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Geology of the Mount St. Helens Area: Record of Discontinuous Volcanic and Plutonic Activity in the Cascade Arc of Southern Washington

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The Quaternary edifice of Mount St. Helens volcano was built upon a deeply eroded terrane of gently folded and altered volcanic and plutonic rocks that represent the core of the Tertiary Cascade magmatic arc. These rocks constitute an east dipping homoclinal sequence, several kilometers thick, of subaerially erupted mafic to silicic flows and volcaniclastic strata; K-Ar ages from this section range from about 28 to 23 Ma (late Oligocene and earliest Miocene), which corresponds to an apparent lull in Cascade volcanism to the north of Mount Rainier. Volcanism was essentially continuous during this period of time, and neither a well-defined base nor top of the section is exposed within the mapped area. Basalt and basaltic andesite dominate the lower part of the mid-Tertiary section, whereas andesitic and dacitic rocks comprise most of the upper part. This section was intruded by numerous mafic to silicic dikes, sills, and irregular plutonic bodies, most no more than a few million years younger than their host rocks, and subjected to pervasive burial metamorphism and widespread hydrothermal alteration. Large areas of hornfelsed rock surrounding even relatively small intrusions indicate that the proportion of plutonic rock becomes significantly greater at shallow depth beneath the existing erosion surface. A large granitic pluton intruded the mid-Tertiary section north of Spirit Lake at about 21 Ma. The Earl porphyry copper deposit occurs within the pluton but appears too young (17 Ma) to be genetically related to it. In contrast to the rather continuous and voluminous Oligocene to early Miocene activity, volcanism since then in the Mount St. Helens area has been localized and volumetrically minor. Products of three younger eruptive periods have been recognized: a sequence of 15 m.y. old pyroxene andesite flows resting unconformably on mid-Tertiary strata south of Mount St. Helens, widespread shallow dikes and sills of pyroxene andesite between 10 and 8 m.y. old, and compositionally diverse rocks erupted during the past 3 m.y. The Quaternary lavas are more potassic than the Tertiary lavas and typically contain phenocrysts of hornblende and biotite, which are absent from the older rocks. A number of Tertiary structures define a broad NNE trending zone that may reflect a deep-seated lithospheric flaw that has controlled the locus of Cascade magmatism in southern Washington for the past 25 m.y. Mount St. Helens lies within this zone at the intersection of the NNW striking St. Helens seismic zone (SHZ) and an ENE trending alignment of Pleistocene silicic plug-domes. No surface breakage has been detected along the SHZ, which is apparently very young. The linear zone of silicic vents is probably controlled by a fault that has been interpreted from seismic records to occur directly beneath the volcano. This zone parallels the directions of regional maximum horizontal compressive stress and North America/Juan de Fuca plate convergence. Mount St. Helens is an example of a low-volume tectonically controlled magmatic system in an early stage of development.

INTRODUCTION

The imposing composite cones of the Cascade Range represent only the youngest and most prominent manifestation of Cenozoic volcanism in the Pacific Northwest. In the southern Washington Cascades, the Quaternary edifices of Mounts St. Helens, Adams, and Rainier were constructed upon the deformed and deeply dissected remains of their Tertiary predecessors. In contrast to the wealth of information available regarding the eruptive history of Mount St. Helens volcano (see *Mullineaux and Crandell* [1981] for synopsis), knowledge of the older volcanic rocks beneath it is sketchy. With few exceptions, most notably the benchmark report on the geology of Mount Rainier National Park by *Fiske et al.* [1963], published geologic mapping in the Washington Cascades is reconnaissance in nature [e.g., *Hammond*, 1980], and supporting geochemical and isotopic age data are sparse.

In this contribution we describe some results of continuing studies in the Mount St. Helens area based on detailed geologic mapping supported by potassium-argon (K-Ar) and fission track geochronology and geochemical analyses. Extensive Pleistocene glaciation sculpted the area into a terrain of considerable relief (the distribution of partially buried bedrock ridges around the Quaternary volcano suggests that a NW trending ridge with perhaps as much as 500 m of relief lies beneath the cone). Despite the rugged topography, however, investigations of bedrock geology in the western Cascades are typically hampered by poor exposures due to heavy vegetation and a thick mantle of glacial drift and tephra. The May 18, 1980, eruption of Mount St. Helens leveled the temperate rain forest that had covered much of the area immediately north of the volcano. Subsequent salvage logging and erosion of overburden have produced exposures of the Tertiary bedrock unsurpassed in the Cascades, providing an exceptional opportunity to examine stratigraphic and structural details in the older volcanic rocks. These details provide insights into the evolution of the Cascade volcanic arc and yield important constraints for geophysical modeling of the Mount St. Helens magmatic system and the subjacent crust. They may also have implications for volcanological and petrological interpretations of

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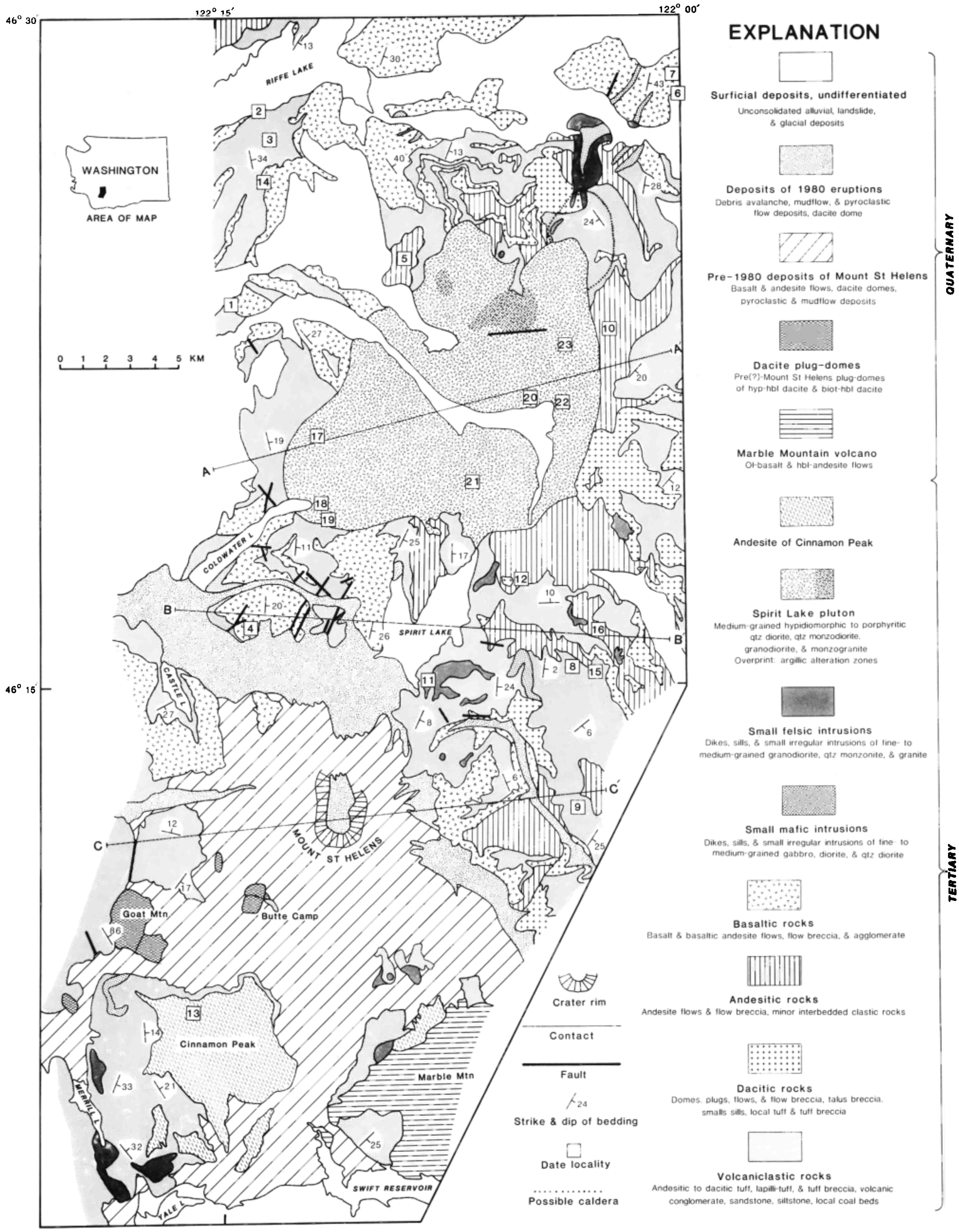

Fig. 1. Generalized geologic map of the Mount St. Helens area, showing lines of cross sections for Figure 2 and sample localities for dated rocks listed in Tables 1 and 2.

the volcano and for the geothermal resource potential of the region.

Difficulties in applying conventional stratigraphic techniques to deformed and eroded volcanic terranes have been discussed extensively by *Williams and McBirney* [1979, pp. 310–316] and *Fisher and Schmincke* [1984, pp. 346–382]. Factors that may impede progress in understanding the tectonic and geochemical evolution of continental volcanic arcs include poor exposure, limited lateral extent of individual lithologic units, repeated appearance over millions of years of lithologically indistinguishable volcanic products, diversity of products that may be erupted from individual volcanoes (present-day Mount St. Helens being a good example), absence of adequate fossil control or regionally extensive and distinctive marker units, and superimposed metamorphism and hydrothermal alteration.

In order to sort out the stratigraphic complexities, we made extensive use of K-Ar age determinations. Because fresh rocks suitable for whole-rock dating are rare, most of our data are from mineral separates of unaltered phenocrysts, primarily low-K plagioclase. Many extractions had high atmospheric Ar contents, resulting in poor precision in the ages [*Tabor et al.*, 1985]. To address this problem, we analyzed a large number of samples in order to increase confidence in the stratigraphic correlations. Even so, some of our suggestions regarding the timing of volcanic activity in the Mount St. Helens area are admittedly founded on provisional age data and require additional dating to confirm their validity.

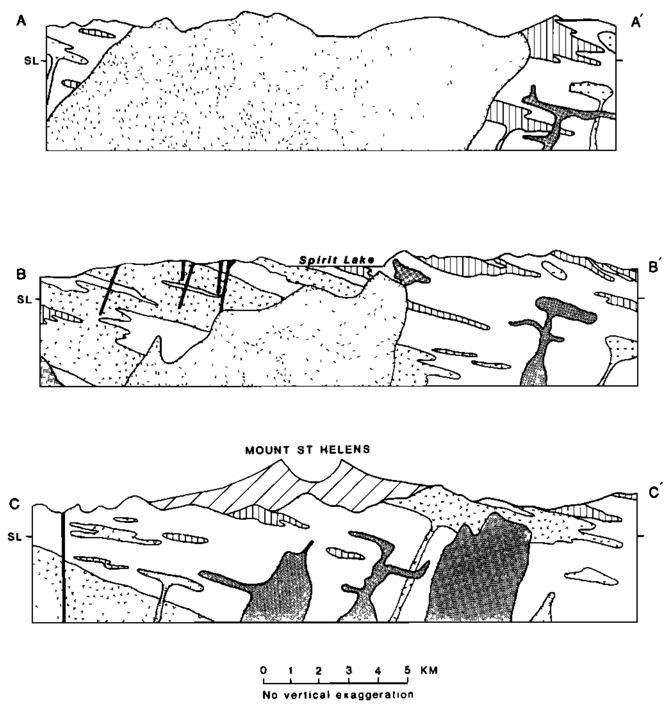

Fig. 2. Generalized geologic sections along lines A-A', B-B', and C-C' of Figure 1. Patterns of units same as in Figure 1. Quaternary units, except for the cone of Mount St. Helens, are not shown.

VOLCANIC STRATIGRAPHY

Bedrock exposed in the Mount St. Helens area (Figure 1) consists entirely of subalkaline volcanic and volcaniclastic rocks and shallow-level intrusions that represent the core of the Tertiary Cascade volcanic arc. These rocks constitute a structurally simple but stratigraphically complex and lithologically heterogeneous section several kilometers thick that strikes approximately north-south and dips about 20° east (Figure 2) [*Evarts and Ashley*, 1984]. Neither the base nor the top of this largely subaerial volcanic sequence is exposed in the area shown in Figure 1.

The detailed mapping and K-Ar geochronology reveal evidence for four significant eruptive episodes, separated by periods of apparent inactivity, in the area. By far the most important episode, in terms of the volume of eruptive products, was that of mid-Tertiary (Oligocene to early Miocene) age. Volcanic rocks produced by generally contemporaneous activity underlie much of the western Cascade Range in Washington and Oregon [*Peck et al.*, 1964; *Hammond*, 1979, 1980]. Near Mount St. Helens, rocks of this eruptive episode range in age from about 28 to 23 Ma (Table 1) and have been intruded by widespread broadly coeval epizonal granitic stocks, including the 21-Ma Spirit Lake pluton immediately north of Spirit Lake (Figures 1 and 2 and Table 2).

A second episode is represented by a sequence of 15 m.y. old porphyritic andesite flows, probably all derived from a single volcanic center, which unconformably overlie volcaniclastic strata of the first episode on Cinnamon Peak southwest of Mount St. Helens (Figure 1).

The third eruptive episode is recorded by small andesite dikes and sills that are widely scattered throughout the older section but are most common east and northeast of Mount St. Helens. K-Ar dates from these intrusions fall between 10 and 8 Ma. No effusive equivalents of these andesites have survived the extensive erosion of the past 2 m.y. [*Tolan and Beeson*, 1984].

The youngest volcanic activity in the southern Washington Cascades produced a compositionally diverse, though predominantly basaltic, suite of lava flows and pyroclastic rocks. This suite, erupted largely during the past 3 million years. [*Hammond*, 1980; *Hammond and Korosec*, 1983], rests unconformably on the folded and eroded older volcanic rocks. Near Mount St. Helens (Figure 1), this episode is represented by Marble Mountain volcano and several dacite plug-domes, all of which are probably Quaternary.

Mid-Tertiary Volcanism

Geology. The Oligocene to early Miocene rocks dominating the bedrock geology of the Mount St. Helens region constitute a varied assemblage of mafic to silicic lava flows intercalated with an array of volcaniclastic rocks of diverse origins and intruded by a variety of subvolcanic dikes, sills, and epizonal plutons. The abundance of lava flows, pumiceous lapilli tuff, coarse lithic tuff-breccia, intrusive rock, and zones of hydrothermal alteration indicate predominantly near-vent depositional environments. Well-bedded, subaqueously deposited sedimentary rocks of more distal character, such as those that comprise most of the Tertiary section (Ohanapecosh Formation) beneath Mount Rainier [*Fiske et al.*, 1963], are common only in the southwestern part of the mapped area (Figure 1). Minor stratigraphic discontinuities are common, but significant unconformities were not detected in the mid-Tertiary sequence. No major hiatuses are apparent from the K-Ar data (Table 1). Interestingly, this period of continuous volcanism from roughly 28 to 23 Ma occurred during an apparent lull in volcanic (though not plutonic) activity in the Snoqualmie Pass area 125 km northeast of Mount St. Helens and corresponds in part with the hiatus in deposition recorded by the unconformity separating the Ohanapecosh Formation from the overlying Stevens Ridge and Fifes Peak formations near Mount Rainier [*Fiske et al.*, 1963; *Frizzell et al.*, 1984; *Frizzell and Vance*, 1983]. The Oligocene/early Miocene strata near Mount St. Helens constitute only part of a thick sequence of subaerial volcanic rock that contin-

TABLE 1. K-Ar Age Determinations for Tertiary Rocks of the Mount St. Helens Area

Locality on Figure 1	Sample Number	Rock Type	Location		Material Dated and Treatment	Potassium Analyses, wt % Oxide				Radiogenic Argon, mol g^{-1}	Radiogenic Argon, %	Age*, Ma	Comments (Informal Unit Designation)
			Latitude North	Longitude West		First	Second	Third	Average				
1	S82-A3-E32	Andesite porphyry	46°23.73′	122°14.36′	plag	0.274	0.279		0.277	1.406×10^{-11}	13	35.0 ± 2.0	Anomalously old age
					plag	0.274	0.279		0.277	1.144×10^{-11}	11	28.5 ± 1.1	Geologically more reasonable age than first determination
2	S80-A1-S02	Dacitic ash flow tuff	46°27.94′	122°13.44′	plag	0.306	0.307		0.307	1.268×10^{-11}	14	28.5 ± 0.9	South shore of Riffe Lake
3	S78-A1-E209A	Hornblende andesite	46°27.03′	122°13.35′	hbl	0.270	0.256	0.269	0.265	1.040×10^{-11}	10	27.1 ± 2.0	Landers Creek
4	S81-A5-R48	Basaltic andesite	46°16.19′	122°13.73′	plag	0.201	0.202		0.202	8.103×30^{-12}	3.3	27.7 ± 3.7	North Fork Toutle River
5	S78-B2-E49A	Pyroxene andesite	46°24.75′	122°09.33′	plag	0.253	0.256		0.255	9.117×10^{-12}	2.8	24.7 ± 3.5	(Andesite of Vanson Peak)
6	S81-D1-E19	Basaltic andesite	46°28.06′	121°59.99′	plag	0.251	0.259	0.262	0.257	8.673×10^{-12}	34	23.3 ± 0.8	(Basalt of Huffaker Mountain)
7	S82-D1-E106	Basalt	46°28.51′	122°00.14′	plag	0.529	0.533		0.531	1.819×10^{-11}	46	23.6 ± 1.2	(Basalt of Huffaker Mountain)
					plag	0.529	0.533		0.531				
										1.787×10^{-11}	41	23.2 ± 0.7	
8	S78-D5-E199A	Vitrophyric welded tuff	46°15.39′	122°03.72′	plag	0.208	0.206		0.207			23.3 ± 0.6	Weighted mean age
					plag	0.208	0.206		0.207				
										7.296×10^{-12}	15	24.3 ± 0.9	Bean Creek
										7.129×10^{-12}	16	23.8 ± 0.8	
												24.0 ± 0.6	Weighted mean age
9	84SH-V82	Vitrophyric welded tuff	46°12.27′	122°03.69′	plag	0.232	0.223	0.221	0.225	8.123×10^{-12}	14	24.9 ± 1.0	Smith Creek Butte
10	S77-D3-R12	Pyroxene andesite	46°23.35′	122°02.27′	plag	0.310	0.313		0.312	1.020×10^{-11}	14	22.6 ± 0.7	Partially reset by Spirit Lake pluton; minimum age
11	S81-B5-E43	Quartz diorite sill	46°15.08′	122°08.55′	hbl	0.218	0.224		0.221	7.789×10^{-12}	8.1	24.3 ± 1.3	Windy Ridge, SE of Spirit Lake
12	S78-C5-E123A	Hornblende andesite dike	46°17.38′	122°05.47′	hbl	0.478	0.484		0.481	1.387×10^{-11}	15	19.9 ± 0.7	Unmetamorphosed; cuts contact aureole of Spirit Lake pluton
13	84CG-V29	Pyroxene andesite	46°07.72′	122°15.96′	wr, nit	1.248	1.254		1.251	2.778×10^{-11}	24	15.4 ± 0.5	(Andesite of Cinnamon Peak)
14	S78-A2-R128	Basaltic andesite sill	46°26.30′	122°12.75′	wr, nit	0.852	0.856		0.854	1.059×10^{-11}	14	8.6 ± 0.3	
15	S78-D5-M88A	Andesite dike	46°15.11′	122°02.91′	wr, nit	1.259	1.267		1.263	1.704×10^{-11}	21	9.3 ± 0.3	

16	S78-D5-E168A	Pyroxene andesite sill	46°16.10′	122°02.83′	wr, nit, hf	0.704	0.704	0.704	8.817×10^{-12}	15	8.7 ± 0.3	
17	S79-A4-R128	Granodiorite	46°20.92′	122°12.10′	biot	9.18	9.25	9.225	2.811×10^{-10}	63	21.1 ± 0.6	Main phase, Green River area
18	S80-A4-R06	Granodiorite	46°19.07′	122°12.04′	biot	8.82	8.96	8.89	2.681×10^{-10}	62	20.8 ± 0.6	Main phase, Green River area
19	S80-A4-R08	Granodiorite	46°18.72′	122°12.14′	biot	9.07	9.15	9.11	2.923×10^{-10}	65	22.2 ± 0.7	Main phase, Green River area
20	MDH6-408/410	Altered granodiorite	46°21.33′	122°04.86′	sec biot	8.89	8.89	8.89	2.225×10^{-10}	54	17.3 ± 0.5	Earl porphyry Cu deposit, potassic zone
20	MDH7 684/687	Altered granodiorite	46°21.42′	122°04.86′	sec ser	10.52	10.52	10.52	2.572×10^{-10}	67	16.9 ± 0.5	Earl porphyry Cu deposit, phyllic zone

Potassium determined by flame photometry by P. R. Klock, B. Z. Lai, S. R. MacPherson, S. T. Neil, and D. V. Vivit; argon isotope analyses by L. B. G. Pickthorn and J. G. Smith. Constants are $^{40}K/K_{total} = 1.167 \times 10^{-4}$ atom percent; $\lambda_e + \lambda_{e'} = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}.

Here plag, plagioclase; hbl, hornblende; biot, biotite; ser, sericite; sec, secondary; wr, whole rock; nit, treated with nitric acid; and hf, treated with hydrofluoric acid.

* Precision of the data, shown as the plus-or-minus value, is the estimated analytical uncertainty at one standard deviation. It represents uncertainty in the measurement of radiogenic ^{40}Ar and K in the sample and is based on experience with replicated analyses in the laboratories of the U.S. Geological Survey, Menlo Park, California.

ues to the east and west. Because neither top nor bottom of this sequence is exposed in the map area (Figure 1), definition of a formal stratigraphic unit is premature and must await additional detailed mapping and dating, especially in the poorly known region between Mounts St. Helens and Rainier.

The lavas erupted in the Mount St. Helens area during this period of activity range from olivine basalt to pyroxene dacite [*Evarts and Ashley*, 1984]. Individual flows can be traced for up to 6 km but are typically no longer than 1 km. Many "flows" are probably subvolcanic sills, which can be distinguished from extrusive units only if contacts are exposed, which is uncommon. In general, mafic compositions dominate the older part of the section to the west, whereas relatively silicic rocks are more abundant in the younger eastern part (Figure 1). However, minor amounts of rocks of any composition occur at all stratigraphic levels.

Interbedded mafic flows and flow breccia form thick (up to 500 m), more or less lensoid bodies within coarse laharic breccia, agglomerate, and scoriaceous lapilli tuff in a NNE trending zone along the western margin of the mapped area (Figure 1). Within this zone, concentrations of dikes, agglomerate, and zones of hydrothermal alteration define at least two vent areas, one near the east end of Riffe Lake and the other south of Coldwater Lake. The crudely stratiform disposition of these sequences, and K-Ar ages from within and adjacent to this zone (Figure 1 and Table 1, localities 1, 2, 3, 4, and 5), suggest that the zone may represent a cross section through a field of basaltic cones or small shields more or less simultaneously active about 27 to 28 Ma. Younger basaltic edifices occur in the northernmost part of the mapped area and east of Mount St. Helens; the former was dated at about 23–24 Ma (Figure 1 and Table 1, localities 6 and 7).

Andesite is more widespread than basalt, occurring more commonly as isolated flows throughout the Oligocene/early Miocene section. The most notable occurrences, however, are thick stacks of uniform, porphyritic, two-pyroxene andesite flows. These sequences are more resistant than the clastic rocks that envelop them and commonly form ridge-capping units throughout the map area. Erosion has totally destroyed evidence of their original configurations, but some could be remnants of the basal shields of stratovolcanoes analogous to the Miocene Tieton volcano described by *Swanson* [1966]. Others, which contain minor amounts of interbedded clastic debris, are probably piles of lava flows deposited in valleys many kilometers from their sources.

Flow-banded felsic volcanic rocks, predominantly dacite in the International Union of Geological Sciences (IUGS) classification [*Le Bas et al.*, 1986], are an important component of the Tertiary section north and east of Mount St. Helens (Figure 1). They form flow-dome complexes composed of massive dacite cores mantled by monolithologic dacite breccia. These complexes exhibit complicated contact relationships, in part intrusive, with surrounding pyroclastic units. Effects of hydrothermal alteration, including abundant disseminated pyrite, are more prevalent in the dacite dome complexes than in less silicic rocks. Because viscous, glass-rich dacite tends to pile up directly above source vents, we attribute the pervasive alteration mainly to extended fumarolic activity.

The unit of volcaniclastic rocks shown in Figure 1 encompasses an extremely diverse assemblage ranging from epiclastic sedimentary rocks composed entirely of volcanic

TABLE 2. Zircon Fission-Track Age Determinations for Granodiorite Samples From the Main Phase of the Spirit Lake Pluton

Locality in Figure 1	Sample Number	Location: North Latitude	Location: West Longitude	Number of Crystals Counted	N_s	ρ_s, $\times 10^6$ T cm^{-2}	N_i	ρ_i, $\times 10^6$ T cm^{-2}	ρ_s/ρ_i	ϕ, $\times 10^{14}$ n cm^{-2}	$P(\chi^2)$	r	Age,* Ma
17	S79-A4-R128	46°20.92′	122°12.10′	10	2456	2.7578	2290	5.1428	0.536	6.73 ± 0.21	13	0.951	21.6 ± 0.9
18	S80-A4-R06	46°19.07′	122°12.04′	11	2804	3.3152	2623	6.2025	0.535	6.89 ± 0.21	93	0.999	21.9 ± 0.9
21	S79-C4-E16	46°19.46′	122°07.18′	11	1839	1.9485	1800	3.8144	0.511	6.75 ± 0.21	90	0.986	20.6 ± 0.9
22	S76-C3-N38	46°21.23′	122°03.67′	12	2955	2.4228	2762	4.5291	0.535	6.84 ± 0.21	86	0.988	21.8 ± 0.9
23	S77-C3-J18	46°23.09′	122°04.27′	6	2718	5.1167	2738	9.9464	0.514	6.81 ± 0.21	<0.1	0.739	20.9 ± 1.8

External detector method employed for track density determinations using techniques described by *Naeser* [1978]; analyst, R. C. Evarts; constants in age equation $\lambda_f = 7.03 \times 10^{-17}$ yr^{-1}, $\lambda_D = 1.55125 \times 10^{-10}$ yr^{-1}, ${}^{235}\sigma = 580.2 \times 10^{-24}$ cm^2, and $I = {}^{235}U/{}^{238}U = 7.2527 \times 10^{-3}$.

N_s, number of spontaneous tracks counted; ρ_s, spontaneous track density; N_i, number of induced tracks counted; ρ_i, induced track density, equal to twice measured trace density; ϕ, neutron fluence determined using NBS glass standard 962 and Cu foil calibration; $P(\chi^2)$, probability of obtaining observed χ^2 value for ν degrees of freedom (ν = number of crystals − 1); and r, correlation coefficient between individual crystal track counts (N_s and N_i).

*Errors in ages (1 σ) calculated using the conventional method [*Green*, 1981] except for S77-C3-J18, where error was calculated following method B of *Green* [1981].

debris to primary pyroclastic rocks. Tuff-breccia and lapilli-tuff consisting of angular volcanic lithic fragments in a matrix containing variable proportions of pumice-lapilli and ash are much more common than conglomerate and finer grained sedimentary rocks throughout most of the area, testifying to the near-vent environment. Most of the coarse clastic rocks were derived from unconsolidated primary pyroclastic deposits, highly fractured lava flows and domes, and hydrothermally altered rocks that were stripped off subaerial volcanoes and redeposited in aprons around their bases. The products of many different mass-flowage processes are represented, including landslide, debris avalanche [*Siebert*, 1984], debris flow, hyperconcentrated flood flow [*Smith*, 1986], and high-gradient, high-discharge streamflow deposits.

Pumice-lapilli tuff, in beds from a few centimeters to tens of meters thick, is typically lithic rich and commonly displays eutaxitic foliation produced by compaction during burial. These rocks include air-fall tuff, nonwelded to poorly welded ash flow tuff, reworked pyroclastic material, and pumiceous mudflow deposits. Welded tuffs, including some with still-glassy vitrophyre zones, are also common. The absence of quartz-phyric tuff indicates that the Stevens Ridge Formation, prominent near Mount Rainier, does not extend into the Mount St. Helens area.

Up to several hundred meters of massive poorly sorted tuff-breccia and lapilli-tuff, possibly representing caldera-fill deposits, crop out immediately northeast of the Spirit Lake pluton (Figure 1). This section lacks lava flows but contains numerous small irregular intrusions of dacite. The volcaniclastic rocks exhibit widely varying proportions of angular volcanic lithic fragments and pumice; some exceptionally coarse-grained units match *Lipman*'s [1984] description of mesobreccia created during caldera collapse events. In the examples cited by *Lipman* [1984], intracaldera breccia is recognized in part by its content of large exotic blocks of precaldera Mesozoic and Paleozoic sedimentary or Precambrian crystalline rock. Unfortunately, the Tertiary volcanic terrane surrounding this possible caldera fill lacks distinctive lithologies that could be recognized as exotic blocks within the breccia. Both the dacite intrusions and the volcaniclastic rocks are pervasively hydrothermally altered. Furthermore, this volcaniclastic sequence is structurally anomalous, being the only area we have mapped that displays westerly dips (Figure 1) [*Evarts and Ashley*, 1984]. We suggest this area may be a downsag caldera, a subtle structure lacking a well-defined ring fault system. According to *Walker* [1984], downsag calderas may be more common than classical subsiding-piston type calderas, especially in terranes that do not overlie thick Precambrian crust. The westward dipping strata in the eastern half of the area underlain by the thick volcaniclastic section [*Evarts and Ashley*, 1984] are strongly suggestive of the radially inward dips characteristic of downsag calderas. The vague structural manifestation of downsag calderas, combined with the lack of strong lithologic contrast between caldera-fill and precaldera rocks, probably explains why so few of the expected source calderas for the abundant pyroclastic deposits in Tertiary Cascade strata have been recognized.

Chemistry. Analyses of least altered mid-Tertiary volcanic rocks (Table 3) show that they have quartz-normative, tholeiitic to calcalkaline compositions typical of volcanic arc environments [*Ewart*, 1982]. When plotted on a potash-silica variation diagram (Figure 3), they display generally low K_2O contents compared with recent Cascade volcanic rocks and a preponderance of mafic compositions. The Oligocene and Miocene lavas of the Mount St. Helens area also tend to be lower in K_2O than Tertiary rocks elsewhere in the Cascade Range [*Peck et al.*, 1964; *Tabor and Crowder*, 1969; *Swanson*, 1966; *Ort et al.*, 1983]. Fresh silicic flows and tuffs are uncommon, and much silicic magma erupted as pyroclasts that mixed with nonjuvenile debris and became incorporated into sedimentary deposits. Therefore dacite is somewhat underrepresented in the chemical data base compared with its volumetric proportion in the section. Furthermore, the wide variation in K_2O content of dacitic rocks (Figure 3) may partly reflect substantial alkali exchange with groundwater during hydration of groundmass glass. Nevertheless, field and petrographic studies support the chemical evidence for a dominantly basalt-to-basaltic andesite, low-K suite.

A closer petrochemical affinity of the Oligocene/early Miocene rocks near Mount St. Helens with those of evolved ensimatic arcs such as the Aleutians than with the classic calcalkaline trend displayed by Quaternary Cascade volcanoes is also apparent from the AFM (Al_2O_3, total Fe as FeO, and MgO) diagram (Figure 4). The chemical similarities between early Cascade and island-arc volcanic rocks suggest comparable tectonic environments. Thus the lower crust of southern Washington during middle Tertiary time may have been relatively thin and composed mainly of mafic rocks of oceanic character like those exposed in the Coast Ranges to the west.

TABLE 3. Representative Chemical Analyses of Tertiary Volcanic Rocks From the Mount St. Helens Area

	Oligocene/Early Miocene Rocks									
	OE38	2R14	3E57	7N26	8M74	8W21	7N144	3E52	2E125B	8E181
SiO_2	47.1	49.9	51.0	51.4	52.4	53.3	54.5	55.4	55.7	56.4
Al_2O_3	17.6	15.7	17.3	18.2	17.5	18.2	16.4	14.2	17.3	15.1
Fe_2O_3	3.84	6.76	3.32	3.7	4.3	3.2	3.5	4.56	2.59	5.0
FeO	6.97	5.89	6.20	5.0	4.0	5.1	4.6	6.25	4.85	5.3
MgO	8.36	4.45	5.99	5.5	4.0	4.4	4.9	3.09	3.54	3.0
CaO	10.6	8.31	9.46	10.3	8.4	8.7	8.3	7.02	7.68	6.2
Na_2O	2.18	2.76	2.87	2.8	2.9	3.2	2.9	3.09	2.95	3.7
K_2O	0.34	0.20	0.44	0.42	0.80	0.56	0.88	0.34	1.10	0.69
H_2O+	0.70	1.86	0.70	0.50	1.10	0.50	1.3	2.32	1.54	0.80
H_2O-	1.25	1.46	0.75	1.2	2.2	0.90	0.97	0.75	0.75	1.1
TiO_2	1.30	2.17	1.37	0.97	1.2	1.0	0.93	1.95	1.06	1.8
P_2O_5	0.11	0.32	0.22	0.15	0.22	0.18	0.27	0.37	0.17	0.31
MnO	0.18	0.22	0.16	0.16	0.16	0.15	0.17	0.19	0.12	0.16
CO_2	0.05	0.05	0.06	0.15	0.78	0.32	0.42	0.02	0.46	0.35
Total	100.58	100.05	99.84	100.45	99.96	99.71	100.04	99.55	99.81	99.91

	Oligocene/Early Miocene Rocks						Andesite of Cinnamon Peak	8- to 10-Ma Sills		
	2E35B	2E42A	3E30A	8E199A*	8R35	7R49	84CG-V29*	8E168A*	8M88A*	8R128*
SiO_2	57.2	58.0	59.3	63.8	64.1	71.3	58.4	58.4	57.6	54.7
Al_2O_3	15.1	18.0	15.2	13.5	14.9	13.3	16.1	16.2	15.8	15.8
Fe_2O_3	2.46	3.99	3.95	3.17	5.0	1.11	2.26	1.92	3.2	3.3
FeO	5.62	3.20	4.09	2.55	1.0	2.07	4.78	5.42	5.6	6.1
MgO	2.36	2.21	2.38	0.65	1.1	0.88	3.56	2.60	2.1	3.3
CaO	5.74	6.76	5.87	5.04	3.4	1.97	7.09	6.51	5.9	7.4
Na_2O	3.76	4.36	3.71	3.21	4.4	3.24	3.38	3.60	4.0	3.5
K_2O	0.77	0.80	1.15	0.50	2.0	1.71	1.08	0.99	1.1	1.5
H_2O+	3.14	0.70	0.96	4.83	0.50	2.97	1.68	2.15	1.3	1.5
H_2O-	1.06	0.27	0.90	1.72	1.3	0.86	0.51	0.89	0.81	0.64
TiO_2	1.63	1.16	1.40	0.62	0.83	0.56	1.11	1.27	1.4	1.5
P_2O_5	0.41	0.22	0.24	0.14	0.27	0.11	0.23	0.34	0.36	0.55
MnO	0.14	0.14	0.13	0.16	0.11	0.07	0.12	0.12	0.15	0.19
CO_2	0.07	<0.02	0.79	0.06	0.04	0.01	0.03	0.02	0.02	0.16
Total	99.46	99.81	100.07	99.95	98.95	100.16	100.33	100.43	99.34	100.04

See appendix for sample locations and descriptions.
* Dated samples listed in Tables 1 and 2.

Middle Miocene Volcanism

The top of the mid-Tertiary (Oligocene to early Miocene) volcanic section is not exposed in the mapped area, but the scarcity of published radiometric dates younger than about 17 Ma on volcanic or plutonic rocks from southern Washington suggests that the major period of magmatism in this part of the Cascades had waned by the time of the first eruptions of the Columbia River Basalt Group to the east [*Swanson et al.*, 1979]. Greatly diminished volcanic activity in the Washington Cascades is also evident from the paucity of downwind tephra interbedded with the flood basalt flows. This apparently rather abrupt decrease in intensity of Cascade volcanism contrasts strongly with voluminous and more continuous post-middle Miocene arc activity in Oregon [*McBirney and White*, 1982; *Fiebelkorn et al.*, 1983; *Keith et al.*, 1985].

Our work revealed evidence for relatively minor andesitic volcanism during mid-Miocene time in the Mount St. Helens area. East of Merrill Lake (Figure 1), the andesite of Cinnamon Peak consists of a stack of relatively fresh lava flows and flow breccia, with minor intercalated andesite-clast conglomerate, that rests with slight angular discordance on probable Oligocene volcaniclastic sedimentary rocks. The lavas are all porphyritic two-pyroxene andesites similar in appearance to many flows in the Oligocene to early Miocene section, but one of them yielded a whole-rock K-Ar date of 15 Ma (Figure 1 and Table 1, locality 13). Similar pyroxene andesite, unconformably overlying clastic rocks, occurs about 50 km southeast of Cinnamon Peak and has been dated at 15.7 Ma [*Berri and Korosec*, 1983]. Cinnamon Peak lavas are relatively uniform in composition (Table 3) and chemically indistinguishable from the older andesites (Figures 3 and 4).

Late Miocene Volcanism

A second renewal of volcanic activity, following a 5-m.y. hiatus, is recorded by widespread small dikes and sills of andesitic composition north and east of Mount St. Helens (too small to show on Figure 1) that have been dated at between 8 and 10 Ma (Figure 1 and Table 1, localities 14, 15, and 16). They differ petrographically from older andesites of the area only in possessing an unaltered black glassy groundmass. The largest bodies are sills, up to 50 m thick, with well-developed columnar jointing, which is rare in the older rocks. We tentatively regard these rocks as representing a discrete magmatic episode but recognize the possibility that further dating of similar rocks over a larger region in southern Washington may reveal relatively continuous, though volumetrically minor, activity throughout the latter half of the Miocene. Extrusive equivalents may once have covered an extensive area but, if so, have been stripped by extensive Plio-Pleistocene erosion. The intrusive rocks include aphyric and highly porphyritic varieties of basaltic andesite and pyroxene andesite; SiO_2 ranges from 54 to 61 wt %. The limited data (Table 3 and Figures 3 and 4) indicate that they are chemically similar to mid-Tertiary andesites.

Quaternary Volcanism

Voluminous products of Pliocene to Recent volcanism constitute the entire eastern half of the Cascade Range in Oregon [*Wells and Peck*, 1961; *Hammond*, 1979; *McBirney and White*, 1982], but correlative volcanic rocks in Washington are localized and much less abundant [*Hammond*, 1980]. They are most common near the eastern margin of the

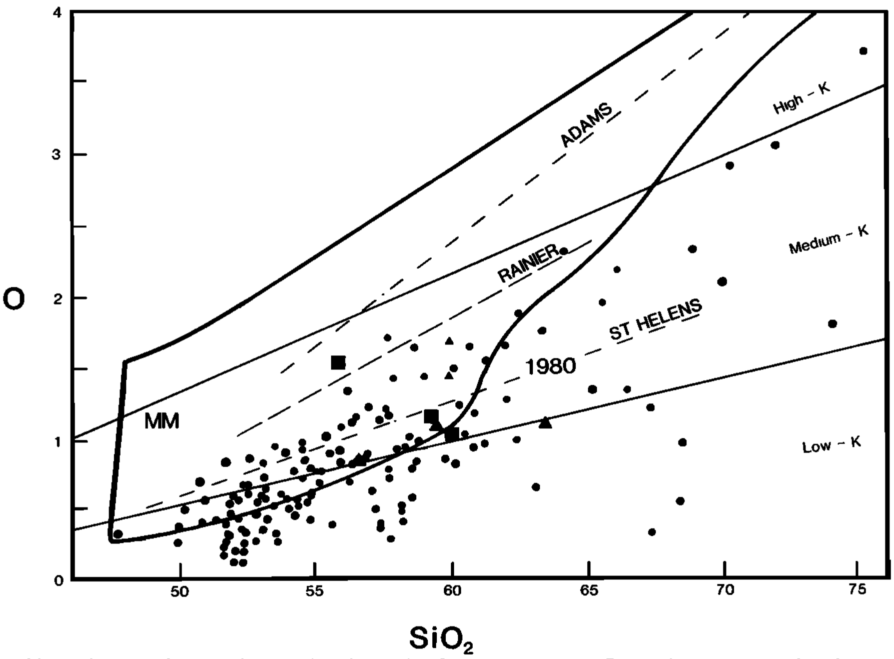

Fig. 3. K_2O-SiO_2 diagram for Tertiary volcanic rocks from the Mount St. Helens area. Triangles, andesite of Cinnamon Peak; squares, 8- to 10-Ma andesite sills. Heavy solid line delineates field of Quaternary volcanic rocks in the southern Washington Cascades from *Hammond and Korosec* [1983]. General trends for the Quaternary volcanoes Mount St. Helens, Mount Adams, and Mount Rainier based on data in the works by *Greeley and Hyde* [1972], *Condie and Swenson* [1973], *Hoblitt et al.* [1980], and *Hildreth and Fierstein* [1985]. MM is composition of basalt from Marble Mountain [*Greeley and Hyde*, 1972]. Label 1980 represents composition of dacite extruded from Mount St. Helens during current phase of activity [*Hoblitt et al.*, 1980]. Boundaries between high-, medium-, and low-K fields are from *Ewart* [1982].

range and along the Columbia River. Basalt is by far the most abundant rock type, forming large fields in the vicinity of Mount Adams, but isolated and compositionally variable centers are scattered throughout the region between Mount St. Helens and the Columbia River. Most radiometrically dated centers yield Quaternary ages, but a few are as old as 4.5 Ma [*Hammond*, 1980; *Hammond and Korosec*, 1983]. Near Mount St. Helens, basalt, andesite, and dacite were erupted from several isolated vents during the Pleistocene. In contrast to the pyroxene-phyric Tertiary lavas, young intermediate to silicic rocks usually contain hydrous minerals, chiefly hornblende and biotite, as phenocrysts, and tend to have higher K_2O contents (Figure 3).

Marble Mountain volcano. Blocky lava flows of gray, vesicular, microporphyritic olivine basalt interbedded with red, oxidized, scoriaceous zones form an eroded edifice between Mount St. Helens and Swift Reservoir (Figure 1). Activity culminated in eruption of thick flows of blocky, light gray, microporphyritic, hornblende andesite from a still-visible crater on its southern flank about 160,000 years ago [*Hammond and Korosec*, 1983]. Chemical analyses of the basalt [*Greeley and Hyde*, 1972; *Hammond and Korosec*, 1983] show markedly higher K_2O (Figure 3), Na_2O, P_2O_5, TiO_2, and normative olivine than in the pre-Quaternary mafic rocks of the area.

Goat Mountain plug. Young silicic volcanic rocks are uncommon in southern Washington, but several dacitic plug-domes occur in a linear zone extending about 12 km west-southwest from Mount St. Helens (Figure 1). The largest of these is Goat Mountain, an 850-m-tall, steep-sided, talus-mantled exhumed plug containing about 50% phenocrysts, up to 1 cm, of plagioclase, quartz, biotite, and hornblende in a groundmass of light gray friable glass. This same rock type forms two other plugs that poke through young deposits of Mount St. Helens volcano low on its southwestern flank. Discordant K-Ar dates of 3.0 Ma (hornblende) and 1.0 and 0.74 Ma (biotite) have been ob-

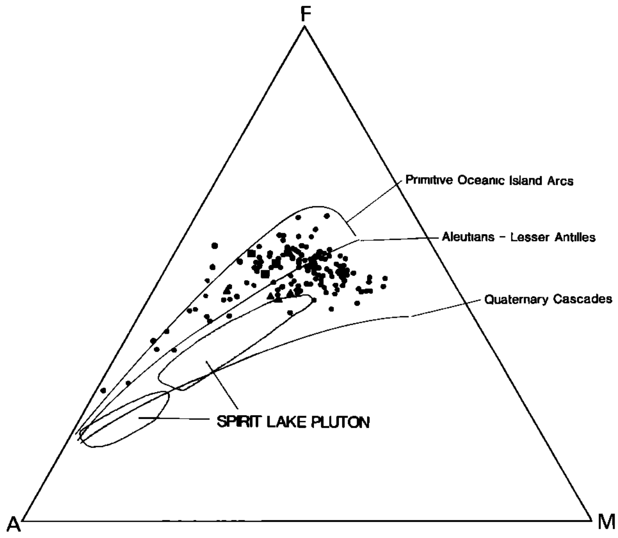

Fig. 4. AFM diagram for Tertiary volcanic and plutonic rocks from the Mount St. Helens area. Triangles, andesite of Cinnamon Peak; squares, 8- to 10-Ma andesite sills. Trend lines for rocks from several volcanic arcs, including the Quaternary Cascades, are from *Brown* [1982].

tained from Goat Mountain by Tabor (cited by *Engels et al.* [1976]). Its rugged (unglaciated?) countenance suggests that the biotite dates are more likely correct.

Butte Camp dome. A composite dome about 4 km southwest of the crater of Mount St. Helens, and a smaller dome about 8 km farther southwest (Figure 1), consist of light gray to pink, vesicular, seriate, hypersthene-hornblende dacite. Neither has been dated, but their geomorphic appearances indicate that they must be very young. They petrographically resemble old domes of Mount St. Helens now exposed in the crater wall [*Hopson and Melson*, 1982] and may be peripheral members of the dome field of the ancestral volcano [*Hopson*, 1971]; if so, their (cummingtonite-free) petrography indicates that they are probably no older than about 12,000 years [*Mullineaux*, 1986].

SYNVOLCANIC PLUTONISM

Oligocene to Miocene volcanic activity in the Washington Cascades was accompanied by widespread emplacement of plutons at shallow crustal levels. Intrusive bodies range in size from small dikes and sills of basalt, andesite, and dacite, intruded into genetically related extrusive rocks in the cores and flanks of active volcanoes, to large granitic intrusions of batholithic dimensions [*Hammond*, 1980], Phaneritic medium-grained intrusions ranging in composition from gabbro to granite are widespread around Mount St. Helens (Figures 1 and 2). They are analogous to the hypabyssal sill complexes developed in the well-bedded Ohanapecosh Formation in Mount Rainier National Park (*Fiske et al.*, 1963], but in the stratigraphically complex Mount St. Helens area they commonly assume more irregular shapes. Most are pyroxene-phyric, like the volcanic rocks they intrude; hornblende-bearing varieties are scarce. Contact metamorphic zones surround many of the intrusions, and pervasive deuteric alteration similar to that described from the Oregon Cascades by *Peck et al.* [1964] and *Taylor* [1971] is nearly ubiquitous. A large composite sill-like body of quartz diorite just southeast of Spirit Lake (Figure 1 and Table 1, locality 11) yielded a hornblende K-Ar age of 24 Ma, within 2 Ma of the probable age of the volcanic rocks it intrudes. Despite the wide variety of rock types represented among the Tertiary intrusions, none matches the prominent gabbro inclusions in many Mount St. Helens lavas [*Verhoogen*, 1937; *Heliker*, 1983].

Spirit Lake Pluton

Emplacement of a large, early Miocene, epizonal granitic pluton (Figure 1) appears to mark the culmination of the major period of mid-Tertiary volcanism in the Mount St. Helens area. The Spirit Lake pluton occurs within a northeast trending belt of large granitic intrusions that stretches from near the Columbia River to Glacier Peak. This belt includes the Silver Star, Tatoosh, and Cloudy Pass plutons and the Snoqualmie batholith [*Grant*, 1969; *Hammond*, 1979, 1980]. Published ages for most of these bodies fall within a relatively narrow span of 17–24 Ma [*Tabor and Crowder*, 1969; *Engels et al.*, 1976; *Power et al.*, 1981; *Tabor et al.*, 1982; *Frizzell et al.*, 1984], although *Mattinson* [1977] obtained U-Pb ages as young as 14.2 Ma for part of the Tatoosh. Multiple K-Ar (biotite) and fission track (zircon) ages we have obtained from the main phase of the Spirit Lake pluton (Figure 1 and Tables 1 and 2, localities 17–23) range from 20.6 to 22 Ma, in agreement with a previously published K-Ar amphibole age of 21.4 ± 0.3 Ma [*Engels et al.*, 1976].

The Spirit Lake pluton consists of three major phases, from oldest to youngest: the early granodiorite, main, and granite phases [*Evarts and Ashley*, 1984]. Each phase is itself an aggregate of multiple small intrusions. Only the main phase has been dated directly, and relative ages of the other two phases are inferred from somewhat ambiguous field relations.

The early granodiorite phase is actually a complex dike swarm, with numerous screens of thoroughly recrystallized country rock, exposed in a crudely ellipsoidal but poorly exposed area about 4 km in diameter in the northwestern part of the pluton [*Evarts and Ashley*, 1984]. The dikes consist of fine-grained porphyritic to seriate pyroxene quartz diorite and granodiorite that have been subjected to strong deuteric alteration. Exposures are inadequate to determine whether the dikes are preferentially oriented, but the unit as a whole is elongated in a NE-SW direction (Figure 7).

The main and granite phases are coarse grained and more massive than the early granodiorite phase. They together comprise a NE elongated massif that displays relatively simply external contacts against volcanic country rock. Emplacement, for the most part, generated neither marginal intrusion breccias nor multiple sill complexes [*Fiske et al.*, 1963], although narrow dikelike offshoots locally extend up to 30 m away from the main body of the pluton. The contact sharply truncates country rock stratigraphy and is generally nearly vertical except along the eastern edge, where it locally dips eastward at low to moderate angles, approximately concordant with the stratigraphy. This suggests that the pluton is shaped like a flat-roofed cylinder.

The depth of emplacement is not well constrained. It could not have been great, as indicated by the common occurrence of porphyritic and micrographic textures (suggesting venting and consequent pressure quenching), miarolitic cavities, and the presence of andalusite but not garnet in the contact metamorphic aureole. Eruptive products and other information necessary to establish stratigraphic control for reliable estimates of the thickness of cover must be sought in the relatively poorly known area east of the mapped area; available data [*Hammond*, 1980] suggest that the thickness was probably less than 3 km.

In detail, the main and granite phases are texturally and compositionally heterogeneous. Each phase consists of myriads of small irregular bodies with complex and subtle, often gradational contacts. Apparently similar units in the Peruvian batholith are termed "surges" by *Cobbing and Pitcher* [1972], who attribute them to differential movement of variably crystallized liquids within silicic magma chambers. Individual units of the main phase range in composition from quartz diorite to monzogranite (Figure 5), and in texture from hypidiomorphic granular to coarsely porphyritic. Nearly all contain augite and hypersthene as primary mafic minerals; hornblende and biotite, where present, crystallized late and in minor amounts. No correlations between composition, texture, or age are apparent within the main phase, but internal units from the western part of the pluton tend to be larger, coarser grained, more equigranular, and more consistently biotite bearing than those to the east. The pluton was apparently tilted eastward along with its host rocks, exposing deeper levels to the west.

Large exposures of the granite phase occur only in the eastern half of the Spirit Lake pluton [*Evarts and Ashley*, 1984]. However, many thin dikes of aplitic granite (alaskite) occur widely throughout the main phase and are probably related to the granite phase. Contacts with the main phase are sharp and often marked by apophyses of granite within main phase rock or by intrusion breccia consisting of angular to subangular blocks of main phase rock in a granite matrix. Rocks of the granite phase are compositionally distinct from those of the main phase (Figure 5). They are also finer grained, possessing textures ranging from allotriomorphic granular to micrographic to porphyritic. As in the main phase, pyroxenes are the dominant mafic minerals.

The mineralogical and chemical characteristics of the Spirit Lake pluton are those of typical I-type granitic rocks [*White and Chappell*, 1983]. SiO_2 ranges from 56 to 68 wt % for the main phase and 67 to 75 wt % for the granite phase; the few analyzed samples from the early granodiorite phase are generally similar to the main phase granodiorite. Analyses from the main and granite phases display a discontinuity in K_2O values (Figure 6), suggesting they are not genetically related via simple crystal fractionation. Silica variation diagrams for the other major elements, however, exhibit no discontinuities. K_2O and total alkalies are markedly higher in the granitic rocks than in the slightly older volcanic host rocks (Figures 3, 4, and 6). At SiO_2 = 57.5%, K_2O is about 1.2 wt % versus 0.7 wt % in the volcanics.

METAMORPHISM AND HYDROTHERMAL ALTERATION

Oligocene and early Miocene rocks throughout the southern Washington Cascades have been overprinted by zeolite-facies burial metamorphism [*Fiske et al.*, 1963; *Wise*, 1970; *Hammond*, 1980]. The time span during which this occurred no doubt roughly coincided with that of volcanism, and metamorphism probably reached its peak during early Miocene emplacement of large granitic plutons. Late Miocene subvolcanic intrusive rocks in the Mount St. Helens area are fresh and glassy.

The most common manifestation of burial metamorphism is conversion of glass to iron-rich smectites that give the rocks their characteristic green colors. This alteration is particularly well developed in originally glass-rich fragmental rocks such as pumiceous tuff. The clay minerals are often accompanied by calcite or calcic zeolites, the most common of which are laumontite, stilbite, epistilbite, and heulandite. The distribution of secondary minerals, especially the zeolites, is primarily controlled by rock porosity and proportion of unstable glass. Neither degree of textural reconstitution nor secondary mineralogy varies systematically with stratigraphic depth within the several-kilometer-thick Tertiary section around Mount St. Helens.

The regional geothermal regime responsible for zeolite-facies burial metamorphism was repeatedly perturbed during early Miocene time by intrusion of the plutons. The observed effects may extend large distances from exposed intrusions, and even the smallest bodies are commonly rimmed by prominent contact metamorphic aureoles. The best developed aureole, from 1.5 to 4 km wide, is that around the Spirit Lake pluton. It is composed of an inner zone of black, flinty, aphanitic amphibole hornfels (amphibole + chlorite + magnetite + quartz + plagioclase ± biotite ± cordierite ± diopside) and an outer zone of green albite-epidote hornfels (albite + epidote + chlorite + quartz + sphene ± muscovite). Pyroxene hornfels (calcic plagioclase + diopside + hypersthene + quartz + magnetite ± cordierite) occurs locally along the pluton margin and in rare inclusions of country rock within it. Subtle contact metamorphism extends beyond the visible aureole as a fringe zone containing sporadic occurrences of prehnite and pumpellyite.

Scattered throughout the Tertiary section are localized irregular zones in which the rocks have been pervasively replaced by assemblages of fine-grained clay and carbonate. Typical minerals include kaolinite, montmorillonite, illite, calcite, siderite, dolomite, ankerite, quartz, and limonite. Such zones are commonly associated with areas containing abundant dikes but are not restricted to such areas. Most appear to be the products of low-temperature, near-surface, geothermal phenomena penecontemporaneous with Tertiary volcanism. The presence of active CO_2-rich springs in the region [*Barnes et al.*, 1981], however, suggests that similar alteration may be occurring now.

Larger, deeper seated, higher temperature hydrothermal

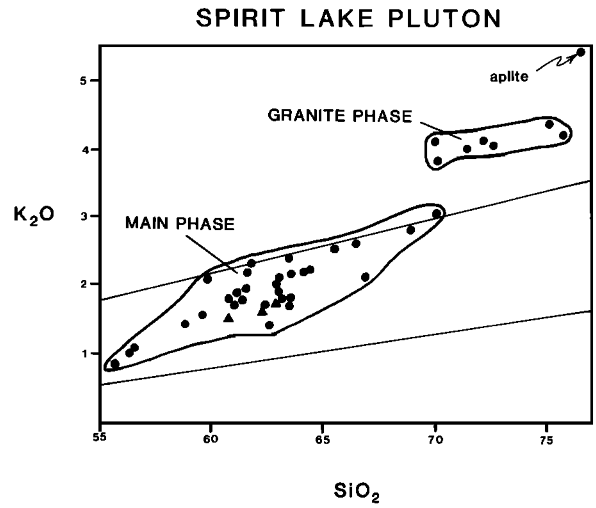

Fig. 6. K_2O-SiO_2 variation diagram of analyzed rocks from the Spirit Lake pluton. Triangles are samples from the early granodiorite phase.

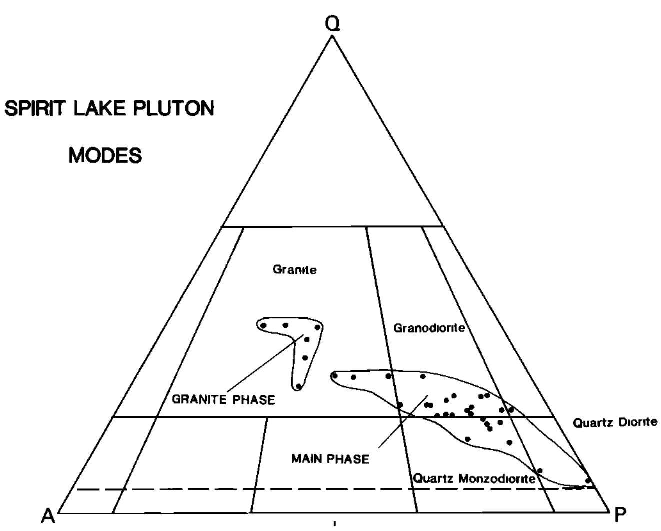

Fig. 5. Modes of coarse-grained rocks of the Spirit Lake pluton plotted on the IUGS quartz-plagioclase-alkali feldspar ternary diagram; field boundaries from *Streckeisen* [1976].

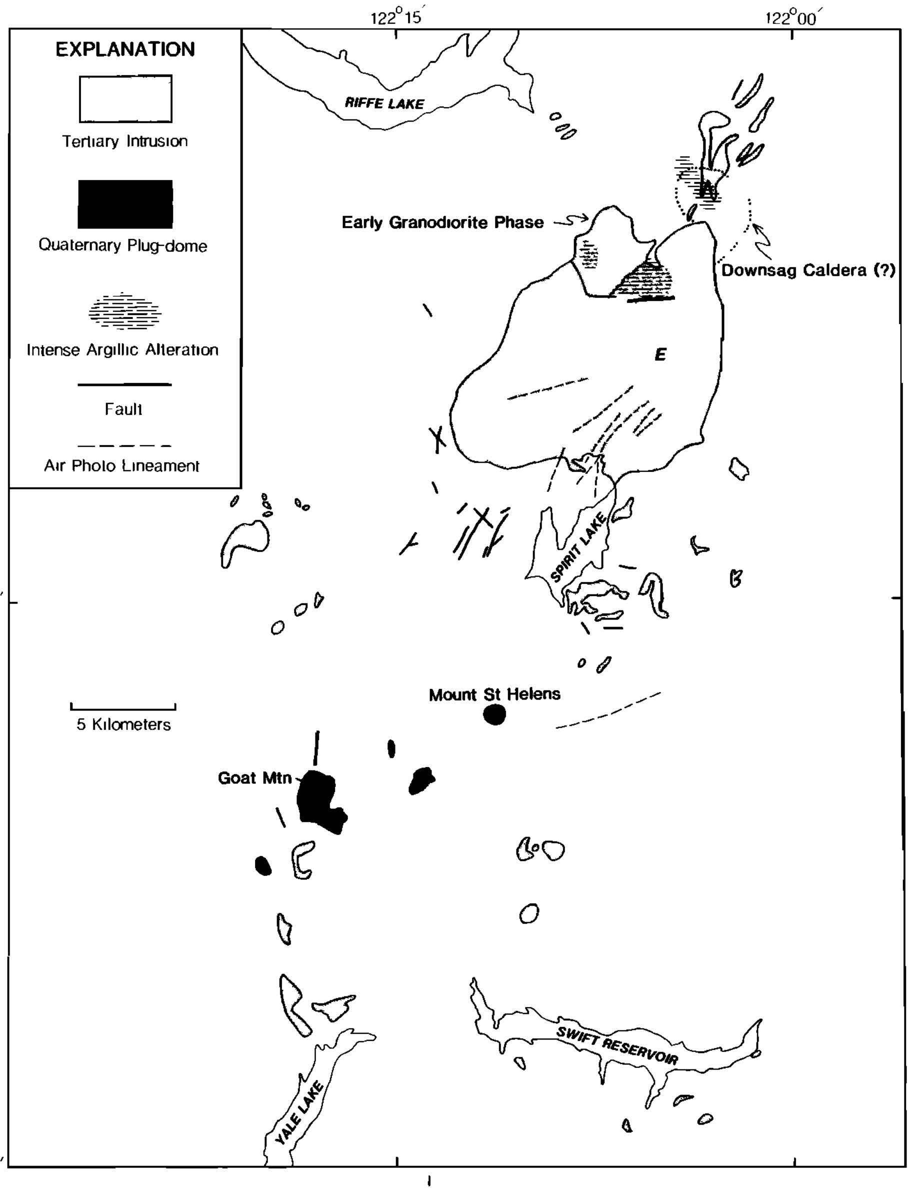

Fig. 7. Map showing features contributing to the dominant structural trends in the Mount St. Helens area. Information from *Hammond* [1980], *Evarts and Ashley* [1984], *Phillips* [1987], and unpublished mapping by the authors. Location of Earl porphyry copper deposit marked by point E.

systems produced three zones of advanced argillic alteration within and adjacent to the northern part of the Spirit Lake pluton (Figures 1 and 7). Another independent system was responsible for the Earl porphyry copper deposit in the main phase. Within the advanced argillic zones, the original rocks were totally replaced by fine-grained quartz, rutile, limonite, and sericite or pyrophyllite, accompanied locally by diaspore, andalusite, topaz(?), and various clay minerals. A vague brecciated texture is often evident in hand specimen. Protoliths are usually obscure but include porphyritic volcanic and hypabyssal plutonic rocks and possibly volcaniclastic rocks. The age of this alteration, other than being younger than the main phase of the pluton, is unknown.

The Earl deposit is one of several known porphyry copper-molybdenum systems in the Washington Cascades [*Hollister*, 1979]. Although it is located entirely within the Spirit Lake pluton (Figure 1, locality 20), K-Ar dates on secondary biotite and sericite (Table 1 and *Armstrong et al.* [1976] show that it is much too young (around 17 Ma) to be genetically related to the main phase. A relationship with the undated granite phase is possible, but altered dikes of quartz porphyry and hornblende dacite in the immediate vicinity of the deposit raise the possibility that an unexposed stock provided the heat source and metals.

STRUCTURAL ELEMENTS

The Tertiary rocks beneath Mount St. Helens strike roughly north-south and dip east at an average of 20°–25° (Figure 1 and 2), forming the northeastern limb of a broad regional anticline that plunges gently south. The axis of the corresponding syncline lies several kilometers east of the mapped area. Such broad open folds are the dominant structures in the Cascade province of southern Washington [e.g., *Fiske et al.*, 1963; *Fisher*, 1961; *Wise*, 1970; *Hammond*, 1980; *Swanson and Clayton*, 1983; *Frizzell et al.*, 1984]. Local deviations from this pattern in the area north of Mount St. Helens [*Evarts and Ashley*, 1984] may reflect variations in primary depositional attitudes on the flanks of volcanoes rather than regional tectonics or emplacement of the Spirit Lake pluton.

The age of the folding is not well constrained by present data, and studies elsewhere in the Cascades [*Fiske et al.*, 1963; *Wise*, 1970; *Hammond*, 1979, 1980] suggest that folding may have taken place over an extended period of time. Eastward tilting of the Spirit Lake pluton, inferred from west-to-east textural variations within the main phase described above, implies that the age of folding in the Mount St. Helens area is post-21 Ma. East of the mapped area, rocks as young as 18 Ma are folded. South of the volcano, the 15 m.y. old andesite flows of Cinnamon Peak (Figure 1) rest unconformably on east dipping volcaniclastic strata. The angular discordance is only about 10°, and the contact itself dips irregularly southeastward. This indicates that some folding occurred prior to 15 Ma, but whether the dipping unconformity reflects continued deformation or an irregular erosion surface is unclear. According to *Hammond* [1980], the main fold system of the Cascades has been overprinted in the eastern part of the province by the transverse Yakima fold belt (late Miocene to Pliocene) of the Columbia Plateau. The scarcity of documented middle and late Miocene rocks hinders attempts to further refine the structural history of the Washington Cascades, but in general the interference pattern expected from superposition of fold systems has not been reported in the literature.

Remarkably few faults have been observed in the Tertiary rocks near Mount St. Helens, due partly to the dense cover of tephra, glacial deposits, and vegetation, and partly to the lack of distinctive marker beds. However, few faults were observed even in the deforested area around Spirit Lake (Figure 1), and all are minor features displaying no more than a few meters of apparent offset. Rock adjacent to the fault planes is generally altered to clay carbonate assemblages mineralogically similar to those of the low-temperature hydrothermally altered zones. Slickensided surfaces indicate both horizontal and vertical slip. Most of these faults are old structures; many are occupied or crossed, without offset, by dikes of mid-Tertiary volcanic rocks. None displaces Quaternary deposits, and no fault has been detected along the trend of the St. Helens seismic zone (SHZ) of *Weaver and Smith* [1983]. A young fault, marked by a zone of sheared but unaltered gouge trending due north from the Goat Mountain plug west of Mount St. Helens (Figure 1), is associated with severe localized disruption of the nearby Tertiary strata and almost certainly formed during emplacement of the plug at about 1 Ma.

DISCUSSION

The complexity of the geology of the southern Washington Cascades is not restricted to the uppermost part of the crust, as revealed by the recently published results of a regional magnetotelluric survey by *Stanley* [1984]. One of his profiles runs east-west along the northern edge of the mapped area and indicates that the volcanic rocks exposed at the surface are underlain at shallow depth (<3 km) by an electrically resistive (100–500 ohm m) unit about 3.5 km thick referred to as "upper crustal rocks." Stanley interpreted the unexposed moderately resistive unit as pre-Tertiary rocks representing either the leading edge of the North American plate during Mesozoic time or an accreted terrane. However, the stratigraphic thickness of the volcanic section in the Mount St. Helens area exceeds 6 km, and the nearest exposures of pre-Tertiary rocks are more than 40 km away. The existence of pre-Tertiary rocks at shallow depth is therefore unlikely, and we prefer an alternative possibility that the moderately resistive unit consists of a relatively large proportion of highly resistive granitic plutons in a section of variably hornfelsed and moderately conductive Tertiary volcanic rocks.

No individual faults of regional significance occur in the Mount St. Helens area, but a combination of several rather subtle features delineates a roughly N25E trending belt (Figure 7) of possible fundamental importance. Contributing to this belt are (1) preferential NNE orientation of faults near Spirit Lake, (2) elongation of the Spirit Lake pluton and its early granodiorite phase, (3) prominent air photo lineaments that mark pyrite-bearing joints within the pluton, (4) distribution of Tertiary intrusions, and (5) orientation of dioritic dikes northeast of the pluton. Furthermore, major zones of advanced argillic alteration, the postulated caldera structure, and the Earl ore deposit also fall along this trend, as do Mount St. Helens, the cluster of dacite plug-domes immediately southwest of the volcano, and Tertiary intrusions near Merrill Lake. On a broader regional scale, most other large Miocene intrusions in the Cascades and the Quaternary stratovolcanoes of Mount Rainier and Glacier Peak are aligned along the projection of this trend, which crosses the Olympic-Wallowa lineament [*Hammond*, 1979] without apparent deflection. All of these features may reflect a long-lived deep-seated lithospheric flaw that has exerted major control on transfer of magma to the upper crust of southern Washington for approximately the last 25 m.y. This old northeast trending structure could be responsible for the orientation of the segment of the modern volcanic arc between Mount St. Helens and Glacier Peak [*Hughes et al.*, 1980].

Mount St. Helens is located at the apparent intersection of the hypothesized N25E trending structure and a second feature defined by the ENE-WSW bearing array of Pleistocene plug-domes west of the volcano (Figure 7). This array is distributed along the projection of an active fault inferred from the seismic record of the May 18, 1980, eruption by *Shemata and Weaver* [1987]. The seismically defined structure lies beneath the mountain about 2 km north of the active vent and is interpreted to form the northwestern boundary of the shallow magma reservoir that fed the eruption. A prominent topographic lineament east of the volcano parallels the ENE trend (Figure 7). This lineament results from differential weathering of a Tertiary dike swarm; offset along it is negligible. The ENE trend also marks a local northwestern limit of Quaternary volcanism in the western Cascade Range of southern Washington [see *Hammond*, 1980; *Hammond and Korosec*, 1983]. The N55E azimuth of this trend is parallel to both the maximum compressive stress axis in the Mount St. Helens area [*Weaver and Smith*, 1983] and to the convergence direction between the North American and Juan de Fuca plates [*Riddihough*, 1977].

Bacon [1985], following *Nakamura* [1977], has recently discussed some of the relationships between crustal stress, magma supply rates, and vent distributions in volcanic fields. With its linear array of silicic vents parallel to the maximum horizontal compressive stress direction, repeated appearance of basaltic lava in the area during the Quaternary, and seismic evidence for a 10- to 20-km^3 silicic magma chamber at 7- to 13-km depth [*Scandone and Malone*, 1985; *Shemata and Weaver*, 1987], Mount St. Helens well exemplifies the class of small, tectonically controlled volcanic fields discussed by Bacon.

SUMMARY

Mount St. Helens volcano was constructed during Pleistocene to Holocene time on a glaciated and deeply dissected terrane of folded and altered Tertiary volcanogenic rocks. Geologic mapping and geochemical and geochronologic studies reveal a Tertiary section dominated by the products of an Oligocene to early Miocene period of vigorous subaerial volcanism and plutonism. This heterogeneous mid-Tertiary assemblage includes the remains of basaltic cones and shields, andesitic composite cones, dacite domes, and possibly a small caldera, all intruded by a myriad of subvolcanic to epizonal intrusions. The age data indicate that magmatic activity was essentially continuous during the roughly 5 m.y. span (28–23 Ma; Table 1) represented by the stratigraphic section near Mount St. Helens. Mafic volcanism prevailed during the early part of this period. Younger activity was more variable, although predominately andesitic to dacitic, and culminated in emplacement of the Spirit Lake granitic pluton about 21 Ma. Neither the top nor bottom of the mid-Tertiary section is exposed in the mapped area, but evidence from elsewhere in southern Washington suggests that Cascade arc volcanism had declined greatly by the time of the eruption of the Columbia River Basalt Group beginning approximately 17 Ma. Pervasive zeolite-facies burial metamorphism affected all of these rocks, and those adjacent to the numerous epizonal intrusions of the area have been converted to amphibole- or epidote-hornfels facies rocks. The widespread occurrence of contact metamorphic rocks implies that the proportion of plutonic rocks is substantially greater at shallow depth than at the present level of exposure.

The mid-Tertiary strata dip rather uniformly east (aside from variations in initial dips) at 20°–25°, forming part of a regional low-amplitude, long-wavelength fold system. The age of deformation is poorly constrained, but most folding may have taken place between 15 and 20 Ma.

Volcanism in the area around Mount St. Helens since early Miocene time has been restricted to a few relatively small local centers. Based primarily on K-Ar dates, we recognize three periods of post-Miocene to early Miocene activity: eruption of andesite flows in the vicinity of Cinnamon Peak about 15 Ma, widespread emplacement of shallow dikes and sills of andesite between 8 and 10 Ma, and construction of basaltic to andesitic cones and dacitic plugdomes, leading to the formation of the active volcano, during the Pleistocene. Additional geologic mapping and radiometric dating over a much larger area in southern Washington are necessary to demonstrate whether or not the middle and late Miocene rocks represent discrete pulses of regional significance. The Quaternary rocks are petrologically distinct from the older volcanic rocks in their more "continental" affinities; they typically contain phenocrysts of hydrous minerals and are distinctly richer in alkalies than the tholeiitic to calcalkaline Tertiary rocks.

Mount St. Helens is located at the intersection of NNE and ENE trends in the underlying rocks. The broad NNE trend, reflected in the alignment of a variety of Tertiary features in the area, may be the manifestation of an ancient deep-seated lithospheric flaw that has controlled the main locus of volcanism in the Cascade arc of central Washington since at least Oligocene time. The ENE trend appears related to the tectonic stresses currently affecting the region; it parallels the maximum horizontal stress axis in the crust and the convergence direction between the North American and Juan de Fuca plates [*Riddihough*, 1977; *Weaver and Smith*, 1983], Geologic evidence suggests that these stresses have reactivated a set of older Tertiary fractures, permitting leakage of silicic magma to the surface several times during the past million years or so. Seismic data [*Shemata and Weaver*, 1987] suggest that one segment of this set forms the northwestern boundary of the shallow magma chamber tapped by the May 18, 1980, eruption of Mount St. Helens. The vent of the active volcano is evidently localized within the broad NNE trend at the intersection of the ENE fracture zone and the SHZ of *Weaver and Smith* [1983]. The SHZ seems to be a very young feature with no recognizable geologic expression.

APPENDIX: DESCRIPTIONS AND SAMPLE LOCATIONS FOR ANALYZED ROCKS

OE38 40°28.26'N, 122°00.94'W, porphyritic (phenocrysts of plagioclase-olivine-augite-magnetite, in order of decreasing abundance) olivine basalt.

2R14 46°16.64'N, 122°12.83'W, aphyric holocrystalline basalt.

3E57 46°28.13'N, 122°11.60'W, porphyritic-seriate (plagioclase-olivine) basalt.

7N26 46°28.38'N, 122°03.58'W, seriate (plagioclase-olivine) basaltic andesite.

8M74 46°15.45'N, 122°05.36'W, medium-grained pyroxene gabbro sill.

8W21 46°25.90'N, 122°08.62'W, porphyritic (plagioclase-olivine) basaltic andesite.

7N144 46°25.53'N, 122°05.66'W, porphyritic (plagioclase-hypersthene-augite-olivine-magnetite) pyroxene andesite.

3E52 46°16.25'N, 122°04.33'W, sparsely phyric (plagioclase-augite-hypersthene) andesite.

2E125B 46°17.14'N, 122°06.66'W, medium-grained hypidiomorphic-granular pyroxene diorite sill.

8E181 46°16.27'N, 122°06.43'W, aphyric andesite.

2E35B 46°23.52'N, 122°14.42'W, aphyric andesite.

2E42A 46°16.39'N, 122°03.18'W, porphyritic (plagioclase-augite-hypersthene-magnetite) pyroxene andesite dike.

3E30A 46°27.51'N, 122°06.84'W, aphyric andesite.

8E199A 46°15.39'N, 122°03.72'W, porphyritic (plagioclase-augite-magnetite) vitrophyric dacite welded tuff.

8R35 46°26.52'N, 122°07.03'W, porphyritic (plagioclase-augite-hypersthene-magnetite) pyroxene dacite.

7R49 46°26.87'N, 122°06.20'W, porphyritic (plagioclase-augite-magnetite) pyroxene rhyolite.

84CG-V29 46°07.72'N, 122°15.96'W, porphyritic (plagioclase-augite-hypersthene-magnetite) vitric pyroxene andesite.

8E168A 46°16.10'N, 122°02.83'W, porphyritic (plagioclase-augite-hypersthene-magnetite) vitric pyroxene andesite sill.

8M88A 46°15.11'N, 122°02.91'W, sparsely phyric (plagioclase-augite-magnetite) vitric andesite sill.

8R128 46°26.30'N, 122°12.27'W, sparsely phyric (plagioclase-augite) vitric andesite sill.

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