A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006
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Chapter 28

The Pleistocene Eruptive History of Mount St. Helens, Washington, from 300,000 to 12,800 Years Before Present

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Abstract

We report the results of recent geologic mapping and radiometric dating that add considerable detail to our understanding of the eruptive history of Mount St. Helens before its latest, or Spirit Lake, stage. New data and reevaluation of earlier work indicate at least two eruptive periods during the earliest, or Ape Canyon, stage, possibly separated by a long hiatus: one about 300–250 ka and a second about 160–35 ka. Volcanism during this stage included eruption of biotite- and quartz-bearing dacite domes and pyroclastic flows in the area west of and beneath the present-day edifice, accompanied by the deposition of set C tephras. Ape Canyon-stage rocks are compositionally similar to younger Mount St. Helens dacite.

The Cougar stage, about 28–18 ka, was probably the most active eruptive stage in Mount St. Helens' history before the Spirit Lake stage. During the Cougar stage, a debris avalanche buried the area south of the present-day edifice, and voluminous pyroclastic flows, dacite domes, tephra, and a large-volume pyroxene andesite lava flow were erupted. Two tephra sets, M and K, were deposited midway through this stage.

Swift Creek-stage deposits were emplaced in two phases, beginning about 16 ka and ending about 12.8 ka. During the first phase, set S tephras and three large fans and at least one smaller fan of dacitic fragmental material were deposited on the northwest, west, south, and southeast flanks of Mount St. Helens. The fans are dominated by lithic pyroclastic-flow deposits associated with dome building but include both primary and reworked material from pumiceous pyroclastic flows and lahars. One Swift Creek-age dome on the west flank of the volcano has been located, and others must have been nearby. During the second phase, set J tephras were deposited, but no pyroclastic flows or domes are known to be associated with the andesitic set J tephras.

Preliminary petrographic analysis of these older rocks suggests that the volcano's magmatic system was simpler during the Ape Canyon stage than during subsequent stages and that the magmatic system has evolved from relatively simple to more complex as the volcano matured. Compositional cycles as envisioned by C.A. Hopson and W.G. Melson for the Spirit Lake stage probably did not occur during the Ape Canyon stage but developed later during the Cougar and Swift Creek stages.

Introduction

The general eruptive history of Mount St. Helens was established through the work of U.S. Geological Survey (USGS) scientists D.R. Mullineaux and D.R. Crandell. Although the edifice was constructed primarily by eruptions of lava domes and flows, the volcano's fallout tephra record is extensive; and away from the mountain and its fragmental apron, pumice and ash locally bury the older landscape, commonly to a depth of 3 m or more. Detailed study of these tephra deposits over a period of 30 years (see Mullineaux, 1996, and references therein) has established a general geochronologic framework for understanding the volcano's eruptive history. Four periods of intermittent volcanism, called stages, are recognized (fig. 1) on the basis of observed time-stratigraphic groups, or "sets," of similar-age tephras, separated by weathered intervals. Tephra set C is the dominant tephra of the earliest, or Ape Canyon, stage; tephra sets M and K mark the Cougar stage, tephra sets S and J mark the Swift Creek stage, and tephra sets Y, P, B, and W (and several less extensive ash layers) were deposited during the latest, or Spirit Lake, stage. An extensive apron of fragmental deposits surrounds the volcano and fills valleys draining the mountain

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(fig. 2). Study of these deposits, which include sequences of pyroclastic flows, lahars, and debris avalanches, placed them into the general geochronologic framework (see Crandell, 1987, and references therein).

Age control on the eruptive history of Mount St. Helens was established by radiometric (^{14}C) dating of organic material in or directly beneath tephra, pyroclastic, and lahar deposits (Crandell and others, 1981; Crandell, 1987; Mullineaux, 1996); however, most dating focused on the youngest and best-preserved part of the volcano. Verhoogen (1937) published a crude geologic map, and Hopson (2008) a more detailed geologic map, of the edifice, both of which focus on the youngest part (Spirit Lake stage) of the volcano and provide little information on the older rocks.

New geologic mapping and radiometric dating allow us to refine and extend the general geochronologic framework—especially in the older part of the record that predates construction of the modern volcanic edifice. Here we report new radiometric (primarily $^{40}Ar/^{39}Ar$) ages of Ape Canyon- and Cougar-stage lavas and pyroclastic deposits and describe the older rocks erupted from Mount St. Helens and preserved in its debris apron and in river valleys draining the volcano. We integrate the tephrochronology of Mullineaux (1996) and the age information on lahars and pyroclastic flows reported by Crandell (1987) into a stratigraphy of the fragmental apron of the volcano. Although we modify the age ranges and intervals between eruptive stages at Mount St. Helens, we retain Mullineaux and Crandell's terminology. The single major modification to their scheme is that we assign volcanism substantially earlier than about 40 ka and not recognized by them to their Ape Canyon stage, which thus lasted from about 300 to about 35 ka. In all, ranges of the four stages are Ape Canyon, 300–35 ka; Cougar, 28–18 ka; Swift Creek, 16–12.8 ka; and Spirit Lake, 3.9–0 ka, as summarized in figure 1.

The eruptive products of Mount St. Helens are dominated by varied hypersthene-hornblende dacite but include olivine basalt, olivine and pyroxene andesite, and quartz- and biotite-bearing dacite. Since the 1980 eruption, a tremendous volume of geochemical data has been generated. Most analyses are of Spirit Lake-stage rocks, obtained to determine the general chemistry of the youngest part of the volcano; some analyses were applied to determining the origin of Mount St. Helens magmas, but most analyses were not carefully correlated with stratigraphy. Unlike their well-studied younger counterparts, the products of the earlier eruptive stages are inadequately characterized. Here we combine major-element geochemical data from the literature with data generated by USGS laboratories and correlate them with the petrography of the rocks to characterize the Ape Canyon, Cougar, and Swift Creek stages of Mount St. Helens.

Stage and age	Period and age	Tephra set
Spirit Lake stage, 3.9–0 ka	Modern period, 1980–present	**1980**
	Goat Rocks period, 1800–1857 C.E.	**layer T**
	Kalama period, 1479–1750 C.E.	**set X** **set W**
	Sugar Bowl period, 1,200–1,150 yr B.P.	**layer D**
	Castle Creek period, 2,200–1,895 yr B.P.	**set B**
	Pine Creek period, 3,000–2,500 yr B.P.	**set P**
	Smith Creek period, 3,900–3,300 yr B.P.	**set Y**
Dormant interval, 12.8–3.9 ka		
Swift Creek stage, 16–12.8 ka		**set J** **set S**
Dormant interval, 18–16 ka		
Cougar stage, 28–18 ka		**set K** **set M**
Dormant interval, 35–28 ka		
Ape Canyon stage, 300–35 ka		set C

Figure 1. Mount St. Helens eruptive history.

Analytical Techniques

K-Ar and $^{40}Ar/^{39}Ar$ Geochronology

Using $^{40}Ar/^{39}Ar$ incremental-heating techniques, we analyzed whole rock, groundmass, or plagioclase phenocrysts from 17 lava samples (see fig. 3 for locations). For whole rock experiments, samples were crushed, ultrasonicated, and sized to narrow ranges (typically 500–1,000 µm). For groundmass separates, samples were crushed, ultrasonicated, and sized to narrow ranges (typically 250–350 µm), depending on the distance between phenocrysts. Dense, clean groundmass was concentrated by using a Frantz magnetic separator and careful handpicking under a binocular microscope. For plagioclase separates, samples were crushed and sieved to narrow size ranges, depending on the sizes of inclusion-free plagioclase (typically 300–400 µm), and purified by using magnetic and density techniques, dilute HF etching, and handpicking. Samples were irradiated in six different packages between March 2000 and May 2005, all with identical technique. For irradiation, samples weighing 150–250 mg were packaged in Cu foil and placed in cylindrical quartz vials, together with 27.87-Ma Taylor Creek sanidine fluence monitors and K-glass and fluorite to measure interfering K and Ca isotopes; quartz vials were wrapped in 0.5-mm-thick Cd foil to shield samples

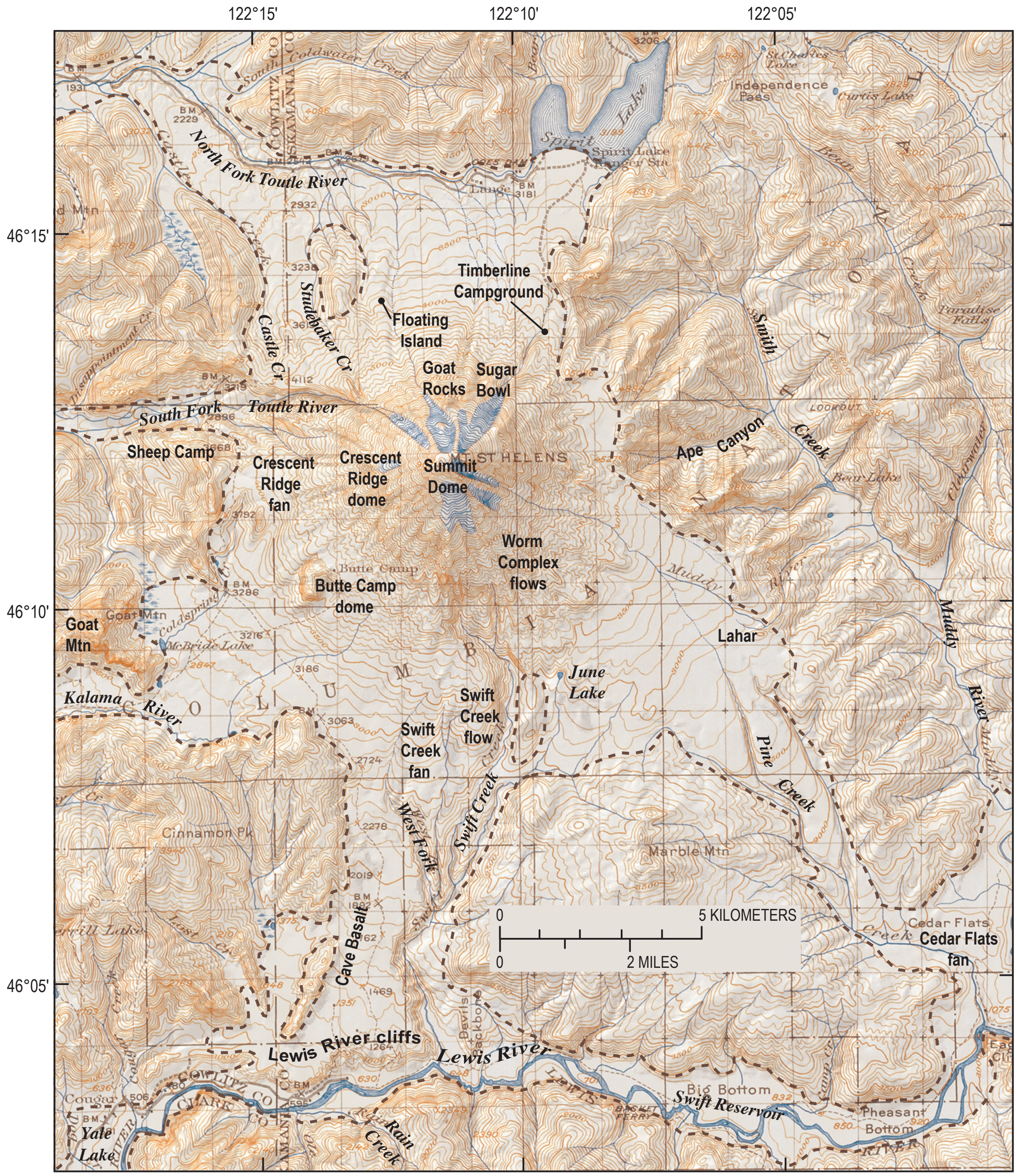


Figure 2. Mount St. Helens area, southwestern Washington, before the 1980 eruption. Dashed outline denotes approximate limit of Mount St. Helens debris apron. Fragmental deposits derived from Mount St. Helens extend farther down all major drainages heading on volcano. Swift Reservoir fills the Lewis River valley between Swift Creek and Pine Creek, and Yale Lake fills valley west of Rain Creek. Base is pre-1980 topographic quadrangle map (U.S. Geological Survey, 1919) in North American datum (later renamed North American Datum 1927), enhanced by D.W. Ramsey to create hillslope shading as if illuminated from northwest.

from thermal neutrons during irradiation. Samples were irradiated for 2 hours in the central thimble of the TRIGA reactor at the USGS laboratory in Denver, Colo. (Dalrymple and others, 1981); reactor vessel was rotated continuously during irradiation to avoid lateral neutron-flux gradients. The reactor constants determined for these irradiations were indistinguishable from those in other recent irradiations, and a weighted mean of constants obtained over the past 5 years yields $^{40}Ar/^{39}Ar_K$ = 0.000±0.0004, $^{39}Ar/^{37}Ar_{Ca}$ = 0.000706±0.000051, and $^{36}Ar/^{37}Ar_{Ca}$ = 0.000281±0.000009. Sanidine TCR-2 from the Taylor Creek Rhyolite (Duffield and Dalrymple, 1990) is a secondary standard calibrated against the primary intralaboratory standard, SB-3, which has an age of 162.9±0.9 Ma (Lanphere and Dalrymple, 2000). Fluence monitors were analyzed using a continuous laser system and a MAP 216 mass spectrometer, as described by Dalrymple (1989). Argon was extracted from groundmass and plagioclase separates using a Mo crucible in a custom resistance furnace modified from the design of Staudacher and others (1978) attached to the aforementioned mass spectrometer. Heating temperatures were monitored with an optical-fiber thermometer and controlled with an Accufiber model 10 controller. Gas was purified continuously during extraction using two SAES ST-172 getters operated at 2.5 and 4 A.

Mass-spectrometric discrimination and system blanks are important factors in the precision and accuracy of the $^{40}Ar/^{39}Ar$ age determinations of Pleistocene lavas because of low radiogenic yields. Discrimination was monitored by analyzing splits of atmospheric Ar from a reservoir attached to the extraction line. Typical system blanks, including mass-spectrometer backgrounds, were 1.5×10^{-18} mol of m/z 36, 9×10^{-17} mol of m/z 37, 3×10^{-18} mol of m/z 39, and 1.5×10^{-16} mol of m/z 40, where m/z is the mass/charge ratio.

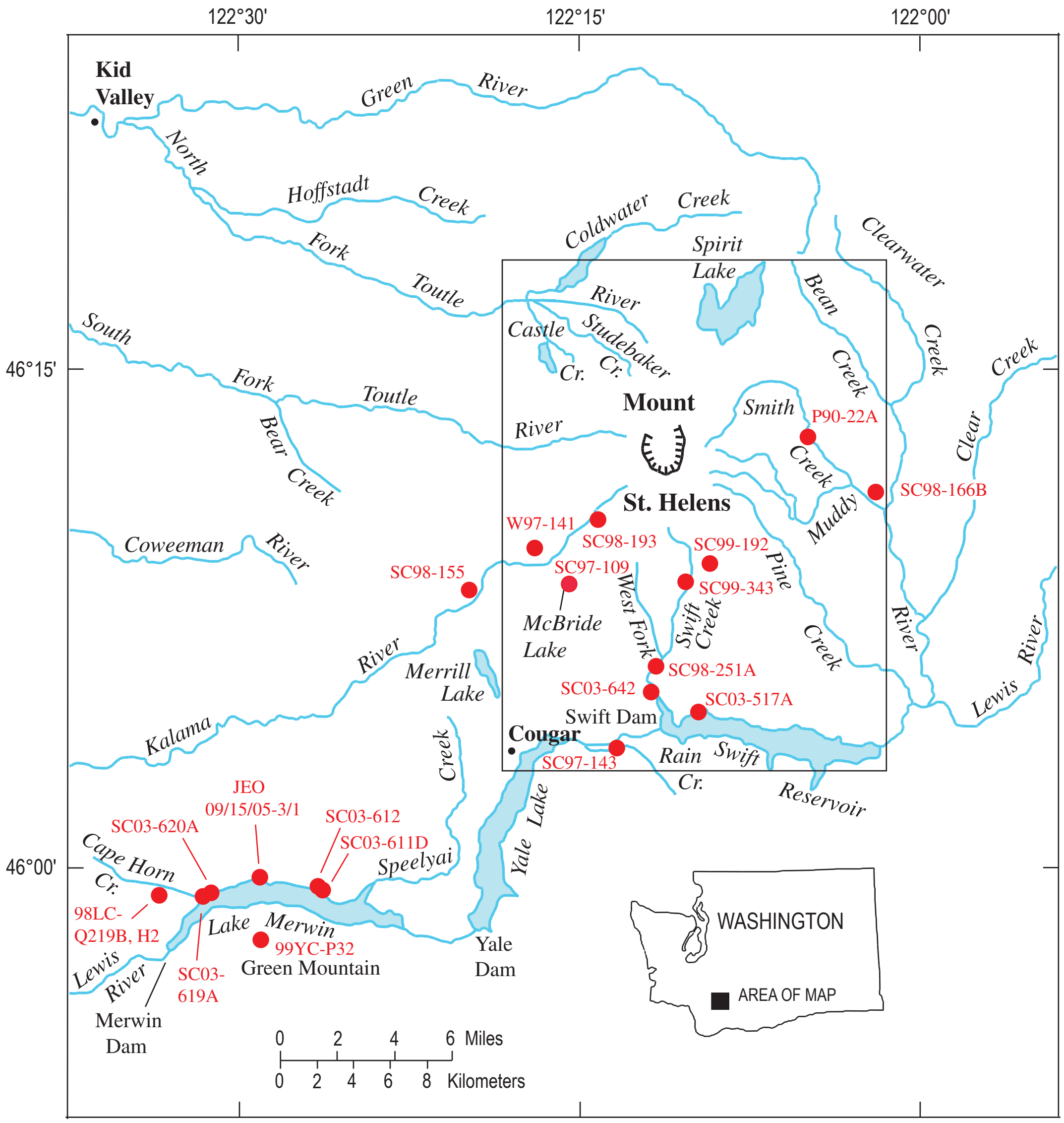


Figure 3. Sketch map of Mount St. Helens area, showing locations of newly dated samples reported in this chapter. Rectangle, area of figure 2.

Commonly accepted criteria (McDougall and Harrison, 1999) for a meaningful incremental-heating age are (1) a well-defined plateau (horizontal age spectrum with no significant slope) comprising more than 50 percent of ^{39}Ar released, (2) a well-defined isochron for plateau gas fractions, (3) concordant plateau and isochron ages, and (4) an ^{40}Ar/^{36}Ar isochron intercept not significantly different from 295.5. Because several of the samples violate one or more of these criteria, for those samples we favor the isochron age or report a plateau comprising less than 50 percent of ^{39}Ar released.

For isochron plots, data are not corrected by using an atmospheric ratio. Reported isochron ages include plateau steps on well-behaved samples or a data subset that includes the most steps yielding a reasonable goodness of fit. We commonly exclude the highest and lowest temperature steps because they are most strongly affected by ^{39}Ar recoil. We show normal isochron plots for these low-radiogenic-yield rocks because the data are easier to visualize. Isochron ages with a high probability-of-fit regression (a low mean square of weighted deviates, [MSWD ~1]; York, 1969) and an ^{40}Ar/^{36}Ar intercept not within the error of the present-day air ratio are interpreted to contain nonatmospheric initial Ar. For these samples, we interpret the isochron age as most meaningful. Isochron ages with an MSWD value greater than the critical value defined by Mahon (1996) are here reported with errors expanded by $\sqrt{\text{MSWD}}$ (Ludwig, 1999); errors are reported at the 1σ level.

The K-Ar ages for samples SC97-141 and SC97-143 were determined in Menlo Park, Calif., using techniques delineated in Hildreth and Lanphere (1994).

Radiocarbon Dating

The samples with a laboratory number prefixed by "WW" were prepared at the USGS laboratory in Reston, Va., by John McGeehin and analyzed at the Center for Accelerator Mass Spectrometry of Lawrence Livermore National Laboratory in Livermore, Calif. The samples were pretreated with an acid-alkali-acid leaching process to remove contaminant C in the form of inorganic carbonates and organic soil acids before conversion to CO_2 and reduction with H_2 to pure C in the form of graphite over an Fe catalyst. Additional details of sample processing and analysis were reported by McGeehin and others (2001) and Roberts and others (1997), respectively.

All ^{14}C ages were calculated using the Libby 5,568-year half-life with $\delta^{13}C = -25$ and given in years before present (B.P.), defined as 1950 C.E. Errors as stated include one standard deviation (1σ) of counting statistics and an additional uncertainty attributable to isotope fractionation and sample processing. Radiocarbon ages of 0–22,000 yr B.P. were calibrated to calendar years by using the INTCAL04 terrestrial age calibration (Reimer and others, 2004); older ^{14}C ages were calibrated by using the method of Cutler and others (2004).

Geochemistry

Analytical methods for USGS major-element analyses by wavelength-dispersive X-ray spectroscopy were routine, as described by Taggart and others (1987). All analyses were recalculated to 100 percent anhydrous, with the Fe_2O_3/FeO ratio set to 0.2 of the total Fe analyzed as Fe_2O_3. Analyses from the literature were recalculated by using the same scheme. A few analyses, however, lack either P_2O_5 or MnO content, and so those two components were estimated on the basis of analyses of similar rocks. John Pallister, Cynthia Gardner, and Rick Hoblitt provided additional USGS analyses.

Results

K-Ar and ^{40}Ar/^{39}Ar Analyses

The results of K-Ar and ^{40}Ar/^{39}Ar analyses of Mount St. Helens rocks are summarized in table 1, and the data for incremental-heating experiments are listed in appendix 1. Plateau and isochron ages are plotted in figure 4. The dated samples are briefly described below, from youngest to oldest in the same order as in table 1. Sample locations (fig. 3) are referable to North American Datum 1927 (NAD 27).

Sample SC98-155.—Dacite of Kalama Dome (Evarts and Ashley, 1990a), a small dome of porphyritic hornblende dacite with sparse resorbed biotite overlying till of Hayden Creek age in the Kalama River valley (lat 46º07.79' N., long 122º19.76' W.). Generally, only a single population of plagioclase is present, although a few phenocrysts are resorbed and all display oscillatory zoning with thick sodic rims. The groundmass is fresh and contains abundant microlites in clear glass. The whole-rock sample yielded all-negative apparent ages but has a well-constrained 16.3±12.9-ka isochron age comprising 94 percent of ^{39}Ar released, with an ^{40}Ar/^{36}Ar intercept of 289.2±0.9 and MSWD = 1.4. Higher-temperature steps contained little K-derived ^{39}Ar and had older apparent ages (see chemical analysis in table 5).

Sample SC99-343.—Andesite of Swift Creek, a thick andesite lava flow of porphyritic hornblende-augite-hypersthene andesite to dacite overlying Cougar-stage pyroclastic flows on the south flank of the volcano (lat 46º08.60' N., long 122º10.27' W.). Several populations of plagioclase phenocrysts are present, and most hornblende is converted to an aggregate of plagioclase, pyroxene, and Fe-Ti oxide. The groundmass is turbid, with tiny crystals set in cryptofelsite. The whole-rock sample yielded an excellent plateau age of 17.8±2.7 ka and an equivalent isochron age. The andesite of Swift Creek, named not for the stage but for its location along Swift Creek, was emplaced late in Cougar time.

Sample SC03-611D.—A clast of coarsely porphyritic hornblende dacite with sparse quartz from a Cougar-stage lahar deposit along the north shore of Lake Merwin in the Amboy quadrangle (lat 45º58.91' N., long 122º26.35'

Table 1. Summary of $^{40}Ar/^{39}Ar$ and K-Ar ages.

[See text for discussion of preferred ages, shown in bold. Maximum ages in italics. K-Ar ages calculated by using 1976 International Union of Geological Sciences constants (Steiger and Jäger, 1977): $\lambda_\beta = 4.962\times10^{-10}$/yr, $\lambda_\varepsilon = 0.581\times10^{-10}$/yr, $^{40}K/K_{total} = 1.167\times10^{-4}$ mol/mol. Errors are estimates of analytical precision at the 68-percent confidence level.]

$^{40}Ar/^{39}Ar$ data			**Plateau age**			**Isochron age**			
Sample	**Material**	**Total-gas age (ka)**	**%^{39}Ar (steps)**	**Age (ka)**	**Error (1σ)**	**Age (ka)**	**Error (1σ)**	**MSWD**	**$^{40}Ar/^{36}Ar_i$**
SC98-155	Whole rock	-95.1±8.6	72 (9 of 27)	-51.2	7.3	**16.3**	**12.9**	1.4	289.2±0.9
SC99-343	Whole rock	-52.4±8.7	79 (7 of 14)	**17.8**	**2.7**	18.7	4.5	0.94	294.1±1.4
SC03-611D	Groundmass	15.2±3.0	37 (4 of 14)*	21.7	1.8	**21.2**	**2.9**	1.8	298.7±2.3
SC03-612	Plagioclase	363.8±7.3	37 (3 of 9)	***24***	***11***	84.5	13.6	2.7	288.4±1.6
SC98-192	Whole rock	29.1±2.2	80 (6 of 14)	**27.9**	**1.7**	28.5	4.0	0.80	295.5±3.0
SC97-109	Groundmass	7.8±6.2	88 (6 of 12)	**34.9**	**4.6**	39.5	5.4	0.41	290.0±0.8
SC03-619A	Whole rock	34.1±1.1	97 (12 of 14)	**39.8**	**1.0**	40.0	2.4	1.6	295.0±2.2
P90-22A	Plagioclase	302.7±8.4	36 (2 of 8)	***54***	***10***				
SC03-620A	Plagioclase	754.1±8.5	36 (3 of 9)	***74***	***11***	79.8	29.9	1.8	293.2±5.1
SC98-251A	Whole rock	-361.9±12.4	83 (10 of 18)	*-184*	*10*	91.5	24.2	1.3	281.5±1.1
SC98-193	Groundmass	-42±18	20 (2 of 9)	112	24	147	37	0.65	289.7±1.8
SC98-193	Plagioclase	369.2±35.9	69 (5 of 9)	**107.4**	**39.2**	134	169	0.52	294.1±8.3
SC97-143	Plagioclase	695±31	42 (2 of 8)	113.8	40.8	-71.4	145.4	0.61	322.6±16.0
SC03-642	Plagioclase	530.4±8.8	52 (3 of 10)	**160**	**8.8**	166.6	46.0	2.9	288.8±4.1
99YC-P32	Plagioclase	519±122	77 (7 of 13)	**247**	**12**	155	55	1.3	318±15
98LC-Q219H2	Plagioclase	366±17	62 (3 of 9)	**263**	**19**				
98LC-Q219B	Plagioclase	404±28	85 (7 of 9)	**269**	**13**	276	19	0.81	292.2±4.1

K-Ar data				**K_2O**			**Argon**	
Sample	**Material**	**K-Ar age (ka)**	**Weight (g)**	**wt %**	**No.**	**S.D.**	**$^{40}Ar_{rad}$ (mol/g)**	**$^{40}Ar_{rad}$ %**
SC97-143	Whole rock	**109±24**	25.421	1.456	2	0.005	2.277×10^{-13}	1.8
W97-141	Whole rock	**296±7**	26.198	1.856	2	0.011	7.891×10^{-13}	25.4

* Weighted mean age, because the plateau does not comprise the required 50 percent of ^{39}Ar released.

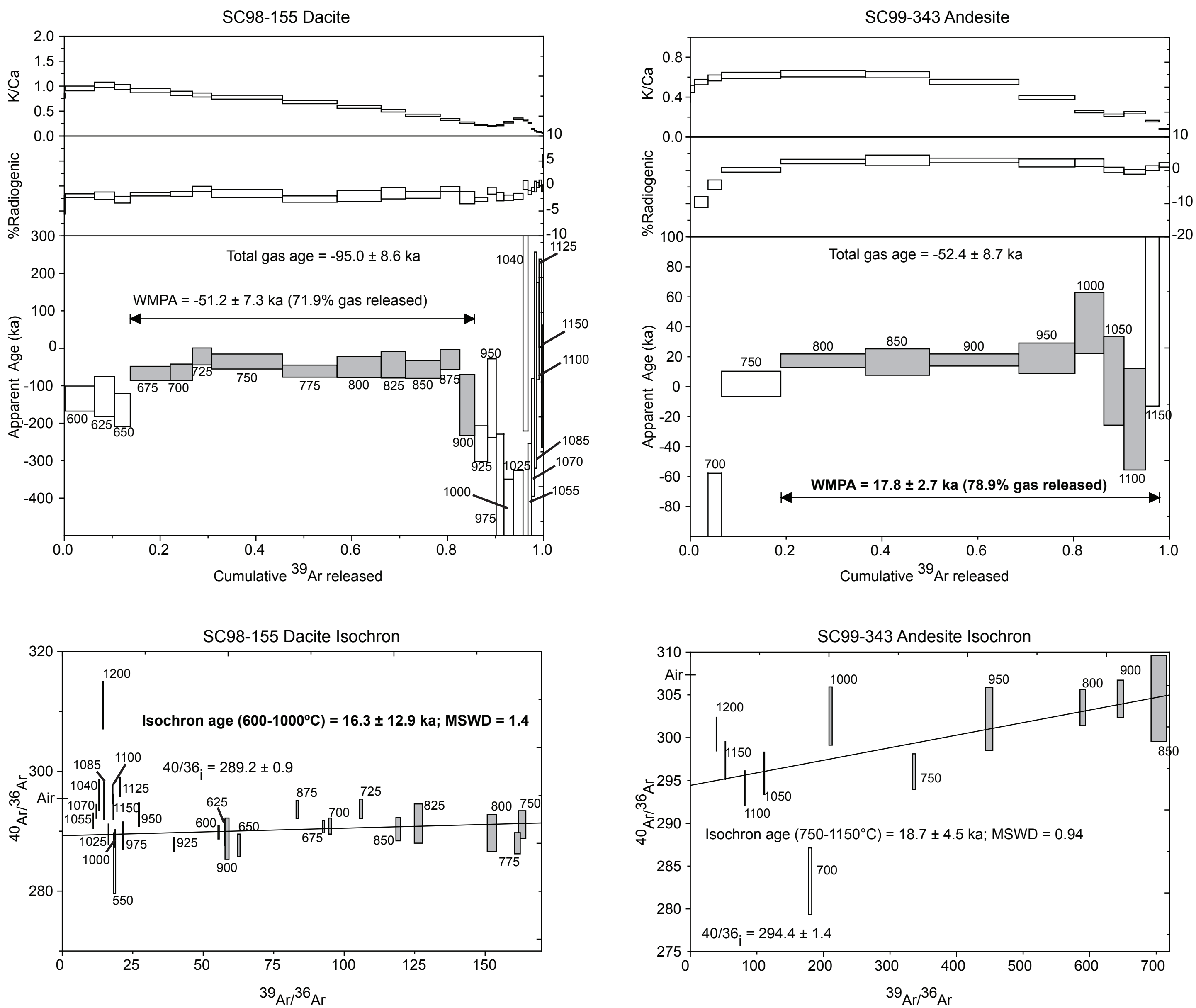
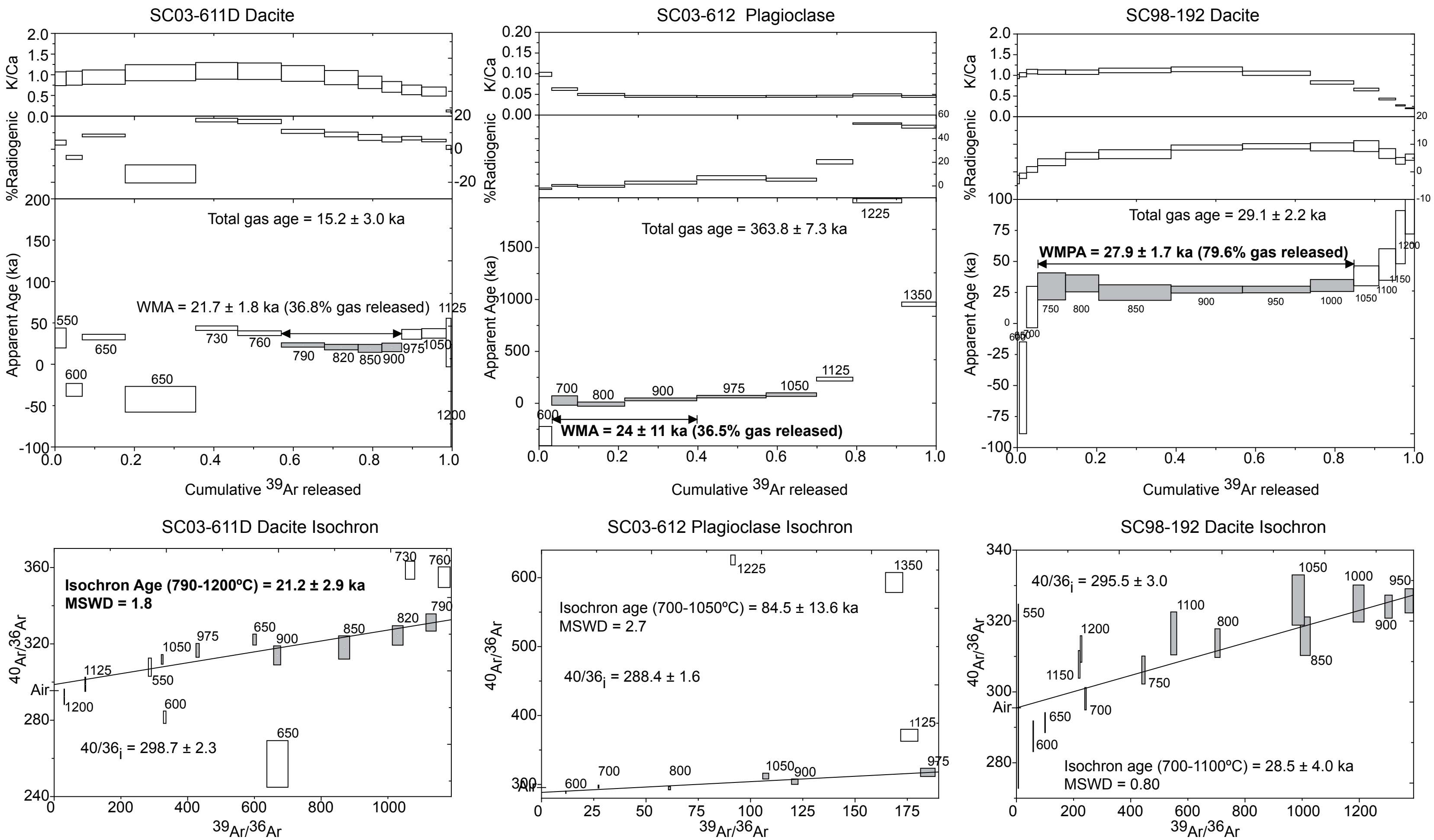


Figure 4. Argon plateau and isochron diagrams for dated samples from Mount St. Helens deposits (see fig. 3 for locations).



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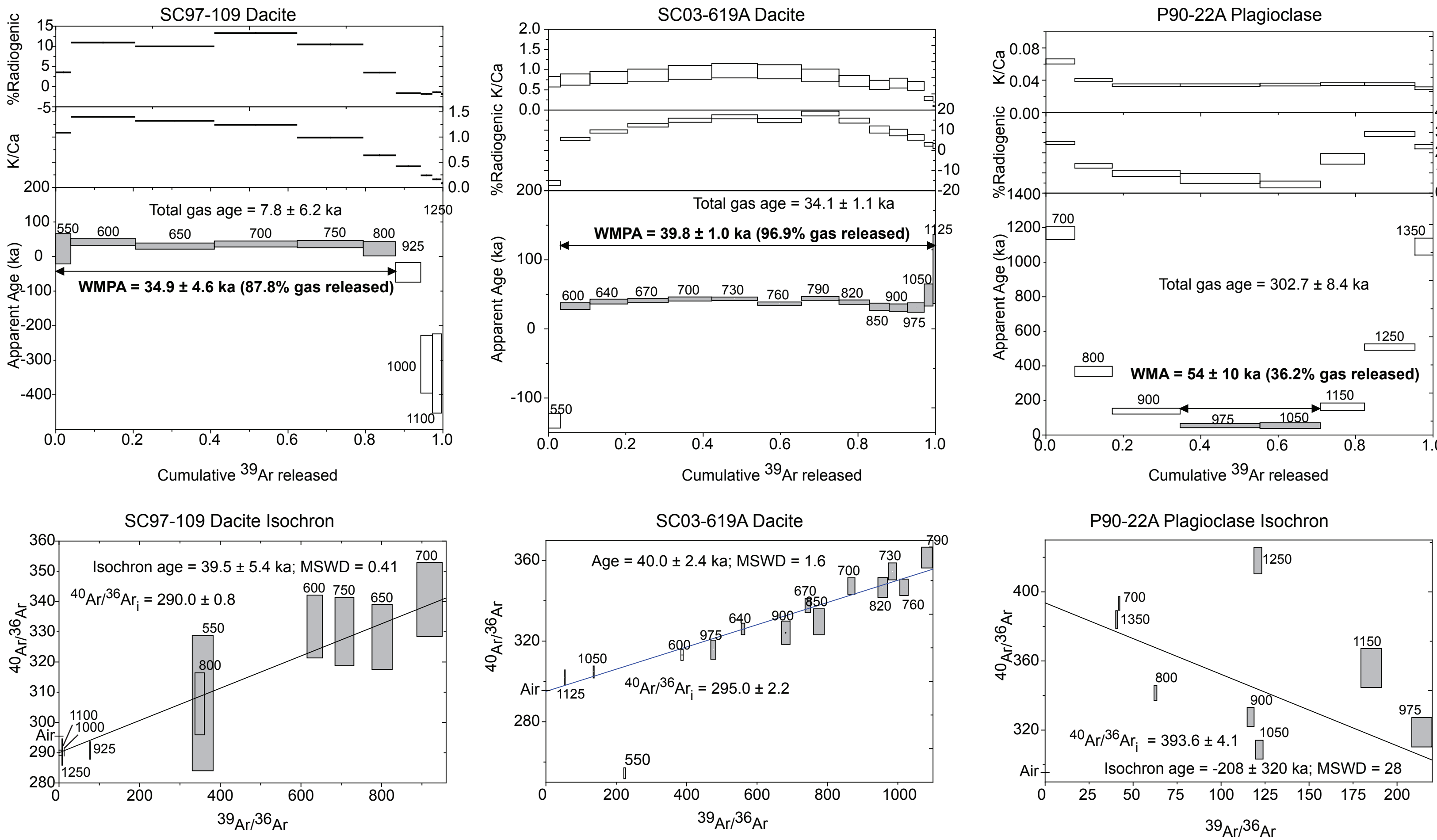

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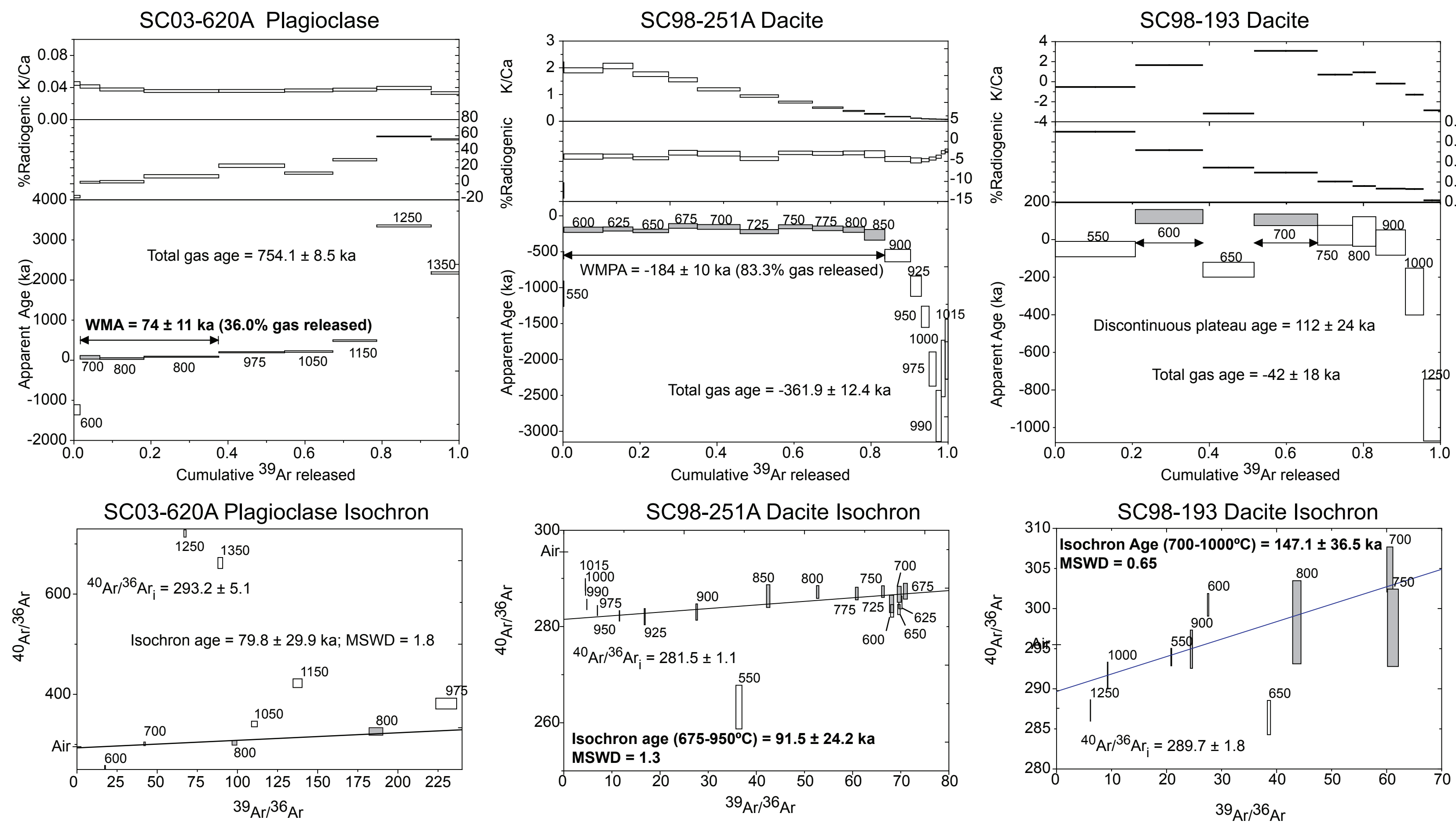

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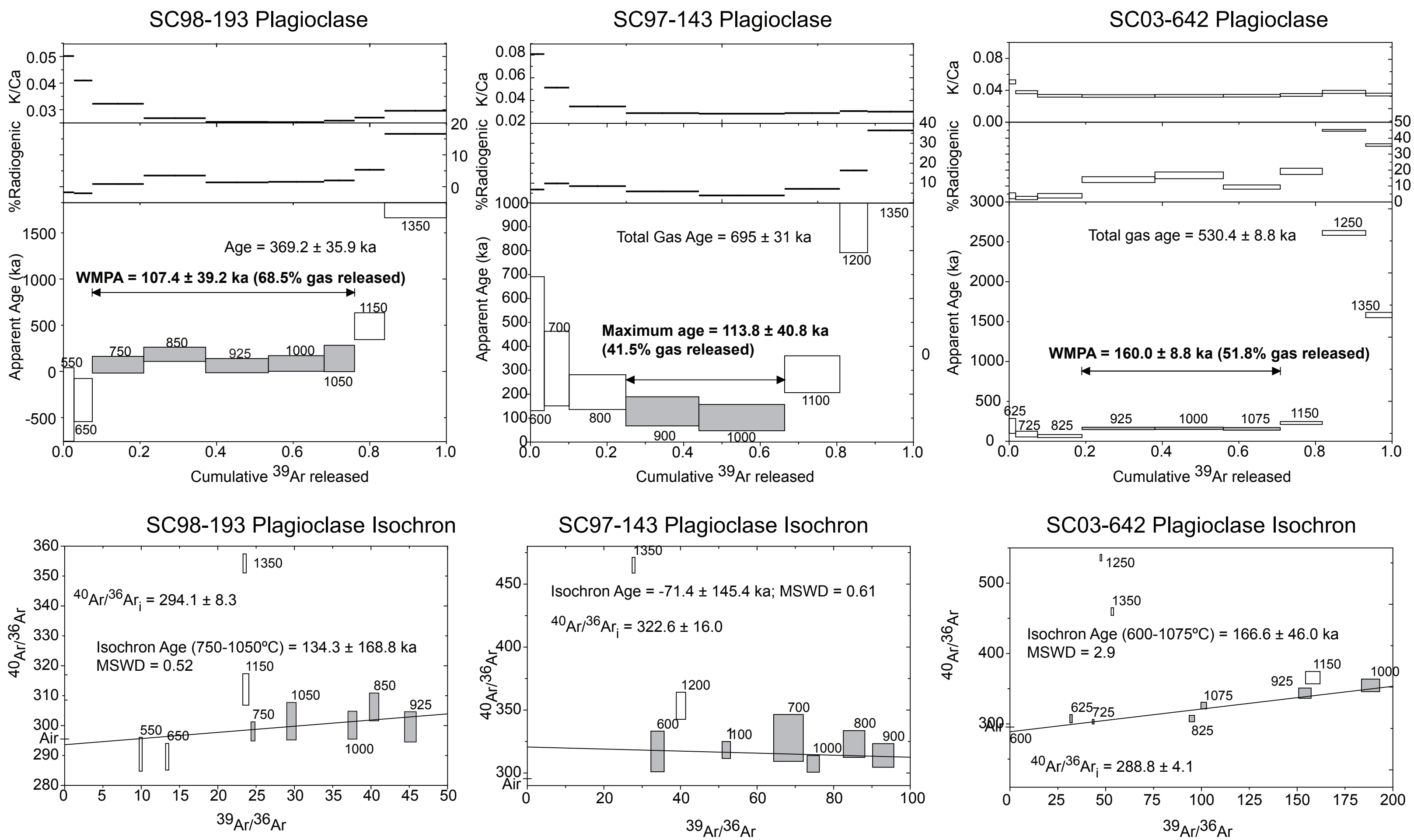

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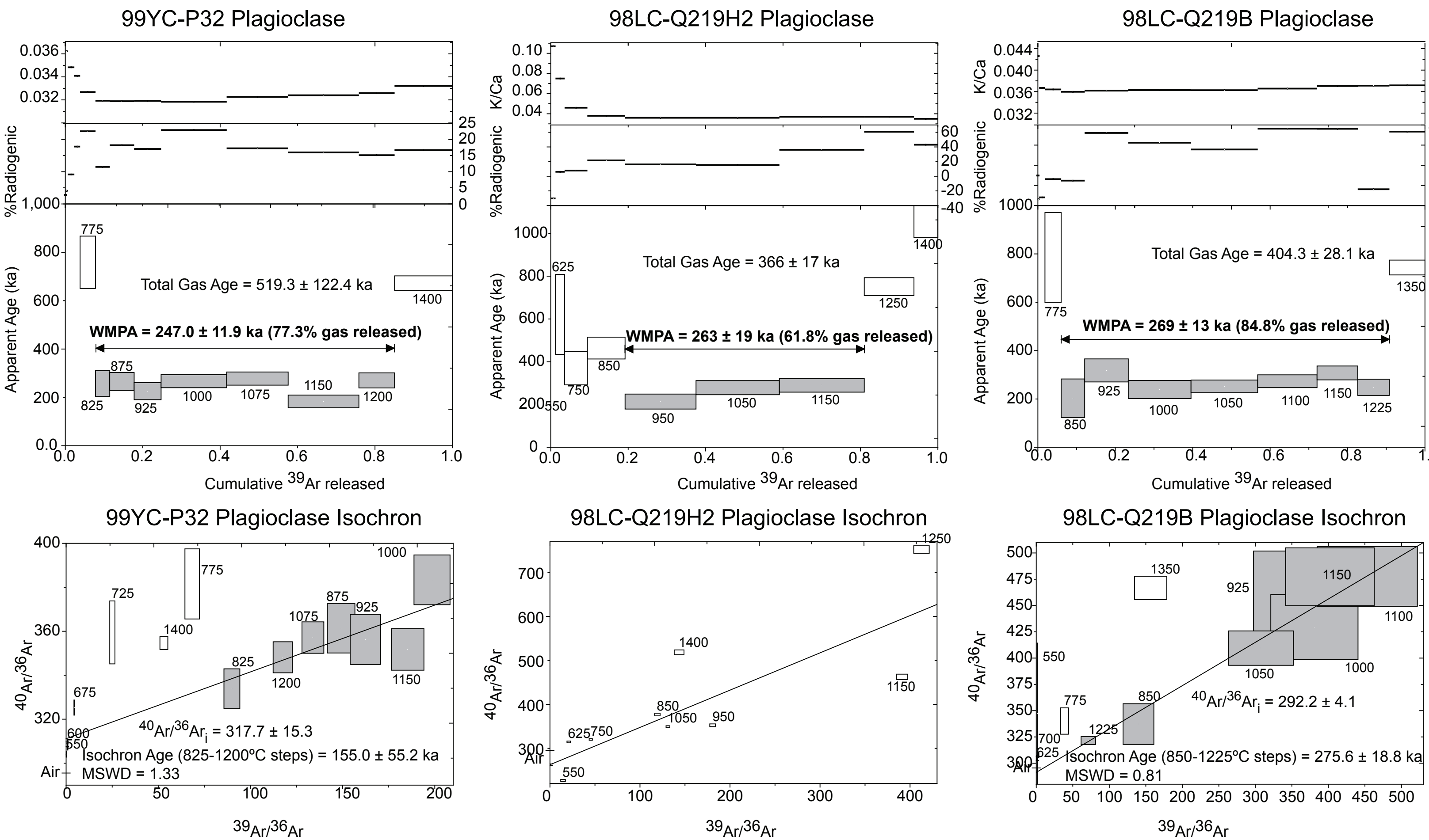

Figure 4.—Continued.

W.). The lahar deposit contains debris-avalanche dacite and, probably, andesite of Swift Creek, and so it must have been emplaced late in Cougar time. The amphibole is mostly converted to an aggregate of pyroxene, oxide, and plagioclase and originally may have been cummingtonite. Plagioclase displays various zoning patterns, but resorbed phenocrysts are relatively uncommon. The groundmass is mostly devitrified to a relatively coarse-grained intergrowth of plagioclase and quartz. The groundmass sample yielded a disturbed age spectrum containing only four concordant steps, with a weighted-mean age of 21.7±1.8 ka. A 21.2±2.9-ka isochron age comprising 43 percent of the ^{39}Ar released is indistinguishable from the weighted-mean age and has a higher-than-atmospheric intercept and a good fit. We interpret the isochron age as the most reliable (see chemical analysis in table 5).

Sample SC03-612.—A clast of porphyritic hornblende dacite with sparse quartz from a Cougar-stage lahar deposit along the north shore of Lake Merwin in the Amboy quadrangle (lat 45º58.93' N., long 122º26.45'W.). The lahar deposit contains debris-avalanche dacite and, probably, andesite of Swift Creek and is of late Cougar age. Plagioclase displays various zoning patterns, but resorbed phenocrysts are relatively uncommon. The groundmass is fresh and consists of crystallite-poor glass. A plagioclase separate from this rock yielded a climbing age spectrum from 27 ka to nearly 2 Ma. We interpret the weighted-mean age of three concordant low-temperature steps (24±11 ka) as a maximum age for the rock.

Sample SC98-192.—Dacite of June Lake, a thick, weakly welded lithic pyroclastic-flow deposit exposed at June Lake (lat 46º09.14' N., long 122º09.65' W.) on the south flank of the volcano. The deposit overlies mid-Tertiary arc volcanic rocks and is overlain by Cougar- and Swift Creek-stage pyroclastic-flow deposits. The rock is a porphyritic hypersthene-hornblende dacite. Most amphibole is converted to an anhydrous assemblage of pyroxene, plagioclase, and Fe-Ti oxides and may have originally been cummingtonite. The groundmass contains abundant tiny microlites and is nearly completely devitrified to cryptocrystalline material. The whole-rock sample yielded an excellent 27.9±1.7-ka plateau age and an equivalent isochron age.

Sample SC97-109.—Dacite of McBride Lake, a coarsely porphyritic hornblende dacite with sparse quartz from a Cougar-stage debris-avalanche or lahar deposit (loc. 55 of Crandell, 1987) near McBride Lake, on the southwest flank of the volcano (lat 46º08.49' N., long 122º15.45' W.). The rock is a common component of the lahar and reworked lahar deposits along the north shore of Lake Merwin (fig. 3). Plagioclase displays various zoning patterns, and a small proportion of phenocrysts have resorbed zones. The groundmass is cryptocrystalline and fresh. The groundmass sample yielded an excellent 34.9±4.6-ka plateau age comprising 88 percent of ^{39}Ar released. The highest-temperature steps have very low $^{40}Ar/^{36}Ar$ ratios, forcing the $^{40}Ar/^{36}Ar$ intercept to be low and the isochron age to be slightly older. We interpret the plateau age as the most reliable (see chemical analysis in table 4).

Sample SC03-619A.—Coarsely porphyritic hornblende dacite with sparse quartz from an Ape Canyon-stage lahar deposit that overlies Hayden Creek Drift and is exposed just above high water along the north shore of Lake Merwin in the Ariel quadrangle (lat 45º59.07' N., long 122º31.55' W.). The rock is a common component of Ape Canyon-stage lahar deposits in the Lewis River valley (fig. 2). The amphibole is mostly converted to an aggregate of pyroxene, Fe-Ti oxide, and plagioclase. Plagioclase displays various zoning patterns, and a small proportion of the phenocrysts have resorbed zones. The groundmass is mostly devitrified to a relatively coarse grained intergrowth of plagioclase and quartz. The groundmass sample yielded an excellent plateau age of 39.8±1.0 ka and an equivalent isochron age (see chemical analysis in table 4).

Sample P90-22A.—Porphyritic quartz-biotite-hornblende dacite clast from a pumiceous pyroclastic-flow deposit overlying Hayden Creek Drift. John Pallister collected this sample from locality 16 of Crandell (1987, probably unit P1, his fig. 7) in Smith Creek valley (lat 46º12.35' N., long 122º05.05' W.). At this locality, the pyroclastic-flow deposits are interbedded with set C tephras, and the abundance of hornblende and paucity of cummingtonite suggest that these pyroclastic-flow deposits may be equivalent to tephra layer Cy. Crandell and others (1981) reported an age older than 46.4 ka cal yr B.P. for this deposit. The rock is pumiceous and consists of plagioclase, abundant hornblende, biotite, quartz, and sparse cummingtonite in a glassy groundmass with very sparse microlites. Plagioclase displays various zoning patterns but phenocrysts are generally fresh and lack sieve textures. A plagioclase separate from this rock yielded a U-shaped age spectrum; no good fit to the isochron data is evident. We interpret the weighted mean of the youngest apparent ages (54±10 ka) as a maximum age for the rock.

Sample SC03-620A.—Coarsely porphyritic quartz-biotite-hornblende dacite from a lahar deposit exposed along the north shore of Lake Merwin in the Ariel quadrangle (lat 45º59.16' N., long 122º31.22' W.). The rock is a common component of Ape Canyon-stage lahar and derivative sedimentary deposits in the Lewis River from Yale Dam to Woodland, 32 km west. Smaller hornblende phenocrysts are converted to an aggregate of pyroxene, Fe-Ti oxide, and plagioclase, and larger ones have opacite rims. Plagioclase displays various zoning patterns, but resorbed phenocrysts are relatively uncommon. The groundmass is fresh and composed of crystallite-rich glass. A plagioclase separate from this rock yielded a climbing age spectrum from 72 ka to older than 3 Ma. We interpret the weighted-mean age of three concordant low-temperature steps (74±11 ka) as a maximum age for the rock.

Sample SC98-251A.—Light-colored, porphyritic hornblende-hypersthene dacite pumice from the two-pumice pyroclastic-flow deposit exposed in the cliffs west of Swift Creek (lat 46º05.87' N., long 122º11.95' W.). Most amphibole is converted to an anhydrous assemblage of pyroxene, plagioclase, and Fe-Ti oxide. Plagioclase is the most abundant phenocryst phase and displays several textures but is generally fresh and unresorbed. The groundmass consists of fresh glass choked with abundant tiny crystallites. The whole-rock sample yielded negative ages. An isochron comprising intermediate steps of the incremental-heating experiment yielded a good fit at 91.5±24.2 ka; however, we interpret the 24,380-yr age for laboratory No. W-2540 (table 2) as more reliable.

Sample SC98-193.—Andesite of Butte Camp, a porphyritic hypersthene-hornblende andesite from a glaciated lava dome at Butte Camp, collected from talus in an unnamed creek on the northwest side of the dome (lat 46º10.5' N., long 122º14.3' W.). The rock consists of porphyritic hypersthene-hornblende dacite without quartz and biotite. This rock is a component of Hayden Creek-age glacial deposits and Ape Canyon-age lahars in the Lewis River and North Fork of the Toutle River (fig. 3). Resorbed phenocrysts of plagioclase and hornblende are sparse; some phenocrysts are probably derived from disaggregation of cumulate-textured inclusions. The groundmass glass is clear and fresh but crowded with microlites. Age experiments on plagioclase and groundmass separates were attempted for this rock. Plagioclase yielded a good plateau age of 107.4±39.2 ka comprising 69 percent of ^{39}Ar released; isochron age is concordant but has a large error because of low radiogenic yields. The groundmass experiment was disturbed but yielded a 147.1±36.5-ka isochron, within the error of the plagioclase result. We interpret the plateau age as the most reliable (see chemical analysis in table 4).

Sample SC97-143.—Unnamed hypersthene-hornblende dacite from a Cougar-stage lahar deposit (lat 46º03.78' N., long 122º13.48' W.) along (Forest Service) Road 90, approximately 1 km west of Crandell's (1987) locality 45. The rock consists of coarsely porphyritic hypersthene-hornblende dacite with sparse quartz. This rock is a minor component of Cougar- and Ape Canyon-age lahar deposits in the Lewis River from Swift Dam to Woodland, 46 km west-southwest. Amphibole phenocrysts are fresh but have thin opacite rims; plagioclase phenocrysts are fresh and are present mostly in a single population. The groundmass consists of microlite-choked clear glass. A plagioclase separate yielded a U-shaped age spectrum; no good fit to the isochron data is evident. We interpret the weighted mean of the youngest apparent ages (113.8±40.8 ka) as a maximum age for the rock. This age is equivalent to a 109±24-ka K-Ar age obtained in a pilot study, which we interpret as the most reliable (see chemical analysis in table 4).

Sample SC03-642.—Unnamed porphyritic hypersthene-hornblende dacite from a megablock in the Cougar-stage debris-avalanche deposit exposed in Swift Creek (lat 46º05.25' N., long 122º12.40' W.). The rock consists of porphyritic hypersthene-hornblende dacite with no quartz or biotite. This rock is a minor component of the Cougar-stage debris-avalanche deposit (see "Discussion" section). Plagioclase displays various zoning patterns, including a few phenocrysts with resorption zones. The groundmass is fresh and consists of crystallite-choked glass. A plagioclase separate from this rock yielded a climbing age spectrum. Three intermediate incremental-heating steps yielded a plateau age of 160±8.8 ka, and an isochron age comprising the first 71 percent of ^{39}Ar released yielded a similar age of 167±46 ka. We interpret the plateau age as the most reliable (see chemical analysis in table 4).

Sample W97-141.—Dacite of Goat Mountain (Evarts and Ashley, 1990b), a coarsely porphyritic hornblende-biotite dacite with abundant quartz from the southeast flank of Goat Mountain (lat 46º08.85' N., long 122º16.96' W.). The rock is a common component of Hayden Creek-age glacial deposits and Ape Canyon-age lahars in the Lewis River from Yale Dam 32 km west to Woodland and in the Kalama River west of (Forest Service) Road 81 (fig. 3). Our K-Ar age of 296±7 ka (table 1) is significantly younger than the discordant K-Ar ages on hornblende (3.18±0.3 Ma) and biotite (1.06±0.6 and 0.76±0.6 Ma) reported by Engels and others (1976).

Sample 99YC-P32.—Bed of set C tephra beneath Amboy Drift (equivalent to Hayden Creek Drift) on the crest of Green Mountain, about 33 km southwest of the volcano in the Amboy quadrangle (lat 45º57.84' N., long 122º29.04' W.). The bed, which is about 2 m thick, is composed of coarse ash and scattered lapilli of weathered dacitic glass containing crystals of plagioclase, quartz, biotite, green hornblende, and cummingtonite, contains charred woodchips, and overlies a soil developed on Tertiary bedrock. Plagioclase yielded a plateau age of 247±12 ka comprising 78 percent of ^{39}Ar released. Isochron results suggest a high ^{40}Ar/^{36}Ar intercept but within the error of air. We interpret the plateau age as the most reliable.

Sample 98LC-Q219H2.—Block of slightly vesicular, coarsely and densely porphyritic dacite from a debris-flow(?) bed in the sequence of ice-contact deposits at Cape Horn Creek in the Ariel quadrangle (lat 45º59.16' N., long 122º33.48' W.). Phenocrysts of plagioclase, quartz, biotite, green hornblende, and cummingtonite occur in a groundmass of hydrated glass. Plagioclase exhibits complex zoning and some resorption but is fresh and free of inclusions. Some hornblende grains are zoned to cummingtonite rims. Plagioclase yielded a three-step plateau age of 263±19 ka comprising 62 percent of ^{39}Ar released but no usable isochron age.

Sample 98LC-Q219B.—Pumice-lapilli bed in a 9-m-thick sequence of ice-contact deposits exposed in a roadcut on the south valley wall of Cape Horn Creek, about 37 km southwest of the volcano in the Ariel quadrangle (lat 45º59.16' N., long 122º33.48' W.). The deposits consist almost entirely of Mount St. Helens-derived dacite debris and overlie Amboy Drift (Hayden Creek Drift). The sample, from a 0.5-m-thick bed of slightly reworked pumice lapilli, consists of phenocrysts of plagioclase, quartz, biotite, green-brown hornblende, and cummingtonite within a matrix of totally weathered glass. Plagioclase yielded an excellent plateau age of 269±13 ka comprising 85 percent of ^{39}Ar released and a comparable isochron age of 276±19 ka.

Radiocarbon Ages

Absolute time control for Crandell and Mullineaux's stratigraphy of the Ape Canyon and Cougar stages was based

Table 2. Radiocarbon and calibrated ages of Ape Canyon- and Cougar-stage deposits.

[All values in years ± 1σ. Samples with laboratory numbers prefixed by "WW" were prepared at the U.S. Geological Survey laboratory in Reston, Va., and analyzed by John McGeehin at Lawrence Livermore National Laboratory in Livermore, Calif. by accelerator mass spectrometry. These samples were pretreated with standard acid-alkali-acid wash, and ages were calculated with a ^{14}C half-life of 5,568 yr and $\delta^{13}C = -25$ (see text for sample descriptions and locations). Samples with laboratory numbers prefixed by "W" are from Crandell and others (1981) and were not pretreated (see Crandell and others, 1981, for sample descriptions and locations). Sample MS-5 is from Major and Scott (1988), and sample Scott BC from Scott (1989). Samples younger than 22 ka were calibrated by using the curve of Reimer and others (2004); samples older than 22 ka were calibrated by using the curve of Cutler and others (2004). Calibrated ages are reported as calendar years before 1950 C.E. Calibration curve of Cutler and others (2004) does not give uncertainties, which are rounded upward from the uncalibrated age.]

Laboratory No.	Sample No.	Radiometric age (^{14}C yr B.P.)	Calibrated age
	Cougar-stage deposits		
W-2413	—	18,560±180	22,170 (+190/−240)
W-4531	—	19,160±250	22,620 (+520/−210
WW-4543	SC03-517A	19,670±60	23,590 (+120/−150)
—	Scott BC	19,700±550	23,650 (+485/−965)
W-2540	—	20,350±350	24,380 (+510/−480)
—	MS-5	22,720±1,400	28,850 ±1,400
	Ape Canyon-stage deposits		
WW-3481	SC98-166B	42,950±560	47,430±600
WW-5561	JEO 09/15/05-3/1	44,960±930	49,540±1,000

on several uncalibrated ages of samples that were not pretreated before analysis (Crandell and others, 1981). Radiocarbon samples, when not pretreated to reduce contamination by modern organic material, commonly yield inconsistent or minimum ages. Furthermore, the calibrated ages, especially those in the range 20–50 ka, are 2–6 ka older than the uncalibrated ages. These factors lead to differences between the ages reported here and those reported by Crandell and others (1981), Crandell (1987), and Mullineaux (1996).

Brief descriptions of three new samples from the Ape Canyon and Cougar stages and two samples from the report by Crandell and others (1981) are given below and listed in table 2. Sample locations, which are referable to NAD 27, are shown in figure 3.

Sample WW-4543 (SC03-517A).—Charcoal from a Cougar-stage hypersthene-hornblende dacite pyroclastic-flow deposit ("Cougar-stage white pumice") exposed at lake level on the north shore of Swift Reservoir (figs. 2, 3), overlying set K tephra (lat 46º04.22' N., long 122º09.67' W.), in the Mount Mitchell quadrangle. The sample is stratigraphically equivalent to laboratory No. W-2413 (table 2, Crandell and others, 1981) from nearby locality 46 of Crandell (1987) and approximately stratigraphically equivalent to laboratory No. W-4531 (table 2; Crandell and others, 1981) on a hypersthene-hornblende dacite pyroclastic-flow deposit at locality 36 of Crandell (1987) in Pine Creek (figs. 2, 3).

Sample Scott BC.—Wood from sediment interbedded with Cougar-stage lahar deposits in the South Fork of the Toutle River (fig. 1) about 0.5 km upstream from the confluence with Bear Creek (approx. lat 46º14.0' N., long 122º12.65' W.) in the Elk Mountain quadrangle. The sample was described by Scott (1989, p. B32) as from the Bear Creek section but was unnumbered.

Sample W-2540.—Charcoal from a pumiceous pyroclastic-flow deposit ("two-pumice pyroclastic flow") exposed near Rain Creek, west of the Swift Reservoir (loc. 46 of Crandell, 1987), and underlying sets M and K tephras (approx. lat 46º03.25' N., long 122º12.9' W.) in the Mount Mitchell quadrangle.

Sample MS-5.—Charcoal from alluvial sediment below a lahar deposit (Major and Scott, 1988) at the intersection of Washington Highway 503 and Baker Road, near Speelyai Bay, Lake Merwin (lat 45º59.78' N., long 122º23.95' W.) in the Amboy quadrangle. The deposit contains Cougar-stage dacite but lacks debris-avalanche dacite, and so the deposit is Cougar age but predates the Cougar-stage debris-avalanche deposit (see next section).

Sample WW-3481 (SC98-166B).—Charcoal from unit 2, measured section C-2, upper zone of layer Cb, in the Muddy

River quarry (lat 46º11.06' N., long 122º03.09' W.) at the confluence of the Muddy River and Smith Creek (Mullineaux, 1996, p. 21) in the Smith Creek Butte quadrangle. The sample is equivalent to laboratory No. W-2661, the age of which is 37,600±1,300 ^{14}C yr B.P. (Crandell and others, 1981).

Sample WW-5561 (JEO 09/15/05-3/1).—Charcoal collected from a sandy lahar deposit along the north shore of Lake Merwin near Woodland Park (lat 45º59.48' N., long 122º29.11' W.) in the Amboy quadrangle. The clast population of the deposit is dominated by quartz-biotite dacite pumice, possibly equivalent to layer Cw (Vogel, 2005). Age courtesy of Jim O'Connor (U.S. Geological Survey).

Other Ages

Crandell and others (1981) reported 17 uncalibrated ages for the Swift Creek stage. Although these ages span a substantial period, some are internally inconsistent, and many are inconsistent with the ages reported by other workers from places where set S tephras are preserved. Here we present the most consistent raw ages and calibrated equivalents for the Swift Creek stage from Crandell and others (1981) and other literature (table 3).

Discussion

Ape Canyon Stage

Before the Ape Canyon stage, the Mount St. Helens area was an eroded terrain of moderate relief carved into mid-Tertiary (32–23 Ma) arc volcanic rocks (Evarts and others, 1987). The Cascade Range in southern Washington was repeatedly glaciated during the middle and late Pleistocene, and glaciers extended from the vicinity of the volcano westward to as low as about 30-m altitude in the Lewis River valley as recently as 60 ka (Grigg and Whitlock, 2002; Evarts, 2004b). Thus, the early record of Mount St. Helens volcanism is poorly preserved and incomplete. A few set C tephras and lava domes are locally preserved, but the most extensive record of early volcanism in the area is preserved as clasts in the Cougar-stage debris-avalanche deposit (see discussion below) and in glacial deposits and lahars in the lower Lewis River valley (Evarts, 2004a, b, 2005) and the valleys of the North and South Forks of the Toutle River (Scott, 1989; Evarts, 2001). Clasts of similar rock types in many younger Mount St. Helens pyroclastic deposits indicate that these older rocks also underlie the present-day edifice. New and existing radiometric ages of rocks and deposits emplaced during the Ape Canyon stage are plotted in figure 5.

Domes in the Goat Mountain and Butte Camp Area

Recent geologic mapping has established the extent of lava domes and remnants of lava domes that project above younger deposits in the area between Goat Mountain and the dome at Butte Camp (fig. 2), and additional rock types have been recognized in the Cougar-stage debris-avalanche deposit (see discussion below). The quartz-biotite dacite of Goat Mountain contains 68–69 weight percent SiO_2 and yielded a K-Ar age of 296±7 ka (sample W97-141, table 1). The hypersthene-hornblende andesite of Butte Camp contains 62–63 percent SiO_2 and yielded an $^{40}Ar/^{39}Ar$ plateau age of 107.4±39.2 ka (sample SC98-193, table 1). A small remnant of another dome east of Butte Camp is a quartz-biotite dacite containing 68 percent SiO_2. All these rocks occur in younger glacial deposits and lahars in the Toutle, Kalama, and Lewis River valleys. Similar rock types have been recognized as lithic clasts in Spirit Lake-stage pyroclastic deposits (for example, the Sugar Bowl blast deposit).

Debris-Avalanche Dacite and Rocks Preserved in the Cougar-Stage Debris-Avalanche Deposit

A substantial part of the Ape Canyon-stage edifice was removed by the Cougar-stage debris avalanche (see discussion below). A quartz-biotite dacite, called debris-avalanche dacite, which occurs as a few dome remnants and composes about 90 percent of the debris-avalanche deposit, is lithologically similar to other Ape Canyon-stage quartz-biotite dacites but is hydrothermally altered. Preliminary ion microprobe U-Th dating of zircons in debris-avalanche clasts indicates an age of about 71±9 ka for the dacite (J.S. Pallister, written commun., 2004). The debris-avalanche dacite and dome remnants vary little in composition and contain 64–65 percent SiO_2.

A few other dacite types constitute the remaining 10 percent of the Cougar-stage debris-avalanche deposit. A hornblende dacite containing 64 percent SiO_2 yielded an $^{40}Ar/^{39}Ar$ plateau age of 160±8.8 ka (sample SC03-642, table 1). A sample of the dacite of McBride Lake from the deposit at McBride Lake (sample SC97-109, fig. 3; loc. 44 of Crandell, 1987) yielded an age of 34.9±4.6 ka (table 1), one of the youngest ages from Ape Canyon-stage deposits.

Deposits Associated with Hayden Creek Drift in the Lewis River Valley

Near Mount St. Helens, the oldest preserved volcanic deposits overlie till that Crandell (1987) correlated with the Hayden Creek Drift of the Mount Rainier region (Crandell and Miller, 1974) on the basis of similar weathering characteristics. Crandell concluded that activity at the Mount St. Helens volcanic center entirely postdated this glaciation, which he inferred was age equivalent to marine isotope stage 4 (~60–75 ka)—too young, as we show below.

Equivalent deposits in the lower Lewis River valley mapped as Amboy Drift by Mundorff (1964) and Evarts (2004a, b, 2005), contain clasts of quartz- and biotite-bearing dacite compositionally indistinguishable from Ape Canyon-stage rocks, recording the occurrence of preglacial or syn-

Table 3. Radiocarbon and calibrated ages of Swift Creek-stage deposits.

[All values in years ± 1σ. Calibrated ages are reported as calendar years before 1950 C.E. All samples were pretreated except those with a laboratory number prefixed by "W." Most of those are from Crandell and others (1981) except samples W-5719 and W-5724, which are from Mullineaux (1996), and sample W-2983, which is from Hyde (1975) (see Crandell and others, 1981, for sample descriptions and locations). Samples Porter 1 and Porter 2 are from S.C. Porter and T.W. Swanson (written commun., 2006); sample Porter 3 is from Porter and others (1983); sample USGS-684 is from Waitt (1985); sample USGS-2780 is from Carrara and Trimble (1992); sample QL-1436 is from Davis and others (1982); sample WSU-2714 is from Baker and Bunker (1985); and sample Clague 1 is from Clague and others (2003). All samples were calibrated by using the curve of Reimer and others (2004).]

Laboratory No.	Description	Radiometric age (^{14}C yr B.P.)	Calibrated age
W-3548	Wood below layer Jg, South Fork of the Toutle River	10,710±150	12,790 (+80/−180)
W-5724	Peat below layer Jg, Fargher Lake	10,980±250	12,900 (+300/−150)
USGS-2780	Peat directly above and below layer Jyn	12,020±60	13,855 (+90/−50)
W-5719	Peat below layer Jy(?), Fargher Lake	11,580±250	13,400 (+300/−200)
W-2832	Base set J, east of Lahar	11,700±90	13,570 (+90/−130)
W-2441	Base set J, Smith Creek	11,880±110	13,750 (+120/−140)
W-2655	Pre-set J lahar, Muddy River, Cedar Flats fan	11,800±90	13,730 (+160/−260)
W-2866	Post set S, pre-set J lithic pyroclastic-flow deposit, Smith Creek, Cedar Flats fan	11,900±190	13,775 (+200/−225)
W-2870	Post set S, pre-set J lithic pyroclastic-flow deposit, Smith Creek, Cedar Flats fan	11,550±230	13,400 (+250/−200)
W-2868	Post set S, pre-set J lithic pyroclastic-flow deposit, Smith Creek, Cedar Flats fan	12,110±110	13,970 (+100/−140)
W-3145	Pre-set J lahar, South Fork of the Toutle River, Crescent Ridge fan	12,270±90	14,130 (+190/−140)
W-3133	Peat above set S, Tower Peak quadrangle	12,120±100	13,990 (+100/−140)
Porter 1	Sediment above set S, Skykomish Valley, Wash.	13,460±70	15,970 (+110/−180)
Porter 2	Sediment above set S, Skykomish Valley, Wash.	13,560±70	16,110 (+240/−160)
Porter 3	Peat above set S, Ohop Valley, Wash.	13,600±70*	16,150 (+230/−170)
QL-1436	Peat above set S, Davis Lake, Wash.	13,800±210	16,425 (+335/−320)
W-2983	Pyroclastic-flow deposit between layers Sg and So, mouth of Swift Creek	13,130±350	15,525 (+540/−470)
W-3141	Pumiceous pyroclastic-flow deposit, early set S, Forest Road 90 at Swift Creek	12,910±160	15,225 (+270/−210)
Clague 1	Estimated layer Sg age, Mono-Fish Lake paleomagnetic record	13,350±100*	15,850 (+200/−230)
WSU-2714	Shells below layer Sg, Mabton, Wash.	13,325±185	15,800 (+300/−300)
USGS-684	Shells below layer Sg, Touchet, Wash.	14,060±450	16,750 (+800/−600)

* Uncertainty not given and arbitrarily assumed to be 70 or 100 yr, respectively.

glacial eruptions at the Mount St. Helens volcanic center. Furthermore, small remnants of alluvial and possible debris-flow deposits composed mostly of Mount St. Helens-derived quartz-biotite±cummingtonite dacite are interbedded with drift at scattered sites in the Lewis River valley (Evarts and others, 2003; Evarts, 2004a, b, 2005). The largest such deposit, in the valley of Cape Horn Creek (fig. 3) about 37 km southwest of the modern volcano, is composed of well-bedded silt, sand, pumiceous pebble gravel, and probable debris-flow beds that contain prismatically jointed dacite clasts as large as 35 cm across. These beds, as thick as 9 m, consist almost entirely of quartz-biotite dacite debris and overlie till that contains sparse clasts of similar lithology. Several quartz-biotite dacite clasts from the Cape Horn Creek locality contain 65–67 percent SiO_2. The paucity of Tertiary rock fragments indicates that these beds are not typical fluvial sedimentary deposits of the Lewis River system, and their position—nearly 460 m above the valley floor—is much too high for them to be an erosional remnant of a valleywide fill. The sedimentary deposits are interpreted as freshly erupted dacitic debris that was transported across the surface of a glacier that occupied the Lewis River valley at that time and that accumulated in a small lake at the glacier margin. Plagioclase separated from a pumice-lapilli bed in the Cape Horn Creek section yielded an $^{40}Ar/^{39}Ar$ plateau age of 263±19 ka (sample 98LC-Q219H2, table 1), and plagioclase separated from a lithic dacite block in a debris-flow(?) bed yielded an analytically similar plateau age of 269±13 ka (sample 98LC-Q219B, table 1). Although both these ages are somewhat younger than the conventional K-Ar age of 296±7 ka for the dacite of Goat Mountain, they all indicate that the earliest activity at the Mount St. Helens volcanic center was considerably earlier than inferred by Crandell (1987) and Mullineaux (1996), and that the Hayden Creek or Amboy Drift is, at least partly, considerably older than inferred by Crandell and represents a glacial advance during marine isotope stage 8 (~300–250 ka).

Lahar Deposits in the Lewis River Valley

The most diverse known record of Ape Canyon-stage volcanism is preserved in lahar and related sedimentary deposits of post-Hayden Creek Drift age in the Lewis River valley. The occurrence of various similar rock types suggests the presence of several lava domes in the vicinity of the volcano and Goat Mountain before construction of the present-day edifice. Rocks from these domes are preserved in till and lahar deposits around Speelyai Bay, along the shores of Lake Merwin (fig. 3; Evarts, 2004a, b), and as far as 15 km farther downstream near Woodland (Evarts, 2005; Vogel, 2005). The lahar and lahar-runout deposits are dominated by Ape Canyon-stage dacite and contain little Tertiary bedrock material. Most of these deposits consist of dense dacite lava clasts that are well rounded, suggesting that they originated as stream alluvium derived from near the volcano and were incorporated into and transported by lahars. Typically, a few rock types dominate each lahar deposit, but several of the deposits are monolithologic, for example, the deposit exposed near the Speelyai Bay boat ramp (loc. E of Major and Scott, 1988) composed of dacite of McBride Lake. The dacite of McBride Lake from the deposit near McBride Lake (loc. 44 of Crandell, 1987) yielded a plateau age of 34.9±4.6 ka (sample SC97-109, table 1). Three other clasts of common, quartz-bearing hornblende dacite containing 65–66 percent SiO_2 collected from Ape Canyon- and Cougar-stage lahar deposits in the Lewis River valley yielded a plateau age of

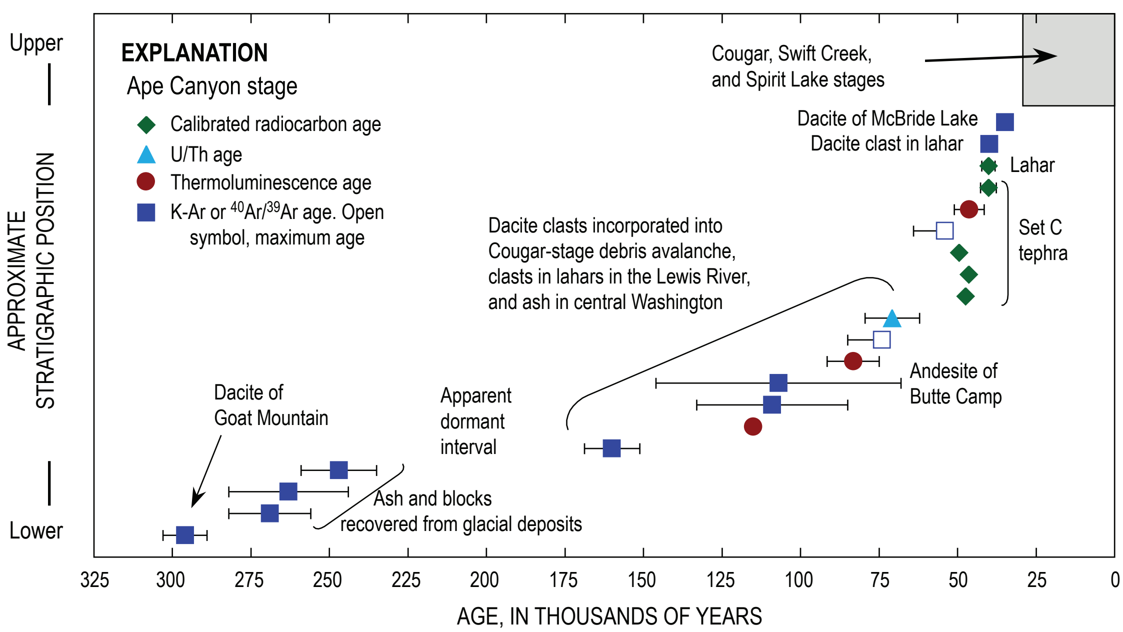

Figure 5. Dated samples for the Ape Canyon stage of Mount St. Helens' eruptive history, showing ages and analytical (1σ) errors. Samples without error bars have uncertainties smaller than symbol, except for oldest thermoluminescence age, which lacks an estimated error. Open symbols, maximum ages. Arranged in approximate stratigraphic order; direct stratigraphic relations do not exist or are unknown for some samples and deposits. See tables 1 and 2 and text for data and references. Radiocarbon ages in calibrated years before 1950 C.E. The Ape Canyon stage lasted from nearly 300 to about 35 ka, with a long hiatus from about 250 to about 160 ka. A second, smaller hiatus may have occurred from about 70 to about 50 ka; however, additional, as-yet-undated samples from glacial and lahar deposits in the Lewis River may partly or completely fill these gaps. Cougar, Swift Creek, and Spirit Lake stages of Mount St. Helens eruptive history fit into the small box at the upper right.

39.8±1.0 ka (sample SC03-619A, table 1), a K-Ar age of 109±24 ka (sample SC97-143, table 1), and a maximum age of 74±11 ka (sample SC03-620A, table 1). Some deposits that consist almost exclusively of well-rounded quartz-biotite dacite pumice clasts within a sandy matrix are interpreted as reworked set C tephra emplaced as lahars or reworked from lahar deposits, as discussed below.

Terraces of laharic gravel and dacite-bearing alluvium occupy several levels along the shore of Lake Merwin (fig. 3). These deposits, as high as 40 m above the pre-reservoir river level, demonstrate that during the Ape Canyon and Cougar stages and after the Hayden Creek-age glacier had retreated, the lower Lewis River valley (fig. 2) contained an extensive fill of volcaniclastic debris from Mount St. Helens. Alternatively, these deposits may represent remnants of lahars and till deposited along the margins of the valley at times when it was filled with glacial ice. The rock types in similar deposits in the North Fork of the Toutle River and lower Cowlitz River valleys (Evarts, 2001) are poorly studied.

Set C Tephra

The oldest deposits from Mount St. Helens recognized by Crandell and others (1981) are set C tephras, with age about 40 ka. A new calibrated age of 47,430±600 yr B.P. (laboratory No. WW-3481, table 2) for tephra layer Cb in the Muddy River quarry is from the same locality as laboratory No. W-2661 (uncalibrated age 37,600±1,300 yr B.P.) of Crandell and others. Charcoal from a monolithologic and probably syneruptive pumiceous sandy lahar on the north shore of Lake Merwin (fig. 3, loc. H of Major and Scott, 1988) yielded a calibrated age of 49,540±1,000 yr B.P. (laboratory No. WW-5561, table 2). Near the volcano, set C deposits that overlie Hayden Creek till are all younger than about 50 ka because any older tephras have been removed or obliterated by glaciation.

Deposits of quartz- and biotite-bearing tephra mineralogically equivalent to set C of Crandell (1987) and Mullineaux (1996) are widespread southwest of the volcano, where they are locally more than 2 m thick (Mundorff, 1964; Evarts and Ashley, 1990a, b; Evarts, 2004a, b, 2005). These deposits, which generally overlie Hayden Creek or Amboy Drift, were assumed to be coeval with the proximal C tephra and are no older than about 50 ka. However, at a few sites in the Lewis River valley (fig. 2), fallout beds of set C tephra underlie till (Evarts, 2005). Plagioclase from a tephra bed beneath till on Green Mountain, about 33 km southwest of Mount St. Helens (fig. 3; Evarts, 2005), yielded an $^{40}Ar/^{39}Ar$ plateau age of 247±12 ka (sample 99YC-P32, table 1), confirming that much-older set C tephras are preserved locally. Furthermore, two other tephras in central Washington that are correlated chemically with Mount St. Helens yielded thermoluminescence ages of 83.2±8.3 and about 115 ka (Busacca and others, 1992; Berger and Busacca, 1995). A thermoluminescence age of 46±5 ka for tephra layer Cy (Berger and Busacca, 1995) agrees closely with the calibrated ages for the adjacent layer Cb and the reworked set C pumice emplaced as lahars, as discussed above.

Set C tephras and related pyroclastic-flow deposits consist of coarsely porphyritic quartz-biotite-cummingtonite-hornblende dacite, mineralogically similar to dense quartz-biotite dacite of the Ape Canyon stage. Fresh set C pumice is rare because most deposits are deeply weathered. Two samples of set C tephra and pumice from pyroclastic-flow deposits at locality 16 of Crandell (1987) have compositions consistent with Ape Canyon-stage dacite. They contain 65–68 percent SiO_2, but most analyses have a loss on ignition of more than 5 percent and plot off the trends defined by dense dacites for most components, suggesting that their compositions have been affected by hydration and alkali and silica loss (fig. 6).

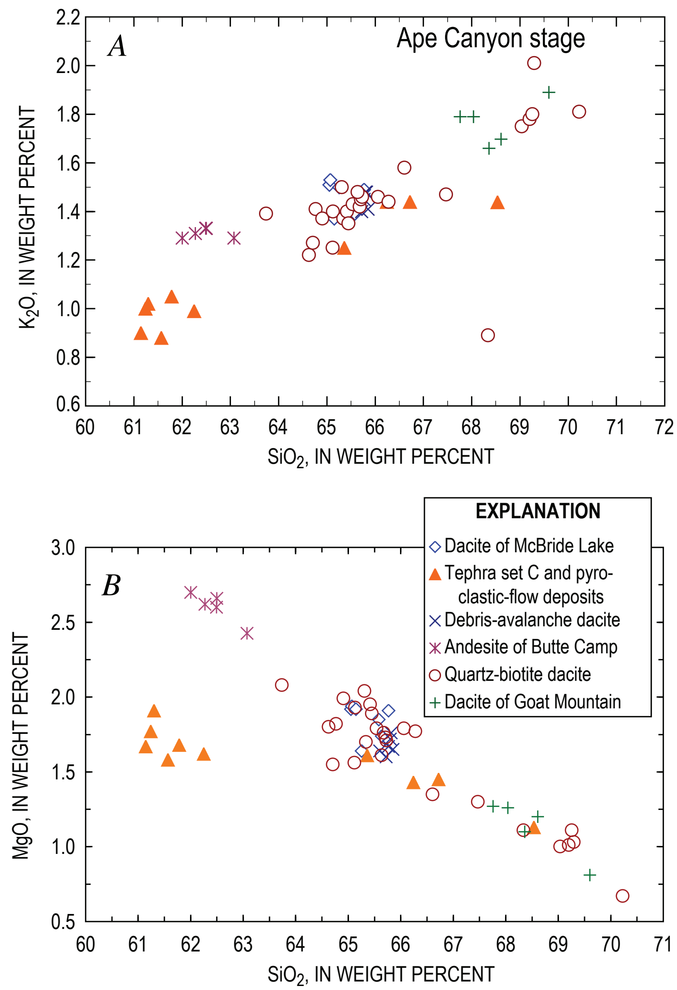

Figure 6. Silica-variation diagrams for Ape Canyon-stage rocks from the Mount St. Helens area (see figs. 2, 3). Samples are mostly U.S. Geological Survey analyses but include some analyses compiled from published reports (Crandell, 1987; Smith and Leeman, 1987; Mullineaux, 1996). *A*, K_2O versus SiO_2. *B*, MgO versus SiO_2.

Ape Canyon-Stage Petrography and Chemistry

Most Ape Canyon-stage rocks consist of coarsely porphyritic hornblende dacite characterized by the presence of quartz and, commonly, biotite. Phenocrysts typically constitute 30 to 40 volume percent of the rock. Plagioclase dominates the phenocryst assemblage and is commonly 0.5 to 1 cm across; complex zoning patterns are present, but resorption textures are sparse. Rounded and embayed quartz is generally present and locally abundant; in a few rocks, quartz is euhedral. Biotite is sparsely present in about half of Ape Canyon-stage dacites, and abundant in a few. Biotite phenocrysts are generally small but can be as large as 5 mm across—for example, in the dacite of Goat Mountain. Small phenocrysts of hypersthene are typically present, especially in rocks lacking biotite, but are generally sparse. Hornblende, commonly 0.5 to 1 cm long, is present in most Ape Canyon-stage dacites. Cummingtonite is sparsely present in a few samples. Complex zoning patterns in hornblende are sparse. Coarse-grained cumulate-textured inclusions and small quench-textured andesitic inclusions are rare in Ape Canyon-stage dacites (except in the andesite of Butte Camp).

Representative analyses of samples of Ape Canyon-stage rocks are listed in table 4, and a larger dataset is plotted in figure 6. The samples range in SiO_2 content from about 62 to 70 weight percent and, despite mineralogic differences, are compositionally similar to dacite from the other volcanic stages at Mount St. Helens (fig. 7). About half of the samples of Ape Canyon stage-rocks contain about 64–66 percent SiO_2, similar to the dacite from later volcanic stages, especially the Cougar and Swift Creek stages. Their contents of all other oxides are also similar to those of younger rocks, including high Na_2O, which distinguishes Mount St. Helens from other Cascade volcanoes. A few Ape Canyon-stage dacites have higher SiO_2 contents, as much as 68–69 percent. Andesite is the primary composition of the andesite of Butte Camp, and some weathered set C tephras may be andesitic. In summary, although little is known in detail about Ape Canyon-stage rocks, they are clearly related to younger Mount St. Helens dacites and are derived from the Mount St. Helens magmatic system.

Summary of Ape Canyon-Stage Volcanism

Radiometric dating of Ape Canyon-stage deposits indicates at least two periods of volcanism at Mount St. Helens during Ape Canyon time—one about 300–250 ka and another about 160–35 ka—possibly separated by a long hiatus. Alternatively, the evidence for eruptive events between 250 and 160 ka has been buried by younger volcanic deposits or simply not yet recognized. The earlier period is represented by the dacite dome of Goat Mountain (fig. 2), just west of the volcano, and by tephra and sediment associated with glacial till in the Lewis River valley and elsewhere (fig. 2). The later period is represented by megablocks in the Cougar-age debris-avalanche deposit, dacite clasts in lahar deposits in the river valleys draining the mountain, the andesite of Butte Camp and a few nearby eroded remnants of unnamed lava domes, set C tephra near the volcano, and older tephra in central Washington. A second, shorter hiatus may have occurred during the later period between about 70 and 50 ka. Some eruptions occurred while the Lewis River valley was occupied by ice.

An extensive hydrothermal system existed at Mount St. Helens late in Ape Canyon time. Most of the debris-avalanche dacite in the Cougar-stage debris-avalanche deposit and some

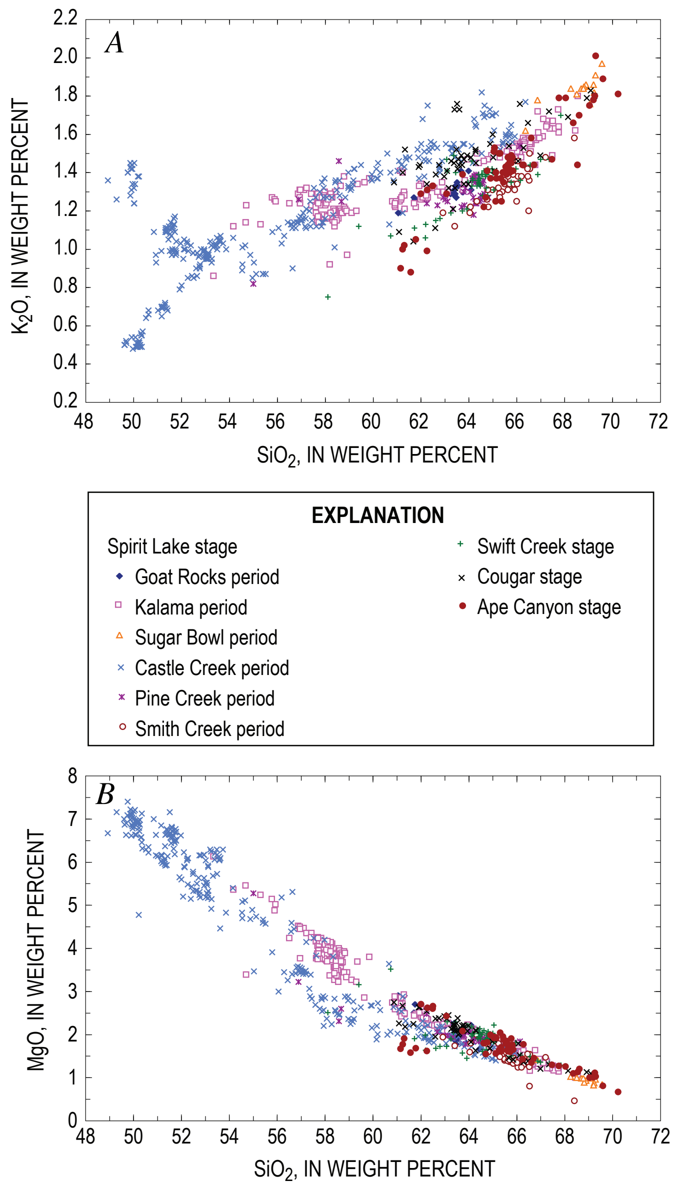

Figure 7. Silica-variation diagrams for 700 Mount St. Helens rocks plotted by eruptive stage or, for Spirit Lake-stage rocks, by eruptive period. Not shown are 1980–86 or 2004–6 rock compositions. Samples are mostly U.S. Geological Survey analyses but include some analyses compiled from published reports (Halliday and others, 1983; Crandell, 1987; Smith and Leeman, 1987, 1993; Gardner and others, 1995; Mullineaux, 1996; Hausback, 2000). *A*, K_2O versus SiO_2. *B*, MgO versus SiO_2.

Table 4. Composition of representative Ape Canyon-stage rocks.

[All samples analyzed at the U.S. Geological Survey laboratory in Denver, Colo.; analysts, David Siems and Joseph E. Taggart, Jr. All values in weight percent, recalculated to 100 weight percent on an anhydrous basis, with Fe_2O_3 = 0.2 total Fe, analyzed as Fe_2O_3. LOI, loss on ignition (in percent). Samples are coded to stratigraphic units as follows: abc, andesite of Butte Camp; dad, debris avalanche dacite; gm, dacite of Goat Mountain; hbd, quartz-bearing hornblende dacite; mcb, dacite of McBride Lake; qbp, quartz-biotite dacite; qbp*, lithic clast in the Sugar Bowl blast deposit.]

Sample --------	**SC98-193**	**SC03-642**	**SC03-619C**	**SC02-539A**	**SC97-143**	**SC03-603A**	**SC03-619A**
Unit------------	**abc**	**hbd**	**qbp**	**qbp**	**hbd**	**qbp***	**hbd**
Latitude N -----	**46°10.5′**	**46°05.25′**	**45°59.07′**	**45°59.19′**	**46°03.78′**	**46°14.05′**	**45°59.07′**
Longitude W --	**122°14.3′**	**122°12.40′**	**122°31.55′**	**122°33.49′**	**122°13.48′**	**122°09.08′**	**122°31.55′**
Major-element analyses, weight percent							
SiO_2	62.00	63.74	64.63	65.12	65.13	65.31	65.34
Al_2O_3	17.74	17.67	18.07	18.78	17.11	16.91	17.60
Fe_2O_3	1.08	0.93	0.89	0.82	0.94	0.93	0.82
FeO	3.90	3.33	3.22	2.93	3.38	3.35	2.96
MgO	2.70	2.08	1.80	1.56	1.93	2.04	1.70
CaO	5.68	5.38	4.74	4.18	4.64	4.56	4.75
Na_2O	4.53	4.48	4.53	4.62	4.48	4.48	4.62
K_2O	1.29	1.39	1.22	1.25	1.40	1.50	1.37
TiO_2	0.80	0.69	0.61	0.56	0.66	0.65	0.59
P_2O_5	0.20	0.22	0.23	0.11	0.26	0.21	0.18
MnO	0.08	0.07	0.07	0.07	0.08	0.07	0.07
LOI	0.02	1.02	1.93	3.04	0.84	0.14	0.20
FeO*/MgO	1.80	2.02	2.24	2.35	2.19	2.06	2.18

Sample --------	**SC03-620A**	**SC97-109**	**SC02-484**	**SC02-539B**	**P90-22A**	**W97-141**	**SC03-620B**
Unit------------	**qbp**	**mcb**	**dad**	**qbp**	**C pf**	**gm**	**qbp**
Latitude N -----	**45°59.16′**	**46°08.49′**	**46°04.03′**	**45°59.19′**	**46°12.36′**	**46°08.85′**	**45°59.16′**
Longitude W--	**122°31.70′**	**122°15.45′**	**122°11.85′**	**122°33.49′**	**122°05.04′**	**122°16.96′**	**122°31.70′**
Major-element analyses, weight percent							
SiO_2	65.54	65.77	65.82	66.61	67.42	67.76	70.23
Al_2O_3	17.24	16.91	17.12	18.20	16.73	16.78	17.00
Fe_2O_3	0.86	0.93	0.86	0.85	0.78	0.66	0.49
FeO	3.09	3.34	3.11	3.05	2.80	2.39	1.75
MgO	1.79	1.91	1.76	1.35	1.40	1.27	0.67
CaO	4.62	4.44	4.55	3.54	4.03	3.92	2.73
Na_2O	4.56	4.32	4.43	4.01	4.52	4.63	4.81
K_2O	1.43	1.49	1.48	1.58	1.57	1.79	1.81
TiO_2	0.59	0.65	0.60	0.60	0.53	0.48	0.34
P_2O_5	0.20	0.17	0.20	0.12	0.17	0.25	0.13
MnO	0.07	0.08	0.07	0.08	0.06	0.07	0.04
LOI	0.12	0.29	2.19	2.94	2.32	0.29	1.15
FeO*/MgO	2.15	2.19	2.21	2.81	2.49	2.36	3.26

remnants of similar rocks in the area between Goat Mountain and Butte Camp (fig. 2) are propylitically altered. Calcite is abundant and pyrite sparse within the matrix; mafic minerals are altered and replaced by chlorite and, rarely, epidote; and the groundmass of these rocks is thoroughly recrystallized, indicating alteration by hot water. Although the timing of this alteration is unclear, the debris-avalanche dacite is about 70 ka in age, and the absence of older altered rocks suggests that the hydrothermal system was active in the interval after about 70 ka and before about 30 ka.

The long period of intermittent volcanism during the Ape Canyon stage produced a cluster of dacite domes at an altitude as high as about 1,800 m slightly west of and at the present site of Mount St. Helens. In tephra sections, the interval between sets C and M (Cougar stage) is occupied by ash deposits, as thick as 1 m, that contain at least three weathering profiles (Mullineaux, 1996). Thus, the nature and duration of the hiatus between the Ape Canyon and Cougar stages is poorly constrained, but no lava flows or domes related to Mount St. Helens have ages corresponding to the period 35–28 ka.

Cougar Stage

The Cougar stage, between about 28 and 18 ka, was probably the most active stage in the volcano's history before its most recent, or Spirit Lake, stage. During the Cougar stage, voluminous pyroclastic flows, dacite domes, tephra, and a large-volume pyroxene andesite lava flow accompanied a debris avalanche. A few events have recently been recognized that preceded previous reconstructions of the Cougar stage. In combination with calibrated radiocarbon ages, these events reveal that the Cougar stage began somewhat before the 21–18 ka range proposed by Crandell (1987) and Mullineaux (1996). Cougar-stage stratigraphy is summarized in figure 8, and the ages of Cougar-stage rocks and deposits are listed in tables 1 and 2. These new ages and those presented in the subsection below entitled "Swift Creek stage" suggest that the Cougar and Swift Creek stages may have been separated by only a short hiatus; nevertheless, herein we retain the terminology of Crandell (1987) and Mullineaux (1996). The eruptions and deposits related to tephra sets M and K are designated "Cougar stage," whereas those related to tephra sets S and J are designated "Swift Creek stage."

Early Domes and Lahar Deposits

Early in the Cougar stage, an unknown number of hornblende dacite domes were erupted under the area covered by the present-day volcano (fig. 2). Though buried by younger volcanic deposits, these domes are represented by blocks in

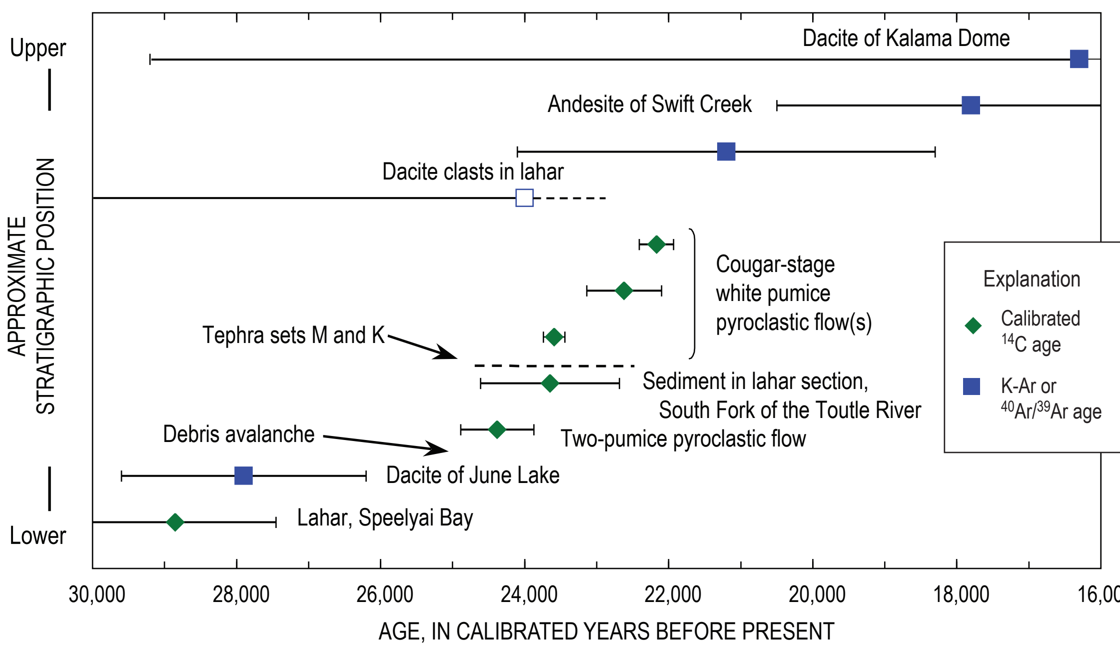

Figure 8. Dated samples for the Cougar stage of Mount St. Helens' eruptive history, showing ages and analytical (1σ) errors. Open symbols, maximum ages. Arranged in approximate stratigraphic order; direct stratigraphic relations do not exist or are unknown for some of these samples and deposits. Radiocarbon ages in calibrated years before 1950 C.E. The Cougar stage lasted from about 28 ka to about 18 ka. See tables 1 and 2 and text for data and references. Stratigraphic position of dacite clasts in Cougar-stage lahar is shown at approximate position of parent domes, which may be related to dome building that accompanied Cougar-stage white pumice eruptions. Lahar containing dacite clasts also contains andesite of Swift Creek and slightly postdates it. Same symbols and error bars as in figure 5.

lithic pyroclastic-flow deposits, blocks in the Cougar-stage debris-avalanche deposit, and clasts in Fraser-age glacial till and lahar deposits in the Lewis River valley. Lahar deposits containing various hypersthene-hornblende dacite clasts occur in the area around the east end of Swift Reservoir and in the lower Lewis River valley overlying Ape Canyon-stage lahar deposits. Some of these lahars probably traversed the Pine Creek drainage from a source in the vicinity of the present-day volcano. Lahar deposits and their reworked equivalents that lack debris-avalanche dacite are extensive in the Lewis River valley from Swift Dam to the east end of Lake Merwin and probably predate the Cougar-stage debris-avalanche deposit (see below). Charcoal in sediment from beneath a lahar deposit near Speelyai Bay yielded a calibrated age of 28,850±1,400 yr B.P. (sample MS-5, table 2) that is interpreted as a maximum age for the deposit (Major and Scott, 1988). A dacite clast from a similar nearby lahar deposit yielded an $^{40}Ar/^{39}Ar$ isochron age of 21.2±2.9 ka (sample SC03-611D, table 1). Lahar deposits of similar age and lithology also occur in the South Fork of the Toutle River and Cowlitz River drainages (fig. 3; Crandell, 1987; Scott, 1989; Evarts and Ashley, 1990b). Wood from sediment interbedded with these lahar deposits yielded a radiocarbon age of 23,650 (+485/−965) cal yr B.P. (sample Scott BC, table 2; Scott, 1989).

A small dome of hypersthene-hornblende dacite containing 63.5 percent SiO_2 in the Kalama River valley 13 km southwest of Mount St. Helens (figs. 1, 2) was informally designated the "dacite of Kalama Dome" by Evarts and Ashley (1990a). The rock yielded an $^{40}Ar/^{39}Ar$ isochron age of 16.3±12.9 ka (sample SC98-155, table 1), but the large uncertainty of the age and absence of stratigraphic context for this dome prevents interpreting its relation to other Cougar-stage events. The dacite of Kalama Dome probably was erupted during the Cougar stage, but a Swift Creek age is also possible. A small exposure of a cummingtonite-hypersthene-hornblende dacite lithic pyroclastic-flow deposit, called the dacite of June Lake, underlies Swift Creek-stage deposits near June Lake. The rock, which contains nearly 69 percent SiO_2, yielded an $^{40}Ar/^{39}Ar$ plateau age of 27.9±1.7 ka (sample SC98-192, table 1), indicating deposition during the Cougar stage. Fragments of this rock type also occur as lithic clasts in the two-pumice pyroclastic-flow deposit (see below). Early Cougar-stage rocks in the Cougar-stage debris-avalanche and lahar deposits near the east end of Swift Reservoir consist mostly of porphyritic hypersthene-hornblende dacite containing 64–65 percent SiO_2 that was emplaced as domes and lithic pyroclastic flows.

Cougar-Stage Debris-Avalanche Deposit and Two-Pumice Pyroclastic-Flow Deposit

The most devastating Cougar-stage event was a debris avalanche composed primarily of Ape Canyon-stage rocks. First noted by Mullineaux and Crandell (1981) and described briefly by Newhall (1982), the debris avalanche emplaced a 200- to 300-m-thick sheet of mostly hydrothermally altered debris in the drainage of ancestral Swift Creek as far south as the Lewis River (fig. 2). Crandell suggested that this debris avalanche originated in the area between Butte Camp and Goat Mountain. The approximately 17-km runout of the debris avalanche, however, suggests an origin from an altitude of about 2,000 to 2,200 m, estimated by using the length/distance relation of Siebert (1984). Together with remnants of the debris-avalanche deposit that are buried under younger deposits in the Cedar Flats area, the evidence suggests a source in the area of the present-day edifice. The volume of the Cougar-stage debris-avalanche deposit was at least 1 km^3, probably nearly 2 km^3, similar in volume to the 1980 debris avalanche. The Cougar-stage debris avalanche blocked the Lewis River at the present site of Swift Creek, and incision of the temporary dam generated flood-breakout lahars downstream in the Lewis River valley as far as the Columbia River and filled the lower Lewis River valley with lahar deposits to depths of at least 75 m. Filling of Yale Lake and Lake Merwin flooded many exposures of these lahar deposits, but they crop out sporadically along the shores of both reservoirs (Evarts, 2004a, b) and are well exposed in the vicinity of the community of Cougar. These lahar deposits are interpreted to be of Cougar age because they contain abundant clasts of debris-avalanche dacite and pumice from the overlying two-pumice pyroclastic-flow deposit. Lahar deposits and material eroded from the Cougar-stage debris-avalanche deposit also filled the east end of the valley now covered by Swift Reservoir to a depth of about 75 m.

Emplacement of the Cougar-age debris-avalanche deposit was followed immediately by a large dacitic pyroclastic eruption that produced the two-pumice pyroclastic-flow deposit, charcoal from which has a calibrated age of 24,380 (+510/–480) yr B.P. (laboratory No. W-2540, table 2). The contact between these two deposits displays no evidence of erosion or soil formation; thus, onset of the eruption that produced the two-pumice pyroclastic flow probably initiated the Cougar-stage debris avalanche, which in the Swift Creek drainage is buried under as much as 100 m of pumice and ash.

The two-pumice pyroclastic-flow deposit consists of many individual flow units and has a volume of at least 1 km^3. These flow units contain pumice of two distinct lithologic and compositional types: light-colored pumice of hypersthene-hornblende dacite containing 66–68 percent SiO_2, and homogeneous light- to dark-brown pumice of augite-hypersthene-hornblende dacite containing 63.5–64.5 percent SiO_2 (fig. 9; table 5). Blocks of banded pumice of both compositions are rare. The two-pumice pyroclastic-flow deposit can be recognized by abundant blocks of pumice, several meters across, as far as 12 km from the volcano. Dense, prismatically jointed blocks of dacite near the top of the two-pumice pyroclastic-flow deposit demonstrate that late in the eruption, dacite domes grew in the vent. Small amounts of the two-pumice pyroclastic-flow deposit or its reworked equivalent also occur in the Cedar Flats area and in some lahar deposits in the lower Lewis River and in the South Fork of the Toutle River west of Sheep Camp (fig. 3;

loc. 71 of Crandell, 1987). The distribution of the two-pumice pyroclastic-flow deposit is similar to that of the underlying Cougar-stage debris-avalanche deposit, suggesting that the vent was in the area of the present-day edifice.

Tephra Sets M and K and Cougar-Stage White Pumice

Sets M and K tephra were erupted in quick succession after the two-pumice pyroclastic flow and were followed by a second large-volume dacitic pyroclastic eruption that produced the herein-named Cougar-stage white pumice. Early-emplaced set M tephras consist of cummingtonite-hornblende dacite and are overlain by hypersthene-hornblende-cummingtonite dacite tephra, also in set M (Mullineaux, 1996). The composition of set M tephra is poorly known, because only a few analyses of weathered pumice that yielded andesitic compositions are available. Set K tephra consists of hypersthene-hornblende dacite (Mullineaux, 1996), and a single analyzed sample contains 67 percent SiO_2.

Extensive pyroclastic-flow deposits of the Cougar-stage white pumice overlie sets M and K tephras and the two-pumice pyroclastic-flow deposit on the south flank of Mount St. Helens from the Lewis River cliffs eastward to Marble Mountain (fig. 2). Smaller exposures occur in the Smith and Pine Creek drainages. Three calibrated ages for the Cougar-stage white pumice (samples W-2413, W-4531, WW-4543, table 2) range from 22.2 to 23.6 ka. The Cougar-stage white pumice consists of porphyritic hypersthene-hornblende dacite, with subtle variations in phenocryst content and abundance. Six analyses fall into two groups: one containing about 63 percent SiO_2 and a second containing about 65 percent SiO_2. The variations in lithology, composition, and age suggest that the Cougar-stage white pumice may represent more than one eruption, although no stratigraphic breaks within the unit have been observed.

Andesite of Swift Creek

The Cougar stage culminated with emplacement of the andesite of Swift Creek, a lava flow on the south flank of Mount St. Helens (fig. 2). The vent for the lava flow was near an altitude of about 1,830 m, probably at or near the summit of the volcano at that time. The andesite of Swift Creek consists of porphyritic hornblende-augite-hypersthene andesite to dacite containing 61–63.5 percent SiO_2 with a complex phenocryst assemblage. About 0.75 km^3 in volume, this lava flow was probably the largest in the history of Mount St. Helens. Its varying composition and multiple populations of plagioclase and mafic phenocrysts indicate a magma-mixing origin.

The andesite of Swift Creek, as thick as 200 m, flowed nearly 6 km down Swift Creek, where it presently forms the divide between the West Fork and main stem of Swift Creek. In contrast to the interpretation by Crandell (1987), the lava flow appears to overlie the two-pumice pyroclastic-flow deposit and probably overlies the Cougar-stage white pumice. Our radiometric dating of this lava flow indicates an $^{40}Ar/^{39}Ar$ plateau age of 17.8±2.7 ka (sample SC99-343, table 1). Fraser-age till (for example, locs. 39, 40, 47, and 49 of Crandell, 1987) contains abundant clasts derived from the andesite of Swift Creek and so must at least partly postdate its emplacement.

Petrography of Cougar-Stage Rocks

Most Cougar-stage rocks are less coarsely porphyritic than Ape Canyon-stage rocks. Crystal content commonly approaches 50 volume percent, although the crystals in Cougar-stage rocks are generally smaller. Cougar-stage rocks are dominated by plagioclase, with hornblende and hypersthene as the major mafic phenocryst phases. Cummingtonite and augite are present in a few units, especially set M tephra, but quartz and biotite are generally absent, even in high-silica dacite. Plagioclase phenocryst populations vary, but plagioclase in most Cougar-stage dacite displays complex zoning

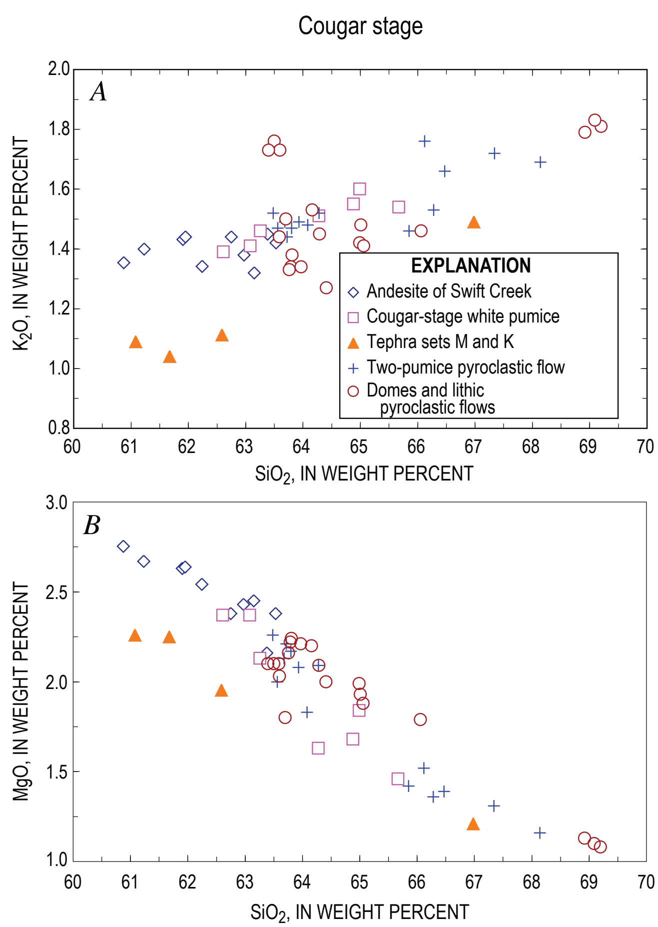

Figure 9. Silica-variation diagrams for Cougar-stage rocks from the Mount St. Helens area (figs. 2, 3). Samples are mostly U.S. Geological Survey analyses but include some analyses compiled from published reports (Crandell, 1987; Smith and Leeman, 1987, 1993; Evarts and Ashley, 1990a, b; Mullineaux, 1996). *A*, K_2O versus SiO_2. *B*, MgO versus SiO_2.

Table 5. Composition of representative Cougar-stage rocks.

[All samples analyzed at the U.S. Geological Survey laboratory in Denver, Colo.; analysts, David Siems and Joseph E. Taggart, Jr. All values in weight percent, recalculated to 100 weight percent on an anhydrous basis, with Fe_2O_3 = 0.2 total Fe, analyzed as Fe_2O_3. LOI, loss on ignition (in percent). Samples are coded to stratigraphic units as follows: asw, andesite of Swift Creek; djl, dacite of June Lake; dk, dacite of Kalama Dome; hbd, hornblende dacite clasts in debris-avalanche and lahar deposits at the east end of Swift Reservoir and in lahar deposits in the lower Lewis River valley; two-pum dk or two-pum lt, dark or light-colored pumice in two-pumice pyroclastic flow; white, Cougar-stage white pumice.]

Sample -------	SC97-114	SC97-141	SC98-251A	SC98-250	SC01-440	SC02-487	SC98-155
Unit-----------	asw	two-pum dk	two-pum dk	two-pum lt	white	white	dk
Latitude N ----	46°07.24′	46°04.19′	46°05.87′	46°05.16′	46°03.25′	46°06.62′	46°07.79′
Longitude W--	122°12.17′	122°11.84′	122°11.95′	122°12.25′	122°12.88′	122°10.69′	122°19.76′
Major-element analyses, weight percent							
SiO_2	61.23	63.72	64.28	66.12	64.88	63.26	63.50
Al_2O_3	17.66	17.29	17.24	17.16	17.56	17.87	17.55
Fe_2O_3	1.15	1.05	1.00	0.83	0.96	1.04	0.97
FeO	4.13	3.80	3.61	2.97	3.44	3.75	3.51
MgO	2.67	2.21	2.09	1.52	1.68	2.13	2.10
CaO	5.97	4.80	4.70	4.18	4.23	4.82	4.90
Na_2O	4.50	4.47	4.50	4.57	4.67	4.53	4.63
K_2O	1.40	1.44	1.52	1.76	1.55	1.46	1.76
TiO_2	0.84	0.77	0.72	0.58	0.63	0.76	0.73
P_2O_5	0.36	0.35	0.26	0.24	0.33	0.31	0.27
MnO	0.09	0.09	0.08	0.07	0.07	0.08	0.08
LOI	0.08	0.96	1.17	0.95	2.29	1.85	0.06
FeO*/MgO	1.93	2.14	2.17	2.44	2.56	2.20	2.09
Sample -------	**SC98-192**	**SC03-611D**	**SC03-580**	**SC03-581**	**SC04-696**	**SC04-700C**	**SC03-612**
Unit-----------	**djl**	**hbd**	**hbd**	**hbd**	**hbd**	**hbd**	**hbd**
Latitude N ----	**46°09.14′**	**45°58.91′**	**46°06.29′**	**46°06.30′**	**46°02.43′**	**46°02.66′**	**45°58.93′**
Longitude W--	**122°09.65′**	**122°26.35′**	**122°00.40′**	**122°00.39′**	**122°04.53′**	**122°05.55′**	**122°26.45′**
Major-element analyses, weight percent							
SiO_2	68.92	66.06	65.01	65.06	63.70	64.41	69.24
Al_2O_3	16.46	17.05	17.32	17.20	18.11	17.54	16.34
Fe_2O_3	0.62	0.86	0.88	0.89	1.01	0.92	0.60
FeO	2.23	3.09	3.16	3.21	3.64	3.32	2.18
MgO	1.13	1.79	1.93	1.88	1.80	2.00	1.08
CaO	3.51	4.37	4.87	4.78	4.62	5.04	3.43
Na_2O	4.72	4.45	4.46	4.66	4.50	4.58	4.68
K_2O	1.79	1.46	1.48	1.41	1.50	1.27	1.80
TiO_2	0.44	0.60	0.63	0.62	0.71	0.64	0.43
P_2O_5	0.14	0.19	0.18	0.21	0.32	0.21	0.17
MnO	0.06	0.07	0.07	0.08	0.08	0.08	0.05
LOI	0.09	0.46	1.28	0.04	2.58	0.01	1.30
FeO*/MgO	2.47	2.16	2.05	2.14	2.53	2.08	2.51

patterns; the zoning in larger crystals preserves an extended history of repeated crystallization and resorption, whereas smaller crystals are generally weakly zoned. Hornblende phenocrysts can be complexly zoned and commonly have thick to thin breakdown rims—features typical of those observed in younger Mount St. Helens dacites (Rutherford and Hill, 1993; Rutherford and Devine, this volume, chap. 31; Thornber and others, this volume, chap. 32).

Coarse-grained inclusions with cumulate or plutonic textures are present in Cougar-stage rocks but generally are smaller and less conspicuous than in Swift Creek- or Spirit Lake-stage rocks. Inclusions with quenched textures have been observed only in the dacite of June Lake and the two-pumice pyroclastic-flow deposit. Features indicating strong disequilibrium are generally absent in Cougar-stage dacite; however, Mullineaux (1996) reported the presence of olivine in separates of tephra layer Mo that suggests a basaltic component in the magmatic system at that time. Despite the petrographic differences, Cougar-stage rocks are compositionally similar to Ape Canyon-stage dacite (figs. 6, 9) and to younger Swift Creek- and Spirit Lake-stage dacites (fig. 7). The petrography and chemistry of Cougar-stage rocks indicate production from various magma batches of similar composition that were fractionated under similar conditions. Andesitic composition, shown by some set M tephras and the andesite of Swift Creek, suggest the presence of a more mafic component during the Cougar stage than earlier in Mount St. Helens' history. The magmatic system of the Spirit Lake stage probably first evolved during the Cougar stage.

Summary of Cougar Stage Volcanism

The earliest known Cougar-stage eruptive events were lahars in the South Fork of the Toutle River, Pine Creek, and the Lewis River (fig. 2) and lithic pyroclastic flows on the south flank of Mount St. Helens, which are about 28 ka in age. These deposits probably originated from lava domes erupted in the area of the present-day edifice. Many Ape Canyon-stage deposits in that area were removed and redeposited in ancestral Swift and Pine Creeks by the Cougar-stage debris avalanche, which was followed immediately by the two-pumice pyroclastic flow (about 24.4 ka) and then by sets M and K tephras and the Cougar-stage white pumice (about 23.6–22.2 ka). The debris flow and pyroclastic eruptions formed a thick sequence of fragmental deposits on the south flank of the volcano that blocked the Lewis River at Swift Creek. Subsequent failure of this blockage generated flood-breakout lahars that traversed the lower Lewis River. Emplacement of the andesite of Swift Creek about 18 ka divided the south flank into the West Fork of Swift Creek and the Swift Creek drainages.

At the end of the Cougar stage, Mount St. Helens consisted of a cluster of dacite domes at the site of the present-day edifice. No eruptions of the volcano are known between about 18 and about 16 ka, corresponding to the demise of the Cougar stage and the onset of the Swift Creek stage. The hiatus is probably shorter than that envisioned by Crandell (1987) and Mullineaux (1996), because additional eruptions, unrecognized by them, occurred between the Cougar-stage white pumice and the basal set S tephra of the Swift Creek stage.

Swift Creek Stage

During the Swift Creek stage, the widespread sets S and J tephras were erupted, and three extensive fans of fragmental debris were emplaced on the southeast, south, west, and northwest flanks of Mount St. Helens from dacite domes. Crandell (1987) speculated that these fans were emplaced by disruption of a single dome approximately in the center of the present-day edifice. However, though broadly lithologically similar, the dacitic clasts that occur within the Swift Creek, Crescent Ridge, and Cedar Flats fans are lithologically distinct and must each have had separate sources.

Swift Creek Fan

The Swift Creek fan covers much of the south flank of Mount St. Helens in the drainage of the West Fork of Swift Creek (fig. 2), where it overlies Cougar-stage deposits and Fraser-age till. This fan includes some of the deposits described by Hyde (1975) as the Swift Creek assemblage. The lower part of the fan, which predates late set S tephra (Crandell, 1987), consists of pumiceous and lithic pyroclastic-flow deposits of cummingtonite-bearing hypersthene-hornblende dacite containing about 67 percent SiO_2. The upper part of the fan, which postdates set S tephra, consists of lithic pyroclastic-flow deposits of hypersthene-hornblende dacite containing 64–65 percent SiO_2. The total thickness of the fan is about 30 m. Lahar deposits dominated by clasts of Swift Creek age cap the fan. Similar deposits in the small canyon just south of the old Timberline Campground at 1,340 m altitude on the northeast flank of the volcano are correlated with the Swift Creek fan. The site of the dome(s) that erupted the Swift Creek fan is poorly known, but it must have been in the vicinity of the present-day edifice. Hausback (2000) suggested that the Loowit and Archybacter domes, which are exposed in the walls of the 1980 eruption crater, are of Swift Creek age. If so, their petrography and lithology are most similar to Swift Creek fan rocks. The Swift Creek fan is smaller in volume than the Crescent Ridge or Cedar Flats fan. A lahar deposit exposed below Merwin Dam on the Lewis River (fig. 3) is probably related to the Swift Creek fan, and some lahar deposits in the vicinity of Cougar may be of Swift Creek age (Crandell, 1987).

Crescent Ridge Dome and Crescent Ridge Fan

The Crescent Ridge fan is a wedge of fragmental material that stretches from the Studebaker Creek area southward to Butte Camp on the northwest and west flanks of Mount St. Helens (fig. 2). This fan is at least 200 m thick, approximately centered below the Crescent Ridge dome, and consists dominantly of lithic pyroclastic-flow deposits. Pumiceous pyroclastic-flow deposits are also common in the lower part of the fan. Lahar deposits from the Crescent Ridge fan are preserved locally in the South Fork of the Toutle River (for example, loc. 72 of Crandell, 1987; Evarts and Ashley, 1990b) and in the Toutle River north of Silver Lake (Evarts, 2001).

Rocks of the Crescent Ridge fan are well exposed in the headwaters of the South Fork of the Toutle River (loc. 76 of Crandell, 1987) and in Studebaker Creek (fig. 2). The rocks fall into two lithologic groups: an early, primarily pumiceous group of cummingtonite-hornblende dacite (sparse small hypersthene) and a later, dominantly lithic group of augite-hypersthene-hornblende dacite (abundant hypersthene and sparse augite). Lithology varies somewhat in each group, especially in the abundances of different size ranges of plagioclase, but the textural characteristics of plagioclase are similar. The abundance of relatively large plagioclase crystals derived from gabbroic inclusions also varies. Both groups contain 64–65 percent SiO_2, although a few samples contain less. The composition and phenocryst mineralogy of the Crescent Ridge dome are similar to those of the lower, pumiceous part of the fan.

Most, and possibly all, of the Crescent Ridge fan probably postdates set S tephra (Crandell, 1987). No set S tephras have been observed within the fan, and layer Jg tephra overlies the fan. Preliminary paleomagnetic data (D.E. Champion, written commun., 2005) suggest that the early and late parts of the fan differ in age, possibly by decades or centuries. The distribution and mineralogy of the Crescent Ridge pyroclastic-fan deposits suggest that they originated partly from the currently exposed part of the Crescent Ridge dome, as well as from a now-buried uphill extension of the Crescent Ridge dome or from nearby domes no longer exposed. On the west flank of Mount St. Helens, drainage radial to the Crescent Ridge dome incised the Crescent Ridge pyroclastic fan; some of that drainage is still active, but part was later buried by voluminous pyroclastic-fan deposits of Spirit Lake (Kalama) age.

Cedar Flats Fan

The Cedar Flats fan completely filled the valley of Pine Creek and spilled into the Lewis River valley in the vicinity of Cedar Flats (fig. 2) during the period between the eruption of sets S and J tephra. This fan is at least 100 m thick in Pine Creek and 50 to 100 m thick in the Cedar Flats area. Remnants of lahar and lithic pyroclastic-flow deposits in the Smith Creek and Ape Canyon drainages indicate that a small component of the Cedar Flats fan originated on the east flank of Mount St. Helens and traveled down the Muddy River. The fan is dominated by lahar deposits but also contains lithic pyroclastic-flow deposits of dense hypersthene-hornblende dacite similar to set S tephra that were produced by hot collapses of growing domes which must have been situated near the present-day edifice. The Cedar Flats fan filled the Lewis River valley to a depth of at least 50 m in the area around the west end of Swift Reservoir and flowed an unknown distance down the Lewis River. Most clasts in the fan contain 64–65 percent SiO_2.

Age of Swift Creek-Stage Volcanism

The age of set S tephras (specifically the late set S layers Sg and So) is disputed. Radiocarbon ages (fig. 10; table 3) cited by Mullineaux (1996) seem to establish the onset of set S volcanism at about 15.5 ka, on the basis of the age of a pyroclastic flow interbedded in the set. However, additional radiocarbon ages from localities where layers Sg and So are interbedded with Missoula Flood deposits in eastern Washington and Vashon Drift in the Puget Lowland are as old as 16.5 ka (Davis and others, 1982; Porter and others, 1983; Baker and Bunker, 1985; Waitt, 1985; S.C. Porter and T.W. Swanson, written commun., 2006). These radiocarbon ages were determined on shells, peat, or sediment, and the results are neither internally nor stratigraphically consistent. Furthermore, in at least one sample, it is unclear which set S layer was being dated. The samples from set S pyroclastic flows were not pretreated, and so their ages may be slightly too young. Correlation using the Mono Lake-Fish Lake paleosecular-variation curve suggests an age for layers Sg and So of about 15.8 ka (Clague and others, 2003), depending on the assumptions used. Consideration of all these ages suggests the most reliable age for layers Sg and So is about 16 ka. The older set S tephras are probably no more than a few hundred years older, because they lack weathering zones (Mullineaux, 1996).

The precise ages of the Swift Creek-stage pyroclastic fans are unknown. Accumulation of the Swift Creek fan probably began around 16 ka and continued for an unknown period. The Crescent Ridge fan at least partly overlies set S tephras and is overlain by set J tephras. These fans may have accumulated quickly; a dated lahar deposit overlying the Crescent Ridge fan is younger than about 14 ka. The Cedar Flats fan postdates set S tephra and predates set J tephra; determinations on unpretreated samples from within the fan indicate an age of about 14 ka if the age for tephra layer Jyn is accurate. The apparent hiatus shown in figure 10 in the period of about 15–14 ka separates volcanism related to the older set, S, and the younger set, J, and is corroborated by the weak soil zone at the top of set S tephra (Mullineaux, 1996). However, nonexplosive volcanism probably continued during at least part of this period and formed the Crescent Ridge and Cedar Flats fans.

All three fans of Swift Creek stage are overlain by set J tephra. Calibrated ages are slightly contradictory, probably owing to a lack of pretreatment among the samples processed before 1990. The best single age may be that of Carrara and Trimble (1992) for layer Jyn in northeastern Washington. The sample was pretreated, and its calibrated age, 13,855 (+90/−50) yr B.P. (laboratory No. USGS-2780, table 3), suggests that set J tephra probably began accumulating at least as early as about 13.86 ka. Other ages suggest that the later set J tephras may be as young as about 12.8 ka. Additional geochronologic data are needed to refine the period represented by Swift Creek-stage volcanism.

Swift Creek Stage Petrography

Set S tephras consist of cummingtonite- and hornblende-bearing silicic andesite and dacite (fig. 11; table 6), and all but layer Sw also contain hypersthene (Mullineaux, 1986). Analyses indicate that layer So contains about 62–63 percent SiO_2 and layer Sg about 64 percent SiO_2. Varyingly porphyritic dacite, containing 63 to 67 percent SiO_2 and containing combinations of hornblende, hypersthene, and augite, were erupted from Mount St. Helens during the period equivalent to and shortly after set S tephras and deposited as the fans described above. Though similar macroscopically, the pyroclastic fans are distinguishable on the basis of their relative proportions of phenocrysts, textural characteristics of phenocryst minerals, and systematic differences in bulk chemistry. Plagioclase and hornblende display complex zoning patterns and evidence of reheating, resorption, and reaction.

Early set J tephras, layers Js and Jy, consist of hypersthene-hornblende silicic andesite containing 62–63 percent SiO_2; and later set J tephras, layers Jb and Jg, of hypersthene-hornblende andesite containing 58–61 percent SiO_2 (Mullineaux, 1996; Smith and Leeman, 1987). The youngest and most widespread set J tephra, layer Jg, also contains augite. No lava domes or flows are known to be associated with set J tephra; however, a dacite lava flow adjacent to, but clearly younger than, the Crescent Ridge dome may be similar in age to set J.

Some Swift Creek-stage dacite contains reacted cummingtonite or augite. Complexly sieve-textured plagioclase with thin overgrowth rims is common in tephra layer Jg, much more so than in any set S-related Swift Creek rocks described to date. Complexly zoned hornblende is also common. Coarse-grained inclusions with cumulate or plutonic textures are locally common in rocks of the Crescent Ridge and Cedar Flats fans but generally smaller and less conspicuous than in Spirit Lake-stage rocks. Inclusions exhibiting quench texture are absent in Swift Creek-stage rocks. Although no temperature data are available, the presence of cummingtonite in early Swift Creek-stage rocks suggests that the magmas may have evolved from relatively cool and wet to relatively hot and dry (Geschwind and Rutherford, 1992).

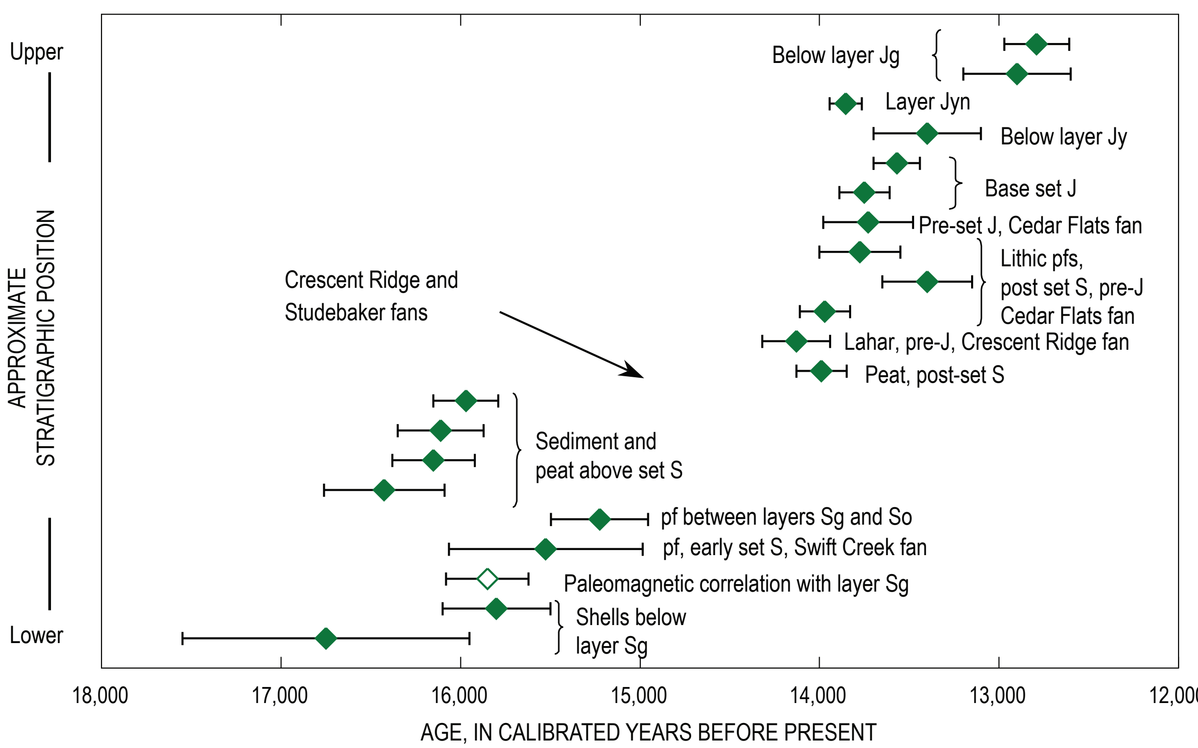

Figure 10. Dated samples for the Swift Creek stage of Mount St. Helens' eruptive history, showing ages and analytical (1σ) errors. Arranged in approximate stratigraphic order; direct stratigraphic relations do not exist or are unknown for some samples and deposits. Radiocarbon ages in calibrated years before 1950 C.E. The Swift Creek stage lasted from about 16 ka to possibly as late as about 12.8 ka. See table 3 and text for data and references. Same symbols and error bars as in figure 5, except open symbol, which represents estimated age for tephra layer Sg on the basis of correlation of radiocarbon ages with Fish Lake and Mono Lake paleomagnetic records.

Summary of Swift Creek-Stage Volcanism

Volcanism was intense during the relatively short Swift Creek stage, from about 16.0 to about 12.8 ka. Eruptions during this stage were dominated by the extrusion of dacite domes and the generation of lithic pyroclastic flows derived from them. Lithic pyroclastic-flow deposits were extensively reworked in the Pine Creek drainage, and two widespread tephra sets were erupted: set S before most of the dome building and set J after the dome building. The composition and lithology of Swift Creek-stage dacite vary little, but set J tephras are andesitic. At the end of the Swift Creek stage, Mount St. Helens consisted of a cluster of dacite domes with a summit altitude as high as about 2,100 m. Thick sequences of fragmental deposits filled the drainages of the mountain from Studebaker Creek south around to Pine Creek. Additional fans were probably emplaced on the north flank but, if so, have been buried by younger deposits. No eruptions are known between about 12.8 ka and the beginning of the Spirit Lake stage at about 3.9 ka (Crandell, 1987; Mullineaux, 1996).

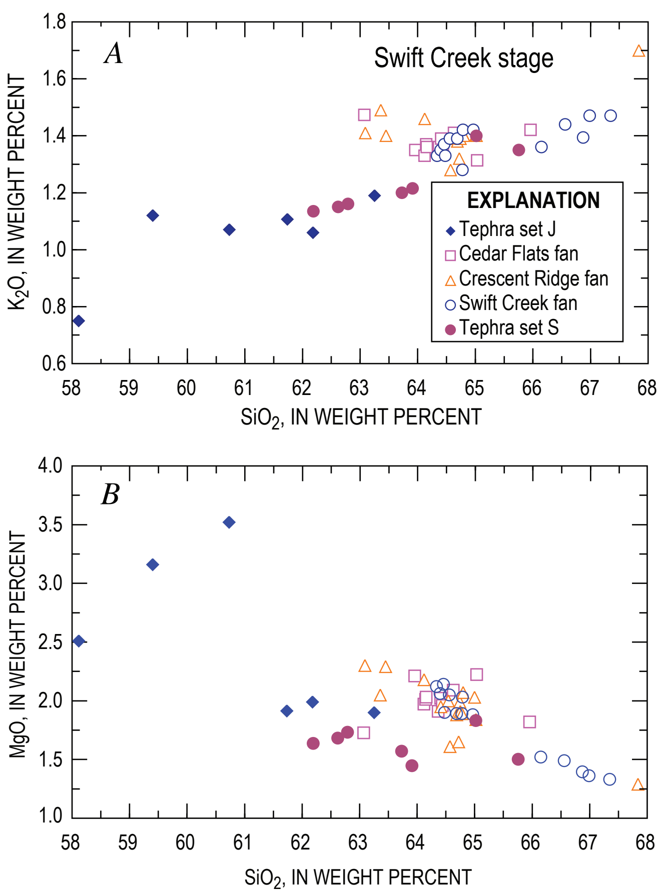

Figure 11. Silica-variation diagrams for Swift Creek-stage rocks from the Mount St. Helens area (figs. 2, 3). Samples are mostly U.S. Geological Survey analyses but include some analyses compiled from published reports (Halliday and others, 1983; Crandell, 1987; Smith and Leeman, 1987; Mullineaux, 1996; Hausback, 2000). *A*, K_2O versus SiO_2. *B*, MgO versus SiO_2.

Spirit Lake Stage

The Spirit Lake stage (3.9–0 ka), which includes the youngest and most complex part of the eruptive history of Mount St. Helens, has been described in several reports, particularly those by Hoblitt and others (1980) and Mullineaux and Crandell (1981), and so only a brief summary is given here. The excellent preservation of deposits, abundance of radiocarbon ages (Crandell and others, 1981; Hausback and Swanson, 1990), tree-ring chronology (Yamaguchi, 1983, 1985; Yamaguchi and Lawrence, 1993; Yamaguchi and Hoblitt, 1995; Yamaguchi and others, 1990) and paleomagnetic work (Hagstrum and others, 2002) have elucidated considerable detail for this period. Although volcanism was intermittent, with hiatuses of a few to about 600 years, at the scale of our knowledge of other stages the Spirit Lake stage appears continuous. The Spirit Lake stage is divided into seven eruptive periods (fig. 1): the Smith Creek (3.9–3.3 ka), Pine Creek (3–2.5 ka), Castle Creek (2.2–1.9 ka), Sugar Bowl (1,200–1,150 yr B.P.), Kalama (1479–1750 C.E.), Goat Rocks (1800–1857 C.E.), and Modern (1980–present) (data and terminology of Mullineaux, 1996; slightly modified by Clynne and others, 2004; Clynne and others, 2005). Volcanism during the Spirit Lake stage is dominated by dacite, as were earlier stages, but various compositions from basalt to high-silica dacite have also been erupted (fig. 7). Basalt and basaltic andesite dominated during the Castle Creek period, andesite was erupted during the Pine Creek and Kalama periods, and basaltic to andesitic magmatic inclusions sparsely occur in some dacites of the Pine Creek, Sugar Bowl, and Kalama periods.

The bulk of the pre-1980 edifice of Mount St. Helens above about 1,800-m altitude was constructed during the Spirit Lake stage. During the Smith Creek period, Mount St. Helens was highly explosive and erupted mostly tephra and pyroclastic flows, but at least one lava dome was also emplaced, and large lahars swept down the North Fork of the Toutle River to at least the Columbia River. During the Pine Creek period, Mount St. Helens erupted at least three dacite domes, and two large fans of lithic dacite were deposited by lithic pyroclastic flows and lahars, one in the Pine Creek and Swift Creek drainages and another in the Studebaker and Castle Creek drainages. During the late Pine Creek period, Mount St. Helens erupted andesite and basaltic andesite lava flows; then, after a short hiatus, volcanism resumed. During the Castle Creek period, Mount St. Helens erupted dacite, andesite, and basalt as tephra, pyroclastic flows, and lava domes and flows. During the Pine Creek and Castle Creek periods, Mount St. Helens gained much of its cone shape, and by their end, it had attained an altitude of about 2,450 m. During the Sugar Bowl period, three dacitic lava domes were emplaced, and a small lateral blast and tephra layer were erupted. The early Kalama period was initiated by two large tephra eruptions and followed by the growth of dacite lava domes and pumiceous and lithic pyroclastic flows; the middle Kalama period was dominated by eruption of andesite lava flows; and during the

Table 6. Composition of representative of Swift Creek-stage rocks.

[All samples analyzed at the U.S. Geological Survey laboratory in Denver, Colo.; analysts, David Siems and Joseph E. Taggart, Jr. All values in weight percent, recalculated to 100 weight percent on an anhydrous basis, with Fe_2O_3 = 0.2 total Fe, analyzed as Fe_2O_3. LOI, loss on ignition (in percent). Samples are coded to stratigraphic units as follows: cd, Crescent Ridge dome; cff, Cedar Flats fan; csf, Crescent Ridge fan; J, layer Jg pumice; S, set S pumice; swf, Swift Creek fan.]

Sample -------	**SC98-201**	**SC03-573**	**SC03-583**	**SC03-587A**	**W95-84**	**W94-32**
Unit-----------	**Jg**	**cff**	**cff**	**cff**	**cd**	**csf**
Latitude N ----	**46°11.4′**	**46°04.53′**	**46°04.45′**	**46°09.92′**	**46°12.04′**	**46°11.47′**
Longitude W--	**122°14.1′**	**122°00.25′**	**122°00.07′**	**122°05.51′**	**122°12.73′**	**122°13.85′**
Major-element analyses, weight percent						
SiO_2	59.40	64.63	64.44	63.96	64.41	64.75
Al_2O_3	19.02	17.32	17.59	17.33	17.46	17.39
Fe_2O_3	1.26	0.90	0.91	0.97	0.95	0.91
FeO	4.54	3.23	3.27	3.50	3.40	3.29
MgO	3.16	2.09	1.96	2.21	1.95	1.91
CaO	5.94	4.98	4.91	5.13	4.97	4.78
Na_2O	4.29	4.54	4.64	4.55	4.58	4.65
K_2O	1.12	1.41	1.34	1.35	1.36	1.40
TiO_2	0.93	0.63	0.63	0.71	0.67	0.63
P_2O_5	0.25	0.19	0.22	0.22	0.18	0.20
MnO	0.10	0.07	0.08	0.08	0.08	0.08
LOI	2.73	0.20	0.01	0.15	0.09	0.14
FeO*/MgO	1.79	1.93	2.09	1.98	2.18	2.16
Sample -------	**W94-72B**	**W01-211**	**SC98-270A**	**SC98-266**	**SC98-269**	**SC03-587B**
Unit-----------	**csf**	**swf**	**swf**	**swf**	**swf**	**S**
Latitude N ----	**46°12.81′**	**46°07.79′**	**46°05.64′**	**46°07.21′**	**46°07.23′**	**46°09.92′**
Longitude W--	**122°14.13′**	**122°12.02′**	**122°13.36′**	**122°12.08′**	**122°12.35′**	**122°05.51′**
Major-element analyses, weight percent						
SiO_2	65.02	64.46	64.69	64.97	66.99	65.76
Al_2O_3	17.41	17.48	17.65	17.37	17.14	18.12
Fe_2O_3	0.87	0.90	0.91	0.90	0.75	0.81
FeO	3.15	3.24	3.28	3.23	2.72	2.93
MgO	1.84	2.14	1.89	1.88	1.36	1.50
CaO	4.90	4.98	4.80	4.73	4.09	4.17
Na_2O	4.57	4.54	4.52	4.63	4.74	4.52
K_2O	1.40	1.37	1.39	1.42	1.47	1.35
TiO_2	0.60	0.63	0.64	0.62	0.50	0.57
P_2O_5	0.17	0.19	0.16	0.17	0.15	0.21
MnO	0.07	0.07	0.08	0.08	0.07	0.07
LOI	0.96	0.55	0.20	0.06	0.15	3.58
FeO*/MgO	2.14	1.89	2.17	2.14	2.49	2.44

late Kalama period, a large dome was emplaced at the summit of the volcano. Overall, during the Kalama period, lava flows and a summit dome added about 500 m height to the volcano and gave Mount St. Helens its pre-1980 form. During the Goat Rocks period, a tephra layer, lava flow, and a dome and small lithic pyroclastic fan were emplaced.

Implications of Older Rocks for the Mount St. Helens Magmatic System

Although only limited data are available to characterize the magmatic system of Mount St. Helens before the Spirit Lake stage, a few generalizations are possible. On the basis of the data discussed above, we infer that the general interpretations of Smith and Leeman (1987, 1993) that were derived primarily from their study of the Spirit Lake stage are generally applicable to the earlier stages. Dacite at Mount St. Helens probably originates by melting of mafic rocks in the lower crust (Smith and Leeman, 1987), and andesite is the result of mixing between dacite and basalt derived from the mantle (Smith and Leeman, 1993). The more detailed mixing model of Pallister and others (1992) for the Kalama period is probably applicable to other periods of the Spirit Lake stage. Disaggregation of the abundant coarse-grained inclusions in many Mount St. Helens dacites and andesites are a complicating factor for interpreting these rocks (Cooper and Reid, 2003).

Hopson and Melson (1990) recognized similarities in the composition of Mount St. Helens rocks that were repeated over time, and they introduced the concept of compositional cycles. They noted a tendency for eruptions early in a cycle to be highly explosive and the magma to contain cummingtonite and (or) quartz plus biotite. They inferred that the magma is relatively cool and water rich at the beginning of a cycle. As the cycle proceeds, the magma becomes hotter and less water rich, eruptions less explosive, and the mafic phenocrysts dominated by hornblende and hypersthene. The volcano tends to produce dacite that varies only slightly lithologically over a period of decades to centuries, probably indicating replenishment of the shallow magma chamber with hotter and dryer magma from deeper in the magmatic system. Cycles end with effusive eruptions of relatively mafic composition containing an anhydrous mineral assemblage of hypersthene, augite, and, sporadically, olivine. Hopson and Melson (1990) attributed the cycles to establishment of a compositional gradient in the magmatic system during repose of the volcano, eruption of part of the system, and reestablishment of the compositional gradient during the following repose.

Hopson and Melson's compositional-cycle concept, which was developed before any comprehensive understanding of the eruptive history of Mount St. Helens, fails to explain many details of this history. These details are probably better explained by the occasional interaction of a fundamentally dacitic magmatic system with basalt from the mantle. Nevertheless, evidence suggests that volatile enrichment of the shallow magmatic system from below plays a role in the evolution of Mount St. Helens magmas.

Compositional cycles as envisioned by Hopson and Melson (1990) for the Spirit Lake stage were probably absent during the Ape Canyon stage. The common presence of biotite and quartz during the Ape Canyon stage indicates that early Mount St. Helens magmas were generally cooler and wetter than those later in its eruptive history. Successive eruptive units vary considerably petrographically, and equilibrium phenocryst textures suggest probably much less interaction between magma batches, possibly because recharge and eruptions were more intermittent. The volume erupted per unit of time was smaller and the magmatic system less integrated during the Ape Canyon stage, especially before about 50 ka. However, the detailed stratigraphy of the Ape Canyon stage is poorly known, and the incomplete preservation of Ape Canyon-stage deposits makes recognition of compositional cycles difficult.

By the Cougar stage, the magmatic system was beginning to resemble that of the present day. At times during the Cougar stage, Mount St. Helen erupted cool and wet magmas containing cummingtonite, although most Cougar-stage rocks lack cummingtonite, biotite, or quartz, are less crystalline than most Ape Canyon-stage rocks, and probably represent hotter, less evolved magma. Although the magmatic system was still primarily dacitic, more interaction occurred between magma batches, and the volcano was probably more continually active than during the Ape Canyon stage. Sequences of pumiceous pyroclastic-flow deposits as thick and widespread as those emplaced in Cougar time have not been erupted since. The Cougar stage probably culminated with eruption of the voluminous andesite of Swift Creek, a mixed-magma lava flow.

The Swift Creek stage may be the first well-developed magmatic cycle at Mount St. Helens. The thin weathering zone between the Cougar and Swift Creek stages and the return to cummingtonite-bearing magma suggests a short hiatus between the stages. After an initial explosive phase, the Swift Creek stage was primarily a period of dacite dome building. During this period, the volcano erupted dacite with decreasing chemical variation and an increasingly anhydrous mafic phenocryst assemblage. Complex zoning of plagioclase and hornblende phenocrysts and evidence of disequilibrium conditions indicate that interaction between dacitic magma batches was extensive. These features suggest cryptic interaction of the Swift Creek dacitic magma with a hotter, probably more mafic magma as the Swift Creek stage progressed. The Swift Creek stage ended with the eruption of set J tephras, which are sparsely porphyritic and andesitic and contain resorbed phenocrysts, indicating interaction with hot or mafic magma.

During the earlier stages, the Mount St. Helens magmatic system erupted proportionately more dacite than during the Spirit Lake stage. The mafic component is subtler, possibly because it represents a smaller proportion of the total magmatic system. Alternatively, interaction with mafic magma may have occurred at a deeper level during the earlier stages than during the Spirit Lake stage. Much additional study of the petrology of rocks from the Ape Canyon, Cougar, and Swift Creek stages is needed to further evaluate the magmatic system during the early history of Mount St. Helens.

Summary

The stratigraphy and radiometric dating described herein provide more detail on the early history of Mount St. Helens than was previously available, and the petrographic and bulk-rock chemical data are useful for a preliminary evaluation of the long-term magmatic history of the volcano. Radiometric dating of rocks preserved in debris-avalanche, lahar, and glacial deposits demonstrates that Mount St. Helens has a much longer history than previously appreciated. Rocks as old as 300 ka are recognized and assigned to the Ape Canyon stage of Crandell (1987) and Mullineaux (1996). Many Ape Canyon-stage rocks are recognized by the presence of quartz and (or) biotite but are chemically similar to younger Mount St. Helens dacite.

During the Cougar and Swift Creek stages, the eruptive style of Mount St. Helens changed from intermittent dacitic activity of the Ape Canyon stage to the episodic and compositionally varying activity of the Spirit Lake stage. Significant eruptive events of the Cougar stage included dacite dome building, removal of part of the edifice by a debris avalanche, and emplacement of large-volume pyroclastic flows and an andesite lava flow. The Swift Creek stage was relatively short lived and dominated by the construction of dacite domes on the edifice and fans of fragmental material on the flanks of the volcano. Preliminary petrographic analysis of Cougar- and Swift Creek-stage rocks suggests that Cougar-stage rocks resemble Ape Canyon-stage rocks, whereas Swift Creek-stage rocks are more like those of the Spirit Lake stage. These characteristics indicate that the volcano's magmatic system has evolved from relatively simple to more complex as the volcano matured and that interaction between dacitic magma batches with more mafic magma increased from the Ape Canyon to Spirit Lake stages. Further work may allow us to subdivide the history of the Ape Canyon stage and will clarify the magma processes active during the Ape Canyon, Cougar, and Swift Creek stages.

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Appendix 1. $^{40}Ar/^{39}Ar$ Analyses of Mount St. Helens Rocks

[This appendix appears only in the digital versions of this work—in the DVD-ROM that accompanies the printed volume and as a separate file accompanying this chapter on the Web at: http://pubs.usgs.gov/pp/1750.]

Complete incremental-heating, gas extraction, and radiometric age data from 17 experiments on 16 rock samples are tabulated in nine worksheets of a Microsoft Excel file.