# *Isotopic and fission-track ages of volcanic and plutonic rocks and hydrothermal alteration in the Spirit Lake quadrangle and adjacent areas, southwestern Washington*

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# ISOTOPIC AND FISSION-TRACK AGES OF VOLCANIC AND PLUTONIC ROCKS AND HYDROTHERMAL ALTERATION IN THE SPIRIT LAKE QUADRANGLE AND ADJACENT AREAS, SOUTHWESTERN WASHINGTON

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This report presents age determinations obtained in support of geologic mapping of the Spirit Lake 15-minute quadrangle in southwestern Washington by the U.S. Geological Survey in cooperation with the Washington Division of Geology and Earth Resources. The geology of the area and locations of the dated samples are shown on 1:24,000-scale maps of the four constituent 7.5-minute quadrangles (see fig. 1): Spirit Lake East, Vanson Peak, Spirit Lake West, and Cowlitz Falls (Evarts and Ashley, 1993 a, b, c, d).

The Spirit Lake quadrangle is located in the Cascade Range north of Mount St. Helens (fig. 1). It is underlain by a diverse assemblage of largely subaerial volcanic and volcaniclastic rocks and shallow-level intrusive rocks of middle Tertiary age (fig. 2; Evarts and others, 1987). The volcanic rocks form an eastward-dipping sequence more than 5 km thick on the western limb of a broad, N-S trending, regional syncline. They are intruded by a large epizonal granitic body, the Spirit Lake pluton, and several satellitic stocks as well as many subvolcanic dikes, sills, and plugs. Structural disruption due to pluton emplacement or faulting is insignificant, but stratigraphic relations are complex, and fossils and lithologically distinctive marker beds are lacking. The age determinations are essential for clarifying and refining the observed geologic relationships and placing them in a regional context.

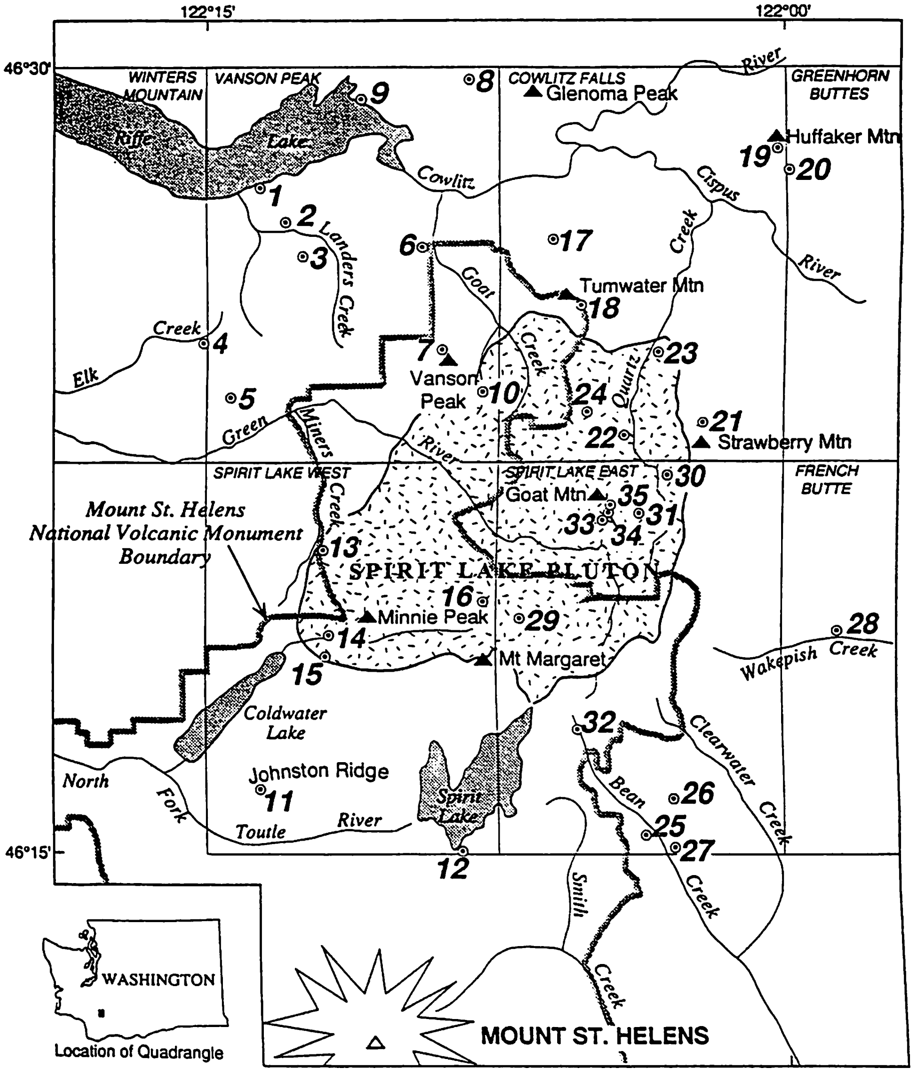



**FIGURE 1. Map of Spirit Lake 15-minute quadrangle and adjacent area showing 7½-minute quadrangles, major topographic features, and sample locations.**

We dated volcanic and intrusive rocks using K-Ar, $^{40}Ar/^{39}Ar$, fission-track and U-Pb techniques, the method employed depending chiefly on the character of available material. Most Tertiary rocks in the quadrangle display the effects of burial metamorphism under zeolite-facies conditions, and even the freshest samples typically show minor replacement of glass by

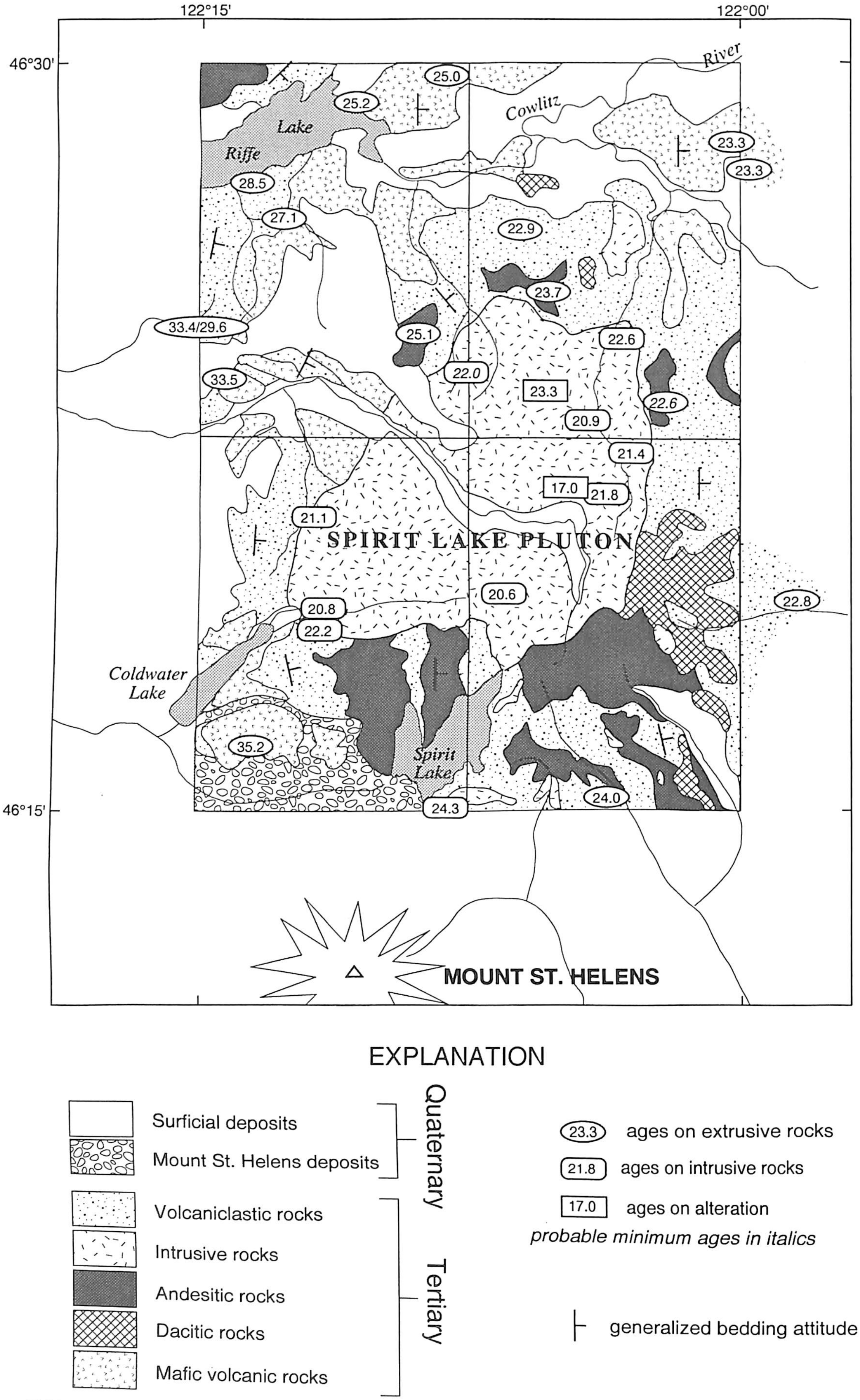



**FIGURE 2.** Simplified geologic map of the Spirit Lake 15-minute quadrangle showing preferred ages of dated samples (excluding hydrothermally altered rocks).

smectitic clay minerals. Because of this alteration, we consider K-Ar whole-rock ages suspect, and worked mostly with separates of unaltered igneous minerals. Plagioclase is the only primary potassium-bearing mineral commonly found in the middle Tertiary extrusive rocks of the area. Hornblende was found in only one extrusive rock in the quadrangle, and biotite and sanidine are absent. Attempts to extract zircon from silicic lavas and tuffs proved fruitless. Hornblende, biotite, and zircon are present in some coarse-grained intrusive rocks of the area, particularly the Spirit Lake pluton, and were dated by appropriate methods where available. Locations of samples dated for this study are shown on figure 1. Responsibility for the age determinations reported in the paper are as follows: conventional K-Ar ages—J. G. Smith and L. B. Gray; $^{40}Ar/^{39}Ar$ incremental heating and laser-fusion ages—L. B. Gray; $^{40}Ar/^{39}Ar$ laser incremental heating ages—B. D. Turrin; Fission-track ages—R. C. Evarts; U-Pb age—R. M. Tosdal.

## ANALYTICAL PROCEDURES

Mineral separates were prepared using standard density and magnetic separation procedures, followed in most cases by hand picking to obtain greater than 99% purity. Most of the plagioclase samples were treated with 5% HF and 14% $HNO_3$ to remove minor adhering glass and alteration products (chiefly zeolites and clay minerals). Hornblende separates were treated with warm dilute HCl to remove secondary alteration minerals. For the whole-rock K-Ar determinations, Fe-Ti oxides and pyroxenes were removed from crushed material (between 100- and 150-mesh) by sinking in methylene iodide (2.9 g/cm$^3$) in order to concentrate the potassium-bearing phases feldspar and glass. The residue was treated with 14% $HNO_3$ followed in some cases by treatment with 5% HF.

### K-Ar age determinations

Most of our whole-rock, plagioclase, hornblende, and biotite samples were dated by the conventional K-Ar technique (Dalrymple and Lanphere, 1969) at U.S.G.S. laboratories in Menlo Park, California. Argon extractions and isotopic analyses were done by standard isotope-dilution procedures using either a 60° sector, 15.2-cm radius Nier-type mass spectrometer or a multicollector mass spectrometer (Stacey and others, 1981), both operated in the static mode. Potassium was determined on representative splits by flame photometry using lithium metaborate flux fusion, the lithium serving as an internal standard (Ingamells, 1970). Physical constants used in the age calculations are: $^{40}K/K_{total} = 1.167 \times 10^{-4}$; $\lambda_\varepsilon+\lambda'_\varepsilon = 0.581 \times 10^{-10}$ yr$^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10}$ yr$^{-1}$, (Steiger and Jäger, 1977). Assigned errors are estimates of analytical precision at one standard deviation, calculated as discussed in Cox and Dalrymple (1967). For samples with replicate Ar analyses, we calculated weighted mean ages, with weighting proportional to the inverse of the variance for each analysis (Taylor, 1982).

### $^{40}Ar/^{39}Ar$ age determinations

$^{40}Ar/^{39}Ar$ age determinations were obtained by three techniques: standard induction-furnace incremental heating, laser-fusion, and laser incremental heating. Samples and appropriate mineral-standard flux monitors were irradiated with fast neutrons to produce the reaction $^{39}K(n,p)^{39}Ar$ (Dalrymple and Lanphere, 1971; Dalrymple and others, 1981) in the USGS. TRIGA reactor (Denver, Colorado) or the Los Alamos (New Mexico) National Laboratory Omega West reactor. For irradiation in the TRIGA reactor, the samples were wrapped in Al-foil packets and encapsulated in quartz tubes. The sample package was placed in a 3-cm diameter aluminum tube and irradiated in the central thimble of the reactor core for 10 hours at 1 MW. For irradiation in the Omega West reactor, samples were encapsulated in aluminum cups and placed in a cadmium-lined, 2.5-cm diameter, aluminum tube and irradiated with fast neutrons for 2 hours at 8 MW in the hydraulic rabbit. The ages were calculated from the $^{40}Ar/^{39}Ar$ ratio after correcting for contamination by atmospheric Ar and for interfering K- and Ca-derived Ar isotopes. (Brereton, 1970; Dalrymple and Lanphere, 1971; Dalrymple and others, 1981). Assigned errors are estimates of analytical precision at one standard deviation, calculated using standard error propagation methods as discussed in Taylor (1982) and Dalrymple and others (1981).

#### *$^{40}Ar/^{39}Ar$ induction-furnace incremental heating analyses*

Incremental heating experiments (table 1) were done using a conventional argon extraction line with induction heating as described in Dalrymple and Lanphere (1969). For each heating step the sample was held at temperature for 30 minutes; temperatures were estimated using an optical pyrometer. Argon measurements were made using the multicollector mass spectrometer (Stacey and others, 1981). Data were reduced as both spectra and isochrons as described by Dalrymple and others (1987) using criteria recommended by Lanphere and Dalrymple (1978) and modified by Pringle (1993).

**TABLE 1. $^{40}Ar/^{39}Ar$ incremental heating analytical data, Spirit Lake quadrangle and vicinity, Washington.**

| Temp. | $\%^{39}Ar$ released | $^{40}Ar/^{39}Ar$ | $^{37}Ar/^{39}Ar$ | $^{36}Ar/^{39}Ar$ | Moles $^{40}Ar$ ($\times 10^{-13}$) | $\%^{40}Ar^*$ | Age (Ma) ± 1σ |
|---|---|---|---|---|---|---|---|
| ***83FB-V06 (plagioclase, ash-flow tuff)*** | | | | | | | |
| *550** | *6.2* | | | | | | |
| 700 | 28.0 | 12.3617 | 16.4443 | 0.0254 | 30.70 | 49.5 | 22.64 ± 0.31 |
| 810 | 23.2 | 11.1527 | 15.8665 | 0.0210 | 25.69 | 55.4 | 22.84 ± 0.33 |
| 925 | 22.1 | 12.2180 | 15.4081 | 0.0244 | 24.55 | 50.9 | 22.97 ± 0.35 |
| *1060* | *10.8* | *13.0824* | *13.0098* | *0.0285* | *10.98* | 43.4 | *20.95 ± 0.40* |
| *1300* | *9.6* | *13.8292* | *13.5320* | *0.0309* | *9.88* | 41.5 | *21.20 ± 0.43* |
| *J* = 0.00204 ± 0.00001[1] | | | | | | **Plateau age:** | **22.78 ± 0.19 Ma** |
| Isochron age: 23.26 ± 1.75 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 288.9 ± 24.3 | | | MSWD: 0.5752 |
| Inverse isochron age: 23.26 ± 1.68 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 289.0 ± 23.36 | | | MSWD: 0.6377 |
| ***S78-D5-E18A (plagioclase, andesite sill)*** | | | | | | | |
| *550* | *4.6* | *21371.1* | *18.3536* | *7.0455* | *35.45* | *2.4* | *182.7 ± 79.0* |
| 700 | 12.9 | 24.9156 | 23.5548 | 0.0681 | 12.86 | 26.5 | 24.55 ± 1.21 |
| 810 | 31.5 | 11.7563 | 22.8700 | 0.0229 | 32.3 | 57.6 | 25.15 ± 0.50 |
| 925 | 34.6 | 8.8233 | 23.3393 | 0.0142 | 33.6 | 72.9 | 23.88 ± 0.45 |
| 1050 | 9.4 | 15.3999 | 21.6586 | 0.0378 | 8.37 | 38.5 | 21.98 ± 1.66 |
| 1300 | 7.1 | 16.8871 | 20.4060 | 0.0423 | 6.33 | 35.3 | 22.11 ± 2.17 |
| *J* = 0.00204 ± 0.00001[1] | | | | | | **Plateau age:** | **24.32 ± 0.34 Ma** |
| Isochron age: 24.17 ± 1.20 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 296.4 ± 15.0 | | | MSWD: 2.5799 |
| Inverse isochron age: 24.24 ± 1.18 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 296.84 ± 14.74 | | | MSWD: 2.5025 |
| ***S78-D5-M88A (whole-rock, andesite dike)*** | | | | | | | |
| 550 | 32.5 | 12.9958 | 0.4433 | 0.0402 | 12.32 | 8.7 | 9.98 ± 0.51 |
| 600 | 15.0 | 9.9651 | 0.9544 | 0.0296 | 6.40 | 12.8 | 11.28 ± 0.77 |
| 650 | 9.1 | 9.9481 | 1.6641 | 0.0292 | 4.29 | 14.2 | 12.44 ± 0.67 |
| 700 | 10.0 | 8.9587 | 2.7996 | 0.0256 | 5.32 | 17.8 | 14.04 ± 1.1 |
| 760 | 8.3 | 9.0308 | 3.6295 | 0.0256 | 4.82 | 19.1 | 15.20 ± 1.31 |
| 830 | 7.4 | 8.8914 | 3.5442 | 0.0254 | 4.06 | 18.4 | 14.46 ± 1.47 |
| 925 | 5.4 | 8.5053 | 3.4355 | 0.0238 | 3.11 | 20.2 | 15.18 ± 1.31 |
| 1050 | 7.0 | 8.1213 | 6.2404 | 0.0224 | 4.61 | 24.3 | 17.43 ± 1.56 |
| FUSE | 5.3 | 8.0088 | 11.7568 | 0.0224 | 4.12 | 28.81 | 20.45 ± 2.04 |
| *J* = 0.00490 ± 0.00001[2] | | | | | | **Integrated age:** | **12.92 ± 0.36 Ma** |

Data shown in italics not used in age calculation.

*Overflowed spectrometer; this step used only for determination of $\%^{39}Ar$ released.

Flux monitor was internal-laboratory standard SB-3 biotite, separated from same rock as SB-2 (Dalrymple and others, 1981), with an age of 162.9 Ma (M. A. Lanphere, oral commun., 1993).

[1]Reactor correction factors for interfering isotopes: $^{39}Ca/^{37}Ca$, 0.00067; $^{36}Ca/^{37}Ca$, 0.000264; $^{40}K/^{39}K$, 0.0057.

[2]Reactor correction factors for interfering isotopes: $^{39}Ca/^{37}Ca$, 0.0007; $^{36}Ca/^{37}Ca$, 0.000278; $^{40}K/^{39}K$, 0.0332.

### *$^{40}Ar/^{39}Ar$ laser-heating analyses*

$^{40}Ar/^{39}Ar$ laser-fusion analyses (table 2) were done at USGS. in Menlo Park, Calif., and laser-heating incremental heating experiments (table 3) were conducted at the Institute of Human Origins, Geochronology Center (I.H.O.G.C.), Berkeley, California. Both facilities employ a continuous Ar-ion laser with principal wavelengths at 488 and 514 nm for sample heating and fusion. The U.S.G.S. system consists of an automated $^{40}Ar/^{39}Ar$ laser-fusion micro-extraction system in-line with a Mass Analyzer Products MAP 216, 90° sector mass spectrometer of 15 cm radius with a Baur-Signer ion source (Dalrymple and Duffield, 1988; Dalrymple, 1989). The I.H.O.G.C. system consists of an automated $^{40}Ar/^{39}Ar$ laser-fusion micro-extraction system in-line with a Mass Analyzer Products MAP 215 90° sector extended geometry mass spectrometer with Nier ion source and an effective radius of 21.5 cm (Turrin and others, 1991). Both spectrometers were operated in the static mode, using automated data-collection procedures.

Irradiated samples were transferred into the Ar-extraction system for overnight bake-out at 250°C. Heating and fusion of the samples was induced by a 6-W continuous Ar-ion laser beam focused to a 2-3 mm spot, applied for 30-60 seconds. The released gases were scrubbed of reactive gasses such as $H_2$, $CO_2$, CO, and $N_2$ by exposure to a Zr-Fe-V alloy getter and, at the Menlo Park Laboratory, an additional Zr-Al getter (Dalrymple, 1989; Turrin and others, 1991). The remaining inert gases, principally Ar, were then admitted to the mass spectrometer, and the argon-isotopic ratios determined.

$^{40}Ar/^{39}Ar$ laser incremental heating data were reduced in the same manner as the induction-furnace incremental heating data. Ages from laser fusions are weighted means where the individual analyses are weighted by the inverse of their respective variances; the reported errors are calculated as described in Taylor (1982). We also provide the MSWD as a measure of the dispersion of the data. The MSWD was calculated by applying the incremental heating isochron-reduction procedure of Dalrymple and others (1987) using the individual laser-fusion results instead of incremental heating steps.

### Fission-track age determinations

Fission-track ages were determined by the external detector method for zircons and the population method for apatites (Naeser, 1978). Hand-picked euhedral zircon crystals were mounted in 20-mil FEP Teflon™ on a hot plate at 350°C, ground with wet #600 and #400 silicon carbide abrasive paper, and polished using 6-μ, 1-μ, and 1/4-μ diamond polishing compound. They were then etched for 12 to 13 hours in NaOH-KOH eutectic melt in a Teflon™ container placed in a furnace kept at 235°C. The mounts were covered with external detectors of low-U muscovite and stacked in aluminum irradiation tubes along with four flux monitors consisting of National Bureau of Standards (NBS) SRM 612 fission-track glass-standard wafers (U content of 37.88 ± 0.08 ppm; $^{235}U$ isotopic abundance = 0.2392 atom percent) that had previously been calibrated against identical glasses (NBS SRM 962) irradiated under known fluence by NBS; the NBS Cu-foil reactor calibration was used. Pairs of the NBS glasses were placed at each end of the stack of samples in order to detect flux gradients in the reactor. The apatite mineral separates were split into two aliquots, one of which was annealed in a muffle furnace at approximately 500°C for 3 hours and wrapped in aluminum foil for irradiation. Irradiations were performed in the lazy susan facility of the USGS TRIGA reactor at nominal fluences of $10^{-15}$ thermal neutrons/cm$^{-2}$ for the zircons and $2 \times 10^{-15}$ thermal neutrons/cm$^{-2}$ for the apatites. Samples of the Fish Canyon Tuff zircon and apatite age standards (Naeser and others, 1981) were included in each irradiation package as a check on the flux determinations.

Following irradiation, the muscovite detectors were removed from the zircon and glass-standard mounts and etched in 48% HF; etch times were 15 minutes for the detectors of the zircon samples and 1 hour for the detectors held against the flux monitors. The apatites from both splits were mounted separately in epoxy and polished in the same manner as the zircon mounts. Each pair of mounts was etched together in 7% $HN0_3$ at room temperature for 23 seconds. Counting of fission tracks in the mineral samples and their detectors was performed in transmitted light under immersion oil at 1250X magnification.

The neutron flux to which the samples were exposed was determined by counting fission tracks induced in the muscovite detectors held against the NBS glass standards during the irradiations. The tracks were counted in air using a 45X fluorite objective on a Leitz Dialux™ microscope with a total magnification of 1250X. Sufficient tracks were counted to achieve precisions of close to 1%. Where the track densities indicated the presence of flux gradients in the reactor, the fluence value used for each sample was interpolated based on its position in the irradiation tube. In those cases were the differences in track densities between the ends of the tube fell within Poissonian error limits, all counts were pooled and a single fluence value was applied to all samples in the tube. Ages calculated for the Fish Canyon standards are 27.3 ± 1.3 and 27.0 ± 0.9 Ma (zircon) and 27.3 ±

**TABLE 2. $^{40}Ar/^{39}Ar$ laser-fusion analytical data, Spirit Lake quadrangle, Washington.**

| $^{40}Ar/^{39}Ar$ | $^{37}Ar/^{39}Ar$ | $^{36}Ar/^{39}Ar$ | Ca/K | Moles $^{40}Ar^{*}$ ($\times 10^{-14}$) | %$^{40}Ar^{*}$ | Age (Ma) ± 1σ |
|---|---|---|---|---|---|---|
| ***S80-A3-E32 (plagioclase, basaltic andesite)*** | | | | | | |
| **295.977* | *20.8476* | *0.09849* | *43.15* | *1.413* | *2.2* | *63.87 ± 12.3* |
| 4.0334 | 18.8554 | 0.00701 | 38.97 | 3.055 | 82.4 | 33.08 ± 0.76 |
| 4.5132 | 18.8462 | 0.00825 | 38.95 | 3.144 | 76.1 | 34.19 ± 0.79 |
| 3.9195 | 18.8503 | 0.00653 | 38.96 | 3.393 | 85.4 | 33.34 ± 0.69 |
| *J* = 0.005442 ± 0.000027 | | | | | **Weighted mean age:** | **33.51 ± 0.42 Ma** |
| Combined total-fusion age: 35.78 ± 0.93 | | | $^{40}Ar/^{36}Ar$ intercept: 355.3 ± 62.9 | | | MSWD: 0.272 |
| ***S78-B2-E49A (plagioclase, andesite)*** | | | | | | |
| **647.4668* | *31.3589* | *2.21117* | *65.38* | *-0.229* | *-0.6* | *-37.35 ± 29.0* |
| *39.2945 | 24.2924 | 0.13167 | 50.40 | 0.480 | 5.47 | 21.56 ± 8.31 |
| 5.5054 | 19.6835 | 0.01520 | 40.71 | 3.146 | 44.3 | 24.34 ± 0.77 |
| 3.4962 | 20.2442 | 0.00794 | 41.88 | 1.582 | 74.7 | 26.08 ± 0.75 |
| 2.9849 | 19.3976 | 0.00644 | 40.11 | 2.852 | 83.2 | 24.80 ± 0.66 |
| *J* = 0.005440 ± 0.000027 | | | | | **Weighted mean age:** | **25.05 ± 0.41 Ma** |
| Combined total-fusion age: 23.57 ± 1.15 | | | $^{40}Ar/^{36}Ar$ intercept: 291.0 ± 7.0 | | | MSWD: 1.306 |
| ***S80-B 1-L28 (plagioclase, basalt)*** | | | | | | |
| **4959.45* | *112.0261* | *16.81933* | *247.21* | *-0.027* | 0.0 | *-25.83 ± 665* |
| *91.887* | *83.9252* | *0.32781* | *181.50* | *0.656* | *1.3* | *12.64 ± 4.73* |
| 9.1188 | 70.9539 | 0.04027 | 152.04 | 0.494 | 26.8 | 25.28 ± 3.07 |
| 10.2595 | 69.2929 | 0.04409 | 148.31 | 0.585 | 22.7 | 24.10 ± 2.77 |
| 3.9440 | 79.7226 | 0.02533 | 171.89 | 0.445 | 59.2 | 24.29 ± 3.41 |
| 6.9743 | 69.7062 | 0.03253 | 149.24 | 0.522 | 35.8 | 25.77 ± 2.31 |
| *J* = 0.005446 ± 0.00002 | | | | | **Weighted mean age:** | **24.99 ± 1.40 Ma** |
| Combined total-fusion age: 19.85 ± 5.49 | | | $^{40}Ar/^{36}Ar$ intercept: 294.1 ± 17.4 | | | MSWD: 1.1445 |
| ***S81-A5-R48A (plagioclase, basaltic andesite)*** | | | | | | |
| 12.2961 | 29.6062 | 0.03672 | 61.65 | 1.696 | 29.3 | **36.10 ± 1.03 Ma** |
| *J* = 0.005460 ± 0.000027 | | | | | | |
| ***S77-C2-NI144 (plagioclase, basaltic andesite)*** | | | | | | |
| 2.7034 | 20.7210 | 0.00614 | 42.88 | 5.114 | 88.3 | **23.66 ± 0.57 Ma** |
| *J* = 0.005454 ± 0.000027 | | | | | | |

Data shown in italics not used in age calculation.

*Degassing steps; see text for procedures.

Flux monitor was intralaboratory standard SB-3 biotite, separated from same rock as SB-2 (Dalrymple and others, 1981), with an age of 162.9 Ma (M. A. Lanphere, oral commun. 1993).

Reactor correction factors for interfering isotopes: $^{39}Ca/^{37}Ca$, 0.000671; $^{36}Ca/^{37}Ca$, 0.000251; $^{40}K/^{39}K$, 0.0285.

**TABLE 3. $^{40}Ar/^{39}Ar$ laser incremental heating analytical data, Spirit Lake quadrangle and vicinity, Washington.**

| Power Level (W) | %$^{39}Ar$ released | $^{40}Ar/^{39}Ar$ | $^{37}Ar/^{39}Ar$ | $^{36}Ar/^{39}Ar$ | Moles$^{40}Ar^{*}$ ($\times10^{-15}$) | %$^{40}Ar^{*}$ | Age (Ma) ± 1σ |
|---|---|---|---|---|---|---|---|
| ***S79-A2-E156 (plagioclase, ash-flow tuff)*** | | | | | | | |
| *0.4* | *2.2* | *21.8157* | *0.3408* | *0.1017* | *2.43* | *-37.7* | *-21.85 ± 9.79* |
| *0.8* | *3.7* | *26.3147* | *2.3736* | *0.0930* | *2.59* | *-3.7* | *-2.58 ± 5.81* |
| *1.1* | *3.8* | *14.0788* | *7.4411* | *0.0442* | *2.65* | *11.2* | *4.18 ± 5.07* |
| 2.0 | 9.2 | 15.1955 | 10.5022 | 0.0184 | 4.02 | 69.6 | 27.91 ± 2.07 |
| 2.7 | 9.9 | 15.1318 | 12.6335 | 0.0234 | 3.49 | 60.7 | 24.30 ± 5.89 |
| 3.5 | 8.2 | 12.4536 | 12.8925 | 0.0120 | 2.96 | 79.5 | 26.19 ± 3.24 |
| 5.0 | 59.0 | 13.8707 | 11.8072 | 0.0117 | 12.1 | 81.6 | 29.89 ± 0.53 |
| *8.0* | *4.0* | *10.5478* | *11.7228* | *0.0433* | *2.22* | *-12.7* | *-3.57 ± 6.78* |
| *J* = 0.0014646 ± 0.0000013 | | | | | | **Plateau age:** | **29.64 ± 0.50 Ma** |
| Isochron age: 27.18 ± 1.78 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 381.8 ± 72.4 | | | MSWD: 7.6902 |
| Inverse isochron age: 29.64 ± 1.62 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 298.1 ± 96.1 | | | MSWD: 3.5963 |
| ***S78-B2-R46 (plagioclase, basaltic andesite)*** | | | | | | | |
| *1.0* | *21.8* | *29.1825* | *49.3446* | *0.1211* | *2.38* | *-9.7* | *-7.61 ± 7.16* |
| 2.25 | 40.9 | 16.6041 | 194.2079 | 0.0801 | 2.15 | 46.6 | 22.86 ± 3.75 |
| 2.7 | 10.0 | 9.3441 | 172.1663 | 0.0438 | 0.524 | 102.2 | 27.68 ± 53.59 |
| 3.5 | 11.6 | 9.8299 | 148.2228 | 0.0438 | 0.439 | 83.3 | 23.33 ± 12.2 |
| *4.0* | *6.4* | *11.0549* | *207.4865* | *0.2440* | *0.265* | *-409.1* | *-141.08 ± 48.55* |
| *J* = 0.0014322 ± 0.0000015 | | | | | | **Plateau age:** | **22.92 ± 3.58 Ma** |
| Isochron age: 27.29 ± 0.10 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 227.1 ± 5.3 | | | MSWD: 119.28 |
| Inverse isochron age: 25.24 ± 1.92 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 268.0 ± 23.4 | | | MSWD: 1.1246 |
| ***S81-A5-R48A (plagioclase, basaltic andesite)*** | | | | | | | |
| 1.0 | 29.6 | 483.1285 | 14.5796 | 1.5797 | 337.0 | 3.6 | 46.03 ± 12.61 |
| 1.8 | 40.2 | 29.4091 | 27.2257 | 0.0610 | 29.0 | 45.7 | 35.88 ± 0.67 |
| 2.5 | 12.3 | 14.8364 | 30.5651 | 0.0145 | 5.41 | 86.8 | 34.45 ± 0.99 |
| 2.8 | 9.3 | 14.3878 | 29.1906 | 0.0144 | 4.42 | 85.8 | 33.01 ± 2.01 |
| 3.2 | 4.8 | 13.9401 | 30.5489 | 0.0133 | 2.07 | 88.6 | 33.03 ± 5.47 |
| 8.0 | 3.7 | 14.6175 | 29.0819 | 0.0138 | 1.69 | 87.2 | 34.06 ± 3.84 |
| *J* = 0.0014610 ± 0.0000029 | | | | | | **Plateau age:** | **35.23 ± 0.52 Ma** |
| Isochron age: 33.75 ± 0.21 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 302.8 ± 2.6 | | | MSWD: 4.2899 |
| Inverse isochron age: 33.97 ± 0.28 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 302.3 ± 2.6 | | | MSWD: 2.5509 |
| ***S79-B4-I05B (hornblende, hornblende-porphyry dike)*** | | | | | | | |
| *1.0* | *8.1* | *24.6053* | *2.8157* | *0.0734* | *9.45* | *12.8* | *8.10 ± 0.38* |
| 1.8 | 36.7 | 13.5797 | 3.6495 | 0.0327 | 23.5 | 30.9 | 10.85 ± 0.65 |
| 2.5 | 34.3 | 12.5907 | 3.2560 | 0.0308 | 17.1 | 29.7 | 9.66 ± 0.15 |
| 2.8 | 7.9 | 13.4587 | 3.8682 | 0.0339 | 2.94 | 27.8 | 9.65 ± 0.63 |
| 3.2 | 6.4 | 13.2788 | 4.4875 | 0.0344 | 2.75 | 26.0 | 8.91 ± 0.76 |
| 8.0 | 6.6 | 12.4798 | 6.4654 | 0.0303 | 3.57 | 32.2 | 10.40 ± 0.71 |
| *J* = 0.0014322 ± 0.0000015 | | | | | | **Plateau age:** | **9.72 ± 0.14 Ma** |
| Isochron age: 7.91 ± 4.41 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 318.5 ± 56.6 | | | MSWD: 1.7183 |
| Inverse isochron age: 6.97 ± 2.11 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 330.7 ± 62.0 | | | MSWD: 1.8549 |

*continued*

**TABLE 3. $^{40}Ar/^{39}Ar$ laser incremental heating analytical data, Spirit Lake quadrangle and vicinity, Washington *(continued).***

| Power Level (W) | %$^{39}Ar$ released | $^{40}Ar/^{39}Ar$ | $^{37}Ar/^{39}Ar$ | $^{36}Ar/^{39}Ar$ | Moles$^{40}Ar^{*}$ ($\times 10^{-15}$) | %$^{40}Ar^{*}$ | Age (Ma) ± 1σ |
|---|---|---|---|---|---|---|---|
| ***S78-C2-R36 (plagioclase, ash-flow tuff)*** | | | | | | | |
| *1.0* | *16.2* | *25.1089* | *1.5183* | *0.0734* | *6.19* | *14.1* | *9.15 ± 1.11* |
| 2.25 | 26.0 | 14.7837 | 6.7660 | 0.0224 | 6.70 | 58.8 | 22.40 ± 0.76 |
| 2.7 | 5.6 | 9.3334 | 8.9777 | 0.0123 | 1.39 | 68.5 | 16.53 ± 8.03 |
| 3.5 | 7.5 | 10.9879 | 8.4960 | 0.0870 | 1.43 | 82.5 | 23.40 ± 2.61 |
| 4.0 | 2.6 | 6.2801 | 8.0877 | 0.0496 | 0.807 | 86.5 | 14.05 ± 7.56 |
| 4.5 | 3.4 | 10.4483 | 8.5319 | 0.0133 | 0.970 | 68.6 | 18.54 ± 9.28 |
| 8.0 | 38.7 | 14.7081 | 8.5524 | 0.0211 | 6.77 | 62.1 | 23.57 ± 0.74 |
| *J* = 0.0014322 ± 0.0000015 | | | | | | **Plateau age:** | **22.94 ± 0.52 Ma** |
| Isochron age: 19.14 ± 2.56 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 370.0 ± 52.5 | | | MSWD: 1.9177 |
| Inverse isochron age: 18.17 ± 2.01 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 394.9 ± 50.9 | | | MSWD: 1.8886 |
| ***S77-C2-N144 (plagioclase, basaltic andesite)*** | | | | | | | |
| 1.0 | 62.4 | 571.9211 | 4.1529 | 1.8861 | 706. | 2.6 | 38.97 ± 8.17 |
| 2.25 | 40.9 | 113.475 | 15.3193 | 0.3610 | 40.2 | 7.0 | 21.10 ± 3.67 |
| 2.7 | 4.6 | 42.7987 | 14.5655 | 0.1138 | 6.07 | 24.0 | 27.15 ± 2.39 |
| 3.5 | 9.7 | 24.4428 | 19.0299 | 0.0503 | 7.77 | 45.1 | 29.22 ± 0.98 |
| 4.0 | 3.8 | 12.6395 | 19-6669 | 0.0091 | 2.06 | 90.5 | 30.31 ± 3.31 |
| 4.5 | 1.2 | ·7.9699 | 20.8461 | 0.0130 | 0.897 | 71.8 | 15.24 ± 9.9 |
| *J* = 0.0014611 ± 0.0000029 | | | | | | **Plateau age:** | **28.61 ± 0.84 Ma** |
| Isochron age: 29.35 ± 0.58 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 295.5 ± 1.6 | | | MSWD: 2.8732 |
| Inverse isochron age: 29.38 ± 0.59 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 295.4 ± 1.5 | | | MSWD: 3.0133 |
| ***S78-D5-E168A (plagioclase, andesite sill)*** | | | | | | | |
| 1.0 | 26.1 | 1252.07 | 5.8148 | 4.2000 | 181. | 0.9 | 29.39 ± 78.41 |
| 2.25 | 18.5 | 233.986 | 17.5966 | 0.7490 | 25.5 | 6.0 | 36.26 ± 8.80 |
| 2.7 | 6.5 | 75.3305 | 16.7358 | 0.2164 | 2.74 | 16.8 | 32.76 ± 125.87 |
| 3.5 | 24.7 | 21.9949 | 22.649 | 0.0431 | 3.88 | 49.9 | 28.59 ± 2.85 |
| 4.0 | 11.0 | 11.9965 | 22.2553 | 0.0060 | 0.965 | 99.6 | 31.08 ± 5.21 |
| 4.5 | 4.0 | 11.3197 | 20.3877 | 0.0108 | 0.394 | 85.5 | 25.18 ± 5.22 |
| 8.0 | 9.2 | 11.6082 | 23-6049 | 0.0087 | 0.758 | 93.4 | 28.25 ± 2.42 |
| *J* = 0.0014322 ± 0.0000015 | | | | | | **Plateau age:** | **28.61 ± 1.62 Ma** |
| Isochron age: 30.22 ± 0.04 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 245.0 ± 3.5 | | | MSWD: 935.90 |
| Inverse isochron age: 28038 ± 0.29 Ma | | | | $^{40}Ar/^{36}Ar$ intercept: 298.3 ± 3.8 | | | MSWD: 1.2230 |

Data shown in italics not used in age calculation.
Flux monitors were Fish Canyon Tuff sanidine with an age of 27.84 Ma (Kunk and others, 1985), MMhb-1 hornblende with an age of 520.4 Ma (Samson and Alexander, 1987), and an internal-laboratory sanidine standard.
Reactor correction factors for interfering isotopes: $^{39}Ca/^{37}Ca$, 0.00667; $^{36}Ca/^{37}Ca$, 0.0002582; $^{38}K/^{39}K$, 0.01077; $^{40}K/^{39}K$, 0.0008.

1.6 Ma (apatite), which compare favorably with the accepted age of 27.8 Ma (Kunk and others, 1985).

The physical constants used in the age equation are: $\lambda_f = 7.03 \times 10^{-17}$ yr$^{-1}$; $\lambda_D = 1.55125 \times 10^{-10}$ yr$^{-1}$; $^{235}\sigma = 580.2 \times 10^{-24}$ cm$^2$; $I = {}^{235}U/{}^{238}U = 7.2527 \times 10^{-3}$. Errors in the ages, shown by the ± values, represent the analytical uncertainty at one standard deviation and were calculated using the conventional method (Green, 1981) except for zircon samples S77-C3-J18 and S77-C3-N98. For these two samples, grain-to-grain differences in $\rho_s/\rho_i$ exceed those attributable solely to Poissonian variation, hence the larger errors calculated using "method B" of Green (1981) are considered more realistic. For some samples, the errors given here are smaller than those previously reported by Evarts and others (1987), which were calculated incorrectly. The stated errors are principally a function of the number of fission tracks counted and thus are much larger for the low-U apatites than for the zircons.

### U-Pb age determination

The zircon separate (nonmagnetic on a Frantz Isodynamic separator at 1.7 amps and 1° side slope) was split into coarse (>163 mm) and fine (<102 mm) fractions. Sample dissolution and separation of U and Pb by HCl exchange chemistry followed procedures modified from Krogh (1973) and Mattinson (1985). Isotopic data were measured on a Finnigan-MAT 262 multiple collector mass spectrometer at the U.S.G.S. in Menlo Park. The laboratory procedural blank Pb was determined to be 0.1 nm of $^{206}$Pb. Observed isotopic ratios collected on Faraday cups were corrected for 0.125% per unit mass fractionation based on replicate analyses of NBS 981. Uncertainties in the measured isotopic ratios are less than 0.1% for $^{208}$Pb/$^{206}$Pb and $^{207}$Pb/$^{206}$Pb, and about 2.0% for $^{206}$Pb/$^{204}$Pb. Ages were calculated using the following constants: $^{238}U/^{235}U = 137.88$; $\lambda^{235}U = 0.98485 \times 10^{-9}$ yr$^{-1}$; $\lambda^{238}U = 0.155125 \times 10^{-9}$ yr$^{-1}$. For the common Pb corrections we used the Pb isotopic compositions of feldspar in the nearby Tatoosh volcanic-plutonic complex determined by Mattinson (1977): $^{208}$Pb/$^{204}$Pb = 38.6, $^{207}$Pb/$^{204}$ = 15.57, and $^{206}$Pb/$^{204}$ = 18.9. Errors are reported to 2 standard deviations (table 4); error analysis follows Mattinson (1987).

## ANALYTICAL RESULTS

We sought to avoid the uncertainties in dating weakly metamorphosed rocks of the western Cascade Range by working chiefly with mineral separates. Unfortunately, the only mineral widely available for dating in Tertiary Cascade volcanic rocks is K-poor plagioclase ($K_2O$ contents typically below 0.3 weight percent). Although we worked only with plagioclase that appeared petrographically fresh, we found this mineral to be prone to high levels of atmospheric argon contamination; the resultant low proportion of radiogenic $^{40}$Ar ($^{40}$Ar*) - commonly less than 10 percent - translates into poor precision of the conventional K-Ar ages (Tabor and others, 1985). We attempted to improve the resolution of the dating by experimenting with several variations of the $^{40}$Ar/$^{39}$Ar method, using induction-furnace and recently developed laser-fusion techniques. In the $^{40}$Ar/$^{39}$Ar method, loosely bound atmospheric $^{40}$Ar can be driven off the sample at low temperature, thus boosting the effective radiogenic $^{40}$Ar yield and improving precision.

Two plagioclase separates and one whole-rock that gave questionable conventional K-Ar ages, owing to atmospheric $^{40}$Ar contents exceeding 97%, were analyzed with the $^{40}$Ar/$^{39}$Ar induction-furnace incremental heating system (table 1). Most of the atmospheric $^{40}$Ar in the feldspars was released during the first step (T=550°C). Subsequent steps generally gave $^{40}$Ar* yields between 30 and 60% and produced interpretable plateau ages. For the whole-rock sample, the percentage of atmospheric $^{40}$Ar decreased fairly evenly during the experiment from 91% in the first step to 72% in the highest temperature increment, but the data produced a spectrum of progressively increasing age (fig. 3c) from which we were able to extract only a minimum age.

Five plagioclase samples (table 2) were dated using the $^{40}$Ar/$^{39}$Ar laser-fusion facility (Dalrymple, 1989). This system offers two important advan-

**TABLE 4. U/Pb analytical data for S84-C3-R03 zircon**

| Fraction[1] | Weight (mg) | $^{206}$Pb* (ppm) | $^{238}$U (ppm) | Observed ratios $^{206}$Pb/$^{204}$Pb | $^{207}$Pb/$^{206}$Pb | $^{208}$Pb/$^{206}$Pb | Atomic ratios $^{206}$Pb*/$^{238}$U | $^{207}$Pb*/$^{235}$U | $^{207}$Pb*/$^{206}$Pb* | Ages ± 2σ (Ma) $^{206}$Pb*/$^{238}$U | $^{207}$Pb*/$^{235}$U | $^{207}$Pb*/$^{206}$Pb* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N>163μm | 21.6 | 1.41 | 552 | 293 | 0.0973 | 0.2433 | 0.002960 | 0.019260 | 0.047253 | 19.1±0.1 | 19.4±0.5 | 62±66 |
| N<102μm,F | 29.6 | 1.02 | 396 | 313 | 0.0934 | 0.2251 | 0.002971 | 0.019050 | 0.046504 | 19.1±0.1 | 19.1±0.5 | 19.4±65 |

[1]N-Nonmagnetic on a Franz Isodynamic separator at 1.7 amps and a 1° side slope. F, fine-grained fraction.
*Denotes radiogenic Pb.

tages over the conventional K-Ar and $^{40}Ar/^{39}Ar$ methods: the very small sample size required and the high precision achievable (Dalrymple, 1989). For our samples, less than 10 mg of sample was needed, thus hand-picking of mineral separates to obtain exceptionally pure material was feasible. The ability to rapidly analyze multiple groups of mineral grains from a single sample means that precision can be easily improved simply by increasing the number of replicate measurements (Dalrymple and Duffield, 1988).

To address the atmospheric contamination problem, we modified the normal laser-fusion procedure by heating the sample briefly (≤2 minutes) with a defocused beam to drive off loosely bound atmospheric argon. The measured isotopic composition of the gas released during these degassing steps confirmed that it was largely atmospheric. The sample was then divided into as many as four groups, depending on the amount of material available, that were each fused separately (table 2). The reported ages are weighted means calculated from all fusions (and for S78-B2-E49A, a second degassing step). In each case, dispersion of the individual fusions as shown by the (MSWD) is low, and the weighted mean is concordant with the combined total-fusion (integrated) age (table 2).

We used the $^{40}Ar/^{39}Ar$ laser incremental heating system to date nine samples, seven of which gave usable results (table 3; fig 4). This system offers the combined advantages of small required sample size and the data analysis capabilities of step-heating. However, because of the low potassium contents and young ages of the mineral samples, the absolute amount of $^{40}Ar^*$ analyzed in each step was small relative to the sensitivity of the spectrometer, which limited the precision achievable. The laser-degassing/fusion and induction-furnace techniques provided the most consistently reliable ages for our volcanic rock samples.

## GEOLOGIC RESULTS

### Volcanic and hypabyssal rocks

The new data extend and supplement the ages published by Evarts and others (1987), and require revision of some of the tentative conclusions presented in that paper. The age determinations show that the volcanic rocks of the Spirit Lake quadrangle were erupted from earliest Oligocene to earliest Miocene time, between about 36 and 23 Ma, and that intrusive and

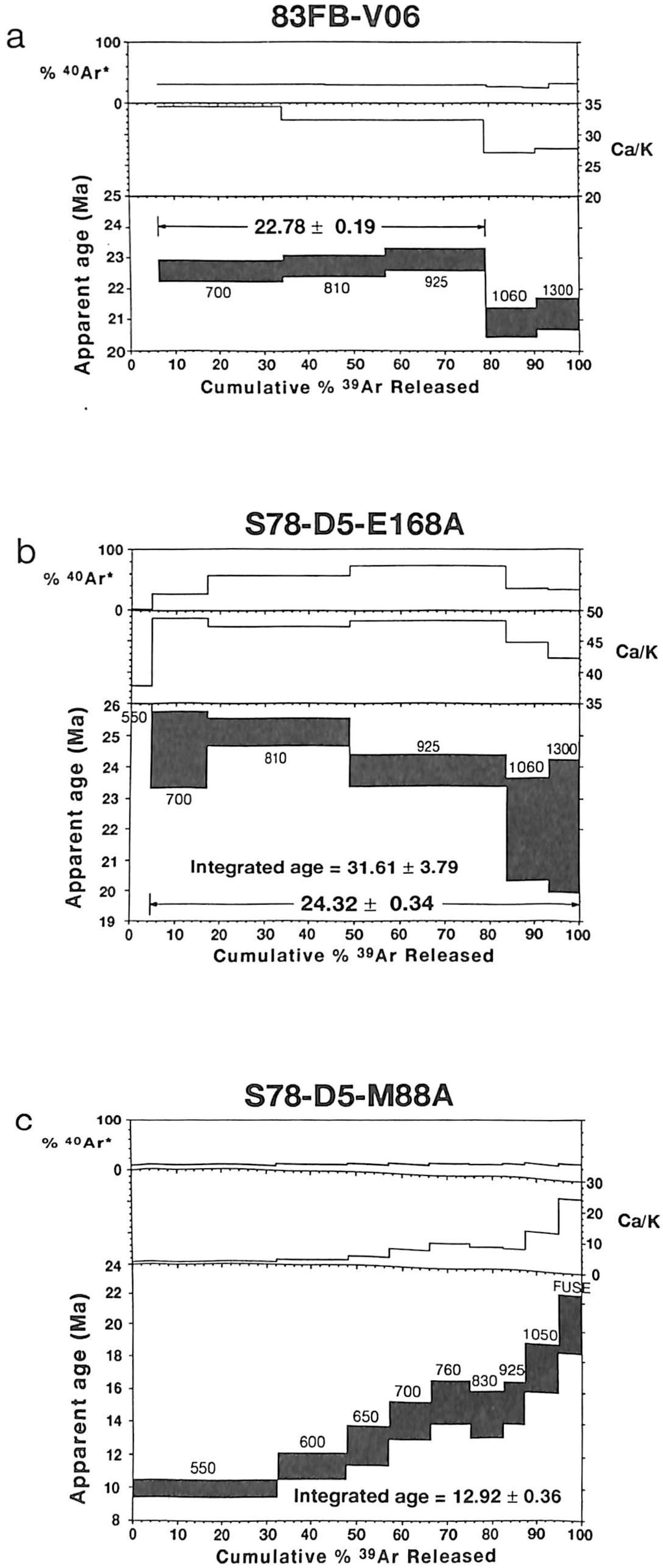
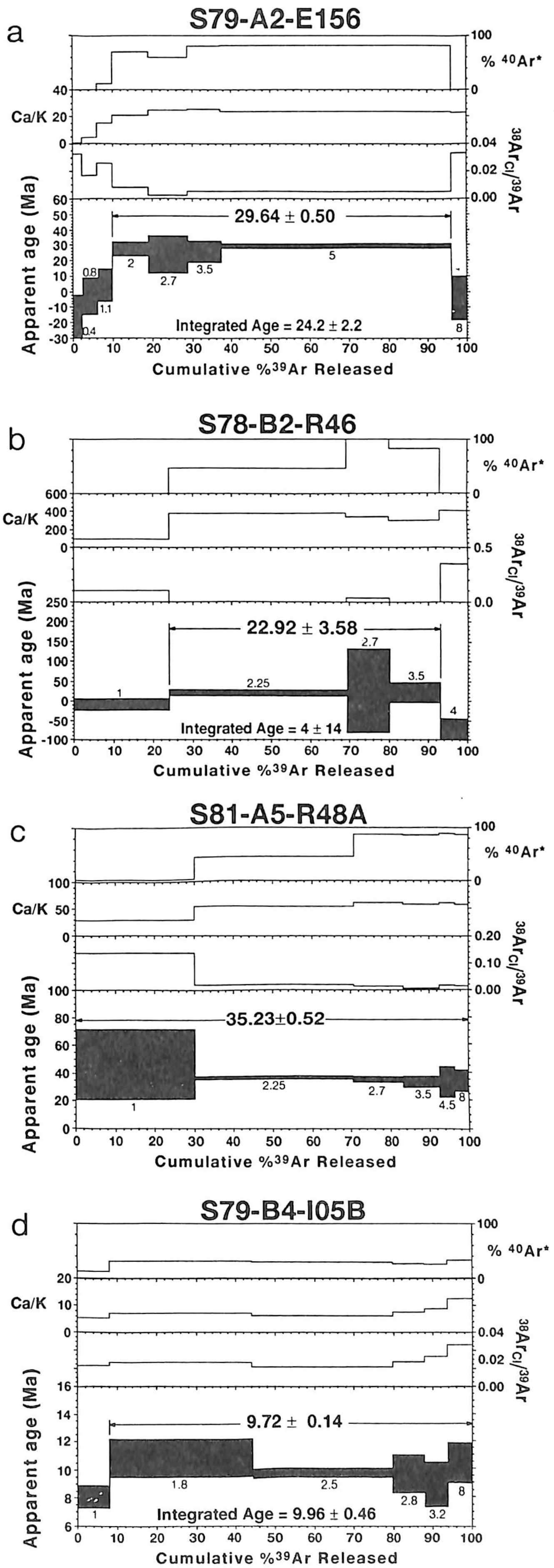



**FIGURE 3. Plateau diagrams for incremental heating $^{40}Ar/^{39}Ar$ age determinations: a, 83FB-V06; b, S78-D5-E168A; c. S78-D5-M88A. Error range shown for each step is at 1σ.**



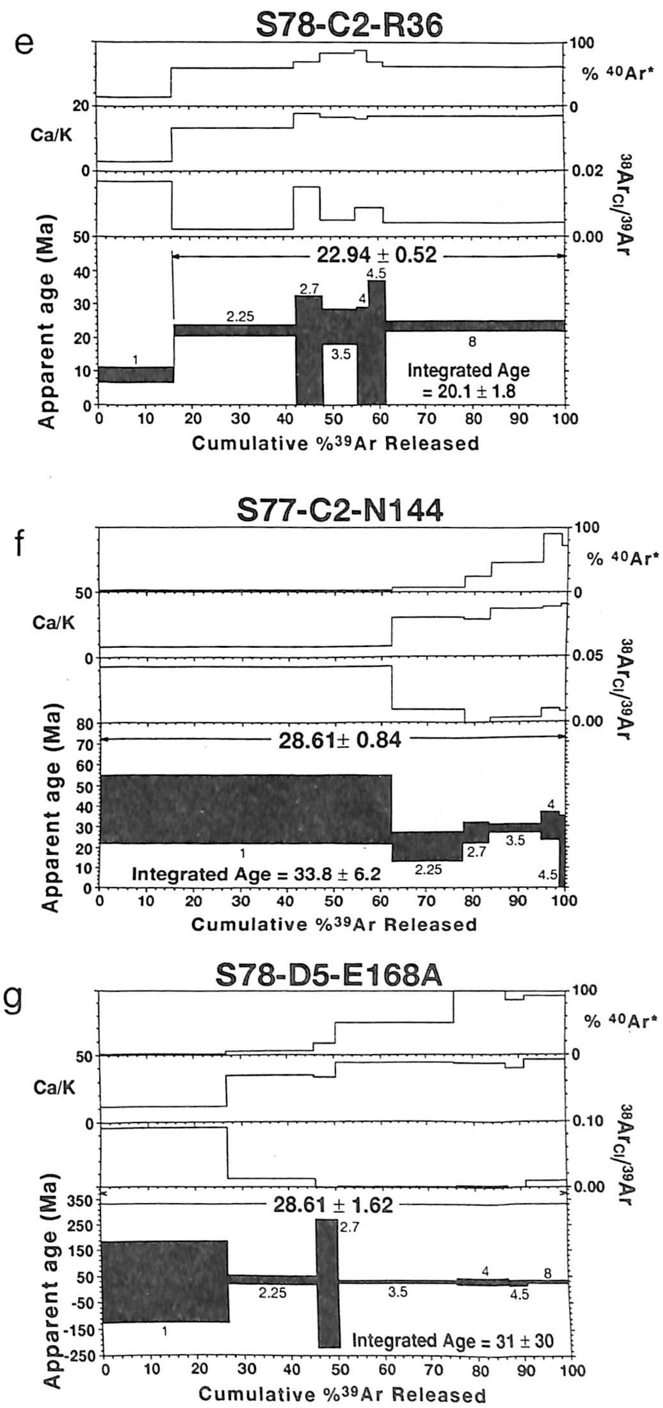




**FIGURE 4.** Plateau diagrams for $^{40}Ar/^{39}Ar$ laser incremental heating determinations: a, S79-A2-E156; b, S78-B2-R46; c, S81-B5-R48A; d, S79-A4-105B; e, S78-C2-R36; f, S77-CI-N144; g, S78-D5-E168A. Error range shown for each step is at 2σ; number shown for each step is laser power level in W.

related hydrothermal activity continued until about 17 Ma (fig. 2). Although minor disconformities are common within the subaerially erupted strata, the age determinations show that volcanism was generally continuous during this time, and reveal no convincing evidence for regionally significant hiatuses in magmatic activity.

Although the youngest eruptive rocks dated are about 23 Ma, a few hypabyssal intrusive rocks in the Spirit Lake quadrangle have given ages younger than 17 Ma. Evarts and others (1987) reported whole-rock K-Ar ages of 8 to 10 Ma for three widely scattered and exceptionally fresh andesitic intrusive rocks (S78-A2-R128, S78-D5-E168A, and S78-D5-M88A) and suggested that these subvolcanic dikes and sills were the only record of a late Miocene period of modest volcanic activity, extrusive equivalents having been eroded completely away. However, additional determinations for two of these samples (S78-D5-E168A and S78-D5-M88A; table 3, fig. 4) failed to substantiate this conclusion. Although not conclusive, the new data suggest that these glass-rich dikes and sills are penecontemporaneous with their Oligocene and early Miocene host rocks, and the late Miocene ages previously obtained from them are considered spurious. All three of these andesites contain a glassy mesostasis that appears mineralogically unaltered but has probably undergone some hydration, judging from the whole-rock $H_2O$ contents of 2.1 to 3.1 weight percent. Evidently, all three have lost $^{40}Ar^*$ by exchange with ground waters at very low temperatures (Kaneoka, 1972; Cerling and others, 1985).

One sample (S79-B4-I05B) yielded a late Miocene age that we consider reliable. Hornblende from a mafic hornblende-porphyry dike cutting the southern part of the Spirit Lake pluton gave a $^{40}Ar/^{39}Ar$ laser-fusion incremental heating age with a well-defined plateau of 9.72 ± 0.14 Ma. This is the only evidence for magmatism in the Spirit Lake quadrangle after 17 Ma. Significant magmatic activity occurred to the east of the quadrangle during middle to late Miocene time (Swanson, 1991; Smith and others, 1989), but contemporaneous activity in the Spirit Lake area was evidently very meager and localized.

### Spirit Lake pluton

The Spirit Lake pluton has been divided on the basis of field, petrographic, and chemical criteria into (from oldest to youngest) quartz diorite, main, and granite phases (Evarts and others, 1987). Zircon fission-track ages were determined on samples from all three phases, and biotite K-Ar ages were obtained from three samples from the main phase (see fig. 1). Two main phase rocks yielded both K-Ar and fission-track ages. Attempts to acquire fission-track dates for apatites from the pluton were thwarted by the presence of abundant minute inclusions in all apatite crystals. The biotite-zircon pairs are concordant, as expected from their similar closure temperatures near 250°C (Harrison and McDougall, 1980; Hurford, 1986). All 11 ages fall within the narrow range of 20.6 to 22.6 Ma and are identical within their 1$\sigma$ limits of error. A similar hornblende K-Ar age of 22.0 ± 0.3 Ma was determined for a sample from the main phase by R. W. Tabor (data published in Engels and others (1976) recalculated using currently accepted physical constants).

A crystallization age of about 21 ± 1 Ma for the Spirit Lake pluton is consistent with the tight constraints imposed by our other age determinations. The youngest rocks intruded by the pluton are dacites and tuffs exposed along the eastern margin (top) of the pluton. This section has been traced eastward into the French Butte quadrangle (Swanson, 1989) where it contains a welded tuff that yielded a plagioclase $^{40}Ar/^{39}Ar$ incremental heating age of 22.8 ± 0.2 Ma. The pluton and its contact aureole are cut by widely scattered dikes ranging in composition from basalt to quartz porphyry. Three of these dikes (S78-C5-E123A, S79-B4-I05B, S84-C3-R03) were dated using four different techniques and gave ages of 19.9 ± 0.7, 19.1 ± 0.1, and 9.72 ± 0.14 Ma.

### Hydrothermal alteration

The Spirit Lake 15-minute quadrangle contains many areas of intense hydrothermal alteration; conventional K-Ar ages have been determined for samples from the two largest and most intensely altered areas: the Margaret (or Earl) porphyry Cu-Mo deposit in the Spirit Lake pluton (Hollister, 1979; Derkey and others, 1990) and an extensive area of advanced argillic alteration near the northern margin of the pluton north of Red Springs Creek (Evarts and Ashley, 1993 b). Secondary sericite (MDH7-684/687) and biotite (MDH6-408/410) in drill core from the Earl deposit gave ages of 16.9 ± 0.5 Ma and 17.3 ± 0.5 Ma respectively, concordant with the age of 16.6 ± 0.6 Ma (recalculated using currently accepted decay constants, Steiger and Jäger, 1977) published by Armstrong and others (1976). These ages appear to preclude a direct genetic relationship between the hydrothermal system responsible for the porphyry deposit and either the 21-Ma host pluton or the spatially associated 19-Ma quartz porphyry dikes.

Hypogene alunite from the Red Springs area (S77-C3-J49) yielded concordant K-Ar ages with a weighted mean of 23.2 ± 0.4 Ma. The age and distribution of this advanced argillic alteration suggest that it is related to a post-25 Ma caldera in the Quartz Creek area northeast of the Spirit Lake pluton (Evarts and others, 1987). The alteration locally overprints rocks of the quartz diorite phase of the pluton, and is in turn intruded by unaltered granodiorite like that of the main phase of the pluton.

## CONCLUSIONS

We have attempted to constrain the geologic history of part of the western Cascade Range in southern Washington by dating well-mapped volcanic and plutonic rocks using several geochronologic techniques. Our experience illustrates some of the difficulties that must be recognized in evaluating age determinations from the Tertiary Cascade arc. In general, we obtained excellent results for plutonic rocks by dating zircon using both fission-track and U-Pb techniques and dating biotite by conventional K-Ar analysis. We also successfully dated potassic hydrothermal minerals, such as sericite, biotite, and alunite, using the conventional K-Ar technique. However, K-rich minerals and zircon are extremely rare in Tertiary Cascade volcanic rocks, and most published dates from volcanic rocks of the region are K-Ar determinations on whole-rock or, less commonly, plagioclase samples. Whole-rock ages are suspect owing to minor but pervasive zeolite-facies metamorphism. Plagioclase, even if appearing unaltered under petrographic examination, commonly yields poor results because of high levels of atmospheric contamination. $^{40}Ar/^{39}Ar$ dating of hand-picked plagioclase separates, employing either laser-degassing/fusion or standard furnace incremental heating techniques, appears to effectively address both the alteration and atmospheric-contamination problems, and is therefore the most reliable and widely applicable geochronologic method for investigations of the evolution of the Tertiary Cascade volcanic arc.

## ACKNOWLEDGMENTS

Geologic mapping of the Spirit Lake quadrangle by the senior author and R. P. Ashley was accomplished under a cooperative program between the Washington Division of Geology and Earth Resources and the U.S. Geological Survey. K. R. Bishop did most of the mineral separations and contributed substantial help with the fission-track work. C. W. Naeser provided helpful advice along with the apatite and zircon standards needed for the fission-track technique. W. M. Phillips provided a spilt of sample BP0516851. Potassium analyses were performed by P. R. Klock, B. Z. Lai, S. R. MacPherson, S. T. Neil, and D. V. Vivit. Malcolm Pringle helped with the laser-fusion analyses. We thank J. E. Conrad and R. P. Ashley for technical reviews of the manuscript.

## SAMPLE DESCRIPTIONS

1. *S80-A1-S02* K-Ar, fission-track
Porphyritic dacite crystal-vitric lapilli tuff (46°27′56″N, 122°13′26″W; NE¼,SE¼, S6,T11N, R5E; outcrop at elevation of 790′ along S shore of Riffe Lake 1.5 km ENE of mouth of Landers Creek, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.306, 0.307%, $^{40}Ar^*$ = $1.268 \times 10^{-11}$ mol/gm, $^{40}Ar^*/\Sigma^{40}Ar$ = 14%; fission-track (apatite—50 grains) $N_s$ = 129, $\rho_s$ = 0.0689 $\times 10^6$ tracks/cm$^2$, $N_i$ = 297, $\rho_i$ = 0.1587 $\times 10^6$ tracks/cm$^2$, $\rho_s/\rho_i$ = 0.434, $N_\phi$ = 4187, $\phi$ = 13.72 $\times 10^{14}$ n/cm$^2$. *Collected by:* R. C. Evarts. *Comments:* Pale green zeolitic tuff containing phenocrysts of plagioclase (generally fresh but locally replaced by albite, smectite, heulandite), augite, altered hypersthene and Fe-Ti oxide in matrix of montmorillonitized and zeolitized vitric debris. K-Ar age is preferred because of its better precision and consistency with dates on nearby units.

**K-Ar (plagioclase) 28.5 ± 0.9 Ma**
**fission-track (apatite) 35.6 ± 3.7 Ma**

2. *S78-A1-E209A* K-Ar
Hornblende andesite flow-breccia (46°27′01″N, 122°13′21″W; NE¼,SE¼, S7,T11N,R5E; roadcut on abandoned spur road off Champion International Co. logging road no. 2150, at elevation of 1610′ on north side of valley of Landers Creek 0.9 km ENE of confluence with Wakeawasis Creek, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (hornblende) $K_2O$ = 0.270, 0.256, 0.269%, $^{40}Ar^*$ = $1.040 \times 10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 10%. *Collected by:* R. C. Evarts. *Comments:* Friable zeolitized hornblende andesite flow breccia (or

agglomerate) containing phenocrysts of plagioclase (largely altered to albite, montmorillonite, and zeolite), augite, hypersthene (replaced by smectite, Fe-Ti oxide, titanite, quartz and zeolite) and orange-brown hornblende (partly replaced by green smectite/chlorite and actinolite (?)) in a highly altered intersertal groundmass of plagioclase, Fe-Ti oxide, hematite, and clay minerals.

**K-Ar (hornblende) 27.1 ± 2.0 Ma**

3. *S78-A2-R128* K-Ar
Aphyric basaltic andesite sill (46°26′18″N, 122°12′45″W; SE¼,NW¼, S17,T11N,R5E; rockpit on Champion International Co. logging road no. 2156 at elevation of 2570′ 1.9 km SE of confluence of Landers and Wakeawasis Creeks, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (whole-rock) $K_2O$ = 0.852, 0.856%; $^{40}Ar^*$ = 1.059 x $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 14%. *Collected by:* R. C. Evarts. *Comments:* Columnar-jointed sill of virtually aphyric andesite containing scarce phenocrysts of plagioclase and microphenocrysts of augite in a pilotaxitic to intersertal groundmass of plagioclase, augite, Fe-Ti oxide, and brown isotropic glass (locally replaced by traces of carbonate and smectite). Age is believed to be too young as a result of Ar loss during hydration of interstitial glass.

**K-Ar (whole-rock) 8.6 ± 0.3 Ma**

4. *S79-A2-E156* K-Ar, fission-track, $^{40}Ar/^{39}Ar$ laser incremental heating
Porphyritic lithic-rich lapilli tuff (46°24′43″N, 122°15′04″W; NW¼,NE¼, S25,T11N,R4E; roadcut on Weyerhaeuser Corp. logging road no. 2636 at elevation of 2630″ on south valley wall of Elk Creek 3.8 km NNE of Soda Spring, Winters Mountain 7.5′ quad., Cowlitz Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.239, 0.238%; $^{40}Ar^*$ = 1.157 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 15%; $^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase)—see table 3 and figure 4a. Fission-track (apatite—50 grains) $N_s$ = 47, $\rho_s$ = 0.0689 × $10^6$ tracks/cm$^2$, $N_i$ = 113, $\rho_i$ = 0.0251 × $10^6$ tracks/cm$^2$, $\rho_s/\rho_i$ = 0.416, $N_\phi$ = 4187, $\phi$ = 13.72 × $10^{14}$ n/cm$^2$. *Collected by:* R. C. Evarts. *Comments:* Green zeolitic ash-flow tuff containing phenocrysts of plagioclase, (ranging from fresh to totally replaced by albite±heulandite), augite, and hypersthene in matrix of vitric ash totally replaced by smectite, quartz, alkali feldspar, hematite, leucoxene, and trace analcime; all feldspar in lithic clasts is altered. $^{40}Ar/^{39}Ar$ laser incremental heating plateau age is defined by four steps comprising 86% of the $^{39}Ar$ released, is concordant (within 2σ) with the isochron and inverse isochron ages, and is considered the most reliable of the three age determinations.

**K-Ar (plagioclase) 33.4 ± 1.3 Ma**
**$^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase) 29.6 ± 0.5 Ma**
**fission-track (apatite) 34.1 ± 5.9 Ma**

5. *S80-A3-E32* K-Ar, $^{40}Ar/^{39}Ar$ laser fusion
Porphyritic basaltic andesite (46°23′44″N, 122°14′22″W; SW¼,NW¼, S31,T11N,R5E; roadcut near end of spur road off Weyerhaeuser Corp. logging road no. 2645, at elevation of 3340′ on top of knob north of Green River, 1.9 km NNW of mouth of Miners Creek, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.274, 0.279%, $^{40}Ar^*$ = 1.406 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 13%, $^{40}Ar^*$ = 1.144 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 11%; $^{40}Ar/^{39}Ar$ laser fusion (plagioclase)—see table 2. *Collected by:* R. C. Evarts. *Comments:* Coarsely porphyritic basaltic andesite flow containing phenocrysts of plagioclase (up to 1 cm long), hypersthene, augite, and olivine in an intergranular groundmass of plagioclase, pyroxene, Fe-Ti oxide, and interstitial glass totally altered to smectite and quartz; groundmass locally replaced by patchy calcite. $^{40}Ar/^{39}Ar$ laser fusion age is the weighted mean of three fusions performed following a degassing step which released 7.7% of the total $^{39}Ar$ and about 96% of the total atmospheric $^{40}Ar$; the high age given by the degassing step may indicate $^{39}Ar$ recoil (McDougall and Harrison, 1988), which would result in a calculated age that is too young.

**K-Ar (plagioclase) 35.0 ± 2.0 Ma**
**(plagioclase) 28.5 ± 1.1 Ma**
**$^{40}Ar/^{39}Ar$ laser-fusion (plagioclase) 33.5 ± 0.4 Ma**

6. *S78-B2-R46* $^{40}Ar/^{39}Ar$ laser incremental heating
Porphyritic basaltic andesite (46°26′30″N, 122°09′40″W; NE¼,NE¼, S15,T11N,R5E; roadcut on USFS Road 2750 at elevation of 1940′, 2.1 km S of Cowlitz River, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* $^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase)—see table 3 and figure 4b. *Comments:* Porphyritic basaltic

andesite flow with phenocrysts of plagioclase, olivine (replaced by smectite, quartz, hematite, and calcite), and augite in a coarse-grained intergranular groundmass of plagioclase, pyroxene, Fe-Ti oxide, and minor altered interstitial glass. Age is controlled by the first plateau step because of its relatively high analytical precision; however, the isochron and reverse isochron ages are concordant with the plateau age. This age is analytically indistinguishable from those of about 25 Ma obtained on correlative rocks (S80-B1-L28 and BP0516851).

**$^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase) 22.9 ± 3.6 Ma**

7. *S78-B2-E49A* K-Ar, $^{40}Ar/^{39}Ar$ laser fusion
Porphyritic pyroxene andesite (46°24′45″N, 122°09′19″W; NE¼,NE¼, S27,T11N,R5E; outcrop at elevation of 4460′ near west end of cliffs, 0.5 km NW of summit of Vanson Peak, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.253, 0.256%; $^{40}Ar^*$ = 9.117 × $10^{-12}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 2.8%; $^{40}Ar/^{39}Ar$ laser-fusion (plagioclase)—see table 2. *Collected by:* R. C. Evarts. *Comments:* Porphyritic pyroxene andesite flow containing phenocrysts of plagioclase (local minor alteration to albite and smectite), augite, hypersthene (slightly altered to smectite), and Fe-Ti oxide in a fine-grained groundmass of feldspar, quartz, Fe-Ti oxide, smectite, and minor calcite. $^{40}Ar/^{39}Ar$ laser fusion age is the weighted mean of a high temperature degassing and three fusions performed following a low temperature degassing step in which 2% of the total $^{39}Ar$ was released. Both ages are indistinguishable within reported 1σ error limits.

**K-Ar (plagioclase) 24.7 ± 3.5 Ma**
**$^{40}Ar/^{39}Ar$ laser-fusion (plagioclase) 25.1 ± 0.4 Ma**

8. *S80-B1-L28* $^{40}Ar/^{39}Ar$ laser fusion
Porphyritic basalt (46°29′55″N, 122°08′16″W; SE¼,NE¼, S26,T12N,R5E; abandoned rockpit at elevation of 2220′ near top of mountain immediately E of Riffe Lake, 3.0 km W of Glenoma Peak and 0.7 km NE of radio tower, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* $^{40}Ar/^{39}Ar$ laser-fusion (plagioclase)—see table 2. *Collected by:* R. C. Evarts. *Comments:* Porphyritic basalt flow with phenocrysts of plagioclase and altered olivine in coarse intergranular groundmass of plagioclase, augite, orthopyroxene containing cores of altered olivine, Fe-Ti oxide, and interstitial glass replaced by smectite. $^{40}Ar/^{39}Ar$ laser fusion age is the weighted mean of four fusions performed following two degassing steps in which 39% of the total $^{39}Ar$ was released; the isochron and inverse isochron ages are concordant with the weighted mean age.

**$^{40}Ar/^{39}Ar$ laser-fusion (plagioclase) 25.0 ± 1.4 Ma**

9. *BP0516851* K-Ar
Porphyritic basalt (46°29′07″N, 122°10′52″W; NE¼,NE¼, S31,T11N,R5E; rockpit at elevation of 810′ on Champion International Co. logging road no. 2100 along E shore of Riffe Lake 2.7 km NW of bridge over Cowlitz River, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (whole-rock) $K_2O$ = 0.551, 0.557%; $^{40}Ar^*$ = 2.021 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 46%. *Collected by:* W. M. Phillips. *Comments:* Porphyritic basalt containing phenocrysts of plagioclase containing abundant inclusions of altered glass, minor altered olivine, and traces of augite and orthopyroxene in an intergranular groundmass of plagioclase, augite, Fe-Ti oxide, and minor interstitial glass replaced by smectite. Sample is split of rock dated by Teledyne Isotopes as 24.4 ± 1.2 Ma (published in Phillips and others, 1986; sample no. 31).

**K-Ar (whole-rock) 25.2 ± 0.6 Ma**

10. *S79-B3-E149D* fission-track
Porphyritic quartz diorite (46°24′04″N, 122°08′02″W; SW¼,SW¼, S25,T11N,R5E; outcrop in Goat Creek at elevation of 3680' 1.6 km SE of summit of Vanson Peak, Vanson Peak 7.5′ quad., Lewis Co., WA). *Analytical data:* Fission-track (zircon—11 grains) $N_s$ = 2907, $\rho_s$ = 4.8050 × $10^6$, $N_i$ = 6396, $\rho_i$ = 11.5339 × $10^6$, $\rho_s/\rho_i$ = 0.417, $N_\phi$ = 4363, $\phi$ = 8.83 × $10^{14}$, r = .981, $P(\chi^2)$ = 25. *Collected by:* R. C. Evarts. *Comments:* Porphyritic quartz diorite in the quartz diorite phase of the Spirit Lake pluton; contains phenocrysts of variably altered plagioclase and completely uralitized pyroxenes in a fine-grained hypidiomorphic granular groundmass of plagioclase, altered pyroxene, Fe-Ti oxide, quartz, K-feldspar, calcite, and traces of brown hornblende; intense deuteric alteration. Minimum age; probable track fading owing to intrusion of nearby main phase of pluton at

about 21 Ma; quartz diorite phase overprinted by alteration dated at 23.2 ± 0.4 Ma (S77-C3-J49).

**fission-track (zircon) 22.0 ± 0.6 Ma**

11. *S81-A5-R48A* K-Ar, $^{40}Ar/^{39}Ar$ laser fusion, $^{40}Ar/^{39}Ar$ laser incremental heating
Porphyritic basaltic andesite (46°16′11″N, 122°13′44″W; SW¼, SE¼, S7,T9N,R5E; outcrop at elevation of 3300′ along base of Johnston Ridge, at northern margin of May 18, 1980 debris avalanche deposit in North Fork Toutle River valley, 5.2 km west of Spirit Lake, Spirit Lake West 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.201, 0.202%; $^{40}Ar^*$ = 8.103 × $10^{-12}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 3.3%; $^{40}Ar/^{39}Ar$ laser fusion (plagioclase)—see table 2; laser incremental heating (plagioclase)—see table 3 and figure 4c. *Collected by:* R. C. Evarts. *Comments:* Porphyritic basaltic andesite containing phenocrysts of plagioclase, altered olivine, augite, and hypersthene in coarse intergranular groundmass of plagioclase, pyroxene, and interstitial glass altered to smectite and quartz; plagioclase exhibits slight alteration to smectite, and calcite along fractures. Laser incremental heating plateau age is well defined by six steps and 100% of the $^{39}Ar$ released, but is not concordant (at $\alpha$ = 95%) with the isochron and inverse isochron ages. $^{40}Ar/^{39}Ar$ ages are indistinguishable within their reported $1\sigma$ error limits and are considered more reliable than the less precise conventional K-Ar determination.

**K-Ar (plagioclase) 27.7 ± 3.7 Ma**
**$^{40}Ar/^{39}Ar$ laser-fusion (plagioclase) 36.1 ± 1.0 Ma**
**$^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase) 35.2 ± 0.5 Ma**

12. *S81-B5-E43* K-Ar
Porphyritic quartz diorite dike (46°15′05″N, 122°08′33″W; NW¼,NE¼, S24,T9N,R5E; outcrop at elevation of 3510′ in small creek 250 m southeast of southeast corner of Spirit Lake, Spirit Lake West 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (hornblende) $K_2O$ = 0.218, 0.224%; $^{40}Ar^*$ = 7.789 × $10^{-12}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 8.1%. *Collected by:* R. C. Evarts. *Comments:* Offshoot of sill complex of Windy Ridge; porphyritic quartz diorite containing phenocrysts of plagioclase (altered to albite, calcite, epidote, chlorite), pyroxene (replaced by chlorite, actinolite, calcite, magnetite), and fresh brown hornblende (up to 8 mm long) in a murky altered groundmass of plagioclase, Fe-Ti oxide, chlorite, titanite, actinolite, quartz, calcite, and K-feldspar.

**K-Ar (hornblende) 24.3 ± 1.3 Ma**

13. *S79-A4-R128* K-Ar, fission-track
Granodiorite (46°20′56″N, 122°12′06″W; NE¼,SE¼, S17,T10N,R5E; roadcut at elevation of 3570' on Weyerhaeuser Corp. logging road no. 2596 at boundary of Mount St. Helens National Volcanic Monument, 1.5 km ENE of Lonesome Lake and 2.5 km NNW of summit of Minnie Peak, Spirit Lake West 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (biotite) $K_2O$ = 9.18, 9.25%; $^{40}Ar^*$ = 2.811 × $10^{-10}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 63%; fission-track (zircon—10 grains) $N_s$ = 2456, $\rho_s$ = 2.7578 × $10^6$ tracks/cm², $N_i$ = 2290, $\rho_i$ = 5.1428 × $10^6$ tracks/cm², $\rho_s/\rho_i$ = 0.536, $N_\phi$ = 4260, $\phi$ = 6.73 × $10^{14}$ n/cm², r = 0.951, $P(\chi^2)$ = 12. *Collected by:* R. P. Ashley. *Comments:* Pyroxene granodiorite in main phase of Spirit Lake pluton; hypidiomorphic-granular texture, composed of plagioclase, uralitized pyroxenes, quartz, K-feldspar, Fe-Ti oxide, biotite, and traces of brown hornblende, allanite, and tourmaline.

**K-Ar (biotite) 21.1 ± 0.6 Ma**
**fission-track (zircon) 21.6 ± 0.7 Ma**

14. *S80-A4-R06* K-Ar, fission-track
Quartz monzodiorite (46°19′03″N, 122°12′06″W; NE¼,SE¼, S29,T10N,R5E; outcrop at elevation of 2580′ in Coldwater Creek, 1.5 km SW of summit of Minnie Peak, Spirit Lake West 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (biotite) $K_2O$ = 8.82, 8.96%; $^{40}Ar^*$ = 2.681 × $10^{-10}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 62%; fission-track (zircon—11 grains) $N_s$ = 2804, $\rho_s$ = 3.31542 × $10^6$ tracks/cm², $N_i$ = 2623, $\rho_i$ = 6.2025 × $10^6$ tracks/cm², $\rho_s/\rho_i$ = 0.535, $N_\phi$ = 4260, $\phi$ = 6.89 × $10^{14}$ n/cm², r = 0.999, $P(\chi^2)$ = 92. *Collected by:* R. P. Ashley. *Comments:* Pyroxene quartz monzodiorite in main phase of Spirit Lake pluton; hypidiomorphic-granular texture composed of plagioclase, partly uralitized augite and hypersthene, Fe-Ti oxide, quartz, K-feldspar, and biotite.

**K-Ar (biotite) 20.8 ± 0.6 Ma**
**fission-track (zircon) 21.9 ± 0.7 Ma**

15. *S80-A4-R08* K-Ar
Granodiorite (46°18′41″N, 122°12′15″W; NW¼,

NE¼, S32,T10N,R5E; roadcut at elevation of 3590′ near end of former Weyerhaeuser logging road no. 3511 2.1 km SW of summit of Minnie Peak and 2.1 km NW of summit of Coldwater Peak, Spirit Lake West 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (biotite) $K_2O$ = 9.07, 9.15%; $^{40}Ar^*$ = 2.923 × $10^{-10}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 65%. *Collected by:* R. P. Ashley. *Comments:* Pyroxene granodiorite in main phase of Spirit Lake pluton: hypidiomorphic-granular texture composed of plagioclase, thoroughly uralitized or chloritized pyroxene, Fe-Ti oxide, quartz, K-feldspar, biotite and traces of red-brown hornblende.

**K-Ar (biotite) 22.2 ± 0.7 Ma**

16. *S79-B4-I05B* $^{40}Ar/^{39}Ar$ laser incremental heating
Hornblende porphyry dike (46°19′45″N, 122°08′07″W; SE¼,SE¼, S23,T10N,R5E; outcrop at elevation of 5300′ on N flank of Mount Whittier 0.5 km NW of summit, Spirit Lake West 7.5′ quad., Skamania Co., WA). *Analytical data:* $^{40}Ar/^{39}Ar$ laser incremental heating (hornblende)—see table 3 and figure 4d. *Collected by:* R. C. Evarts. *Comments:* Hornblende porphyry dike cutting the main phase of the Spirit Lake pluton; contains phenocrysts of plagioclase, augite, and partially embayed but otherwise fresh brown hornblende in a murky intergranular groundmass. Age is based on a five-step plateau composed of 92% of the total $^{39}Ar$ released; the isochron and inverse isochron ages are concordant with the plateau age.

**$^{40}Ar/^{39}Ar$ laser incremental heating (hornblende) 9.72 ± 0.14 Ma**

17. *S78-C1-R36* $^{40}Ar/^{39}Ar$ laser incremental heating
Crystal-vitric lapilli tuff (46°26′55″N, 122°06′20″W; SE¼,SW¼, S7,T11N,R6E; roadcut at elevation of 2560′ along Champion International Corp. logging road on N side of Tumwater Mountain 2.2 km S of Cowlitz Falls, Cowlitz Falls 7.5′ quad., Lewis Co., WA). *Analytical data:* $^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase)—see table 3 and figure 4e. *Collected by:* R. C. Evarts. *Comments:* Pale olive-green, zeolitized, ash-flow tuff with large, flattened, dark-green pumice lapilli; contains phenocrysts of plagioclase (showing minor local alteration to calcite or laumontite) and mafic silicates (totally replaced by smectite) in a matrix of vitric ash totally replaced by smectite, mordenite, quartz and alkali feldspar; rare lithic clasts are mostly felsic volcanic rocks. Plateau age is defined by six steps comprising 86% of the $^{39}Ar$ released and is concordant (within 2(σ) with the isochron and inverse isochron ages.

**$^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase) 22.9 ± 0.5 Ma**

18. *S77-C2-N144* $^{40}Ar/^{39}Ar$ laser fusion, $^{40}Ar/^{39}Ar$ laser incremental heating
Porphyritic basaltic andesite (46°25′32″N, 122°05′40″W; SE¼,NE¼, S19,T11N,R6E; outcrop at elevation of 5040′ on boundary of Mount St. Helens National Volcanic Monument 0.7 km ESE of summit of Tumwater Mountain, Cowlitz Falls 7.5′ quad., Lewis Co., WA). *Analytical data:* $^{40}Ar/^{39}Ar$ laser fusion (plagioclase)—see table 2; laser incremental heating (plagioclase)—see table 3 and figure 4f. *Collected by:* R. C. Evarts. *Comments:* Porphyritic basaltic andesite flow containing phenocrysts of plagioclase (fresh except for minor alteration to montmorillonite(?) along fractures), augite, much-altered hypersthene and totally altered olivine in an intergranular groundmass of plagioclase, pyroxene, Fe-Ti oxide, and interstitial glass replaced by smectite and quartz. Repeated attempts to date this rock by conventional K-Ar methods failed owing to high atmospheric $^{40}Ar$ yields ($^{40}Ar^*/\Sigma^{40}Ar$ <3%). Laser incremental heating experiment yielded a crudely saddle-shaped spectrum, suggestive of excess Ar, and an anomalously old age of 28.6 ± 0.8 Ma. Laser fusion age is consistent with geologic relations and ages of nearby units, so is preferred.

**$^{40}Ar/^{39}Ar$ laser-fusion (plagioclase) 23.7 ± 0.6 Ma**

**$^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase) 28.6 ± 0.8 Ma**

19. *S82-D1-E106* K-Ar
Seriate basalt (46°28′31″N 122°00′05″W; NE¼,NW¼, S1,T11N,R6E; outcrop at elevation of 3600′ at top of cliffs about 50 m west of summit of Huffaker Mountain, Cowlitz Falls 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.529, 0.533%; $^{40}Ar^*$ = 1.819 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 46%; $^{40}Ar^*$ = 1.787 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 41%. *Collected by:* R. C. Evarts. *Comments:* Seriate basalt containing

phenocrysts of plagioclase, altered olivine, augite, and Fe-Ti oxide in relatively coarse-grained intergranular groundmass of plagioclase, augite, Fe-Ti oxide, and minor interstitial glass replaced by smectite.

**K-Ar (plagioclase) 23.6 ± 1.2 Ma**
**23.2 ± 0.7 Ma**
**weighted mean age 23.3 ± 0.6 Ma**

20. *S81-D1-E19* K-Ar
Porphyritic pyroxene andesite (46°28′04″N, 121°59′58″W; NW¼,SE¼, S1,T11N,R6E; outcrop at elevation of 1970′ near base of landslide scarp 250 m south of 3586′ benchmark on summit of Huffaker Mountain, Greenhorn Buttes 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.251, 0.259, 0.262%; $^{40}Ar^*$ = 8.673 × $10^{-12}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 34%. *Collected by:* R. C. *Evarts. Comments:* Porphyritic pyroxene andesite containing phenocrysts of plagioclase (fresh except for traces of smectite along fractures and minor inclusions of altered glass), hypersthene, augite, and Fe-Ti oxide in a microporphyritic groundmass of plagioclase, Fe-Ti oxide, pyroxene, and abundant glass altered to smectite and minor hematite.

**K-Ar (plagioclase) 23.3 ± 0.8 Ma**

21. *S77-D3-R12* K-Ar
Porphyritic pyroxene andesite (46°23′14″N, 122°02′17″W; SW¼,SE¼, S34,T11N,R6E; outcrop at elevation of 5420′ along Strawberry Mountain Trail (no. 220) on top of Strawberry Mountain ridge 4.0 km north of intersection of trail with USFS Road 2516, Cowlitz Falls 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.310, 0.313%; $^{40}Ar^*$ = 1.020 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 14%. *Collected by:* R. C. Evarts. *Comments:* Porphyritic pyroxene andesite containing phenocrysts of plagioclase (locally slightly altered to albite and epidote), augite, altered hypersthene, and Fe-Ti oxide in a fine-grained granular groundmass of plagioclase, Fe-Ti oxide, and quartz. Rock appears unaltered but locally is cut by epidote- and actinolite-bearing veinlets related to contact metamorphism by Spirit Lake pluton, and may have undergone some argon loss as a result.

**K-Ar (plagioclase) 22.6 ± 0.7 Ma**

22. *S77-C3-J18* fission-track
Granodiorite porphyry (46°23′05″N, 122°04′16″W; NW¼,NE¼, S5,T10N,R6E; roadcut at elevation of 2070′ on U.S. Forest Service road no. 2608, 300 m WNW of bridge over Quartz Creek and 300 m SE of bridge over Red Spring Creek, Cowlitz Falls 7.5′ quad., Skamania Co., WA). *Analytical data:* Fission-track (zircon—6 grains) $N_s$ = 2718, $\rho_s$ = 5.1167 × $10^6$ tracks/cm², $N_i$ = 2738, $\rho_i$ = 9.9464 × $10^6$ tracks/cm², $\rho_s/\rho_i$ = 0.514, $N_\phi$ = 4260, $\phi$ = 6.81 × $10^{14}$ n/cm², r = 0.739, $P(\chi^2)$ = <0.001. *Collected by:* R. C. Evarts. *Comments:* Pyroxene granodiorite porphyry in main phase of Spirit Lake pluton containing phenocrysts of dark plagioclase, altered pyroxenes (replaced by fine-grained amphibole, biotite, magnetite, titanite), Fe-Ti oxide, and minor green hornblende in a micrographic groundmass of quartz + K-feldspar.

**fission-track (zircon) 20.9 ± 2.2 Ma**

23. *S77-C3-N98* fission-track
Monzogranite (46°24′33″N, 122°03′32″W; NW¼, SE¼, S28,T11N,R6E; roadcut at elevation of 2180′ on U.S. Forest Service road no. 26, 2.0 km NE of mouth of Red Spring Creek, Cowlitz Falls 7.5′ quad., Lewis Co., WA). *Analytical* data: Fission-track (zircon—11 grains) $N_s$ = 1176, $\rho_s$ = 1.9648 × $10^6$ tracks/cm², $N_i$ = 2146, $\rho_i$ = 4.7642 × $10^6$ tracks/cm², $r_s/r_i$ = 0.412, $N_\phi$ = 8282, $\phi$ = 9.19 × $10^{14}$ n/cm², r = 0.936, $P(\chi^2)$ = <0.001. *Collected by:* R. C. Evarts. *Comments:* Monzogranite in granite phase of Spirit Lake pluton; equigranular texture composed of blocky plagioclase (replaced by albite, epidote, chlorite, sericite) and pyroxenes (replaced by chlorite, epidote, titanite), equant Fe-Ti oxide, and anhedral intergrown quartz and K-feldspar; intense deuteric alteration.

**fission-track (zircon) 22.6 ± 1.9 Ma**

24. *S77-C3-J49* K-Ar
Silicified rock (46°23′35″N, 122°05′24″W; NW¼, SW¼, S32,T11N,R6E; outcrop in creek at elevation of 3420′ 1.8 km WNW of mouth of Red Spring Creek, Cowlitz Falls 7.5′ quad., Lewis Co., WA). *Analytical data:* K-Ar (alunite) $K_2O$ = 3.51, 3.55%; $^{40}Ar^*$ = 1.205 × $10^{-10}$, $^{40}Ar^*/\Sigma^{40}Ar$ = 54%; $^{40}Ar^*$ = 1.172 × $10^{-10}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 51%. *Collected by:* J. M. Schmidt. *Comments:* Porous limonitic rock from Red Spring altered area; completely recrystallized to fine-grained

aggregate of quartz, alunite, rutile, and pyrite (totally replaced by limonite).

**K-Ar (alunite) 23.5 ± 0.6 Ma**
**22.9 ± 0.6 Ma**
**weighted mean age 23.2 ± 0.4 Ma**

25. *S78-D5-E199A* K-Ar

Porphyritic vitrophyre (46°15′24″N, 122°03′44″W; SW¼,SE¼, S16,T9N,R6E; roadcut at elevation of 2880′ on U.S. Forest Service road no. 9403, 200 m SW of bridge over Bean Creek; Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (plagioclase) $K_2O$ = 0.208, 0.206%; $^{40}Ar^*$ = 7.296 × $10^{-12}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 15%; $^{40}Ar^*$ = 7.129 × $10^{-12}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 16%. *Collected by:* R. C. Evarts. *Comments:* Dacitic welded-tuff vitrophyre containing phenocrysts of plagioclase, augite, and trace Fe-Ti oxide in matrix of deep red-orange isotropic glass; rare lithic fragments of altered intermediate to felsic lavas.

**K-Ar (plagioclase) 24.3 ± 0.9 Ma**
**23.8 ± 0.8 Ma**
**weighted mean age 24.0 ± 0.6 Ma**

26. *S78-D5-E168A* K-Ar, $^{40}Ar/^{39}Ar$ incremental heating, $^{40}Ar/^{39}Ar$ laser incremental heating

Porphyritic pyroxene andesite sill (46°16′06″N, 122°02′50″W; NW¼,NW¼, S15,T9N,R6E; roadcut at elevation of 4070′ on U.S. Forest Service road no. 2560, just west of ridgecrest on divide between Smith Creek and Bean Creek, 1.8 km southeast of Curtis Lake, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (whole-rock) $K_2O$ = 0.704, 0.704%; $^{40}Ar^*$ = 8.817 × $10^{-12}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 15%; K-Ar (plagioclase) $K_2O$ = 0.227, 0.216, 0.218%; $^{40}Ar^*$ = 1.030 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 3.7%; $^{40}Ar/^{39}Ar$ incremental heating (plagioclase)—see table 1 and figure 3b; $^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase)—see table 3 and figure 4g. *Collected by:* R. C. Evarts. *Comments:* Columnar-jointed sill of porphyritic pyroxene andesite containing phenocrysts of plagioclase (rarely replaced by colorless montmorillonite), augite, and hypersthene in a pilotaxitic groundmass of plagioclase, pyroxene, and Fe-Ti oxide set in reddish brown glass (locally replaced by orange smectite). Whole-rock age is too young, probably due to loss of $^{40}Ar^*$ during hydration of glassy groundmass. K-Ar plagioclase age is too old relative to concordant age determinations averaging 24.0 ± 0.6 Ma on underlying ash-flow tuff (S78-D5-E199A) and has a large error owing to very low $^{40}Ar^*/\Sigma^{40}Ar$. $^{40}Ar/^{39}Ar$ incremental heating plateau age is based on a five-step plateau composed of 95% of total $^{39}Ar$ released, is concordant with isochron and inverse isochron ages, and is consistent with the age of the underlying ash-flow tuff; however, the monotonically decreasing age spectrum suggests $^{39}Ar$ recoil, which would produce a calculated age that is too young. $^{40}Ar/^{39}Ar$ laser incremental heating age is based on a seven-step plateau comprising 100% of total $^{39}Ar$ released, but like the K-Ar plagioclase age, appears too old relative to the age of the underlying tuff. Although none of these ages can be considered highly reliable, a late Oligocene to early Miocene age is indicated.

**K-Ar (whole-rock) 8.7 ± 0.3 Ma**
**K-Ar (plagioclase) 32.2 ± 3.5 Ma**
**$^{40}Ar/^{39}Ar$ incremental heating (plagioclase) 24.3 ± 0.3 Ma**
**$^{40}Ar/^{39}Ar$ laser incremental heating (plagioclase) 28.6 ± 1.6 Ma**

27. *S78-D5-M88A* K-Ar, $^{40}Ar/^{39}Ar$ incremental heating

Sparsely-phyric pyroxene andesite dike (46°15′06″N, 122°02′55″W; NW¼,NW¼, S22,T9N,R6E; outcrop at elevation of 2780′ on west slope of small knob just east of U.S. Forest Service road no. 9403, 1.1 km SE of bridge across Bean Creek, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (whole-rock) $K_2O$ = 1.259, 1.267%; $^{40}Ar^*$ = 1.704 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 21%; $^{40}Ar/^{39}Ar$ incremental heating (whole-rock)—see table 1 and fig. 3c. *Collected by:* R. C. Evarts. *Comments:* Columnar-jointed dike of sparsely phyric andesite containing phenocrysts of plagioclase (rarely altered to montmorillonite, albite, and prehnite (?)) and microphenocrysts of augite, and olivine (?) in a trachytic groundmass of plagioclase, augite, Fe-Ti oxide, and reddish glass. K-Ar age apparently too young owing to suspected Ar loss during hydration of glass. $^{40}Ar/^{39}Ar$ incremental heating experiment was performed in nine steps and yielded a spectrum of progressively increasing age with temperature; the small plateau near 15 Ma comprises only 31% of the total $^{39}Ar$ released and thus fails the criteria for interpreting a plateau age (Lanphere and Dalrymple, 1978). Reported age is a recombined total-fusion (integrated) age and is considered a minimum age. The higher $^{37}Ar/^{39}Ar$ (proportional to Ca/K) of the last two steps (17 and 20 Ma) suggests that they are dominated by Ar released from unaltered plagioclase and may approach the crystallization age of the dike.

**K-Ar (whole-rock) 9.3 ± 0.3 Ma**
**$^{40}Ar/^{39}Ar$ incremental heating (whole-rock) 12.9 ± 0.3 Ma**

28. *83FB-V06* $^{40}Ar/^{39}Ar$ incremental heating
Dacitic welded-tuff vitrophyre (46°19′32″N, 121°58′41″W; NW¼,NE¼, S30,T10N,R7E; roadcut at elevation of 2910′ on U.S. Forest Service road no. 99 on N side of valley of Wakepish Creek, 0.5 km west of junction with U.S. Forest Service road no. 25, French Butte 7.5′ quad., Skamania Co., WA). *Analytical* data: $^{40}Ar/^{39}Ar$ incremental heating (plagioclase)—see table 1 and figure 3a. *Collected by:* R. C. Evarts. *Comments:* Moderately porphyritic, lithic-poor, dacitic welded-tuff vitrophyre containing phenocrysts of plagioclase, augite, hypersthene, and Fe-Ti oxide in a matrix of hydrated but still vitreous densely welded ash and pumice. Plateau age, defined by three steps comprising 73% of the $^{39}Ar$ released, is concordant with the isochron and inverse isochron ages.

**$^{40}Ar/^{39}Ar$ incremental heating (plagioclase) 22.8 ± 0.2 Ma**

29. *S79-C4-E16* fission-track
Quartz monzodiorite (46°19′28″N, 122°07′11″W; NW¼, NE¼, S25,T10N,R6E; outcrop at elevation of 4610′ on small northeast-trending bedrock ridge 250 m SW of SW end of Boot Lake, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* Fission-track (zircon—11 grains) $N_s$ = 1839, $\rho_s$ = 1.9485 × $10^6$ tracks/cm$^2$, $N_i$ = 1800, $\rho_i$ = 3.8144 × $10^6$ tracks/cm$^2$, $\rho_s/\rho_i$ = 0.511, $N_\phi$ = 4260, $\phi$ = 6.75 × $10^{14}$ n/cm$^2$, r = 0.986, $P(\chi^2)$ = 91. *Collected by:* R. C. Evarts. *Comments:* Quartz monzodiorite in main phase of Spirit Lake pluton; hypidiomorphic-granular texture composed of plagioclase, thoroughly biotitized pyroxene, Fe-Ti oxide, quartz, and K-feldspar.

**fission-track (zircon) 20.6 ± 0.8 Ma**

30. *S76-C3-N38* fission-track
Granodiorite porphyry (46°21′13″N, 122°03′40″W; NW¼,NE¼, S16,T10N,R6E; roadcut at elevation of 3310' on U.S. Forest Service road no. 2612, 200 m E of Ryan Lake and 100 m W of junction with U.S. Forest Service road no. 26, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* Fission-track (zircon—12 grains) $N_s$ = 2955, $\rho_s$ = 2.4228 × $10^6$ tracks/cm$^2$, $N_i$ = 2762, $\rho_i$ = 4.5291 × $10^6$ tracks/cm$^2$, $\rho_s/\rho_i$ = 0.535, $N_\phi$ = 4260, $\phi$ = 6.84 × $10^{14}$ n/cm$^2$, r = 0.988, $P(\chi^2)$ = 94. *Collected by:* R. C. Evarts. *Comments:* Pyroxene granodiorite porphyry in the main phase of the Spirit Lake pluton; phenocrysts of plagioclase, completely uralitized pyroxenes, and Fe-Ti oxide in a medium-grained groundmass of micrographic quartz + K-feldspar.

**fission-track (zircon) 21.8 ± 0.7 Ma**

31. *S79-C3-R127* fission-track
Porphyritic pyroxene granite (46°22′17″N, 122°03′12″W; SE¼,SE¼, S4,T10N,R6E; roadcut at elevation of 2610′ on U.S. Forest Service road no. 26, 1.0 km north of bridge over Quartz Creek, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* Fission-track (zircon—11 grains) $N_s$ = 1905, $\rho_s$ = 1.7720 × $10^6$ tracks/cm$^2$, $N_i$ = 2448, $\rho_i$ = 4.5570 × $10^6$ tracks/cm$^2$, $\rho_s/\rho_i$ = 0.389, $N_\phi$ = 8282, $\phi$ = 9.22 × $10^{14}$ n/cm$^2$, r = 0.967, $P(\chi^2)$ = 81. *Collected by:* R. C. Evarts. *Comments:* Pyroxene granite porphyry in the granite phase of the Spirit Lake pluton; contains phenocrysts of sausseritized plagioclase, uralitized pyroxene, Fe-Ti oxide, and quartz in a groundmass of granophyric quartz and K-feldspar, with traces of brown hornblende and biotite; exhibits intense deuteric alteration.

**fission-track (zircon) 21.4 ± 0.7 Ma**

32. *S78-C5-E123A* K-Ar
Hornblende porphyry dike (46°17′23″N, 122°05′29″W; NW¼,SW¼, S5,T10N,R6E; outcrop at elevation of 4060′ on E bank of Bean Creek just N of U.S. Forest Service road no. 99 and 400 m W of St. Charles Lake, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (hornblende) $K_2O$ = 0.478, 0.484%; $^{40}Ar^*$ = 1.387 × $10^{-11}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 15%. *Collected by:* R. C. Evarts. *Comments:* Hornblende porphyry dike containing phenocrysts of pale-greenish-brown hornblende (displaying

minor local alteration to smectite and calcite) in a felty groundmass of altered feldspar, altered pyroxene, Fe-Ti oxide, quartz, chlorite, and titanite. Cuts albite-epidote hornfels in the outer part of the contact metamorphic aureole surrounding the Spirit Lake pluton, but is not itself recrystallized.

**K-Ar (hornblende) 19.9 ± 0.7 Ma**

33. *S84-C3-R03* U-Pb, fission-track
Quartz porphyry dike (46°21′21″N, 122°05′ 00″W; NE¼,NW¼, S17,T10N,R6E; roadcut at location of Duval diamond drill hole #84, at elevation of 3470′ along abandoned drill-rig road on S side of Goat Mountain 1.5 km W of Ryan Lake, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* U-Pb (zircon)—see table 4; fission-track (zircon—9 grains) $N_s$ = 1827, $\rho_s$ = 2.0971 X $10^6$ tracks/$cm^2$, $N_i$ = 2766, $\rho_i$ = 6.3499 × $10^6$ tracks/$cm^2$, $\rho_s/\rho_i$ = 0.389, $N_\phi$ = 8282, $\phi$ = 9.51 × $10^{14}$ n/$cm^2$, r = 0.994, $P(\chi^2)$ = 43. *Collected by:* R. C. Evarts. *Comments:* Dike of thoroughly sericitized quartz porphyry cutting the main phase of the Spirit Lake pluton in the vicinity of the Earl porphyry Cu-Mo deposit; relict quartz phenocrysts and accessory zircon are the only surviving igneous minerals; plagioclase and possible mafic phenocrysts are totally altered. Age is considered to date time of crystallization rather than alteration.

**(zircon: coarse fraction) $^{238}U/^{206}Pb$ 19.1 ± 0.1 Ma**
**$^{235}U/^{207}Pb$ 19.4 ± 0.5 Ma**
**$^{207}U/^{206}Pb$ 62 ± 66 Ma**
**(zircon: fine fraction) $^{238}U/^{206}Pb$ 19.1 ± 0.1 Ma**
**$^{235}U/^{207}Pb$ 19.1 ± 0.5 Ma**
**$^{207}U/^{206}Pb$ 19.4 ± 65 Ma**
**fission-track (zircon) 18.8 ± 0.6 Ma**

34. *MDH6-408/410* K-Ar
Biotitized quartz diorite (46°21′20″N, 122°04′ 52″W; NW¼,NE¼, S17,T10N,R6E; drill-core sample from Duval diamond drill hole #6, located at elevation of 3490′ along abandoned drill-rig road on S side of Goat Mountain 1.3 km W of Ryan Lake, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (biotite) $K_2O$ = 8.89, 8.89%; $^{40}Ar^*$ = 2.225 × $10^{-10}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 54%. *Collected by:* R. P. Ashley. *Comments:* Secondary biotite from potassic zone of the Earl porphyry Cu-Mo deposit; highly altered quartz diorite from main phase of Spirit Lake pluton containing slightly chloritized secondary biotite, quartz, K-feldspar, chalcopyrite, pyrite, titanite, apatite, calcite, and relict igneous plagioclase.

**K-Ar (biotite) 17.3 ± 0.5 Ma**

35. *MDH7-684/687* K-Ar
Sericitized granodiorite (46°21′25″N, 122°04′ 52″W; SW¼,SE¼, S8,T10N,R6E; drill-core sample from Duval diamond drill hole #7, located at elevation of 3790′ along abandoned drill-rig road on S side of Goat Mountain 1.3 km W of Ryan Lake, Spirit Lake East 7.5′ quad., Skamania Co., WA). *Analytical data:* K-Ar (sericite) $K_2O$ = 10.52, 10.52%; $^{40}Ar^*$ = 2.572 × $10^{-10}$ mol/g; $^{40}Ar^*/\Sigma^{40}Ar$ = 67%. *Collected by:* R. P. Ashley. *Comments:* Phyllic zone of the Earl porphyry Cu-Mo deposit; pervasively altered granodiorite from the main phase of the Spirit Lake pluton containing sericite, secondary quartz, pyrite, carbonate, titanite, and rutile.

**K-Ar (sericite) 16.9 ± 0.5 Ma**

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