating. Obsidian-dating is still in the stage of convincing people that the method is valid and that the problems lie in poor field archaeology and incorrect assumptions about obsidian hydration rates.

FISSION TRACK GEOCHRONOLOGIC METHOD

For nearly twenty years, the fission track geochronologic method has been used to determine the ages of archaeological obsidian specimens. This technique consists of counting the fairly distinct damage sites that are created in minerals by the spontaneous fission (at a constant rate) of ^{238}U, a uranium isotope. The density of the fission tracks is proportional to the amount of time that has elapsed since the extrusion of the obsidian and to the density of atoms of ^{238}U present in the obsidian. The density of ^{238}U in the obsidian is determined by inducing fission of ^{235}U atoms by bombarding the glass with a known dose of thermal neutrons (usually using a nuclear reactor as a neutron source). To determine the age of the sample, then, it is necessary only to count the proportion of the uranium atoms that have fissioned. The principles of this geochronologic method have been discussed in detail by Fleischer et al. (1975).

The uranium tends, because of its large ionic radius and charge, to be concentrated in silicic volcanic rocks that are formed through differentiation or partial melting (Zielinski, 1978). Because of this, obsidian tends to contain uranium in large enough quantities (typically from 1 to 30 parts per million) to make it a good candidate for fission track dating.

While obsidians usually contain a great enough density of fission tracks to allow age determinations, they often also contain small crystallites and tiny bubbles, both of which are easily confused with fission tracks. This problem can be overcome using a pre-annealing technique described by Wagner et al. (1976).

Fission tracks are sensitive to elevated temperatures. The heating of obsidian, for example, will tend to partially or completely erase the existing fission tracks, in effect "resetting the fission track clock" in a sample. If the reheating event is culturally-related, the amount of time that has elapsed since the track erasure can be calculated, providing an age for the cultural event. The ages of thermally-altered obsidian tools have been determined by Fleisher et al. (1965) and Watanabe and Suzuki (1969). The fission track dating of most obsidian artifacts, though, reflects the geologic age of the tool. While this event is clearly culturally unrelated, its age may be used in the characterization and geologic source identification of obsidian artifacts (see the next chapter for a discussion).

The archaeological applications of the fission track geochronologic method have been discussed by Walker et al. (1971), Fleischer et al. (1975:159-231), Fleischer (1975 and 1976) and Wagner (1978). Obsidian artifacts have been dated, though usually for the purpose of characterization and geologic source identification, by Fleischer et al. (1965), Watanabe and Suzuki (1969), Suzuki (1970), Kaneoka and Suzuki (1970), Durrani et al. (1971 - see Anonymous, 1972), Bigazzi and Bonadonna (1973), Suzuki (1973 and 1974), Yegingil and Gokshu(1981) and Miller and Wagner (1981).

POTASSIUM-ARGON GEOCHRONOLOGIC METHOD

Another way in which the age of obsidian can be directly determined is through the method of potassium-argon dating. This technique measures the amount of radiogenic argon that is present in a rock. This argon, the product of the decay of ^{40}K found in most rocks, accumulates at a known rate through time and thus acts as an indicator of the thermal age of the rocks. Argon is lost when a rock is heated to a temperature of several hundred degrees centigrade and so the potassium-argon geochronologic method can be used to determine the period of time that has elapsed since the last major thermal event in the history of a rock. This event is usually the one associated with its formation (Dalrymple and Brent, 1969:43-51).

Though argon can be lost as a result of hydration in obsidian (Kaneoka, 1972), fresh, unaltered obsidian is an excellent material for use in potassium-argon dating. Ages can be reliably determined for samples as young as 0.3 to 0.4 million years and as old as the oldest sources of obsidian (early Cenezoic to late Mesozoic).

THERMOLUMINESCENCE GEOCHRONOLOGIC METHOD

The release of stored energy as light when a substance is heated is known as thermoluminescence (Michels, 1973). This property has been used by researchers to determine the thermal age of sediments, flint, marble and pottery, and has been recently applied to obsidian. Though obsidian samples yield distinctive thermoluminescence curves that have been used to characterize indivisual sources, no attempts at geochronologic determinations have yet been made (Leach, 1977b; Huntley and Bailey, 1978).

ASSOCIATION OF OBSIDIAN ARTIFACTS WITH RADIOCARBON-DATED MATERIALS

Though many sources of obsidian are older than the approximately 50,000 years that the radiocarbon geochronologic method encompasses, a number of obsidian flows and domes do fall into the age range of this dating technique. Materials suitable for radiocarbon dating can often be found beneath the margins of obsidian flows or in association with airborne tephra and welded ash-flow deposits that often immediately precede the extrusion of obsidian. Geologic sources of obsidian whose ages are known may be used by archaeologists to set age "ceilings" for recovered archaeological obsidian. Obsidian artifacts that have been characterized and correlated with an obsidian source of a known age could, of course, have been fashioned only since the eruption of the glass. The ages of most dated obsidian flows have been determined by the radiocarbon geochronologic method, though a few flows have also been dated using the obsidian hydration geocheonologic technique (see Appendix Five, this project). Similarly, the minimum ages of recently erupted obsidian sources can be suggested using characterized artifacts whose ages have been determined through archaeologically-obtained evidence.

3 Obsidian Characterization and the Reconstruction of Prehistoric Contact and Exchange Systems

> Just as flint or chert can only be derived from particular strata, and must have been carried by trade if found at any distance from these centres, so the presence of obsidian objects in a non-volcanic country is proof of trade with some centre of volcanic activity. Unhappily the scientific identification of any given piece of obsidian with specimens from any one deposit is beset with difficulties, so that it is at present impossible to say categorically that the given piece did, or did not, come from a certain locality. Yet, however, within limits, it is possible to attain a considerable degree of probability as to the place of origin, and further to eliminate other places as hithero having produced nothing comparable to the material under discussion. This is useful as indicating the trade routes.
>
> G.A. Wainwright (1927:77)

Scientific methods have advanced a great deal since Wainwright wrote the above statement in his study of obsidian sources and artifacts in the region of Egypt. Techniques now exist that can be used to identify the geologic source of obsidian artifacts with a degree of reliability undreamed of in Wainwright's day. With the exception of a few isolated efforts, these techniques of obsidian characterization have been largely developed over the last twenty years. A paper in 1964 by Cann and Renfrew concerning obsidian trade in the Mediterranean area marks the beginning of this modern period of obsidian characterization research. In that paper, the authors investigated several methods of characterization, eventually choosing the abundances of selected trace elements in the glass as the most discriminatory and reliable. Using the trace element composition of obsidian sources and artifacts, they sketched out preliminary routes of trade in the eastern and western Mediterranean region. This investigation, followed by several others by the same authors (Renfrew et al., 1965, 1966 and 1968), touched off a still continuing period of research in which artifactual obsidian has been characterized (most often using trace element analyses), its geologic source identified and this information used to reconstruct prehistoric patterns of trade and contact.

Though trace element abundances have often been used to characterize obsidian (see Part Four, Chapter Seven of this project), many other methods are also available (see Table 2). These other characterization techniques, while not as effective as trace element analyses in discriminating or distinguishing discrete sources of obsidian, are, nevertheless, important tools for archaeological research. Geochemical analyses require expensive analytical equipment and trained

Characterization Attributes

- Color
  - Opaque glass color
  - Powdered glass color
  - Translucent glass color
- Composition
  - Isotopic abundances in glass
  - Major element abundances in glass
  - Trace element abundances in glass
  - Trace element abundances in phenocryst inclusions
- Density of Glass
- Electrical Conductivity of Glass
- Fission-Tracks
  - Fission-track age of glass
  - Fission-track density in glass
  - U composition determined by fission-track analysis
- Fracture Characteristics of Glass
- Luster of Glass
- Magnetic Susceptibility of Glass
- Petrographic Characteristics
  - Accessory minerals present
  - Degree of crystallinity
  - Microlitic structures in glass
- Potassium-argon Age of Glass
- Refractive Index of Glass
- Spherulite Presence in Glass
- Thermoluminescence Characteristics of Glass
- Alpha and Beta Counting

Table 2 : Attributes that have proved successful or that have been suggested for the characterization of obsidian glass.

personnel, while many of the other characterization methods are much less expensive and less time-consuming to master. These less powerful techniques can also be combined to create a reliable obsidian characterization tool (see Appendix 11, this project).

Phyical, optical, petrographic or geochemical properties of obsidian must share two key qualities in order to be useful as attributes for characterization - they must exhibit a small degree of intraunit variability and a large degree of interunit variability. The characterization properties must be homogeneous within a source but must be heterogeneous between sources. Archaeological research has indicated that the trace element composition of obsidian (followed closely by the major element composition) best fulfills these qualifications. Most of the other properties of obsidian that can also be used to characterize the glass simply reflect the composition of the obsidian and can be considered to be dependent on the composition. They generally show, however, less intraunit homogeneity and intraunit heterogeneity. These methods of characterization are discussed later in this chapter.

Obsidian characterization as it is applied to archaeological problems is a tool - a means to an end. In the study of prehistory, this end lies in the value of obsidian to indicate prehistoric patterns of trade, contact and exchange and to shed light on the economic and social dynamics of long-vanished cultures. Cann and Renfrew (1964:111), in their initial article on obsidian characterization, summarize the value of reconstructing prehistoric patterns of trade:

> Evidence of contact between cultural groups is of great importance to the study of prehistory. Although the development of absolute dating methods has decreased our dependence on the discovery of such contacts

> for chronology, they are essential materials when the origin and spread of culture is being studied. In the past, cultural contacts have generally been demonstrated by typological similarities of artifacts, but...it can be exceedingly difficult to be certain of direct contact by this means alone.
> The importance in this respect of the study of raw materials used in places far from their origin and presumably deliberately imported has long been realized. Demonstrations of trading links made by such [characterization] methods, if based on a sure identification and a comprehensive survey of possible sources, are not open to the criticism and doubt which may be directed at typological similarities.

The reconstruction of exchange patterns, though, is only a step in the recognition and understanding of the cultural framework of trade and the function of exchange in a prehistoric culture (Earle, 1982). The analytical concepts used to understand and interpret the spatial patterning of exchanged obsidian are discussed in the last section of this chapter.

The validity of the utilization of characterized obsidian to initially reconstruct patterns of contact and exchange rests on several different assumptions:

1. The methods of obsidian characterization and artifact to source correlation are reliable and valid.
2. The processes responsible for the transport of obsidian from its primary to secondary contexts are cultural and are not attributable to other natural processes (discussed in Part Two, Chapter Three of this project).
3. The temporal structure used to organize the patterns of trade over time is reliable (beware, for example, of chronologies based only on obsidian hydration dating or the presence of only a few diagnostic projectile points).
4. The characterized obsidian is a representative sample of the total obsidian population present and accurately shows actual patterns of obsidian sources drawn on (the larger the sample, the more reliable are the results).
5. The human movement of obsidian from a geologic source to a spatially removed site does represent some sort of identifiable cultural process, whether that may be exchange or trade or some other cultural dynamic such as territoriality.

These assumptions, whether openly or tacitly acknowledged, must be met for obsidian characterization studies in archaeology to have real value. That these conditions often are not met is a subject discussed in more detail in Part One of this project. The last of these five assumptions is perhaps the most implicit of all. Just what does the spatial patterning of obsidian mirror? Perhaps the most valuable source of information for answering this vital question will come from the careful reexamination of ethnographic accounts describing the *observed* role of obsidian in cultural settings.

METHODS OF OBSIDIAN CHARACTERIZATION

There currently exist a variety of different techniques that have been used or that have the potential to be used to characterize volcanic glass. All of these methods measure some distinctive attribute or characteristic of obsidian that exhibits a large degree of intraunit homogeneity and interunit heterogeneity.

The success of any of these methods in characterizing a geologic source or artifact of obsidian is dependent, though, not only on the technique used but also on the degree of variation and the sheer number of sources found in a source universe. In a region where only a few geologic sources are found, attributes with a limited degree of discriminating power (such as color) in the characterization of obsidian may prove quite sufficient. When many sources are known to be found in a region, though, more reliable methods may be needed to adequately characterize or identify individual sources. On the other hand, even when a large number of sources are being considered, a few may possess very characteristic and easily determinable features (such as color or the presence of spherulites) that can serve to reliably distinguish them. The choice of the methods to be used in the characterization of the glass depends, then, not only on technological factors, but on a knowledge of the geologic characteristics of the sources that are available. No single method of obsidian characterization can always be said to be the best one in every situation.

The Color of Opaque Obsidian as an Attribute for Characterization

The color of an opaque specimen of obsidian was one of the first attributes that was used by archaeologists to characterize natural glass. Since the first reported use of obsidian color by Wainwright (1927) to assign a geologic source to archaeological obsidian, this attribute has been employed with varied degrees of success by archaeologists (Cann and Renfrew, 1964; Renfrew et al., 1965 and 1966; Cann et al., 1970; Ward, 1974a; Wheeler and Clark, 1977; Bettinger, 1982; Healan et al., 1983). Bettinger (1982) evaluated the reliability of color to distinguish a California obsidian source by characterizing a sample group of obsidian artifacts using both their color and trace element composition. He found a nearly total agreement between the two methods with only two specimens out of a total of 54 being incorrectly identified.

While some success has been reported using color as a characterization attribute, most archaeologists view the identification of the geologic source of an obsidian artifact using color alone as a risky exercise. Color should be used with caution as an indicator of the geologic source of natural glass.

The use of color as a characterization attribute is discussed in further detail in Part Four, Chapter Four of this project.

The Color of Powdered Obsidian as an Attribute for Characterization

The use of the color of powdered obsidian as a characterization attribute was first suggested by Boyer and Robinson (1956), who noted a distinctive difference in color between samples of obsidian and obsidian-like vitrophyre. It was also found during the preparation of obsidian samples for the investigation reported in Part Four of this project that different sources yielded different shades of powdered glass. These differences were found to be too small, though, to allow for the identification of individual sources or source groups of obsidian (see Part Four, Chapter Four of this project for further discussion of this method).

The Color of a Translucent Obsidian Flake as an Attribute for Characterization

That the color of a translucent flake of obsidian could be used to characterize a particular source was apparently first suggested by Wainwright (1927). The range of colors that are distinguishable in a thin flake of obsidian is considerably greater than it is in opaque specimens. The use of this attribute to characterize obsidian is discussed in Part Four, Chapter Four of this project.

Isotopic Abundances as Attributes for Characterization

Gale (1981), in determining $^{87}Sr/^{86}Sr$ ratios for obsidian from the Mediterranean region, found that the $^{87}Sr/^{86}Sr$ ratio, when plotted against the Rb abundance, effectively discriminated individual geologic source from among a group of sources. He also adds that Rb and Sr analyses, a byproduct of his investigation of Sr isotopic abundances to characterize obsidian, were sufficient by themselves to identify individual obsidian sources.

Major Element Composition as an Attribute for Characterization

Obsidian is composed almost entirely of a limited number of elements known as the major elements. These major elements, usually presented in weight percent oxides as SiO_2, TiO_2, Al_2O_3, MgO, Fe_2O_3, MnO, CaO, Na_2O, K_2O and P_2O_5, are found in relatively homogeneous concentrations throughout individual obsidian sources. There is often considerable variation, though, in the abundances of selected major elements among different sources, making possible the characterization of obsidian through the determination of its major element composition. While the degree of intraunit homogeneity and interunit heterogeneity is not as great as with the trace elements, facilities for major element analysis are more widely available and often more inexpensive than are those for trace element analysis.

The major element composition of obsidian has been used sporadically for many years to characterize obsidian artifacts and geologic sources. The first reported application was by Damour on Mesoamerican obsidian in 1865 (Harbottle, 1982). Following an exceptionally long hiatus, the method was again used, with only limited success, by Georgiades (1956 - results summarized by Cann and Renfrew, 1964). Since that time, research by Umschler (1975), Duerden et al. (1978) and particularly Michels (1982) strongly suggests that major element abundances may be used, albeit with some caution, to successfully characterize obsidian.

The use of major element composition as an attribute for characterization is discussed in more detail in Part Four, Chapter Seven of this project.

Trace Element Composition of Obsidian as an Attribute for Characterization

A large number of elements make up obsidian, but the bulk of these are present in very small quantities ranging from only a few parts per million to about a thousand parts per million. These trace elements, while existing in small abundances, are often remarkably homogeneous in their distribution throughout silicic bodies such as obsidian. Additionally, considerable variation is usually found among different flows and domes of obsidian, making the trace element composition of obsidian the most discriminatory of the many characterization techniques available.

Interest in the trace element characterization of obsidian began with the appearance of Cann and Renfrew's study of Mediterranean and Far East obsidian sources in 1964. Up until that time, interest in obsidian characterization studies of any type in archaeological research were infrequent. The article by Cann and Renfrew proved to be the forerunner of the many archaeological obsidian studies that have appeared since then. A sampling of the wide array of trace element combinations that have been used to characterize archaeological and geological obsidian can be seen in Table 3. The fact that obsidian characterization studies, most often using trace element analyses, are rapidly becoming regular components of archaeological research projects is probably directly attributable to the interest generated by the work of Renfrew and his associates in the 1960's.

The use of trace element abundances as an attribute for obsidian characterization is discussed in detail in Part Four, Chapter Seven of this project.

Trace Element Composition of Phenocryst Inclusions as an Attribute for Characterization

Obsidian is rarely totally glassy in texture and often contains microscopic and occasionally megascopic phenocrysts. Selected trace elements have been found to be preferentially incorporated into the various crystalline phases of a body of magma, resulting in phenocrysts that are richer in some elements than the magmatic liquid from which they are derived (Dudas et al., 1971). This partitioning of elements between the crystalline and liquid phases of a melt varies from source to source, making it possible to identify specific sources of rhyolitic and dacitic rocks on the basis of the trace element composition of certain mineral phenocrysts, specifically magnetite, hypersthene and hornblende (Dudas et al., 1973). All of these mineral phenocrysts are occasionally found in obsidian, making possible the characterization of individual sources of glass on the basis of the trace element composition of the included minerals. Though dacitic tephra has been characterized using this method (Dudas et al., 1973), the problem of separating phenocrysts from their glassy matrix in obsidian probably precludes the casual use of this technique in the characterization of natural glass.

Density as an Attribute for Characterization

That the density of obsidian might be used to characterize obsidian artifacts and sources was first suggested by Frankfort in 1927. Later work by Cann and Renfrew (1964) and Reeves and Armitage (1973 - also see Reeves and Ward, 1976 for a summary) further suggested that a limited use of the method in characterizing obsidian was possible, though there was considerable overlap in density among many sources. The determination of obsidian density is a simple procedure using very small amounts of glass and appears to be useful in distinguishing some broad source groups in different areas of the world.

The relationship of the chemical composition and density of obsidian and the use of obsidian as a characterization attribute is discussed, respectively, in Part Three, Chapter Three and Part Four, Chapter Four of this project.

Electrical Conductivity as an Attribute for Characterization

Kostakis (1982) reports that the electrical conductivity of obsidian from three proximate sources was identical at different temperatures. He concludes that, "Experimental determinations ...in the obsidians of the archaeologically imporoccurrences could give a possibility to locate the source areas of obsidian artifacts." Further research is needed to determine if sufficient interunit variability is present among different sources, a point not demonstrated in this study.

RATIOS	LITERATURE SOURCE
$CaO:Fe_2O_3$	Umschler,1975.
Na:Mn	Frison *et al.*,1968; Gordus *et al.*,1967; Gordus *et al.*,1968; Gordus *et al.*,1971; Griffin,1969a; Griffin,1969b; deMendoza, 1977; Patton and Miller,1970; Pires-Ferreira,1975; Pires-Ferreira, 1976; Wheeler and Clark,1977; Wright,1969; Wright and Gordus,1969a; Wright and Gordus,1969b; Wright *et al.*,1969.
$Na_2O:Sm$	Umscler,1975.
K:Mn	Reeves and Armitage,1973.
Sc:Mn	Wright,1969.
Mn:Fe	Hammond,1972.
Rb:Sr	Condie and Blaxland,1970; Gale,1981; Parks and Tieh,1966; Umschler, 1975.
Rb:Zr	Cobean *et al.*,1971.
Sr:Zr	Condie and Blaxland,1970; Umschler,1975.
Y:Nb	Cann and Renfrew,1964.
Zr:Ba	Cann and Renfrew,1964; Dixon *et al.*,1968; Hallam *et al.*,1976; Renfrew *et al.*,1965; Renfrew *et al.*,1966; Wright,1969.
Ba:Ti	Hammond,1972.
La:Sm	Umschler,1975.
F/Na:Al/Na	Bird and Russell,1976; Bird *et al.*,1978.
Be/Ca:Zr/Mn	Green *et al.*,1967.
Zr/Ca:Zr/Mn	Green *et al.*,1967.
Cs/Sc:La/Sc	Hallam *et al.*,1976.
$\frac{1}{Sc}(Cs+Ta+\frac{Rb}{100}+\frac{Th+La+Le}{10}):Fe/Sc$	Aspinall *et al.*,1972.
$Li+\frac{Ca}{100}+\frac{Mg}{10} : \frac{1}{2}Zr+Nb+Pb+\frac{1}{100}Fe$	Renfrew *et al*,1965
Ti:Mn:Ba	Nelson and Holmes,1979; Nelson *et al.*,1965.
Ti:Mn:Fe	Nelson *et al.*,1978.
Ti:Mn:Fe	Nelson and Holmes,1979; Nelson *et al.*,1978.
$MnO:Fe_2O_3/10:Ba$	Nelson and Voorhies,1980.
Mn:Rb:Sr	Stross *et al.*,1968; Stross *et al.*,1971.
Fe:Mn:Ba	Nelson *et al.*,1977.
Rb:Sr:Zr	Jackson,1971; Jackson,1973; Jackson,1974; Graham *et al.*,1972; Hammond,1972; Hester *et al.*,1972; Hester *et al.*,1975; Hughes, 1978; Jack,1971; Jack and Heizer,1968; Jack *et al.*,1972; Jackson and Schulz,1975; Nelson and Holmes,1979; Nelson *et al.*,1977; Nelson *et al.*,1978; Nielson *et al.*,1976; Sappington,1980a; Stross *et al.*,1968; Stross *et al.*,1971.
Rb:Zr:Ba	Sappington,1980a.
Rb:Sn:Nb	Sappington,1980b.
Sr:Y:Zr/2	Smith *et al.*,1977
Mn/Fe:Rb/Zr:Ba/Ti	Stross *et al.*,1971.

Table 3: Various two and three variable combinations of trace elements that have been used, with varied degrees of success, to characterize obsidian.

Fission Track Age as an Attribute for Characterization

As was mentioned in the previous chapter, the fission track age of obsidian can be used not only to determine the length of time since the extrusion of the glass, but also to characterize sources and artifacts. Similarly, fission track ages of artifacts can be used to indicate the number of different geologic sources that were utilized, even though the sources may remain unidentified.

The characterization of obsidian by the determination of its fission trace age does have two major limitations. Two or more geographically distant obsidian sources may have erupted at about the same time or eruptive activity at a source area may have taken place over a long period of time (Durrani et al., 1971). These weaknesses, while pointing out the need for a thorough geologic knowledge of an obsidian source area, are not likely to be serious in most instances. The use of the fission track geochronologic method to characterize artifactual materials has proven to be a generally reliable, if not often used, technique.

Archaeological applications of fission track analysis to determine the geologic sources of archaeological materials have not been extensive. Durrani et al. (1971 - see Anonymous, 1972, for a summary), Bigazzi and Bonadonna (1973) and Wagner et al. (1976) have carried out limited studies of Mediterranean area obsidians. The most extensive use of the method has been in Japan where characterized obsidian has been used to reconstruct prehistoric trade patterns (Suzuki, 1970, 1973 and 1974; Kaneoka and Suzuki, 1970). The presence of multiple geologic sources (not identified) of artifactual obsidian, as indicated by fission track age groupings, has also been noted by Miller and Wagner (1981) and Yegingil and Gokshu (1982).

Fission Track Density as an Attribute for Characterization

The density alone of fission tracks in obsidian can also be used to characterize the glass. Though the calculated fission track age of natural glass has been most often used to characterize obsidian, the use of the number of fossil tracks (those not induced by laboratory irradiation) counted per unit area has also been mentioned as adequate to sometimes distinguish among geologic sources (Bigazzi et al., 1974). The use of this method would eliminate the need for counting both fossil (original) and induced fission tracks, reducing the time needed to characterize the obsidian. This technique would also obviate the need for access to a nuclear reactor (typically, the neutron source used to induce fission tracks), making the technique available to a wide range of researchers.

Uranium Composition as an Attribute for Characterization

One of the byproducts of the application of the fission track geochronologic technique is that the Uranium content of the glass is easily determined as part of the geochronologic method (Suzuki, 1970). There is often enough variation among sources so that the U abundances alone may be used to identify the geologic source of an artifact or to suggest a limited group of sources (Suzuki, 1970 and 1973; Durrani et al., 1971; Leach et al., 1978). The use of the U content of obsidian to characterize the glass, as determined by other methods than fission track analysis, has been reported by Gale (1981), Wall (1976) and Ambrose (1976).

Fracture Characteristics as an Attribute for Characterization

Though all obsidians exhibit a characteristic conchoidal fracture, the amount of force required to detach a flake from a core of obsidian has been noted to vary from source to source (Crabtree, 1967). It may be possible to distinguish individual sources or groups of sources based on the compressive strength of the glass, though no attempts have been reported. Procedures for measuring the compressive strength of obsidian are described by Purdy (1974).

Luster as an Attribute for Characterization

Obsidian typically displays a vitreous, glassy luster, but occasionally sources with striking quantities of glass with a pearly, iridescent luster are found. Since this pearl-like luster is based on a physical characteristic (the presence of microscopic bubbles in the glass), rather than a compositional one, there may be considerable variability at a single source. Cann and Renfrew (1964), however, have suggested that luster can sometimes be used to characterize sources of obsidian, but only if the method is used with caution and in a limited geographic region.

Magnetic Susceptibility as an Attribute for Characterization

The iron content of obsidian is often a property that displays a large degree of intraunit variability coupled with a measurable variability among different sources (Nelson and Holmes, 1979; Sappington and Toepel, 1981). This characteristic makes it possible to characterize some sources of obsidian through the measurement of their magnetic susceptibility, a measure of the degree to which a rock is attracted to a magnet (Senftle and Thorpe, 1959; Leach, 1977a). The magnetic susceptibility of obsidian has been found, however, to sometimes exhibit a marked variability on a small scale. Senftle and Thorpe (1959) found that the magnetic susceptibility of a banded obsidian artifact was very high for the dark bands (high in Fe) and low for the light-colored bands (low in Fe). Almost no research has been reported in which magnetic susceptibility has been used to characterize obsidian, though some initial work by Leach (1977a), using New Zealand sources, suggests that the method is very promising.

Refractive Index as an Attribute for Characterization

The use of the index of refraction of obsidian to characterize the glass has met with mixed reviews by researchers who have employed the method. Frankfort (1927) first used this technique on archaeological obsidian with rather indeterminate results other than demonstrating that some variation between sources did exist. The next application of the method in determining the geologic source of archaeological obsidian was by Boyer and Robinson (1956). They found sufficient variation in the refractive index of a limited number of geologic sources to suggest the probable sources of artifactual materials recovered from sites in southern Colorado and New Mexico. Green (1962 - see Reeves and Ward, 1976, for a summary) reported some success in characterizing obsidian originating from New Zealand, though Cann and Renfrew (1964) did not consider the method worth pursuing in their study of Mediterranean obsidian. Cherry (1968), however, in a poorly-documented study of obsidian sources and artifacts from Oregon, concluded that the index of refraction could be used to characterize natural glass.

In summary, research into the use of the refractive index of obsidian to characterize the glass is still not complete. This is despite the fact that it is a relatively simple procedure that was first used with archaeological obsidian more than half a century ago. Further research is indicated.

The relationship of the chemical composition and index of refraction of obsidian is discussed in Part Three, Chapter Three of this project.

Accessory Minerals as Attributes for Characterization

The use of accessory minerals (phenocrysts) in obsidian to characterize the glass has been suggested by Boyer and Robinson (1956), though no archaeological applications of this possible characterization method have been reported.

Degree of Crystallization as an Attribute for Characterization

Ericson (1977:114,120; 1981:73) suggests that the degree of crystallinity (expressed in percent) of an obsidian might be used to characterize the glass. This technique has not yet been used in archaeological studies of obsidian, though it may prove useful when describing the amount of microlitic structures found in natural glass.

Microlitic Structures as Attributes for Characterization

Almost all obsidians, when examined with a microscope, are found to contain microscopic structures known as crystallites or microlites. These poorly-understood microlitic structures assume a large variety of different shapes and sizes and tend to be classified not on the basis of their chemical or mineralogic composition, but rather on the basis of their morphological characteristics.

Though the characteristics and genesis of microlitic structures are not well-known, some types appear to be relatively homogeneously distributed throughout individual sources of obsidian. This intrasource homogeneity , along with an observed degree of intersource heterogeneity, makes the presence or absence of certain varieties of microlites and crystallites an attribute for obsidian characterization.

The use of microlitic structures to characterize obsidian is discussed in more detail in Part Four, Chapter Six of this project.

Potassium-Argon Age as an Attribute for Characterization

Obsidian artifacts and sources could be identified using the age of the glass as determined by the potassium-argon or other isotopic geocheonologic methods. No mention of the use of isotopic geochronologic methods to characterize artifactual obsidian were found in the literature, however.

Spherulite Presence as an Attribute for Characterization

The presence of small spherulites has occasionally been used in an attempt to characterize obsidian, though little information is available as to the reliability of this technique. Evans used this method in 1921 to place the source of Minoan obsidian found in Crete at the Island of Lipari, but trace element studies over forty years later proved his conclusion incorrect (Cann and Renfrew, 1964; Renfrew et al., 1965).

Thermoluminescence Characteristics as an Attribute for Characterization

Several researchers have found that the shape and peak of thermoluminescence (TL) glow curves vary among different sources of obsidian and that TL characteristics can be used to characterize geologic and artifactual samples (Kashkarova and Hashkarov, 1969; Leach, 1977a; Huntley and Bailey, 1978; Yegingil and Gokshu, 1981). Leach (1977a) also reports that the glow curve is related to the trace element composition of the glass and that pronounced differences in TL glow curves were found using obsidians from New Zealand sources.

Alpha and Beta Counting as Attributes for Characterization

Uranium and Thorium are incorporated as trace elements in obsidians, their abundances ranging from 1 to 30 parts per million for U and 5 to 100 parts per million for Th. As these isotopes decay, alpha (α) and beta (β) particles are emitted in a quantity that is roughly proportional to the content of U and Th in the glass. Since these two elements typically show a significant degree of intrasource homogeneity and intersource heterogeneity, it is possible to characterize obsidian by counting the α or β emissions from the glass. Leach (1977a) and Leach et al. (1978) first used this method to count β emissions from obsidian originating primarily from New Zealand. They found that groups of obsidian sources could be clearly distinguished using the rate of their β emissions. They also reported that they were unable to distinguish source groups on the basis of α-particle emissions. Cormie (1981:91-92) and Cormie et al. (1982), on the other hand, were successful in identifying several sources of rhyolitic tephra when three sources were characterized by counting their α emissions. Some overlap in α emissions among sources was reported, though, likely making the counting of α emissions, as well as β emissions, best suited for distinguishing groups of potential obsidian sources rather than individual ones.

THE CORRELATION OF GEOLOGIC OBSIDIAN SOURCES AND OBSIDIAN ARTIFACTS

Once geologic sources and artifacts of obsidian have been characterized (through the measurement of one or more attributes), some method to correlate the artifact with its source must be found. An examination of archaeological studies utilizing characterized obsidian shows that this is inevitably accomplished using one of two different types of techniques, visual or statistical.

Visual Methods

Visual methods are employed in the correlation of three or less obsidian characterization attributes. These may reflect the physical and optical characteristics of the glass (index of refraction, density, etc.) as well as geochemical properties (major or trace element abundances). These attributes are compared on either one, two or three axes using linear, binary or ternary graphs or scatter plots.

The simplest of these visual methods is the linear plot, which compares the attributes on a straight line (with ranges of variation added). The linear plot is severely limited and not often used because even small degrees of variation in samples quickly lead to overlap as different sources are represented on the plot (a modified linear plot is pictured in Figure 41 of this project).

When two or three attributes are used for correlation, the differences between sources are visually displayed on the scatter plots, individual sources being indicated by clustered data points on the graph. The source of the artifactual obsidian is then visually determined by the source cluster that the obsidian characterization data falls into. Binary and ternary scatter plots have been widely used in archaeological obsidian characterization studies and are an effective way in which to correlate obsidian sources with artifacts when only a few characterization attributes are being considered. These scatter plots may become difficult to interpret due to visual overcrowding, however, when large numbers of data points are present. Several examples of binary and ternary scatter plots appear in Part Four, Chapters Four through Seven, in this project.

Statistical Methods of Correlation

When more than three attributes are used in the correlation of geologic obsidian sources and artifactual obsidian, statistical methods must be used. This is often the case when multiple trace element abundances have been used to characterize the glass. The most commonly used of these statistical methods is discriminant function analysis, a multivariate technique making possible the assignment of samples of unknown provenience to those of known sites or sources. The first reported use of this technique to correlate obsidian sources and artifacts was by Ward (1972; 1974b) in his study of New Zealand obsidian, though the sources of rhyolitic tephra had earlier been identified in the 1960's through the application of the discriminant function analysis method. Since Ward's study, a number of other researchers have also begun to use the method and its popularity among archaeologists using trace element concentrations to characterize obsidian seems on the rise (Findlow et al., 1975; Ramirez, 1976; Allen and Ramirez, 1977; Ericson and Kimberlin, 1977; Sidrys, 1977b; Nelson et al., 1978; Nelson and Holmes, 1979; Sappington and Toepel, 1981; Sappington, 1982; Toepel and Sappington, 1982).

A variety of computerized discriminant function analysis programs are now available (see Harbottle, 1982:26-31, for a discussion), the most frequently used in recent years for archaeological research being the SPSS subprogram, DISCRIMINANT (Nie et al., 1975:434-467). This subprogram, combining variables in a stepwise fashion, is useful not only in being able to calculate the probability that a sample of unknown provenience (artifact) originated from a given source, but in determining the value of each variable (trace element, in most applications) as a discriminating function.

The use of other statistical methods for the classification of archaeological obsidian has been discussed by Kowalski et al. (1972) and de Bruin et al. (1976).

It is clear that while statistical methods of correlation offer powerful ways in which to manipulate large quantities of complex data, the same statistical techniques can provide self-defeating results. Nie et al. (1975:3) caution:

> The wide dissemination of statistical packages such as SPSS, containing large numbers of complex statistical procedures, have, almost overnight, made these techniques available to the social science community. There is little doubt that social scientists are using them, and there is equally little doubt that in many instances statistical techniques are

> being utilized by...researchers who understand neither the assumptions of the methods nor their statistical or mathematical bases. There can also be little doubt that this situation leads to some "garbage-in, garbage-out" research. The statistical procedures in SPSS have little ability to distinguish between proper and improper applications...

Ward (1977) has also argued that similarities between artifacts and sources (whether statistically determined or not) are, by themselves, not adequate criteria for the identification of the geologic sources of artifactual material. He writes (1977:192):

> ...geochemical or petrographic similarity is insufficient argument for a similar source; but characterizational dissimilarity *is* a good argument for difference in geographic source. In other words, the 'identification' of sources of material can be made suggestively but not absolutely; confidence in such tentative identification is gained from rejection of the other possible identifications that can occur within a universe of possibilities which is sometimes difficult to delimit.

It is not enough, then, to show that a similarity exists between an artifact and its geologic source, but that the artifact is also dissimilar from other members of a universe of possible geologic sources. This points to problems that currently exist in many archaeological studies, that the universe of possible obsidian sources being considered may be incomplete (sometimes grossly so), that the sources may be inadequately represented and that the source universe may be too geographically restricted. In an area, for example, such as the State of Oregon, with its proclivity of natural sources of obsidian, any obsidian characterization studies of artifactual material will have to be considered as preliminary and somewhat tentative until a good deal more geologic study has been focused on the sources of natural glass.

THE RECONSTRUCTION OF PREHISTORIC PATTERNS OF CONTACT AND EXCHANGE

Many archaeological obsidian characterization studies have discussed characterization methodologies and technologies or have identified the probable geologic sources of obsidian artifacts. Another large fraction of these studies have also attempted to identify or suggest possible routes of trade that may have been used in the exchange and trade of obsidian.

But, once the geologic source of an obsidian artifact has been determined and a trade route suggested to tie together the source and the artifact, what next? Assuming that geological and geomorphological investigations of the primary obsidian sources have eliminated modes of transport other than human ones (see Part Two, Chapter Four), what does the human movement of obsidian indicate when placed in a cultural context? What cultural processes are reflected in the patterns of obsidian exchange that are identified through the characterization of natural glass?

To answer these and other related questions it is necessary to move out from the perspective of the individual find or site and to examine characterized obsidian from a regional perspective. Only then can large-scale patterns of regional interaction emerge and only then can obsidian characterization studies be used to reconstruct or infer the political, economic, sociological or geographic factors that influenced the distribution of natural glass.

The archaeologist who attempts to describe patterns of exchange using obsidian is faced with three tasks: the identification of the geologic sources of the artifactual obsidian; the description of the spatial patterning of the glass and the reconstruction of the organization of the exchange system (Earle, 1982). The first of these steps is carried out using the techniques described earlier in this chapter to characterize obsidian (though a few studies have been made, under special circumstances, utilizing obsidian that was not characterized - see Sidrys, 1977a, and Findlow and Bolognese, 1980). The second and third stages are the subject of the remainder of this chapter.

Definition of an Exchange System

Access to obsidian sources by prehistoric peoples can be assumed to have taken place through two processes, direct access and exchange system access. The procurement of natural glass by direct access simply means that the user or user group obtained obsidian at a geologic source and then carried it to the site where the glass was utilized. Exchange system access infers that the obsidian was exchanged or traded from social group to social group and that the spatial distribution of the utilized obsidian reflects the operation of an exchange system. Ericson clarifies this last point (1977:146-147):

> The geographic distribution of obsidian, originating from a specific source, which is the consequence of the process of exchange and utilization, and its subsequent deposition in the archaeological record, is referred to...as a *regional exchange system*. It is important to note that the spatial distribution of the obsidian is not a system but rather it is the consequence of a system. Nevertheless...if we are to study regional exchange systems, we must treat the spatial distributions of exchange items as systems, which will allow us to study their structural characteristics, internal organization, diachronic stability, and cultural interrelationships.

The evidence provided by characterized obsidian of the existence of extinct exchange systems is, however, quite indirect and is subject to influences by many variables. The question of whether the presence of artifactual obsidian long distances from an identified source represents exchange or whether it reflects long-distance direct access is also a problematical and somewhat thorny issue. Archaeologists have attempted to approach this problem from the standpoint of the efficiency of raw material procurement methods. Ericson (1977:156), for example, argues: "...there is increased energy cost of acquiring items through direct access rather than through exchange which would favor the development of a regional [exchange] system."

Variables Affecting Exchange Systems

Exchange systems or networks exhibit a variety of characteristics that are of interest to archaeologists. These include: the *content* of the network (the raw materials being traded); the *magnitude* of the network (the quantity of materials exchanged); the *diversity* of the network (the variety of goods exchanged); the *size* of the network (the territory involved); the *temporal duration* of the network; the *directionality* of the network (whether goods move one way or both ways in the system); the *symmetry* of the network (whether more goods flow one way than another in the system); the *centralization* of the network (where resources are substantially greater at some point in the system than others) and the *complexity* of the network (the degree of variation in all the previously mentioned characteristics) (Plog, 1977).

These characteristics of exchange systems are affected and controlled by many different environmental, socioeconomic and political variables. The spatial distribution of an exchange commodity (in this case, obsidian) is, of course, determined by these same variables. Conversely, the variables that have operated in the past to shape the structure and pattern of an exchange system are themselves reflected by the spatial patterning of the archaeological obsidian that is later recovered and identified. It is through the determination of large-scale regional patterns of obsidian distribution that these cultural influences can be identified or at least inferred.

A number of variables have been suggested as influencing the characteristics of exchange systems and the patterns of the ensuing obsidian distribution. These include:

1. *The location of alternative sources of lithic materials.* The source of obsidian that is exploited by a group is usually the one that is closest to them (though this utilitarian situation may not always be the case). It follows, then, that when the energy cost of obtaining obsidian from a source becomes too high and alternative sources are available, those other sources will be utilized (at the expense of the old source)(Ericson, 1977 and 1981; Zeitlin, 1982). Ericson (1977:189; 1981) found, for example, that the presence of obsidian at sites in California decreased abruptly where alternative (and closer) sources of chert became available. Sidrys (1977b) also noted that the nearest source was not used at some Mesoamerican sites and cited political or aesthetic factors as influencing obsidian distribution. It also follows that the fewer the number of competing or interacting sources there are in a region, the less difficult and more straightforward will be the analysis of the data.
2. *The location of trails.* It would be expected that trails would act as lines along which obsidian would be transported and distributed. Ericson (1977: 183-186) found that artifactual obsidian distribution in California did indeed coincide with the locations of identified trails.
3. *The location of navigable streams or rivers.* It would be expected that streams or rivers would provide an efficient means of moving obsidian through an exchange network. The movement of obsidian by boat has been suggested in the Near East (Cann et al., 1968) and in Mesoamerica (Hammond, 1972; Johnson, 1976).
4. *The presence of ethnolinguistic boundaries.* Acting as a dependent variable (reflecting cultural affiliations and territorial boundaries), ethnolinguistic boundaries would be expected to coincide with obsidian exchange networks. Interestingly, Ericson (1977:189-190; 1981) found this not to be the case in his study of California exchange systems.

5. *The distance from the obsidian source.* Some of the most innovative research and analysis of prehistoric exchange systems has involved the relationship of obsidian frequency and source distance. Renfrew (1977: 72) summarizes the relationship: "When a commodity is available only at a highly localized source or sources...its distribution in space frequently conforms to a generalized pattern. Finds are abundant near the source, and there is a fall-off in frequency or abundance with distance from the source." That distance is an important variable influencing the spatial distribution of natural glass has been demonstrated in a number of archaeological studies (Renfrew et al., 1968; Pires-Ferreira, 1975; Pires-Ferreira and Flannery, 1976; Ericson, 1977 and 1981; Renfrew, 1977; Findlow and Bolognese, 1980 and 1982). Attempts to quantify and identify patterns of obsidian "fall-off" as a function of distance have also been made by several investigators. Their results will be discussed shortly.

6. *Population stability and mobility.* Stable populations are more likely to develop exchange systems in order to procure distant raw materials. Transhumant groups such as those that existed in the Great Basin of the United States might be expected to procure many of their lithic raw materials during their seasonal rounds (Ericson, 1977:248; 1981). It follows, then, that the use of characterized obsidian to reconstruct prehistoric contact and exchange systems will be most successful when applied to stable populations such as those that are known to have existed in western Oregon and California.

7. *Population density.* The higher the population density in an area, the more likely would be the evolution and development of complex exchange networks (Cobean et al., 1971; Pires-Ferreira, 1975; Pires-Ferreira and Flannery, 1976).

8. *The presence of physiographic barriers.* Topographic barriers such as open stretches of water and mountain ranges would be anticipated to influence the direction of movement of obsidian from a source and this does often seem to be the case. Ericson (1977:189; 1981) found, though, that the lack of alternative sources of lithic materials *is* an overriding factor over physiographic barriers. This has been most dramatically illustrated by the discovery of archaeological sites and sources separated by considerable distances of open water. The ocean or sea transport of obsidian has been documented in California (Jack, 1976), in the Mediterranean (Cann and Renfrew, 1964; Renfrew et al., 1965, 1966 and 1968; Dixon et al., 1968), in Oceania (Key, 1968 and 1969; Ambrose and Green, 1972; Ambrose, 1976b; Smith et al., 1977) and in Japan (Suzuki, 1974).

9. *Sociopolitical boundaries or restrictions.* A sudden drop-off in the frequency of obsidian originating from a specific source has been interpreted by some archaeologists to mark territorial or political boundaries (de Mendoza, 1977:88; Bettinger, 1982; Zeitlin, 1982; Condie and Blaxland, 1970). On the other hand, the distribution of obsidian from a single source throughout different cultural groups suggests the possibility of socioeconomic affiliations and some degree of contact.

10. *Site function.* Different archaeological sites may have served different functions and only sites where similar activities were undertaken would be expected to produce similar lithic assemblages (Findlow and Bolognese, 1980; Zeitlin, 1982). A habitation site, for example, would yield an artifactual assemblage quite distinct from a hunting camp where only a limited range of activities was carried out. In their analysis of obsidian from New Mexico sites, Findlow and Bolognese (1980) overcame this difficulty by limiting their analysis to a specific site type, the habitation site.

11. *Cultural preference.* Though the nearest obsidian source was the one that was most often used by prehistoric populations, cultural preferences, such as for specific colors or for superior tool-making qualities, may have sometimes influenced the choice of sources (Zeitlin, 1982). Similarly, cultural taboos may have influenced which obsidian sources were exploited. Heizer and Treganza (1944: the Bertrand Ranch source) and Ericson (1976a) mention that obsidian from Mono Craters was considered "toxic" to aboriginal groups in California.

12. *Post-occupational disturbance.* Site disturbance, either through natural processes or human intervention, may significantly skew the type of obsidian artifacts recovered for analysis (Findlow and Bolognese, 1980).

13. *Sociopolitical structure.* The presence of socially stratified or ranked cultures may also act as a significant variable influencing the spatial distribution of natural glass. Differential acquisition of obsidian resources because of the presence of central places or differences in status would be represented by anomalous spatial patterning of artifactual obsidian. Zeitlin (1982) has pointed out, for instance, that ceremonial centers during the Classic period in Mesoamerica received a higher per capita allotment of obsidian than lower order settlements even though the centers were sometimes farther removed from the geologic sources of the glass. The pooling of obsidian (and subsequent redistribution) has also been used to infer the possibility of lineage or moiety control of obsidian (Pires-Ferreira and Flannery, 1976; de Mendoza, 1977:103,118) and to suggest social differentiation in a local context (Winter and Pires-Ferreira, 1976).

14. *Trade network bifurcation.* The branching of trade networks has also been cited as a factor influencing the distribution of obsidian (Ericson, 1977: 173; 1981).

15. *Sampling error.* Patterns of regional obsidian utilization are, of course, only as informative as the obsidian sample is representative of the glass actually present. Obsidian studies that rely on small sample sizes or that do not attempt to differentiate site function at sampling locations are liable to lead to conclusions as imaginative as they are inaccurate.

In summary, there are many variables that can influence the spatial patterning of obsidian throughout a region. Research concerning the importance of individual influences is still in its early stages as are the analytical methods used to interpret the distribution of the obsidian

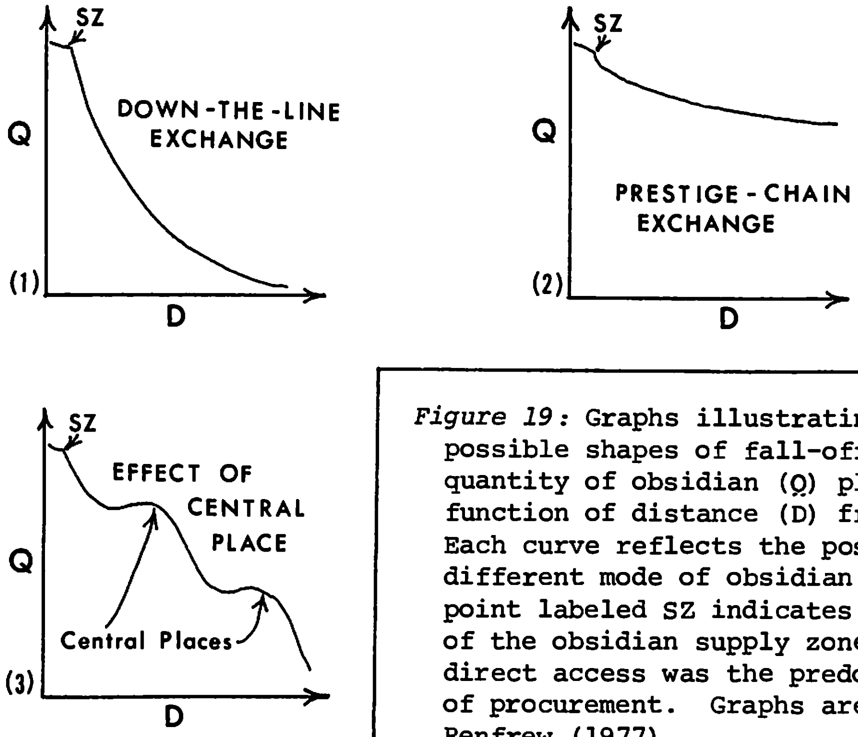


Figure 19: Graphs illustrating some of the possible shapes of fall-off curves of the quantity of obsidian (Q) plotted as a function of distance (D) from a source. Each curve reflects the possibility of a different mode of obsidian exchange. The point labeled SZ indicates the boundary of the obsidian supply zone in which direct access was the predominant means of procurement. Graphs are adapted from Renfrew (1977).

Analytical Methods

Two major methods of data analysis are currently being used to interpret the regional distribution of obsidian, the distance-decay model and synagraphic map analysis.

Distance-decay. The distance-decay model, first proposed by Renfrew et al. in 1968, graphically compares the quantity of obsidian (expressed as an absolute or relative abundance index) as a function of the distance from a geologic source. This technique is illustrated in Figure 19. Renfrew and his associates, in the 1968 and later studies, attempted to identify the nature of the exchange system on the basis of the resultant fall-off curve. Simple group-to-group, "down-the-line" exchange was interpreted to result in an exponential obsidian fall-off past the boundaries of the obsidian supply zone (Figure 19-1). A low slope curve was interpreted to reflect a high-prestige or high-value component of the obsidian traded, a "prestige-chain" exchange (Figure 19-2). The influence of central places was expected to produce a curve similar to that in Figure 19-3. The nature of these and other distance-decay curves is discussed in detail by Renfrew (1977).

The next step in the development of the distance-decay model was the regression analysis of the data - the identification of the equation which would best describe fall-off curve. It was hoped that specific equations would be representative types of exchange systems (Renfrew et al., 1968; Renfrew, 1977; Sidrys, 1977a; Findlow and Bolognese, 1980 and 1982).

This two-dimensional analysis of obsidian patterns worked relatively well in the study of Near Eastern obsidians by Renfrew and his colleagues because the obsidian was transported unidirectionally, from north to south (Pires-Ferreira, 1975; Zeitlin, 1982). In other areas of the world where multiple sources of obsidian are distributed throughout a region (such as in the Far West of the United States), though, the distance models used by Renfrew et al. run into problems. They assume a spatial symmetry to the obsidian with the source as the focus and in only a few instances has this situation been shown to actually exist (Ericson, 1977 and 1981; Zeitlin, 1982). As Ericson (1977: 172) details: "...in two-dimensional analysis *only* the magnitude of an observation and its distance from a source is considered. The spatial position of an observation is not considered in its local context, so that this simplification often masks significant variability in the data." Hodder (1982) also objects to the use of formalistic approaches such as regression analysis because of the problems in trying to identify patterns apart from their social context. These problems and limitations led to the development of a three-dimensional analytical technique, synagraphic mapping.

Synagraphic mapping. Synagraphic mapping methods, first applied to the obsidian analysis of California exchange systems by Ericson in 1977, has seen only limited applications to date (Ericson, 1977 and 1981; Findlow and Bolognese, 1980 and 1982).

Synagraphic mapping is a three-dimensional representational method in that it exhibits (using computer-generated graphics) obsidian frequencies as contour lines, much as a topographic map shows elevation as contour lines. This technique, described in detail by Ericson (1977 and 1981), illustrates the spatial patterning of exchanged items, the directionality and degree of symmetry of exchange systems, regional trends, local trends and spatial anomalies. Ericson, using synagraphic mapping, found that obsidian distribution patterns were not symmetrical around California sources, that trails coincided with obsidian fall-off gradients and that physiographic barriers such as mountains did not prevent source exploitation when alternative sources were not available. Once obsidian distribution data has been plotted on a synagraphic map, it is then possible to speculate, on the basis of the morphology of the system (such as extension or compression) on the effects or existence of the exchange system variables previously discussed.

Diachronic Variations in Obsidian Spatial Distribution

The variation of regional patterns of obsidian distribution over time is perhaps the most important and least-understood indicator of cultural exchange processes. A comprehension of the diachronic stability or instability of spatial patternings of natural glass can provide some revealing clues as to the nature of the exchange systems that were operating.

Chronological depth to obsidian distribution studies is usually provided through radiocarbon dates of materials from stratum containing obsidian. Occasionally, obsidian hydration measurements have been used, either alone or in conjunction with radiocarbon geochronologic methods (Ericson, 1977, 1981 and 1982)(The use of obsidian hydration geochronologic techniques, though, demands a cautious attitude on the part of both researcher and reader - see the previous chapter for a discussion).

Changes through time in the spatial distribution of archaeological obsidian and diachronic shifts in the sources being exploited could be explained by a variety of variables related to time. These include:

1. *The improvement of routes of access to some obsidian sources* (Zeitlin, 1982).
2. *The replacement of obsidian foot transport by movement by boat* in areas where rivers and streams were available (Zeitlin, 1982). Similarly, the introduction of new travel technologies, such as the sea canoe, could influence patterns of transport over time (Sidrys, 1977a; Renfrew, 1977).
3. *The increase of population density in intermediate areas,* a change that would modify existing patterns of exchange and contact (Zeitlin, 1982).
4. *The depletion of a source of obsidian* (Zeitlin, 1982). Though many sources of obsidian are extensive, small deposits of glass or heavy utilization of a source over a long time period may completely exhaust a source. This situation has been noted in Washington State by Weld (1962).
5. *The consolidation of trade systems in the interest of efficiency* (Zeitlin, 1982).
6. *The evolution of increasingly complex forms of social, political and social organization* in the groups exploiting the obsidian sources. This is suggested by Findlow and Bolognese (1980) in their study of New Mexico obsidian: "It is suggested that movement towards increasing societal stratification promote a concomitant movement from a linear direct access exchange system to a directionally oriented one keyed into the hierarchial arrangement of the local settlement system." The appearance of central places or redistributional centers and the degree of social complexity implied in the existence of these centers would also be reflected by changing or anomalous patterns of obsidian (Sidrys, 1977a). Patterns of exchange among band level-egalitarian groups would be expected to be different than those of ranked societies such as chiefdoms in which resource distribution plays a significant role (de Mendoza, 1977; Zeitlin, 1982). A simple increase through time in the number of sources being utilized at a site certainly suggests an expanded and diversified economy in which exchange may have played a significant role (Nelson and Voorhies, 1980).
7. *The changes in sociopolitical and economic relationships within and between groups or societies involved in the exchange network* (de Mendoza, 1977:92; Zeitlin, 1982). Obsidian pattern shifts have been used in Mesoamerican archaeological research to suggest the emergence of a culture group (specifically Kaminaljuya) as a dominant regional economic center and to infer the possibilities of successful and unsuccessful attempts of territory takeovers from other groups (Hurtado de Mendoza, 1977:91-92).

At the very least, diachronic shifts in obsidian patterns can be used as indicators of change in the inter- and intraregional interactions between culture groups. Other aspects of social, political and economic behavior are also inferred by the changing patterns of obsidian distribution - further research will hopefully reveal the internal cultural processes that are reflected by these changes.

An Investigation of Selected Methods of Obsidian Characterization Utilizing Obsidian Collected at Prehistoric Quarry Sites in Oregon

1 An Introduction to the Investigation

Though methods of obsidian characterization are becoming increasingly important in archaeological research today, there are still several problem areas that must be addressed before these studies can be considered truly reliable. These extant problems, discussed in detail in Part One of this project, include a marked lack of systematic investigation of the obsidian characteristics, or attributes, that can be used to discriminate among or "fingerprint" different obsidian sources.

Development of the different techniques used in the characterization of geological and archaeological obsidian has come almost entirely through the archaeological utilization of these methods. While there is no question that reliable information about the geological sources of archaeological obsidian could be used to infer extinct patterns of contact and exchange, there still must remain some doubt about the reliability of the obsidian characterization techniques currently in use. The cart has proceeded the horse, in a sense, in the development of the obsidian characterization methods.

The investigation that is reported in this part of the project was designed to examine systematically the usefulness and reliability of several techniques of obsidian characterization. To this end, seven attributes for characterization were chosen (Table 4), as well as were ten geologic sources of obsidian in Oregon (Figure 22).

The attributes for study were selected for a variety of reasons.

Trace element characterization, the most popular technique currently in use, has been assumed to be valid by most researchers, but has still not been ade-

ATTRIBUTES

1. Color
   - Powdered Glass
   - Opaque Hand Specimen
   - Thin Flake
2. Density
3. Microscopic Petrography
   - Presence or Absence of Glass Shards
   - Presence of Microlitic Structures
4. Chemical Composition
   - Major Element Abundances
   - Trace Element Abundances

Table 4 : Obsidian characterization attributes selected for study in this investigation.

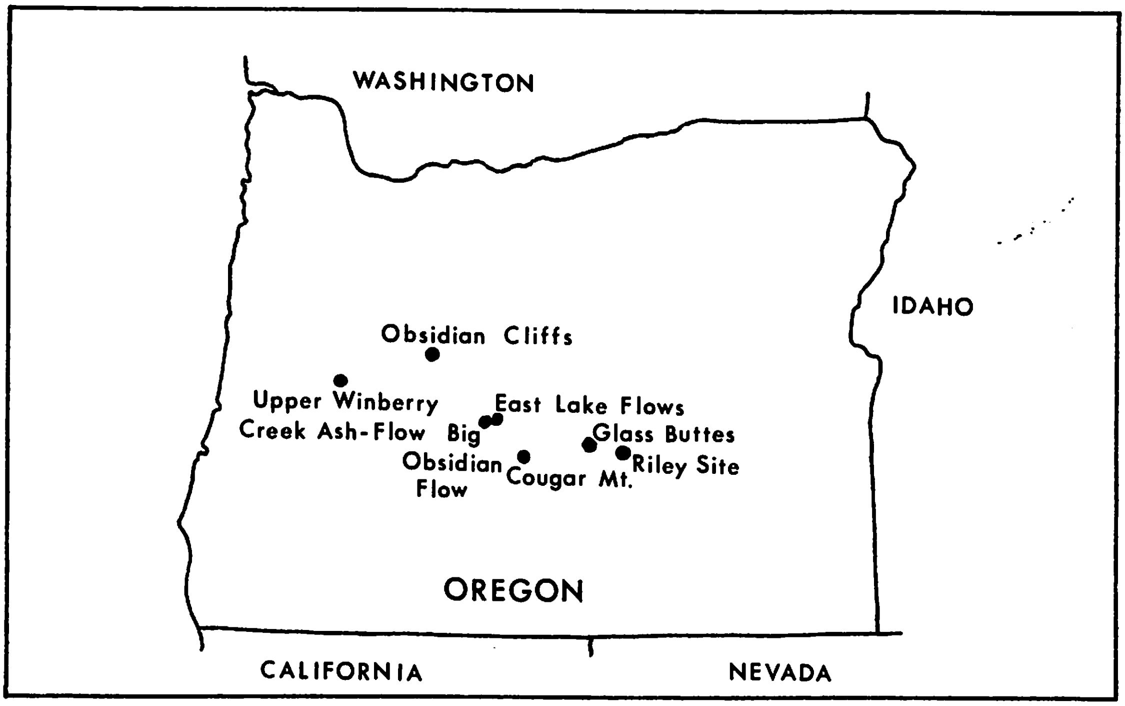


Figure 22: Location of obsidian sources in Oregon that were selected for study.

quately tested in a controlled context. The verification of the reliability of this method would attest to the reliability of the research that has used trace element characterization, provided that other methodological conditions (discussed in Part One) are also met.

The use of major element abundances to characterize obsidian has also been suggested, but has seen little application in archaeological research. It was decided, then, to examine the effectiveness of differences in major element composition as a discriminating agent in the characterization of obsidian sources. Facilities for the determination of major element abundances are often more available (and less expensive) than those needed for trace element analysis. The availability of a reliable major element obsidian characterization method might provide a useful tool for archaeological research, particularly for the contract archaeologist.

While an obsidian sample may be characterized *directly* through the determination of its chemical composition, it may also be possible to characterize the obsidian *indirectly* through the determination of physical or optical properties that reflect composition. Two of these properties, density (specific gravity) and color (of opaque, translucent and powdered obsidian), were chosen as attributes for examination in this study. While a few attempts have been made to characterize obsidian through its color and density, no systematic studies have been made. These two attributes are easy and inexpensive to determine and it was felt that even if only limited use could be made of these attributes in obsidian characterization, they would warrant inclusion in this study.

The last of the attributes used in the characterization of obsidian in this project was the structure and form of microscopic microlitic structures that are often found in rhyolitic obsidian glass. The characterization of obsidian through the identification of microlitic structures has been suggested by a few authors, though no examples of its use in archaeological research are found in the literature. This method of characterization is relatively easy to accomplish, requiring only the preparation of a thin section of obsidian and the availability of a microscope.

The remainder of Part Four of the project that follows concerns itself with the description of the methods used for characterization of the obsidian, the geological and archaeological features of the obsidian sources sampled and the results of the research that was carried out.

2 Obsidian Source Sample Locations

One of the first problems of the research described in Part Four of this project was to choose ten Oregon obsidian sources among the many possibilities in the state for sampling. The selected areas, described in some detail in the remainder of this chapter, were chosen so as to represent a variety of the contexts in which obsidian is found - recent and erosionally-modified obsidian flows, primary and secondary obsidian sources, geographically proximate and widely-separated sources, rhyolite-obsidian domes and obsidian-like vitrophyre from welded ash-flows. Specific sample localities at each source are indicated on the map that accompanies the aerial stereo pair of each source.

A stereoscope is normally required to obtain the three-dimensional effect produced by the pair of aerial photographs. It is possible, however, to examine all the aerial photographs in this chapter stereoscopically without the use of a stereoscope. This can be done by looking at the pair of photographs and letting the eyes fall out of focus until the two photographic images merge, producing a stereoscopic effect. This method is described by Compton (1962:79-80) and is surprisingly effective, once mastered.

Obsidian Sources	Sec.	T.	R.	County
1. Obsidian Cliffs	15 19	16S. 16S.	8E. 8½E.	Lane
2. Upper Winberry Creek	20	19S.	2E.	Lane
3. Big Obsidian Flow	1	22S.	12E.	Deschutes
4. Eastern East Lake Obsidian Flow	32	21S.	13E.	Deschutes
5. Western East Lake Obsidian Flow	32	21S.	13E.	Deschutes
6. Cougar Mountain	24	25S.	15E.	Lake
7. Glass Buttes Site 35 LK 304	23-24	23S.	22E.	Lake
8. Glass Buttes Site 35 LK 306	23	23S.	22E.	Lake
9. Glass Buttes Site 35 LK 337	15	23S.	22E.	Lake
10. Riley Site	19	24S.	27E.	Harney

Table 5 : Location of the obsidian sources sampled for the project.

The collection of ten obsidian sources chosen for sampling is listed in Table 5 and represents a reasonably good cross-section of the contexts in which obsidian occurs. The only major omission is that of obsidian found associated with perlite deposits - Oregon sources were not located until after the sampling phase of the research was completed. An intriguing secondary source of obsidian, also located after sampling was completed, was found in western Oregon in the Willamette Valley and is described in Appendix Five.

THE OBSIDIAN CLIFFS OBSIDIAN SOURCE

Obsidian Cliffs is located in the Three Sisters Wilderness Area of Oregon's High Cascades about 4.8 km (3 miles) west-northwest of the summit of North Sister. The cliffs and the plateau above them (see Plates 13 and 14) that define this large obsidian flow are accessible by trails which begin near Highway 242 to the west. The nearest trailhead is about 6.7 km (4.2 miles) distant. The Obsidian Cliffs flow is located at an elevation of 1830 m (6000 feet) and, owing to the heavy snowfall and winter closure of Highway 242 (the McKenzie Pass Highway), can be visited only from June through October. Wilderness permits are required for travel in the Wilderness area.

Geologic Setting of Obsidian Cliffs Flow

70 to 90 m (230 to 300 foot)-high cliffs of rhyolite and obsidian mark the northwest end of the 2.4 km (1.5 mile)-long rhyolite and obsidian flow that originated near the western base of the North Sister. The prominent cliffs (Plate 13) give this flow its name. Above the cliffs is a sloping, glacially-scoured plateau that reaches to the vent area at an elevation of 2130 m (7000 feet).

The first mention of the Obsidian Cliffs flow was by C.E. Dutton in 1889 (p.162) who wrote:

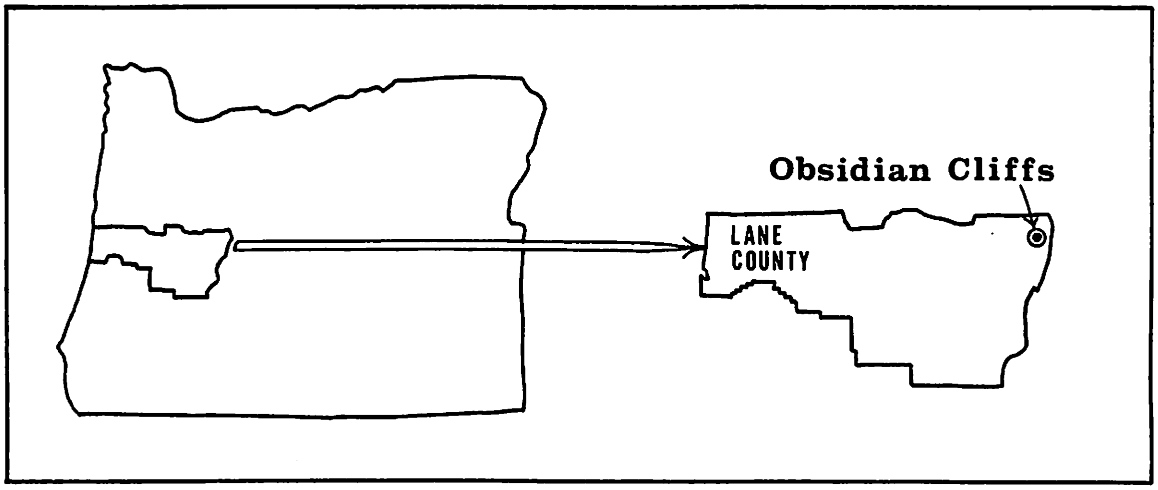


Figure 23: Location of Obsidian Cliffs , Lane County, Oregon.

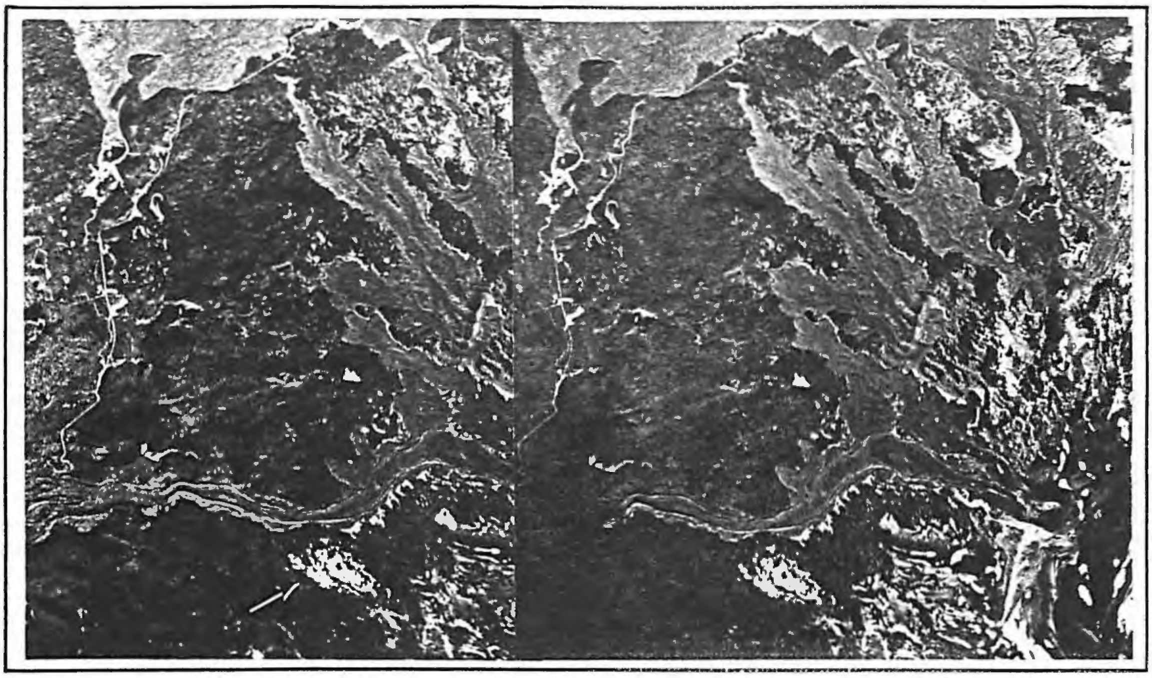


Plate 12: Aerial stereo pair of Obsidian Cliffs and the McKenzie Pass region. The Obsidian Cliffs Obsidian Flow, located near the bottom center of the photographs, is bordered on the north by a recent lava flow with well-developed levees. 1 cm = approximately 1.1 km. (U.S. Army Corps of Engineers, 1955).

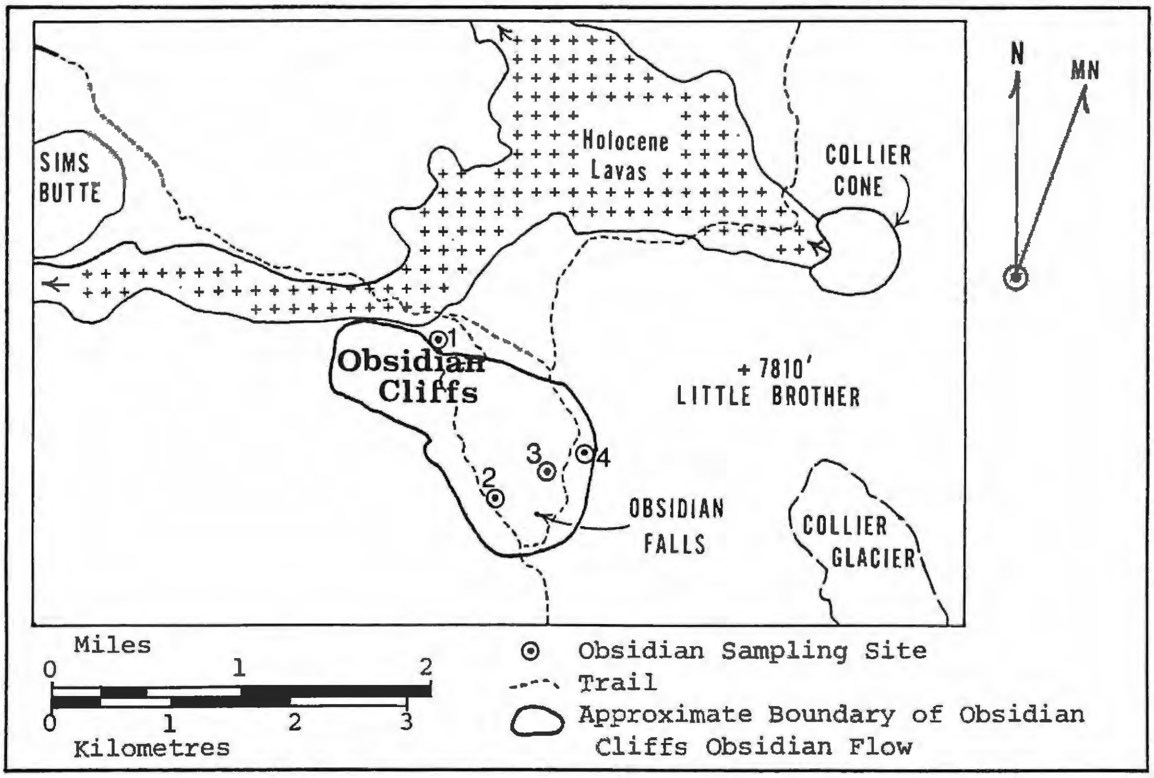


Figure 24 : Sketch map of the Obsidian Cliffs area, High Cascades. The map is adapted from a geologic map by Peterson and Groh (1965).

> There are large masses of obsidian, many of which present those spherulitic concretions which are so characteristic of the acid lavas of Yellowstone Park. In many places the same lavas show a curious admixture of the highly glassy with the lithoid form, and the two are intermingled in thin, contorted bands from a few millimeters to a few inches in thickness, and thoroughly kneaded together.

The spherulitic structures that Dutton describes are typical throughout the flow. All outcrops examined during the sampling of this flow were very spherulitic. Only the obsidian surface float that has weathered out of the rhyolitic matrix of the flow is free of spherulites. The striking spherulites and outcrops of obsidian-rhyolite breccia (see Plate 4) are also mentioned in two later brief geologic summaries of the Obsidian Cliffs flow by Williams(1916:85-90) and Campbell (1923:21-22).

The first formal geologic study of the Obsidian Cliffs area was made by Hodges, who described the obsidian flow as a glaciated mass of rhyolite, rhyolite vitrophyre and black obsidian (Hodges, 1925:103-108).

The next, and last, geologic study of this area was by Williams, who perhaps best described the Obsidian Cliffs flow (1944:48):

> A large mass of glassy [rhyolite] also escaped from fractures at an elevation of about 7,000 feet, forming a tabular sheet bordered by walls up to 300 feet in height, referred to as Obsidian Cliffs. Much of this [rhyolite] , particularly the surficial and distal portions, consists of black obsidian, though the bulk is composed of pale, gray pumicieous lava. Here and there, the two varieties are finely interlaminated; elsewhere, they alternate with spherulitic and lithophysal bands. That the [rhyolite] was extremely viscous is manifest not only from the abruptness with which the thick flows came to an end, but also from the intense convolution of the banding and the autobrecciation.

Outcrops of the spherulitic obsidian and rhyolite are most frequent at the borders of the flow and in the upper part near the vent. The top of the flow, now a glaciated plateau sloping upward towards the Middle Sister, is covered in many areas by obsidian nodules. The entire area is blanketed by a layer of tephra, probably originating from either Mount Mazama or from a nearby vent at the South Sister now covered by the Rock Mesa Obsidian Flow.

The major and trace element composition of rhyolitic obsidian from Obsidian Cliffs appears in Anttonen (1972:92; see Table IV-1, this appendix), as well as in Chapter Six of this part of the project.

The age of the Obsidian Cliffs flow is not known, though it is most certainly Pleistocene. McBirney (1968b:101) has reported that the entire sequence or rocks at the Three Sisters is normally polarized and is younger than about 700,000 years in age, the time of the last reversal. The last major glacial period, the Wisconsin, recognized locally as the Cabot Creek Advance, has been studied by Scott (1974:63-66; 1977) at Mount Jefferson, 65 km (40 miles) to the north of Obsidian Cliffs. Scott places the age as late Wisconsin or very late Pleistocene, setting the minimum age of Obsidian Cliffs at this point.

Plate 13: Obsidian Cliffs. These 90 m-high cliffs of mixed obsidian and rhyolite mark the western end of the Obsidian Cliffs Obsidian Flow. Taken facing southwest from the top of the very recent Collier Cone basaltic andesite flow.

Plate 14: The Obsidian Cliffs Obsidian Flow appears in the center of the photograph as a large lobe projecting westward from near the base of the Middle Sister. The glaciated plateau on top of the flow is littered with nodules and outcrops of obsidian. Sims Butte lies 2.4 km directly behind the flow. Taken facing west from the summit of the Middle Sister.

The glacier that swept over the Obsidian Cliffs flow extended west down the Lost Creek Valley to the McKenzie River. Taylor reports (1968:15) that during the latest Wisconsin glaciation, this canyon was completely full of ice and overflowed the north rim, depositing morainal obsidian down at least one adjacent valley. Obsidian nodules can be found today on the Lost Creek Valley floor and in exposures of glacial till near the intersections of Highways 126 and 242 (Taylor, 1968:14).

The glacially-transported obsidian found its way into the McKenzie River and was carried farther west into the Willamette Valley, creating a secondary obsidian source in the gravels of the McKenzie and Willamette Rivers. Obsidian pebbles from the McKenzie River gravels on the southeastern edge of the Willamette Valley have been geochemically characterized and found to originate from Obsidian Cliffs (White, 1974:220;1975:171). Sanford (1975:229) also mentions that obsidian is available from the gravels of the Willamette River at the upper end of the Willamette Valley.

Archaeological Setting of the Obsidian Cliffs Source

Little is known of the archaeologic features of the Obsidian Cliffs source. Minor and Pecor (1977:138) mention its existence as an archaeological site, but say nothing else. Hopson (1946:327) writes: "Indians knew of this deposit and visited it, as is evidenced by the numerous obsidian arrowheads and spearpoints that have been picked up in close by the meadows [on the plateau on top of the flow]."

The Obsidian Cliffs flow lies close to a natural pass over the central Cascades (Newman, 1966:2), making it a convenient stop for prehistoric travelers crossing over into central Oregon or the Willamette Valley. The Scott Trail, an early pioneer trail that crossed the Cascade Divide close to Obsidian Cliffs, was reputed to have followed an Indian trail on the south side of the lava fields immediately north of the North Sister (Minor and Pecor, 1977:155).

Bennett and D'auria (1974) and Nelson et al. (1975)report on research in which the trace element characterization of obsidian artifacts from British Columbia indicated a geologic source at the Three Sisters, probably Obsidian Cliffs. Very few geologic sources were included in their source universe, though, and the results of their studies should be treated cautiously.

Recent investigations of archaeological obsidian from a southeastern Willamette Valley site, the Halverson Site (35 LA 261), also indicate that Obsidian Cliffs was a major source of obsidian in the valley (Toepel and Sappington, 1982). 53% of the obsidian assemblage found at this site was identified, through its trace element composition, as originating from Obsidian Cliffs.

Another recent study also points to the use of obsidian from the Obsidian Cliffs source east of the Cascades. Several obsidian artifacts from the Lava Island Rockshelter, 10 km (6 miles) south of Bend and 35 km (22 miles) from Obsidian Cliffs, have been identified as originating from the North Sister obsidian source (presumably Obsidian Cliffs)(Sappington, 1982). One temporally-diagnostic broad-necked projectile point originating from Obsidian Cliffs was recovered, suggesting that the Obsidian Cliffs source was being utilized at least 2000 years ago (Minor and Toepel, 1982:80-81).

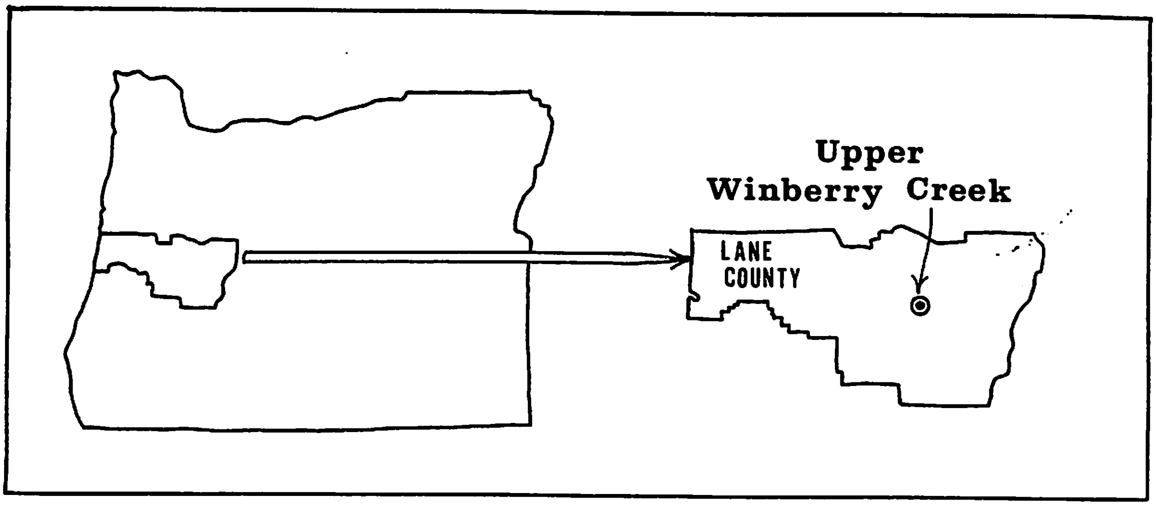


Figure 25: Location of the Upper Winberry Creek welded ash-flow, Lane County, Oregon.

THE UPPER WINBERRY CREEK ASH-FLOW AND OBSIDIAN-LIKE VITROPHYRE SOURCE

A welded ash-flow next to Upper Winberry Creek was sampled as part of this investigation and is found exposed in a road cut on the north side of U.S. Forest Service Road 1802 about 1.6 km (1 mile) east of the entrance to the Winberry Creek Campground. Access to the area, located in the Willamette National Forest 14 km (9 miles) east of the town of Lowell at an elevation of about 300 m (1000 feet) is only occasionally blocked by winter snowfall. The ash-flow that is exposed in the road cut includes a black, obsidian-like zone that was sampled for this study.

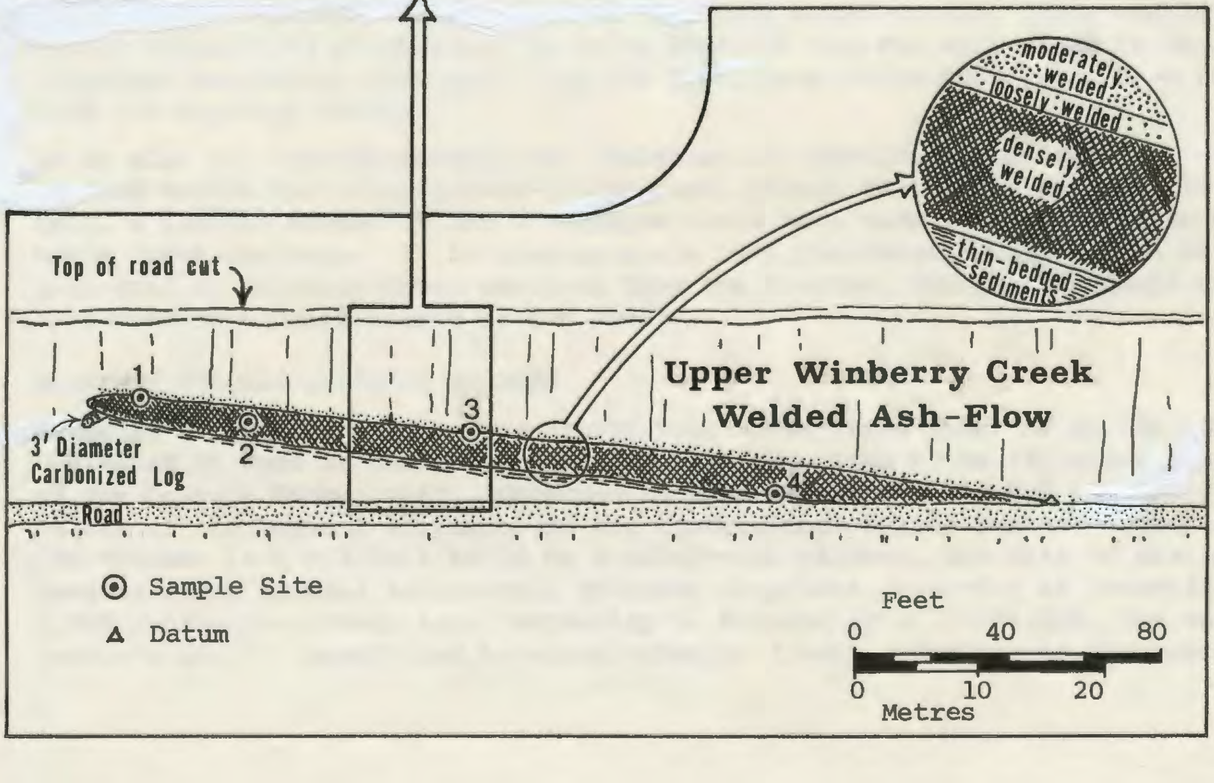
Geologic Setting of the Upper Winberry Creek Vitrophyre Source

The welded ash-flow exposed in the road cut alongside Winberry Creek consists of a black, glassy, densely-welded aone at the base of the ash-flow unit that directly overlies thinly-bedded pond or lake sediments. Carbonized wood can be found near the contact point of the ash-flow and the sediments and one log nearly 1 m in diameter is exposed in the western end of the road cut. The densely-welded zone is about 3 m (10 feet) thick and is overlain by a loosely-welded zone approximately a metre thick. Above this loosely-welded zone to the top of the roadcut is a tan-colored, moderately-welded zone of the same ash-flow. The ash-flow dips to the north about 10 degrees and it is likely that the obsidian-like part of the flow was exposed, prior to its excavation, in a bank about 20 m (65 feet) above Winberry Creek. The areal extent of the obsidian-like component is not known, though it is probably limited. Ashworth (1951:18) mentions that small lake and pond deposits were found in Oligocene tuffs only a few kilometres north of the Upper Winberry Creek ash-flow exposure and that they were limited in size.

The only geologic field work in this area was done by Ashwill (1951), who mapped and described the adjoining township (T.19S., R.1E.). He reported occurrences of welded tuff in Secs. 15, 16 and 22, T.19S., R.1E., about 6 km (4 miles) northwest of the Upper Winberry site, and lists their ages as lower Oligocene to upper Miocene. Whether these welded tuffs (ash-flows) are equivalent to the Upper Winberry Creek ash-flow is not known, though it is possible.

Plate 15: The Upper Winberry Creek welded ash-flow. The circled and barely-visible rock hammer marks the top of the densely-welded zone of the ash-flow. This black, obsidian-like zone is overlain by a lighter-colored less-welded zone. The bottom of the 3 m-thick densely-welded zone and the thin-bedded sediments that it overlies are covered are covered by talus in this photograph but are visible in other exposures in the road-cut.

Figure 26 (below): Sketch of the road cut exposure of the welded ash-flow unit pictured in the plate to the left. From a compass and rangefinder survey by the author.



The occurrence of an obsidian-like zone at the base, rather than at the center, of an ash-flow, is unusual, but not rare, and can be easily explained by the context of the ash-flow. The presence of thinly-bedded sediments and of carbonized wood directly under the ash-flow indicates direct contact of the ash-flow with a lake or pond. What happened next is best detailed by McBirney (1968a), in his description of a similar phenomenon in Nicaragua:

> Although the immediate base of the sheet was strongly chilled, the interior, which still retained a large amount of heat, absorbed water vapor steaming up through the fractured base. Because the rate of inward diffusion of water exceeded outward diffusion of heat, the water content of the rocks became high enough to depress the melting point until it intersected the steep temperature gradient. There followed a brief period of refusion...

This refusion of the base of the ash-flow created the densely-welded black glass now found at the Upper Winberry Creek exposure.

Archaeological Setting of the Upper Winberry Creek Vitrophyre Source

That the obsidian-like glass of the Upper Winberry Creek ash-flow was ever utilized as an archaeological resource is not certain. The flaking characteristics of the vitrophyre are not particularly good and the quality of tools made from this material would be limited. Several shallow archaeological sites were reported by Cole (1968) during excavations in the nearby Fall Creek Reservoir area. The artifactual material recovered from these sites is stored at the Museum of Natural History at the University of Oregon and was examined by the author. A graver from site 35 LA 33 *may* have originated at the Upper Winberry Creek vitrophyre source, though positive identification was not attempted because of the damage to the artifact that this would entail. This single artifact (classified as obsidian by Cole, 1968:19) was the only piece in the artifactual assemblage recovered from the Fall Creek sites that could have come from the ash-flow source.

It is also not certain whether the obsidian-like portion of the ash-flow was exposed before the construction of the road, though it is likely. If this is true, a limited amount of the vitrophyre would have made its way into the Winberry Creek drainage. It is also possible that the densely-welded zone is intersected by Winberry Creek upstream from the roadcut, though this could not be confirmed in a brief search of the area.

NEWBERRY VOLCANO OBSIDIAN SOURCES

Newberry Volcano is a large Quaternary Volcano centered about 32 km (20 miles) southeast of Bend in central Oregon. The volcano lies 60 km (40 miles) east of the Cascade Range crest. Covering an area of nearly 1300 km^2 (500 mi^2), it is one of the largest volcanoes in the conterminous United States. Surmounting the volcano is a 6.5 to 8 km (4 to 5 mile)-wide caldera, the site of East and Paulina Lakes as well as numerous Holocene eruptions occurring as recently as 1,300 radiocarbon years ago. According to MacLeod et al.(1981:85), the volcano consists of, "...basalt and basaltic andesite flows, andesitic to rhyolitic

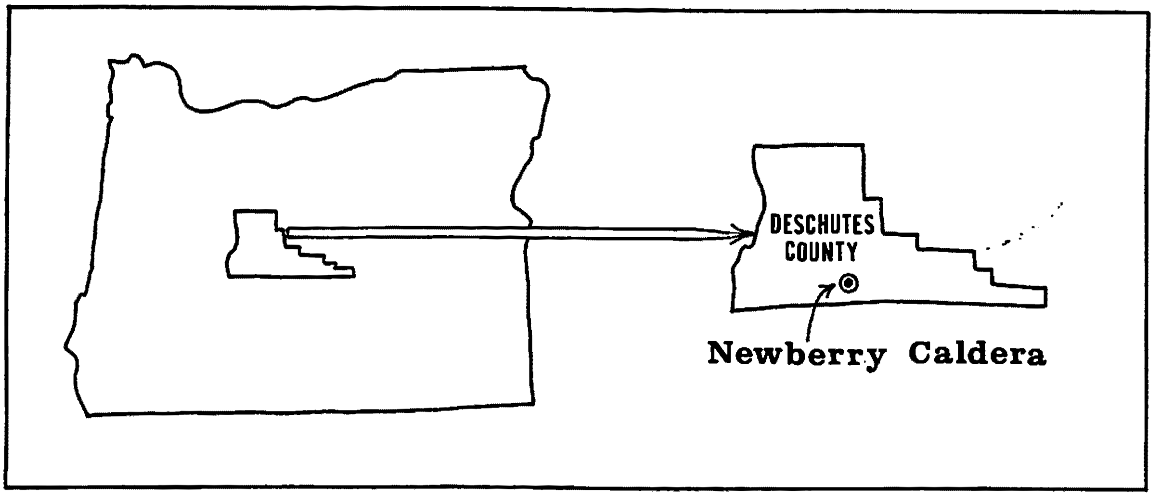


Figure 27: Location of Newberry Volcano and Newberry Caldera, Deschutes County, Oregon.

ash-flow and air-fall tuffs and other types of pyroclastic deposits, dacite to rhyolite domes and flows, and alluvial sediments produced during periods of erosion on the volcano."

The caldera area of the volcano, at an elevation of about 1935 m (6350 feet), is generally accessible from the west from May through November. The main highway is paved, but not plowed during the winter when heavy snowfalls typically cover much of the volcano.

Geologic Setting of Newberry Volcano

Newberry Caldera, first visited by Europeans in 1826 (Linck, 1945:97), has been investigated by several geologists since that time. Israel C. Russell visited the volcano as part of a horseback reconnaissance of eastern and central Oregon in 1903 and was the first to describe the geology of the volcano (Russell, 1905:97-110). He misinterpreted the summit caldera as a glacial structure. Howel Williams later undertook the first comprehensive geologic investigation of the volcano, concentrating on the caldera and the younger flows on the northwest flanks. Most later geologic investigations also focused on the spectacular caldera area and the Holocene basaltic andesite flows on the flanks of the mountain (Peterson and Groh, 1965 and 1969; Higgins and Waters, 1967, 1968 and 1970; Higgins, 1968, 1969 and 1973; Beyer, 1973; Peterson et al., 1976).

The next, and most recent, phase of research was initiated by interest in the geothermal potential of Newberry Volcano. During this period, beginning in 1976, the flanks of the volcano were mapped for the first time in detail and geothermal exploration wells drilled on the volcano. This recent mapping and research has been reported by several authors (Anonymous, 1979 and 1980; MacLeod, 1978; Sherrod and MacLeod, 1979; MacLeod et al., 1981 and 1982; Black, 1982; MacLeod and Sammel, 1982).

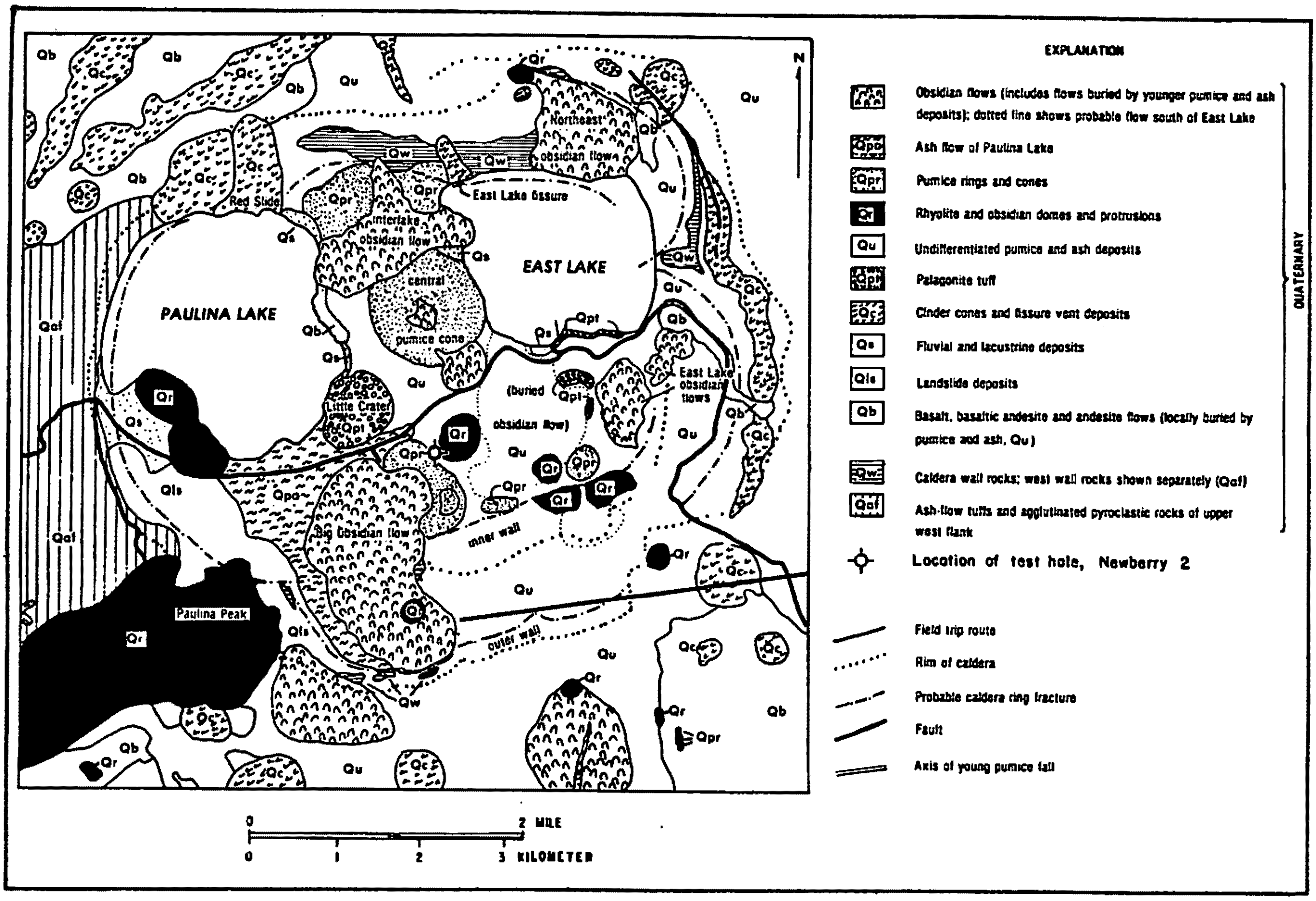


Figure 28: Geologic sketch map of the Newberry Caldera area, Deschutes County, Oregon. Map reproduced from MacLeod and Sammel, 1982.

Sources of obsidian are abundant in the summit caldera and on the upper flanks of Newberry Volcano. Three of these flows, the Big Obsidian Flow and the two East Lake obsidian flows, were sampled as part of the investigation reported in this project. MacLeod et al.(1982:6) report the existence of six post-Mazama obsidian flows within the caldera, as well as several more pre-Mazama flows and domes inside or near the caldera (see Appendix Four for details).

Archaeological Setting of the Newberry Caldera Sources

The prehistory of the Newberry Caldera area is almost unknown. Several small sites have been located on the flanks of the volcano within 25 km (15 miles) of the caldera (Cressman and Perry, 1938; Osborne, 1950; Combes, 1961; Ice, 1962; Dudley et al., 1979; Minor and Toepel, 1982; Loring and Loring, 1982; also see Appendix Six, this project). Though the information from the limited archaeological research carried out in this area is still incomplete, it appears that the occupation in the general area of Newberry Caldera may date back at least 10,000 years with possible cultural affiliations with the northern Great Basin and the Columbia Plateau (Minor and Toepel, 1982).

Plates 16 and 17: Panorama of the Big Obsidian Flow and the southern half of the summit caldera of Newberry Volcano. The near skyline is the approximate boundary of the caldera rim. East Lake is in the middle background. This obsidian flow is the most recent volcanic event in the caldera and is about 1,300 radiocarbon years old. The vent of the Big Obsidian Flow, marked by a raised dome or spine (left center of the right-hand plate), was also the source vent for an earlier eruption that spread a narrow lobe of tephra more than 80 km to the east. Taken facing east from near the summit of Paulina Peak.

Within the caldera, obsidian artifacts have been found and minor sites reported on the shores of East and Paulina Lakes, but no formal archaeological study has been carried out (Dana , 1932; Brogan, 1960; Beckham, 1976; U.S. Forest Service, 1978:531). A single historical account places Snake Indians in the caldera in about 1873 (Stern, 1965:270). A less reliable source mentions that the East Lake Hot Springs on the southern shore of East Lake had been used by the Indians for medicinal purposes (Linck, 1945:62).

The extent of the prehistoric distribution of obsidian from the many sources on Newberry Volcano is only now beginning to be reconstructed. Sappington and Toepel (1981), using trace element characterization methods, determined the probable source of 167 obsidian artifacts collected along a transect running north from near Silver Lake in the northern Great Basin to the Maupin area. They found that 46 artifacts, largely found in the Silver Lake area, appeared to have originated from Newberry Caldera (though the source is not specified). Of these 46 specimens, temporally-diagnostic projectile points among them indicated that the caldera was used as an obsidian source from early, pre-Mazama times. The same authors also identified the source of several artifacts recovered from pre-Mazama levels in the Fort Rock and Connley Caves as the caldera.

In a more recent investigation at the Lava Island Rockshelter, located at the northwestern base of Newberry Volcano, 52% of the obsidian artifacts recovered were found to have their geologic source at Newberry Caldera. Several early style projectile points were among these, indicating again that the caldera has been a favored source of lithic material over a long period.

One of the most fascinating accounts of Indian use of obsidian from this area is an ethnographic account related by Gould (1966:61). Though it is not known whether the source mentioned was at Newberry Volcano, it was clearly close by:

> Sam Lopez [an Indian informant] described how his father had been engaged in a regular overland trade for obsidian from the vicinity of Bend, Oregon. Much of this material was brought down the Klamath, too, mainly by Hupa, Karok, and Yurok traders. The material was held in such esteem by the ethnographic Tolowa [a group on the northwest California coast] that it was reserved mainly for very large and finely-worked double-pointed blades...used only in ceremonial displays. Such a high value was placed on these objects that the dancer displaying one during a ceremony would generally tie it to his wrist...to avoid dropping it...during the dance. The material was traded to the historic Tolowa in large blocks.

Ethnographic and archaeological data suggest, then, that Newberry Volcano has been a major source of obsidian from early, pre-Mazama periods to historic times. Archaeological study and characterization of the obsidian sources from Newberry Volcano are still in their early phases, though. Sappington, currently the major investigator in obsidian characterization research in Oregon, mentions only one characterized source out of the many available (Sappington, 1981). In a geologic study germane to the archaeological study of caldera obsidian, MacLeod et al.(1982:6) write of the rhyolitic obsidian flows there: "Chemical similarities suggest that all the young relatively evolved rhyolites are derived from the same magma, even though erupted over an interval exceeding 6,000 years. Chemical differences, though slight, suggest the SiO_2 and K_2O

content is systematically lower for progressively younger rocks and that systematic changes also occur for other major oxides and trace elements."

More extensive geochemical characterization of the Newberry obsidian may make it possible, because of these systematic differences, to identify individual sources within the caldera. It may also be possible to assign sources to currently characterized samples of artifactual obsidian to which no geologic source is currently known.

The Big Obsidian Flow

The Big Obsidian Flow, located in the summit caldera, is the most recent volcanic event found on Newberry Volcano. The existence of this obsidian flow was first acknowledged by Russell in 1904 and was described in some detail by him in 1905. Howel Williams (1935:274-275), though, provides the best description:

> By far the largest of the obsidian flows, and the youngest, lies to the south of the inter-lake road and covers almost exactly a square mile. Composed, for the greater part, of glistening, black, obsidian blocks...it forms an outstanding feature of the landscape.
>
> The vent of the 'Big Obsidian Flow' lies close to the steep south wall of the caldera, and is now occupied by a dome partly enclosed by an earlier cone of pumice. From this vent, at an elevation of about 7,100 feet, the lava poured northward for more than a mile... and terminated in an abrupt front, up to 100 feet in height.
>
> The surface of this great flow is traversed by large blocky ridges and deep furrows. Viewed from such vantage point as the lookout station on Paulina Peak, the ridges appear as concentric waves most encircling the vent like a race-track...

The obsidian flow is well-illustrated in Plates 1, 16, 17 and 18 and has been described by several other authors (Russell, 1905:107-110; Peterson and Groh, 1965:11-17; Higgins and Waters, 1967; Higgins, 1968:231-238; Peterson et al., 1976:29).

The radiocarbon age of the Big Obsidian Flow is about 1,300 years, placing it as the most recent volcanic activity in the caldera (Pearson et al., 1966; Tamers, 1969; Kelley et al., 1978; MacLeod et al., 1982). The extrusion of the Big Obsidian Flow was preceded by an ash-flow eruption that deposited ash, lapilli and blocks of accidental fragments as far north as the shore of Paulina Lake (Libby, 1952; MacLeod et al., 1982). About 300 years prior to the eruption of the latter two closely-spaced events, the same vent was also the source of a single eruption of tephra that spread to the east in a narrow lobe (Higgins, 1969; Doak, 1969;51; Spiker et al., 1978; MacLeod et al., 1982). The compositions of the Big Obsidian Flow, the ash-flow and the tephra are identical (MacLeod et al., 1982).

The major and trace element composition of the Big Obsidian Flow is also very well-documented. Few other comparable units in the world have had their chemical composition as thoroughly studied as this flow (Williams, 1935:295; Green, 1965:40; Laidley et al., 1968; Jack and Carmichael, 1969; Osborn and Schmitt, 1970; Laidley and McKay, 1971; Higgins, 1973; Murase and McBirney, 1973;

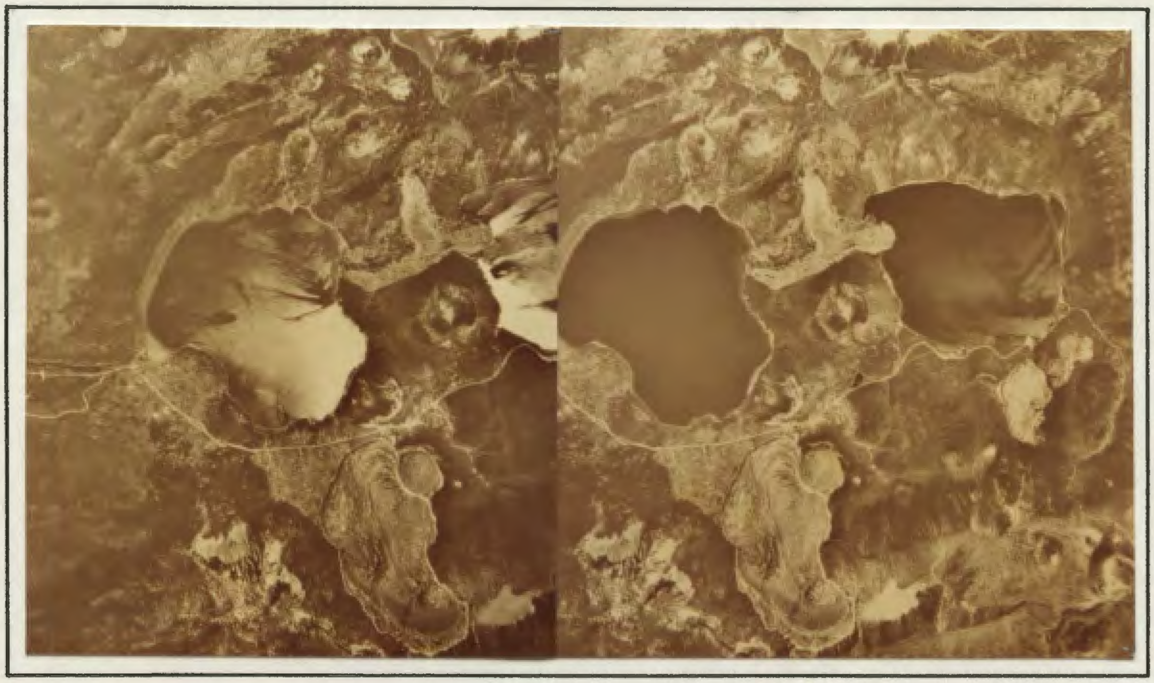


Plate 18: Aerial stereo pair of the western portion of Newberry Caldera. The Big Obsidian Flow stretches from near the southern wall of the caldera north nearly to Paulina Lake. 1 cm = approximately .95 km. (U.S. Army Corps of Engineers, 1954b).

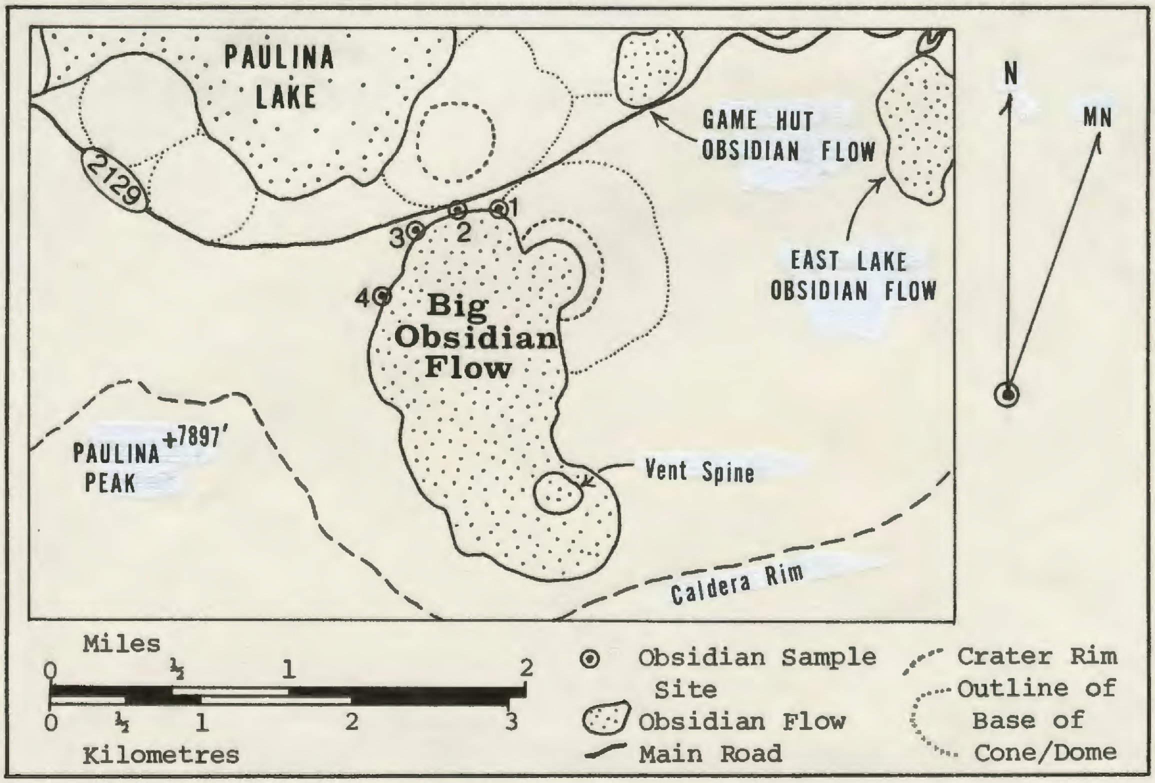


Figure 29 : Sketch map of the Big Obsidian Flow, Newberry Caldera. This flow moved north from a vent near the caldera wall, partially filling the crater of an older cone. The map is adapted from a geologic map by Higgins and Waters (1967).

Beyer, 1973:18; see Table VI-1, Appendix Four of this project, for analyses). The Big Obsidian Flow has proved to be remarkably homogeneous, particularly in its trace element composition.

This obsidian flow has been a favorite source of obsidian for a variety of research projects. Nichols (1941) attempted, with little success, to calculate the velocity of the flow as it was extruded. Green (1965) used obsidian from the flow in his research on possible lunar sources of water. Murase and McBirney (1973) used obsidian from this source as part of their study of the high temperature behavior of igneous rocks. Osborn and Schmitt (1970) used the obsidian flow to examine the chemical homogeneity of large silicic bodies. Leich (1974) and Lee et al.(1974) used naturally and artificially hydrated obsidian from the Big Obsidian Flow in their work on the measurement of hydrogen depth profiles. Obsidian thermoluminescence characterization studies were made by Huntley and Bailey (1978). Finally, the glass was used by Friedman and his associates in their research on the hydration dating of obsidian (Friedman, 1977; Friedman and Long, 1976; Friedman and Trembour, 1978; Friedman and Obradovich, 1981). The Big Obsidian Flow, a very accessible obsidian source, has attracted a retinue of researchers.

The East Lake Obsidian Flows

The two East Lake obsidian flows were erupted, probably contemporaneously, from a fissure vent on the south wall of the caldera. The westernmost of the flows is the largest with a length of about 1 km (.6 miles), while the eastern flow is less than half that length. About 1 m of tephra from the vent now

Plate 19: East Lake Obsidian Flows. The easternmost of the two flows (ELB) is in the background while the westernmost flow (ELA) is in the foreground. The two flows are separated by about 100 m at this point. Taken facing east from atop the western obsidian flow.

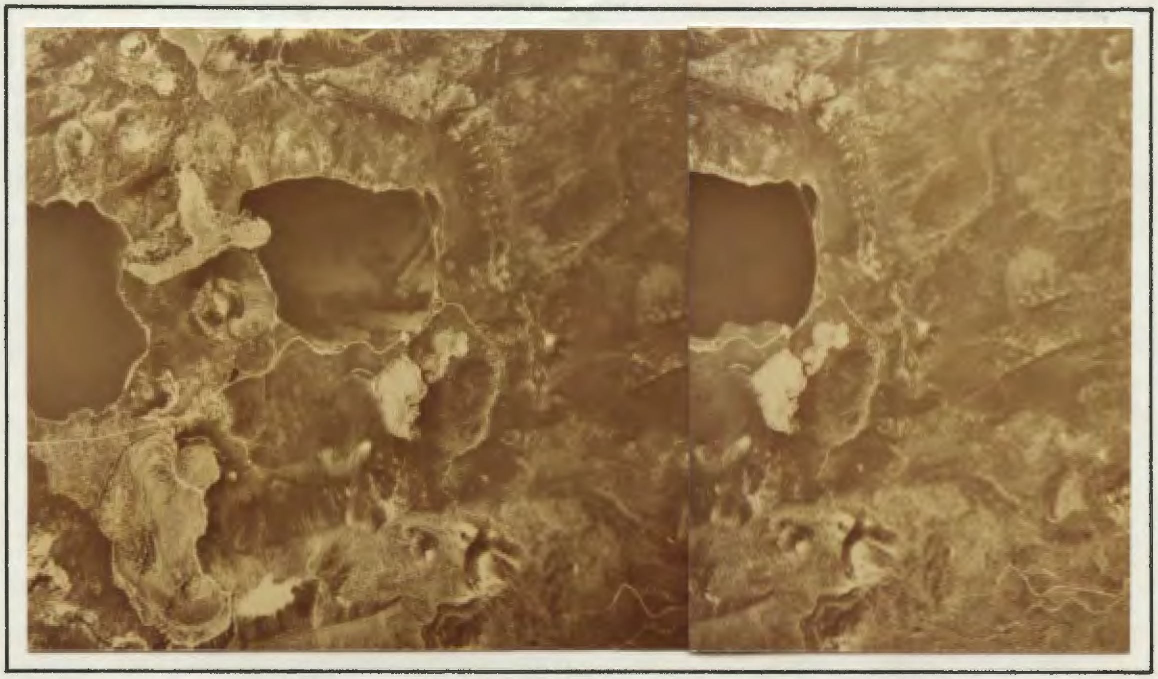


Plate 20: Aerial stereo pair of the East Lake Obsidian Flows and the eastern portion of Newberry Caldera. The East Lake flows are located just south of the southeast corner of East Lake. 1 cm = approximately 1 km (U.S. Army Corps of Engineers, 1954b).

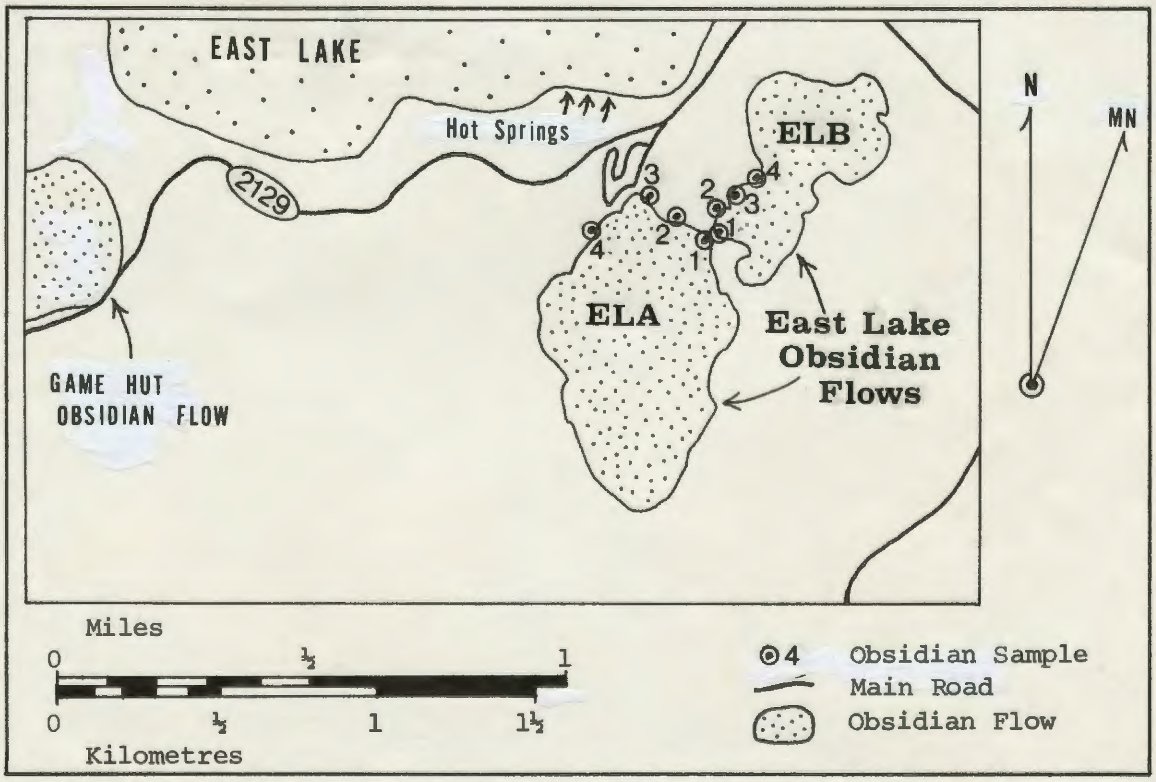


Figure 30: Sketch map of the two East Lake Obsidian Flows, Newberry Caldera. These two flows, located 2.5 km east of the Big Obsidian Flow, were probably extruded at about the same time from a common fissure vent. The map is adapted from a geologic map by Higgins and Waters (1967).

covered by the Big Obsidian Flow covers the two narrowly separated flows. The northern end of the western flow lies only 200 m (650 feet) south of East Lake Hot Springs. Both obsidian flows have been briefly described by Williams (1935:275-276), Peterson and Groh (1965:11-18), Higgins and Waters (1967), Higgins (1968:196-198) and MacLeod et al. (1981 and 1982).

Prior to the development of radiometric geochronologic methods, the East Lake flows were estimated to be only 300-400 years old (Williams, 1935:276). The ages of the two flows are now known to lie somewhere between those of the eruption of the Big Obsidian Flow tephra and the Mazama ashfall, respectively dated at about 1,700 and 7,000 radiocarbon years B.P. Obsidian hydration geochronology has also been used in an attempt to more closely establish the ages. Friedman and his associates place the ages of both flows at 3,500 obsidian hydration years (Friedman, 1977; Friedman and Trembour, 1978; Friedman and Obradovich, 1981).

The two obsidian flows are indistinguishable in their major and trace element composition. The composition of both flows has been previously reported by several authors (Jack and Carmichael, 1969; Laidley and McKay, 1971; Higgins, 1973; Friedman and Long, 1976; see Table IV-1, Appendix Four, for analyses).

THE COUGAR MOUNTAIN OBSIDIAN SOURCE

Cougar Mountain is a 210 m (700 foot)-high eroded rhyolite dome that rises abruptly at the northern border of the Fort Rock Valley in south-central Oregon (Allison, 1979:19). This dome, once rising as an island from the late Pleistocent Pluvial Fort Rock Lake, displays wave-eroded cliffs on the southern and western sides in which a number of littoral caves were carved along faults in the rhyolite. On the north and west, the dome is surrounded by the early Holocene basalts of the Devils Garden lava field. The summit of the mountain is 1556 m (5140 feet) above sea level. Access to Cougar Mountain is by secondary roads from the south. The area is snow-free most of the year.

Geologic Setting of Cougar Mountain

Hampton (1964:7) describes the obsidian at Cougar Mountain: "The obsidian on Cougar Mountain is mostly black, but some of it contains red streaks and nearly

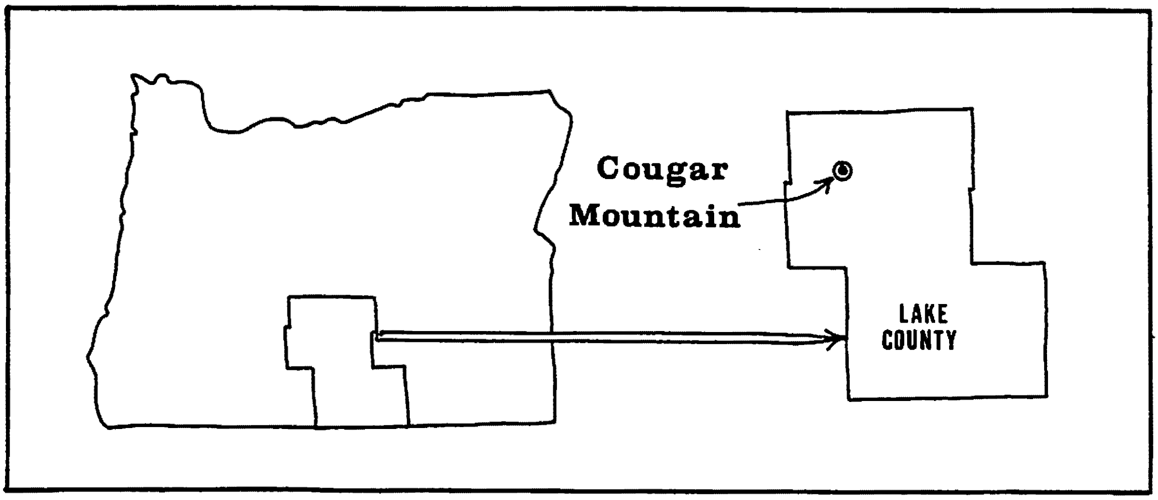


Figure 31: Location of Cougar Mountain, Lake County, Oregon.

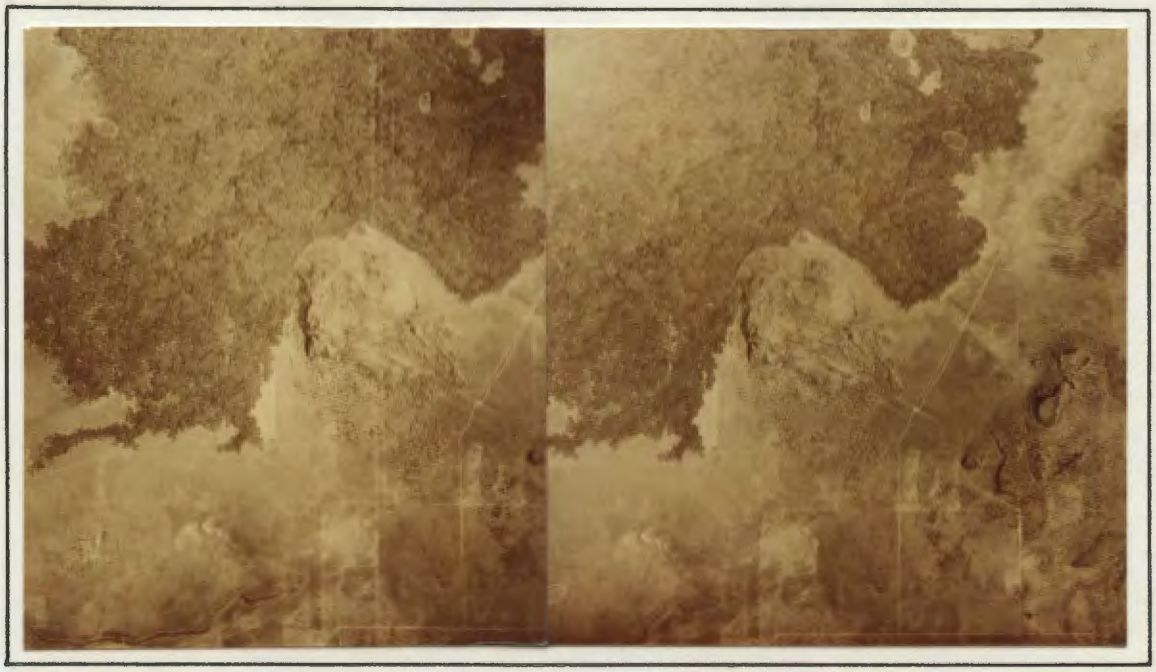


Plate 21: Aerial stereo pair of Cougar Mountain. The wave-cut cliffs of the west and east sides of the mountain are the sites of several archaeological cave sites. These caves may have been inhabited when the adjacent Devils Garden lava flows erupted between 7,000 and 13,000 radiocarbon years ago. 1 cm = approximately 1 km. (U.S. Army Corps of Engineers, 1954c).

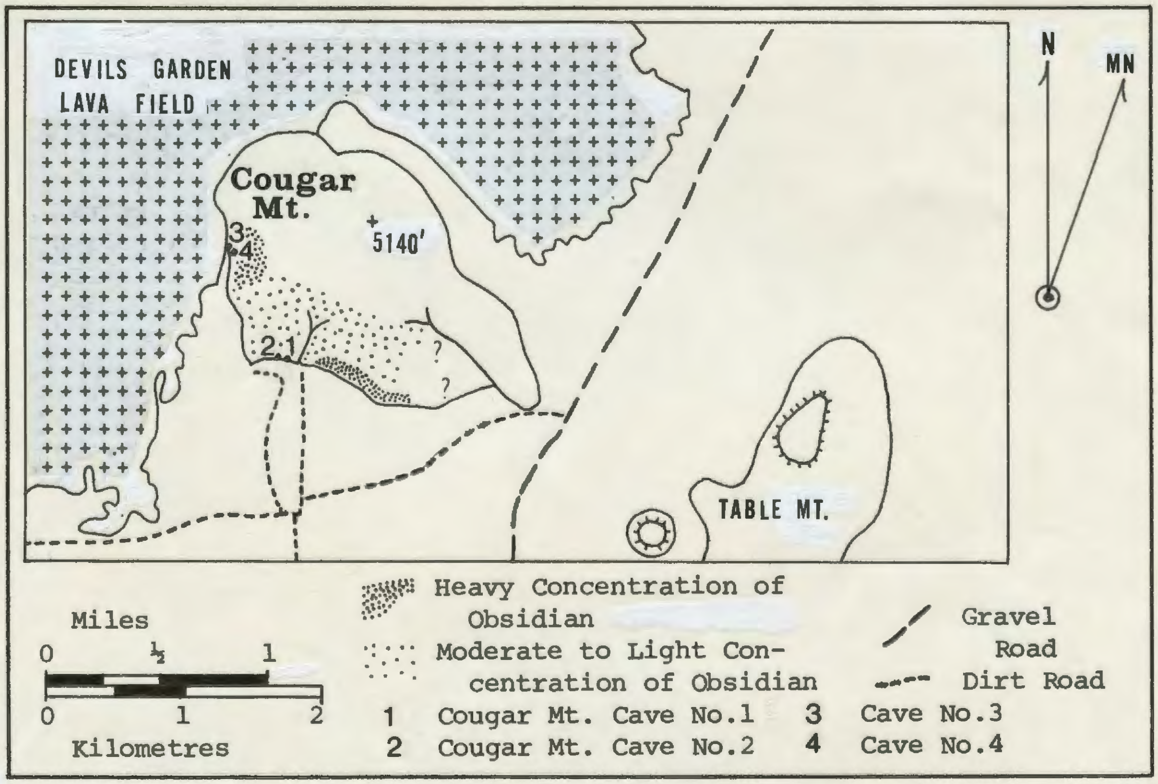


Figure 32 : Sketch map of Cougar Mountain, northern Lake County. Obsidian samples were collected for this study in the area directly north and east of Cougar Mountain Caves No.1 and No.2. The map is adapted from the aerial photographs above.

all the obsidian is transparent or translucent on thin edge. The obsidian lies in streaks within the rhyodacite, and there is a complete gradation from the frothy fine-grained light-colored rhyodacite to dense obsidian." Occasional specimens of gray obsidian were reported by Layton (1972), though only one example was found by the author in a search of the southwest quadrant of the mountain. Obsidian nodules as much as 30 cm in diameter and occasionally larger are abundant on the western and southern flanks of the dome where they have weathered out of their rhyolite matrix. Lenses of obsidian in the rhyolite are particularly well-displayed at Cougar Mountain Caves No.3 and No.4 and on the slopes above these caves. Nodules on the surface and *in situ* often display a reddish surface hue caused by the hydrothermal alteration of magnetite in the glass. Obsidian pebbles from the primary source at Cougar Mountain can be found far out into the now dry lake basin to the south of the dome and have also been found in lapilli-tuff layers at nearby Table Mountain, a Pleistocene maar or tuff-ring (Heiken, 1972:55).

Obsidian from this rhyolite-obsidian dome has been assigned a K-Ar age of 4.31 ± 0.34 million years (MacLeod et al., 1975; McKee et al., 1976).

Archaeological Setting of the Cougar Mountain Source

Four archaeological cave sites have been identified at the base of the wave-cut cliffs on the western and southern sides of the mountain (Figure 32).

Two of these caves, Cougar Mountain Caves No.3 and No.4, are found on the western side of the mountain and were excavated by a amateur sometime prior to 1958. Little is known of what was recovered there except that notched points similar to those found near the bottom of Cougar Mountain Cave No.1 were present (Cowles, 1960:3).

The largest of the caves at the mountain, Cougar Mountain Cave No.1, was excavated by a collector who later published a short book describing his finds there (Cowles, 1960). A substantial collection of obsidian, basalt, bone, fiber and leather artifactual materials were recovered. Though Cowles did maintain some stratigraphic control during his excavations, the distribution of the artifacts was not well-established. Layton (1972), using projectile points recovered by Cowles in the cave, made a relative seriation study using obsidian hydration analysis.

The nearby Cougar Mountain Cave No.2 was excavated in the late 1960's by a University of Oregon team (Bedwell, 1970 and 1973). A radiocarbon age of 11,950 ± 350 years B.P. was determined for material associated with worked flakes in the cave, establishing the considerable antiquity of the site and of the use of Cougar Mountain as an obsidian source.

Archaeologic features of the Cougar Mountain caves are also briefly summarized by Minor et al.(1979:33,51), Strong (1969:78-80,203), Butler (1961:7-15), Atherton (1966:27-30) and Skinner (1981).

The naturally-occurring obsidian found at Cougar Mountain is of excellent tool-making quality and this source was clearly a well-utilized obsidian quarry site over a long period. Sappington and Toepel (1981), after determining the sources of 167 obsidian artifacts collected from a transect running

Plate 22: The southwestern end of Cougar Mountain. The arrows point to the entrances to Cougar Mountain Caves No.1 and No.2, two well-known archaeological cave sites at the northern edge of the Fort Rock Basin. Obsidian nodules that have weathered out of this obsidian and rhyolite dome are common in the area above the caves.

Plate 23: Cougar Mountain Cave No.1 This littoral cave looks out over the former basin of Pluvial Fort Rock Lake. Approximately 13,000 radiocarbon years ago, the shoreline of the lake would have been found about 3 km to the southeast of the cave. Taken facing southwest - the Connley Hills are in the far right background.

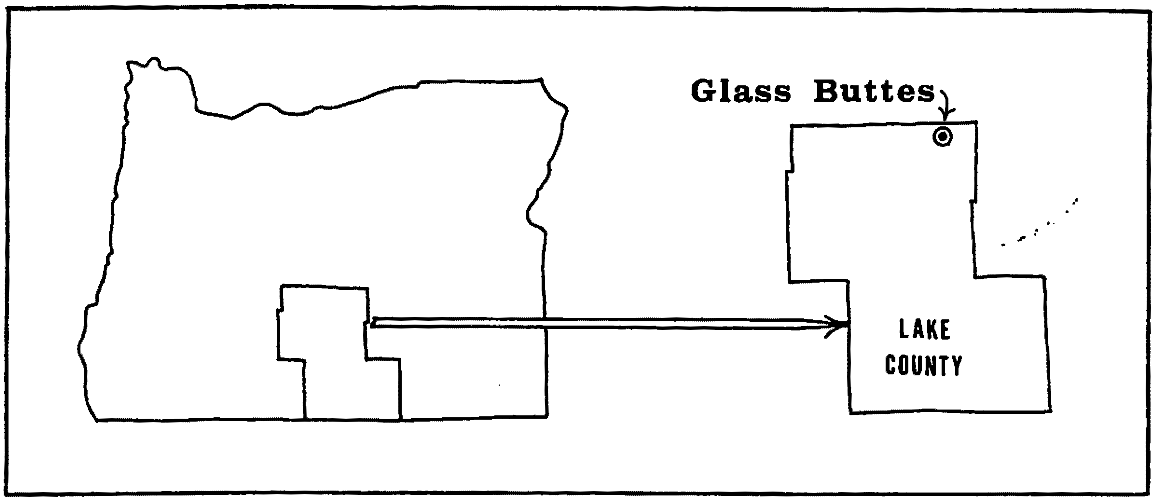


Figure 33: Location of Glass Buttes, Lake County, Oregon.

north from Silver Lake to near Maupin, identified 64 artifacts as originating from the Cougar Mountain obsidian source. Most were found in the Silver Lake - Fort Rock area. In a closely-related study, 26 pre-Mazama artifacts from the Fort Rock and Connley Caves were geochemically characterized. Of these, five appeared to have originated from the Cougar Mountain source (Sappington and Toepel, 1981). The source of several other artifacts from the Fort Rock and Connley caves has also been found to be Cougar Mountain (see Appendix Nine, this project).

THE GLASS BUTTES OBSIDIAN SOURCE

> After the mountains had burned for several days, there came a shower having a beautiful rainbow. The rainbow shone all day on one spot on the south side of the mountain and at evening seemed to enter the ground at this particular spot. After the fire they found that some of the mountain had melted and had made heaps of glass for their arrow and spear points, but the rainbow had settled into one heap and left the beautiful colors there.
>
> Indian legend (?) explaining the origin of the many colors of obsidian found at Glass Buttes (Ball, 1941:8; quoted in Steele, 1982)

The Glass Buttes are a large complex of rhyolite and obsidian domes located immediately south of Highway 20 in the northeastern corner of Lake County. Sketch maps of the local roads and of the locations of colored obsidian at Glass Buttes appear in Heflin (1963 and 1979) and in Broughton (1974). The general location of this hard-to-miss landmark (see Plate 27) is shown on most highway maps. The obsidian at Glass Buttes can be found in an area reported to cover between 100 and 130 km^2 (40 to 50 mi^2). Three identified archaeological obsidian quarry sites at Glass Buttes were sampled as part of this investigation.

Plate 24: Glass Buttes. This large rhyolite and obsidian dome complex is Oregon's best-known obsidian source. Though largely ignored by archaeologists, Glass Buttes has been frequented by artifact collectors for more than 50 years. Taken facing southwest.

Geologic Setting of Glass Buttes

The first mention in the geologic literature of obsidian at Glass Buttes was by Israel Russell in 1884 (p.440), who briefly described the obsidian that he found there. A few other short descriptions in the literature can also be found in Iddings (1888:293) and Waring (1908:22). The most extensive geologic investigation of Glass Buttes was made by Waters (1927a and 1927b), who identified the rhyolitic activity at the buttes as the second of three stages of volcanic activity in the immediate area (the first and third were basaltic). Alt and Hyndman (1978:188) describe the buttes as, "...an oversized lava flow which was so thick and viscous that it piled up around the vent to make a mountain instead of spreading across the countryside." The rhyolitic domes that form the buttes have been extensively faulted since their extrusion.

The obsidian at Glass Buttes is found on the surface as float - pebbles, nodules and small boulders are found in many locations on and bordering the two major peaks that make up Glass Buttes. Obsidian has been reported to occur in an almost unprecedented variety of colors including black, red, mahogany, gold, blue, silver, silvery-green, purple, pink, brown and "rainbow". Often, two or more colors occur together in bands or as a mottled combination. The selection of colors and the presence of large quantities of obsidian with an iridescent sheen have made Glass Buttes a favorite source of obsidian for gem collectors for many years (Forbes, 1934; Randolph, 1935; Dake, 1947, 1949, 1958-59; Heflin, 1963 and 1979; Gail, 1966; Broughton, 1974). The petrologic mechanisms responsible for the varicolored obsidian found at Glass Buttes have also been examined by Fuller (1927).

The major and trace element composition of obsidian from Glass Buttes has been reported by Jack and Carmichael (1969), Keller and Huang (1971), Griffin et al. (1969), Stevenson et al. (1971) and Ericson (1977; see Table IV-1, Appendix Four, for analyses).

Cherry (1968), in a study of the usefulness of the index of refraction of obsidian as a method of characterization, sampled the obsidian at Glass Buttes in several locations. Though he reported that the refractive index did not vary from sample to sample, his data are scantily reported.

A K-Ar age for Glass Buttes of 4.91 ± 0.73 million years is reported by MacLeod et al. (1975) and McKee et al. (1976).

Archaeological Setting of the Glass Buttes Obsidian Source

Considering Glass Buttes' well-known reputation as a prehistoric quarry site and source of artifacts, surprisingly little archaeological activity has taken place there.

Relic collectors have known about the area for years and one of them, P.L. Forbes, wrote in 1934: "Blades have been found 14 inches long but 8 inches is the general length found. To date, about 20,000 of these broken arrowheads have been found on various spots on Glass Butte." Other collectors have also written of the richness of the area as a source of artifacts (Dake, 1956 and 1958-59; Randolph, 1935; Heflin, 1963 and 1979). Heflin (1963) had ages of two artifacts estimated with the then newly-developed obsidian hydration method and mentioned 800 years as the resultant age (based on a hydration rim of about 1.5 microns - the 800 years figure should now be looked on only as a very approximate age). Atherton (1966:33-34) also provided a sparse archaeological sketch of the area.

Systematic work at Glass Buttes has consisted only of a partial surface archaeological survey conducted as part of a cultural resource survey of the area (Mack, 1975). Several extensive obsidian quarry sites were located as well as numerous campsites and knapping stations. Time-sensitive diagnostic projectile points found during this survey suggest that the Glass Buttes area has been occupied by hunters and gatherers of the northern Great Basin for more than 12,000 years (Mack, 1975:46-49; Toepel et al., 1980:83).

For years, obsidian from Glass Buttes has been said to have been found in burial mounds in the Midwestern United States (Dake, 1956 and 1958-59) but a study of obsidian from the Midwest by Griffin et al. (1969a) failed to substantiate this rumor. Only recently have obsidian characterization studies begun to show the distribution patterns of obsidian from the Glass Buttes source.

An obsidian characterization study reported by Nelson et al. (1975) and Bennett and D'Auria (1974) suggested that an artifact recovered in British Columbia may have originated from Glass Buttes (the methodology of this research, though, was rather dubious). More reliable work by Hughes (1978) has placed the possible source of one or two artifacts found in a Eureka, California, site (Loud, 1918) at Glass Buttes. Sappington and Toepel (1981) also placed the source of two artifacts found in the Fort Rock Basin at Glass Buttes. Other obsidian characterization studies that have considered Glass

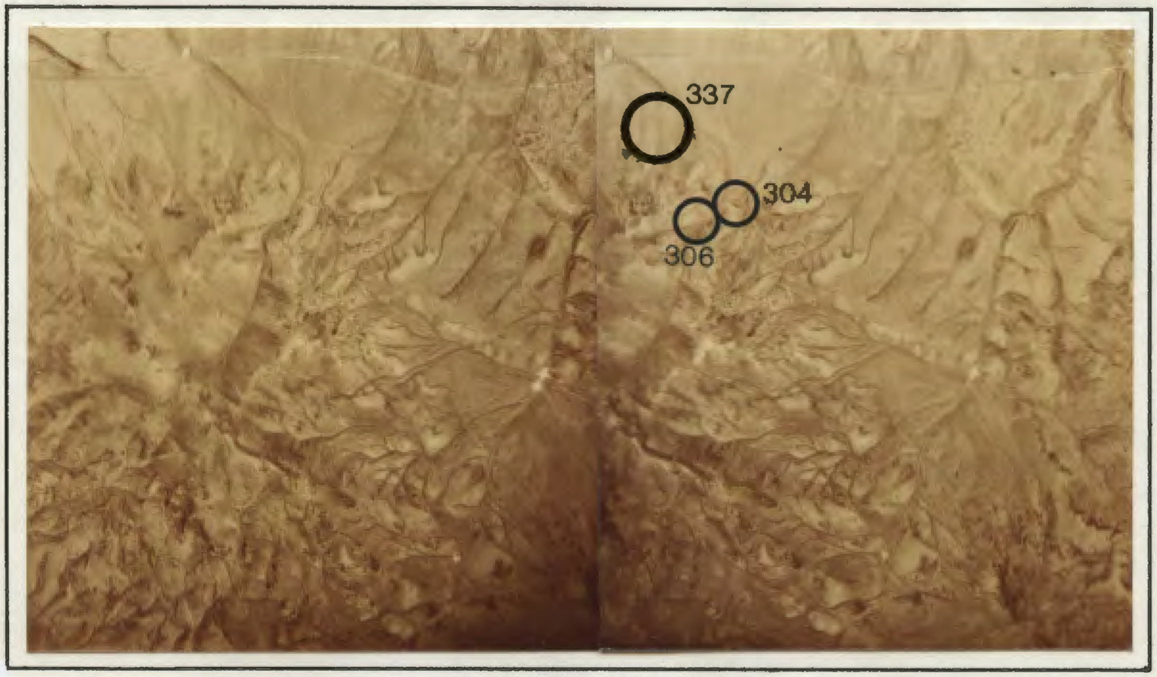


Plate 25: Aerial stereo pair of Glass Buttes. The approximate locations of the obsidian quarry sites indicated in the maps below are circled. Highway 20 is visible at the top of the photographs. 1 cm = approximately 1 km (U.S. Army Corps of Engineers, 1954a).

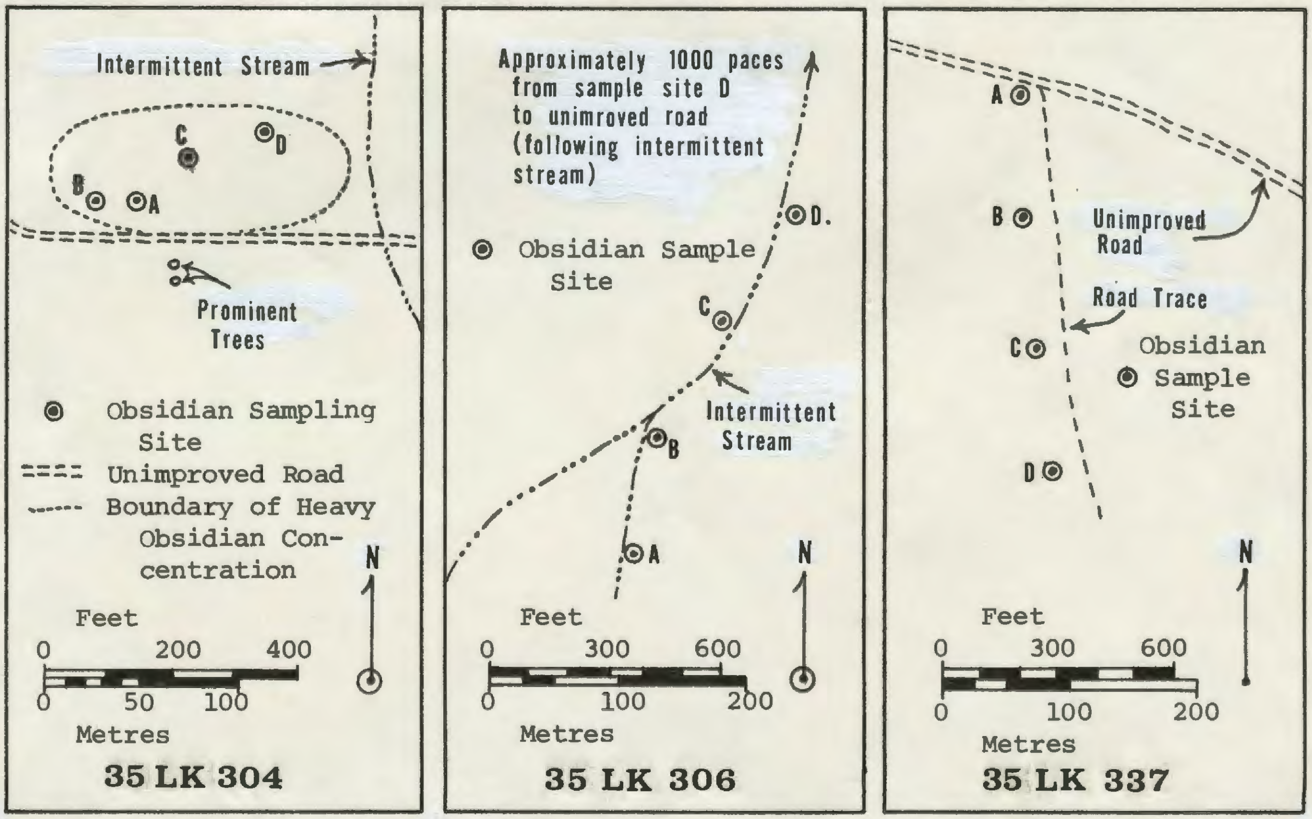


Figure 34: The three Glass Buttes obsidian quarry sites identified by Mack (1975) that were sampled for this study. Surface obsidian is abundant at these sites and in many other locations around the buttes. The map is adapted from a compass and rangefinder survey by the author.

Plate 26: Glass Buttes obsidian quarry site 35LK304. The level area that the person is standing in is covered with nodules of weathered obsidian. Taken facing north.

Plate 27: Glass Buttes obsidian quarry site 35LK306. The yellow pack is located at sample collection point B adjacent to an intermittent stream. Abundant quantities of obsidian nodules and worked flakes were found alongside this small streambed. Taken facing south (uphill).

Buttes as a possible obsidian source have failed to correlate artifactual obsidian with that source. Despite a common belief to the contrary, the widespread use of obsidian from Glass Buttes has yet to be established.

Obsidian Sampling Locations at Glass Buttes

Three obsidian quarry sites were selected for sampling at Glass Buttes as part of this investigation. All of them had been previously identified by Mack (1975:20,28). Three different archaeological quarry sites from a single geologic source were chosen to test the casual hypothesis that systematic intraunit variation in a single geologic source, particularly an extensive one such as at Glass Buttes, might make the identification of individual obsidian quarry sites or areas possible. Nelson et al. (1975:93) had reported that the spectra of obsidian samples randomly collected at Glass Buttes were divisible into three distinct sub-groups, indicating the presence of different compositional populations. The results of major and trace element analysis of obsidian from the three quarry sites sampled by the author, though, failed to indicate any compositional sub-groups. The composition of the obsidian from Glass Buttes was very homogeneous.

It should also be mentioned that while an attempt was made to accurately relocate each quarry site, and while quarry sites apparently corresponding to those described by Mack (1975) were located (Plate 25), it was not possible to be sure that the sites sampled and those listed by Mack are the same. The rugged topography of the area and the general nature of the directions by Mack made absolute identification of the quarry sites impossible.

The three obsidian quarry sites (descriptions are adapted from Mack, 1975:20, 28) that were sampled are:

1. 35 LK 304, an extensive quarry site and knapping station located on a saddle and two round hill tops. The saddle is bisected by an exposure of obsidian nodules (Plate 26). One of the hill tops is covered by flakes, the other by nodules and broken bifaces.
2. 35 LK 306, an extensive campsite, knapping station and quarry. Spread over a ridge between two intermittent streams, the site is covered by obsidian flakes and tools. Obsidian nodules are abundant. The two diagnostic projectile points recovered suggest an age of between 1000 and 4000 years B.P.
3. 35 LK 337, an extensive quarry site on the lower north slopes of Glass Buttes. Flakes, obsidian bifaces and obsidian nodules are found, though it is not possible to estimate the age of the site.

After each site was located, it was mapped and sampling locations noted (Figure 34).

THE RILEY SITE OBSIDIAN SOURCE

The Riley obsidian quarry site is located 6.8 km (4.2 miles) southwest of Riley, Oregon, and is adjacent to Highway 395.

The major source area at the Riley Site is a raised arm of land that extends several hundred metres southeast of Highway 395. The source locality is

Plate 28: Aerial stereo pair of the Riley Site (U.S. Department of Agriculture, 1958). 1 cm = approximately .4 km. The regional topographic features are largely controlled by the north-northwest trending Brothers Fault Zone, clearly visible in the upper right quadrant of the photographs.

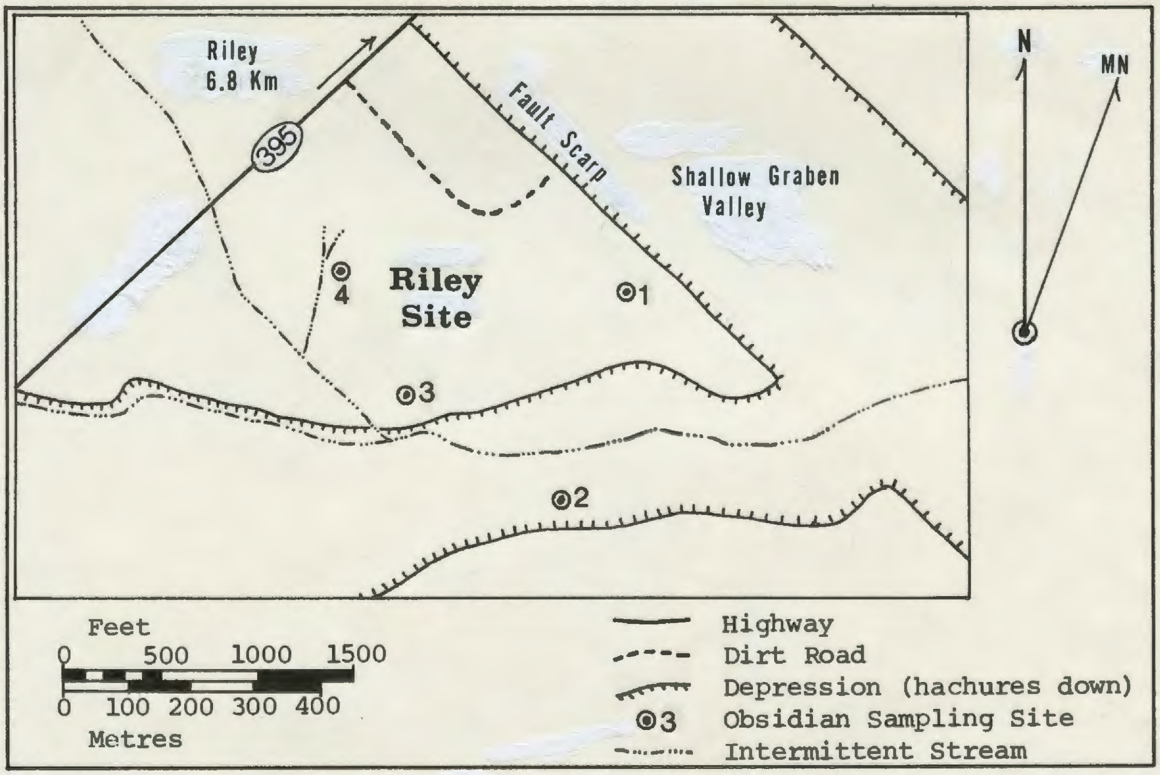


Figure 35: Sketch map of the Riley Site, Harney County. The main part of this obsidian quarry site is bounded on the northeast by a distinctive linear fault scarp and on the south by a shallow stream valley. The map is adapted from the photographs above and from a sketch map by Atherton (1966).

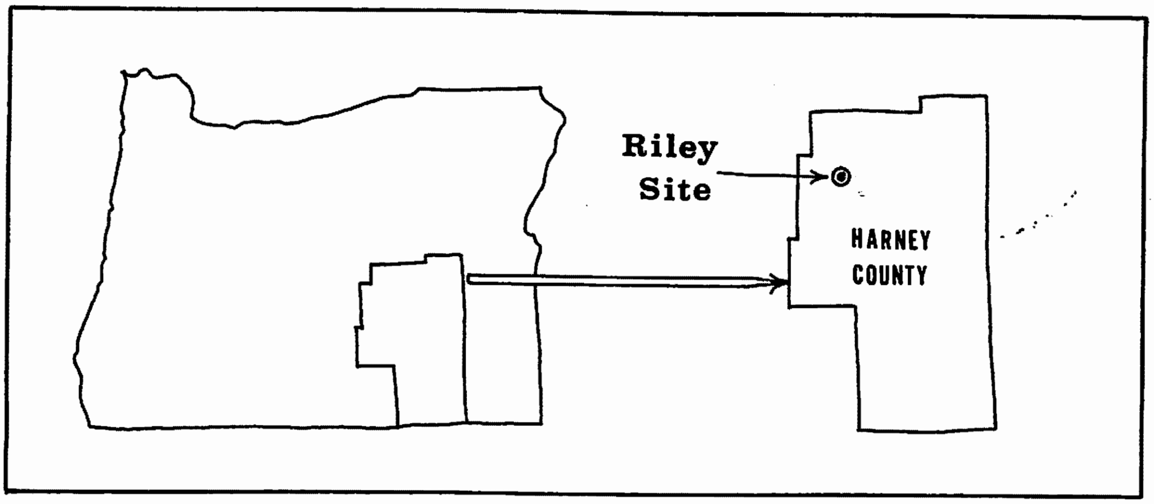


Figure 36: Location of the Riley Site, Harney County, Oregon.

bordered on the northeast by a 10 m (30 foot)-high fault scarp and a shallow *graben valley*, on the northeast by the highway and on the south by a prominent intermittent stream ravine. Black obsidian nodules and thousands of flakes are abundant on the surface throughout this area, particularly towards the southern end.

Geologic Setting of the Riley Site Obsidian Source

Geologic characteristics of the Riley Site were not examined in any detail. Large-scale geologic mapping by Walker (1977) suggests that obsidian at the site is associated with a faulted, late Tertiary rhyolite dome. Numerous exogenous domes exist in the region and many are known to be sources of obsidian (MacLeod et al., 1975; McKee et al., 1976).

Archaeologic Features and Prehistory of the Riley Site

The only archaeological examination of the Riley quarry site was reported in a Master's thesis by Atherton (1966:37-72). Atherton sampled the quarry site and exhaustively described the cores, blanks and worked flakes that he found.

Trace element studies by Sappington and Toepel (1981) indicate that a small amount of artifactual obsidian collected along a transect running from the Silver Lake area to the Prineville area originated from the Riley quarry source. No temporally-diagnostic artifacts were found from the Riley Site and no estimation of the period during which this source area was utilized is yet possible.

3 Methods of Collection, Preparation and Analysis

Once the ten obsidian sources were selected, plans were made to sample each location so as to provide information about the intraunit and interunit variation that was present for each characterization attribute. The obsidian sources were located on U.S. Geological Survey topographic maps and on aerial photographs. All ten obsidian sites were sampled in the summer and fall of 1981.

The basic sampling unit used in this study was archaeological in nature, the obsidian quarry site. In the case of the three sampling units located at Glass Buttes, this involved more than one sample group or quarry site from the same geologic source. No attempt was made to collect a representative sample of the entire geologic source. Rather, the samples were chosen to reflect the portions of an obsidian source that would have been easily available to the prehistoric occupants of an area. For obsidian flows, samples were collected along the accessible margins of the flows, while at obsidian-rhyolite domes, obsidian was collected randomly on the surface of the dome. While no attempt was made to collect according to any systematic random sampling scheme, it is likely that the obsidian samples recovered represent essentially a random sample. The only sampling bias introduced, other than that of the ease of accessibility at the collecting site, was that only the best quality obsidian available at a sampling area was recovered.

Four double fist-sized samples were collected, if possible, from each sampling site in a obsidian quarry locality. These were immediately labeled and bagged, then stored for later analysis. The specific sample location was noted at all sources except Cougar Mountain (see Chapter Two for specific sampling sites at obsidian quarry localities). While it would have been preferable to recover more than four samples at each obsidian source, funds were available for the geochemical analysis of only 40 specimens. It was felt that four samples from ten different quarry sites would furnish adequate parameters of intrasite variability while providing a suitable number of discrete sources for intersite comparison.

INITIAL SAMPLE PREPARATION

Each sample of obsidian was initially broken into small fragments with a sledge hammer. A minimum of 100 gm of the fragments free of any weathered surface were then collected and reduced to small (~3 mm) chips in a "chipper" (small jaw crusher). The jaw crusher has ceramic jaws which will introduce a small quantity of Al and Si into the sample.

These chips were placed in a tungsten carbide Spex shatterbox for six minutes, reducing the obsidian to a fine powder. Small amounts of W and Co, neither of which was determined in this investigation, are introduced to the sample during this procedure (Cunningham, 1978).

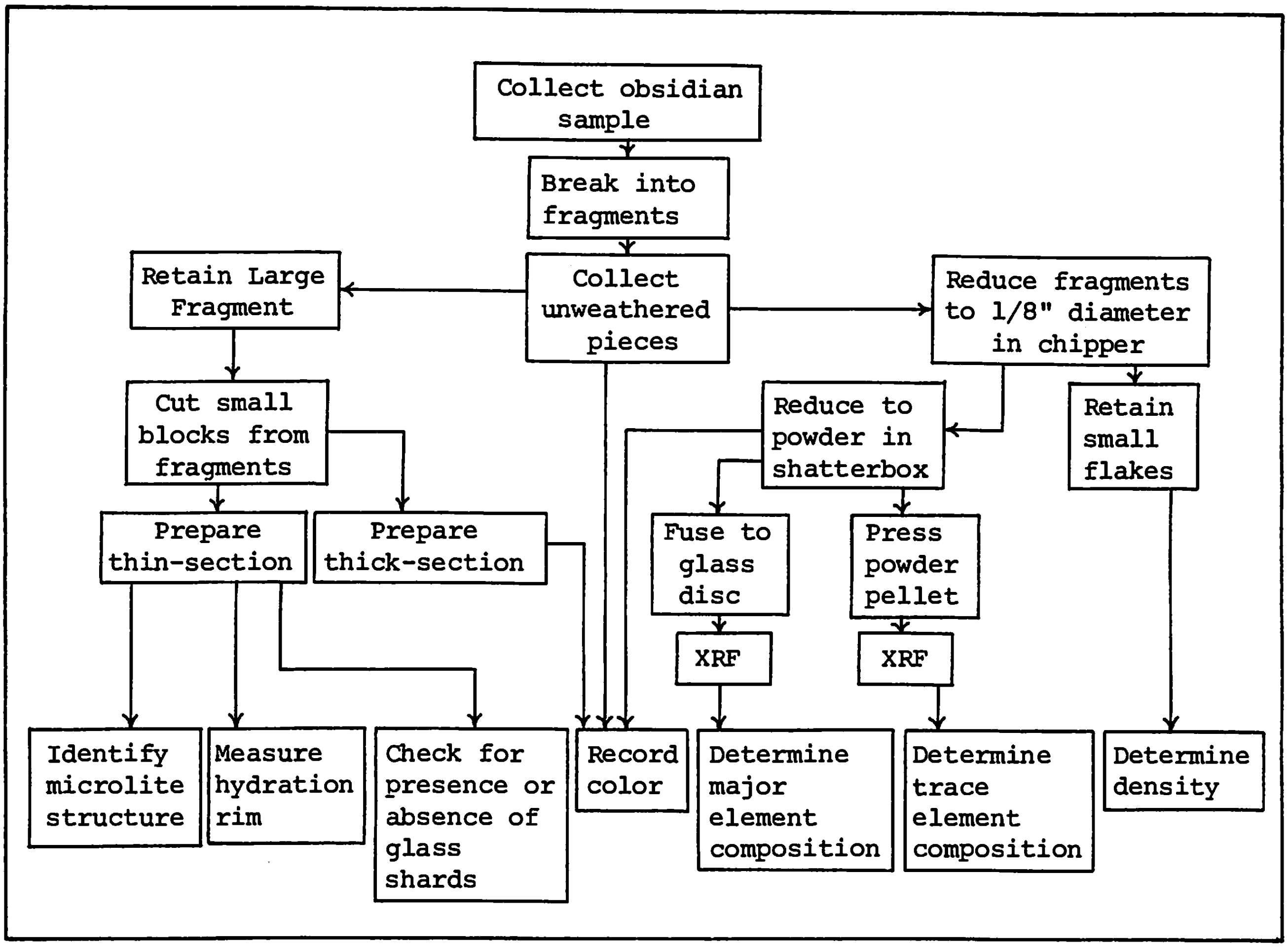


Figure 37 : Sample preparation and data-gathering network for obsidian examined in this investigation.

Small amounts of flakes, chips and powder were then retained for later stages of analysis and sample preparation (Figure 37).

COLOR DETERMINATION

The color of the obsidian was determined in three different ways, each of which yielded different results. These results are reported in Chapter Four.

Powder Color

Small fractions of finely-powdered obsidian were selected from each obsidian sample. The color of each specimen was determined by comparison with a Munsell Soil-Color Chart (Munsell, 1975).

Opaque Hand Specimen Color

An opaque hand specimen of obsidian from each sampling location was also selected and the color recorded. Colors were established by comparison with a Rock-Color Chart (Goddard et al., 1948).

Thin Flake Color

A small block (approximately 2 by 3 cm) was cut from each obsidian sample, ground smooth on one face with carborundum grit on a revolving disc and then mounted on a standard petrographic slide with epoxy cement. After the cement had dried and set, each sample was cut to a standard thickness of 1 mm with a thin-section cutting saw. The color of each slide (equivalent to a thin flake of obsidian) was determined by placing one end of the slide on a white sheet of paper and tilting the other end up to a 45 degree angle (glass slide side facing the observer). The color was established by comparing the slides with a Rock-Color chart (Goddard et al., 1948).

DENSITY DETERMINATION

The density of each sample was determined with a Berman density torsion balance (Bethleham Instrument Co., Inc.). This balance compares the weight of a sample in air with the weight of the sample in a liquid of known density (in this case, toluene). Prior to the determination of sample density, the balance and the toluene were allowed to equilibrate in a draft-free room of stable temperature. A sample weighing between 15 and 25 mg was then selected from each sample. The homogeneity of samples is essential for an accurate determination of density and pieces of obsidian with bubbles or possible heterogeneous features were discarded. The weight of the samples in air and the liquid were then established using the method described by Hutchison (1974) and the density computed according to the following formula:

$$G = \frac{W_1 \times L}{W_1 - W_2}$$

where, W_1 = Weight of the specimen in air
W_2 = Weight of the specimen in liquid
L = Specific gravity of immersion liquid corrected for temperature
G = Density or specific gravity

PREPARATION FOR MICROSCOPIC EXAMINATION

The same small blocks that were used in the preparation of slides for the thin flake color determination were also used in the preparation of thin-sections of obsidian for microscopic examination. Each block was leveled on one side using a slurry of carborundum grit on a revolving disc. The block was then heated and glued to a standard petrographic slide with epoxy cement. After drying overnight, the slide was cut and ground on a thin-section machine to a thickness of about 50 microns. It was then hand-ground to a thickness of 30-40 microns using the birefringence color of microphenocrysts of plagioclase in the obsidian, when present, as a guide to thickness. A cover glass was then attached using Canada Balsam after which the slide was thoroughly cleaned in acetone.

After preparation, each slide was examined with a petrographic microscope and the various microlitic structures were noted. The presence or absence of flattened glass shards (typical of the obsidian-like vitrophyre found associated with densely-welded portions of ash-flows) were also noted.

DETERMINATION OF CHEMICAL COMPOSITION

The major and trace element composition of each of the 40 samples was established by X-ray fluorescence (XRF) spectrographic methods using a GE XRD-7 Vacuum Spectrometer located at the University of Oregon X-Ray Fluorescence Laboratory. The only exception to this was Na, which was determined by Christine McBirney at the Atomic Absorption Laboratory at the University of Oregon.

In X-ray fluorescence spectrography, excitation of elements in the sample is by means of a primary X-ray beam. The elements are made to emit in the X-ray wavelength region and these emissions can be detected and used to identify the elements and their abundances in a sample. An X-ray spectrograph such as the one used in this investigation is simply an instrument that disperses X-rays and then measures their intensity as a way of making quantitative or qualitative analyses (Norrish and Chappell, 1967).

Analysis by XRF is a comparative method, and standards of known composition are required to obtain quantitative results. Standards should approximate the samples analyzed in as many respects as possible and, in the determination of several elements such as in this investigation, the use of several standards is often required. U.S. Geological Survey standards AGV-1, BCR-1, DTS-1, G-2, GSP-1, PCC-1 and W-1 were used in the determination of major and trace element abundances of the obsidian samples analyzed in this project (Abbey, 1973; Flanagan, 1974).

Sample Preparation for Major Element Analysis

Samples were prepared for major element analysis by fusion into a homogeneous glass disc. 0.56 gm of powdered sample was combined with 3.0 gm of flux (lithium tetraborate, lithium carbonate and lanthanum oxide) and 0.4 gm of sodium nitrate and was then melted in a platinum crucible and poured into a graphite mold to create a glass disc. After annealing for 48 hours to prevent cracking, the disc was ready for analysis. This method is described in detail by Norrish and Chappell (1967) and Norrish and Hutton (1969).

Sample Preparation for Trace Element Analysis

Pressed powder pellets were used for the determination of trace element abundances in the samples. Though the amount of powdered sample used in pellet preparation may vary, it must appear as "infinitely thick" to the X-ray beam of the spectrometer. To ensure this, 5 gm of powdered sample were placed in a mold that utilizes boric acid as a backing. The mold is pressed at 10,000 pounds pressure, creating a cohesive pellet that can be used for analysis in the XRF spectrometer. This method is described by Norrish and Chappell (1967).

A detailed description of the analytical and data reduction methods used at the University of Oregon XRF Laboratory is provided by Cunningham (1978 and N.D.).

4 Color as a Characterization Attribute

The most obvious of any of the physical properties of obsidian is its color and in this chapter the possibility of characterization through color determination is examined.

While obsidian has been noted to occur in an unusual variety of colors including green, gray, red, mahogany, brown, blue, silver, turquoise, orange and yellow (Gail, 1966), the most common color is black. The predominance of black obsidian is attributable to the presence of tiny particles of magnetite in the glass (Boyer and Robinson, 1956; Senftle and Thorpe, 1959). When magnetite is oxidized to hematite, it becomes red or brown and, not surprisingly, these are both colors not uncommon for obsidian (Randolph, 1935; Ross, 1962). The origin of other colors that obsidian may assume has not been adequately explained.

There appears to be some relationship between the color of obsidian and its composition, though this is not a well-examined area. Black obsidian would be expected to be richer in Fe than is very light-colored or clear obsidian (when both are seen in thin flakes ; even a small amount of magnetite in obsidian gives it a black appearance when seen in an opaque hand specimen). A casual comparison of the Fe_2O_3 abundances of obsidian used in this investigation (see Chapter Seven) and the intensity of dark colors seen in the thin flakes of some of the samples (see Table 6) suggests that this is the case. Senftle and Thorpe (1959) also found that the magnetic susceptibility of dark bands in obsidian was greater than in clear glass. Other authors have noted color distinctions between obsidian of perkalkaline composition and obsidian of alkaline and calc-alkaline composition (Renfrew et al., 1966; Renfrew, 1969; Cann et al., 1970).

Attempts have been made by archaeologists for many years to use the color of obsidian as an attribute through which the geologic source of obsidian might be identified. As early as 1927, Wainright (1927) ascribed the source of some Egyptian obsidian artifacts, based on the color of a translucent flake of the glass, to a source in Armenia. Several other researchers have also claimed at least limited success with the source identification of archaeological obsidian using color, though their attitude has typically been a cautious one (Cann and Renfrew, 1964; Renfrew et al., 1965; Renfrew et al., 1966; Renfrew, 1969; Cann et al., 1970; Ward, 1974a; Wheeler and Clark, 1977). Most archaeologists would agree, however, that the identification of a geologic source of obsidian based on the color of a specimen alone is an unreliable and hazardous method of source characterization (Wright, 1969:22; Jackson, 1974:7; Leach, 1977a; Leach and Anderson, 1978). At best, opinion holds among archaeologists that color can only be useful as an adjunct to other more discriminatory methods of obsidian characterization (Renfrew et al., 1965).

The limited success of obsidian color characterization does suggest that this method might be useful in distinguishing groups of sources, if not indivisual sources. Any characterization method that can reliably identify groups of

SAMPLE	COLOR: OPAQUE SPECIMEN		COLOR: THIN FLAKE		COLOR: POWDER	
	COLOR	NOTATION	COLOR	NOTATION	COLOR	NOTATION
BOF-1	GB	N2	OG*	5Y 4/1	VLG	7.5YR 7.5/0
			LOG*	5Y 6/1		
BOF-2	GB	N2	OG*	5Y 4/1	VLG	7.5YR 7.5/0
			LOG*	5Y 6/1		
BOF-3	GB	N2	OG	5Y 4/1	VLG	7.5YR 7.5/0
BOF-4	GB	N2	OG*	5Y 4/1	VLG	7.5YR 7.5/0
			LOG*	5Y 6/1		
CGM-1	GB	N2	GB*	N2	VLG	7.5YR 7.5/0
			MDG*	N4		
CGM-2	B	N1	GB*	N2	VLG	7.5YR 7.5/0
			LG*	N7		
CGM-3	B	N1	LG*	N7	VLG	7.5YR 7.5/0
			GB*	N2.5		
CGM-4	B	N1	GB*	N2	VLG	7.5YR 7.5/0
			MLG*	N6		
ELA-1	GB	N2	OG	5Y 4/1	VLG	7.5YR 7.5/0
ELA-2	GB	N2	OG*	5Y 4/1	VLG	7.5YR 7.5/0
			OB*	5Y 2/1		
ELA-3	GB	N2	OG*	5Y 4/1	VLG	7.5YR 7.5/0
			OB*	5Y 2/1		
ELA-4	GB	N2	OG*	5Y 4/1	VLG	7.5YR 7.5/0
			OGB*	5Y 3/1		
ELB-1	GB	N2	OG*	5Y 4/1	VLG	7.5YR 7.5/0
			OB*	5Y 2/1		
ELB-2	GB	N2	OG	5Y 4/1	VLG	7.5YR 7.5/0
ELB-3	GB	N2	OG	5Y 4/1	VLG	7.5YR 7.5/0
ELB-4	GB	N2	OG	5Y 4/1	VLG	7.5YR 7.5/0

Table 6: Hand specimen, translucent thin flake and powder colors of obsidian samples. Color notations for opaque specimens and thin flakes are from Goddard et al. (1948); powder colors are from Munsell Soil Color Charts (1975). Where more than one color is indicated for a single sample, the first color listed is the most abundant, the last color the least abundant. Table is continued on the following two pages.

SAMPLE	COLOR: OPAQUE SPECIMEN		COLOR: THIN FLAKE		COLOR: POWDER	
	COLOR	NOTATION	COLOR	NOTATION	COLOR	NOTATION
GLB-304A	B*	N1	VLG	N7.5	VLG	7.5YR 7.5/0
	MRB*	10R 4/6				
GLB-304B	B	N1	VLG	N7.5	VLG	7.5YR 7.5/0
GLB-304C	B	N1	VLG	N7.5	VLG	7.5YR 7.5/0
GLB-304D	B	N1	LG	N7.5	VLG	7.5YR 7.5/0
GLB-306A	GB	N2	MLG*	N6	VLG	7.5YR 7.5/0
			GB*	N2		
GLB-306B	B	N1	MLG**	N6	VLG	7.5YR 7.5/0
			GB**	N2		
GLB-306C	B	N1	MDG*	N4	VLG	7.5YR 7.5/0
			GB*	N2		
GLB-306D	B	N1	MDG*	N4	VLG	7.5YR 7.5/0
			LG*	N7		
GLB-337A	B*	N1	MDG*	N4	VLG	7.5YR 7.5/0
	MRB***	10R 4/6	VLG*	N7.5		
			GB*	N2		
			MRB***	10R 4/6		
GLB-337B	B*	N1	VLG*	N7.5	VLG	7.5YR 7.5/0
	MRB***	10R 4/6	MRB***	10R 4/6		
			GB*	N2		
GLB-337C	B*	N1	VLG*	N7.5	VLG	7.5YR 7.5/0
	MRB***	10R 4/6	GB*	N2		
			MRB*	10R 4/6		
GLB-337D	B*	N1	MDG*	N4	LG	5YR 7/1
	MRB***	10R 4/6	MRB***	10R 4/6		
			VLG*	N7.5		
			MLG*	N6		
			GB*	N2		
LOW-1	B	N1	B****	N1	G	5YR 5/1
LOW-2	B	N1	B****	N1	G	5YR 5/1
LOW-3	B	N1	B****	N1	G	5YR 5/1
LOW-4	B	N1	B****	N1	G	5YR 5/1

Table 6 continued from the preceding page.

SAMPLE	COLOR: OPAQUE SPECIMEN		COLOR: THIN FLAKE		COLOR: POWDER	
	COLOR	NOTATION	COLOR	NOTATION	COLOR	NOTATION
OBC-1	GB	N2	MG* GB*	N4.5 N2	VLG	7.5YR 7.5/0
OBC-2	GB	N2	LG* MG* DG*	N6.5 N4.5 N3	VLG	7.5YR 7.5/0
OBC-3	DG	N3	MG* GB*	N4.5 N2	VLG	7.5YR 7.5/0
OBC-4	GB	N2	MDG* LG* DG*	N4 N7 N3	VLG	7.5YR 7.5/0
RIL-1	B	N1	DYB	10YR 3/2	VLG	7.5YR 7.5/0
RIL-2	B	N1	DB* DYB*	10YR 3/2 5YR 2/2	LG	5YR 7/1
RIL-3	B	N1	DB	5YR 2/2	VLG	7.5YR 7.5/0
RIL-4	B	N1	DYB	10YR 4/2	VLG	7.5YR 7.5/0

VLG: Very light gray
LG: Light gray
MLG: Medium light gray
MG: Medium gray
MDG: Medium dark gray
DG: Dark gray
GB: Grayish black
B: Black

LOG: Light olive gray
OG: Olive gray
OGB: Olive gray-black
OB: Olive black
MRB: Medium reddish brown
DYB: Dark yellowish brown
DB: Dusky brown

* Banded ▨
** Veined ▦
*** Variegated ●
**** Opaque (with small translucent phenocrysts)

Table 6 continued from the preceding page.

obsidian sources may be effectively used, in conjunction with other characterization methods, to identify specific sources (see Appendix Eleven for an explanation and demonstration).

RESULTS OF COLOR DETERMINATIONS

Three different ways of determining obsidian color were eventually chosen for this investigation - the color of powdered obsidian, the color of opaque hand specimens of obsidian and the color of thin translucent flakes of obsidian. The results of the color determinations are recorded in Table 6.

The colors of the obsidian samples were determined using a Munsell Soil-Color Chart (Munsell Color Co., 1975) and a Rock-Color Chart (Goddard et al., 1948). Both of these color charts use similar color classification schemes. These charts contain a wide range of color plates, each with a specific color notation such as 5YR 5/1. The color notation refers, respectively, to the *hue* (relation of the color to red, yellow, green, blue and purple), the *value* (lightness of the color) and the *chroma* (the strength of the color). Thus, in the designation 5YR 5/1, the 5YR refers to hue, the 5 to value and the 1 to chroma. Colors falling between the plates in color may be represented with decimals. Numbers preceded by N refer to neutral colors falling between white and black.

The resultant color determinations were plotted on graphs (Figures 38, 39 and 40) with hue and chroma on one axis and value on the other. This arrangement seemed to indicate most clearly color clusters or groups that were present in the obsidian source universe that was used.

Opaque Hand Specimen Color

The colors of an opaque specimen of obsidian from each sampling location were recorded (Table 4) and the resultant colors plotted in Figure 38. There was little variation in the colors of the specimens with black and grayish-black colors predominating. The exceptions to this were several variegated samples from Glass Buttes where medium reddish-brown and black obsidian were often found in the same hand specimens. It is also known that several other colors of obsidian are found at Glass Buttes (Heflin, 1963 and 1979; Broughton, 1974), indicating that a sample size of four samples is not adequate to show the degree of intraunit variation at this site and perhaps at other sites as well.

Colors are relatively homogeneous at each quarry site, with no more than two colors recorded at each source. The only color, though, with any discriminative value appears to be the medium reddish-brown of the Glass Buttes sources.

Thin Flake Colors

The widest range of color variation appeared when the obsidian was prepared as a thin flake. A variety of color clusters appear in Figure 39, indicating the diversity of different colors that becomes apparent using flakes prepared with this method.

Several of these clusters or groupings indicated sufficient intraunit color homogeneity to suggest some discriminative value. The medium reddish-brown color of GLB-337 suggests that that this can serve to distinguish this quarry

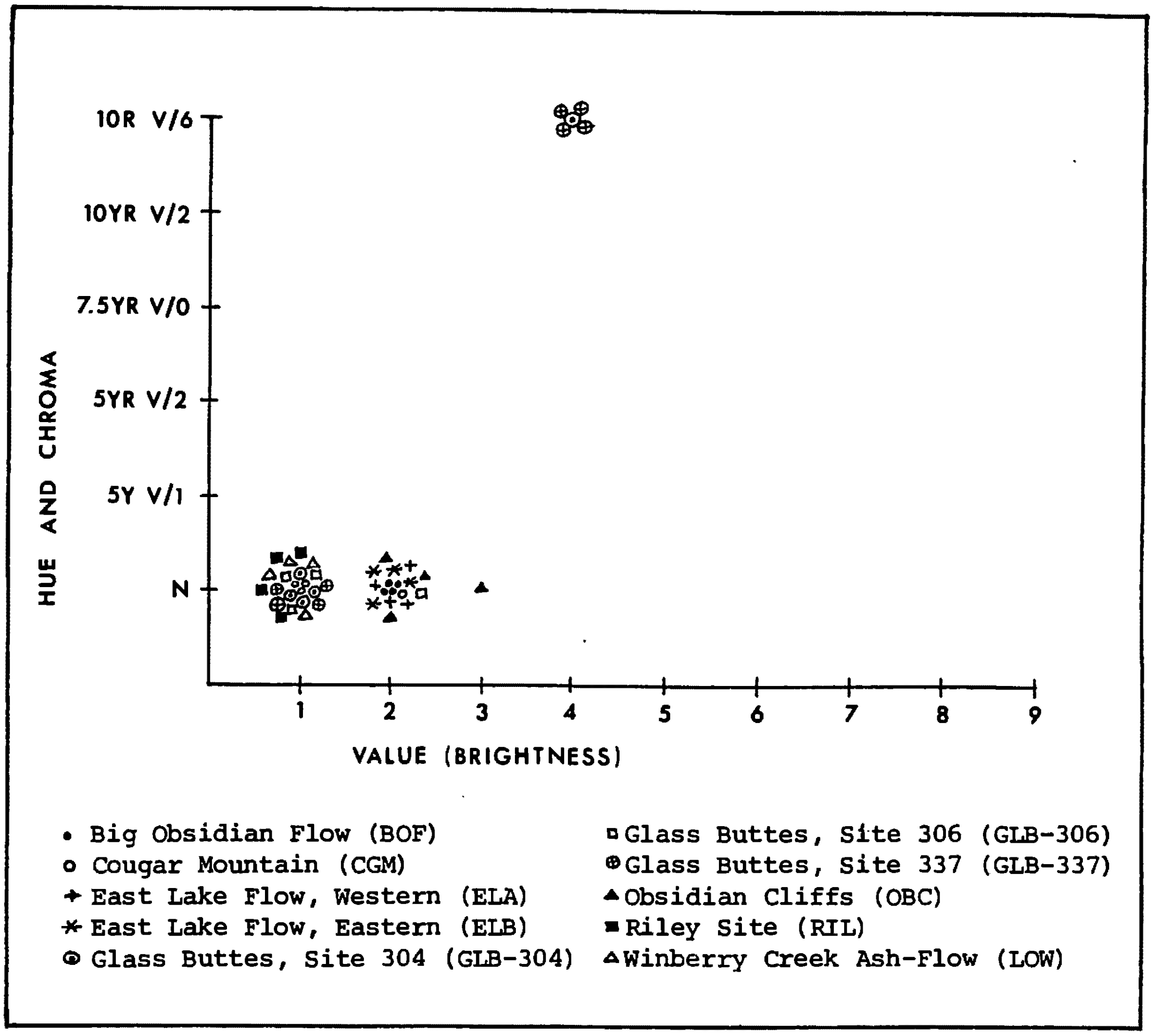


Figure 38 : Color hue and chroma plotted against color value (V) for opaque hand specimens of obsidian. When more than one color was present, each was plotted individually. Color notations are from Goddard et al. (1948).

site from all others (though it is doubtful that this color would distinguish the site from others at Glass Buttes - the limited appearance of the color in this investigation is probably more an artifact of the small sampling size rather than its uniqueness at site GLB-337). The yellow-brown and dark yellow-brown of the RIL samples were also quite distinct among the sources in the sampling universe. The sources in Newberry Caldera (BOF, ELA and ELB) were also very homogeneous (as a group) in their color hue and chroma, though the value of the samples varied. All were varying shades of olive when seen in thin flakes, a color characteristic shared by no other geologic sources in the sampling universe. The neutral colors showed the least discriminative value, with samples from several sources scattered along the color continuum from very light to very dark. The exception to this, though it is not well-illustrated in Figure 39, was the LOW samples. All of the thin flakes from this welded ash-flow were virtually opaque and only large phenocrysts in the vitrophyre were translucent.

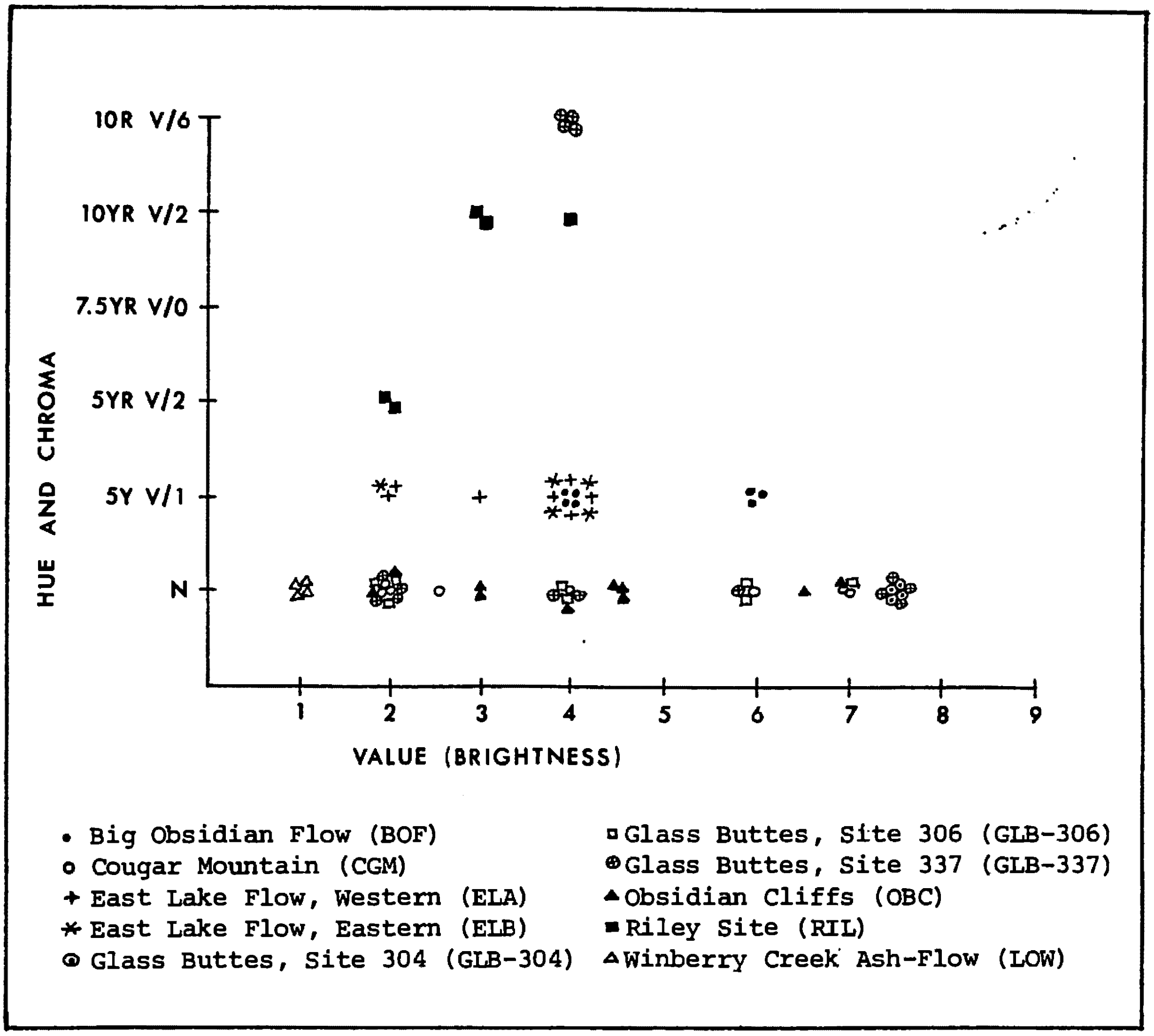


Figure 39 : Color hue and chroma plotted against color value (V) for thin (1 mm thick) flakes of obsidian. When more than one color was present, each was plotted separately. Color notations are from Goddard et al. (1948).

Powder Colors

As is graphically demonstrated in Figure 40, the colors of obsidian that had been powdered were virtually identical for all of the sources. The LOW source of obsidian-like vitrophyre does, however, fall into a distinct group. It appears that the color of powdered obsidian reflects only two classes - true obsidian and obsidian-like vitrophyre. Boyer and Robinson (1956) have also commented on this same distinction.

CONCLUSIONS

Of the three methods of color determination utilized, the one clearly demonstrating the most value as an attribute for obsidian characterization is the color of a thin flake. The source discriminating value of the color of opaque

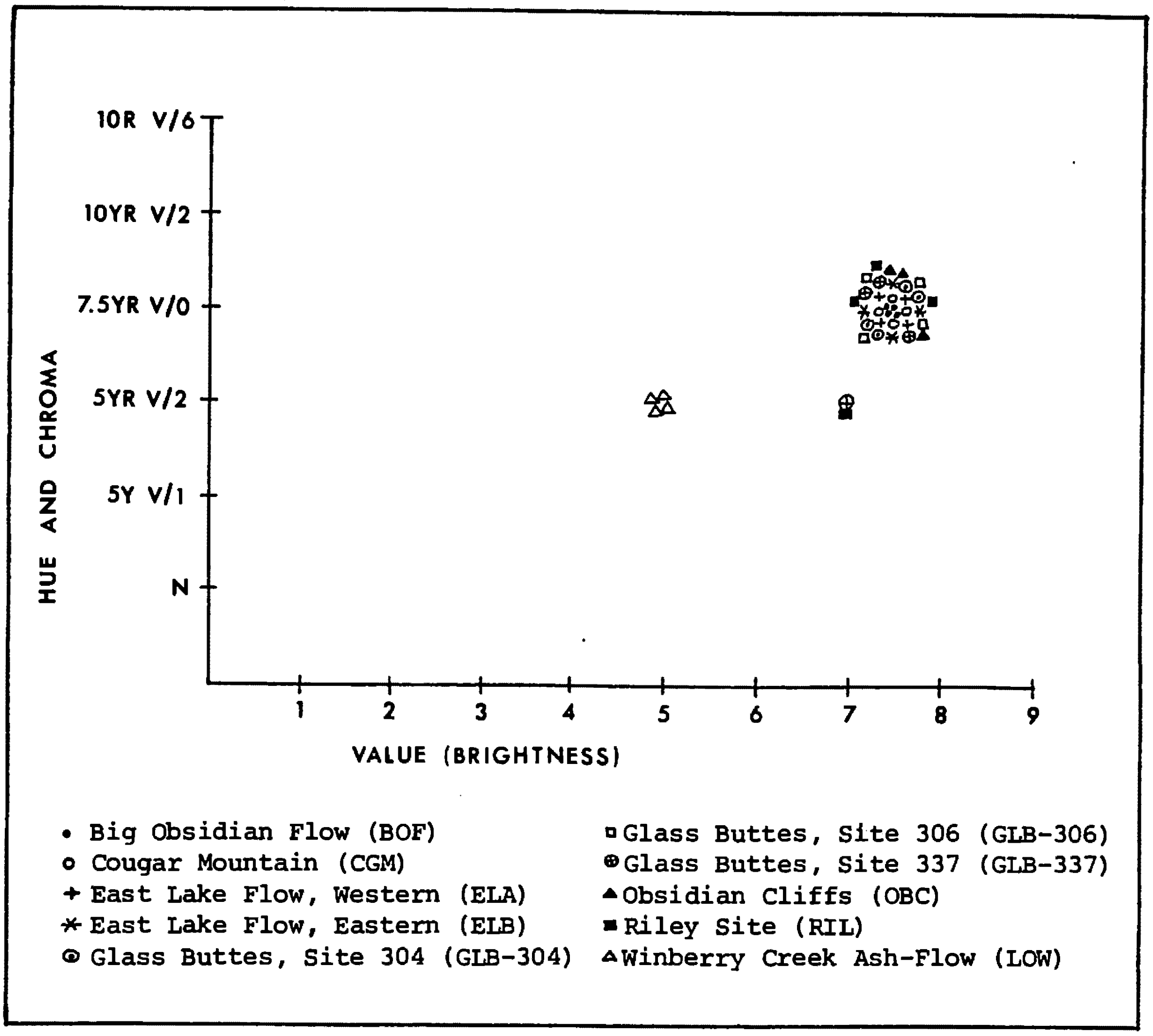


Figure 40 : Color hue and chroma plotted against color value (V) for powdered obsidian samples. Color notations are from Munsell Soil Color Charts (1975).

specimens and of powdered obsidian is very low. The thin flake colors (excluding the neutral shades), on the other hand, exhibit sufficient intraunit homogeneity and interunit heterogeneity to warrant their consideration as a possible attribute for obsidian characterization.

The discrepancy between the colors found in the Glass Buttes samples and the colors reported to exist there suggests that considerable intraunit color variation can be found at a single geologic source. Obsidian sources distinguished by their thin flake colors should be characterized using a much larger sample size than the four specimens that were used in this investigation. Color characterization should be approached cautiously, but it does appears that it may hold some value as an attribute for obsidian characterization, particularly when used in combination with other obsidian characterization attributes.

5 Density as a Characterization Attribute

Another fundamental and characteristic property of obsidian that may be used to characterize the glass is its density or specific gravity.

The specific gravity of an object is the ratio of its density to that of water. The resultant figure can be of diagnostic value in the identification of many rocks and minerals, including the natural glasses. The typical density of rhyolitic obsidian ranges from 2.13 to 2.46 gm/cm^3 (George, 1924; Reeves and Armitage, 1973; Ericson et al., 1975; Ambrose, 1976b; Ericson, 1977:100-103). The variation in density is attributable to a number of factors, the most important of which is the range of composition of the obsidian. It is the variability of composition between different geologic sources of obsidian that makes possible the consideration of the density of obsidian as an characterization attribute.

A number of different components influence the density of rhyolitic obsidian. Ericson et al. (1975) suggest the following:

$$D = D_g + D_c + D_p + D_v + D_a$$

where, D = Density
D_g = Density of the glass phase of the obsidian
D_c = Density of the crystalline component of the glass (usually a small proportion of the whole).
D_p = Density of the pore structure
D_v = Density of the volatile component, especially water
D_a = Whether or not the glass is annealed

Taken as a whole, though, these components primarily reflect the overall composition of the glass, the main factor in determining the density of obsidian (Larsen, 1909; Tilley, 1922; George, 1924; Huggins, 1940a; Cann et al., 1970).

The use of the density of obsidian as an attribute for characterization was first indirectly suggested by Frankfort in 1927. In later research, Cann and Renfrew (1964) also considered density as a potential property for the characterization of geological and archaeological obsidian, but did not consider the method worth pursuing because of considerable overlap in density between sources. The viability of obsidian characterization through density measurements was finally established by Reeves and Armitage (1973; reported in Reeves and Ward, 1976). They concluded that density measurements could be used, albeit in a limited way, to distinguish a few New Zealand sources with a reasonable degree of confidence, though too much overlap existed among most sources to allow their identification.

The most unusual application of obsidian density in an archaeological study was by Ambrose (1976b), who plotted the U abundance of obsidian against the density of the glass in order to distinguish source populations. The success of his effort once again suggested that obsidian density could be used to characterize natural rhyolitic glass.

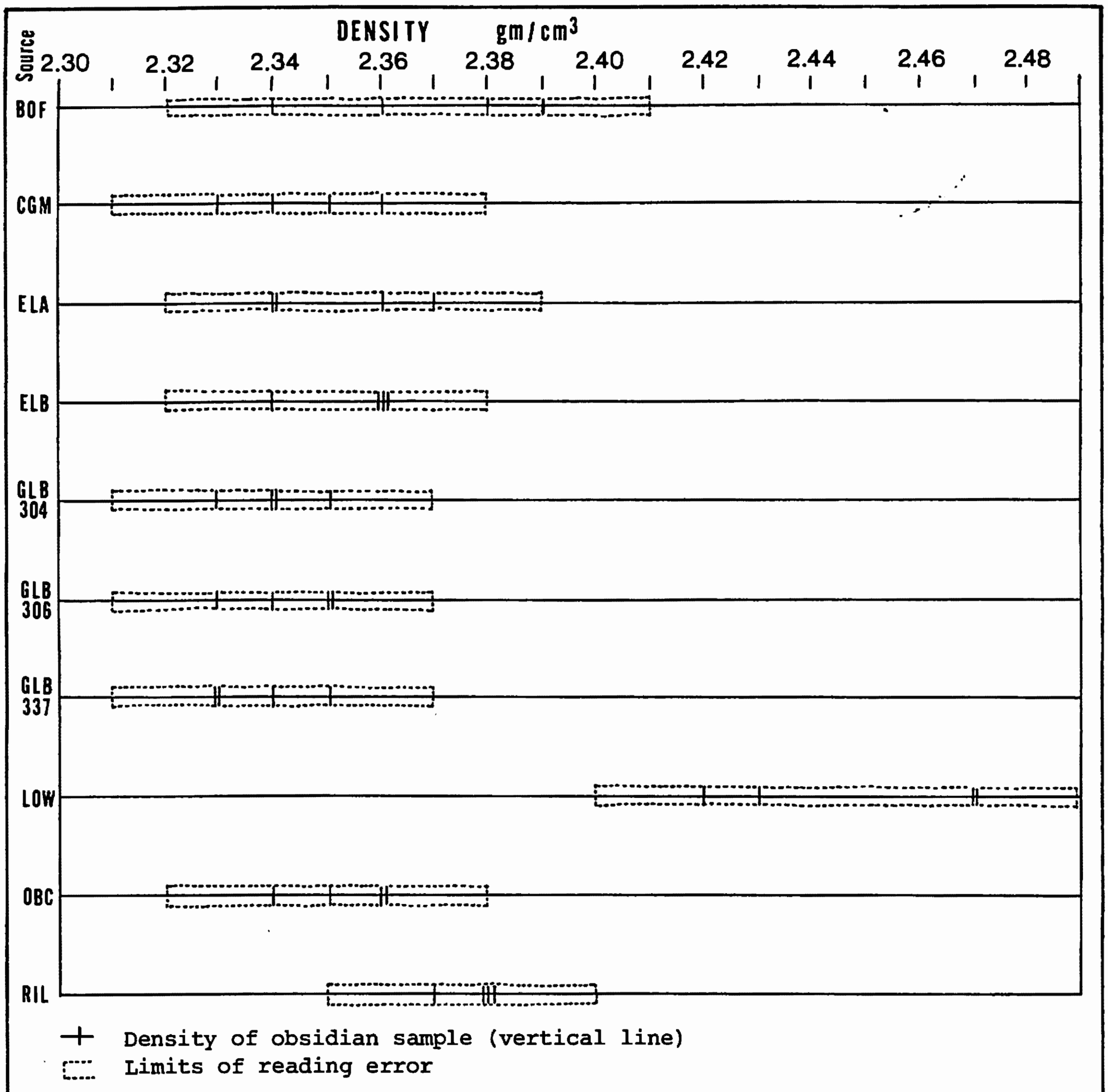
Sample	Density (± .02)	Sample	Density (± 02)
BOF-1	2.39	GLB-304A	2.34
BOF-2	2.34	GLB-304B	2.35
BOF-3	2.36	GLB-304C	2.33
BOF-4	2.39	GLB-304D	2.34
CGM-1	2.35	GLB-306A	2.34
CGM-2	2.33	GLB-306B	2.33
CGM-3	2.34	GLB-306C	2.35
CGM-4	2.36	GLB-306D	2.35
ELA-1	2.36	GLB-337A	2.33
ELA-2	2.34	GLB-337B	2.35
ELA-3	2.34	GLB-337C	2.33
ELA-4	2.37	GLB-337D	2.34
ELB-1	2.36	OBC-1	2.36
ELB-2	2.36	OBC-2	2.34
ELB-3	2.34	OBC-3	2.36
ELB-4	2.36	OBC-4	2.35
LOW-1	2.42	RIL-1	2.38
LOW-2	2.47	RIL-2	2.38
LOW-3	2.47	RIL-3	2.37
LOW-4	2.43	RIL-4	2.38

Table 7 : The density of obsidian examined in this project (gm/cm^3). The error refers to the reading error only.

Even though the scant previous research has indicated only limited success in the use of density as an attribute for obsidian characterization, any method that can reliably generate classes or groups of sources is potentially useful. This is particularly true when, as suggested in Chapter Four (and demonstrated in Appendix Eleven), different characterization methods of low discriminative ability are used in conjunction with each other.

RESULTS OF DENSITY DETERMINATIONS

The density of four samples of obsidian from each of the ten quarry sites was determined and recorded in Table 7. When plotted in Figure 41 (after the method of Reeves and Armitage, 1973), it is evident, after the reading error is taken into account, that there is considerable overlap between the different sources of rhyolitic obsidian. The degree of interunit homogeneity is very limited, though intraunit variability is small. A few weak trends can be observed, though, and it is possible that more accurate methods of density determination might delimit more distinct subgroups from among an obsidian source population. The obvious exception to the lack of variation exhibited between the obsidian sources was the nearly discrete subgroup formed by the LOW samples. The presence of a sizeable proportion of lithic and crystal materials (of greater density than the glassy component) in the ash-flow is likely the major cause of the consistently greater density figures for the samples from the Upper Winberry Creek obsidian-like vitrophyre.



┼ Density of obsidian sample (vertical line)

⬚ Limits of reading error

BOF: Big Obsidian Flow	GLB-306: Glass Buttes, Site 306
CGM: Cougar Mountain	GLB-337: Glass Buttes, Site 337
ELA: East Lake Flow, Western	LOW: Winberry Creek Ash-Flow
ELB: East Lake Flow, Eastern	OBC: Obsidian Cliffs
GLB-304: Glass Buttes, Site 304	RIL: Riley Site

Figure 41 : Density of obsidian.

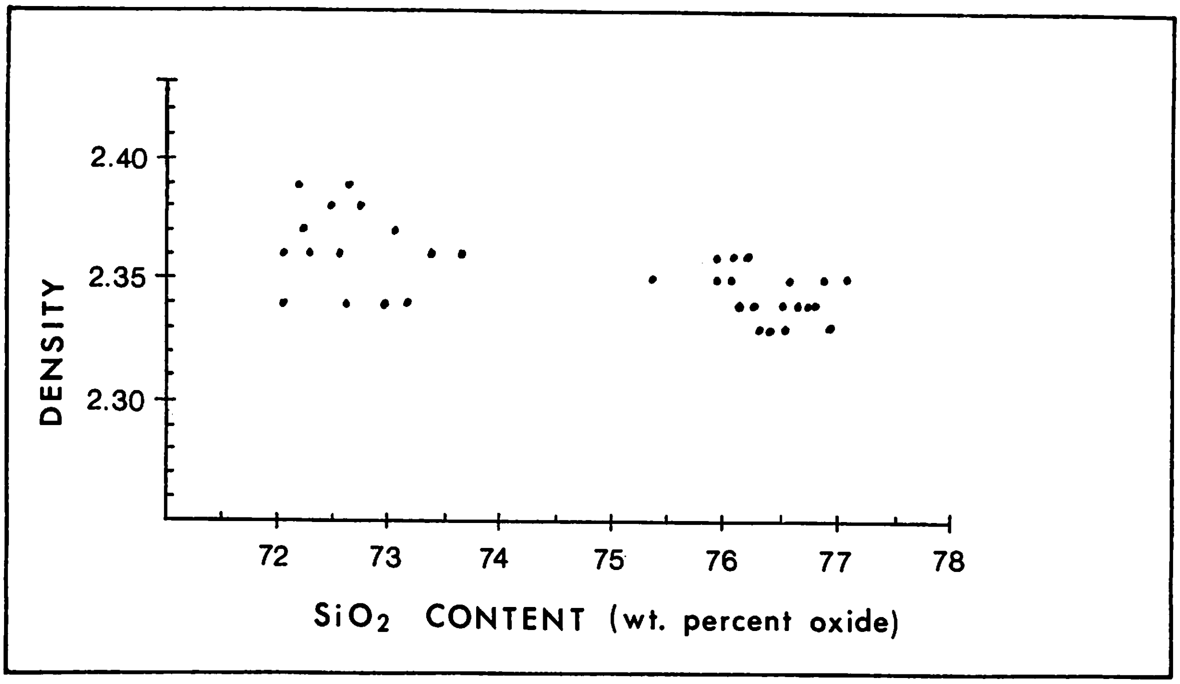


Figure 42: The density of obsidian sampled for this project plotted against the SiO_2 composition of the glass. The graph shows a systematic, though weak, inverse relationship of density and silica content. The compositional data are from Chapter Seven of this part of the project.

CONCLUSIONS

It appears than obsidian density has only a limited usefulness as an attribute for characterization. The results of this investigation demonstrate, though, that obsidian and obsidian-like vitrophyre may be easily distinguished from one another on the basis of their density. Because of the ease and low-cost of the determination of density in obsidian, it is suggested that the study of more precise methods of ascertaining density is warranted. The use of more accurate instrumentation for the establishment of density as well as improved preparation methods such as annealing (to eliminate bubbles and cracks that might introduce error) are two lines of investigation that could be pursued.

In the only study of its kind, George (1924) found that the density of obsidian appeared to be related to the SiO_2 content of the glass. When the density of the obsidian used in this investigation was plotted against the SiO_2 content of the samples (from Chapter Seven), a similar trend was noted (Figure 42), supporting the results of George's early study.

6 Microscopic Petrographic Features as Characterization Attributes

One of the most neglected of the possible characterization attributes of obsidian has been that of the presence of distinctive microscopic petrographic features in the glass. In this chapter, two types of petrographic features, the presence or absence of welded vitric shards and the presence of certain types of microlitic structures, will be examined. The first of these features, the presence or absence of welded shards of glass, can be used to distinguish between samples of true obsidian and obsidian-like vitrophyre associated with welded ash-flows. The presence of distinctive microlitic structures, the second petrographic feature, *may* have value in distinguishing sources of true obsidian.

THE PRESENCE OF WELDED GLASS SHARDS AS A PETROGRAPHIC SIGNATURE

An active volcanic ash-flow is a turbulent combination of high-temperature pyroclastic materials and gases erupted explosively from a volcanic vent. Pumice blocks and siliceous, glass-rich portions of the ash-flow may collapse and weld during the emplacement of the ash-flow, creating an obsidian-like vitrophyre sometimes called fiamme (Ross and Smith, 1960; Smith, 1960; Gibson and Tazieff, 1967; McBirney, 1968a; Williams and McBirney, 1979). Ross and Smith (1960:24) describe the obsidian-like material:

> Extreme conditions of welding may produce a zone of dense obsidian-like glass. This may be homogeneous or it may range into a "porphyritic"glass with a high percentage of crystals or rock fragments, depending on the makeup of the magma at the time of its eruption. Examination with a hand lens of glasses formed by extreme welding will usually reveal their fragmental nature.

Though the obsidian-like vitrophyre of welded ash-flows may macroscopically resemble obsidian, microscopic examination reveals marked petrographic differences between two. True obsidian consists of a glassy, isotropic groundmass inhabited by microlites, microphenocrysts and grains of magnetite. Obsidian-like vitrophyre, on the other hand, is made up of distinctive glass shards as well as commonly a large proportion of lithic and crystal materials (see Plates 29 and 30 for a comparison). There is little chance of confusing the true obsidian and the obsidian-like vitrophyre when the two are compared under a microscope.

The presence of welded glass shards in an obsidian-like sample, then, can be taken as clear proof of the ash-flow origin of the sample. When the samples used in this investigation were examined with a microscope, the specimens from the Upper Winberry Creek ash-flow (see Plate 30) were easily distinguishable from all other true obsidian sources on the basis of the presence of the welded glass shards.

MICROLITIC STRUCTURES IN OBSIDIAN

When examined with a microscope, most natural volcanic glasses are found to contain one or more types of microscopic structures called in this investigation microlitic structures. Though a thorough investigation of these structures has never been conducted, they are usually placed into two groups, microlites and crystallites. Microlites (sometimes called microliths) are minute, incipient crystals that polarize light and which have some determinable optical properties. Crystallites are generally considered to be isotropic forms, though the terminology describing crystallites and microlites is somewhat vague and the literature rather hazy (Zirkel, 1876:206-215; Iddings, 1888:273-274; Rutley, 1891; Johannsen, 1931:11-15; Williams et al., 1954:13-14; Heinrich, 1956:21; Clark, 1961:99-114; Ross, 1962). Because of the uncertainty in the classification and description of microlites and crystallites, both were termed microlitic structures for the purpose of this investigation. The major types of these structures are illustrated and defined in Part Two of this project.

Ross (1962) found that prismatic microlites were characteristically pyroxene, occasionally sanidine and rarely amphibole and biotite. The prismatic microlites are often found oriented in a similar direction (see Plate 31 for an example) and this was taken by Ross (1962) to be due to flow movement during emplacement. Clark (1970), though, has found that microlites are mobile under static stress at temperatures below the melting point of obsidian and that the alignment of microlites in flow bands may take place during cooling *in situ*.

The relationship of the structure and the presence or absence of microlitic structures with the composition of the glass is only poorly-known. Ross (1964) notes that obsidians with a small volatile content (0.10 to 0.12% in his examples) usually do not contain microlites while obsidians with a large volatile content (0.32 to 0.34% in his examples) usually do contain microlites. The low volatile content would lead, he concluded, to a higher obsidian viscosity which would inhibit microlite growth. He also found exceptions to this relationship, suggesting that volatile contect is only one of the variables contolling the presence or absence of microlites.

The history of microlite structures as an attribute for the characterization of archaeological obsidian has also been a brief one.

Microlitic structures were first superficially considered as a method of characterizing archaeological obsidian by Frankfort (1927:191-192) who, nevertheless, dismissed the method as too unreliable to be of any use. Heizer et al. (1965), citing the results of Ordonez (1892), suggested that the characterization of obsidian using the microlitic structures found in the glass seemed worth pursuing. Clark (1961:105,107) also suggested the use of microlitic structures for obsidian characterization when he wrote:

> ...it appears to this observer that there are minute differences in each [microlite] type in glass from widely separated areas, such that an experienced analyst might be able to identify obsidian from different areas into further subdivisions, simply by inspection. Thus, the writer feels that he has sufficient familiarity with obsidian from Central California, Central Mexico, Guatemala, Ecuador and Hokkaido that he could make significant guesses as to the provenience of specimens deriving from those areas.

Suzuki (1973:303-304) mentions three studies in Japan in which artifactual obsidian was assigned a geologic source based on the microcrystalline features of the obsidian (this apparently included microlitic structures). In his research, though, Suzuki (1973:304) found that, "...identification of obsidian source by these crystallites and microlites or their combination is very awkward due to duplication of some of the sources. Hence, by this method, several geologic sources must be nominated." He mentions, however, that some of the microlite features were unique, specifically the presence of asteroidal trichites at one source and the high density of prismatic microlites at two other sources.

On the basis of this review of the literature considering microlitic structures, it seems likely that some of the structures may be characteristic of specific sources or groups of sources and that the microscopic petrographic features of obsidian may have some utility as an attribute for characterization.

THE DETERMINATION OF THE PRESENCE OF DISTINCTIVE MICROLITIC STRUCTURES

After thin-sections had been prepared from each of the obsidian samples, each was examined to identify the different types of selected microlitic structures present. The results appear in Table 8. The measures of abundance (abundant, occasional and rare) were qualitative. No attempt was made to quantify the density or ratios of microlitic structures in this stage of the research, though this would be recommended for further studies. As it turned out, there was considerable variation in the densities of microlitic structures in the obsidian for each of the abundance categories. The prismatic microlites seen in the Obsidian Cliffs and Big Obsidian Flow samples were, for instance, both judged as abundant, though the microlite concentration in the Obsidian Cliffs obsidian was significantly greater. There was also considerable intrasample variation - a type of microlitic form might vary considerably in its abundance in parts of a slide, but as a whole, might be judged as abundant. The abundance categories are, then, only a general reflection of the average abundance in a slide of a particular microlitic structure. The qualitative nature of these determinations coupled with the still rudimentary knowledge of microlitic structures leave the results of this chapter as the most tentative of any component of the research reported in this part of the project. Any conclusions drawn about the utility of obsidian characterization through the presence or absence of microlitic structures is necessarily more preliminary than conclusions reached about the color, density or chemical composition as characterization attributes.

Once the types of microlitic structures were identified, they were plotted against the sources of obsidian in Figure 43 to give an indication of the distribution of the structures at each source or source area.

The only type of microlitic structures restricted to a single geologic source were the acicular prismatic microlites of the Obsidian Cliffs source (Plate 29). The needle-like prismatic microlites of this source averaged only about half the diameter of what I have termed here normal prismatic microlites.

Normal prismatic microlites (averaging about one micron in diameter) were abundant at all three of the Newberry Caldera sources (Plates 31 and 32), though they were also found in lesser amounts at Cougar Mountain and at the Riley Site.

SOURCE	NORMAL PRISMATIC MICROLITES				ACICULAR PRISMATIC MICROLITES				ACICULAR TRICHITES				ASTEROIDAL TRICHITES				MARGARITES				LONGULITES				SCOPULITES			
BOF	■	■	■	■	□	□	□	□	▨	▩	▩	▩	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
CGM	□	▨	▩	□	□	□	□	□	■	■	■	■	▩	■	■	□	□	□	□	□	■	■	□	■	□	□	□	▩
ELA	■	■	■	■	□	□	□	□	□	□	□	□	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
ELB	■	■	■	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
GLB 304	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	▩	▩	▩	▩	□	□	□	□	□	□	□	□
GLB 306	□	□	□	□	□	□	□	□	■	▩	▩	▩	■	□	□	□	□	■	□	■	▩	□	■	□	□	□	□	□
GLB337	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	■	■	■	■	□	□	□	□	▨	□	□	□
LOW	Not Applicable																											
OBC	□	□	□	□	■	■	■	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
RIL	▨	▨	▨	▩	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□	▨	▩	▩	▩	□	□	□	□
Sample No.	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

■ ABUNDANT

▨ RARE

▩ OCCASIONAL

□ NOT PRESENT

Table 8: Selected microlitic structures observed in obsidian from the nine obsidian sources examined. No identification of microlitic forms was made for the LOW samples because of the distinctive appearance of the glass shards. No attempt was made to quantify the abundances of the microlitic structures; the abundance classes are qualitative only.

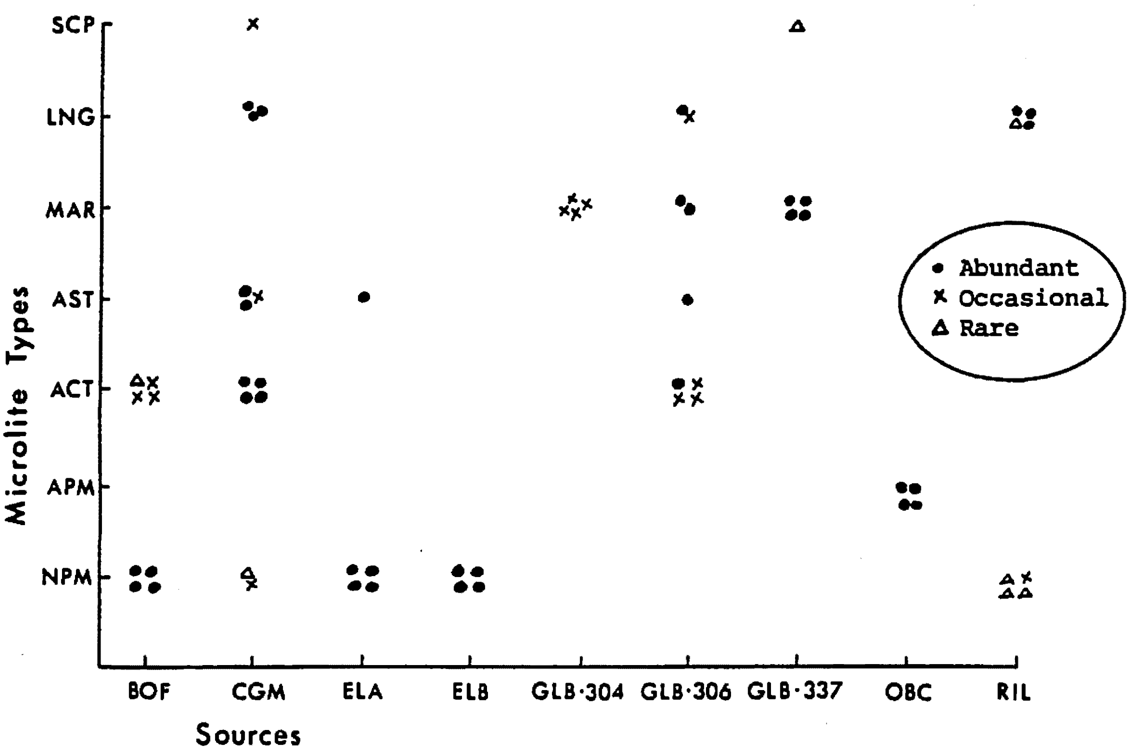
The presence of abundant quantities of normal prismatic microlites appears to be a distinguishing characteristic, out of the source universe considered, of obsidian originating from Newberry Caldera.

Acicular trichites were found at three sources, the Big Obsidian Flow, Cougar Mountain and Glass Buttes Site 35LK306, though they were abundant only at Cougar Mountain and in one anomalous sample from 35LK306 (GLB-306A; to be discussed shortly).

Abundant numbers of asteroidal trichites were characteristic of the Cougar Mountain obsidian source (Plate 33), but were also abundant in single anomalous specimens from an East Lake obsidian flow (ELA-1) and Site 35LK306 (GLB-306A; to be discussed shortly).

Margarites appeared to be diagnostic of obsidian from the Glass Buttes sites (Plates 34, 35 and 36), but were limited to portions of the obsidian free of any color.

Longulites were noted at Cougar Mountain, Glass Buttes Site 35LK306 and the Riley Site. Their presence at the Riley Site, along with an almost total lack of other microlitic structures, might be considered as characteristic of that site.



MICROLITE TYPES

Normal Prismatic Microlites (NPM)
Acicular Prismatic Microlites (APM)
Acicular Trichites (ACT)
Acteroidal Trichites (AST)
Margarites (MAR)
Longulites (LNG)
Scopulites (SCP)

SOURCES

Big Obsidian Flow (BOF)
Cougar Mountain (CGM)
East Lake Flow, Western (ELA)
East Lake Flow, Eastern (ELB)
Glass Buttes, Site 304 (GLB-304)
Glass Buttes, Site 306 (GLB-306)
Glass Buttes, Site 337 (GLB-337)
Obsidian Cliffs (OBC)
Riley Site (RIL)

Figure 43: The distribution of different selected microlitic structures at each of the sources of obsidian. Data are from Table 8.

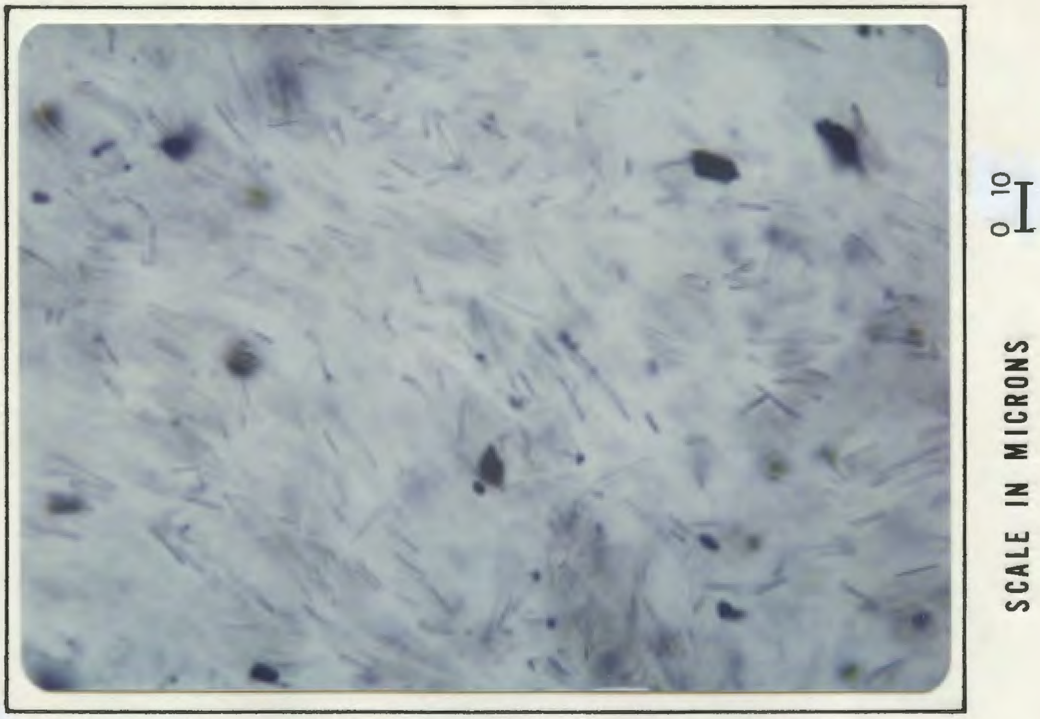


Plate 29: Photomicrograph of obsidian from Obsidian Cliffs, Lane County (sample OBC-4). Large concentrations of acicular prismatic microlites are typical of obsidian from this source. The black particles in this photograph, as well as in the other photographs in this chapter, are magnetite. Nicols not crossed, x 150.

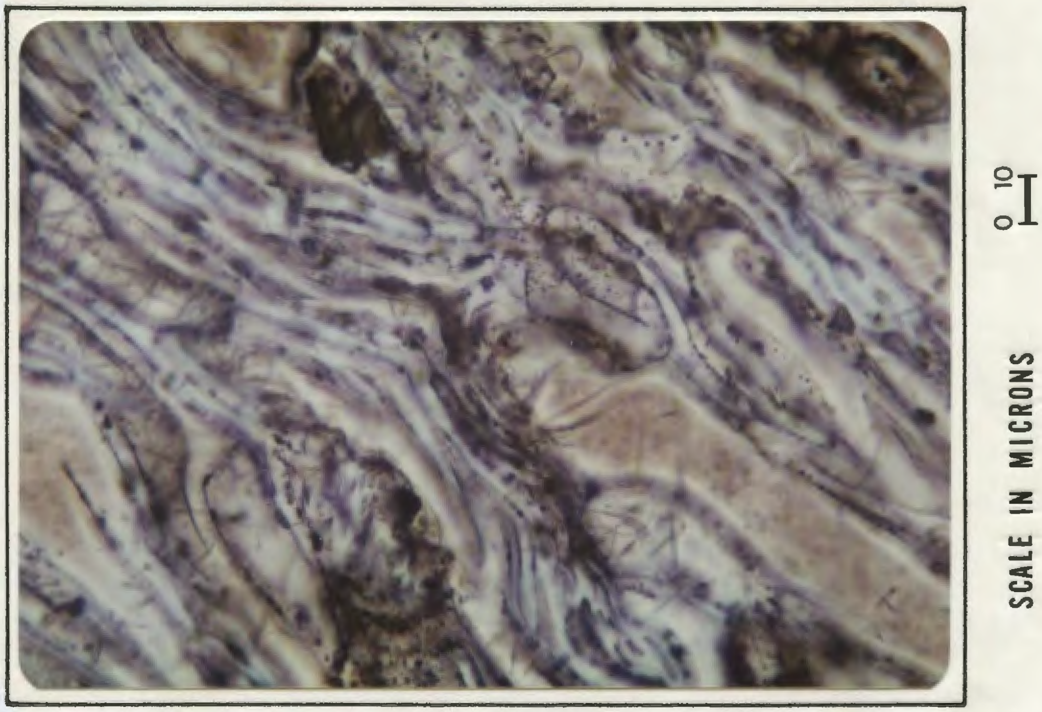


Plate 30: Photomicrograph of obsidian-like vitrophyre recovered from the densely-welded zone of the Upper Winberry Creek welded ash-flow (sample LOW-4). The glass shards are molded against each other and all pore space has been eliminated by the very complete welding. The glass shards contain acicular prismatic microlites as well as acicular and asteroidal trichites. Nicols not crossed, x 150.

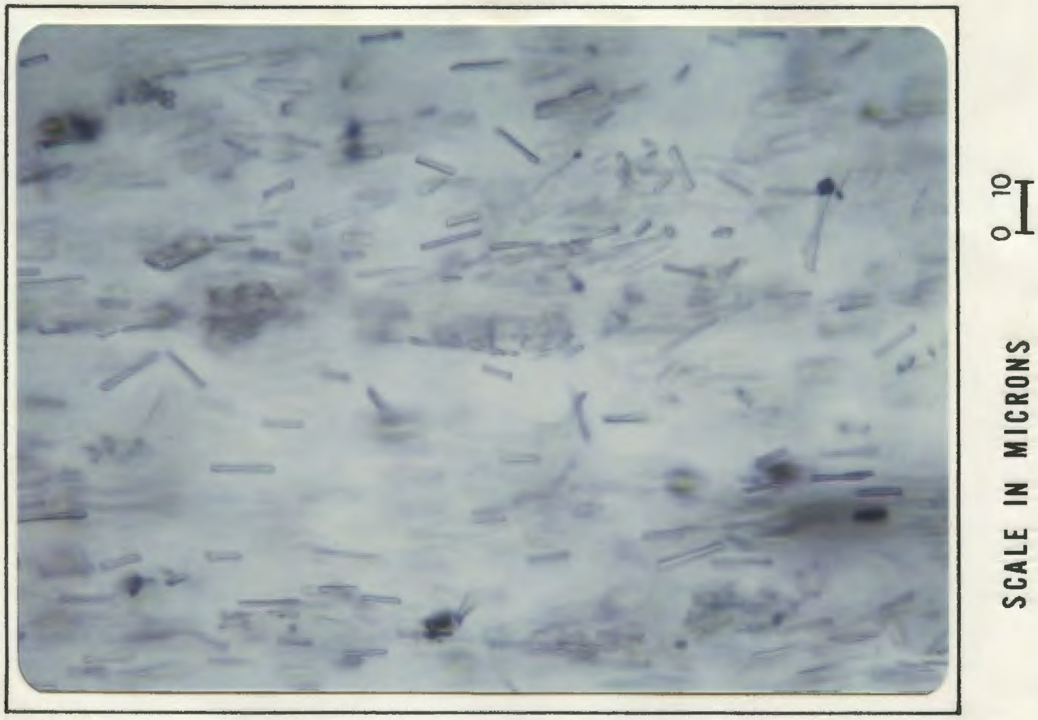


Plate 31: Photomicrograph of obsidian from the Big Obsidian Flow, Newberry Caldera (sample BOF-4). Prismatic microlites, concentrated in banded areas of the glass, but present throughout the obsidian, are found in all of the recent obsidian flows in the caldera. Nicols not crossed, x150.

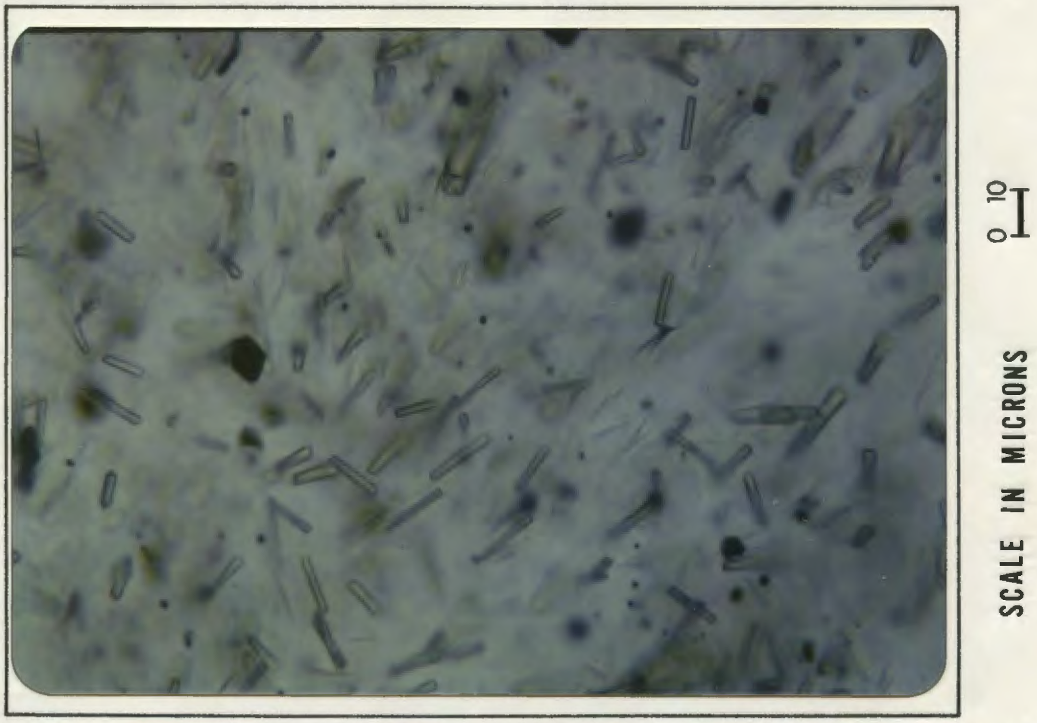


Plate 32: Photomicrograph of obsidian from the westernmost of the two East Lake obsidian flows in Newberry Caldera (sample ELA-4). The obsidian from both flows is essentially identical and is petrographically indistinguishable from the Big Obsidian Flow. Nicols not crossed, x150.

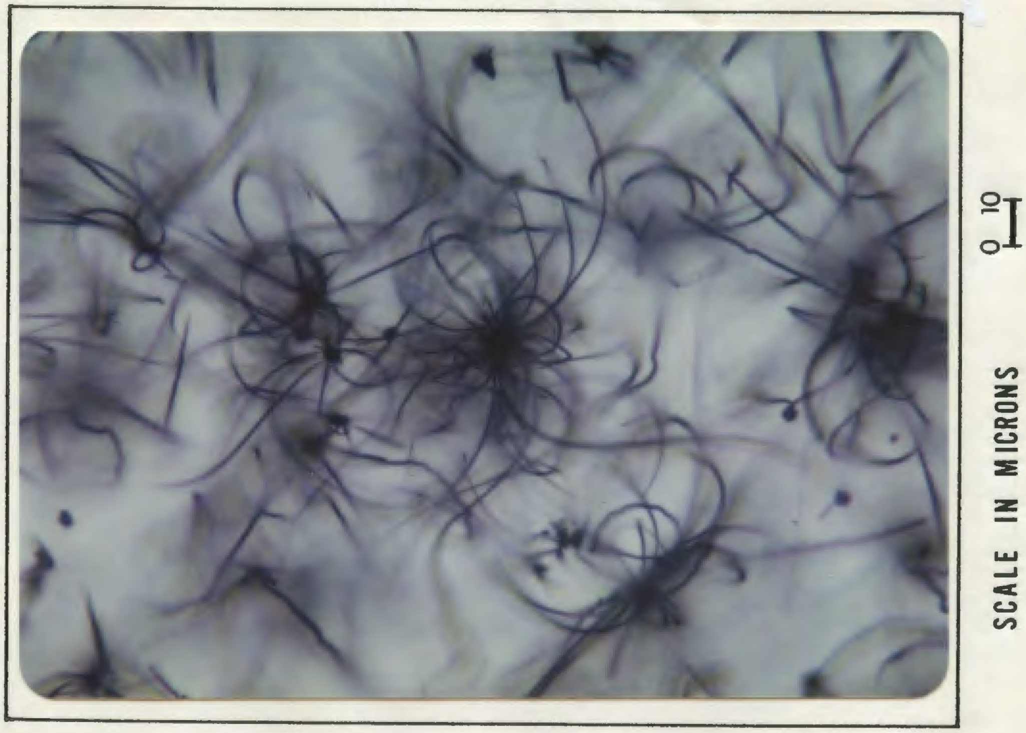


Plate 33: Photomicrograph of obsidian from Cougar Mountain, Lake County (sample CGM-2). The dominant microlitic structures in the photograph are the spider-like asteroidal trichites. The curved trichites that make up these structures appear to radiate from a magnetite grain nucleus. Abundant acicular trichites are also found. Nicols not crossed, x150.

Plate 34: Photomicrograph of obsidian from Glass Buttes, site 35LK304 (sample GLB-304D). Clusters of magnetite and the ends of margarites are seen in the photograph. Other microlitic structures are absent from the glass of this site, accounting for the unusual clearness of thin flakes of obsidian at this location. Nicols not crossed, x150.

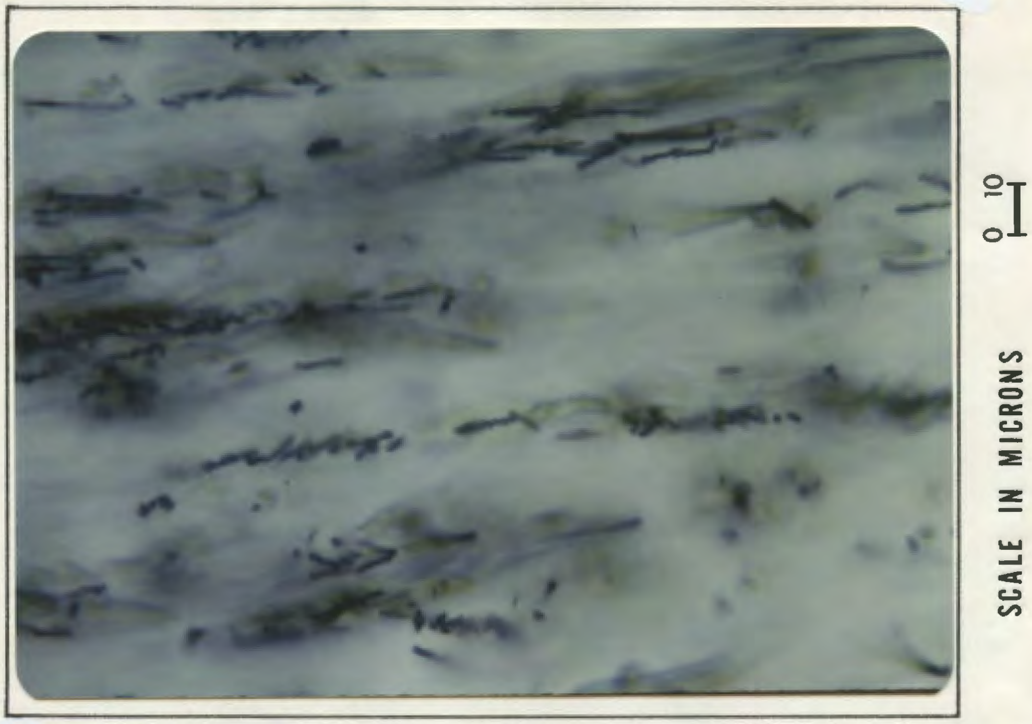


Plate 35: Photomicrograph of obsidian from Glass Buttes, site 35LK306 (sample GLB-306C). Bands of margarites and magnetite are common in obsidian from this quarry site. Nicols not crossed, x150.

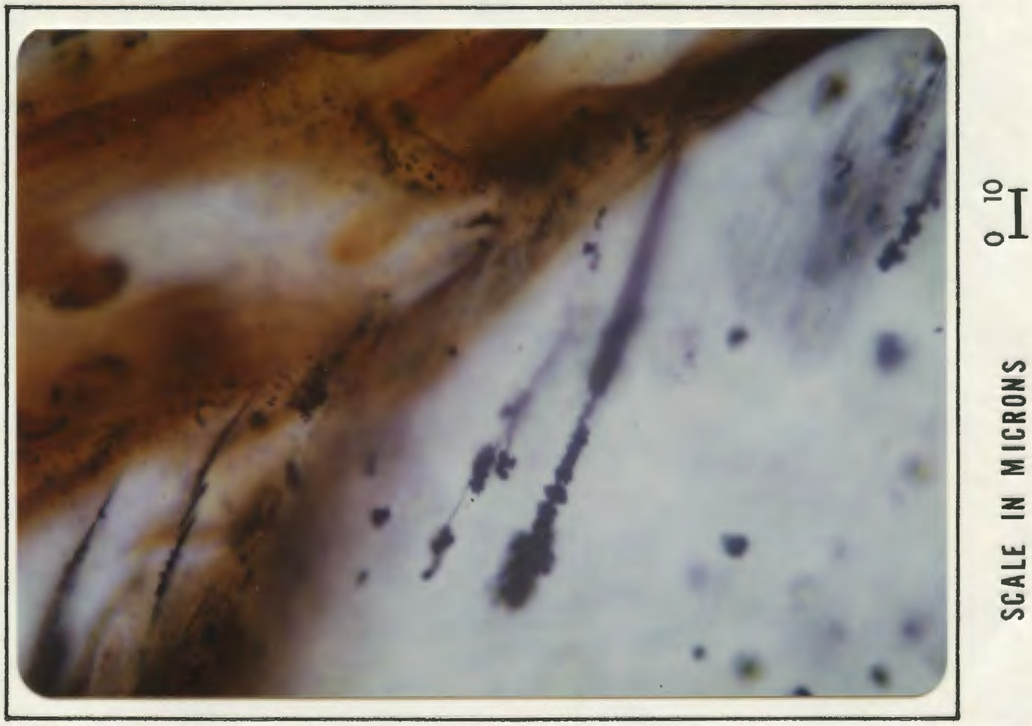


Plate 36: Photomicrograph of obsidian from Glass Buttes, Site 35LK337 (sample GLB-337D). Red and black variegated and banded obsidian is typical of this site. The photograph was taken at the boundary of the two colors of glass. Rows of magnetite grains make up the microlitic structures known as margarites, common structures at all of the Glass Buttes sites. Nicols not crossed, x150.

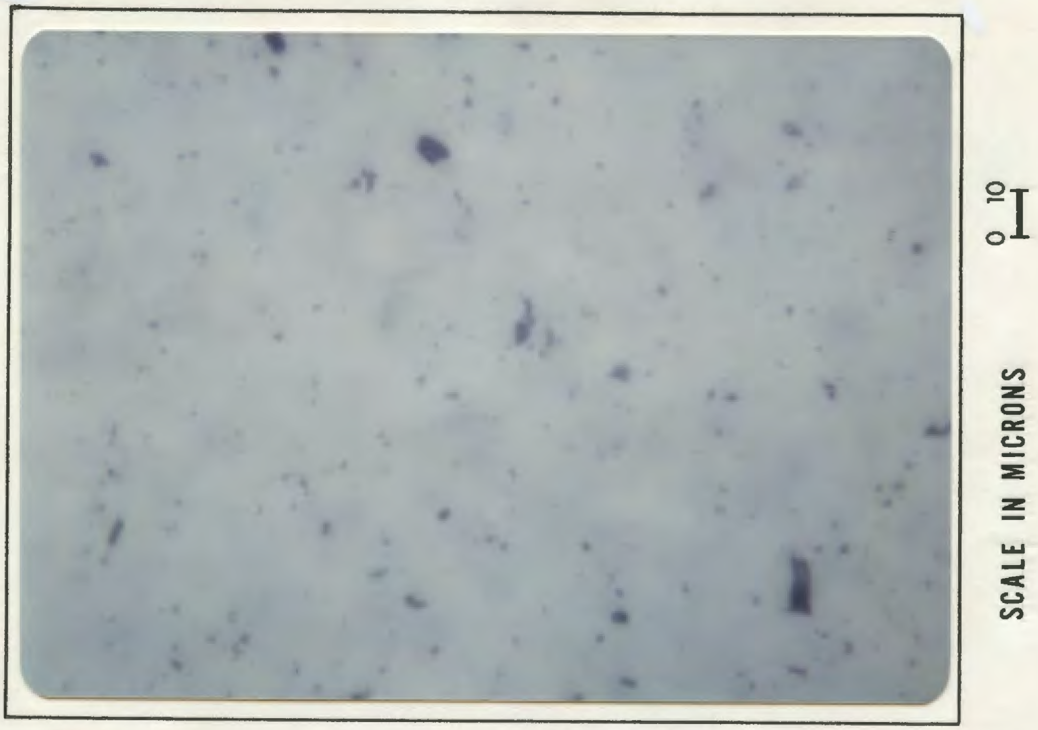


Plate 37: Photomicrograph of obsidian from the Riley Site, Harney County (sample RIL-4). The obsidian at this site was unusually free of microlitic structures, though some were present in small quantities. Nicols not crossed, x150.

Scopulites were found in only two of the samples and, in both cases, appeared to be associated with oxidized grains of magnetite.

Two very anomalous samples were noted, ELA-1 and GLB-306A. Both fell well outside of the general range of intrasource homogeneity that the observations of this study suggest exist in individual geologic obsidian sources. ELA-1 was littered with structures that resembled asteroidal trichites, though they were somewhat smaller in size that asteroidal trichites found at other sources. Each of the asteroidal structures originated at a very small bubble in the glass and may have a different origin than similar structures (not associated with bubbles) in other examples. GLB-306A, quite unlike any of the other specimens from Glass Buttes, was almost identical in appearance to samples from Cougar Mountain and may be a mislabeled specimen. Whether these two specimens represent sample or collection errors, unidentified processes or simply the range of intraunit variability that exists in the obsidian sources is not known.

CONCLUSIONS

The distribution of microlitic structures found in the different sources among the obsidian source universe considered in this investigation certainly suggests that this characterization attribute is capable of distinguishing source groups from a population. In addition, occasional discrete sources, such as Obsidian Cliffs, may also be distinguishable through the presence of a unique microlitic form. The preliminary results reported in this chapter, though they must be treated with caution because of the limited sample size, indicate that further study of obsidian characterization using microlitic forms could likely be fruitful. Used alone, or more appropriately, in conjunction with other methods, the petrographic characterization of natural glass could prove a valuable addition to currently available techniques of obsidian characterization.

7 Chemical Composition as a Characterization Attribute

Study of the chemical composition of obsidian as an attribute for characterization is the most widely-used method of obsidian characterization employed today. In this method, the abundances of selected trace elements (elements found in quantities less than about 1000 parts per million), or occasionally, major elements (elements found in quantities greater than 1000 parts per million) are determined and used to "fingerprint" the obsidian. The techniques used to determine the composition of the obsidian vary - X-ray fluorescence (XRF), atomic absorption (AA), particle-induced X-ray emission (PIXE), instrumental neutron activation analysis (INAA) and flame photometry have all been commonly used.

In the investigation that is reported in this chapter, X-ray fluorescence spectographic techniques were used to the determine the major element and selected trace element composition of samples from the ten obsidian quarries. The effectiveness of chemical composition as an attribute for obsidian characterization and as an archaeological tool is the subject of the remainder of this chapter.

MAJOR ELEMENT CHARACTERIZATION OF OBSIDIAN

The major element characterization of archaeological obsidian has enjoyed only a very limited popularity in its relatively short history as a method available for archaeological research.

Cann and Renfrew (1964) and Cann et al.(1970), citing a study by Georgiades (1956) of obsidian from the Aegean, stated that the major element characterization method had been successful in distinguishing some of the Aegean sources, though not all. They seemed skeptical of the method, though, because of the restricted range of major element composition in obsidian which they felt would limit the methods effectiveness when it was applied to more than a few sources. Umschler (1975), in characterizing archaeological obsidian from a site in Utah, found Fe and Ca contents to be useful in determining the geologic sources of the artifactual obsidian from Micronesia using the major element composition of the glass. Na, K, Ca and Mg contents were mentioned by Reeves and Ward (1976) to show significant variation among New Zealand sources. Most recently, research reported tion among New Zealand obsidian sources. Most recently, an experiment reported by Michels (1982) found only a 70% success rate in the assignment of Guatemalan obsidian artifacts to their geologic sources using major element abundances. He did report, however, nearly 100% reliability in the differentiation of several Mediterranean sources using only their CaO and MgO compositions.

The advantages of major element characterization over trace element characterization, as has been pointed out by Michels (1982), lie in the greater ease of determination and in the relatively low cost of the analytical equipment involved. The availability of major element characterization as a reliable obsidian characterization tool could help to make it a worthwhile addition to any archaeological tool kit.

TRACE ELEMENT CHARACTERIZATION OF OBSIDIAN

The best known and most extensively-reported obsidian characterization technique currently in use by archaeologists is through the determination of its trace element composition. A substantial number of the many trace elements found in obsidian typically exhibit considerable homogeneity within a single source while varying in composition from nost other obsidian sources (see Table IV-1, Appendix IV, for examples). This association of intraunit homogeneity and interunit heterogeneity has contributed to the present popularity of the method.

Early studies in trace element obsidian characterization were made by Cann and Renfrew (1964), Weaver and Stross (1965), Heizer et al.(1965), Renfrew et al. (1965 and 1966), Parks and Tieh (1966) and Green et al.(1967). All of these studies seemed to indicate that the trace element characterization of geologic and archaeological obsidian was perhaps the best method available in providing data needed for the reconstruction of prehistoric exchange systems.

The cornerstone of trace element characterization rests on the critical assumption of source homogeneity. While this is usually the case (Gordus et al.,1968; Osborn and Scmitt, 1970; Laidley and McKay, 1971; Wall, 1976; Gale, 1981), there has been at least one notable exception reported in California (Bowman et al., 1973a and 1973b). This exception necessitates the empirical determination of the range of compositional variation for each potential obsidian source (Stross et al., 1976).

Since the early periods of development of trace element characterization, the method has been well-received. Articles documenting its application in archaeological research in many parts of the world have appeared with increasing frequency over the years. By major geographic area, these include:

1. The Mediterranean (including Eastern Europe, Northern Africa and the Near East) - Cann and Renfrew, 1964; Renfrew et al., 1965; Renfrew et al., 1966; Renfrew et al., 1968; Dixon et al., 1968; Wright, 1969; Wright and Gordus, 1969a; Wright and Gordus, 1969b; Cann et al., 1970; Gordus et al., 1971; Aspinall et al., 1972; Dixon, 1976; Hallam et al., 1976; Muir and Hivernel, 1976; Longworth and Warren, 1979; Gale, 1981.
2. Oceania (New Zealand, Micronesia and Melanesia) - Green et al., 1967; Key, 1968; Key, 1969; Leach, 1969; Ambrose and Green, 1972; Armitage et al., 1972; Ward, 1972; Ward, 1974a; Ward, 1974b; Ambrose, 1976b; Bird and Russell, 1976; Wall, 1976; Reeves and Ward, 1976; Smith et al., 1977; Bird et al., 1978; Leach and Anderson, 1978; Duerden et al., 1979.
3. Mexico and Central America - Heizer et al., 1965; Stross et al., 1968; Jack and Heizer, 1968; Stevenson et al., 1971; Hester et al., 1971a; Hester et al., 1971b; Stross et al., 1971; Jack et al., 1972; Hammond, 1972; Graham et al.,1972; Pires-Ferreira, 1973; Hester et al., 1975; Nielson, 1975; Pires-Ferreira, 1975; Ramirez, 1976; Pires-Ferreira, 1976; Winter and Pires-Ferreira, 1976; Hammond, 1976; Johnson, 1976; Kimberlin, 1976; Stross et al., 1976; Nielson et al., 1976; Allen and Ramirez, 1977; Ericson and Kimberlin, 1977; Hurtado de Mendoza, 1977; Sidrys, 1977b; Stross et al., 1977; Nelson et al., 1977; Nelson et al., 1978; Charlton et al., 1978; Asaro et al., 1978; Stross et al., 1978; Hurtado de Mendoza and Jester, 1978; Zeitlin and Heimbuch, 1978; Zeitlin, 1979; Sidrys and Kimberlin, 1979; Nelson and Voorhies, 1980; Zeitlin, 1982; Stross et al., 1983; Hester et al., 1972; Spence, 1981.

4. South America - Burger and Asaro, 1978.
5. North America (excluding Oregon) - Heizer et al., 1965; Parks and Tieh, 1966; Gordus et al., 1967; Griffin and Gordus, 1967; Gordus et al., 1968; Frison et al., 1968; Griffin et al., 1969a; Griffin et al., 1969b; Wright et al., 1969; Jack and Carmichael, 1969; Condie and Blaxland, 1970; Patton and Miller, 1970; Jack, 1971; Jackson, 1971; Stevenson et al., 1971; Stross et al., 1971; Kowalski et al., 1972; Jackson, 1973; Ericson and Berger, 1974; Jackson, 1974; Bennett and D'Auria, 1974; Findlow et al., 1975; Umschler, 1975; Jackson and Schulz, 1975; Jack, 1976; Wheeler and Clark, 1977; Ericson, 1977; Hughes, 1978; Nelson and Holmes, 1979; Sappington, 1980a; Sappington, 1981; Garfinkel and Schiffman, 1981; Hughes, 1982; Sanders et al., 1982; Ericson, 1982; Findlow and Bolognese, 1982.
6. Oregon - Wright et al., 1969; Stevenson et al., 1971; Bennett and D'Auria, 1974; White, 1974; White, 1975; Nelson et al., 1975; Ericson and Berger, 1976; Ericson, 1977; Hughes, 1978; Sappington, 1980a; Sappington, 1980b; Sappington, 1981; Sappington and Toepel, 1981; Toepel and Sappington, 1982; Sappington, 1982.

Virtually the only disadvantage of the trace element method of obsidian characterization, apart from the methodological problems discussed in Part One of this project, is that the method is often not readily available for use by archaeologists. While the technique appears reliable when carefully used, the analytical facilities needed to accurately determine the trace element composition of obsidian are not widely available and may be rather expensive, especially when the work is contracted out. This is particularly true for archaeologists without major university connections or access to university facilities, often the case for archaeologists engaged in contract or conservation work. For those archaeologists with access to the analytical resources needed for trace element characterization, it appears to be the obsidian characterization technique of choice.

RESULTS OF MAJOR ELEMENT COMPOSITION DETERMINATION

Results of X-ray fluorescence analyses of obsidian samples from the ten obsidian quarry sites are shown in Table 9. The major element oxides exhibiting the greatest intraunit homogeneity and interunit heterogeneity, in addition to a low analytical error (see Appendix X), proved to be SiO_2, CaO and Fe_2O_3. These three major element oxides are plotted, in order to distinguish compositional subgroups, on a ternary diagram (Figure 44) and on binary diagrams (Figures 44, 45 and 46).

When major element abundances are plotted on the ternary diagram (Figure 44), five different subgroups are differentiated: the Riley source, the Upper Winberry Creek source; all the Newberry Caldera sources; all the Glass Butte sources; and the Obsidian Cliffs/Cougar Mountain sources. When the SiO_2/Fe_2O_3 compositions of the samples are plotted against each other (Figure 45), the results are similar to those of the ternary plot. In Figure 46, SiO_2 plotted versus CaO, six distinct subgroups are indicated, with a seventh subgroup (BOF) only weakly differentiated from the Newberry Caldera sources. When the CaO composition of the obsidian is plotted against the Fe_2O_3 composition (Figure 47), seven distinct subgroups emerge. Only the three Glass Buttes sources and the two East Lake flows remain inseparable on the basis of their major element composition.

Sample	SiO_2	TiO_2	Al_2O_3	MgO	Fe_2O_3	MnO	CaO	Na_2O	K_2O	P_2O_5	Total
BOF-1	72.28	0.21	13.98	0.05	2.27	0.06	0.85	5.20	3.90	0.02	98.91
BOF-2	72.05	0.21	14.01	0.17	2.26	0.06	0.89	5.11	4.03	0.04	98.82
BOF-3	72.26	0.22	14.02	0.18	2.22	0.06	0.89	5.28	4.07	0.03	99.23
BOF-4	72.62	0.21	14.04	0.16	2.22	0.06	0.88	5.25	4.02	0.03	99.49
CGM-1	76.60	0.05	12.88	0.13	1.17	0.04	0.71	4.34	3.89	0.02	99.83
CGM-2	76.41	0.05	12.76	0.12	1.18	0.04	0.69	4.32	3.86	0.01	99.43
CGM-3	76.63	0.05	13.07	0.20	1.18	0.04	0.72	4.47	3.92	0.03	100.30
CGM-4	76.11	0.05	12.85	0.14	1.21	0.04	0.69	4.59	3.86	0.02	99.56
ELA-1	72.07	0.22	13.80	0.38	2.04	0.04	1.01	4.86	4.18	0.04	98.62
ELA-2	72.99	0.23	13.89	0.30	2.04	0.05	1.01	4.81	4.23	0.04	99.57
ELA-3	72.63	0.23	13.94	0.30	2.05	0.04	1.03	4.84	4.24	0.04	99.29
ELA-4	73.08	0.23	14.02	0.30	2.05	0.05	1.01	4.82	4.19	0.03	99.75
ELB-1	73.64	0.23	14.13	0.28	2.05	0.04	1.01	4.95	4.20	0.04	100.56
ELB-2	73.40	0.23	14.12	0.28	2.03	0.04	1.02	4.98	4.20	0.03	100.30
ELB-3	73.17	0.23	13.95	0.41	2.04	0.05	1.02	4.92	4.23	0.04	100.05
ELB-4	72.56	0.23	13.99	0.36	2.04	0.05	1.01	4.88	4.25	0.04	99.41
GLB-304A	76.50	0.06	12.90	0.21	0.84	0.04	0.55	4.26	4.21	0.01	99.57
GLB-304B	75.98	0.06	12.78	0.17	0.84	0.04	0.54	4.18	4.21	0.00	98.79
GLB-304C	76.56	0.06	12.70	0.11	0.82	0.03	0.53	4.18	4.18	0.00	99.17
GLB-304D	76.81	0.05	12.80	0.15	0.84	0.04	0.53	4.22	4.18	0.00	99.62
GLB-306A	76.30	0.06	12.85	0.21	0.83	0.04	0.53	4.68	4.20	0.00	99.69
GLB-306B	76.40	0.06	12.76	0.23	0.83	0.04	0.53	3.96	4.19	0.00	98.99
GLB-306C	77.09	0.06	12.73	0.23	0.84	0.04	0.54	3.80	4.21	0.00	99.54
GLB-306D	76.80	0.06	13.03	0.32	0.84	0.04	0.60	4.24	4.23	0.07	100.22

BOF: Big Obsidian Flow
CGM: Cougar Mountain
ELA: East Lake Flow, Western
ELB: East Lake Flow, Eastern
GLB-304: Glass Buttes, Site 304
GLB-306: Glass Buttes, Site 306

Table 9 : Major element composition of obsidian examined in Part Four of the project. Abundances are reported in weight percent oxides. All elements except Na were determined by X-ray fluorescence spectrometry. Na established by atomic absorption. Analyses continued on the following page. For analytical uncertainties, see Appendix Ten in Volume Two of this project.

Sample	SiO_2	TiO_2	Al_2O_3	MgO	Fe_2O_3	MnO	CaO	Na_2O	K_2O	P_2O_5	Total
GLB-337A	76.92	0.06	12.88	0.26	0.84	0.04	0.54	4.14	4.20	0.00	99.88
GLB-337B	76.06	0.06	12.82	0.22	0.84	0.04	0.54	3.79	4.18	0.01	98.55
GLB-337C	76.27	0.06	12.76	0.16	0.83	0.04	0.54	4.17	4.22	0.00	99.05
GLB-337D	76.73	0.06	12.79	0.17	0.83	0.04	0.54	4.14	4.20	0.00	99.49
LOW-1	67.24	0.31	13.41	0.36	4.39	0.12	2.13	4.90	2.08	0.05	94.99
LOW-2	68.00	0.29	13.46	0.24	4.16	0.11	2.01	4.72	2.29	0.05	95.35
LOW-3	67.90	0.30	13.31	0.37	4.14	0.11	2.13	4.47	2.41	0.05	95.19
LOW-4	67.69	0.31	13.46	0.30	4.40	0.12	2.19	4.76	2.47	0.07	95.77
OBC-1	75.92	0.10	13.12	0.16	1.16	0.04	0.93	4.40	3.44	0.03	99.28
OBC-2	76.19	0.09	12.95	0.25	1.09	0.04	0.88	4.41	3.46	0.02	99.37
OBC-3	76.22	0.08	13.00	0.19	1.09	0.04	0.89	4.33	3.50	0.05	99.38
OBC-4	75.31	0.09	12.90	0.22	1.09	0.04	0.88	4.23	3.48	0.03	98.26
RIL-1	72.71	0.21	13.52	0.24	2.43	0.08	0.58	4.88	4.71	0.04	99.39
RIL-2	73.28	0.21	13.38	0.28	2.46	0.08	0.57	5.01	4.73	0.03	100.03
RIL-3	72.21	0.21	13.46	0.37	2.45	0.08	0.57	5.00	4.68	0.03	99.04
RIL-4	72.49	0.21	13.19	0.22	2.41	0.08	0.54	4.86	4.67	0.02	98.68

GLB-337: Glass Buttes, Site 337
LOW: Winberry Creek Ash-Flow
OBC: Obsidian Cliffs
RIL: Riley Site

Table 9 : Major element composition of obsidian (continued from preceding page).

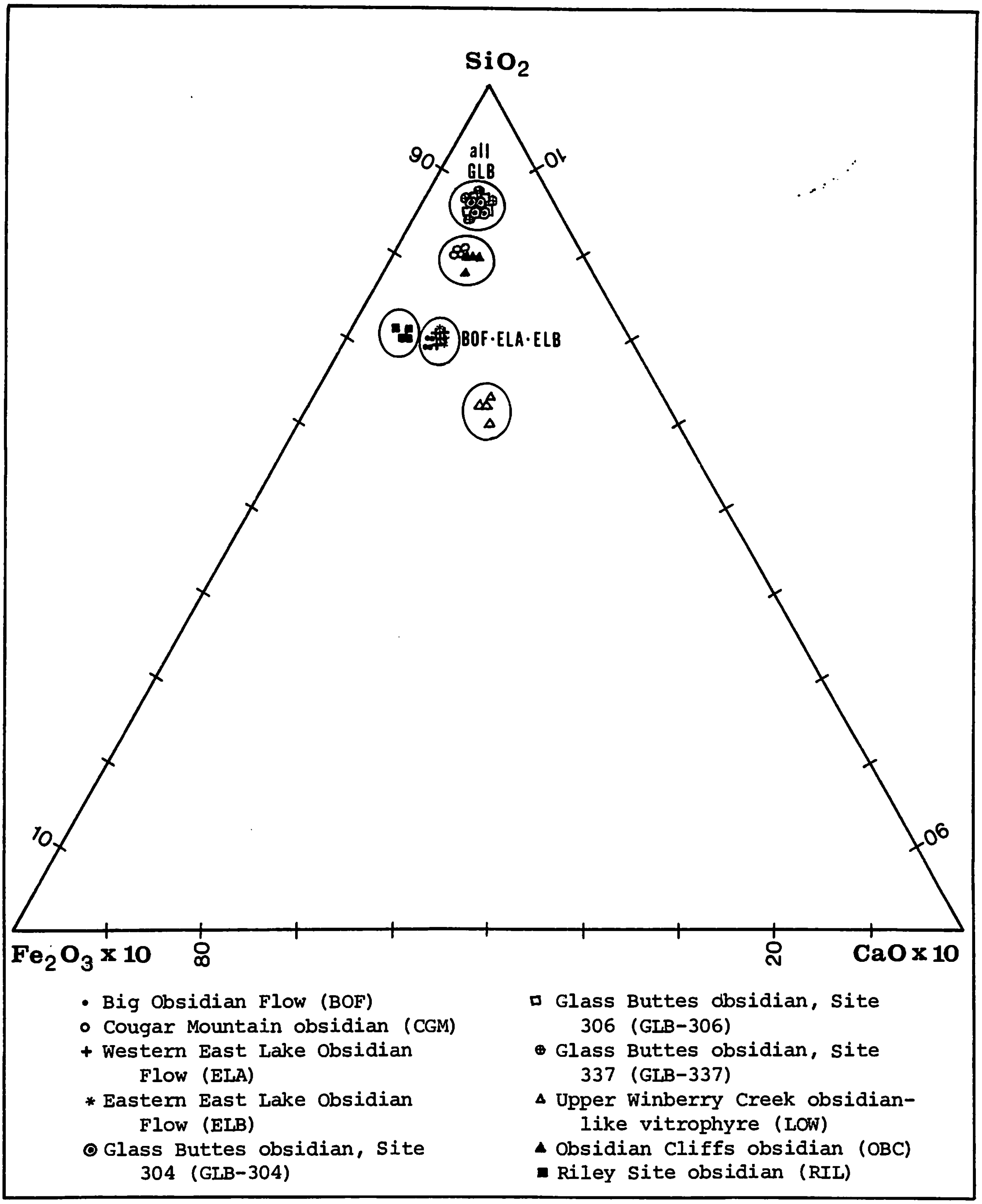


Figure 44: Ternary diagram illustrating the relative abundances of SiO_2, Fe_2O_3 and CaO found in obsidian collected at the ten quarry sites.

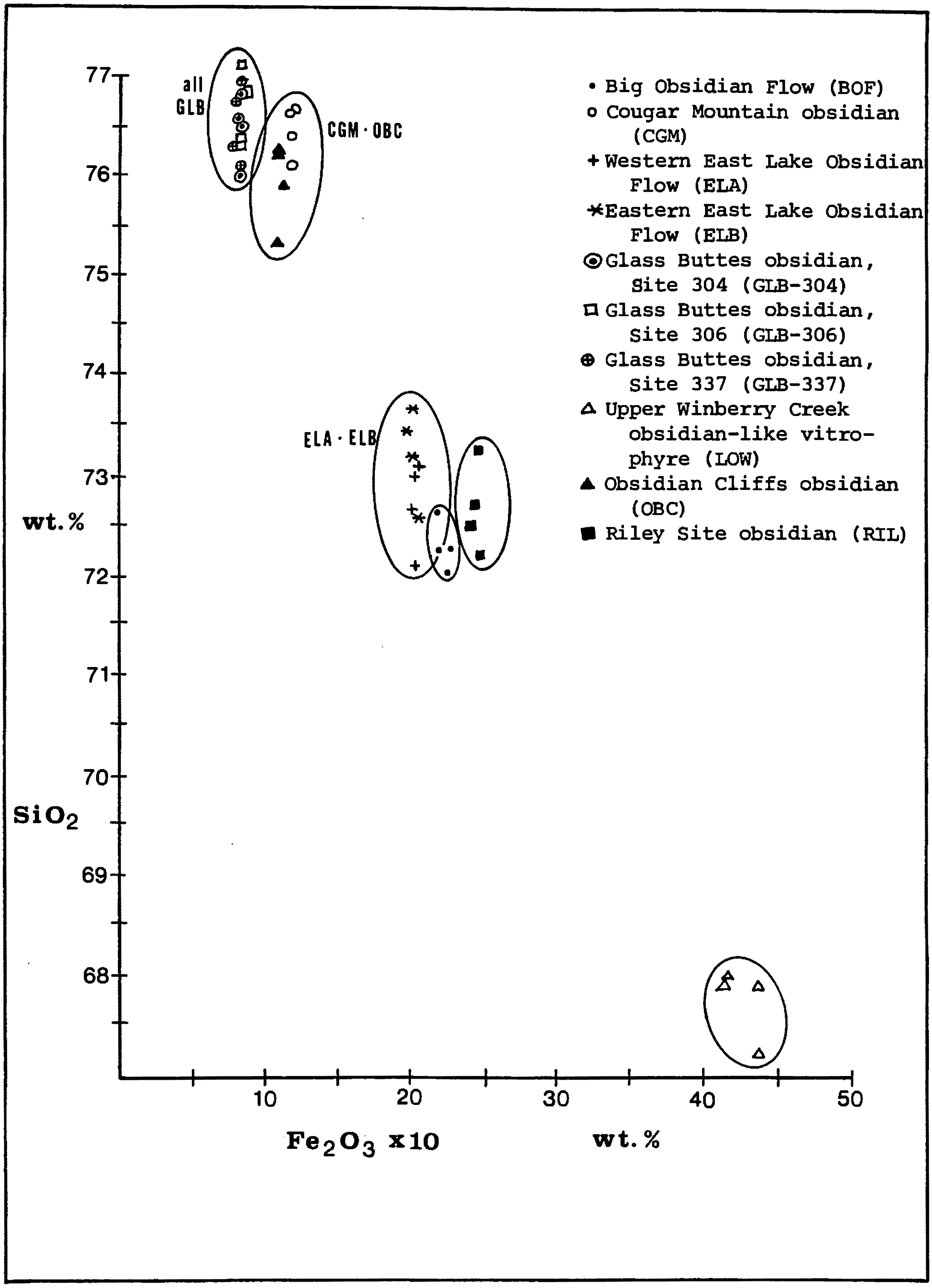


Figure 45: SiO_2 composition of obsidian samples plotted versus Fe_2O_3 composition.

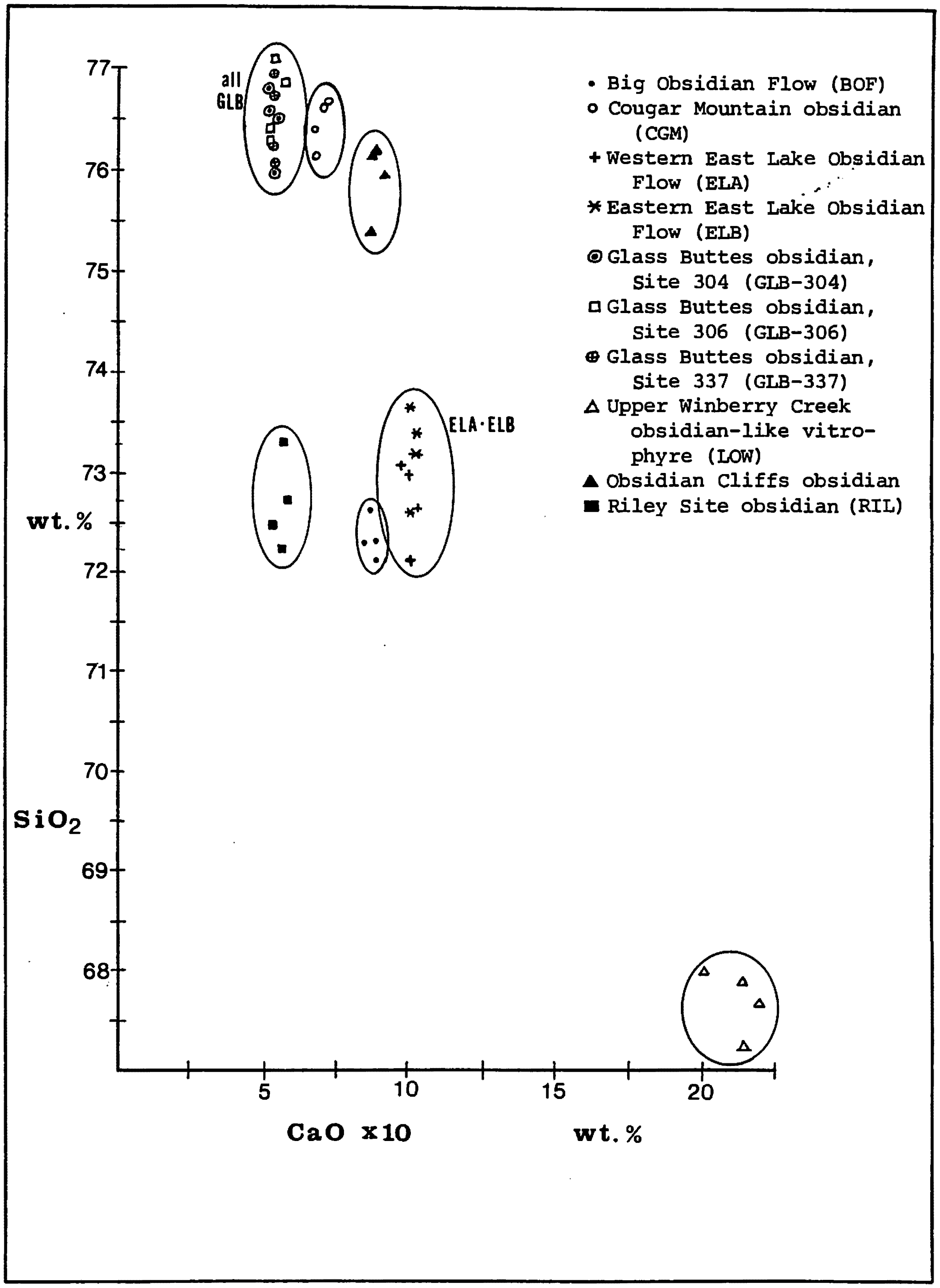


Figure 46: SiO_2 composition of obsidian samples plotted versus CaO composition.

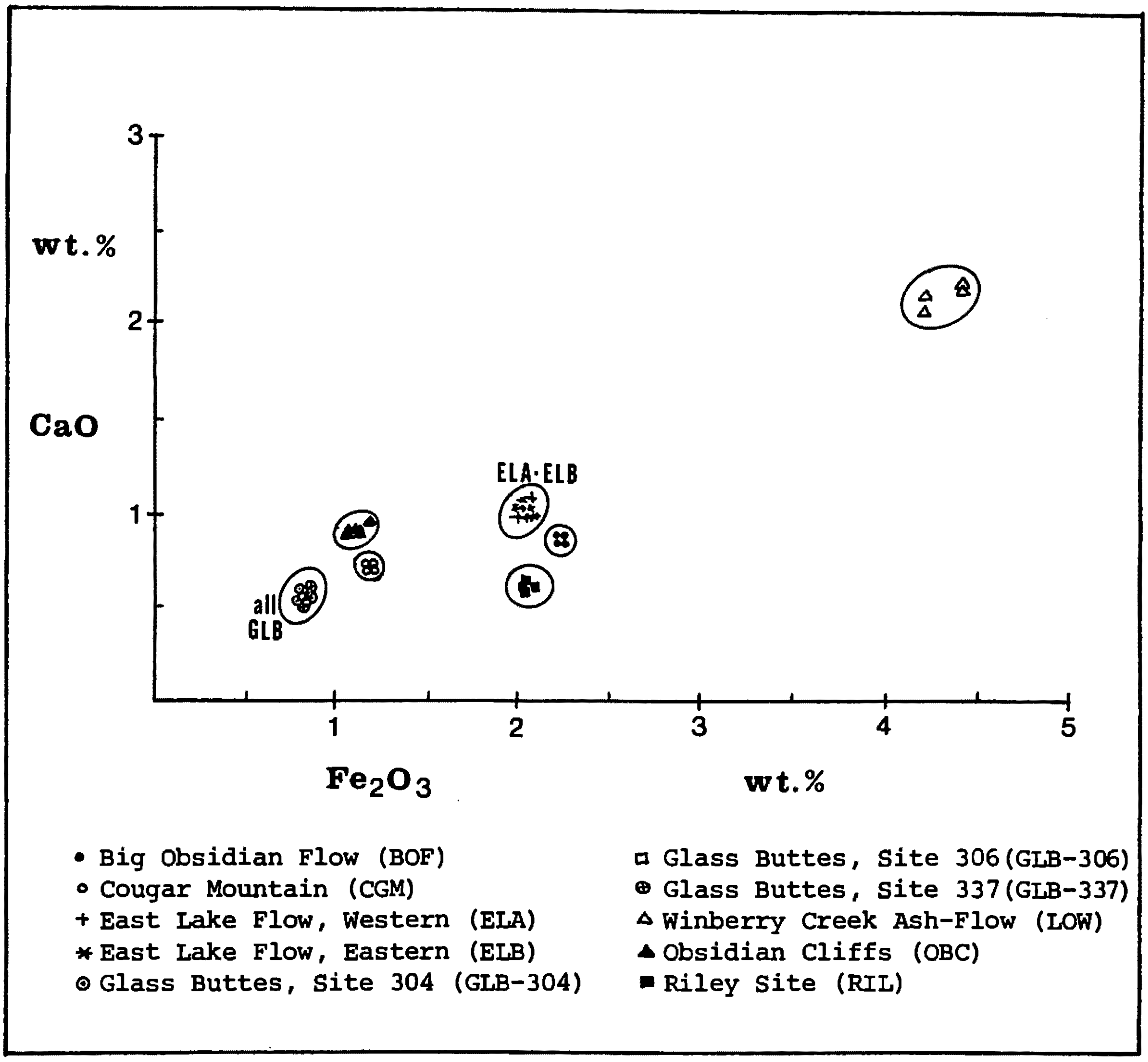


Figure 47: CaO composition of obsidian samples plotted versus Fe_2O_3 composition.

RESULTS OF TRACE ELEMENT COMPOSITION DETERMINATION

The results of the X-ray fluorescence analysis of the samples from the quarry sites are shown in Table 10. Of the five trace elements determined, Zr, Sr and Rb all demonstrated a high degree of intrasource homogeneity combined with intersource variability. The relative abundances of these three trace elements are plotted on a ternary diagram (Figure 48) and on three binary diagrams (Figures 49, 50 and 51) so as to indicate which combination of trace elements best distinguishes individual sources or subgroups in the source universe.

Very similar results are indicated when the trace elements are plotted against each other in Figures 48, 49 and 50. Rb-Sr-Zr, Sr-Zr and Sr-Rb plots all differentiate seven distinct subgroups. Only the Glass Buttes subgroup and East Lake obsidian flows subgroup contain more than one member (quarry site). When Rb is plotted versus Zr (Figure 51), six subgroups are distinguishable

Sample	Rb	Sr	Y	Zr	Nb
BOF-1	123	48	40	361	16
BOF-2	127	50	40	360	19
BOF-3	126	51	40	356	17
BOF-4	125	48	40	358	20
CGM-1	101	33	48	130	12
CGM-2	101	33	48	132	8
CGM-3	101	34	51	132	11
CGM-4	101	32	48	131	12
ELA-1	141	62	35	291	13
ELA-2	136	61	40	293	14
ELA-3	138	63	37	289	13
ELA-4	143	62	36	290	16
ELB-1	142	60	36	295	15
ELB-2	141	62	34	293	13
ELB-3	140	62	38	293	14
ELB-4	139	57	33	293	17
GLB-304A	90	18	43	90	8
GLB-304B	90	19	46	93	8
GLB-304C	89	22	44	91	12
GLB-304D	93	19	45	91	9
GLB-306A	93	23	44	95	7
GLB-306B	90	19	45	90	8
GLB-306C	89	20	44	93	10
GLB-306D	92	19	43	90	10
GLB-337A	87	16	43	89	7
GLB-337B	89	19	44	94	11
GLB-337C	89	18	42	90	9
GLB-337D	90	21	48	91	11
LOW-1	72	159	42	324	14
LOW-2	75	149	41	333	18
LOW-3	75	149	43	332	20
LOW-4	70	159	45	328	21
OBC-1	84	110	11	102	6
OBC-2	79	103	14	93	5
OBC-3	85	104	15	98	12
OBC-4	84	103	12	96	5
RIL-1	120	5	52	464	23
RIL-2	115	5	52	469	21
RIL-3	118	6	55	468	21
RIL-4	117	6	53	472	21

BOF: Big Obsidian Flow
CGM: Cougar Mountain
ELA: East Lake Flow, West
ELB: East Lake Flow, East
GLB-304: Glass Buttes, Site 304
GLB-306: Glass Buttes, Site 306
GLB-337: Glass Buttes, Site 337
LOW: Winberry Creek Ash-Flow
OBC: Obsidian Cliffs
RIL: Riley Site

Table 10: Trace element composition of obsidian examined in Part Four of this project. Abundances are reported in parts per million. For analytical uncertainties, see Appendix Ten in Volume Two of this project.

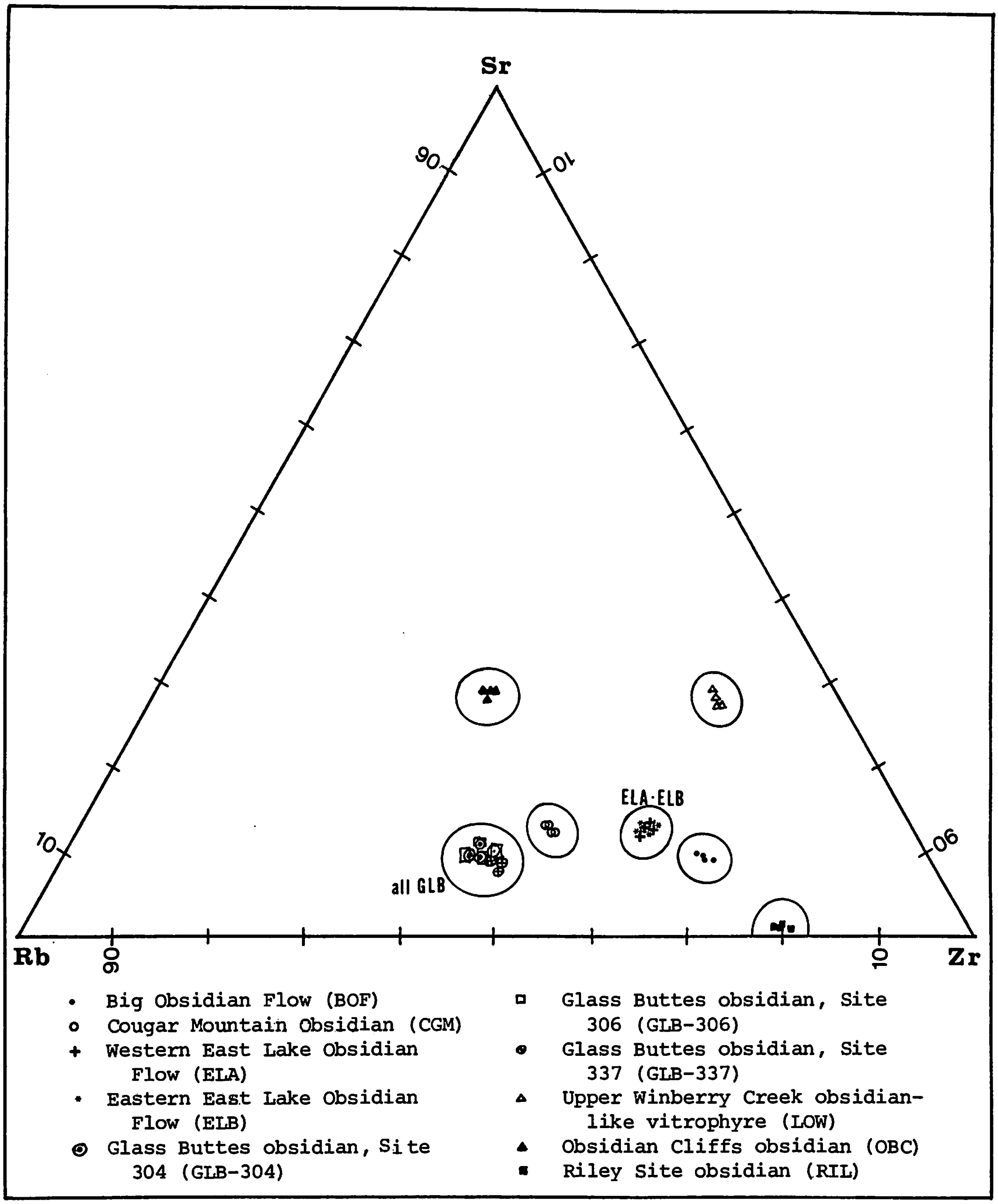


Figure 48: Ternary diagram illustrating the relative abundances of Rubidium, Strontium and Zirconium found in obsidian collected at the ten quarry sites.

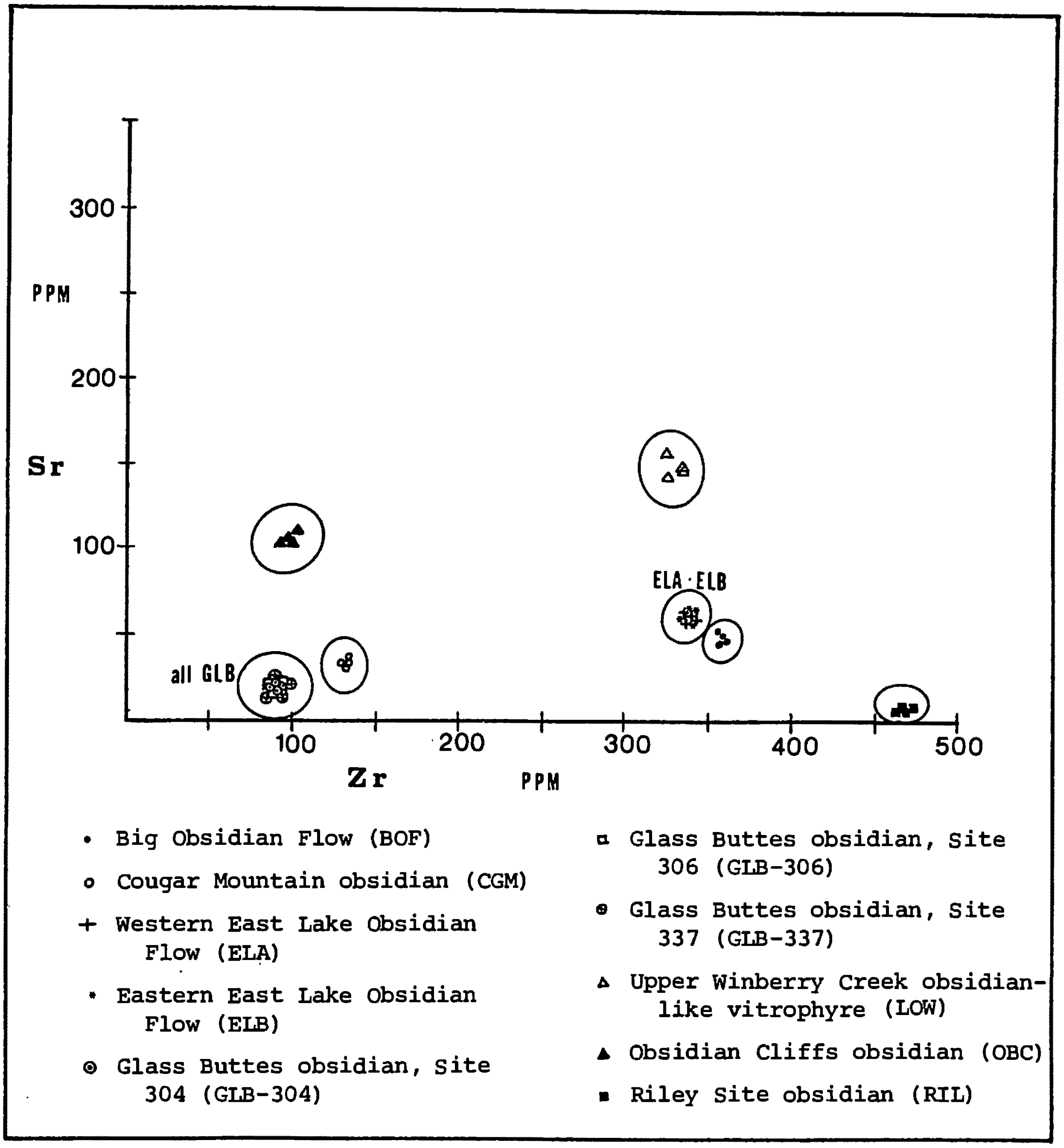


Figure 49: Strontium abundances of obsidian samples plotted versus Zirconium abundances.

with the Obsidian Cliffs source overlapping with the Glass Buttes source. (An ambiguity like this could be easily cleared up with the application of the petrographic characterization methods described in the preceding chapter). Though no attempt was made to differentiate source groups on the basis of the abundance of a single trace element (the effects of analytical error are increased considerably when only a single element is used) it would be possible to distinguish several of the sources on this basis alone.

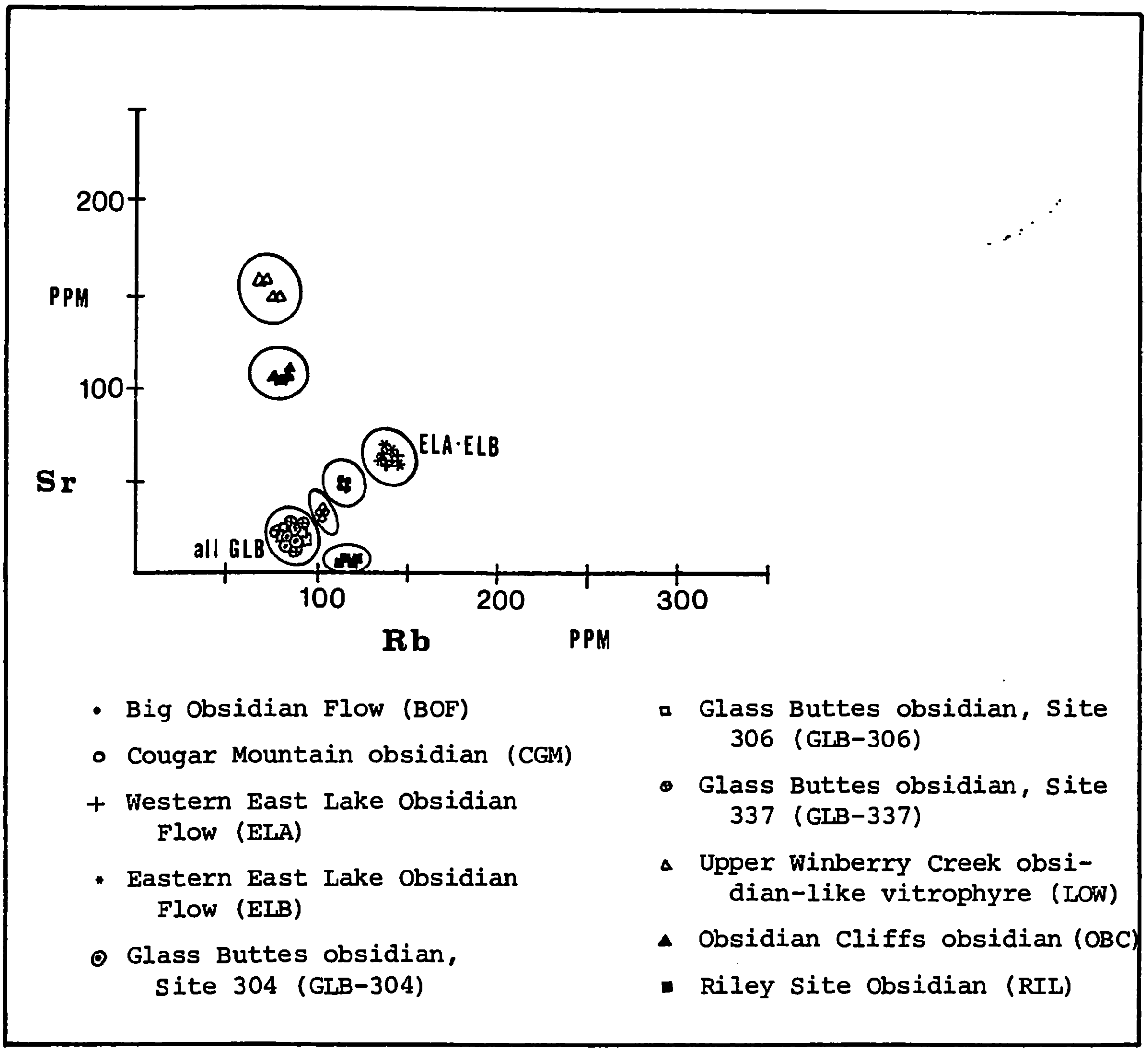


Figure 50: Strontium abundances of obsidian samples plotted versus Rubidium abundances.

CONCLUSIONS

The major and trace element characterization of obsidian, based on the data collected during this investigation, were both found to be useful in the discrimination of obsidian sources from a source universe.

Major Element Characterization Conclusions

1. Of the ten major element oxides determined for the samples from the obsidian source universe, SiO_2, CaO and Fe_2O_3 are the best suited for the purposes of obsidian characterization (large intrasource homogeneity and large intersource heterogeneity).
2. When abundances of SiO_2, CaO and Fe_2O_3 are plotted against each other in different combinations, the best discrimination of subgroups of obsidian sources is achieved by the CaO versus Fe_2O_3 plot. Only the Glass Buttes

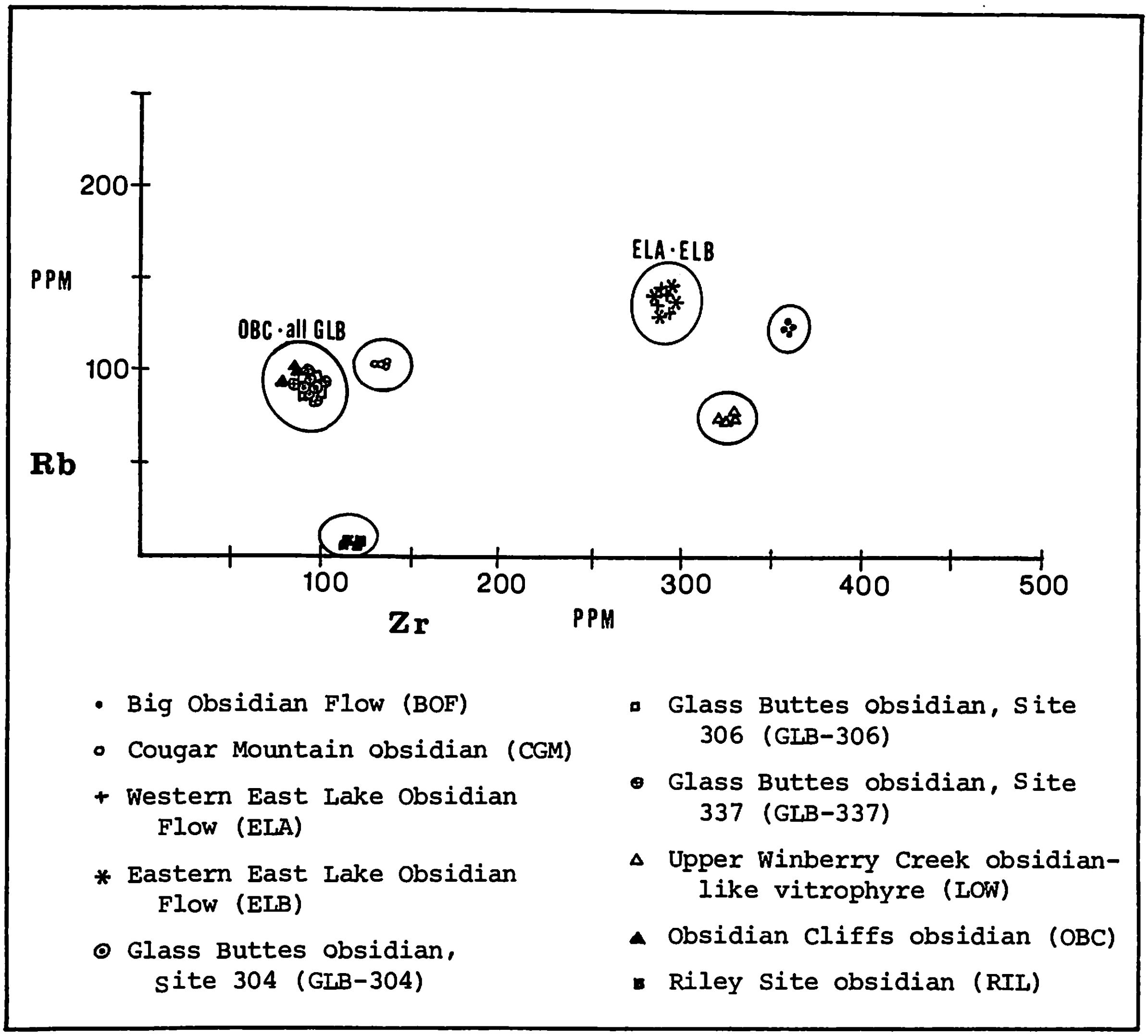


Figure 51: Rubidium abundances of obsidian samples plotted versus Zirconium abundances.

subgroup and the East Lake obsidian flows subgroup are left containing multiple sources. This was not unexpected at either source location - Glass Buttes is a single geologic unit with little apparent major element heterogeneity, while the two East Lake flows were probably erupted contemporaneously from the same magma source. The difficulty in distinguishing among the three Newberry Caldera sources that were sampled points to their probable origin from the same magma, a conclusion that corroborates that of MacLeod et al. (1982:6). Small, though systematic, trends toward smaller SiO_2 and K_2O contents were noted by MacLeod et al. in the progressively younger rhyolites of the caldera. The results of the present investigation also support this, additionally suggesting trends toward smaller abundances of MgO and CaO, as well as towards larger quantities of Na_2O. It is these systematic differences in composition that make it possible to distinguish among at least some of the individual caldera obsidian sources.

3. Based on the results of this investigation, major element abundances may be successfully used to characterize archaeological and geologic samples of obsidian. While CaO and Fe_2O_3 abundances, in particular, were successful in differentiating among the sources in the source universe that was sampled, it is unlikely that these elements can be applied universally. The major elements that best characterize a source or geographic region will have to be determined empirically and will be dependent on the volcanic suites that are involved.

Trace Element Characterization Conclusions

1. Of the five trace elements determined in this study, Zr, Rb and Sr exhibited a large degree of intrasource homogeneity and intersource heterogeneity, making them excellent candidates for the trace element characterization of obsidian.
2. Of these three trace elements, several combinations were found to identify a maximum of seven subgroups from the source universe. The least successful results were obtained when Rb was plotted versus Zr. Only the Glass Buttes subgroup and the East Lake obsidian flows subgroup remained with more than one source (for reasons previously discussed). The Big Obsidian Flow and East Lake obsidian flows were easily differentiated using their trace element composition, suggesting that systematic trends in trace, as well as major element composition, are present for the progressively younger rhyolites in the caldera. In this case, Rb and Sr abundances appear to decrease, while Zr abundances appear to increase. Further geochemical investigations of Newberry Caldera obsidian sources would be likely to indicate that many of the individual sources are identifiable using their trace element composition.
3. All of the nine true obsidian sources exhibit a remarkable degree of intrasource homogeneity. Only a few percent variation exists at the different sources, supporting the critical assumption by most researchers of the high level of compositional homogeneity in most obsidian sources. Though significant variations in trace element composition have been noted by investigators at a few sources - multiple sampling of individual sources to test for homogeneity in composition is still recommended - the results of the present study suggest that as little as four sampling sites per source may be sufficient to represent a single obsidian source. The obsidian-like vitrophyre of Upper Winberry Creek also was found to be surprisingly homogeneous in its trace element composition. Considerable vertical variation in ash-flow composition (the Upper Winberry Creek ash-flow was sampled so as to reflect this) has been reported by Noble et al.(1969) and Cox et al.(1979). This previous work suggested that the geochemical characterization of obsidian-like vitrophyre might not be a reliable application of the method, though the relative homogeneity of the Winberry Creek ash-flow does not support this possibility. The sampling of densely-welded ash-flows for the purpose of characterization, however, should include the vertical as well as the areal component of the unit considered.
4. The trace element characterization (Rb, Zr and Sr) of obsidian, of all the characterization methods examined in this investigation, exhibited the greatest ability to discriminate source subgroups from an obsidian source universe. This conclusion, though not a particularly surprising one, supports the validity of existing trace element studies of obsidian.

1 Summary and Conclusions

Obsidian, a naturally-occurring volcanic glass, has been of interest to geologists and archaeologists for more than a century. While geologists have examined many of the physical and chemical properties of obsidian, archaeologists have, until recently, been interested primarily in the cultural properties of the glass. Obsidian, because of its workability and capacity to attain a sharp edge, has been a preferred lithic material by most pre-metal cultures that have had access to the glass. Elaborate exchange networks sometimes evolved to move the glass into areas where it was not naturally available and obsidian in these areas attained a position of unusual value. Over the past few decades, archaeologists have come to recognize that the ability to identify geologic sources of archaeological obsidian provides a key to the reconstruction of these now extinct systems of movement, contact and trade. Different patterns of obsidian distribution may also shed light on the social structures of the prehistoric peoples that were involved in the trade and movement of the glass.

A number of different methods have been developed to "fingerprint" or characterize obsidian, allowing the correlation of archaeological obsidian with geologic sources. The most popular and often-used technique involves the determination of selected trace element abundances of obsidian sources and artifacts and while the method has proved successful, it is limited in its availability to many archaeologists. In addition, the location and extent of many sources of obsidian in regions of the world have yet to be well-documented, leaving researchers often without a "full deck to deal with." These problems have left the characterization of obsidian as only an occasional component of archaeological research programs. While the obsidian characterization method is still not widely used, it does have an optimistic future and as problems affecting the reliability of the method are ironed out it will likely become a routine part of most archaeological research.

It was recognized that the availability of other obsidian characterization methods (in addition to trace element characterization) might help to make the characterization analysis of obsidian a more commonplace part of archaeological studies (for archaeologists without the necessary technical or monetary resources for trace element analyses). For this reason, it was decided to conduct an experimental investigation of several attributes of obsidian that might be used to characterize the glass. The attributes chosen were:

1. The color of obsidian hand specimens.
2. The color of a thin obsidian flake.
3. The color of powdered obsidian.
4. The density of obsidian.
5. The presence of microscopic glass shards in thin-sections of obsidian (used to distinguish true obsidian from the obsidian-like vitrophyre that is sometimes found associated with welded ash-flows).
6. The presence of microscopic microlitic structures in the obsidian glass (when observed in a thin-section).
7. The major element composition of the glass (SiO_2, TiO_2, Al_2O_3, MgO, Fe_2O_3, MnO, CaO, Na_2O, K_2O, P_2O_5)

8. The trace element composition of the glass (to provide an independent evaluation of the trace element characterization method) (Sr, Zr, Rb, Y and Nb).

Obsidian samples were collected from ten source localities in Oregon (including one source of obsidian-like vitrophyre), chosen to represent a wide geographic and contextual sample of sources. The attributes chosen for characterization were determined for four samples from each source and evaluated for intrasource homogeneity and intersource heterogeneity. All of the attributes possessed some discriminatory ability; that is, they were able to delimit subgroups of sources from the sample universe of ten sources. Some attributes were considerably more powerful than others in this ability. The effectiveness (ability to delineate subgroups of sources from the source universe) of the characterization attributes examined, in rank order (most effective first), was:

1. Trace element composition (Sr, Rb, Zr).
2. Major element composition (SiO_2, Fe_2O_3, Cao).
3. Microlite structures present.
4. Color of thin flakes.
5. Color of hand specimen.
6. Density of glass.
7. Color of powdered glass.

The presence or absence of microscopic glass shards, not included in the list above, was 100% successful in distinguishing between true obsidian sources and sources of obsidian-like vitrophyre.

In addition, the nine obsidian sources all proved to be remarkably homogeneous in their trace element (and major element) composition, supporting the reliability of the trace element obsidian characterization now commonly in use.

The results of the experimental study suggest that, while trace element characterization of obsidian remains the preferred method when available, other techniques could be developed for use by archaeologists. In particular, the use of major element composition, microlite structures and thin flake colors as attributes for the characterization of obsidian is possible and further investigation of these methods is warranted.

2 Recommendations for Further Research

RECOMMENDATION 1: FURTHER EMPIRICAL AND APPLIED STUDIES OF OBSIDIAN CHARACTERIZATION METHODS NEED TO BE PURSUED.

The investigation reported in Part Four of this project further confirmed what many researchers had already taken for granted, that the trace element characterization of obsidian is one of the best, if not the best, obsidian characterization method available. What this study also points out, though, is that other methods are also available for obsidian characterization (see also Part Three, Chapter Three). As I have mentioned previously, trace element studies of obsidian, for reasons of lack of money and equipment, are often not available to many archaeologists, particularly those without direct university connections. Most archaeologists are also likely to view obsidian characterization studies as desirable, but simply not worth the time and trouble that the development of alternative characterization methods would require.

The most appropriate setting in which new research in obsidian characterization methods could take place would be as part of university graduate research. University graduate departments specializing in archaeology would do well to encourage obsidian characterization studies as thesis or dissertation topics. These studies could be a combination of experimental and applied research and could complement existing archaeological research programs.

RECOMMENDATION 2: GEOLOGIC STUDIES OF OBSIDIAN SOURCES PRIOR TO OBSIDIAN CHARACTERIZATION STUDIES ARE NEEDED

Too often, the characterization of geologic obsidian sources for comparison with archaeological obsidian is done with little or no knowledge of the geologic context of the obsidian. Specimens hopefully representing the geologic source are simply collected and analyzed and these data used to characterize the source. While this approach is surprisingly successful, owing to the homogeneous composition of most obsidian sources, an investigation of the source by a geologist prior to sampling would certainly improve the probability of obtaining a representative sample. Often, geologic studies of obsidian sources already exist in professional journals and in graduate theses and dissertations, though archaeologists may sometimes be hard-pressed to locate and decipher them. At the very least, aerial photograph interpretation combined with minimal field study of a source or source area is called for, particularly for older and more complex obsidian sources.

A case in point is the Glass Buttes obsidian source described in Part Four, Chapter Two of this project. When this source was sampled as part of this project, it was assumed (based on a single 55 year-old study) that the Glass Buttes obsidian could be considered as a single unit that was erupted at about the same time. Research by Berri (1982), appearing after the sampling and laboratory phases of the project were completed, suggests that the geologic history of the Glass Buttes was more complex than was previously thought, with several obsidian-rhyolite domes and flows of different ages represented. The process of fractional crystallization of a magma body beneath Glass Buttes would be expected to produce lavas varying (though perhaps similar) in composition over time. A single major element analysis of obsidian by Berri (1982:62) seems to indicate that this was the case at Glass Buttes - there is a significant difference between the composition of obsidian reported in this project and that of the sample analyzed by Berry. Without some knowledge of the extent of the different geologic units at Glass Buttes, it would be impossible to accurately sample and characterize the obsidian found at this source. Based on the study by Berri, it is likely that the Glass Buttes obsidian can best be considered a geographically proximate group of compositionally related, but discrete sources. Any attempt to characterize the obsidian at Glass Buttes would have to consider each of the sources as a separate sampling unit.

RECOMMENDATION 3: PRIMARY AND NATURAL SECONDARY SOURCES OF OBSIDIAN MUST BOTH BE DETERMINED BEFORE ARCHAEOLOGICAL STUDIES OF CHARACTERIZED OBSIDIAN CAN BE CONSIDERED TO REFLECT HUMAN, AND NOT NATURAL PROCESSES.

The human transport of obsidian is only one of several different channels in which obsidian may find its way from a primary to a secondary context. The concepts of obsidian transport from a primary to a secondary context have been discussed in Part Two, Chapter Four of this project and will not be belabored here. It is essential, though, that factors other than trade or exchange be considered when archaeological obsidian is being used to infer patterns of human movement and trade. Take the previously-discussed Obsidian Cliffs source as an example. It would be easy to imagine, based on the characterization of artifactual obsidian from the Willamette Valley, that a complex network of exchange and trade interactions were responsible for distributing the obsidian from the Obsidian Cliffs source through the valley. In reality, it is natural processes that are probably responsible for transporting most of the obsidian, first as glacial till, then as fluvially-carried pebbles, throughout the valley. Though this example is an obvious one, it should serve to demonstrate the point that natural processes need to be taken into account when attempting to reconstruct extinct trade networks on the basis of characterized obsidian artifacts.

RECOMMENDATION 4: ETHNOGRAPHIC EXAMPLES OF THE TRADE PATTERNS OF OBSIDIAN OR OTHER VALUED COMMODITIES MUST BE CAREFULLY EXAMINED WHEN RECONSTRUCTING EXTINCT EXCHANGE NETWORKS.

It is important that ethnographic analogies involving the trade and exchange of obsidian be located and examined so that the reconstruction of extinct trade networks does not fall prey to overgeneralization and oversimplicity. Many different patterns of trade and exchange, shaped and influenced by a variety of environmental, social and economic factors, could have existed in the past. Just how well or what kinds of socioeconomic processes are reflected by obsidian distribution patterns, as indicated by characterized artifactual obsidian, is a key area of concern. Earle and Ericson (1977:9) addressed this when they wrote:

> The archaeologist, however, must be cautious in his use of ethnographic analogy. Because of the rapid changes in economic organization following contact, traditional systems of exchange are now

> virtually extinct following colonialization and postcolonial development. As a result of imposed peace, decreased transportation cost, and the introduction of cash economies, the economic organizations now investigated by ethnographers are radically altered from the aboriginal form.

As technology and sampling methods for characterizing obsidian are improved and made more reliable, the techniques or "maps" used in the interpretation of the data must also follow suit if the archaeological constructs of past exchange systems are to bear a resemblance to those which actually once existed.

RECOMMENDATION 5: OBSIDIAN DEBITAGE IS A SIGNIFICANT ARCHAEOLOGICAL RESOURCE AND MUST BE AFFORDED INCREASED LEVELS OF PROTECTION IN CULTURAL RESOURCE MANAGEMENT PROGRAMS.

The most commonly found archaeological site, at least in the Far West of the United States, is probably the lithic surface scatter, usually a collection of a few dozen to several thousand obsidian waste flakes found in a restricted area. While other more archaeologically-revealing and perhaps time-sensitive artifacts may be found associated with these scatters of obsidian flakes, the likelihood of the finished artifacts surviving the onslaught of weekend artifact hunters decreases with each passing year. The lithic scatter is considered the lowliest of sites in the West, but as time passes and the remaining few stratified sites are excavated or destroyed by pothunters, these lithic scatters (along with the obsidian waste flakes discarded from pothunted sites) may be all that remain of the aboriginal cultures that once existed.

Currently these isolated scatters of flakes are afforded little archaeological significance in cultural resource surveys and management plans, particularly those on public lands. Because of this and because of their unspectacular nature, lithic scatters are particularly prone to accidental destruction or disturbance, though they are, ironically, safe from collectors who are searching for finished artifacts.

Characterized obsidian from lithic scatters (or other disturbed sites) may be used in the reconstruction of generalized patterns of movement. Without some measure of time, though, these patterns remain of only limited use, being unable to reflect changes through time. Occasionally, diagnostic artifacts may be found in surface scatters, adding a temporal dimension to the artifactual material, but in general it is difficult to impossible to estimate the age of surface sites. Obsidian hydration geochronology has been used by Layton (1973) to estimate ages of archaeological surface materials. Difficulties in controlling the thermal variable of obsidian found in surface contexts, though, leaves it unlikely that hydration geochronology will prove useful. In some areas where Recent obsidian flows occur, it is possible to set maximum ages of site occupation using the ages of obsidian flows (if known) - characterized obsidian waste material, even when recovered in disturbed contexts, can be particularly informative in this case (see Appendix VI).

Though there are still obvious limitations in the *current* methods of surface collection analysis, a little information is still preferable to no information. If a measure of time can be added to these sites, perhaps through improved techniques of obsidian hydration geochronology, surface obsidian scatters could prove to be a particularly valuable resource in archaeological research.

On the basis, then, of current archaeological technologies (not to mention future ones), surface scatters of obsidian flakes should not be overlooked, but recorded and described. If threatened with disturbance or destruction, they should be systematically collected or preserved for future study.

RECOMMENDATION 6: REGIONAL EFFORTS IN THE GEOCHEMICAL CHARACTERIZATION OF ARCHAEOLOGICAL AND GEOLOGICAL OBSIDIAN NEED TO BE COORDINATED TO THE EXTENT THAT INTERLABORATORY COMPARISONS MIGHT BE POSSIBLE.

Many different analytical facilities around the world are now involved in the geochemical characterization of obsidian (and other archaeological materials), often with more than one facility serving a single region. It would obviously be of advantage to all concerned if the results from different laboratories could be directly compared, in effect pooling the resources of different research groups.

The first step in the interlaboratory comparison of geochemical data is the presentation of comparable units of measurement in published results (i.e. quantitative units such as parts per million or weight percent). As Ives (1975:235) has pointed out: "The presentation of either raw data or results in non-quantitative units...can only have an adverse effect on another researcher's ability to compare or replicate a particular study." Without comparable data a study would be virtually useless for further research.

The second step, and the more difficult one to make, is the intercalibration of data from different laboratories. A number of researchers have noted interlaboratory differences and variations in the results obtained by different analytical methods in the trace element composition of obsidian (Stross et al., 1976; Nielson et al., 1976; Brenner et al., 1976; Hurtado de Mendoza, 1977:34-36; Zeitlin and Heimbuch, 1978; Yellin et al., 1987; Sarna-Wojcicki et al., 1979; Nelson and Voorhies, 1980; Harbottle, 1982; Stross et al., 1983). Attempts have been made to compare analytical results and in some cases to compute conversion factors, but the results so far have been mixed with only a few authors reporting the successful calibration of interlaboratory results (Stross et al., 1976; Yellin et al., 1978; Nelson and Voorhies, 1980; Stross et al., 1983).

Variations in analytical results between laboratories are due to a number of factors, including differences in analytical methods used (XRF versus INAA, for example), differences in the calibration standards used, differences in the preparation of samples (for example, whole rock versus pressed powder pellets) and whether or not the background and interference radiation between elements has been corrected for. The best interlaboratory results have come from different laboratories using the same analytical, preparation and data reduction methods (Yellin et al., 1978), and regional analytical facilities attempting to pool data would be advised to standardize as many of their procedures as possible.

RECOMMENDATION 7: THE UNIVERSITY TRAINING OF ARCHAEOLOGISTS, IF IT IS TO MAKE FULL USE OF THE METHODS AVAILABLE IN OTHER DISCIPLINES, SHOULD INCLUDE A BROADER-BASED BACKGROUND IN THE PHYSICAL AND NATURAL SCIENCES.

> I am therefore arguing for a contextual archaeology rather than an anthropological archaeology. My plea is for deliberate exploration and development of an approach that will transcend the traditional preoccupation with artifacts and with sites in isolation, to arrive at a realistic appreciation of the environmental matrix and of its potential spatial, economic, and social interactions with the subsistence - settlement system. The human ecosystem so defined will open up truly ecological vistas that have been largely neglected. This contextual approach, heavily dependent on archaeobotany, zoo-archaeology, geo-archaeology, and spatial archaeology, is new not in terms of its components but by virtue of its integrated, general goal of understanding the human ecosystem.

As Karl Butzer has pointed out above (1982:11-12; also see the quotes in the front of this project), the view that archaeology is anthropology or it is nothing (Willey and Phillips, 1958:2) is a paradigm that limits archaeological approaches to prehistory rather than expanding them. Archaeology *is* anthropology, but it is also ecology, geology, botany, geomorphology and much more. The university training of archaeologists is still largely grounded in the view that archaeology is essentially anthropology applied to prehistoric periods - studies outside the realm of anthropology, hence outside of the archaeologist's training, are too often seen as simply "add-ons" to the primary research. Butzer (1975:110) elucidates this point:

> ...the past 15 yr have seen considerable technical advances essential to a more effective ecological approach to archaeology and prehistory. Yet progress in the direction has not been as substantial as it might have been, primarily as a result of attitudes - attitudes of archaeologists, of collaborating scientists, of students, of university departments and administrations, and of granting agencies.
>
> All lip service to the contrary, interdisciplinary research encounters much academic and administrative opposition.

When study areas such as obsidian characterization are left to specialists from other disciplines, the results will continue to be, as they often are now, not well-integrated with overall archaeological goals and objectives.

Another advantage in broader-based archaeological training is that the archaeologist can better understand how the different research strategies (that may have been previously left to others) operate. This can make it easier to integrate interdisciplinary archaeological research into a coherent piece, rather than a collection of related studies. Harbottle (1982:38) addresses this in discussing the chemical characterization of archaeological materials: "The archaeologist who has carried out the analyses and data processing alone gains a new respect for the statistical and taxonomic limitations of chemical data, and will collect the next of field samples with these limitations in mind." While it is not necessary (or often practical) for the archaeologist to carry out all of the often time-consuming analytical research alone, it is more than just a little useful if he or she has a real understanding of the analytical methods involved.

Interdisciplinary education in archaeology requires a strong background not only in the social sciences, but in the natural and physical sciences - geology, chemistry, physics, statistics, geomorphology, botany and ecology, to name a few of the most important. Students of archaeology need not only to be permitted, but encouraged (or perhaps required) to include the physical and natural sciences as a *major* part of their training program. Instructors and principal investigators of archaeological projects may also need to face the prospect of additional training in areas formerly left exclusively to others.

I end with a last excerpt from Butzer (1982:12):

> No one paradigm deserves to be enshrined as superlative; alternative viewpoints are essential to scientific practice. By systematically developing the methodology of an alternative (rather than exclusive) paradigm,then applying it to the fundamental issues of adaptation, stability, and change, it will be possible for students and professionals to appreciate the procedural potentials and to evaluate the merits of a contextual approach.

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Abbreviations used:

GSA = Geological Society of America
NZAAN = New Zealand Archaeological Association Newsletter

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OBSIDIAN STUDIES IN OREGON:

AN INTRODUCTION TO OBSIDIAN and AN INVESTIGATION OF SELECTED METHODS OF OBSIDIAN CHARACTERIZATION UTILIZING OBSIDIAN COLLECTED AT PREHISTORIC QUARRY SITES IN OREGON

Volume Two: Appendices

A TERMINAL PROJECT

Presented to the Department of Interdisciplinary Studies
(Individualized Program) and the Graduate School of the
University of Oregon in partial fulfillment of the
requirements for the degree of Master of Science

June 1983

Craig Eugene Skinner

Contents of Appendices

Front Cover: This is a portion of a map from Edwin Hodge's classic study of the McKenzie Pass and Three Sisters area of Oregon's High Cascades (1925). One of the quarry sites examined in this project is also shown - Obsidian Cliffs and the glaciated plateau to the east. The X's designate the hypothetical boundary of Hodge's mythical Mount Multnomah, a huge volcano that he believed had collapsed, leaving the Three Sisters as remnants. A later geologic study of the region by Howel Williams (1944) proved Hodge's theory to be only wishful thinking

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Back Cover: This map is from Israel C. Russell's 1883 study of the fault basins and lakes in southeastern Oregon. Russell, a pioneer geologist in the Far West, passed through the area shown on the map. His route is shown by the solid line that runs by Glass Buttes, Christmas Lake and Summer Lake. The first mention of obsidian at Glass Buttes appeared in the U.S. Geological Survey publication that resulted from Russell's investigations here.

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APPENDIX I

Atomic Numbers and Symbols of the Elements

Atomic Number	Symbol	Element	Atomic Number	Symbol	Element
1	H	Hydrogen	48	Cd	Cadmium
2	He	Helium	49	In	Indium
3	Li	Lithium	50	Sn	Tin
4	Be	Beryllium	51	Sb	Antimony
5	B	Boron	52	Te	Tellurium
6	C	Carbon	53	I	Iodine
7	N	Nitrogen	54	Xe	Xenon
8	O	Oxygen	55	Cs	Cesium
9	F	Fluorine	56	Ba	Barium
10	Ne	Neon	57	La	Lanthanum
11	Na	Sodium	58	Ce	Cerium
12	Mg	Magnesium	59	Pr	Praseodymium
13	Al	Aluminum	60	Nd	Neodymium
14	Si	Silicon	61	Pm	Promethium
15	P	Phosphorus	62	Sm	Samarium
16	S	Sulfur	63	Eu	Europium
17	Cl	Chlorine	64	Gd	Gadolinium
18	Ar	Argon	65	Tb	Terbium
19	K	Potassium	66	Dy	Dysprosium
20	Ca	Calcium	67	Ho	Holmium
21	Sc	Scandium	68	Er	Erbium
22	Ti	Titanium	69	Tm	Thulium
23	V	Vanadium	70	Yb	Ytterbium
24	Cr	Chromium	71	Lu	Lutetium
25	Mn	Manganese	72	Hf	Hafnium
26	Fe	Iron	73	Ta	Tantalum
27	Co	Cobalt	74	W	Tungsten
28	Ni	Nickel	75	Re	Rhenium
29	Cu	Copper	76	Os	Osmium
30	Zn	Zinc	77	Ir	Iridium
31	Ga	Gallium	78	Pt	Platinum
32	Ge	Germanium	79	Au	Gold
33	As	Arsenic	80	Hg	Mercury
34	Se	Selenium	81	Tl	Thallium
35	Br	Bromine	82	Pb	Lead
36	Kr	Krypton	83	Bi	Bismuth
37	Rb	Rubidium	84	Po	Polonium
38	Sr	Strontium	85	At	Astatine
39	Y	Yttrium	86	Rn	Radon
40	Zr	Zirconium	87	Fr	Francium
41	Nb	Niobium	88	Ra	Radium
42	Mo	Molybdenum	89	Ac	Actinium
43	Tc	Technetium	90	Th	Thorium
44	Ru	Ruthenium	91	Pa	Protactinium
45	Rh	Rhodium	92	U	Uranium
46	Pd	Palladium	93	Np	Neptunium
47	Ag	Silver	94	Pu	Plutonium

Atomic Number	Symbol	Element
95	Am	Americium
96	Cm	Curium
97	Bk	Berkelium
98	Cf	Californium
99	Es	Einsteinium
100	Fm	Fermium
101	Md	Mendelevium
102	No	Nobelium
103	Lr	Lawrencium
104	Ku	Kurchatovium
105	Ha	Hahnium

APPENDIX II

Major Geochronologic Units

Subdivisions in use by the U.S. Geological Survey

					Age in Millions of Years
Phanerozoic Eon[1] or	Cenezoic Era[2] or	Quaternary Period[3]		Holocene Epoch[4]	0.010
				Pleistocene Epoch	2
		Tertiary Period	Neogene Subperiod[5]	Pliocene Epoch	5
				Miocene Epoch	24
			Paleogene Subperiod	Oligocene Epoch	38
				Eocene Epoch	55
				Paleocene Epoch	63
	Mesozoic Era	Cretaceous Period		Late Cretaceous[6]	96
				Early Cretaceous[7]	138
		Jurassic Period			205
		Triassic Period			∼ 240[8]
	Paleozoic Era	Permian Period			290
		Carboniferous Periods	Pennsylvanian Period		∼ 330
			Mississippian Period		360
		Devonian Period			410
		Silurian Period			435
		Ordovician Period			500
		Cambrian Period[9]			∼ 570
Proterozoic Eon	Proterozoic Z				800
	Proterozoic Y				1,600
	Proterozoic X				2,500
Archean Eon	Oldest known rocks in U.S.				3,600

1. All Eons may also be referred to as Eonothems.
2. All Eras may also be referred to as Erathems.
3. All Periods may also be referred to as Systems.
4. All Epochs may also be referred to as Series.
5. All Subperiods may also be referred to as Subsystems.
6. Also known as Upper Cretaceous Series.
7. Also known as Lower Cretaceous Series.
8. Age boundaries not closely bracketed by existing data are shown by ∼.
9. Rocks older than 570 million years are also called Precambrian.

This chart is adapted from one appearing in the front cover of Isochron/West, issue no.32, 1981.

APPENDIX III

Glossary of Terms

AA: Atomic absorption (an analytical method).

Acidental inclusion: Enclosed rocks or crystals having no genetic connection with the igneous rock in which they are found.

Acicular: Needle-like in form.

Acicular trichites: A hairlike trichite.

Alkaline: Generally refers to rocks high in sodium and/or potassium.

Andesite: Volcanic rocks with an SiO_2 composition ranging from about 58% to 63%.

Apache tears: Rounded obsidian masses found associated with deposits of perlite.

Ash-flow: Avalanche of very hot gas-rich pyroclastic material erupted explosively from a volcanic vent.

Ash-flow tuff: Ash-flow deposit indurated by compaction and heat.

Asteroidal trichites: Spiderlike arrangements of trichites radiatiating from a central point.

Autolith: An inclusion or fragment of older igneous rock that is genetically related to the rock in which it is found.

Basalt: Extrusive volcanic rock with an SiO_2 content ranging from about 45% to 53%.

Basaltic andesite: Extrusive volcanic rock with an SiO_2 content ranging from about 53% to 58%.

Belonite: An elongated or acicular crystallite having rounded or pointed ends.

Biface: Artifact with flake scars on both faces.

Breccia: Fragmented rock whose components are angular.

Calc-alkaline: A rock where $Al_2O_3 \geqslant 12 + 0.08P$ and where P (which is a figure derived by taking $100 \times An/(An + Ab)) = 40$ to 100. Suffice it to say that most rocks in the Oregon Cascades are calc-alkaline in composition.

Caldera: Large basin-shaped volcanic depression roughly circular in form.

Characterization: A distinguishing attribute or characteristic.

Conchoidal fracture: Smoothly-curved fracture surface; typical of obsidian and quartz.

Crystallite: A broad term applied to a minute body of unknown mineralogic composition or crystal form which does not polarize light.

Dacite: Volcanic rock with an SiO_2 composition ranging from about 63% to 70%.

Devitrification: Process by which glassy rocks break up into definite minerals; obsidian devitrifies to perlite.

Diagnostic artifact: An artifact, often a projectile point, with a stylistic or other characteristic distinctive of a certain time period or cultural affiliation.

En echelon: Approximately parallel and offset structural features such as faults.

Erratics: see *glacial erratics*

Eutectic point: The lowest melting temperature obtainable with mixtures of given components where the components remain in a liquid state.

Exogenous dome: Volcanic dome built by the discharge of viscous flows from a summit vent.

Felsic: Light-colored.

Felsite: General term for a light-colored igneous rock with a grain size so small that constituents cannot be megascopically determined.

Fission-track age: The age of a rock or mineral as determined by the fission-track dating method.

Float: Rocks found separated from parent veins or strata by weathering processes.

Fluvial: Pertaining to river or stream action.

Glacial erratic: Ice-transported rocks.

Globulite: A spherical crystallite commonly found in glassy igneous rocks.

Graben: Block that has been downthrown along bordering faults relative to rocks on either side.

Graver: An artifact with a point or points; assumed to have been used to incise or form organic materials or soft stone.

Hydration rate: Rate at which water hydrates into the surface of obsidian.

Hydration rim: Visible rim (under a microscope) that forms on the surface of obsidian as the glass slowly hydrates with water.

Ignimbrite: See *ash-flow tuff.*

Index of refraction: See refractive index.

In situ: In its natural position or place.

INAA: Instrumental neutron activation analysis (analytical method)

Isotropic: Exhibiting the same optical properties (when viewed under polarized light) in all orientations.

K-Ar age: See *potassium-argon age*.

Knapping station: Term applied to an archaeological site where lithic materials were worked; characterized by small fragments of waste material.

Lahar: Landslide or mudflow of pyroclastic material on the side of a volcano.

Lapilli: Pyroclastic material ranging in size from 2 to 64 mm.

Lath: Long, thin crystal.

Lithoidal: Term applied to devitrified glass.

Lithophysae: Hollow, bubblelike structures composed of concentric shells of finely crystalline materials; often found in rhyolites and obsidians.

Longulite: A cylindrical or conical belonite thought to have been formed by the coalescence of globulites.

Mafic: Dark-colored.

Magnetic polarity: Refers to the direction of the north and south magnetic poles. The magnetic polarity of the poles periodically reverses and the direction of the polarity can be recorded in volcanic rocks erupted in the past (paleomagnetic polarity). Reversed polarity refers to reversed magnetic poles, i.e., the polarity of the north and south poles reverse; normal polarity refers to polarity as it exists today. The last reversal took place about 690,000 years ago.

Major element: Elements occurring in abundances greater than about 0.1 percent.

Margarite: Bead-like string of globulites commonly found in glassy igneous rocks.

Marakenite: Obsidian nodules found associated with perlite depoits; apache tears.

Mazama tephra or ashfall: Tephra or volcanic ash originating about 7,000 radiocarbon years ago from the present site of Crater Lake in the southern Cascades.

Microlite: A microscopic crystal with determinable optical properties.

Microlith: A microlite.

Micron: One-millionth of a metre.

Microphenocryst: Microscopic phenocryst set in a very fine-grained glassy groundmass.

Microlitic structure: A general term referring to the variety of microscopic structures classified as microlites and crystallites.

Normal paleomagnetic polarity: See *magnetic polarity*.

Obsidian hydration years: The age of obsidian as determined by the obsidian hydration dating method.

Obsidian-like vitrophyre: Vitrophyre that is macroscopically similar to obsidian; sometime associated with the densely-welded zones in welded ash-flows.

Paleomagnetic polarity: See *magnetic polarity*.

Peralkaline: Rock in which $Na_2O + K_2O > Al_2O_3$ (in molar units).

Perlite: Volcanic glass similar in composition to obsidian but with a higher water content; devitrified obsidian.

Perlitic texture: Distinctive weathering pattern in which the rock fractures along concentric shells presenting a pearl-like appearance.

Petrography: The branch of geology dealing with the description and classification of rocks.

Phenocryst: A relatively large crystal set in a finer-grained groundmass.

Porphyritic: Textural term for igneous rocks in which larger crystals are set in a finer groundmass that may be crystalline or glassy.

Post-Mazama: Event occurring after the Mazama ashfall of about 7,000 radiocarbon years ago.

Potassium-argon age: The age of a rock or mineral as determined by the potassium-argon dating method.

Pre-form: Unfinished, unused form of a proposed artifact.

Pre-Mazama: Event occurring prior to the Mazama ashfall of about 7,000 radiocarbon years ago.

Primary obsidian source: Source of obsidian found in the vicinity of its vent.

Prismatic Microlite: Rod-shaped microlite.

Pyroclastic: General term applied to volcanic material that has been explosively or aerially ejected from a volcanic vent.

Quarry site: An archaeological site centered around around a source of a natural raw material.

Radiocarbon years: The age of organic material (charcoal, bone, shell, etc.) as determined by the radiocarbon dating method. Calibration methods have been developed so that calendrical dates may be calculated from radiocarbon dates.

Radiometric dating: Determination of the age of geological or archaeological materials by any of several methods based on the decay of naturally-occurring radioactive isotopes.

Refractive index: A characterizing number which expresses the ratio of the velocity of light in a vacuum to the velocity of light in a substance.

Reversed paleomagnetic polarity: See *magnetic polarity*.

Rhyodacite: A rather vague term often used synonomously with rhyolite.

Rhyolite: Volcanic rocks with an SiO_2 content greater than 70%.

Rhyolite dome: Steep-sided volcanic dome created by the extrusion of viscous, rhyolitic lavas.

Scopulite: Rodlike or stemlike crystallite that terminates in branches or plumes.

Secondary obsidian source: Source of obsidian transported from the original primary source by a variety of natural and cultural processes.

Selvage: The edge of a volcanic body; sometimes refers to a volcanic dome or flow in which a glassy border is formed by the rapid chilling of the lavas.

Spherulite: Small, radiating, and usually concentrically arranged aggregation of minerals of a spherical or spheroidal shape formed by the rapid growth of crystals in a rigid glass.

Tachylite: Volcanic glass of basaltic composition.

Temporally-diagnostic artifacts: See *diagnostic artifact*.

Tephra: Ejecta blown through the air by explosive volcanic eruptions.

Thin-section: A very thin slice (~30 micron) of rock mounted on a slide for microscopic petrographic examination.

Time-sensitive artifact: See *diagnostic artifact.*

Trace element: Element occurring in quantities of less than about 1000 parts per million.

Trachytic: Textural term describing microlites arranged in a parallel or subparallel manner bending around phenocrysts and corresponding to flow lines in the lavas in which they are found.

Trichite: A straight or curved hairlike crystallite, usually black. Trichites occur singly or radially arranged in clusters and are found in glassy igneous rocks.

Tuff: Rock formed of small fragmental volcanic rocks.

Type: Classification of an artifact so that the class reflects cultural or behavioral characteristics.

Vent: Opening or channel in the earth's crust through which magmatic material is transported.

Vitreous: Glassy; amorphous.

Vitrophyre: Any porphyritic igneous rock having a glassy groundmass.

Welded ash-flow: See *ash-flow tuff.*

Welded tuff: See *ash-flow tuff.*

XRF: X-ray fluorescence (an analytical method).

Xenolith: A rock fragment foreign to the body of igneous rock in which they occur; an inclusion.

General References Used to Construct the Glossary:

American Geological Institute. 1972. Glossary of Geology, American Geological Institute: Falls Church, VA.

Crabtree, Don E. 1972. An Introduction to Flintworking, Occasional Papers of of the Idaho State Univ. Museum: Pocatella, ID, 98p.

Dietrich, Richard V. and Brian J. Skinner. 1979. Rocks and Rock Minerals, John Wiley & Sons: New York, NY, 319p.

Irvine, T.N. and W.R.A. Baragar. 1971. "A Guide to the Chemical Classification of Common Volcanic Rocks", Canadian Journal of Earth Sciences, Vol.8, p.523-548.

Middlemost, E.A.K. 1972. "A Simple Classification of Volcanic Rocks", Bulletin Volcanologique, Vol.36, no.2, p.382-397.

Williams, Howel and Alexander R. McBirney. 1979. Volcanology, Freeman, Cooper and Co.: San Francisco, CA, 397p.

APPENDIX IV

A Preliminary Compilation of Reported Sources of Obsidian and Obsidian-Like Vitrophyre in Oregon

Oregon contains more discrete sources of obsidian than any other state in the United States and perhaps any other comparable geographic region in the world. Somewhat surprisingly, though, considering the long-time importance of obsidian in archaeology and the recently recognized value of obsidian characterization studies in the reconstruction of prehistoric exchange and contact systems, little has been done to systematically identify the many Oregon obsidian sources. Some notable headway has been made recently in the work of Lee Sappington (see the bibliography at the end of this appendix) into the trace-element characterization of obsidian sources in the Far West, but this work is still very incomplete and the geologic and geomorphic context of the sources remains poorly known.

It became clear early in my search for possible Oregon obsidian sources to use in the laboratory phase of the project reported in Part Four of this paper, that my final sampling universe of ten source localities represented only a small proportion of the available sources within Oregon. Lacking an already assembled information base for the sources of this lithic material in the state, I began to compile my own. The result is this appendix, the product of a thorough search of archaeological and geological literature dealing with Oregon. The number of possible sources that eventually turned up were considerably more than I had expected - if I had known how long the list would become, it's likely that I would never have begun it.

This compilation is, nevertheless, still a preliminary one. There are a number of reasons for this, all of which collectively point out the need for more and better-coordinated research into the problems of obsidian characterization in Oregon and the Far West. As to the reasons for the preliminary title:

1. It is likely that a number of sources that are listed here do not contain obsidian of any archaeological value. This is particularly true of the obsidian-like vitrophyre found in welded ash-flows.
2. It is certain that obsidian sources exist that have not been reported in any literature. Because this appendix was compiled primarily from literature sources, unreported obsidian sources would have escaped my research net.
3. Geologic field work is fragmentary for Oregon obsidian sources. For a directory of sources to have real archaeological value, both the extent of the primary sources and the aerial distribution of secondary sources need to be known. Archaeologists, lacking geological training and time, may end up identifying secondary sources as discrete source localities. Geologists, on the other hand, view obsidian more as a curiosity than as an important resource, and rarely find a need to describe sources in any great detail.
4. It is sometimes not clear in literature descriptions whether the obsidian described in association with welded ash-flows represents the densely-welded portion of the ash-flow or whether it may be fragments of obsidian transported by the ash-flow from another area.

5. A number of the sources that are listed separately in this appendix may refer to a single primary source area. Many times the locations of the sources were not well-described in the literature. Additionally, each author may have assigned a different name to the same source. Possible examples in this appendix are the Silver Lake area, Hager Mountain and Frog Mountain sources - the exact locations of all these sources were not specifically reported, but it is clear that they are all in the same vicinity and may be one and the same. An examination of Figures IV-1 through IV-4 will show a number of locations where obsidian sources are seemingly clustered. Keep in mind that these may not always represent discrete primary obsidian sources, but may reflect ambiguity in the literature.
6. Systematic obsidian sampling schemes are virtually non-existent and even general sampling locations are not often mentioned in reports. Obsidian characterization schemes are based on the need for homogeneity in the attribute or attributes that are being used in the characterization of a source. Without careful sampling, it becomes impossible to know just what characteristics are homogeneously distributed throughout a source. In any case, to assume that an obsidian source is compositionally or physically homogeneous is asking for trouble.

The necessary steps in the establishment of a base for regional obsidian characterization and prehistoric exchange system study have already been discussed in Parts One and Three of this project. It is clear, though, from examining this preliminary list of obsidian source localities, that any attempt to accurately and confidently correlate archaeological obsidian with geologic sources will require considerably more *interdisciplinary* field and laboratory study than has so far taken place.

**

A few words about the format of the following list of obsidian sources is in order:

Location: The whereabouts of the reported source is given as accurately as can be ascertained from the related literature. When possible, the section, township and range are designated.

Geologic Setting: The geologic and geomorphic context of the obsidian source, if known, are described.

Petrographic and Optical Characteristics: When available, the petrographic properties of the obsidian are briefly described. They include such characteristics as the identification and abundance of phenocrysts in the glass, the presence and identification of microlites and crystallites, banding characteristics, color and so on. The index of refraction of the obsidian is also occasionally reported.

Composition: The major and trace-element composition of any Oregon obsidian source, if reported in the literature, is reproduced in Table IV-1 of this appendix. A look at the table also gives a good sampling of the ranges of major and trace-element abundances in obsidian.

Age: The age of the obsidian and the method of determination are reported here.

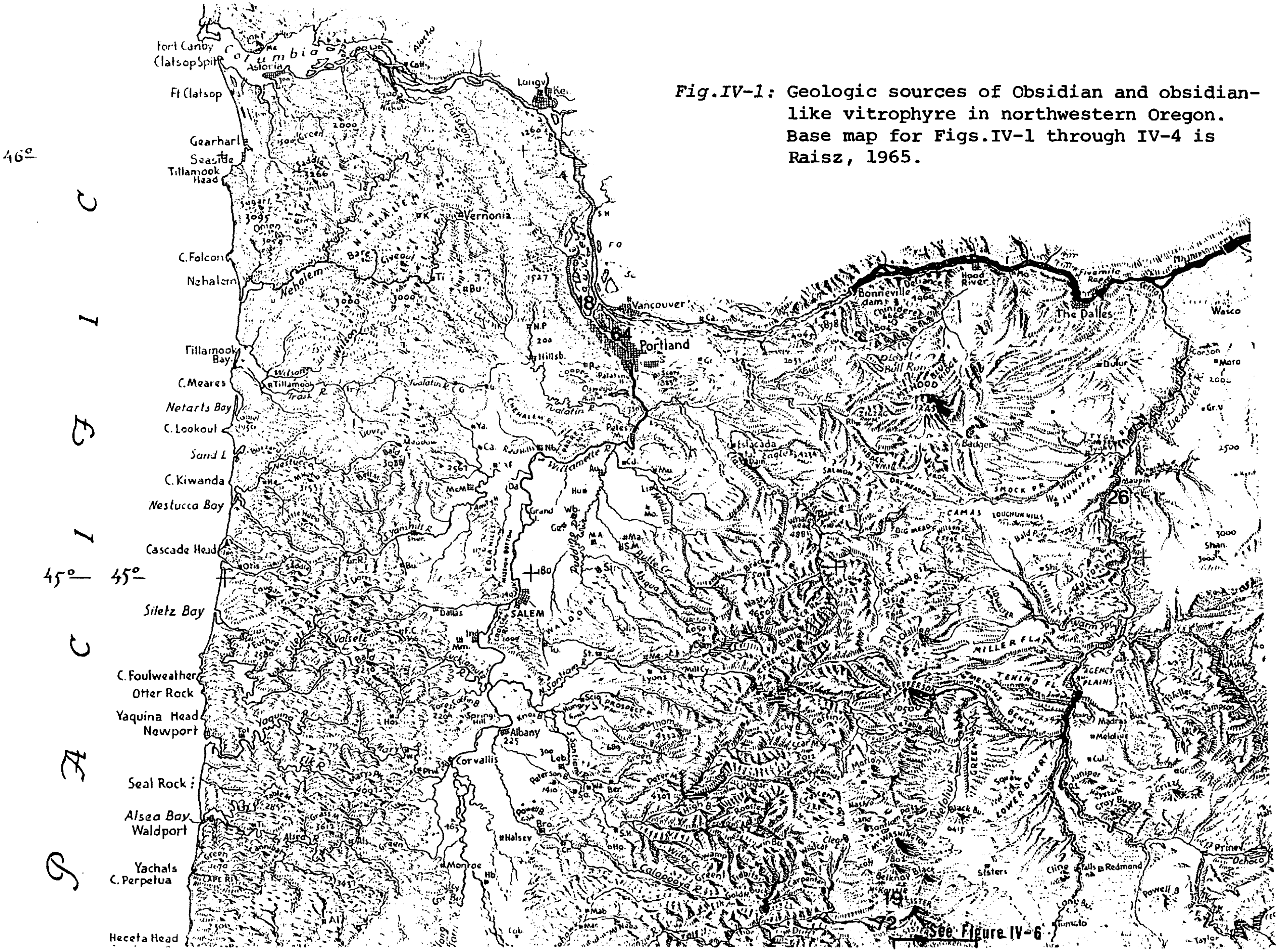
Archaeological Significance: Associated archaeological sites, access to the obsidian, quality of the glass for artifact manufacture and the results of characterization studies involving the source area are all qualities that are considered to be significant for a given source of obsidian.

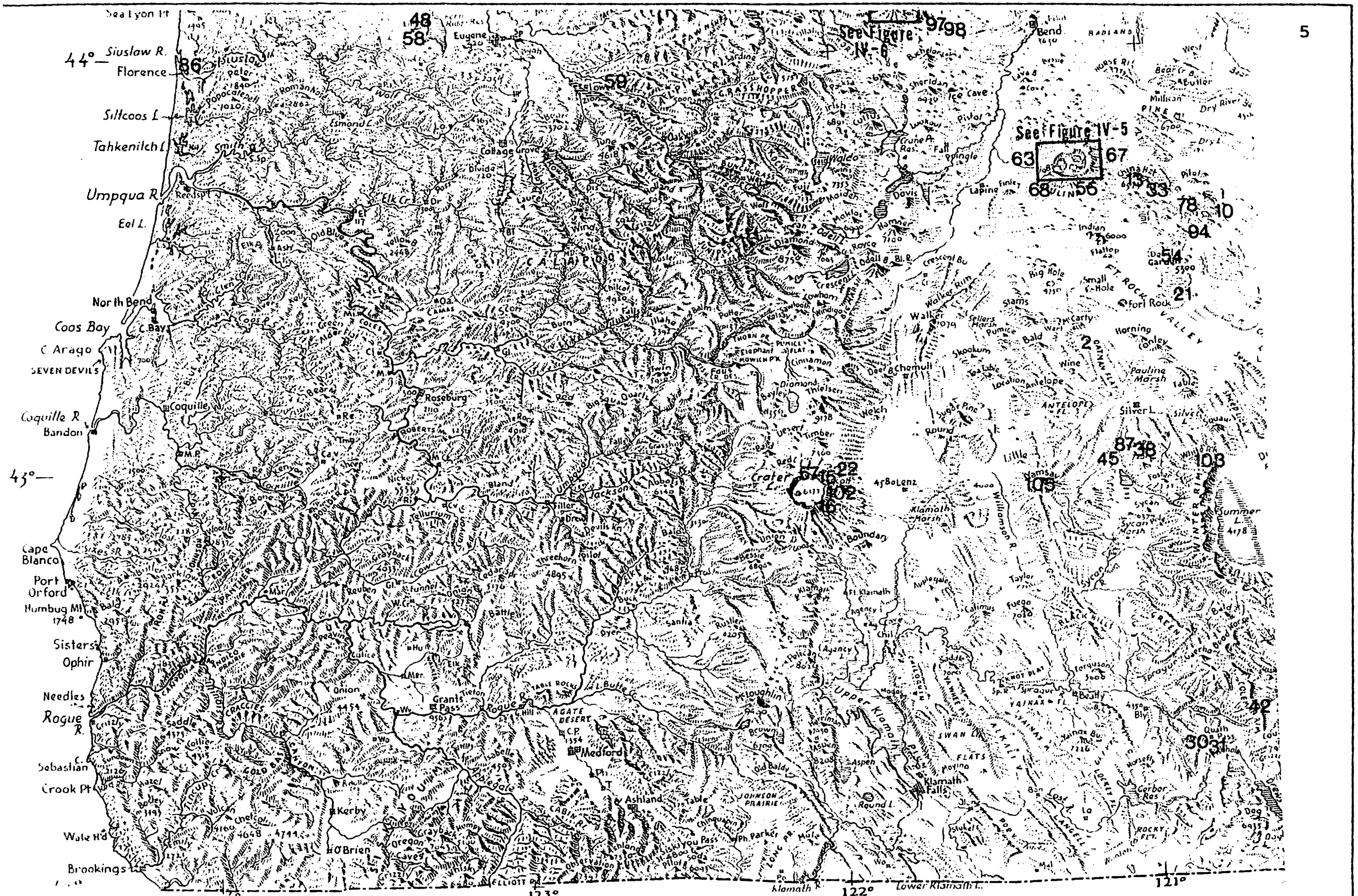
Additional details for the ten sources examined in the course of this project may be found by consulting Part Four and selected appendices in this paper.

In the bibliography, I have retained the full and unabbreviated titles of sources in most cases to make life easier for those dealing here in unfamiliar literary terrain. The only abbreviations used in either the obsidian source listings or the bibliography are: B.P., for before present; DOGAMI, for Oregon Department of Geology and Mineral Industries; GSA, for Geological Society of America; K-Ar, for potassium-argon and m.y., for million years.

Photographs of a few of the obsidian sources are included in this appendix. Additional photographs of the sources that were sampled for the characterization phase of the project can also be found in Part Four of this paper. Many of the Newberry Caldera obsidian sources can also be identified by comparing Figure IV-5, this appendix, with the aerial stereo photographs that appear in Part Four, Chapter Two of the main body of the paper.

Fig.IV-1: Geologic sources of Obsidian and obsidian-like vitrophyre in northwestern Oregon. Base map for Figs.IV-1 through IV-4 is Raisz, 1965.



5
44°
43°
123°
122°
121°
Sea Lyon Pt
Siuslaw R.
Florence
Siltcoos L
Tahkenitch L
Umpqua R
Reedsport
Eel L.
North Bend
Coos Bay
C. Bay
C. Arago
SEVEN DEVILS
Coquille R
Bandon
Coquille
Cape Blanco
Port Orford
Humbug Mt 1748
Sisters
Ophir
Needles
Rogue R.
C. Sebastian
Crook Pt
Wale H'd
Brookings
Eugene
Cottage Grove
Roseburg
Elk Cr.
Yellow B
CALAPOOYA
Camas
Tellurium
Grants Pass
Rogue R.
Table Rocks
Agate Desert
Medford
Ashland
Kerby
O'Brien
Oregon Caves
Grayback
Collier
Saddle
Vulcan
Chetco
Onion
Jackson
Aubrey
Threehorn 4895
Pilot
Bessie
Crater L.
Boundary
Union
Ft. Klamath
Agency
Pelican
Mt. Loughlin
Upper Klamath L.
Klamath Falls
Round L.
Johnson Prairie
Siskiyou Pass
Pilot
Lower Klamath L.
Klamath R.
Ph. Parker
Diamond
Thielsen
Bayley
Timber
Desert
Cinnamon
Mowich Pk
Elephant
Pumice Flat
Thorn Pr.
Chemult
Walker Rim
Walker
Crescent
Odell
Davis
Waldo
Maiden
Royce
Windigo
Cowhorn
Irish
Sheridan
Ice Cave
Pistol
Crane Pr.
Fall
Pringle
Lookout
Buckhorn
Bachelor
Bend
Badland
Horse Ri
Bear Cr. B.
Butler
Millican
Pine Mt.
Dry River
West
China Hat
Indian
Flattop
Big Hole
Small Hole
Fort Rock
Ft. Rock Valley
Horning
Conley
Skookum
Sellers Marsh
Pumice
Bald
Wine
Antelope
Antelope Fl.
Pauline Marsh
Table
Silver L.
Silver L.
Sugar Pine
Round
Little
Yamsay
Bolenz
Klamath Marsh
Williamson R.
Sycan
Sycan Marsh
Summer L.
Winter Rim
Applegate
Calimus
Fuego
Taylor
Black Hills
Green
Ferguson
Knot Flat
Sprague
Yainax Fl.
Beatty
Bly
Swan L.
Flats
Moyina
Lost R.
Lo
Carbon Ras
Rocky Flt.
Quartz
Dog
Laping
Finley
Paulina
See Figure IV-5
See Figure IV-6
48
58
59
86
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68
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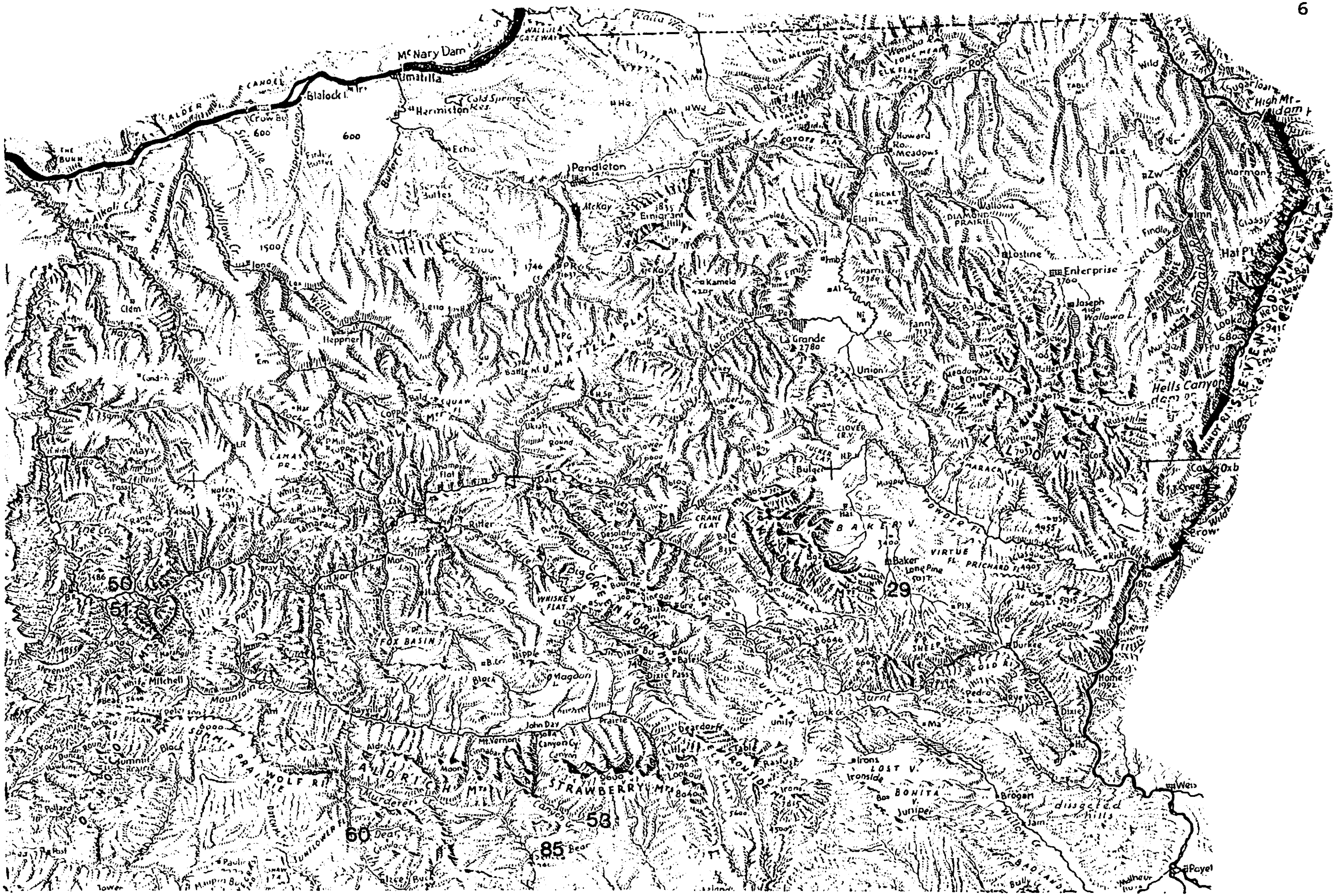

Fig.IV-3: Geologic sources of obsidian and obsidian-like vitrophyre in northeastern Oregon.

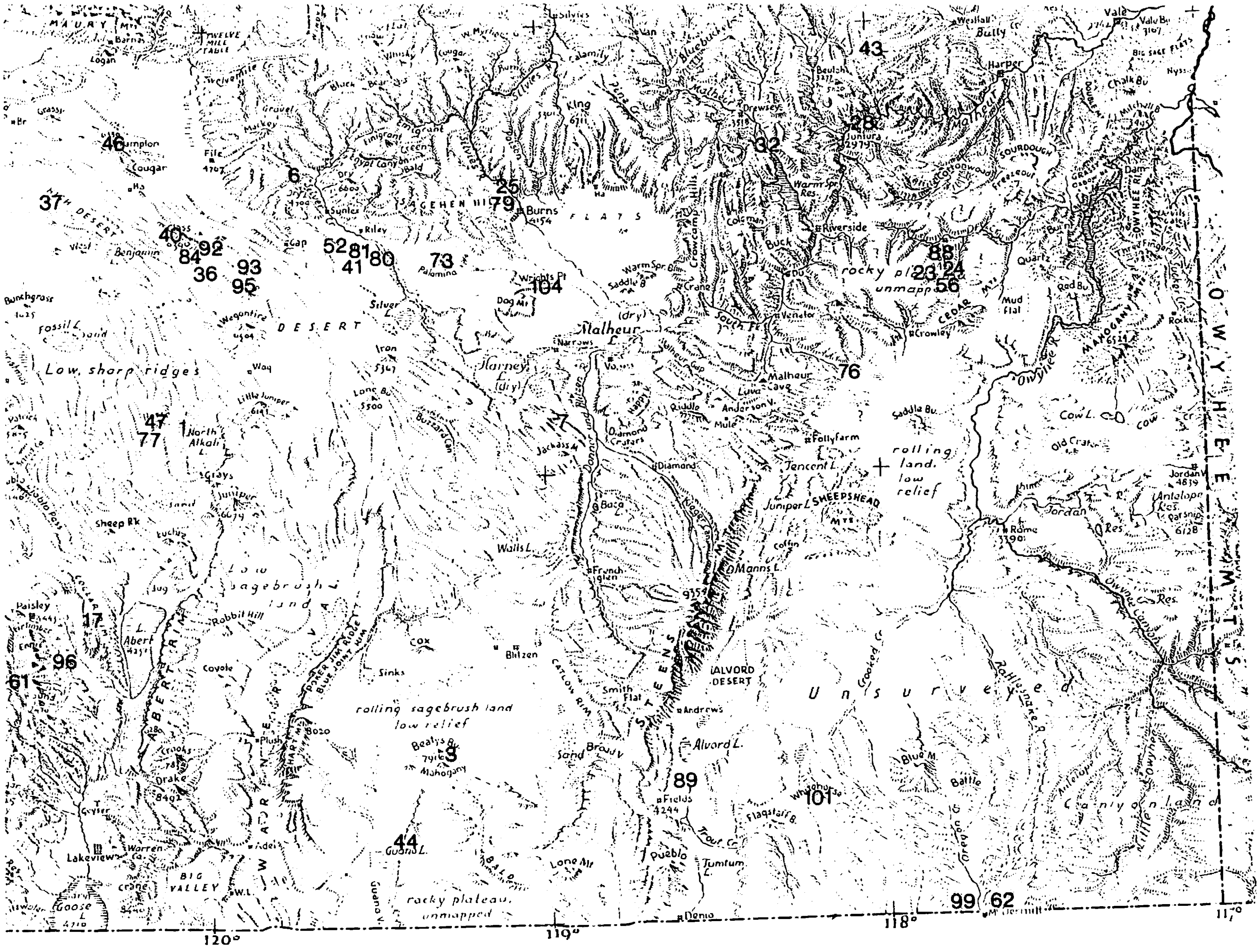

Fig.IV-4: Geologic Sources of obsidian and obsidian-like vitrophyre in southeastern Oregon.

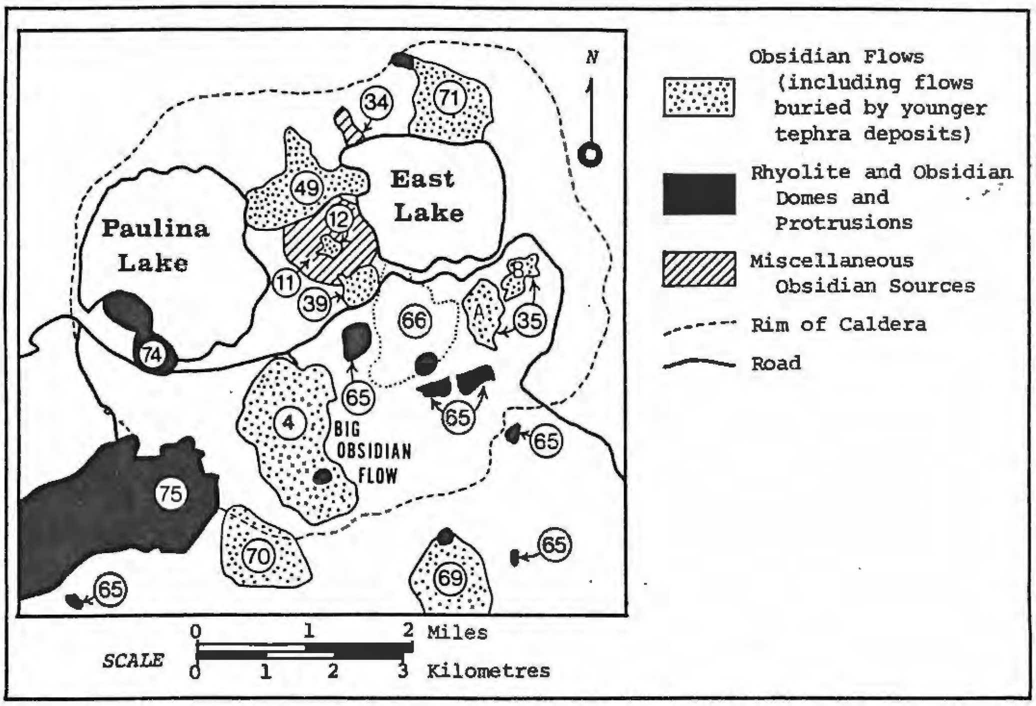

Fig. IV-5: Geologic sketch map of the caldera and upper flanks of Newberry Volcano, Central Oregon (map adapted from MacLeod et al., 1981:89).

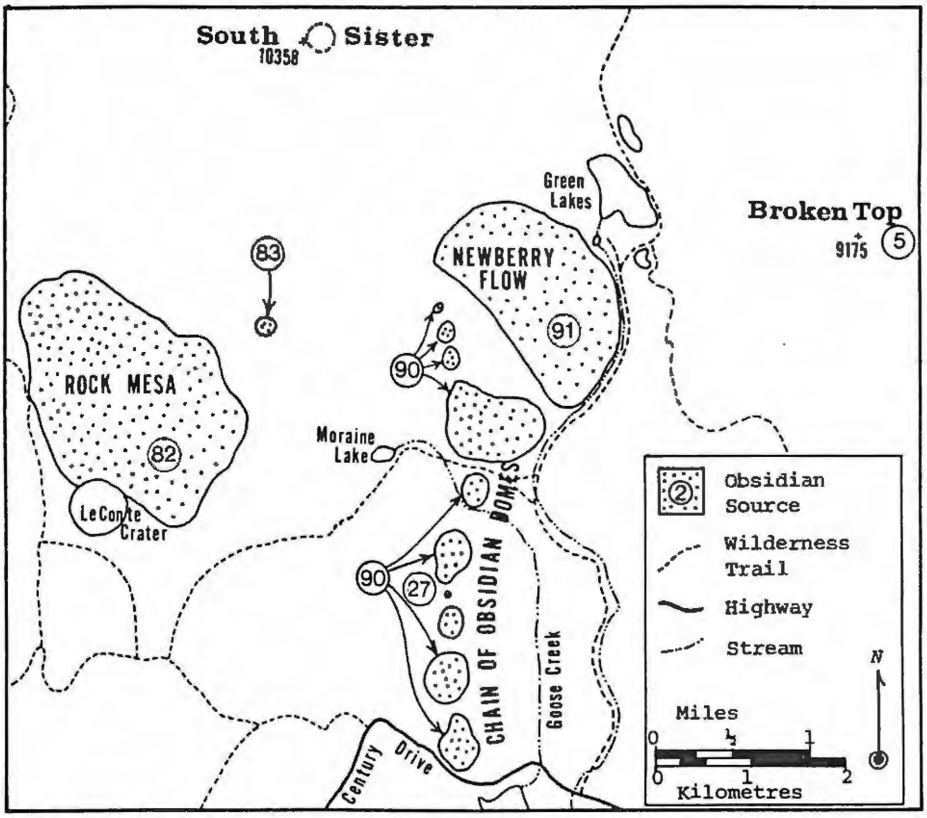

Fig. IV-6: Geologic sketch map of the South Sister and Broken Top vicinity, High Cascades (map adapted from Peterson and Groh, 1965:5).

A PRELIMINARY COMPILATION OF KNOWN AND POTENTIAL GEOLOGIC SOURCES OF OBSIDIAN AND OBSIDIAN-LIKE VITROPHYRE IN OREGON

1. *ALKALI LAKE OBSIDIAN*

Location: The location of this source, mentioned as an obsidian quarry site by Atherton (1966:34), is not clear. Only one Alkali Lake is noted by McArthur (1974:10), this one located just east of Highway 395 in Lake County. See Figure IV-4.

The obsidian is found in a canyon on the northwest side of Alkali Lake. Atherton (1966:34) reports that the obsidian flake concentration is greatest in the upper part of the canyon, with some flakes being found as far east as the lake bed.

It is almost certain that the Alkali Lake Canyon obsidian source is the same as those sources independently reported at Horse Mountain and Poverty Basin (see this appendix).

Archaeological Significance: Not known.

2. *ASH-FLOW OBSIDIAN WEST OF FORT ROCK*

Location: 43°22.5'N lat., 121°17.3'W long.; Lake County. See Figure IV-2.

Geologic Setting: A rhyolitic ash-flow (McKee et al., 1976:38).

Age: A K-Ar age of 3.34 ± 0.44 m.y. is reported by McKee et al.(1976:38) for obsidian from this ash-flow.

Archaeological Significance: Not known.

3. *BEATYS BUTTE OBSIDIAN* *(Also see Addendum)*

Location: Beatys Butte is centered in Sec.8, T.36S., R.28E.; Lake County. 42°25.5' N lat., 119°18.8' W long. See Figure IV-4.

Geologic Setting: The Beatys Butte source, a rhyolite dome, is described by Ericson et al.(1976:234) as a westward-trending obsidian bomb splay with its probable origin at a "collapse cavity" on the west side of the butte. Obsidian is found primarily on the east or southeast slopes of hills with the size of the bombs decreasing with the distance from the butte. With Beatys Butte in the apex, obsidian is distributed in a westward fan-shaped pattern for about eleven miles.

Sappington (1981:16) adds that obsidian is also found on the north and west sides of the butte in Secs. 11 and 19, T.36S., R.29E.

Composition: Major and trace element abundances are found in Ericson (1977: 19,92; see analysis 1, Table IV-1, this appendix).

Age: A K-Ar age of 10.36 ± 0.53 m.y. is reported by McKee et al.(1976:41) Laursen and Hammond (1978:19). MacLeod et al.(1975:468) reports a similar age of 10.37 ± 0.53 m.y.

Archaeological Significance: Numerous obsidian quarries are found on the east and southeast slopes of hills within the obsidian zone to the west of the butte (Ericson et al.,1976:234). Weide (1968:325) writes: "...aboriginal work was concentrated on the banks of Guano Slough where it enters a narrow canyon in the Tertiary basalts as it drains northeast into the Catlow Valley. The scatter of obsidian nodules is thicker here...and the occasional presence of water in Guano Slough may have resulted in this locale being the focus of chipping activity. On the banks large quantites of flakes and many blank fragments were observed."

Sappington (1980b:42), in trace-element characterization studies of obsidian from sites in southern Malheur County, has tentatively correlated a single item from archaeological site 35ML259 to the Beattys Butte source. He also writes: "Beatys Butte obsidian apparently also appeared as single items at three sites in the Whitehorse area and at Dirty Shame Rockshelter [a site in southeastern Malheur County] ."

Sappington and Toepel (1981:253) also report a tentative trace element correlation of one obsidian preform recovered in the Fort Rock Basin at the Connley Caves with the Beatys Butte source.

4. *BIG OBSIDIAN FLOW*

Location: The southeastern corner of Newberry Caldera, Deschutes County. See Figures IV-2 and IV-5 and Plate IV-1, this appendix.

Geologic Context: The Big Obsidian Flow, a one and one-half mile long obsidian flow in the summit caldera of Newberry Volcano, is without a doubt the most thoroughly studied obsidian flow in Oregon. The first mention of the obsidian flow in the literature was by Israel Russell in 1904; since then, many descriptions of the obsidian have appeared (Russell, 1905; Williams, 1935; Nichols, 1941; Higgins, 1968; Higgins, 1973; Higgins and Waters, 1967; Higgins and Waters, 1968; Peterson and Groh, 1965; U.S. Geological Survey, 1980; Sherrod and MacLeod, 1980; MacLeod et al.,1981; MacLeod and Sammel, 1982; MacLeod et al., 1982).

Howel Williams describes the easily accessible and spectacular flow (1935:274-275): "By far the largest of the obsidian flows, and the youngest...covers almost exactly a square mile. Composed, for the greater part, of glistening black obsidian blocks...it forms an outstanding feature of the landscape. The vent of this 'big obsidian flow' lies close to the steep south wall of the caldera, and is now occupied by a dome partly enclosed by an earlier cone of pumice. From this vent...the lava poured northward for more than a mile...and terminated in an abrupt front up to 100 feet in height."

Petrographic Features: The recent obsidians in Newberry Caldera are all similar in thin-section and have been briefly described by Green (1965:38), Higgins (1968:234-241; 1973:464) and Williams (1935:284-285). The obsidian of the BOF can be characterized as a banded gray glass with occasional laths or small phenocrysts of alkali feldspar. Rod-shaped microlites are found throughout the glass and are densely concentrated in the banded areas. Occasional grains of magnetite are also found. Rare xenoliths up to six inches long have also been reported.

Refractive Index: 1.493 ± 0.002 (Murase and McBirney, 1973:3564); 1.494 (Friedman and Long, 1976:349); and 1.493 (Williams, 1935:284).

Composition: The chemical composition of this obsidian flow is particularly well-known and no less than twenty-five analyses have appeared in the literature (Williams, 1935:295; Green, 1965:40; Osborn and Schmitt, 1970:212; Laidley and McKay, 1971; Beyer, 1973:18; Higgins, 1973:475; Murase and McBirney, 1973:3564 - see analyses 2 through 21 and 76 through 80, Table IV-1, this appendix). Variation in major element composition is summarized by Laidley et al., 1967.

Age: The Big Obsidian Flow looks very recent and Williams (1935:276) first thought that it was no older than 300 or 400 years. Since then, several radiocarbon dates associated with events preceding the eruption of the flow have placed the age at closer to 1300 radiocarbon years (Libby, 1952:678; Pearson et al.,1966:459; Peterson and Groh-1969:76; Tamers, 1969:411; Higgins, 1969; Spiker et al., 1978:148; Kelley, Spiker and Rubin, 1978:288; U.S. Geological Survey, 1980; MacLeod et al., 1980).

Archaeological Significance: Not known. If culturally-associated obsidian were characterized and correlated with this source, it could be used to set a limiting date or to calibrate obsidian hydration rates for obsidian hydration dating. Neither of these, though, have been attempted. Obsidian from the Big Obsidian Flow was also used by Huntley and Bailey (1978) in a study of the usefulness of thermoluminescence as an obsidian characterization method.

For more information about the Big Obsidian Flow, see Part Four of this project.

5. BROKEN TOP OBSIDIAN

Location: The eastern flank of Broken Top near Three Creek Lake, Deschutes County; T.17S., R.9E. See Figures IV-2 and IV-6.

Geologic Setting: Broken Top is a heavily-glaciated Pleistocene volcano located not far east of the South Sister in the High Cascades. Williams (1944:45) writes: "...silicic lavas are particularly common on the eastern flank [of Broken Top volcano] , in the vicinity of Three Creek Lake. The topmost flow in the cliffs a short distance west of the Lookout Station is notable as the only obsidian erupted by any of the older group of volcanoes. Its crust and bottom consist of black and varicolored, streaky glass; the interior, on the other hand, is composed of dense, gray lithoidal lava so closely joined parallel to the banding as to appear from a distance like slate." The geologic features of this flow are also briefly summarized by Harris (1976:127).

Age: Pleistocene.

Archaeological Significance: Not known.

6. BUCK SPRING OBSIDIAN

Location: SE¼ Sec.22, T.20S., R.25E., Crook County. See Figure IV-4.

Geologic Setting: Sapppington (1981:16) reports that vitrophyre and/or obsidian has been found at this source.

Archaeological Significance: A single biface base from Fort Rock Cave has been characterized with trace-element abundances by Sappington and Toepel (1981:252) and correlated to the Buck Spring obsidian source.

7. BUENA VISTA OVERLOOK OBSIDIAN

Location: Directions to the Buena Vista Overlook are provided by Ferguson and Ferguson (1978:126), who mention that obsidian nodules are exposed in rock faces near the parking area. This site may be located near the western edge of the Malheur National Wildlife Refuge about 15 miles south of the Refuge Headquarters. See Figure IV-4.

Archaeological Significance: Not known.

BURNS AREA OBSIDIAN

Non-specific references to obsidian from the Burns area, Harney County, appear in Sappington (1980:256), Sappington and Toepel (1981) and Wright et al. (1969:27). This obsidian source or sources had been sampled for source characterization studies by these authors but the exact location of the obsidian was not mentioned. There are several obsidian sources in the Burns area (see Figure IV-4) described elsewhere in this appendix.

Sappington (1981:17), in describing several Oregon obsidian sources, writes that, "A series of well known obsidian flows occur northwest of Burns with material available in a number of locations including T23S, R30E, sec.27..."

A total of 283 obsidian artifacts collected in a surface survey running from the Silver Lake area north to past Prineville yielded several specimens, characterized by their trace-element abundances, that probably originated from sources in the Burns area (Sappington and Toepel, 1981).

8. BURNS BUTTE OBSIDIAN

Location: Immediately west of Burns in Sec.20 T.23S., R.30E.; Harney County. See Figure IV-4.

Geologic Setting: Burns Butte is described by Niem (1974:37) as, "A flow-banded rhyodacitic mass...with abundant obsidian at the surface..." Niem also speculated that obsidian found in fluvial deposits at Wright's Point, twelve miles to the south, may have originated at Burns Butte.

Age: A K-Ar age of 7.54 ± 0.10 m.y. is reported by McKee et al. (1976:41) and Laursen and Hammond (1978:21).

Archaeological Significance: Not known.

9. BUTCHER FLAT OBSIDIAN

Location: Somewhere in Oregon east of the Cascades. Butcher Flat has been mentioned by Cherry (1968:93) as a geologic source of obsidian in Oregon, but no other geographic information was provided. It is likely that this is an alternate name for one of the many other obsidian sources listed in this appendix. A Butcher Flat is noted, however, in Harney County on the Surveyors Lake U.S. Geological Survey quadrangle map.

Archaeological Significance: Not known. This source was apparently sampled by Cherry (1968) for a source characterization study that utilized the refractive indices of several Oregon obsidian sources. The results were not discussed in any detail.

10. *BUTTON SPRINGS AREA OBSIDIAN*

Location: A few miles south of Button Springs (Sec.13., T.23S., R.16E.), Lake County. See Figure IV-2.

Geologic Setting: A reference to obsidian near Button Springs was made by Russell (1905:75), who wrote: "Beginning about 2 miles south of the spring and extending far into the forest to the southwest are abundant outcrops of...variegated tuff beds, which contain large masses of black obsidian. These rocks weather into bold cliffs..." Obsidian in the area mentioned may also include sources described in this appendix as the Squaw Ridge Obsidian and the Squaw Ridge Area Rhyolite Dome.

Archaeological Significance: Not known.

11. *CENTRAL PUMICE CONE FLANKS AND CRATER WALLS OBSIDIAN*

Location: The center of Newberry Caldera, Deschutes County. See Figure IV-5.

Geologic Setting: The Central Pumice Cone rises directly between East and Paulina Lakes in the caldera of Newberry Volcano. The obsidian of the flanks and crater walls of this cone was first described by Williams (1935:272), who wrote: "Gray and buff pumice-lapilli form the bulk of the cone...and there are plentiful chips of obsidian due to the shattering of interbedded flows. Clearly, the growth of the cone proceeded by an alternation of explosive eruption and quiet effusion, the former predominating. Some of the interbedded obsidians are to be seen both inside the crater and on the flanks of the cone." Higgins (1968:200) also mentions the several horizons of black and green-gray obsidian in the summit crater walls.

Petrographic Features: Obsidian collected near the top of the north wall of the Central Pumice Cone is described by Williams (1935:238): "The banding is extremely fine, the alternating gray and colorless streaks varying from about 0.2 millimeter to almost ultramicroscopic width. The colorless streaks are entirely glassy, and the gray ones are crowded with belonites, presumably of oligoclase, accompanied by microliths of augite and clouds of irresolvable dust. Phenocrysts are wholly lacking."

Refractive Index: 1.493-1.494 (Williams, 1935:283).

Composition: Major and trace element composition of the summit crater wall obsidian appears in Higgins (1973:474,483; see Table IV-1, analyses 26 and 27, this appendix).

Age: Uncertain, except that the cone is of post-caldera formation age (an event whose age is not known) and the obsidian of the flanks and crater wall must pre-date the eruption of a post-Mazama obsidian flow on the summit crater floor (see source 12 in this appendix).

Archaeological Significance: Not known.

12. *CENTRAL PUMICE CONE SUMMIT CRATER OBSIDIAN FLOW*

Location: The crater of the Central Pumice Cone, Newberry Caldera, Deschutes County. See Figure IV-5.

Geologic Setting: The Central Pumice Cone is a 700-foot high cone of rhyolitic pumice, lapilli and blocks that lies directly between East and Paulina Lakes. This prominent feature is the largest cone of any type within the Newberry Caldera rim. Rising from the floor of the more than 200-foot deep summit crater is a small flow or dome of blocky and pumiceous obsidian (Williams, 1935:272; Higgins, 1973: Higgins, 1968:200-201).

Petrographic Features: Higgins (1968:239-240; 1973:464) describes the recent obsidian flows in the caldera as being very similar when examined in thin-section, and discusses them as a unit.

Composition: Major element composition is reported by Higgins (1973: 475; see Table IV-1, analyses 22 and 23, this appendix). Trace and major element abundances appear in Laidley and McKay (1971:339, see analysis 24, Table IV-1, this appendix).

Age: Despite numerous published discussions of obsidian hydration ages and contact relationships with the obsidian, the age of the Central Pumice Summit Crater Obsidian Flow is still in doubt. Peterson and Groh (1969:78) first placed the obsidian hydration age at 5,000 years. Higgins and Waters (1972:1260) argued that the age of the obsidian had to be less than what they believed was the last eruptive event of the cone, the eruption of the Newberry Ashfall Deposit No.2, dated at 1720 ± 250 radiocarbon years B.P. (Higgins, 1969:31). Friedman et al. (1972:1260) later pointed out that the ashfall may have originated at the Big Obsidian Flow vent prior to the eruption of the Big Obsidian Flow. This was later corroborated by Sherrod and MacLeod (1979) and MacLeod et al. (1981:91). Friedman originally assigned an obsidian hydration age of 4,500 years to the Central Pumice Cone Flow (Friedman, 1977:340) and has only slightly altered that age in later publications to 4,300 obsidian hydration years B.P. (Friedman and Trembour, 1979:49; Friedman and Obradovich, 1981:43).

Archaeological Significance: Not known.

13. *CHINA HAT OBSIDIAN*

Location: Eight miles east-southeast of the Newberry Caldera rim in Secs.10 and 11, T.22S., R.14E.; Deschutes County. China Hat is locally well-marked. See Figure IV-2.

Geologic Setting: China Hat was originally misidentified by Williams (1935:273; see Higgins, 1969:31, for a discussion) as a volcanic pumice-producing cone. Higgins (1968:272) later correctly described China Hat as a nearly perfect rhyolitic dome. Higgins describes the rocks of China Hat as chiefly gray, platy and spherulitic rhyolites and massive gray and black obsidians. Heflin (1979:79) also mentions China Hat as a source of obsidian.

Age: A K-Ar date of .78 ± 0.2 m.y. for obsidian from China Hat is reported in a number of sources (Walker, 1974; MacLeod et al., 1975; McKee et al., 1976:38; Laursen and Hammond, 1978:27).

Archaeological Significance: Not known.

14. *CLARNO OBSIDIAN*

Location: The Clarno area, probably in Wheeler County. This source was reported by Ericson (1977:316), who offered no further details.

Archaeological Significance: Not known.

15. *CLEETWOOD OBSIDIAN*

Location: Crater Lake National Park, Klamath County. See Figure IV-2.

Geologic Setting: The Cleetwood dacite flow is described by Williams (1942:183): "In general, the top and the bottom of the Cleetwood flow are composed of glistening obsidian. Locally, this glassy part of the flow is crowded with pink spherulites; alsewhere, the jet-black glass is streaked in shades of red and brown owing to the oxidation of iron along zones of brecciation and gas concentration." The Cleetwood dacite is one of several dacite flows located along the northern edge of the Crater Lake caldera; these are known, collectively, as the Northern Arc of Vents (Williams, 1942).

16. *CLOUDCAP OBSIDIAN* *(Also see Addendum)*

Location: Crater Lake National Park, Klamath County. See Figure IV-2.

Geologic Setting: An obsidian sample was collected at Cloudcap, near the road to the summit (Jack and Carmichael, 1969:31). Cloudcap, one of several dacite domes and flows on the northern border of the Crater Lake caldera, is described by Williams (1942:52-54).

Composition: Trace element composition is reported by Jack and Carmichael (1969:26-27; see analysis 29, Table IV-1, this appendix).

Archaeological Significance: Not known.

17. *COGLAN BUTTES OBSIDIAN*

Location: Coglan Buttes are located several miles north of Tucker Hill (another obsidian source) and west of Lake Abert, Lake County. The buttes are centered in the southeast quarter of T.33S., R.20E. The presence of obsidian in this area is known by local BLM archaeologists and is included in the sources identified by Lee Sappington (Rick Pettigrew, personal communication). See Figure IV-4.

Archaeological Significance: Not known.

18. *COLUMBIA RIVER AND WILLAMETTE RIVER GRAVEL OBSIDIAN*

Location: River gravels in the Columbia and Willamette Rivers. See Figure IV-1.

Geologic Setting: Minor (1977:619) reports that most of the obsidian from archaeological sites near the confluence of the Columbia and Willamette Rivers was found as nodules in the gravels of these two rivers. The primary source of the obsidian is unknown, but obsidian found in the Willamette River probably originated from sources in the High Cascades or the Oregon Coast Range (also see the Inman Creek Obsidian, the Long Tom Obsidian and Obsidian Cliffs Obsidian, this appendix).

Archaeological Significance: Minor has calculated from hydration measurements of this obsidian a regional hydration rate of 1.3μm^2 per thousand radiocarbon years (Minor, 1977:617). Radiocarbon dates that provided the time frame for calibration of the hydration rate came from five sites in the Portland-Vancouver area. Unfortunately, the work of Ericson (1975) and others (see Part Three of this paper) has rendered the idea of a regional, non source-specific obsidian hydration rate obsolete.

19. *CONDON BUTTE AREA OBSIDIAN DOME*

Location: This unnamed obsidian dome is located just southwest of Condon Butte and is about two miles south of Highway 242, Lane County, High Cascades. The dome is visible from the Dee Wright observatory at McKenzie Pass as a knob to the left of Condon Butte. See Figure IV-1.

Geologic Setting: This landform is described by Taylor (1968:21; 1981: 66) as a glaciated dome of rhyodacitic obsidian. Taylor feels that the obsidian formed as selvage at the outer part of the dome, this outer layer being later completely removed by glaciation. He attributes very small fragments of obsidian found to the east in airfall deposits as originating from this source (E. Taylor, personal communication). Fragments of gray obsidian from this dome are also found in surficial glacial deposits a few miles to the west in the Hand Lake area (Taylor, 1968:18). A search by the author in 1981 revealed no remaining obsidian at the dome, though a small surface scatter of obsidian flakes originating from Obsidian Cliffs (see Appendix Seven) was found near the base of the dome.

Age: Pleistocene.

Archaeological Significance: Not known. Obsidian flakes attributed to this source are reported as too small to be of any artifactual value (E. Taylor, personal communication). It is possible, however, that archaeologically-useable obsidian from this source may have ended up, like the obsidian of nearby Obsidian Cliffs, in the McKenzie River drainage.

20. *COOK WELL OBSIDIAN*

Location: Lake County. Sappington (1980:256) lists this as an Oregon obsidian source, but no additional details are available.

Archaeological Significance: Not known.

21. *COUGAR MOUNTAIN OBSIDIAN* *(Also see Addendum)*

Location: Northwest Lake County, at the upper edge of the Fort Rock Valley. See Figure IV-2.

Geologic Setting: Cougar Mountain is a 700-foot high eroded rhyolite dome that rises abruptly above the old Pluvial Fort Rock lakebed at the northern border of the Fort Rock Valley. Hampton (1964:7) describes the obsidian at the mountain: "The obsidian on Cougar Mountain is mostly black, but some of it contains red streaks and nearly all the obsidian is transparent or translucent on thin edges. The obsidian lies in streaks within the rhyodacite, and there is a complete gradation from frothy fine-grained light-colored rhyodacite to dense obsidian." Obsidian nodules that have weathered out of the rhyolite matrix are abundant on the western and southern flanks of the mountain. Brief descriptions of Cougar Mountain also appear in Allison (1979:19-20) and Forbes (1973:108). Obsidian pebbles from the primary source at the mountain can be found far out into the Pleistocene lake basin that borders the dome. Obsidian pebbles have also been found in lapilli-tuff layers in nearby Table Mountain, a nearby Pleistocene maar or tuff-ring (Heiken, 1972:55).

Age: A K-Ar age of 4.31 ± 0.34 m.y. is reported by MacLeod et al.(1975: 468), McKee et al.(1976:38) and Laursen and Hammond (1978:25). Fission-track ages of 2.5 ± 0.6 m.y. and 3.2 ± 0.4 m.y. also appear in Naeser et al.(1980:19); the discrepancy between the K-Ar and fission-track ages is presumably due to the annealing, or fading, of the fission tracks in the glass.

Refractive Index: Cherry (1968), after sampling obsidian from Cougar Mountain, apparently found that the refractive index was consistent for all his samples. The study, though, is rather vaguely described, and no refractive indices were reported.

Archaeological Significance: Striking wave-cut cliffs are found in the southern and western sides of Cougar Mountain. Littoral caves were carved along small faults in the cliff by the waters of Pluvial Fort Rock Lake and at least four of these caves have been identified as archaeological sites.

Two of the caves, Cougar Mountain Cave No.3 and No.4, are found on the western side of the mountain and were excavated by an amateur sometime prior to 1960. Little is known of what was recovered except that notched points similar to those found near the bottom of Cougar Mountain Cave No.1 were present (Cowles, 1960:3).

The largest of the caves at Cougar Mountain, Cave No.1, was excavated in 1958 by a collector who later published a short book describing his finds there (Cowles, 1960). A substantial collection of obsidian, basalt, bone, fiber, bone and leather artifactual materials was recovered. The stratigraphic distribution of the artifacts was not well-established, though Layton (1972), using projectile points recovered by Cowles, made a relative seriation study using obsidian hydration analysis.

Nearby Cougar Mountain Cave No.2 was also excavated in the late 1960's by a University of Oregon team (Bedwell, 1970 and 1973). A radiocarbon date of 11,950 ± 350 years B.P. was determined for materials associated with worked flakes found in the cave, establishing the considerable antiquity of the site.

The archaeological features of the Cougar Mountain Caves are also described by Minor et al.(1979:33,51), Strong (1969:79-80,203), Butler (1961: 7-15), Atherton (1966:27-30) and Skinner (1981).

The naturally-occurring obsidian found at Cougar Mountain is of excellent tool-making quality and this source was clearly a well-utilized obsidian quarry site. Sappington and Toepel (1981), after determining the trace-element composition of 283 obsidian artifacts collected along a transect running from the Silver Lake area north to the Maupin vicinity, identified 64 artifacts as originating from the Cougar Mountain source. Most were found in the Silver Lake-Fort Rock area. In a closely-related study, 26 pre-Mazama obsidian artifacts from the Fort Rock Cave and Connley Cave sites were characterized. Of these, 5 appeared to have originated at Cougar Mounttain (Sappington and Toepel, 1981:248-254). The source of several other artifacts from the Fort Rock and Connley Caves has also been found to be Cougar Mountain (see Appendix IX, this project).

For more information about the Cougar Mountain obsidian quarry, see Part Four of this project.

CRATER LAKE OBSIDIAN

Non-specific references to Crater Lake obsidian appear in Wright et al. (1969) and Griffin et al.(1969; see Table IV-1, analyses 30 and 31, this appendix). There are several possible sources of obsidian near the caldera of Crater Lake.

22. *CRATER LAKE RIM DRIVE OBSIDIAN*

Location: Crater Lake National Park, Klamath County. See Figure IV-2.

Geologic Setting: Not known. A specimen of obsidian was collected about one-quarter mile north of the Cleetwood Lake Trail on the rim drive that circles Crater Lake. It is not clear from the reference whether the sample is dacite or dacitic obsidian (Jack and Carmichael, 1969:31).

Composition: Trace element composition is reported by Jack and Carmichael (1969:26-27; sample Cam 125).

Archaeological Significance: Not known.

23. *CROWLEY AREA ASH-FLOW TUFF A*

Location: The ash-flow is exposed in Secs.14,23,26 and 36, T.25S., R.38E.; Malheur County. See Figure IV-4.

Geologic Setting: The Ash-Flow Tuff A, where exposed, exhibits three zones of welding - an upper zone of moderate welding; a second, thin zone of dense welding (not always present below the upper zone); and a lower zone of no welding. The weathered surface of the densely-welded zone is described by Green (1962:79) as, "...black, hard and obsidian-like with perlitic texture." Also see the Crowley Area Ash-Flow Tuff B.

Petrographic Features: The densely-welded zone is composed of a dark gray vitreous matrix containing pumice fragments up to 1 cm long. Phenocrysts are not present and glass shards can be seen only in thin-section (Green, 1962:79).

Age: The lower zone of no welding rests directly on a sandstone of Barstovian (mid-Miocene) age, establishing a minimum age for the ash-flow unit (Green, 1962:80).

Archaeological Significance: Not known. The perlitic texture of the densely-welded zone, however, probably leaves the obsidian-like unit as a poor archaeological resource.

24. CROWLEY AREA ASH-FLOW TUFF B

Location: Malheur County. This ash-flow unit is exposed in outcrops in three distinct areas. Outcrops are found near the head of Wildcat Creek in W½Sec.20, E½Sec.29 and Sec.33, T.24S., R.40E. The unit is also exposed in much of Sec.4, T.25S., R.39E. See Figure IV-4.

Geologic Setting: A zone of gray to black densely-welded ash occurs in this unit. The surface of this zone is described by Green (1962:81) as: "...obsidian-like and displays perlitic cracks. Green also reports that this zone weathers rapidly to form slopes. This ash-flow unit occupies the same stratigraphic position as the Crowley Area Ash-Flow Tuff A and these separately described units are likely one and the same.

Archaeological Significance: The perlitic texture and the erodability of the obsidian-like unit probably minimized the possibility that this material had any archaeological utility.

25. DANFORTH FORMATION WELDED TUFF OBSIDIAN INCLUSIONS

Location: Obsidian inclusions in a welded ash-flow unit of the Danforth Formation are reported by several sources to be exposed in a number of locations near the Silvies River, Harney County. The individual exposures are listed below. See Figure IV-4.

Geologic Setting: The Danforth Formation of the Harney Basin is composed of lake-deposited sediments, basalt flows and welded ash-flows. Obsidian inclusions are typically found associated with the upper lithophysae zone of the ash-flow unit. Bateman (1961:71) describes what appears to be a typical obsidian setting: "Larger inclusions of obsidian (up to 6 inches in length) occur in cavities [lithophysae] lined with spherulites of sanidine and crystobalite. The weathered-out obsidian inclusions are common in rubble derived from the upper lithophysae zone and are easily identified by the concave impressions left by the spherulites that line the cavity. The index of refraction of this obsidian ranges from 1.485-1.490...Bubbles and and microlites occur in most samples examined."

Measured and described sections of the obsidian-containing welded ash-flow unit are reported by several authors:

1. SE¼Sec.36, T.22S., R.30E. (Piper et al., 1939:44).
2. SW¼Sec.23, T.22S., R.32½E. (Piper et al., 1939:45).
3. Center Sec.36, T.22S., R.30 E. (Lund, 1966:165-166).
4. Sec.36, T.20S., R.28E. (Bateman, 1961:64).
5. Sec.1, T.21S., R.28E. (Bateman, 1961:66).

Crowley (1960:26, Plate 1) also reports of the Danforth Formation: "...rhyolitic tuff containing pumice and lenses of obsidian...intercalated within rhyodacite," in several locations in T.17 and 18S., R.32E.

Age: Early Pliocene to late Miocene. K-Ar ages of 9.2 and 6 m.y. for the Danforth Formation are reported in Laursen and Hammond (1974:27).

Archaeological Significance: Not known.

26. *DESCHUTES RIVER PERLITE AND OBSIDIAN*

Location: The perlite zone described below extends through the SW¼ Sec.16 into the SE¼Sec.17, T.6S, R.14E.; Wasco County. This is about nine miles south of Maupin on the north side of the Deschutes River. Specific directions are given by Allen (1947). See Figure IV-1.

Geologic Setting: A perlite zone varying in thickness from 40 to 180 feet is reported by Allen (1947:61). He writes: "The lower 10 to 40 feet of the perlite section is made up of dark crumbly perlite containing occasional marakanite (black glass) cores..."

Archaeological Significance: Not known.

27. *DEVILS HILL OBSIDIAN*

Location: Adjacent to the South Sister Chain of Obsidian Domes on the south flank of the South Sister, Deschutes County; Sec.3, T.18S., R.8E. See Figures IV-2 and IV-6.

Geologic Setting: Devils Hill is a prominent, glaciated dacite dome that appears to also be a source of obsidian, though the literature is rather vague as to that point. Howel Williams (1944:51) writes: "First, thick piles of viscous, glassy lava were expelled. Some flows are finely banded and spherulitic; others are frothy and have breadcrusted blocky crusts. Later, still more viscous dacite rose above the vent to form a steep-sided dome with fan-shaped internal structure." Hodge (1925:96) also provides a description of Devils Hill, while a geologic map of the area appears in Peterson and Groh (1965:5).

Age: Pleistocene (Peterson and Groh, 1965:5).

Archaeological Significance: Not known.

28. *DINNER CREEK WELDED TUFF*

Location: The Malheur Gorge area, a few miles east of the town of Juntura, Malheur County. Kittleman (1973:19) reports an exposure of the welded tuff 3.9 miles east of Juntura alongside Highway 20. See Figure IV-4.

Geologic Setting: The Dinner Creek welded ash-flow is a large unit that probably originated at Castle Rock. Kittleman (1973:19) writes: "Near the bottom of the flow, where the weight of the overlying lava and degree of entrapped heat were greatest, the froth was compressed into a dense, glassy ledge that resembles obsidian." The zone of dense welding in the Malheur Gorge area is found at the bottom of a prominent, reddish ledge which marks the Dinner Creek ash-flow. Haddock (1967:44) also mentions obsidian xenoliths in the lower zone of partial welding of the Dinner Creek Ash-Flow, though he gives no details. Whether these two different occurrences are related is not known.

Age: Late Miocene (Kittleman, 1973:6,18). Laursen and Hammond (1978: 19) also report a K-Ar age for the Dinner Creek Ash-Flow Tuff as 14.3 ± .04 m.y.

Archaeological Significance: Not known.

29. *DOOLEY MOUNTAIN OBSIDIAN*

Location: South of Baker, near the Baker-Unity Highway, Baker County; Sec.32, T.11S., R.40E. This source is mentioned by Ericson (1977: 315), but no additional information is available. See Figure IV-3.

Archaeological Significance: Not known.

30. *DREWS CREEK OBSIDIAN*

Location: Sec.18, T.38S., R.16E.; Lake County (Ericson, 1977:316). See Figure IV-2.

Archaeological Significance: Not known. This source is close to the Drews Valley Ranch obsidian source and may also be associated with perlite deposits.

31. *DREWS VALLEY RANCH OBSIDIAN*

Location: Just north of Highway 66 on Drews Valley Ranch in Secs.16 and 17, T.38S., R.17E.; Lake County. See Figure IV-2.

Geologic Setting: A large deposit of light gray perlitic rock is found associated with glassy dacite and a zone of obsidian. This deposit occurs in low rounded hills and may be remnants of a thick flow (Peterson, 1961:23; Peterson and McIntyre, 1970:60).

Age: A K-Ar age of 7.13 ± 0.34 m.y. is reported by McKee et al.(1976: 40) and by MacLeod et al.(1975:468). A fission track age of 4.2 ± 0.3 m.y. is reported by Naeser et al. (1980:19). The discrepancy between these two dates is probably due to the annealing or fading of fission tracks in obsidian.

Archaeological Significance: Not known. Obsidian that is found associated with perlite is reported by Crabtree (1967:18) usually to be of poor quality for the manufacture of flaked tools.

32. *DRINKING WATER PASS WELDED ASH FLOW OBSIDIAN*

Location: The Drinking Water Pass area, Harney and Malheur Counties. See Figure IV-4.

Geologic Setting: Gray (1956:20) reports that welded tuffs are found interbedded in Owyhee basalts. The base of this tuff, where exposed, overlies a light gray tuff that grades upward to a dark-colored baked tuff. The base of the welded tuff is obsidian-like with spherulites 2 to 4 cm in diameter. In thin-section, this bed is clearly composed of welded glass shards. The obsidian-like bed grades upward into a grayish-purple tuff that is not found at the base of all the localities that Gray examined. He also reports that devitrification was completely lacking in the "obsidian".

Refractive Index: 1.500 (Gray, 1956:26).

Age: Late Miocene (Gray, 1956).

Archaeological Significance: Not known.

33. *EAST BUTTE OBSIDIAN*

Location: Ten Miles east-southeast of the Newberry Caldera rim, Deschutes County; Sec.13, T.22S., R.14E. East Butte is located two miles southeast of China Hat, a well-known landmark in the area. See Figure IV-2.

Geologic Setting: Initially misidentified as a pumice-producing cone by Williams (1935:273; see Higgins, 1969, for a discussion), East Butte was correctly identified by Higgins (1968:273) as a dome of rhyolite and obsidian. Heflin (1979:72) and Ericson (1977:316) also refer to East Butte as a source of obsidian.

Age: A K-Ar age of .84 ± .04 m.y. has been reported by McKee et al.(1976: 38) and Laursen and Hammond (1978:27). A similar K-Ar age of .85 ± .05 m.y. is also reported by Walker (1974:11), MacLeod et al.(1975:468) and Laursen and Hammond (1978:27).

Archaeological Significance: Not known.

34. *EAST LAKE FISSURE OBSIDIAN INCLUSIONS*

Location: On the north wall of Newberry Caldera directly above East Lake, Deschutes County. See Figure IV-2 and IV-5.

Geologic Setting: The East Lake Fissure is the southernmost end of a zone of *en echelon* faulting and basaltic andesite fissure eruptions that stretches from East Lake to Lava Butte, a prominent cinder cone about 20 miles to the northwest. Mixed with the basalt of the fissure are inclusions of rhyolitic obsidian, a geological enigma that stimulated interest in this feature for several decades. Howel Williams best summarizes the unusual basalt-obsidian relationship at the fissure (Williams, 1935:276): "Particularly interesting are the foreign fragments admixed with the basalt. Near the lake edge...the recent scoria are crowded with fragments of black obsidian, different from any of the old lavas exposed in the adjacent wall. The edges of the obsidian fragments are usually rounded, indicating either that the basalt was sufficiently hot to render the obsidian partly viscous or that it eas already in that condition when incorporated." Williams tentatively concluded that the obsidian had somehow been intruded into the cooled basalt.

Michael Higgins, in his dissertation, agonized for many pages over this problem (Higgins, 1968:245-261) and finally concluded that Williams' field observations were in error and that the obsidian was the product of the melting of older rhyolitic fragments by the basaltic lava. A later paper by Higgins and Waters (1970) nicely summarizes the problem and the conclusion that the obsidian inclusions are actually remelted rhyolites.

Composition: Major element composition of obsidian at the fissure is reported by Higgins and Waters (1970:2841; see analysis 38, Table IV-1, this appendix).

Age: Williams (1935) first thought that the fissure represented one of the last eruptions within the caldera and that it was roughly contemporaneous in age with the Big Obsidian Flow. Higgins, based on his later field work, concluded that the fissure eruptions were at least a century old (Higgins, 1968:261). Friedman, using the obsidian hydration dating method, came up with a date of 2,900 ± 400 years B.P. (Friedman and Peterson, 1971; Friedman, 1977:341). The hydration rate used in this attempt, though, was a regional one, and was likely in error. Higgins and Waters placed the age of the fissure at no more than 1720 ± 250 radiocarbon years B.P., the date associated with the last caldera ash and pumice eruption (Higgins, 1969:31; Spiker et al., 1978). They reasoned that the deposits of the fissure were not covered by pumice and therefore must be younger than the last tephra fall. Friedman and Higgins later inconclusively argued their conflicting points of view in the literature (Higgins and Waters, 1972; Friedman et al., 1972). Last, and probably the most accurate, is the conclusion reported by MacLeod et al.(1981:89, and 1982:23) and MacLeod and Sammel (1982:125) that the age of the fissure is most likely about the same as a basaltic andesite flow along the same fissure dated at about 6,090 radiocarbon years B.P.

Archaeological Significance: Not known.

35. *EAST LAKE OBSIDIAN FLOWS*

Location: About 400 m southeast of the shore of East Lake within the Newberry Volcano summit caldera, Deschutes County. See Figures IV-2 and IV-5.

Geologic Setting: These two obsidian flows, known collectively as the East Lake Obsidian Flows, were erupted from a fissure vent on the south wall of the caldera. The westernmost of the flows is the largest with a length of about one km while the eastern flow is less than half that length. One to two feet of rhyolitic tephra can be found on top of the two narrowly separated flows. The obsidian flows have been briefly described by Williams (1935:275-276), Higgins and Waters (1967:51), Higgins (1968:196-198), Higgins (1973:6470) and Peterson and Groh (1965:1965:11,18).

Petrographic Features: The petrographic characteristics of the East Lake Obsidian flows are similar to those of the other recent caldera obsidians. Higgin (1973:464) describes the glass as banded (colorless and gray) with tiny rod-shaped crystallites, small grains of magnetite, feldspar microlites and rare prisms of pyroxene.

Refractive Index: 1.493 (Friedman and Long, 1976:349).

Composition: The two flows are compositionally indistinguishable. The composition of the obsidian has been reported by Higgins (1973:274), Friedman and Long (1976:349), Jack and Carmichael (1969:26) and Laidley and McKay (1971:339; see analyses 32 through 37, Table IV-1, this appendix).

Age: The two flows are mantled with tephra from a vent now covered by the Big Obsidian Flow, but are not covered by Mazama tephra. This places the age of the flow at some point between these two events, or somewhere between about 1,700 and 7,000 radiocarbon years ago (Spiker et al., 1978:143; Higgins, 1969). Both of these flows are assumed to have erupted at about the same time.

Obsidian hydration dating has also been used in an attempt to fix the age of these obsidian flows. Friedman and his associates (Friedman, 1977:339; Friedman and Obradovich, 1981:40; Friedman and Trembour, 1978:49) have placed the age of the flows at about 3,500 years.

Archaeological Significance: Not known. The East Lake Hot Springs, though, are located a short distance from the flows and have been reported to have been used by Indians for medicinal purposes prior to their development by Whites (Linck, 1945:62). Obsidian from one of the East Lake Flows was also used by Huntley and Bailey (1978) in a study of the usefulness of thermoluminescence as an obsidian characterization method.

36. *EGLI RIDGE OBSIDIAN*

Location: 43°22.8' N lat., 119°51.0' W long.; Harney. See Figure IV-4.

Geologic Setting: The ridge is a rhyolite dome (McKee et al., 1976:40).

Age: Similar K-Ar ages of 6.41 ± 0.19 m.y. and 6.42 ± 0.19 m.y. are reported, respectively, by McKee et al.(1976:40) and MacLeod et al. (1975:468) for obsidian from Egli Ridge.

Archaeological Significance: Not known.

37. *FREDERICK BUTTE*

Location: Deschutes County; Sec.32, T.22S., R.19E. (Heflin, 1979:72). See Figure IV-4.

Geologic Setting: The butte is a rhyolite dome (Peterson et al., 1976).

Archaeological Significance: Not known.

38. *FROG MOUNTAIN OBSIDIAN* *(Also see Addendum)*

Location: Obsidian from SW¼Sec.11, T.30S., R.14E., Lake County, and from several other areas in that vicinity has been reported by Sappington (1981:17). This may also be the same source as those called by others the Hager Mountain obsidian and the Silver Lake obsidian(see those entries, this appendix). See Figure IV-2.

Archaeological Significance: Out of a large (n=283) sample of characterized obsidian artifactual material collected during an archaeological survey of a power transmission line, only one artifact found near Silver Lake was determined to originate from the Frog Mountain source (Sappington and Toepel, 1981:246).

39. *GAME HUT OBSIDIAN FLOW*

Location: At the southeast margin of the Central Pumice Cone, Newberry Caldera, Deschutes County.

Geologic Setting: The Game Hut Obsidian Flow is found at the southeast base of the Central Pumice Cone and spreads about 400 m to the southeast of the cone (Higgins, 1968:201; Higgins, 1973:470). The flow may have been created by the draining of a lava lake in the summit crater of the Central Pumice Cone (MacLeod et al., 1982:6).

Composition: Major element composition appears in Higgins (1973:475; see analyses 39 and 40, Table IV-1, this appendix).

Age: This flow is mantled by the Newberry Ashfall No.2, dated at 1720 ± radiocarbon years. Friedman and his associates have assigned an age of 6,400 to 6,700 obsidian hydration years to the Game Hut eruption (Friedman, 1977:339; Friedman and Obradovich, 1981:40; Friedman and Trembour, 1978:49).

Archaeological Significance: Not known.

40. *GLASS BUTTES OBSIDIAN* (Also see Addendum)

Location: Just south of Highway 20 in the northeastern corner of Lake County; S½T.23S., R.22E. Sketch maps of the roads and of the location of colored obsidian at Glass Buttes appear in Heflin (1963 and 1979) and Broughton (1974). The general location of the Buttes is shown on most highway maps. The obsidian at Glass Buttes can be found in an area reported to cover between 40 and 50 square miles. See Figure IV-4.

Geologic Setting: The first mention of Glass Buttes obsidian in the geologic literature was by Russell (1884:440), who briefly described the obsidian he found there. A few other early short appearances in the literature can also be found in Iddings (1888:293) and Waring (1908:22). The most extensive geologic investigation of Glass Buttes was made by Waters (1927a and 1927b), who identified the rhyolitic activity at the Buttes as the second of three stages of volcanic activity in the immediate area (the first and the third were basaltic). Alt and Hyndman (1978:188) describe Glass Buttes as, "...an oversized lava flow which was so thick and viscous that it piled up around the vent to make a mountain instead of spreading across the countryside." The rhyolitic domes that form the Buttes have been extensively faulted since their extrusion.

The obsidian at Glass Buttes occurs on the surface as float - pebbles, nodules and small boulders are found in many locations on and bordering the two major peaks that make up the Buttes. Obsidian has been reported to occur in an almost unprecedented variety of colors including black, red, mahogany, gold, silver, silvery-green, blue, purple, pink, brown and "rainbow". Often, two or more colors occur together in bands or as a mottled combination. The selection of colors and the presence of large quantities of obsidian with an iridescent sheen has made the Buttes a favorite source of obsidian for gem collectors for many years (Forbes, 1934; Randolph, 1935; Dake, 1958; Heflin, 1963 and 1979; Gail, 1966; Broughton, 1974). The petrologic mechanisms responsible for the varicolored obsidian at Glass Buttes have also been examined by Fuller (1927).

Composition: The composition of obsidian from Glass Buttes has been reported by Jack and Carmichael (1969:26), Keller and Huang (1971: 310), Griffin et al. (1969:6), Stevenson et al. (1971:23) and Ericson (1977:20,92; see analyses 41 through 45, Table IV-1, this appendix).

Refractive Index: Cherry (1968), in a study of the usefulness of the index of refraction of obsidian as a method of characterization, sampled the obsidian at Glass Buttes in numerous locations. He reported that the refractive index did not vary from sample to sample, though the indices were not listed in his report.

Age: A K-Ar age of 4.91 ± 0.73 m.y. is reported by MacLeod et al. (1975: 468), McKee et al. (1976:39) and Laursen and Hammond (1978:25). A fission-track age of 4.4 ± 0.3 m.y. also appears in Naeser et al. (1980:19); the small discrepancy between the K-Ar and the fission-track dates is probably due to the fading of tracks in the glass.

Archaeological Significance: Considering Glass Buttes well-known reputation as a prehistoric quarry site and source of artifacts, surprisingly little archaeological activity has taken place here.

Relic collectors have known about the area for years and one of them, P.L. Forbes, writes in 1934 that, "Blades have been found 14 inches long but 8 inches is the general length found. To date, about 20,000 of these broken arrowheads have been found at various spots on Glass Butte" (Forbes, 1934). Other collectors have also written of the richness of the area as a source of artifacts (Dake, 1956; Dake, 1958-59; Randolph, 1935; Heflin, 1963 and 1979). Heflin (1963 and 1979) had two artifacts dated with the then newly-developed obsidian hydration method and mentioned an age of 800 years for the resultant age (based on a hydration rim of about 1.5 microns - the 800 year figure should now be looked on only as a "ballpark" age). Atherton (1966:33-34) also provided a sparse archaeological sketch of the area.

Systematic work at Glass Buttes has consisted only of a partial surface archaeological survey conducted as part of a cultural resource survey of the area (Mack, 1975). Several extensive obsidian quarry sites were located as well as numerous campsites and knapping stations. Time-sensitive projectile points found during this survey suggest that the Glass Buttes area has been occupied by hunters and gatherers for more than 12,000 years (Mack,1975:46-49; Minor et al., 1979:76-77; Toepel et al., 1980:83).

For years, obsidian from Glass Buttes has been said to have been found in burial mounds in the Midwestern United States (Dake, 1956; Dake, 1958-59; a study of obsidian from the Midwest by Griffin et al., 1969, failed to substantiate this rumor), but only recently have obsidian characterization studies begun to show the distribution patterns of obsidian from the Buttes.

An obsidian characterization study reported by Nelson et al. (1975) and Bennett and D'Auria (1974) suggested that an artifact recovered in British Columbia may have originated at Glass Buttes (the methodology of this research, though, was dubious). More reliable work by Hughes (1978) has placed the possible source of one or two artifacts found at a Eureka, California, site (Loud, 1918) at Glass Buttes. Sappington and Toepel (1981) also placed the source of two artifacts found in the Fort Rock Basin at Glass Buttes. Other obsidian characterization studies that have considered Glass Buttes as a possible obsidian source have failed to find a correlation with artifactual obsidian and that source. Despite a common belief to the contrary, the widespread use of obsidian from Glass Buttes has yet to be established.

Obsidian from Glass Buttes was also used by Huntley and Bailey (1978) in research examining the utility of thermoluminescence as a method of characterization.

For more information about obsidian from Glass Buttes, see Part Four of this project.

41. *GLASS MOUNTAIN OBSIDIAN*

Location: Obsidian is exposed in a road cut on Highway 395, 7.4 miles south of the junction between Highways 20 and 395; SE¼SE¼Sec.13, T.24S., R.26E.; Harney County. See Figure IV-4.

Geologic Setting: This source is described by Ericson et al. (1976:234) as a rhyolitic obsidian flow interbedded between thin flow units of platy andesite.

Composition: Major and trace element composition is reported by Ericson (1977:20,92; see analyses 46, 47 and 48, Table IV-1, this appendix).

Archaeological Significance: Not known. It is not clear whether the obsidian is also found on the surface, as well as in the road cut. The Riley Site, a large obsidian quarry site, is located only two miles north of the Glass Mountain source.

42. *GLASS SLIPPER OBSIDIAN*

Location: Sec.14, T.37S., R.18E.; Lake County. See Figure IV-2.

Geologic Setting: Peterson (1961:68) reports that obsidian in the form of "apache tears" is common in a perlite deposit adjacent to the Marty K uranium prospect.

Archaeological Significance: Not known.

43. *GREGORY CREEK OBSIDIAN*

Location: Obsidian from SE¼Sec.29 and SE¼Sec.31, T.18S., R.40E. is reported by Sappington (1981:17).

Archaeological Significance: A sample of 283 obsidian artifacts collected predominantly in the Fort Rock-Silver Lake Valley region were characterized by Sappington and Toepel (1981) and compared with obsidian from sixteen Oregon sources, one of which was Gregory Creek. None of the artifacts appeared to originate from this source.

44. *GUANO LAKE OBSIDIAN* *(Also see Addendum)*

Location: Guano Lake is located in T.39S., R.27E., Lake County. See Figure IV-4.

Geologic Setting: L.S. Cressman (1936:12) describes the geology of the Guano Lake Valley in a report of his archaeological investigations there: "The lavas exposed by the absence of topsoil on the highlands surrounding Guano Valley are flows of basalt...which covered to a considerable depth the underlying Miocene basalt flows.
These flows are of the type generally found on the Columbia Plateau - remarkably uniform horizontal flows of great extent and thickness, the lava of which welled up quietly through fissures in the earth's crust. All volcanic action of the region does not, however, seem to have been of this quiet type, since there are great tuff beds... interbedded between these flows.
On the bottom of many of these flows there is a thin layer of obsidian, formed by the rapid chilling of the molten lava. At places, where the overlying lava has been stripped off, there is a large concentration of this obsidian. This is...the case in a small area southwest of but adjacent to Desert Lake [12 miles north of Guano Lake] , in a spot about ten miles northeast of Beatty's Butte on the road to Blitzen, and in a large area north of Big Spring."

Archaeological Significance: This source is mentioned by Sappington and Toepel (1981) in a characterization study of artifacts recovered in the Fort Rock-Silver Lake area, but no artifactual material was found to originate from the Guano Lake source. Cressman (1936:12) states that the presence of obsidian and water was responsible for the location of Indian camps in the region.

45. *HAGER MOUNTAIN OBSIDIAN*

Location: 43°29.0' N lat.; 121°1.2'W long.: Lake County. See Figure IV-2.

Geologic Setting: Described by McKee et al. (1976:39) as a rhyolite dome.

Age: Obsidian recovered at Hager Mountain yielded a K-Ar age of 5.90 ± 0.09 m.y. (McKee et al.,1976:39 and MacLeod et al.,1975:468).

Archaeological Significance: Not known. Hager Mountain is in the same general vicinity as the Silver Lake Area and Frog Mountain obsidian sources (see those sources, this appendix).

46. *HAMPTON BUTTE OBSIDIAN*

Location: The butte is located six miles north of Highway 20 and eight miles north-northwest of the town of Hampton; Sec.2, T.21S., R.20E.; Deschutes County. See Figure IV-4.

Geologic Setting: Heflin (1979:72) mentions the presence of an obsidian flow at Hampton Butte, while Johnson (1973:55) refers to the site as a source of sheen blue, green and black obsidian.

Archaeological Significance: Not known.

47. *HORSE MOUNTAIN OBSIDIAN*

Location: Horse Mountain, reported as an obsidian source by Ericson (1977:315) and Sappington (1980:256), as well as others, is centered in Sec.18, T.28S., R.22E.; Lake County. The Horse Mountain source is almost certainly the same as those sources reported at Poverty Basin and Alkali Lake Canyon (see this appendix).

Geologic Setting: The obsidian at Horse Mountain, a rhyolite dome, occurs as surface float. Sappington (1981:17) describes the obsidian as macroscopically variable but compositionally unique.

Age: Two nearly identical K-Ar ages are reported for obsidian found at Horse Mountain, 6.91 ± 0.14 m.y. by McKee et al. (1976:40) and 6.92 ± 0.14 m.y. by MacLeod et al. (1975:468). A fission-track age of 4.8 ± 0.5 m.y. years is also reported by Naeser et al. (1980:19). The difference between the fission-track and the K-Ar ages is attributable to fission-track fading in the obsidian.

Archaeological Significance: Six prehistoric obsidian quarry sites were recorded in the N½T.28S., R.22E., by Toepel et al. (1980:134-135). This is the area directly to the east of and including Horse Mountain. The six sites are all typified by anomalous quantities of obsidian flakes. No time-sensitive artifacts were found associated with any of the quarry sites.

283 specimens of artifactual obsidian collected during an archaeological survey of a 251 km-long corridor beginning near Silver Lake were characterizaed by Sappington and Toepel (1981) using trace-element abundances. Four of the artifacts, found mainly in the Fort Rock Valley, appear to have originated at Horse Mountain. One of the characterized pieces was a diagnostic lanceolate projectile point, characteristic of the early period (pre-7,000 years B.P.) in this region. 26 pre-Mazama artifacts from Fort Rock Valley cave sites were also characterized in the same study. Of these, one, a biface from Connley Cave No.4, was found to originate at the Horse Mountain source.

48. INMAN CREEK OBSIDIAN *(Also see Addendum)*

Location: Inman Creek is a short tributary of the Fern Ridge Reservoir, entering on the northwest side in NW¼Sec.8, T.17S., R.6W.; Lane County. See Figure IV-2.

Geologic Setting: Abundant nodules of obsidian are found in the stream gravels of Inman Creek, apparently being eroded out of the alluvial deposits that the creek runs through. Inman Creek is located in the western Willamette Valley on a former high flood plain of the Willamette River (Frank, 1973). Obsidian at this site is clearly secondary, though the primary source of the glass has not been established.

The original source of the obsidian at Inman Creek may lie in the Oregon Coast Range to the west. Small pieces of obsidian have been reported in the Siuslaw River at Florence (Rick Minor, personal communication) and a single piece has been recovered in a Long Tom River terrace near Noti in the Coast Range (Rick Pettigrew, personal communication). Inman Creek was a tributary to the Long Tom River prior to being drowned by the reservoir. The Long Tom River is a former tributary to the Siuslaw River (Baldwin and Howell, 1949) and the presence of obsidian in both rivers strongly suggests a source of obsidian in the Coast Range. A geologic study of the Long Tom River drainage (Zimmerman, 1927) failed, though, to mention any obsidian.

It is also possible that sources in the High Cascades to the east may have contributed to the obsidian at Inman Creek.

Archaeological Significance: Two excavated sites, the Lingo Midden and the Benjamin Midden (Cordell, 1975; Miller, 1975) are located next to the Long Tom River not far downstream from its reservoir-covered confluence with Inman Creek. Both sites have yielded obsidian as a common lithic component, suggesting the local availability of the obsidian. This is supported by Miller (1975:321), who writes of the Benjamin Site: "Large obsidian artifacts are extremely rare and the very small size of obsidian flakes throughout the site suggest that the primary source of this material was as riverborne pebbles."

For more information about the Inman Creek Obsidian Source, see Appendix Five of this project.

49. *INTERLAKE OBSIDIAN FLOW*

Location: The north-central portion of Newberry Caldera, Deschutes County. See Figure IV-5.

Geologic Setting: The Interlake Obsidian Flow, one of the more prominent of the Recent Caldera obsidian flows, has been described by several different authors over the years (Russell, 1905:105; Williams, 1935: 274; Higgins and Waters, 1967:33; Higgins, 1968:229-230). The flow issued from a vent at the base of the north caldera wall at a point directly between East and Paulina Lakes. The obsidian moved down the neck of land separating the two lakes where it was divided into two branches by the Central Pumice Cone. One branch flowed to the shore of East Lake, the other to the edge of Paulina Lake. Williams (1925: 274) writes: "Much of the obsidian is of the massive, black type, although gray varieties...are far from rare. Careful search reveals sporadic, small xenoliths of older rhyolites and basalt..."

Petrographic Features: Williams (1935:283) mentions that a few minute, corroded phenocrysts of oligoclase and green augite can be found in thin-sections of obsidian from the Interlake Obsidian Flow.

Composition: Major element composition is found in Higgins (1973:475; see analysis 51, Table IV-1, this appendix). Major and trace element abundances are reported by Higgins (1973:475,483), Beyer (1973:18) and Laidley and McKay (1971:339; see analyses 49, 50 and 53, Table IV-1, this appendix). Trace-element abundances are also reported by Jack and Carmichael (1969:26; see analysis 52, Table IV-1, this appendix).

Age: The Interlake flow is post-Mazama and, having been deflected by the Central Pumice Cone, is clearly younger than that feature. Peterson and Groh (1969:78) first reported an obsidian hydration age of 1,700 years. This was later revised by Friedman and his associates (Friedman, 1977:339; Friedman and Obradovich, 1981:40; Friedman and Trembour, 1978:49) to 6,400 to 6,700 obsidian hydration years.

Archaeological Significance: Not known.

50. *JOHN DAY FORMATION OBSIDIAN*

Location: About six miles northwest of Mitchell, in tuff about 1550 feet above the base of the John Day Formation, SW¼Sec.31, T.10S., R.21E.; Wheeler County. See Figure IV-3.

Geologic Setting: Obsidian was found in a tuff deposit (Laursen and Hammond, 1974:27).

Age: A K-Ar age of 25.5 m.y. is reported for obsidian from this site (Laursen and Hammond, 1974:27).

Archaeological Significance: Not known.

51. *JOHN DAY IGNIMBRITE OBSIDIAN*

Location: About 15 miles north of Mitchell and just north of the John Day River, Sec.27, T.9S., R.21E.; Wheeler County. See Figure IV-3.

Geologic Setting: Angular to subangular fragments of obsidian are reported by Fisher (1966:sample 63-176) to occur from two to five feet above the base of a measured section of welded ash-flow. Fragments range up to 5 cm in diameter and are composed of fresh brown glass. The origin of the glass is not clear; it is not found in the densely-welded zone of the ash-flow, but in the unwelded zone at the base of the unit and may have been transported from another source.

Age: Miocene (Fisher, 1966).

Archaeological Significance: Not known.

52. *JUNIPER RIDGE OBSIDIAN*

Location: Sec.36, T.23S., R.25E. and Sec.1, T.24S., R.25E.; Harney County. A map of this location appears in Harrison (1942:Plate I). See Figure IV-4.

Geologic Setting: Harrison (1942), after investigating a rumor of tin associated with obsidian (not true, it turned out), wrote: "Within the area studied, the most widely distributed rock type is the platy felsite which...forms all the 'rim rock' with the exception of the basalt in the northeast corner of the area. Lenses of perlitic obsidian occur below the massive felsite cliffs at several places...The length of the perlite lenses in this area is from a few tens of feet to nearly a thousand feet. Their thickness is from a few inches to several tens of feet. Red pumiceous obsidian was observed in four localities on the level bench-surface of the main block, where it appears in narrow vertical...dikes or lenses. The gray pumiceous obsidian occurs as float covering most of the flat-topped portions of the main block." The general geology is also summarized by Allen (1942).

Petrographic Features: Harrison (1942:20-22) generally describes the different varieties of obsidian as containing 5-8 percent phenocrysts, microlites and abundant magnetite (his description is considerably more detailed).

Archaeological Significance: Not known.

53. *LITTLE BEAR CREEK OBSIDIAN*

Location: Sec.21, T.16S., R.33E.; Grant County (Ericson, 1977:316). See Figure IV-3.

Archaeological Significance: Not known.

54. *LITTLE GARDEN OBSIDIAN* *(Also see Addendum)*

Location: In the center of the northern end of the Devils Garden Lava Field, Lake County; SW¼Sec.2, SE¼Sec.3 and NW¼Sec.11, T.23S., R.15E. See Figure IV-2.

Geologic Setting: The Little Garden is a complex of two rhyodacite domes of uncertain age that rise as kipukas, or islands, above the surrounding basalts of the early Holocene Devils Garden lava field (Peterson and Groh, 1965:23). Black obsidian can be found on the surface as weathered nodules and pebbles (occasionally up to 10 cm in diameter) on the lower southeastern slopes of the northernmost dome and on the northwestern slopes of the central dome. Obsidian at this previously unreported site was found on a 1982 visit by the author. Several other rhyodacite domes (not visited) are also found in the area and may prove also to be sources of obsidian.

Age: Upper Miocene to Pliocene (Peterson and Groh, 1965:23).

Archaeological Significance: A portion of the Little Garden was reported as an archaeological site (35LK1023) by Dudley et al. (1979:511-514), who described the site as a lithic scatter of obsidian flakes and nodules distributed over a large area. No diagnostic artifacts were found. The site was apparently not recognized as a geologic source of obsidian at that time. Other nearby sites bordering the Devils Garden lava field have also been reported by Toepel and Beckham (1981) and Dudley et al. (1979:564-572). Numerous scatters of obsidian flakes were also noted by the author on the Recent basalts east and southeast of the Little Garden.

55. *LITTLE OBSIDIAN FLOW*

Location: Two and one-half miles south-southeast of the south rim of Newberry Caldera, near Topso Butte and probably in Sec.16, T.22S., R.13E.; Deschutes County. See Figure IV-2.

Geologic Setting: Higgins (1968:273-274) reports the presence of this small obsidian flow on the flanks of Newberry Volcano. The areal extent of the flow is about one-eighth square mile and the top is deeply cut by northwest-trending fissures.

Age: Holocene. The flow is not covered with tephra from the Newberry Ashfall No.2 (Higgins, 1968:274). This places the upper age limit of the flow at 1720 ± 250 radiocarbon years, the date associated with the ashfall.

Archaeological Significance: Not known.

56. *LITTLEFIELD MEMBER (WILDCAT RIDGE) OBSIDIAN*

Location: A ridge immediately north of Wildcat Reservoir, Malheur County; NW¼NE¼Sec.28, T.24S., R.40E. See Figure IV-4.

Geologic Setting: Obsidian inclusions in a laharic breccia are reported by Green (1962:68) as present in the lower 20 feet of a 100-foot measured section of the Littlefield Member of the Crowley Formation.

The Littlefield Member is overlain unconformably by the Crowley Area Ash-Flow Tuff B (also described in this appendix). The laharic breccia unit is composed predominantly of pumice fragments partially altered to clay.

Archaeological Significance: Not known.

57. *LLAO ROCK OBSIDIAN AND DACITE FLOW* *(Also see Addendum)*

Location: At the northern caldera rim in Crater Lake National Park, Klamath County. See Figure IV-2.

Geologic Setting: Llao Rock is a large dacite flow composed mainly of locally spherulitic obsidian and more vesicular and lithoidal dacite. Diller and Patton (1902:36-37) first mentioned the obsidian at this site and wrote: "The edge of the flow, in fact, the entire periphery, is practically obsidian; the interior portion is more crystalline." The obsidian is commonly streaked with very pumiceous layers and is locally transversed by red and chocolate-colored streaks (Williams, 1942:137). A detailed description of Llao Rock appears in Howel Williams 1942 study of Crater Lake National Park. A Master's thesis by Ryden (1968) details the structure of Llao Rock, though no mention is made of the obsidian there.

Petrographic Features: Williams (1942:137) writes: "In thin-section, the black obsidians show beautiful fluidal banding owing to the alignment of minute augite rods, acicular microliths of feldspar, and curved black trichites." A photomicrograph of obsidian from Llao Rock appears in Kittleman (1979:26).

Composition: Trace element composition appears in Jack and Carmichael (1969:26; see analysis 54, Table IV-1, this appendix).

Age: About 7,000 radiocarbon years (Cranson, 1982:73).

Archaeological Significance: Not known.

58. *LONG TOM RIVER OBSIDIAN*

Location: The Long Tom River, an eastward-flowing river that originates in the Coast Range, flows into the Willamette Valley near the Fern Ridge Reservoir and eventually joins the Willamette River near Albany. See Figure IV-1.

Geologic Setting: Obsidian has reportedly been found in the river gravels of the Long Tom River (Rick Minor, personal communication), though the context is not known. A single piece of obsidian has also been recovered from the gravels of a Long Tom River terrace near Noti (Rick Pettigrew, personal communication) in the Oregon Coast Range. Small pieces of obsidian have also been found near the mouth of the Siuslaw River at Florence (Rick Minor, personal communication) and Baldwin and Howell (1949) have determined that the Long Tom River was once a tributary to the Siuslaw River. These pieces of evidence suggest the presence of a primary source of obsidian somewhere in the Oregon Coast Range, though its location is not known. See the Inman Creek Obsidian, this appendix, for more details.

Archaeological Significance: Not known.

59. *LOWELL (UPPER WINBERRY CREEK) OBSIDIAN-LIKE VITROPHYRE*

Location: About one mile east of the entrance to the Winberry Creek Campground on USFS Road 1802, Lane County. The ash-flow is exposed on the north side of the road in a road cut; Sec.20, T.19S., R.2E. See Figure IV-2.

Geologic Setting: A dense, black glassy layer about 3 m thick is found at the base of the welded ash-flow exposed in the location next to Winberry Creek. The glassy layer directly overlies thinly-bedded sediments. At the west end of the exposure, a large carbonized log lies directly under the densely-welded zone. The direct contact of sediments with the densely-welded zone, the position of this zone at the bottom of the ash-flow, the carbonized log and the unusual thickness of the glassy zone all suggest a rather unusual genesis. The ash-flow probably passed over a pond or swampy area here; the steam from the water lowered the melting point of the rhyolitic ash sufficiently to allow it to remelt into an obsidian-like glass (Alexander McBirney, personal communication). This process is described in more detail by McBirney (1968b). It also seems likely that this black glassy outcrop is a localized phenomenon. Ashwill (1951:25-27) has described a welded ash unit a few miles to the west of the Winberry outcrop that may be a continuation of this same welded ash-flow.

Age: Possibly late Oligocene or late Miocene (Ashwill, 1951:31).

Archaeological Significance: Not known. Several shallow sites were reported by Cole (1968) during an archaeological survey and excavations of the nearby Fall Creek Reservoir area. All artifactual material recovered from these sites is in storage at the Natural History Museum at the University of Oregon and was examined by the author. A single uniface graver from 35LA33 was made of what *appeared* to be an obsidian-like vitrophyre, and was the only artifact that could possibly have originated from the welded ash-flow on Winberry Creek. It is also not known whether the obsidian-like glass was exposed on the surface prior to the construction of the road.

For a more detailed description of the ash-flow at Upper Winberry Creek, see Part Four of this project.

60. *MASCALL FORMATION IGNIMBRITE MEMBER OBSIDIAN*

Location: The Mascall Formation is exposed in several locations west and northeast of Suplee, Crook County. Most of the exposures are restricted to a small basin south of Shaw Table and north of Wade Butte. A measured section of the Mascall Formation at the confluence of Deer Creek and the South Fork of the John Day River (SW¼NW¼Sec.17, T.16S., R.27E.) is reported by Davenport (1971:124) to contain dark gray and black obsidian chunks. See Figure IV-3.

Geologic Setting: The Mascall Formation is a 800-1000 foot thick unit composed chiefly of volcanic ash and tuff with minor gravel, sand and silt lenses. Near the base of the formation is a welded ash unit called by Davenport the Mascall Formation Ignimbrite Member. Davenport (1970:17) writes: "In certain exposures this unit bears a striking resemblance to the Rattlesnake Ignimbrite...However, on close observation small obsidian spheres or chunks are generally visible in amounts up to five percent. These are characteristic of this unit and never occur in other ash flows." The obsidian fragments are up to one cm in diameter.

Age: Davenport (1970:13), relying on stratigraphic position and associated Barstovian fauna, assigns a late Miocene age to the ignimbrite member. A K-Ar age of 15.8 m.y. is also reported for this formation in Laursen and Hammond (1974:27).

Archaeological Significance: Not known.

61. *McCOMB BUTTE OBSIDIAN*

Location: 42°34.6'N lat., 120°37.1'W long.; Lake County. See Figure IV-4.

Geologic Setting: McComb Butte is described by McKee et al. (1976:41) as a rhyolite dome.

Age: Similar K-Ar ages of 7.70 ± 0.09 m.y. and 7.71 ± 0.09 m.y. are reported, respectively, by McKee et al. (1976:41) and MacLeod et al. (1975:468) for obsidian from McComb Butte. A fission-track age of 2.2 ± .06 m.y. is also reported by Naeser et al. (1980:18). The large discrepancy between the two dates is presumably due to the fading of fission-tracks in the obsidian.

Archaeological Significance: Not known.

62. *McDERMITT AREA OBSIDIAN* *(Also see Addendum)*

Location: NE¼Sec.36, T.40S., R.41E.; Malheur County. This source is reported by Sappington (1981:17), but no additional details are available. Another obsidian source, the Valley of the Giants quarry site (see this appendix), has also been reported in the same area, and these two sources may be same. See Figure IV-4.

Archaeological Significance: Not known.

63. *McKAY BUTTE OBSIDIAN*

Location: McKay Butte is located on the western flanks of Newberry Volcano, about five miles west of Paulina Lake, Deschutes County. The butte is centered in NE¼NE¼Sec.26, T.21S., R.11E., while two other associated domes are found in nearby Secs.24 and 19.

Geologic Setting: McKay Butte is the westernmost of an alignment of three conical rhyolite domes about 500 feet in height. All three domes are composed of platy rhyolites with the central dome providing the best exposure of the internal structure (Williams, 1935:278; Higgins, 1968: 270). Heflin (1979:72) and Peterson et al. (1976:27) both mention the presence of black streaky obsidian at the buttes while Williams (1935: 260), in a geologic sketch map, shows the McKay Butte group as obsidian domes.

Composition: The major and trace element abundances of two rhyolitic samples from McKay Butte (not specified as obsidian) are reported by Beyer (1973:18; samples MC-2A and MC-2B).

Age: A K-Ar age of 0.58 m.y. ± 0.10 m.y. is reported by McKee et al. (1976:38) for obsidian recovered from McKay Butte.

Archaeological Significance: Not known.

MIDDLE OBSIDIAN FLOW - *See EAST LAKE OBSIDIAN FLOWS (The name Middle Obsidian Flow has been used to refer to the westernmost East Lake Flow).*

64. *MOUNT TABER OBSIDIAN*

Location: Portland, Multnomah County. This reference by Atherton (1966:34) is probably a misspelling of Mount Tabor.

Geologic Setting: Atherton (1966:34) mentions that an obsidian quarry site is found at Mount Taber (Tabor?) in Portland. A review of the literature related to Portland and Mount Tabor geology (Treasher, 1942; Trimble, 1963; Allen, 1975; Beeson and Nelson, 1978) failed to reveal the mention of anything but basaltic activity at Mount Tabor. It may be that Atherton was in error about this site.

Archaeological Significance: Not known.

65. *NEWBERRY CALDERA AREA MISCELLANEOUS RHYOLITE AND OBSIDIAN DOMES*

Location: Newberry Caldera and the extreme upper flanks of Newberry Volcano, Deschutes County. See Figure IV-5.

Geologic Setting: This heading refers to several undescribed rhyolite and obsidian domes and protrusions that are found inside Newberry Caldera and on the upper flanks immediately outside the caldera. These domes are shown on maps by MacLeod et al. (1981:89; 1982) and MacLeod and Sammel (1982:126).

Archaeological Significance: Not known.

66. *NEWBERRY CALDERA BURIED OBSIDIAN FLOW SOUTH OF EAST LAKE*

Location: Directly south of East Lake, Newberry Caldera. See Figure IV-5.

Geologic Setting: This flow is mentioned by MacLeod et al. (1981:89) and MacLeod and Sammel (1982:126), but is best described by MacLeod et al. (1982:13): "[A] dome exposed near inner caldera wall south of East Lake and an associated obsidian flow that extends northward to East Lake. Flow is buried beneath Mazama ash and 4 to 5 m of pumiceous tephra deposits, but was identified in deep holes dug through them; large blocks of obsidian along the south shoreline of East Lake are derived from it."

Age: Pre-Mazama.

Archaeological Significance: Not known.

67. *NEWBERRY VOLCANO NORTHEAST FLANK ASH-FLOW OBSIDIAN*

Location: An ash-flow containing obsidian is exposed in a ravine about ten miles north of China Hat in the vicinity of the junction of roads 1821 and 2113 (1835), Deschutes County; T.21S., R.14E. Detailed directions to this site appear in MacLeod et al. (1981:102; Stop 13). See Figure IV-2.

Geologic Setting: This dark-colored ash-flow tuff is exposed in ravine walls for several miles. The ash-flow is characterized by porphyritic obsidian as a common accidental lithic component in an ashy crystal and lithic-rich matrix. Further downslope, the ash-flow is buried by later basalt flows, while upslope it is covered by alluvial deposits and basalt flows (MacLeod et al., 1981:102). The source of the ash-flow has not been identified.

Age: Quaternary, probably late Pleistocene.

Archaeological Significance: Not known.

NEWBERRY VOLCANO CALDERA OBSIDIAN SOURCES - *See:*

BIG OBSIDIAN FLOW
CENTRAL PUMICE CONE SUMMIT CRATER OBSIDIAN FLOW
CENTRAL PUMICE CONE WALL AND FLANKS OBSIDIAN
EAST LAKE OBSIDIAN FLOWS
GAME HUT OBSIDIAN FLOW
INTERLAKE OBSIDIAN FLOW
NEWBERRY CALDERA AREA MISCELLANEOUS RHYOLITE AND OBSIDIAN DOMES
NEWBERRY CALDERA BURIED OBSIDIAN FLOW SOUTH OF EAST LAKE
NORTHEAST CALDERA OBSIDIAN FLOW
PAULINA LAKE RHYOLITE AND OBSIDIAN DOMES
PAULINA PEAK OBSIDIAN

Non-specific references to obsidian from Newberry Caldera also appear in Bennett and D'Auria (1974), Nelson et al. (1975), Sappington (1980), Sappington and Toepel (1981), Sappington (1982) and Toepel et al., (1983).

NEWBERRY VOLCANO FLANKS OBSIDIAN SOURCES - *See*

CHINA HAT OBSIDIAN
EAST BUTTE OBSIDIAN
LITTLE OBSIDIAN FLOW
McKAY BUTTE OBSIDIAN
NEWBERRY CALDERA AREA MISCELLANEOUS RHYOLITE AND OBSIDIAN DOMES
NEWBERRY VOLCANO NORTHEAST FLANK ASH-FLOW OBSIDIAN
NEWBERRY VOLCANO SOUTHWEST FLANK OBSIDIAN DOME
NEWBERRY VOLCANO SOUTH FLANK OBSIDIAN FLOW DIRECTLY SOUTHWEST OF THE BIG OBSIDIAN FLOW
NEWBERRY VOLCANO SOUTH FLANK OBSIDIAN FLOW SOUTHEAST OF THE BIG OBSIDIAN FLOW

68. *NEWBERRY VOLCANO SOUTHWEST FLANK OBSIDIAN DOME*

Location: About five miles west-southwest of the Newberry Caldera rim at Paulina Peak, Newberry Volcano, Deschutes County. See Figure IV-2.

Geologic Setting: An obsidian flow on the southwest flanks of Newberry Volcano is reported by MacLeod et al. (1981:87) and by Peterson et al. (1976:29). This small rhyolitic obsidian dome or flow is located directly on an extension of an axis from Paulina Peak and was possibly erupted from the same now-buried fissure as was the Paulina Peak rhyolite dome.

Age: A K-Ar date of 0.4 m.y. is reported by MacLeod et al. (1981:98).

Archaeological Significance: Not known.

69. *NEWBERRY VOLCANO SOUTH FLANK OBSIDIAN FLOW SOUTHEAST OF BIG OBSIDIAN FLOW*

Location: On the upper flanks of Newberry Volcano, about one mile southeast of the south end of the Big Obsidian Flow, Newberry Caldera, Deschutes County. See Figure IV-5.

Geologic Setting: An obsidian flow is shown on geologic maps of Newberry Caldera that appear in MacLeod et al. (1981:89; 1982) and MacLeod and Sammel (1982:126). The flow is covered by tephra from Mount Mazama.

Age: Pleistocene.

Archaeological Significance: Not known.

70. *NEWBERRY VOLCANO SOUTH FLANK OBSIDIAN FLOW DIRECTLY SOUTHWEST OF THE BIG OBSIDIAN FLOW*

Location: Directly south-southwest of the Big Obsidian Flow and outside of the caldera, but very near the rim, Newberry Caldera, Deschutes County. See Figure IV-5.

Geologic Setting: An obsidian dome or flow is shown on geologic maps of Newberry Caldera in MacLeod et al. (1981:89; 1982) and MacLeod and Sammel (1982:126). The obsidian is covered by Mazama tephra.

Composition: The SiO_2 content is 72.4 percent. This flow is indistinguishable in major and trace-element composition from the Northeast Newberry Caldera Obsidian Flow, suggesting that they are coeval and comagmatic (MacLeod et al., 1982:17).

Age: Pleistocene.

Archaeological Significance: Not known.

NORTH OBSIDIAN FLOW - *See INTERLAKE OBSIDIAN FLOW*

71. *NORTHEAST NEWBERRY CALDERA OBSIDIAN FLOW*

Location: The northeast corner of Newberry Caldera, Deschutes County. See Figure IV-5.

Geologic Setting: This obsidian flow is mentioned by MacLeod et al. (1981:89; 1982:17), but is best described by Williams (1935:274): "The earliest of the rhyolitic flows to be poured out after the enlargement of the caldera issued from a fissure close to the north rim, whence it ran down a deep, V-shaped canyon for about a mile, ending in a bold line of cliffs on the shore of East Lake. Lithologically, there is a wide variation in the flow, but in general its lower parts consist of platy, gray rhyolite; the upper parts are streaked in gray and black, are glassier, and are crowded with large pink spherulites. The thickness of the flow in these cliffs is approximately 250 feet."

Composition: The trace element composition of obsidian collected on the north shore of East Lake, possibly from this flow, is reported by Jack and Carmichael (1969:31; see analysis 55, Table IV-1, this appendix).

Age: Pre-Mazama.

Archaeological Significance: Not known.

NORTHEAST OREGON OBSIDIAN

A non-specific reference to obsidian from northeast Oregon is found in Stevenson et al. (1971; see Table IV-1, analysis 56, this appendix, for the composition of the obsidian).

72. OBSIDIAN CLIFFS OBSIDIAN FLOW *(Also see Addendum)*

Location: About three miles west-northwest of the North Sister, Three Sisters Wilderness Area, Lane County. The upper end of the Obsidian Cliffs Flow is crossed by the Oregon Skyline Trail. See Figure IV-2.

Geologic Setting: The 70-90 m high Obsidian Cliffs mark the northwest end of a 2.4 km-long obsidian flow that originated at the western base of the north Sister. Williams (1944:48) describes the flow: "A large mass of glassy [rhyolite] also escaped from fractures at an elevation of about 7,000 feet, forming a tabular sheet bordered by walls up to 300 feet in height, referred to as the Obsidian Cliffs. Much of this [rhyolite] , particularly the surficial and distal portions, consists of black obsidian, though the bulk is composed of pale gray, pumicieous lava. Here and there, the two varieties are finely interlaminated; elsewhere, they alternate with spherulitic and lithophysal bands." The top of the Obsidian Cliffs Flow is a glaciated plateau covered in many places with nodules of obsidian. The glacier that swept over the plateau extended west down the Lost Creek Valley to the McKenzie River. Obsidian nodules can now be found on the floor of the Lost Creek Valley and in exposures of glacial till near the intersection of Highways 126 and 242 (Taylor, 1968:14).

Glacially transported obsidian found its way into the McKenzie River and was carried further west into the Willamette Valley, creating a secondary obsidian source in the gravels of the McKenzie and Willamette Rivers. Obsidian pebbles from the Hurd Site (35LA44) on the eastern edge of the upper Willamette Valley were characterized and found to originate at the Obsidian Cliffs source (White, 1975:171). Sanford (1975:229) also mentions that obsidian in the upper Willamette River Valley is available in the gravels of the Willamette River.

The Obsidian Cliffs Flow was first mentioned by Dutton (1889:162) and was later briefly described by Williams (1916:85-90) and Campbell (1923: 21-22).

Composition: The major and trace element composition of the obsidian from Obsidian Cliffs appears in Anttonen (1972:92; see analyses 57, 58 and 59, Table IV-1, this appendix).

Age: Pleistocene.

Archaeological Significance: Little is known of the archaeological aspects of the Obsidian Cliffs source. Minor and Pecor (1977:138)mention its existence as an archaeological site, but say nothing else. Hopson (1946: 327) writes: "Indians knew of this deposit and visited it, as is evidenced by the numerous obsidian arrow points and spearheads that have been picked up close by the meadows [on the plateau on top of the flow] ."

Bennett and D'Auria (1974:364) and Nelson et al. (1975:95) both report on research in which an obsidian artifact recovered in British Columbia was characterized and found to come from a source at the Three Sisters, probably the Obsidian Cliffs Flow. This study, though, was methodologically suspect, and the conclusion should be treated cautiously.

For more information about the Obsidian Cliffs Obsidian Flow, see Part Four and Appendix Seven of this project.

73. *PALAMINO BUTTES OBSIDIAN*

Location: Twelve miles southwest of Burns, Harney County; 43°28.8'N lat., 119°18.0'W long. See Figure IV-4.

Geologic Setting: Palamino Buttes are a complex of rhyodacite domes. Niem (1974:46) refers to Palamino Buttes as a possible source location for obsidian found in conglomerates at Wright's Point (see Wright's Point Obsidian, this appendix).

Age: No obsidian from Palamino Buttes has been dated, but plagioclase and biotite collected at this location yielded K-Ar ages, respectively, of 6.5 ± 0.3 m.y. and 6.1 ± .02 m.y. (Laursen and Hammond, 1978:23).

Archaeological Significance: Not known.

74. *PAULINA LAKE RHYOLITE AND OBSIDIAN DOMES*

Location: These two domes are found on the southwest shore of Paulina Lake, Newberry Caldera, Deschutes County. See Figure IV-5.

Geologic Setting: The two rhyolite domes are aligned along a northwest-southeast line and are considered by Higgins (1968:180) to likely lie along, "...arcuate fissures connected with the formation of the lake basin." Williams (1935:271) best describes the obsidian at the domes: "...the smaller, western dome is made up of banded obsidian rich in spherulites and lithophysae, the flow planes standing vertically and striking between north and northeast. In the larger dome, less spherulitic types of obsidian predominate. Here, also, the banding is usually steep and shows a tendency to be disposed concentrically with respect to the margin of the mass."

Composition: The major element composition of one of the domes is reported by Higgins (1973:472; see Table IV-1, analysis 60, this appendix).

Age: K-Ar ages of .56 ± .4 m.y. and .58 ± .4 m.y. are reported by MacLeod et al. (1982:17).

Archaeological Significance: Not known. A poorly-documented archaeological site was known to exist nearby on the shore of Paulina Lake (Beckham, 1976; USFS, 1978:531), but the obsidian found there could have come from many different sources within the caldera.

75. *PAULINA PEAK OBSIDIAN*

Location: Paulina Peak, found on the southwest side of Newberry Caldera, is the highest peak on Newberry Volcano. See Figure IV-5.

Geologic Setting: Paulina Peak is made up of a pile of rhyolites with three main rock types - gray, platy rhyolites (85 to 90 percent), red, massive rhyolites (less than 2 percent) and black obsidians (5 to 7 percent). The obsidian is found interbedded in layers generally 4 to 12 feet in thickness (Higgins, 1968:77; 1973:469). Obsidian examined by the author in the summit area of Paulina Peak was all quite porphyritic.

Petrographic Features: Higgins (1968:78) writes: "In thin-section, the rock is seen to consist of clear, nearly colorless glass sprinkled with very tiny (less than 0.001 mm long) aligned microlites. Flow banding... varies from well-developed to non-existent. Most sections contain a few microlites of feldspar...up to 0.1 mm long. They are generally lath-shaped with forked ends, and contain inclusions of clear colorless glass. Irregular patches of silica minerals (about 0.15 mm long) are seen in some sections. Occasionally, a tiny grain of clinopyroxene is seen."

Refractive Index: Averages 1.494 (Higgins, 1973:465).

Age: K-Ar ages of .24 ± .07 m.y. and .58 ± .4 m.y. are reported by MacLeod et al. (1982:17).

Composition: Trace element composition is reported by Jack and Carmichael (1969:26; see analysis 61, Table IV-1, this appendix).

Archaeological Significance: Not known.

76. *PETROGLYPHS OBSIDIAN*

Location: NW¼Sec.24, T.28S., R.37E.; Malheur County. This source is reported by Sappington (1981:17), but no additional details are available. See Figure IV-4.

Archaeological Significance: Not known.

77. *POVERTY BASIN OBSIDIAN*

Location: Lake County; T.28S., R.21E. and 22E. Poverty Basin is located not far south of Horse Mountain and is probably the same obsidian source as those reported as the Horse Mountain and Alkali Lake Canyon obsidian sources.

Archaeological Significance: One obsidian artifact from Dirty Shame Rockshelter was geochemically characterized and correlated with the Poverty Basin source (Sappington, 1980:250). The archaeological features and lithic materials at Dirty Shame Rockshelter are discussed in more detail by Aikens et al. (1977), Kittleman (1977) and Hanes (1977 and 1980).

Out of a large sample (n=283) of characterized obsidian artifacts found mainly in the Fort Rock and Silver Lake Valleys, four artifacts were found to have originated at the Poverty Basin obsidian source (Sappington and Toepel, 1981:245). In addition, one biface fragment recovered from pre-Mazama levels in Connley Cave No.4 was also found to come from the Poverty Basin source.

78. *QUARTZ MOUNTAIN OBSIDIAN*

Location: Sec.26, T.22S., R.15E.; Deschutes County. See Figure IV-2.

Geologic Setting: McKee et al. (1976:38) describes Quartz Mountain as a rhyolite dome. Walker (1974:116) refers to the obsidian found at Quartz Mountain as being from chilled selvages of massive rhyolite flows. Heflin (1979:72) and Ericson (1977:316), while offering no details, also mention the presence of obsidian at this site.

Age: Walker (1974:115) and McKee et al. (1976:38) report a K-Ar age of 1.10 ± 0.05 m.y. for obsidian collected at Quartz Mountain.

Archaeological Significance: Atherton (1966:34) mentions an obsidian quarry located at Quartz Mountain (there are several Quartz Mountains in Oregon, but this is probably the one mentioned above), but gives no details.

79. RADAR HILL-SKULL CREEK AREA OBSIDIAN

Location: Obsidian is reported by Heflin (1979:72), Ericson (1977:316) and Gail (1966) to be found not far northwest of Burns, Harney County.

Gail (1966) reports finding obsidian, particularly plentiful at Radar Hill, for an area as far as twenty miles north and west of Burns. He also gives fairly detailed directions for locating the different-colored varieties of obsidian found in the area (Gail, 1966:112).

Geologic Setting: Gail (1966) notes that he found many different colors of obsidian in the hills around Burns, including black, pale green, smoky gray, turquoise, silver sheen, orange, blue and red.

Archaeological Significance: Not known.

80. REILY OBSIDIAN

Location: Sec.18, T.24S., R.27E.; Harney County. See Figure IV-4.

Archaeological Significance: Not known. This location is mentioned by Ericson (1977:316) and is only a few miles east of the Riley Site, a significant prehistoric obsidian quarry site. The name of the Reily source also suspiciously looks like a misspelling of Riley, and these two sources may be the same.

RHYOLITE DOMES IN OREGON

Many of the obsidian sources found in Oregon are associated with exogenous rhyolitic volcanic domes. These volcanic structures, formed by the extrusion of viscous, silicic magmas, are found in a number of locations in the High Cascades and are particularly plentiful in the south-central and southeastern part of the state. The rhyolite domes in eastern Oregon form many of the higher ridges and hills and are found primarily in two broad belts trending about N.75°-80°W. (MacLeod et al., 1975). Many of these domes have been radiometrically dated (Walker, 1974; MacLeod et al., 1975; McKee et al., 1976; Laursen and Hammond, 1978) and were found to show a well-defined progression in age from less than one m.y. in the west to about ten m.y. in the east.

While the presence of obsidian has been reported at many of these domes, it is probable that obsidian sources are found at many of the others. It is likely that many as yet unreported sources of obsidian could be located using the reports of the domes cited above (particularly MacLeod et al., 1975) and available geologic maps of Oregon (Peck, 1981; Walker, 1977, and many others).

81. *RILEY SITE OBSIDIAN* *(Also see Addendum)*

Location: Four and one-half miles southwest of Riley, Oregon, and adjacent to Highway 395, Harney County; Sec.19, T.24S., R.27E. See Figure IV-4.

Geologic Setting: The geology of the Riley area has not been examined in any detail. A look at a geologic map suggests that the obsidian at the Riley Site is probably associated with a faulted, late Tertiary rhyolite dome (Walker, 1977). There are numerous exogenous rhyolite domes in the region and many are known to be sources of obsidian.

The major source area at the Riley Site is a raised arm of land that extends several hundred meters southeast of Highway 395. The source locality is bounded on the northeast by a 10 m high fault scarp, on the northwest by the highway and on the south by a prominent stream ravine. Black obsidian nodules are abundant on the surface throughout the area, particularly toward the southern end of the source area.

Archaeological Significance: The only archaeological examination of the Riley Site was as part of a Master's thesis by John Atherton (1966: 37-72). Atherton sampled the quarry site at the Riley source and noted the presence of numerous cores, blanks and worked flakes.

Sappington and Toepel (1981) report that of 283 characterized obsidian artifacts collected along a transect running from the Silver Lake area north to Maupin, seven obsidian pieces appeared to originate at the Riley Site obsidian source.

For more information about the Riley Site source, see Part Four of this project.

82. *ROCK MESA OBSIDIAN FLOW* *(Also see Addendum)*

Location: The Rock Mesa obsidian flow is located just east of the South Sister Chain of Obsidian Domes in SE¼T.17S., R.8E., High Cascades. The flow lies on the boundary of Lane and Deschutes Counties at the southwest base of the South Sister. See Figures IV-2 and IV-6.

Geologic Setting: The extrusion of this obsidian flow, with an area of about 5 km^2 the largest of several domes and flows in the immediate vicinity , was preceded by eruptions of rhyodacitic ash and lapilli which blanketed the surrounding area. Williams (1944:58) describes the flow that erupted after the tephra eruptions: "On all sides, it ends in high banks of talus. Seen from the air, the arcuate block ridges and spires on the surface show in a most graphic manner how the viscous lava spread from the vent in successive waves. Part of the flow was suddenly chilled to black glass: the rest, cooling more slowly and perhaps being richer in gas, frothed to a pale gray pumice. As activity drew to a close, the lava became increasingly viscous and ultimately, unable to spread laterally, it accumulated over the vent as a domical mound."

The flow is also briefly described in Peterson et al. (1976:27,29), by Hodge (1925:55) and in Peterson and Groh (1965:5).

Composition: The major and trace element composition of the Rock Mesa flow appears in Anttonen (1972:92; see analysis 62, Table IV-1, this appendix).

Age: Charcoal found associated with the Rock Mesa Obsidian has been radiocarbon dated at 2,300 ± 150 years B.P. (Taylor, 1978:1).

Archaeological Significance: Not known.

83. ROCK MESA VICINITY SMALL OBSIDIAN DOME *(Also see Addendum)*

Location: About one-half mile east-northeast of the Rock Mesa Obsidian Flow, Deschutes County, High Cascades; SE¼T.17S., R.8E. See Figure IV-6.

Geologic Setting: Williams (1944:58) briefly describes this small obsidian dome: "The amount extruded was small and the lava was so viscous that it congealed immediately over the source, forming a plug, approximately 150 by 200 yards across. Slender pinnacles and jagged towers of glass rise from its shattered tops and aprons of blocky talus encircle it. A deep gash splits the dome longitudinally, and beyond the gash is continued by a gully that connects with the remnant of an older dome of dacite."

Age: Holocene (Peterson and Groh, 1965:5).

Archaeological Significance: Not known.

84. ROUND BUTTE OBSIDIAN

Location: Sappington (1980:259) lists Round Butte as a Lake County source of obsidian and locates the butte not far southeast of Glass Buttes, probably in Sec.15, T.24S., R.23E. See Figure IV-4.

Archaeological Significance: Not known.

85. SENECA AREA OBSIDIAN

Location: Several obsidian and welded ash-flow units are reported in the general area of Seneca. See Figures IV-3 and IV-4. Obsidian from the Seneca area is also reported by Bransford and Mead (1975), Sappington (1980:25) and Sappington and Toepel (1981), but no specific locations are mentioned.

Archaeological Significance: Bransford and Mead (1975) report that during a 1974 archaeological reconnaissance of federal lands in the Malheur National Forest near Seneca, several large deposits of obsidian were located. Artifacts were found in association with the quarry sites, though no further details were given.

Sappington and Toepel (1981) also report that three out of 283 characterized obsidian artifacts were tentatively correlated with a source in the Seneca area. The artifacts were collected during a surface survey for sites predominantly in the Fort Rock and Silver Lake Valleys.

86. *SIUSLAW RIVER OBSIDIAN*

Location: Near the mouth of the Siuslaw River, coastal Lane County. See Figure IV-2.

Geologic Setting: Small (less than 2 cm diameter) pebbles of obsidian have been reported in the river gravels of the Siuslaw River near the mouth at Florence (Rick Minor, personal communication). The primary source of the obsidian is not known, though obsidian has also been reported in the gravels of the Long Tom River, a former tributary of the Siuslaw River that now drains into the Willamette Valley (Baldwin and Howell, 1949). This suggests the possibility of a common source in the Oregon Coast Range.

Archaeological Significance: Not known. If usable obsidian is available at this source (and upstream), it would be the only known geologic source of obsidian along the Oregon Coast and could be archaeologically significant.

87. *SILVER LAKE AREA OBSIDIAN*

Location: About ten miles southwest of the town of Silver Lake. See Figure IV-2.

Geologic Setting: This obsidian quarry site was reported by Atherton (1966:30) to extend over at least a four to five square mile area at an altitude of 5000 to 6000 feet. The obsidian is found as nodules up to a foot or greater in size. Two types of obsidian were distinguished, a glossy black one and a duller, gray to black-colored variety with a rough, tar-like finish.

Archaeological Significance: Atherton (1966:31-34) observed that traces of worked obsidian were found throughout the quarry area, but that flakes and worked artifacts were concentrated around zones of obsidian nodules on the surface. He recovered several roughly-worked pieces and a few large finished artifacts of unknown utility.

Wright et al. (1969:27) mention that a Silver Lake obsidian source was one of sixteen considered in the geochemical characterization of obsidian from the Veratic Rockshelter in Idaho. No further information or record of the composition, though, was published.

88. *SKULL SPRINGS OBSIDIAN*

Location: Sappington (1981:17) indicates that this source extends over a broad area that includes T.24S., R.40E., Sec.8, T.23S., R.41E. (Coyote Wells), Sec.22, T.22S., R.41E. (Mesa Reservoir) and Sec.34, T.22S., R.41E. (Buckboard Reservoir).

Archaeological Significance: Not known.

89. *SOAP LAKE OBSIDIAN*

Location: Soap Lake is probably a local name for Borax Lake, a heavily-mineralized thermal lake five miles northeast of Fields, Harney County; Sec.15, T.37S., R.33E. Directions to the site are provided in a road log by Ferguson and Ferguson (1978:145), who mention the presence of many wind-polished nodules of obsidian near the parking area.

Archaeological Significance: Not known.

90. SOUTH SISTER CHAIN OF OBSIDIAN DOMES *(Also see addendum)*

Location: The south flank of the South Sister, Deschutes County. The domes are found in portions of Secs.3, 10 and 16, T.18S., R.8E. and Secs.34, 35 and 27, T.17S., R.8E. See Figure IV-5.

Geologic Setting: An excellent description of the South Sister Chain of Obsidian Domes (also known as the Devils Hill or Goose Creek chain of domes) is found in Howel Williams study of the Three Sisters area (1944:58): "A remarkable chain of dacite domes and flows runs for more than three miles, from an elevation of about 8,000 feet, high on the southeast slope of South Sister, down to Century Drive, at an elevation of about 5,500 feet. The chain trends north to south, parallel to the axis of the Cascade Range. No doubt the extrusions occurred in rapid succession, possibly within a few days or weeks, and by analogy with other fissure eruptions in other regions it is likely that activity began at the upper end of the chain and moved progressively downward. Between the third and fourth domes from the southern end, a short stretch of the throughgoing fissure is exposed." Similar descriptions are also found in Peterson et al. (1976:27), Harris (1976:128-129) and Peterson and Groh (1965:1,4-5).

Age: Holocene. The domes, unlike adjacent features, show no signs of glaciation. Taylor (1978:8) places their age of extrusion at slightly later than that of Rock Mesa, dated at 2,300 ± 150 radiocarbon years B.P.

Composition: Major element composition of the northernmost dome is reported by Taylor (1978:43; see analysis 63 in Table IV-1, this appendix). Trace element abundances are also reported by Jack and Carmichael (1969:26-27; sample Cam 137).

Archaeological Significance: A pictograph site (35DS59) is reported near Century Drive next to the southernmost of the obsidian domes, apparently on the obsidian. This group of pictographs, obviously postdating the extrusion of the dome, was first mentioned by Cressman (1937:15), while a more detailed description appears in Dudley et al. (1979:426-458)(see page 167, this project).

91. SOUTH SISTER NEWBERRY OBSIDIAN FLOW *(Also see Addendum)*

Location: Directly northeast of the northernmost obsidian dome in the South Sister Chain of Obsidian Domes, Deschutes County. See Figure IV-6.

Geologic Setting: The Newberry Obsidian Flow is one of several dacitic obsidian flows found on the south slopes of the South Sister and appears to be considered by some to be the northernmost member of the South Sister Chain of Obsidian Domes.

Age: Holocene (Peterson and Groh, 1965:5).

Composition: Major element composition is reported by McBirney (1968a: 104; see Table IV-1, analysis 65, this appendix)and by Taylor (1978: 37,41,43; see analyses 66, 67, 68 and 69, Table IV-1, this appendix).

Major and trace-element composition is also reported by Anttonen (1972:92; see Table IV-1, analysis 64, this appendix).

Archaeological Significance: Not known.

92. SQUAW BUTTE AREA DOME

Location: East of Squaw Butte, Harney County; 43°29'N lat., 119°32.1'W long. See Figure IV-4.

Geologic Setting: Obsidian is found associated with a rhyolite dome and was used for dating purposes.

Age: Obsidian at this location yielded a K-Ar age of 5.69 ± 0.67 m.y. (McKee et al., 1976:39; MacLeod et al., 1975:468). Fission-track ages of 4.7 ± 0.4 m.y. and 4.2 ± 0.5 m.y. are also reported by Naeser et al. (1980:19). The variations in the results from these two dating methods is probably due to the annealing or fading of fission tracks in the obsidian.

Archaeological Significance: Not known.

93. SQUAW BUTTE OBSIDIAN

Location: Harney County; 43°30.0'N lat., 119°46.7'W long. See Figure IV-4.

Geologic Setting: The butte is described by McKee et al. (1976:39) as a rhyolite dome.

Composition: The composition of obsidian at this location was reported by Bennett and D'Auria (1974) and Nelson et al. (1975). The results of these two XRF studies in obsidian source characterization were reported in spectra peak intensities, though, making the results difficult to compare with other studies.

Archaeological Significance: Not known.

94. SQUAW RIDGE OBSIDIAN

Location: Northern Lake County, directly northeast of the early Holocene Squaw Ridge Lava Field; 43°31.8'N lat., 120°46.8'W long. See Figure IV-2.

Geologic Setting: The southern flanks of this Pliocene rhyolite dome are covered with abundant weathered nodules of porphyritic obsidian with a diameter up to at least 15 cm. The glassy matrix is filled with closely-spaced spherulites about 1 mm in diameter. This site was visited by the author in 1980 and 1981. Walker (1974:116) describes the obsidian as originating from flows related to the dome.

Composition: Major and trace element abundances are found in Table IV-1, analysis 70, this appendix.

Age: A K-Ar age of 3.59 ± 0.07 m.y. has been determined from obsidian collected at Squaw Ridge (MacLeod et al., 1975:468; McKee et al., 1976: 38; Walker, 1974:116).

Archaeological Significance: Not known. The Squaw Ridge Fault Zone (Skinner, 1980), a 3 km-long open fault and fault trace is found adjacent to the Squaw Ridge obsidian source. This sheltered locality, a likely campsite or workshop area, was examined by the author in 1980 and 1982. Numerous flakes and fragments of obsidian artifacts were found near the western end of the fault. All of the worked obsidian, though, was free of the characteristic small spherulites of the Squaw Ridge source and appear to have originated from another obsidian source. A number of sources of high-quality obsidian are available in this region, most notably at Cougar Mountain, six miles to the south of the fault.

95. *SQUAW RIDGE AREA RHYOLITE DOME*

Location: 43°32.2'N lat., 120°01.3'N long.; Lake County. See Figure IV-4.

Geologic Setting: The obsidian is described as flow selvage by Walker (1974:113).

Age: A K-Ar age of 4.9 ± 0.3 m.y. is reported by Walker (1974:113) for obsidian from this dome.

Archaeological Significance: Not known.

SOUTH SISTER AREA OBSIDIAN - See:
BROKEN TOP OBSIDIAN
DEVILS HILL OBSIDIAN
ROCK MESA OBSIDIAN FLOW
ROCK MESA VICINITY SMALL OBSIDIAN DOME
SOUTH SISTER CHAIN OF OBSIDIAN DOMES
SOUTH SISTER NEWBERRY OBSIDIAN FLOW
UPPER NORTH FORK TUMALO CREEK OBSIDIAN NO.1
UPPER NORTH FORK TUMALO CREEK OBSIDIAN NO.2

Non-specific references to obsidian from the South Sister area appear in Nelson et al. (1975) and Stevenson et al. (1971; see Table IV-1, analysis 71, this appendix).

T OBSIDIAN FLOW - See INTERLAKE OBSIDIAN FLOW

96. *TUCKER HILL OBSIDIAN (Also see Addendum)*

Location: Tucker Hill is located about ten miles southeast of Paisley, Lake County; Secs.25 and 36, T.34S., R.19E.

Geologic Setting: Tucker Hill is described by Peterson (1961:68) and Peterson and McIntyre (1970:61) as an elongate dome-shaped mass of glassy flow-banded rhyolite. Deposits of perlite, glassy rhyolite, perlitic glass and abundant obsidian in the form of "apache tears" are all found at Tucker Hill.

Age: Obsidian from Tucker Hill has yielded a K-Ar age of 7.41 ± 0.19 m.y. (McKee et al., 1976:40).

Archaeological Significance: Sappington and Toepel (1981) have characterized 283 obsidian artifacts collected along a 251 km-long north-south corridor beginning near Silver Lake. Out of these, a total of fourteen, predominantly from the Fort Rock and Silver Lake Valleys, were found to have probably originated at the Tucker Hill source. In an additional study by the same authors (1981:248-255), 26 pre-Mazama obsidian artifacts from the Connley Cave sites and Fort Rock Cave were characterized. Of these artifacts, one each from the Connley Caves No.4 and No.5 were correlated with the Tucker Hill obsidian source.

97. *UPPER NORTH FORK OF TUMALO CREEK OBSIDIAN NO.1*

Location: Sec.28 and W½Sec.17, T.17S., R.9E.; Deschutes County (see Taylor, 1978:20, for a map of the location; unit PsRdPtl1). See Figure IV-2.

Geologic Setting: Taylor (1978:34-35) reports that beds composed of white-to-yellow devitrified pumice, obsidian and rock fragments are found in a tuff cone on the upper North Fork of Tumalo Creek. Near the top of the tuff cone Taylor also found clots of rhyodacitic obsidian associated with layers of silicic spatter.

Age: Pleistocene. The tuff cone associated with the obsidian is glaciated, indicating a pre-Holocene age. These deposits are underlain by lavas from Ball Butte, known to overlie a unit of normal paleomagnetic polarity (Taylor, 1987:35), indicating an age of less than 690,000 years B.P.

Archaeological Significance: Not known.

98. *UPPER NORTH FORK OF TUMALO CREEK NO.2*

Location: Secs.28, 33, 34, T.17S., R.9E. and N½Sec.3, T.18S., R.9E.; Deschutes County (see Taylor, 1978:20, for a location map; unit PsRdLa12). See Figure IV-2.

Geologic Setting: Taylor (1978:35) reports glaciated aphyric lavas on the upper North Fork of Tumalo Creek with partly spherulitic black, dull-luster obsidian crusts. The interior of the lava is gray, lithoidal and platy. The source is a dike exposed in the south wall of the North Fork of Tumalo Creek at an elevation of about 7100 feet. This obsidian may be the same as that reported by Williams (1944:45; see Broken Top Obsidian, this appendix).

Petrography: Rare microphenocrysts of plagioclase in a trachytic groundmass of An_{20-25} microlites (Taylor, 1978:35).

Composition: Major element composition is reported by Taylor (1978:38; see analysis 73, Table IV-1, this appendix).

Age: Pleistocene. Paleomagnetic polarity is normal (Taylor, 1978:35), indicating an age of less than 690,000 years B.P. The obsidian is glaciated, placing the lower age limit as pre-Holocene.

Archaeological Significance: Not known.

UPPER WINBERRY CREEK WELDED ASH-FLOW - *See LOWELL OBSIDIAN-LIKE VITROPHYRE*

99. *VALLEY OF THE GIANTS OBSIDIAN* *(Also see Addendum)*

Location: West of Highway 95 near the Oregon-Nevada border; Malheur County. See Figure IV-4.

Geologic Setting: This reported obsidian source, possibly the same as the McDermitt Area source (62) is found in the vicinity of the McDermitt Caldera Complex (Rytuba et al., 1981:2; Greene, 1976).

Archaeological Significance: Atherton (1966:34) reports that large obsidian blanks have been found at this site.

100. WATERSHED QUARRY OBSIDIAN

Location: Malheur County? 120 km north of Dirty Shame Rockshelter.

Archaeological Significance: Sappington (1980), using trace-element source characterization methods, determined that obsidian found at Dirty Shame Rockshelter in Malheur County originated at a site identified as Watershed Quarry (specific locality not mentioned). Obsidian from this source was found in several of the six identified cultural levels at the Dirty Shame site. Additional details of lithic materials recovered at this site can be found in other sources (Aikens et al., 1977; Kittleman, 1977; Hanes, 1977 and 1980). It is possible that the Watershed obsidian source may not be in Oregon, but near the border in Idaho.

101. WHITEHORSE OBSIDIAN *(Also see Addendum)*

Location: Not far west of Dirty Shame Rockshelter, Malheur County. See Figure IV-4.

Geologic Setting: Obsidian nodules are apparently found over a large area (Sappington, 1980b:39). Hanes also mentions that gray obsidian, brownish-green tinted obsidian and black vitrophyre have all been determined, through trace-element characterization methods, to have originated at the Whitehorse source (Hanes, 1980:265-336).

Archaeological Significance: Sappington (1980a), in characterizing 136 obsidian artifacts from Dirty Shame Rockshelter, found that obsidian identified as originating from the Whitehorse source comprised the single largest source grouping from the archaeological site. Obsidian from the Whitehorse source was found in all six identified cultural levels at Dirty Shame. Additional detail on lithic materials from the Dirty Shame Rockshelter can be found in other sources (Aikens et al., 1977; Hanes, 1977 and 1980; Kittleman, 1977).

Sappington (1980b:39-41) also characterized 27 artifacts collected in an intensive archaeological survey of a portion of southern Malheur County. He found that the Whitehorse source represented 93 percent (by weight) of the sample.

102. WINEGLASS WELDED TUFF

Location: Near the top of the caldera wall between Pumice Point and Grotto Cove, Crater Lake National Park, Klamath County. See Figure IV-2.

Geologic Setting: The Wineglass welded tuff is exposed in a four-mile section of the Crater Lake caldera wall, forming a conspicuous cliff. The type section is located at the Wineglass and is described by Williams (1942:60): "Most of the dacite consists of compact and finely streaked glass in shades of pink, red, orange, brown and gray. Black strings of obsidian accentuate the banding of the varicolored matrix. Some of these measure a foot long though less than half an inch in thickness."

Age: Late Pleistocene.

Archaeological Significance: Not known.

103. *WINTER RIDGE OBSIDIAN*

Location: Obsidian is found at the base of White Rock, a prominent landmark not far west of Highway 31 and about one mile north of the town of Summer Lake, Lake County; T.30S., R.16E. See Figure IV-2.

Geologic Setting: A striking exposure of light-colored pumice and ash known as White Rock occurs on the east side of Winter Ridge. Ikeagwuani (1965:39) reports that, "Brecciated pieces of obsidian up to 5 inches in diameter embedded in ashy matrix occur in lenses in the tuff." Travis (1977:11) writes that, "The lower portion of White Rock is a 90 meter cliff of breccia and obsidian boulders up to one meter in diameter." The unit containing the obsidian is overlain by light-gray rhyolitic ash about 90 m thick.

Age: Miocene (Travis, 1977:11).

Archaeological Significance: Not known. Several important archaeological sites have been reported in the Summer Lake region (Cressman, 1942) and the White Rock obsidian source is located only a short distance from Ana Warm Springs, the source of the Ana River and a major year-around water source in the area.

104. *WRIGHT'S POINT OBSIDIAN*

Location: Ten miles south of Burns, Harney County. See Figure IV-4.

Geologic Setting: Wright's Point is a flat-topped, six-mile long and 250-foot high ridge that projects eastward into the Harney Basin. Niem (1974:39) reports the presence of clasts of obsidian in conglomerate units at Wright's Point: "The volcanic conglomerate units of Wright's Point are a distinctive pale olive-green color. They are cross-bedded, poorly-sorted, and many units are lens-shaped. The subangular to subrounded pebble- to cobble-sized clasts range in composition from obsidian to...mudstones." The obsidian may have originated at Burns Butte to the northwest or Palamino Buttes to the west and later been transported (fluvially) to the Wright's Point area.

Archaeological Significance: Not known.

105. *YAMSAY MOUNTAIN OBSIDIAN* *(Also see Addendum)*

Location: Two obsidian dome outcrops have been reported south of Round Butte in Sec.31, T.30S., R.13E. and above the West Fork of Silver Creek in Sec.11, T.30S., R.13E. (Hering, 1980:20). See Figure IV-2.

Geologic Setting: The two rhyolitic obsidian domes were extruded low on the sides of the volcanic shield that makes up Yamsay Mountain. The obsidian is found on the surface as abundant, hand-sized fragments. Both of the domes have been nearly buried by younger flows of basaltic andesite, but a greater areal extent for the domes is inferred from the distribution of obsidian float in the surrounding area (Hering, 1981:20).

Petrographic Features: Obsidian from the domes is black, faintly-banded and contains rare plagioclase phenocrysts. The glass also contains fine crystallites, needles and laths of plagioclase. The flow banding was observed to result from the differential concentration of feldspar microlites in the glass (Hering, 1981:21).

Composition: Major and trace element abundances for the two domes are reported by Hering (1981:174; see analyses 74 and 75, Table IV-1, this appendix).

Age: A minimum Pliocene age (Hering, 1981:18).

Archaeological Significance: In a sample of 283 characterized obsidian artifacts recovered primarily from the Fort-Rock Silver Lake Valleys, a total of nineteen specimens were tentatively identified as originating from the Yamsay Mountain source. Several obsidian artifacts recovered from pre-Mazama levels at Fort Rock Cave and the Connley Caves also were found to have originated at Yamsay Mountain (Sappington and Toepel, 1981).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO_2	63.80	73.2	72.2	72.22	72.4	72.6	73.4	72.02	72.02	71.79	73.4	--	--	--	--
TiO_2	0.12	0.26	0.21	0.23	0.22	0.20	0.20	0.24	0.24	0.24	0.20	--	--	--	--
Al_2O_3	14.58	14.0	14.6	14.41	14.4	14.4	14.2	14.61	14.64	14.58	14.20	--	--	--	--
Fe_2O_3	1.39	--	0.72	0.50	0.64	0.64	0.24	2.43	2.46	2.36	0.24	--	--	--	--
FeO	--	2.02	1.7	1.62	1.6	1.6	1.76	--	--	--	1.76	--	--	--	--
MnO	--	0.06	0.06	0.06	0.06	0.05	Tr	0.064	0.064	0.064	0.06	--	--	--	--
MgO	0.13	0.23	0.32	0.18	0.18	0.24	0.18	0.164	0.165	0.166	0.18	--	--	--	--
CaO	0.93	0.88	0.92	0.84	0.87	0.92	1.35	0.85	0.85	0.86	1.35	--	--	--	--
Na_2O	3.48	5.07	5.3	5.28	4.9	4.7	4.15	5.16	5.10	5.14	5.15	--	--	--	--
K_2O	4.29	4.08	4.0	4.01	4.1	3.9	4.1	3.89	3.89	3.89	4.10	--	--	--	--
P_2O_5	--	0.02	0.06	0.03	0.03	0.09	Tr	--	--	--	0.03	--	--	--	--
H_2O^+	--	--	0.31	0.12	0.50	0.63	0.40	--	--	--	0.40	--	--	--	--
H_2O^-	--	--	0.02	0.01	0.06	0.03	0.10	--	--	--	0.10	--	--	--	--
CO_2	--	--	0.01	0.00	<0.05	<0.05	Nil	--	--	--	--	--	--	--	--
Loss	--	0.13	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	88.73	--	100.00	99.51	100.1	100.00	100.08	--	--	--	101.17	--	--	--	--
Na	2.97%	3.73%	--	--	--	--	--	--	--	--	--	--	40950.	41330.	39450.
Mg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
P	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
K	4.84%	--	--	--	--	--	--	--	--	--	--	3.30%	--	--	--
Ca	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sc	--	--	--	--	--	--	10.	--	--	--	--	--	--	--	--
Ti	--	--	--	--	--	--	--	--	--	--	--	1420.	--	--	--
V	--	--	--	--	--	--	<10.	--	--	--	--	--	--	--	--
Cr	--	--	--	--	--	--	2.	--	--	--	--	--	--	--	--
Mn	442.	--	--	--	--	--	--	--	--	--	--	605.	439.	438.	439.
Fe	--	1.57%	--	--	--	--	--	--	--	--	--	--	--	--	--
Co	--	0.9	--	--	--	--	--	--	--	--	--	25.	--	--	--
Ni	--	--	--	--	--	--	<4.	--	--	--	--	5.	--	--	--
Cu	--	--	--	--	--	--	9.	--	--	--	--	5.	--	--	--
Zn	--	--	--	--	--	--	--	133.	143.	123.	--	55.	--	--	--
Ga	--	--	--	--	--	--	--	--	--	--	--	15.	--	--	--
Rb	--	113.	--	--	--	--	150.	152.	153.	155.	--	120.	--	--	--
Sr	--	--	--	--	--	--	64.	--	--	--	--	50.	--	--	--
Y	--	--	--	--	--	--	70.	--	--	--	--	45.	--	--	--
Zr	--	230.	--	--	--	--	390.	--	--	--	--	355.	--	--	--
Cs	--	4.2	--	--	--	--	2.	--	--	--	--	--	--	--	--
Ba	--	980.	--	--	--	--	870.	--	--	--	--	960.	--	--	--
La	--	31.	--	--	--	--	--	--	--	--	--	50.	--	--	--
Ce	--	--	--	--	--	--	--	--	--	--	--	80.	--	--	--
Pr	--	--	--	--	--	--	--	--	--	--	--	5.	--	--	--
Nd	--	35.	--	--	--	--	--	--	--	--	--	30.	--	--	--
Sm	--	6.7	--	--	--	--	--	--	--	--	--	--	--	--	--
Eu	--	0.92	--	--	--	--	--	--	--	--	--	--	--	--	--
Tb	--	1.2	--	--	--	--	--	--	--	--	--	--	--	--	--
Yb	--	4.7	--	--	--	--	--	--	--	--	--	--	--	--	--
Lu	--	0.76	--	--	--	--	--	--	--	--	--	--	--	--	--
Hf	--	9.0	--	--	--	--	--	--	--	--	--	--	--	--	--
Ta	--	1.5	--	--	--	--	--	--	--	--	--	--	--	--	--
Pb	--	--	--	--	--	--	<20.	--	--	--	--	20.	--	--	--
Th	--	13.9	--	--	--	--	--	12.1	--	--	--	15.	--	--	--
U	--	--	--	--	--	--	--	4.9	--	--	--	--	--	--	--

Table IV-1: Major element and trace element abundances of obsidian from sources in Oregon. Sources and references appear at the end of the table. The figures in the top portion of the table are expressed in weight percent oxide, while those in the bottom section are shown in parts per million, except where otherwise noted.

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
SiO_2	--	--	--	--	--	73.40	72.8	72.9	73.23	72.35	72.8	72.35	--	--	--
TiO_2	--	--	--	--	--	0.20	0.21	0.22	0.24	0.25	0.22	0.25	--	--	--
Al_2O_3	--	--	--	--	--	14.20	14.6	14.1	14.59	13.98	13.9	13.98	--	--	--
Fe_2O_3	--	--	--	--	--	0.24	0.44	0.66	2.13	0.60	0.67	0.60	--	--	--
FeO	--	--	--	--	--	1.76	1.6	1.4	--	1.78	1.3	1.78	--	--	--
MnO	--	--	--	--	--	Tr	0.05	0.05	0.053	Nil	0.06	Nil	--	--	--
MgO	--	--	--	--	--	0.18	0.25	0.27	0.208	0.30	0.21	0.30	--	--	--
CaO	--	--	--	--	--	1.35	1.0	0.98	0.93	1.30	1.4	1.3	--	--	--
Na_2O_3	--	--	--	--	--	4.15	4.2	4.6	4.76	5.04	4.5	5.04	--	--	--
K_2O	--	--	--	--	--	4.10	3.8	4.2	4.11	3.92	4.1	3.92	--	--	--
P_2O_5	--	--	--	--	--	Tr	0.09	0.10	--	Tr	0.02	Tr	--	--	--
H_2O^+	--	--	--	--	--	0.40	0.76	0.58	--	0.05	0.45	0.45	--	--	--
H_2O^-	--	--	--	--	--	0.10	0.14	0.02	--	0.45	0.05	0.05	--	--	--
CO_2	--	--	--	--	--	Nil	<0.05	<0.05	--	Nil	<0.05	Tr	--	--	--
Loss	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	--	--	--	--	--	100.08	99.9	100.1	--	100.02	99.7	100.02	--	--	--
Na	42070.	41780.	41200.	40890.	40950.	--	--	--	--	--	--	--	--	--	4.09%
Mg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
P	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
K	--	--	--	--	--	--	--	--	--	--	--	--	2.08%	--	--
Ca	--	--	--	--	--	--	--	--	--	--	--	--	--	2.32%	--
Sc	--	--	--	--	--	--	--	--	--	--	7.	--	--	--	7.7
Ti	--	--	--	--	--	--	--	--	--	--	--	--	3000.	2600.	--
V	--	--	--	--	--	--	--	--	--	--	<10.	--	--	--	--
Cr	--	--	--	--	--	--	--	--	--	--	2.	--	--	--	--
Mn	456.	469.	442.	454.	454.	--	--	--	--	--	--	--	570.	455.	483.
Fe	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.5%
Co	--	--	--	--	--	--	--	--	--	--	--	--	30.	20.	--
Ni	--	--	--	--	--	--	--	--	--	--	<4.	--	5.	5.	--
Cu	--	--	--	--	--	--	--	--	--	--	8.	--	15.	15.	--
Zn	--	--	--	--	--	--	--	--	48.	--	--	--	40.	35.	--
Ga	--	--	--	--	--	--	--	--	--	--	--	--	15.	15.	--
Rb	--	--	--	--	--	--	--	--	178.	--	180.	--	50.	65.	36.
Sr	--	--	--	--	--	--	--	--	--	--	70.	--	360.	270.	--
Y	--	--	--	--	--	--	--	--	--	--	60.	--	20.	20.	--
Zr	--	--	--	--	--	--	--	--	--	--	300.	--	235.	235.	--
Cs	--	--	--	--	--	--	--	--	--	--	5.	--	--	--	--
Ba	--	--	--	--	--	--	--	--	--	--	740.	--	820.	900.	--
La	--	--	--	--	--	--	--	--	--	--	--	--	30.	30.	45.
Ce	--	--	--	--	--	--	--	--	--	--	--	--	50.	50.	--
Pr	--	--	--	--	--	--	--	--	--	--	--	--	5.	5.	--
Nd	--	--	--	--	--	--	--	--	--	--	--	--	20.	20.	--
Sm	--	--	--	--	--	--	--	--	--	--	--	--	--	--	5.6
Eu	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tb	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Yb	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Lu	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Hf	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Ta	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pb	--	--	--	--	--	--	--	--	--	--	<20.	--	15.	15.	--
Th	--	--	--	--	--	--	--	--	14.2	--	--	--	5.	5.	--
U	--	--	--	--	--	--	--	--	5.6	--	--	--	--	--	--

	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
SiO_2	--	73.2	71.5	72.5	--	72.59	72.59	71.8	72.8	72.9	79.69	--	--	74.50	--
TiO_2	--	0.24	0.25	0.23	--	0.26	0.25	0.3	0.24	0.21	0.06	--	--	0.13	--
Al_2O_3	--	14.3	14.3	14.3	--	14.51	14.38	14.5	14.6	14.0	12.51	--	--	14.46	--
Fe_2O_3	--	0.55	0.87	0.33	--	2.25	2.21	0.7	0.77	0.77	0.91	--	--	0.96	--
FeO	--	1.5	1.3	1.7	--	--	--	1.5	1.3	1.3	--	--	--	0.13	--
MnO	--	0.05	0.05	0.05	--	0.054	0.054	0.1	0.04	0.06	--	--	--	0.07	--
MgO	--	0.28	0.30	0.33	--	0.239	0.225	0.3	0.34	0.28	0.08	--	--	0.18	--
CaO	--	1.0	1.1	1.1	--	0.99	0.98	1.1	1.1	1.0	0.49	--	--	1.25	--
Na_2O_3	--	4.5	4.5	4.6	--	4.78	4.81	5.2	4.3	4.6	3.49	--	--	4.50	--
K_2O	--	3.8	4.1	4.1	--	4.01	4.05	4.0	4.0	4.2	4.25	--	--	2.50	--
P_2O_5	--	0.04	0.13	0.1	--	--	--	--	0.10	0.09	--	--	--	0.08	--
H_2O^+	--	--	1.2	0.43	--	--	--	0.3	0.43	0.51	--	--	--	0.05	--
H_2O^-	--	--	0.30	0.03	--	--	--	--	0.00	0.02	--	--	--	--	--
CO_2	--	<0.05	<0.05	<0.05	--	--	--	--	<0.05	<0.05	--	--	--	--	--
Loss	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	--	100.	99.9	99.8	--	--	--	99.8	100.0	99.9	101.49	--	--	98.74	--
Na	3.93%	--	--	--	--	--	--	--	--	--	3.38%	3.41%	--	--	--
Mg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
P	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
K	--	--	--	--	--	--	--	--	--	--	3.46%	--	3.26%	--	--
Ca	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1850.
Sc	7.3	--	--	--	--	--	--	--	--	--	--	6.2	--	--	--
Ti	--	--	--	--	1459.	--	--	--	--	--	--	--	520.	--	560.
V	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Cr	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Mn	435.	--	--	--	480.	--	--	--	--	--	345.	367.	405.	--	315.
Fe	1.6%	--	--	--	--	--	--	--	--	--	--	0.88%	--	--	.70%
Co	--	--	--	--	35.	--	--	--	--	--	--	--	20.	--	--
Ni	--	--	--	--	10.	--	--	--	--	--	--	--	5.	--	--
Cu	--	--	--	--	5.	--	--	--	--	--	--	--	5.	--	--
Zn	--	--	--	--	45.	127.	107.	--	--	--	--	--	30.	--	--
Ga	--	--	--	--	15.	--	--	--	--	--	--	--	15.	--	--
Rb	39.	--	--	--	40.	177.	173.	--	--	--	--	80.	80.	--	100.
Sr	--	--	--	--	60.	--	--	--	--	--	--	--	30.	--	75.
Y	--	--	--	--	30.	--	--	--	--	--	--	--	45.	--	60.
Zr	--	--	--	--	285.	--	--	--	--	--	--	--	95.	--	145.
Cs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Ba	--	--	--	--	930.	--	--	--	--	--	--	--	1300.	--	1290.
La	41.	--	--	--	40.	--	--	--	--	--	--	60.	40.	--	--
Ce	--	--	--	--	70.	--	--	--	--	--	--	--	90.	--	--
Pr	--	--	--	--	5.	--	--	--	--	--	--	--	5.	--	--
Nd	--	--	--	--	25.	--	--	--	--	--	--	--	25.	--	--
Sm	5.5	--	--	--	--	--	--	--	--	--	--	6.3	--	--	--
Eu	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Tb	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Yb	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Lu	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Hf	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Ta	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pb	--	--	--	--	20.	--	--	--	--	--	--	--	10.	--	--
Th	--	--	--	--	25.	13.1	13.6	--	--	--	--	--	10.	--	--
U	--	--	--	--	--	5.7	5.4	--	--	--	--	--	--	--	--

	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
SiO_2	70.59	73.82	--	73.6	72.9	73.1	--	73.02	--	--	--	75.5	75.6	76.2	69.7
TiO_2	0.18	0.18	--	0.26	0.23	0.21	--	0.24	--	--	--	0.05	0.05	0.09	0.36
Al_2O_3	12.79	12.05	--	13.8	13.9	14.0	--	14.44	--	--	--	13.4	13.1	13.0	15.2
Fe_2O_3	7.7	2.68	--	--	0.56	0.33	--	2.11	--	--	--	--	--	--	0.66
FeO	--	--	--	1.80	1.4	1.7	--	--	--	--	--	1.6	1.6	1.1	2.4
MnO	--	--	--	0.06	0.12	0.05	--	0.053	--	--	--	--	--	--	0.09
MgO	0.04	0.06	--	0.35	0.24	0.28	--	0.197	--	--	--	0.3	0.2	0.22	0.39
CaO	0.45	0.47	--	0.96	1.6	0.99	--	0.92	--	--	--	0.9	1.1	0.83	1.7
Na_2O	4.03	4.16	--	4.71	4.4	4.6	--	4.75	--	--	--	--	--	4.46	5.4
K_2O	4.58	4.76	--	4.25	4.1	4.2	--	4.10	--	--	--	3.35	3.40	3.51	3.1
P_2O_5	--	--	--	0.03	0.02	0.09	--	--	--	--	--	--	--	--	0.12
H_2O^+	--	--	--	--	0.42	0.45	--	--	--	--	--	--	--	--	0.61
H_2O^-	--	--	--	--	0.06	0.00	--	--	--	--	--	--	--	--	0.07
CO_2	--	--	--	--	0.05	<0.05	--	--	--	--	--	--	--	--	<0.05
Loss	--	--	--	0.14	--	--	--	--	--	--	--	--	--	--	--
Total	95.36	98.19	--	--	100.0	100.0	--	--	--	--	--	--	--	--	99.8
Na	--	--	4.08%	3.46%	--	--	--	--	--	--	--	--	--	--	--
Mg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
P	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
K	--	--	4.27%	--	--	--	3.44%	--	2.16%	--	--	--	--	--	--
Ca	--	--	--	--	--	--	--	--	--	--	2300.	--	--	--	--
Sc	--	--	--	5.36	6.	--	--	--	--	--	--	3.	2.	--	--
Ti	--	--	--	--	--	--	1400.	--	2825.	2150.	1400.	--	--	--	--
V	--	--	--	--	<10.	--	--	--	--	--	--	--	--	--	--
Cr	--	--	--	2.	2.	--	--	--	--	--	--	1.	15.	22.	--
Mn	--	--	796.	--	--	--	470.	--	540.	660.	445.	198.	217.	229.	--
Fe	--	--	--	1.39%	--	--	--	--	--	--	1.7%	--	--	--	--
Co	--	--	--	1.2	--	--	20.	--	25.	25.	--	--	--	--	--
Ni	--	--	--	--	<4.	--	5.	--	5.	5.	--	--	5.	9.	--
Cu	--	--	--	--	16.	--	5.	--	10	5.	--	4.	6.	4.	--
Zn	--	--	--	--	--	--	40.	62.	40.	50.	--	--	--	--	--
Ga	--	--	--	--	--	--	15.	--	15.	15.	--	--	--	--	--
Rb	--	--	--	133.	140.	--	135.	177.	55.	95.	80.	--	--	--	--
Sr	--	--	--	--	70.	--	55.	--	295.	100.	<30.	90.	99.	123.	--
Y	--	--	--	--	60.	--	40.	--	25.	40.	55.	--	--	--	--
Zr	--	--	--	--	280.	--	280.	--	240.	315.	340.	117.	123.	112.	--
Cs	--	--	--	5.	2.	--	--	--	--	--	--	--	--	--	--
Ba	--	--	--	1000.	920.	--	970.	--	860.	960.	1000.	1030.	1010.	1480.	--
La	--	--	--	30.	--	--	40.	--	30.	40.	--	--	--	--	--
Ce	--	--	--	--	--	--	80.	--	60.	70.	--	--	--	--	--
Pr	--	--	--	--	--	--	5.	--	<5.	<5.	--	--	--	--	--
Nd	--	--	--	30.	--	--	30.	--	25.	30.	--	--	--	--	--
Sm	--	--	--	6.6	--	--	--	--	--	--	--	--	--	--	--
Eu	--	--	--	0.79	--	--	--	--	--	--	--	--	--	--	--
Tb	--	--	--	1.	--	--	--	--	--	--	--	--	--	--	--
Yb	--	--	--	4.9	--	--	--	--	--	--	--	--	--	--	--
Lu	--	--	--	0.74	--	--	--	--	--	--	--	--	--	--	--
Hf	--	--	--	4.7	--	--	--	--	--	--	--	--	--	--	--
Ta	--	--	--	1.2	--	--	--	--	--	--	--	--	--	--	--
Pb	--	--	--	--	--	--	25.	--	20.	20.	--	--	--	--	--
Th	--	--	--	--	--	--	25.	14.8	15.	15.	--	--	--	--	--
U	--	--	--	--	--	--	--	5.4	--	--	--	--	--	--	--

	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
SiO_2	--	73.1	71.6	71.9	71.94	72.0	72.3	72.0	72.3	75.09	--	72.3	69.0	74.69	74.70
TiO_2	--	0.28	0.30	0.32	0.40	0.30	0.35	0.30	0.35	0.13	--	0.30	0.50	0.17	0.18
Al_2O_3	--	14.8	15.0	14.70	14.31	15.0	14.9	15.0	14.0	12.91	--	14.8	14.6	13.07	13.25
Fe_2O_3	--	--	--	--	0.61	--	--	--	--	1.81	--	--	--	--	--
FeO	--	1.9	3.0	2.40	1.77	2.4	2.6	2.2	2.4	--	--	2.2	3.9	1.79	1.79
MnO	--	--	--	--	0.05	--	--	--	--	0.04	--	--	--	0.08	0.09
MgO	--	0.40	0.8	0.70	0.41	0.5	0.4	0.8	0.4	0.03	--	0.7	0.3	0.22	0.20
CaO	--	1.7	1.9	2.10	1.75	2.1	2.1	2.0	2.0	0.77	--	1.9	1.8	0.38	0.43
Na_2O	--	--	4.3	--	4.69	4.4	4.4	4.5	4.2	4.50	--	4.8	6.2	5.09	5.42
K_2O	--	3.35	3.0	3.09	3.00	3.1	3.1	2.95	3.05	4.07	--	2.95	--	4.34	4.21
P_2O_5	--	--	--	--	0.07	--	--	--	--	0.01	--	--	--	0.03	0.03
H_2O^+	--	--	--	--	0.48	--	--	--	--	--	--	--	--	--	--
H_2O^-	--	--	--	--	0.16	--	--	--	--	--	--	--	--	--	--
CO_2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Loss	--	--	--	--	--	--	--	--	--	--	--	--	--	0.73	0.65
Total	--	--	99.9	--	99.64	99.8	100.15	99.75	99.60	99.28	--	99.95	98.95	100.59	100.95
Na	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Mg	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
P	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
K	2.47%	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Ca	--	--	--	--	--	--	--	--	--	--	2300.	--	--	--	--
Sc	--	4.	--	5.	--	--	--	--	--	--	--	--	--	--	8.2
Ti	1800.	--	--	--	--	--	--	--	--	--	680.	--	--	--	--
V	--	23.	--	27.	--	--	--	--	--	--	--	--	--	--	--
Cr	--	2.	--	2.	--	--	--	--	--	--	--	--	--	--	--
Mn	845.	325.	--	428.	--	--	--	--	--	--	300.	--	--	--	--
Fe	--	--	--	--	--	--	--	--	--	--	0.76%	--	--	--	--
Co	25.	2.	--	2.	--	--	--	--	--	--	--	--	--	--	--
Ni	5.	1.	--	1.	--	--	--	--	--	--	--	--	--	--	--
Cu	<5.	6.	--	7.	--	--	--	--	--	--	--	--	--	--	--
Zn	70.	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Ga	20.	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Rb	75.	--	--	--	--	--	--	--	--	119.5	90.	--	--	125.	117.
Sr	85.	188.	--	237.	--	--	--	--	--	41.2	55.	--	--	<5.	15
Y	35.	--	--	--	--	--	--	--	--	46.3	55.	--	--	--	--
Zr	350.	156.	--	193.	--	--	--	--	--	226.8	110.	--	--	346.	348.
Cs	--	--	--	--	--	--	--	--	--	--	--	--	--	--	5.7
Ba	970.	835.	--	915.	--	--	--	--	--	--	1440.	--	--	--	769.
La	40.	--	--	--	--	--	--	--	--	--	--	--	--	--	35.9
Ce	80.	--	--	--	--	--	--	--	--	--	--	--	--	--	78.
Pr	5.	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Nd	30.	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Sm	--	--	--	--	--	--	--	--	--	--	--	--	--	--	8.7
Eu	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.93
Tb	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.58
Yb	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6.0
Lu	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.89
Hf	--	--	--	--	--	--	--	--	--	--	--	--	--	--	8.9
Ta	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2.07
Pb	20.	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Th	10.	--	--	--	--	--	--	--	--	--	--	--	--	--	10.9
U	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3.3

	76	77	78	79	80
SiO_2	72.8	72.8	72.8	72.8	72.8
TiO_2	0.23	0.23	0.23	0.23	0.23
Al_2O_3	14.3	14.3	14.4	14.3	14.3
Fe_2O_3	0.6	0.6	0.5	0.6	0.6
FeO	1.6	1.7	1.6	1.6	1.6
MnO	0.07	0.07	0.07	0.07	0.07
MgO	0.06	0.06	0.06	0.06	0.06
CaO	1.0	1.0	1.0	1.0	1.0
Na_2O	5.4	5.3	5.4	5.4	5.2
P_2O_5	0.03	0.03	0.03	0.03	0.03
H_2O^+	0.20	0.20	0.15	0.23	0.25
H_2O^-	0.10	0.10	0.10	0.15	0.10
CO_2	0.0	0.0	0.0	0.0	0.0
Loss	--	--	--	--	--
Total	100.4	100.2	100.1	100.4	100.1
Na	--	--	--	--	--
Mg	--	--	--	--	--
P	--	--	--	--	--
K	--	--	--	--	--
Ca	--	--	--	--	--
Sc	--	--	--	--	--
Ti	--	--	--	--	--
V	--	--	--	--	--
Cr	--	--	--	--	--
Mn	--	--	--	--	--
Fe	--	--	--	--	--
Co	--	--	--	--	--
Ni	--	--	--	--	--
Cu	--	--	--	--	--
Zn	--	--	--	--	--
Ga	--	--	--	--	--
Rb	--	--	--	--	--
Sr	--	--	--	--	--
Y	--	--	--	--	--
Zr	--	--	--	--	--
Cs	--	--	--	--	--
Ba	--	--	--	--	--
La	--	--	--	--	--
Ce	--	--	--	--	--
Pr	--	--	--	--	--
Nd	--	--	--	--	--
Sm	--	--	--	--	--
Eu	--	--	--	--	--
Tb	--	--	--	--	--
Yb	--	--	--	--	--
Lu	--	--	--	--	--
Hf	--	--	--	--	--
Ta	--	--	--	--	--
Pb	--	--	--	--	--
Th	--	--	--	--	--
U	--	--	--	--	--

Table IV-1 (Continued): Collection localities and literature sources for obsidian analyses listed in Table IV-1.

1. *Beatty's Butte, Southern Oregon.* Collected somewhere not far west of Beatty's Butte. Source is Ericson, 1977:20,92 (sample 17-1-0-4).
2. *Big Obsidian Flow, Newberry Caldera.* Collected at the toe of the flow. Source is Beyer, 1973:18 (sample BOF).
3. *Big Obsidian Flow, Newberry Caldera.* Source is Friedman and Long, 1976:349.
4 - 7. *Big Obsidian Flow, Newberry Caldera.* Source is Higgins, 1973:475 (samples no.54, 55, 56, 57; trace-element abundances for 54 appear on p.483).
8. *Big Obsidian Flow, Newberry Caldera.* Source is Laidley and McKay, 1971:339.
9. *Big Obsidian Flow, Newberry Caldera.* Collected from the earlier extruded part of the flow. Source is Laidley and McKay, 1971:339.
10. *Big Obsidian Flow, Newberry Caldera.* Collected from the later extruded part of the flow. Source is Laidley and McKay, 1971:339.
11. *Big Obsidian Flow, Newberry Caldera.* Source is Murase and McBirney, 1973:3564 (sample NRO).
12. *Big Obsidian Flow, Newberry Caldera.* The figure shown is the mean for a set of seven specimens collected every 50 m in a vertical traverse at the northwest tongue of the flow. Source is Osborn and Schmitt, 1970:212 (set no.1).
13 - 20. *Big Obsidian Flow, Newberry Caldera.* Each analysis is a mean figure for a set of obsidian samples containing from four to six specimens. Each of the seven sets was collected at a widely separated location on the flow. Source is Osborn and Schmitt, 1970:212 (sets no.2 through 8).
21. *Big Obsidian Flow, Newberry Caldera.* Pumicieous obsidian collected from the plug dome at the head of the obsidian flow. Source is Williams, 1935:295 (sample no.11).
22 - 23. *Central Pumice Cone Summit Crater Obsidian Flow, Newberry Caldera.* Source is Higgins, 1973:475 (samples no.50 and 51).
24. *Central Pumice Cone Summit Crater Obsidian Flow, Newberry Caldera.* Source is Laidley and McKay, 1971:339 (sample PCOF).
25. *Central Pumice Cone Summit Crater Obsidian Flow, Newberry Caldera.* Collected at "massive, black flow on north wall of crater." Source is Williams, 1935:295 (sample no.10).
26 - 27. *Central Pumice Cone Wall Obsidian, Newberry Caldera.* Source is Higgins, 1973:474 (samples no.42 and 43; trace-element abundances for 42 appear on p.483).
28. *Cleetwood Dacitic Obsidian, Crater Lake.* Collected at rim drive about ¼ mile north of Cleerwood (Cleetwood?) trail. Source is Jack and Carmichael, 1969:26 (sample Cam 125).
29. *Cloudcap Obsidian, Crater Lake.* Collected near the road junction to the summit. Source is Jack and Carmichael, 1969:26 (sample Cam 126).
30 - 31. *Crater Lake Obsidian.* No specific collection locality is indicated. Source is Griffin *et al*, 1969a:6 (samples no.302 and 303).
32. *East Lake Obsidian Flow, Newberry Caldera.* Specific flow is not indicated, but a later paper by Friedman (1977) identifies the westernmost of the two East Lake flows as *the* East Lake Flow. Source is Friedman and Long, 1976:349.
33 - 34. *East Lake Obsidian Flows, Newberry Caldera.* Specific flow sampled is not indicated. Source is Higgins, 1973:274 (samples no.39 and 40).
35. *East Lake Obsidian Flow, Newberry Caldera.* Obsidian locality is described as "from south of East Lake", probably from one of the two East Lake obsidian flows. Source is Jack and Carmichael, 1969:26 (sample Cam 130).
36. *East Lake Obsidian Flow, Newberry Caldera.* Collected at the easternmost of the two East Lake obsidian flows. Source is Laidley and McKay, 1971:339 (sample EOF).
37. *East Lake Obsidian Flow, Newberry Caldera.* Collected at the westernmost of the two East Lake obsidian flows. Source is Laidley and McKay, 1971:339 (sample MOF).
38. *East Lake Fissure Obsidian Inclusions, Newberry Caldera.* Analysis is a composite of five obsidian inclusions collected at the East Lake Fissure. Source is Higgins and Waters, 1970:2841 (sample no.4).
39 - 40. *Game Hut Obsidian Flow, Newberry Caldera.* Source is Higgins, 1973:475 (samples no.48 and 49).
41. *Glass Buttes, Central Oregon.* Collected next to the highway near Glass Buttes. Source is Ericson, 1977:20,92 (sample 20-1-0-1).
42. *Glass Buttes, Central Oregon.* Source is Griffin *et al*, 1969a:6 (sample no.315).
43. *Glass Buttes, Central Oregon.* Collected in scree by road off Highway 20. Source is Jack and Carmichael, 1969:26 (sample Cam 126).
44. *Glass Buttes, Central Oregon.* Source is Keller and Huang, 1971:310.
45. *Glass Buttes, Central Oregon.* Source is Stevenson *et al*, 1971:23.
46 - 48. *Glass Mountain, Central Oregon.* Collected in a road cut 7.4 miles south of the junction between Highways 20 and 395. The trace-element abundances in analysis probably came from one of the specimens associated with analyses 68 and 70, but this was not made clear in the source, Ericson, 1977:20,92 (samples 19-1-0-6 and 19-2-0-2).
49. *Interlake Obsidian Flow, Newberry Caldera.* Collected near Paulina Lake. Source is Beyer, 1973:18 (sample ILO).
50 - 51. *Interlake Obsidian Flow, Newberry Caldera.* Source is Higgins, 1973:475 (samples no.52 and 53; trace-element abundances for no.52 appear on p.483).

52. *Interlake Obsidian Flow, Newberry Caldera.* Obsidian collected from "between Paulina and East Lake". This could refer to any of several sources, but the Interlake Flow is the most prominent. Source is Jack and Carmichael, 1969:26 (sample Cam 133).

53. *Interlake Obsidian Flow, Newberry Caldera.* Source is Laidley and McKay, 1971:339 (sample TOF).

54. *Llao Rock Dacite, Crater Lake.* Source is Jack and Carmichael, 1969:26 (sample Cam 124).

55. *Northeast Caldera Obsidian, Newberry Caldera.* No specific locality mentioned. Source is Jack and Carmichael, 1969:26 (sample Cam 129).

56. *Northeast Oregon Obsidian.* No specific location is given. Source is Stevenson *et al*, 1971:23.

57 - 59. *Obsidian Cliffs, High Cascades.* 59 was collected at the mid-point of the flow; 60 came from near the vent at the western foot of the Middle Sister. Source is Anttonen, 1972:92 (samples no.91, 92 and 93).

60. *Paulina Lake Obsidian and Rhyolite Dome, Newberry Caldera.* Not specified which of the two domes at this site were sampled. Source is Higgins, 1973:473 (sample no.33).

61. *Paulina Peak Obsidian, Newberry Caldera.* Porphyritic obsidian collected near Paulina Peak, the highest point on Newberry Volcano. Source is Jack and Carmichael, 1969:26 (sample Cam 132).

62. *Rock Mesa Obsidian Flow, South Sister.* Source is Anttonen, 1972:92 (sample no.90).

63. *South Sister Chain of Obsidian Domes.* Collected from the northern margin of the north dome of the Devils Hill obsidian dome alignment. Source is Taylor, 1978:43 (sample no.448).

64. *South Sister Newberry Obsidian Flow.* Collected on the southwest side of Green Lakes. Source is Anttonen, 1972:92 (sample no.92).

65. *South Sister Newberry Obsidian Flow.* Source is McBirney, 1968:104 (sample no.7, table 12).

66. *South Sister Newberry Obsidian Flow.* Collected 0.5 km west of Green Lake. Source is Taylor, 1978:37 (sample no.26).

67. *South Sister Newberry Obsidian Flow.* Collected at the south tip of the flow. Source is Taylor, 1978:37 (sample no.28).

68. *South Sister Newberry Obsidian Flow.* Red and black banded obsidian collected at 6620' elevation at the south margin of the flow. Source is Taylor, 1978:41 (sample no.271).

69. *South Sister Newberry Obsidian Flow.* Glassy block collected at 7260' elevation about 0.5 km east of the source vent. Source is Taylor, 1978:43 (sample no.446).

70. *Squaw Ridge Obsidian, Central Oregon.* Loose piece of weathered obsidian collected near the eastern base of Squaw Ridge, Lake County, about ¼ mile south of a prominent west-northwest trending fault scarp (see Skinner, 1980, for location). Unpublished XRF analysis by the author.

71. *Three Sisters Obsidian.* No specific source is mentioned. Source is Stevenson *et al*, 1971:23.

72. *Three Sisters Obsidian Block, South Sister.* A block of obsidian collected at the northeast margin of Holocene lava, 0.5 km north of Moraine and Green Lakes trail junction. Source is Taylor, 1978:38 (sample no.134).

73. *Tumalo Creek Obsidian, Three Sisters.* Collected from the base of a flow exposed in cliffs at 7160' elevation on the southwest fork of the North Fork of Tumalo Creek. Source is Taylor, 1978:38 (sample no.134).

74. *Yamsay Mountain Obsidian, Central Oregon.* Collected in NE¼NW¼ Sec.11, T.30S., R.13E. Source is Hering, 1981:174 (sample 54).

75. *Yamsay Mountain Obsidian, Central Oregon.* Collected in SW¼NE¼ Sec.31, T.31S., R.13E. Source is Hering, 1981:174 (sample 55).

76 - 80. *Big Obsidian Flow, Newberry Caldera.* All specimens collected at an unspecified part of the obsidian flow with about a 2 m diameter area. Source is Green, 1965:40 (samples 1, 4, 7, 8 and 14).

Plate IV-1 (left): The Big Obsidian Flow and other Newberry Caldera obsidian sources. The Big Obsidian Flow is in the near foreground. Directly in the center of the picture, but obscured by trees, the Game Hut Obsidian Flow is closely skirted by the road. The cliffs in the left background mark the end of the Northeast Obsidian Flow, one of the earliest obsidian flows in the caldera. Taken facing northeast from Paulina Peak.

Plate IV-2 (below): The Interlake Obsidian Flow, Newberry Caldera. This Holocene obsidian flow, the area of few trees in the center of the photograph, broke out from a vent at the base of the north caldera wall. The flow was split by the Central Pumice Cone whose slopes can be seen on the right of the picture. One arm of the flow extended to East Lake, the other to Paulina Lake (in the lower left corner of the photograph). Taken facing north from the summit of Paulina Peak.

Plate IV-3: Squaw Ridge Obsidian Source. Squaw Ridge is the mountain in the middle distance on the left of the photograph. The mountain is bisected by the prominent north-northwest trending fault that runs through the center of the picture. Much of the area to the left of the fault-controlled valley is covered by small nodules of obsidian. Taken facing north from Lava Mountain.

Plate IV-4: East Lake Fissure. This fissure, the southern end of the Northwest Rift Zone, rises several hundred metres above the north shore of East Lake. Mixed with the basaltic andesite at this fissure vent are inclusions of obsidian. Taken facing north from the East Lake Hot Springs.

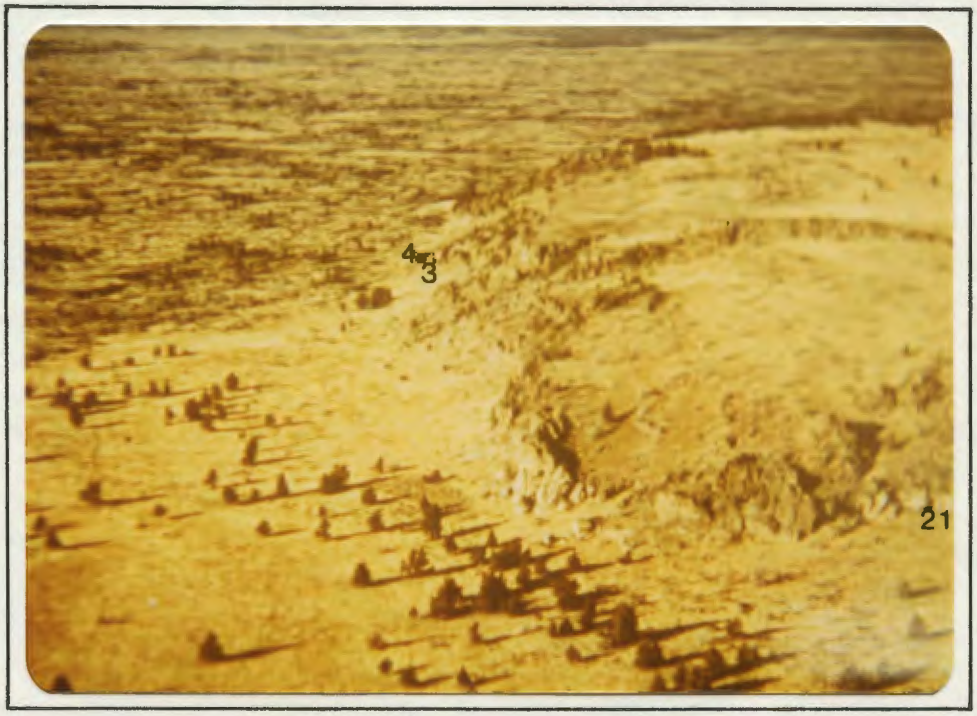

Plate IV-5: Aerial oblique view of the north end of Cougar Mountain. The numbers mark the location of the four Cougar Mountain archaeological cave sites. Many areas on the sides and top of this volcanic dome are littered with nodules of obsidian that have weathered out of the rhyolitic matrix of the mountain. The early Holocene basalts of the Devils Garden are in the background. Taken facing north (from a photograph in Cowles, 1973:109).

Plate IV-6: Winter Ridge. The striking exposure of white rock, a rhyolitic ash-flow, overlies a cliff of breccia and obsidian boulders. Taken facing southwest.

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ADDENDUM (Additions since the completion of the main body of this appendix)

Berri, Dulcy A. 1982. Geology and Hydrothermal Alteration, Glass Buttes, Southeast Oregon, unpubl. Master's thesis, Portland State Univ.: Portland, OR, 125p.

The geologic structure, petrogenesis and hydrothermal alteration of the eastern half of the Glass Buttes are described and several obsidian units are mentioned (and shown on an accompanying geologic map). The major element composition of one obsidian sample is included.

Berri, D.A.; M.L. Cummings and M.J. Johnson. 1983. "Geology and Alteration of a Pliocene Silicic Volcanic Center, Glass Buttes, Oregon (Abstract)", GSA Abstracts With Programs, Vol.15, no.5, p.326.

The geology of Glass Buttes is very briefly summarized.

Beeson, Marvin H. 1969. A Trace Element Study of Silicic Volcanic Rocks, unpubl. Ph.D. dissertation, Univ. of California: San Diego, CA, 130p.

Includes the trace element composition of a single Glass Buttes obsidian sample.

Clark, James G. 1983. Geology and Petrology of South Sister Volcano, High Cascade Range, Oregon, unpubl. Ph.D. dissertation, Dept. of Geology, Univ. of Oregon: Eugene, OR, 235p.

The major and trace element composition of several of the South Sister Chain of Domes (90), the South Sister Newberry Obsidian Flow (91), the Rock Mesa Flow (82) and the Rock Mesa Vicinity Small Obsidian Dome (92) are listed on pages 204 and 205. These flows are also briefly described on pages 29 through 33. A geologic map locating the flows is included.

Fiebelkorn, Robin B.; George W. Walker; Norman S. MacLeod; Edwin H. McKee and James G. Smith. 1982. Index to K-Ar Age Determinations for the State of Oregon, U.S. Geological Survey Open-File Report 82-596, 40p.

Potassium-argon dating information is listed for obsidian found at the Ash-flow West of Fort Rock (source 2, this appendix), Beatys Butte (3), Burns Butte (8), China Hat (13), Cougar Mountain (21), Drews Valley Ranch (31), East Butte (33), Egli Ridge (36), Hager Mountain (45), Horse Mountain (47), Glass Buttes (40), the John Day Formation (50), McComb Butte (61), McKay Butte (63), Newberry Volcano (several sources), Quartz Mountain (78), the Squaw Butte Area Dome (92), Squaw Butte (93) and Tucker Hill. In addition, obsidian from two other sources not listed in the main body of this appendix are also named. They are:

1. Venator obsidian (43°21.2'N lat., 118°31.6'W long.; Harney County) - K-Ar ages of 16.1 ± 0.3 and 15.7 ± o.3 m.y.
2. Dome with obsidian (43°14.0'N lat., 118'30.7' W long.; Harney County) - K-Ar age of 9.3 ± 0.2 m.y.

Greene, Robert C. 1976. Volcanic Rocks of the McDermitt Caldera, Nevada, Oregon, U.S. Geological Survey Open-File Report 76-753, 80p.

Several outcrops of obsidian are described from this large Miocene caldera on the Oregon-Nevada border, though none was reported from within the Oregon portion of the caldera. Obsidian is often found associated with calderas and sources may well exist in the caldera in Oregon. The McDermitt Area (62) and Valley of the Giants (99) sources described in this appendix may lie in the boundaries of the McDermitt Caldera.

Hughes, Scott S. 1983. Petrochemical Evolution of High Cascade Volcanic Rocks in the Three Sisters Region, Oregon, unpubl. Ph.D. dissertation, Oregon State Univ.: Corvallis, OR, 199p.

The major and trace element composition of the Obsidian Cliffs (72) and Rock Mesa (82) obsidian flows and two of the South Sister Chain of Domes (90) is listed on page 131.

Rytuba, James J.; Scott A. Minor and Edwin H. McKee. 1981. Geology of the Whitehorse Caldera and Caldera-Fill Deposits, Malheur County, Oregon, U.S. Geological Survey Open-File Report 81-1092, 19p., geologic map.

Black perlitic obsidian was found in the rocks underlying the Whitehorse Caldera in southeastern Oregon (at a depth of 170-180 m), though no surface obsidian was reported.

Sappington, Robert L. 1982. "X-Ray Fluorescence Analysis of Obsidian Artifacts from Lava Island Rockshelter", in Lava Island Rockshelter: An Early Hunting Camp in Central Oregon, by R. Minor and K.A. Toepel, Heritage Research Associates Report No.11: Eugene, OR, p.125-139.

103 obsidian artifacts were characterized, using their trace element abundances, and compared with 19 characterized obsidian sources. One of these sources, called by Sappington the Fort Rock Source, is not listed in the preceding list of Oregon obsidian sources, but may represent a source described under another name.

Toepel, Kathryn A. and Robert L. Sappington. 1982. "Obsidian Use in the Willamette Valley: Trace Element Analysis of Obsidian from the Halverson Site", Tebiwa Journal, Vol.19, p.27-40.

98 obsidian artifacts from the Halverson Site (located in the southeast Willamette Valley) were characterized, using their trace element composition, and compared with 16 characterized obsidian sources located in central and eastern Oregon. 51 items (only 13.6% by weight) appear to have originated from Tucker Hill, a source 260 km east of the Halverson Site, while 36 specimens came from the Obsidian Cliffs source in the High Cascades. The presence of Tucker Hill obsidian in the Willamette Valley was attributed to contact between the Kalapuya of the Willamette Valley and the Molala of the western Cascades.

Toepel, Kathryn A.; Robert L. Spear; Robert L. Sappington; Ruth L. Greenspan and Paul W. Baxter. 1983. "Patterns of Prehistoric Land Use in Central Oregon: A BPA Transmission Line Study", in Contributions to the Archaeology of Oregon, 1981-1982, ed. by D.E. Dumond, Association of Oregon Archaeologists Occasional Papers No.2: Portland, OR, p.99-122.

This paper provides a summary of the obsidian characterization information presented in detail in Toepel and Beckham (1981) and Sappington and Toepel (1981).

Tucker, Elizabeth R. 1975. Geology and Structure of the Brothers Fault Zone in the Central Part of the Millican SE Quadrangle, Deschutes County, Oregon, unpubl. Master's thesis, Oregon State Univ.: Corvallis, OR, 88p.

Tucker mentions (on page 35) that small grains of obsidian are found in aeolian deposits of sand found on the south side of Pine Mountain. While this is of little archaeological interest, the presence of the obsidian particles suggests the presence of a nearby more massive deposit of natural glass.

Walker, George W. 1981. Uranium, Thorium, and Other Associations in Silicic Volcanic Complexes of the Northern Basin and Range, A Preliminary Report, U.S. Geological Survey Open-File Report 81-290, 47p.

Obsidian samples collected in southern Malheur County are described: "...vitrophyre or rhyolite obsidian from glassy selvages on either flows or possibly ash-flow tuffs. These glassy selvages, which occur in places on top of flow units, are thought to represent chilled upper surfaces of flows, inasmuch as eutaxitic features are not recognizable in thin-section; however, they may be chilled parts of thick, thoroughly remobilized ash-flows in which vitro-clastic (eutaxitic) textures have been largely or completely destroyed through remelting and flowage."

Wozniak, Karl C. 1982. Geology of the Northern Part of the Southeast Three Sisters Quadrangle, Oregon, unpubl. Master's thesis, Oregon State Univ.: Corvallis, OR, 98p.

Rock Mesa (82) and the South Sister Chain of Domes (90) are briefly described and placed at between 1900 and 2200 radiocarbon years in age. A dacite unit (PsDaLa3) exposed on the north flank of the South Sister between Carver and Skinner glaciers that may be a source of obsidian is also described on page 37: "At scattered localities in the pumiceous breccia, thin ribbons and lenses of dense, black glass are intercalated with lenses and bands of red pumice to form undulated bodies of ribboned rock." The composition of the glass is reported (as sample 1718).

Workers of the Writers' Program of the Work Projects Administration in the State of Oregon. 1940. Oregon: End of the Trail, Binfords & Mort: Portland, OR, 549p.

On page 470, obsidian from Glass Buttes is described as having been found in Ohio mounds. This book is probably the major source of the unsubstantiated rumor that obsidian artifacts made from Glass Buttes obsidian have been found in the Midwest of the United States.

Hales, P.O. 1974. Geology of the Green Ridge Area, Whitewater River Quadrangle, Oregon, unpubl. Master's thesis, Oregon State Univ.: Corvallis, OR, 90p.

Fiamme (obsidian-like) lenses were noted in an outcrop of ash-flow tuff in the Middle Fork of the Street Creek drainage in the Central Cascades. The outcrop, located on the east slope of the Cascades, is located in SW¼ Sec.28, T.11S., R.10E. at an elevation of 3700 feet.

Hook, Richard C. 1982. The Volcanic Stratigraphy of the Mickey Hot Springs Area, Harney County, Oregon, unpubl. Master's thesis, Oregon State Univ.: Corvallis, OR, 66p.

A thin and very localized dacite obsidian-like ignimbite layer was located at an elevation of 8,000 feet in the upper part of the Mosquito Creek Canyon. The outcrop is located in the Steens Mountains near Mickey Hot Springs.

Stafford, Howard S. 1935. A Regional Geographical Study of Guano Valley, A Section of the Basin Range Area of Southeastern Oregon, unpubl. Master's thesis, Dept. of Geography, Univ. of Oregon: Eugene, OR, 79p.

Obsidian is mentioned from the Guano Lake area. This description is virtually identical to the one provided by Cressman (1936) in his description of the archaeology of the Guano Lake Valley.

Little Garden Obsidian Update (see source 54): This source was tentatively characterized using the trace element composition of two samples collected at this source (Rb = 119 and 120 p.p.m.; Sr = 6 and 5 p.p.m.; Zr = 227 and 223 p.p.m.). A single artifactual obsidian flake collected approximately 1 km south of the Little Garden obsidian-rhyolite domes in a large surface site (several hundred thousand obsidian flakes) was similarly characterized (Rb = 96 p.p.m.; Sr = 32 p.p.m.; Zr = 126 p.p.m.). The trace element composition of this single flake suggests that it originated from the Cougar Mountain quarry site located about 6 km south of the surface site. Numerous scatters of obsidian flakes are found in the vicinity of the Derrick Lava Tube System (see Skinner, 1983, main bibliography of this project, for a description of this 4.2 km long largely collapsed lava tube system).

Johnson, Keith E. and Eugene V. Ciancanelli. 1984. "Geothermal Exploration at Glass Buttes, Oregon", Oregon Geology, Vol.46, no.2, p.15-18.

The geology of Glass Buttes is described.

Bacon, Charles R. 1983. "Eruptive History of Mount Mazama and Crater Lake Caldera, Cascade Range, U.S.A.", Journal of Volcanology and Geothermal Research, Vol.18, no.1/4, p.57-115.

The late eruptive history of Mount Mazama (which included the extrusion of several obsidian-dacite flows or domes) is described in detail.

Fiebelkorn, Robin B.; George W. Walker; Norman S. MacLeod; Edwin H. McKee and James G. Smith. 1983. "Index to K-Ar Determinations for the State of Oregon", Isochron/West, August.

Adapted from Fiebelkorn et al., 1982.

Priest, George R.; Beverly F. Vogt and Gerald L. Black, eds. 1983. Survey of Potential Geothermal Exploration Sites at Newberry Volcano, Deschutes County, Oregon, DOGAMI Open-File Report O-83-3, 174p.

Articles by several authors describe the geology and geothermal potantial of Newberry Volcano.

APPENDIX V

A Preliminary Investigation of Obsidian Recovered from a Geologic Source in the Inman Creek Area, Western Willamette Valley, Lane County, Oregon

An unexpected secondary source of artifact-grade obsidian has been found in alluvial gravels on the western side of Oregon's Willamette Valley in the Inman Creek area. Three samples were characterized using their trace-element composition and compared with known sources of obsidian that occur in the High Cascades to the east. Preliminary results indicate that no known sources contributed obsidian to the Willamette Valley source. In addition, two distinct sources, based on distinctive trace-element populations, are suggested. The original source of the obsidian is suspected to lie in the Oregon Coast Range or, possibly, may be an unidentified or glaciated source in the Cascades. Future obsidian hydration or characterization studies of obsidian archaeological material found in the Willamette Valley will need to take the Inman Creek source into account.

INTRODUCTION

Inman Creek is a short tributary to the Fern Ridge Reservoir in Lane County, entering the northwest side of the reservoir in NW¼ Sec.8, T.17S., R.6W. Fern Ridge Reservoir, located on the western margin of the Willamette Valley not far from Eugene, is fed primarily by the Long Tom River, a westward-flowing river originating in the Oregon Coast Range. Prior to the construction of the reservoir in the 1940's by the U.S. Army Corps of Engineers, Inman Creek was a tributary to the Long Tom River.

Inman Creek, now only a few kilometres long, would be of little interest to geologists or archaeologists were it not for the fact that in the gravels of this diminutive stream is an unusual and puzzling occurrence of water-worn obsidian nodules. When broken open, these heavily-eroded rocks are revealed to be a fine, artifact-grade of jet-black and occasionally red and black volcanic glass.

OBJECTIVES OF THIS STUDY

The objectives of the brief investigation presented in this appendix were designed to shed some light on the origins of the obsidian found at Inman Creek. They were:

1. To examine the geologic and geomorphic context of the obsidian.
2. To characterize the obsidian found here through the determination of trace element abundances by X-ray fluorescence spectrometry.
3. To attempt to correlate, using trace element compositions, the obsidian found at Inman Creek with that of obsidian from known sources of obsidian in the western drainage of the Cascade Mountains east of the Willamette Valley.
4. To ascertain the impact that this Willamette Valley obsidian source might have on the study of Willamette Valley prehistory.

A one day investigation of the Inman Creek area was made in January, 1982, and several samples were easily found and collected at the lower end of Inman between the road and the reservoir. These samples were used for the characterization study reported in this appendix.

Several later trips were also made to the west and south sides of Fern Ridge Reservoir during the annual low-water periods from December to March. Additional obsidian nodules and flakes with attached cortex were found in numerous locations along the western and southern sides of the reservoir (see Figure V-1). The additional obsidian was all collected in the gravel bars of stream beds normally submerged for most of the year. Obsidian has also been reported south of Fern Ridge Reservoir in the Coyote Creek drainage (E. Baldwin, personal communication), but no attempt was made to verify this or to collect samples. A search was made in the Long Tom River channel below Fern Ridge Reservoir to collect more obsidian. The entire length of the Long Tom from the reservoir to the Willamette River, though, has been channelized and lined with rip-rap. No obsidian was found.

THE GEOLOGIC AND GEOMORPHIC CONTEXT OF THE OBSIDIAN

Inman Creek is a small intermittent stream that cuts as much as 2 m into the Ingram geomorphic unit, a former high flood plain of the Willamette River (Balster and Parsons, 1968:9). At least 60 m (200 feet) of alluvial sand, gravel and mudstone were deposited in this area during the late Pleistocene

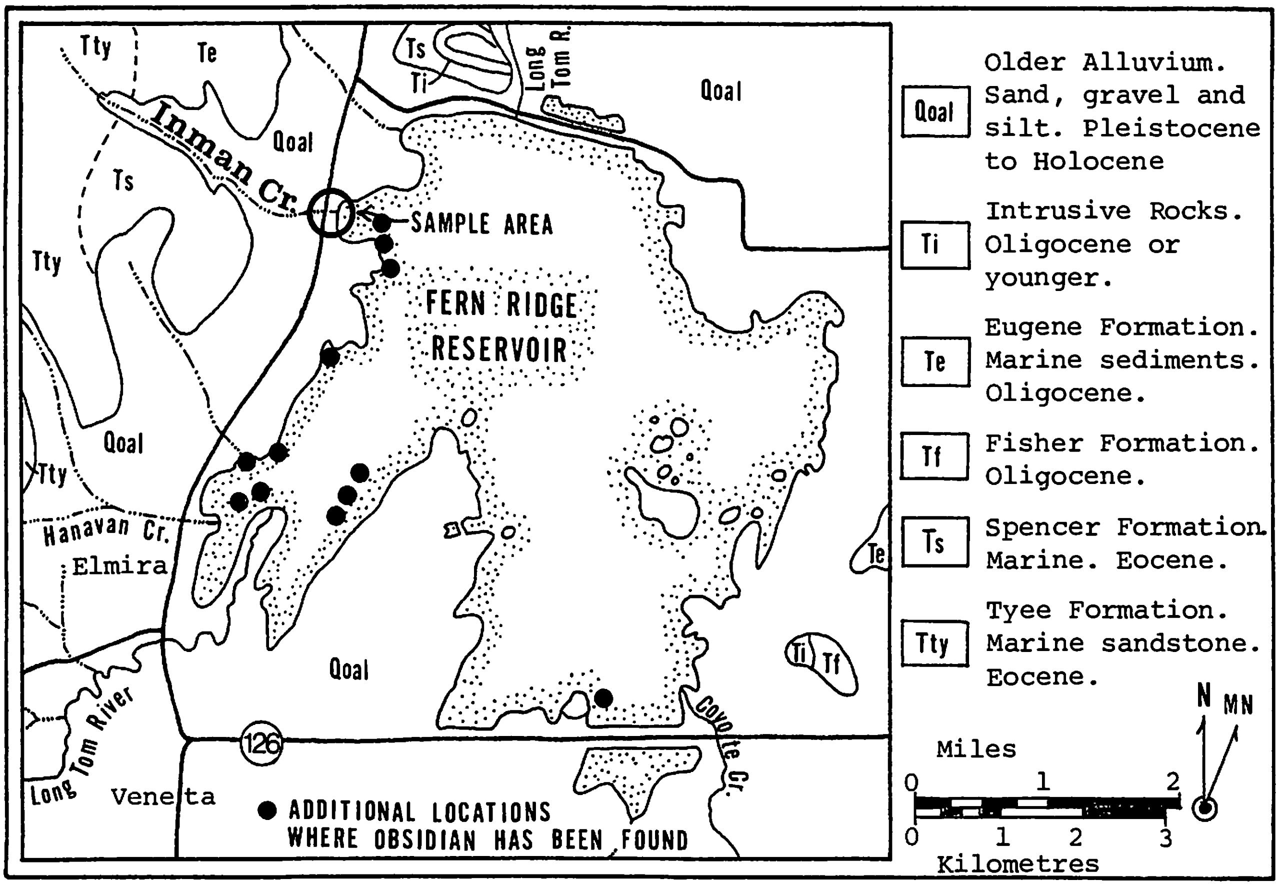

Figure V-1: Geologic sketch map of the Fern Ridge Reservoir and Inman Creek area. Obsidian for this investigation was collected in the stream gravels of Inman Creek in the circled area. Base map is adapted from Frank (1973). Several additional obsidian samples were collected during winter low water-level periods.

and Holocene (Baldwin and Howell, 1949:116-117; Frank, 1973:Plate I). The deposits originated from the western Cascades and the east-central Coast Range of Oregon and were fluvially transported to the Fern Ridge area. Some of the alluvial fill in this area may also have been deposited during the multiple Pleistocene floodings of the Willamette Valley caused by the repeated failure of the ice dam that contained Glacial Lake Missoula (Allison, 1978). Evidence of this catastrophic flood, dated at sometime older than 13,000 years B.P. (Allison, 1978:200) has been found in the southern Willamette Valley as ice-rafted boulders with glacial striations.

Numerous nodules of rounded obsidian can be found in small bars of gravel in the bed of Inman Creek and in other creeks entering the Fern Ridge Reservoir on the west and south sides. The obsidian that was located in a leisurely search of the Inman Creek bed ranged in diameter from 15 cm to less than 1 cm. Nodules in the 5 to 10 cm range were common (see Plate V-1). Near the highway by Inman Creek, nodules were also found *in situ* in a bed of rounded gravels well-cemented by clay. This context of the obsidian is best seen in the banks of Inman Creek about 2 m below the ground surface. It appears that the obsidian found in the Inman Creek gravels originates from this bed and is being removed by the waters of the creek. The clay and gravel-bearing bed dips gently to the east-northeast (towards the Willamette Valley floor) and appears to be widespread in the Fern Ridge area. Obsidian found in other creek or river beds on the western and southern sides of the reservoir always occurred after the water had intersected a bed of resistant gravel and clay identical to the one found at Inman Creek. This bed is easily-identified by the presence of ripples in the stream where it passes over the more resistant layer and by the presence of gravel bars.

The age of this bed is as yet undetermined. A layer of Mazama ash, dated at about 7,000 radiocarbon years, is sometimes found in Willamette Valley sediments (Hansen, 1941; Balster and Parsons, 1968:8), but none was found in the stream-cut channels of the Inman Creek area. Organic matter suitable for radiocarbon dating, if it is present, has yet to be located.

The obsidian source in the Inman Creek area is clearly not a primary one, but is a secondary deposit that has been fluvially transported here. Just where that primary source might have been located is the subject of the next two sections of this appendix.

THE CHARACTERIZATION OF THE OBSIDIAN

The preliminary characterization of the Inman Creek obsidian was done through the determination of selected trace element abundances. The trace element composition of a single obsidian unit is usually, though not always, relatively homogeneous, though it often differs substantially among other regional sources. This combination of intraunit homogeneity and interunit heterogeneity makes it possible to "fingerprint" a source and to correlate an isolated specimen with its original geologic source. This method has often been used to determine the source of artifactual material in archaeological studies (Cann et al., 1970; many other sources also can be found in the archaeological literature), but, to my knowledge, has not been applied to a geologic or geomorphic problem such as the one at Inman Creek.

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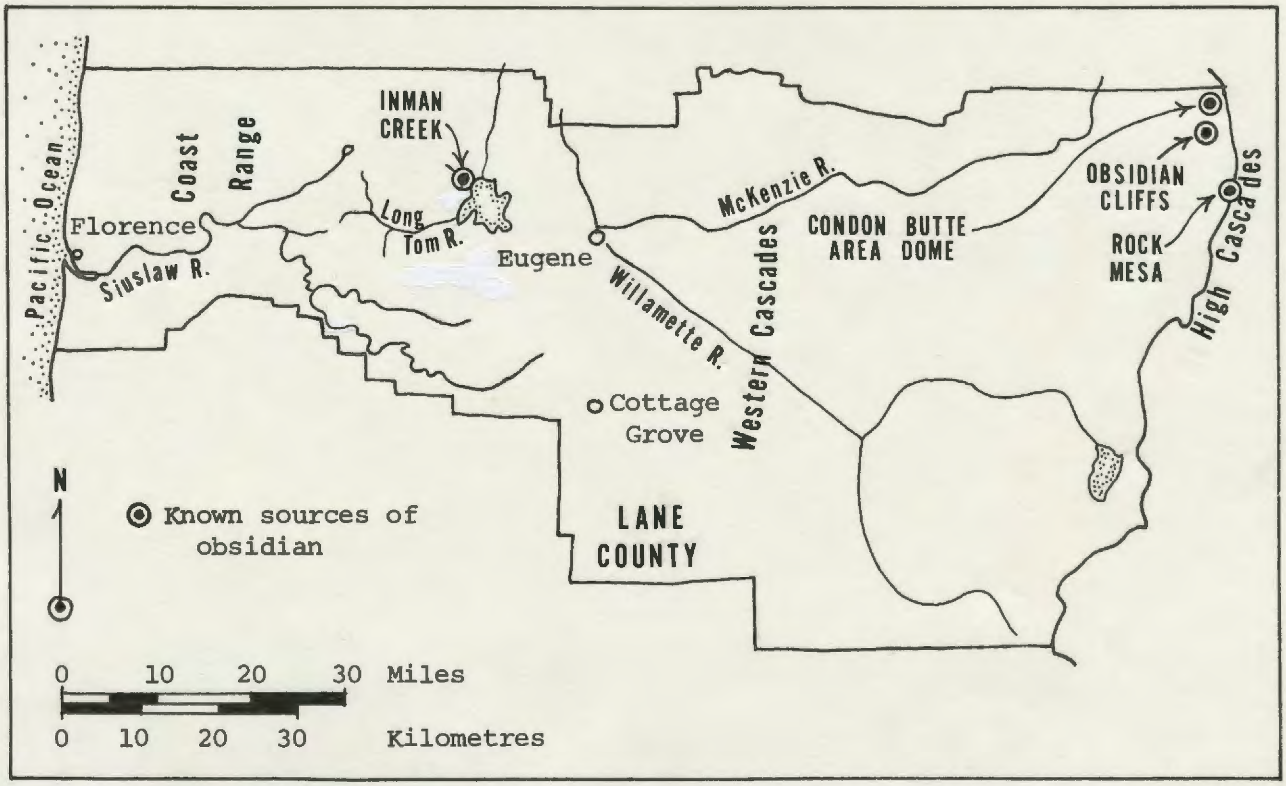

Figure V-2: Known sources of obsidian in the southern Willamette Valley drainage system.

Plate V-1: Typical examples of obsidian nodules recovered from the Inman Creek area.

Plate V-2 (above): A nodule of obsidian is shown *in situ* in a bed of clay and gravel that is intersected here by Inman Creek. Several other streams in this area also cross this same bed, washing out obsidian in the process.

Plate V-3 (left): Obsidian-bearing gravels exposed in the north bank of Inman Creek. The nodule of obsidian shown in the photograph above lies just to the left of the compass and shovel. The obsidian-bearing bed begins just above the shovel handle - nodules up to 10 cm in diameter can be found here and in gravel bars downstream. The bed is somewhat more resistant than the overlying sediments, creating a small shelf at the creek's edge. The shovel is 45 cm long.

Rubidium, Strontium and Zirconium, elements easily determined by the X-ray fluorescence spectrometer at the University of Oregon and ones that have proved useful in previous archaeological characterization studies, were used to characterize the Inman Creek obsidian.

The Method

Three fist-sized obsidian samples were selected from those collected from the Inman Creek gravels in the area shown in Figure V-1. Each nodule was thoroughly cleaned with water and acetone and was then broken into small fragments with a sledge hammer. Pieces free of the weathered cortex were picked and then ground to a fine powder in a Spex shatterbox. 5 gm of the powdered obsidian was placed in a mold with a powdered boric acid backing and pressed at 10,000 pounds pressure to create a cohesive disc.

The disc was placed in a GE XRD-7 Vacuum Spectrometer. Each sample was counted for 200 seconds per element in an air pathway along with U.S. Geological Survey standards of a known composition.

Abundances of Rb, Sr, Y, Zr and Nb were all determined, though only Rb, Sr and Zr were used to characterize the obsidian. Four samples collected by the author at widely dispersed locations on the Obsidian Cliffs flow in the High Cascades were also analyzed along with the Inman Creek specimens. Results of the X-ray fluorescence analysis are reported in Table V-1 along with trace element abundance reported by other authors for the Obsidian Cliff and Rock Mesa flows.

Petrographic Observations

Thin-sections were prepared from two of the Inman Creek samples, INM-1 and INM-2. These were examined for any distinctive microlite structures that might serve to characterize petrographically the Inman Creek source. Both specimens exhibit the presence of prismatic microlites averaging about 10 microns in length in a clear glass groundmass. Particles of magnetite 5 to 10 microns in diameter are also common in both samples. In addition, curved and asteroidal trichites are found in the glass of INM-2. The presence of trichites in obsidian, while not a rare characteristic, is unusual enough to give it some potential as an attribute for characterization. It should also be noted that INM-1 and INM-2 are from geochemically distinct populations, possibly originating from two different primary sources. The presence of distinctive microlite structures may serve to identify from which of the two groups a sample of obsidian originated. This approach would particularly be useful in hydration studies of archaeological materials. These very tentative results suggest that further petrographic study of obsidian from the Inman Creek area may be warranted.

POSSIBLE PRIMARY SOURCES OF THE INMAN CREEK OBSIDIAN

Several different possible primary source areas were considered to be candidates as the original source of the Inman Creek area obsidian. The High Cascades were initially seen as the most likely source area while some tentative evidence pointed to the possibility of an as yet unreported source in the Oregon Coast Range. The only other possible, but unlikely scenarios that could be imagined were that the obsidian arrived on rafts of ice as part of the previously mentioned enormous floods that resulted from the sudden failure of glacially-dammed lakes or that it was carried in by the early valley inhabitants.

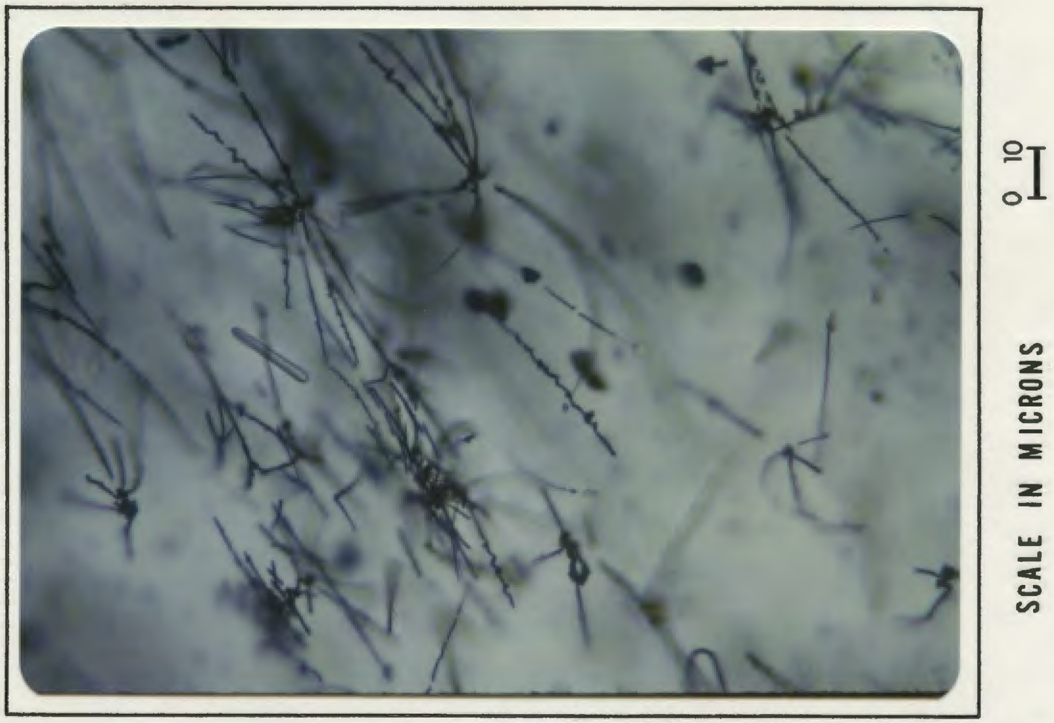

Plate V-4: Photomicrograph of a thin-section cut from INM-2. Spider-like asteroidal trichites, relatively unusual microlitic structures, are the dominant microscopic features in the photograph. Nicols not crossed, x150.

The High Cascades Sources

Three obsidian sources are known to exist in the High Cascades in areas where westward drainage networks might eventually transport material into the southern Willamette Valley. One of these, Rock Mesa, was erupted only about 2,300 radiocarbon years ago, and was considered too recent and unmodified by erosion to be a possibility.

The second possible High Cascades obsidian source is a glaciated unnamed obsidian dome reported about 5 km (3 miles) southwest of the Dee Wright Observatory at the McKenzie Pass (Taylor, 1968:21; 1981:66). A visit to this dome in 1981 revealed that obsidian is no longer present at this site. Taylor surmised that obsidian found at this dome as glassy a glassy selvage had been removed completely by late Pleistocene glaciation and that only small fragments were still found in surficial glacial deposits a few kilometres to the west (Edward Taylor, personal communication).

The third source, and the one considered to be the most likely Cascade contributor to the Inman Creek deposits is the Obsidian Cliffs flow, a large glaciated obsidian flow located west of the North Sister. Obsidian from this flow found its way into the McKenzie River as glacial till and was fluvially transported from there to the southern Willamette Valley in the form of glacial and stream-worn nodules and pebbles. Obsidian recovered from the lower McKenzie River near the Hurd archaeological site has been identified, from trace element analysis, as originating from Obsidian Cliffs (White, 1974:220; 1975:171).

	1	2	3	4	5	6	7	8	9	10	11
Rb	96	88	85	84	79	85	84	--	--	--	--
Sr	116	156	150	110	103	104	103	188	90	99	123
Y	15	20	15	11	14	15	12	--	--	--	--
Zr	79	111	107	102	93	98	96	156	117	123	112
Nb	7	9	7	6	5	12	5	--	--	--	--

1. Obsidian from the Inman Creek gravels (INM-1). X-ray fluorescence analysis by the author.
2. Obsidian from the Inman Creek gravels (INM-2). Collected by Rick Minor. X-ray fluorescence analysis by the author.
3. Obsidian from the Inman Creek gravels (INM-3). X-ray fluorescence analysis by the author.
4. Obsidian from Obsidian Cliffs, Lane County. Collected at the lower portion of the flow by the author. X-ray fluorescence analysis by the author.
5. Obsidian from Obsidian Cliffs, Lane County. Collected near the mid-point of the flow by the author. X-ray fluorescence analysis by the author.
6. Obsidian from Obsidian Cliffs, Lane County. Collected near the vent area by the author. X-ray fluorescence analysis by the author.
7. Obsidian from Obsidian Cliffs, Lane County. Collected at the upper margin of the flow by the author. X-ray fluorescence analysis by the author.
8. Obsidian from Rock Mesa, Lane and Deschutes Counties. Spectrographic analysis by E.M. Taylor (Anttonen, 1972:92: analysis 90).
9. Obsidian from Obsidian Cliffs, Lane County. Spectrographic analysis by E.M. Taylor (Anttonen, 1972:92; analysis 91).
10. Obsidian from Obsidian Cliffs, Lane County. Collected at the mid-point of the flow. Spectrographic analysis by E.M. Taylor (Anttonen, 1972:92; analysis 92).
11. Obsidian from Obsidian Cliffs, Lane County. Collected near the vent. Spectrographic analysis by N.R. Suhr (Anttonen, 1972:92; analysis 93).

Table V-1: Trace element abundances of obsidian from the Inman Creek gravels and from possible sources in the western drainage of the Cascades. Abundances are reported in parts per million.

The Sr and Zr abundances of the Inman Creek obsidian were plotted on a binary graph (Figure V-3) in order to compare them with the Rock Mesa and Obsidian Cliffs sources (only Sr and Zr had reported by other authors for those sources). Abundances were also plotted on a ternary diagram (Figure V-4) so as to compare the Inman obsidian with the Obsidian Cliffs flow.

The results of the trace element analyses for both the Inman Creek obsidian and its comparison with the High Cascades obsidian were rather surprising.

The geochemical data for the admittedly small sample collected at Inman Creek suggest that not one, but two different populations of obsidian are represented. There is a marked variation in Sr and Zr between INM-1 and INM-2/3 that falls well outside the range of analytical error. These two populations are easily distinguishable in Figures V-3 and V-4. While it is possible that a systematic trace element variation like the one indicated at Inman Creek could exist in a single unit (Bowman et al., 1973a; 1973b), the overwhelming majority of obsidian sources are remarkably homogeneous in their trace element composition.

Another surprise came when the composition of the obsidian from Inman Creek was compared to that of Obsidian Cliffs and Rock Mesa. Not only were the Inman Creek samples differentiated, as expected, from the Rock Mesa flow, but were also not part of the Obsidian Cliffs population. It is apparent that the primary source of the Inman Creek obsidian is neither Obsidian Cliffs or Rock Mesa. It may be that the glaciated Condon Butte obsidian dome was the source, as no obsidian from that source was found and analyzed. Also possible is the presence of an unreported source elsewhere in the Cascades.

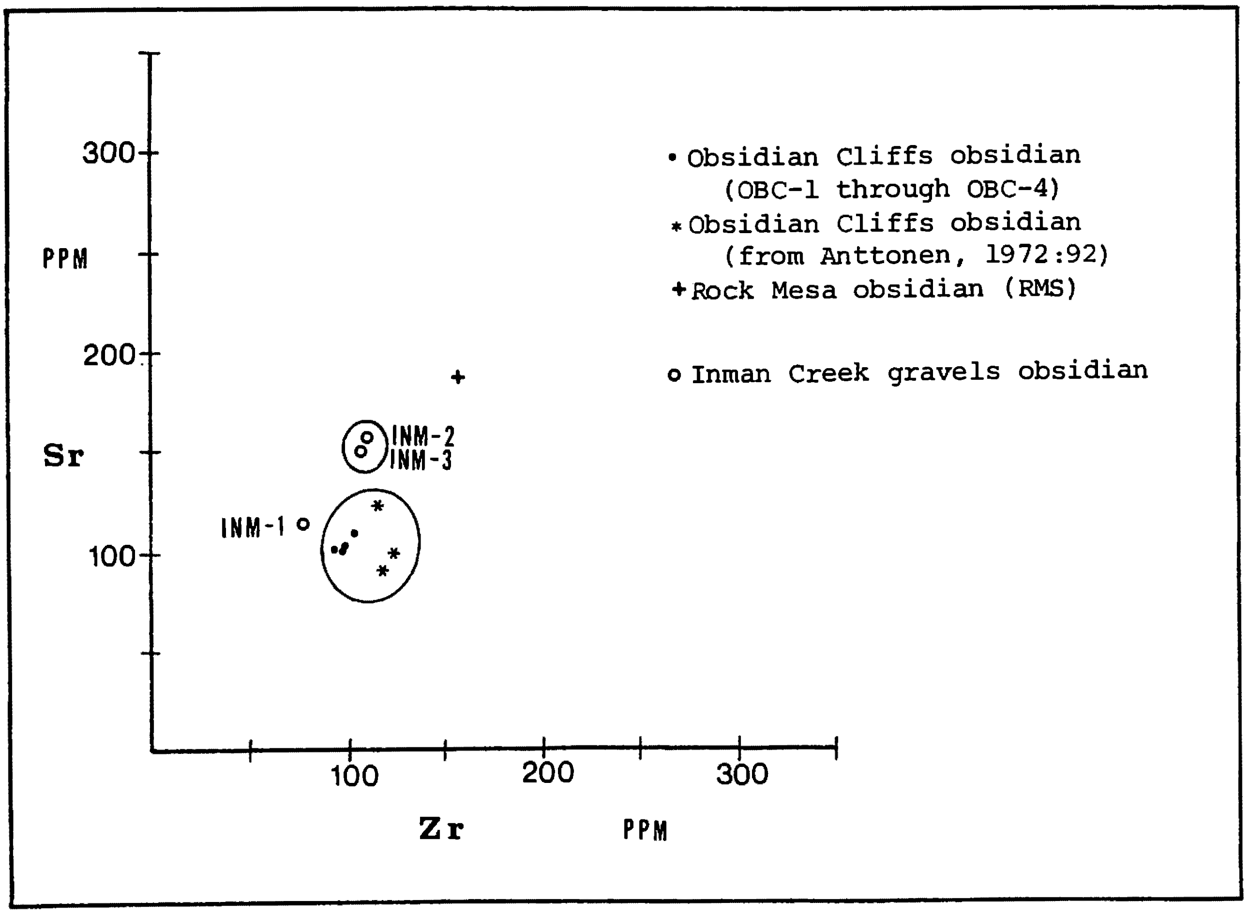

Figure V-3: Graph comparing the ratios of Zirconium and Strontium abundances of obsidian collected at Inman Creek and at possible geologic sources in the western High Cascades.

Coast Range Obsidian Sources

No obsidian has ever been reported in the Oregon Coast Range whose rocks are dominated by early Tertiary marine sediments, basalts and intrusive formations. Geologic field studies of the Long Tom River drainage were made by Zimmerman (1927) and Gandera (1977), both of whom reported no obsidian. There is, in fact, no post-Pliocene volcanism reported anywhere in the central Coast Range (E. Baldwin, personal communication), leading to the conclusion that any original outcrops of obsidian would have become devitrified by now. The Coast Range would not, then, be considered as a likely point of origin for the Inman Creek obsidian were it not for several scattered pieces of evidence that suggest that this is the case:

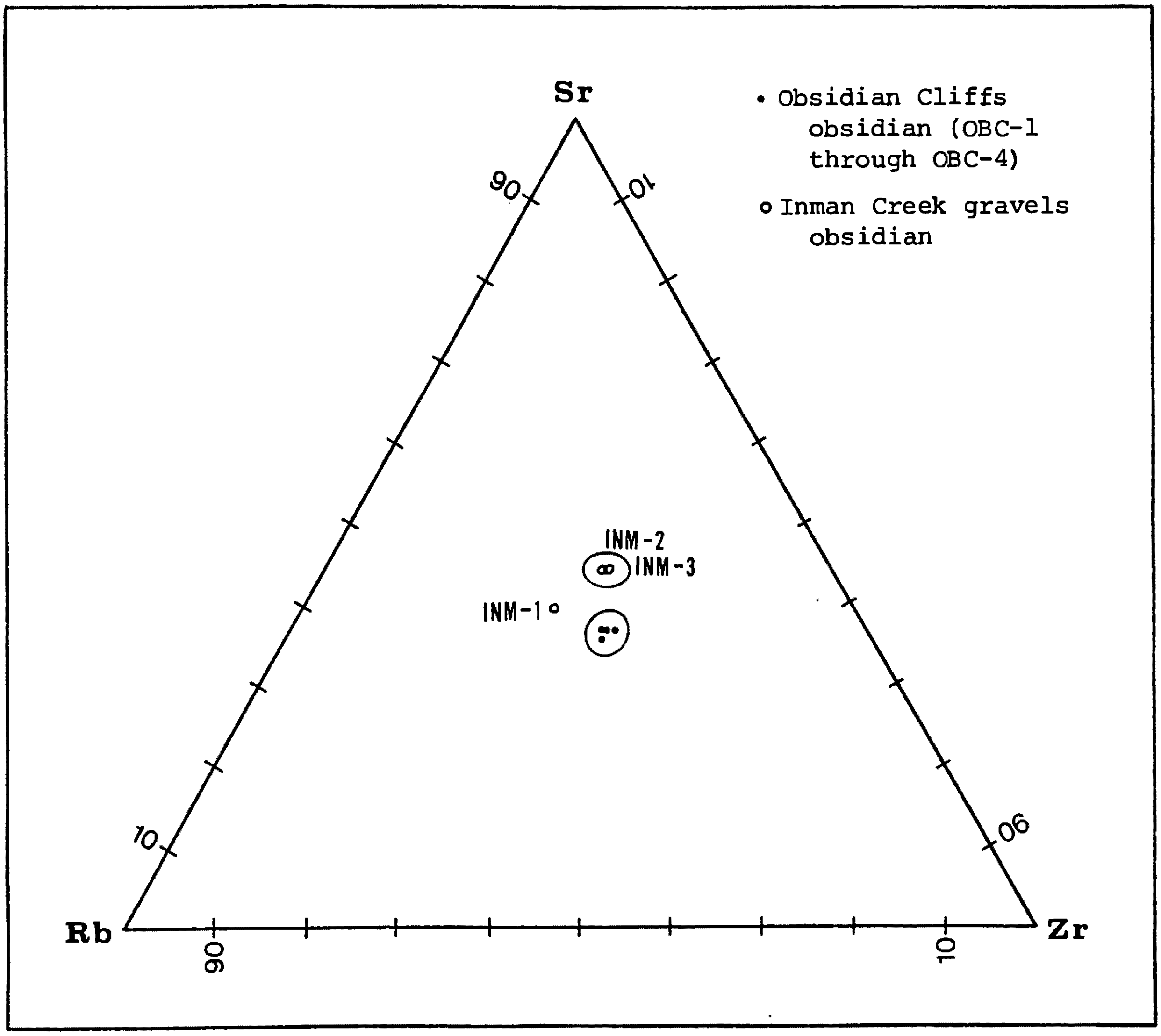

Figure V-4: Ternary diagram comparing the Rubidium, Strontium and Zirconium abundances of obsidian recovered from Inman Creek and from Obsidian Cliffs in the High Cascades, a possible source of the Inman Creek obsidian.

1. Small obsidian pebbles (up to 2 cm, and occasionally larger, in diameter) have been found near the mouth of the Siuslaw River in Florence on the Oregon Coast (Rick Minor, personal communication).
2. A single piece of obsidian was recovered in alluvium (not more that a few metres below the surface) near Noti on a former Long Tom River terrace (Rick Pettigrew, personal communication).
3. The Long Tom River, now a westward-flowing tributary of the Willamette River , was found by Baldwin and Howell (1949) to be a former tributary of the eastward-draining Siuslaw River. A later roadcut in the area of the divide now separating the Siuslaw and Long Tom rivers further substantiates this hypothesis (E. Baldwin, personal communication). It is possible that an obsidian source in the upper Long Tom or Siuslaw River drainages could have contributed volcanic glass both to the east and the west of the Coast Range.
4. A study by a group of Czechoslovakian students (reported by O'Keefe, 1976:29) on the weight loss of pieces of glass as a function of the distance from their source showed that 99% of the mass of the glass was lost in a 40 km distance. The relatively large size of many of the obsidian nodules in the Inman Creek area hints that the primary source of the obsidian is not far removed from this area.

All these points strongly suggest the existence, albeit an unexpected and enigmatic one, of a source or sources of obsidian somewhere in the eastern portion of the Oregon Coast Range.

Human-Introduced Exotic Sources

Another possibility that should be examined is that the obsidian in the Inman Creek area is an exotic introduced by the early pre-White inhabitants of the Willamette Valley. While this would account for the presence of obsidian in a geologic environment where none is expected, it is not considered to be a likely explanation. The sheer quantity of unworked nodules, their apparent distribution over a wide area and their presence *in situ* in alluvial deposits almost certainly negates the possibility that they were introduced from another primary source by human means.

Glacial Erratic Exotic Sources

Allison (1935:622) reports the presence of glacial erratics about 5 km (3 miles) east of Inman Creek in Sec.2, T.17, R.5E., leading to the speculation that the obsidian may have been introduced during one of the flooding episodes mentioned earlier. Allison, however, nowhere notes the existence of any obsidian at any of the 249 localities in the Willamette Valley where erratics were found. This, in addition to the arguments that were advanced about the human-introduced obsidian possibility, makes it very unlikely that obsidian at Inman Creek could have arrived in an iceberg.

THE ARCHAEOLOGICAL IMPLICATIONS OF THE INMAN CREEK AREA OBSIDIAN SOURCE

The obsidian found at Inman Creek, in addition to being a geological curiosity, is also of importance to archaeologists working with lithic materials from the Willamette Valley.

Several archaeological sites are located in the general vicinity of the Fern Ridge Reservoir and the Inman Creek obsidian source. It seems possible, if not likely, that the presence of obsidian, an important lithic material, was known to the prehistoric inhabitants of the southern Willamette Valley. The Virgin Ranch, Smithfield and Perkin's Peninsula sites are all located in the Immediate area of Inman Creek and the Inman area sources. Obsidian artifacts are reported from all three sites, though documentation of the excavations at these locations is minimal (Collins, 1951:58-62). Several kilometres downstream from the reservoir and adjacent to the Long Tom River is the Lingo Site, a midden that yielded numerous artifacts, largely of obsidian (Cordell, 1967; 1975). Obsidian was also a common lithic component at the Benjamin midden sites located not far from the Lingo Site (Miller, 1970; 1975).

Also in the area, about 6 km (4 miles) northwest of the confluence of the Willamette and McKenzie Rivers, is the Flanagan Site, the oldest archaeological site so far located in the Willamette Valley. Obsidian was the least common, but still significant, lithic material represented at the Flanagan Site, making up 21% of the lithic assemblage (Toepel and Minor, 1980:21). The McKenzie River gravels were proposed as the most likely source for the obsidian found at this site.

The only Willamette Valley site in which artifactual obsidian has been characterized is the Halverson Site, a shallow seasonal campsite located in the Mohawk River Valley east of Eugene. Obsidian made up 22% of the lithic assemblage and was the second most frequently used raw material at this site. A representative sample of obsidian from this site was characterized and found to originate primarily from two sources: Obsidian Cliffs in the High Cascades (52% by weight) and Tucker Hill in south-Central Oregon (13% by weight)(Toepel and Sappington, 1982). Inman Creek was, unfortunately, not included in the possible source universe for this study. Only a few obsidian artifacts, though, were not assigned sources, suggesting that Inman Creek was not a source of obsidian for inhabitants of the Halverson Site. Curiously, two obsidian artifacts found at the Lava Island Rockshelter near Bend in central Oregon were found to have probably originated from the Inman Creek source (Sappington, 1982).

Obsidian from the McKenzie River gravels was again the most probable source of the Obsidian Cliffs obsidian found at the Halverson Site. Obsidian in the Willamette and McKenzie River gravels has also been reported by others (U.S. Geological Survey, 1893; White, 1975:171; Minor, 1977; Toepel and Sappington, 1982).

There is no direct evidence from any of these Willamette Valley sites that the Inman area obsidian provided obsidian for artifacts found at these locations. Additional characterization studies will be necessary to determine this. The propensity of obsidian as a raw material, though, certainly inplies that it was readily available in the area. Miller (1975:321) corroborates this when he writes of the Benjamin sites:"Large obsidian artifacts are extremely rare and the very small size of obsidian flakes throughout the site suggest that the primary source of this material was a riverborne pebbles." Whether these pebbles came from the Inman Creek area source, the McKenzie River or the convenient gravels of the Long Tom is not known.

The presence of an obsidian source at Inman Creek and in the Long Tom River gravels downstream from its link with Inman creek carries with it several implications for archaeologists working in the area:

1. Obsidian would have been widely-available in the Willamette Valley as water-transported nodules and pebbles originating from both the High Cascades and the Inman Creek area. This obsidian could have been carried throughout the entire length of the Willamette Valley by the McKenzie, Long Tom and Willamette Rivers.
2. At least three geochemically distinct sources of obsidian (one from Obsidian Cliffs, two from Inman Creek) would have been widely available in the Willamette Valley. This fact is particularly significant in the obsidian hydration analysis of artifactual material from the valley area. Chemical composition is one of the major variables influencing the rate of hydration of obsidian. The presence of three distinct sources implies that obsidians with three different rates of hydration were available as a lithic material. This possibility would lead to the necessity of source-specific obsidian hydration analysis (Ericson, 1975). It is interesting to note that Minor (1980), in working with obsidian artifacts from the Flanagan Site, found a widely scattered distribution of hydration rim thicknesses throughout different excavation levels. Expecting obsidian from just one source (the McKenzie River gravels), he attributed the distribution to mixing or site disturbance. The same scattered rim thickness distribution could also be attributable to the presence of obsidian with different compositions, i.e. different rates of hydration.
3. Any attempt at using obsidian characterized with trace elements to reconstruct prehistoric exchange or contact relationships must consider the existence and possible valley-wide distribution of at least three indigenous and geochemically-distinct obsidian sources.

SUMMARY AND CONCLUSIONS

An unusual and unexpected source of artifact-quality obsidian has been located in alluvial gravels on the western side of the Willamette Valley about 13 km (8 miles) west-northwest of Eugene. The primary source of the obsidian was hypothesized to be in the western drainage of the Cascades. The best-known of these sources was Obsidian Cliffs, a prominent glaciated flow just west of the North Sister. Trace element characterization of three samples of the Eugene area obsidian shows, though, that Obsidian Cliffs was not the primary source of the obsidian found in the Willamette Valley to the west. Additionally, the geochemical data suggest that not one, but two, primary sources are represented in the western Willamette Valley source. Scattered pieces of evidence indicate that the most likely location of the primary obsidian source lies in the Coast Range. Additional field study and characterization will be necessary to identify and locate this primary source or sources of obsidian.

The occurrence of an abundant source of obsidian in the Willamette Valley is also archaeologically-significant. Heretofore, archaeological obsidian recovered in the valley was usually considered to originate in the gravels of the McKenzie River, carried there from the Obsidian Cliffs flow. The presence of several geochemically-discrete secondary sources of obsidian in the Willamette Valley will have to be considered in future studies involving obsidian hydration or the reconstruction of contact and exchange networks based on the characterization and correlation of obsidian artifacts.

Further field sampling and characterization, now currently in progress, will be needed to determine the aerial extent of obsidian distribution and the range of composition of the obsidian found at Inman Creek and in the Willamette Valley.

Acknowledgements

My thanks to Rick Minor, who first told me of the Inman Creek and Siuslaw River sources of obsidian and who provided directions and some of the samples. Thanks also to Dr. Ewart Baldwin for his discussion of the problem and his suggestions and to Rick Pettigrew and Edward Taylor for their helpful information. I only wish that I could tell them where the obsidian came from.

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APPENDIX VI

A Brief Investigation of the Geological and Surface Archaeological Features of the Lava Top Butte Vicinity, Deschutes County, Oregon

Lava Top Butte is an early Holocene to Pleistocene cinder cone located on the northern flanks of Newberry Volcano in central Oregon. Numerous lava caves, including a perennial ice cave and water source, were located in a survey of two basalt flows associated with volcanic activity at the butte. Three of these caves, severely disturbed by artifact collectors, were identified as minor archaeological sites. Artifactual obsidian flakes recovered from two of the three sites were geochemically and petrographically characterized and appear to have originated from one of the two East Lake obsidian flows in nearby Newberry Caldera. Obsidian hydration studies, though originally planned, were abandoned because of the lack of control of the temperature variable in disturbed contexts. This investigation demonstrates that geochemical and petrographic methods may be useful in the study of disturbed sites. The potential importance of ice caves as an archaeological resource in semi-arid climates is also pointed out.

INTRODUCTION

Lava Top Butte is one of more than 400 late Pleistocene to early Holocene basaltic cinder cones located on the flanks of Newberry Volcano, a massive composite volcano centered about 48 km (30 miles) southeast of Bend, Oregon (MacLeod et al., 1981). First described briefly by Williams (1935:279), Lava Top Butte rises about 60 m (200 feet) above the surrounding flows of basalt that make up most of the surface of this area. The summit elevation of the butte is 1662 m (5452 feet). Final eruptive activity at this cinder cone deposited large quantities of welded spatter in the summit area, giving the cone its name and one of the most striking profiles of any of the many cinder cones in this region. The butte is located within the Deschutes National Forest and is generally accessible by unimproved roads from March to November. Topographic map coverage is provided by the Kelsey Butte and Fuzztail Butte 7½' U.S. Geological Survey topographic maps.

OBJECTIVES

The objectives of the brief study that is reported in this appendix were to locate several small cave sites that were reported in the Lava Top Butte area, to evaluate their archaeological significance and to sample any artifactual obsidian that was found. In addition, a geological reconnaissance study, particularly of the flows in which the caves were found, was planned. The obsidian would be later characterized and an attempt would be made to identify its geologic source. Obsidian hydration studies were originally planned, but were later abandoned for reasons that will be discussed below.

Another objective grew out of the discovery of three severely-disturbed (by artifact hunters) archaeological cave sites near the Butte. This was to examine the potential of obsidian analysis in extracting information from surface or disturbed sites, a problem touched on by only a few authors (Talmage et al., 1977). An increasing number of archaeological sites in central Oregon (or almost anywhere where they still exist, for that matter) are being accidentally or deliberately destroyed each year. Low-cost methods of utilizing out-of-context artifactual materials from archaeological sites will become increasingly important in the probable poorly-funded future of archaeological research on Public Lands.

The Lava Top Butte area was visited briefly in 1979, 1980 and 1981. The results of survey and field work made during these visits and the subsequent laboratory study of the recovered obsidian appear in the remainder of this appendix.

GEOLOGY OF THE LAVA TOP BUTTE AREA

Lava Top Butte is found near the northern end of a broad zone of cinder cones that runs north-northwest from the summit caldera of Newberry Volcano. This group of cones is colinear with a zone of faults that extends from the Newberry Volcano summit area to Green Ridge in the Cascade Range (MacLeod et al., 1981:86). Some of the most recent volcanic activity on the flanks of Newberry Volcano is found in this northwestern zone of faults and cinder cones. The Northwest Rift Zone fissure eruptions, dated at about 6,000 radiocarbon years, are located 6.5 km (4 miles) west of Lava Top Butte. A small, unnamed post-Mazama flow of basaltic andesite is also found about 3 km (2 miles) west of the butte (see Figure VI-1).

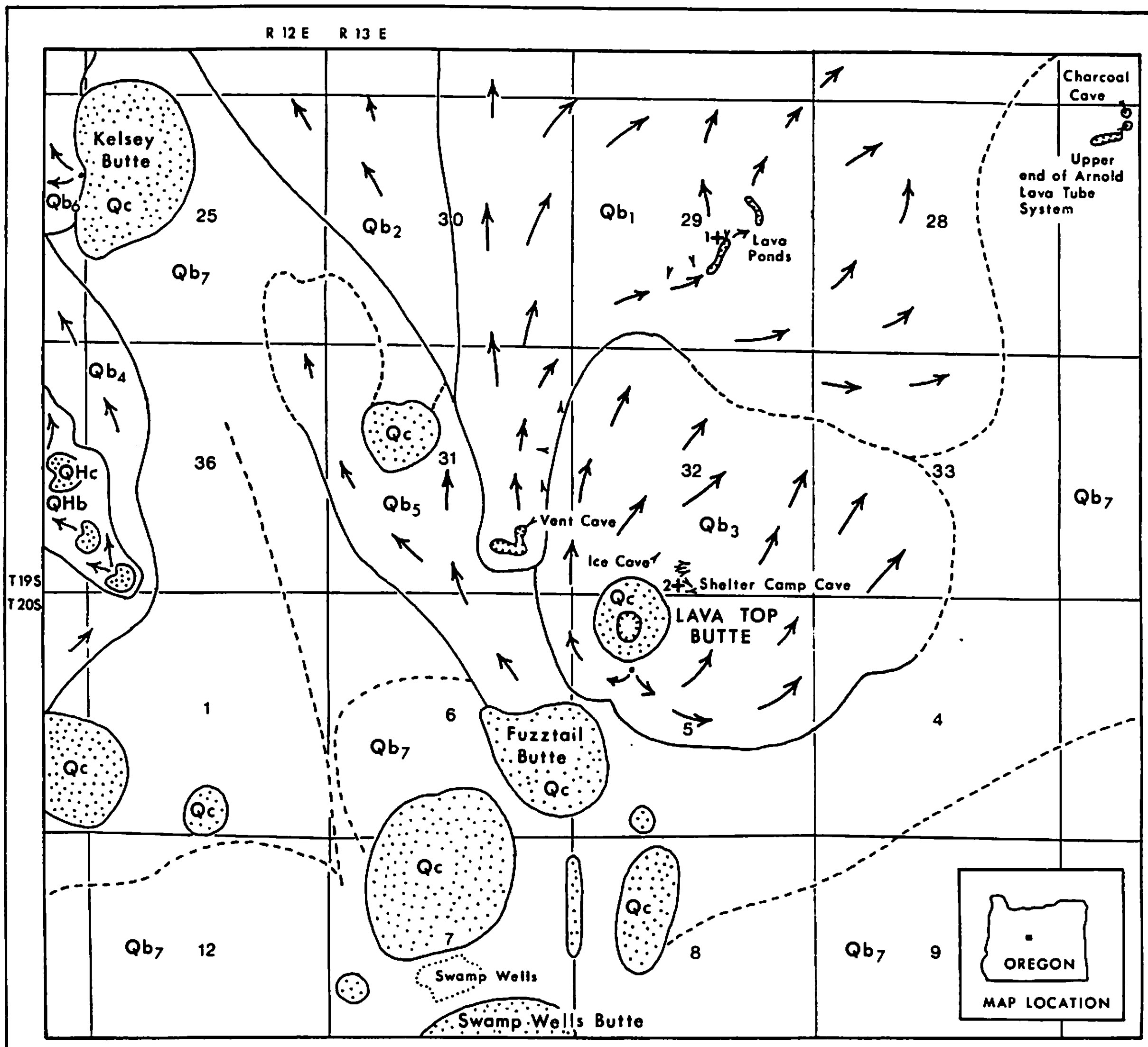
Most of the cinder cones in the Lava Top Butte area also have associated basalt flows, but only those at Lava Top Butte are known to contain lava caves. The basalt flows and cinder cones in the vicinity of Lava Top Butte are summarized and illustrated in Figure VI-1.

Cave-Forming Lava Flows at Lava Top Butte

Two different cave-forming diktytaxitic basalt flows or related groups of flows are found in the immediate vicinity of Lava Top Butte.

A vent at the southern margin of the cone was the source of one of these flows (unit $\underline{Q}b_3$ in Figure VI-1). This basalt flow is referred to here as the South Vent Flow. Basalts from this vent flowed around both sides of the butte and moved downslope to the north and northeast, probably in several eruptive episodes. Basalts on the eastern side of the butte appear better-preserved than those on the western and northern sides, and were probably among the last issued from this vent. Much of the detail of the pahoehoe lavas that were erupted from the south vent has been obscured by a mantle of Mazama tephra and by recent tree-thinning operations. One 4 m (13 foot)-deep rockshelter, a 15 m (50 foot)-diameter chamber entered through a surface blister and a short system of related surface lava tubes were found in this unit. In addition, a 55 m (180 foot)-long perennial ice cave known as the Lava Top Butte Ice Cave was located near the northern base of the butte in an older portion of the South Vent Flow. This cave, the most significant of the three archaeological cave sites located, will be discussed in more detail shortly.

Less than 1 km (.6 miles) northwest of the base of Lava Top Butte is a prominent, irregularly-shaped vent crater up to 14 m (45 feet) deep and about .5 km (.3 miles) long (see Plate VI-1). This vent was the source of a basalt flow or



Geologic Sketch Map of the Lava Top Butte Area, Deschutes County, Oregon

EXPLANATION

QHb	*Unnamed basaltic andesite aa flow. Post-Mazama. Probably same age as nearby NW Rift Zone flows (C_{14} ages of about 6,000 years B.P.).*	Holocene
QHc	*Cinder cones associated with QHb.*	
Qb1	*Northwest Vent Flow. Pahoehoe, olivine, diktytaxitic basalts with well-preserved tumuli, pressure ridges and short lava tubes.*	Early Holocene - Late Pleistocene
Qb2	*Pahoehoe basalt flow, possibly from same vent as Qb_1. Well-preserved surface features suggest only slightly younger than Qb_1.*	
Qb3	*South Vent Flow. One or more flows of olivine flows from vent at south base of cone. Well-preserved surface features and lava tubes.*	
Qb4	*Basalts from vent area about 1 km southwest of QHb. Overlies Qb_6.*	
Qb5	*Pahoehoe basalt flow from unknown vent, probably either at Lava Top or Fuzztail buttes.*	
Qb6	*Basalt flow originating at west margin of Kelsey Butte.*	
Qb7	*Somewhat older flows of basaltic pahoehoe lavas. Overlain by Qb_{1-6}*	
Qc	*Cinder cones. Composed of mafic ash, lapilli, blocks, bombs and agglutinated spatter.*	

2+	Basalt sample location
╱ ⋰	Boundaries of lava flows; solid where known, dashed where indistinct
↙	Direction of lava flow
➤	Cave (lava tube)
○	Depression (collapse depression, crater, or drained lava pond

Geology by C. Skinner - aerial photograph interpretation and field study (1978, 1980). Base map from USGS 7½' topographic maps Kelsey Butte and Fuzztail Butte.

Figure VI-1: Geologic sketch map of the Lava Top Butte vicinity showing the locations of local flows of basalt and basaltic andesite. Several lava caves, three of which were found to be archaeological sites, were found.

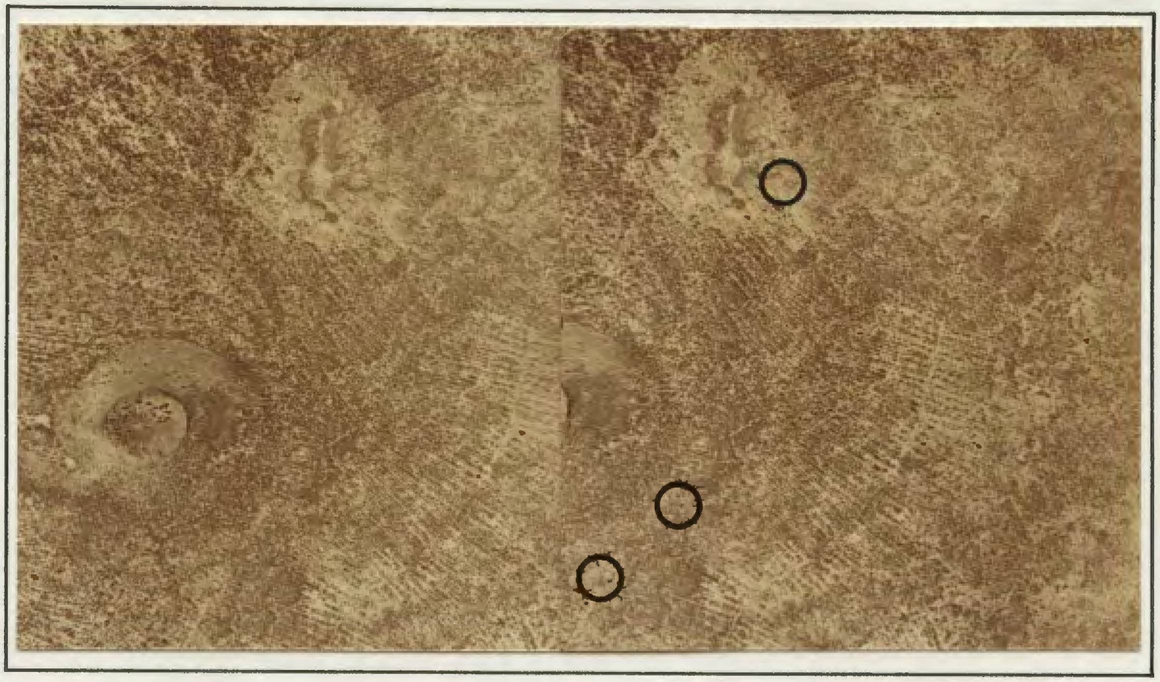


Plate VI-1: Aerial stereoscopic pair showing the Lava Top Butte vicinity. North is to the right. The archaeological cave sites are circled: Vent Cave lies at the northern end of the distinctive vent crater to the northwest of the butte; the Lava Top Butte Ice Cave can be found near the northeast base of the cone; Shelter Camp Cave is directly south of the butte (U.S. Forest Service, 1959).

flows that spread several kilometres downslope to the north and northeast. This basalt unit is designated here the Northwest Vent Flow (unit Qb_1 in Figure VI-1). The flow is characterized by numerous pressure ridges, tumuli, lava channels, occasional drained former lava ponds and several short (6 to 25 m-long) lava tubes. The tubes are found along an axis trending almost due north from the northeast end of the vent crater. Vent Cave, one of six lava caves in this flow described by Greeley (1971:33) passes through the rim of the vent crater, possibly having acted as a drain for lava ponded in the vent crater. Farther downslope, a similar but smaller tube drained another former pond of lava. The largest of the caves known to be found in the Northwest Vent Flow is a 30 m (100 foot)-long lava tube named Log Crib Cave by Greeley (1971:33). This cave was not relocated in a search of the area.

Age of the Cave-Forming Lava Flows

The ages of the two cave-forming lava flows at the butte are difficult to fix with any degree of certainty. They are both covered by Mazama tephra, placing them as older than about 7,000 radiocarbon years B.P. All basalt flows on Newberry Volcano that have been checked for magnetic polarity have been found to be normally polarized, and are almost certainly younger than about 700,000 years (MacLeod et al., 1982:14). The presence of well-preserved lava tubes (uncollapsed with remelted interior linings intact) and relatively unweathered surface features suggests a comparatively recent age for both of these units.

	1	2	3
SiO_2	50.80	50.88	50.70
TiO_2	1.20	1.21	1.30
Al_2O_3	17.89	17.82	18.05
Fe_2O_3	9.17	9.25	1.62
FeO	--	--	6.96
MnO	0.14	0.15	0.40
MgO	7.31	6.86	7.60
CaO	9.40	9.21	9.70
Na_2O	3.19	3.02	2.70
K_2O	0.64	0.47	0.68
P_2O_5	0.30	0.27	0.23
Total	100.04	99.1	100.04
Rb	10	12	--
Sr	449	444	--
Y	21	21	--
Zr	111	119	--
Nb	9	18	--

1. Northwest Vent Flow. Collected at north end of drained lava pond (from Skinner, 1982).
2. South Vent Flow. Collected at entrance to lava tube near Shelter Camp Cave (from Skinner, 1982).
3. Flow on Lava Top Butte (from Williams, 1935:295).

Major elements reported in weight percent oxide; trace elements in parts per million.

Table VI-1: Major and trace element composition of basalts from the Lava Top Butte vicinity.

MacLeod et al. (1982:14) speculate on ages of from perhaps 8,000 to 15,000 years for the younger, pre-Mazama flows on the northwest flanks of Newberry Volcano, though those dates are, of course, conjectural. The Northwest Vent Flow overlies the South Vent Flow, placing it as more recent. The degree of weathering of both of these flows is very similar, though, intimating that activity at the two vents was not greatly separated in time. This is supported by the very similar trace element composition of the two units (Table VI-1), suggesting that they originated from the same body of basaltic magma at about the same time. The durations of 42 observed eruptions in which cinder cones and lava flows have been produced have been compiled by Wood (1980:402-403). He found that cinder cones typically had lava flows originating from their bases and that the range in eruption was from 1 day to 15 years. Ninety-three percent of the eruptions lasted than a year. These observations further suggest that the flows at Lava Top Butte were nearly contemporaneous.

Composition of the Cave-Forming Lava Flows

Basalt samples were collected from the Northwest and South Vent flows (see Figure VI-1) and their composition determined by X-ray fluorescence spectrometry at the University of Oregon (Na determined by atomic absorption). The basalts are of a high alumina calc-alkaline composition typical for this region (MacLeod et al., 1982:14). The nearly identical trace element composition of the two flows strongly suggests a genetic relationship between the two. The composition of a basalt from Lava Top Butte is also shown in Table VI-1 for comparison.

ARCHAEOLOGICAL OVERVIEW OF THE LAVA TOP BUTTE AREA

The prehistory of the Lava Top Butte area is known to date back more than 7,000 radiocarbon years (the approximate date of the Mazama eruption and ashfall) and probably extends back even farther. Despite the relative antiquity of human occupation in this area, only limited archaeological research has been carried out. A number of archaeological sites, though, have been identified in surveys of the area (see Figure VI-4).

An early find in 1934 of two obsidian knives or side scrapers lying below the Mazama tephra horizon first established the length of occupation in the Lava Top Butte region. These artifacts were found near the present site of the Wickiup Reservoir (not shown in Figure VI-4), 42 km (26 miles) west-southwest of Lava Top Butte (Cressman, 1937).

In a later archaeological survey of the Deschutes River margins about 20 km (13 miles) west of Lava Top Butte, 32 small surface sites (sites 1 through 32 in Figure VI-4) were located. The surface collection of artifacts recovered there was noted by Osborne (1950) to show a great deal of similarity to material from Oregon's northern Great Basin to the east, as well as to the nearby Wickiup Reservoir artifacts.

A pipeline survey through the Lava Butte area 13 km (8 miles) west of Lava Top Butte established the presence of two more sites (Combes, 1961:4). One of these, the Lava Butte Site (35DE33), was excavated by the University of Washington in 1961. This major excavation, one of only two in the Lava Butte area, yielded a large quantity of artifacts, some of which were diagnostic. This artifactual material suggested a rather late occupation from about 200 to 500 B.P., as well as cultural affiliations with the northern Great Basin and the Columbia Plateau (Ice, 1962; Toepel et al., 1980: 107-108).

Two small sites, one of which was excavated, were located in a survey of the Sunriver area (Cole, 1977). Both were characterized by a quantity of obsidian flakes. The limited amount of finished artifacts suggested a late occupation date and a possible cultural relationship with the Columbia River area.

The most recent and extensive excavation in the area was at the Lava Island Rockshelter, an early hunting camp found 10 km (6 miles) northwest of Lava Butte and 21 km (13 miles) west of Lava Top Butte. A radiocarbon date of 2150 ± 300 years (DIC-2202) was associated with cultural materials at this site, though the stylistic features of projectile points found suggest a considerably longer period of occupation, possibly as long as 10,000 years.

Another small site in the Lava Butte area, the Rocky Top Site, was reported by Dudley et al. (1979:516). The site was identified as a lithic workshop or campsite-hunting area and was represented by a large scatter of obsidian flakes.

Closer to Lava Top Butte, poorly-documented sites are known to have existed within Newberry Caldera, a source of prodigious quantities of obsidian located 16 km (10 miles) south of the butte (Dana, 1932; Brogan, 1960; Combes, 1961; U.S. Forest Service Service, 1978:531).

Swamp Wells, one of the few sources of water on the north side of Newberry Volcano and only a few kilometres south of Lava Top Butte, has also been identified as an archaeological site (Dudley et al., 1979:506). Though severely impacted by modern recreational use, several thousand obsidian flakes still remain.

Only two kilometres northeast of Lava Top Butte is the southern end of the Arnold Lava Tube System (see the upper right corner of Figure VI-1). This collection of over a dozen intact segments of a 7 km (4.3 mile)-long unitary lava tube exhibits many signs of pre-White use. Charcoal Cave, a segment of the Arnold System, was briefly examined by L.S. Cressman, who in 1936 found evidence that a large amount of wood had been burned in the cave (Cressman and Perry, 1938). Though he was unable to more than hypothesize about the origin of the inexplicably large amounts of charcoal found in the cave, he

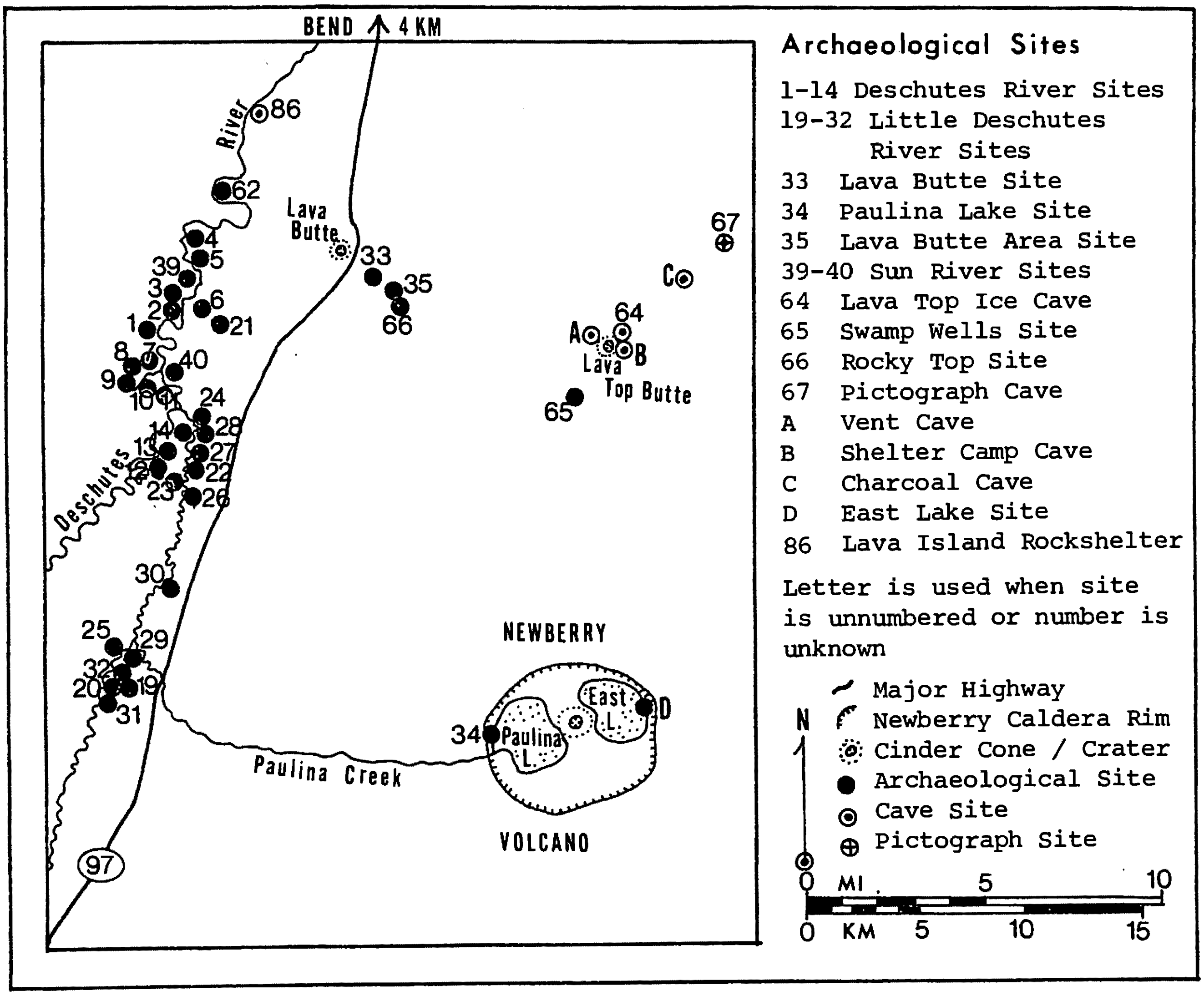


Figure VI-2: Reported and previously unreported archaeological sites in the Lava Top Butte area. The numbers refer to the archaeological site numbers used by the Oregon Museum of Anthropology, i.e. 64 = 35 DS 64, where 35 is the State of Oregon number, DE is the county abbreviation and 64 is the county site number.

mentions that a piece of wood recovered from the cave had been tentatively assigned a dendrochronological age of about 580 years B.P. Also mentioned in the same article were the existence of the remains of two lodges, age unknown, that were found in a collapse depression just southwest of Charcoal Cave. The depression and associated cave are now known as the Hidden Forest Cave (Larson, 1982:17,20,24).

150 m (500 feet) east of Charcoal Cave is Arnold Ice Cave, a well-known perennial ice cave and early source of ice for Bend. Several pictographs are reported from the immediate vicinity of this cave (Loring and Loring, 1982:260-261). The historical or near-historical occupation of the area near Arnold Ice Cave is suggested in this excerpt from an 1889 account of a trip to the cave (Anonymous, 1889): "Ahead of us is the frame of an Indian Wickiup, a few hundred yards beyond a log house [historical] and then, to right and left, huge rock-walled pits [possibly the Hidden Forest Cave] .

Pictograph Cave, another large collapsed segment of the Arnold Lava Tube System, lies a few kilometres northeast of Charcoal Cave. Additional deposits of charcoal (Larson, 1982:29), as well as an assortment of pictographs, have been found at this site (Dudley et al., 1979:526-536,548-557; Larson, 1982:24,29; Loring and Loring, 1982:262-265). Charcoal Cave No.2, a short lava tube near the lower (northern) end of the Arnold Cave System, is also reported to contain charcoal (Larson, 1982:20).

ARCHAEOLOGICAL CAVE SITES AT LAVA TOP BUTTE

Three cave sites, all of them disturbed by artifact hunters, were located in a survey of the Lava Top Butte vicinity.

Shelter Camp Cave

Shelter Camp Cave is a 4 m (13 foot)-long roofed segment of a lava channel located in the South Vent Flow (see Plate VI-1). The south-facing, 2 m (7 foot)-high entrance of this short tube lies at the end of a 12 m (40 foot)-long trench formed by the levees of the former channel. The tephra-covered area in front of the cave that is bounded by the levees contains numerous flakes of obsidian and appears to have been disturbed, possibly by artifact collectors or possibly by the logging operations on this side of the butte about 45 years ago (U.S. Forest Service, 1978:550). The cave provides excellent shelter and the smoke-blackened ceiling and hand-polished protuberances of basalt inside hint that it has seen long use. No obsidian was collected at this cave site. The only mention of this site in any literature was a passing one by Larson (1976), who mentioned the possibility of prehistoric occupation there.

The Lava Top Butte Ice Cave (35 DS 64)

This 55 m (180 foot)-long lava tube is located near the northern base of Lava Top Butte. The north-facing entrance to the cave is at the west end of a 35 m (110 foot)-long and 9 m (30 foot)-wide shallow collapse depression. The area defined by the entrance depression has been almost entirely overturned by collectors searching for artifacts. The presence of several thousand obsidian flakes attests that this was a well-used campsite and possibly a significant archaeological site prior to its virtual destruction.

Plate VI-2: The northern entrance of Vent Cave. The sand in the entrance zone of the cave is littered with obsidian flakes. Taken facing south.

Plate VI-3 (below): The southern entrance of Vent Cave. This entrance leads into the topographically distinct vent crater area that can be seen in Plate VI-1. Lava Top Butte appears through the trees in the right background. Taken facing southeast.

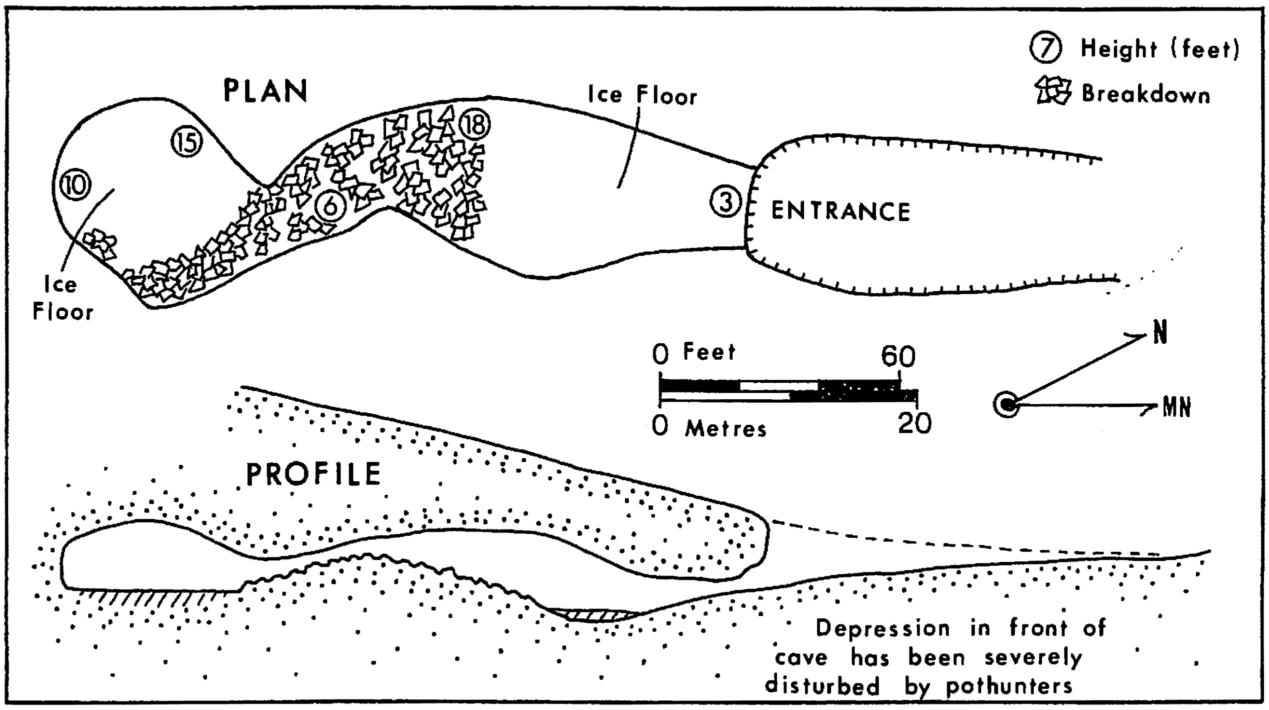


Figure VI-3: The Lava Top Butte Ice Cave. Map is adapted from Larson (1976). This perennial ice cave, one of three archaeological cave sites located in the Lava Top Butte area, has been severely disturbed by collectors in search of artifacts.

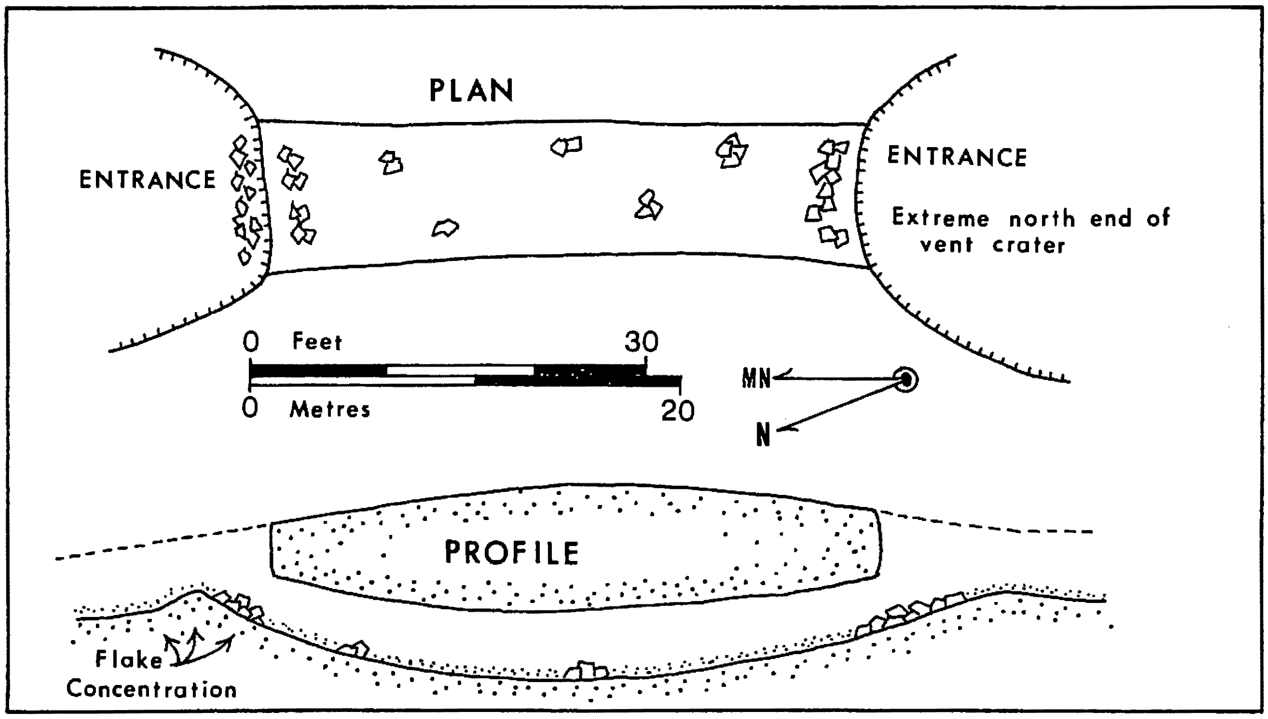


Figure VI-4: Sketch map of Vent Cave. Penetrating the vent crater wall of the Northwest Vent Flow, this cave probably acted as a drain for lavas ponded at this vent. Flakes and fragments of obsidian are found in the pumiceous sand inside the short tube and in front of both entrances.

The existence of the Lava Top Butte Ice Cave was first reported in the early 1960's by Knutson (1963; 1964:7) and Ashworth (1963), who mentioned the presence of screen sifters inside the cave. The ice cave was later relocated and mapped by Larson (1976; map reproduced in Larson, 1982:54), who described the carnage at the site: "Overshadowing all...was the discouraging destruction of archaeological sites by pot hunters who have literally turned the area upside-down in a wanton search for artifacts. Cave entrances -- and cave floors if soft enough to dig -- are pocked with ugly, unfilled holes. Pot hunter's paraphanelia -- sapling tripods, screens, cans, plastic jugs, even empty oil barrels -- is scattered about."

The badly disturbed condition of the site was later noted by Dudley et al. (1979:501), who were unable to locate any diagnostic artifacts inside the cave or in the area in front of the entrance. The site was classified as a campsite and/or lithic workshop.

The ice cave was located by the author in 1979 and several flakes of obsidian from the entrance area were collected in a later visit in 1981.

That the cave was used as a campsite, probably during the dry summer months, is not surprising. It lies halfway and in-line between Charcoal Cave and Swamp Wells, and along with these two sites, is one of the few sources of water on the northern slopes of Newberry Volcano.

Vent Cave

Greeley (1971:33) describes this cave as, "...a short tunnel passing through the north rim of the vent crater...Its passage (13 m long x 2 m high, maximum) contains a few preserved sections of tube lining and small lavacicles. The tube probably formed in one of the last basalt flow units issuing from the vent crater." The floor and entrance areas of this short tube are covered with pumiceous sand mixed with abundant flakes of obsidian. This site also appears to be thoroughly disturbed - a large bucket containing fragments of obsidian was found during an initial visit to the site in 1978. During a return trip in 1981, several flakes were collected for analysis, the results of which are reported in the next section of this appendix. Vent Cave is the only one of several caves located in the Northwest Vent Flow in which any signs of occupation were found. The nearest source of water is the Lava Top Butte Ice Cave, 1 km (.6 mile) to the east-southeast.

THE CHARACTERIZATION AND GEOLOGIC SOURCE DETERMINATION OF OBSIDIAN FROM THE CAVES OF LAVA TOP BUTTE

Obsidian flakes collected at Vent Cave and the Lava Top Butte Ice Cave were characterized geochemically and petrographically and compared with obsidian from several known sources of obsidian in this region, particularly those of Newberry Caldera.

Geochemical Characterization of the Lava Top Butte Obsidian

The trace element composition (Rb, Sr, Y, Zr and Nb) of a single obsidian flake from both of the sampled cave sites was determined by X-ray fluorescence spectrometry at the University of Oregon X-Ray Fluorescence Laboratory.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	--	72.64	72.28	72.05	72.07	72.99	73.64	73.40	72.9	--	72.8
TiO_2	--	0.21	0.21	0.21	0.22	0.23	0.23	0.23	0.23	--	0.22
Al_2O_3	--	13.80	13.98	14.01	13.80	13.89	14.13	14.12	13.9	--	13.9
Fe_2O_3	--	1.97	2.27	2.26	2.04	2.04	2.05	2.03	.56		0.67
FeO	--	--	--	--	--	--	--	--	1.4	--	1.3
MnO	--	0.04	0.06	0.06	0.05	0.05	0.04	0.04	0.12	--	0.06
MgO	--	0.26	0.05	0.17	0.38	0.30	0.28	0.28	0.24	--	0.21
CaO	--	0.98	0.85	0.89	1.01	1.01	1.01	1.02	1.6	--	1.4
Na_2O	--	4.77	5.20	5.11	4.86	4.81	4.95	4.98	4.4	--	4.5
K_2O	--	4.26	3.90	4.03	4.18	4.23	4.20	4.20	4.1	--	4.1
P_2O_5	--	0.05	0.02	0.04	0.04	0.04	0.04	0.03	0.02	--	0.02
Total	--	98.97	98.91	98.82	98.62	99.57	100.56	100.30	--	--	--
Rb	142	141	123	127	141	136	142	141	140	135	180
Sr	55	55	48	50	62	61	60	62	70	55	70
Y	37	37	40	40	35	40	36	34	60	40	60
Zr	286	290	360	360	291	293	295	293	280	280	300
Nb	13	13	16	19	13	14	15	13	--	--	--

1. Artifactual obsidian from Vent Cave, Lava Top Butte. Collected at the north entrance in a disturbed area of pumiceous sand. XRF analysis by the author (LTV-5).
2. Artifactual obsidian from the Lava Top Butte Ice Cave. Collected in the collapse trench in front of the entrance to the Ice Cave in a heavily disturbed area (LTI-5).
3. Obsidian from the Big Obsidian Flow, Newberry Caldera. X-ray fluorescence analysis by the author (BOF-1).
4. Obsidian from the Big Obsidian Flow, Newberry Caldera. X-ray fluorescence analysis by the author (BOF-2).
5. Obsidian from the westernmost of the East Lake obsidian flows, Newberry Caldera. X-ray fluorescence analysis by the author (ELA-1).
6. Obsidian from the westernmost of the East Lake obsidian flows, Newberry Caldera. X-ray fluorescence analysis by the author (ELA-2).
7. Obsidian from the easternmost of the East Lake obsidian flows, Newberry Caldera. X-ray fluorescence analysis by the author (ELB-1).
8. Obsidian from the easternmost of the East Lake obsidian flows, Newberry Caldera. X-ray fluorescence analysis by the author (ELB-2).
9. Obsidian from the Interlake Obsidian Flow, Newberry Caldera. Analysis by Higgins (1973:475,483).
10. Obsidian from a flow between Paulina and East Lake, probably the Interlake Obsidian Flow. Analysis by Jack and Carmichael (1969:26; sample Cam 133).
11. Obsidian from the summit crater walls of the Central Pumice Cone, Newberry Caldera. Analysis by Higgins (1973:474,483).

Table VI-2: Major and trace element composition of archaeological obsidian from the Lava Top Butte area and of possible geologic sources of obsidian in the Newberry Caldera. Major elements are reported in weight percent oxides, trace elements in parts per million.

In addition, samples from several other possible geologic sources were collected and analyzed as part of a conjoint research project. Samples were cleaned with water and acetone, then reduced to a fine powder in a ball mill. Because of the small size of the flakes, the weathered hydration rinds were not removed prior to powdering - previous research had indicated that the effects of the thin hydration band on the surface of the obsidian were not significant for trace elements determined in the present study (Bennett and D'Auria, 1974:363). For major element analysis, the powder was combined with a flux, fused into a glass disc and then analyzed with a GE XRD-7 Vacuum Spectrometer along with U.S. Geological Survey standards of a known composition. For trace element analysis, 5 gm of the sample powder, along with a boric acid backing, were pressed into a cohesive disc. The results of the X-ray fluorescence analysis appear in Table VI-2 (the basalt samples whose compositions appear in Table VI-1 were prepared in an identical manner). Both of the Lava Top Butte obsidian samples exhibit almost identical compositions and are almost surely from the same original geologic source.

Petrographic Characterization of the Lava Top Butte Obsidian

The obsidian from the Lava Top Butte caves was also characterized petrographically on the basis of the type and structure of the microlites found in the

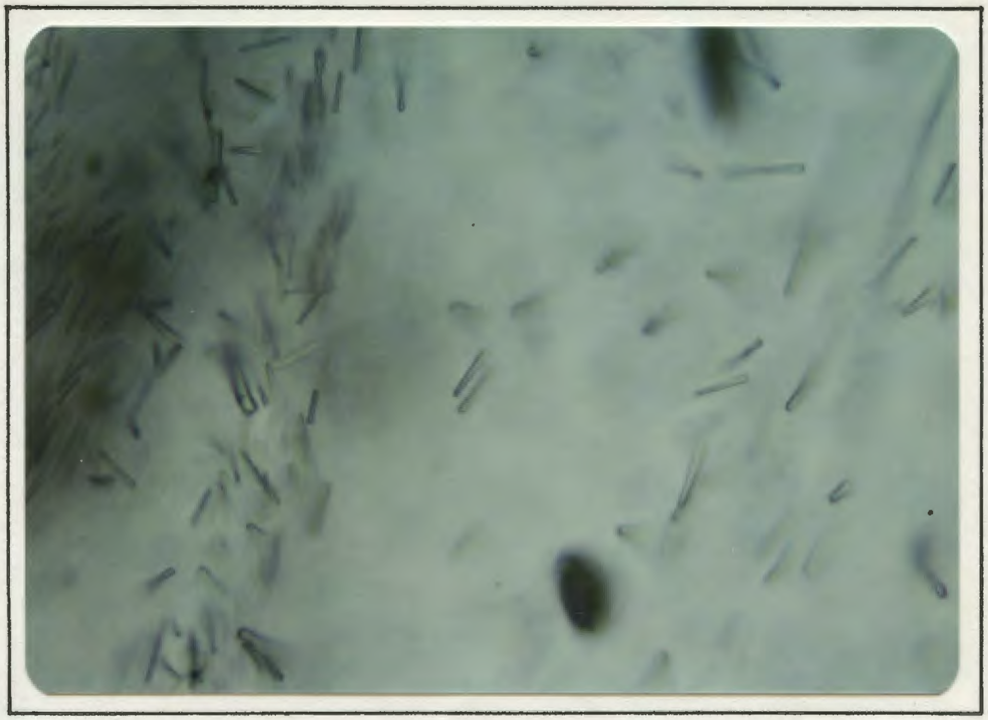


Plate VI-4: Photomicrograph of a thin-section cut from a flake recovered from the Lava Top Butte Ice Cave. The prismatic, rod-shaped microlites and grayish-green tint of the glass are typical of obsidian from nearby Vent Cave and of the numerous obsidian sources in Newberry Caldera. The denser concentration of microlites in the left of the photograph would appear macroscopically as banding in the glass. Nicols not crossed, x150.

glass. Though results are still preliminary, it appears that microscopic microlitic structures are useful in the characterization of obsidian (see Part Four of the main body of this project).

Thin-sections were prepared from two artifactual obsidian flakes from Vent Cave and five flakes from the Lava Top Butte Ice Cave. These included sections from the two samples that were also geochemically characterized.

All of the thin-sections exhibited the same general microlite types, suggesting that they may have all originated from the same source or group of related sources. Rod-shaped prismatic microlites averaging about 10 microns in length were common in all of the obsidian flakes examined. Occasional microphenocrysts of plagioclase were also found. The petrographic characteristics of the artifactual obsidian (see Plate VI-4) are identical to the sources collected or described from Newberry Caldera, all of which show very similar petrographic characteristics (Higgins, 1968:239-240; 1973:464). Though the distinguishing ability of this characterization method is much less than that of the geochemical methods, it can be used with some reliability.

Potential Geologic Sources of the Obsidian

There are many potential geologic sources of obsidian in the Lava Top Butte region - dozens of lava flows or obsidian-rhyolite domes are found on Newberry Volcano, in the central High Cascades and in the High Lava Plains to the east of Newberry Volcano (see Appendix Four for details). The nearest and most likely source of obsidian recovered from the caves of Lava Top Butte is in the caldera of Newberry Volcano, only 16 km (10 miles) to the south of the butte. Many flows of late Holocene to Pleistocene age can be found in the caldera or on the upper flanks of the mountain (Williams, 1935; Higgins, 1968 and 1973; Friedman, 1977; MacLeod et al., 1981 and 1982). Even though these many sources are close to Lava Top Butte, though, there is good reason not to assume *a priori* that the geologic source of the obsidian found there lies in or near the caldera. Sappington (1982) found that only 52% of the artifactual obsidian from the nearby Lava Island Rockshelter originated from Newberry Volcano. 25% of the remaining obsidian was found to be from other sources in south-central Oregon, the High Cascades and the Willamette Valley (23% were from unknown sources).

The Source of the Lava Top Butte Obsidian

Rb, Zr and Sr abundances of the artifactual obsidian from the cave sites were compared with those of sources from Newberry Caldera and from some other sources known to be prehistoric quarry sites. Nb and Y were not used because of their typical small abundances and minimal interunit variation. Keeping in mind that trace element and petrographic information for all possible sources was not available for comparison, some tentative conclusions can be reached.

The use of trace element composition is a well-known method of obsidian characterization and source correlation and has been used successfully by archaeologists for nearly twenty years (Cann et al., 1970; many other references are also available). This method of characterization is dependent on the trait that obsidian sources, while generally proving very homogeneous in their trace element composition, often show considerable variation between different sources.

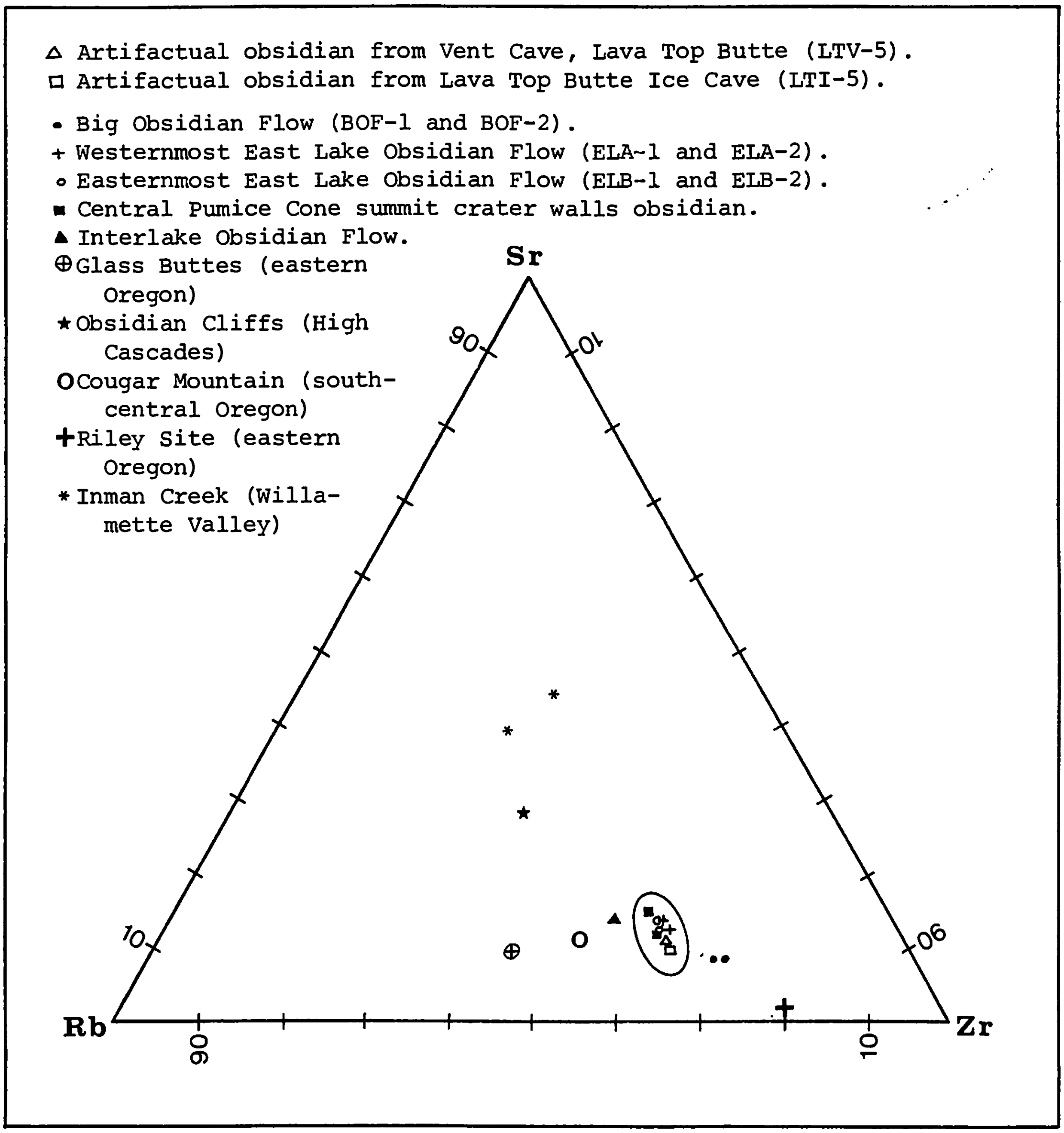


Figure VI-5: Ternary diagram showing the relative abundances of Strontium, Rubidium and Zirconium found in artifactual obsidian from Vent Cave and the Lava Top Butte Ice Cave. Also shown are trace element abundances of obsidian from nearby Newberry Caldera, a likely source of the obsidian found at the Lava Top Butte caves. Average trace element abundances from other sources not on Newberry Volcano are added for comparison.

In figure VI-5, the abundances of Sr, Rb and Zr in the artifactual obsidian, trace elements showing a high degree of intraunit homogeneity and interunit heterogeneity, are plotted on a ternary diagram along with a number of potential sources. The circled cluster includes obsidian from the Lava Top Butte caves, the two East Lake obsidian flows (Newberry Caldera), the Interlake Obsidian Flow (Newberry Caldera) and the Central Pumice Cone summit crater obsidian flow (Newberry Caldera). All of these geologic sources, therefore, must be considered, using this diagram, as potential sources of the artifactual obsidian.

When only the Rb and Zr abundances, however, are plotted against each other in Figure VI-6, the Central Pumice Cone and Interlake flows fall out of the grouping, leaving the geochemically indistinguishable East Lake flows as the most likely candidates as the geologic sources of the Lava Top Butte obsidian.

While the chemical composition of the younger rhyolitic obsidians in Newberry Caldera indicates that they were all derived from the same magmatic body, there are small and systematic differences in the major and trace element composition of the rocks (MacLeod et al., 1982:6). These differences should make it possible to distinguish individual sources from among the various geographically proximate caldera obsidian sources on the basis of composition.

That the source of the Lava Top Butte obsidian lies in the caldera is also corroborated by the examination of the microlitic structures in the glass.

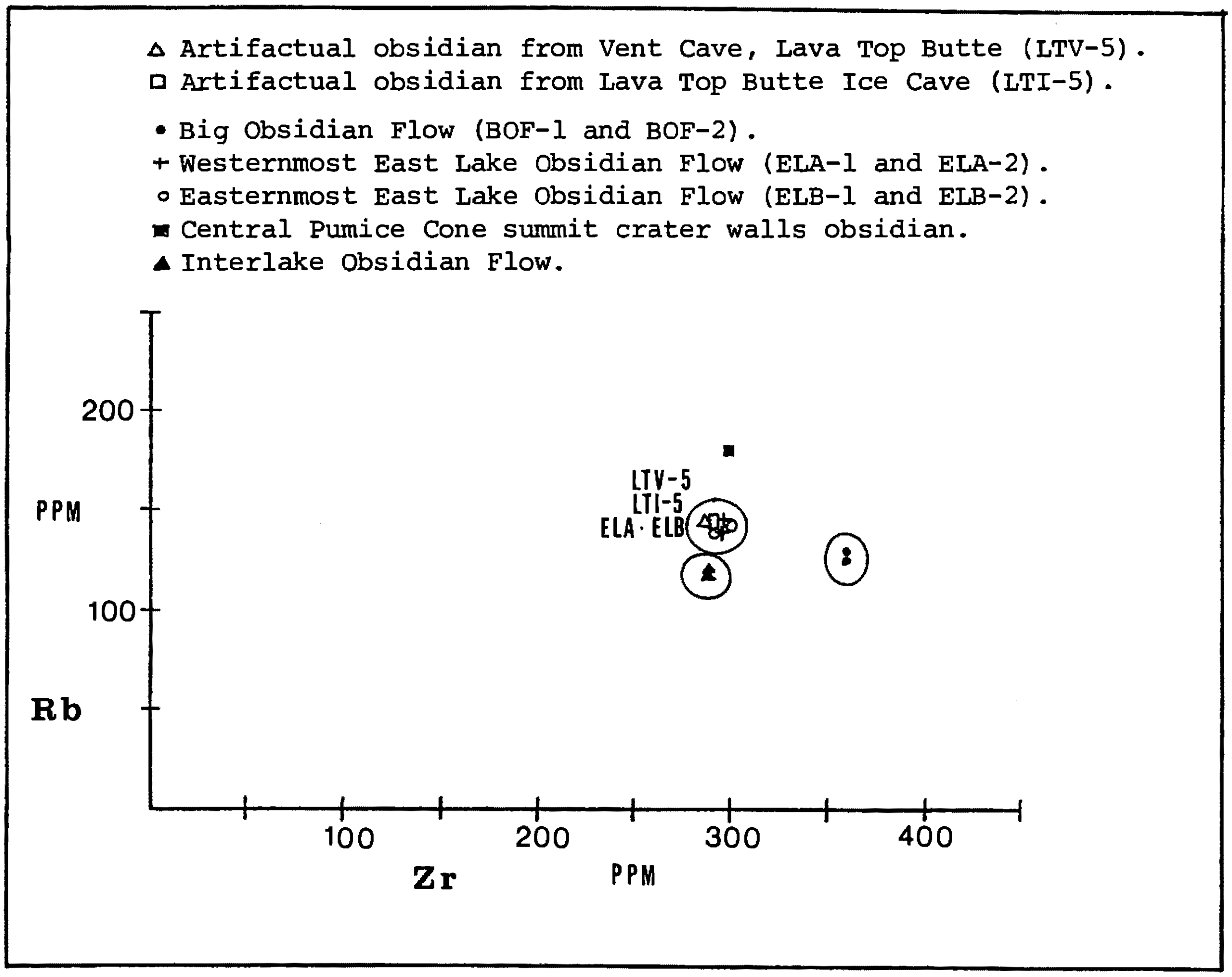


Figure VI-6: Ratios of Rubidium and Zirconium found in archaeological obsidian recovered from the Lava Top Butte cave sites and from several of the many Newberry Caldera obsidian sources.

The type and structure of the microlites present in the artifactual obsidian and in the Newberry Caldera sources is virtually identical, while differing in several respects from obsidian from other sources. The petrographic features of the caldera sources are much too similar, though, to make any more specific source distinction. The petrographic similarity of all of the artifactual flakes examined also suggests that a single geologic source or related source area was used by the prehistoric inhabitants of the caves at Lava Top Butte.

THE CAVES OF LAVA TOP BUTTE AND LOCAL PREHISTORY

On the basis of the limited sample size used in this study, there are a few provisional conclusions that can be drawn about the role of the Lava Top Butte caves in the prehistory of the local area:

1. The caves, particularly the ice cave, likely acted as a seasonal hunting camp and workshop area for the local inhabitants. The area is covered by snow for several months of the year and the caves were probably utilized primarily during the summer and fall when little water was available on the north slopes of Newberry Volcano. The fact that the caves lie between two water sources and that the ice cave is a water source makes the Lava Top Butte caves attractive campsites.
2. The presence, albeit from a limited sample, of obsidian from only one nearby source suggests that the traffic through this area was primarily local, possibly limited to movement from the lower northern slopes of Newberry Volcano to the caldera area. This could have been in conjunction with hunting activities and seasonal rounds or with the procurement of obsidian from the caldera.
3. It is difficult to speculate about the time period covered by the occupation of the cave sites from the information at hand, though an upper and lower limit can be suggested. The presence of a still intact wickiup frame only 3.2 km (2 miles) northeast of Lava Top Butte near Charcoal Cave certainly indicates the possibility of activity in this area up to historical times (Anonymous, 1889). A convenient lower limit is provided through the obsidian sources utilized at the caves, the East Lake obsidian flows. These two obsidian flows originated from the same fissure vent in Newberry Caldera, and were probably erupted at about the same time. The flows have obsidian hydration ages of 3,500 years and are bracketed in time by two dated ashfall events, one (the Newberry ashfall) at about 1,720 radiocarbon years ago, the other (the Mazama ashfall) at about 7,000 radiocarbon years ago (Friedman, 1977).

THE ARCHAEOLOGICAL SIGNIFICANCE OF THIS STUDY OF THE CAVES OF LAVA TOP BUTTE

The conclusion of this investigation that the artifactual obsidian recovered at the caves in the Lava Top Butte vicinity originated from Newberry Caldera is not particularly significant in itself. The sites at the butte are small and have been thoroughly sifted by non-archaeologists for culturally significant materials. As a result, only a limited number of rather speculative conclusions can be advanced about the prehistory of the caves by themselves.

There are larger issues touched on in this investigation, though, that bear more discussion. These issues are: the use of obsidian characterization studies in the investigation of disturbed archaeological sites; the value of petrographic methods of obsidian characterization; the importance of ice caves as archaeological resources and the viability of obsidian hydration dating in the study of disturbed sites.

Obsidian Characterization and Disturbed Archaeological Sites

Archaeological sites can become disturbed through natural erosional processes, agricultural development, logging operations and other related activities. The most pressing threat to archaeological sites, though, comes from the artifact collector, the pothunter and the pseudo-archaeologist. The amount of once archaeologically-significant artifacts that are now lying on coffee tables and residing on bookshelves has never been quantified, but is probably staggering. The collector, while removing the showcase items such as projectile points,is fortunately not interested in the debitage. It is with the study of this waste material that the future of archaeology in some places may eventually lie. Obsidian waste flakes such as those found at Lava Top Butte, even though they are thoroughly out-of-context, can still provide information about the exchange and contact systems of the areas in which they are found. These flakes, when characterized and correlated with geologic sources, may be about the only source of information available from many sites. In an area where relatively recent obsidian sources such as on Newberry Volcano exist, it may also be possible to infer from geochronological information the potential range of occupation of a site.

Petrographic Methods of Obsidian Characterization

While research about the reliability of petrographic methods of obsidian characterization is still not complete, it still appears from some limited applications such those carried out at Lava Top Butte (see also Part Four and appendices Five, Seven, Nine and Eleven, this project) that there may be some future in the technique. The characterization of obsidian through the identification of microlite structures, while not as effective as geochemical methods in locating obsidian sources, can still provide some information about the sources of artifactual obsidian. The method is certainly more available than most to archaeologists without access to the equipment needed for geochemical characterization. The preparation of obsidian thin-sections for petrographic examination is not difficult and requires a minimal amount of training and equipment. Professional thin-section preparation services are also readily available. The petrographic characterization of obsidian can be used, as it was at Lava Top Butte, as an adjunct to trace element characterization and as a way to "stretch" the geochemical analyses. Even if it is not possible to identify the geologic source of the obsidian through petrographic means, it might still be possible to identify the number of different source populations present.

The Archaeological Significance of Ice Caves

Perennial or seasonal ice caves are sources of water and in semi-arid climates such as in central Oregon they may be important point resources. There are, for example, many ice caves on Newberry Volcano, in the High Cascades and in the High Lava Plains to the east, not to mention many caves and fissures where winter snow persists well into the summer (Larson, 1982). Many of these cave sites, like the one at Lava Top Butte,have already been destroyed by collectors, but a few undisturbed sites may still remain. Cooperative efforts with cave enthusiasts and local chapters (grottos) of the National Speleological Society may allow archaeologists a head start in locating these potential archaeological sites.

Obsidian Hydration Studies of Artifactual Obsidian from Disturbed Sites

One of the original aims of the Lava Top Butte study was to utilize obsidian hydration measurements to add a temporal dimension to the characterized obsidian found there. The recovered obsidian was, in fact, prepared for hydration dating and hydration rims were found on the flakes. It became clear, however, as research progressed, that the hydration measurements were not going to add any valid information, and they were eventually reluctantly discarded from the investigation.

The reason for this concerns the thermal environment of disturbed sites. Temperature, along with chemical composition and time, is one of the major variables to be considered in the hydration of obsidian. Experimental work also indicates that the temperature-hydration relationship is an exponential one. The higher the temperature, the greater the rate of hydration (Ambrose, 1976:100-104). Friedman (1976:178) found that obsidian placed in the sun hydrated at a rate as much as five times greater than obsidian buried in the ground. Unless the thermal environment is constant over the emplacement history of an obsidian artifact or unless the thermal history has been the same for all the artifacts examined, obsidian hydration measurements are going to result in misleading data.

Layton (1973), in a study of the hydration rate of a surface collection of obsidian artifacts, found the hydration rate to be double that of nearby buried artifacts. He concluded that temporal ordering of surface-collected artifacts was a useful method, but it must be considered that the thermal history of all his surface specimens was probably the same and that the site was undisturbed.

For disturbed sites, the thermal history may be quite different for much of the artifactual obsidian eventually ending up on the surface (this would also hold true for sites where artifacts had been concentrated by deflation). The thermal history of a deeply-buried object will have been different than for one buried at a shallow depth. When all these artifacts end up on the surface, perhaps well-mixed with materials that have spent most of their history on the surface, the results of obsidian hydration dating could be quite deceiving. This mixing of artifacts with different thermal histories could easily be the case in a site, such as at Lava Top Butte, where the context had been disturbed by collectors or other processes. Unless a way is found to somehow control this temperature variable, the hydration study of obsidian from disturbed archaeological sites is, unfortunately, not going to be a useful technique.

CONCLUSIONS

1. Two cave-forming basalt flows are found associated with volcanic activity at Lava Top Butte, a Quaternary cinder cone on Newberry Volcano in central Oregon.
2. Several caves, three of which were identified as archaeological sites, have been located in the Lava Top Butte vicinity in the associated basalt flows.
3. The archaeological cave sites have all been severely-disturbed by artifact collectors. The most extensive of these disturbed sites is a perennial ice cave and water source.
4. Obsidian waste flakes from two of the cave sites were geochemically and petrographically characterized and found to originate from the East Lake obsidian flows in Newberry Caldera.
5. The range of occupation of these caves, based on a historical account and on geochronological data, was potentially from historical times to a maximum of 3,500 obsidian hydration years ago.

6. Characterization studies of obsidian waste material from disturbed archaeological sites will play an increasingly important role in the future of archaeological research, particularly in those areas where few significant or undisturbed sites remain.
7. Obsidian hydration study of obsidian flakes or artifacts from disturbed archaeological contexts is not a feasible research strategy at this time.
8. The petrographic characterization of obsidian may be a useful method, either when used alone, or an adjunct to other characterization methods. More study is recommended.
9. Ice caves and caves with persistent late-season water may be important archaeological resources, but only if archaeologists find them before the collectors do.

RECOMMENDATIONS FOR FURTHER STUDY AT LAVA TOP BUTTE

Lava Top Butte has been recently recommended for consideration as a medium priority Research Natural Area, satisfying the need in the Deschutes National Forest for an entire low-elevation forested cinder cone (U.S. Forest Service, 1978:550). While this administrative move would offer some degree of protection for the area, it would also probably increase the amount of human traffic and interest in the area. In the event that Lava Top Butte is declared a Research Natural Area or is otherwise considered for other uses which might impact the area, additional archaeological survey, site testing and analysis would be recommended.

Acknowledgements

My thanks to Scott Murdock and Bill Cattrall for their good company and help in finding the caves and to Charlie Larson for providing location information for the hard-to-find caves of the Lava Top Butte vicinity.

ADDENDUM

After the completion of this appendix, the caves of Lava Top Butte were visited in April of 1983 for further sampling of artifactual obsidian flakes. The purpose of this brief addendum is to provide additional information about the caves in the area.

An additional perennial ice cave was located in SE¼SE¼ Sec.31, T.19S., R.13E. in unit Qb_3. Though no flakes were found in the entrance area of this 7 m-long ice cave, a few hundred obsidian flakes were noted on the surface in a clear area about 30 m south of the cave entrance. This cave is located approximately 200 m from Vent Cave and is the nearest year-around water source to Vent Cave.

A small lava tube about 15 m in length was found 100 m east-northeast of Vent Cave. No obsidian flakes or other signs of prehistoric use were noted.

Vent Cave showed signs of additional pothunting activity since the site was last visited in late 1980. The north end of the cave immediately inside the entrance had been thoroughly dug out, though probably not for the first time.

The most serious signs of pothunting activity were found at Shelter Camp Cave. Though this site had seen some disturbance prior to late 1980, it did not appear extensive. Since that time, though, the length of the cave has been more than doubled, with an 8 m-long section excavated since 1980. 1-2 m of fill in the back of the cave had been removed and dumped in front of the cave, leaving little of the rockshelter now undisturbed. The extent of the excavations suggest that this site may have been a significant one. The only artifactual materials remaining are several hundred small obsidian flakes.

Two small lava tubes were also located in NE¼NE¼ Sec.31, T.19S., R.13E. The tubes are about 5 m and 12 m in length and show no signs of prehistoric use. Both are located in the reported vicinity of Log Crib Cave, which was not relocated.

A modified version of this appendix will also appear in 1984 as a bulletin published by the Western Speleological Survey (Vancouver, Washington). Additional geochemical data incorporated into the bulletin indicate that the source of most of the artifactual obsidian from the caves of Lava Top Butte was either the East Lake, Interlake or Game Hut obsidian flows, all recent obsidian flows within Newberry Caldera. The title of the bulletin will be Geological and Archaeological Investigations of the Lava Top Butte Vicinity, Deschutes County, Oregon.

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APPENDIX VII

The Characterization and Geologic Source of Archaeological Obsidian Recovered from a Surface Site Near Condon Butte, Lane County, Oregon

Flakes of artifactual obsidian were recovered from a small surface site located in the McKenzie Pass area of Oregon's High Cascades. The flakes were characterized, using X-ray fluorescence spectrometry, by their major and trace element composition and were compared with local natural obsidian sources. Comparison of both major and trace element data suggests that nearby Obsidian Cliff was the source of the artifactual obsidian. Examination of thin-sections of the obsidian showed that the size and structure of microlites in the glass from Obsidian Cliffs are virtually identical to those of the obsidian flakes. This suggests the possibility that microlite characteristics may be useful in the characterization and correlation of obsidian from natural and archaeological sources.

INTRODUCTION

Condon Butte is a Holocene cinder cone located inside the Three Sisters Wilderness Area about 3 km (1.8 miles) south of Highway 242. South of this cone less than 1 km (.6 mile) is a small lake (see Plate VII-2) situated at the base of a glaciated rhyolite dome (Taylor, 1968:21; 1981:218). Approximately 150 m (500 feet) north of the north edge of this unnamed lake and near the edge of a prominent open area is a small surface scatter of obsidian flakes. This lithic scatter, here referred to as the Condon Butte Site, is about 60 m (200 feet) in diameter and is represented by a few hundred obsidian waste flakes.

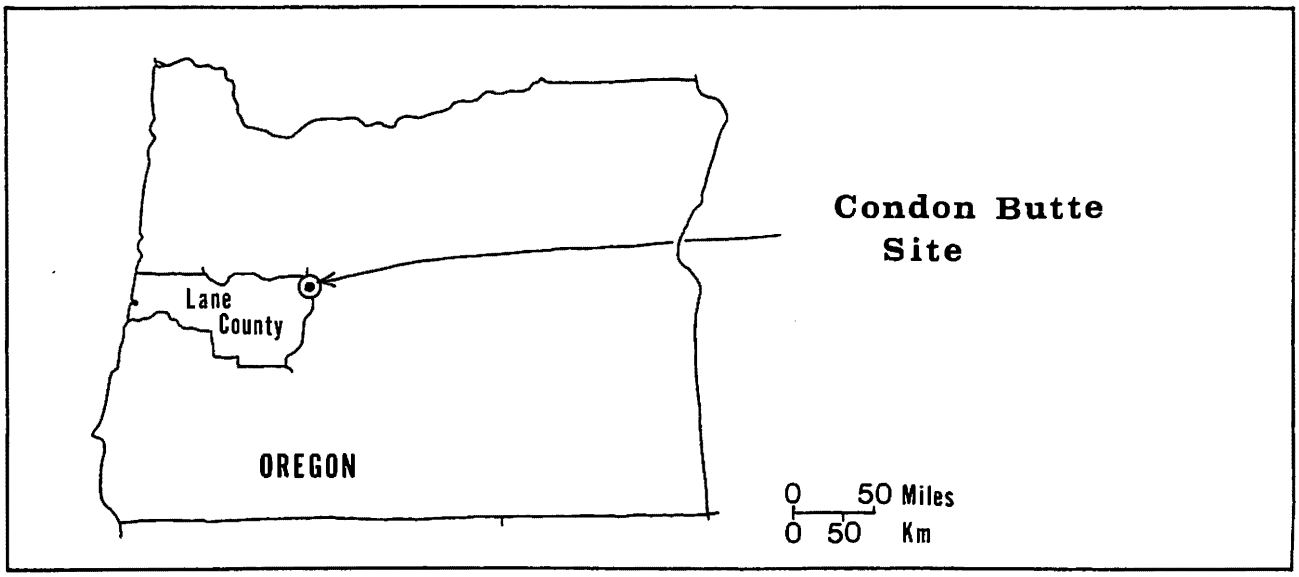

Figure VII-I: Location of the Condon Butte Site in the northeastern corner of Lane County.

This unimposing archaeological site was found in August of 1981 during an unsuccessful search for obsidian that was believed to have been once associated with the nearby glaciated dome. Several of the larger flakes from the Condon Butte Site were collected at this time for later study, the results of which appear in this appendix.

The major objective of this brief investigation was to characterize the obsidian at the Condon Butte Site and to identify, if possible, the geologic source of the obsidian.

The location of the Condon Butte Site is also shown as a small dot located to the north of Obsidian Cliffs in Plate 12, Part Four, Chapter Two, of the main body of this project.

ARCHAEOLOGICAL SETTING

The archaeological history of the High Cascades is not well-known, although a few speculations can be made about the Condon Butte area.

Found at an elevation of about 1700 m (5600 feet), the Condon Butte Site is covered by deep snow for several months of the year. Regardless of *what* paleoclimatic scheme one subscribes to, this has undoubtedly been the case throughout the Holocene Period. In all likelihood, the site was used primarily as a temporary campsite and/or knapping station in the summer and fall months by people crossing the Cascades or visiting nearby Obsidian Cliffs to obtain obsidian. The McKenzie and Santiam passes are two of the few natural passes over the Cascades and their use by prehistoric hunting parties and migratory groups has been suggested (Newman, 1966:2). The Scott Trail, an early pioneer trail that crossed the Cascade Divide close to Condon Butte, was reputed to have followed an Indian trail on the south side of the lava fields immediately north of the North Sister (Minor and Pecor, 1977:155). Obsidian Cliffs has also been identified as a major obsidian quarry site (Hopson, 1946:326-327; Minor and Pecor, 1977:138), but archaeological details are lacking. Obsidian artifacts have additionally been reported from several locations in the vicinity of Obsidian Cliff (Sappington, 1980).

The maximum age of the Condon Butte Site is set by both the glacial and the volcanic activity in the area. Extensive high mountain glaciers, the last advance represented by the Cabot Creek Glaciation, covered the Condon Butte area until the beginning of the Holocene Period about 10-12,000 years ago (Scott, 1977). Following the retreat of the more extensive glaciers (remnants of which exist today) was a period of basaltic volcanic activity lasting until only a few thousand years ago (Taylor, 1965 and 1968). Condon Butte, an unglaciated cinder cone, was formed at some unknown point in time near the beginning of the Holocene Period. A rather recent age for the Condon Butte Site is also suggested by the lack or near lack of hydration rims on the flakes collected there.

CHARACTERIZATION OF THE OBSIDIAN

I decided to characterize the obsidian primarily through the determination of major and trace element abundances. Several petrographic thin-sections of small artifactual flakes were also prepared.

Plate VII-1 (above): The forested hill in the background is a glaciated obsidian dome. The Condon Butte Site is located not far to the left (west) of this dome. Taken facing north from atop a Holocene basalt flow originating at nearby Four-In-One Cone.

Plate VII-2 (below): A small lake located at the western base of the dome shown above in Plate VII-1. The Condon Butte Site is found a few hundred metres to the north of this lake. Taken facing southeast.

	CON-1	OBC-1	OBC-2	OBC-3	OBC-4	RMS	NEW
SiO_2	75.40	75.92	76.19	76.22	75.31	73.10	71.90
TiO_2	0.09	0.10	0.09	0.08	0.09	0.28	0.32
Al_2O_3	13.06	13.12	12.95	13.00	12.90	14.80	14.70
Fe_2O_3	1.15	1.16	1.09	1.09	1.09	--	--
FeO	--	--	--	--	--	1.90	2.40
MnO	0.04	0.04	0.04	0.04	0.04	--	--
MgO	0.20	0.16	0.25	0.19	0.22	0.40	0.70
CaO	0.92	0.93	0.88	0.89	0.88	1.70	2.10
Na_2O	4.42	4.40	4.41	4.33	4.23	--	--
K_2O	3.48	3.44	3.46	3.50	3.48	3.35	3.09
P_2O_5	0.04	0.03	0.02	0.05	0.03	--	--
Total	98.79	99.28	99.37	99.38	98.26	--	--
Rb	83	84	79	85	84	--	--
Sr	110	110	103	104	103	188	237
Y	14	11	14	15	12	--	--
Zr	98	102	93	98	96	156	193
Nb	8	6	5	12	5	--	--

CON-1: Artifactual obsidian from a small surface scatter near Condon Butte, Lane County. X-ray fluorescence analysis by the author.

OBC-1: Obsidian from Obsidian Cliffs, Lane County. Collected at the lower portion of the flow by the author. X-ray fluorescence analysis by the author.

OBC-2: Obsidian from Obsidian Cliffs, Lane County. Collected near the mid-point of the flow by the author. X-ray fluorescence analysis by the author.

OBC-3: Obsidian from Obsidian Cliffs, Lane County. Collected near the upper vent area by the author. X-ray fluorescence analysis by the author.

OBC-4: Obsidian from Obsidian Cliffs, Lane County. Collected near the vent area by the author. X-ray fluorescence analysis by the author.

RMS: Obsidian from Rock Mesa, Lane and Deschutes Counties. Spectrographic analysis by E.M. Taylor (Anttonen, 1972:92; analysis 90).

NEW: Obsidian from the Newberry Obsidian Flow, located on the south flank of the South Sister, Deschutes County. Spectrographic analysis by E.M. Taylor (Anttonen, 1972:92; analysis 88).

Table VII-1: Major and trace element composition of artifactual obsidian from the Condon Butte site and from selected geological sources of obsidian in the Three Sisters area. Abundances of the major elements are reported in weight percent; those of the trace-elements are shown in parts per million.

The major and trace element composition of the Condon Butte obsidian was determined by X-ray fluorescence using the facilites available through the Geology Department of the University of Oregon. The results of these analyses are listed in Table VII-1 (also see Appendix X for more complete information). In addition to the single specimen of archaeological obsidian analyzed, four samples were collected at widely scattered points on the Obsidian Cliff obsidian flow (see Chapter Two, Part Four of the main body of this project for a detailed description of this source). This is the nearest geologic source of obsidian for the Condon Butte Site. These samples were also analyzed and major and trace element compositions were determined.

All the obsidian samples were washed prior to preparation for X-ray fluorescence analysis. The Obsidian Cliff samples were fragmented and the weathered cortex removed while the Condon Butte obsidian, because of the small quantity available, was prepared only after a thorough cleaning with acetone. Other researchers (Bennett and D'Auria, 1974) have noted that hydration effects (the altered composition of the outer hydrated layer) are negligible in the analysis of obsidian artifacts. The obsidian was then finely powdered in a Spex shatterbox and prepared as artificial glass discs for major element analysis and as pressed powder pellets for trace element analysis (the details of the analytical procedure are explained in Part Four of the main project).

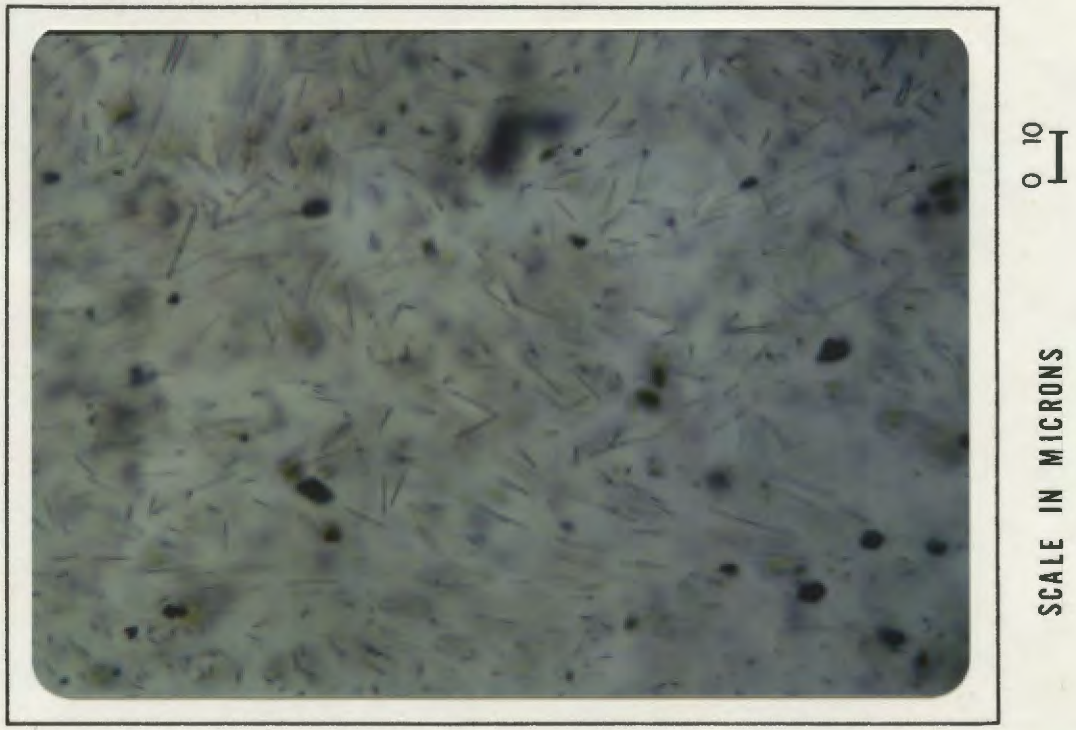

Plate VII-3: Archaeological obsidian from the Condon Butte Site. The crowded and rather small prismatic microlites in this photomicrograph are typical for the flakes from this site and their source, Obsidian Cliffs. The black specks are particles of magnetite. Nicols not crossed, x150.

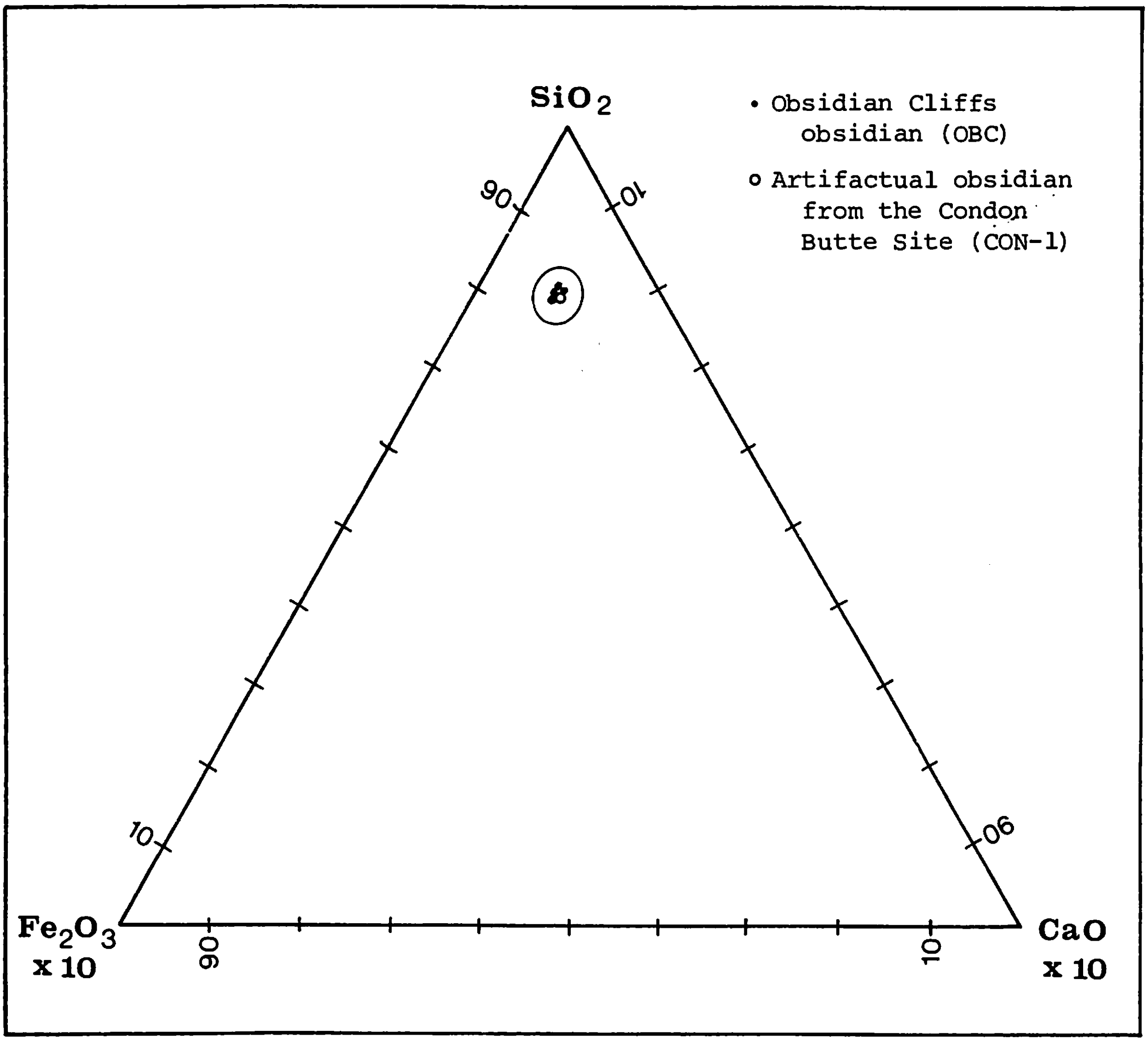

Figure VII-? Ternary diagram showing the ratio of selected major elements present in obsidian from the Condon Butte Site and from nearby Obsidian Cliffs. The relative abundances of obsidian from these two locations are very similar.

Examination of the thin-section prepared from five artifactual flakes showed each flake to be microscopically indistinguishable from the others. The obsidian is densely crowded with thin prismatic microlites that show a strong, if somewhat chaotic, alignment (see Plate VII-3). The microlites average less than 10 microns in length and are typically less than one micron in diameter. The obsidian flakes were prepared so that surface hydration profiles would also be visible, but no signs of hydration rims were found on any of the flakes. This observation suggests a relatively recent age to the archaeological componene of the site.

POSSIBLE SOURCES OF THE OBSIDIAN

It was reasoned that the geologic source of the obsidian was probably local, as there are several potential sources in the region of the site. Obsidian Cliff is found only 4 km (2.5 miles) south of the Condon Butte Site and was considered to be the most likely source. Several other obsidian flows are found about 16 km (10 miles) to the south on the south slope of the South Sister. These include Rock Mesa, the Newberry Obsidian Flow and an alignment of several small obsidian domes. No attempt was made to sample or characterize any of the South Sister sources. The composition of the glass from the Rock Mesa and Newberry flows had been reported previously by Anttonen (1972:92) and his figures are used in this appendix for comparative purposes.

THE SOURCE OF THE CONDON BUTTE SITE OBSIDIAN

Other studies (see Part Four of this project) have shown that combinations of major and trace element abundances are useful in correlating obsidian artifacts with their geologic sources (Cann et al., 1970 provides an overview). Three different combinations were used in this study and all three pointed to the same geologic source of the artifactual flakes.

First, the SiO_2, Fe_2O_3 and Cao abundances of the archaeological obsidian and the Obsidian Cliff source were plotted on a ternary diagram (see Figure VII-2). Keeping in mind that only one source was being used for comparison, the results nevertheless suggest Obsidian Cliff as a likely source.

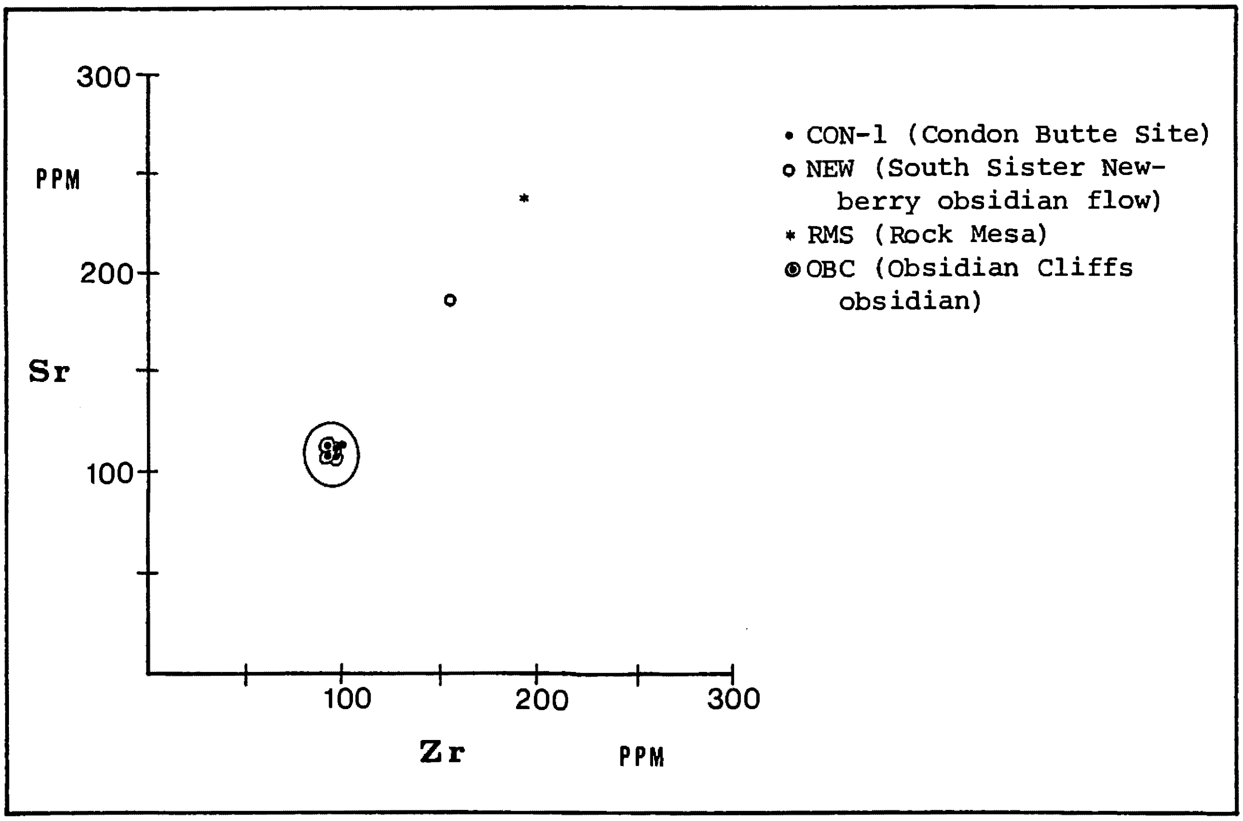

Figure VII-3: Ratios of the abundances of Strontium and Zirconium in obsidian from the Condon Butte Site and from geologic sources in the Condon Butte area for which geochemical data are available.

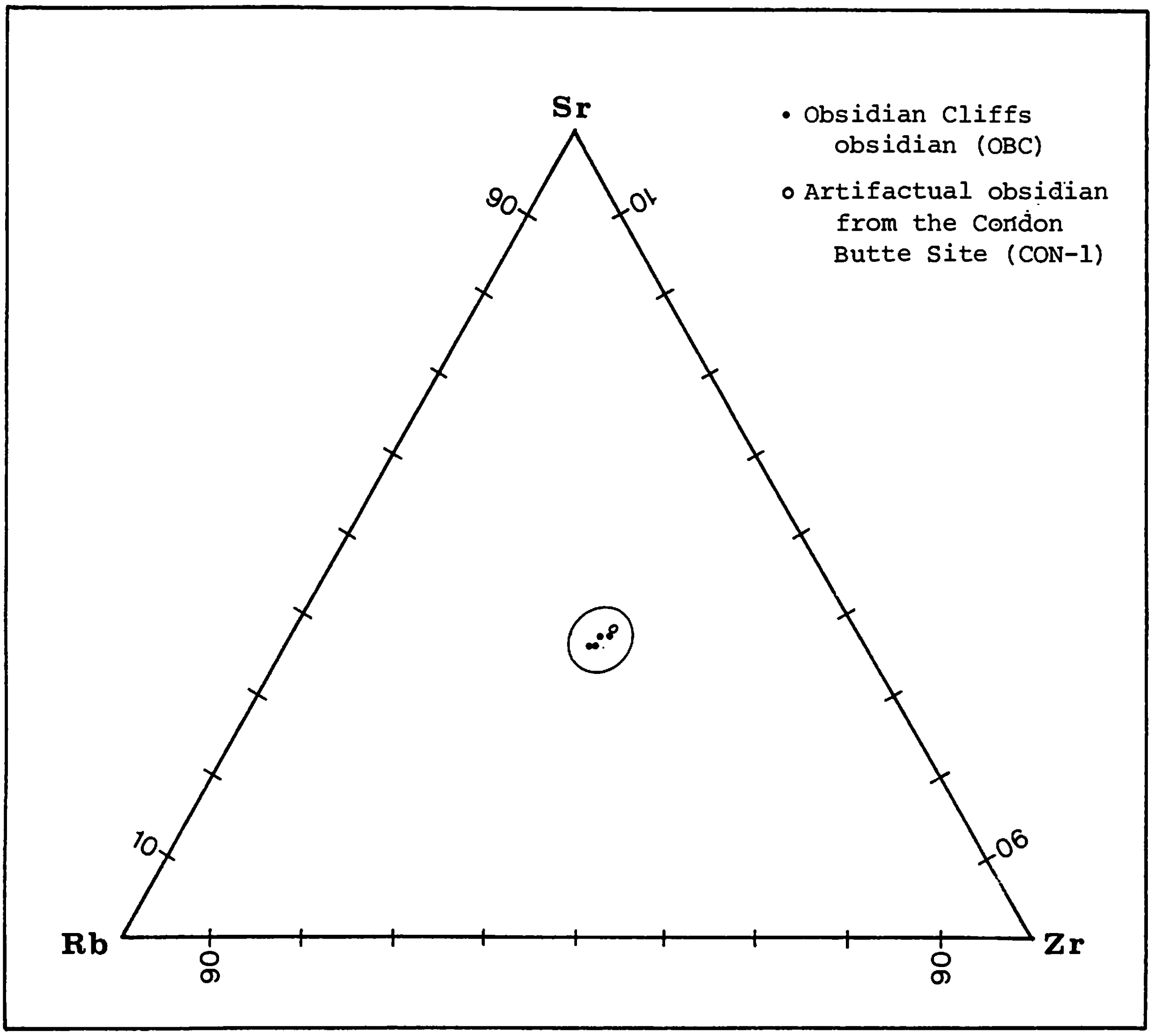

Figure VII-4: Ternary diagram showing the relative abundances of Strontium, Rubidium and Zirconium present in obsidian from the Obsidian Cliffs obsidian source and from the Condon Butte Site. The relative abundances of trace-elements in obsidian from these two sources are very similar.

Next, the abundances of Strontium and Zirconium were plotted on a binary graph (see Figure VII-3). The Condon Butte Site obsidian was compared here with obsidian from Obsidian Cliffs, Rock Mesa and the South Sister Newberry Obsidian Flow. Though analytical results from different laboratories using different methods (here, X-ray fluorescence and neutron activation) need to be compared with caution, the results again strongly suggest Obsidian Cliff as the source.

Finally, Strontium, Zirconium and Rubidium abundances of obsidian from the Condon Butte Site and Obsidian Cliff were compared using a ternary diagram (see Figure VII-4). Once again, the results indicate Obsidian Cliff as the source.

As a further check, several thin-sections prepared from the Obsidian Cliff samples were also examined. It is known that different sources of obsidian may exhibit different and sometimes distinctive types and sizes of microlitic structures (see Part Four of this project). The microlites in the Obsidian Cliff specimens proved to be indistinguishable when compared to thin-sections of flakes collected at the Condon Butte Site.

The demonstration obsidian source identification computer program described in Appendix XI of this project was also utilized to determine the source of the archaeological obsidian. Given that the source universe of the identification program did not include regional obsidian sources other than Obsidian Cliff, the Condon Butte obsidian once again appeared to originate from Obsidian Cliff.

CONCLUSIONS

Artifactual obsidian from the Condon Butte Site, a small lithic scatter near Condon Butte, was collected and geochemically characterized. Major and trace element abundances were determined by X-ray fluorescence spectrometry and compared with obsidian from several local sources. The closest and best-characterized of the local geologic sources was the Obsidian Cliff obsidian flow. Comparison of the major and trace element abundances strongly suggests that Obsidian Cliff was the source of the artifactual obsidian found at the Condon Butte Site. Microscopic examination of microlitic structures in obsidian thin-sections also supports that conclusion.

That Obsidian Cliff was the probable source of the obsidian flakes found at the Condon Butte Site is not a surprising or particularly significant discovery. What is more important is the possibility that a number of different geochemical and petrographic "signatures" might be used to distinguish obsidian from Obsidian Cliff in more distant sites, particularly those to the west in the Willamette Valley. More geochemical and petrographic study of obsidian originating from Obsidian Cliff and other regional sources, though, will be needed before these different methods of characterization can be reliably used to trace artifactual obsidian to its original source.

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APPENDIX VIII

Obsidian Source Sampling Localities

See Part Four, Chapter Two for maps indicating numbered sampling locations.

Big Obsidian Flow, Newberry Caldera, Deschutes County:

BOF-1	Collected alongside paved trail leading from the main parking area across the obsidian flow. Sample is from near the margin of the flow at sampling location 1.
BOF-2	Collected from an obsidian talus block at the margin of the flow at sampling location 2.
BOF-3	Collected from an obsidian talus block at the margin of the flow at sampling location 3.
BOF-4	Collected from an obsidian talus block at the margin of the flow at sampling location 4.

Cougar Mountain, Lake County:

CGM-1	Collected just below the plateau area above Cougar Mountain Caves No.1 and No.2 about 150 m west of the entrance of Cougar Mountain Cave No.1.
CGM-2	Collected on the plateau area above Cougar Mountain Caves No.1 and No.2. The exact location was not recorded.
CGM-3	Collected on the plateau area above Cougar Mountain Caves No.1 and No.2. The exact location was not recorded.
CGM-4	Collected on the plateau area above Cougar Mountain Caves No.1 and No.2. The exact location was not recorded.

East Lake Obsidian Flow A (Westernmost of the Two East Lake Flows), Newberry Caldera, Deschutes County:

ELA-1	Collected from an obsidian talus block at the base of the obsidian flow at sampling location 1.
ELA-2	Collected from an obsidian talus block at the base of the obsidian flow at sampling location 2.
ELA-3	Collected from an obsidian talus block at the base of the obsidian flow at sampling location 3.
ELA-4	Collected from an obsidian talus block at the base of the obsidian flow at sampling location 4.

East Lake Obsidian Flow B (Easternmost of the Two East Lake Flows), Newberry Caldera, Deschutes County:

ELB-1	Collected from an obsidian talus block at the base of the obsidian flow at sampling location 1.
ELB-2	Collected from an obsidian talus block at the base of the obsidian flow at sampling location 2.
ELB-3	Collected from an obsidian talus block at the base of the obsidian flow at sampling location 3.
ELB-4	Collected from an obsidian talus block at the base of the obsidian flow at sampling location 4.

Upper Winberry Creek Welded-Ash Flow, Lane County:

LOW-1	Collected near the top of the densely-welded portion of the welded ash-flow at sampling location 1.
LOW-2	Collected near the center of the densely-welded portion of the welded ash-flow at sampling location 2.
LOW-3	Collected at the top of the densely-welded portion of the welded ash-flow at sampling location 3.
LOW-4	Collected at the base of the densely-welded portion of the welded ash-flow at sampling location 4.

Glass Buttes, Site 35LK304, Lake County:

GLB-304A	Collected on the surface at 35LK304 at sampling location A.
GLB-304B	Collected on the surface at 35LK304 at sampling location B.
GLB-304C	Collected on the surface at 35LK304 at sampling location C.
GLB-304D	Collected on the surface at 35LK304 at sampling location D.

Glass Buttes, Site 35LK306, Lake County:

GLB-306A	Collected on the surface next to an intermittent stream at site 35LK306, sampling location A.
GLB-306B	Collected on the surface next to an intermittent stream at site 35LK306, sampling location B.
GLB-306C	Collected on the surface at the confluence of two intermittent streams at site 35LK306, sampling location C.
GLB-306D	Collected on the surface next to an intermittent stream at site 35LK306, sampling location D.

Glass Buttes, Site 35LK337, Lake County:

GLB-337A	Collected on the surface at site 35LK337, sampling location A.
GLB-337B	Collected on the surface at site 35LK337, sampling location B.
GLB-337C	Collected on the surface at site 35LK337, sampling location C.
GLB-337D	Collected on the surface at site 35LK337, sampling location D.

Obsidian Cliffs, Site 35LA172, Lane County:

OBC-1	Collected at the base of Obsidian Cliffs due south of the point where the trail from Frog Camp meets the Holocene lavas from Collier Cone, sampling location 1.
OBC-2	Collected midway between the trail and the small creek that cross the lower part of the Obsidian Cliffs plateau at sampling location 2.
OBC-3	Collected on a rise overlooking a small lake due north of Obsidian Falls at sampling location 3.
OBC-4	Collected on top of a knoll overlooking an unnamed spring at the extreme edge of the obsidian flow just east of the Oregon Skyline Trail, sampling location 4.

Riley Site, Harney County:

RIL-1	Collected about 75 m south of a valley border at the Riley Site, sampling location 1 (approximately corresponds to area B, sample 3, of Atherton, 1966:39).

RIL-2	Collected on the southern edge of a ravine bisected by an intermittent stream at sampling location 2 (approximately corresponds to area C, sample 7, of Atherton, 1966:39).
RIL-3	Collected about 75 m north of the edge of a ravine at sampling location 3 (approximately corresponds to area B, sample 4, of Atherton, 1966:39).
RIL-4	Collected about 50 m east of a gully at sampling location 4 (approximately corresponds to area A, sample 2, of Atherton, 1966:39).

APPENDIX IX

The Characterization of Archaeological Obsidian from Several Cave Sites in the Fort Rock Basin, Lake County, Oregon

Abstract

Four samples of artifactual obsidian from Fort Rock Cave and from two of the Connley Caves were characterized geochemically and petrographically and found to originate from the nearby Cougar Mountain obsidian quarry site. Attempts to fix a source-specific hydration rate for this obsidian quarry were not successful. All of the artifactual obsidian originating from Cougar Mountain was recovered from pre-Mazama occupation levels in the caves. A fifth sample from one of the Connley Caves, petrographically and geochemically distinct from the other samples, came from a post-Mazama stratum. The geologic source of this sample was not established. Though many regional sources of obsidian have been located, it is almost certain that unreported ones still exist. Identification of these sources is essential for further characterization studies of obsidian from this region.

The results of this investigation support a previous study that identified Cougar Mountain as a major, though not exclusive, source of obsidian for the early inhabitants of the Fort Rock Basin. The results of this study also point to the potential importance of petrographic characterization of obsidian from this region, particularly for the petrographically-distinctive Cougar Mountain obsidian source. Further investigation of petrographic characterization methods are warranted and, if successful, could help make the characterization of obsidian in the Fort Rock Valley a more routine and easily-carried out component of archaeological research there.

INTRODUCTION

The Fort Rock Basin is a large topographic basin lying at the northern border of the Great Basin in south-central Oregon. With an area of about 6,159 km^2 (2,378 mi^2), the basin reaches a maximum width of 132 km (82 mi) along an east-west axis and a width of as much as 93 km (58 mi) along a north to south transect (Forbes, 1973:13).

Near the center of this interior-draining basin is the Fort Rock Lake Basin, an area of low relief bordered by volcanic highlands, early Holocene lava fields, tilted fault-blocks, tuff rings and volcanic domes (Figure IX-1). During the late Pleistocene and early Holocene much of this lake basin was occupied by Pluvial Fort Rock Lake, one of the many pluvial lakes that existed in the Great Basin. The waters of Pluvial Fort Rock Lake carved several caves along the shorelines of the lake and most of these caves and rockshelters were later occupied by the early inhabitants of the basin. Archaeological evidence indicates that the Fort Rock Lake Basin was continuously occupied from more than 13,000 radiocarbon years ago until at least a few thousand years ago.

Since 1938, several of the former cave occupation sites have been excavated by archaeologists and collectors. These sites have produced thousands of artifacts, revealing that a culture once existed here that was well-adapted to the

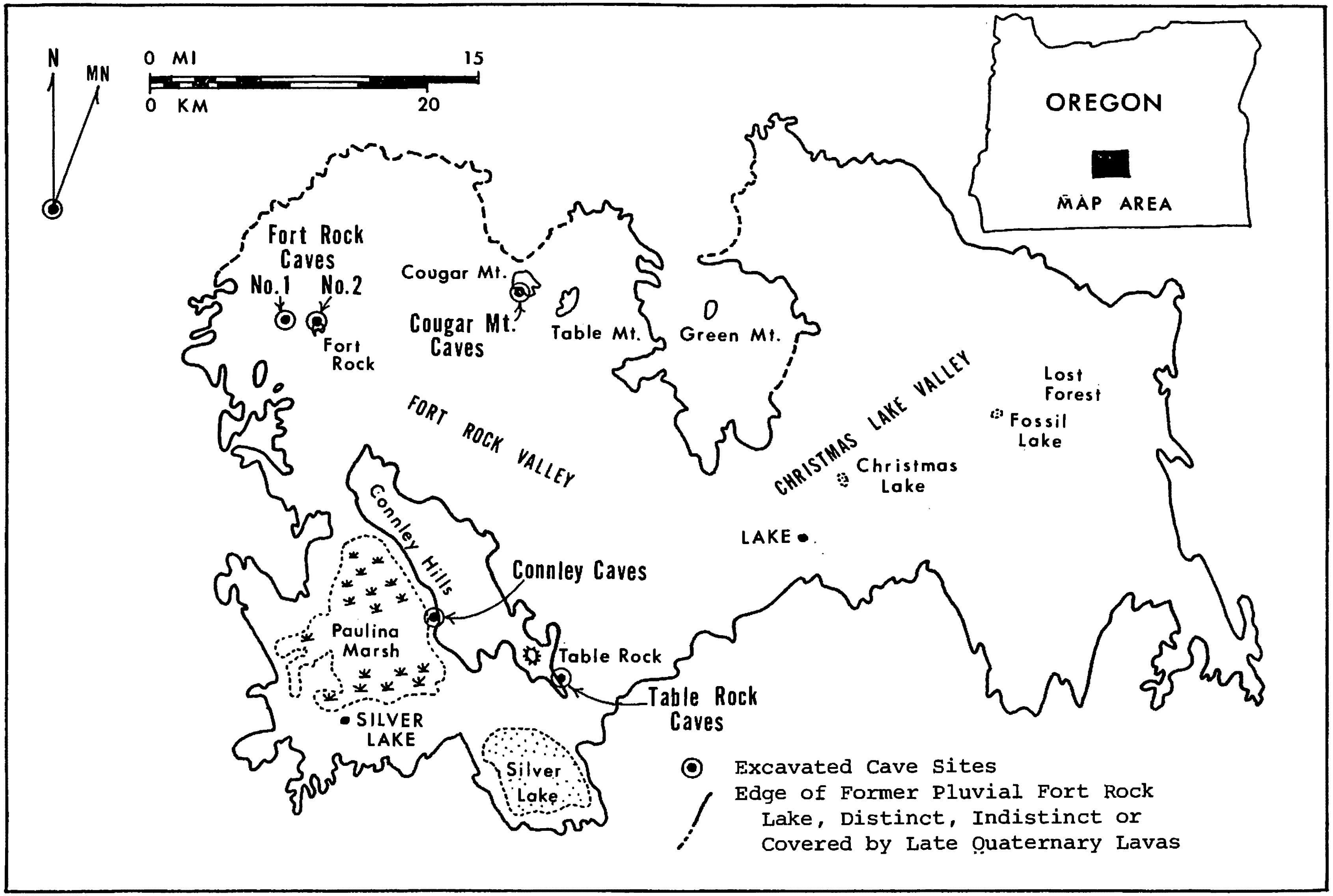

Figure IX-1: The Fort Rock and Christmas Lake Valleys of Central Oregon. Cougar Mountain, Fort Rock and the Connley Hills were once islands in the extensive late Pleistocene Pluvial Fort Rock Lake.

exploitation of the shallow lakes and marshes of the region. Though the artifactual materials recovered here have been made of many different raw materials - bone, shell, plant fibers, basalt, skin, wood, chert and others - one material, obsidian, has clearly dominated the lithic assemblage found in the cave sites (Bedwell, 1970:320,392). Surface collections in the Fort Rock Lake Basin also support this predominance of obsidian as a raw material (Colvin, 1970; Toepel and Beckham, 1980; Toepel et al., 1981).

The importance of obsidian in the archaeological research and reconstruction of the extinct contact and exchange systems once involving the Fort Rock Basin has been noted previously by Toepel et al. (1980:96), who writes:

> In addition to obtaining more information from subsurface sites in the region, much can be learned about cultural relations and trade through trace element studies of obsidian...artifacts. Four major obsidian sources are located in or near the basin, and a number of other sources are found further south and east. Many of these sources have been identified, and x-ray fluorescence studies can now usually identify the original sources of obsidian artifacts. Distributional sourcing studies of temporally diagnostic artifacts and samples from sites in various portions of the Fort Rock Basin, as well as in adjacent basins and drainages, can provide a valuable means of charting utilization patterns within and between regions through time.

Problems for further research regarding obsidian in the Fort Rock Basin are also proposed (Toepel et al., 1980:79).

> How early were the aboriginal people utilizing the various obsidian sources within the region? Did the pattern with which these sources were used change over time? Can routes of prehistoric trade be traced from the Fort Rock Basin into surrounding areas through trace element studies?

The remainder of this appendix concerns itself with these questions and with the obsidian that was available to the people that inhabited this region for at least thirteen millenia - the location of regional geologic obsidian sources (now known to be more plentiful than expected), the characterization of archaeological and geological obsidian and the identification of the geologic sources of archaeological obsidian from the cave sites in the basin. Though this investigation is a preliminary one, it is hoped that it will provide a baseline for further study of this lithic material that was so important to the early people of the Fort Rock Basin.

OBJECTIVES OF THE INVESTIGATION

At the outset of this brief investigation, several objectives were delineated. They were:

1. To identify regional sources of obsidian that would have been available to the early inhabitants of the Fort Rock Basin.
2. To geochemically and petrographically characterize artifactual obsidian from several archaeological cave sites in the Fort Rock Valley and from some of the possible geologic sources.

3. To identify the geologic source(s) of the characterized archaeological obsidian.
4. To compare the results of this investigation with other recent studies of obsidian in the region.

Obsidian hydration studies of the artifactual materials were also originally planned, but were reluctantly abandoned owing to disappointing preliminary results. It was reasoned that the relatively stable thermal environment of the sheltered cave sites sampled for obsidian, the identification of the geologic sources of the artifactual obsidian and the association with radiocarbon-dated materials would make possible the establishment of a source-specific hydration rate for the Cougar Mountain quarry site (expected to be a major source of the artifactual obsidian). Both the chemical composition and the temperature of the environment are major variables that must be taken into account in the assignment of a source-specific rate of hydration (Ericson, 1975 and 1977; Ambrose, 1976; Friedman, 1976). Two thin-sections were prepared from each of the five artifacts characterized and their hydration rims were then measured photographically using the method described by Findlow and DeAtley (1976). It soon became apparent, though, that each artifact identified as originating from Cougar Mountain was yielding a different rate of hydration. Whether this was due to site disturbance, to incorrect slide preparation or to differences greater than were expected in the thermal contexts of the artifactual obsidian is not known. At this point, though, the hydration rate determination part of this investigation was discontinued and full attention was shifted to the characterization of the obsidian and the identification of local obsidian sources.

ARCHAEOLOGICAL RESEARCH IN THE FORT ROCK BASIN

Formal archaeological research in the Fort Rock Basin began in 1938 when Luther S. Cressman and a party from the University of Oregon excavated a portion of Fort Rock Cave (Plate IX-1). This cave, located not far from the local landmark of Fort Rock, is one of the many littoral caves found along the old shoreline of Pluvial Fort Rock Lake (Cressman, 1942; Cressman and Williams, 1940).

Since that time, several other archaeological cave sites in the Fort Rock Lake Basin have been excavated by professional and amateur archaeologists (Figure IX-1). A University of Oregon team excavated five cave sites near the southern end of the Connley Hills in 1966 and 1967 (Plate IX-2), as well as Cougar Mountain Cave No.2 (Plate IX-3) and two rockshelters at Table Rock. The same group also re-excavated part of Fort Rock Cave, recovering charcoal that yielded a radiocarbon age of 13,200 ± 720 years B.P. (Gak-1738)(Bedwell, 1970 and 1973). This age, the oldest reported from the Fort Rock Lake Basin, established the considerable antiquity of occupation in the region.

Fort Rock Cave No.2, a small cave site on the east side of Fort Rock, was excavated in 1955, producing a small collection of textile, shell, leather and stone (primarily obsidian) artifacts (Scheans, 1956). Cougar Mountain Cave No.1, a major workshop and quarry site located on the south side of Cougar Mountain, was excavated by John Cowles, a collector, in 1958 (Cowles, 1960). Cowles also mentioned earlier excavations by a relic collector in caves on the west side of the mountain.

Plate IX-1: The Beggars Heel, an eroded volcanic vent located about 1.5 km west of Fort Rock. Fort Rock Cave, now known as Reub Long Cave, is found in the western portion of the former vent (entrance circled). Taken facing west from the base of Fort Rock.

Plate IX-2: The Connley Caves. The entrances to several small littoral caves, eroded by the waters of Pluvial Fort Rock Lake, can be seen at the base of the prominent fault scarp in the photograph. Circled person for scale. Taken facing west.

Plate IX-3: Cougar Mountain caves No.1 (1) and No.2 (2), two archaeological cave sites found at the southwestern, wave-eroded margin of Cougar Mountain. This rhyolite-obsidian dome was a major obsidian quarry site for the prehistoric occupants of the region.

Archaeological research at these cave sites and at numerous other surface sites in the Fort Rock Valley, as well as the results of archaeological surveys, is summarized by Minor et al. (1979:48-53), Toepel et al. (1980:15-26) and Toepel and Beckham (1981:13-20).

Two archaeological studies carried out in the Fort Rock Basin are particularly germane to the objectives of the investigation reported in this appendix.

The first of these was an obsidian hydration study by Layton (1972) of 102 obsidian projectile points that had been recovered during Cowles' excavation of Cougar Mountain Cave No.1. Though neither the compositional or thermal environment variables were taken into account, Layton was nevertheless able to draw some conclusions from his analyses. Through relative seriation of hydration rim thicknesses he identified four temporally overlapping projectile point traditions for the Fort Rock Valley. This seems to support Bedwell's discovery of changing projectile point traditions over the period of occupation of the nearby Connley Caves and Fort Rock Cave (Bedwell, 1970:207-213; 1973:157-160). Layton also concluded that the occupational sequences at Cougar Mountain Cave No.1, Fort Rock Cave and the Connley Caves were similar.

In a later study by Sappington and Toepel (1981), 283 samples of artifactual obsidian collected on the surface as part of a 251 km (156 mi)-long survey transect stretching from Silver Lake north to near Maupin were geochemically characterized. This survey corridor ran through the Fort Rock Valley between the Fort Rock and Connley Caves. The geologic sources of 167 of these specimens, after comparison with 16 known characterized geologic sources, were identified. The sources of the remaining 116 artifacts remained unknown. Of the 167 obsidian artifacts whose sources were determined, 38% originated from Cougar Mountain, 27% came from Newberry Caldera, 11% were from Yamsay Mountain, 14% were from Tucker Hill and the remaining 16% came from seven other sources to the east and south of the Fort Rock Valley. Almost all (97%) of the artifacts originating from the Cougar Mountain source were found in the Fort Rock Valley or within 40 km (25 mi) of the source.

In a related study by the same authors (Sappington and Toepel, 1981:248-156), 26 obsidian artifacts from pre-Mazama levels in Fort Rock Cave and Connley Caves No.4 and No.5 were geochemically characterized. Of the 14 artifacts from Fort Rock Cave, three were found to have come from Cougar Mountain, three from Newberry Caldera, two from other sources and six from unknown sources. A total of two specimens from the Connley Caves originated at Cougar Mountain, while of the remaining ten specimens, six came from unidentified geologic sources. Though the authors were attempting to test the hypothesis that artifactual obsidian originating from Newberry Caldera would be less than about 5,000 years old (apparently unaware, at that time, that numerous sources in the Newberry Caldera area are older than this), their results did identify Cougar Mountain as a major source of obsidian during early periods of occupation in the Fort Rock Valley.

Plate IX-4: Obsidian artifacts from Fort Rock Cave and the Connley Caves prior to their preparation for X-ray fluorescence analysis and thin-section examination.

SOURCES OF ARCHAEOLOGICAL OBSIDIAN EXAMINED

The archaeological obsidian utilized in this investigation was recovered during the University of Oregon excavations of 1966 and 1967 in the Fort Rock Valley. Five crude, flaked obsidian tools from Fort Rock Cave (35LK1) and Connley Caves No.4 (35LK50/4), No.5 (35LK50/5) and No.6 (35LK50/6) were obtained from the State of Oregon Museum of Anthropology at the University of Oregon (Plate IX-4). Each artifact was associated with a stratum in which material had been radiocarbon-dated (see Table IX-1). All of the obsidian tools, with the exception of the one from Connley Cave No.6, were recovered from pre-Mazama levels in the caves. Mazama tephra, originating from the present site of Crater Lake about 7,000 radiocarbon years ago, forms a widespread stratigraphic marker in this region. The obsidian tools were all classified as uniface or biface scrapers except for the example from Connley Cave No.6, which was described as an unshaped knife. None of the scraper or knife types used in this investigation were considered temporally diagnostic (Bedwell, 1970 and 1973).

REGIONAL GEOLOGIC SOURCES OF OBSIDIAN

There are many potential geologic sources of obsidian located not far from the Fort Rock Lake Basin that might have provided obsidian for the early occupants of the area (Figure IX-2).

Geologic sources to the northeast of the basin have been reported at China Hat (Higgins, 1968:272), at East Butte (Higgins, 1968:273), in the caldera and on the upper flanks of Newberry Volcano (Higgins, 1968 and 1973; MacLeod et al., 1981 and 1982), at Quartz Mountain (Atherton, 1966:34; Heflin, 1979), at Squaw Mountain near the Squaw Ridge Fault Zone (McKee et al., 1976; Skinner, 1980), in the Little Garden area of the Devil's Garden lava field (Skinner, 1983) and at Cougar Mountain (Hampton, 1946:7; Atherton, 1966:27-30; Layton, 1972; Forbes, 1973:108-111; Allison, 1979:19-20).

Northeast of the basin, obsidian has been located at Frederick Butte (Heflin, 1979), at Hampton Butte (Heflin, 1979), at Round Butte (Sappington, 1980), at Squaw Butte (McKee et al., 1976) and at Glass Buttes (Waters, 1927).

South of the Fort Rock-Christmas Lake Valleys, additional obsidian sources have been found in the Frog Mountain area (Atherton, 1966:30-33; Sappington, 1981), at Winter Ridge (Travis, 1977:11), at Tucker Hill (Peterson, 1961), at Coglan Buttes (Sappington, 1982) and in the Horse Mountain/Poverty Basin area (Toepel et al., 1980:44-45; Sappington, 1981).

Sappington (1982) has also referred to a source in the Fort Rock area, possibly one of those already mentioned.

There may well be other as yet unreported sources of obsidian in the Fort Rock Lake Basin region. All of the previously mentioned sources, with the exception of some flows in the Newberry Caldera vicinity, are associated with volcanic rhyolite-obsidian domes less than 5 million K-Ar years in age (McKee et al., 1976). Many other Pliocene to Pleistocene rhyolite domes are also found in this region and it seems likely that some of these might prove to be sources of obsidian (Walker et al., 1967; McKee et al., 1976; Walker, 1977).

Origin of Artifact	Lab No.	Square	Level	Stratum	Artifact Number	Coordinates	Elevation	Associated C^{14} Date
Fort Rock Cave (35LK1)	FTR-1	66	--	--	72	8-10x/12-14y	98.07-97.97	10,200 ± 230 (GAK-2147)
Connley Cave No.4 (35LK50/4)	CNL-1	4B	30	3	13	12-14x/45.5-47.5	98.84-98.74	7,240 ± 150 (GAK-2140)
Connley Cave No.4 (35LK50/4)	CNL-2	4B	32	3	3	12-14x/45.5-47.5y	98.64-98.54	9,670 ± 180 (GAK-2142)
Connley Cave No.5 (35LK50/5)	CNL-3	5B	27	3	13	9,12x/32,35y	99.44-99.34	7,430 ± 140 (GAK-2135)
Connley Cave No.6 (35LK50/6)	CNL-4	6	20	4	16	7,8x/16,20y	98.94-98.84	4,720 ± 200 (GAK-2132)

Table IX-1: Provenience and associated radiocarbon dates of the characterized obsidian artifacts. The numbering system is from the State of Oregon Museum of Anthropology.

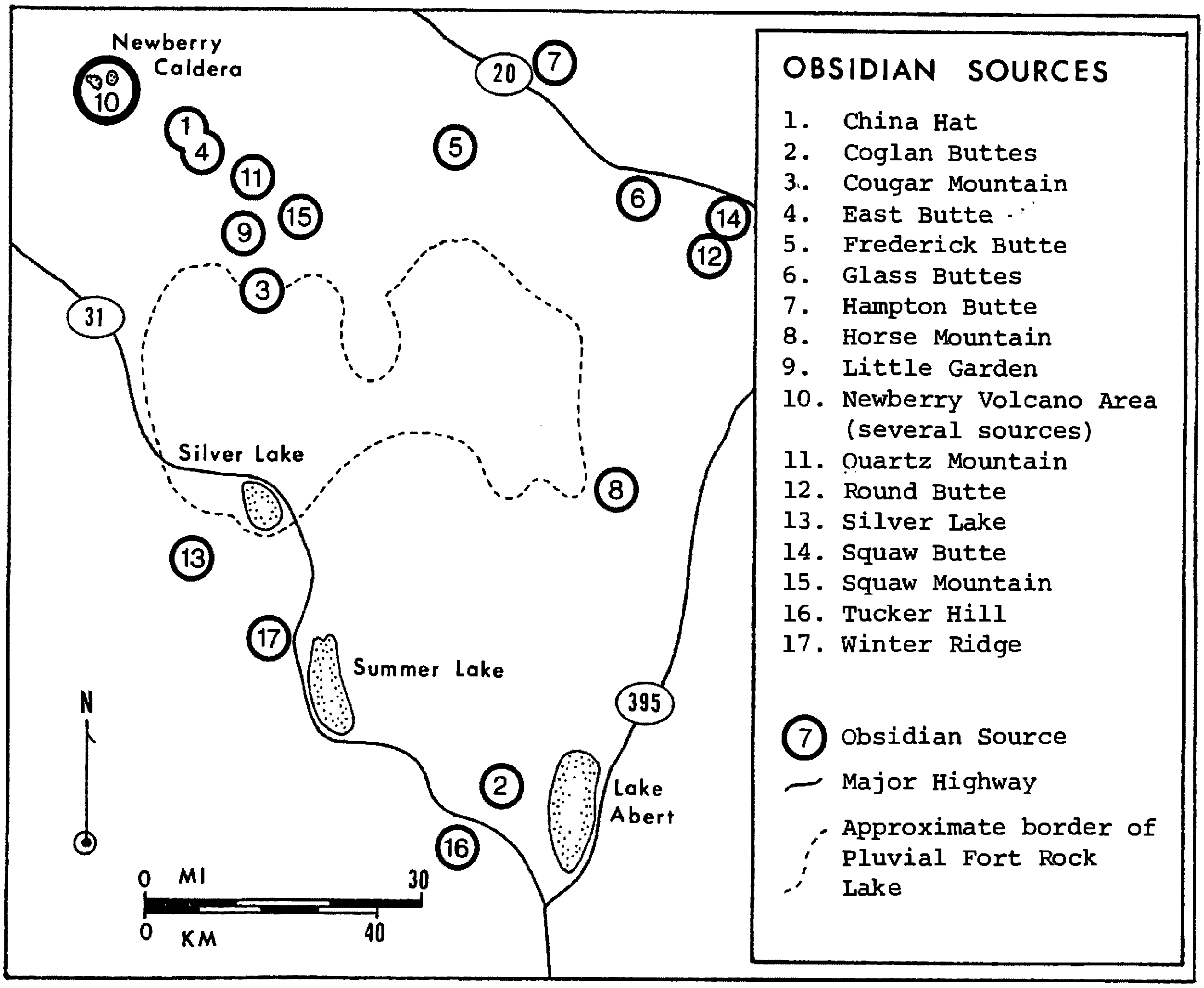

Figure IX-2: Reported sources of obsidian in the region of the Fort Rock-Christmas Lake Valleys. Numerous other sources of obsidian are not far removed from the area covered by this map.

Cougar Mountain, the obsidian source located nearest to the Fort Rock and Connley Caves, was suspected to be a major supplier of the artifactual obsidian recovered from these sites. The source is only 16 km (10 mi) from Fort Rock Cave and 24 km (15 mi) from the Connley Caves. In the previously-mentioned study by Sappington and Toepel (1981), though, obsidian artifacts from the Fort Rock and Connley Caves had originated not only from Cougar Mountain, but also from Newberry Caldera, the South Sister area, Yamsay Mountain and Buck Spring (the last three sources, not located on Figure IX-2, are found, respectively, to the west and northeast of the Fort Rock Lake Basin).

THE CHARACTERIZATION AND GEOLOGIC SOURCES OF THE ARCHAEOLOGICAL OBSIDIAN

The artifactual obsidian from the Fort Rock and Connley Caves was characterized using abundances of selected trace elements in the glass and the presence of distinctive microscopic microlitic structures in the glass. Geochemical and petrographic data were also available for comparison from several other

	FTR-1	CNL-1	CNL-2	CNL-3	CNL-4	CGM-1	CGM-2	CGM-3	CGM-4
Rb	101	102	98	103	127	101	101	101	101
Sr	35	31	31	32	5	33	33	34	32
Y	44	46	45	46	45	48	48	51	57
Zr	127	129	128	127	344	120	132	132	131
Nb	11	11	11	9	14	12	8	11	12

FTR-1: A crudely-shaped obsidian scraper recovered from Fort Rock Cave (35 LK 1). This artifact was found in association with material radiocarbon dated at 10,200 ± 230 years B.P. X-ray fluorescence analysis by the author.

CNL-1: An unshaped obsidian scraper recovered from Connley Cave No.4 (35 LK 50/4). This artifact was found in association with material radiocarbon dated at 7,240 ± 150 years B.P. X-ray fluorescence analysis by the author.

CNL-2: A crudely-shaped obsidian scraper recovered from Connley Cave No.4 (35 LK 50/4). This artifact was found in association with material radiocarbon dated at 9,670 ± 180 years B.P. X-ray fluorescence analysis by the author.

CNL-3: An unshaped obsidian scraper recovered from Connley Cave No.5 (35 LK 50/5). This artifact was found in association with material radiocarbon dated at 7,430 ± 140 years B.P. X-ray fluorescence analysis by the author.

CNL-4: An unshaped knife recovered from Connley Cave No.6. This artifact was found in association with material radiocarbon dated at 4,720 years B.P. X-ray fluorescence analysis by the author.

CGM-1, CGM-2, CGM-3, CGM-4: Obsidian collected at Cougar Mountain, an obsidian quarry site located nine miles east-northeast of Fort Rock Cave and twelve miles northeast of the Connley Caves. X-ray fluorescence analysis by the author.

Table IX-2: Trace element abundances of artifactual obsidian recovered from Fort Rock Cave and the Connley Caves as well as from the Cougar Mountain obsidian quarry site. Abundances are reported in parts per million.

possible geologic sources (Cougar Mountain, Glass Buttes, Squaw Mountain, the Big Obsidian Flow and the East Lake obsidian flows, the former and the latter located in Newberry Caldera). It should be noted that not all of the known regional sources of obsidian were characterized for this preliminary study.

Geochemical Characterization of the Obsidian

The trace element composition (Rb, Sr, Y, Zr and Nb) of each of the five obsidian artifacts was determined by X-ray fluorescence spectrometry at the University of Oregon X-Ray Fluorescence Laboratory. Samples from other potential geologic sources were also collected and analyzed as part of a conjoint research project.

After the removal of small portions to be prepared as thin-sections, the artifactual obsidian was thoroughly cleaned with water and acetone, then reduced to a fine powder in a ball mill. Because of the relatively small size of the artifacts (5 to 10 gm), no attempt was made to remove the weathered hydration rims prior to powdering. Previous research has indicated that the presence of the hydration rim was not a significant factor in the determination of the trace elements used in the current study (Bennett and D'Auria, 1974). 5 gm of the powdered glass, along with a boric acid backing, were pressed into a cohesive disc and analyzed using a GE XRD-7 Vacuum Spectrometer. Each sample was counted for 200 seconds per element in an air pathway along with U.S. Geological Survey standards. The results of the analysis of the artifactual obsidian and of the Cougar Mountain obsidian appear in Table IX-2 (analytical data for other sources used for comparison with the artifactual obsidian appear in Appendix Ten and Part Four of this project).

Petrographic Characterization of the Obsidian

The artifactual obsidian from the cave sites was also characterized on the basis of the structure of microlitic forms that were found in the glass. The

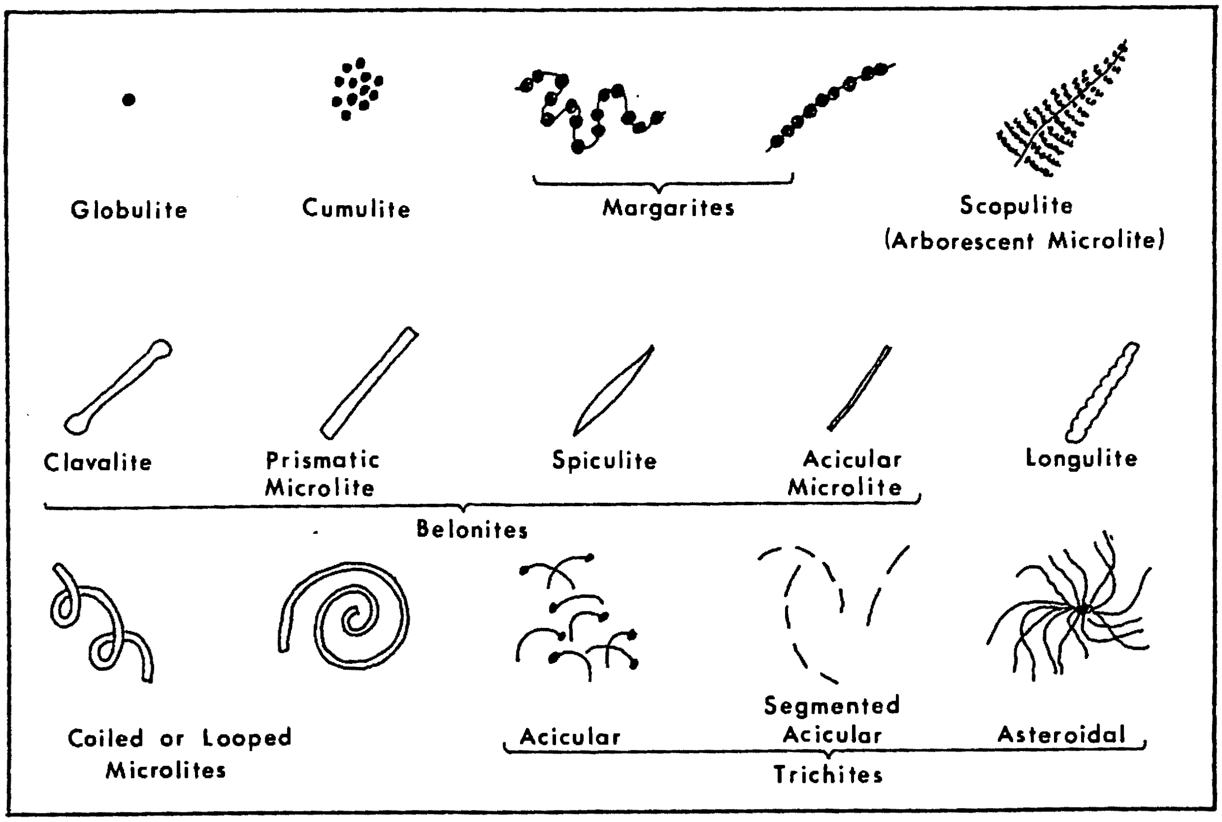

Figure IX-3: Assortment of microlitic structures that are commonly found in volcanic glasses. Compiled from several sources (Rutley, 1891; Johannsen, 1931; Clark, 1961; Ross, 1962).

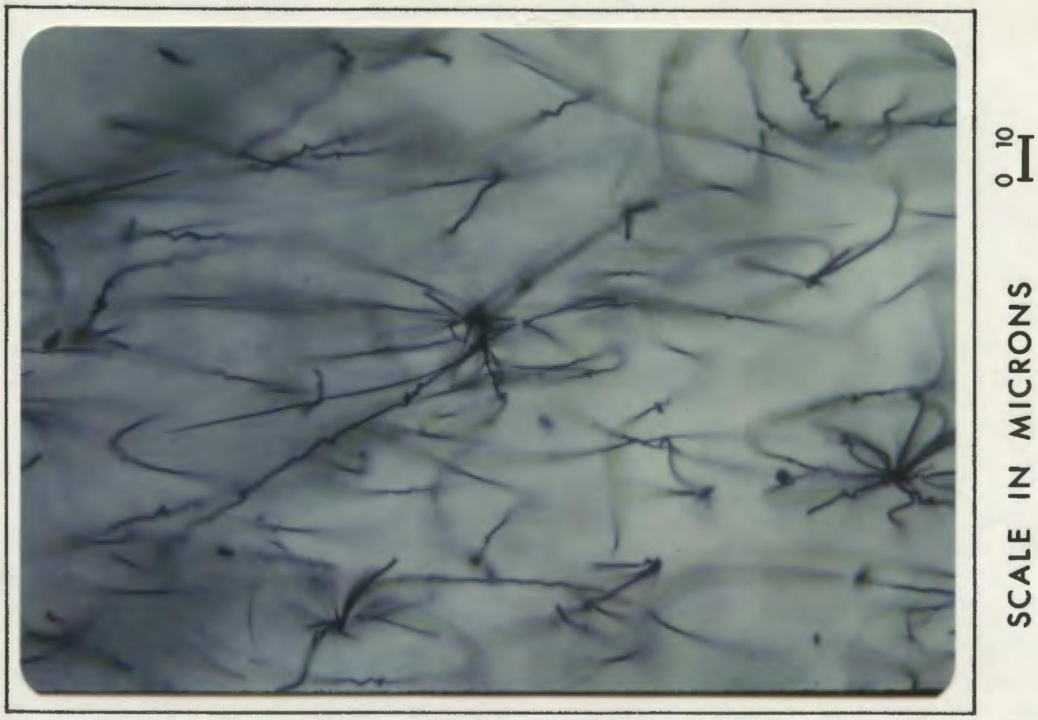

Plate IX-5: Photomicrograph of a thin-section cut from artifactual obsidian recovered from Connley Cave No.4. The striking microlitic structures, asteroidal trichites, are typical of obsidian from Cougar Mountain, the source of this artifact. Nicols not crossed, x150.

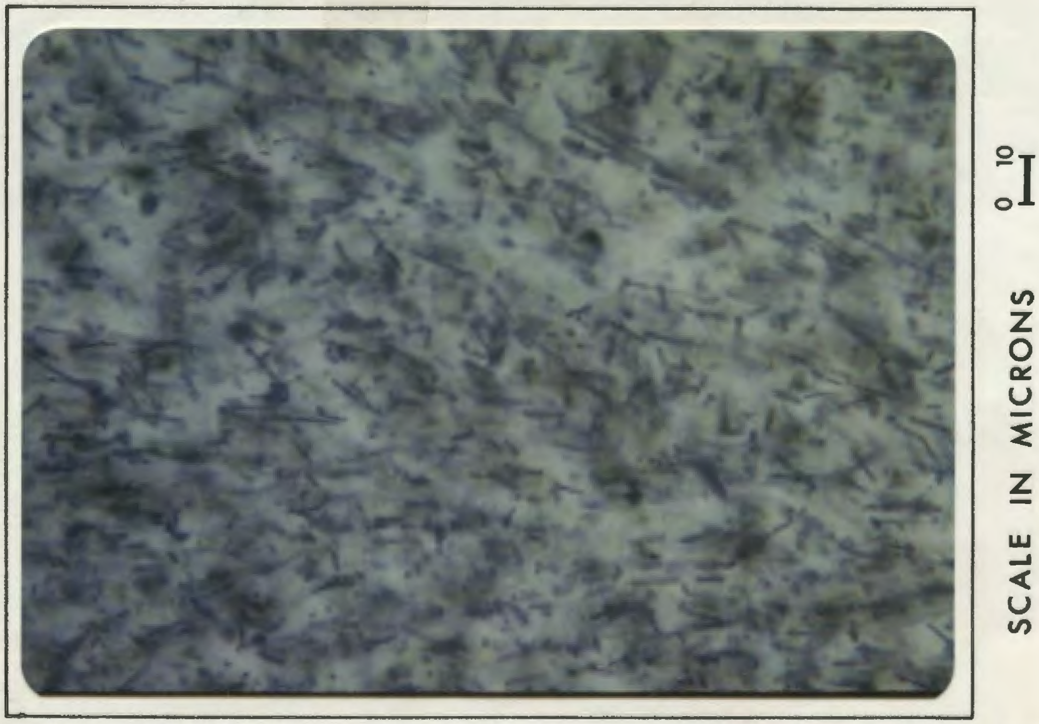

Plate IX-6: Photomicrograph of a thin-section of artifactual obsidian excavated at Connley Cave No.6. The geologic source of this obsidian artiact is currently unidentified. Very thin prismatic microlites dominate the microlitic structures in the photograph. Nicols not crossed, x150.

petrographic characterization of obsidian, though not well-understood or documented, was hypothesized to be possible because of results of an associated research project (reported in Part Four of this project).

When prepared as a thin-section and viewed with a microscope, most natural glasses exhibit one or more types of microlitic structures in the glass known as microlites. Though study of these microlitic structures has been incomplete, a variety of different forms have been identified (Rutley, 1891; Johannsen, 1931; Clark, 1961; Ross, 1962 - see Figure IX-3). The term *microlite* is a general one and most of the microlitic structures are named, not on the basis of their composition or mineralological characteristics, but on the basis of their morphology. Some of the microlitic structures polarize light and have determinable optical properties while others do not.

Thin-sections were made from a fragment of each obsidian artifact as well as from samples of the geologic sources also being considered. When the artifactual samples were examined, they were found to fall into two petrographically-distinct groups.

The obsidian artifacts from Fort Rock Cave (FTR-1) and Connley Caves No.4 and No.5 (CNL-1, CNL-2 and CNL-3) were virtually indistinguishable. Abundant acicular and asteroidal trichites were the predominant microlitic structures found. Longulites were also common and occasional prismatic microlites were also present. Scattered grains of magnetite dust were found throughout the glass (Plate IX-5). Because of the petrographic similarities between these samples, it was hypothesized that they had originated from a single geologic source. The results of the geochemical characterization of the obsidian confirmed this.

The single remaining artifact, a crude knife from Connley Cave No.6, proved to be petrographically, as well as geochemically, discrete from the other artifactual samples. The glass was crowded with prismatic microlites typically ranging from three to ten microns in length and with a diameter of about one micron. Grains of magnetite were common (Plate IX-6). The obsidian from Connley Cave No.6 bears little petrographic resemblance to any of the other characterized geologic sources used for comparison.

The Geologic Sources of the Artifactual Obsidian

After being characterized, the obsidian from the cave sites was compared with obsidian from the potential characterized geologic sources in the Fort Rock Lake Basin region.

Rb, Sr and Zr abundances of the artifactual obsidian were used in the comparison of trace element abundances. Nb and Y were not used because of their small abundances and small interunit variation. The use of trace element composition is a well-known method of characterization and source correlation and has been successfully used by archaeologists for nearly twenty years (Cann et al., 1970; Ericson, 1977). This method of characterization assumes the homogeneity of individual sources (small intraunit variation) along with differences in composition between individual sources (measurable interunit variation). Keeping in mind that trace element (and petrographic) information was not available for all potential sources, it is still possible to identify the probable source of most of the archaeological obsidian.

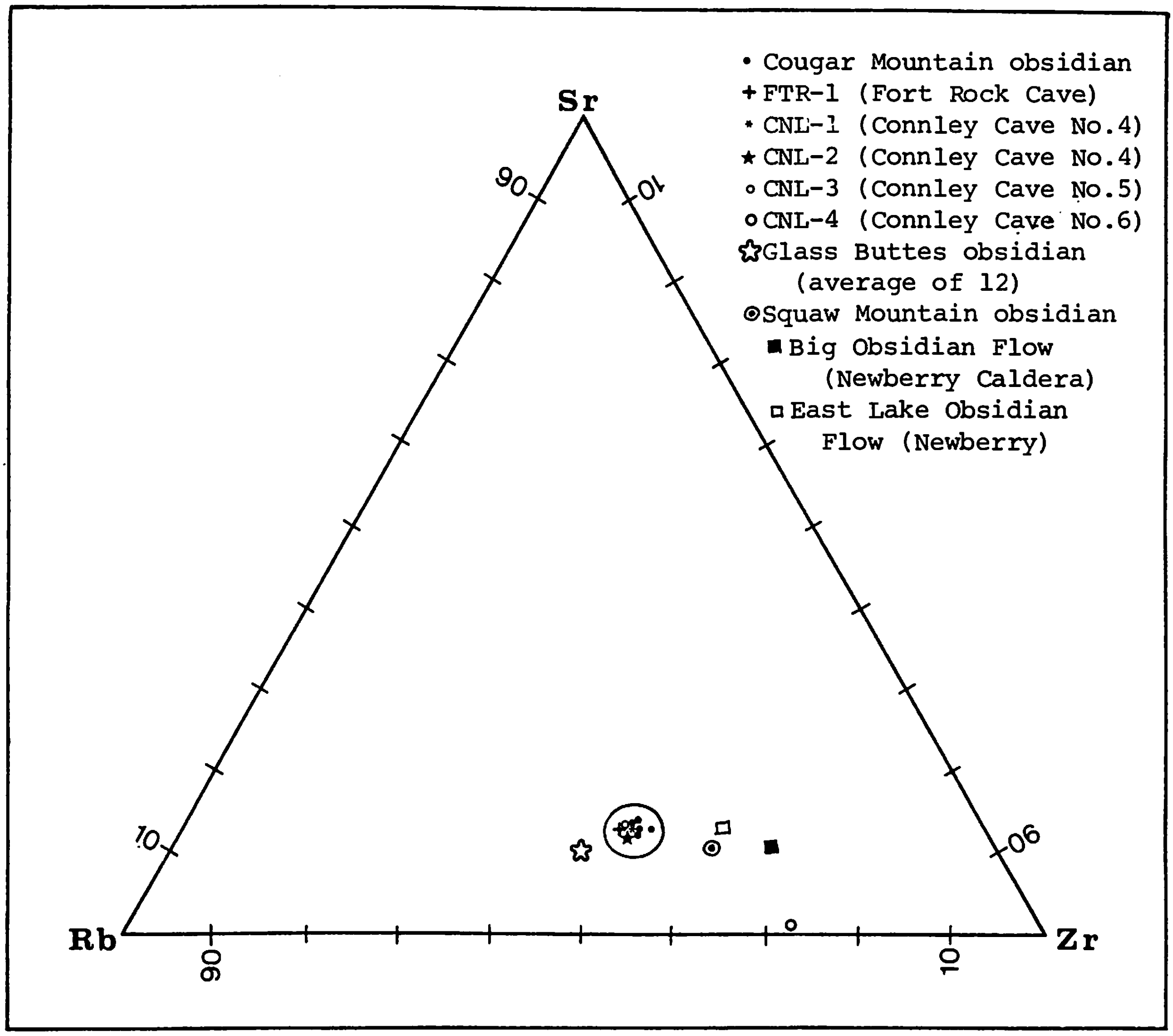

Figure IX-4: Ternary diagram illustrating the relative abundances of Rubidium, Zirconium and Strontium found in the artifactual obsidian recovered from the Fort Rock and Connley Caves. Also shown are the trace element abundances of obsidian from several other regional sources.

In Figure IX-4, the abundances of Rb, Zr and Sr in the artifactual obsidian, elements demonstrating a high degree of interunit heterogeneity and intraunit homogeneity, are plotted on a ternary diagram along with possible geologic sources. Two distinct populations are indicated with the artifactual samples from Fort Rock Cave and Connley Caves No.4 and No.5 falling into one group and the single artifact from Connley Cave No.6 falling into the other. The first group also includes the Cougar Mountain obsidian source, strongly suggesting that Cougar Mountain was the original source of this obsidian. The obsidian from Connley Cave No.6 exhibits a trace element ratio unlike any of the sources used for comparison and no geologic source identification is possible.

The same group of artifactual samples (FTR-1, CNL-1, CNL-2 and CNL-3) that appear to have originated from Cougar Mountain also show strong petrographic similarities with the Cougar Mountain source. When thin-sections from the potential geologic sources were examined, acicular and asteroidal trichites were noted only in the specimens from Cougar Mountain. These similarities suggest that microlite structures can be used to characterize obsidian and to identify the source of at least some of the artifactual obsidian recovered from sites in the Fort Rock Lake Basin.

CONCLUSIONS

1. The geologic source of four characterized obsidian artifacts recovered from pre-Mazama levels in Fort Rock Cave (35LK1) and Connley Caves No.4 (35LK50/4) and No.5 (35LK50/5) was found to be Cougar Mountain. The geologic source of a fifth specimen from a post-Mazama stratum in Connley Cave No.6 (35LK50/6) remains unidentified.
2. Cougar Mountain was probably the major obsidian source in the Fort Rock Valley during early occupation periods there, though it also appears that there was noticeable traffic between the valley and Newberry Caldera to the northwest (Sappington and Toepel, 1981). (The contact between the Fort Rock Valley and the Newberry Caldera area does, incidentally, suggest the possibility of as yet unreported early sites in the poorly-surveyed area between these two points). When the results of this investigation are combined with those of Sappington and Toepel (Table IX-3), Cougar Mountain is clearly shown to be the most utilized obsidian source. The long period of occupation at the Cougar Mountain Caves (Bedwell, 1970:75; 1973:49; Layton, 1972), the presence of excellent quality obsidian at the

Sites	Sources of Obsidian						
	NEWBERRY CALDERA	COUGAR MOUNTAIN	SOUTH SISTER	TUCKER HILL	HORSE MT.-POVERTY BASIN	BUCK SPRING	UNKNOWN
Fort Rock Cave (35LK1)	3	7	1	0	0	1	6
Connley Cave No.4 (35LK50/4)	0	1	0	1	1	0	3
Connley Cave No.5 (35LK50/5)	1	1	0	1	0	0	3
Total	4	9	1	2	1	1	12

Table IX-3: The geologic sources of 30 specimens of pre-Mazama artifactual obsidian recovered from the Fort Rock and Connley Caves. This table is modified from Sappington and Toepel (1981:254) to include the data from the investigation reported in this appendix.

mountain and the presence of Cougar Mountain obsidian in other cave sites in the Fort Rock Valley all point towards Cougar Mountain as being a major focus of activity in the early history of the Fort Rock Valley.

3. Many geologic sources of obsidian in the Fort Rock Lake Basin region remain to be identified and characterized. In the study by Sappington and Toepel (1981), the geologic sources of 46% of the 26 artifacts from the Fort Rock and Connley Caves remained unidentified while 41% of their sample of 283 specimens from this region remained without a known geologic source. Further investigation of possible obsidian sources is definitely warranted and should be the first step of any further studies of obsidian from this region.
4. The distinctive petrographic qualities of obsidian originating from Cougar Mountain may be an important factor in future characterization studies of archaeological obsidian from this region. Though other regional sources need to be located and examined to verify this, the presence of abundant microscopic trichites in the obsidian glass of Cougar Mountain may prove to be a distinctive petrographic source marker. The petrographic analysis of obsidian is a relatively simple procedure that can use very small quantites of obsidian, including waste flakes. This method could prove to be a valuable adjunct to the geochemical study of obsidian in the Fort Rock region.

Acknowledgements

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APPENDIX X

Major and Trace Element Analyses of Obsidian Examined in this Project

The major and trace element analyses reported in this appendix (along with the calculated error of the results) were established by X-ray fluorescence on a GE XRD-7 Vacuum Spectrometer. The only exception to this were the Na abundances, which were determined by the Atomic Absorption Laboratory at the University of Oregon.

XRF MAJOR ELEMENT RUN - MARCH, 1981

Sample	SiO_2	TiO_2	Al_2O_3	*MgO*	Fe_2O_3	*MnO*	*CaO*	Na_2O	K_2O	P_2O_5	*Loss*	*Total*
BOF-1	72.38	0.21	13.98	0.05	2.27	0.06	0.85	5.20	3.90	0.02	0.00	98.91

STATISTICAL EVALUATION FOR XRF MAJOR ELEMENT RUN - MARCH, 1981

Precision Estimate (2 S.D.):

USGS Standard	SiO_2	TiO_2	Al_2O_3	*MgO*	Fe_2O_3	*MnO*	*CaO*	Na_2O	K_2O	P_2O_5	*Loss*
BCR-1	0.95	0.63	0.61	3.50	0.32	8.08	0.20	0.00	2.45	0.00	0.00
AGV-1	0.71	0.00	0.57	0.98	0.21	0.00	0.29	0.00	1.44	2.86	0.00
GSP-1	0.39	0.00	0.92	12.71*	0.33	0.00	0.70	0.00	0.52	4.96	0.00
TMS-1	1.08	11.17*	1.47	55.56*	8.53	5.33	2.45	0.00	0.55	8.06	0.00
Avg. Rel. % 2 S.D.	0.78	0.21	0.89	2.24	2.35	3.35	0.91	0.00	1.24	3.97	0.00

* Indicates value excluded from average.

Accuracy Estimate (percent difference between average and Flanagan, 1973):

USGS Standard	SiO_2	TiO_2	Al_2O_3	*MgO*	Fe_2O_3	*MnO*	*CaO*	Na_2O	K_2O	P_2O_5	*Loss*
BCR-1	1.15	2.05	1.54	-6.65	0.11	-2.78	1.23	0.00	2.06	-0.00	0.00
AGV-1	0.88	0.00	0.43	-5.56	0.07	-10.00	0.51	-0.00	1.90	1.02	0.00
GSP-1	1.67	-0.00	1.18	-7.29	-0.81	0.00	-0.25	0.00	-0.72	1.79	0.00
Avg. Rel. % 2 S.D.	1.23	0.68	1.05	6.50	0.33	4.26	0.66	0.00	1.56	0.94	0.00

XRF TRACE ELEMENT RUN - APRIL, 1981

	Results			*Error (± PPM)*		
Sample	*Rb*	*Sr*	*Zr*	*Rb*	*Sr*	*Zr*
BOF-1	118.6	50.3	358.2	2.3	1.7	3.0

XRF MAJOR ELEMENT RUN - JANUARY, 1982

Sample	SiO_2	TiO_2	Al_2O_3	*MgO*	Fe_2O_3	*MnO*	*CaO*	Na_2O	K_2O	P_2O_5	*Loss*	*Total*
BOF-2	72.05	0.21	14.01	0.17	2.26	0.06	0.89	5.11	4.03	0.04	0.00	98.82
BOF-3	72.26	0.22	14.02	0.18	2.22	0.06	0.89	5.28	4.07	0.04	0.00	99.23
BOF-4	72.62	0.21	14.04	0.16	2.22	0.06	0.88	5.25	4.02	0.03	0.00	99.49
CGM-1	76.60	0.05	12.88	0.13	1.17	0.04	0.71	4.34	3.89	0.02	0.00	99.83
CGM-2	76.41	0.05	12.76	0.12	1.18	0.04	0.69	4.32	3.86	0.01	0.00	99.42
CGM-3	76.63	0.05	13.07	0.20	1.18	0.04	0.72	4.47	3.92	0.03	0.00	100.30
CGM-4	76.11	0.05	12.85	0.14	1.21	0.04	0.69	4.59	3.86	0.02	0.00	99.56
CON-1	75.40	0.09	13.06	0.20	1.15	0.04	0.92	4.42	3.48	0.04	0.00	98.79
ELA-1	72.08	0.22	13.80	0.38	2.04	0.04	1.01	4.86	4.18	0.04	0.00	98.62
ELA-2	72.99	0.23	13.89	0.30	2.04	0.05	1.01	4.81	4.23	0.04	0.00	99.57
ELA-3	72.63	0.23	13.94	0.30	2.02	0.04	1.03	4.84	4.24	0.04	0.00	99.29
ELA-4	73.08	0.23	14.02	0.30	2.05	0.05	1.00	4.82	4.19	0.03	0.00	99.75
ELB-1	73.64	0.23	14.13	0.28	2.05	0.04	1.01	4.95	4.20	0.03	0.00	100.56
ELB-2	73.40	0.23	14.12	0.28	2.03	0.04	1.02	4.98	4.20	0.04	0.00	100.30
ELB-3	73.17	0.23	13.99	0.41	2.04	0.05	1.02	4.92	4.23	0.04	0.00	100.05
ELB-4	72.56	0.23	13.95	0.36	2.04	0.05	1.01	4.88	4.25	0.03	0.00	99.41
GLB-304A	76.50	0.06	12.90	0.21	0.84	0.04	0.55	4.26	4.21	0.01	0.00	99.57
GLB-304B	75.98	0.06	12.78	0.17	0.84	0.04	0.54	4.18	4.21	-0.00	0.00	98.79
GLB-304C	76.56	0.06	12.70	0.11	0.82	0.03	0.53	4.18	4.18	-0.00	0.00	99.17
GLB-304D	76.81	0.05	12.80	0.15	0.84	0.04	0.53	4.22	4.18	-0.00	0.00	99.62

XRF Major Element Run - January, 1982 (continued):

Sample	SiO_2	TiO_2	Al_2O_3	*MgO*	Fe_2O_3	*MnO*	*CaO*	Na_2O	K_2O	P_2O_5	*Loss*	*Total*
GLB-306A	76.30	0.06	12.85	0.21	0.83	0.04	0.53	4.68	4.20	-0.00	0.00	99.69
GLB-306B	76.40	0.06	12.76	0.23	0.83	0.04	0.53	3.96	4.19	-0.00	0.00	98.99
GLB-306C	77.09	0.06	12.73	0.23	0.84	0.04	0.54	3.80	4.21	-0.00	0.00	99.54
GLB-306D	76.80	0.06	13.03	0.32	0.83	0.04	0.60	4.24	4.23	0.07	0.00	100.22
GLB-337A	76.92	0.06	12.88	0.26	0.84	0.04	0.54	4.14	4.20	-0.00	0.00	99.88
GLB-337B	76.06	0.06	12.82	0.22	0.84	0.04	0.54	3.79	4.18	0.07	0.00	98.55
GLB-337C	76.27	0.06	12.76	0.16	0.83	0.04	0.54	4.17	4.22	-0.00	0.00	99.05
GLB-337D	76.73	0.06	12.79	0.17	0.82	0.04	0.54	4.14	4.20	-0.00	0.00	99.49
LOW-1	67.24	0.31	13.41	0.36	4.39	0.12	2.13	4.90	2.08	0.05	0.00	94.99
LOW-2	68.00	0.29	13.46	0.24	4.16	0.11	2.01	4.72	2.29	0.05	0.00	95.34
LOW-3	67.90	0.30	13.31	0.37	4.14	0.11	2.13	4.47	2.41	0.05	0.00	95.19
LOW-4	67.69	0.31	13.46	0.30	4.40	0.12	2.19	4.76	2.47	0.07	0.00	95.77
LTI-5	72.64	0.21	13.80	0.26	1.97	0.04	0.98	4.77	4.26	0.05	0.00	98.97
OBC-1	75.92	0.10	13.12	0.16	1.16	0.04	0.93	4.40	3.44	0.03	0.00	99.28
OBC-2	76.19	0.09	12.95	0.25	1.09	0.04	0.88	4.41	3.46	0.02	0.00	99.37
OBC-3	76.22	0.08	13.00	0.19	1.09	0.04	0.89	4.33	3.50	0.05	0.00	99.38
OBC-4	75.31	0.09	12.90	0.22	1.09	0.04	0.88	4.23	3.48	0.03	0.00	98.26
RIL-1	72.71	0.21	13.52	0.24	2.43	0.08	0.58	4.71	4.71	0.04	0.00	99.39
RIL-2	73.28	0.21	13.38	0.28	2.46	0.08	0.57	4.73	4.73	0.03	0.00	100.03
RIL-3	72.21	0.21	13.46	0.37	2.45	0.08	0.57	4.68	4.68	0.03	0.00	99.04
RIL-4	72.49	0.21	13.19	0.22	2.41	0.08	0.54	4.67	4.67	0.02	0.00	98.68
SQM-1	75.09	0.13	12.91	-0.03	1.81	0.04	0.77	4.50	4.07	0.01	0.00	99.28

STATISTICAL EVALUATION FOR XRF MAJOR ELEMENT RUN - JANUARY, 1982

Precision Estimate (2 S.D.):

USGS Standard	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	*MnO*	*MgO*	*CaO*	Na_2O	K_2O	P_2O_5	*Loss*
W-1	1.37	0.00	0.26	0.10	0.00	2.68	0.46	0.00	0.00	0.00	0.00
BCR-1	1.16	0.86	0.25	0.43	11.43*	7.38	0.36	0.00	2.03	7.74	0.00
AGV-1	0.49	0.00	1.18	0.61	27.18*	14.77	0.81	0.00	0.34	3.14	0.00
GSP-1	0.37	1.53	0.13	0.81	40.31*	19.07	0.82	0.00	0.46	8.75	0.00
G-2	1.26	0.00	0.82	0.53	0.00	11.16*	1.47	0.00	1.88	0.00	0.00
MHA-1	1.06	1.44	0.88	1.00	13.32*	3.34	0.57	0.00	6.15	17.32*	0.00
BOYD	0.14	43.40*	6.40	0.45	0.00	1.22	4.22	35.29*	0.00	0.00	0.00
Avg. Rel. % 2 S.D.	0.83	0.64	1.42	0.56	0.00	8.08	1.25	0.00	1.55	3.27	0.00

* Indicates value excluded from average.

Accuracy Estimate (percent difference between average and Flanagan, 1973):

USGS Standard	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	*MnO*	*MgO*	*CaO*	Na_2O	K_2O	P_2O_5	*Loss*
W-1	0.35	-2.80	0.93	-0.06	-0.00	1.16	0.24	0.00	-3.13	0.00	0.00
BCR-1	-0.07	1.48	-0.13	0.13	-2.78	-0.65	0.40	0.00	-1.03	7.64	0.00
AGV-1	0.08	0.96	-0.59	-0.04	-5.00	1.96	0.20	-0.00	1.12	6.12	0.00
GSP-1	-0.12	-1.14	-0.74	-1.04	18.75	5.73	-0.99	0.00	-0.32	5.36	0.00
G-2	0.74	0.00	1.14	0.57	0.00	-0.00	-0.52	-0.00	0.22	7.14	0.00
Avg. Rel. % 2 S.D.	0.27	1.28	0.71	0.37	5.31	1.90	0.47	0.00	1.16	5.25	0.00

XRF TRACE ELEMENT RUN - FEBRUARY, 1982

	Abundances (PPM)					*Errors (PPM) 2 S.D.*				
Sample	*Rb*	*Sr*	*Y*	*Zr*	*Nb*	*Rb*	*Sr*	*Y*	*Zr*	*Nb*
BOF-1	122.9	47.9	40.4	360.5	16.0	3.5	2.4	4.2	3.9	2.4
BOF-2	126.9	49.8	39.9	360.0	19.0	3.5	2.4	4.2	3.9	2.4
BOF-3	125.7	51.4	40.2	356.2	17.4	3.5	2.4	4.2	3.8	2.4
BOF-4	124.6	47.9	39.7	358.3	20.3	3.5	2.4	4.1	3.9	2.4
CGM-1	100.8	33.0	48.1	130.0	12.1	3.1	2.2	4.8	2.6	2.2
CGM-2	101.0	32.7	47.7	131.8	8.3	3.1	2.2	4.7	2.6	2.2
CGM-3	100.6	34.3	50.9	132.2	10.5	3.1	2.2	5.0	2.6	2.2
CGM-4	100.5	32.0	47.1	131.4	12.3	3.1	2.2	4.7	2.6	2.2

XRF Trace Element Run - February, 1982 (continued):

	Abundances (PPM)					*Errors (PPM) 2 S.D.*				
Sample	*Rb*	*Sr*	*Y*	*Zr*	*Nb*	*Rb*	*Sr*	*Y*	*Zr*	*Nb*
CNL-1	102.4	30.7	46.3	129.4	10.7	3.2	2.2	4.6	2.6	2.2
CNL-2	98.3	30.6	44.9	127.7	11.3	3.1	2.2	4.5	2.6	2.2
CNL-3	103.5	31.6	45.7	127.4	9.4	3.2	2.2	4.6	2.6	2.2
CNL-4	126.7	5.0	45.0	344.0	13.6	3.5	11.8	4.5	3.7	2.3
CON-1	82.7	110.4	14.4	98.2	7.9	3.0	2.6	2.3	2.5	2.2
ELA-1	141.1	61.6	35.5	290.7	13.0	3.7	2.4	3.8	3.5	2.3
ELA-2	136.3	60.5	40.3	292.6	13.7	3.6	2.4	4.2	3.5	2.3
ELA-3	137.7	63.1	37.3	288.5	13.4	3.6	2.4	4.0	3.5	2.3
ELA-4	143.1	62.1	36.1	290.3	16.6	3.7	2.4	3.9	3.5	2.4
ELB-1	142.1	59.9	36.3	294.7	15.2	3.7	2.4	3.9	3.5	2.3
ELB-2	140.7	61.7	34.2	293.2	13.1	3.7	2.4	3.7	3.5	2.3
ELB-3	140.0	61.6	38.4	293.4	13.8	3.7	2.4	4.0	3.5	2.3
ELB-4	138.9	57.2	32.8	292.9	17.0	3.7	2.4	3.6	3.5	2.4
FTR-1	101.1	34.7	43.6	127.4	10.6	3.1	2.2	4.4	2.6	2.2
GLB-304A	89.9	17.7	43.1	90.0	7.6	3.0	2.1	4.4	2.4	2.2
GLB-304B	90.2	19.3	46.3	93.2	8.4	3.0	2.1	4.6	2.4	2.2
GLB-304C	89.2	21.9	44.1	91.3	11.6	3.0	2.1	4.4	2.4	2.2
GLB-304D	92.7	19.0	44.5	91.5	8.6	3.0	2.1	4.5	2.4	2.2
GLB-306A	92.8	23.3	43.9	94.7	7.2	3.0	2.1	4.4	2.4	2.2
GLB-306B	90.4	18.9	45.2	89.7	8.4	3.0	2.1	4.5	2.4	2.2
GLB-306C	88.9	20.2	43.6	92.6	9.9	3.0	2.1	4.4	2.4	2.2
GLB-306D	91.7	18.9	42.7	89.8	10.0	3.0	2.1	4.3	2.4	2.2
GLB-337A	87.2	16.2	43.5	88.5	7.3	3.0	2.1	4.4	2.4	2.2
GLB-337B	89.5	19.1	44.2	93.8	11.2	3.0	2.1	4.4	2.4	2.2
GLB-337C	88.6	18.4	42.4	90.2	9.3	3.0	2.1	4.3	2.4	2.2
GLB-337D	89.9	21.3	48.3	90.9	10.7	3.0	2.1	4.8	2.4	2.2
INM-1	96.0	115.9	15.3	79.3	7.5	3.1	2.6	2.4	2.4	2.2
INM-2	88.2	155.9	20.1	110.6	8.9	3.1	2.9	2.7	2.6	2.2
INM-3	85.1	150.6	15.3	107.4	7.1	3.0	2.8	2.4	2.6	2.2
LOW-1	72.0	159.4	42.2	323.6	13.8	3.0	3.0	4.4	3.8	2.4
LOW-2	74.9	148.6	40.7	333.5	18.2	3.0	2.9	4.2	3.8	2.4
LOW-3	75.4	148.8	42.8	332.2	19.9	3.0	2.9	4.4	3.8	2.4
LOW-4	70.0	159.3	45.0	328.4	20.8	3.0	3.0	4.6	3.8	2.5
LTI-5	140.8	55.4	37.0	290.3	13.0	3.7	2.4	3.9	3.5	2.3
LTV-5	141.7	55.0	36.8	286.0	12.9	3.7	2.4	3.9	3.5	2.3
OBC-1	86.3	110.0	10.9	101.6	6.1	3.0	2.6	2.2	2.5	2.2
OBC-2	79.4	103.4	14.2	92.9	5.0	2.9	2.5	2.3	2.5	2.6
OBC-3	85.1	103.6	14.7	98.0	12.0	3.0	2.5	2.3	2.5	2.2
OBC-4	83.9	102.7	11.8	95.6	5.2	2.9	2.5	2.2	2.5	2.2
RIL-1	119.7	5.0	52.0	463.6	22.9	3.5	2.8	5.1	4.4	2.5
RIL-2	115.0	5.0	52.1	469.3	21.3	3.4	3.3	5.2	4.5	2.4
RIL-3	118.1	6.1	55.5	467.7	21.2	3.4	2.2	5.4	4.5	2.4
RIL-4	117.0	5.7	53.0	471.6	21.5	3.4	2.2	5.2	4.5	2.5
SQM-1	119.5	41.2	46.3	226.8	11.7	3.4	2.3	4.7	3.1	2.3

If calculated abundance is less than detection limit, abundance is set to the following lower limits:

Rb - 5 PPM
Sr - 5 PPM
Y - 3 PPM
Zr - 10 PPM
NB - 5 PPM

APPENDIX XI

A Demonstration Obsidian Source Identification Program for the Timex/Sinclair 1000 Computer

While obsidian characterization studies are now accepted as a valuable contribution to many studies in prehistory, they have yet to become a routine component in archaeological research.

There is an apparent reason for this.

Though many attributes of obsidian are suitable for characterization (see Part Three of this project for a discussion), only the geochemical methods have proven to be powerful enough to discriminate single sources from among a large group of potential obsidian sources. These geochemical methods, while very effective for characterization purposes, require expensive equipment and trained personnel. This tends to limit the facilities necessary for geochemical characterization to either universities or, occasionally, state geologic agencies. It is not surprising to find, then, that most obsidian characterization studies are performed by archaeologists with direct connections to universities. Clearly, if the benefits of obsidian characterization study are going to make their way into non-university domains, i.e. cultural resource management work on federal and state lands, other methods of obsidian characterization are going to be needed.

A number of techniques for characterization are available, though, at both a low-cost and a minimal training investment. The index of refraction, color, density, magnetic susceptibility and microscopic structures of the obsidian glass are only some of the techniques that have been examined in the past. They have all been rather casually dismissed, however, as not being effective enough in discriminating single sources from among groups of obsidian sources. The application of these characterization attributes will generally separate a source universe into only a few subgroups of sources, the subgroups having little or no archaeological value.

This brings me to the purpose of this appendix - to demonstrate how the less discriminative, but more available, obsidian characterization attributes like those mentioned above, can be used to effectively identify sources of archaeological obsidian.

The structure of the method used in this appendix is not new. It is essentially the same as that which is used in plant identification keys. These keys are construced by identifying distinctive morphological characteristics of plants and then placing them in a decision structure or decision network that leads the user to a particular species or genus. If obsidian characterization attributes are substituted for plant structures, the same method can be used to identify obsidian sources.

The decision structure of an obsidian identification key is also one that lends itself ideally to a computer application. While the morphological parameters of an identification key are difficult to change in a standard key, they would be relatively easy to modify in a computer program. New data about obsidian sources could be rapidly assimilated into a computerized obsidian identification program. This, along with the speed of identification and the recent availability of low-cost microcomputer systems, led to the development of the computerized obsidian identification key reported in this appendix.

THE COMPUTER

The computer that I selected for this key is the newly-introduced Timex/ Sinclair 1000 microcomputer. The computer was equipped with an optional 16K memory. This very low-cost and widely-available system seemed quite adequate to the task at hand. The program that appears in this appendix is written in Sinclair BASIC, a modified BASIC language.

THE ATTRIBUTES

The obsidian characterization attributes used for the program were all determined by the experimental work reported in Part Four of this project. The attributes selected were:

1. The color of an opaque hand-specimen of obsidian.
2. The color of a thin flake (1 mm thick) of obsidian.
3. The density of the obsidian.
4. The presence or absence of glass shards in a thin-section prepared from a sample (this was included to indicate any sources of obsidian-like vitrophyre that are sometimes found in the densely-welded zones of ash-flows).
5. The presence or absence of certain microscopic microlite structures that can be seen in magnified thin-sections of obsidian.

All of these attributes had proved to have some discriminative value, though none were able to discriminate among all the sources examined.

THE SOURCE UNIVERSE

The source universe used in the construction of the identification program consists of the same sources that were examined in Part Four of the project. They are:

1. Obsidian Cliffs, Lane County, Oregon.
2. The Big Obsidian Flow, Newberry Caldera, Deschutes County, Oregon.
3. The two East Lake obsidian flows, Newberry Caldera, Deschutes County, Oregon.
4. Cougar Mountain, Lake County, Oregon.
5. Glass Buttes, Lake County, Oregon.
6. The Riley Site, Harney County, Oregon.
7. The Lowell (Upper Winberry Creek) welded ash-flow (a source of obsidian-like vitrophyre), Lane County, Oregon.

The obsidian identification program that was developed using these sources is *strictly* for demonstration purposes only. Only seven sources are included in the source universe (hardly a large proportion of even the available Oregon sources), while the intraunit parameters of variation of the attributes were determined using only four samples from most of the sources (eight for the East Lake flows and twelve for Glass Buttes). More extensive sampling would be advisable for serious applications.

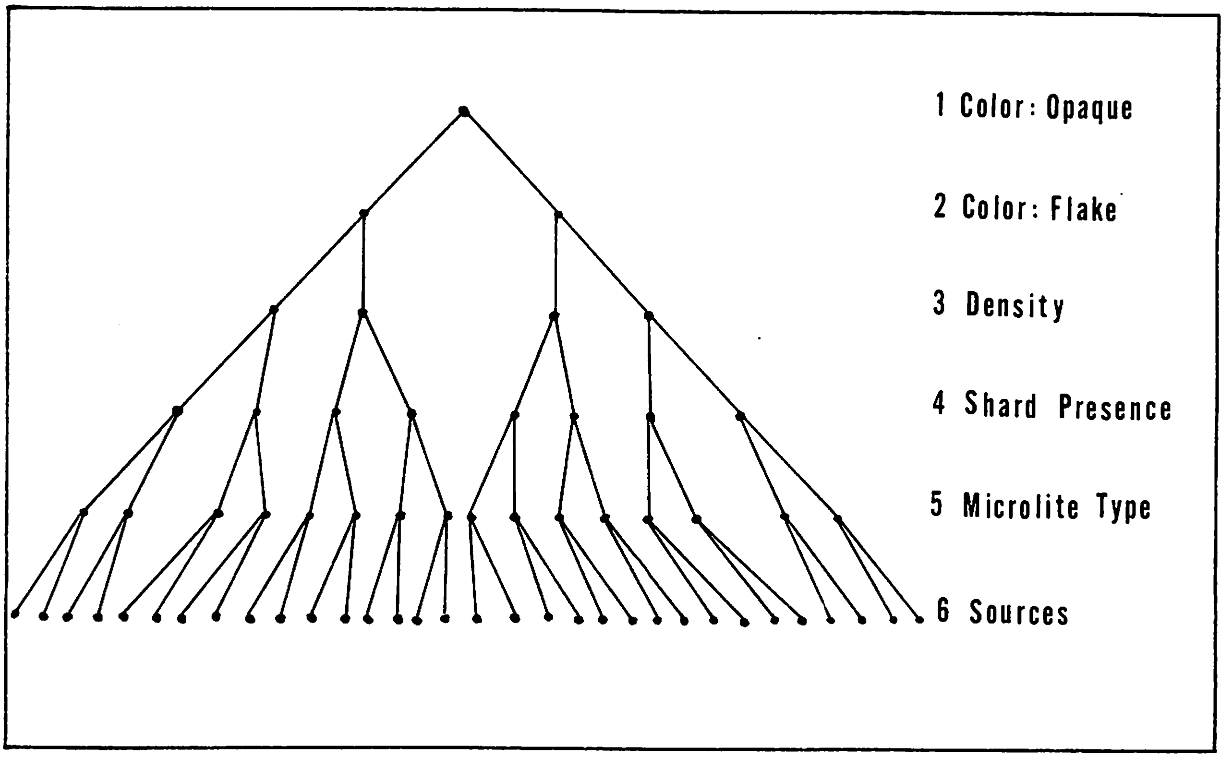


Figure XI-1: Idealized decision network structure for an obsidian identification program.

A sample from outside the source universe or from outside the boundaries set for intraunit variation in the program will simply be bounced out of the decision structure (giving this method an advantage over statistical methods of correlation that determine only the degree of fit between known and unknown samples).

The size of the actual source universe that could be used is limited only by the size of the computer memory. The program in this appendix, for instance, uses about 14 of the available 16 kilobytes of memory available. The Timex/ Sinclair 1000 will accept up to 64K of total memory, enough for almost any obsidian identification application. It would also be a relatively simple matter to expand the demonstration program in this appendix to include other characterization attributes, though again, more memory would be needed.

THE DECISION STRUCTURE

The decision structure used in this program is represented simplistically in Figure 11-1. The attributes are arranged hierarchically with attribute 1, the hand-specimen color, the easiest to ascertain and attribute 5, the microlite types, the most difficult to determine.

Unlike a botanical identification decision structure, this obsidian identification network can be entered at any level and any levels for which information is lacking can be skipped (though considerable less memory would be used in the program design if a fixed number of attributes were used). The more information that is available and the higher in the hierarchy the network is entered, the more likely it is that a single obsidian source will be identified.

The program will attempt to identify the obsidian source at the attribute level (thin flake color, for example) where it is entered. If, however, the attribute is unable to distinguish a single geologic source, the structure of the program will direct the user to the next lower attribute able to distinguish among the remaining source candidates.

If the program is entered at a lower level than the hand-specimen color or if an attribute level is bypassed (by entering a 9), the program structure will assume that the information is not available, even though it may later have some discriminative value.

THE PROGRAM

Despite the explanation, the structure of the obsidian identification key can be best understood by using the demonstration program. In the following program listing, Sinclair BASIC commands are underlined and inverse graphics (used for emphasis) are italicized. Explanatory notes are included in the right-hand margin.

```
OBSIDIAN SOURCE
 IDENTIFICATION

TIMEX/SINCLAIR 1000(16K)
```

OREGON OBSIDIAN IDENTIFICATION PROGRAM

Timex/Sinclair 1000 (8K ROM/16K RAM)
Loading Time - 5:45

```
10      GOSUB 5000
15      PRINT AT 10, 9;"█████████████████"      17 Inverse graphic spaces
20      PRINT AT 11, 9;" OBSIDIAN SOURCE "
25      PRINT AT 12, 9;"  IDENTIFICATION "
30      PRINT AT 13, 9;"█████████████████"      17 Inverse graphic spaces
35      PRINT AT 18, 5;"TIMEX/SINCLAIR 1000 (16K)"
40      PAUSE 600
45      CLS
50      GOTO 200

100     PRINT
105     PRINT AT 21, 0;"ENTER C TO CONTINUE"
110     RETURN

200     PRINT "THIS IS A DEMONSTRATION SOURCE"  All words in italics are
205     PRINT "IDENTIFICATION PROGRAM FOR"       entered into the program
210     PRINT "OREGON OBSIDIAN SOURCES. THIS"    in inverse graphics.
215     PRINT "PROGRAM, SIMILAR IN STRUCTURE"
220     PRINT "TO A BOTANICAL KEY, IS DESIGNED"
225     PRINT "TO IDENTIFY WHICH OF 7 SELECTED"
230     PRINT "SOURCES A SAMPLE OF UNKNOWN"
235     PRINT "PROVENIENCE ORIGINATED FROM."
240     PRINT
245     PRINT "THIS PROGRAM WAS CONSTRUCTED TO"
250     PRINT "SHOW THAT THE LESS POWERFUL,"
255     PRINT "BUT MORE ACCESSIBLE, CHARACTER-"
260     PRINT "IZATION ATTRIBUTES CAN BE USED"
265     PRINT "TO SUCCESSFULLY LOCATE SOURCES"
270     PRINT "OF OBSIDIAN. FOR THIS REASON,"
275     PRINT "MAJOR AND TRACE ELEMENT ATTRI-"
280     PRINT "BUTES WERE EXCLUDED FROM THE"
285     PRINT "DECISION STRUCTURE."
290     GOSUB 100
295     STOP
300     PRINT "THE ATTRIBUTES USED IN THIS PRO-"
305     PRINT "GRAM WERE DETERMINED BY THE"
310     PRINT "RESULTS OF THE EXPERIMENTAL"
315     PRINT "STUDY REPORTED IN PART 4 OF THIS"
320     PRINT "PROJECT. THEY ARE:"
325     PRINT
330     PRINT "1. COLOR: HAND-SPECIMEN"
335     PRINT "2. COLOR: THIN FLAKE"
340     PRINT "3. DENSITY"
345     PRINT "4. PRESENCE OR ABSENCE OF GLASS"
350     PRINT TAB 3; "SHARDS"
355     PRINT "5. MICROLITE TYPES PRESENT"
360     GOSUB 100
365     STOP
```

```
370    CLS
375    PRINT "THE PROGRAM WILL ONLY WORK"
380    PRINT "SUCCESSFULLY IF YOUR SAMPLE IS"
385    PRINT "FROM MY SOURCE UNIVERSE:"
390    PRINT
395    PRINT "1. BIG OBSIDIAN FLOW(NEWBERRY)"
400    PRINT "2. EAST LAKE FLOWS (NEWBERRY)"
405    PRINT "3. COUGAR MT.(FT. ROCK VALLEY)"
410    PRINT "4. OBSIDIAN CLIFFS(3 SISTERS)"
415    PRINT "5. GLASS BUTTES(E. OREGON)
420    PRINT "6. THE RILEY SITE(E. OREGON)"
425    PRINT "7. LOWELL WELDED ASH(W. OREGON)"
430    PRINT
435    PRINT "WOULD YOU LIKE TO SEE THESE"
440    PRINT "OBSIDIAN SITES DISPLAYED ON AN"
445    PRINT "OREGON MAP BEFORE YOU BEGIN?"
450    PRINT "(ENTER 1 FOR YES; 2 FOR NO)"
455    INPUT A
460    IF A = 1 THEN GOTO 500
465    IF A = 2 THEN GOTO 700

500    CLS
505    FAST
510    GOSUB 5000
515    SLOW
520    PLOT 28, 18
525    PRINT AT 11, 14; "NEWBERRY CALDERA"
530    PLOT 31, 15
535    PRINT AT 15, 10; "COUGAR"
540    PRINT AT 16, 11; "MT."
545    PLOT 23,21
550    PRINT AT 10, 11; "OBSIDIAN CLIFFS"
555    PLOT 35, 15
560    PRINT AT 13, 18; "GLASS BUTTES"
565    PLOT 39, 14
570    PRINT AT 14, 21; "RILEY SITE"
575    PLOT 19, 19
580    PRINT AT 12, 2; "LOWELL"
585    PRINT AT 13, 3; "ASH FLOW"
590    PRINT AT 20,10; " OREGON "
595    PRINT AT 5, 6; "ENTER C TO CONTINUE"
600    STOP
605    GOTO 700

700    CLS
705    PRINT "▬▬▬                              ▬▬▬"
710    PRINT "    ARE YOU READY TO BEGIN?"
715    PRINT "▬▬▬                              ▬▬▬"
720    PRINT
725    PRINT "O.K. WE ARE READY TO GO. I AM"
730    PRINT "ASSUMING THAT YOU NOW HAVE YOUR"
735    PRINT "OBSIDIAN ATTRIBUTE DATA AT HAND."
```

Lines 500 through 605 locate the obsidian sites on an Oregon outline map

Lines 705 and 715 are identical: 4 inverse graphic spaces followed by 23 shifted 5 graphics symbols followed by 4 inverse graphic spaces.

```
740     PRINT
745     PRINT "TO ENTER A NUMBER DURING THE"
750     PRINT "COURSE OF THE PROGRAM, SIMPLY"
755     PRINT "PRESS THE APPROPRIATE NUMBER"
760     PRINT "KEY(S) AND THEN THE ENTER KEY."
765     PRINT
770     PRINT "IF THE PROGRAM SHOULD CRASH"
775     PRINT "WHILE YOU ARE RUNNING, YOU CAN"
780     PRINT "RESTART THINGS BY PRESSING THE"
785     PRINT "R, THEN 1300, THEN THE ENTER"
790     PRINT "KEY. IF THIS DOES NOT WORK THE"
795     PRINT "FIRST TIME, TRY AGAIN."
800     GOSUB 100
805     STOP
810     GOTO 1300

900     PRINT
905     PRINT "ENTER THE NUMBER OF THE CLASS"
910     PRINT "THAT BEST DESCRIBES YOUR SAMPLE."
915     PRINT "IF NO DATA, ENTER A 9."
920     RETURN

950     PRINT "THE AMOUNT OF MEMORY USED IS"
955     PRINT PEEK 16404 + 256 * PEEK 16405 - 16384
960     PRINT AT 1, 7; "BITS"
965     STOP
```

Lines 950 through 965 are a subprogram that keeps track of the memory available.

```
1000    CLS
1005    PRINT " COLOR OF HAND SPECIMEN "
1010    PRINT
1015    PRINT
1020    PRINT "THE FIRST ATTRIBUTE IS THE COLOR"
1025    PRINT "OF AN OPAQUE HAND SPECIMEN. IS"
1030    PRINT "YOUR SAMPLE:"
1035    PRINT
1040    PRINT "1. BLACK, DARK GRAY OR DARK"
1045    PRINT TAB 3; "GREEN?"
1050    PRINT "2. RED, BROWN OR MAHOGANY?"
1055    PRINT "3. A COMBINATION OF COLORS"
1060    PRINT TAB 3; "FROM 1 AND 2 ABOVE?"
1065    PRINT "4. SOME OTHER COLOR?"
1070    GOSUB 900
1075    RETURN

1300    GOSUB 1000
1305    INPUT B
1310    IF B = 1 THEN GOTO 7100
1315    IF B = 2 THEN GOTO 6850
1320    IF B = 3 THEN GOTO 6850
1325    IF B = 4 THEN GOTO 8100
1330    IF B = 9 THEN GOTO 2150
```

Lines 1300 through 1330 are a decision juncture for hand-specimen color.

```
2000    CLS
2005    PRINT " THIN FLAKE COLOR "
2010    PRINT
2015    PRINT
2020    PRINT "FOR THIS, YOU WILL NEED A THIN"
2025    PRINT "FLAKE OF OBSIDIAN ABOUT 1 MM"
2030    PRINT "THICK. WHEN YOU HOLD IT TO A"
2035    PRINT "LIGHT SOURCE, WHAT DO YOU SEE."
2040    PRINT
2045    PRINT "1. NO COLOR VISIBLE (CLEAR)"
2050    PRINT "2. SOME COLOR VISIBLE (LIGHT TO"
2055    PRINT TAB 3; "OPAQUE"
2060    GOSUB 900
2065    RETURN

2150    GOSUB 2000
2155    INPUT D
2160    IF D = 1 THEN GOTO 8500
2165    IF D = 2 THEN GOTO 7130
2170    IF D = 9 THEN GOTO 2600
```

Lines 2150 through 2170 are a decision juncture for the thin flake color.

```
2500    CLS
2505    PRINT " DENSITY "
2510    PRINT
2515    PRINT
2520    PRINT "ENTER YOUR SAMPLE DENSITY (IN"
2525    PRINT "GM/CM3)"
2528    PRINT
2530    GOSUB 915
2535    RETURN

2600    GOSUB 2500
2605    INPUT E
2610    IF E <= 2.49 AND E >2.41 THEN GOTO 8450
2615    IF E <= 2.41 AND E >2.4  THEN GOTO 6035
2620    IF E <= 2.4  AND E >2.39 THEN GOTO 6150
2625    IF E <= 2.39 AND E >2.38 THEN GOTO 6240
2630    IF E <= 2.38 AND E >2.37 THEN GOTO 6350
2635    IF E <= 2.37 AND E >=2.35 THEN GOTO 6450
2640    IF E <  2.35 AND E  >=2.32 THEN GOTO 6600
2645    IF E <  2.32 AND E  >=2.31 THEN GOTO 6290
2650    IF E <  2.31 AND E >9 THEN GOTO 8100
2655    IF E <  9 AND E > 2.49 THEN GOTO 8100
2660    IF E = 9 THEN GOTO 3200
```

Lines 2600 through 2660 set the parameters for density at a decision juncture.

```
3000    CLS
3010    PRINT " PRESENCE OR ABSENCE OF SHARDS "
3015    PRINT
3020    PRINT
3025    GOSUB 3100
```

```
3030    PRINT
3035    PRINT "1. GLASS SHARDS (COLLAPSED"
3040    PRINT TAB 3; "BUBBLE WALLS)"
3045    PRINT "2. NO SHARDS VISIBLE"
3050    GOSUB 900
3055    RETURN

3100    PRINT "WHEN PREPARED AS A THIN-SECTION"
3105    PRINT "AND VIEWED UNDER THE MICROSCOPE,"
3110    PRINT "WHICH DO YOU SEE?"
3115    RETURN

3200    GOSUB 3000
3205    INPUT F
3210    IF F = 1 THEN GOTO 8450
3215    IF F = 2 THEN GOTO 6830
3220    IF F = 9 THEN GOTO 4200
```

Lines 3200 through 3220 are a decision juncture for the presence or absence of glass shards.

```
4000    CLS
4010    PRINT " MICROLITE STRUCTURE "
4015    PRINT
4020    PRINT
4025    GOSUB 3100
4030    PRINT
4035    PRINT "1. ABUNDANT TRICHITES (HAIR-LIKE"
4040    PRINT TAB 3; "STRUCTURES"
4045    PRINT "2. ASTEROIDAL TRICHITES (SPIDER-"
4050    PRINT TAB 3; "LIKE STRUCTURES"
4055    PRINT "3. VERY THIN ( < .5 MICRON) PRIS-"
4060    PRINT TAB 3; "MATIC MICROLITES"
4065    PRINT "4. NO MICROLITES"
4070    PRINT "5. NORMAL PRISMATIC MICROLITES ONLY"
4075    PRINT
4080    GOSUB 900
4085    RETURN

4200    GOSUB 4000
4205    INPUT G
4210    IF G = 1 OR G = 2 THEN GOTO 8600
4215    IF G = 3 THEN GOTO 8025
4220    IF G = 4 THEN GOTO 6800
4225    IF G = 5 THEN GOTO 6510
4230    IF G = 9 THEN GOTO 8750
```

Lines 4200 through 4230 are a decision juncture for microlite attributes.

```
5000    FOR S = 6 TO 58
5005    PLOT S, 1
5010    NEXT S
5015    FOR T = 1 TO 22
5020    PLOT 58, T
5025    PLOT 58, 1
5030    NEXT T
5035    PLOT 57, 23
5040    PLOT 56, 24
5045    PLOT 56, 25
```

Lines 5000 to 5485 plot the outline map of Oregon

```
5050   PLOT 56, 25
5055   PLOT 57, 26
5060   PLOT 57, 27
5065   PLOT 57, 28
5070   PLOT 58, 28
5075   PLOT 58, 29
5080   PLOT 59, 30
5085   PLOT 59, 31
5090   PLOT 59, 32
5095   PLOT 60, 33
5100   PLOT 60, 34
5105   PLOT 60, 35
5110   PLOT 61, 36
5115   PLOT 61, 37
5120   PLOT 60, 38
5125   PLOT 59, 38
5130   PLOT 58, 39
5135   FOR U = 43 TO 57
5140   PLOT U, 40
5145   NEXT U
5150   PLOT 43, 39
5155   PLOT 42, 39
5160   PLOT 41, 39
5165   PLOT 40, 39
5170   PLOT 39, 39
5175   PLOT 39, 38
5180   PLOT 38, 38
5185   PLOT 37, 38
5190   PLOT 36, 37
5195   PLOT 35, 37
5200   PLOT 34, 37
5205   PLOT 33, 37
5210   PLOT 32, 37
5215   PLOT 31, 37
5220   PLOT 30, 36
5225   PLOT 29, 36
5230   PLOT 28, 36
5235   PLOT 28, 37
5240   PLOT 27, 37
5245   PLOT 26, 37
5250   PLOT 25, 37
5255   PLOT 24, 37
5260   PLOT 23, 36
5265   PLOT 22, 36
5270   PLOT 21, 35
5275   PLOT 20, 35
5280   PLOT 20, 36
5285   PLOT 19, 36
5290   PLOT 18, 36
5295   PLOT 18, 37
5300   PLOT 18, 38
```

```
5305    PLOT 18, 39
5310    PLOT 17, 40
5315    PLOT 16, 41
5320    PLOT 15, 41
5325    PLOT 14, 41
5330    PLOT 14, 42
5335    PLOT 13, 42
5340    PLOT 12, 42
5345    PLOT 11, 42
5350    FOR V = 33 TO 42
5355    PLOT 10, V
5360    PLOT 10, 33
5365    NEXT V
5370    FOR W = 27 TO 32
5375    PLOT 9, W
5380    PLOT 9, 27
5385    NEXT W
5390    FOR X = 19 TO 26
5395    PLOT 8, X
5400    PLOT 8, 19
5405    NEXT X
5410    FOR Y = 15 TO 19
5415    PLOT 7, Y
5420    PLOT 7, 15
5425    NEXT Y
5430    PLOT 6, 14
5435    PLOT 6, 13
5440    PLOT 5, 12
5445    PLOT 5, 11
5450    PLOT 5, 10
5455    PLOT 5, 9
5460    FOR Z = 3 TO 8
5465    PLOT 5, Z
5470    PLOT 5, 3
5475    NEXT Z
5480    PLOT 6, 2
5485    RETURN

6000    CLS
6005    PRINT "YOUR SOURCE IS EITHER THE BIG"
6010    PRINT "OBSIDIAN FLOW OR THE LOWELL"
6015    PRINT "ASH FLOW"
6020    GOSUB 100
6025    STOP
6030    RETURN
6050    GOSUB 6000
6055    GOSUB 3000
6060    INPUT W
6065    IF W = 1 THEN GOTO 8450
6070    IF W = 2 THEN GOTO 8050
6075    IF W = 9 THEN GOSUB 6000
6080    GOTO 8200
```

Lines 6000 to 6995 are subprograms that control the individual decision networks from each attribute level.

```
6100    CLS
6105    PRINT "YOUR SOURCE IS EITHER THE BIG"
6110    PRINT "OBSIDIAN FLOW OR THE RILEY SITE"
6115    GOSUB 100
6120    STOP
6125    RETURN
6150    GOSUB 6100
6155    GOSUB 4000
6160    INPUT V
6165    IF V = 1 OR V = 2 OR V = 3 THEN GOTO 8100
6170    IF V = 4 THEN GOTO 8000
6175    IF V = 5 THEN GOTO 8050
6180    IF V = 9 THEN GOSUB 8900
6185    GOTO 8200

6200    CLS
6205    PRINT "YOUR SOURCE IS EITHER THE BIG"
6210    PRINT "OBSIDIAN FLOW, ONE OF THE EAST"
6215    PRINT "LAKE FLOWS OR THE RILEY SITE"
6220    GOSUB 100
6225    STOP
6230    RETURN

6240    GOSUB 6200
6245    GOSUB 4000
6250    INPUT U
6255    IF U = 1 OR U =2 OR U = 3 THEN GOTO 8100
6260    IF U = 4 THEN GOTO 8000
6265    IF U = 5 THEN GOSUB 6650
6270    IF U = 9 THEN GOSUB 8900
6275    GOTO 8200

6290    GOSUB 6700
6295    GOTO 8650

6300    CLS
6305    PRINT "YOUR SOURCE COULD BE ONE OF SEV-"
6310    PRINT "RAL: THE RILEY SITE, THE BIG"
6315    PRINT "OBSIDIAN FLOW, THE EAST LAKE"
6320    PRINT "FLOWS, COUGAR MT. OR OBSIDIAN"
6325    PRINT "CLIFFS"
6330    GOSUB 100
6335    STOP
6340    RETURN
6350    GOSUB 6300
6355    GOSUB 4000
6360    INPUT T
6365    IF T = 1 OR T = 2 THEN GOTO 8600
6370    IF T = 3 THEN GOTO 8025
6375    IF T = 4 THEN GOTO 8000
6380    IF T = 5 THEN GOSUB 6650
6385    IF T = 9 THEN GOTO 8750
6390    GOTO 8200
```

```
6400    CLS
6405    PRINT "YOUR SOURCE SOULD BE ONE OF SEV-"
6410    PRINT "ERAL: THE RILEY SITE, THE BIG"
6415    PRINT "OBSIDIAN FLOW, THE EAST LAKE"
6420    PRINT "FLOWS, COUGAR MT., OBSIDIAN"
6425    PRINT "CLIFFS OR GLASS BUTTES"
6430    GOSUB 100
6435    STOP
6440    RETURN
6450    GOSUB 6400
6455    GOSUB 4000
6460    INPUT S
6465    IF S = 1 OR S = 2 THEN GOTO 8600
6470    IF S = 3 THEN GOTO 8025
6475    IF S = 4 THEN GOSUB 6750
6480    IF S = 5 THEN GOTO 6495
6485    GOSUB 8900
6490    GOSUB 8200
6495    GOSUB 6650
6500    GOTO 8200

6510    CLS
6515    GOSUB 6650
6520    GOSUB 8200

6550    CLS
6555    PRINT "YOUR SOURCE IS EITHER THE BIG"
6560    PRINT "OBSIDIAN FLOW, GLASS BUTTES OR"
6565    PRINT "COUGAR MT."
6570    GOSUB 100
6575    STOP
6580    RETURN

6600    GOSUB 6550
6605    GOSUB 4000
6610    INPUT R
6615    IF R = 1 OR R = 2 THEN GOTO 8600
6620    IF R = 3 THEN GOTO 8100
6625    IF R = 4 THEN GOTO 8500
6630    IF R = 5 THEN GOTO 8050
6635    IF R = 9 THEN GOTO 8750

6650    CLS
6655    PRINT "YOUR SOURCE IS EITHER THE BIG"
6670    PRINT "OBSIDIAN FLOW OR ONE OF THE"
6675    PRINT "EAST LAKE FLOWS"
6680    GOSUB 100
6685    STOP
6690    GOSUB 8900
6695    RETURN
```

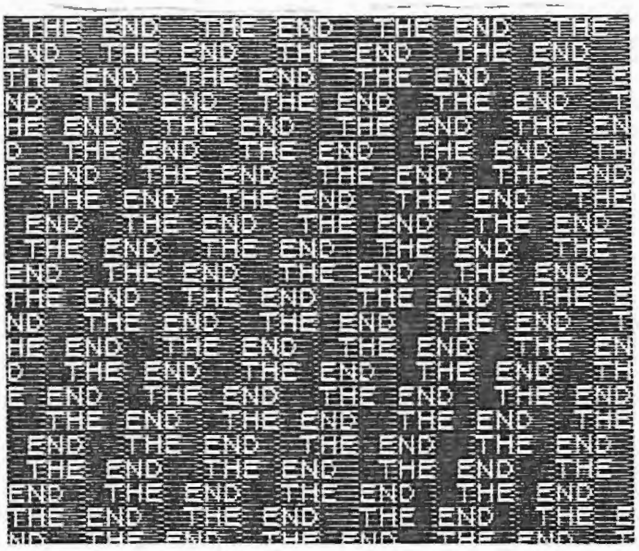
```
6700   CLS
6705   PRINT "YOUR SOURCE IS EITHER GLASS"
6710   PRINT "BUTTES OR COUGAR MT."
6715   GOSUB 100
6720   STOP
6725   RETURN

6750   CLS
6755   PRINT "YOUR SOURCE IS EITHER GLASS"
6760   PRINT "BUTTES OR THE RILEY SITE"
6765   GOSUB 100
6770   STOP
6775   RETURN

6800   GOSUB 6750
6805   GOSUB 8900
6810   GOTO 8200

6830   GOSUB 6400
6835   GOTO 4200

6850   CLS
6855   GOSUB 6700
6860   GOSUB 2000
6865   INPUT C
6870   IF C = 1 THEN GOTO 8500
6875   IF C = 2 THEN GOSUB 6700
6880   IF C = 9 THEN GOSUB 2500
6900   GOSUB 2500
6905   INPUT S
6910   IF S <= 2.38 AND S >2.37 THEN GOTO 8600
6915   IF S <= 2.37 AND S >= 2.31 THEN GOSUB 6700
6920   IF S  <2.31 AND S >2.38 THEN GOTO 8100
6925   GOSUB 4000
6930   INPUT Z
6935   IF Z = 1 OR Z = 2 THEN GOTO 8600
6940   IF Z = 3 THEN GOTO 8100
6945   IF Z = 4 THEN GOTO 8500
6950   IF Z = 5 THEN GOTO 8600
6955   IF Z = 9 THEN GOTO 6960
6960   GOSUB 6700
6965   GOSUB 8900
6970   GOTO 8200

7000   CLS
7010   PRINT "THIS ATTRIBUTE WILL NOT DISTIN-"
7020   PRINT "AMONG ANY OF THE SOURCES."
7030   PRINT
7040   GOSUB 100
7050   STOP
7060   RETURN

7100   GOSUB 7000
7110   GOTO 2150
```

```
7130   GOSUB 7000
7140   GOTO 2600

7170   GOSUB 7000
7180   GOTO 3200

7200   GOSUB 7000
7210   GOTO 4200

8000   CLS
8005   GOSUB 8260
8010   PRINT "THE RILEY SITE"
8015   GOTO 8275

8025   CLS
8030   GOSUB 8260
8035   PRINT "OBSIDIAN CLIFFS"
8040   GOTO 8275

8050   CLS
8055   GOSUB 8260
8060   PRINT "THE BIG OBSIDIAN FLOW"
8065   GOTO 8275

8075   CLS
8080   GOSUB 8260
8085   PRINT "ONE OF THE TWO EAST LAKE FLOWS"
8090   GOTO 8275

8100   CLS
8105   PRINT "SORRY - YOUR DATA DOES NOT COM-"
8110   PRINT "PUTE. EITHER YOUR SAMPLE IS"
8115   PRINT "FROM A SOURCE NOT INCLUDED IN MY"
8120   PRINT "SOURCE UNIVERSE OR THE SAMPLING"
8125   PRINT "DONE TO DETERMINE THE PARAMETERS"
8130   PRINT "OF INTRAUNIT VARIATION FOR THE"
8135   PRINT "SOURCE UNIVERSE WAS INADEQUATE."
8140   PRINT "YOU MAY WANT TO RERUN YOUR DATA "
8145   PRINT "IN CASE YOU MADE AN ENTRY ERROR."
8150   GOTO 8200

8200   PRINT
8205   PRINT
8210   PRINT "DO YOU WANT TO TRY ANOTHER"
8215   PRINT "SAMPLE?"
8220   PRINT
8225   PRINT "ENTER 1 FOR YES; 2 FOR NO"
8230   INPUT C
8235   IF C = 1 THEN GOTO 1300
8240   IF C = 2 THEN GOTO 9500


8260   PRINT "THE SOURCE OF YOUR OBSIDIAN IS"
8265   RETURN

8275   PAUSE 180
8280   GOTO 8200
```

```
8450    CLS
8455    PRINT "YOUR SAMPLE IS NOT OBSIDIAN BUT"
8460    PRINT "IS AN OBSIDIAN-LIKE VITROPHYRE"
8465    PRINT "FROM THE LOWELL SOURCE"
8470    GOTO 8200

8500    CLS
8505    GOSUB 8260
8510    PRINT "GLASS BUTTES"
8515    GOTO 8275

8600    CLS
8605    GOSUB 8260
8610    PRINT "COUGAR MT."
8615    GOTO 8275

8750    CLS
8755    PRINT "THAT WAS THE LAST ATTRIBUTE."
8760    PRINT "DID YOU DRAW A BLANK?"
8765    PAUSE 300
8770    GOTO 8200

8900    CLS
8905    PRINT "THIS IS AS FAR AS I CAN GO WITH"
8910    PRINT "THE INFORMATION THAT YOU HAVE"
8915    PRINT "ENTERED. MORE DATA WILL BE"
8920    PRINT "NEEDED TO FURTHER DISTINGUISH"
8925    PRINT "FROM AMONG THE POSSIBLE SOURCES OF"
8930    PRINT "YOUR OBSIDIAN."
8935    GOSUB 100
8940    STOP
8945    RETURN

9500    CLS
9505    PRINT "THIS IS THE END OF THE PROGRAM."
9510    PRINT "AS YOU CAN SEE, THIS METHOD IS"
9515    PRINT "AN EASY AND EFFECTIVE WAY TO"
9520    PRINT "DETERMINE THE SOURCE OF ARCHAEO-"
9525    PRINT "LOGICAL (OR GEOLOGICAL) OBSIDIAN"
9530    PRINT "FROM AN UNKNOWN SOURCE."
9535    PAUSE 450
9540    PRINT
9545    PRINT "THIS HAS BEEN A DEMONSTRATION"
9550    PRINT "OF HOW A LOW-COST COMPUTING"
9555    PRINT "SYSTEM LIKE THE TIMEX/SINCLAIR"
9560    PRINT "1000 (WITH 16K MEMORY) CAN BE"
9565    PRINT "USED TO AUGMENT AN ARCHAEOLOGI-"
9570    PRINT "CAL RESEARCH PROGRAM THROUGH"
9575    PRINT "THE CORRELATION OF GEOLOGICAL"
9580    PRINT "AND ARCHAEOLOGICAL SOURCES OF"
9585    PRINT "OBSIDIAN. THIS KIND OF INFORMA-"
9590    PRINT "TION CAN BE USED TO RECONSTRUCT"
9595    PRINT "PREHISTORIC EXCHANGE AND CONTACT"
9600    PRINT "NETWORKS AND IS A VALUABLE AD-"
9605    PRINT "JUNCT TO AREA STUDIES."
```

```
9610   PAUSE 1200
9615   CLS
9620   PRINT " HASTA LUEGO"
9625   PAUSE 60
9630   CLS
9635   PRINT "▬THE END▬";
9640   GOTO 9635
```

2 inverse graphic spaces
before and after "the end"



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THE VERY LAST WORD:

An alternative explanation of obsidian petrogenesis

Theft of Obsidian

Some people called a time at the flat named Tok'. They were going to hunt deer. They set snares on the runway at Blood Gap. Adder had real obsidian. The others made their arrows out of just anything. They did not know about obsidian. When deer were caught in snares, Adder shot and ran as fast as he could to the deer, pulled out the obsidian and hid it in his quiver. The obsidian was very powerful. The others would shoot too, but only sometimes would they kill a deer. Adder always killed them. Adder always killed them. He killed so many, the blood began running down both sides of the gap into the creeks. That is how the gap got its name. That night they carried the deer back to camp and had a big feast.

The next day the same thing happened. For three or four days this kept on happening. Adder always killed most of the deer. The others became jealous and talked things over among themselves. They decided that Adder must have some very powerful weapon. They told the fast runners like Humming Bird and Fox to watch Adder and race to the deer before Adder could get there.

On the following day the fast runners stationed themselves near Adder. One man called Puimɛminbɛs was near. When Adder shot, all began running. Puimɛminbɛs got there first. He put his hand in the wound and pulled the obsidian out and ran away. When Adder came he put his fingers in the wound and could not find his obsidian. He knew it had been stolen and he was very angry. He went right back to camp and got his things ready to go back down south from where he had come. He told the others his obsidian had been stolen and he was going to get even...

When puimɛminbɛs got to the top of the ridge Sandhill Crane was there, and so was Ground Squirrel who was to run with the obsidian. The obsidian was very large by now. Puimɛminbɛs gave Ground Squirrel the pack and told him to run. Sandhill Crane...said, "When you hear my voice getting dim you will know that you are far enough away."

So squirrel started going. He went north, and went north, and went north. He went past Mount Shasta. He could still hear Crane... He kept on going until he could hardly hear Crane's voice, then he dropped his load. That is where Glass Mountain is today.

A Wintu myth reported by C. Dubois and D. Demetracopoulou (Univ. of Calif. Publ. in American Arch. and Ethnography, 1931, Vol.28, p.306). This flow erupted only a few hundred years ago and could have easily been witnessed by the Wintun Indians.