1985

Structure and petrology of the Rhodes Peak cauldron Montana and Idaho

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STRUCTURE AND PETROLOGY OF THE RHODES PEAK
CAULDRON, MONTANA AND IDAHO

by

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B.A. University of Montana, 1983

Presented in partial fulfillment of the
requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1985

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11-12-85
Date

ABSTRACT

Simpson, Stephen J., M.S., Autumn 1985 Geology

Structure and Petrology of the Rhodes Peak Cauldron, Idaho and Montana.

Director: Donald W. Hyndman DWH

The Rhodes Peak cauldron is a volcanic subsidence structure located along the Idaho-Montana border west of Missoula, Montana. The cauldron is within the east-central portion of the area mapped as Lolo Hot Springs batholith on the state geologic map of Idaho. The cauldron volcanics and underlying sediments of the Belt Supergroup divide the batholith into two lobes. The cauldron is partially encircled on the north by a porphyritic ring dike which ranges from syenogranite to quartz-syenite. South of the ring dike the intracauldron block consists of about 1km of welded rhyolite tuff and volcaniclastic sediments overlying Belt quartzite. These volcanics are intruded by andesite dikes and overlain by andesite flows.

The cauldron appears to pre-date the intrusion of the Lolo Hot Springs batholith. The intracauldron volcanics dip steeply away from the batholith near the contact. The magma which formed the Rhodes Peak cauldron was probably similar in composition to the magma which formed the Lolo batholith. In the cauldron the magma differentiated extensively to form a gas rich roof zone which led to ash eruption and cauldron collapse, whereas in the batholith differentiation was limited and most of the volatiles remained in the magma in the form of miarolitic cavities.

North-northest trending normal faults cut the volcanics and the ring dike; the relatively straight NNE trending contact between the Lolo batholith and the cauldron suggests that a fault of similar orientation may have provided structural control during emplacement. These faults and numerous NNE trending dikes in the region indicate a tensional environment during magma generation and emplacement.

ACKNOWLEDGEMENTS

Many people were instrumental in the completion of this study, and I would like to acknowledge their assistance. My advisors, Don Hyndman and Dave Alt, were very helpful during every stage of the project, from initial planning through final revisions of the manuscript. I especially want to thank Don for helping me reorganize my investigation after I returned from my first trip into the "batholith" with a pack full of welded tuff and a rather puzzled look on my face. John Scott helped me with some of the chemical aspects, and his assistance is greatly appreciated. Many useful ideas and concepts were brought to my attention by Grey Thompson and Ian Lange in the course of a seminar on calderas and ash-flow tuffs, and I thank them and my classmates for many interesting lectures and discussions.

Funding for the chemical analyses was provided by a grant from Sigma Xi and from a university grant to Don Hyndman.

Finally, I wish to thank my wife, Kathleen, for providing both patience and pressure at the proper times and in the proper quantities. She deserves much of the credit for getting this study completed in a reasonable amount of time.

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CHAPTER I

INTRODUCTION

The primary objective of this study was to map and describe the volcanic and plutonic lithologies in an area along the Idaho-Montana border west of the Lolo Hot Springs batholith and determine the genetic and temporal relationships between them. Determination of a volcanic vent or the delineation of a caldera or cauldron subsidence structure was a major goal. Field data were supplemented by thin section petrography and some chemical analyses. This report presents field, petrologic, and chemical data which describe the volcanic and plutonic history of the area.

The study area is underlain by sediments of the Belt Supergroup, welded rhyolite tuff, andesite flows, porphyritic granite mineralogically similar to the Lolo Hot Springs batholith, and granodiorite which appears unrelated to the batholith. The rhyolite appears to have been erupted from a cauldron whose outline is shown in part by a dike of porphyritic granite that encircles the northern margin of the volcanic field. This cauldron is approximately 6 by 12 kilometers in size and is referred to here as the Rhodes Peak cauldron.

Location And Previous Work

The study area covers about 95 square kilometers along the Idaho-Montana border 20 kilometers northwest of Lolo pass (Fig. 1). The Montana portion is in Mineral county while the Idaho portion is in Clearwater county. The entire area lies within the Rhodes Peak 7 1/2 minute quadrangle. Elevation ranges from 4400' to just under 8000'. Access to the area is entirely by trail and cross-country travel, with some fairly well maintained pack trails in the Cache and Kelly Creek valleys. Closest vehicular access from the north is from Surveyor Creek road no.7743, while the best access for the southern part of the area is from the Blacklead Mountain spur road which branches off Toboggan Ridge road about 7 miles north of Cayuese junction.

Previous work in the area has been sparse, but some neighboring areas have been well studied. Ross and Burke in 1947 mapped the Cache Creek area for the state geologic map of Montana, and on this map is shown a small area of Tertiary volcanic rocks just west of Shale Mountain and Leo Lake. The state geologic map of Idaho, compiled by Bond (1978), shows the entire upper portion of the Kelly Creek drainage as Lolo batholith, with no mention of volcanic rocks.

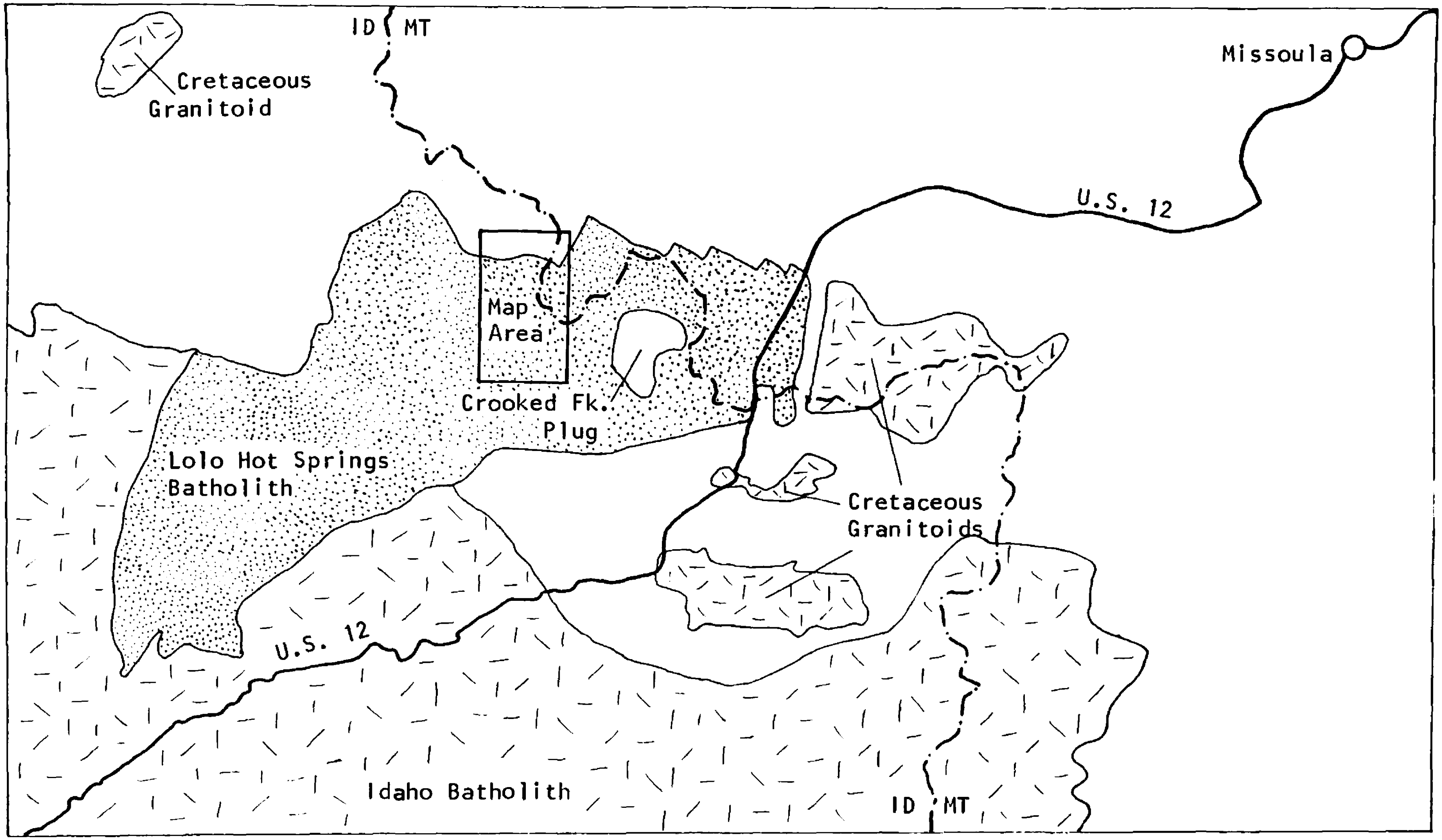


Figure 1. Location of study area. Lolo Hot Springs batholith is shown as it appears on the state geologic map of Idaho and Nolds (1968) thesis map.

Mapping in the area of Lolo Hot Springs, just east of the Rhodes Peak cauldron, Leischner (1959) was the first to describe the Lolo batholith as a body mineralogically distinct from the Idaho batholith. John Nold (1968) mapped the eastern portion of the Lolo batholith as part of a much larger area. Nold mapped a rhyolite intrusion, the Crooked Fork plug, within the area of the batholith. Outcrop within the area was poor and the relationship of the batholith to the rhyolite could not be conclusively determined. However, Nold believed the rhyolite was intrusive because 1) the contacts show no relationship to topography and 2) flow foliation appears vertical.

Williams (1977) noted a body of granite similar to the Lolo Hot Springs batholith along the Lolo Trail road 25-30 km southwest of Lolo Pass. Williams referred to this as the Indian Grave Peak-Horseshoe Lake complex, and he believed it to be Eocene in age. The complex is shown on the geologic map of Idaho as the southwestern portion of the Lolo Hot Springs batholith, although this study has shown that the two bodies are separated by the volcanic rocks of the Rhodes Peak Cauldron and Belt sediments.

Present Investigation

This study was originally intended to be a detailed investigation of the petrology, form, emplacement and cooling history of the Lolo batholith. Most of the area of the Rhodes Peak quadrangle is shown on the state map of Idaho as Lolo batholith, and the large amount of vertical relief shown on the topographic map made the area seem an appropriate place to investigate the three-dimensional structure of the batholith. However, once I began field work I discovered that most of the area was in fact underlain by rhyolite tuff, hypabyssal granite, granodiorite, and Belt sedimentary rocks. The emphasis of the study was then shifted from the batholith to this complex suite of intrusive and extrusive rocks, which appear to be a deeply eroded volcanic cauldron.

Seven volcanic, hypabyssal, and plutonic lithologic units were mapped within the study area, which covers a major portion of the Rhodes Peak cauldron. Limited field time precluded a detailed analysis of the ash-flow tuff stratigraphy or a complete investigation of the structure and faulting.

Field work took place during four 7-10 day periods between mid-July and mid-September, 1984, and mapping was done using the 1:24,000 scale Rhodes Peak 7 1/2' quad as a base. Most traverses were along stream valleys and ridge tops, and much of the geology of the slopes was inferred using binoculars. Exposure along many slopes is good, but ropes and climbing gear would be required for close inspection of some features.

Regional Geology

The study area lies 15-20 km north of the northern edge of the Bitterroot lobe of the Idaho batholith. Country rocks in the region are Precambrian sedimentary rocks of the Belt Supergroup. These sediments were deposited during middle Proterozoic time in a vast embayment of the continental shelf (Harrison, 1972) or an inland sea basin (Winston, 1984). The stratigraphy of the Belt is not well understood due to the lack of fossils, incredible thickness of similar lithology, and the tendency for nearly identical lithologies to occur at many different stratigraphic levels. A generalized stratigraphic column of the Belt is shown in figure 2. The section of the Belt of interest to this study is the portion from middle Ravalli through the Mount Shields Formation of the Missoula Group.

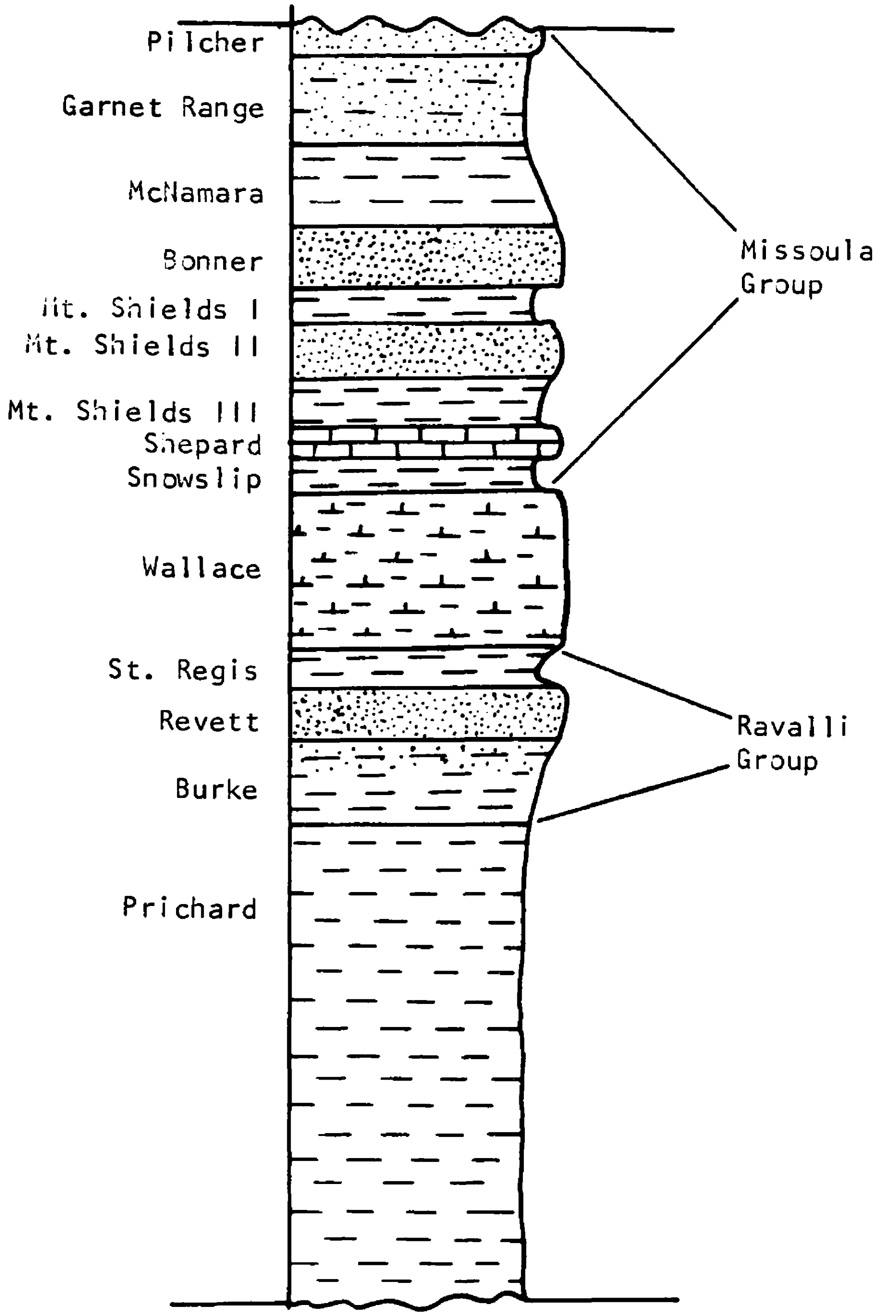


Figure 2. Generalized stratigraphic column of the Belt Supergroup, western Montana and northern Idaho.

Regional structure north of the Idaho batholith is characterized by rocks of the Belt Supergroup dipping away from the batholith, so that rocks of the Prichard and Ravalli group occur in the south and are overlain to the north by the Wallace Formation, Missoula Group, and Cambrian rocks. Just east of the study area a transect from the Prichard through the Cambrian section covers about 60km. Metamorphic grade increases nearer the batholith, probably due to the deeper position in the section rather than to any contact effect of the batholith.

Idaho Batholith

The Idaho batholith covers an area of about 30,000 square kilometers in north-central Idaho southwest of the study area. The batholith is divided into two lobes, the Atlanta and Bitterroot lobes, by the high grade metamorphic rocks of the Salmon River arch (see Fig. 3). The batholith is mostly biotite granite, with a discontinuous border zone of granodiorite. Tonalite occurs in the western border zone, and this zone appears to have been the earliest portion of the batholith to be emplaced. The tonalite conforms to the "I-type" granitoid series of Chappell and White (1974). The granite in the main body of the batholith

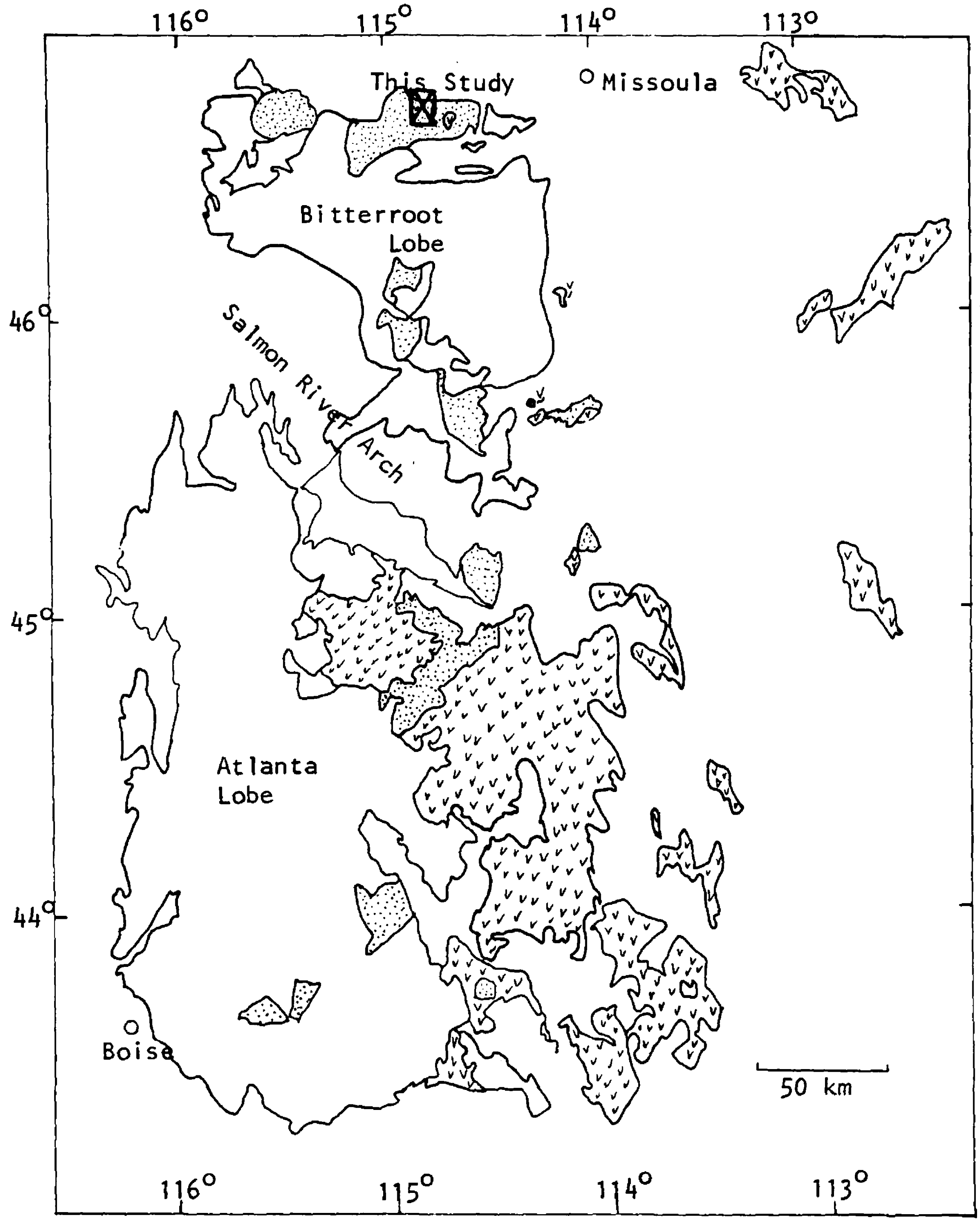


Figure 3. Idaho batholith, Eocene volcanics (v pattern), and Eocene intrusives (stippled). Modified from Hyndman (1983)

is a two-mica granite that contains many features of "S-type" granite but also contains many features that make classification by this scheme ambiguous (Hyndman, 1985).

The Idaho batholith is generally believed to have formed between 100 and 70 million years ago in an Andean-type arc above a subduction zone along the western margin of North America. During Cretaceous time the Farallon plate was being subducted under the westward-moving North American plate. Magma generation occurred along most of the western margin of North America forming the Coast Plutonic Complex, the Idaho batholith, and the Sierra Nevada batholith. The Idaho batholith occupies a position well inland from its contemporaries to the north and south, and connections between the three bodies are ambiguous at best. The southern end of the batholith is covered by the Snake River Plain basalts, and the north end is bounded by a zone of regionally metamorphosed Belt Rocks. Numerous smaller Cretaceous intrusions occur in a zone extending northwest from the north end of the batholith toward the south end of the Coast Range plutonic complex.

The magma source for the main body of the Idaho batholith was probably partially melted Precambrian continental basement and possibly some lower Belt sediments. The batholith was emplaced at mid-crustal levels (15-20 km), and this was probably not very far above the zone in which the magma had been generated (Hyndman, 1983). The magma does not appear to have vented to the surface. No late Cretaceous volcanic rocks have been found in the region.

Eocene Intrusions and Volcanic Fields

Volcanic rocks of Eocene age are extremely widespread in the Northwestern states. Major volcanic fields of the period include the Lowland Creek and Absaroka volcanic fields in Montana, the Challis volcanic field in Idaho, the Clarno volcanic field in Oregon, and the Sanpoil volcanic field of the Republic graben in Washington (Fig. 4). The rocks in these fields are mostly intermediate to felsic in composition and most are products of explosive volcanism. Nearly all of the radiometric ages obtained from these areas fall between 55 and 40 million years (Armstrong, 1974). The Eocene volcanic-plutonic episode appears to have been a period of intense and widespread magma production and eruption bracketed on both ends by periods of nearly total quiescence. Activity appears to have begun in northern Washington or southern British Columbia and spread slowly southward through the period.

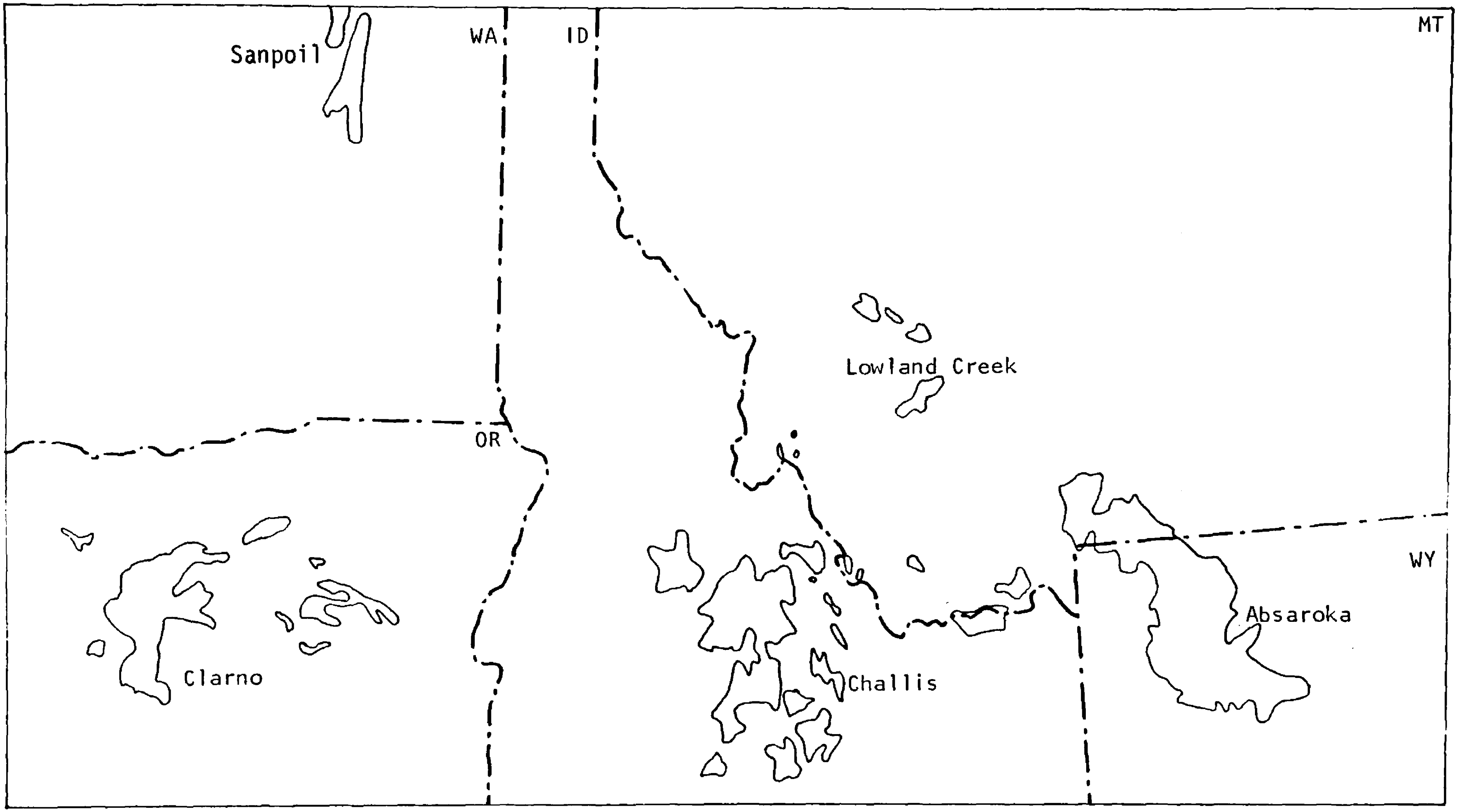


Figure 4. Eocene felsic to intermediate volcanic fields of the Northwest. Modified from Stewart and Carlson, 1978.

Eruption of intermediate to felsic volcanic rocks is generally accompanied by the emplacement of intrusions at depth, and Eocene age intrusions are abundant in the area of the Idaho batholith. Bennett (1980) identified some 40 of these intrusions, including the Lolo batholith (Fig. 3). Typical features of these intrusions include miarolitic cavities, smokey quartz crystals, perthitic potassium feldspar, and high concentrations of uranium, thorium, and potassium-40 relative to the Idaho batholith. Potassium-argon dates on 17 intrusions are reported in Bennett (1980), and most of the ages lie between 40 and 50 million years. Many other intrusions that have not been dated (including the Lolo batholith) are very similar in mineralogy and appearance to the dated plutons and were probably emplaced during the same period.

Some of these intrusions, such as the Casto batholith, Painted Rocks pluton, and Lolo Hot Springs batholith, are closely associated with volcanic rocks. However, many of the intrusions in the western and southern Bitterroot lobe and northern Atlanta lobe apparently have no associated volcanic rocks. Some volcanic remnants in these areas probably do exist, but outcrop is very limited in large portions of the area. I have encountered a great number of small exposoures of rhyolitic tuff in roadcuts and ridgetops throughout the Bitterroot lobe, particularly along Tobaggan Ridge road and the Lolo Trail road. It seems very likely that a good many (if not all) of the Eocene plutons in the Idaho batholith area had associated volcanic rocks, and there may have been a continuous cover of volcanics from the Challis area north over the Idaho Batholith and east to the Lowland Creek volcanics during mid-Eocene time. The volcanic rocks exposed now in the Challis and Lowland Creek areas are clearly erosional remnants of what were once much larger fields, and it is clear that there has been a great deal of erosion since Eocene time. The Rhodes Peak cauldron lies about 200 km north of the present northern margin of the Challis volcanic field and a little less than 200 km west of the Lowland Creek field.

The Challis Volcanic Field

The Challis volcanic field covers an area of about 6000 square km along the eastern margin of the Atlanta lobe of the Idaho batholith. The volcanic rocks of the area have been divided into two categories that erupted at different times. The earliest lavas were of intermediate to mafic composition and were erupted between 51 and 45 million years ago. These lavas were erupted from a large number of vents scattered throughout the area, mostly in non-explosive eruptions. the second group of lavas is more silicic, ranging in composition from rhyodacite to alkali rhyolite. These lavas were erupted between 48.4 and 45 million years ago in the form of ash flow tuffs and some lava flows and domes.

The second cycle of volcanic activity in the Challis field produced at least one major cauldron complex, the Van Horn Peak complex. This complex is approximately 50 by 40 km in size and has been intruded on the west by the Eocene Casto batholith. Northwest of the Casto batholith another cauldron complex, the Thunder Mountain complex, is believed to be part of the same large cauldron complex which was bisected by the Casto batholith (McIntyre and others, 1985).

Within the Van Horn Peak cauldron complex only one individual caldera (the Twin Peaks caldera) has been clearly identified, although portions of several others are preserved (McIntyre, 1985). This caldera appears to have been the last caldera in the complex to collapse, and therefore it has not been obscured by any other overlapping collapse structures. The Twin Peaks caldera is nearly circular and is about 20 kilometers in diameter. Intracaldera tuff reaches a thickness of nearly a kilometer and consists of two major cooling units 300-400 meters thick with an intervening layer of nonwelded pyroclastic debris. Outflow tuff is generally less than 40 meters thick, and occurs as much as 40 kilometers away from the caldera rim. The tuff is alkali rhyolite containing 25-35% phenocrysts of quartz and alkali feldspar with minor plagioclase, pyroxene, and biotite.

The Casto batholith probably is a portion of the now crystalline magma chamber whose volatile-rich differentiates were erupted from the Van Horn Peak-Thunder Mountain cauldron complex. The batholith appears to have been forcibly emplaced into the overlying volcanic rocks, and the elongate pluton now forms the core of a northeast trending anticline with volcanics on the limbs dipping to the northwest and southeast. Leonard and Marvin (1985) believe that the pluton was emplaced by diapiric rise after it had crystallized. They cite the absence of a contact aureole and hydrothermal mineral deposits as evidence of this diapiric rise, but the idea lacks definitive evidence and has not been suggested in the emplacement of other Eocene plutons.

Tectonic Environment During Eocene Time

Calc-alkaline magmas of the Eocene igneous episode are similar in mineralogy to those which occur in Island Arc settings. This factor has led many workers to propose a subduction related source for the magmas (Lipman and others, 1972, Snyder, 1976). The Farallon plate was undoubtedly being subducted along the western margin of North America in Eocene time (Atwater, 1970), but it is difficult to visualize any configuration of a subduction zone that could produce the widespread area of volcanism that existed during Eocene time. Lipman and others (1972) proposed an imbricate, gently dipping subduction zone under the northwest to explain the pattern. This model was derived by estimating the depth to the paleo-Benioff zone by measuring the K_2O/SiO_2 ratios of Eocene volcanic rocks from throughout the region. In modern Island arc volcanics a trend has been observed where K_2O/SiO_2 ratios increase with distance landward from the trench, and it has been proposed that at a standard silica content (55% silica), a given potassium oxide percent corresponds to a certain depth to the Benioff zone (Dickinson and Hatherton, 1967). The relationship is apparently good within an individual island arc system, but values vary widely between different arcs and the relationship has been found to be an unreliable guide to the configuration of ancient subduction zones (Carr and others, 1979, Nielson and Stoiber, 1973). Considering that imbricate subduction is very difficult to rationalize structurally and the only evidence in favor of the model has been shown to be unreliable, some other model must be considered.

Paleomagnetic studies of sedimentary and volcanic rocks of Eocene age or older in the Coast Range of Oregon have shown that the region has rotated between 50 and 75 degrees clockwise since mid to late Eocene time (Simpson and Cox, 1977). Plate tectonic reconstructions that attempt to explain this rotation have provided a slightly more reasonable model for the development of the Challis-Absaroka volcanic fields in an arc-type setting (Magill and others, 1981). The configuration of subduction zones shown in figure 5 is similar to the present day configuration of the Izu, Bonin, and Ryukyu trenches, and is therefore tectonically feasible.

The Clarno volcanic field does not fit in this model, but the dates from the Clarno field indicate that volcanism there did not begin until about 47 million years ago. This was actually near the end of the Challis-Absaroka activity, which began at about 55 million years. Magill and others

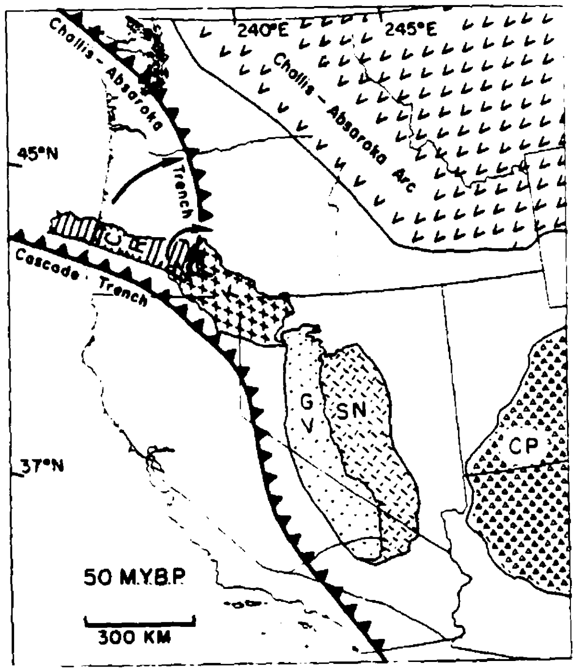


Figure 5. Reconstruction of the western margin of the U.S. fifty million years ago based on paleomagnetic evidence. (Magill and others, 1981)

(1981) suggest that the Clarno volcanic field was produced by subduction in the Cascade trench after the Challis-Absaroka trench had been shut off by the rotation of the Coast Range block. The Clarno volcanic field shows a clockwise rotation of only 20%.

While this model has merit in explaining the observed geologic structure of western Oregon it still has problems relating to the configuration of the Challis-Absaroka arc. The position of the Absaroka volcanic field more than 1000 km inland from the proposed Challis-Absaroka trench is much greater than the 50-300 km arc-trench gap observed in most modern island arcs. The problem may be significant or it may just be a problem of locating the precise position of the trench. The Columbia Plateau basalts make it difficult to prove whether or not the trench ever existed, let alone determine its exact position. One factor that seems to have been overlooked by most workers is the increasing evidence that, at least in the Idaho batholith area, the Eocene igneous episode was accompanied by a great deal of crustal extension. This extension is shown by abundant north to northeast trending dikes and steep normal faults indicating east-west or southest-northwest extension of up to 30% in some localities (Luthy,1981, Motzer, 1985).

While the apparent rotation of the Oregon Coast Range may eventually be found to hold the key to understanding the tectonic events that gave rise to the Eocene igneous episode, no single model has yet gained wide acceptance. The situation has not improved much since Armstrong (1978) lamented:

"Farther back in time than the Columbia event, the tectonic situation remains obscure. I do not have even a speculative plate model to offer in explanation of the earlier Cenozoic volcanic patterns and I am skeptical of all models that have been offered. There is still something missing--a lack of critical data or inadequate or false conceptions prevent the reconciliation of observed history with actualistic plate models. The salient features which are most puzzling are the broad extent of volcanic fields perpendicular to the continental margin and their irregular, but well-documented, southward time transgression. The challenge of more work and thinking remains." (Armstrong, 1978, p278)

CHAPTER II

DESCRIPTION OF MAP UNITS

Sedimentary Rocks of the Belt Supergroup:

Wallace Formation: Sediments of the Wallace Formation occur in the area north of the ring dike and consist of fine grained carbonate bearing clastics. The rocks are grey to brown to nearly black, and typically weather to a light buff-brown. Bedding is on a scale of less than one to several centimeters, with layers of siltite alternating with layers of argillite. Ripple marks and mud cracks are present, though not abundant. Coarse breccias of Wallace sediments occur just north of the study area. The structure of the Wallace Formation was not investigated in detail, but in the study area the bedding commonly shows dips of 30 degrees or less to the north, northeast, or northwest. Some small scale fold axes plunge to the northwest.

Purple Quartzite-Mount Shields II?: Purple quartzite crops out south of the ring dike in the western portion of the study area and as isolated windows beneath the tuff farther east. This unit also forms a 20 to 30 meter thick screen between the Lolo batholith granite and the Kelly Creek tuff. Fragments of quartzite are common throughout the tuff. In outcrop this quartzite shows planar laminations 2-20mm thick with some cross-bedding. Laminations are shown by concentrations of heavy minerals, now mostly specular hematite. Mineralogy is mostly quartz with about 10% feldspar, mostly orthoclase.

Quartzite in the study area occurs as an isolated package, cut off from the Wallace Formation by the ring dike. No other Belt formations are exposed in conformable contact with this unit, which makes it difficult to determine the stratigraphic position. Several Belt formations have quartzite units similar to this, notably the Revett Formation of the Ravalli Group and the Mount Shields II Formation of the Missoula Group. However, several factors favor the designation of these rocks as Mount Shields Formation. These include; predominance of orthoclase over plagioclase, presence of specular hematite rather than magnetite, degree of induration (less than would be expected for Ravalli), and lack of biotite except where subjected to contact metamorphism. (D. Winston, pers. comm., 1985)

Goat Lake Granodiorite

Granodiorite occurs in the southwestern portion of the study area and is well exposed around Goat Lake. It is more mafic and less potassic than either the Lolo granite or the ring dike granite. The rock is coarse grained and the texture is largely characterized by subhedral laths of andesine. Biotite generally predominates over hornblende as the major mafic phase, and potassium feldspar is present in the form of plaid twinned microcline. Some myrmekitic plagioclase-quartz intergrowth is present. Mineralogically and texturally this granodiorite is very similar to some of the small stocks and plugs of Cretaceous age adjacent to the Idaho batholith. Nold (1968) mapped several of these intrusions in the areas east and southeast of the study area.

The Goat Lake granodiorite clearly pre-dates intrusion of the ring dike granite and the Kelly Creek tuff. A dike of ring dike granite intrudes the granodiorite just west of Goat Lake, and granodiorite clasts are common in the tuffs at many locations in the southwest portion of the study area, especially around Kellys Finger. Granodiorite probably underlies the tuff in this region.

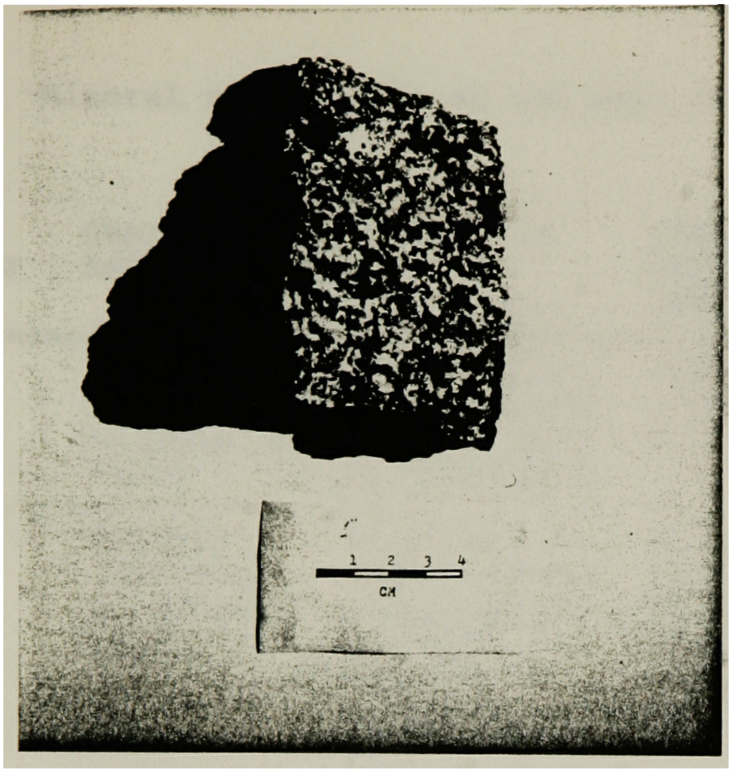


Figure 6. Hand sample of Goat Lake granodiorite (Kg).

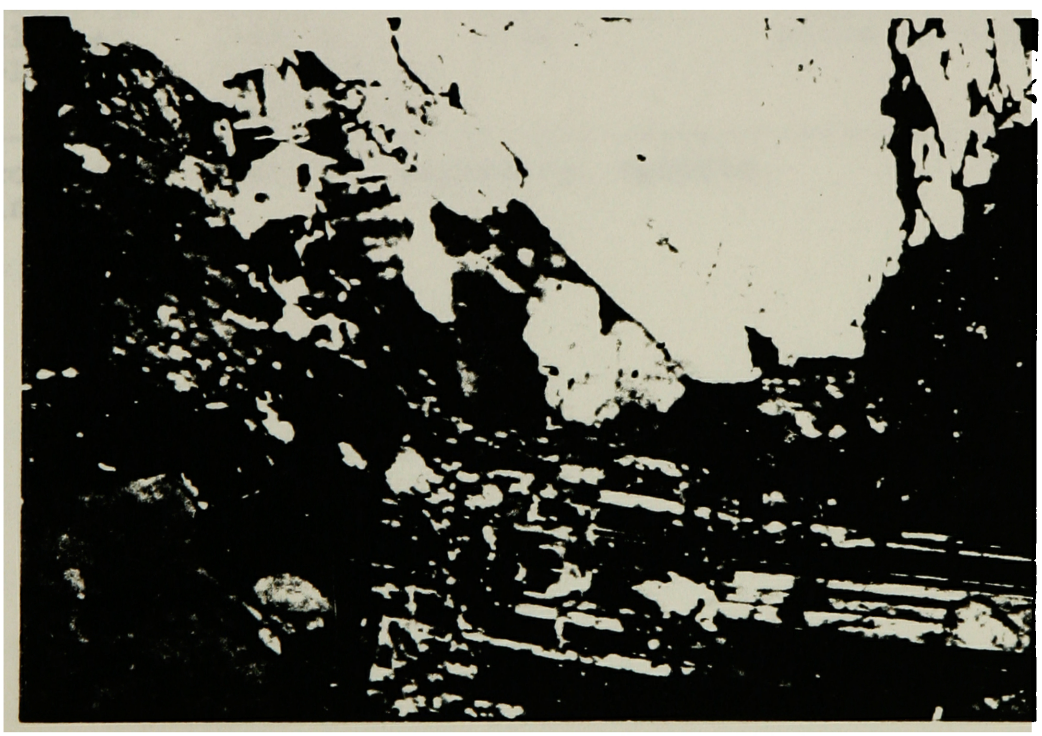


Figure 7. Thin section of Goat Lake granodiorite, crossed nichols. Note plaid twinned microcline in upper left. (field of view is 3mm)

Table 1. Mineral composition of the Goat Lake granodiorite (Kg).

MINERAL, % OF ROCK	GRAIN SIZE AND SHAPE	PROPERTIES	COMMENTS: TEXTURES AND ALTERATION
Biotite 5-10%	0.5-2mm subhedral to euhedral laths	Z'=brown to grey-green X'=pale yellow brown	Commonly kinked. Altering to chlorite around edges.
Plagioclase 50-60%	0.5-6mm subhedral to euhedral laths	An_{35}-An_{45} (centered bisectrix and carlsbad-albite methods)	Normal zoning. Albite twins common, some carlsbad and pericline twins. Altering to sericite and epidote.
Quartz 15-35%	0.5-5mm anhedral	undulose extinction	
Potassium Feldspar 1-15%	2-4mm interstitial and as megacrysts	Plaid twinning	Very minor alteration to clays.
Accessory Minerals:	apatite, magnetite, epidote.		

Kelly Creek Volcanic Field

This unit is composed of a great variety of lithologies which could probably be broken down into several different map units if field time had allowed. Because of this variability the petrology of individual samples has been catalogued in tables 2 and 3 and sample locations are marked on plate 1. The samples have been grouped into 2 categories; those that show evidence of ash-flow origin, and those that are characterized by predominantly clastic textures. All of the samples are devitrified to some degree; many are so badly devitrified that original textures are nearly impossible to see. Most samples have also undergone low grade propylitic alteration, with feldspars being altered to sericite, clays, and epidote. Alteration has also affected the groundmass, which is locally sericitized.

Most of the rocks in the Tv unit appear to be ash-flow tuffs that have undergone varying degrees of welding, devitrification, and alteration. Samples from this group, whose mineral composition is summarized in table 2, are generally dark brown, purple, or black in hand sample. On fresh surfaces the rock most commonly appears massive, but weathered surfaces may show faint to well-defined eutaxitic structure (Fig. 8). The dark lenses have the form of

Figure 8. Eutaxitic texture in Kelly Creek tuff (Tv).

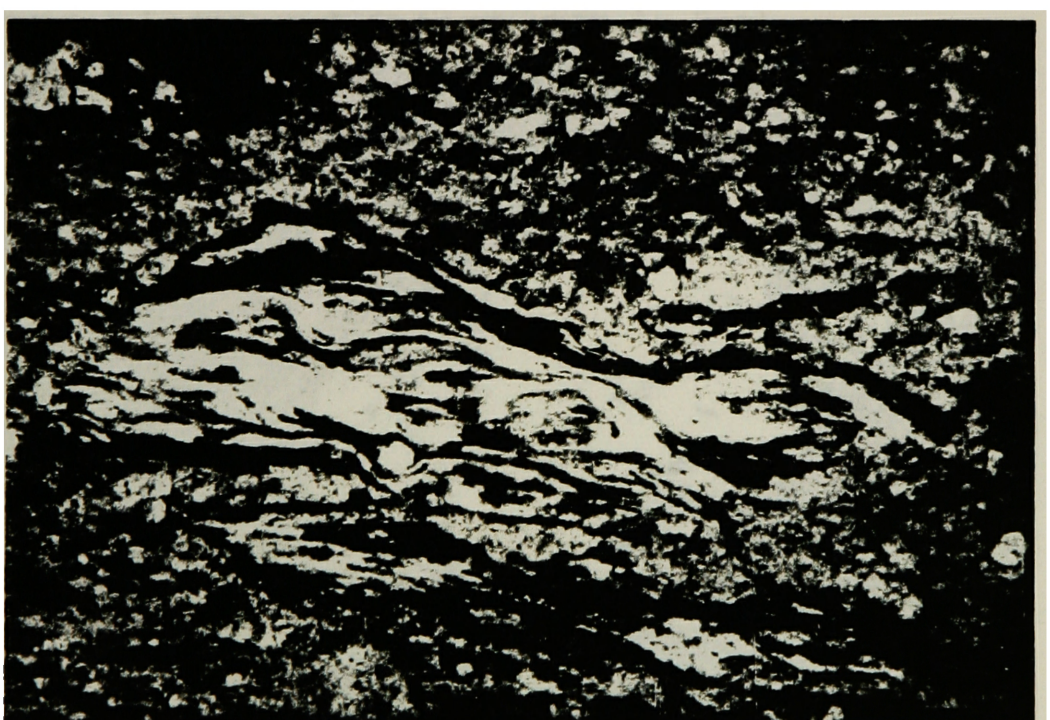


Figure 9. Kelly Creek tuff in thin section, plane light, showing laminations of opaque oxide in pumice. sample # L-5 (field of view is 1.9mm)

Figure 10. Thin section of Kelly Creek tuff showing axiolitic devitrification of shards.
sample # Lt-37 (field of view is 2mm)

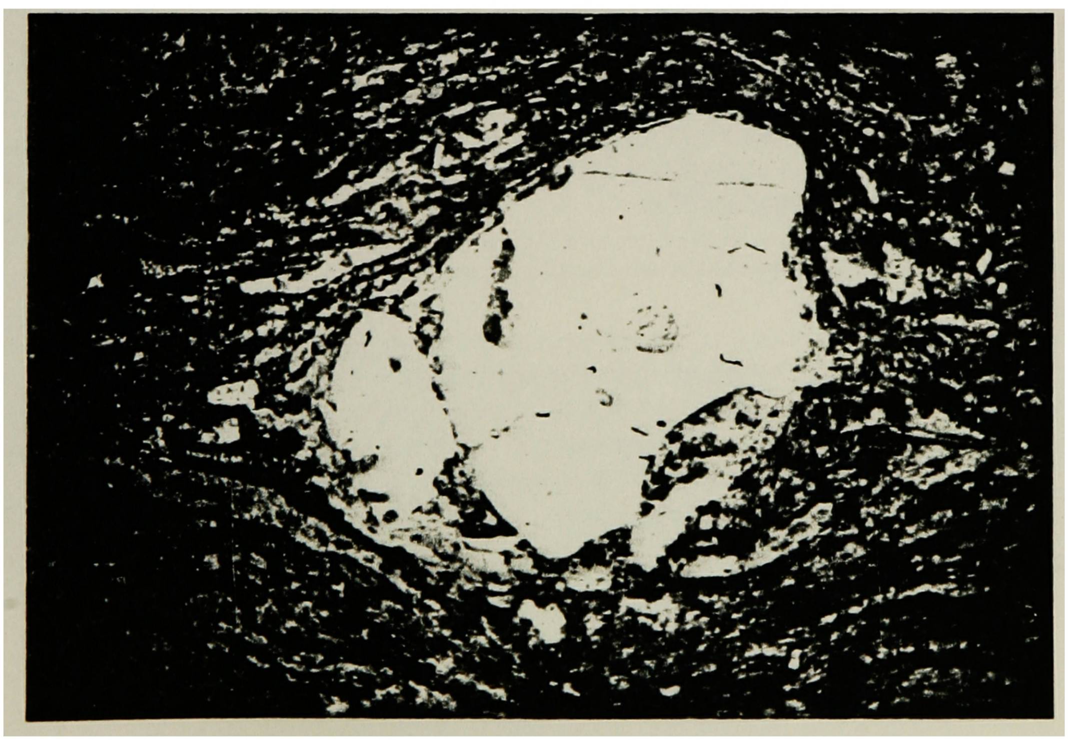


Figure 11. Thin section of strongly welded tuff, plane light. sample # Lt-8 (field of view is 3mm)

Table 2. Mineral composition of the Kelly Creek volcanics (Tv), ash-flow tuff samples.

Sample no.		Lt-33	Lt-37
Phenocrysts:			
	% of rock	50-60%	10-15%
	Mineral Composition	Quartz: 40% Sanidine: 40% Plagioclase: 20%	Quartz: 40% Sanidine: 40% Plagioclase: 20% Biotite: Tr-2%
	Size and Shape	0.1-3mm mostly fragments	0.1-1.5mm mostly fragments, some euhedral plag.
Shards		Scarce. Devtrified to med. grained qtz and feldspar, not axiolitic.	Abundant. Prominant axiolitic texture, very fine grained.
Lithic Fragments		5-10% Quartzite, Kg granodiorite, andesite	5-10% Fine grained crystalline rhyolite with phenocrysts similar to tuff.
Pumice			some glassy, laminated pumice
Comments			Shards are not flattened. Nearly round bubbles are visible, surrounded by axiolitic structures.

Lt-22	Lt-10	Lt-6
10%	5%	10%
Sanidine: 50% Plagioclase: 30% Quartz: 20%	Sanidine: 80% Quartz: 10% Plagioclase: 10%	Sanidine: 60% Quartz: 30% Plagioclase: 10%
0.1-2mm mostly fragments, some euhedral plag.	0.1-2mm mostly fragments	0.1-1mm mostly fragments
Abundant. Flattened, devitrified to med. grained qtz and feldspar. Not axiolitic.	Abundant, not flattened. Axiolitic devitrification common.	Scarce, not flattened. Some bubble shapes visible.
<5% rhyolite similar to Lt-37	Tr quartzite and rhyolite	10-15% mostly quartzite and argillite, some rhyolite
		Sericite lenses may be altered pumice.
Massive in H.S.,but flattened shards define clear foliation in T.S.. Sanidine shows incipient exsolution of albite.	Pale green in H.S., appears hydrothermally bleached. Feldspars altered to clay and opal.	Badly altered. Some clasts appear to be altered to sericite.

Table 2. (continued)

Sample no.		Lt-2	L-4
Phenocrysts:			
	% of rock	10-15%	5%
	Mineral Composition	Plagioclase: 50% Quartz: 25% Sanidine: 25% Biotite: Tr	Plagioclase: 50% Sanidine: 50% Biotite: Tr
	Size and Shape	0.1-1.5mm mostly fragments	0.1-2mm euhedral with some fragments
Shards		Abundant, very flattened. Deformed around phenocrysts. Axiolitic texture.	
Lithic Fragments		quartzite, argillite, rhyolite	<5% quartzite
Pumice		Possibly some glassy pumice with perlitic cracks.	Severely flattened, forming discontinuous wavy laminations.
Comments		Massive in hand sample.	Some sanidine exsolving to perthite. Biotite dusted with magnetite.

Lt-8	Lt-8a
10-15%	10-15%
Quartz: 40% Plagioclase: 30% Sanidine: 30% Biotite: Tr	Plagioclase: 40% Sanidine: 40% Quartz: 20% Biotite: Tr
0.1-2mm mostly euhedral	0.1-3mm euhedral with some fragments
Flattened to fine wavy laminations which wrap around grains.	Fine, wavy laminations.
Delicately embayed quartz phenocrysts are unbroken. Plagioclase slightly altered to sericite.	Sanidine exsolving to perthite. Minor alteration of feldspars to clay, biotite dusted with magnetite.

flattened pumice lapilli, but in thin section they are found to consist of a fine grained intergrowth of quartz and sericite, quartz and limonite, or nearly pure fine grained sericite or biotite. These lenses are probably pumice lapilli that have undergone a two-stage process of devitrification and alteration. The first stage is the devitrification of the pumice to an intergrowth of quartz and feldspar. Ross and Smith (1961) note that pumice fragments tend to devitrify more readily than shards in ash-flow tuffs, and that pumice structures are commonly totally destroyed in tuffs whose shard structure is still plainly visible. In the Kelly Creek tuffs, an episode of hydrothermal alteration appears to have altered the feldspars in the intergrowth to sericite.

Within individual lenses the intergrowth tends to be structureless, except that in limonitic lenses the limonite is concentrated along thin wavy laminae between quartz-rich layers. In some of the less altered tuffs pumice lapilli are characterized in plane light by dark and light streaks in which the dark streaks are apparently formed by concentrations of magnetite or other metallic opaques (Fig. 9). During hydrothermal alteration these streaks may have altered to limonite rather than sericite, giving rise to the observed small scale structure.

Angular glass shards are visible in a number of samples, although all have been devitrified and altered to some extent. Samples LT-37 and LT-10 are composed almost entirely of relatively undeformed shards that show classic axiolitic devitrification (Fig. 10). Axiolitic texture is developed by minute, acicular quartz and feldspar crystals which grow inward from the margins of a glass shard, becoming coarser grained toward the interior of the shard (Ross and Smith, 1961). In other tuffs devitrification has produced a more random, medium grained quartz-feldspar intergrowth, and in some samples shards are not detectable in plane light and barely visible under crossed nichols.

Crystal content of the tuffs ranges from less than 5 percent to more than 50%, averaging around 10-15%. Mineral species include quartz, plagioclase, perthitic potassium feldspar, sanidine, and biotite. These minerals occur most commonly as broken fragments rather than euhedral grains, and it is difficult to determine which are phenocrysts and which are accidental fragments torn from the country rocks. A few fragments of plaid twinned microcline from tuff samples collected near Kellys Finger are probably derived from the Goat Lake granodiorite, and some large clasts of granodiorite nearby verify that this tuff erupted through granodiorite. Many tuffs contain abundant small quartz crystals 0.05-0.2 mm in size. These quartz crystals are somewhat rounded and are very similar in size to the quartz grains of the purple quartzite that occurs as lithic fragments in nearly all samples. These quartz crystals are probably derived from attrition of quartzite during eruption.

The presence of some euhedral crystals of quartz, plagioclase, potassium feldspar, and biotite suggests that these minerals formed as phenocrysts from the melt. Quartz phenocrysts are frequently hexagonal in cross section, typical of high temperature quartz, and they are commonly deeply embayed. Some sanidine phenocrysts are also embayed, but much less commonly than quartz. Most sanidine has a negative 2V angle of 30 degrees or less, but some sanidine with a positive 2V was noted. While some sanidine is as fresh and clear as quartz, most samples have at least some sanidine which has begun to exsolve to form perthite. In some grains exsolution appears to proceed from the grain margins inward, and the core of the grain shows no exsolution. Some carlsbad twinning was noted in sanidine. Plagioclase commonly forms the largest phenocrysts in a sample, and these phenocrysts seem to be a little more resistant to fracturing than the quartz and sanidine. Most grains show albite twinning, and carlsbad twins are fairly common. The plagioclase has a lower index of refraction than balsam and therefore must be fairly sodic. Compositions of a few grains were determined by the centered bisectric method (Troger, 1952) and ranged from an_8 to an_{30}.

Lithic fragments occur in nearly all samples and include quartzite, argillite, granodiorite, and fine grained porphyritic rhyolite. These fragments may comprise up to 40% of the rock and are generally oriented with their long axes aligned with the compaction foliation, where present. Porphyritic rhyolite is very common as lithic fragments, but is rare in outcrop. In the tuff this rhyolite commonly has large, deeply embayed quartz phenocrysts in a groundmass intergrowth of spherulitic quartz and feldspar. This rock is very similar to that found in a number of dikes that crop out along Montana and Surveyor Creeks several kilometers northeast of the study area. The abundance of this lithology in the tuff suggests that rhyolite dikes may be very common in the lower levels of the intracauldron block. These dikes may form a roof zone above the underlying batholith similar to that envisioned by Fiske (1963) for the Tatoosh pluton in Mount Rainier National Park.

A few samples of very densely welded tuff were collected in the northeast part of the study area (table 2). Hand samples of these rocks are dark brown, grey, or green and contain thin wavy bands of light tan color. These bands look almost like flow laminations, but they are not very continuous and commonly bend tightly around phenocrysts (Fig. 11). Thin sections reveal that the pumice bands are coarser grained than the rest of the rock; elongate lenses of quartz are common. Phenocryst percent and mineral composition are similar to the less-welded ash-flow tuffs, but in these rocks there is a much greater percentage of euhedral crystals. Many very delicately embayed quartz phenocrysts are preserved unbroken in these rocks. Lithic fragments are very rare, and only a few clasts of quartzite were noted.

A lack of shards and pumice, presence of many unbroken phenocrysts, and relative lack of lithic fragments suggest that these rocks solidified from a magma rather than from a pyroclastic flow. However, discontinuous laminations and other features visible in thin section and hand sample have the appearance of an ash-flow tuff. These rocks occur near the cauldron rim and the ring dike and may be a feeder dike where magma solidified before it could erupt to form ash. Strikes and dips of pumice bands are quite random, but a

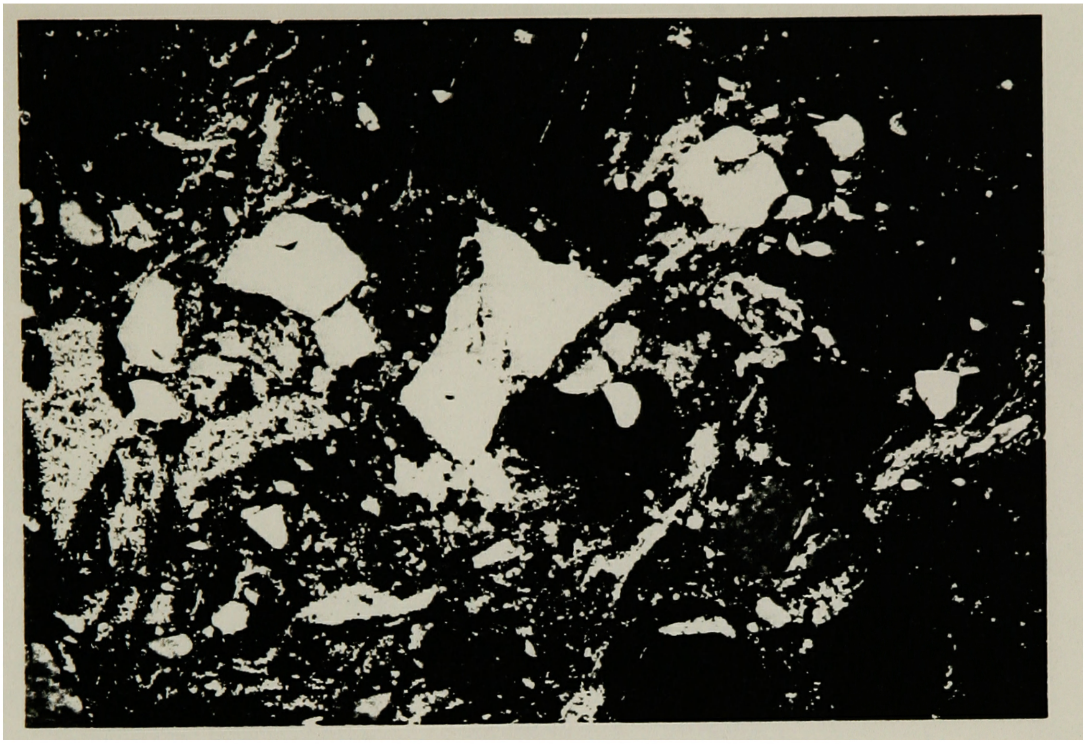


Figure 12. Thin section from a probable lahar deposit (sample L-8), crossed polars. Note angular fragments of crystals and rock. (field of view is 4.8mm)

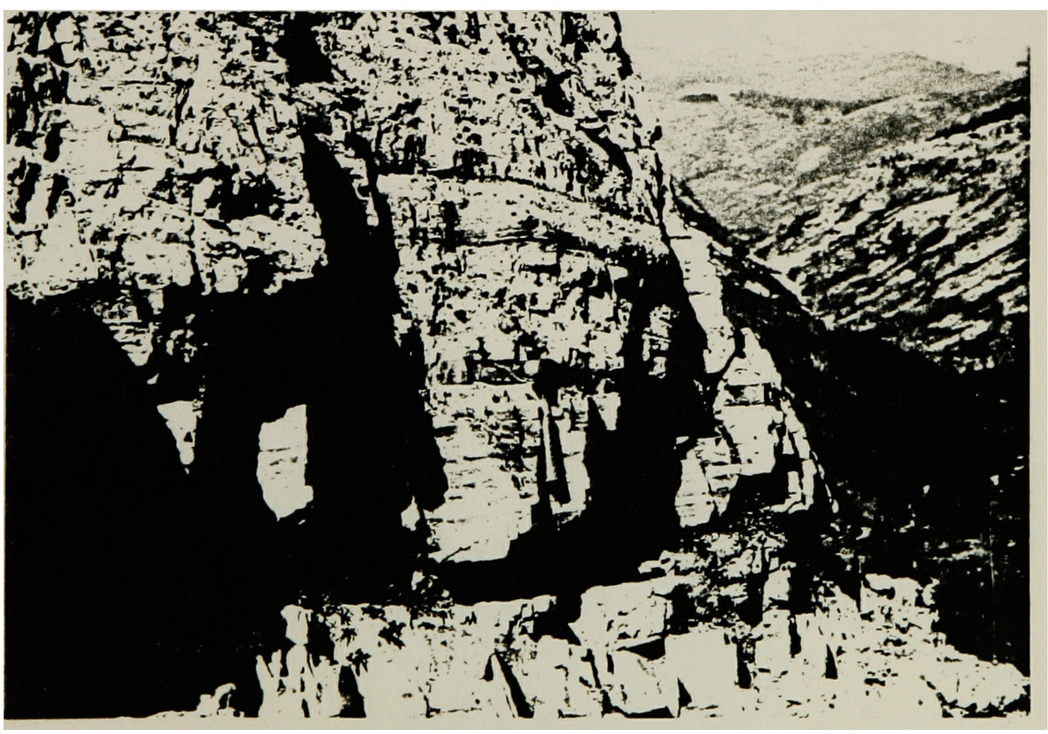


Figure 13. Bedded volcaniclastic sediments near Williams Peak.

Table 3. Mineral composition of the Kelly Creek volcanics (Tv), lahar or debris flow samples.

Sample no.		L-8	Lt-5
Phenocrysts and crystal fragments:			
	% of rock	10%	30-40%
	Mineral Composition	Quartz: 40% Plagioclase: 40% Sanidine: 20% Biotite: Tr	Quartz: 40% Plagioclase: 20% Sanidine: 20% Orthoclase: 20%
	Size and Shape	0.1-0.5mm Mostly fragments, some euhedral plagioclase.	0.1-3mm mostly fragments
Clasts		approx 50% Ash-flow tuff in various stages of compaction and welding.	30-40% quartzite, rhyolite argillite, andestite
Matrix		Fine crystalline quartz and feld-spars.	Very fine grained, barely anisotropic with sericite patches in shapes resembling pumice fragments and shards.
Comments		Massive in hand sample, in T.S. rock is character-by patches of well defined flattened shards in random orientations. Feldspars altering to sericite.	Little or no alter-ation in crystals, much sericite in matrix.

Lt-28
====================

30-40%

Plagioclase: 60%
Quartz: 20%
Sanidine: 20%

0.1-3mm
mostly fragments

1-3%
quartzite, rhyolite,
pumice with wavy
streaks of magnetite

Very fine, partly
anisotropic glass with
small anisotropic grains.

Some shards in groundmass.
Feldspars show minor
alteration to clays
and sericite.

large proportion are sub-vertical.

Samples L-8 and LT-5 are characterized by a large proportion of clasts in a fine matrix. In sample L-8 the clasts are mostly tuffs that show shards in various stages of welding and compaction. The clasts are angular and make up more than 50% of the rock. Matrix material is very fine grained and shows no evidence of shards. This rock may be a mudflow deposit formed by mass wasting of a freshly deposited ash-flow tuff. Clasts in LT-5 are more diverse in lithology and include quartzite, rhyolite, and a fine grained mafic rock. This sample was collected less than a meter above the contact between the purple quartzite and the Kelly Creek volcanic rocks, near the top of a small hill. It may be a clast-rich layer at the base of a pyroclastic flow or it may be a mudflow deposit. In thin section some wavy lenses of quartz-sericite intergrowth resemble the altered pumice noted in the ash-flow tuffs. Crystal fragments in the matrix are only slightly altered, and a greater degree of alteration would be expected if this were a mudflow deposit.

Andesite and Basalt

Porphyritic andesite occurs on some ridgetops and as dikes cutting the Kelly Creek tuff. Phenocrysts of plagioclase and hornblende are common, and small phenocrysts of biotite, quartz, and apatite also occur (see table 4). Plagioclase phenocrysts are mostly euhedral laths with well developed albite twinning and some pericline and carlsbad twins. Most plagioclase is unzoned, but a few grains show strong oscillatory zoning. Inclusions of brown glass and hornblende are common within the plagioclase phenocrysts. Hornblende phenocrysts are common in some samples and rare in others. In one sample well defined euhedral hornblende crystals 0.2-0.5mm in size make up 10-15% of the rock (Fig. 15).

Groundmass textures are variable, with dike andesite tending to be coarser than that occurring on ridgetops. In some of the coarser samples plagioclase in the groundmass may be 0.2-0.3mm in size, whereas in the finer samples the groundmass consists of tiny plagioclase microlites in slightly devitrified glass. Like most of the intracauldron volcanic rocks the andesite is badly altered. Plagioclase is altering to clays, epidote, and calcite whereas hornblende is altering to chlorite and magnetite.

Figure 14. Andesite dike intruding Kelly Creek tuff near junction of Williams Creek and the south fork of Kelly Creek.

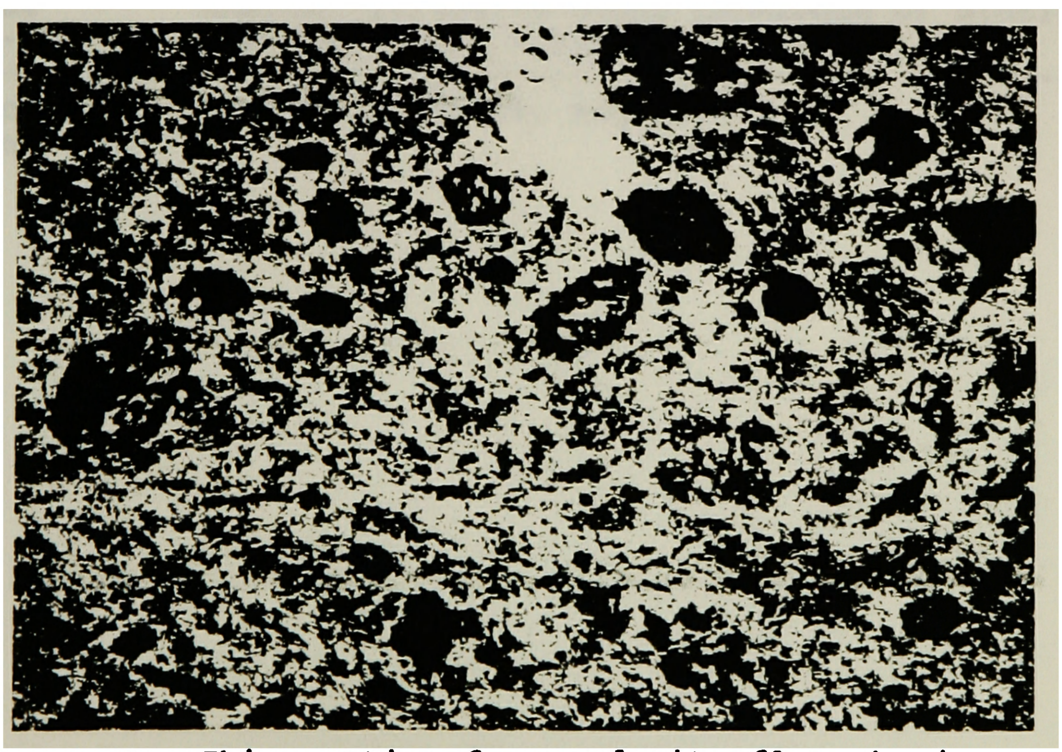


Figure 15. Thin section from andesite flow showing euhedral hornblenbe in matrix composed largely of plagioclase microlites. (field of view is 3mm)

Table 4. Mineral composition of the andesite unit.

MINERAL, % OF ROCK	GRAIN SIZE AND SHAPE	PROPERTIES	COMMENTS: TEXTURES AND ALTERATION
Plagio-clase 10-15%	0.5-4mm Euhedral, lath-shaped phenocrysts	An_{38}-An_{53} (centered bi-sectrix and carlsbad-al-bite methods)	Albite and Carlsbad twins common. Altering to fine clays.
Amphi-bole 10-15%	0.1-2mm subhedral to euhedral	Y=mahagany brown X=pale brown Z=med. brown	Altering to chlorite.
Biotite 0-2%	0.5-1mm euhedral laths	Z=dark brown X=pale yellow	Altering to chlorite and magnetite.
Ground-mass 50-80%	Fine plagioclase microlites in glass. In coarser varieties brown amphibole or biotite and quartz are visible.		
Accessory Minerals:	apatite, calcite, magnetite		

Table 5. Mineral composition of the basalt (Tvb).

MINERAL % OF ROCK	GRAIN SIZE AND SHAPE	PROPERTIES	COMMENTS: TEXTURES AND ALTERATION
Plagio-clase 55-65%	0.1-2mm euhedral laths	An_{77}-An_{81} (centered bi-sectric and carlsbad-albite methods)	Good preferred or-ientation in flow rocks. Larger grains altering to clays.
Augite 15-25%	0.1-0.5mm anhedral	(+)2V=55-65 Strong dis-persion r<<v	Extensive alteration to amphibole.
Amphi-bole 15-25%	0.1-0.5mm fiberous masses		
Quartz <1%	0.1-0.2mm anhedral	straight extinction	
Accessory Minerals:	magnetite		

The andesite tends to be very massive, with no compaction foliation or flow banding visible in hand sample. In thin section plagioclase microlites show some preferred orientation in the groundmass, and a faint flow banding appears to wrap around some phenocrysts. Lithic fragments and pumice fragments are rare to non-existent, and it appears that the ridge-top andesite be one or more flows. The euhedral plagioclase and hornblende phenocrysts with few broken grains also support an origin as lava flows rather than ignimbrite. Some of the dikes may have served as feeders to the flows, although no direct connection was observed in the field.

Basalt, or basalt-like fine grained dark igneous rock, occurs in a few localities in the eastern part of the study area. A dike 1-2 meters thick was observed in the cirque southeast of Shale Peak, and some flows occur on the eastern slopes of Williams Peak. These flows are the lowermost volcanic rocks in the sequence, resting on Belt quartzite. The flow rocks are very fine grained and the mineral composition is difficult to determine. The actual mineral composition may in fact be more like andesite than basalt. A few plagioclase phenocrysts are up to 1mm in size, but most of the rock consists of a fine grained intergrowth of plagioclase laths and augite. In the more altered samples this intergrowth is composed of plagioclase and fine brown amphibole; most grain boundaries have been destroyed. Samples from the flows around Williams Peak exhibit a fairly well-defined lineation of plagioclase laths, but the dike rocks are massive. Vesicles are rare in the basalt.

Volcanic Sediments and Breccias

Bedded, water lain tuff and volcanic sediments occur near Williams Peak in what is believed to be a lake deposit (Fig. 13). These deposits consist of planar beds of sediments ranging from black cherty beds to coarse clastics a cm or more in size. Bedding ranges from 1 to 10 cm, and some bedding planes show ripple marks. Other apparently water lain tuffs occur just northwest of the 7515' peak 1 1/2km northwest of Goat Lake. These rocks appear in a sequence which starts with large angular clasts of rather andesitic looking tuff up to a meter in size in a matrix of porphyritic andesite. The clasts become smaller and more rounded upward in the section, and the highest levels are composed of medium to fine grained sandstone that has fine planar laminations and ripple marks. The sequence is then overlain by coarse conglomerate that again grades upward into fine bedded sandstone. A third sequence is then overlain by andesite.

A breccia of quartzite clasts up to a meter in size was noted in the vicinity of Leo Lake. Clasts are angular, and the matrix is mostly finer clasts with some interstitial magnetite or specular hematite.

Lolo Hot Springs Batholith

The Lolo Hot Springs batholith underlies an area of about 250 square kilometers along the eastern margin of the study area. To the east, Nold (1968) mapped a large portion of the batholith, with about 20 square km of rhyolite in the center. Nold called this rhyolite the Crooked Fork plug, and believed that the plug intrudes the batholith.

The Lolo Hot Springs batholith is alkali feldspar granite or syenogranite and is characterized by the distinctive pink color of the abundant perthitic potassium feldspar. Also distinctive is the abundance of miarolitic cavities and the presence of smokey quartz. The mineral composition is summarized in table 6. Modal mineral composition, chemical composition, and textures in the Lolo Hot Springs batholith are all typical of "A" type granite as defined by Collins and others (1982). In thin section the

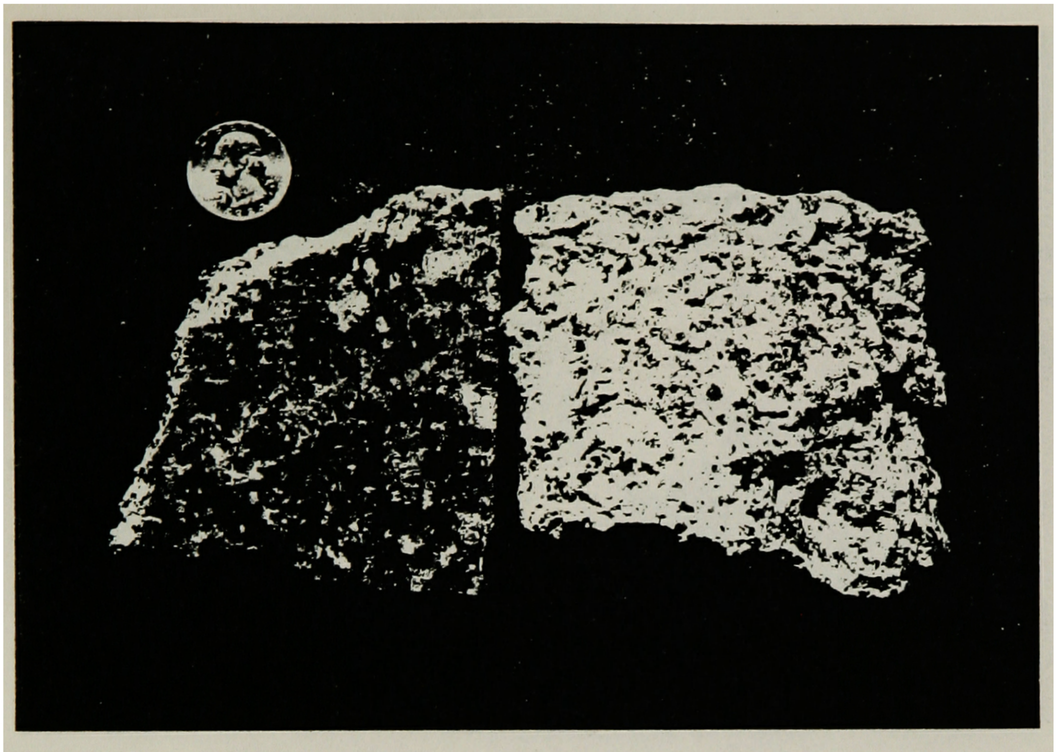


Figure 16. Hand sample of Lolo Hot Springs batholith granite (Tg) and cut surface stained for K-feldspar.

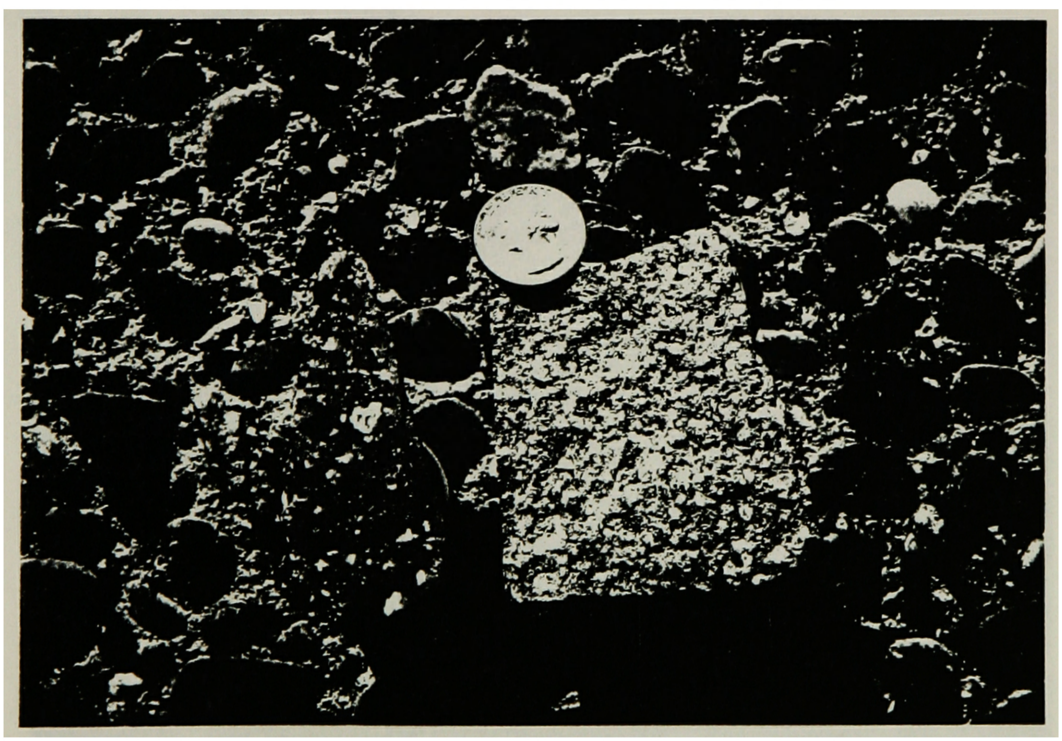


Figure 17. Hand sample and stained slab of ring dike granite (Tpg).

Figure 18. Thin section of Lolo Hot Springs batholith granite showing quartz glomerocryst. Crossed nichols. (field of view is 1cm)

Figure 19. Perthitic K-feldspar in Lolo granite, crossed nichols. Note twinning in exsolved albite. (field of view is 3mm)

Table 6. Mineral composition of the Lolo Hot Springs batholith (Tg).

MINERAL, % OF ROCK	GRAIN SIZE AND SHAPE	PROPERTIES	COMMENTS: TEXTURES AND ALTERATION
Biotite 1-5%	1-2mm short euhedral laths	Z'=very dark brown X'=pale yellow brown	Straight crystals, often with hornblende and sphene. Minor chlorite alteration.
Plagioclase 10-25% avg. 15	1-7mm euhedral to subhedral	An_{15}-An_{27} (centered bisectrix method)	Large euhedral grains commonly zoned, sericitized in core. Smaller anhedral grains are fresh and unzoned.
Quartz 20-45% avg. 25-30%	1-7mm anhedral, some are rounded	patchy undulose ext.	Some glomerocrysts. Smokey grey in hand sample.
Potassium Feldspar 30-65% avg. 50-55%	1-7mm anhedral	perthitic	Albite exsolved from orthoclase in strings and patches. Some twinning in exsolved albite. Very little alteration.
Accessory Minerals:	apatite, hornblende, sphene, zircon, magnetite, fluorite.		

rock appears equigranular and hypidiomorphic. potassium feldspar occurs as orthoclase, perthite, and sanidine. Sanidine occurs only as small inclusions within plagioclase grains. Biotite and magnetite are also included within plagioclase grains, and plagioclase also rims some grains of potassium feldspar. The reverse also occurs, with potassium feldspar partially or completely rimmed by plagioclase. Inclusions of plagioclase, biotite, and quartz are common in potassium feldspar. Graphic intergrowths of potassium feldspar and quartz make up a small percentage of the rock, and such intergrowths are especially abundant in the finer grained phases. Development of perthite is irregular, with some grains showing well developed exsolution of twinned albite (Fig. 19), others having small blebs of untwinned albite exsolved from portions of the grain while other portions of the grain show no exsolution.

Aplite Phase of the Lolo Hot Springs Batholith

Near the headwaters of Cache Creek a zone of very fine grained granite appears to grade into the coarser grained granite. Grain size decreases at higher elevations, and the finest grained phase has an average grain size of 0.5mm. Quartz grains are somewhat rounded whereas the feldspars are

Table 7. Mineral composition of the aplite unit (Tga).

MINERAL % OF ROCK	GRAIN SIZE AND SHAPE	PROPERTIES	COMMENTS: TEXTURES AND ALTERATION
Quartz 20-25%	0.1-0.7mm rare phenos to 3mm rounded or anhedral	straight extinction	
Plagio-clase 10-15%	0.1-0.8mm subhedral	albite twinning	Altered slightly to clays.
Potassium Feldspar 50-60%	0.1-0.8mm anhedral	strongly perthitic	
Biotite <1%	0.1-2mm subhedral laths, embayed	Z'=dk green-brown X'=pale yel-low	
Accessory Minerals:	magnetite		

more angular; there are few well developed crystal faces. Miarolitic cavities lined with limonite are common, and rare phenocrysts of biotite or plagioclase may be several milimeters in size. The decrease in grain size is gradational over a distance of nearly a kilometer and a vertical distance of 400 meters.

Similar aplite zones have been noted in Tertiary stocks near the Sawtooth batholith (Luthy, 1981) and in the Whistling Pig and Bungalow stocks in the western part of the Bitterroot lobe (Motzer, 1985). Such zones may be a common feature of Tertiary pink granite intrusions and may be a differentiated cap that formed over the crystallizing magma.

Ring Dike Granite

Though roughly similar to the Lolo batholith granite in mineral composition, the ring dike granite has several distinctive characteristics in hand sample and thin section. The porphyritic texture is very distinct in hand sample, with 2-5 mm phenocrysts of quartz and plagioclase and smaller phenocrysts of quartz, biotite, and hornblende in a fine grained groundmass. No miarolitic cavities were observed in this rock, which contrasts sharply with the Lolo granite. Hornblende, a blue-green pleochroic hastingsite, is commonly the dominant mafic mineral. blue-green

Figure 20. Mafic inclusions in ring dike granite.

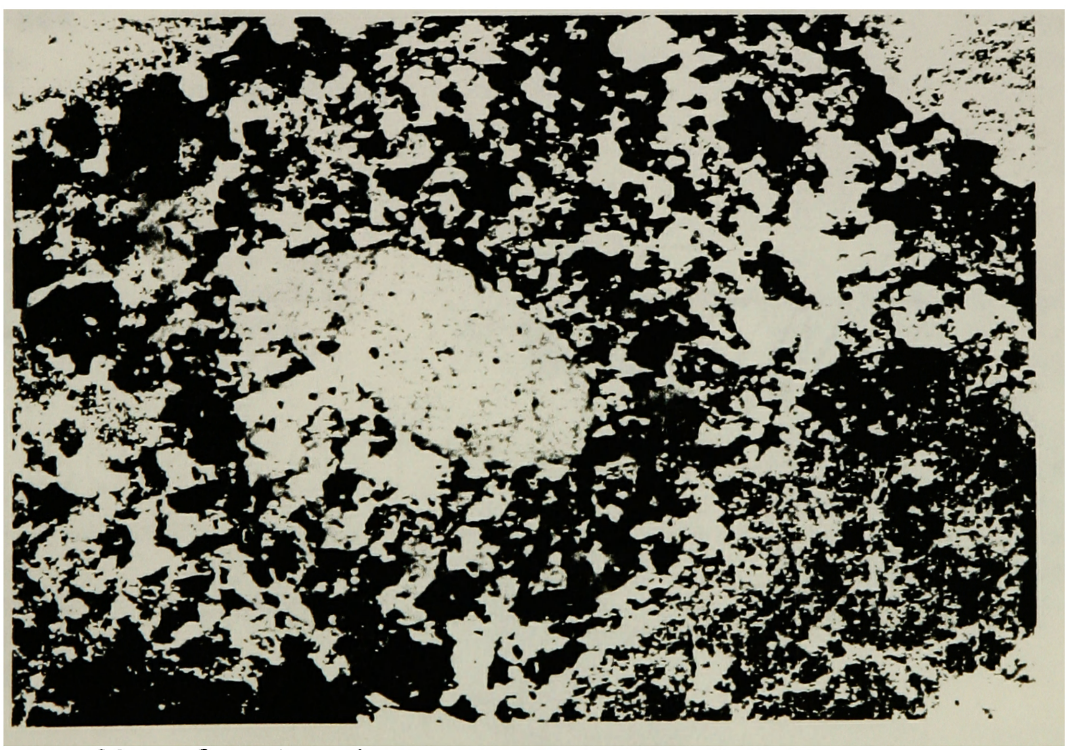


Figure 21. Quartz phenocryst surrounded by intergrowth of quartz and feldspar, crossed nichols. Quartz grain is just a few degrees away from extinction, note that quartz in intergrowth is in optical continuity with the phenocryst. (field of view is 3mm)

Table 8. Mineral composition of the ring dike granite (Tpg)

MINERAL % OF ROCK	GRAIN SIZE AND SHAPE	PROPERTIES	COMMENTS: TEXTURES AND ALTERATION
Quartz 8-35% avg. 10-15%	0.5-3mm rounded phenocrysts, angular in groundmass	straight extinction	Very common intergrowth rings of quartz and k-feldspar surrounding quartz phenocrysts.
Plagioclase 5-30% avg. 5-10%	0.5-4mm mostly as short euhedral laths	An_{20}-An_{30} (centered bisectrix method)	Pronounced normal zoning. Albite, carlsbad, and pericline twinning. Sericite alteration, especially in cores of grains.
Potassium Feldspar 50-80% avg. 65%	1-8mm subhedral phenocrysts, anhedral in groundmass	sanidine (-)2V=10-20 orthoclase (-)2V=70	Some perthite with fine stringers and blebs of albite in orthoclase. Some sanidine shows perthitic exsolution along grain boundries.
Biotite tr-8% avg. 5%	0.5-2mm euhedral laths	Z'=dark green-brown X'=pale yellow-brown	Two generations; phenocrysts and small grains in groundmass. some grains kinked. Altered to magnetite and hydrobiotite around borders.
Hornblende 0-5% avg. 3%	0.1-0.5mm anhedral	Z=dk blue-green Y=dk green-brown X=pale yellow green	Altering to biotite and magnetite.
Accessory Minerals:	pyroxene, zircon, epidote, apatite, magnetite sphene, allanite, fluorite.		

pleochroic hastingsite. The ring dike granite tends to be slightly more mafic in overall composition than the Lolo granite, ranging from syenogranite to quartz syenite.

In thin section the groundmass appears to be an angular intergrowth of quartz and feldspars about 0.5-1 mm in size. Small grains of hornblende and accessories also occur within the groundmass. Fluorite is absent or nearly absent from the ring dike granite. Relict grains of pyroxene, altered to hornblende around the edges, are present in the more mafic varieties. Quartz phenocrysts are commonly rounded and embayed and are typically surrounded by a ring of quartz-potassium feldspar intergrowth in which the quartz is in optical continuity with the phenocrysts (Fig. 21). Such intergrowth rings may have formed when an increase in the rate of crystallization of a eutectic magma caused rapid simultaneous crystallization of quartz and potassium feldspar. Venting of the magma and loss of vapor pressure may be one way in which this increase in the rate of crystallization could occur.

Mafic inclusions are common in the ring dike granite (Fig. 20), but have not been observed within the Lolo batholith. These inclusions are generally quite round and may be up to 25 cm in diameter. One thin section of an inclusion was made and it was found to consist of plagioclase, olivine, and pyroxene phenocrysts in a groundmass of very fine plagioclase microlites and hornblende. Phenocrysts are nearly unaltered and range up to 5 mm in size. No rocks of this composition were found in outcrop within the study area. Basalts of the intracauldron volcanic rocks do not contain olivine, but they may have before alteration.

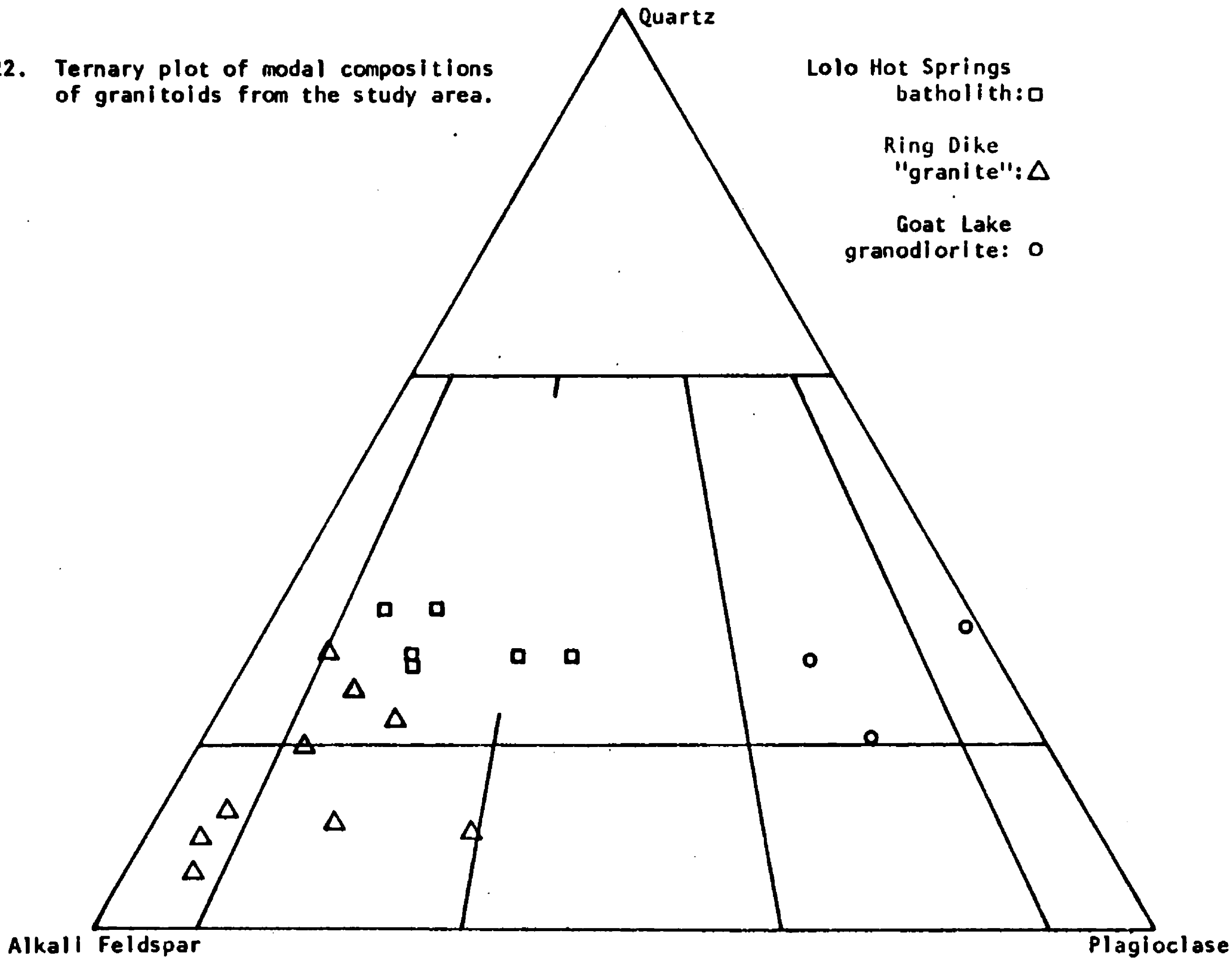


Figure 22. Ternary plot of modal compositions of granitoids from the study area.

CHAPTER III

WHOLE ROCK COMPOSITIONS

Major element chemical analyses were obtained for seven samples from the study area; 2 from the Lolo Hot Springs batholith, 2 from the ring dike, 2 samples of ash-flow tuff, and one sample of "andesite". These are X-ray spectroscopic analyses performed by X-ray Assay Laboratories Limited, Toronto, Ontario. The analysed compositions are shown in table 9, along with average compositions of each rock type, for comparison, from LeMaitre (1976).

Granite of the Lolo Hot Springs batholith shows a close correlation to the average granite of LeMaitre except for the higher sodium and potassium and lower calcium values in the Lolo granite. The reason for these deviations from the average granite can be seen in the modal plot in figure 22, where the Lolo granite tends to plot in the syenogranite field, close to the alkali feldspar corner of the diagram. The rhyolite analyses are very similar to the Lolo granite and show similar deviations from the average, although the sodium values are well in line with the average.

Rock Type:	Lolo granite			avg.* granite	ring dike "granite"	
Sample no.	L-50	L-55	DWH		Lc-1	Lg-1
SiO2	74.8	74.4	71.32	71.30	70.7	65.5
Al2O3	13.1	13.1	14.09	14.32	14.5	16.7
CaO	0.42	0.64	1.08	1.84	0.96	1.97
MgO	0.19	0.26	0.52	0.71	0.38	0.68
Na2O	4.33	4.29	4.15	3.68	4.75	4.97
K2O	4.93	4.83	4.98	4.07	5.15	5.37
Fe(tot)	1.53	1.75	1.17	2.85	2.62	3.68
MnO	0.05	0.05	0.05	0.05	0.07	0.09
TiO2	0.19	0.21	0.35	0.31	0.31	0.54
P2O5	0.04	0.04	0.08	0.12	0.08	0.15

*Averages from LeMaitre, 1976

Sample DWH from Hyndman, 1983, p.226.

Table 9. Whole rock chemical analyses of study area rocks. X-ray fluorescence analyses by X-ray Assay Laboratories Limited, Toronto, Ontario.

Rock type	Kelly Creek tuff		avg* rhyolite	ande- site	avg. trachy- andesite*
sample no.	Lt-22	Lt-37		Lt-29	
SiO2	75.5	75.3	72.82	58.1	58.15
Al2O3	13.2	13.2	13.27	17.3	16.70
CaO	0.47	0.61	1.14	4.20	4.96
MgO	0.23	0.16	0.39	2.48	2.57
Na2O	3.21	3.85	3.55	4.07	4.35
K2O	5.56	5.02	4.30	3.78	3.21
Fe(tot)	1.25	1.30	2.59	5.19	6.47
MnO	0.02	0.04	0.06	0.07	0.16
TiO2	0.13	0.14	0.28	0.77	1.08
P2O5	0.02	0.03	0.07	0.20	0.41

Table 9. (continued)

Rock type	Lolo granite		ring dike granite		Kelly Creek tuff		ande-site
sample no.	L-50	L-55	Lc-1	Lg-1	Lt-22	Lt-37	Lt-29
qt	29.79	29.57	21.29	11.42	34.37	32.32	7.68
co	--	--	--	--	1.09	0.39	--
or	29.28	28.68	30.59	31.85	33.02	29.79	23.22
ab	36.78	36.44	40.35	42.16	27.27	32.68	35.76
an	1.74	2.22	3.03	7.41	2.21	2.84	18.45
di	0.06	0.46	0.44	0.48	--	--	0.89
he	0.01	0.10	0.59	0.71	--	--	0.61
en	0.39	0.33	0.23	0.61	0.55	0.35	4.45
fo	0.08	0.08	0.36	1.03	0.04	0.07	3.53
mt	--	--	1.66	2.97	--	--	3.42
il	0.11	0.18	0.59	1.03	0.04	0.09	1.52
hm	1.54	1.72	0.67	--	1.26	1.30	--
ap	0.09	0.09	0.19	0.35	0.05	0.07	0.48
ru	0.13	0.11	--	--	0.11	0.10	--

Table 10. Nomative mineral compositions of rocks from the study area (weight percent). Analyses listed in table 9.

The ring dike "granite" ranges from syenogranite to quartz syenite to alkali feldspar quartz syenite on the IUGS classification (Streckiesen, 1976). The analyses do not compare closely to any of the averages of LeMaitre. Sample LC-1 is fairly similar to the average granite composition, but shows an even greater enrichment in alkalis and depletion in calcium compared with the Lolo granite. Sample LG-1 plots as quartz syenite on the IUGS chart, but LeMaitre does not list an average composition for quartz syenite. The difference in silica content between the two samples approximately represents the range of compositions within the ring dike, as the samples were specifically chosen to be among the most felsic and mafic, respectively.

The "andesite" sample was collected from one of the ridge top locations and is probably from a lava flow. The sample appeared fresh in hand sample but in thin section appears extensively altered, with hornblende largely altered to chlorite and plagioclase partly altered to sericite. The analysis is very similar to the trachyandesite of LeMaitre, but this composition may be quite different from the original composition before alteration.

Modal analyses of the coarse grained plutonic rocks have been plotted on the IUGS ternary diagram and classified accordingly (Fig. 22). However, the ash-flow tuffs and fine grained chilled granite (LC-1) cannot be classified in this manner. Classification schemes based on phenocryst mineralogy tend to be ambiguous, and the only other mineralogical data on these rocks is in the form of normative mineral compositions calculated from the chemical analyses (table 10). These normative compositions are difficult to compare to the modal compositions because in the norms the feldspars are calculated as end member Or, Ab, and An whereas in the mode they are measured as alkali feldspar and plagioclase. LeMaitre (1976) proposed a system for recalculating Or, Ab, and An to alkali feldspar and plagioclase by using the following formulas:

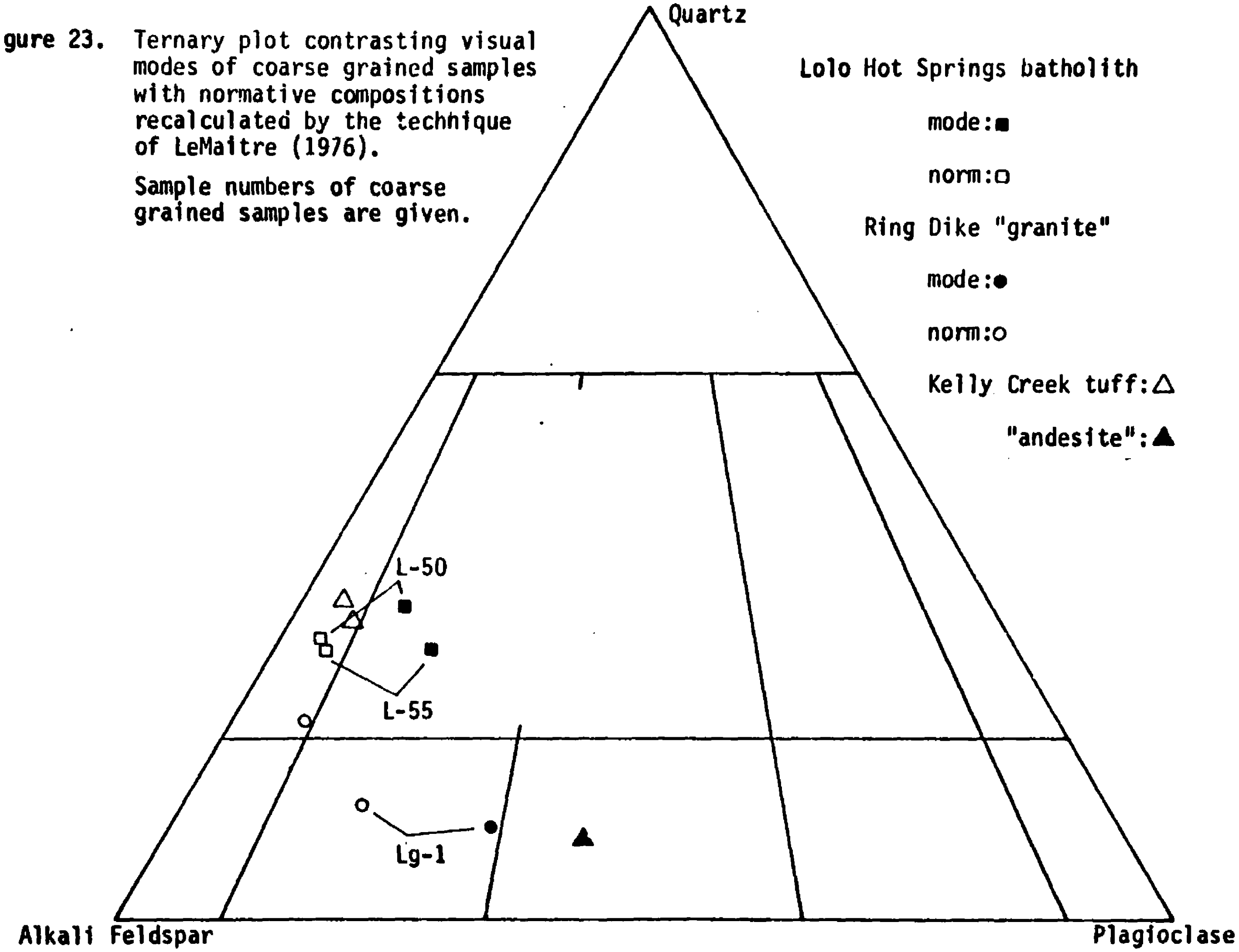
Alkali feldspar = Or X (Or + Ab + An / Or + An)

Plagioclase = An X (Or + Ab + An / Or + An)

The normative mineral compositions of the analysed samples were recalculated using these formulas and plotted in figure 23. The coarse grained Lolo batholith and ring dike samples plot significantly closer to the alkali feldspar corner of the diagram than the modal analyses of the same samples. If the recalculation had accurately reproduced the feldspar proportions in the rock a closer

Figure 23. Ternary plot contrasting visual modes of coarse grained samples with normative compositions recalculated by the technique of LeMaitre (1976).

Sample numbers of coarse grained samples are given.



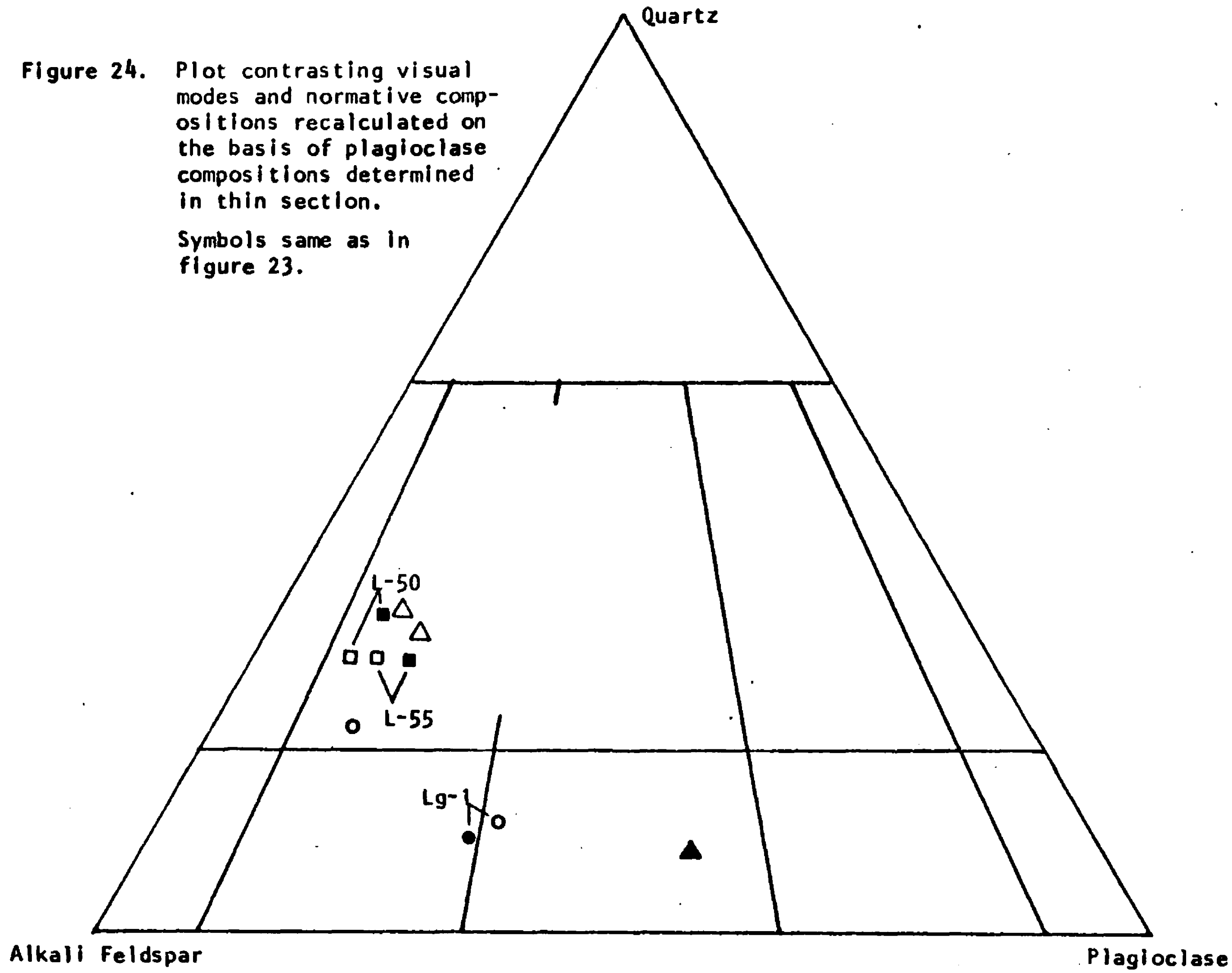
agreement between the two plots would be expected.

Since the An content of the plagioclase in the samples can be determined optically, a more accurate reassignment of feldspars might be based on the observed An content. Thus in the Lolo granite, where the average An content of plagioclase is 20%, the normative %An would be multiplied by a factor of 5 to give the percent of plagioclase of An_{20} composition. The remaining Ab is assigned to the alkali feldspar corner of the diagram.

Normative compositions recalculated by this method are plotted in figure 24. These plots agree closely with the plots of the modal analyses of the coarse grained rocks. Therefore the plots of the fine grained samples are probably fairly accurate representations of the mineral compositions that would have resulted if they had crystallized into coarse grained rocks. By this classification the tuffs fall within the rhyolite field close to, but not within, the alkali rhyolite field. The chilled ring dike sample plots as syenogranite, in contrast to the coarse, more mafic sample which plots between quartz syenite and quartz monzonite.

Figure 24. Plot contrasting visual modes and normative compositions recalculated on the basis of plagioclase compositions determined in thin section.

Symbols same as in figure 23.



The "andesite" sample plots here as quartz latite, but this may be inaccurate due to the hydrothermal alteration. No potassium feldspar was observed in the sample in thin section, but the plagioclase was extensively sericitized. Most of the potassium that in the norm calculations was assigned to potassium feldspar probably occurred as sericite in the rock. This potassium may have been introduced by hydrothermal fluids, or it may have originally been present in solid-solution in plagioclase.

Silica Variation Diagrams

Variation diagrams of silica plotted against 9 other oxides have been plotted in figure 25. The andesite sample was not included in the diagrams because of its extensive hydrothermal alteration. Straight or curved linear trends with no discontinuities on such diagrams are commonly used as evidence that a suite of rocks was derived through some evolutionary process from a common magma source (Wilcox, 1979; Hyndman, 1985). Straight trends have been taken to indicate compositional evolution by assimilation or by liquid state diffusive differentiation whereas curved trends indicate evolution by fractional crystallization. Even with abundant data, controversy often arises as to whether a

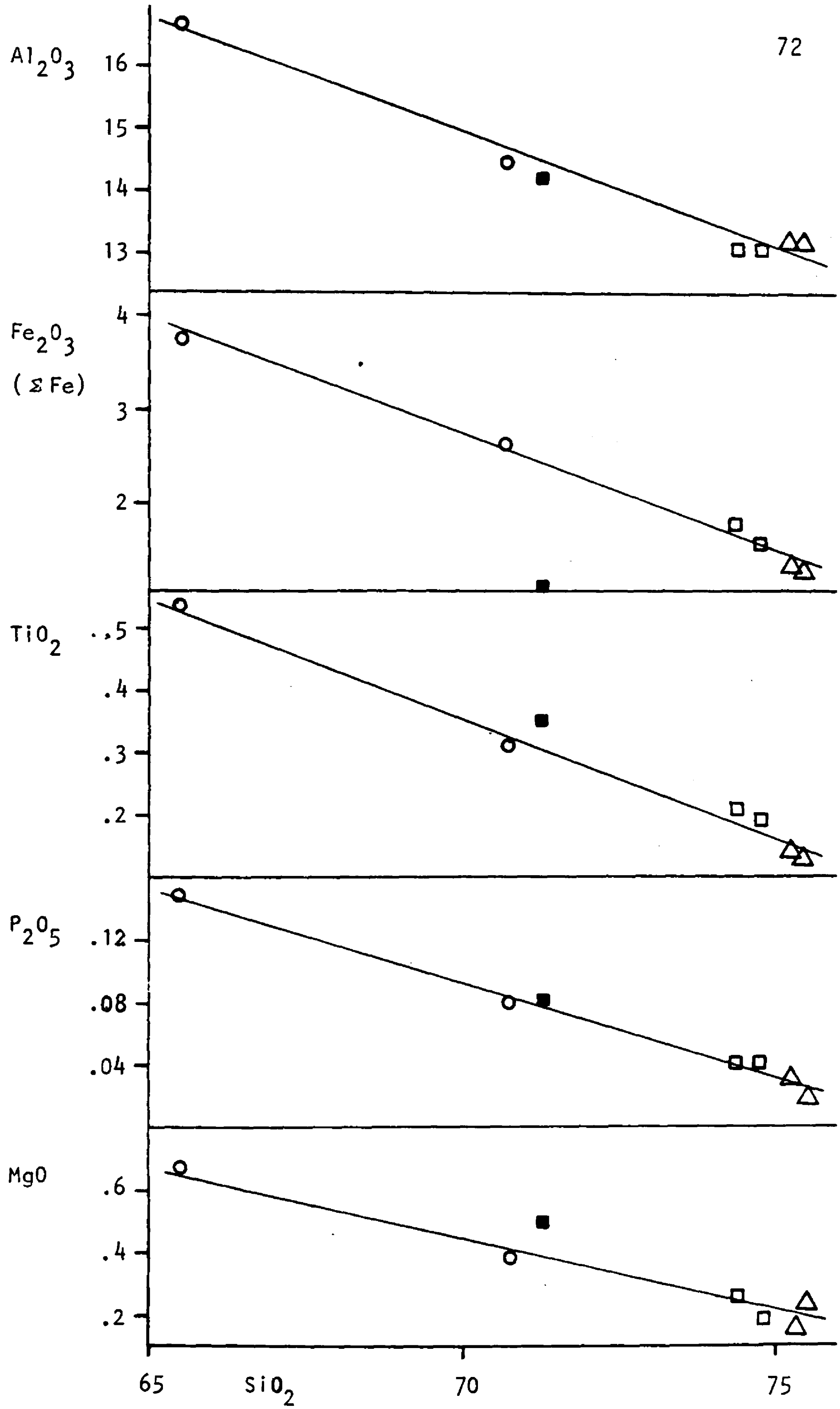
Figure 25. Variation diagram, weight percent oxide plotted against SiO_2. Values from table 9.

Lolo Hot Springs batholith: □

Hyndman sample of Lolo hot Springs batholith: ■

Ring dike "granite": ○

Kelly Creek tuff: △



Al_2O_3
16
15
14
13
Fe_2O_3
(Σ Fe)
4
3
2
TiO_2
.5
.4
.3
.2
P_2O_5
.12
.08
.04
MgO
.6
.4
.2
65
SiO_2
70
75

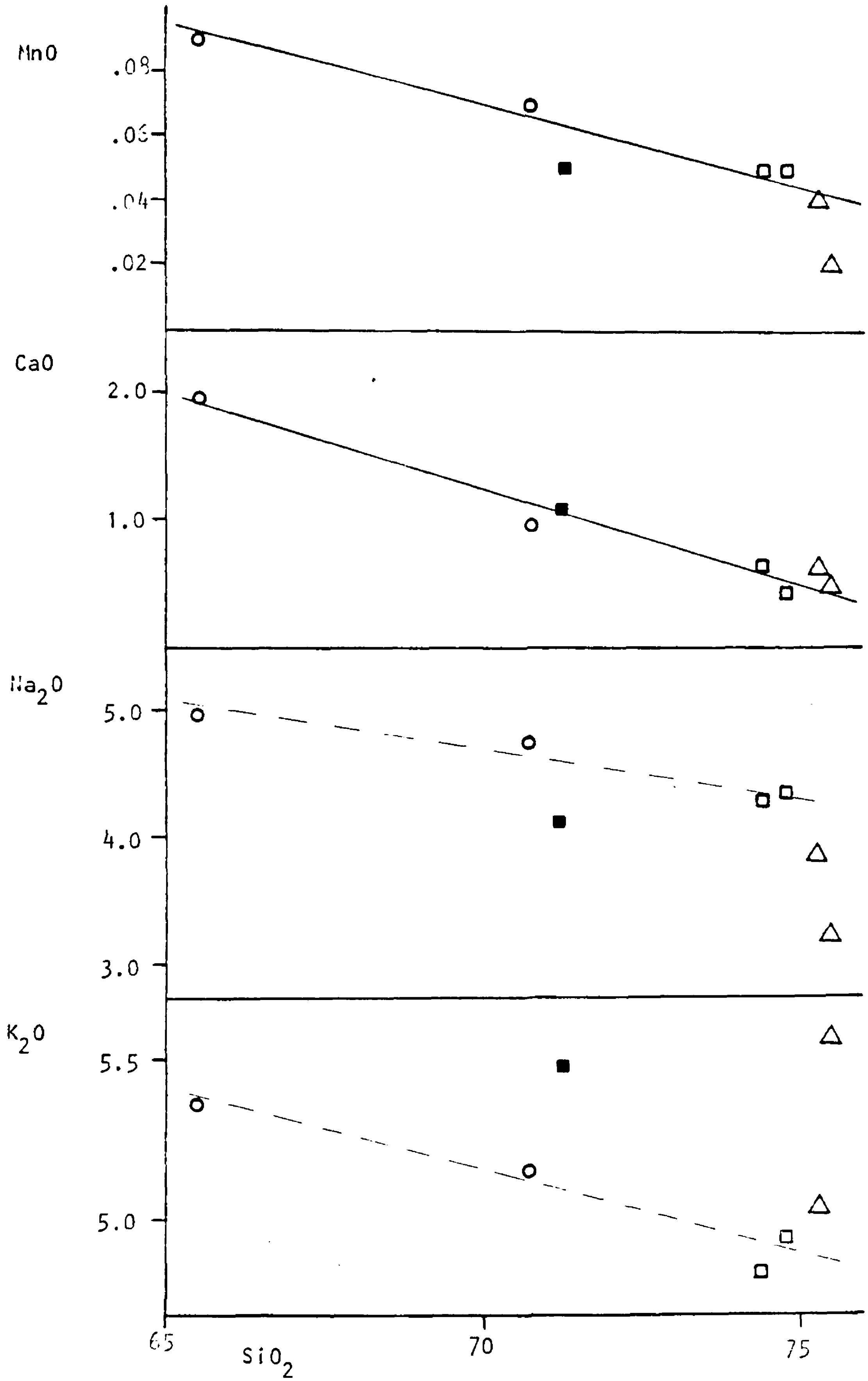


Figure 25, continued

curved or straight line provides the best fit for the data, and with such a small sampling here no such interpretation is attempted.

The plots of the oxides of titanium, phosphorus, calcium, aluminum, and magnesium all follow nearly linear trends. This is compatible with the idea that all have differentiated from a common parent magma. The plots of sodium and magnesium show fairly linear trends for the ring dike granite and Lolo granite samples collected for this study, but the tuffs and Hyndman sample of the Lolo granite plot well below these trends. In the case of sodium the deviation may well be due to hydrothermal alteration, since sodium is very easily transported by hydrothermal solutions (Meyer and Hemley, 1967). Mangenese depletion may also be due to leaching by hydrothermal solutions.

The plot of potassium oxide vs Silica is notable for its lack of a well defined trend, and the actual variation between samples is small. The scatter may be due to varying amounts of potassium metasomatism during hydrothermal alteration, or it may reflect compositional variations in the original magma. Most samples of igneous rocks in the area show some evidence of sericitization, especially in plagioclase, and this sericitization is most pronounced in the tuffs. The two samples of tuff show a fairly large difference in potassium content, and in thin section it is clear that sample LT-22, which has the higher potassium content, has undergone more extensive sericitization than samCle LT-37. Sample Lt-22 also shows the greatest depletion in sodium, and Lipman (1984) notes that this type of alkali exchange (extreme potassium enrichment and sodium depletion) is commonly associated with silicic ash-flow calderas.

The analysis of Lolo batholith granite reported in Hyndman (1983) shows several significant deviations from the trends established by the samples analysed for this investigation. The relative depletion in manganese and sodium and enrichment in potassium is similar to that noted in the tuffs, and this granite may have been subjected to a similar type of hydrothermal alteration. The marked deviation in the total iron is more difficult to account for and, together with the different silica content, indicates that the Lolo batholith is compositionally inhomogeneous. This inhomogeneity suggests that the batholith may have been formed by more than one influx of magma.

If the ash-flow tuff samples and the Hyndman sample of the Lolo granite are excluded, a negative correlation between potasium and silica is observed. Although the trend is expressed by only four data points, it is worth noting because this is contrary to the commonly observed sympathetic relationship between silica and potassium in granitic rocks. However, Hildreth (1979) has noted that in certain circumstances potassium is preferentially partitioned into the lower levels of some differentiating magma chambers, and such partitioning my be responsible for the observed relationship.

Except for the plots of elements which may have been affected by hydrothermal alteration and the total iron plot of the Lolo granite, the variation diagrams tend to show nearly linear trends. This is permissive evidence that the suite is comagmatic. It is interesting to note that on most of the plots the Lolo granite occupies an intermediate position on the trend between the ring dike granite and the Kelly Creek tuff. The suggestion is made below that the ring dike granite and the tuff may have evolved by differentiation of a magma similar in composition to the Lolo batholith.

CHAPTER IV

STRUCTURE AND FORMATION OF THE RHODES PEAK CAULDRON

Major Structural Features

The most striking structure in the Rhodes Peak cauldron is the ring dike of porphyritic granite that partially encircles the northern margin of the cauldron. This dike is 300-500 meters thick and appears to taper in the southeast and southwest limbs. Porphyritic granite similar to the ring dike occurs in a small dike west of Goat Lake, a small dike-like occurence 1 kilometer southwest of Shale Peak, and as fragments and grus in several fault zones that cut the intracauldron block. The presence of this rock type at such diverse locations suggests that porphyritic granite may underlie most of the intracauldron block south of the ring dike.

The southern contact of this dike is vertical or nearly vertical. The northern contact is not well exposed, but appears to dip steeply away from the cauldron. North of the ring dike the bedrock is Wallace Formation calcareous sediments, and to the south the bedrock is purple quartzite which resembles the Mt. Shields II Formation. This quartzite is overlain by porphyritic rhyolite tuff and other intracauldron volcanic rocks (Fig. 26), and the contact of the ring dike with both the quartzite and the intracauldron volcanic rocks is marked by a fine grained chill zone in the ring dike.

The intracauldron volcanic rocks have a maximum exposed thickness of 1 km just east of the junction of Williams Creek and the south fork of Kelly Creek. The base of the section is not exposed here and the actual thickness may be greater. 1 km is a minimum value for the thickness of the intracauldron pile and for the amount of subsidence within the cauldron, although the presence of windows of quartzite within the volcanic pile indicates a well developed topography on the pre-volcanic surface and consequent variable thickness of the volcanic pile.

Stratigraphic displacement of the Belt sediments can also be used to infer the amount of subsidence, although unknown structural complexities which existed prior to the cauldron collapse provide for much ambiguity. If the purple quartzite is in fact the Mt. Shields II Formation, then the entire Snowslip and Shepard Formations are missing from the stratigraphic sequence. If the Belt sediments were flat lying before subsidence, a vertical displacement of 1 km would be required to bring the lowermost Mt. Shields

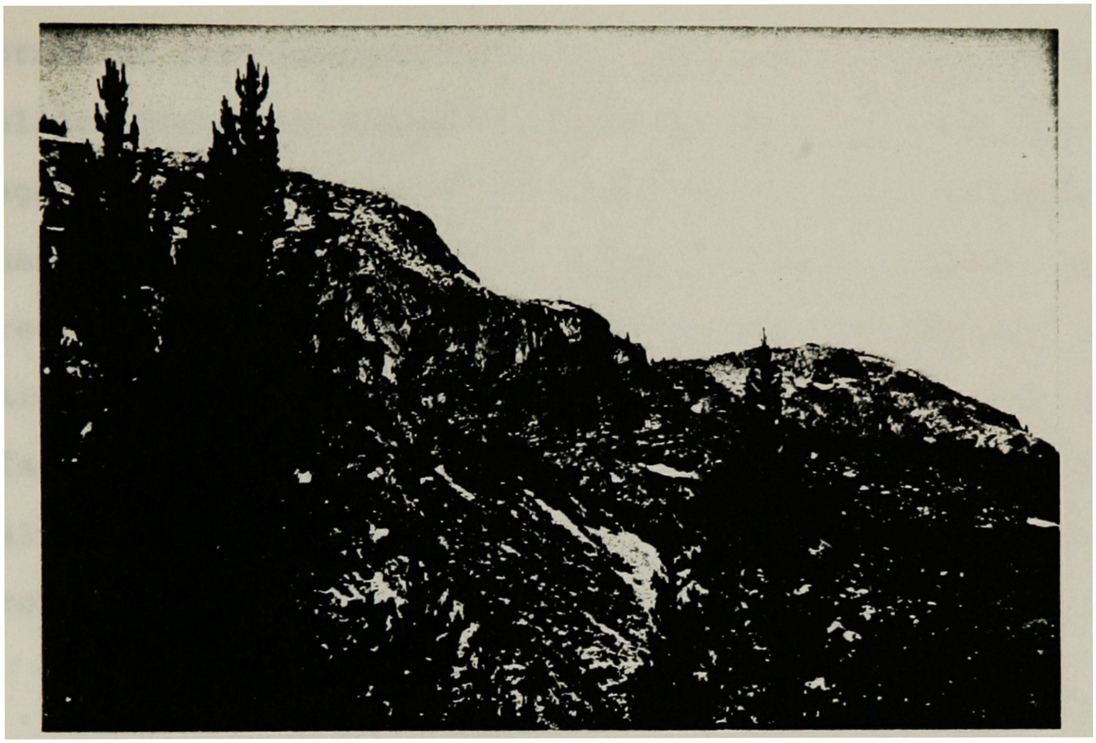


Figure 26. View looking west across upper Frog Creek valley showing volcanics overlying purple quartzite. Ring dike is about 1 1/2 km north of the right edge of the photograph.

Figure 27. Williams Peak area from a vantage point on Rhodes Peak. Basalt flows, volcaniclastic sediments, and tuff all dip steeply away from the batholith.

Formation into contact with the uppermost Wallace Formation. Wallace Formation sediments north of the ring dike dip 20-30 degrees to the north or northwest, and intracauldron quartzite commonly dips at steeper, more random angles. Precise stratigraphic positions within the Wallace and Mt Shields Formations were not determined, and the actual displacement could be much greater than the 1km minimum value. Cauldron subsidence in the Rhodes Peak cauldron can probably be reasonably estimated at between 1 and 2 km.

Interpretation. The presence of the ring dike on the north and its absence on the south (except for the small dike west of Goat lake) suggests that subsidence may have been assymetric. A "trap-door" type of movement may be indicated, with a hinge zone from Williams Peak to Doe Creek and the greatest subsidence occuring along a major fault in the area of the present ring dike. This hinge zone would have involved bending and possibly some normal faulting. The granite dike west of Goat Lake and the parallel normal fault 1km to the north probably formed in response to this bending.

One problem with this model is the lack of northeast dips in the intracauldron volcanic rocks. The few strikes and dips available on compaction foliation and bedding in volcanic sediments show southwest dips, away from the ring dike. It is possible that this is simply an effect of the small number of strikes and dips available in the predominantly massive intracauldron tuff, and that a greater number of data points would show that the major trend of the intracauldron block is a northeast dip with some small blocks having opposite orientations. Another possibility is that the intracauldron block was tilted during intrusion of the ring dike. In such a small cauldron any resurgent doming due to a buildup of magma pressure probably would have occurred along the ring fracture, tilting the intracauldron block and opening up the fracture zone to make room for emplacement of the ring dike.

Uneven cauldron subsidence is apparently common in calderas that erupt less than 50-1000 cubic kilometers of pyroclastic debris (Lipman, 1984). A very rough estimate of the amount of material ejected at Rhodes Peak is 120 cubic kilometers. This figure assumes an average thickness of 1 km for the intracauldron pile over the 60 square km of the subsided area. The amount of material inside the caldera is generally considered approximately equal to the volume of the extracaldera tuff (Lipman, 1984) and the initial figure is therefore doubled to account for this material. This is a minimum figure, since an unknown thickness of intracauldron volcanic rocks have been eroded from the area.

For a cauldron of this size, 1-2 km would be a maximum reasonable amount of subsidence, based on the findings at other calderas where subsidence is more easily calculated (Lipman,1984). With 2km of subsidence, a volume of 240 cubic kilometers would have been ejected.

Faulting

The intracauldron tuffs and underlying sediments and granodiorite are cut by a series of NE trending normal faults. These faults generally strike between N 10 E and N 40 E and are vertical or very steeply dipping. A considerable amount of vertical displacement is evident along some of these faults, but a precise determination of the displacement is impossible without a detailed knowledge of the stratigraphy of the intracauldron volcanic rocks. At least 100 meters of displacement is evident where the Frog Creek fault cuts through the ridge west of Shale Peak. At this location 100 meters of purple quartzite is exposed beneath the basal Rhyolite tuff on the west side of the fault, whereas on the east or downdropped side, rhyolite outcrops right down to the fault.

Some strike-slip motion may also be indicated where the Frog Creek fault crosses the ring dike. The southern contact of the ring dike appears nearly vertical along the valley wall, yet there is left-lateral offset across the fault. This apparent strike-slip offset could be produced by purely vertical motion if the ring dike contact dips steeply inward instead of being truly vertical.

Interpretation. Normal faults of similar orientation were noted by Nold (1968) along the northern contact of the Lolo Hot Springs Batholith. These faults produce left lateral offsets of the contact of up to a mile, but could not be traced into the poorly exposed interior of the batholith. Northeast trending Rhyolite dikes are also common in the area north of the batholith. As part of an undergraduate research paper (Simpson, 1983) I mapped a swarm of these dikes 10-15 km NNE of the study area. This dike swarm could be traced for 5-10 km along the trend of the Cache Creek valley and the western contact of the Lolo batholith. The dikes are composed of a porphyritic rhyolite with phenocrysts similar to those in the Tpg granite, but with a finer groundmass. This dike swarm and the western contact of the batholith may occupy a major fault zone which existed prior to the intrusion of the batholith. In the north this zone was intruded by rhyolitic magma, possibly during emplacement of the ring dike. Farther south this zone appears to have exerted strong structural control over emplacement of later intrusions. The ring dike makes a nearly right angle bend near Cache Creek and follows the trend of the zone for 3 km before it ends. The western contact of the Lolo batholith roughly follows this trend throughout the map area.

Northeast trending normal faults probably were formed before, during and after the development of the cauldron. Some faults, such as the Cache Creek fault, apparently existed before the emplacement of the ring dike and the Lolo batholith and exercised some structural control on their emplacement. Other faults cut the ring dike, batholith, and volcanic rocks and clearly post-date the igneous activity. These faults and dikes suggest a tensional environment during the emplacement of the granitoids and formation of the cauldron. This agrees with the findings of Luthy (1981), and Motzer (1985) in similar intrusions farther south and west.

Relationship Between Lolo Hot Springs Batholith and Rhodes Peak Cauldron

The Lolo Hot Springs batholith covers an area of about 250 square kilometers, mostly to the east of the study area. The western contact follows a north-northeast trend throughout the area and dips steeply northwest. The btholith contact zone is moderately well exposed in some localities, but it is not very helpful in revealing the relationship between the batholith and the cauldron. Where observed the purple quartzite forms a thin screen less than 30 meters thick between the batholith and the cauldon volcanic rocks and effectively obscures the relationship between them. The contact between quartzite and the batholith is clearly intrusive, with dikes of aplite criss-crossing the quartzite. The contact between the volcanic rocks and the quartzite is less clear, but the volcanics appear to conformably overly the quartzite. The quartzite within the screen shows extremely variable strikes and dips, and it appears to be broken up by numerous faults. Near Williams Peak compaction foliation of intracauldron volcanic rocks and bedding of volcanic sediments dip away from the batholith at angles of 40-50 degrees. These are the steepest dips recorded in the cauldron area; the dips become 10-15 degrees shallower 1/2 km west of the contact. The appearance from a vantage point on Rhodes Peak is that the tuffs and volcanic of Williams Peak have been tilted away from the batholith (Fig. 27).

In the area southeast of Shale Peak the batholith does contact the tuff, but in this region the batholith consists of fine aplite. The contact zone is characterized by dikes of aplite intruding the tuff and blocks of tuff suspended in aplite. The tuff is recrystallized near the contact and in thin section the rock appears to be mostly composed of a medium grained granoblastic intergrowth of quartz and feldspar with some phenocrysts of quartz, plagioclase and potassium feldspar.

The contact between the Lolo Hot Springs batholith and the ring dike is very poorly exposed and provides minimal information. The contact lies along the steep, thickly forested west slope of the Cache Creek valley where outcrop is virtually non-existent. At the base of the slope there are some good outcrops of Lolo granite, and on the upper slopes and ridgetops ring dike granite is well exposed. On a traverse up a boulder filled gully east of Leo Lake, individual boulders of ring dike granite and Lolo granite could be easily distinguished in the lower parts of the gully, but about 1/3 of the way up the slope the boulders of

Lolo granite disappear, leaving only ring dike granite boulders. Therefore, although the contact could not be directly observed, it is believed to be a fairly sharp contact and not a gradation of one granite type into the other.

Interpretation. Field relationships indicate that the Lolo Hot Springs batholith post-dates the volcanic rocks, intruding along a zone of weakness in the quartzite and tilting a thin layer of quartzite along with the overlying volcanics. The relationship between the batholith and the ring dike is less clear, since the contact zone is nowhere well exposed. It is tempting to speculate that the ring dike is a high level differentiated phase of the Lolo batholith and that the cauldron was formed during venting of the magma that formed the batholith. However, some factors of petrology and field relations argue against this scenario. Mineralogically the ring dike granite is richer in potassium feldspar and poorer in quartz than the Lolo batholith granite. It is difficult to conceive of a differentiated cap above a magma chamber that is lower in silicon than the main body of the chamber. A cap of this type should also contain a large proportion of volatiles and consequently possess miarolitic cavities and hydrous minerals. The ring dike has no miarolitic cavities and has a fairly large proportion of hornblende, which forms under less hydrous conditions than biotite.

The felsic aplite of Cache Creek possesses the expected characteristics of a differentiated cap (abundant quartz, miarolitic cavities, biotite) and even has a well exposed gradational contact with the coarser portion of the batholith. It is unlikely that two lithologies with such different characteristics could both be differentiates of the same magma. The presence of mafic inclusions in the ring dike but not in the batholith further serves to indicate that the two bodies formed from different magmas. These magmas may have originated as separate intrusions or they may have separated from the same magma at considerably different depths or through different processes.

The relative timing of the two intrusions is a difficult problem. Both of the granitoids intrude the intracauldron volcanic rocks and clearly post-date the eruption and cauldron collapse, but without a well exposed contact between the two any description of the temporal relationship between them remains speculative.

CHAPTER V

DISCUSSION

Summary of Major Events in the Evolution of the Rhodes Peak Cauldron

Igneous activity in the area of the Rhodes Peak cauldron probably began at about the same time as in the Challis area (approx. 50 million years ago; McIntyre, 1985), and as in the Challis volcanism the first magmas erupted were mafic to intermediate in composition. The only remnant of this early stage is the basalt flows which occur in the area of Williams Peak. Elsewhere in the study area rhyolite tuff rests directly on purple quartzite, where the basal contact is observed. Structural developments at this time probably included the formation of north-northeast trending normal faults, including the Cache Creek fault. The basalts of Williams Peak lie within a kilometer or two of the trend of the Cache Creek fault, and the basalts may have risen along the fault.

The next stage in the development of the area involved the eruption of the extensive rhyolite tuff of the Kelly Creek volcanic field. Rhyolite tuff eruption and cauldron subsidence in the Challis field occurred between 48.4 and 45

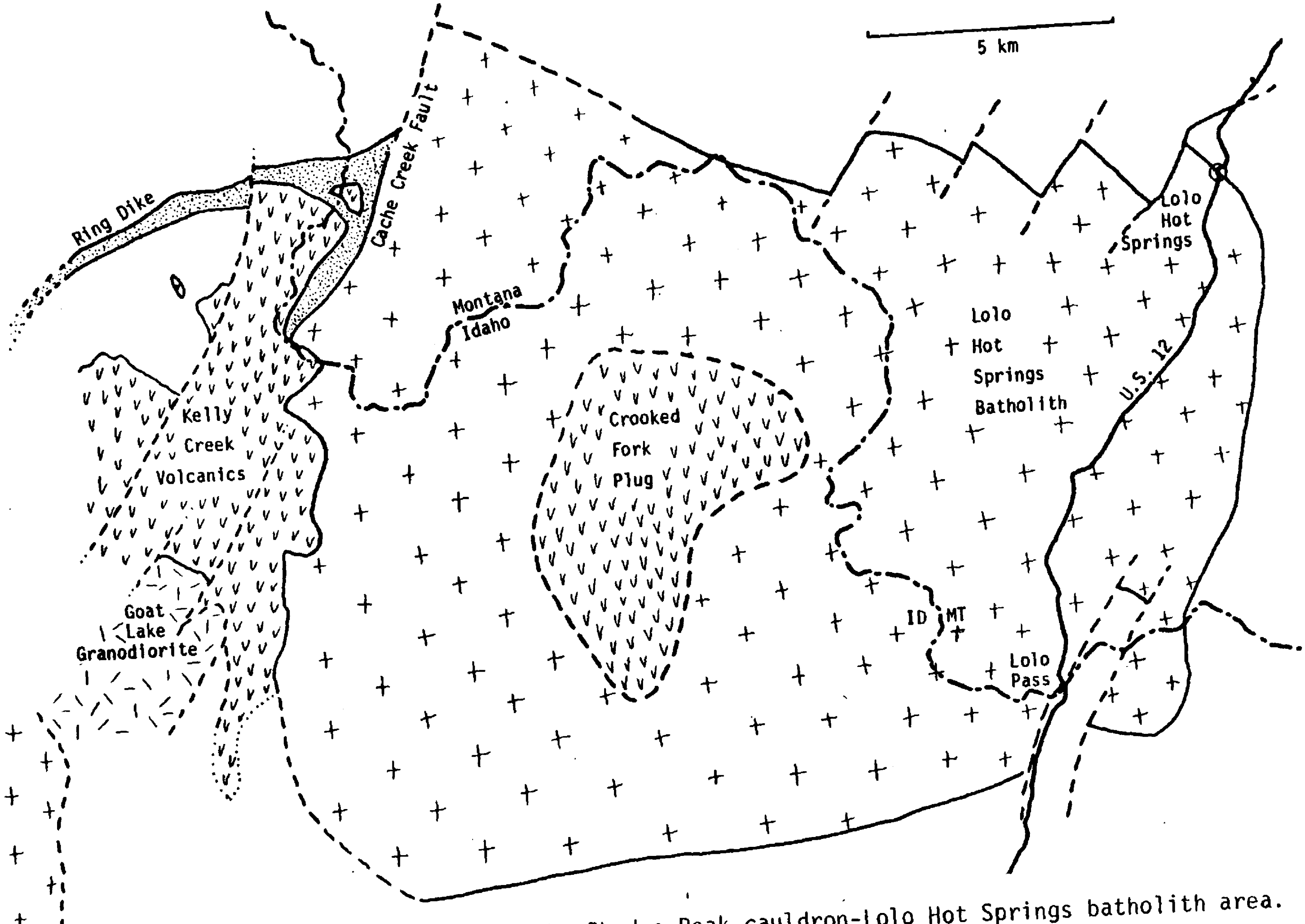


Figure 28. Generalized geologic map of the Rhodes Peak cauldron-Lolo Hot Springs batholith area.

M.Y. ago (McIntyre and others, 1984), and probably occurred at Rhodes Peak at about the same time or a little earlier. Two samples of rhyolite tuff from the Ninemile Creek area, about 50km NE of the study area, have been dated at 50.2 +/- 2.2 M.Y. and 49.3 +/- 2.0 M.Y. (J. Sears, pers. comm.). This tuff may be a distant portion of an ash flow from the Kelly Creek tuff or it may have come from an as yet undetermined source. In any case the mineral composition is similar to the Kelly Creek tuff and the dates suggest the time frame of rhyolite volcanism in the area.

The Kelly Creek tuff was probably erupted during several different episodes to create the 1000 meter thickness of the intracauldron pile. Subsidence during or shortly after the the eruption appears to have occurred in a trap door fashion, with one kilometer or more of subsidence along a ring fracture zone at the northern margin and along an adjacent part of the Cache Creek fault. This caused a northeast tilting of the intracauldron block and development of a hinge zone along the southwest margin.

Since andesite intrudes and overlies the tuff, intrusion of the andesite dikes and eruption of the flows clearly post-dates the Kelly Creek tuff. However, the timing if this event relative to the intrusion of the ring dike and Lolo batholith is poorly constrained. In the area southeast of Shale Peak a boulder was found which showed a small dike of andesite that is cut by a dike of Lolo batholith aplite. No evidence of timing relative to the intrusion of the ring dike has been found.

The northeast tilt of the intracauldron block was later reversed to a southwest dip when resurgent doming occurred along the ring fracture during emplacement of the ring dike. The area near Williams Peak was tilted to a northwest dip of 45-50 degrees, probably by the intrusion of the Lolo batholith. Field relations do not give much evidence as to which of these events occurred first, but it is possible to make some reasonable speculations. If the Lolo batholith had been intruded first, it seems likely that the magma would have invaded the zone of weakness formed by the ring fracture. The fact that this did not occur suggests that the ring fracture had already been intruded and sealed by the ring dike granite.

Low grade propylitic alteration of the tuffs and andesite probably was caused by circulating groundwater set in motion by the heat of the Lolo batholith or the magma chamber beneath the cauldron. Criss and Taylor (1978) have found that large areas near Eocene intrusions in the Atlanta lobe of the Idaho batholith are depleted in oxygen-18, presumably from the action of convective cells set up by the intrusions. The greatest oxygen-18 depletion is found in a ring shaped "moat" surrounding major intrusions such as the Sawtooth batholith. Criss and Taylor believe that this moat may mark the deeply eroded ring fracture zone of a major cauldron subsidence structure.

Magma Source and Tectonic Environment

Several ideas about tectonic processes that led to the Eocene plutonic-volcanic episode have been summarized in the introductory chapter of this report, and most of these have attempted to relate igneous activity to subduction. Because of the broad areal extent of the igneous activity, subduction models have shown many shortcomings in explaining the event. One piece of data that seems to have been overlooked in these models is the petrologic data on A-type granites that has recently been assembled and which provides some insight into the type of environment in which these magmas form.

A-type granites and alkali-rich volcanic caldera complexes appear to form as a final igneous episode in many cordillieran-type batholith belts. Petrologic and trace element data suggest that these magmas were produced by partial melting of depleted lower crustal rocks from which the magmas of the cordillieran batholith had previously been derived (Collins and others, 1982). These A-type magmas tend to be rich in alkalis, fluorine, and chlorine and low in water.

After the generation of "minimum melt" magmas, the lower crust below a cordillieran batholith like the Idaho batholith would probably consist of a granulite containing the assemblage quartz + plagioclase + potassium feldspar + orthopyroxene +/- clinopyroxene (Collins and others, 1982). This granulite would be near its liquidus temperature, and a relatively minor additional input of heat could lead to remelting and the production of A-type magmas (Pitcher, 1982). Alternatively, melting could be initiated by a decrease in load pressure due to crustal extension and thinning. Extension could also cause melting in the lower crust in a more indirect way, by triggering partial melting in the aesthenosphere that sends a flux of basaltic magma rising into the lower crust (Fig. 29). This basalt could pond at the base of the crust and provide the heat necessary for the production of a granitic magma from the depleted lower crustal rocks (Hildreth, 1981).

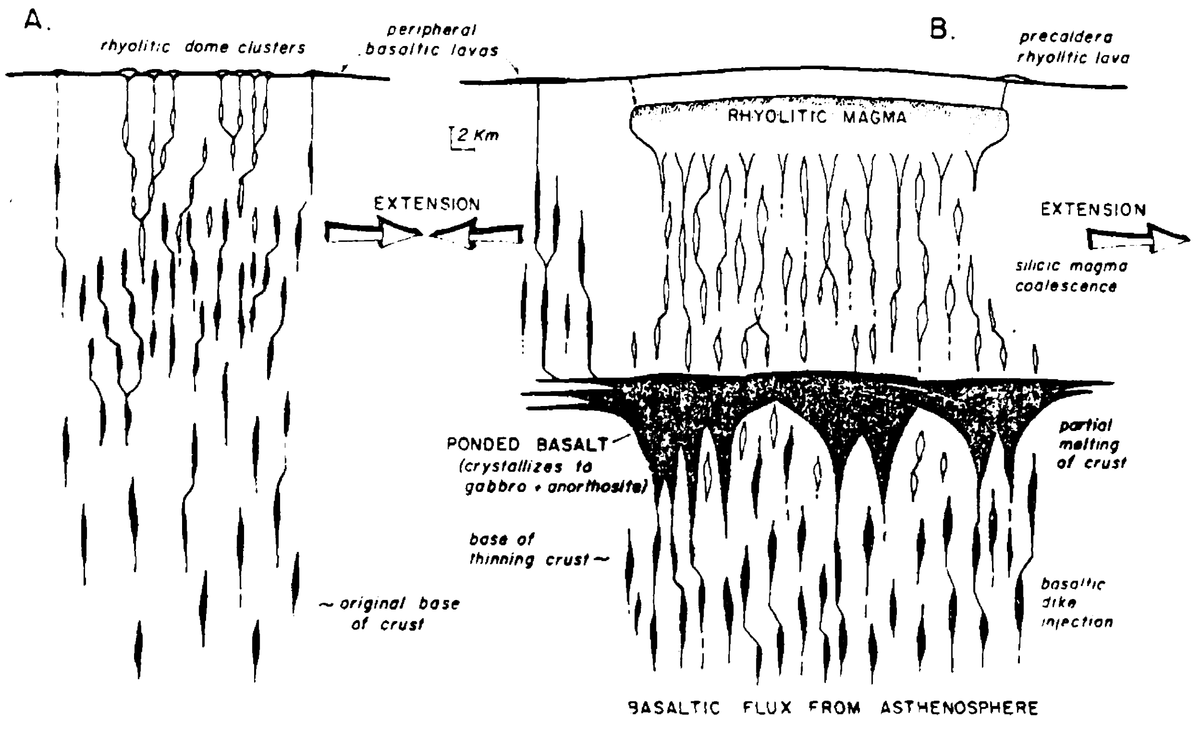


Figure 29. Model for magma generation in a tensional environment: (A) minor extension or early stage; (B) major extension, advanced stage (from Hildreth, 1981, p.10179). Figure B may be a realistic representation of processes occurring in the vicinity of the Rhodes Peak cauldron and the Lolo Hot Springs batholith during Eocene time. The magmas of the Rhodes Peak cauldron may have been an early phase of the magmatic cycle, containing a moderate amount of basaltic component in the form of mafic xenoliths and an overall slightly more mafic composition. At a later stage, when the magmas of the Lolo Hot Springs batholith were being produced, the large quantity of low density granitic melt prevented the denser basaltic magma from rising far into the zone of melting.

The "fundamentally basaltic view of magmatism" espoused by Hildreth can be used to provide a model for the development of the Rhodes Peak cauldron and Lolo batholith which accurately describes the observed features. One possible scenario is outlined below:

During extension and crustal thinning, basaltic magma intrudes the lower crust beneath the Idaho batholith and heats the rock, initiating partial melting. Some early magmas penetrate to the surface after fractionating and mixing with the crustal rocks to some degree, forming the basalt-like flows of the Williams Peak area. As a greater proportion of melt is produced in the lower crust the mafic magmas are prevented from rising through the less dense granitic melt and they pond at the base of the crust. When a sufficient portion of the lower crustal rocks have been melted the new felsic magma begins to rise, perhaps aided by the deep fractures generated by crustal thinning. The first magma to rise would probably contain a significant amount of unassimilated mafic magma derived from dikes that intruded the zone of melting before the presence of the developing magma chamber blocked their rise. This mafic material would probably be mechanically reduced during the rise of the magma to rounded blebs similar those found in the ring dike.

As the magma rises to a shallow depth it differentiates extensively through volatile transfer and thermo-gravitational diffusion, producing a volatile-rich cap zone. This cap then erupts to form the Kelly Creek tuffs and the roof of the chamber collapses to form the Rhodes Peak cauldron. At some later time an increase in magma pressure in the chamber, possibly due to the rise of additional magma, causes resurgent doming along the northeast margin and intrusion of the ring dike. Later, after the magma chamber has crystallized to a large extent, intermediate magmas are once again able to reach the surface, forming the andesite dikes and flows.

After the activity in the cauldron area ceases, another mass of similar magma is emplaced just to the east, tilting the cauldron rocks near the contact. While this magma is similar in composition to the magma of the Rhodes Peak cauldron, it has a slight difference in some critical variable, perhaps water content. With a very low volatile content in this second magma, exsolution of a vapor phase may not occur until the magma contains a large proportion of crystals. By this stage the magma would be too viscous to undergo any large scale volatile-driven differentiation, and what little vapor there was in the magma would be trapped in the crystallizing magma in the form of miarolitic cavities.

The scenario outlined above is only one of several that could be devised using various models of magma generation. It is provided here as a plausible explanation which is compatible with availible data. It should be noted that some of the chronologic relationships used in the scenario, such as the relationship between the Lolo batholith and the ring dike, are based on very scanty data. However, such speculation may provide tests that lead to a clearer understanding.

Summary

This study has identified and described a major volcanic cauldron of probable Eocene age in an area where none had previously been noted. Ash erupted from this cauldron at one time probable covered much of the surrounding area, but erosion has almost completely removed the outflow tuff sheet. A few erosional remnants in the Clark Fork Valley near Alberton and Ninemile, and perhaps a few ridgetop exposures west of the cauldron in Idaho, are all that remain outside of the cauldron.

The Rhodes Peak cauldron appears to have undergone a pattern of development similar to that of the Challis field farther south. This pattern involves the early eruption of mafic to intermediate lavas followed by the eruption of major rhyolite ash flows and associated caldera collapse. Later intrusion of felsic magmas occurs within the ring fracture, probably during caldera resurgence. In the Rhodes Peak cauldron this formed a ring dike of syenogranite or quartz-syenite composition, whereas in the Twin Peaks caldera of the Challis field numerous rhyolite dikes and latite intrusions occur within the ring fracture zone (McIntyre and others, 1985). In both the Challis field and the Rhodes Peak cauldron a major intrusion of A-type granite has intruded and tilted the volcanic cover. This appears to have been the last major event of the Eocene igneous episode in both areas.

Within the study area volcanic rocks of probable Eocene age are exposed in close proximity to intrusive granitoids of the same time period. Although some contact relations are obscure, this is a good locality for study of the relationship between an Eocene volcanic center and its related granitic intrusions. Further investigation of this area may give valuable insight into the processes and controls of Eocene plutonism and volcanism.

Some areas that this study has only touched upon and which would make good subjects for further study include: 1) A detailed investigation of the stratigraphy of the intracauldron volcanic pile. Although the pervasive alteration may make such a study difficult, there are some excellent, nearly continuous exposures of sections through the volcanic pile. One of the best localities is the hill just east of the junction of Williams Creek and the South Fork of Kelly Creek. 2) A continuation of mapping to the south and west to complete the map of the cauldron. Outcrop to the west is not nearly as good as in the study area and such a study may prove difficult. 3) A detailed investigation of the petrologic and genetic relationship between the Lolo batholith and the ring dike based on numerous major element and trace element chemical analyses.

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