AN ABSTRACT OF THE THESIS OF SCOTT STEVENS HUGHES for the degree of DOCTOR OF PHILOSOPHY in GEOLOGY presented on December 8, 1982 PETROCHEMICAL EVOLUTION OF HIGH CASCADE VOLCANIC Title: ROCKS IN THE THREE SISTERS REGION, OREGON Redacted for Privacy Abstract approved: Edward M. Taylor

Multi-element abundances and petrographic data are compiled for a suite of 50 volcanic rocks and selected mineral separates located within the Three Sisters area. Major element oxides, obtained by x-ray fluorescence and atomic absorption spectrophotometry, and trace element concentrations, obtained by sequential instrumental neutron activation analyses, enable classifications of normal basalts, divergent basalts, Mount Washington (MW) and North Sister (NS) type basaltic andesites, dacites and rhyodacites. Petrochemical types and geochemical models are evaluated in light of field studies (E.M. Taylor, Oregon State University), regional geologic environment and comparisons with similar systems.

High-alumina olivine tholeiites exhibit low Fe' values and fractionated abundances of K, Ba, Sr, REE and Sc which produce nonchondritic monotonic patterns relative to ionic radii. Primary basalts are modeled as 14% melts, with minor olivine crystallization, from a LIL element-enriched spinel lherzolite source. Divergent basalts represent contaminated magmas or different sources. Basaltic andesites having up to ${\sim}62$ wt.% SiO $_2$ also exhibit low Fe' and fractionated monotonic trace element patterns and are modeled as 10% primary melts from similar source regions. Basalts and basaltic andesites contain source-equilibrated olivine and plagioclase phenocrysts attesting to their primary origin. One andesite sample (SiO₂ = 58.6 wt.%) is derived by significant fractionation of a basalt parent and represents a low-SiO $_2$ and high-TiO $_2$ member of an early Pleistocene silicic system. Dacites and rhyodacites

(SiO₂ = 62.2-75.8 wt.%) have strongly fractionated non-monotonic trace element patterns and are derived by extensive (>60%) fractionation from primary NS basaltic andesite magmas. A petrochemical hiatus is recognized between mafic and silicic compositions.

A comprehensive model of High Cascades volcanic evolution is presented which incorporates a series of events in a subduction zone-mantle-crust system: Hydrous fluids, expelled from a dehydrating subducted slab, become enriched in incompatible elements through processes of liquid extraction and small amounts of partial melting. These fluids ascend through the overlying mantle wedge contaminating and catalyzing mafic melts which accumulate and fractionate in upper mantle and lower crust regions. Mafic magmas erupt as near-primary liquids or are intruded into upper crust regions where extensive fractionation produces siliceous dacites and rhyodacites. The magmatic events are conceptualized as vertical sequences of basalt-basaltic andesite-dacite-rhyodacite magmas produced in response to the advancing front of hydrous fluids and erupted during tensional readjustments of a thermally weakened crust.

PETROCHEMICAL EVOLUTION OF HIGH CASCADE VOLCANIC ROCKS IN THE THREE SISTERS REGION, OREGON

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Scott Stevens Hughes

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Redacted for Privacy

Associate Professor of Geology in Charge of Major

Redacted for Privacy

Head of Department of Geology

Redacted for Privacy

Dean of Graduate School

Date Thesis Presented December & 1982

Thesis Typed by Donna Lee Norvell-Race for Scott S. Hughes

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PETROCHEMICAL EVOLUTION OF HIGH CASCADE VOLCANIC ROCKS IN THE THREE SISTERS REGION, OREGON

1. INTRODUCTION

1.1 Physiography and Geologic Setting

Volcanoes of the High Cascade Range comprise a system of diverse topographic and compositional features which extends from Mt. Garibaldi in British Columbia to Mt. Lassen in northern California. The High Cascade Range, which is bordered on the west by predominantly Miocene-Pliocene Western Cascades volcanic and intrusive rocks and on the east by Miocene Columbia River Basalt, Deschutes Formation and Basin-Range volcanic rocks (Fig. 1-1), represents the latest Plio-Pleistocene to Holocene volcanism within the Cordillera of western North America.

Impressive snow-capped, glaciated composite volcanoes, of which Mt. Rainier at 4392 meters is the tallest, are separated by volumetrically greater mafic shield volcanoes, cinder cones, lava flows and subordinate composite cones. The most recent activity within the range is represented by the dacitic ash eruptions and subsequent dome emplacements of Mount St. Helens which commenced in the Spring of 1980. The High Cascades volcanic system, as well as earlier volcanism in the western U.S., is widely recognized as being one of many orogenic volcanic systems characterized by calc-alkaline series rocks in association with subduction zones along the Pacific margins.

Volcanism during the Neogene of the Pacific Northwest predominantly occurred during two major episodes, the middle Miocene Columbian (16 to 14 m.y. ago) and the Pleistocene Cascadian (~ 2 m.y. ago to the present), and less important intermittent periods occurring roughly at 5 m.y. intervals (McBirney et al., 1974; Kennett et al., 1977). The circum-Pacific study by Kennett et al. (1977) also indicates that synchronous episodes of Ceneozoic orogenic volcanism are subject to global rather than



Figure 1-1 Generalized map showing extent of High Cascades system (adapted from McBirney, 1969a) and location of study area.

regional tectonic control and possibly represent amplified responses to changes in rates of sea-floor spreading and subduction.

A compilation of data from numerous sources by Armstrong (1978) has shown that widespread quiescence prevailed between about 38 and 18 m.y. ago until the sudden commencement of large outpourings of Columbia River Basalt along with the initiation of bimodal volcanism (basalt/rhyolite) in southwestern Idaho and throughout all of southeastern Oregon. During the period 13 m.y. to recent, siliceous calc-alkaline volcanic centers in Oregon retreated back to the Cascade system, while bimodal volcanism migrated eastward with the evolution of the Snake River Plain and Yellowstone systems (MacLeod et al., 1976). Volumetric approximations of selected areas in the Cascade region were correlated to overall chemical variations by White and McBirney (1978) and indicate that while total volumes probably decreased, the basaltic proportion increased in volcanic products erupted since late Oligocene time.

Pleistocene High Cascade volcanism was apparently initiated during subsidence along the earlier Cascades crest in response to a late Pliocene crustal readjustment. Taylor (1978, 1980, 1981) recognizes a north-south fault system that was probably activated 4 to 5 m.y. ago and resulted in extensive (1000 meters or more) downward displacement of the eastern part of the Western Cascades in latest Miocene to early Pliocene time. The subsidence occurred in a 30- to 40-km-wide graben possibly ranging from Mt. Adams to Crater Lake (although time-space continuity may be lacking) and is exemplified by numerous fracture systems, in the form of north-south vent alignments, which provided channelways for later magma migration. Graben development in the Oregon central High Cascades is consistent with stratigraphy and ages contrasted with older units to either side (Taylor, 1980; Armstrong et al., 1975) and obvious topographic

features such as the imposing trend of Green Ridge which marks the eastern fault boundary of the Pleistocene-Holocene units. Early High Cascade volcanism in the Three Sisters region is typified by broad flows of diktytaxitic basalt and construction of shield volcanoes within the north-south graben comprising a mafic platform upon which silicic centers have emerged.

Geologic mapping of the east flank of the Three Sisters system (Taylor, 1973) provides evidence that voluminous volcaniclastic material was ejected on the eastern slope beginning 12 m.y. ago, but the activity terminated approximately 4-5 m.y. ago (Taylor, 1978; Armstrong et al., 1975). Termination of explosive Pliocene volcanic activity probably correlates with the initiation of the late-Pliocene subsidence and may indicate the period of change in tectonic stress regime. The actual age of initial graben development was estimated at 2.5 to 3.5 m.y. by Taylor (1978), but recently has been updated to \sim 3.8 m.y. (E. M. Taylor, pers. comm.).

Early Pleistocene basaltic lavas on the western margin of the mafic platform have ages of 2.0 and 2.5 m.y. (Armstrong et al., 1975) and basaltic volcanism has recurred through Holocene time in the Three Sisters region. However, early Pleistocene dactic volcanism ensued in the areas east of South Sister (Taylor, 1978) as a broad silicic highland of domes, lava flows and ash-flow tuffs developed on the east edge of the predominantly mafic High Cascade system. The silicic highland, interrupted and largely covered by extensive mafic volcanism, is primarily represented by summit areas of silicic domes at higher elevations and silicic lavas exposed in marginal glaciated canyons. Late Pleistocene to Holocene activity is characterized by continued development of mafic shield volcanoes (e.g., Belknap Crater), emergence of large basaltic andesite composite cones (Mount Washington, North Sister, Broken Top), numerous

brief eruptions of smaller cinder cones (Yapoah Cone, Nash Crater, Sims Butte) and emplacement of dacite and rhyodacite domes, flows and pyroclastic deposits (Rock Mesa, South Sister dome chain, Obsidian Cliffs) (Williams, 1944; Taylor, 1980; Wozniak, 1982). Total relief within the Three Sisters area is approximately 2700 meters exemplified by South Sister volcano at 3157 meters contrasted to the lowest dissected areas of the mafic platform near McKenzie Bridge (Fig. 1-2).

1.2 Concepts of Calc-Alkaline Systems

While the association of calc-alkaline volcanism, especially andesite, with orogenic systems is generally accepted, speculations on magma genesis and petrologic evolution have been diverse. Prior to the advent of global tectonics theory, continental margin/island-arc volcanism was correlated with eugeosynclinal models (e.g., Tilley, 1950) in explanation of the orogenic features. More recently (Isacks et al., 1968; Hamilton, 1969) the association of calc-alkaline magmas with subduction zones has developed into a well-tested, acceptable theory, but not without profusive digressions concerning the discrepancies of magma genesis. The details of magma production and evolution in the vicinity of subduction zones and the structural development of adjacent orogenic provinces have emerged as the major contestible topics of recent studies on andesite volcanism.

It is well-documented that "andesite" comprises the overall bulk composition of many calc-alkaline suites, but compositions ranging from basaltic to rhyolitic occur in substantial proportions (Kuno, 1966, 1968; McBirney, 1969b; S.R. Taylor, 1969; Dickinson, 1968; Dickinson and Hatherton, 1967). Basaltic magmas which typically occur in the early stages of island-arc or continental margin development, are predominantly high-

alumina tholeiites. These magmas generally yield to more silicic compositions with time, but recurrence of mafic products throughout eruptive sequences is possible.

The recognition of the basalt-andesite-dacite-rhyolite rock series by Bowen (1928), which exhibits little iron enrichment with differentiation, was contrasted by Fenner (1929) arguing the possibilities of iron enrichment without substantial increase Delineation of subalkaline rock series in island arcs in silica. was later detailed by several authors (e.g., Kuno, 1959; Jakes and Gill, 1970; Jakes and White, 1972). Miyashiro (1974) further outlined the differences between the calc-alkaline (CA) and tholeiitic (TH) differentiation series which are best illustrated on an MgO-FeO*-Na₂O + K_2O (AFM) ternary diagram. It is also suggested (Miyashiro, 1974) that the ratio of CA series rocks to TH series rocks, in any particular system, increases with crustal thickness and/or development of continental crust in island arcs although definite temporal relations between eruptive sequences and CA vs. TH series are not necessarily apparent.

While orogenic suites of both island arcs and continental margins have been traditionally labelled "calc-alkaline" chemical (and petrographic) distinctions are evident between the island-arc tholeiitic series and the continental calc-alkaline series (Jakes and Gill, 1970; Jakes and White, 1972). Volcanic rocks in arcs typically have chondritic rare earth element (REE) patterns, a moderate iron enrichment trend and low abundances of K_20 and similar large ions. In contrast, continental calc-alkaline rocks exhibit fractionated REE patterns with light REE (LREE) enrichment, a lack of iron enrichment and higher total large-ion lithophile (LIL) element abundances with increases in SiO₂ content. The chemical variations between these two related systems are essentially gradational and their boundaries are arbitrary, but overall systematic changes with space and time are apparent

(Jakes and White, 1972). Green (1980) summarizes the concepts of island-arc and continental margin rock series to include the K-rich series and acknowledges a continuum between tholeiitic, calc-alkaline and alkaline suites. His list of major chemical features of convergent-plate volcanism includes, in addition to those mentioned above, low TiO_2 (less than 1.2% in mafic rocks to less than 0.3% in silicic units), a predominance of basaltic andesite (53% SiO_2) in the island-arc series and a predominance of andesite (60% SiO_2) in the calc-alkaline series.

Structural development and growth of continental margins is largely associated with orogenic andesite volcanism, the chemistry of which resembles the crustal average (Taylor and White, 1965). Orogenic systems having comparable growth stages or histories possibly exhibit similar chemical evolutions and petrologic features. For example, the Cascades system is somewhat comparable to the Andean system with respect to plate convergence rates, crustal thickness (Miyashiro, 1974) and structural development (Fyfe and McBirney, 1975) although specific details of these features are subject to reinterpretation.

In addition, Andean seismic studies (Baranzangi and Isacks, 1976; Thorpe and Francis, 1979) indicate variable crustal thicknesses and depths to the Benioff Zone. The northern (Columbia and Ecuador) and southern (southern Chile) zones have crustal thicknesses of 30-45 km, whereas the central (southern Peru and northern Chile) zone has up to a 70 km crustal thickness. The northern and central systems occur approximately 140 km above the Benioff Zone while the southern Benioff Zone has a 90 km depth. Intermontane depressions (grabens) parallel to the trench axis also exist throughout the Andean province (Goosens, 1972; Williams and McBirney, 1979, p. 294, after Gerth, 1955) into which later volcanics and continental sediments have been deposited. Gravity and seismic studies in the Pacific Northwest

(Braman, 1981; Johnson and Couch, 1970, respectively) imply a crustal thickness of 30-40 km beneath the Cascades, which may allow for comparison to the Andean northern and/or southern zones.

The apparent physiographic and structural similarities between the Cascade and Andean provinces provide evidence for the presence of a subduction zone beneath the Cascades, although existence of active convergent plate motion is questionable due to the lack of a distinct Benioff Zone of earthquakes. However, composition and structural setting of volcanism throughout Cenozoic time, compared to the better-known active systems, implies a subduction mechanism at least during the production of calc-alkaline magmas (McBirney, 1978; Fyfe and McBirney, 1975; Armstrong, 1978). Plate motion studies by Atwater (1970) indicate the possible existence of a presently active subduction zone with the paucity of conclusive seismicity being consistent with a slow rate of convergence and a young (not very thick or cool) downgoing plate.

Compositional variations within Andean volcanics (Thorpe and Francis, 1979) suggest reasonable correlations of geochemistry and eruptive styles with geophysical parameters. It might be speculated that geochemical characteristics are also comparable between the Cascades and Andean systems for those regions with similar physiography. Although specific comparisons as such are beyond the scope of this study, it is interesting to note the variability of processes within the "type-section" of andesites. Subsequent sections on geochemical modeling refer to some of the detailed studies of the Andean system in order to make petrogenetic comparisons.

1.3 Calc-alkaline Magma Genesis

Magma generation in calc-alkaline settings has been subject

to speculation and experimental investigation by many workers (e.g., Green and Ringwood, 1968; Nicholls and Ringwood, 1973; Wyllie, 1971a; Dickinson, 1970; and many others). Comprehensive treatment of various models of magma evolution (Boettcher, 1973) preclude, on the basis of isotopic compositions and geologic setting, the production of most andesitic liquids by crustal anatexis or contamination of basaltic magma. A widely accepted model is reviewed by Ringwood (1975), such that calc-alkaline magmas are products of low-density segregations of bodies within the mantle wedge which have been modified by fluids rising from an oceanic slab. Actual magma separation takes place at some stage during diapiric ascent with possible subsequent differentiation. The influence of volatiles in calc-alkaline magmatism (Wyllie, 1971b, 1977) seems widely admitted and necessarily requires introduction of fluids into the source regions or at some intermediate stage of magma evolution. Although constraints for High Cascade magma evolution are necessarily unique to the province, underlying reasons for the many hypotheses should be outlined.

Efforts in experimental petrology (Yoder and Tilley, 1962; D. Green and Ringwood, 1967; T. Green and Ringwood, 1968; O'Hara, 1965) have increased the understanding of phase transitions and liquidus phases in natural compositions at elevated pressures. Coexisting liquid and solid phases in equilibrium will have essentially consistent chemical compositions regardless of solid/ liquid proportions. Ringwood (1975) states that liquidus phases present in natural compositions and at higher pressures will represent the mineralogy of the melting source that is in equilibrium with liquid under the same conditions.

In order to meet the requirements of experimental petrologists and calc-alkaline rock characteristics several detailed models of andesite magma genesis have been proposed. Osborn (1969)

suggests that the interaction of high-alumina basalt magma with connate water in geosynclinal sediments causes the water to become dissociated. With oxidation, magnetite is free to precipitate along with other phases as hydrogen escapes into the surroundings. An iron enrichment trend is prohibited and the cumulate products of fractional crystallization comprise complementary alpine peridotite terrains. Many objections have countered this hypothesis, but one of the most augmentive is that of Taylor et al. (1969a) who argue that ferromagnesian trace elements (Ni, Co, V, Sc, Cr) are too high in andesites to allow for significant magnetite fractionation.

Amphibole fractionation can also be invoked as a means of andesite production and notably occurs in some provinces. At elevated water pressures, the field of amphibole crystallization is expanded while the field for plagioclase is diminished in basaltic liquids (Yoder and Tilley, 1962). As a mechanism of generating andesite magma, $low-SiO_2$ amphibole is known to exist at temperatures close to the H20-saturated liquidus in the 12 to 20 kbar range and is probably limited to depths less than 100 km (Boettcher, 1973; Ringwood, 1974). A comprehensive study by Cawthorn and O'Hara (1976) confirms earlier suggestions that the petrologic features and bulk chemistry of andesites are retained during hornblende crystallization from a hydrous basaltic magma. It should also be pointed out that amphibole-controlled fractionation is also synonymous with melting of an amphibolite source under proper conditions which yield andesitic magmas (Ringwood, 1975).

Petrochemical studies during the last two decades have indicated that primary andesite or calc-alkaline magmas may be generated by partial melting of an eclogite (Green and Ringwood, 1968) or wet peridotite (O'Hara, 1965; Yoder, 1969) source. Gill (1974), however, demonstrates that fractionation effects of garnet in an

eclogite source produces REE patterns inconsistent with some calc-alkaline rocks. Recent isotopic and trace element studies in Andean systems have shown that andesitic magmas are probably not single stage melting products of any primary source. Models of calc-alkaline magma genesis include: fractional crystallization of primary mantle melt (Déruelle, 1978; Lopez-Escobar et al., 1977; Thorpe et al., 1979), anatexis of LIL element-enriched upper mantle regions (Dostal et al., 1977a, 1977b), partial fusion of lower or upper crust (Pichler and Zeil, 1972) and mixing of primary basaltic magma with young crustal material (Klerkx et al., 1977).

Perhaps one of the most elaborate conceptual models is that developed and reviewed by Ringwood (1975). Accordingly, subducted oceanic crust, as amphibolite which contains serpentinite bodies, transforms to quartz eclogite and partially melts in the depth range of 100 to 150 km leaving a bi-mineralic refractory residuum. The silica-rich liquids interact with overlying mantle to produce pyroxenite diapirs which, upon ascent, partially melt and segregate "primary" magma at various levels in the mantle wedge. Upon magma segregation, fractionation is depth-controlled (70 to 100 km, garnet and pyroxene; 40 to 70 km, amphibole, pyroxene and olivine; less than 40 km, pyroxene and plagioclase) to produce a wide range of liquids within the calc-alkaline trend.

Any of the foregoing mechanisms may be operative in a situation that depends on geologic history, crustal thickness, plate convergence rate, dip of Benioff Zone and numerous other variables. Thorpe and Francis (1979) have effectively characterized the problem with their comment: "Andean andesite magmas are a result of a complex interplay of partial melting, fractional crystallization and 'contamination' processes at mantle depths, and contamination and fractional crystallization in the crust." Details of these interacting parameters are, in many cases, approximations

based on failure of existing models to explain petrologic data. Multi-stage schemes are effective when data are consistent, but the need to evaluate a system on the basis of chemical data supported by extensive field and petrographic work is apparent (Gill, 1978).

It is also apparent that, while systematic variations probably occur, a unifying feature is the role of volatiles, water in particular, in the production of calc-alkaline and island arc magmas. Retention of water in the downgoing slab provides a viable mechanism for the introduction of volatiles into mantle source regions. In addition to H_20 , fluids that enrich peridotite source rocks may also contain the constituents that are responsible for distinctive calc-alkaline geochemistries (Wyllie, 1979). Reviews of this mechanism by Wyllie (1977), Anderson et al. (1978) and Fyfe and McBirney (1975) indicate that water is initially contained in pore spaces of sediments and basaltic crust and as structurally bound water in hydrous minerals, although retention ability varies widely. Specifically, fluids entrapped by pore spaces will be expelled or forced to enter hydrating phases during transformation of the oceanic crust with increasing pressure. Metamorphism of wet basaltic crust to amphibolite (Yoder and Tilley, 1962) with other hydrous phases will extend the depth of water retention to depths within the mantle.

As pointed out by Wyllie (1973) muscovite, amphibole, serpentine and talc cannot exist at depths much greater than 100 km, but the presence of phlogopite, especially within the cooler interior of a crustal slab, allows retention of water to depths of 250 to 350 km. This variable retention mechanism not only accounts for introduction of volatiles into deeper mantle source regions, but may also explain increases in K_20 abundances with distances inland from continental margins due to delayed

breakdown of K-rich phases until greater depths are achieved (Dickinson and Hatherton, 1967; Thorpe and Francis, 1979).

1.4 Research Objectives

The relatively continuous volcanism of the earlier Miocene to Pliocene Western Cascade system was dominantly andesitic lavas and ash-flow tuffs (Peck et al., 1964). The High Cascade Pleistocene-Holocene system should reflect this prehistory of calc-alkaline volcanism, although the general preponderance of Pleistocene to Holocene basaltic lavas indicates divergent mechanisms of magma production and evolution. The hiatus between earlier Western Cascade eruptions and later High Cascade eruptions offers unique volcanological problems which can be solved only through the understanding of magma evolution since the inception of Pleistocene activity. Attention of this study is directed toward a region in the Oregon central High Cascades, known as the Three Sisters area, in order to gain further knowledge of this latest Pleistocene to recent system and possibly provide impetus for future studies of similar systems.

Assuming that many processes may be operative in a particular system, delineation of magmatic evolution in the central High Cascades is not warranted by a singular approach. Sampling and analytical programs may be extensive and provide overall mechanisms, but may also fail to account for local irregularities. Too often geochemists attempt an explanation based on random sampling with the assumption of consistency within and between their systems of study.

Complete knowledge of the petrochemical evolution of High Cascade volcanic products, or products of any system, would require exhaustive field, petrographic and chemical work on every unit. The impracticality of such a project is evident, but the

approach has obvious merit. To optimize regional petrologic knowledge through analytical studies, prior research on age relations, structural and physiographic features and eruptive events is essential. Geochemical sampling should be directed toward those units which represent the system as a whole, yet include anomalous members which can provide information on atypical processes that might otherwise be mistaken for normal.

Extensive field and major-element studies by E. M. Taylor (pers. comm.) have lead to a reasonable understanding of the volcanology in the central High Cascade region. This research must now incorporate more detailed assessment of petrologic and trace-element characteristics in order to derive the magmatic histories of units comparable by field relations. Although the area is quite large, it is possible to designate a suite of rocks (Fig. 1-2) which best represents High Cascade petrologic trends and divergences. Samples are selected on the basis of several factors which include: (1) location in time and space such that regional and temporal consistencies may be tested, (2) relative volumes which relate to importance in magma production, (3) inhomogeneity within units that might exhibit preeruptive differentiation, (4) structural controls that affect eruption of similar rock types, (5) erratic chemical or petrographic character to understand divergent processes, and (6) compliance with the overall silica-enrichment trend such that excessive redundancies are avoided.

The primary objective of this thesis is to provide detailed petrochemical evaluations on a highly selective suite of samples from the Three Sisters region in the central High Cascades. It is expected that studies on a representative suite will create a foundation for continued research on comparative systems in the High Cascades and other similar systems. A total of fifty samples (including two South Sister samples from work by



K. Wozniak, 1982) were obtained for major/trace element analyses of whole rock and selected phenocryst phases in conjunction with optical studies of thin sections and mineral separates. These samples were chosen to span a range of 48 to 76 wt. % SiO₂ as determined by previous bulk analyses.

As implied earlier, basalts $(48-53\% \text{ SiO}_2)$ and basaltic andesites $(53-58\% \text{ SiO}_2)$ comprise a greater total volume in the region than the more silicic members. Dacites $(63-68\% \text{ SiO}_2)$ and rhyodacites (> 68\% \text{ SiO}_2), although less voluminous, occur in substantial proportions as thick flows or domes, but there is an apparent paucity of andesites $(58-63\% \text{ SiO}_2)$ which are supposedly typical of calc-alkaline systems. These differences are reflected in the sampling program and introduce additional aspects of genetic models, especially in light of andesite production.

Major element analyses were obtained by x-ray fluorescence (XRF) and atomic absorption (AA) spectrophotometry. Samples were crushed and ground in a standard jaw-crusher and rotary mill with subsequent pulverization in a Pitchford ball-mill apparatus. Aliquants of powdered rock were mixed with lithium metaborate (flux) in the weight ratio of 1:3 sample to flux, fused in graphite crucibles at 1000°C and molded into glass disks. One side of each glass button was ground uniformly and analyzed by XRF utilizing an argon gas-proportional counter in conjunction with goniometer-controlled peak and background settings. Analyses for SiO₂, TiO₂, Al₂O₃, FeO, CaO and K₂O were made by comparison with predetermined standard curves of synthesized High Cascade compositions (to avoid absorption difficulties) and the incorporation of a standard plate (Columbia River Basalt) to correct for minor in-strumental variations.

Each button was re-pulverized and aliquants were allowed to dissolve in dilute nitric acid, with continual stirring, for at least six hours. Analysis for Na₂O and MgO were obtained using a Perkin-Elmer AA spectrophotometer with air (for Na₂0) and nitrous oxide (for MgO) as oxidants. Standard solutions were checked before and after each set of five analyses and more often during periods of greater instrumental variation.

Trace element analyses were acquired through a sequential instrumental neutron activation analysis (INAA) procedure outlined by Laul (1979) using the Oregon State University TRIGA reactor, ND600 and ND2200 multichannel analyzer systems coupled with Ge(Li) crystal gamma-ray detectors and followed by computer reduction of spectral data. To avoid possible contamination, clean chips from broken rock samples were crushed and pulverized in a Lemaire jaw-crusher and rotary mill which utilizes 99.5% pure alumina plates. In normal runs, approximately twenty sample aliquants (about I gram each) were activated at one megawatt for two hours (or longer for smaller samples) in the rotating rack of the reactor. First counts of 10k seconds commenced after 5 to 7 days of decay time for analyses of Ba, La, Sm, Yb, Lu and U. Longer counts of about 40k seconds were made after one month for Fe, Co, Cr, Ni, Rb, Cs, Sr, Ce, Nd, Eu, Tb, Sc, Hf, Ta, Th and Zr.

Phenocryst and groundmass separates were additionally analyzed by short (5-minute) activations at 15 kilowatts using the pneumatic transfer system ("rabbit runs") in order to obtain abundances of TiO₂, AI_2O_3 , MgO, CaO, Na₂O, K₂O, V and Mn. Clean separates of olivine, plagioclase and groundmass (0.2 to 0.5 g) were obtained by sieving and washing a crushed sample in order to isolate sand-sized grains which were selectively hand-picked using fine forcepts and a stereo microscope. Neutron activation analyses were made with U.S.G.S. standards BHVO, GSP-1, PCC-1 and BCR, as well as in-house standards prepared by O.S.U. Radiation Center personnel. Tables 1-1 and 1-2 list pertinent INAA parameters; chemical analyses are tabulated in the following chapters.

Stable Isotope (% abundance)	Thermal Neutron ^b Cross Section, Resonance Int. (I _r) (barns)	Radionuclide produced)	t _{j2}	Eγ, keV (% abundance)	Interferences (measured contributions)
		Count	#1		
²⁶ Mg (11.01)	0.036, 0.025	²⁷ Mg	9.46m	1014 (27)	$^{27}A1$ (n,p) ^{27}Mg
²⁷ A1 (100)	0.23, 0.17	^{2 8} A1	2.24m	1779 (100)	(1 g A) ♥ 0.24 g Mg) 28Si (n,p) 28Al (1 a Si ♥ 0.0052 g A))
⁴⁸ Ca (0.187)	1.1, 0.5	^{h 9} Ca	8.72m	3084 (92)	
⁵ °Ti (5.2) ⁵¹ V (99.8)	0.18, 0.11 4.91, 2.7	5 2 V	5.79m 3.75m	320 (95) 1434 (100)	^s "Cr (negligible)
		Count	#2		
²³ Na (100)	0.53, 0.32	^{2 4} Na	15.0h	1369 (100)	²⁷ Al (n,α) ²⁴ Na (negligible)
					24 Mg (n,p) 24 Na /1 a Ma = 0 00051 a Na
⁵⁵ Mn (100) ¹⁶⁴ Dy (28.1)	13.3, 14.2 2700, 340	^{5 6} Мп ^{3 6 5} Dy	2.58h 2.33h	847 (100) 94.7 (4.4)	(1 9 69 % 0.00051 9 60)

Table 1-1. Relevant nuclear^a and counting parameters for short activations.

b) Ratio of epithermal "neutron flux" to thermal neutron flux is ~ 0.05 .

Stable Isotope (% abundance)	Thermal Neutron Radionucl Cross Section, produced Resonance Int. (barns)	Radionuclide produced	t _{l2}	Ey, keV (% abundance)	Interferences (measured contributions	
	Count #1	5-7 days decay.	Count	time 10k seconds	S.	
²³ Na (100)	0.53, 0.32	²⁴ Na	15.0h	1369 (100)	²⁷ Al (n,α) ²⁴ Na (negligible) ²⁴ Mg (n,p) ²⁴ Na	
50Cr (4.35)	158.76	5100	27 71d	220 (0 0)	(lµg Mg ⇒= 0.00051µg Na)	
130 Ba (0.11) 139 La (99.1)	13.0, 7.0 14, 200 8.9, 11.4	131Ba 1401a	11.7d	496 (7.3)		
¹⁴⁶ Nd (17.2)	1.3, 2.8	1 4 7 Nd	10.99d	531 (12)	²³⁵ U (fission) (insignificant)	
¹⁵² Sm (26.7)	208, 3000	1 5 3 Sm	46.8h	103 (28)	(msrghth icalic)	
¹⁷⁴ Yb (31.6)	65, 30	175Yb	4.21d	396 (6.5)		
¹⁷⁶ Lu (2.6)	2000, 1200	¹⁷⁷ Lu	6.74d	208 (11)	176 Yb (n, γ) 177 Yb $\frac{\beta}{2}$ 177 Lu $(1)u$ Yb = 0.004 u a Lu)	
²³⁸ U (99.28)	2.7, 270 23	² U ^β (23.5m) ²³⁹ Np	2.35d	228 (13)	(Thờ Th ~ 0.004hỹ từ)	
	Count #2	4-6 weeks decay	. Count	time 30k-60k se	conds.	
⁴⁵ Sc (100)	27, 12	4 ⁶ Sc	83.8d	889 (100)		
⁵⁸ Fe (0.33)	1.2, 1.2	⁵ ⁹ Fe	45.6d	1099 (100) 1099 (100) 1292 (77)		
⁵ °Co (100)	37.75	6 °Co	5.27v	1333 (100)		
⁵⁸ Ni (68.3)	0.12 ^C	5 8 Co	70.8d	811 (99)	152Eu (810 KoV)	
⁸⁵ Rb (72.17)	0.45, 7	86Rb	18.65d	1077 (8.8)	ra (010 Kev)	
⁸⁴ Sr (0.56)	0.8, 11	8 5Sr	65.2d	514 (100)		
⁹⁴ Zr (17.4)	0.05, 0.3	95Zr	64.0d	757 (45)		

Table 1-2. Relevant nuclear and counting parameters^a for long activations.

Table 1-2. (continued)

Stable Isotope (% abundance)	Thermal Neutron Cross Section, Resonance Int. (barns)	Radionuclide produced	t _{ıź}	Eγ, keV (% abundance)	Interferences (measured contributions)
	Count #2	(continued)			
¹³³ Cs (100) ¹⁴⁰ Ce (88.48)	29.6, 421 0.58, 0.48	¹³⁴ Cs ¹⁴¹ Ce	753.15d 32.5d	796 (98.8) 145 (49)	²³⁵ U fission \rightarrow ¹⁴¹ Ce
¹⁵¹ Eu (47.9)	924, 3300	¹⁵² Eu	13.4y	344 (28)	(1µg U ⇔ 0.25µg Ce)
¹⁵⁹ Tb (100) ¹⁰⁰ Hf (35.2) ¹⁸¹ Ta (100) ²³² Th (100)	23.5, 400 13, 34 21.5, 720 7.4, 85 ²³	¹⁶⁰ Tb ¹⁸¹ Hf β- ¹⁸² Ta ³ Th∓(22.2m) ²³⁹ Pa	72.1d 42.4d 115d a 27.0d	1408 (22) 299 (27) 482 (83) 1221 (29) 312 (38)	²³³ Pa (300 keV)

a) Lederer et al. (1967) and General Electric 12th ed., Chart of the Nuclides (1977).

b) Ratio of epithermal "neutron flux" to thermal neutron flux is ~ 0.05 .

c) Cross section value for fission neutron spectrum reaction of ${}^{58}Ni$ (n,p) ${}^{58}Co$.

Additional separate-phase analyses were performed by optical methods (olivine, orthopyroxene, plagioclase) or combined x-ray diffraction (XRD)/XRF techniques (titaniferous magnetite). 01ivine and pyroxene compositions were determined by refractive index and 2V measurements on grains oriented with a spindle stage mechanism (Bloss, 1980). Plagioclase grains were finely ground in an agate mortar and fused to a glass bead (carbon-arc), the fragments of which were checked for index of refraction (Deer et al., 1966, p. 328). Spinel grains were extracted magnetically, cleaned, powdered and analyzed by XRD for unit cell dimension. The powders were then mixed with a Li-tetraborate flux, fused at 1100°C, repulverized, mixed with cellulose and compressed into wafers for XRF analysis. Ratios of Ti to Fe were obtained and compared with unit cell calculations as a means of determining post-eruptive alterations in oxidation state (Akimoto et al., 1957).

Mathematical models and statistical manipulations were produced with the assistance of a desk top (HP-85) mini-computer utilizing basic language programming. A comprehensive program, based on mathematical relations outlined in Appendices B and C, was developed to incorporate successive processes of melting, crystallization or mixing under equilibrium or dynamic conditions. Additional programs were developed for data compilation, geochemical evaluation and regression analysis which further enhanced the efficiency of geochemical modeling. Numerous models were effectively tested and retested with widely varying geologic parameters, such that viable models represent the most probable scheme which constrains major and trace element abundances, petrographic data and phase compositions.

Major and trace element variations are delineated in the following chapters for the entire suite of samples and selected groups with particular attention being paid to petrologically significant relations. Models of magma genesis and evolution are discussed in three groups: basalts, intermediate units (basaltic andesites and andesites) and silicic units. A final discussion of the overall evolutionary scheme is presented in Chapter 5 along with an assessment of the regional geologic setting.

2. BASALTS

2.1 Sample Descriptions and Petrography

Basaltic lavas (≤ 53 wt. $\% SiO_2$) primarily represent the earliest development of the High Cascade platform of shield volcanoes. Later units include the aforementioned succession of basaltic andesite flows and silicic centers although some interbedded basalts recur throughout the volcanic sequence. The early High Cascade (EHC) basalts are normally dicktytaxitic and porphyritic to subphyric (contain microphenocrysts or sparse phenocrysts) with olivine and subordinate plagioclase as liquidus phases. Later High Cascade (LHC) basalts are dicktytaxitic to granular and chemically similar to EHC basalts. Divergent basaltic compositions occur within the High Cascade province and some are shown in this study to represent erratic magma histories.

Representative samples of EHC basalts obtained for this work include the following:

- MB-134 Intracanyon lens of high FeO-TiO₂ olivine basalt which occurs near the base of the exposed EHC sequence; columnar basalt in Scott Creek logging road.
- MB-133 Intracanyon flow in ancestral McKenzie River (2.05 ± 0.52 m.y. dated by Utah Research Institute, 1980); west end of Foley Ridge.
- EM-89 EHC basalt, part of which is pillowed; U.S. 126 roadcuts east of Carmen Smith powerhouse.
- EM-90 Very coarse, plagioclase porphyritic EHC basalt; near Fish Lake.
- TS-620 Stratigraphically above MB-134; Scott Creek logging road.
WR-225 EHC basalt at Canyon Creek and Metolius River junction in northern part of study area.

S-91 EHC basalt west of Black Butte, N.E. side of U.S. HWY 20.

BT-382 High-CaO augite basalt, S.E. of Trout Creek Butte; EHC east flank.

BT-387 EHC basalt at W. base of Pole Creek cinder cone.

All of the EHC basalts, with the exception of BT-382, exhibit the dicktytaxitic, medium- to coarse-grained texture typical of EHC units.

Later High Cascade basalts that erupted intermittently with more evolved units are represented by the following samples:

EM-91 Holocene (3800 y) lava from early Nash Crater.

- TFJ-435 Extensive Pleistocene lava flow on the High Cascade crest between U.S. 20 and Mt. Washington.
- TFJ-438 Late Pleistocene lava from cones between Black Crater and N. Matthieu Lake.
- TFJ-440 Glaciated lava flow from cinder cone at summit of Cache Mountain; contains rare quartz xenocrysts, high K₂0 abundance.
- TS-621 Very late Pleistocene lava from Two Buttes.
- TS-630 Sample from top of thick glaciated unit (fine-grained margin) S.W. of Scott Lake.
- TS-688 Basalt porphyry which comprises a large part of Middle Sister; contains plagioclase phenocrysts up to 1 cm.
- BT-393 Holocene lava from chain of cones S. of Todd Lake.
- S-92 Holocene lava from early Belknap Crater.

The later basalt flows are either dicktytaxitic or granular with the exception of TS-688. Petrographic data are listed in Tables 2-1 and 2-2 for EHC and LHC basalts, respectively.

Although textural contrasts are roughly apparent between the two groups (LHC basalts tend to be less dicktytaxitic, finergrained, and more granular), only minor variations in mineralogy are evident. Compositions of phenocrysts, obtained via thinsection analysis and/or spindle stage grain mounts, are roughly consistent in absolute values and ranges between both groups. Geochemical data presented in the following section also indicate that chemical variations and consistencies are independent of temporal setting. The following mineralogic descriptions, therefore, apply to the entire suite of High Cascade basalts and relevant discrepancies are noted when applicable.

Olivine phenocrysts of EHC and LHC basalts are subhedral to euhedral, weakly resorbed, occur in all proportions up to approximately 15 percent, and exhibit a compositional range of Fo₈₀-Fo₈₅, as determined by α -index measurements. One exception, TS-688 (Middle Sister basalt), is rich in plagioclase phenocrysts and contains olivine of Fo75 composition determined by INAA. The relatively more Fe-rich composition reflects more evolved magmatic conditions which are discussed in later sections. Inclusions of opaque, titaniferous magnetite grains are common in some units, although many olivines were observed that are devoid of additional Deuteric alteration of olivine is also common in variable phases. degrees ranging from light iddingsite rims to nearly wholesale replacement by Fe-oxide and/or iddingsite. Occurrence of groundmass olivine is typically restricted to a microphenocryst relation with other phases often yielding a seriate overall texture and is rarely present as the latest crystallizing phase.

Plagioclase phenocrysts are also subhedral to euhedral, but usually exhibit stronger effects of disequilibrium such as corroded

Sample	Overall _a	Overall Phenocrysts		avg. size (range)	Groundmass	
	Texture			(mm)	phases	texture
MB-134 ^b	dickty. sP/medium	p] (An ₇₆) 0]	4 2	1.0 (0.5-1.5) 0.5 (0.2-1.5)	pl(An ₇₀),cpx, sp,ol	ophitic
MB-133	dickty. sP/coarse	01	5	0.8 (0.5-1.2)	pl(An ₆₅),cpx, ol,gl,sp	ophitic
EM-89	dickty. sP/medium	0]	2	0.3 (<0.4)	pl(An ₆₂),cpx, ol,sp	ophitic
EM-90	dickty. P/coarse	p] (An ₇₂) o] (Fo ₈₀)	20 5	2.5 (1.0-3.0) 0.6 (0.5-1.0)	pl(An ₆₆),cpx, ol,sp	sub-oph.
TS-620	dickty. sP/medium	ol pl	1	0.8 (0.4-1.0) <0.5	pl(An ₆₃),cpx, ol,sp	ophitic
WR-225 ^b	dickty. sP/coarse	pl (zoned)	2	1.0 (0.5-2.0)	pl(An ₆₆),ol, cpx,sp	inter- granular
S-91	dickty. sP/medium	ol pl (zoned)	2 <1	0.8 (0.2-1.0) 0.5	pl(An ₆₅),cpx, sp,ol	inter- granular
BT-382 ^b	P/fine	pl (An ₈₅) ol (Fo ₈₄) cpx	20 1 1	2.0 (1.0-3.0) 1.0 0.5	p1(An ₆₀ +),cpx, sp,o1	granular
BT-387	dickty. sP/coarse	ol (Fo ₀₁)	1	1.2	pl(An ₆₃),cpx, ol,sp(Usp ₃₅)	sub-oph.

Table 2-1. Petrographic data of Early High Cascades (EHC) platform basalts.

c)

Groundmass phases listed in order of abundance.

a) P=porphyritic, sP=subphyric.b) Denotes divergent basalt type; see text for explanation.

Sample	Overall Toxtumb	Phenocrysts	vol%	avg. size (range)	Groundmass		
	Texture			(mm)	phases	texture	
EM-91	dickty. sP/medium	0]	2	0.6 (0.2-1.0)	pl(An ₆₆),gl,cpx, ol,sp(Usp ₃₉)	granular	
TFJ-435	dickty. sP/medium	0]	<1	0.2	pl(An ₆₁),cpx,ol, sp	sub-oph.	
TFJ-438	dickty. P/fine	o] (Fo ₈₅) p] (An ₇₃)	15 2	$1.0 (0.5-1.5) \\ 0.8 (0.5-1.2)$	p1(An ₆₀),cpx, sp(Usp ₅₂),o1	pilotaxitic	
TFJ-440 ^d	P/med-fine	ol pl (An ₇₈) cpx	8 <1 <1	1.0 (0.2-2.0) <1 0.5	pl,cpx,sp(Usp ₄₆), ol,biotite	granular	
TS-621	sP/fine	ol pl	5 <1	0.5 (0.3-2.0) 0.3 (0.2-0.4)	pl(An ₇₄),cpx,sp, ol	granular	
TS-630	sP/fine	0]	5	1.0 (0.2-1.5)	$pl(An_{60}), cpx, sp, ol$	granular	
TS-688 ^d	P/intersertal	pl (An ₆₁) ol (Fo ₇₅)	30 ⁺ 5	3.0 (0.5-5.0) 0.8 (0.3-1.5)	pl(An ₆₁),cpx, sp(Usp ₃₀),gl,ol	granular	
BT-393	dickty. sP/medium	0]	∿1	0.5 (0.5-1.0)	pl(An ₇₁),cpx,ol sp(Usp ₅₉),hem.alt.	pilotaxitic	
S-92	dickty. sP/medium	ol pl (An _{so})	5 1	0.8 (0.1-1.5) 1.5	pl(An ₇₃),ol,gl, sp(Usp ₄₀)	interserta]	
a) See te	xt for explanati	on.		c) Groundmass pl	hasas listed in order	of shundard	

Table 2-2. Petrographic data of Later^a High Cascades basalts.

b) P=porphyritic, sP=subphyric

c) Groundmass phases listed in order of abundance.d) Denotes divergent basalt type; see text.

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interiors and, to a lesser extent, resorbed boundaries. Normal proportions of plagioclase crystals are less than two percent al-though two units, EM-90 and BT-382, contain approximately 20 percent and sample TS-688 contains 30-40 percent feldspar phenocrysts. The overall compositions of plagioclase phenocrysts typically range An_{72} - An_{80} , except TS-688 (An_{61} , INAA) and BT-382 (An_{85}), as determined in thin section analysis of properly oriented grains or refractive index measurements on fused feldspar powders. Ground-mass plagioclase grains are consistently more sodic (An_{60} - An_{74}) than the phenocryst fraction and probably represent closer approaches to overall compositions due to the low abundance of phenocrysts.

Augite occurs as microphenocrysts in only two units, BT-382 and TFJ-440, in proportions less than one percent, although clinopyroxene dominates with plagioclase in groundmass fractions of all basalts. Groundmass clinopyroxene most often occurs as anhedral crystals in an ophitic or granular relation to groundmass plagioclase. Continuity of single poikilitic augite grains is maintained over distances equal to two or three times the average length of plagioclase microlites (Fig. 2-2a). Ophitic textures are typically represented in the dicktytaxitic basalts.

Anhedral opaque grains are ubiquitous throughout the groundmass in most samples usually as the third most abundant groundmass phase. Glassy rocks exhibit an indeterminable amount of opaque minerals which are masked by a dark brown or black amorphous mesostasis. The combined XRD/XRF analytical technique described in Section 1.4 allowed determination of the percentage of ülvospinel (Fe_2TiO_4) molecules in magnetite (Fe_3O_4) and posteruptive oxidation to titanomaghemite detected by alterations in the unit cell dimension. The titaniferous magnetites of High Cascade basalts are invariably altered deuterically to structures which have unit cell dimensions displaced from the magnetite--ülvospinel join (Fig. 2-1). Opaque mineral compositions, given



Figure 2-1 Iron-titanium oxide tetrahedron illustrating ülvospinel content of titaniferous magnetites in basalts and intermediate rocks (triangles) and silicic rocks (squares). Post-eruptive alteration produces changes in the unit cell dimension. Spinel cell dimension curves are taken from Akimoto et al. (1957).

as mole percent ülvospinel in magnetite, occur in the range Usp_{30} -Usp_{59} for both groups.

Accessory apatite is present as acicular or prismatic inclusions in groundmass feldspars or mesostasis of most samples with discordant orientations of elongate grains in plagioclase. Biotite occurs in the groundmass of TFJ-440 reflecting a high alkali content derived by incorporation of crustal material into a mafic magma. Deuteric alteration products include hematite, magnetite, celadonite and devitrified glass, as well as iddingsite, which occurs sporadically as vesicle lining or olivine rims in some samples. Typically High Cascade platform basalts exhibit no more than slight alteration effects that can be detected optically.

Photomicrographs shown in Figure 2-2 (a-f) illustrate typical basalt textures which exhibit wide variations in grain size and phenocryst/groundmass relations. Two divergent samples are included in Figure 2-2 and illustrate the biotite-bearing contaminated sample from Cache Mountain (2-2e) and the strongly porphyritic plagioclase basalt of Middle Sister (2-2f).

2.2 Geochemistry

Major and trace element abundances of High Cascade basalts are compiled according to two groups. Table 2-3 lists data for basaltic units which are considered on the basis of total geochemistries to represent "normal" basalts and comprise the major volume of mafic units. Table 2-4 lists analyses of units believed to represent variably divergent types, some of which were discussed earlier. Primary consideration is directed toward details of the geochemistry and magmatic evolution of the normal basalts with subsequent comparisons made for the divergent types. Samples which represent the normal group include MB-133, EM-89, EM-90, Figure 2-2 (a-f) Photomicrographs of High Cascades basalts: A) TS-620 (plane light) illustrating ophitic groundmass texture; B) EM-90 (crossed nicols) illustrating coarse grained dicktytaxitic texture of plagioclase and pyroxene;
C) MB-133 (plane light) olivine phenocrysts exhibiting rims of iddingsite alteration;
D) S-92 (crossed nicols) showing intersertal groundmass texture of some porphyritc units;
E) TFJ-440 (plane light) divergent basalt type affected by crustal contamination, exhibits substantial amounts of accessory biotite.
F) TS-688 (crossed nicols) plagioclase porhyritic basalt of Middle Sister.



2 mm

Figure 2-2

	MB-133	EM-89	EM-90	EM-90 (dup1.)	EM-91	TS-620
SiO ₂	49.1	49.5	Major Oxides (%)		<u></u>
TiO ₂ Al ₂ O ₂	1.50	1.45	1.40		50.1	50.0
FeÖČ	10.7	10.9	17.3		16.9	17.7
Mg0	8.7	8.9	8.4		9.1	9.7
Na ₂ 0	8.5	9.1	8.9		9.0	9.0
K₂0	0.55	0.45	0.50		3.3 0.80	3.0 0.55
		1	race Elements (n	••••••••••••••••••••••••••••••••••••••	************	******
Sc	28.7	30.6	28.5	26 9	26.0	
Cr ·	310	305	170	155	25.8	30.2 185
Ni	140	45.2 170	41.0		40.2	38.5
25	•	270	120	150	160	120
Sr	450	3	3	8	7	13
Çs	0.18	0.11	550 0.08	520	510	420
Sa	210	150	190	170	190	0.05
La	11.0	7.9	12.1	10.2	14 0	
Nd	21.9	19.2	25.7	27.6	33.5	8.8
Sm	4.38	4.05	19	22	13	11
Eu Th	1.58	1.46	1.64	3.88	4.82	3.95
Yb	2.51	0.70	0.73	0.74	0.69	1.40
Lu	0.41	0.38	2.24	2.11	2.45	2.30
Zr	40	en		0.31	0.34	0.39
Hf	2.95	6.50	2.54		110	90
ia Th	0.47	0.39	0.41	2.00	3.35	2.90
U	1.5	1.5	0.52	0.56	1.22	0.53
*********			1.0		1.5	0.2
		no	rmative mineralog	IJ		
Mt	2.9	2.8	2.7		2.8	28
Or	3.3	2.7	2.6	**	2.2	2.3
AD An	24.8	28.2	26.5		4.7 28.2	3.3
Di-Hd	8.4	29.8	31.6		28.7	33.0
Hy	12.8	4.6	10.2		12.9	9.5
Qz	12.5	16.6	14.5	**	16.6	14.7
· 	-			÷=		

Table 2-3. Chemical abundances^a and CIPW normative calculations^b of normal High Cascade basalt samples

Table 2-3. (cont.)

	TS-621	TS-630	TFJ-435	TFJ-438	TFJ-438 (dupl.)	S-91
			Major Oxides (%)	· · · · · · · · · · · · · · · · · · ·		
SiO ₂ TiO ₂ Al ₂ O ₃ FeO MgO CaO Na ₂ O K ₂ O	50.2 1.35 17.1 9.4 9.1 9.0 3.3 0.55	51.5 1.35 17.7 9.2 7.4 8.0 3.5 0.85	49.5 1.55 17.5 9.3 7.7 9.4 3.3 0.65	49.5 1.50 16.4 9.7 9.4 8.5 3.3 0.70		50.6 1.45 17.6 9.3 7.6 9.0 3.1 1.70
		T	race Elements (ppm	n)		
SC Cr Co Ni	28.2 280 41.3 160	24.9 210 36.3 140	29.0 190 36.5 110	27.2 325 44.9 240	22.3 325 36.3 220	29.3 190 36.1 100
Rb Sr Cs Ba	3 410 0.15 150	12 540 0.25 280	6 590 0.08 200	5 470 0.21 180	4 	6 430 0.28 230
La Ce Nd Sm Eu Tb Yb Lu	7.5 14.6 17 3.79 1.40 0.64 2.40 0.50	12.9 33.2 31 4.80 1.54 0.73 2.35 0.40	13.8 33.5 10 5.03 1.78 0.80 2.51 0.49	11.6 22.8 17 1.55 0.59 2.09 0.31	11.1 10 4.19 1.69 0.70 2.10 0.32	13.6 33.0 12 4.93 1.57 0.77 2.68 0.43
Zr Hf Ta Th U	170 2.77 0.35 0.64 1.3	160 3.60 0.66 0.98 0.3	110 3,31 0,36 0,81 1.6	60 4.45 0.90 0.87 1.5	3.18 0.41 0.73	200 3.24 0.80 1.25 1.5
		no	rmative mineralog	y	*****	********
II Mt Dr Ab Di-Hd Hy Di-Hd Qz	2.6 2.3 3.3 28.2 30.0 11.8 6.1 15.7	2.6 2.2 5.0 30.0 29.9 8.0 13.2 8.65	2.9 2.3 3.8 28.2 30.8 12.8 3.8 14.2	2.9 2.4 4.1 28.2 27.7 11.7 4.4 17.6		2.8 2.3 10.1 26.5 28.9 12.8 0.7 16.4

Table 2-3. (cont.)

	S-92	BT-387	BT-393	uncertainty ^d (%)	average (±1σ)	
			Major Oxides (%)		
	49.0 1.65 18.0 9.5 7.9 8.7 3.5 0.80	50.2 1.55 17.5 9.3 8.2 8.8 3.4 0.70	49.1 1.50 17.1 10.0 8.6 8.3 3.6 0.45	4-6 2-5 4-8 2-5 2-5 2-5 4-6 4-6	49.8 ±0.7 1.48±0.08 17.3 ±0.4 9.7 ±0.5 8.3 ±0.7 8.8 ±0.3 3.3 ±0.2 0.71±0.33	
		T	race Elements (p	pm)		
SC Cr Co Ni	25.3 165 38.1 130	24.8 210 38.6 160	27.7 250 45.2 170	1-2 2-4 2-3 10-20	27.4 ±2.3 238 ±61 39.9 ±3.3 150 ±35	
Rb Sr Cs Ba	1 530 0.21 220	3 460 0.05 230	3 430 0.14 150	50 5-10 50 5-10	5 ±4 486 ±69 0.15±0.07 198 ±37	
La Ce Sm Eu Tb Yb Lu	13.0 36.1 19 4.73 1.70 0.77 2.36 0.41	13.8 30.1 14 4.92 1.60 0.72 2.49 0.39	7.9 14.4 16 4.01 1.51 0.74 2.34 0.36	1-3 5 10-30 1 1-3 5-10 5-10 10-20	11.2±2.5 25.2±7.6 16 ±6 4.42±0.46 1.56±0.11 0.71±0.06 2.33±0.16 0.40±0.05	
Zr Hf Ta Th U	100 3.33 1.00 0.90 1.5	350 0.98 1.23 1.6	80 2.73 0.41 0.51 1.5	50 3-8 8-12 5-15 5-15	124 ±83 3.45±1.03 0.63±0.24 0.83±0.28 1.3 ±0.5	
			ormative mineral	ogy	******	********
II Mt Or Ab An Di-Hd Hy Qz	3.1 2.3 4.7 30.0 30.8 10.0 2.4 16.6	2.9 2.3 4.1 29.1 30.2 10.9 5.8 14.3	2.9 2.4 2.7 30.8 29.0 11.9 1.1 18.8			

a) Major oxides by XRF and AA; trace elements by INAA.

b) Il=ilmenite, Mt=magnetite, Or=orthoclase, Ab=albite, An=anorthite, Di-Hd=diopside-hedenbergite, Hy=hypersthene, Ol=olivine, Qz=quartz. Calculations assume Fe₂O₃/FeO=0.20 (wt.%).

c) Total Fe analyzed as FeO.

d) Uncertainties correspond to counting statistics.

	MB-134(dup1.)	WR-225	TFJ-440(dup1	.) ^{TS-688}	BT-382	uncertainty ^d (%)
Si02 Ti02 Al203 Fe0 Mg0 Ca0 Na20 K20	48.5 2.15 15.9 12.1 8.0 9.2 3.2 0.50	49.1 1.10 16.8 10.5 8.3 10.6 2.7 0.50	Major Oxides (%) 49.9 1.20 16.3 8.7 10.2 9.4 2.9 1.50	52.0 1.20 19.0 8.3 6.6 8.5 3.7 0.65	52.1 1.25 19.4 7.5 5.5 10.0 3.5 0.75	4-8 2-5 4-10 2-5 2-5 2-5 4-8 4-8
Sc Cr Co Ni	36.1 (37.4) 175 (170) 47.5 (45.3) 110 (110)	34.4 205 46.1 30	Trace Elements (ppm) 27.1 (27.0) 370 (350) 42.4 (44.0) 230	24.7 105 34.2 100	29.4 115 29.0 35	1-2 2-4 2-3 10-20
Rb Sr Cs Ba	5 (2) 340 (320) 0.03 (0.03) 210 (230)	1 830 0.06 240	1 1490 (1500) 0.10 (0.07) 580 (550)	3 530 0.19 200	9 650 0.05 330	50 5-10 50 5-10
La Ce Nd Sm Eu Tb Yb Lu	12.5 (13.2) 29.6 (29.8) 24 (21) 5.87 (5.86) 2.04 (2.17) 0.96 (1.09) 3.71 (3.76) 0.56 (0.58)	7.3 21.2 7 2.94 1.23 0.40 1.53 0.24	21.0 (21.3) 58.3 (59.1) 27 (35) 6.47 (6.07) 2.15 (2.11) 0.62 (0.62) 1.35 (1.76) 0.28 (0.28)	8.2 19.1 8 3.60 1.29 0.54 1.83 0.28	16.0 37.8 23 4.94 1.69 0.66 2.12 0.38	1-3 5 10-30 1 1-3 5-10 5-10
Zr Hf Ta Th U	80 (180) 3.83 (3.88) 0.64 (0.72) 0.74 (0.81) 1.9	60 1.60 0.13 0.35	70 3.68 (3.98) 0.30 (0.27) 0.61 (0.69) 1.9	50 2.71 0.31 0.77 1.1	140 3.24 0.59 1.55 1.6	50 3-8 8-12 5-15 5-15
			normative mineralogy	****	****	******
Il Mt Or Ab An Di-Hd Hy Ol Qz	4.1 2.9 3.0 27.4 27.4 14.9 3.7 16.2	2.1 2.5 3.0 23.1 32.1 16.7 6.2 14.0	2.3 2.1 8.9 24.8 26.9 15.9 3.4 17.6	2.3 2.0 3.8 31.7 33.1 7.4 12.4 7.3	2.4 1.8 4.4 30.0 34.8 12.1 10.2 4.4	

Table 2-4. Chemical abundances^a and CIPW normative calculations^b of divergent High Cascade basalts.

a) Major oxides by XRF and AA; trace elements by INAA.

b) Same parameters as Table 2-3.

c) Total Fe analyzed as FeO.

d) Uncertainties correspond to counting statistics.

See text for explanations.

		basalt.	S EXCLACTED TOM T	5-000, Middle 515	<u></u>
		olivine	plagioclase	groundmass	
$Ti0_{2}$ $A1_{2}0_{3}$ $Fe0$ $Mn0$ $Mg0$ $Ca0$ $Na_{2}0$ $K_{2}0$	(%%) (%%%%%) (%%%%%) ((%%%%%) ((%%%%%) (%%%%%) (%%%%%) (%%%%%) (%%%%%) (%%%%%) (%%%%%%) (%%%%%%) (%%%%%%) (%%%%%%%) (%%%%%%%%	0.06±0.05 ^a 2.8 ±0.2 21.8 ±0.1 0.325±0.001 37.2 ±0.5 0.006±0.001	29.3 ±0.2 0.68±0.01 0.007±0.0004 12.3 ±0.5 4.37±0.01	$\begin{array}{c} 1.80 \pm 0.07 \\ 15.3 \pm 0.2 \\ 10.37 \pm 0.04 \\ 0.152 \pm 0.001 \\ 5.0 \pm 0.3 \\ 7.7 \pm 0.4 \\ 4.49 \pm 0.03 \\ 0.8 \pm 0.2 \end{array}$	
Sc V Cr Co Ni	(ppm) (ppm) (ppm) (ppm) (ppm)	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	0.612±0.004 7 ±2 6.9 ±0.3 1.22±0.02 3 ±1	33.30±0.05 283 ±5 134 ±2 34.4 ±0.2 32 ±7	
Rb Sr Cs Ba	(ppm) (ppm) (ppm) (ppm)	<1.9 <0.9 25 ±10	0.8 ±0.3 850 ±10 0.026±0.006 90 ±10	17 ±4 430 ±50 0.44±0.08 430 ±70	
La Ce Nd Sm Eu Tb Yb Lu	(ppm) (ppm) (ppm) (ppm) (ppm) (ppm) (ppm) (ppm)	$\begin{array}{c} 0.12 \pm 0.02 \\ 6 \pm 3 \\ 0.075 \pm 0.004 \\ 0.013 \pm 0.004 \\ \hline \\ 0.26 \pm 0.05 \\ 0.17 \pm 0.006 \end{array}$	0.9 ±0.2 1.66±0.08 3 ±2 0.20±0.01 0.47±0.01 0.02±0.01 0.20±0.05 0.008±0.005	14.7 ±0.8 27.4 ±0.6 18 ±4 6.18±0.04 1.56±0.03 0.79±0.03 3.6 ±0.1 0.56±0.02	
Zr Hf Ta Th	(ppm) (ppm) (ppm) (ppm)	<5 <0.2 0.04 ±0.02 0.2 ±0.1	3 ±2 0.016±0.005 0.003±0.002	40 ±20 3.3 ±0.2 0.47±0.06 1.1 ±0.1	

Table 2-5 Chemical abundances (INAA) of olivine, plagioclase and groundmass separates extracted from TS-688, Middle Sister basalt.

a) Statistical counting error, 1σ.

b) Total Fe as FeO.

EM-91, TS-620, TS-621, TS-630, TFJ-435, TFJ-438, S-91, S-92, BT-387 and BT-393. The divergent types are represented by MB-134, WR-225, TS-688, TFJ-440 and BT-382. Minor variances that occur within the normal group are acknowledged, but present few problems in the overall scheme of magma genesis discussed in Section 2.4.

Normal Basalts

High Cascade normal basalts are typically high-Al $_2$ 0_3 $(\sim 16-19 \text{ wt.\%})$ olivine-normative tholeiites which are usually associated with early-stage development of convergent plate volcanism. Total alkalis $(Na_{2}O + K_{2}O)$ comprise less than 4.4 wt.%, while CaO abundances range 8.5-9.4 wt.%. Values of FeO/(FeO + MgO) molar ratios (Fe') occur within the range Fe' = 0.36-0.42 with total abundances of FeO* (total Fe) = 9.1-10.5 wt.% and MgO = 7.4-9.4 wt.%. Titanium abundances (TiO₂ = 1.35-1.65 wt.%) are relatively higher than would be expected for mafic members of convergent plate volcanism (Green, 1980), although they compare favorably with continental rift basaltic compositions (Basaltic Volcanism Study Project, 1981). Figure 2-3a indicates negligible changes in CaO/Al₂O₃ ratios obtained for normal basalts; however, major element variations are exemplified by a general increase in Fe' with decreasing MgO content, as shown in Figure 2-3b.

Although Fe', by definition, approaches unity as MgO approaches zero, the regression line of Figure 2-3b implies a non-linear relation at lower MgO values and precludes changes in Fe' due solely to changes in MgO content. The systematic trend of Fe' vs. MgO is consistent with fractionation of ferromagnesian minerals, yet the relative stability of CaO/Al_2O_3 ratios precludes substantial inclusion of Ca-rich pyroxene in the separating phases.





Least squares fit and variations in CaO/Al₂O₃ vs. SiO₂ (A) and Fe' vs. MgO (B) for normal basalts²(open circles) and divergent basalts (closed triangles).

Ferromagnesian trace element abundances exhibit fairly consistent values for Sc (25-31 ppm) and Co (36-45 ppm) although greater variation is apparent for Cr (\sim 150-330 ppm) and Ni (\sim 100-240 ppm). Nickel/cobalt ratios display an overall decrease with increase in Fe' (Fig. 2-4) which is consistent with olivine fractionation. The variable Cr abundances might indicate the effects of pyroxene or spinel residual phases. Low abundances of the incompatible elements Zr, Hf, Ta, Th and U are also representative of comparable basaltic suites (Basaltic Volcanism Study Project, 1981). Chondrite-normalized (Appendix A) Sc/Hf ratios of normal basalts occur in the range 0.11-0.24 ($\bar{x} = 0.2$, $\sigma = 0.04$) which reflect a uniform mechanism of magma genesis.

Normal High Cascade basalts are also characterized by moderately fractionated alkalis and rare earth element (REE) abundances. Variable abundances of light REE (LREE), where La = 23-44 x chondrites, as compared to the more consistent heavy REE (HREE), where Yb = 10-13 x chondrites, reflect the higher mobility of LREE. Relatively uniform chondrite-normalized (c.n.) ratios of Ba/Sr (0.91-1.56), Sm/Eu (0.91-1.17) and Yb/Sc (2.85-3.76) preclude substantial effects of crystallizing or residual phases, which selectively incorporate Sr, Eu, or Sc (i.e., plagioclase or clinopyroxene). Figure 2-5 illustrates chondritenormalized abundances of K (x10), Ba, Sr, REE (Gd interpolated between Sm and Tb), and Sc, which display essentially monotonic decreases with decreasing ionic radii. Cesium and Rb are not included because of higher analytical error due to their low abundances in mafic units.

MB-134

Sample MB-134 represents one of the oldest exposed low-SiO₂



Figure 2-4

Variations and least-squares fit of Ni/Co ratios with Fe' values for normal (circles) and divergent (closed triangles) basalt compositions. TFJ-440 represents a primary magma although crustal assimilation has produced substantial enrichments in incompatible elements.



Figure 2-5 Composite plot of chondrite-normalized trace element patterns for normal basalts illustrating the monotonic variations with decreasing ionic radii. Ce and Nd exhibit wider variation due to higher analytical uncertainty. Gd values are obtained by interpolation between Sm and Tb relative to their ionic radii.

basaltic units within the study area. In comparison to the normal High Cascade basalts, MB-134 is not drastically divergent, but exhibits higher Fe' (0.46) and TiO₂ (2.15 wt.%) values and lies off the normal Fe' vs. MgO trend of Figure 2-3b. The CaO/Al₂O₃ ratio is consistent with the normal basalts (Fig. 2-3a) and the Ni/Co ratio occurs on the regression line of Figure 2-4. The trace element pattern for MB-134 is illustrated in Figure 2-6 in comparison to the field (within analytical uncertainties) of normal basalts. The obvious differences are higher HREE and Sc, a lower (La/Yb)_{c.n.} ratio (2.25) and a slight negative Eu anomaly although the relative HREE-Sc pattern is nearly replicate of the normal group. These differences are consistent, although not unequivocably, with greater fractionation of ferromagnesian minerals and possibly minor plagioclase.

The lack of an appreciable Eu anomaly may be due to higher Eu^{3+}/Eu^{2+} ratios under more oxidizing conditions, which prohibits substitution of Eu for Ca²⁺. An alternative explanation, however, is that Eu depletion may not be noticed as readily as Sr depletion for small degrees of plagioclase or clinopyroxene fractionation (Appendix B). Liquidus phases of MB-134 include plagioclase and olivine (Table 2-1) and suggest that these two minerals, as in normal basalts, are the predominant controllers of early fractionation. Clinopyroxene is precluded as a fractionating phase by the consistency of the HREE-Sc pattern of MB-134 to that of normal basalts. Although MB-134 has undergone more fractionation than normal basalts, the overall pattern is inconsistent with simple segregation of olivine with minor amounts of plagioclase from a liquid of normal basalt composition. The lower La/Yb ratio and higher total HREE indicate more substantial effects which probably involve chemical variations in source region.



Figure 2-6 Chondrite-normalized trace element abundances of MB-134 divergent basalt compared to the field of normal High Cascade basalts. MB-134 is derived by greater fractionation of olivine with minor plagioclase than normal units. The normal basalt field is from Figure 2-5 within analytical uncertainty and deleted extraneous values.

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WR-225

Sample WR-225 was obtained from a basalt at the northeast margin of the study area. Divergence from normal basaltic major element compositions, although not extreme, is characterized by lower TiO₂ (1.10 wt.%) and Na₂O (2.7 wt.%) as well as higher CaO (10.6 wt.%) abundances. Magnesium and Fe' values are indistinguishable from the normal trend (Fig. 2-3b) while the slightly higher CaO abundance is portrayed as a higher CaO/Al₂O₃ ratio (Fig. 2-36). On the basis of major elements, divergence of WR-225 is probably related more to the effects of calcic minerals rather than olivine, although the lower Ni/Co ratio (Fig. 2-4) might indicate otherwise.

Incompatible trace elements Hf, Ta, Th and U are systematically lower for WR-225 in concert with relatively low K_20 (0.5 wt.%). Comparison of the K, Ba, Sr, REE and Sc pattern with normal basalts (Fig. 2-7) indicates lower total REE, higher Sc and moderate positive Sr and Eu anomalies. Distribution coefficients shown on Figure A-1 (Appendix A) support the addition of plagioclase and clinopyroxene to a mafic liquid, although variability in source composition is not presently excluded.

TFJ-440

Sample TFJ-440 clearly exhibits the most anomalous chemical as well as lithological composition obtained during this study. Lava erupted from Cache Mountain contains rare quartz xenocrysts and substantial amounts of accessory biotite which coincide with the chamical divergence from normal basalts. Major element differences are characterized by the unique association of high MgO (10.2 wt.%), low FeO (8.7 wt.%) and TiO₂ (1.20 wt.%) with high K₂O (1.5 wt.%). The Fe' vs. MgO diagram (Fig. 2-36)



REE + Sc Ionic Radii

Figure 2-7 Chondrite-normalized trace element abundances of TFJ-440 and WR-225 divergent basalts compared to the field of normal basalts. Both samples represent contaminated magmas: TFJ-440 composition reflects interactions with high-silica units and contains rare quartz xenocrysts. WR-225 composition is the result of assimilation of plagioclase-pyroxene cumulates or crystal settling within the primary magma.

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indicates that TFJ-440, which plots close to the regression line, is actually more primitive than normal basalts. Primitive character is also supported by a higher Ni/Co ratio which lies on the normal trend of Figure 2-4. Slightly higher CaO abundance is reflected in minor divergence from normal CaO/Al_2O_3 ratios shown on Figure 2-3a.

High K₂O abundance is complemented by high concentrations of Ba (\sim 580 ppm) and Sr (\sim 1500 ppm) in addition to higher LREE (La = 64 x chondrites). The trace element pattern illustrated in Figure 2-7 shows a crossover effect (Eu-Tb) as well as a marked enrichment of K, Ba and Sr over normal compositions. Incompatible elements Zr, Hf, Ta, Th and U exhibit no major differences from the normal group of basalt analyses. The primitive character and anomalous composition are consistent with contamination of a hotter, MgO-rich melt by crustal constituents.

TS-688

A large part of Middle Sister is covered with the plagioclaserich basalt porphyry represented by sample TS-688. As one of the most siliceous basalts (SiO₂ = 52.0 wt.%), low abundances of FeO (8.3 wt.%), MgO (6.6 wt.%) and TiO₂ (1.20 wt.%) correlate with high Al₂O₃ (19.0 wt.%) and Na₂O (3.7 wt.%). The TS-688 composition falls on the CaO/Al₂O₃ trend of Figure 2-3a and the Ni/Co trend of Figure 2-4, but is displaced somewhat from the Fe' vs. MgO regression line of Figure 2-3b. One possible explanation for the minor offset of Fe' is that the TS-688 composition may represent the initial departure of High Cascade magmas from a tholeiitic, Fe-enrichment trend.

Chemical analyses of TS-688 separate phases (Table 2-5) indicate disequilibrium crystallization of olivine. Measured olivine/liquid distribution coefficients for Co, Ni, Mn, Cr and

V correspond to magmatic temperatures of ~1050-1100°C and D_{Mn} (2.14) corresponds to MgO contents of less than 4 wt.% according to temperature/composition data compiled by Irving (1978). Using the empirical olivine/liquid geothermometer of Roeder and Emslie (1970) a magma having the composition of TS-688 (FeO = 7.4 mol%, MgO = 10.5 mol%) equilibrates at 1165°C with a Fo₈₂ composition, whereas the analyzed olivine composition of TS-688 is Fo₇₅.

Although the trace element pattern shown in Figure 2-8 indicates normal values for K, Ba and Sr total REE abundances are lower than normal basalt compositions. The overall trace element pattern is essentially identical to normal basalts suggesting possible similarities in their source compositions; however, lower ferromagnesian and higher SiO₂ values of TS-688 are inconsistent with derivation of normal basalts from a TS-688 magma. Differences in the mechanism of magma genesis and/or variability of absolute REE abundances in the source region are implied.

BT-382

Sample BT-382, like TS-688, is not widely divergent in chemistry from the normal basalts and represents a high-SiO₂ (52.1 wt.%) composition. However, the presence of augite phenocrysts may indicate a fundamental change in magma derivation which is evident in the modest geochemical divergence. The most characteristic chemical features of BT-382 are the low ferromagnesian element abundances (FeO = 7.5 wt.%, Mgo = 5.5 wt.%) and high CaO (10.5 wt.%) content. Major element differences are apparent in Figure 2-3b in which a minor offset from the normal Fe' vs. MgO trend is indicated, and in Figure 2-3a a slightly higher CaO/Al₂O₃ ratio is evident. In addition, Figure 2-4 illustrates a more substantial divergence of BT-382 from the



Figure 2-8 Chondrite-normalized trace element abundances of divergent basalts BT-382 and TS-688 compared to the field of normal basalts. Error bars are given for Nd due to greater analytical uncertainty. BT-382 has close affinities with basaltic andesites and represents the transition to more silicic compositions. TS-688 is a sample of the Middle Sister porphyritic (pl) basalt.

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Ni/Co vs. Fe' trend displayed by normal compositions.

Trace element abundances are similar to those of normal basalts which contain relatively higher alkalis and total REE. Abundances of Zr, Hf, Ta, Th and U are essentially identical to normal basalt compositions, although Figure 2-8 shows that BT-382 has higher Ba, Sr and LREE than the normal field. The pattern also indicates a relatively higher $(La/Yb)_{c.n.}$ ratio (4.84), which is not consistent with simple olivine subtraction from a less fractionated liquid and implies possible differences in partial melting behavior or source composition. The trace element pattern of BT-382 is more closely related to those of basaltic andesites which, as shown in the following chapters, represent primary magmas of the calc-alkaline sequence. In light of the unusual lithology (augite phenocrysts) the chemical differences are probably consistent with initial variances in magma evolution related to the inception of more silicic calcalkaline behavior.

2.3 Geochemical Modeling

Geochemical models, presented as a means of interpreting magma evolution, necessarily involve numerous assumptions which may be misconstrued as being more specific than intended. Assumptions, however, are essentially the systematic qualifiers which incorporate known parameters in order to (at best) place constraints on the diversity of mechanisms which may be responsible for the observed compositions. Chemical models presented in this study represent the most probable mechanisms which satisfy all lithologic and chemical observations in accordance with the most logical geologic interpretations. Although the models used in this study are quantitatively described, rejected attempts are too numerous to reproduce wholly and are only qualitatively summarized. Trace elements are modeled with batch melting equations outlined by Shaw (1970, 1977) and with Rayleigh fractionation (Gast, 1968) for subsequent crystallization. Fractional melting, the process of liquid extraction from a successively depleted source, is modeled as small increments of batch melting with continually changing source compositions; however, the most significant results were obtained through batch melting processes as justified by a permeability threshold (Maaløe, 1982) necessary for effective magma segregation. Details of trade element models used to qualitatively constrain source composition and final calculations are outlined in Appendix B.

Distribution coefficients $(D_i^{\alpha/1} = C_i^{\alpha}/C_i^1)$ used in trace element models were obtained through assessment of published experimental values (Appendix B) selected on the basis of to the Cascade system in terms of overall composiaffinities tion and physical conditions of volcanic systems. Plagioclase and olivine distribution coefficients were measured directly for High Cascade rocks via INAA of hand-picked phenocryst and groundmass separates. These values were compared to documented coefficients for consistency of trace element pattern prior to their use in mathematical models. Figure B-1 (Appendix B) illustrates the effect that an included mineral will have on the incompatible trace element patterns (K, Ba, Sr, REE, Sc) of partially melted solid residual crystallizing phases or resultant liquids. It is apparent that minerals with low D values, such as olivine and orthopyroxene, have only monotonic effects on liquid compositions with the possible exception of HREE and Sc in extreme cases. However, notable fractionation and anomalous effects may be produced by introduction of plagioclase (substitution of Sr^{2+} and Eu^{2+} for Ca^{2+}), clinopyroxene (fractionation of REE and Sc) and garnet (selective uptake of the HREE). Trace elements that are compatible with

olivine (Co, Ni, Table 2-5) yielded D values that were determined to be too high for acceptable models, although Co and Ni abundances are consistent with mantle-derived olivine. These relations indicate disequilibrium for phenocryst phases occurring in High Cascade rocks and preclude the use of measured $D_{Co}^{01/1}$ values; however, D_s for incompatible elements were retained because of their extremely low values and consistency with coefficients reported in the literature (e.g., see Irving, 1978).

Constraints on major element concentrations are extremely difficult to quantify through the consideration of bulk compositions (mole %) of melting phases although approximations may be obtained through simplified assumptions. Melting of ideal olivine and Ca-free orthopyroxene, for example, will yield ${\sim}67$ and ~ 50 mole percent ferromagnesian elements (MgO + FeO), respectively, and clinopyroxene with the composition $Ca_4(Mg,Fe)_6SiO_3$ will yield ~ 20 mole % CaO and ~ 30 mole % FeO + MgO. However, petrogenetic models for basaltic magmas depend on the melting congruency of assumed components which, under eutectic or cotectic conditions, will not represent the actual compositions of the melted phases. Major element calculations, therefore, obviously depend on the effective chemical yield during a melting event and absolute abundances should be considered as subordinate to relative compositions, especially the Fe/Mg ratio. During fractional crystallization the rate of increase in $Fé_{1iquid}(Fe' = FeO/(FeO + MgO))$ will necessarily change with the total abundances of both FeO and MgO present in the initial liquid.

Determination of Fe' in liquids derived from peridotitic sources involves the Mg-Fe exchange distribution coefficient, K_D , for olivine and pyroxenes. Substantial experimental work on olivine equilibria by Roeder and Emslie (1970), Roeder (1974) and Longhi et al. (1978) provide a means of calculating Fe' of

liquids in equilibrium with olivine; however, the rate of change of Fe' with subsequent fractionation will depend on total abundances of MgO + FeO in the primary melt. Melts containing low total abundances of MgO will become depleted in MgO sooner and, hence, Fe' will increase more rapidly with fractionation of ferromagnesian minerals. Therefore, mineral crystallization effects are modeled through consideration of approximated absolute abundances of MgO and FeO in primary liquids and the effective compositions of crystallizing phases.

The olivine K_n reviewed by Longhi et al. (1978) is defined:

$$K_{D} = K_{ol-L}^{Fe-Mg} = \frac{\chi_{ol}^{Fe0} \cdot \chi_{L}^{Mg0}}{\chi_{L}^{Fe0} \cdot \chi_{ol}^{Mg0}} = K_{ol-L}^{Fe}/K_{ol-L}^{Mg}$$

and determined for lunar ($K_D = 0.33$) and terrestrial ($K_D = 0.30$) systems by fitting lines to log K_{ol-L}^{Mg} and log K_{ol-L}^{Fe} vs. $10^4/T^{o}K$. Olivine exchange distribution coefficients were found to be nearly independent of temperature and incur only minor effects with combined structural and chemical variations. The terrestrial olivine $K_D = 0.3$ value is used in this study for model calculations. Similar relations hold for other mafic phases (Stolper, 1977; Lindstrom, 1976) which lead to $K_D = 0.3$ and $K_D = 0.22$ for orthopyroxene and clinopyroxene, respectively. The clinopyroxene K_D (0.22) is consistent with an earlier study by Kretz (1963) in which the Fe-Mg partition coefficient for coexisting igneous orthopyroxenes and clinopyroxenes is shown to be approximately $K_D = 0.73$.

Using the empirical data of Roeder and Emslie (1970) equations can be developed (Appendix C) which allow determination of equilibrium solid and liquid compositions. By combining these effective distributions with ideal molar concentrations, M_i , where

 M_i = Fe + Mg in phase i, approximate FeO and MgO total concentrations, as well as the appropriate Fe' value, are determined for derived liquids. It should be noted that the compositions of solid and liquid phases in equilibrium are necessarily dependent on the fraction of liquid remaining or produced; however, for low degrees of melting, Fe'_{L} will remain close to the value determined by $K_D = 0.3$. In addition, the Fe^{\prime} value is affected by the presence of phases such as spinel which, when melted, increase the proportion of MgO in primary liquids. Crystallization models, when a primary magma composition can be estimated, are essentially mass-balance calculations between the proportion of phases extracted and the resultant liquid. Chemical models presented in the following section are facilitated by incorporation of these variances in order to account for major element abundances. As shown in subsequent sections on intermediate and silicic magma models, calculations of CaO and Al_2O_3 are ineffective due to greater degrees of incongruency in melting although the relative compositions of FeO and MgO are obtained.

2.4 Magma Genesis

Geochemical models of magma production are initially subject to the assumption of source composition. Previous studies outlined in Section 1.3 and reviews of basalt petrogenesis (Ringwood, 1975; Yoder, 1976; Wyllie, 1978) support the widely accepted concept that basaltic magmas are generated from ultramafic compositions in the upper mantle. Furthermore, Lopez-Escobar et al. (1977) determined that Chilean high-Al₂O₃ basaltic compositions are consistent with partial melting (10-15%) of garnet-free peridotite followed by crystallization of ferromagnesian minerals. A possible starting bulk compositions obtained

from natural xenoliths (Jagoutz et al., 1979). The spinel
lherzolite composition (Mg0 = 38.3 wt.%, Fe0 = 7.8 wt.%,
Fe' = 0.1) is nearly identical to Ringwood's pyrolite model
and is further supported by additional analyses for similar
ultramafic xenoliths (Basaltic Volcanism Study Project, 1981).

Figure 2-9 illustrates hypothetical La (ppm) and Fe' values obtained by various degrees of batch melting from an initial source of Fe' = 0.1 (spinel lherzolite) with an arbitrary La value of 1 ppm. The trend illustrated for olivine crystallization and plotted values for High Cascade basalt compositions indicate the necessity for a multistage model of magma genesis. Assuming that reasonable uniformity in the degree of partial melting is maintained, the absence of a definite fractionation trend in the basalt compositions leads to the inference of variable source compositions. Variances should be more evident for incompatible trace elements than major elements which require more significant contamination or depletion effects. Most basaltic La and Fe' compositions can apparently be derived by either ${\sim}8\text{--}15\%$ melting of a primitive source followed by ${\sim}28\text{--}32\%$ olivine crystallization or directly by similar degrees of melting from a previously fractionated (higher Fe') ultramafic source. Distinction between these two end-member mechanisms may be impossible; however, assuming that the most primitive basaltic Fe' value (TFJ-440, Fe' = 0.32) represents a nonfractionated primary melt, a probable source composition of Fe' = 0.14 (10% melted) is determined for $K_D = 0.3$. In addition, negligible changes in Co (ppm) abundances with variable Fe' in basalts are consistent with lower distribution coefficients obtained at higher temperatures (Irving, 1978) and suggest equilibration of all basaltic magmas at or near peridotitic source regions. Initial source compositions of Fe' = 0.14 require \sim 14% partial melting with \sim 12-20% fractionation to produce observed basaltic magmas having Fe' = 0.36-0.42.



Figure 2-9

Effects of partial melting and olivine fractionation on La and Fe' in liquids derived from a source of La=1 ppm and Fe'=0.1. Normal basalts (circles) are apparently obtained by a combination of melting and crystallization and indicate variable source compositions. Divergent basalts (filled triangles) are obtained by additional variables in source composition, partial melting, fractional crystallization and contamination in crustal regions (see text). Although the major element compositions may be relatively uniform for many hypothetical sources, additional constraints are needed to determine the relative abundances of trace elements. An earlier report (Hughes and Taylor, 1981) suggested that the High Cascade trace element compositions, particularly Ba, Sr and LREE, are inconsistent with generation from a chondritic, non-fractionated source. The nearly monotonic trace element variations illustrated in Figure 2-5 imply direct melting of an enriched source with subsequent crystallization limited to ferromagnesian minerals that have only minor fractionation effects.

Numerous modeling attempts have lead to fractionated source compositions that are relatively enriched in alkalis and LREE. Model-dependent compositions that are derived from chondritic sources require modal melting to produce observed La/Yb and Yb/Sc ratios, but exhibit trace element patterns that are depleted in relative abundances of Nd to Tb. In order to maintain the observed nearly monotonic pattern which exhibits a slight dropoff at Sc, melting of large fractions of clinopyroxene $(D_{Sc}^{Cpx} = 2.5)$ is required. A residuum which consists mainly of olivine and orthopyroxene (Fig. B-2) creates no significant perturbations in the trace element pattern due to low D values. Therefore, observed monotonic compositions probably reflect consistent source enrichments of K, Ba, Sr and LREE according to ionic size and mobility. These enrichments should lead to a regular pattern of decreasing abundances with decreasing ionic radii and suggest that upward migrating fluids in the upper mantle have been effective prior to magma genesis and have contaminated the source region. Fractionated fluids may have originated at depths where garnet is retained in residual fractions and become intermixed with overlying mantle material. Contamination from a deeper source is consistent with the

prehistory of calc-alkaline volcanism throughout the region (Armstrong, 1978) which required interaction of fluids generated from a down-going slab of mafic (as eclogite) crust. Dostal et al. (1977a, 1977b) suggest similar enrichments for sources of magmas erupted in the Central Andes.

Normal Basalts

Major and trace element compositions of High Cascade normal basalts are modeled with a 14% non-modal partial melt (ol200px35cpx40sp05) from a variably enriched spinel lherzolite source (o1₅₀opx₃₀cpx₁₅sp₀₅) accompanied by 12-22% olivine crystallization. Variable degrees of fractionation are invoked to produce the observed range in Fe' values while maintaining the regular pattern of trace element abundances. Figure 2-10 illustrates a range of source compositions having HREE and Sc abundances of 1.8-2.0 x chondrites and La abundances of 3.1-5.0 x chondrites. In addition, Ba, Sr and K (K plotted as 10 x chondrites) source concentrations indicate substantial increases over LREE abundances due to the higher mobility of alkali elements. The residual mineral $(ol_{55}opx_{29}cpx_{11}sp_{05})$ and trace element compositions (LREE depleted) are similar to those of natural spinel lherzolite xenoliths obtained from alkalic provinces reported by the Basaltic Volcanism Study Project (1981). Such similarities suggest that lherzolitic xenoliths represent refractory residua of mantle source regions, a relation that is supported by the residual Fe' = 0.12 value which is nearly unchanged by low degrees of melting.

Although both olivine and plagioclase represent the only liquidus phases observed in substantial proportions, plagioclase fractionation effects are limited by near-absence of Sr and Eu anomalies in normal basalts. However, relatively high Cr, Co



Figure 2-10 Trace element and Fe' model calculated for the range (shown as upper dashed lines) of High Cascade normal basalts.
and Ni abundances, as well as low Fe' values preclude excessive amounts of mafic mineral fractionation and support the concept of an ultramafic origin. Sources in which garnet is a residual phase are also precluded by unreasonably high melt fractions needed to generate only moderately fractionated REE patterns. Primary melts generated from garnet-bearing sources would also exhibit low HREE abundances and require excessive olivine crystallization to produce the observed pattern.

The geochemical model involves maintenance of olivine as the liquidus phase, probably at elevated P_{H_2O} conditions. Consequential expansion of the olivine stability field observed by Nicholls and Ringwood (1973) allows liquidus occurrence of olivine at pressures up to 27 kbar (\sim 85 km) for PH₂O = P_{total} con-ditions; however, changes in K_{O1-1}^{Fe-Mg} occurred which limit this effect. Less saturated conditions probably allow liquidus occurrence of olivine at lower pressures which might imply that olivine stability is restricted to upper mantle regions $(\sim 30-50 \text{ km})$ when $P_{H_2O} < P_{total}$. Olivine crystallization is, therefore, regarded as a continuum of the melting event and the "phenocrysts" which are derived at depth may not be in perfect equilibrium with the extruded magma. The open-textured nature of most High Cascade olivine tholeiites further supports early involvement of volatiles which may continually exsolve throughout the final period of magma ascent. Olivine stability in source regions is shown in the following chapter to be even more effective in production of basaltic andesites which exhibit primitive (source-derived) olivine phenocrysts through a wide range of SiO₂ compositions.

Generation of normal High Cascade basalts probably occurs in upper mantle regions of spinel stability with contemporaneous fractionation at sub-crustal levels. Thus, the basalt magma reservoir would be located near the indistinct crust/mantle

boundary (\sim 40 km, R. W. Couch, pers. comm.) which is within the stability range of spinel lherzolite mineralogy of the pyrolite composition (Green and Ringwood, 1967).

MB-134

Sample MB-134 exhibits a trace element pattern (Fig. 2-6) with relative REE and Sc abundances similar to those of the least-fractionated normal basalts. It might be assumed that the higher total REE, Sc and Fe' (0.46) can be derived by fractional crystal-lization of olivine from a magma represented by the lower margin of the normal basalt field. However, the MB-134 REE pattern is roughly 1.5 times higher than the normal basalt pattern, thus requiring \sim 30 percent fractionation of normal basaltic liquids. Fractionation of 30 percent olivine from a magma having even the lowest observed Fe' value (0.36) for normal basalts would produce abnormally low Mg0 abundances and, therefore, an extreme Fe' value.

Similarities of modal mineralogy and texture of MB-134 to the normal basalts suggests that the magmas are derived from source regions in close proximity to each other, although different source chemistries are necessitated. A magma corresponding to the MB-134 composition is derived from a source having HREE-Sc abundances of 2.1 x chondrites, moderately fractionated LREE $(La_{c.n.} = 3.2)$ and an Fe' value (0.14) that is similar to the normal basalt source. The composition (Fig. 2-11) is modeled by 14 percent partial melting followed by \sim 38 percent crystallization of olivine and plagioclase in the ratio of \sim 3:1. Plagioclase crystallization is required to produce the small negative Sr anomaly, yet the amount introduced in the crystallizing fraction is insufficient to cause appreciable Eu effects.

The mineralogy determined for the MB-134 source is essentially



Figure 2-11 Trace element and Fe' model determined for the generation of MB-134, a high Fe basalt. Olivine crystallization may occur at various levels within the upper mantle or lower crust although minor plagioclase fractionation occurs at higher levels in lower to upper crust regions.

that which was determined for the normal basalt models. Assuming that these source regions are chemically and spatially related, such that the MB-134 source is a derivative of the normal basalt source region, it is possible that fractionation effects have been operative in the upper mantle region. This effect, observed in major and trace element geochemistries, implies a mechanism of fluid migration upwards as residual solid phases are compacted downward. Petrochemical differences between most High Cascade basalts are, therefore, related to fractionation effects and incompatible element migrations within the upper mantle source region. Although the possibility of shallow-level changes is not altogether excluded, sample MB-134 likely represents magma derived in the upper levels of the source region.

WR-225 and TFJ-440

Geochemical models which account for the production of magmas having compositions of WR-225 and TFJ-440 require drastic changes in source chemistry if these magmas are considered to involve processes similar to those of the normal basalts. The obvious contamination of TFJ-440 (Section 2.2) indicates that such changes in source composition are probably not as effective as selective incorporation of crustal components. The relative alkali-LREE pattern of WR-225 is very similar to that of TFJ-440, although the absolute trace element abundances are lower. While $(Ba/La)_{C.n.}$ ratios of normal basalts are less than ~ 2 , $(Ba/La)_{C.n.}$ ratios of WR-225 and TFJ-440 are 3.0 and 2.6, respectively, in support of the concept of similar crustal histories for these contaminated units.

The primary difference between the magmatic histories of TFJ-440 and WR-225 is probably related to the slight to moderate Sr-Eu anomalies and higher relative Sc in WR-225. Sample

TFJ-440 may be regarded as the result of crustal contamination by a more silicic composition where mobile elements are selectively incorporated into a primary magma; however, WR-225 represents only minor effects from sialic anatexis due to the low total REE. Conversely, the composition of WR-225 is probably related to assimilation of gabbroic components, perhaps during crustal residence, within a primary magma similar to that which was contaminated to produce TFJ-440. The most viable explanation for WR-225 is the incorporation of plagioclase and clinopyroxene representing cumulate minerals in a mafic intrusion, which became resorbed upon entering a hotter primary magma. The addition of these mineral compositions would lower total REE while increasing relative concentrations of Eu, Sr, Sc and Ca.

3. INTERMEDIATE UNITS

3.1 Sample Descriptions and Petrography

Intermediate rock types in the Three Sisters region include units which exhibit the predominant basaltic andesite $(53-58 \text{ wt.\%} \text{ SiO}_2)$ or the subordinate andesite $(58-62 \text{ wt.\%} \text{ SiO}_2)$ compositions. Sixteen basaltic andesites and five andesites are included in this section although two of the andesites (BT-383 and BT-386) represent the early silicic highlands developed on the east flank of the High Cascade system. The remaining three andesites (TFJ-433, TS-627 and TS-686) have close lithologic, geologic and chemical affinities to more mafic systems. The apparent disparity between andesites in the study area implies possible genetic differences between "mafic" andesites and "silicic" andesites. In addition, the paucity of andesitic field representatives probably reflects only a variance of each andesite type from the more predominant mafic or silicic system with which it is associated.

Basaltic Andesites

Petrographic and chemical studies have been used to distinguish two major groupings within the basaltic andesites. The designations are "North Sister" (NS) type and "Mount Washington" (MW) type in reference to prominant eruptive centers within the respective regions of occurrence. Samples classified as Mount Washington type include the following:

EM-92 Holocene (\sim 3000 y) basaltic andesite from late Nash Crater; near Fish Lake Campground.

TS-631 Holocene (\sim 2500 y) basaltic andesite from Four-in-One Cone; terminus of main N.W. lobe of lava flow.

- TFJ-436 Holocene (\sim 2900 y) basaltic andesite from Little Belknap Cone; S.E. of Belknap Crater on Skyline Trail.
- TFJ-491 Basaltic andesite which comprises main part of Mount Washington; from central plug.
- BT-392 Basaltic andesite component of Todd Lake Volcano; cliffs at Century Drive and Todd Lake Road junction.
- BT-394 Basaltic andesite at lower falls on Fall Creek, N. of Sparks Lake.
- BT-396 Basaltic andesite from Broken Top Volcano; east end of Tam McArthur Rim.
- B-143 Early High Cascade basaltic andesite lava flow; N.W. abutment of Tumalo Dam.

Samples EM-92, TS-631, TFJ-436 and TFJ-491 are associated with eruptive centers northwest of North Sister and BT-392, BT-394 and BT-396 are related to vents in the Broken Top area southeast of South Sister. The EHC sample, B-143, occurs east of the Broken Top system and, although not within the immediate proximity, probably represents an early Pleistocene eruption of this type. It will be shown that sample BT-394 is somewhat chemically divergent and is possibly related to the silicic highland derivatives.

Basaltic andesites which are classified as North Sister type include the following samples:

- TS-628 Olivine-rich basaltic andesite of the W. lobe, central gutter of lava from Collier Cone; N.W. flank of North Sister.
- TS-622 Basaltic andesite from midstream of Collier flow on Proxy Falls Trail.

- TS-691 Basaltic andesite from the N. marginal levee of Collier flow; Obsidian Trail.
- TS-629 Basaltic andesite from the S. marginal levee of Collier flow; Linton Lake Trail.
- TS-692 Basaltic andesite which comprises a large part of North Sister, near Lane Mesa.
- TFJ-434 Basaltic andesite on the N. side of HWY 20; N. of Blue Lake.
- TFJ-437 Holocene basaltic andesite from central stream gutter; east lobe of lava flow from Yapoah Cone.
- BT-384 Aphyric Pleistocene basaltic andesite from quarry outcrop N.W. of Black Pine Spring.

All samples except TFJ-434 and BT-384 represent eruptive products of Collier Cone or vents located in the immediate vicinity. The basaltic andesite sample TFJ-434 was obtained approximately 25 km north of North Sister and BT-384, an apparently divergent type, occurs on the east flank of the High Cascade system.

Distinctions between MW and NS basaltic andesite types are based primarily on trace element abundances although subtle petrographic differences are evident. Both types exhibit variable amounts of plagioclase phenocrysts with lesser amounts of olivine and minor amounts of augite and hypersthene as microphenocrysts. In addition, hypersthene microphenocrysts are more prevalent in evolved members of both types suggesting similar trends of magmatic evolution. A wide range of textures is apparent for both types, but MW units are generally more intergranular to intersertal and NS units are most often trachytic. Petrographic details, compiled in Tables 3-1 and 3-2, are summarized for both types in the following discussion. Phenocryst compositional data are based on combined thin-section, spindle stage and chemical

Sample	Overall	Phenocrysts	vo1%	avg. size (range)	Groundmass	
	lexture			(mm)	phases	texture
EM-92	dickty.	pl	<1	3.0		
	sP/medium	01	<1	0.6 (0.2-1.0)	h1,chx,01,2h,d1	sub-oph.
TS-631	P/aphanitic	pl (An _{a+})	15	1.0(0.2-2.0)	nl(An) ony al	4
	seriate	0]	1	0.5 (0.2-1.0)	SP, OPX	Intersertal
TE.1-436	cD/modium	срх	<1	0.3 (0.1-0.8)		
110-430	byalonilitic	p_{1} (An ₈₃)	1	0.8 (0.5-1.0)	pl(An ₇₃),gl,ol,	intersertal
(glomero	(glomerocryst	s)	ł	0.8 (0.2-1.2)	cpx,sp(Usp ₄₁)	
TE.1_401 ^C	B/fing		_			
110-451	rrine	p_1 (An ₈₄)	5	0.8 (0.5-1.2)	p],cpx,sp,o]	granular
		o]	12	0.2(0.1-0.5)		-
		opx	<1	0.2(0.1-0.3)		
BT-392	cD/fina	n]	0			
	3171 me	-pr	2	0.8 (0.5-1.2)	pl,cpx,sp	granular
	xenolith =	$n \left(\Delta n_{} \right)$	<u> 1</u>	0.3(0.1-0.6)		
	$(\sqrt{7}$ mm dia.)		40	0.8 (0.1-1.2)		
		орх	3	0.2		
BT-394	P/medium	n] (An)	15		•	
	· / me a · am	0]	10 ~1	1.5(0.2-2.0)	pl,cpx,sp(Usp ₄₁),	granular,
		CDX	<1	0.4 (0.2-1.2) = 0.4 (0.2-1.2)	01	somewhat
		~ F *	1	0.4 (0.2-1.2)		pilotaxitic

Table 3-1. Petrographic data of Mount Washington type basaltic andesites.

Sample	Overall Texture	Phenocrysts	vo1%	avg. size (range)	Groundma	155
				(mm)	phases	texture
BT-396	P/coarse seriate	pl (An ₈₄) ol (Fo ₇₈) opx	5 2 2	$\begin{array}{c} 1.5 & (1.0-2.0) \\ 1.5 & (1.0-2.0) \\ 0.8 & (0.5-1.2) \end{array}$	pl,cpx,ol,sp,gl	granular
B-143	P/medium dickty.	p] (An ₈₄) cpx o]	10 <1 <<1	1.0 (0.5-1.6) 0.3 (0.2-0.5) 0.2 (0.1-0.3)	pl,cpx,sp,ol	pilotaxitic granular

Table 3-1. (continued)

a) P=porphyritic, sP=subphyric.

b) Groundmass phases are listed in order of abundance.

c) Sample TFJ-491 exhibits two stages of phenocryst growth; see text.

Overall	Phenocrysts	vo]%	avg. size (range)	Groundmass		
lexture			(nm)	phases	texture	
P/aphanitic hyalopilitc	ol (Fo ₈₄) pl (An ₈₅)	10 10	2.0 (1.0-4.0) 1.5 (1.0-3.0)	pl,gl,cpx,ol, sp,opx(tr)	trachytic	
P/medium	p] (An ₈₅) o] (Fo ₈₄) cpx opx	10 2 <1 <1	2.0 (0.5-3.5) 1.5 (1.0-3.0) 0.4 0.3 (0.2-0.4)	pl,cpx,gl,sp,ol	trachytic	
P/fine	p1 (An ₈₅) o1 (Fo ₈₅) cpx opx	3 2 <1 <1	1.2 (0.5-2.0) 2.0 (0.5-2.0) 0.4 <0.2	pl,cpx,opx,gl, sp,ol	granular, somewhat intersertal	
P/fine	p1 (An ₈₅) o1 opx	2 <1 <<1	0.8 (0.2-1.5) 0.2 (0.1-0.4) 0.1	pl,cpx,opx, sp,ol	trachytic	
P/medium seriate	pl (An _{so}) ol	10 <1	1.2 (0.5-2.0) 0.2 (0.1-0.8)	pl(An _{eo}),cpx, ol,gl,sp	trachytic	
sP/fine	p] (An ₈₀) o]	1 <1	0.8 (0.2-1.2) 0.2 (0.1-0.3)	pl,cpx,sp,gl, ol(tr)	intergran- ular	
	Overall Texture P/aphanitic hyalopilitc P/medium P/fine P/fine P/medium seriate sP/fine	Overall TexturePhenocrystsP/aphanitic hyalopilitcol (Fo pl (An $0l$) pl (An $0l$)P/mediumpl (An $0l$) (Fo $0l$) (Fo $0l$) (Fo $0l$) (Fo $0l$) (Fo $0l$) (Fo $0l$) (Fo $0l$) (Fo $0l$) (Fo $0l$)P/finepl (An $0l$) (Fo $0l$) (Fo $0l$)P/finepl (An $0l$) opxP/finepl (An $0l$) opxP/finepl (An $0l$) opxP/finepl (An $0l$) olSP/finepl (An $0l$) ol	Overall TexturePhenocrystsvol%P/aphanitic hyalopilitcol pl (Anøs)10P/mediumpl (Anøs)10P/mediumpl (Anøs)10P/finepl (Anøs)2cpx opx<1	Overall TexturePhenocrystsvol% avg. size (range) (mm)P/aphanitic hyalopilitcol (Fo) pl (An5)102.0 (1.0-4.0) (1.0-3.0)P/mediumpl (An5) ol (Fo)102.0 (0.5-3.5) ol (Fo4)P/mediumpl (An5) 	Overall TexturePhenocrystsvol% avg. size (mm)avg. size (range) (mm)Groundmass phasesP/aphanitic hyalopilitcol (Fogs)102.0 (1.0-4.0)pl,gl,cpx,ol, sp,opx(tr)P/mediumpl (Angs)102.0 (0.5-3.5)pl,gl,cpx,ol, sp,opx(tr)P/mediumpl (Angs)102.0 (0.5-3.5)pl,cpx,gl,sp,olP/mediumpl (Angs)21.5 (1.0-3.0)pl,cpx,gl,sp,olP/finepl (Angs)31.2 (0.5-2.0)0.5-2.0)pl,cpx,opx,gl, sp,olP/finepl (Angs)31.2 (0.5-2.0)0.5-2.0)pl,cpx,opx,gl, sp,olP/finepl (Angs)20.8 (0.2-1.5)0.2 (0.5-2.0)pl,cpx,opx,gl, sp,olP/finepl (Angs)20.8 (0.2-1.5)0.2 (0.1-0.4)pl,cpx,opx, sp,olP/medium seriatepl (Angg)101.2 (0.2 (0.1-0.8)0.1 ol,gl,spP/medium seriatepl (Angg)101.2 (0.2 (0.1-0.8)pl ol,gl,spsP/finepl (Angg)10.8 (0.2-1.2)pl,cpx,sp,gl, ol(tr)	

Table 3-2. Petrographic data of North Sister type basaltic andesites.^a

Table 3-2.	(continued)
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S	Sample	Overall Texture	Phenocrysts	vol%	avg. size (range) (mm)	Groundmass phases	texture
Т	FJ-434	sP/medium	p1 (An ₈₅) o1	<1 <1	1.0 (0.4-1.2) 0.4 (0.1-0.8)	pl(An ₈₅),cpx, sp,ol,opx	trachytic
т	FJ-437	P/medium hyalopilitic	pl (An ₈₆) ol	15 <1	1.0 (0.5-2.0) 0.8 (0.4-1.0)	pl,gl,ol,cpx, sp,opx	intersertal

a) See footnotes on Table 3-1.

b) Samples TS-628, TS-622, TS-691 and TS-629 are representatives of Collier lava; see text.

analyses used to obtain optimum values.

Plagioclase phenocrysts, often present as glomerocrysts, occur in variable proportions up to ~15 percent and sizes up to ~4 mm (Fig. 3-1a). Large phenocrysts are either zoned with resorbed interiors or, more predominantly, very weakly zoned and subhedral, whereas smaller grains are essentially unzoned and euhedral. Seriate textures are common and in some units more than one plagioclase growth stage is evident. Compositions of plagioclase grains (other than microphenocrysts) range An_{80} - An_{88} and are typically around An_{85} regardless of size. These compositions are generally more calcic than basaltic plagioclase compositions which may be indicative of fundamental differences in magma source regions. Plagioclase microphenocrysts in one unit, TFJ-491, have a composition of An_{78} in association with larger phenocrysts of An_{84} , implying that fractionation is not appreciable.

Olivine phenocrysts, with the notable exception of Collier lava (Fig. 3-1b) are not nearly as prevalent in basaltic andesites as in basalts and usually occur as microphenocrysts (< 0.5 mm) or less often phenocrysts in low abundances. Although some phenocrysts of olivine are euhedral to subhedral, most microphenocrysts occur as unaltered, subhedral to anhedral grains. Only three samples (EM-92, TS-692 and BT-396) are olivine normative (ol/qtz norm. cutoff at 54 wt.% SiO₂), indicating that olivine grains in most units exist in disequilibrium with SiO₂enriched glassy mesostasis. Olivine compositions for three Collier lava samples are Fo_{84} - Fo_{85} and one MW sample (BT-396) has an olivine composition of Fo_{78} .

Pyroxene phenocrysts, especially orthopyroxene, are scarce in both types of basaltic andesites. Augite microphenocrysts are present in only a few samples although clinopyroxene occurs as a ubiquitous groundmass phase in all units. Hyperstheme Figure 3-1 (a-d) Photomicrographs of basaltic andesites:
A) TS-622 (crossed nicols) plagioclase porhyritic unit with relatively unzoned phenocrysts;
B) TS-628 (crossed nicols) olivine-rich basaltic andesite exhibiting effects of crystal accumulation; C) TS-631 (crossed nicols) basaltic andesite with two stages of plagioclase growth typical of many units; D) BT-392 (plane light) sample with coarse-grained xenolith of pl+cpx+opx+sp.



Figure 3-1

microphenocrysts are present in the Collier lava, exhibiting variable proportions (all < 1%) with SiO_2 content, and in the Mount Washington (TFJ-491) and Broken Top (BT-396) samples. Groundmass occurrence of orthopyroxene, however, is apparently more predominant in the Collier samples, although this observation is probably provisional.

Titaniferous magnetite is the predominant opaque phase in all units and is locally evident as rare microphenocrysts. Combined XRD/XRF analyses, as outlined in the previous chapters, of two magnetic separates (TFJ-436 and BT-394) indicate a composition of Usp₄₁ for both samples which also plot in the altered region of Figure 2-1. Accessory apatite occurs as acicular or short prismatic crystals in all sections studied, but is more noticeable in coarser-grained units. Brown, translucent glass comprises the remainder of the groundmass in most sections and occurs in a wide range of proportions.

Cooling histories portrayed by petrographic features are essentially consistent among all basaltic andesites. The usual pattern includes an initial growth stage of phenocrysts ($pl \pm ol$), a period of resorption, and later growth stages of microphenocrysts (pl \pm cpx \pm opx \pm ol) followed by final groundmass crystallization and/or quenching. This sequence is best typified by the sample from Mount Washington (TFJ-491), which has ~ 5 percent resorbed plagioclase (An $_{84})$ and ${\scriptstyle \sim}2$ percent olivine phenocrysts along with \sim 15% plagioclase (An₇₈) and \leq 1% orthopyroxene microphenocrysts in a microgranular groundmass. Multiple stages of plagioclase growth are observed in other basaltic andesites as portrayed by the TS-631 photomicrograph of Figure 3-1c. In addition, the samples from Collier lava exhibit a decrease in $pl \pm ol$ phenocrysts with increasing SiO₂ until an andesitic composition is obtained at the vent. These relations suggest a history of crustal or sub-crustal residence for basaltic andesite magmas

prior to eruption. The magmas probably accumulated in a reservoir (initial phenocryst growth) and were later transported to near-surface locations while remaining in the conduit prior to eruption and cooling.

Additional evidence of crustal evolution is provided by sample BT-392 from Todd Lake Volcano which displays variable lithology and textures due to physical mixing. The textural variation, expressed as a sharp sinuous contact between areas of differing grain size, is possibly caused by continual disruption of the cooling surface. However, a coarse-grained xenolith having apophyses, which project into the main mass, represents an earlier-cooled volcanic unit scoured from the walls of the conduit. The xenolith (Fig. 3-1d) is composed of plagioclase (An_{77}), augite, hypersthene, magnetite and apatite enclosed in a light-colored glassy groundmass while the finegrained subphyric host is devoid of orthopyroxene.

Andesites

Andesitic representatives of High Cascade volcanics are probably the least consistent petrographically (Fig. 3-2) and chemically and, like the basaltic andesites, are divisible into two major types. The general geologic association of andesites with either the early silicic highlands or with mafic systems leads to an informal classification into "silicic" andesites and "mafic" andesites, the features of which are discussed separately in subsequent sections. It is also apparent through geochemical characteristics that true andesites probably do not occur as a separate group and are genetically either high-silica basaltic andesites or low-silica dacites.

Units that are tentatively classified as mafic andesites which relate chemically and geologically more to the NS basaltic Figure 3-2 (a-b) Photomicrograph of High Cascade units having "andesite" SiO₂ contents. A) TFJ-433 (crossed nicols) olivine-plagioclase porphyritic unit re-classified as a high-silica basaltic andesite; B) BT-383 (crossed nicols) plagioclase-orthopyroxene-clinopyroxenespinel glomeroporhyritic unit re-classified as a low-silica dacite.



Figure 3-2

andesites include the following samples:

- TS-627 Glassy terminus of platy andesite flow from the W. base of Middle Sister.
- TS-686 Andesite lava from the source vent within Collier Cone; represents high-silica part of the predominantly basaltic andesite lava.
- TFJ-433 Glassy margin of Pleistocene andesite dome which comprises Hogg Rock.

The Collier vent sample (TS-686) represents an obvious genetic relation to basaltic andesites and the Middle Sister flow (TS-627) occurs in close proximity. Hogg Rock (TFJ-433) is located \sim 25 km north of Collier Cone.

Samples obtained from the east flank of the High Cascades which are classified as silicic andesites include two units:

BT-383 Platy andesite collected at the confluence of Squaw Creek and N. Fork Squaw Creek.

BT-386 High-TiO₂ andesite lava collected at the base of Tumalo Falls.

These two samples, collected ~ 15 km apart, are considered to be $1 \circ 0.5 \circ$

Mineralogic similarities are evident between two of the mafic andesite units, TFJ-433 and TS-686, whereas the third sample, TS-627, is nearly aphyric and fine-grained. Plagioclase phenocrysts in these representatives exhibit compositions (An_{84}, An_{86}) that are essentially identical with those of the basaltic andesites. Less abundant olivine phenocrysts, with

Sample Overall Texture		Phenocrysts	vol%	ol% avg. size (range) Groundmass (mm) phases t		ss texture	
TS-686 ^b (mafic)	P/medium hyalopilitic	р] (Ап ₈₆) о] (Fo ₈₅) орх срх	10 1 <1 <<1	3.0 (1.0-8.0) 1.5 (0.5-3.0) 0.8 (0.6-1.0) 0.2	pl,opx,cpx,gl,sp	intersertal	
TS-627 (mafic)	sP/fine hyalopilitic	p] 0]	<<1 <<1	1.5 (resorbed) 0.5 (0.3-0.6)	g],p],opx,cpx	trachytic ∿aphyric	
TFJ-433 (mafic)	P/medium	p] (An ₆₄) ol (Fo ₆₁) opx	10 1 1	1.0 (0.2-1.4) 0.6 (0.2-1.2) 0.6 (0.2-1.5)	pl(An ₇₀),opx, sp,gl	trachytic	
BT-383 ^C (silicic)	P/fine trachytic	p] (An ₅₅) cpx opx (En ₅₆) ol	20 5 1 <<1	1.5 (0.2-2.5) 0.5 (0.1-1.5) 0.8 (0.5-1.2)	pl,cpx,sp	intergran- ular	
BT-386 (silicic)	sP/fine	pl	1	1.0 (0.2-1.2)	pl,cpx,sp(Usp ₅₉), silica	pilotaxitic granular	

Table 3-3. Petrographic data of High Cascades mafic and silicic andesites.^a

a) See footnotes on Table 3-1.

b) Sample TS-686 is the andesitic representative of Collier lava; see text.

c) Sample BT-383 has chemical characteristics of dacites and represents the initial stages of petrogenesis for more silicic compositions.

compositions of Fo $_{85}$ (TS-686) and Fo $_{81}$ (TFJ-433), are also indistinguishable from basaltic andesite olivine compositions and support a mafic affinity. The negligible changes of phenocryst compositions in the Collier lava samples suggest that differentiation in bulk composition (52-60 wt.% SiO_2) is related to nearsource processes. Rapid magmatic ascent may allow sourcegenerated phenocrysts to exist metastably with quartz-normative Hypersthene phenocrysts also occur in low abundance and liquids. rarely display a reaction relation with equilibrating olivine grains. Groundmass phases are principally plagioclase (An₇₀), orthopyroxene, clinopyroxene and titanomagnetite which occur with substantial amounts of light brown amorphous mesostasis and accessory apatite. These mineralogic relations and similarities to basaltic andesites indicate the probability that magmas of variable compositions have equilibrated with common source regions and that chemical differentiation occurred in the primary stages of magma evolution.

The silicic andesites differ considerably from their counterparts associated with mafic systems. Both units sampled are essentially devoid of a glass phase and have mineral constituents indicative of more felsic compositions. Sample BT-383 contains phenocrysts of plagioclase ($\sim 20\%$) exhibiting a composition of An₅₅, lesser amounts of augite ($\sim 5\%$) and minor hypersthene ($\sim 1\%$) having a composition of En₅₈. Microphenocrysts of olivine are present in very low abundance as relicts of a higher liquidus temperature regime. In addition, sample BT-386 is subphyric and exhibits elongate, vein-like zones of light green cryptocrystalline silica. The same unit also contains opaque grains with a composition of Usp₅₉ in concert with the relatively high TiO₂ content and plots in the latered region of Figure 2-2.

3.2 Geochemistry

Geochemical characteristics of High Cascade intermediate compositions $(53-62 \text{ wt.\% SiO}_2)$ are summarized for volcanic groups outlined in the preceding section. The division between basaltic andesite and andesite at SiO₂ = 58 wt.\% is arbitrary and, as shown in trace element data, may be altogether misleading for intermediate units of North Sister association. In addition, the basalt sample BT-382, having the highest SiO₂ content of the basalt group, has chemical as well as petrographic characteristics which necessitate inclusion with the MW type basaltic andesites. Chemical analyses are presented in Tables 3-4, 3-5 and 3-7 for MW basaltic andesites, NS basaltic andesites and andesites, respectively. Table 3-6 lists chemical data obtained for mineral and matrix separates from two samples of Collier lava.

Major element data indicate olivine-normative whole rock compositions for SiO₂ values below 54 wt.% and quartz-normative compositions above that value. Variations in CaO/Al203 ratios with SiO₂ content are minimal (Fig. 3-3) and follow a continuous trend nearly coincident with that of basalts; however, the negligible variation does not substantially support a history of fractionation processes. The systematic trend in Fe' vs. MgO of basalt compositions is not recognized in the intermediate units, although the regression line for basaltic andesites (Fig. 3-4) indicates a rough trend which intersects the trend of basalt compositions. Intermediate rocks have Fe' values of 0.40-0.53 except for TS-628 (ol-rich Collier lava sample, Fe' = 0.32) and the two silicic highland and esites (Fe' > 0.61). While fractionation of olivine and plagioclase may be evident within the basaltic andesite groups, the divergence of Fe' vs. MgO from the normal basaltic trend suggests that they are not derivatives of basaltic liquids represented in the previous chapter.

- <u>-</u>	EM-92	BT-396	TFJ-436	TFJ-491	BT-392	B-143
<u> </u>			Major Oxides (%)		<u>,</u>	<u></u>
SiO_2 TiO_2 AI_2O_3 FeOC MgO CaO Na_2O K_2O	53.1 1.35 18.1 8.7 5.6 8.3 3.9 0.90	53.9 1.00 18.9 7.2 6.0 8.1 4.0 1.05	54.3 1.25 17.6 7.7 5.6 8.3 3.7 0.95	55.4 1.12 17.7 7.7 4.7 8.1 4.2 1.19	55.9 1.20 17.4 8.0 4.1 7.1 4.5 1.15	56.0 1.10 17.8 7.1 3.5 7.4 4.2 1.40
		Ţ	race Elements (pp	m)		
Sc Cr Co Ni	20.1 109 32.3 120	21.8 101 31.3 110	22.7 93 28.7 60	22.9 66 27.0 60	23.7 37 24.5 25	20.9 31 21.5 20
Rb Sr Cs Ba	12 800 0.15 330	6 650 0.19 260	15 740 0.28 310	10 520 0.62 340	23 740 0.55 370	33 650 0.75 370
La Ce Sm Eu Tb Yb Lu	17.0 43.7 22 5.08 1.65 0.70 2.11 0.37	12.7 31.8 18 3.67 1.33 0.58 1.69 0.25	16.4 40.3 25 4.74 1.59 0.74 2.15 0.40	15.2 37.4 17 4.16 1.49 0.73 1.97 0.31	14.6 35.7 18 4.30 1.42 0.60 2.09 0.37	17.5 41.9 22 5.12 1.48 0.69 2.19 0.31
Zr Hf Ta Th U	150 4.14 0.76 1.66 0.2	110 3.03 0.40 1.49 0.4	180 4.25 0.78 1.13 0.4	150 3.79 0.56 1.45 0.5	140 3.67 0.42 1.94 0.4	200 4.23 0.59 2.61 0.4
		л	ormative mineralo	۹y		
Il Mt Or Ab An Di-Hd Hy Ol Qz	2.6 2.1 5.3 33.4 29.0 10.0 14.0 3.6	1.9 1.7 6.2 34.2 30.3 8.0 13.3 4.4	2.4 1.9 5.6 31.7 28.4 10.4 17.5 1.6	2.1 1.9 7.0 36.0 25.7 11.9 14.8 	2.3 1.9 6.3 38.5 23.6 9.6 14.7 2.0	2.1 1.7 8.3 36.0 25.3 9.4 12.2 3.6

Table 3-4. Chemical abundances^a and CIPW normative calculations^b of Mount Washington (MW) type basaltic andesites.

Table 3-4. (cont.)

	BT-394	TS-631	uncertainty ^d (%)	average (±13)		
			Major Oxides (%)			
SiO ₂ TiO ₂ Al ₂ O ₃ FeO MgO CaO Na ₂ O K ₂ O	56.9 1.25 18.3 6.9 3.6 7.0 4.5 1.15	57.7 1.00 17.4 6.6 4.9 6.9 4.2 1.35	4-8 2-5 4-10 2-5 2-5 2-5 4-8 4-8	55.4 ±1.6 1.16 ±0.13 17.9 ±0.5 7.5 ±0.7 4.8 ±1.0 7.7 ±0.6 4.2 ±0.3 1.14 ±0.18		
		T	race Elements (ppm))		
Sc Cr Co Ni	21.2 47 18.8 35	20.5 58 24.0 30	1-2 2-4 2-3 19-20	21.7 ±1.3 68 ±30 26.0 ±4.7 58 ±39		
Rb Sr Cs Ba	24 520 0.40 350	21 530 0.66 370	30 5~10 50 5-10	18 ±9 646 ±111 0.45±0.23 338 ±38		
La Ce Nd Sm Eu Tb Yb Lu	12.2 31.8 19 4.62 1.59 0.76 2.75 0.45	14.1 31.2 20 3.75 1.30 0.63 2.05 0.33	1-3 5 10-30 1 1-3 5-10 5-10 5-10	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	•	
Zr Hf Ta Th U	200 3.92 0.57 1.70 0.4	120 3.55 0.64 2.08 0.7	50 3-8 8-12 5-15 5-15 5-15	156 ±34 3.82 ±0.41 0.59 ±0.14 1.68 ±0.52 0.42 ±0.15		
		n	ormative mineralogy	y		
Il Mt Or Ab An Di-Hd Hy Ol Qz	2.4 1.7 6.8 38.5 26.1 7.1 13.0 4.1	1.9 1.6 8.0 36.0 24.4 8.0 15.8 4.4				

a) Major oxides by XRF and AA; trace elements by INAA.

b) Il=ilmenite, Mt=magnetite, Or=orthoclase, Ab=albite, An=anorthite, Di-Hd=diopside-hedenbergite, Hy=hyperstheme, Ol=olivine, Qz=quartz. Calculations assume Fe₂O₃/FeO=0.20 (wt.%).

c) Total Fe analyzed as FeO.

d) Uncertainties correspond to counting statistics.

	TS-692	BT-384	TS-628	TFJ-434	TS-622	TFJ-437
	· ·		Major Oxides (%)		
SiQ_2 TiO_2 $A1_2O_3$ FeO MgO CaO Na_2O K_2O	53.2 1.11 18.3 7.9 5.6 9.1 4.1 0.80	54.2 1.05 13.4 7.6 5.7 8.2 3.3 0.30	54.6 0.75 18.3 6.8 8.1 6.9 3.7 0.75	55.5 0.85 19.2 6.3 5.2 7.6 3.8 0.75	55.7 0.80 19.5 5.9 4.8 7.6 3.8 1.05	56.4 0.80 18.8 6.1 5.0 7.6 3.9 1.10
		Tr	ace Elements (or	m)		
Sc Cr Co Ni	24.2 51 31.7 70	23.3 84 30.7 70	15.9 150 35.0 260	17.6 36 27.6 80	17.7 68 23.1 70	17.8 71 25.2 60
Rb Sr Cs Ba	4 530 0.18 230	12 570 0.49 200	24 410 0.56 260	11 680 0.25 160	20 610 0.59 290	21 650 0.55 300
La Ce Nd Sm Eu Tb Yb Lu	9.7 22.7 10 3.28 1.26 0.57 1.68 0.26	6.6 18.3 11 2.82 1.13 0.49 1.47 0.32	6.8 16.2 9 2.24 0.84 0.35 1.17 0.23	6.9 16.7 7 2.31 0.89 0.34 1.06 0.15	8.0 19.1 7 2.68 0.95 0.38 1.41 0.27	9.5 21.2 5 2.82 0.92 0.40 1.43 0.20
Zr Hf Ta Th J	80 2.57 0.34 0.89	60 2.46 0.29 0.82 0.4	110 2.24 0.27 1.23 0.4	60 2.06 0.27 0.79 0.2	130 2.59 0.34 1.47 0.7	100 2.75 0.38 1.62 0.5
		nor	mative mineralog	ly		, 4 4 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6
11 At Dr Ab Ji -Hd Jy Ji Ji Ji	2.1 1.9 4.7 35.1 28.9 13.2 7.3 6.8	2.0 1.8 4.7 32.5 30.6 8.2 19.0 0.8	1.4 1.6 4.4 31.7 30.9 2.7 27.1 	1.6 1.5 4.4 32.5 32.9 3.9 13.4 3.9	1.5 1.4 6.2 32.5 32.3 4.0 16.9	1.5 1.5 33.4 30.3 6.0 16.7

Table 3-5. Chemical abundances and CIPW normative calculations of North Sister (NS) type basaltic andesites.

Table 3-5. (cont.)

	TS-691	TS-629	uncertainty (%)	average (±1c	J)		
•		· · ·	Major Oxides (%)				
SiO ₂ TiO ₂ Al ₂ O ₃ FeO MgO CaO Na ₂ O K ₂ O	57.4 1.10 17.8 7.4 4.1 6.6 4.5 1.05	57.9 1.00 17.4 6.9 3.9 6.5 4.4 1.20	4-8 2-5 4-10 2-5 2-5 2-5 4-8 4-8	55.6 ±1.6 0.93 ±0.15 18.5 ±0.7 6.9 ±0.7 4.9 ±0.7 7.5 ±0.9 4.0 ±0.3 0.94 ±0.18	(excludes	TS-628)	
		Tr	ace Elements (ppm)				
Sc Cr Co Ni	21.1 27 22.5 17	19.5 30 20.5 <10	1-2 2-4 2-3 10-20	19.5 ±3.0 52 ±22 27.0 ±5.1 61 ±23	(excludes (excludes	TS-628) TS-628 & TS-629)	
Rb Sr Cs Ba	17 570 0.59 310	20 570 0.58 320	30 5-10 50 5-10	16 ±7 573 ±82 0.49 ±0.18 259 ±57			
La Ce Nd Sm Eu Tb Yb Lu	8.5 20.2 8 3.04 1.08 0.49 1.53 0.23	9.3 23.2 11 3.28 1.11 0.46 1.68 0.24	1-3 5 10-30 1 1-3 5-10 5-10 5-10 5-10	8.2 ±1.3 19.7 ±2.6 3.5 ±2.1 2.31 ±0.39 1.02 ±0.14 0.44 ±0.08 1.43 ±0.22 0.24 ±0.05			
Zr Hf Ta Th U	120 2.92 0.36 1.41 0.2	90 3.13 0.40 1.75 0.4	50 3-8 8-12 5-15 5-15	94 ±26 2.59 ±0.35 0.33 ±0.05 1.25 ±0.38 0.40 ±0.18			
		no	rmative mineralogy	,			
Il Mt Or Ab An Di-Hd Hy Qz	2.1 1.8 6.2 38.5 25.0 6.4 15.6 	1.9 1.7 7.1 37.7 23.9 6.8 14.3 5.8					

a) See footnotes in Table 3- .

	TS-628 olivine	plagioclase	groundmass	TS-622 olivine	plagioclase	groundmass	
TiO ₂ (%) Al ₂ O ₃ FeO MnO MgO CaO Na ₂ O K ₂ O	$\begin{array}{c} & & & & & \\ 4.6 & \pm 0.2^{a} \\ 14.7 & \pm 0.1 \\ 0.173 \pm 0.001 \\ 44.4 & \pm 0.8 \\ \hline 0.052 \pm 0.003 \\ \hline \end{array}$	33.5 ±0.3 0.49 ±0.01 0.0059±0.0002 0.25 ±0.1 1.65 ±0.01	0.88 10.05 18.7 ±0.2 5.92 ±0.03 0.102±0.091 4.3 ±0.2 7.0 ±0.4 3.91 ±0.01 1.1 ±0.2	4.1 ±0.1 14.67 ±0.06 0.179±0.001 44.0 ±0.9 0.053±0.001	33.8 ±0.3 0.52 ±0.01 0.0065±0.0002 0.3 ±0.1 17.3 ±0.7 1.65 ±0.01	1.08 ± 0.07 18.7 ± 0.2 6.15 ± 0.03 0.105 ± 0.001 3.3 ± 0.2 7.6 ± 0.4 4.22 ± 0.02 1.3 ± 0.2	
Sc (ppm V Cr Co Ni	e) 4.26 ±0.02 6 ±1 297 ±1 196 ±1 2730 ±50	0.55 ±0.01 6 ±3 62 ±1 1.16 ±0.03 4 ±1	17.59 ±0.04 146 ±5 101 ±2 23.3 ±0.2 28 ±8	4.48 ±0.03 8 ±2 205 ±2 190 ±1 2300 ±50	$\begin{array}{cccc} 0.62 & \pm 0.01 \\ 8 & \pm 2 \\ 62 & \pm 1 \\ 1.20 & \pm 0.02 \\ 3 & \pm 2 \end{array}$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	
Rb Sr Cs Ba	<0.2	0.5 ±0.4 980 ±10 0.012±0.006 24 ±5	8 ±2 600 ±50 0.61 ±0.09 280 ±40	<0.1 14 ±10	960 ±10 0.006±0.004 31 ±8	8 ±2 560 ±50 0.47 ±0.07 275 ±26	
La Ce Nd Sm Eu Tb YL Lu	0.05 ±0.01 0.023±0.004 0.005±0.003 <0.01 0.03 ±0.01 0.03±0.04	0.7 ±0.1 1.4 ±0.1 <2 0.14 ±0.01 0.24 ±0.01 0.002±0.001 <0.09 <0.004	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0.07 ±0.03 5 ±3 0.030±0.003 0.016±0.005 <0.04 0.12 ±0.04	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	19.3 ±0.5 	
Zr Hf Ta Th	30 ±20 <0.04 0.02 ±0.01	8 ±4 0.04 ±0.01 0.005±0.003 0.008±0.006	30 ±20 2.1 ±0.1 0.30 ±0.05 1.43 ±0.09	<25 0.05 ±0.03 <0.02	8 ±4 0.06 ±0.01 0.010±0.004 0.05 ±0.01	60 ±20 2.5 ±0.1 0.36 ±0.05 1.56 ±0.08	

Table 3-6. Chemical abundances (INAA) of olivine, plagioclase and groundmass separates extracted from TS-628 and TS-622. Collier lava basaltic andesites.

a) Statistical counting error, 1σ .

b) Total Fe as FeO.

	TFJ-433	(mafic) _b TS-686 ^b	TS-627	(si BT-386	licic) BT-383 ^C (dupl.)	uncertainty (%)
			Major Oxides (%)		
SiO_2 TiO_2 AI_2O_3 FeO MgO CaO Na_2O K_2O	59.7 0.70 18.4 5.7 3.8 6.3 4.1 1.05	60.0 0.80 17.5 5.8 4.0 6.0 4.3 1.50	61.7 0.75 16.2 5.4 4.2 5.4 4.1 1.30	58.6 1.90 16.1 8.6 2.6 5.5 5.0 1.40	62.2 1.00 16.5 5.6 2.0 4.3 5.0 1.75	4-8 2-5 4-10 2-5 2-5 2-5 4-8 4-8
	•	Tr	ace Flements (n	(mci		
Sc Cr Co Ni	13.9 39 20.3 35	14.1 56 19.5 70	14.6 70 21.1 70	23.1 3 16.9 11	16.1 (16.0) 6 8.9 (9.1) 	1-2 2-4 2-3 10-20
Rb Sr Cs Ba	15 640 0.29 260	27 490 0.83 360	42 360 1.20 440	35 500 1.06 430	26 420 (450) 0.61 550 (530)	30 5-10 50 5-10
La Ce Nd Sm Eu Tb Yb Lu	8.2 18.7 2.36 0.87 0.27 1.07 0.16	10.5 24.1 9 3.08 0.97 0.44 1.73 0.22	11.0 25.7 14 2.31 0.90 0.43 1.67 0.24	13.9 32.8 22 4.91 1.66 0.85 2.90 0.41	20.6 (18.5) 45.9 35 (23) 6.14 (5.93) 1.77 (2.24) 0.91 (1.15) 3.46 (3.27) 0.55 (0.48)	1-3 5 10-30 1 1-3 5-10 5-10 5-10
Zr Hf Ta Th U	100 2.50 0.25 1.12 0.1	140 3.44 0.46 2.31 0.6	100 3.39 0.51 3.05 0.6	170 4.41 0.67 2.14 0.9	170 (160) 5.22 (4.55) 0.79 (0.91) 3.10 (3.20) 1.3 (0.9)	50 3-8 8-12 5+15 5-15
		no	rmative mineral	ogy		·····
Il Mt Or Ab An Di-Hd Hy Ol Qz	1.3 1.4 6.2 35.1 28.5 2.3 15.1 9.9	1.5 1.4 8.9 36.8 23.8 4.9 14.3 	1.4 1.3 10.6 35.1 20.2 5.3 14.2 	3.6 2.1 8.3 42.8 17.1 8.6 11.0 	1.9 1.4 10.3 51.4 12.7 7.3 7.5 7.1	

Table 3-7. Chemical abundances and CIPW normative calculations of High Cascades andesites associated with mafic and silicic systems.

a) See footnotes in Table 3- .

b) Andesitic component of differentiated Collier lava.

c) Sample BT-383 probably represents a low-silica dacite composition.



Figure 3-3 Variation of CaO/Al₂O₃ with SiO₂ for basalts (circles) and basaltic andesites (closed squares). Uniform values along the regression line (least-squares fit) are maintained due to the absence of felsic mineral controls on differentiation.



Figure 3-4 Fe' vs. MgO comparison of basalts (circles) and basaltic andesites (triangles). Although the regression lines intersect, their divergent trends preclude derivation of basaltic andesites by mafic mineral fractionation from basalt magmas. Closed triangles (not included in regressions) indicate compositions of high silica basaltic andesites which exhibit "andesite" SiO₂ contents.

Substantial variations in Ni concentrations (17-260 ppm)are reflected in diverse Ni/Co ratios (Fig. 3-5) while the expected overall decrease in Ni/Co vs. Fe' is evident. Chromium abundances also vary widely (30-150 ppm); however, Sc (13.9-24.2 ppm) and Co (19-35 ppm) are relatively uniform and exhibit general decreases with increasing SiO₂ content. A marked displacement of siderophile element abundances is also evident in the two silicic type andesites, which exhibit lower concentrations of Cr (3-6 ppm), Co (9-17 ppm) and Ni (10 ppm).

Principal differences between the MW and NS basaltic andesite types are displayed by alkali and incompatible element abundances. Mount Washington units contain higher overall abundances of Na, K, REE, Hf, Ta and Th than NS basaltic andesites and mafic andesites for comparable SiO₂ concentrations. Although Rb, Cs and Zr data are not as distinct (higher analytical uncertainties for low abundances) similar relations are generally apparent for these elements. The two silicic andesites, BT-383 and BT-386, have individual differences in trace element chemistries that are less consistent.

MW Type Basaltic Andesites

Mount Washington type basaltic andesites are characterized by a more strongly fractionated trace element pattern than the normal basalt group. Chondrite-normalized LREE abundances (La = 37.1-53.2) are somewhat higher than those of basalts; however, HREE (Yb_{c.n.} = 8.0-10.3, excluding the divergent BT-394 sample) are indistinguishable from basaltic values and Sc_{c.n.} concentrations (2.54-3.00) are substantially lower and essentially consistent.

Trace element patterns for the Mount Washington sample and Holocene units occurring on the west side of the High Cascade



Figure 3-5 Variations in Ni and Co with Fe' for basalts (circles) and basaltic andesites (squares). Ni variations are consistent with olivine crystallization effects although uniform Co values within each group indicate separate magma generations. BT-386 and BT-383 represent products of greater degrees of crystal fractionation from mafic sources.



Figure 3-6 Chondrite-normalized trace element patterns of MW basaltic andesites erupted on the west side of the High Cascade crest. Uniformly-decreasing patterns suggest similar magmatic histories and are characteristic of primary melts.



Figure 3-7 Chondrite-normalized trace element patterns for MW basaltic andesites erupted on the east side of the High Cascades crest. All units exhibit uniformlydecreasing abundances which are characteristic of primary magmas.

crest are plotted in Figure 3-6 according to the method outlined in the previous chapter. Figure 3-7 illustrates the pattern for Pleistocene units which were erupted on the east flank. The monotonic decrease in chondrite-normalized abundances with decreasing ionic radii suggest that these basaltic andesites have not been substantially affected by crustal contamination or fractionation. Lack of appreciable Sr and Eu anomalies (Sm/Eu = 1.03-1.16) preclude plagioclase effects, although low Sc is consistent with residual clinopyroxene.

NS Type Basaltic Andesites and Andesites

Intermediate NS type volcanics produce strongly fractionated trade element patterns having overall abundances lower than those of MW basaltic andesites. Light REE ($La_{c.n.} = 20.0-33.4$) as well as HREE (Yb_{c.n.} = 5.02-8.20) and Sc (Sc_{c.n.} = 1.78-3.06) concentrations are consistently lower than the normal basalt pattern although K, Ba and Sr show slight overall increases.

Figure 3-8 illustrates the chondrite-normalized trace element patterns for Collier lava samples, including the andesite TS-686, in which only minor variations are evident. The identical relative abundances for samples ranging 54.6-60.0 wt.% SiO_2 can be attributed to fractionation of minerals, such as olivine, which do not significantly affect the relative pattern. The systematic increase of total REE is accompanied by similar increases of incompatible elements Cs, K, Hf, Ta and Th (Fig. 3-8), although the andesitic composition displays decreases in Sr, Eu and Sc probably indicating effects of clinopyroxene and plagioclase fractionation. The increasing Fe' values of Collier basaltic andesite samples (0.32-0.50) are in contrast to a slight decrease of Fe' in the andesite composition (Fe' = 0.45). These differences suggest that variations in magmatic evolution, albeit


Figure 3-8 Chondrite-normalized trace element patterns for NS basaltic andesite samples of the Collier lava flow which erupted on the northwest flank of North Sister. Triangles indicate the abundances for the "andesite" member of the flow.



Figure 3-9 Chondrite-normalized trace element patterns for NS basaltic andesites erupted from vents near North Sister and Hogg Rock (TFJ-434). Slight positive Sr and Eu anomalies for TFJ-434 and BT-384 suggest modests amounts of contamination by cumulate plagioclase ± clinopyroxene or crystal settling within these magmas.

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minor, occur within common reservoirs and eruptive stages. The variations are probably due to effects in the source region which allow retainment of mineral compositions equilibrated at depth.

The remaining NS basaltic andesites are plotted on Figure 3-9. Trace element patterns of these units are, with minor deviations, essentially identical to the pattern represented by the Collier samples. The similarities reflect comagmatic character and consanguineous evolution for intermediate magmas of this group.

Trace element patterns of andesites, regarded as high-silica basaltic andesites, are shown in Figure 3-10. The Collier (TS-686) and Middle Sister (TS-627) units have virtually identical patterns while the Hogg Rock sample (TFJ-433) exhibits lower total abundances. However, the Hogg Rock relative abundances differ in higher Sr, slightly higher Eu and lower Yb/Sc ratio. The differences may be attributed to the accumulation of clinopyroxene with minor amounts of plagioclase into a magma such as that represented by the other two NS type andesite compositions.

Further evidence of the fundamental differences in trace element geochemistries of MW and NS units is portrayed by incompatible elements exemplified by silica-normalized Hf and Ta values. Figure 3-11 illustrates the contrast of higher Hf and Ta for MW units when plotted against SiO_2 contents. In addition, virtually consistent Hf/Ta ratios of all intermediate units are reflected in the nearly identical patterns for Hf and Ta for the respective group. These relations imply common schemes of magma genesis, although sources may vary.

Andesites of Silicic Association

As outlined previously, the disparencies in mineral composition and major element chemistry between the andesites of



Figure 3-10 Chondrite-normalized trace element patterns of rocks which exhibit "andesite" SiO₂ compositions and are included in the NS basaltic andesite group on the basis of mineralogic and other chemical similarities. TS-686 is the high silica member of the Collier lava flow.



Figure 3-11 Comparison of incompatible elements Hf and Ta vs. SiO, for MW (squares) and NS (circles and triangles) basaltic andesites. Uniform Hf/Ta ratios in all units are reflected in the similar patterns generated for each element.

silicic association and MW and NS intermediate rocks are significant. Trace element patterns of BT-383 and BT-386 (Fig. 3-12) also indicate dissimilarities between these two units; however, the pattern of BT-386 is not widely divergent from the MW trace element patterns and closely resembles that of BT-394, a marginally divergent MW basaltic andesite. Although BT-386 and BT-394 maintain a relatively monotonic pattern such as other intermediate units, the HREE abundances ($Yb_{c.n.} =$ 13.0-13.7) are slightly greater yielding higher Yb/Sc ratios (Yb/Sc = 4.70-4.86) than MW units. Consistencies of other trace element abundances between BT-386 and BT-394 support, in addition to the patterns of Figure 3-12, an evolutionary connection relating these two units.

On the other hand, BT-383 exhibits higher LREE ($La_{c.n.} = 62.6$) and HREE ($Yb_{c.n.} = 16.4$) with slight negative anomalies of Sr and Eu (Fig. 3-12). The pattern also indicates a flattening of the HREE and a marked dropoff to Sc yielding a high Yb/Sc (Yb/Sc = 8.05) ratio. These differences may preclude consanguineity between BT-383 and BT-386 and suggest variations in fractionation effects of plagioclase and clinopyroxene or differing source chemistries.

3.3 Magma Genesis

Constraints on Source Composition

Initial considerations of chemical models for genesis of magmas having intermediate compositions concern the problem of parental magma(s). Derivation of basaltic andesites from either basaltic parents or as primary magmas is readily distinguished through cursory examination of major and trace element compositions of whole rock and mineral separates. Fractionation of a







basaltic parent via extraction of mafic minerals is insufficient to produce the steeper trace element pattern of MW intermediate units while maintaining similar HREE and lower Sc abundances. This process is also soundly precluded by the low total REE and Sc abundances of the NS types. These relations, along with the monotonic patterns displayed by both MW and NS types, suggest that primary intermediate magmas are generated by partial melting of different sources than those required for production of basaltic magma compositions. Occurrences of Mg-rich olivine and more calcic plagioclase in the basaltic andesites support this supposition.

Qualitatively the steeper trace element patterns and more mafic liquidus mineralogy are consistent with slightly lower degrees of both melting and fractional crystallization in the source regions. The primitive ol and pl compositions imply crystallization under influences of source chemistry; however, sources that are variably enriched in trace elements are probably required. Conversely, considering the small fractionation effects which occurred since initial magma segregation, the variable and slightly higher Fe' values of intermediate rocks require significant discordant effects of Fe-Mg partitioning during the early stages of magma evolution. The effect is observed in relatively consistent phenocryst compositions (Fo₈₅,An₈₅) in High Cascade intermediate units for whole rock compositions ranging $SiO_2 = 52.1-61.7$ indicating that these magmas were in equilibrium with consanguineous source regions at the time of magma segregation.

Bulk compositional variances in intermediate units is best exemplified by the sequence of Collier lava which exhibits a range of $SiO_2 = 54.6-60.0$. However, the most mafic sample, TS-628 (Fe' = 0.32) can be modeled as the addition of nine percent olivine (Fo₈₅) to a magma possessing the TS-622 composition



Figure 3-13

Variations in MgO (squares) and FeO (circles) vs. SiO₂ for Collier lava samples. Arrows indicate directions to compositions of olivine phenocrysts analyzed by INAA and indicate that TS-628 represents a portion of the lava which accumulated olivine phenocysts (9%) by gravity settling prior to eruption or while cooling. Olivine fractionation is precluded as a mechanism for deriving the remaining samples from TS-622. (Fe' = 0.41) as shown in Figure 3-13. The consequent range of primary Collier lava, $SiO_2 = 55.9-60.0$ and Fe' = 0.42-0.50, cannot be subsequently derived by fractional crystallization. Relatively consistent total MgO (Fig. 3-13) precludes significant extraction of olivine or pyroxene although normative quartz increases steadily.

Using $K_{ol-1}^{Fe-Mg} = 0.30$ (Roeder and Emslie, 1970), olivine with a composition of Fo₈₅ is in equilibrium with a calculated liquid having Fe' = 0.36. The observed normal range of High Cascade intermediate units is Fe' = 0.40-0.53 based on total Fe as FeO; however, significant proportions of Fe' will be represented as Fe₂O₂ in the titanomagnetite or residual dark glass phases observed in thin section. Recalculation of Fe_2O_2/FeO_2 ratios to effect Fe' values appropriate to olivine phenocrysts yields improbable ratios in the range $Fe_2O_3/FeO = 0.2-1.1$. Disequilibrium crystallization soon after segregation of intermediate magmas and/or incongruent melting/crystallization in the regions of magma genesis followed by guenching are retained as viable mechanisms to produce the observed unequilibrated petrologic features. The early formed phenocrysts may represent source-equilibrated compositions indicating that intermediate magmas have probably been derived from sources having Fe' = ∿0.15.

Volatile and Pressure Effects on Bulk Compositions

Low amounts of melting in the presence of a volatile phase (Wyllie, 1979) account for significant variations in bulk composition and place serious constraints on mathematical models of major element abundances. Model calculations as outlined in the previous chapter allow only approximations, especially for Ca and A1, and with lower degrees of melting become increasingly inadequate. Effects on the primary eutectic melt compositions caused by volatile and chemical enrichments are magnified for small degrees of melting; however, continued melting might tend to nullify these effects by allowing liquids to approach the ideal melt composition determined by the melting phases. In addition, the eutectic or peritectic melt composition will become displaced with the addition of volatiles and can only be approximated with experimental studies on phase systems.

Although major element concentrations can be qualitatively estimated via experiments on synthetic and natural systems under various conditions, Wyllie (1977) cautions that the problems with experimental petrology are extensive and usually related to the attainment of true equilibrium, especially during quenching. Experimental studies by Kushiro et al. (1972), Green (1973), Mysen (1973), Mysen and Kushiro (1974) and Mysen and Boettcher (1975, 1976) demonstrate the variability of "primary" liquid compositions produced by hydrous ($P_{H20} = P_{total}$) melting of pyrolite or natural lherzolite compositions at appropriate pressures. Nicholls and Ringwood (1973), for example, effectively argue that the dacitic glass produced by hydrous melting of a natural lherzolite at 26 kb, 1190°C (Kushiro et al., 1972) could not represent the liquid composition obtained during the experimental run. Nicholls (1974) further implies that "andesitic" glasses produced in the melting experiments of Green (1973), Mysen (1973) and Mysen and Kushiro (1974) are results of modification during quench crystallization. Besides, Green (1973) considers that liquids will approach alkali olivine basalt compositions for small degrees of melting of hydrous pyrolite at 20 kb, whereas Mysen (1973) and Mysen and Kushiro (1974) indicate andesite compositions for initial melting of hydrous lherzolite for pressures at least to 25 kb.

Compilation of extensive experimental data obtained for peridotite-H₂O-CO₂ systems by Wyllie (1978, 1979) enable crude estimates to be made of bulk compositions produced under variable conditions. Assuming that intermediate magmas are represented by quartz-normative compositions obtained by Nicholls (1974) and Mysen and Boettcher (1975) the phase diagrams of Wyllie (1979) can be used to approximate the conditions of magma genesis. Wyllie demonstrates that substantial changes in bulk. composition, especially SiO, content, are effected by variations in the degree of melting and CO_2/H_2O ratio within the mantle. Furthermore, the degree of melting is related to the amount of total CO_2 + H_2O as well as temperature for any given pressure regime. The phase diagrams (Wyllie, 1979) indicate that, for similar depths, compositions represented by the initial stages of magma production will change from olivine-normative to quartznormative with increasing (H_20/CO_2) vapor and/or decreasing amounts of total $H_20 + CO_2$ below saturation. These relations are consistent with the conclusion made by Kushiro (1972) that the boundary between the ol and opx fields is shifted towards more SiO₂-rich compositions in water saturated systems.

High Cascade intermediate compositions may be related accordingly to variable hydrothermal conditions which affect H_2O/CO_2 values and degrees of melting. Basaltic andesite magmas possessing lower SiO₂ contents melt out under lower $(H_2O/CO_2)_V$ conditions while units with higher SiO₂ are generated in regions of higher $(H_2O/CO_2)_V$ ratios. Figure 3-14 illustrates possible conditions responsible for continuous changes in bulk composition of initial liquids at the source, although the phase relations (Wyllie, 1979) are partly schematic. The trend shown for High Cascade intermediate units indicates possible P-X conditions which involve only negligible changes in depth of magma genesis $(^30 \text{ km})$.



Figure 3-14 Generalized P-X diagram indicating conditions of nepheline-, olivine- and quartz-normative magmas produced by melting peridotite sources (after Wyllie, 1979). Magma generation is impossible for conditions above the dolomite reaction boundary. The diagram suggests possible H₂O-CO₂ variations in the source as viable mechanisms producing cogenetic olivine- and quartz-normative liquids observed in High Cascades samples of basaltic andesite. BA = basaltic andesite; A = andesite. The degree of volatile saturation in magmas may be understood by comparison to an experimental system which exhibits characteristics analogous to the units analyzed in this work. High Cascade intermediate units are similar in geologic setting, petrography and major element chemistry to the Paricutin series studied by Eggler (1972). Eggler's experimental runs at pressures to 10 kb and $H_20_{melt} = 2-10$ wt.% indicate the presence of an H_20-C0_2 fluid phase during undersaturated conditions. Furthermore, liquidus plagioclase occurs for $H_20_m < \sim 2\%$ while orthopyroxene \pm olivine assumes the liquidus at higher H_20 contents. Eggler (1972) also suggests that the Paricutin lava had a water content of 2.2 \pm 0.5% at an eruption temperature of 1110 \pm 40°C. The predominance of plagioclase with subordinate amounts of olivine and orthopyroxene in High Cascade intermediate units implies similar conditions of H_20_m undersaturation.

Geochemical Models

Possible geochemical models for generation of intermediate magmas are based on the assumption of similar degrees of melting and source mineralogy for both NW and MW types due to their consistencies in major element chemistries and petrography. Source compositions for each type are calculated which yield the observed patterns with \sim 6-12% batch melting accompanied by variable minor amounts of contemporaneous equilibrium crystallization. It is necessary to invoke olivine fractionation for magmas having higher Fe' values, although trace element abundances may also be derived by lower degrees of melting from a similar source. The modeled source mineralogy (ol₅₃opx₃₀cpx₁₂spin₀₅) is very similar to that determined for basalts; however, the calculated melting mineralogy (opx₃₅cpx₆₅) is more appropriate to lower degrees of melting under volatile influence.

Figure 3-15 illustrates MW type liquid compositions derived by 6-12% partial melting of a spinel lherzolite source having $K_{c.n.} = 7.0$, La = 4.0 and HREE $_{c.n.}$ & Sc $_{c.n.} = 1.5$. A calculated liquid composition obtained by 10 percent olivine crystallization from the F = 10% melt is also shown in order to derive higher Fe' compositions. However, the modeled compositions do not predict true K and Ba abundances, probably due to their greater enrichments in the source(s) by rising fluids. In addition, the initial abundances of Co (80 ppm), Fe and Mg (Fe' = 0.15) are invoked to simulate a source that is slightly fractionated from a more primitive (Fe' = 0.1, Co = \sim 100 ppm) pyrolitic source.

Figure 3-16 illustrates NS type liquid compositions that are modeled via similar degrees of melting and fractionation of a source which exhibits lower overall abundances such that $K_{c.n.} = 6.0, La_{c.n.} = 2.4$ and HREE_{c.n.} & Sc_{c.n.} = 1.15. Collier magma, represented by TS-622, is obtained by 10 percent melting in conjunction with 10 percent olivine crystallization from this source. The variability in trace element chemistry between the MW and NS source regions may be more continuous than implied, but regional heterogeneity beneath the High Cascade system is evident. A heterogeneous upper mantle is further supported by the aforementioned spatial segregation of NS and MW vents.

Separation of olivine crystals probably occurs at or near the source of melting which results in primitive olivine compositions and the low abundances of olivine phenocrysts. Incongruent melting of orthopyroxene and the expansion of olivine stability under elevated $P_{\rm H_{20}}$ conditions (Nicholls and Ringwood, 1973) enhance olivine fractionation at the site of melt generation. Plagio-clase phenocrysts, however, are abundant and exhibit similar primitive compositions (largely unzoned) which imply equilibrium crystallization near source regions, but without observed



Figure 3-15 Trace element and Fe' model determined for MW basaltic andesites. Triangles indicate the average abundances for the MW group. Error bars for Nd are included due to greater analytical uncertainty.



Figure 3-16 Trace element and Fe' model calculated for NS basaltic andesites. Hexagons represent the average abundances of the NS group and the modeled dashed line corresponds to the TS-622 composition. Error bars for Nd are included due to greater analytical uncertainty.

fractionation effects on evolved magmas. The subsequent crystallization of plagioclase and pyroxenes, which may remain unsegregated by buoyancy and rapid magma ascent, thus apparently occurs in regions just above the melting zone or in even later stages of magma evolution. The continuum of minor olivine fractionation at the source precludes the generation of a mafic melt which later evolves to basaltic andesite. By contrast, basaltic andesite magmas are probably generated as primary liquids and subsequent sub-crustal or crustal fractionation leads to more silicic compositions.

Andesites associated with NS basaltic andesites can be modeled by the additional extraction of clinopyroxene with olivine $(ol_{70}cpx_{30})$ during initial stages followed by the equilibrium crystallization and segregation of plagioclase and clinopyroxene $(p1_{20}cpx_{80})$. Extraction of approximately 10 percent of these minerals is invoked to obtain the chemistries of TS-686 and TS-627 from the TS-622 basaltic andesite composition. The model-dependent composition is indicated by the lower margin and higher Sc value of the shaded region in Figure 3-17. Optical uniformity of plagioclase and (minor) clinopyroxene grains in basaltic andesites lends additional support to the equilibrium crystallization model which is also consistent with Collier lava evolution in that a change from liquidus ol+cpx to pl+cpx is effected at depth.

Addition of plagioclase to the liquidus at depth may also require plagioclase as a melting phase in the source. The transformation of spinel lherzolite to plagioclase peridotite (ol + opx + cpx + pl) probably occurs in the depth range 25-28 km (Yoder, 1976, p. 28) and primary magmas segregated from these depths or shallower will allow plagioclase on the liquidus. An alternative model, therefore, is also shown in Figure 3-17 for TS-627 and TS-686 which incorporates 5% pl in the source



Figure 3-17

Trace element and Fe' model determined for high silica basaltic andesites of NS association. Shaded region indicates slight range in modeled compositions and source residua obtained from variance in source mineralogies. The dotted line indicates the composition obtained by 10% melting and 10% crystallization (ol cpx_{30}) from the spinel-bearing source. The dashed line indicates the composition obtained by 10% melting of the plagioclase-bearing source. Error bars are given for Nd due to greater analytical uncertainty. See text for details of geochemical model.

mineralogy while maintaining similar source chemistry. A modeled 10 percent melt of $opx_{30}cpx_{20}pl_{50}$ from a source of ol₄₀opx₄₀cpx₁₅pl₀₅ entirely depletes plagioclase, thereby obliterating the effects of Sr and Eu partitioning. Equilibrium crystallization of $ol_{60}^{opx}20^{pl}20$ (30% crystallized) yields a composition similar to the NS andesites as indicated by the top margin and lower Sc value of the shaded region in Figure The slightly lower Sr abundance of TS-627 supports the 3-17. addition of plagioclase in source regions which may not be entirely depleted of feldspar during the melting event. The evolution of basaltic andesite and mafic andesite magmas may be initiated at depths near the boundary pl peridotite/sp lhersolite and require incongruent melting of orthopyroxene which enables immediate olivine crystallization. Both andesite compositions also suggest an alkali enrichment effect above that which would produce the relatively shallow alkali pattern shown in the modeled chemical abundances.

Lower REE and slight positive Sr and Eu anomalies of the Hogg Rock NS andesite composition (TFJ-433) are probably the result of plagioclase and clinopyroxene accumulation in a magma such as represented by Collier andesite (TS-686). The Hogg Rock composition is approximated by the model shown in Figure 3-18 which indicates a mixing of $cpx_{10} + pl_{20} + TS-686_{70}$. The mixing compositions were obtained by the relation $C_i^{\alpha} = C_i^{TS-686} \cdot D_i^{\alpha/L}$ according to the distribution coefficients listed in Appendix A. Hogg Rock, therefore, represents magma having a cumulate composition which has undergone a series of ol + pl + cpx fractionation (to obtain TS-686) followed by reincorporation of cumulate pl + cpx. The composition is also consistent with assimulation of previous pl + cpx cumulates by a TS-686 type magma such as indicated in the previous chapter for WR-225. These relations imply the possibilities of even more extensive fractionation which would result in substantially evolved compositions.



REE + Sc Ionic Radii

Figure 3-18

8 Mixing model for high silica basaltic andesite of Hogg Rock, TFJ-433. The model indicates contamination of a primary basaltic andesite magma, shown by the dashed line, with constituents extracted from cumulate minerals of a previous intrusion or the accumulation of phenocrysts within the TFJ-433 magma. Error bars shown for Nd due to greater analytical uncertainty.

Silicic andesites BT-383 and BT-386 may be the result of such extensive fractionation as exemplified by their relatively high Fe' values and low siderophile trace element abundances. The trace element and Fe' compositions of BT-383 can be obtained by 40 percent equilibrium melting of $opx_{25}cpx_{25}pl_{50}$ from a modeled source composition of TS-686 or TS-627 having a mineralogy of opx₁₀cpx₂₅p1₆₅. The source may be obtained as the (gabbroic) intrusive equivalent of basaltic andesite magmas or the results of extensive crustal fractionation. Figure 3-19 illustrates the effects of 40 percent melting of an NS type basaltic andesite composition which are essentially identical to 60 percent crystallization of pl₆₅cpx₂₅opx₁₀ from a lower crust intrusive magma represented by the same initial composition. Residual or crystallizing olivine (± orthopyroxene) is probably also required in order to deplete Co and Ni although the model-dependent K-Sc pattern is obtained through the effects of plagioclase and clinopyroxene fractionation. Magmas having compositions similar to BT-383 are therefore the result of partial melting in conjunction with equilibrium of + pl crystallization followed by a crustal history dominated by pl and cpx $(\pm opx)$ fractionation effects.

Magmatic compositions represented by BT-383, however, do not support a pl + cpx dominated crustal history and may be derived more directly by olivine crystallization closer to the source regions. Figure 3-20 illustrates a modeled composition which approaches that of BT-386 and exhibits the relatively monotonic pattern characteristic of primary melts. The source composition is calculated for a 10 percent melt of plagioclase peridotite ($ol_{40}opx_{40}cpx_{15}pl_{05}$) in conjunction with 28 percent ol or opx crystallization. The relatively high FeO and TiO₂ abundances of BT-386 may result from mafic mineral separations which produce tholenitic trends within mantle source regions. In such systems extraction of opx rather than dominant ol may be more plausible in producing low SiO₂ compositions with high FeO + TiO₂



Figure 3-19

Trace element and Fe' model calculated for the BT-383 (low-silica dacite) sample. The upper solid line shows the composition derived by either 60% crystallization or 40% melting of a basaltic andesite composition represented by the dashed line. Residual plagioclase, clinopyroxene and orthopyroxene are required for solid or liquid source material. Error bars are shown for Nd due to greater analytical uncertainty.



Figure 3-20 Trace element and Fe' model for evolution of BT-386 magma and comparison with the normal basalt field. The model suggests consanguineity between normal basalts and the BT-386 magma through processes of substantial olivine and pyroxene fractionation and the evolution of alkali-rich volatiles during crustal residence. Error bars are given for Nd which has greater analytical uncertainty.

enrichments. The close affinity of the BT-386 composition with the normal basalt pattern, also shown in Figure 3-20, suggests nearly identical source chemical compositions although slightly different source mineralogies are possible.

Intermediate magmas erupted in the High Cascade system evidently result from an interplay of incongruent melting, a continuum of olivine ± plagioclase ± pyroxene crystallization, assimilation of crustal constituents and/or further crustal fractionation. Regardless of the mechanism required for an individual species, it is apparent that these magmas are ultimately related to evolved upper mantle sources which have been selectively enriched in mobile LIL elements. The following chapter considers the continued effects of crustal influence on more silicic compositions which are largely the products of differentiation from primary intermediate magmas represented by low-Si0₂ basaltic andesites.

4. SILICIC UNITS

4.1 Sample Descriptions and Petrography

Silicic volcanic units in the Three Sisters region are represented by samples having dacitic (SiO₂ = 63-68 wt.%) and rhyodacitic (SiO₂ > 68 wt.%, K₂O < 4.0 wt.%) compositions. Dacites occur predominantly as lava flows of variable lengths, whereas more silicic members tend to be manifested as domes or short glassy lava flows. Rock samples obtained for this study represent units emplaced in the central, southern and southeastern sections of the Three Sisters region and are associated with the development of the early silicic highlands, Middle Sister and South Sister volcanoes (Taylor, 1978; Wozniak, 1982). It will be shown in subsequent sections that dacites and rhyodacites have separate definitive chemistries regardless of temporal and spatial associations. Greater petrochemical affinities exist among those units having similar silica concentrations (i.e., dacites vs. rhyodacites).

Dacites

The following samples were selected to represent High Cascades dacitic compositions:

- TS-687 Glaciated Pleistocene remnant of lava flow which issued from a plug exposed at the base of Middle Sister; black glassy margin at E. base of Lane Mesa.
- TS-689 Glaciated Pleistocene lava from buried vent on N.W. flank of Middle Sister; cliffs E. of Sisters Springs.
- BT-390 Pleistocene flow N.E. of Todd Lake; glassy margin at cliffs adjacent to Three Creek Lake Road.

BT-395 Pleistocene lava which flowed south from South Sister; Century Drive road cut between Goose Creek and Fall Creek.

BT-397 Platy dacite at S.W. margin of Three Creek Lake; possibly part of early silicic highland.

Samples TS-687 and TS-689 are the dacitic representatives of a silicic sequence of flows erupted from the base of Middle Sister. Both units are older than the plagioclase basalt porphyry (TS-688) which veneers much of the TS-687 dacite. The two dacite flows south and east of Broken Top, BT=390 and BT-397, are probably derivatives of the silicic highland which developed adjacent to the mafic High Cascades platform in early Pleistocene time. The remaining sample, BT-395, is obtained from a later Pleistocene unit which, although younger than silicic highland eruptions, is older than the South Sister Holocene domes occurring in general proximity. All dacitic rocks in the area are grey to black and porphyritic with finely crystalline or glassy groundmasses. Petrographic data, compiled in Table 4-1, are largely similar to the BT-383 silicic andesite (Table 3-3) which may be regarded as a low-silica dacite.

Plagioclase, the dominant phenocryst phase, occurs in proportions of 6-15 percent as variably resorbed subhedral laths with glassy interiors. Most units (TS-687 and BT-395 in particular) contain glomerophenocrysts of feldspar enclosing subordinate amounts of mafic phases. Compositions are variable, often due to strong zonation exhibited by some grains; however, where zoning is minimal, relative consistency is maintained throughout the thin section. Overall compositions range $An_{37}-An_{63}$ and probably reflect variable degrees of equilibration during fractionation. Groundmass plagioclase grains typically display indistinct boundaries and often exhibit a trachytic arrangement.

Sample	Overall Texture ^a	Phenocrysts	vol%	avg. size (range) (mm)	Groundmass phases	texture
TS-687	P/v. fine hyalopilitic (glomerocrysts)	p] (An ₃₇) opx (En ₅₄))sp (Usp ₆₂) cpx	10 2 1 <1	$\begin{array}{c} 1.5 & (0.5-3.0) \\ 0.8 & (0.5-1.8) \\ 0.2 & (0.1-0.5) \\ 0.6 & (0.4-1.2) \end{array}$	p],g],sp,cpx(tr)	glassy
TS-689	P/fine	pl (zoned) cpx sp (Usp ₄₆) opx (apatite) ^C	6 2 1 1 <1	$\begin{array}{c} 2.0 & (0.5-3.0) \\ 0.5 & (0.2-0.8) \\ 0.2 & (0.1-0.3) \\ 0.5 & (0.2-1.0) \\ 0.2 & (0.1-0.2) \end{array}$	p1,sp,cpx	granular trachytic ap imbedded in opx
BT-390	P/fine hyalopilitic	p] (An ₅₀) opx (En ₆₅) sp (Usp ₃₀) cpx	15 4 2 <1	2.0 (0.4-3.5) 0.4 (0.1-0.8) 0.2 (0.1-0.3) 0.1 (<0.3)	p],g],cpx,sp	glassy vesicular
BT-395	P/fine hyalopilitic (glomerocrysts)	p] (An ₆₃) cpx opx (En ₆₂) sp (Usp ₄₀)	12 2 1 1	1.0 (0.5-2.5) 0.3 (<1.0) 0.3 (<1.0) 0.2	p],g],sp,cpx(tr)	trachytic
BT-397	P/fine	pl (An₃⁊) opx (En₅₀) sp	10 2 <1	1.5 (0.8-3.5) 0.6 (0.2-1.0) 0.2	p],cpx,g],sp	granular

Table 4-1. Petrographic data of High Cascades dacites.

a) P=porphyritic; most units exhibit glomerocrysts of pl+cpx+opx+sp.

b) Groundmass phases listed in order of abundance.

c) Apatite occurs as euhedral grains associated with pyroxenes; see text.

Orthopyroxene and clinopyroxene phenocrysts (and microphenocrysts) occur as subhedral, slightly rounded prismatic grains in total proportions of 2-4 percent. However, augitehypersthene relative proportions are inconsistent as a result of low overall abundances and the tendency for both pyroxenes to form glomerocrysts with plagioclase. The resultant effect of mutual crystal attachment, which may eventually lead to differential settling velocities, is apparently the disruption of homogeneous nucleation. Hypersthene compositions ranging En_{54} - En_{65} are compatible with plagioclase An contents although orthopyroxenes exhibit much less variation. A reaction relation with olivine is also evident in at least one sample (TS-687, Fig. 4-1a) and further contributes to the evidence of disequilibrium crystallization.

Primary spinel phases occur as microphenocrysts of titaniferous magnetite and are often included within the silicate glomerocrysts. Compositions range Usp_{38} - Usp_{62} and, virtually unoxidized by deuteric effects, plot on the ulvospinel-magnetite join of Figure 2-2. Spinel proportions are < 1-2 volume percent and represent the third or fourth most abundant mineral phase.

Apatite is present in abundances that preclude delimitation solely as an accessory phase. Relatively large prismatic grains of primary apatite are included in pyroxene phenocrysts of TS-689 (Fig. 4-1b) and are present within the glomerocrysts of that sample. In addition, spectacular apatite needles occur imbedded in plagioclase phenocrysts of the BT-390 dacite while other units contain conspicuous amounts of accessory apatite.

Rhyodacites

Use of the term "rhyodacite" rather than "rhyolite" to designate rocks having silica compositions greater than 68 weight percent is made in consideration of their relatively low

Figure 4-1 (a-d) Photomicrographs of High Cascades dacites and rhyodacites. A) TS-687 (crossed nicols) hypersthene-plaqioclase porphyritic dacite which exhibits a reaction relation between olivine and pyroxene; B) TS-689 (plane light) dacite with primary apatite crystals included in pyroxene phenocrysts; C) BT-391 (plane light) rhyodacite showing the variable effects of volatile exsolution and inflation; D) TS-650 (crossed nicols) rhyodacite with strongly corroded plagioclase phenocrysts exhibiting glassy interiors.



Figure 4-1

 K_20 contents (see Taylor, 1978). Originally, four units were selected for petrochemical study, but chemical analysis of two additional samples from the South Sister system (Wozniak, 1982) has enhanced the characterization of rhyodacite evolution. The following samples represent the most chemically evolved magmatic units in the Three Sisters region:

- BT-385 Three Creek Butte early Pleistocene rhyodacite dome; sample from summit.
- BT-391 Rhyodacite at E. base of Todd Lake volcano; waterfalls at Todd Lake outlet stream.
- TS-690 Obsidian flow on N.W. Flank of Middle Sister; Obsidian Cliffs west of Sisters Spring.
- TS-650 Holocene rhyodacite dome on E. flank of Devils Hill; S. end of South Sister dome chain.
- TS-1717 Holocene rhyodacite dome on N.E. flank of South Sister; N. end of dome chain (K. Wozniak, coll.).
- TS-1752 Rock Mesa rhyodacite flow; S.W. flank of South Sister (K. Wozniak, coll.).

Three Creek Butte (BT-385) is the manifestation of a relatively early eruption and one of the most silicic of a series of rhyodacite domes emplaced soon after the Pliocene Cascades subsidence. The series is largely overlain by later flows erupted from the west. Todd Lake volcano, represented by BT-391, is also an older silicic center, although its eruptions represent a later stage of the early silicic highlands. Both systems, in addition to lower Tam McArthur Rim, Melvin Butte, at least nine additional partly buried domes and other silicic lavas of Tumalo and Squaw Creeks (BT-383, BT-386, BT-390 and BT-397) are eruptions of the early Pleistocene highlands described by Taylor (1978).

Later Pleistocene silicic activity commenced with the

Obsidian Cliffs flow, TS-690, which is associated with the two subsequent dacite units, TS-687 and TS-689, occurring within the vicinity. The remaining samples, TS-650, TS-1717 and TS-1752, are essentially contemporaneous representatives of Holocene activity of the South Sister system. Two of the last three samples, TS-650 and TS-1717, emerged from a fissurecontrolled lineament (N.10W.) expressed as a chain of silicic domes (Taylor, 1978) and, along with TS-1752, were probably derived from a common magma reservoir. The Holocene eruptions often produced sluggish surface flows which spread laterally from some of the domes. An additional feature is the development of extensive pumice ramparts in response to the frothing effects of upper-chamber degassing. It is likely, in light of numerous contemporaneous rhyodacite eruptions and fissure ventings, that the activity was accompanied by local foundering of the upper crust although displacements were apparently minor.

Thin section analyses of three rhyodacite samples (Table 4-2, excludes obsidian) indicate a predominant porphyritic texture similar to the dacitic rocks; however, the rhyodacites unsurprisingly exhibit greater effects of inflation (Fig. 4-1c) due to volatile exsolution and expansion. As in dacites, plagioclase is the dominant mineral phase, but yields greater consistency in composition $(An_{27}-An_{28})$ as well as lower An contents. Strong corrosion of plagioclase is evident (Fig. 4-1d) as resorbed phenocrysts strewn with patches of light tan glass.

Subordinate amounts of hypersthene, augite and unaltered titano-magnetite are present usually as microphenocrysts. Iron-titanium analyses of spinel separates from two samples are inconsistent (Usp_{28} and Usp_{54}) and, in the same manner as dacitic spinels, reflect either low siderophile abundances which produce more variability in Fe/Ti ratios or fractionation effects of Fe-Ti oxides along with other ferromagnesian minerals.

Sample	Overall Texture	Phenocrysts ^b	vo1%	avg. size (range) (mm)	Groundmass phases	texture
TS-650	P/fine hyalopilitic	p1 (An ₂₈) cpx opx sp (Usp ₂₈)	15 2 1 <1	0.8 (0.5-2.0) 0.1 (0.02-0.8) 0.1 (0.02-0.8) 0.1	p],g]	glassy inflated
BT-391	P/fine-med.	p] (An ₂₇) opx sp (Usp ₅₄) cpx	15 4 1 <1	1.0 (0.2-3.0) 0.8 (0.1-1.2) 0.1 (0.1-0.2) 0.2 (0.1-0.3)	pl,sp,cpx	variable ^C inflated
BT-385	sP/fine	p] (An ₂₇) sp	1 <1	1.5 (1.0-2.0) <0.1	pl,sp,cpx(tr)	inflated

Table 4-2. Petrographic data of High Cascades rhyodacites.^a

a) See footnotes on Table 4-1.

 b) All units (except obsidian) exhibit strongly resorbed plagioclase phenocrysts with glassy interiors.

c) The variable textures of BT-391 range from nearly aphanitic to medium according to degree of inflation caused by volatile influences.

Generally, a petrographic distinction can be made on the basis of mineral compositions and textures between mafic and silicic members of the entire volcanic suite. The distinction does not preclude the existence of a continuum of petrographic properties within High Cascade units and possibly represents a local break in the petrogenetic trend. The following section provides geochemical arguments concerning the evolution of silicic compositions from mafic parents and outlines additional constraints to the apparent petrochemical hiatus.

4.2 Geochemistry

Dacite and rhyodacite whole rock geochemistries, compiled in Tables 4-3 and 4-5, are notably enriched in alkali, light rare earth and other incompatible elements relative to mafic members of the volcanic suite. Siderophile element concentrations are diminished overall, although a more drastic reduction in Fe, Ti and Sc occurs between dacites and rhyodacites. The average trace element composition of dacites is comparable to the BT-383 (low-silica dacite) sample, a comparison that also precludes recognition of "true andesites" (BT-386?) as intermediate compositions between basaltic andesites and dacites. Major element evidence for a petrochemical hiatus includes a strong increase in Fe' values (0.55-0.90 in silicic rocks) and variably higher Na₂O contents (4.5-6.1 wt.%); however, most major element trends shown in Figures 4-2 and 4-3 indicate continuous differentiation at least from basaltic andesite compositions. The irregularities of ferromagnesian elements are also apparent in erratic variations of MgO/(TiO₂ + FeO) vs. SiO_2 shown in Figure 4-4a, implying possible fractionation of source regions which may variably enhance Fe and Ti contents.

	TS-687	TS-689	BT-390	BT-395	BT-397	uncertainty ^d (%)
			Major Oxides (%	() ()		
Si02 Ti02 Al203 Fe0 Mg0 Ca0 Na20 K20	54.8 0.75 16.3 5.4 1.0 3.0 6.1 1.90	63.3 1.15 15.7 5.3 1.4 3.8 4.8 2.35	68.2 0.65 15.2 3.7 0.4 2.1 5.9 2.60	64.5 1.05 15.7 5.3 1.4 3.8 4.8 2.35	68.0 0.70 15.7 3.9 1.0 2.1 5.9 2.77	4-8 2-5 4-10 10-20 4-8 4-8 4-8 4-3
		 !	Trace Elements (p	opm)		
Sc Cr Co Ni	12.9 4.5 5	15.9 7 7.2 10	11.1 1 2.6 20	13.2 2 9.3 15	11.4 1 2.5 15	1-2 5-10 5-10 20-30
Rb Sr Cs Ba	26 290 0.60 510	28 360 0.42 570	41 220 1.91 550	48 350 1.05 600	47 210 0.72 480	10-20 5-10 10-20 5-10
La Ce Nd Sm Eu Tb Yb Lu	20.4 46.4 25 6.26 1.14 3.75 0.58	22.0 48.3 30 6.44 1.92 0.89 3.35 0.52	22.7 58.5 32 5.81 1.68 1.11 3.73 0.54	20.7 46.0 26 5.12 1.54 0.80 2.70 0.44	25.8 61.3 29 6.07 1.71 1.22 3.76 0.54	1-3 5 10-30 1 1-3 5-10 5-10 5-10
Zr Hf Ta Th U	6.37 0.75 2.52 0.9	180 5.34 0.71 2.54 1.2	220 7.45 1.05 4.84 1.3	170 5.56 0.86 4.29 1.8	210 7.38 1.08 4.66	20-30 3-6 8-12 5-10 5-10
			Normative Minera	logy		
II Mt Or Ab An Di-Hd Hy Qz	1.4 1.3 11.2 52.2 11.1 3.2 7.2 11.6	2.2 1.5 10.6 49.6 11.7 5.6 8.4 10.0	1.2 0.9 15.4 50.5 7.0 3.0 3.5 17.3	2.0 1.3 13.9 41.1 14.1 4.0 7.1 15.5	1.3 0.9 16.4 50.5 7.8 2.2 5.7 15.3	

Table 4-3. Chemical abundances^a and CIPW normative calculations^b of High Cascade dacites.

a) Major oxides by XRF and AA; trace elements by INAA.

b) Same parameters as Table 2-3.

c) Total Fe analyzed as FeO.

d) Uncertainties correspond to counting statistics.

See text for explanations.
	bas	e of Middle Sister.		
		plagioclase	groundmass	معبد
TiO ₂ Al ₂ O ₃ FeO MnO MgO CaO Na ₂ O K ₂ O	(%)	$\begin{array}{r} 0.10 \pm 0.05^{a} \\ 25.9 \pm 0.2 \\ 0.39 \pm 0.01 \\ 0.0053 \pm 0.0004 \\ \hline 7.6 \pm 0.4 \\ 7.05 \pm 0.01 \\ \hline \end{array}$	$\begin{array}{r} 0.64 \pm 0.05 \\ 15.9 \pm 0.2 \\ 4.55 \pm 0.03 \\ 0.117 \pm 0.001 \\ 0.10 \pm 0.05 \\ 2.3 \pm 0.2 \\ 6.37 \pm 0.02 \\ 2.24 \pm 0.34 \end{array}$	
Sc V Cr Co Ni	(mqq)	$\begin{array}{rrrr} 0.238 \pm 0.004 \\ 6 & \pm 4 \\ 1.5 & \pm 0.3 \\ 0.25 & \pm 0.02 \\ 4 & \pm 2 \end{array}$	$ \begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	
Rb Sr Cs Ba		1030 ±20 0.018±0.008 240 ±20	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	
La Ce Nd Sm Eu Tb Yb Lu		$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	
Zr Hf Ta Th		38 ±6 0.034±0.009 0.006±0.004 0.016±0.005	220 ±50 7.0 ±0.3 0.83 ±0.07 3.09 ±0.09	

Table 4-4. Chemical abundances (INAA) of plagioclase and groundmass separates extracted from TS-687 dacite plug at the west base of Middle Sister

- a) Statistical counting error, 1 σ .
- b) Total Fe as FeO.

	TS-650	TS-690	TS-1717	TS-1752	BT-385	8T-391
			Major Oxides (%)	- 	
SiO_2 TiO_2 $A1_2Q_3$ FeO MgO CaO Na ₂ O K ₂ O	71.5 0.35 14.1 2.3 0.7 1.9 4.5 3.30	75.8 0.09 12.8 1.1 0.5 0.9 4.7 3.82	71.8 0.34 14.7 2.4 0.8 1.9 4.9 3.52	72.3 0.29 14.1 2.1 0.8 1.7 4.6 3.72	75.0 0.15 13.4 1.8 <0.2 0.7 5.2 3.55	70.9 0.45 14.6 3.1 <0.2 1.5 5.1 2.65
			frace Elements (p	pm)		
Sc Cr Co Ni	4.1 2 3.2 15	3.1 2 0.9 9	8.5 4 6.4	6.6 5 5.2	8.2 1 1.1 7	22.3 3 4.9 20
Rb Sr Cs Ba	65 200 2.5 750	115 160 4.16 880	135 190 5.3 790	130 170 5.1 830	135 210 3.74 780	105 165 1.67 710
La Ce Nd Sm Eu Tb Yb Lu	20.2 37.1 14 3.17 0.79 0.36 1.86 0.34	21.4 71.5 18 2.83 0.85 0.45 1.70 0.29	20.8 87.2 16 3.39 1.61 0.66 2.21 0.35	21.7 76.9 19 3.45 1.29 0.59 2.28 0.36	29.1 109 28 6.07 1.32 1.71 4.29 0.68	22.4 125 27 6.40 3.30 2.19 3.85 0.62
Zr Hf Ta Th U	140 4.83 0.94 7.36 2.3	130 5.14 1.54 12.2 2.9	310 10.2 1.95 15.4 3.3	260 8.63 1.76 14.7 3.6	300 12.6 2.32 14.7 3.1	520 17.7 2.30 11.6 2.3
			formative Mineral	ogy	*****	
I1 Mt Or Ab An Di-Hd Hy Qz	0.7 0.6 19.5 38.5 8.3 1.0 3.9 26.3	0.2 0.3 22.6 40.2 2.3 1.8 1.7 30.7	0.7 0.6 20.8 41.9 7.4 1.7 3.9 23.4	0.6 0.5 22.0 39.4 6.6 1.6 3.7 25.4	0.3 0.4 21.0 44.5 2.4 0.9 2.3 28.2	0.9 0.8 15.7 52.2 4.3 2.8 2.6 20.4

Table 4-5. Chemical abundances^a and CIPW normative calculations^b of High Cascade rhyodacites.

a) Major oxides by XRF and AA; trace elements by INAA; uncertainties same as in Table 4-3.

b) Same parameters as Table 2-3.

c) Total Fe analyzed as FeO.

See text for explanation.



Figure 4-2 Silica variation diagrams for major elements in mafic (triangles) and silicic (circles) samples. Mafic units include high silica basaltic andesites and silicic units include the BT-386 andesite sample. Erratic FeO/MgO values in silicic compositions accentuate the effects of very low MgO and higher analytical error near the limit of Mg resolution.



Figure 4-3 Silica variation diagrams for High Cascade major elements in mafic (triangles) and silicic (circles) rock types. High K and Na/K values are indicated for contaminated magmas TFJ-440 and possibly S-91.

The felsic characteristics of these more evolved units are attested in their normative mineral compositions, notably with the increase in normative quartz, albite and orthoclase. Figure 4-5 illustrates the ternary plot of normative Or-Ab-An of silicic units compared to basalts and basaltic andesites (including TFJ-433, TS-686 and TS-627). A relatively restricted band of mafic samples yields to a less confined trend in the silicic units while positions of plagioclase compositions (Table 4-4 and earlier sections) indicate possibilities for wide variances in feldspar fractionation. Variances in fractionation trends signify the onset of disequilibrium crystallization expressed as a change from relatively unzoned feldspar in basaltic andesites (An₈₅, INAA) to more intensely zoned feldspar in dacites (An₃₇, INAA). The drastic change in An compositions represents the change from near-source equilibrated phenocrysts to crystallization of plagioclase during crustal evolution.

Plagioclase analyses suggest that alkali elements Cs, Rb and K are exclusively contained in derived liquids and trapped liquid mesostases along with excess SiO_2 . Chemical abundances in the dacitic plagioclase compared to the groundmass composition (Table 4-4) yield partition coefficients, summarized in Appendix A, which are higher than those determined for mafic systems. Higher D_i values, in conjunction with the change in plagioclase compositions from basaltic andesite to dacite, reflect lower temperatures (Drake, 1972) and more evolved conditions although changes in SiO₂ contents are moderate.

Trace element comparisons provide more substantial evidence of bi-modal chemical evolution. Figure 4-4b illustrates segregated fields of compositions having mafic and silicic affinities in a plot of $Ca0/Al_2O_3$ vs. La although the overall negative slope possibly represents a modest fractionation trend. The diagram also indicates the positions of plagioclase compositions which,



Figure 4-4 Variations in MgO/(TiO_+FeO) vs. SiO_ (A) and CaO/Al_O_ vs. La (B) for mafic (Circles) and stlicic (triangles) units illustrating the petrogenetic hiatus between the two groups. Arrows in A reflect trends of olivine addition or subtraction. Plagioclase compositions (INAA) in B indicate the requirements for additional mineralogic controls during differentiation to silicic units.



Figure 4-5 Ternary diagram of normative feldspar compositions illustrating the variability in plagioclase An contents with evolution of silicic units. TFJ-440 and possibly S-91 represent basalt magmas which were contaminated by crustal constituents. Plagioclase compositions determined by INAA on phenocryst separates from dacite (TS-687), basaltic andesite (TS-622 and TS-628), and basalt (TS-688) samples plot as K-free plagioclase along the Ab-An join. if extracted, could not produce the trend without combined effects from additional phases.

Trace element abundances of silicic units are represented in Figures 4-6 and 4-7 which illustrate chondrite-normalized abundances of Cs, Rb, K, Ba, Sr, REE and Sc. Both diagrams indicate non-monotonic decreases in abundances from Cs to Sc with strong negative anomalies of Sr and high Yb/Sc chondritenormalized ratios (6.5-20.5) as compared to mafic units. Only slight negative Eu anomalies are present in some samples due to maintenance of Eu³⁺ at higher f_{02} (Weill and Drake, 1973), probably under volatile influence. Nearly identical dacite patterns exhibit consistent REE and Sc, although they are somewhat variable in alkalis. Conversely, rhyodacite patterns show greater consistency in Cs, Rb, K, Ba and Sr, but widely variable HREE and Sc. The alkali patterns probably explain the consistency of measured rhyodacite plagioclase compositions relative to dacitic plagioclases, while the heavily depleted HREE and Sc abundances of some rhyodacites reflect variable effects of pyroxene fractionation. Rhyodacites also exhibit a moderate positive Ce anomaly, probably caused by changes in Ce^{3+} to Ce^{4+} brought about by volatile interaction. Tetravalent Ce will have a smaller ionic radius than Ce^{3+} (Whittaker and Muntus, 1970) and, therefore, greater compatibility with mafic mineral phases and less compatibility with accessory minerals that are highly enriched in LREE (Exley, 1980).

Wide variations of incompatible and rare earth element abundances are possible through the addition or subtraction of accessory phases, such as apatite, which incorporate large amounts of REE (Nagasawa, 1970), expecially during hydrothermal stages of magma evolution (Exley, 1980). Watson and Capobianco (1981) conclude that apatite-bearing residuals in crust-derived rocks have substantial REE depletion effects in felsic magmas.



Figure 4-6

Chondrite-normalized trace element patterns for dacites in the Three Sisters region.



Figure 4-7 Chondrite-normalized trace element patterns for rhyodacites in the Three Sisters region.

They further argue that, because of dramatic decreases of apatite solubility with falling temperature and increasing SiO_2 content, apatite saturation is inevitable in melts formed by fractional crystallization of an intermediate parent.

4.3 Silicic Magma Evolution

Trace element patterns of Figures 4-6 and 4-7 along with variable Na₂O contents indicate obvious results of plagioclase and clinopyroxene fractionation which notably diminish Sr and Sc and perhaps HREE and Eu (Appendix B). Enrichments in alkalis and LREE as well as irregular Fe' and Fe/Ti values are consistent with additional effects of orthopyroxene and titanomagnetite fractionation. The presence of variable amounts of these four minerals as phenocrysts and glomerocrysts in silicic units provides further evidence of combined mineralogic controls of differentiation.

The role of plagioclase-orthopyroxene/olivine-augitemagnetite (POAM) fractionation is reviewed by Gill (1981) as a viable mechanism of andesite magma genesis. Ferromagnesian minerals provide obviously effective agents for increasing silica contents in residual liquids. Enrichment of SiO₂ is also obtained by subtraction of plagioclase in the presence of water vapor (Johannes, 1978) which effectively raises the An content of plagioclase in equilibrium with liquid. Although problems remain with the probability of magnetite crystallization in some orogenic systems, Gill (1981) argues that magnetite stability, greatly dependent on f_{O_2} , is enhanced by hydration and the presence of apatite and has higher thermal stability in high-K relative to low-K systems. These effects do not seem to predominate in basaltic andesites of the present study although apparently prevail in the silicic representatives. Geochemical modeling of dacites to rhyodacites may be fruitless in light of innumerable mineralogic and compositional parameters only briefly summarized in the preceding sections. However, the average dacite trace element abundances, virtually identical to the BT-383 composition, are obtained similarly through the model used in the previous chapter (Fig. 3-19). Some dacitic compositions are therefore produced by 60 percent or more fractionation of $pl_{65}cpx_{25}opx_{10}$ (± sp) from a NS basaltic andesite magma. Inclusion of Fe-Ti spinel is evidently necessary in variable proportions, although it has little effect on the overall trace element pattern.

Other dacites and rhyodacites may not be generated by the same proportions of POAM fractionation. Figure 4-8 illustrates fractionation controls of pl, cpx and opx on NS and MW type intermediate magmas calculated as Rayleigh fractionation trends under equilibrium conditions according to models outlined in Appendix B. Although the trend of cpx fractionation from a MW source passes through a field of silicic analyses, a better trend (to include pl) is illustrated by the heavy line vector of pl65cpx25opx10 fractionation (60% extracted) from a NS source. Apparently, either wide variations exist in the proportions of the fractionating phases or processes of selective enrichments or depletions by REE-rich accessories and increasing compatibility of REE in major minerals are operative at lower temperatures and higher SiO₂ contents. Quantitative assessment of these influences is presently unobtainable; however, Figure 4-8 may be used as a qualitative model of dacite and rhyodacite evolution if the effects of accessory phases are assumed to be negligible.

The inception of POAM fractionation may be further constrained by the relative abundances of Sr, which behaves incompatibly with early olivine fractionation, and K which is relatively incompatible throughout POAM fractionation. Correlations



Figure 4-8 Fractional crystallization models used to determine mineralogic controls on the evolution of silicic units in the Three Sisters region. Solid lines represent 50% fractionation of individual minerals from an NS source and the dashed lines represent the same for an MW source. The heavy solid line indicates the model used for derivation of BT-383 (low-silica dacite) by 60% fractionation of an NS magma.

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of Sr vs. SiO_2 (Fig. 4-9a) render a mergence of the positive mafic trend, characterized by olivine fractionation in basalts, with the negative POAM fractionation trend. However, as shown in earlier sections, basaltic andesites are not derived from basalts and the basaltic magmas represent sources that are geochemically separated from the intermediate magma sources. The vertical dashed line of Figure 4-9a marks the intersection of linear regression lines generated from uncontaminated mafic and intermediate (up to 68 wt.% SiO₂) geochemistries. It may not be altogether coincidental that the dashed line separating the two trends falls at SiO₂ = 54 wt.%, the division of normative olivine and normative quartz compositions.

A plot of K/Sr ratios vs. SiO_2 (Fig. 4-9b) does not indicate a positive-to-negative change in trends, although it clearly demonstrates the Sr partitioning effect of plagioclase. Basaltic compositions indicate negligible changes in K/Sr ratios while basaltic andesites show a gradual increase with SiO_2 content; however, substantial increases are initiated at $\text{SiO}_2 =$ 58 wt.% within the basaltic andesite range. As shown in the preceding chapter, most intermediate units have close affinities with primary sources and display only the effects of olivine fractionation. The scatter of Sr data in Figure 4-9a also allows for some uncertainty in the inception point of POAM fractionation, which may occur at higher SiO_2 values than indicated. Therefore, POAM fractionation effects are minimal within the low-SiO₂ basaltic andesite range and predominate in the more silicic intermediate magmas.

4.4 Circum-Pacific Dacite Comparisons

Uniformity of dacite trace element patterns shown in Figure 4-6 leads to the inference of similar magmatic histories;



Figure 4-9 Variations in Sr vs. SiO₂ (A) and K/Sr vs. SiO₂ (B) for the High Cascades suite of samples. Both diagrams illustrate the effects of feldspar fractionation during magma evolution and show the inception of extreme fractional crystallization characterized by silicic units.

however, the sequential models developed for Three Sisters volcanism may not be applicable to other systems of the Pacific calc-alkaline belt. Wide variations in trace element concentrations occur for many orogenic andesites (Taylor, 1969), which attest to variables in source enrichments or depletions, degree of melting, volatile influence, mineral stability and many other parameters. Relatively similar patterns for a particular region may, in fact, reflect a degree of uniformity in source geochemistry as well as consistencies in petrochemical evolution and geologic conditions.

Comparisons of the Three Sisters average dacite composition (average of 5 in Figure 4-6) to other patterns of High Cascades dacites (Condie and Swenson, 1973; Dudas et al., 1971; and unpublished Mt. St. Helens analyses by myself and M. R. Smith) are shown in Figure 4-10. The overall patterns are roughly similar in alkalis and LREE which exhibit approximately 2X variability. Greater variations, up to 6X, in Ba, Sr and HREE probably result from non-uniformities in POAM fractionation, notably plagioclase and augite. Negative Sr and Eu anomalies for Crater Lake (Mazama 60), Glacier Peak and Mt. Rainier samples are indicative of extensive crustal histories; however, the nearly monotonic patterns for Mt. St. Helens and Mt. Shasta may be obtained by more direct association with source regions. Dacites from these latter two areas represent upper mantle melts having only subsequent olivine or orthopyroxene effects on their trace element abundances.

Figure 4-11 illustrates comparisons of the Three Sisters average dacite composition to other Pacific calc-alkaline dacite compositions (Taylor et al., 1969; Thorpe et al., 1976; Dostal et al., 1977a; and Dudas et al., 1971). Much greater variation of all dacitic compositions apparently occurs as the result of regional heterogeneities in petrochemical influences.



Figure 4-10 Chondrite-normalized trace element patterns of representative High Cascade dacites compared to the Three Sisters average dacite composition. Original analyses were re-normalized to chondritic values used in this study.



Figure 4-11 Chondrite-normalized trace element patterns for dacites representative of Pacific-margin island-arc or continental calc-alkaline systems compared to the average Three Sisters dacite composition. Original analyses were re-normalized to chondritic values used in this study.

Andean patterns are the most similar to High Cascade units and exhibit characteristics of POAM fractionation. The island-arc sample from Japan also yields negative anomalies of Sr and Eu and a Sc dropoff, although alkalis are depleted relative to REE. A crustal history is indicated for this sample, yet the parent magma probably was melted from an alkali-depleted source. The island-arc sample from Bouganville exhibits less effects of crustal evolution and a pattern similar to those of the Mt. St. Helens and Mt. Shasta dacites. Effects of crustal interaction are apparently minimal and, like the Mt. St. Helens and Mt. Shasta samples, the Bouganville unit probably represents a nearly direct relation to a mantle source.

5. HIGH CASCADES EVOLUTION

5.1 Petrogenetic Sequence

Petrochemical models developed in preceding chapters require variances in initial source geochemistry, fractionation trends and crustal assimilation. Furthermore, fractionation and contamination processes within mantle/lower crust source regions are implied as agents of source variation. Disregarding abnormal rock types such as TFJ-440, WR-225 and MB-134 (basalts) and BT-386 (possibly the only "true" andesite), three primary magma types are evident: normal basalt, NS basaltic andesite, and MW basaltic andesite--the latter two types separate from only slightly different sources. These primary liquids are consistent with Cascades Pb and Sr isotopic data (Church and Tilton, 1973), which indicate primitive sources for andesites and high alumina basalts and rule out large contributions by radiogenic material.

Basalt magma of the High Cascade Platform, erupted in response to late-Pliocene Cascade subsidence, can be derived from LIL element-enriched, spinel lherzolite sources via \sim 14% partial melting. These magmas are represented on the surface as an early platform of shield volcanoes and intercalated basaltic lavas of the High Cascade sequence. Basaltic andesite magmas (also including TS-627, TS-688 and TFJ-433) are divisible into two major types and were generated by \sim 10% melting of variably enriched, spinel lherzolite or plagioclase peridotite sources. Olivine fractionation is primarily responsible for Fe' variance in basalts and basaltic andesites, although consistently primitive olivine and plagioclase compositions of basaltic andesites indicate source-equilibrated crystallization.

Fractionation of basalts is less restricted in location and has probably occurred at various levels in the upper mantle or crust. These relations require generation of basalts and basaltic andesites at different depths. Basaltic andesites are generated at or near the plagioclase peridotite/spinel lherzolite phase-change boundary, whereas basaltic liquids are generated deeper within the spinel lherzolite stability region.

The calc-alkaline differentiation trend, initiated with primary basaltic andesite magma and derived via extensive POAM fractionation of NS type magmas, is virtually unrelated to basalt magma genesis. Figure 5-1 illustrates the Na₂O + K₂O - FeO - MgO (AFM) ternary diagram which displays an obvious differentiation hiatus between mafic and silicic compositions. Although basalts seem to coincide with the trend shown in Figure 5-1, the alignment of many samples suggests an incipient tholeiitic trend of FeO enrichment. Sample BT-386 probably evolved from sources similar to basalts (Fig. 3-20), and represents a divergent analogue to the basaltic andesite-dacite differentiation scheme. In contrast to continuous variations in SiO₂ concentrations, extensive in situ fractionation of mafic magmas is required to produce the observed compositional gap in other major element abundances.

High Cascade magmas, therefore, are not representatives of a continuous magma line of descent, but rather reflect discrete processes of magma accumulation and fractionation. Segregation of these processes is portrayed in a pseudo-ternary phase diagram of "normative" olivine-plagioclase-silica (albite component included in plagioclase) shown in Figure 5-2.* Phase relations

Walker et al. (1973) do not include Na_20 and neglect leftover CaSiO₃ with the plagioclase component being ultimately determined by Al₂O₃ content. Inclusion of Ab in Figure 5-2 also enables Al₂O₃ control of the plagioclase component such that excess CaO, if any, is neglected.



Figure 5-1 A-F-M diagram of High Cascade samples indicating the inception of the calc-alkaline trend from primary basaltic andesites and an alternate trend from basalts which may explain the anomalous composition of the BT-386 andesite.



Figure 5-2 Pseudo-ternary diagram of silica-plagioclase-olivine indicating shifts in cotectic boundaries due to volatile influences on magma evolution and the separation of mafic and silicic members of the magmatic series.

for the low-PO₂ dry system are derived from Walker et al. (1973) and possible shifts in cotectic boundaries due to volatile influences are shown for High Cascade compositions. Cotectic behavior is acknowledged in petrographic analyses which indicate olivine and plagioclase as dominant early phenocrysts and POAM crystallization in silicic units. Three separate fields are represented (basalts, basaltic andesites and dacites + rhyodacites) which include justifiable minor overlaps. The two basaltic compositions plotted within the basaltic andesite trend are actually divergent basalt types BT-382 and TS-688 which have the highest SiO_2 contents of basaltic units. Inclusion with basaltic andesites may be warranted by the fact that BT-382 has basaltic andesite mineralogic and chemical affinities and TS-688 is obtained from the plagioclase-rich porhyritic lava of Middle Sister.

The initial shift in cotectic lines probably occurs during volatile interactions with magma sources which, with the addition of H₂O, exhibit an expansion of the liquidus olivine field of stability (Nicholls and Ringwood, 1973). A secondary shift, shown by the "cotectic" trend for silicic units, relates to accumulation of volatiles evolved contemporaneously with the crustal sequence of POAM fractionation. Each of the three compositional types illustrated in Figure 5-2 corresponds to successive levels within upper mantle-to-crust regions.

5.2 Source Contamination

Primary magma source compositions modeled in Chapters 2 and 3 indicate LIL element enrichments and relatively flat (1.1-2.0 x chondrites) HREE-Sc patterns. However, uniformity of normal trace element patterns preclude significant crustal contamination which is shown to create wide perturbations (TFJ-440 and WR-225) in otherwise similar units. Contamination of a chondritic uniform reservoir (CHUR), such as might be represented by the mantle wedge overlying a subduction zone, is likely during rise of aqueous fluids generated by slab dehydration and recycling (Gill, 1981, p. 256). Enrichment of upper mantle regions by reaction with LIL element-bearing fluids is also consistent with mantle contamination models proposed by Dostal et al. (1977a,b) for some Andean systems.

Fluids enriched in LIL elements are evidently derived from either simple dehydration of a subducted cool slab or partial melting of eclogite or garnet peridotite. High Cascade trace element patterns suggest significant enrichments of volatile alkali elements over more refractory LREE and thus might indicate a greater contribution by the initially extracted cooler fluids. It is possible, however, that siliceous fluids reacting with the overlying mantle also contain significant amounts of melt-derived constituents whose behavior will be determined by melt fractions and source mineralogy. Assuming that alkali element enrichments are partially controlled by initial dehydration and that REE contributions are largely determined by accompanying melts, possible mechanisms of LREE enrichment are obtained from models of melting and mixing.

Source compositions presented earlier exhibit $(La/Sm)_{c.n.}$ ratios of 1.1-1.7 and $(La/Lu)_{c.n.}$ ratios of 1.6-2.7 indicating nearly 3X enrichments of LREE relative to HREE. These values, listed in Table 5-1, are compared to mixing models of a 1.1-2.0 x CHUR with two percent melts of garnet peridotite (1X chondrites) and eclogite (10Xchondrites). The calculated compositions compare favorably with model-dependent source concentrations, although wide variances in melt/mix fractions are possible. Compositions derived from identical melt fractions obviously require less contribution from eclogite melts than peridotite melts if the eclogite slab is assumed to contain

Element	Modeled Source Compositions	CHUR ₉₅ GTP Melt ₀₅ a	CHUR ₉₉ ECL Melt ₀₁ ^b
la	2250		
	2.2-5.0	2.5-3.3	2.8-3.7
Sm	1.5-3.3	1.5-2.4	1.4-2.3
Lu	1.1-2.0	1.1-1.9	1.1-2.0
Sc	1.1-2.0	1.1-2.0	1.1-2.0
La/Sm	1.1-1.7	1.4-1.7	1.3-2.0
La/Lu	1.6-2.7	1.7-2.3	1.9-2.5
Sm/Lu	1.3-1.5	1.3-1.4	1.2-1.3
Lu/Sc	∿1	∿1	∿1

Table 5-1 Comparison of LREE-enriched source compositions and possible mechanisms for "contamination" of a 1.1X-2.0X chondritic uniform reservoir (CHUR) in the overlying mantle wedge. See text for explanation.

a) Garnet peridotite modal melt (ol₅₀opx₂₅cpx₁₅gnt₁₀); 2% melted, 1X chondrites initial composition.
 b) Eclogite modal melt (cpx₅₀gnt₅₀); 2% melted, 10X chondrites initial composition.

 ${\sim}10{\rm X}$ chondrite REE abundances (Basaltic Volcanism Study Project, 1981).

5.3 Tectonic Implications

The regional geologic setting in conjunction with geochemical and lithologic similarities of High Cascade volcanics to calc-alkaline belts having well-documented subduction systems prompts the inference of an active subduction zone during Pleistocene-Holocene magma generation. As mentioned in the introductory chapter, the graben-forming subsidence which occurred prior to High Cascade eruptions (Taylor, 1978) is consistent with structural features noted in other calc-alkaline systems, namely those on the east margin of the Pacific (Fyfe and McBirney, 1975). Although the general consistencies are appealing, platform basaltic magmas, erupted in response to the crustal readjustments, are not required as geochemical precursors to the calc-alkaline rocks and invite the concept of divergent structural controls within the High Cascade system. Evidence for the overprint of an alternate tectonic regime may be possible through comparison of geochemical characteristics with those observed for various basaltic provinces. Inferences made on slight divergences and meager data are, at best, speculative and certainly subject to modification; however, effective assessment of pertinent chemical parameters may lead to conceptual models that are consistent with other geologic data.

Basalt major element analyses (Table 2-3) indicate average total alkalis (Na₂O + K₂O = 4.0 wt.%) and a corresponding SiO₂ average content (49.8 wt.%) which plot slightly within the alkali field (Carmichael et al., 1974, p. 539), although close to the "normal" High Cascade average which falls just within the high alumina range. In addition, the average TiO₂

concentration (1.48 wt.%) is higher than "characteristic" values $(TiO_2 < 1.2 wt.\%)$ of island arc and continental margin mafic members according to Green (1980). Other major elements correspond closely with calc-alkaline basalts; however, wide variations of FeO, MgO and CaO are present in most basalt compositional data compiled by the Basaltic Volcanism Study Project (1981). Relatively high TiO₂ and alkalis might signify some association with magmas normally erupted well within boundaries of continental or oceanic plates.

Comparison of trace element compositions allow further speculation on alternate tectonic regimes although empirical correlations are continually subject to revision. Incompatible (hygromagmatophile) elements provide somewhat effective discriminators when a selected combination varies sufficiently between magma types of different tectonic settings. Wood et al. (1979) propose the use of a triangular tectonomagmatic discrimination diagram based on Th-Hf-Ta relations due to consistencies of Th/Hf and Th/Ta ratios throughout representative magmatic suites, and the observation that relative abundances of these elements are not affected by silica content. They suggest that ocean ridge and within-plate basalts (except Hawaii) are distinguishable and that these types are also distinguishable from Ta-depleted magmas derived at destructive plate margins. The slightly revised Th-Hf-Ta discrimination diagram (Wood, 1980) is reproduced in Figure 5-3, showing the fields of (a) normal (N-type) MORB (mid-ocean ridge basalt), (b) enriched (E-type) MORB and tholeiitic within-plate magmas, (c) alkaline within-plate magmas, and (d) destructive plate-margin basalts and differentiates.

Basaltic andesites, dacites and rhyodacites (with two exceptions, EM-92 and TFJ-436) plot along a restricted band within the orogenic plate margin field as expected; however, basalt analyses plot, with wide variations, predominantly within field B and reflect possible influences of within-plate magma



Figure 5-3 Hf-Ta-Th tectonomagmatic discrimination diagram of Wood (1980) with High Cascade compositions plotted. Field A = N-type MORB, field B = E-type MORB and tholeiitic within-plate magma, field C = alkaline within-plate magma and field D = destructive plate margin compositions. The upper region of field D corresponds primarily to low-Ta, primary island-arc units whereas the lower region contains continental calc-alkaline associations. Also shown for comparison are Snake River Plain basalts (Leeman and Vitaliano, 1976) and Columbia River and coastal basalts (Hill, 1975).

types. The basalt values are effectively segregated from the more silicic compositions, although some previously acknowledged divergent units plot closer to the calc-alkaline field. The upper regions of the destructive plate field (d) normally represent primitive arc tholeiites, whereas the lower portion delineates true calc-alkaline representatives (Wood, 1980). Regions are also shown for Snake River Plain (Leeman and Vitaliano, 1976) and Columbia River and coastal basalts (Hill, 1975) for comparison of basalt types within the vicinity of High Cascade units. Although the Columbia River Group falls within the orogenic field (perhaps due to the spatial and temporal association with calc-alkaline volcanism and/or a crustal history) basalts of this study have marginal affinities with the Snake River Plain analyses. Actual degree of magmatic interactions between Basin and Range type basalts and High Cascades basalts is presently unobtainable; however, assuming that such affinities would be effected at source regions as opposed to subsequent periods of crustal evolution certain lines of evidence are worth consideration.

Extensional tectonics and normal faulting were prevalent throughout much of the western U.S. during the late-Cenozoic period of Basin and Range development (Gilluly, 1963). Comprehensive volcanic and tectonic studies by Christiansen and Lipman (1972), Armstrong (1978) and Lipman (1980) indicate contemporaneous associations, with possible justapositions, of subductiondriven calc-alkaline volcanism and predominantly basaltic or bimodal volcanism related to the extensional stress regime. These reviews support the recognition of an overall decline and westward localization of andesitic volcanism with the inception of predominantly basaltic volcanism throughout much of western North America. Specifically, Christiansen and Lipman (1972) delineate an elongate zone of fundamentally basaltic volcanism

extending through the Snake River Plain and eastern Oregon during the period 3 m.y. to the present. They indicate (their Fig. 7) an abutment of the east-west-oriented basaltic field against the north-south aligned High Cascades volcanic field. Although suggestions for overlap of these two tectonic regimes are not offered, the apparent juncture occurs in the central High Cascades region immediately adjacent to the present study area.

The basaltic terrain lying just to the southeast of the Three Sisters region includes Newberry Volcano which is alternatively attributed by Higgins (1973) to a belt of high-alumina shield volcanoes positioned on the east flank of the Cascade system. Higgins (1973) considers the belt to represent a subprovince of the high-alumina plateau basalt province of Waters (1962) which characterizes much of southeastern Oregon. Discrimination of the provincial setting adjacent to the central High Cascades is beyond the scope of this study, although proximity of the system to predominantly basaltic terrains related to a tensional tectonic regime is evident.

Lipman (1980) further implies that since 17 m.y. ago, extensional volcanism is related to a back-arc environment associated with a diminishing Juan de Fuca plate subduction system. Such extensional tectonics, according to Lipman, are possible though a decreased convergence rate, which allows the undergoing slab to sink gravitationally (or break), thereby allowing counterflow of asthenospheric mantle into the above-slab region, possible heating of the lithospheric base and overprinting extensional rifting (with basalt volcanism) within the region of arc volcanism. These relations are consistent with eruption of High Cascade basalts in conjunction with late-Pliocene subsidence and graben development which, from previous heating by calc-alkaline magmatism, probably resulted through the response of a weakened crust to a relaxation in the compressive regime.

5.4 Evolutionary Model

Evolution of the High Cascades volcanic system certainly involves concepts beyond the realm of present knowledge. Details of the model reviewed in this section represent ideas that are consistent with observations and inferences made in previous sections and are limited to the extent by which those parameters may be projected into speculation. Furthermore, it will become readily apparent that mechanisms offered here relate to the Three Sisters area of the High Cascades Range and will not be applicable to other systems in all respects. However, similar convergent-plate volcanic provinces generally rely on the parameters outlined in this section and exhibit features which support the basic geologic and petrologic concepts. Future studies will certainly elucidate some of the finer points, although many aspects of volcanic evolution within the study area are inescapable. The following model is based upon the petrochemical segregations of basalt, basaltic andesite and dacite/rhyodacite with pertinent exceptions acknowledged.

Figure 5-4 illustrates the petrologic events associated with the development of the High Cascades volcanic province. Volatile fluids and LIL elements are extracted from a dehydrating oceanic slab during active subductionand compression prior to ~ 5 m.y. ago. Interaction of aqueous fluids with eclogite (metamorphosed basaltic crust) or garnet peridotite catalyzes a small degree of partial melting and/or liquid extraction ("scavenging") according to schemes presented by Best (1975) and Gill (1981, p. 245), thereby allowing further enhancement in alkalis and LREE. Continued upward migration of these fluids into garnet-free upper mantle produces chemically variable regions of LIL element enrichment and the



Figure 5-4

5-4 Schematic model of High Cascade magma evolution. Hydrous fluids ascend from a dehydrating subducted oceanic slab and interact with the overlying mantle wedge by liquid extraction and possibly partial melting in regions of garnet stability. Primary basalt (B) and basaltic andesite (BA) magma, generated by more extensive partial melting, accumulates in upper mantle to lower crust regions. Divergent basalt types (B') are produced by crustal contamination or fractionation of primary magma. Extreme fractionation of basalt magma leads to andesitic compositions such as BT-386. Dacites and rhyodacites (D) are evolved in upper crust regions by POAM fractionation (see text) of basaltic andesite magma and become mobilized by increased evolution of volatiles.

accompanied effects of zone refining. More extensive partial melting and liquid accumulation occur within spinel lherzolite and possibly plagioclase peridotite stability regions as the re-sult of an advancing front of enriched fluids.

Basalt magma, generated in the spinel lherzolite zone, migrates upward with contemporaneous olivine fractionation to be concentrated in a highly permeable zone of liquid and solid upper mantle. The MOHO (crust/mantle boundary) is probably defined by a region of less magma accumulation which occurs immediately above the basalt magma reservoir. Excess fluids that were not included in basalt magma production continue advancement upward to catalyze basaltic andesite melts within spinel lherzolite or, less frequently, plagioclase peridotite regions. These magmas accumulate near the phase change boundary and undergo equilibrium fractionation of olivine with subordinate amounts of plagioclase.

Both magma types involve H_2O enhancement of olivine stability and resultant incongruent melting of orthopyroxene. Basaltic magmas are predominantly restricted to the sub-crustal reservoir, although small volumes may feed into crustal chambers and crystallize substantial amounts of olivine \pm pyroxenes to produce silicic andesite magmas such as BT-386. Differentiation of basalt liquids leads to enrichments of TiO₂ and Fe' (tholeiitic trend), although the trace element pattern is essentially unaffected.

Basaltic andesite magmas are either quartz or olivine normative depending on the relative amounts of volatile enrichments and the zone of melting. Ascent of these liquids in upper crustal regions is probably brought about by increased fracture densities and magma buoyancy. Primary basaltic andesite magmas, the precursor to calc-alkaline differentiation, either extrude during the construction of a composite cone or intrude upper crustal regions and crystallize plagioclase, orthopyroxene

 $(\pm \text{ olivine})$, augite and (titaniferous) magnetite (POAM fractionation). The zone of upper crust magma accumulation is sufficiently segregated from the basaltic andesite reservoir such that a petrochemical hiatus is obtained between silicic and mafic compositions.

Magmas that reside in shallow chambers are probably detained until mobility is achieved in derivative liquids. Upper zones of gabbroic to dioritic cumulates are then purged of silicic liquors which erupt through fissures or pre-existing vent systems. The frequency minimum of silicic andesites is probably related to the duration required for sufficient volatile evolution. Remobilization occurs after (1) extensive crystallization which yields saturated zones in the upper regions of magma chambers or (2) the reintroduction of volatiles as the wave of slabderived hydrous fluids passes through the crustal system. The most silicic magmas result from extreme volatile evolution, probably coincident with the upward advancement of the volatile By contrast, basalt magmas equilibrate at deeper levels front. and are allowed to erupt during changes from a compressional to a tensional tectonic regime.

High Cascade eruptions were initiated during such changes which resulted in crustal readjustments. Subsidence of the earlier calc-alkaline "Plio-Cascades" created a north-south graben system into which dicktytaxitic lavas were extruded. Although voluminous outpourings of primary shield-building lava are evident, some basaltic liquids were hot enough to assimilate upper crust material and extrude as contaminated lava (TFJ-440, WR-225 and possibly S-91), often carrying remnants of the contaminant to the surface. The eruptions of early High Cascades basalt lavas were then followed by less punctuated eruptions of calc-alkaline character, which intermittently contributed to growth of diverse composite volcanoes, and sporadic eruptions of later basalt lavas which spread over young shield volcanoes.

Eruptive sequences generally reflect the order of magma generation and evolution such that early or later basalts are followed by basaltic andesites for most of the mafic eruptive centers and silicic eruptions follow their basaltic andesite precursors. Even though a dichotomy is apparent between primary basalt and basaltic andesite magmas, the tendency exists--such as the Sand Mountain and Belknap Crater systems--for coeval eruption of both types from a common vent. Increasing relative enrichments and homogenization of mobile elements such a K, Rb, Cs, Sr and Ba are also apparent with increasing SiO_2 content and support the concept of hygromagmatic controls on volcanism. Numerous subsystems and singular eruptive events are sporadic throughout the High Cascades province and can be individually characterized by field and petrographic data. However, uniformities in magma genesis and evolution result from the regulating effects of hydrous fluid interactions and a vertical transgression of magma genesis in response to the ascending volatiles. These unifying effects allow magmas of similar bulk compositions to evolve through similar processes regardless of the spatial or temporal position within the volcanic province.
6. SUMMARY AND CONCLUSIONS

High Cascade volcanic rocks within the Three Sisters region exhibit variably fractionated major and trace element abundances and mineral compositions which preclude generation entirely by oceanic slab melting, peridotite melting, crustal anatexis or fractionation of primary basalt liquids. Primary magmas represent multiple stages of generation which include source enrichment from ascending oceanic slab-derived fluids, partial melting of peridotite and coincident fractional crystallization. Magmas ascending through upper crust regions are subjected to secondary processes, fractional crystallization and sialic crust assimilation. These effects are responsible for observed compositional variations within and between three major volcanic types: basalts, basaltic andesites and dacites-rhyodacites.

High Cascade basalts have erupted since the early Pleistocene stages of High Cascade mafic platform development and have continued to erupt intermittently into the Holocene epoch. Platform basalts are dicktytaxitic and erupted in response to a tensional tectonic regime associated with the subsidence of the earlier Cascade range. All basalts are separated into normal and divergent classes according to mineralogy and geochemistry. Nearly all units exhibit dominant olivine ± plagioclase phenocrysts and ophitic to intergranular groundmass textures. Basalt compositions are invariably oliving-normative high-alumina tholeiites, indicating a substantial range in Fe0*/(Fe0 + Mg0) molar concentrations. Fractionated LREE-enriched trace element abundances are inconsistent with geologically reasonable melting models using a chondritic source, and high HREE and Sc values preclude the presence of residual garnet during primary melt genesis. Geologically, feasible models indicate non-modal melting of a peridotite source which is enriched in volatile and LREE elements derived from a subducted

dehydrating oceanic slab. Low percentage melting of eclogite or garnet peridotite mantle is allowable and may further enhance the chemistry of source-contaminating ascending fluids which react with the material in the region of basalt melt production and accumulation. Within-mantle olivine fractionation is also evident as a means of Fe' variation in conjunction with magma accumulation.

Divergent basalt types suggest variances in source geochemistry, crustal contamination and depth of melting. Variations in the source, predominantly by olivine fractionation is evident for MB-134, and FeO-rich early platform basalt. Crustal contamination of WR-225 and TFJ-440 magmas is responsible for erratic trace element compositions. The otherwise primitive TFJ-440 composition, strongly enriched in LIL elements and LREE, contains scattered quartz xenocrysts and accessory biotite as further evidence of crustal contamination. Other divergent basalts, BT-382 and TS-688, have higher SiO₂ contents and exhibit mineralogic characteristics of basaltic andesites. These two samples, especially BT-382, mark the geochemical transition to calc-alkaline basaltic andesite magmas and were probably generated at higher levels in the mantle or lower crust.

Basaltic andesite magmas are divisible into two principal classes based on total LIL element and LREE abundances. Although all basaltic andesites are characterized by fractionated, monotonic trace element patterns, NS (North Sister) types have lower total abundances of incompatible elements than MW (Mount Washington) types. Basaltic andesites exhibit primitive, relatively unzoned phenocrysts of olivine and plagioclase as well as sparse microphenocrysts of augite and hypersthene. Relatively low incompatible element abundances preclude derivation of basaltic andesites from basalt magmas and consistently primitive mineralogy indicates equilibrium with peridotite sources. Therefore, basaltic andesites are modeled as partial metls from fractionated and enriched spinel lherzolite or plagioclase peridotite lower crust sources having similar major element chemistries as upper mantle basalt magma sources. Primary magmas for basalts and basaltic andesites are derived from sources having Fe' values of 0.14-0.15, LREE_{c.n.} abundances of 2.2-5.0 and HREE-Sc concentrations of 1.1-2.0 times chondrites.

Five volcanic units originally classified as andesites on the basis of SiO₂ content are shown to have lithologies and geochemistries requiring revised classification. Three of these samples--TS-686, TS-627 and TFJ-433--are high-silica basaltic andesites which, in accordance with their primitive mineralogy and trace element similarities, are derived as primary liquids (TFJ-433 is slightly contaminated by a pl + cpx cumulate) in conjunction with other NS basaltic andesites. One of the five, BT-383, is a low-silica dacite modeled by extensive pl + cpx + opx fractionation from NS basaltic andesite magma and exhibits a nonmonotonic trace element pattern characteristic of other dacites. The remaining sample, BT-386, has high TiO₂ and Fe' and may be the only "true andesite" represented within the study area. The composition is modeled with partial melting and extensive olivine fractionation of sources similar to the basalt magma source. Similar relative trace element abundances of BT-386 and normal basalts indicate close affinities between these two compositions and support the concepts of an ultimately mutual source.

Dacites and rhyodacites represent volumetrically small proportions of the entire High Cascades system. Increases in silica content are accompanied by greater inflation due to (1) volatile evolution, (2) a more evolved phenocryst assemblage consisting of plagioclase, hypersthene, augite and Ti-magnetite (POAM), and (3) highly fractionated non-monotonic trace element patterns. Iron and magnesium relative abundances become erratic and apatite appears as an important accessory phase (probably in conjunction with Ti-Fe spinel phenocrysts) which may be responsible for wide variations of REE in rhyodacites. Silicic compositions are obtained by extensive POAM fractionation in upper crustal regions brought about by emplacement and differentiation of NS basaltic andesites, although residual mineral proportions are variable.

Increased olivine stability at depth, primary dicktytaxitic lavas, strong corrosion of late-stage feldspar phenocrysts, highly inflated silicic samples and explosive volcanism result from the interaction of volatiles during magma production and evolution. Such volatile additions are required introductions into source regions and reflect the presence of an active subduction zone during magma genesis. Trace element similarities with representatives from known subduction-related systems support these conclusions.

The calc-alkaline trend is initiated with basaltic andesite magma production in lower crustal regions. Conversely, less silicic basalts are not parental to basaltic andesites and, on the basis of their timely eruptions following graben formation and empirical trace element affinities with non-orogenic basalts, may be the manifestation of an alternate tectonic regime interacting with the High Cascade system approximately five million years ago. Subsidence of the earlier Cascades does not, however, require this interaction and is probably the response of a thermally weakened crust to a decrease in convergence rate between oceanic and continental lithospheric plates.

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Appendix A

CHONDRITE NORMALIZATION CONSTANTS

Element	Concentration (ppm)
Sc	7.9
K	0.08
Ba	3.8
Sr	11
La	0.329
Ce	0.862
Nd	0.620
Sm	0.206
Eu	0.077
Gd	0.269
Tb	0.048
Yb	0.211
Lu	0.036
Hf	0.18
Ta	0.022
Th	0.041
U	0.011

Table	A-1	Average	ordinary	chondritic	values ^a
		used as	normaliza	ation consta	ants.

a) Reproduced (except K, RA Schmitt, priv. comm.) from Table 2 in Ma et al., 1981.

Appendix B

TRACE ELEMENT MODELING

TRACE ELEMENT MODELING

Mathematical Relations

Equilibrium batch melting is described by Shaw (1970, 1977) using simple mass-balance equations requiring for each element that:

$$C_{0} = C_{L}(F) + C_{S}(1-F)$$
 (1)

where: C_o = initial bulk composition

 C_L = composition of the liquid fraction, F, produced and C_s = composition of the remaining solid fraction, 1-F.

Because of low abundances, liquid structures are indifferent to the concentration of a given trace element, i, whose behaviour is determined by the probability of entering a solid phase. The proportion of element (i) in a mineral phase (j) relative to the concentration in the equilibrated liquid depends on the compatibility with that mineral phase and represents the distribution coefficient for that element. Substitution into equation (1) yields the equation for modal melting:

 $C_{L}/C_{0} = 1/\{\overline{D} + F(1-\overline{D})\}$ (2)

where: \overline{D} = the bulk distribution coefficient according to weight fractions (W_j) of residual solid phases such that $\overline{D} = \Sigma W_j D_j$

and

d D_j= the individual mineral/liquid distribution coefficient for the given element in phase j.

Non-modal melting, preferred in this study due to greater geologic feasibility, produces changes in the bulk distribution coefficient. A

separate bulk distribution coefficient (\overline{P}) is introduced according to weight fractions of the melted phase such that:

$$C_1/C_0 = 1/\{\overline{D} + F(1-\overline{P})\}$$
 (3)

where: $\overline{P} = \Sigma M_{1}D_{1}$ and M_{1} represents the proportion of phase j included in the liquid.

During continual separation of liquid from the residuum by fractional melting each increment of extracted liquid is given by:

$$C_{L}/C_{0} = (1/\overline{D}) \cdot (1-F)^{(\overline{D}^{-1}-1)}$$
 (4)

and the accumulated incremental liquids are obtained by the equation:

$$C_{L}/C_{o} = (1/F) \cdot \{1 - (1-F)^{\overline{D}-1}\}.$$
 (5)

Equilibrium crystallization processes (Gast, 1968) are described by mathematical relations that are similar to equilibrium melting models. The fraction of liquid remaining (F) is usually represented as (1-X)where X is the crystallized fraction relative to the remaining liquid and C_o is the starting liquid composition. Assuming that liquid P values are unity, such that trace element behaviour is determined solely by compatibility with the crystallizing phases, the remaining equilibrated liquid composition is obtained by:

$$C_{L} = (C_{o} - X\overline{D}C_{o})/(1-X)$$
(6)

and fractional crystallization, similar to the reverse of fractional melting (instantaneous solid removal), is expressed by the

$$C_{L} = C_{0}(1-X)^{(\overline{D}-1)}$$
 (7)

Finally, the bulk solid composition i determined by:

$$C_{s} = (C_{o}/X) \cdot \{1 - (1-X)^{\overline{D}}\}$$
 (8)

Distribution Coefficients

Mineral/Liquid distribution coefficients for numerous elements and minerals have been determined largely from analyses of phenocrysts and aphanitic or glassy matrix material extracted from synthesized or natural systems. Assumptions of equilibrium between mineral and host liquid are made when disequilibrium effects are difficult to quantify or seem insignificant. Much of the present knowledge about trace element partitioning is summarized in proceedings from the International Conference on Experimental Trace Element Geochemistry, 1977 (Drake and Holloway, eds., 1978).

Distribution coefficients are predominantly affected by temperature dependencies which may cause variations by factors of 1 to 10 for relatively compatible elements such as Ni, Co, V, Cr and Sc. Incompatible elements usually behave according to a more restricted range in D values and indicate consistent variations in distribution according to ionic size.

The most abundant and largest phenocrysts observed during this study are olivine and plagioclase. Clean separates of phenocrysts (0.2-0.5 mg) and groundmass were extracted by hand-picking (using fine

forceps under a stereomicroscope) in order to obtain characteristic analyses by INAA and the most effective distribution coefficients for the High Cascades system. The compatible elements for olivine (Co, Ni and V) indicate equilibrium with ultramafic sources and are assumed to yield false (high) values when compared to observed mafic groundmass compositions. Incompatible elements Ba, Sr, REE and Sc yield D values close to those reported and are retained as viable for trace element models. Figure B-1 illustrates the trace element patterns obtained for olivine and plagioclase D values. Increase in D with decreasing ionic radii is apparent for olivine and higher compatibility of plagioclase for Sr and Eu is evident. Generally, higher D values are represented by lower An (p1) and lower Fo (o1) compositions although relative coefficients are consistent.

Distribution coefficients used in this study are compiled in Table B-1 and the patterns are illustrated in Figure B-2. Most values represent best estimates obtained from studies of systems similar to High Cascades volcanics or are derived by extrapolation from known general patterns. Although wide variations exist in reported D values, their relative patterns are generally consistent (as observed in partition coefficients of ol and pl) and produce negligible alterations to modeling schemes.

Element	olivine ^a	orthopyroxene ^b cli	nopyroxene ^b	spinel ^C	plagioclase ^a	garnet ^d	
K	0.004*	0.014	0.03	0.01*	0.06*	0.02	
Ba	0.004*	0.022	0.02	0.01*	0.06	0.01	
Sr	0.004*	0.017	0.12	0.01*	1.78	0.02	
La	0.007	0.004	0.07	0.03	0.077	0.004	
Ce	0.008*	0.008	0.11	0.03	0.073	0.008	
Nd	0.009*	0.014*	0.21*	0.04	0.059*	0.028	
Sm	0.010	0.018	0.34	0.05	0.049	0.21	
Eu	0.011	0.018	0.37*	0.06	0.278	0.42	
Gd	0.012*	0.024	0.40	0.07	0.043*	1.01	
Tb	0.013*	0.036	0.43	0.09*	0.042	1.60	
Yb	0.021	0.11	0.42	0.17	0.035*	9.4	
Lu	0.023	0.15	0.42	0.09	0.034*	10.5	
Sc	0.25	0.61*	2.5*	0.05	0.025	10	
Co	2.5*	1.2	0.8	2.5	0.05	0.2	

Table B-1 Mineral/liquid distribution coefficients used in trace element models.

a) Olivine and plagioclase values are best averages of INAA analyses in this study.

b) Pyroxene K, Ba and Sr from reviews by Irving (1978); REE values from Ma et al. (1981).

c) Spinel values are not well known; estimates from Kay and Gast (1973), Sc and Co from Irving (1978).

d) K, Ba and Sr from Philpotts and Schnetzler (1970); REE, Sc and Co from Irving (1978).

* Denotes interpolated value or value inferred from numerous sources.



Figure B-1 Plagioclase and olivine distribution coefficients determined by instrumental neutron activation analyses of separated phenocrysts and groundmass samples.



Figure B-2 Distribution coefficients used in geochemical models.

Appendix C

MAJOR ELEMENT MODELING

Appendix C

MAJOR ELEMENT MODELING

Calculations of major element compositions in liquids derived by equilibrium melting or crystallization is a matter of simple mass-balance when the liquid and solid phases in equilibrium have identical compositions. In such ideal cases, the solid and liquid abundances (C_s and C_1) of an element are given by:

$$C_{s}(\text{mole \%}) = \sum_{\alpha} X_{\alpha}^{s} C_{\alpha}$$
(1)

and

$$C_1 (mole \%) = \sum_{\alpha} x_{\alpha}^1 C_{\alpha}$$

where X_{α} and C_{α} are the molar fraction and composition, respectively, of phase α in either solid or liquid. Additionally, the residual or cumulate composition can be expressed in terms of C_1 and F, the fraction of liquid produced or remaining, such that:

 $C_{s} = (C_{0} - FC_{1})/(1-F)$ (3)

Combining equations (1) and (3) allow determination of a liquid composition produced during crystallization (which necessarily depends on the extracted solid composition) by the following:

$$C_1 = C_0 - \left(\sum_{\alpha} X_{\alpha}^{S} C_{\alpha}\right) \cdot (1 - F) / F \qquad (4)$$

Iron and magnesium cannot be considered in such a simplified

(2)

situation. While the equilibrium liquid and solid compositions of any singular phase are not identical, variations in the $C_{\rm s}/C_{\rm l}$ ratios are also possible and will depend upon total molar percentages in the starting material. Ratios of two compatible elements in the liquid fraction will change more rapidly during crystallization when the total molar concentrations are initially lower. Therefore, determination of molar ratios after a given amount of crystallization (or melting) depends on original estimates of the absolute abundances of these elements. Such is the condition with Mg/Fe partitioning in olivine and pyroxene solid solutions in models of magma genesis and evolution. These concepts are employed here to obtain estimates of absolute major element abundances which, during fractional crystallization, yield more realistic molar ratios, especially for Fe and Mg.

Experimental studies (Roeder and Emslie, 1970; Roeder, 1974; Longhi et al., 1978) provide good estimates of $X_{Fe}/(X_{Fe} + X_{Mg})$ in liquids coexisting with olivine of a given composition. The olivine Mg-Fe exchange distribution coefficient, K_{D} , as reviewed by Longhi et al. (1978), is defined:

$$K_{D} = K_{ol-L}^{Fe-Mg} = \left(x_{ol}^{Fe0} \cdot x_{L}^{Mg0} \right) / \left(x_{L}^{Fe0} \cdot x_{ol}^{Mg0} \right) = K_{ol-L}^{Fe} / K_{ol-L}^{Mg}$$
(5)

which leads to the expression:

$$K_{D} = \left[Fe'_{01} \cdot (1 - Fe'_{1}) \right] / \left[Fe'_{1} \cdot (1 - Fe'_{01}) \right]$$
(6)

where Fe' = $X^{Fe}/(X^{Fe} + X^{Mg})$ molar concentrations. Lines fitted to values of log K_{ol-L}^{Mg} and log K_{ol-L}^{Fe} vs. $10^4/T^{o}K$ are essentially parallel for similar basalt types and the exchange coefficient (K_{D}) is nearly independent of temperature. Comparison of plotted Fe'_01 vs. Fe'_t to lines of constant K_D by Longhi et al. suggest approximate K_D values of 0.33 (average of their low-Ti basalt ol-L pairs) and 0.3 (average of ol-L pairs by Roeder, 1974) for lunar and terrestrial systems, respectively. They also note that proportional and inversely proportional changes of K_D to singular variations in chemistry (e.g., K_D vs. TiO₂ or SiO₂, etc.), but combined chemistry and structural effects normally lead to small overall effects on K_D . Average K_D values can therefore be used as a check for olivine-liquid equilibrium, Fe' determination in models of magma genesis and, under equilibrium conditions, as a means of geothermometry (Roeder and Emslie, 1970) when absolute MgO and FeO (mole %) compositions are known.

It is readily apparent that absolute MgO and FeO compositions in liquid may then be obtained through mass-balance calculations for fractions of equilibrium liquid and olivine compositions. The approach is cumbersome due to changes in Fe' in either liquid during fractional crystallization or in solid residua during melting and, therefore, requires a separate set of manipulations apart from trace element models. Separate calculations of MgO and FeO (mole %) in models of magma genesis can be attained, however, by the incorporation of "effective" distribution coefficients, D*, into equations 2 and 4 in a manner analogous to trace element modeling.

Effective major element distribution coefficients are now defined as:

$$D_{Fe}^{\star} = Fe_{S}^{\prime}/Fe_{L}^{\prime}$$
(7)

and

 $D_{Mq}^{\star} = Mg_{S}^{\prime}/Mg_{L}^{\prime}$

Use of these "D" values, in conjunction with total mole % of Fe and Mg in melting or crystallizing phases, allows

(8)

$$Fe'_{l} = [(0.3/Fe'_{s} - 0.3) + 1]^{-1}$$
(9)

and a similar relation is obtained for Mg such that:

$$Mg'_{L} = [(3.33/Mg'_{s} - 3.33) + 1]^{-1}$$
(10)

Combining equations 7 + 9 and 8 + 10 expressions for D^* can be determined where:

$$D_{Mq}^{\star} = 2.33 (Fe'_{s}) + 1$$
 (11)

and
$$D_{Fe}^{\star} = 0.7 (Fe_{s}') + 0.3 = 0.3 D_{Mg}^{\star}$$
 (12)

If it is assumed that both low-Ca pyroxene and coexistent olivine have nearly identical equilibrium Fe' values then D_1^* expressions for orthopyroxenes (or pigeonites) are synonymous with those of olivine. In addition, Deer et al. (1966, p. 122 after Kretz, 1963) show that K_D values between coexistent orthopyroxene and clinopyroxene are fairly uniform for either igneous (K_D = 0.73) or metamorphic (K_D = 0.54) conditions. Although future determinations will certainly produce refinements, a K_D of 0.73 is used in the following evaluation. The expression

$$K_{D}^{Mg-Fe} = \left[Mg'_{opx}(1-Mg'_{cpx}) \right] / \left[(1-Mg'_{opx})Mg'_{cpx} \right] = 0.73 \quad (13)$$

reduces to: $Mg'_{cpx} = (0.73/Mg'_{opx} + 0.27)^{-1}$ (14)

and allows the calculation of Fe' and Mg' values for clinopyroxenes. Comparison of Fe' and Mg' in cpx to those of equilibrium liquid and orthopyroxene (olivine) via the foregoing procedure enables determination of D^{*}_{Mq} and D^{*}_{Fe} for clinopyroxene where:

$$D_{Mq}^{\star} = 2.94 (Fe'_{s}) + 1$$
 (15)

$$D_{Fe}^{\star} = 0.64 (Fe_{s}') + 0.22 = 0.22 (D_{Mg}^{\star})$$
 (16)

Incorporation of D^{*} values into equations (2) and (4), where $D^* = \sum_{\alpha=1}^{\sum} X_{\alpha} D^*_{1}$, require adjustments of C₁ to molar concentrations of Fe and Mg and initial Fe' or Mg' values. Thus, for olivine the ideal molar percent, M^{Fe+Mg}, is 66.67 and M^{Fe+Mg} for Ca-free orthopyroxene is 50.0. Accordingly, M_a is assumed for individual phases based on their probable compositions such that M^{Fe+Mg} of clinopyroxene is 30.0 for ideal Ca_{.4}(Mg + Fe)_{.6} SiO_{.3} compositions. Initial absolute compositions of Fe or Mg are then obtained by M* \cdot Fe' or M* \cdot Mg' where M* = $\sum_{\alpha} X_{\alpha} M_{\alpha}$. Liquids derived by batch melting can be calculated using the following expressions:

$$C_{L}^{Mg} = Mg_{O} \times M^{*} / [F(1-D_{Ma}^{*}) + D_{Ma}^{*}] = Mg mole \%$$
 (17)

and
$$C_L^{Fe} = Fe_0 \times M^* / [F(1-D_{Fe}^*) + D_{Fe}^*] = Fe_mole \%$$
 (18)

where $F(1-D^*) + D^*$ is the linear variation of D* with amount of liquid remaining. It is apparent from these equations that as F approaches unity, the expression $F(1-D^*) + D^*$ approaches unity, thus equalizing the final and initial compositions. Residual compositions are given by equation (3) and fractional melting can be modeled as successive calculations for small increments of F. Equilibrium or fractional crystallization will involve slight modifications to D^{*} values which correspond to Fe' in an initial liquid rather than initial solid. Therefore, the expression (from equation (9)): $D^*_{Mq} = (1-Fe'_S)/(1-Fe'_I) = 2.33$ (Fe'_S) + 1 reduces to:

$$D_{Mq}^{\star} = 2.33/(3.33/Fe_{L}' - 2.33) + 1$$
 (19)

for olivine and orthopyroxene crystallization with $D_{Fe}^{\star} = 0.3 (D_{Mg}^{\star})$. Equation (13) is modified in a similar manner to:

$$D_{Mg}^{\star} = 2.94/(3.94/Fe_{1}' - 2.94) + 1$$
 (20)

for clinopyroxene fractionation with $D_{Fe}^{\star} = 0.22 (D_{Mg}^{\star})$. Solid Mg (or Fe) compositions derived by equilibrium crystallization are determined by the equation:

$$C_{c} = Mg'M^{*}[1-F(1-D^{*})]$$
 (21)

and, in conjunction with equation (3), the liquid compositions for Mg and Fe are expressed by:

$$C_{L} = [c_{0} - c_{s} (1-F)]/F$$
 (22)

where F is the fraction of liquid remaining.

Additional phases which equilibrate compositions with coexisting liquids can be include in models such that $D_i^* = 1$ and M_i is the mole percent assumed for inclusion in the liquid (melting) or solid (crystallization). For example, ideal spinel (MgAl₂0₄) yields $M^{Mg} = 50$ and $M^{A1} = 50$ and clinopyroxene of the previous composition yields $M^{Ca} = 20$. Natural phases will exhibit variable M_i values, such as obtained during incongruent melting of orthopyroxene, which should be considered for petrogenetic models.