OREGON GEOLOGY

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Seymour appointed to DOGAMI Governing Board

Barbara Ann Proebstel Seymour of Salem was appointed by Governor John Kitzhaber and confirmed by the Oregon Senate at the end of June to serve as Governing Board member of the Oregon Department of Geology and Mineral Industries (DOGAMI). She succeeds Arleen N. Barnett of Portland. In addition to Seymour, the three-member Board includes Donald W. Christensen of Depoe Bay, the current chair, and Vera E. Simonton of Pendleton.

Seymour was born in Baker City, Oregon. Her father, Robert I. Proebstel, was general manager of the general store in Cornucopia at the time of her birth. The region experienced much gold mining activity at that time, so she calls herself "a gold mining child."

She grew up mostly on the family's ranch in Haines in northwest Baker County, went to school in Haines,

Barbara Ann Proebstel Seymour

Baker City, and Pendleton, and received degrees in law from the University of Oregon. After she and her husband had practiced law together in Florence, Oregon, the family moved to Salem in 1964. Here, Barbara Seymour worked in the Office of the Legislative Counsel until her retirement in 1997. The Seymours' three children all live in Oregon and have given them eight grandchildren.

Seymour has a story to tell about the beginning of her contact with DOGAMI. We'll give you her own words: "I was interested in mining as my grandfather was in mining camps as a hardware man and my grandmother taught school in mining camps. Although they were deceased before I was born, I inherited an interest in mining and mining history from my Dad. When my daughter's mother-in-law, Marian Mack, wanted to look into the Sampson Mine at Sumpter because her grandfather was a blacksmith for the Sampson Mining Company, I went in [to the DOGAMI Baker City field office —ed] to locate the mine. There I met a very knowledgeable lady, Jan Durflinger, who helped me locate the mine, one of

(Continued on page 122)

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Cover photo

Metolius River, originating between Three Fingered Jack and Santiam Pass on the eastern slope of the central Oregon High Cascades, is the best known example of the large-volume discharges of groundwater found in the region. The head of the Metolius emerges from the ground as a full-size river. The article beginning on the next page discusses age and provenance of some of the waters that are supplied by the Cascade Range mountains. Photo no. A-823 by Oregon Department of Transportation.

Springs in the Oregon Cascades: Where does the water come from? And how old is it?

by Elizabeth R. James and Michael Manga, Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403, and Timothy P. Rose, Analytical and Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore, California 94550

ABSTRACT

Isotopic and temperature measurements from large, cold springs in the central Oregon Cascades are used to understand where this groundwater comes from and how old it is. In particular, we employ the isotopes of helium, carbon, oxygen, and hydrogen to address these issues and to understand some aspects of the subsurface geology in this region. We find that large, cold springs in the central Oregon Cascades are recharged near the Cascades crest up to 50 km from the springs. We also find that the large springs in the study area discharge water that is a few years old. Finally, we show that deeply circulating groundwater advectively transports geothermal heat and magmatic volatiles to several of the springs such as the Metolius River and Lower Opal Springs.

INTRODUCTION

Surface water is a valuable resource to the east of the High Cascades. Rapid population growth in Deschutes County over the last 25 years has placed heavy demands on available surface water resources in the region (Caldwell, 1998). From Mount Jefferson in Oregon south to Lassen Peak in California, cold springs discharge groundwater in high volume, providing much of the base flow to regional rivers. Some of these springs are so large that they emerge from the ground as mature rivers, and as such, they are arguably among the most scenic spots in the region (Figure 1). Aside from their aesthetic value, however, the springs also provide a unique way of learning about regional hydrogeology. The goal of this paper is to show how natural isotopic tracer measurements and temperature measurements of spring water can be used to study both the hydrology of the area (Figure 2) and some aspects of the subsurface geology.

Where did the water come from? How old is the water? These are two of the most commonly asked questions about the hydrogeology of

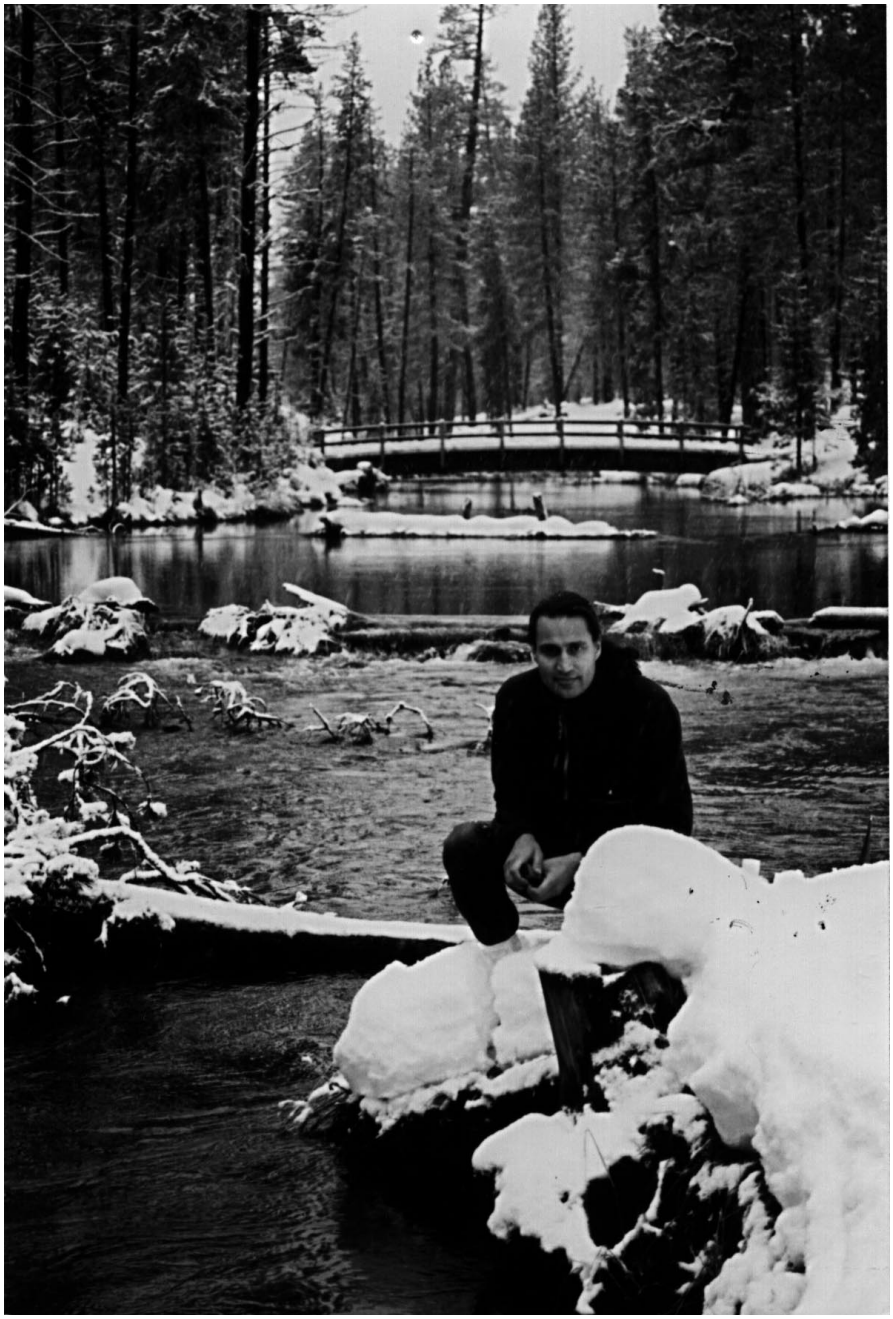

Figure 1. Fall River, central Oregon.

springs. Isotopic tracers present in the water can be used to elucidate both of these questions. After discussing some background information, we describe how tracers and temperature measurements can be used to address the two questions posed above, as well as provide a unique way of studying the subsurface geology.

GEOLOGIC AND HYDROLOGIC SETTING

Local hydrology is determined in large part by local geology. In central Oregon, the local geology is dominated by the Cascade arc, which began to form 40 million years ago as the Farralon Plate subducted beneath the North American plate (Orr and Orr, 1996). Starting around 7.5 million years ago, the line of eruptive centers shifted eastward and the belt of active volcan-

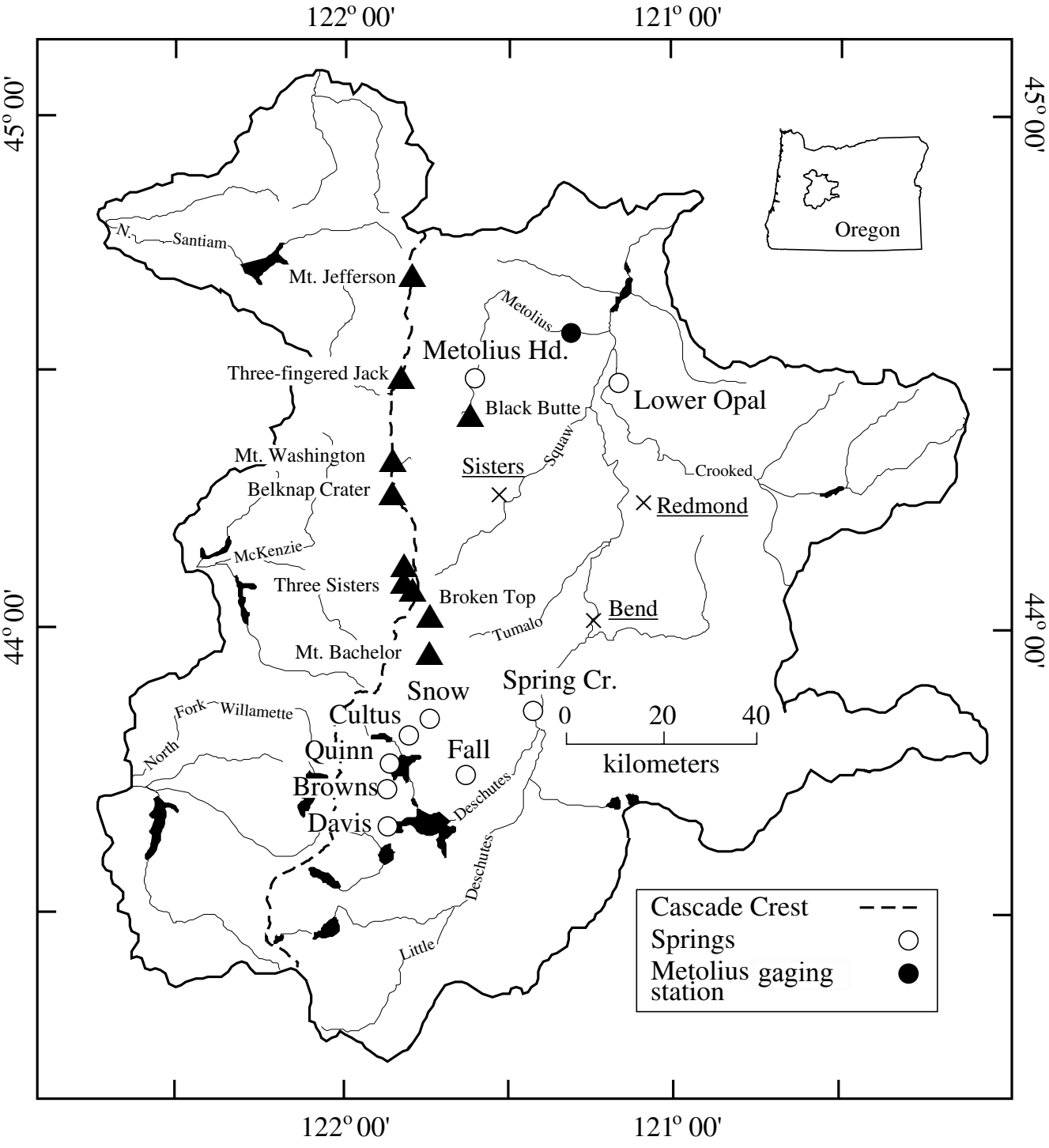

Figure 2. Map of the study region, showing locations of springs discussed in this paper.

ism narrowed to the location of the modern High Cascades. From 7.5 to 5 million years ago, the Cascades volcanoes extruded large volumes of basalt and basaltic andesite lava. The Deschutes Formation to the east of the modern crest of the High Cascades is a remnant of this volcanic episode. During this period, the tectonic regime changed from a compressional to an extensional one, and the early High Cascades subsided (Smith, 1991). This change in tectonic regime may be responsible for some of the unique geologic features of the central Oregon Cascades.

From north of Mount Jefferson to the south of Crater Lake, the crest of the High Cascades is a broad, nearly continuous ridge of overlapping basalt and basaltic andesite lava flows erupted from shield volcanoes (Ingebritsen and others 1994). To the north and south of this region, volcanism occurred primarily at isolated stratovolcanoes (Sherrod and Smith, 1990). The volume of erupted material and regional heat flow are estimated to be higher in central Oregon than in the regions to the north and south (Priest, 1990; Sherrod and Smith, 1990). The most recent volcanic activity in central Oregon occurred at Belknap Crater 1,500 years ago and at South Sister 1,900 years ago (Wood and Kienle, 1990).

The High Cascades produce a dramatic rain-shadow effect to the east of the range. Precipitation in the High Cascades of Oregon is as high as 3 m rainfall equivalent per year, but in the Bend area to the east, precipitation is as low as 0.25 m per year. Along the Cascade crest, the combination of heavy precipitation and permeable volcanic rocks serves to make this the primary recharge area for springs (Ingebritsen and others, 1989; Manga, 1997). Snowmelt is the primary source of groundwater recharge.

East of the crest, where aquifers are typically composed of permeable Quaternary volcanic rocks, most rivers and streams are fed by large-volume springs that discharge cold water, while thermal springs are relatively scarce (Meinzer, 1927). These spring-fed streams are characterized by relatively constant discharge throughout the year, with peak flows only several times larger than base-flow (Whiting and Stamm, 1995). The large cold springs often emerge at the surface contacts between permeable volcanic units and less permeable sediments (Manga, 1998). Cold springs are typically mixed cation bicarbonate waters, with concentrations of total dissolved solids typically ranging from 30 mg/L to 300 mg/L (Caldwell, 1998).

WHERE DOES THE WATER COME FROM?

This question can be addressed by analyzing the oxygen and hydrogen isotope content of the spring water. There are three naturally occurring stable isotopes of oxygen (^{16}O, ^{17}O, and ^{18}O) and two stable isotopes of hydrogen (^{1}H and ^{2}H). The utility of these isotopes in hydrologic investigations stems from the fact that they "fractionate" in a predictable manner (Clark and Fritz, 1997). As water moves through the hydrologic cycle, the relative abundance of the heavy vs. the light isotopes will change depending on the physical processes that are in operation.

In Oregon, air masses predominantly move eastward over the Cascade Range, where adiabatic cooling causes the water vapor to condense and form precipitation. During condensation, the heavy isotopes are preferentially enriched in the condensed phase (rain or snow). The degree of isotope fractionation is highly dependent on temperature and the degree of prior rainout, and, as a result, the degree of fractionation will also change with altitude (Dansgaard, 1964).

In the High Cascades, most precipitation occurs as snow. Local changes in the isotopic composition of a snow pack may occur through cycles of freezing and thawing, but for this analysis we assume that the isotopic composition of the snowmelt is approximately the same when it infiltrates the ground. If we know the relationship between elevation and isotopic composition of precipitation, we can estimate the mean recharge elevation of a spring from its isotopic composition. This is possible because the isotopic composition of groundwater does not change substantially between the recharge area and the spring (except due to mixing processes).

In order to determine recharge areas for the large cold springs in central Oregon, we collected 76 snow samples and 56 spring samples from the region shown in Figure 2. The data and experimental methods are reported in James (1999); selected data are reported in Table 1. All results are reported in the conventional δ-notation as per mil (parts per thousand or ‰) deviations from Standard Mean Ocean Water (SMOW).

Analysis of the snow core data reveals that the $\delta^{18}O$ values systematically decrease by 0.18‰ for every 100-m rise in elevation for the central Oregon Cascades (James, 1999). This is similar to relationships found elsewhere in the Northwest (Clarke and others, 1982; Rose and others, 1996). We assume that the groundwater is young enough to be directly comparable to modern precipitation. As we will show later, this assumption is reasonable. Figure 3 shows graphically how recharge elevations are determined.

In general, the $\delta^{18}O$ values of the springs indicate a significant component of recharge from high elevation areas in the Cascade Range. However, the distance between the recharge area and the discharge point can vary considerably. For example, Quinn River, Cultus River, and Browns Creek are all recharged near the crest of the Cascades, approximately 10 km west of the

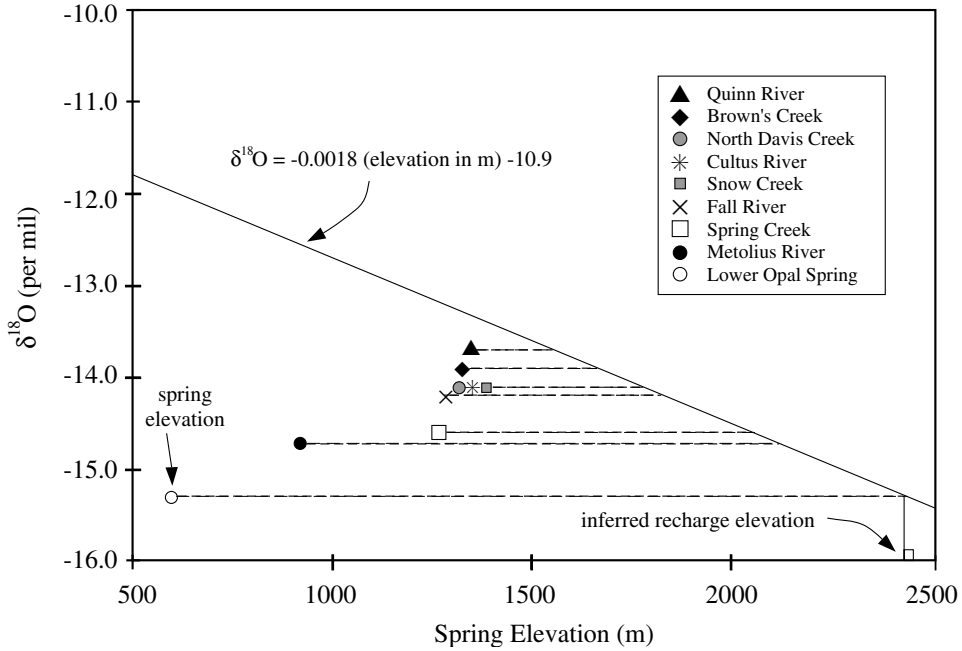

Figure 3. Plot of sample (spring) elevation vs. δ18O values. The mean recharge elevation for springs can be determined by tracing the horizontal lines from the points representing the springs to the least-squares best-fit line of snow-core data from James and others (2000) for the relationship between snowpack δ18O values and altitude.

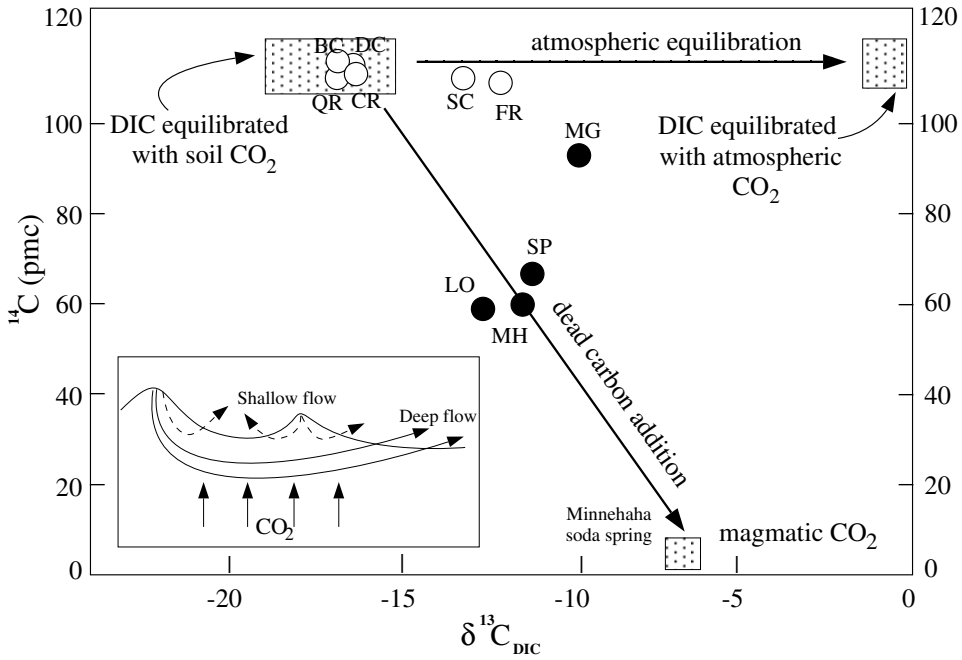

Figure 4. Plot of 14C (in percent of modern carbon–pmc) vs. δ13C values for groundwater samples. The stippled boxes represent the three endmember carbon isotope compositions: Dissolved inorganic carbon (DIC) equilibrated with soil CO_2, atmosphere CO_2, and "dead" CO_2 gas of magmatic origin. The latter endmember composition is represented by Minnehaha soda spring that is located in southern Oregon and has a 14C content near zero. All spring samples have a pH between 7.0 and 8.5. The inset is a schematic illustration of the addition of magmatic CO_2 to deeply circulating groundwater. Solid circles represent deep flow and open cirlces represent shallow flow. Spring abbreviations are described in Table 1.

spring discharge area (Figure 2). Two other springs, the Metolius and Lower Opal, appear to have recharge areas located much farther from the springs. The Metolius River, which is located at an elevation of 920 m, is recharged at a mean elevation of 2,200 m. The $\delta^{18}O$ value of this spring suggests it is derived from recharge areas near the crest of the High Cascades, over 30 km from the spring. Lower Opal spring, which emerges at 520 m, also appears to have a component of recharge derived from the High Cascades (elevation approximately 2,500 m), which is over 50 km from the spring. For the latter two examples, the large elevation difference between the recharge area and the discharge point (Figure 3) implies a deeper, more regional groundwater flow path.

HOW OLD IS THE WATER?

Measuring natural isotopic tracers is one of the most straightforward ways of determining the "age" of the water. An analysis of tracer data, however, is often complicated by the fact that recharge usually occurs not at one particular location but instead along the entire length of an aquifer. Any given water sample is therefore likely to be a mixture of water of different ages. An "apparent age," however, can be determined from an analysis of helium and tritium isotopes (Jenkins and Clarke, 1976).

Three reservoirs may contribute helium to groundwater—the atmosphere, the mantle, and the crust. The $^3He/^4He$ ratio in the atmosphere is 1.386×10^{-6} (Marty and Le Cloarec, 1992). ^3He is also produced in the atmosphere by the decay of tritium (^3H), the radioactive isotope of hydrogen.

Although ^3H is produced naturally in the upper atmosphere, concentrations increased dramatically as a result of thermonuclear weapons testing during the 1950s and 1960s. Tritium undergoes beta-decay to ^3He with a half-life of 12.3 years. Thus, water with a component of groundwater recharged during the era of atmospheric weapons testing may contain a substantial amount of tritogenic helium. The mantle has a $^3He/^4He$ ratio on the order of 10^{-5} (Craig and Lupton, 1981) and is therefore enriched in ^3He relative to the atmosphere. ^4He is produced in the crust from U/Th decay.

Samples were collected from four springs for helium isotope analysis. Analytical procedures are described in James (1999). An apparent age of groundwater (i.e., the age the groundwater would be, assuming no mixing of groundwater of different ages) is obtained from the amount of tritogenic helium, $^3He_{trit}$, and ^3H in the sample (e.g., Poreda and others, 1988), using the formula:

$$\text{apparent age (yrs)} = \frac{12.43}{\ln 2} \times \ln\left[1 + \left(\frac{^3He_{trit}}{^3H}\right)\right].$$

For this method to work, we must subtract the contributions of ^3He from other sources. We assume equilibration with atmospheric helium during recharge. The sample values were corrected for excess air, i.e., air derived from the dissolution of small air bubbles caused by fluctuations in the water table (Heaton and Vogel, 1981), by measuring the concentration of Ar, which is derived solely from the atmosphere. Following this correction, the only two possible sources of excess ^3He in the groundwater are a mantle source or tritium decay. If we assume that there is no mantle contribution to these springs, then the apparent ages of Browns Creek, Quinn River, Cultus River, and Metolius River are 0.7, 2.1, 2.5, and 47.4 years, respectively (James and others, 2000). Our previous assumption that spring water is young enough to be comparable to modern precipitation is reasonable in light of the young ages of three of these springs. As we will show in the next section, the older "age" of the Metolius may be a result of the dissolution of magmatic gases in the groundwater. Indeed, this spring contains both excess ^4He and ^3He, which is indicative of a mantle or possibly a crustal source of Helium.

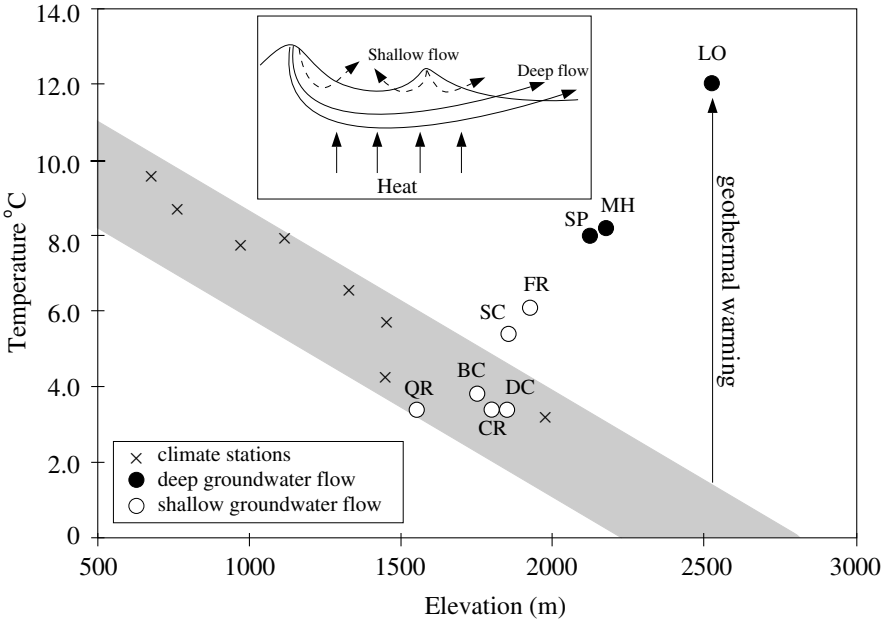

Figure 5. Relationship between elevation and temperature for Oregon climate stations and for springs discussed in this analysis. The climate stations are plotted at their actual elevations and the springs are plotted at their inferred mean recharge elevations as determined from oxygen isotope analyses of the water. The springs that lie significantly outside of the gray band have been warmed substantially from their presumed recharge temperature, represented by the average surface temperature of the recharge area. These springs (solid circles) are likely to discharge deeply circulating groundwater, whereas the spring waters that have lower temperatures (open circles) discharge shallow-circulating groundwater.

WHAT CAN WE LEARN ABOUT SUBSURFACE GEOLOGY FROM TRACER ANALYSES?

As groundwater flows through an aquifer, its solute chemistry may change due to water-rock interaction or dissolution of a volatile phase. Because the central Oregon Cascades are dominated by Quaternary volcanism, dissolved magmatic gases or fluids may be present in the groundwater. Thus, by analyzing the chemistry of the groundwater, we may be able to learn something about the subsurface geology of the region and the nature of the flow path (e.g., depth of the flow path).

A sensitive means of testing this hypothesis is to measure the carbon isotope content of the spring water. The dissolved inorganic carbon in most groundwater is derived from two main reservoirs—the soil CO_2 gas and carbonate minerals. The general lack of carbonate minerals in shallow volcanic aquifers of this region suggests that calcite dissolution has little influence on the dissolved carbon isotopic composition or concentration. Moreover, the amount of calcite that might be present should be negligible in comparison to the volume of water moving through the aquifer system. The volcanic arc, however, may be an additional source of magmatic CO_2.

Three isotopes of carbon are in the terrestrial environment. Of these isotopes, ^{12}C and ^{13}C are stable, and

Table 1. Flow, isotope, and temperature data for springs discussed in this analysis (pmc = percent of modern carbon; TU = tritium units [1 TU = 1 tritium atom per 10^{18} hydrogen atoms]; E = $\times 10$; n.d. = not determined)

Spring	Elevation (m)	Recharge elev. (m)	Temperature (°C)	Discharge[a] (m^3/s)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)	^{14}C (pmc)	^{4}He (atoms/g)	^{3}He (atoms/g)	Ar (atoms/g)	^{3}H (TU)	$^{3}He/^{3}H$ age (yrs)
Browns (BC)	1,332	1,750	3.8	1.1	-13.9	-16.4	115.3	1.18E12	1.63E6	1.13E16	6.9	0.7
Cultus (CR)	1,356	1,800	3.4	1.8	-14.1	-15.8	113.9	1.15E12	1.65E6	1.04E16	9.0	2.5
Fall (FR)	1,286	1,900	6.1	4.2	-14.2	-11.8	110.9	n.d.	n.d.	n.d.	n.d.	n.d.
Lower Opal (LO)[b]	597	2,525	12	6.8	-15.3	-12.7	60.0	n.d.	n.d.	n.d.	0.8	n.d.
Metolius (MH)	920	2,175	8.2	3.1	-14.7	-11.5	61.3	1.71E12	4.89E6	9.56E15	4.0	47.7
Metolius gag.(MG)	602	n.d.	8.4	49.0	-13.5	-9.7	93.7	n.d.	n.d.	n.d.	n.d.	n.d.
N. Davis (DC)	1,323	1,850	3.4	n.d.	-14.1	-15.8	114.0	n.d.	n.d.	n.d.	n.d.	n.d.
Quinn (QR)	1,354	1,550	3.4	0.7	-13.7	-16.5	112.3	1.16E12	1.66E6	1.05E16	8.1[c]	2.1
Snow (SC)	1,378	1,850	5.5	0.8	-14.1	-12.9	111.1	n.d.	n.d.	n.d.	n.d.	n.d.
Spring (SP)	1,268	2,125	8.0	3.5	-14.6	-11.5	67.5	n.d.	n.d.	n.d.	n.d.	n.d.

[a] USGS gaging station measurements, except Metolius: from Meinzer (1927)

[b] Data from Caldwell (1998)

[c] Data from Manga (1997)

^{14}C is radioactive with a half-life of 5,730 years. Because magmatic CO_2 is very old, it does not contain ^{14}C. Given the young ^{3}He-^{3}H ages of these waters, it is logical to assume that if the groundwater has a low amount of ^{14}C, then it may contain dissolved magmatic CO_2 (Allard and others, 1991; Rose and Davisson, 1996; Rose and others, 1996; Sorey and others, 1998).

Water was collected from nine cold springs for carbon isotope analysis. Analytical procedures are described in James and others (1999). ^{14}C results are reported as a percent of modern carbon (pmc) relative to 0.95 times the specific activity of the NIST oxalic acid standard reference material. $\delta^{13}C$ content is reported as the conventional per mil deviation from the Pee Dee belemnite (PDB) standard.

Of the large cold springs in central Oregon, the Metolius, Spring Creek, and Lower Opal, are found to have a low ^{14}C content, which we interpret to indicate the presence of dissolved magmatic CO_2 (Figure 4). Recall that the Metolius River also contains a large amount of excess dissolved ^{3}He. The dissolved magmatic carbon present in this spring is consistent with a magmatic origin for some of the ^{3}He. In this case the "age" of the groundwater may therefore be substantially younger than the 47 years calculated from the tritium and helium analysis.

We can calculate the flux of magmatic CO_2 dissolved in these three springs, given their discharge rates and the magmatic carbon concentrations. For the Metolius River, Spring Creek, and Lower Opal Springs, the annual fluxes of dissolved magmatic CO_2 are 2.4, 1.8, and 4.4×10^6 kg, respectively (James and others, 1999). We also collected a water sample from near the Metolius gaging station. We calculate the flux of magmatic CO_2 at the gaging station to be 8.0×10^6 kg/yr. The Metolius and Lower Opal drainages encompass approximately 75 km of the volcanic arc. This implies that the average dissolved magmatic CO_2 flux for this region is approximately 3.4×10^5 kg/yr per kilometer of arc (see James and others, 1999, for details of this calculation).

Though this flux is small compared to the flux of CO_2 from the craters of active volcanoes (Brantley and Koepenick, 1995), it is consistent with what we would expect on the basis of heat flow data collected in this area. The mean magmatic intrusion rate for this region is estimated to be between 9 and 50 km^3/m.y. per km of arc, based on heat flow measurements (Ingebritsen and others, 1989; Blackwell and others, 1990). For this estimated magmatic intrusion rate, we can calculate the flux of magmatic CO_2 that we would expect to be released from the solidification of a magma with a density of 3.0 g/cm^3. We assume complete degassing of a magma with a CO_2 content between 0.075 and 0.65 weight percent (Garcia and others, 1979; Gerlach and Graeber, 1985; Roggensack and others, 1997; Sisson and Bronto, 1998). With these assumptions, we would predict a flux of magmatic CO_2 between 2.0×10^4 and 9.8×10^5 kg/yr per kilometer of arc. Our estimated flux falls within this range, which is consistent with the fact that the heat and CO_2 fluxes are both produced by the cooling and solidification of magma at depth.

That only three of the large springs contain dissolved magmatic gas suggests that either the diffuse flux of magmatic gas is unevenly distributed or that groundwater circulation dissolves magmatic volatiles only along deep flow paths. Temperature measurements made at the springs indicate that the latter case is more likely. Based on regional estimates of heat flow, it is possible to

calculate the expected amount of geothermal warming of groundwater by using simple mass and energy balance arguments (Brott and others, 1981; Manga, 1998). For this analysis, we assume that groundwater circulation occurs at a sufficient rate that all geothermal heat is discharged at the spring and that there is no surface conductive heat flow (Ingebritsen and others, 1989). Background geothermal heat flow measurements in the region are estimated to range between 110 and 130 mW/m^2 (Blackwell and others, 1982; Ingebritsen and others, 1992).

From the oxygen and hydrogen isotope analysis we found that the recharge area of the Metolius was along the Cascade crest. From this result, we estimate the drainage area to be approximately 400 km^2. The expected change in temperature of the Metolius groundwater can be calculated from the equation

$$\Delta T = \frac{Q}{\rho C} \times \frac{\text{drainage area}}{\text{spring discharge}}$$

where ΔT is the expected geothermal warming, Q is the background heat flow, ρ is the density of water, and C is the heat capacity of water (Manga, 1998). Based on borehole temperature measurements taken near the Cascade crest, near-surface groundwater is about 3°C (Ingebritsen and others, 1994). The Metolius temperature is 8.2°C. From the above equation, we obtain a Q of approximately 160 mW/m^2. This value is higher than the heat flow of 110 to 130 mW/m^2 found by Blackwell and others (1982) and Ingebritsen and others (1992). Our higher value may indicate that the Metolius drains a larger region than previosly assumed, or that the mean discharge is lower than assumed.

Relatively high temperature measurements indicate that the Metolius, Lower Opal, and Spring Creek all discharge deeply circulating groundwater. Because these three springs also show a component of dissolved magmatic CO_2, we can conclude that deeply circulating groundwater advectively transports geothermal heat and magmatic volatiles, whereas the shallow groundwater does not.

Other springs in this region do not appear to have warmed substantially beyond the near-surface temperatures of the recharge area (Figure 5). From this observation we can conclude that Quinn River, Cultus River, Browns Creek, and Davis Creek discharge groundwater from shallow circulation.

CONCLUDING REMARKS

By integrating a suite of tracer measurements with temperature measurements, we have answered the two questions posed at the beginning of this paper. First, we have identified mean groundwater recharge elevations for large, cold springs in the central Oregon Cascades. Three of these springs have average recharge areas that are located farther from the spring than might be assumed by topographic considerations alone. We have also determined that the apparent groundwater ages for large, cold springs in this region are on the order of several years. Thus, in this region of the Cascades, groundwater residence times are short, groundwater flow rates are rapid, and aquifer permeabilities are high. We have also learned about the interaction between geologic and hydrologic processes from these measurements, in particular that deeply circulating groundwater advectively transports geothermal heat and magmatic volatiles to the springs. These findings, which address the pattern of groundwater flow in one small region of central Oregon can help with studies on a larger scale, such as that undertaken by the U.S. Geological Survey (e.g., Caldwell, 1998).

The signs marking the headwaters of two of the large cold springs in central Oregon summarize some of these issues. At the headwaters of the Quinn River, a sign states:

> The crystal-clear water from this spring may have fallen several years ago as snow in the High Cascades. Each year, as the snow melts, most of the water seeps into cracks of this "geologically young" country and travels through underground channels.

Answering the first question posed above involves a determination of the recharge area. As this sign states, the recharge area for the Quinn River is in the Cascades. A more precise recharge elevation can be determined by analyzing the oxygen and hydrogen isotope composition of the water. The "age" of the water can also be determined with isotopic tracers. The sign states that water is several years old. By measuring the concentration of the radioactive isotope of hydrogen (tritium) and its decay product (helium-3) in the spring water, it is possible to determine the mean age of water. The sign also addresses the fact that the water flows through geologically young terrain. As the water flows through the young, volcanic rocks, it may dissolve magmatic gases released at depth by the solidification of intruded magma. Carbon isotopes and helium isotopes, in addition to temperature measurements, can be used to understand these geologic processes.

The Metolius headwaters are marked by a sign stating the following:

> Down this path a full-sized river, the Metolius, flows ice cold from huge springs. The springs appear to originate from beneath Black Butte. However, geologists say this is misleading and believe the springs have their origin in the Cascade Range to the west.

Based on topographic considerations alone, the Metolius River appears to discharge water derived from Black Butte. But a tracer analysis of the water indicates that the spring actually discharges water derived from much farther to the west, in the high-elevation Cascade Range. This sign also emphasizes the cold temperature of the spring water. While these springs are in fact quite cold (about 8°C), they do carry a significant amount of heat derived from geothermal sources at depth. Temperature measurements taken at the springs can be used to estimate the amount of heat acquired as the groundwater flows through the subsurface.

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Oil and gas exploration and development in Oregon, 1999

by Dan E. Wermiel, Geologist, Oregon Department of Geology and Mineral Industries

ABSTRACT

There was an increase in oil and gas leasing activity during 1999, compared to 1998. The increase was in part due to an oil and gas lease sale held by Columbia County where 5,087 acres were acquired by three companies. The acreage leased was located within or in proximity to the Mist Gas Field. Four U.S. Bureau of Land Management (BLM) lease sales were held during the year, and no offers were received. During the year, the BLM sold three over-the-counter noncompetitive leases consisting of 13,885 acres located in Jefferson and Wheeler Counties in eastern Oregon. A total of 56,126 federal acres were under lease at year's end. The State of Oregon conducted no lease sales during the year. Eight State of Oregon tracts were under lease at year's end, comprising 3,741 acres, the same as 1998.

Seven exploratory wells and one redrill were drilled in Oregon by Enerfin Resources during 1999. All were drilled at the Mist Gas Field. Of these, five exploratory wells were successful natural gas wells. The other two exploratory wells and the redrill were plugged and abandoned.

At the Mist Gas Field, 21 wells were productive during 1999. A total of 1.6 billion cubic feet (Bcf) of natural gas was produced during the year with a total value of $3.3 million.

The Oregon Department of Geology and Mineral Industries (DOGAMI) has an oil and gas internet webpage that contains production and other data, drilling application forms, statutes and rules, and other information including links to other webpages. The address is http://sarvis.dogami.state.or.us/oil/homepage.htm.

DOGAMI conducted a triennial review of administrative rules related to oil and gas during the year, and several minor changes were made.

LEASING ACTIVITY

Leasing activity in Oregon increased during 1999, compared to 1998. This was in part due to an oil and gas lease sale held by Columbia County, where 5,087 acres were acquired. The leases were offered through an oral auction bidding system. Enerfin Resources, Houston, Texas acquired the majority of the acreage consisting of 2,931 acres, while, while Anders Elgerd, Lakewood, Colorado, acquired by 1,277 acres for Gold Coast Resources and 879 acres for Oregon Petroleum. The leases were all located within or in proximity to the Mist Gas Field, Columbia County, Oregon. The majority of the acreage was acquired for a minimum bid of $1.00 per acre, and the highest bid of $10.00 per acre was received for a 120-acre parcel located in sec. 29, T. 4 N., R. 4 W., south of Mist Gas Field. Columbia County acquired total receipts of $19,739 for bids and first-year rental of $2.50 per acre at the lease sale.

The total federal acres under lease in Oregon increased during 1999. The U.S. Bureau of Land Management (BLM) held four lease sales during 1999, at which no bids were received. However, the BLM sold three over-the-counter noncompetitive leases consisting of 13,885 acres during the year. These leases are located in Jefferson and Wheeler Counties in eastern Oregon. A total of 56,127 federal acres was under lease at year's end in Oregon, an increase from the 31,374 federal acres under lease at the end of 1998. Total leasing income to the BLM was $62,490 during 1999.

The State of Oregon held no lease sales during 1999, and no new leases were issued. At year's end, eight State of Oregon tracts were under lease, comprising 3,741 acres, which is the same as at the end of 1998. Total rental income to the State of Oregon was $3,741 during 1999.

DRILLING AND EXPLORATION ACTIVITY

Seven exploratory wells and one redrill were drilled by Enerfin Resources in Oregon during 1999. This is about the same drilling level as the six exploratory wells and two redrills drilled during 1998.

All the wells drilled in Oregon during 1999 were located at the Mist Gas Field, Columbia County, where most of the state's oil and gas drilling activity has occurred since the field was discovered in 1979.

Of the wells drilled during 1999, five exploratory wells were successful natural gas wells, while two exploratory wells and the redrill were plugged and abandoned. The successful natural gas wells are the CC 11–34–75, located in NW ¼ sec. 34, T. 7 N., R. 5 W., drilled to a total depth of 3,106 ft; CC 14–22–75, located in SW ¼ sec. 22, T. 7 N., R. 5 W., drilled to a total depth of 2,976 ft.; CC 14–32–75, located in SW ¼ sec. 32, T. 7 N., R. 5 W., drilled to a total depth of 3,229 ft.; CC 32–28–75, located in NE ¼ sec. 28, T. 7 N., R. 5 W., drilled to a total depth of 2,863 ft; and LF 33–22–75, located in SE ¼ sec. 22, T. 7 N., R. 5 W., drilled to a total depth of 3,011 ft. These wells are all located in the northern part of the Mist Gas Field. At year's end, two of the wells were hooked to pipeline and on production, and three were suspended awaiting pipeline connection.

The wells and redrill that were plugged and abandoned during 1999 are the JH 43–26–64, located in SE ¼ sec. 26, T. 6 N., R. 4 W ,

drilled to a total depth of 4,610 ft. This is the easternmost well drilled to date at Mist Gas Field. The CC 12–2–65, located in NW ¼ sec. 2, T. 6 N., R. 5 W., was drilled to a depth of 2,731 ft. and then redrilled to a depth of 2,863 ft., before it was plugged and abandoned.

In addition to drilling exploratory wells at Mist Gas Field, Enerfin Resources plugged and abandoned four suspended natural gas wells that had depleted reservoirs and were determined to have no future beneficial use for underground natural gas storage or any other purpose. These wells are the CC 34–31–65 RD, located in SE ¼ sec. 31, T. 6 N., R. 5 W.; CC 44–8–64, located in SE ¼ sec. 8, T. 6 N., R. 4 W.; LF 31–36–65, located in NE ¼ sec. 31, T. 6 N., R. 5 W.; and the LF 43–32–65, located in SE ¼ sec. 32, T. 6 N., R. 5 W.

During 1999, DOGAMI issued five permits to drill. Permit activity is listed in Table 1.

PRODUCTION

The Mist Gas Field was operated by Enerfin Resources and Northwest Natural during 1999. During the year, 21 natural gas wells were productive at the Mist Gas Field, 17 operated by Enerfin Resources and four operated by Northwest Natural. This is slightly higher than the 19 wells productive at the Mist Gas Field during 1998. Natural gas production for the year totaled 1.6 billion cubic feet (Bcf) of natural gas, a higher volume than the 1.3 Bcf of natural gas produced during 1998. The increase in natural gas production at the Mist Gas Field during 1999 can be attributed to the addition of new exploratory wells being completed by Enerfin Resources and connected to pipeline.

The natural gas price remained constant all year at 24 cents per them, which is slightly higher than the 23 cents per them during 1998. The total value of natural gas produced at Mist Gas Field during 1999 was about $3.3 million, which is greater than the $2.6 million during 1998. This increase is a result of the greater amount of natural gas produced and the higher natural gas price during 1999. Cumulatively, the Mist Gas Field has produced about 65 Bcf of natural gas with a total value of $125 million since it was discovered in 1979.

GAS STORAGE

The Mist and the Calvin Creek Underground Natural Gas Storage Projects are operated by Northwest Natural and were both operational during 1999. The Mist Gas Storage Project has nine injection-withdrawal service wells and 13 monitoring service wells. The Calvin Creek Gas Storage Project currently has 3 injection-withdrawal service wells and four monitoring service wells. Further development to increase storage capacity is expected to occur next year. The two gas storage projects have a total storage capacity of about 15 Bcf of natural gas in the reservoirs at pressures between approximately 400 and 1,000 psi and will provide maximum daily peak capability of approximately 145 million cubic feet (MMcf) of natural gas per day.

A total of 7.6 Bcf of natural gas was injected into, and 7.2 Bcf of natural gas was withdrawn from, the natural gas storage projects during 1999.

During 1999, Northwest Natural began construction of an additional South Mist Feeder natural gas pipeline from Mist Gas Field to the west side of the Portland, Oregon, metropolitan area. This 24-in. pipeline generally follows the route of the existing 16-in. pipeline and will significantly increase the capacity of natural gas that Northwest Natural can deliver from the Mist Gas Field and the Mist and Calvin Creek Underground Natural Gas Storage Projects to the Portland area. Additional pipeline construction is proposed by Northwest Natural to extend the 24-in. South Mist Feeder pipeline to Clackamas County , Oregon.

Northwest Natural continued testing the depleted Busch Pool, located in SW ¼ sec. 15, T. 6 N., R. 5 W., during 1999 to determine if it has any possible future use for underground natural gas storage. Previous natural gas injection testing of this pool was unsuccessful because of water invasion into the reservoir. Northwest Natural began an evaluation during 1998 and continued during 1999 with its attempt to clear the reservoir of water and return it to usefulness for natural gas storage. In this process, natural gas is injected into the reservoir at a pressure slightly greater than initial reservoir pressure, The evaluation was ongoing at year's end.

OTHER ACTIVITIES

DOGAMI has constructed an oil and gas internet homepage. The webpage address is http://sarvis.dogami.state.or.us/oil/homepage.htm.

Included on this homepage are Mist Gas Field production figures and data, oil and gas statutes and administrative rules, permit application forms and other forms, publication list, and other information related to oil and gas exploration and production information as well as other agency activities. A historical database that shows wells drilled in Oregon, locations, dates, total depth, available well logs and samples, references and other data has been completed and will be added to the homepage.

The Northwest Energy Association (NWEA) was active during the year with over 100 members. At its regular monthly meetings, speakers give talks on subjects related to energy matters in the Pacific Northwest. A webpage is being developed which intends to provide information on the NWEA schedule of activities, including the plans for the 2000 fall symposium. For more information, contact the NWEA, P.O. Box 6679, Portland, OR 97228.

Triennial revisions to Oregon Ad-

(Continued on page 98)

Figure 1. During 1999, Enerfin Resources drilled and successfully completed the Columbia County 14–22–75 natural gas well at the Mist Gas Field. The top picture shows the location before drill site construction was begun. The bottom picture shows the same view of the drill site following drilling and completion of the natural gas well, including the wellhead production equipment. The Department's geologic and engineering expertise is applied in the location and design of well drilling, the conduct of development operations, the production of resources, and the final plugging of wells and cleanup and reclamation of drill sites.

Table 1. Oil and gas permit activity in Oregon, 1999

Permit number	Operator, well, API number	Location	Status, depth(ft) TD=total depth PTD=proposed TD
458	Enerfin Resources CC 34-31-65 RD 36-009-00284-01	SE ¼ sec. 31 T. 6 N., R. 5 W. Columbia County	Abandoned; TD 1,902 ft.
459	Enerfin Resources CC 44-8-64 36-009-00285	SE ¼ sec. 8 T. 6 N., R. 4 W. Columbia County	Abandoned; TD 1,810 ft.
477	Enerfin Resources LF 43-32-65 36-009-00302	SE ¼ sec. 32 T. 6 N., R. 5 W. Columbia County	Abandoned; TD 1,909 ft.
478	Enerfin Resources LF 31-36-65 36-009-00303	NE ¼ sec. 36 T. 6 N., R. 5 W. Columbia County	Abandoned; TD 3,987 ft.
511	Enerfin Resources Larkin 43-32-65 36-009-00331	SE ¼ sec. 23 T. 6 N., R. 5 W. Columbia County	Permit extended.
513	Enerfin Resources JH 14-23-64 36-009-00332	SW ¼ sec. 23 T. 6 N., R. 4 W. Columbia County	Permit withdrawn.
516	Enerfin Resources JH 43-22-64 36-009-00335	SE ¼ sec. 22 T. 6 N., R. 4 W. Columbia County	Permit withdrawn.
517	Enerfin Resources CC 14-22-75 36-009-00336	SW ¼ sec. 22 T. 7 N.. R. 5 W. Columbia County	Suspended, gas; TD 2,976 ft.
518	Enerfin Resources CC 32-28-75 36-009-00337	NE ¼ sec. 28 T. 7 N., R. 5 W. Columbia County	Suspended, gas; TD 2,863 ft.
519	Enerfin Resources LF 33-22-75 36-009-00338	NW ¼ sec. 22 T. 7 N., R. 5 W. Columbia County	Suspended, gas; TD 3,011 ft.
520	Enerfin Resources Adams 44-28-75 36-009-00339	SE ¼ sec. 28 T. 7 N. R. 5 W. Columbia County	Permit withdrawn.
522	Enerfin Resources CC 14-32-75 36-009-00341	SW ¼ sec. 32 T. 6 N., R. 5 W. Columbia County	Completed, gas; TD 3,229 ft.
523	Enerfin Resources JH 43-26-64 36-009-00342	SE ¼ sec. 26 T. 6 N., R. 5 W. Columbia County	Abandoned, dry hole; TD 4,610 ft.
524	Enerfin Resources CC 11-34-75 36-009-00343	NW ¼ sec. 34 T. 7 N., R. 5 W. Columbia County	Completed, gas; TD 3,230 ft.
525	Enerfin Resources JH 11-26-64 36-009-00344	NW ¼ sec. 26 T. 6 N., R. 4 W. Columbia County	Permit canceled.
526	Enerfin Resources JH 32-26-64 36-009-00345	NE ¼ sec. 26 T. 6 N., R. 5 W. Columbia County	Application, PTD 4,520 ft.
527	Enerfin Resources CC 12-2-65 36-009-00346	NW ¼ sec. 2 T. 6 N., R. 5 W. Columbia County	Abandoned, dry hole; TD 2,731 ft.
527RD	Enerfin Resources CC 12-2-65 RD 36-009-00346-01	NW ¼ sec. 2 T. 6 N., R. 5 W. Columbia County	Abandoned, dry hole; TD 2,863 ft.
528	Enerfin Resources CC 23-28-75 36-009-00347	SW ¼ sec. 28 T. 7 N., R. 5 W. Columbia County	Application, PTD 2,825 ft.

(Continued from page 96)

ministrative Rules Chapter 632 Division 10 (oil and gas), Division 15 (information and seismic test holes) and Division 20 (geothermal) were completed during the year. Input was solicited from the industry and interested parties for revisions to the regulations. Several minor adjustments were made to the rules but no significant changes. The boundary of the Mist Gas Field was adjusted to the north to include the area of recently completed natural gas wells. The rules are available on the DOGAMI webpage; other information can be obtained by contacting DOGAMI.

The annually updated Mist Gas Field Map, DOGAMI Open-File Report O–00–01, shows the Mist Gas Field divided into quarter sections. It displays location, status, and depth of all wells drilled to date at the field and serves as a basis for locating new ones. It also shows the area and wells that are used for storage of natural gas. The attached production summary for 1993–1999 includes well names, pressures, and production data. Production data are also available on the DOGAMI web page. The map and accompanying production data are useful tools for administrators and planners as well as explorers and producers of natural gas.

A cumulative report of past production at Mist Gas Field between 1979 and 1992 is available in a separate release under the title *Mist Gas Field Production Figures* as DOGAMI Open-File Report O–94–6. Contact the Nature of the Northwest Information Center (503-872-2750) for a complete publication list. □

DOGAMI honored twice

The Oregon Department of Geology and Mineral Industries received two of the five 1999 Awards in Excellence given by the Western States Seismic Policy Council (WSSPC). These awards recognize achievement in different areas of earthquake mitigation, preparedness, and response. The DOGAMI awards were in the category "Educational Outreach Programs," one to schools and the other to business and government.

The school program focused especially on an instructional curriculum for tsunami education, educational exhibits on frequently visited beaches, and information pieces and take-away educational items for visitors to coastal hotels and motels.

The program award for "outreach to business/government" went to the DOGAMI-administered Day Care and Head Start Retrofit program. SAFECO Insurance Company, Fred Meyer, Peake Sun Systems, and CAT-Head Start worked together with DOGAMI.

At DOGAMI, most of the work on these programs was directed and carried out by former State Geologist Donald A. Hull and former administrative assistant Angie Karel. □

K-Ar results from the southern Oregon-northern California Cascade Range

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ABSTRACT

Nearly 180 new whole-rock potassium-argon age dates from the southern Oregon Cascade volcanic province are reported, each with a corresponding major- and trace-element geochemical analysis. K-Ar results from the Klamath River canyon region astride the California-Oregon border delineate no obvious temporal break in volcanic activity. However, 25 mi farther to the north in the Mount McLoughlin-Brown Mountain-Little Butte Creek region, a time gap in volcanic activity has been documented to exist between 17 and 7 Ma. Mafic volcanic activity, which marks the inception of renewed volcanism between 6 and 7 Ma ago, is compositionally quite diverse, ranging from olivine trachybasalt to low-potassium high-alumina olivine tholeiite basalt.

INTRODUCTION

The purpose of this article is to summarize a ten-year accumulation of potassium-argon (K-Ar) whole-rock age determinations that were gathered in support of numerous student mapping projects across the High Cascades of southernmost Oregon and northernmost California (Figure 1). These student mapping projects were part of my long-range goal to map the geology of the region between Mount Shasta and Crater Lake National Park. Naturally, understanding the field relationships is a necessary prerequisite to understanding the geologic history and volcanic petrology of this large area. In large part, the funding to accomplish the field work came from Franklin & Marshall College and the Keck Geology Consortium. The latter organization is an alliance of twelve small liberal arts colleges whose geology departments produce a disproportionate number of graduates who eventually go on and earn Ph.D. degrees. This group of institutions was originally chosen and funded by the William M. Keck Foundation of Los Angeles.

METHODOLOGY

Argon isotopic analysis was performed at Case Western Reserve University in Cleveland, Ohio. K_2O values were determined in duplicate through an XRF (X-ray fluorescence) flux-fusion technique utilized at Franklin & Marshall College to accomplish whole-rock major-element geochemical analysis.

K-Ar age determinations

Over the years, nearly 180 samples have been analyzed for whole-rock K-Ar ages. Preparation of the samples proceeded in the following manner: Samples from which all outward signs of weathering had been removed were crushed. An aliquot of the resulting coarse rock fragments was split from the bulk sample with a stainless-steel geochemical sample splitter and crushed with an alumina-plate-equipped mullite grinder. The output was sieved in order to collect the rock particles within the size fraction of 18–35 mesh. The stainless steel sieves used were reserved for K-Ar work only. Sample powders were washed repeatedly with deionized water and methanol and dried thoroughly to insure powder-free samples.

Between 3 and 8 grams of rock from the 18- to 35-mesh fraction was weighed out to the nearest 0.00001 grams and transferred into a 99.999-percent molybdenum crucible. Six samples at a time were hung in individual quartz bell jars and baked out for at least six hours at 360°F. First, a measured aliquot of ^{38}Ar tracer was extracted under vacuum and frozen onto clean activated charcoal immediately prior to beginning the sample fusion process. With a step-wise heating procedure, the sample was completely fused in an RF induction furnace by holding it at 1,600°C for twelve minutes, during which time the tracer is released to mix thoroughly with the gases from the melted sample. Hot Ti "getters" were employed to remove reactive gases liberated with the inert gases during the fusion process. The gas sample was cooled, frozen onto a second aliquot of clean activated charcoal, thawed and released back to a vapor state, and cleaned again by exposure to a hot SAES Ti "getter." Once cooled, the gas sample was introduced into a MS–10 mass spectrometer interfaced with an IBM personal computer. Peak intensities resulting from ^{40}Ar, ^{38}Ar, and ^{36}Ar in the gas sample were measured with a Carey 401 vibrating reed electrometer; in addition, background counts were measured on both sides of each peak. A data set consisted of measuring ^{40}Ar peak + two background positions down through ^{36}Ar peak + two background positions; and then reversing the process, measuring ^{36}Ar, etc., returning to ^{40}Ar and its background positions. Six to eight data sets were collected per sample measurement. The $^{40}Ar/^{36}Ar$ ratios determined for these data sets (two per set) were used to calculate the age of the sample. Aliquots of an atmospheric Ar sample were measured two to three times during a batch of six samples by measuring five to seven sets of data and calculating the mean of these 10 to 14 $^{40}Ar/^{36}Ar$

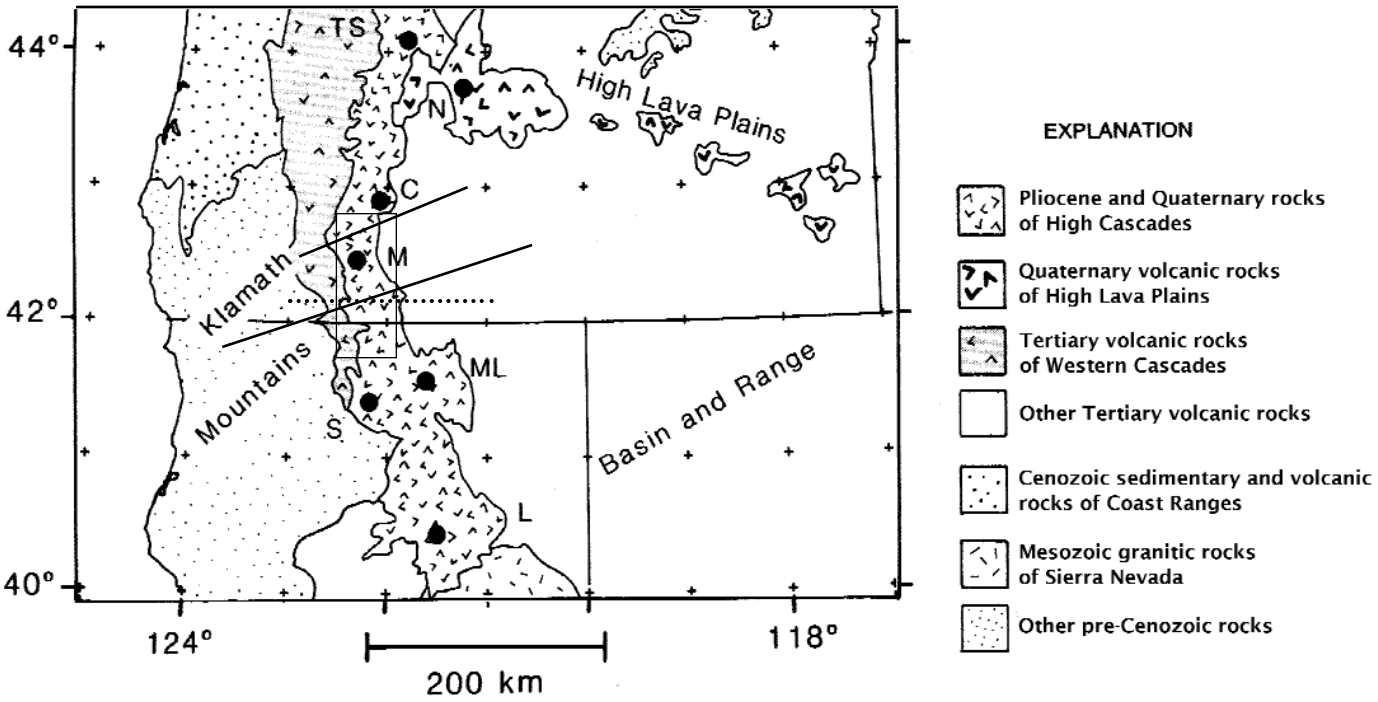

Figure 1. Generalized geologic map showing major Cascade volcanoes (filled circles), the region under discussion in this paper (rectangular outline), the approximate border between the northern and southern segments of the study area (dotted line), and two structural boundary lines discussed in the section "K-Ar results." Letters refer to volcanoes: TS = Three Sisters, N = Newberry Crater, C = Crater Lake, M = Mount McLoughlin, ML = Medicine Lake, S = Mount Shasta, and L = Lassen Peak. Modified from Blakely and Jachens (1990).

ratios, thus providing a correction for the diffusion of atmospheric Ar into the vacuum system.

Uncertainty in the K-Ar ages was determined by assuming a 0.3-percent uncertainty in the measured isotopic compositions of the sample and the ^{38}Ar tracer, a 1.0-percent uncertainty in the volume of the tracer, a 2.0-perent uncertainty in the sample homogeneity, and an uncertainty of 0.8 percent in the measurement of the K_2O content. Naturally, as the age of the sample gets younger and/or the K_2O content gets lower, the age uncertainty will be larger. A thorough petrographic inspection of a potential sample's thin section was conducted to insure an absolute minimum of samples whose age uncertainty was a high percentage of the actual radiometric age. Two considerations have proved successful to the author: (1) Make sure that none of the ferromagnesian minerals show alteration to serpentine (iddingsite seems to make relatively little difference) and that there is very little to no devitrified glass product in the groundmass of a sample; and (2) be aware that for the most part, the ages reported herein represent the actual time at which the sample's temperature passed through its closure temperature for argon retention, approximately 150°–200°C. For many samples this issue presents no problems. However, for some of the older pre-late Miocene samples and those from locations near vent structures, the ages reported could be minimum ages due to the diffusion of ^{40}Ar out of the system. $^{40}Ar/^{39}Ar$ dating is required to determine crystallization ages for those samples with more complex geologic histories.

XRF METHODOLOGY

The coarse rock fragments not used for K-Ar analyses were crushed in an alumina-plate-equipped mullite grinder manufactured by the Bico Corporation and in a Spex shatter box equipped with a ceramic grinding vessel. All rock powder was ground to <80 mesh in particle size. 3.6000 (±0.0002) grams of lithium tetraborate ($Li_2B_4O_7$) was weighed out into a clean glass bottle, followed by 0.4000 (±0.0001) grams of the rock powder, and mixed for 10 minutes in a Spex mixer mill. The homogeneous powder was transferred into a 25-cc., 95-percent Pt/5-percent Au crucible, and 3 drops of a 2-percent solution of lithium iodide (LiI) was added to the powder to reduce the viscosity of the mixture, which was then mounted on a standard ring stand and heated over a Meeker burner. During the heating, the crucible was covered with a 95-percent Pt/5-percent Au lid which also acted as the mold into which the molten sample was poured and cast into a 29-mm-diameter disk. The bottom of the Pt lid is flat and highly polished, thus the side of the disk in contact with the Pt lid is the one that will eventually be exposed

to the primary X-ray beam during the actual XRF analytical determination of chemical composition.

The heating period was normally 10 minutes, with the crucible being held with a pair of Pt-tipped tongs and the sample being vigorously stirred at the three-, six-, and nine-minute marks. After three vigorous stirrings of the molten sample to insure its homogeneity, the Pt lid was removed from the crucible with tongs and held over a second Meeker burner to maintain its high temperature. Simultaneously, the crucible was removed quickly from suspension on the ring stand over the first burner, and its contents were poured into the hot Pt lid in order to cast a glass disk. With some practice, virtually all of the crucible's content was transferred to the lid. Immediately upon completing the pouring event, the still-hot crucible was dropped into a warm beaker containing sufficient 4N HCl to cover the crucible.The lid, which had been held quite level, was now carefully placed onto a flat surface (in our lab, this is a flat polished piece of granite). The sample cooled in 3 to 5 minutes, so that the glass disk could be labeled with a magic marker on the side of the disk exposed to the air. The disk can be stored indefinitely in a desiccator. The major elements are then determined together with Sr, Zr, Cr and V.

Trace element analysis was accomplished by weighing out 7.0000 (±0.0001) grams of whole-rock powder, adding 1.4000 (±0.0002) grams of high-purity microcrystalline cellulose, mixing for 10 minutes, and pressing the sample into a briquette. Copolywax powder was substituted for cellulose when the whole-rock SiO_2 content was >55 weight percent. Data were reported as parts per million (ppm). The elements measured this way included Rb, Sr, Y, Zr, Nb, Ni, Ga, Cu, Zn, U, Th, Co, Pb, Sc, Cr, and V. Elements La, Ce, and Ba were calibrated by means of an L X-ray line and inclusion of a mass absorption correction.

Working curves for each element of interest were determined by analyzing 55 geochemical rock standards. Accepted chemical data for each of these rock standards have been synthesized by Abbey (1983) and Govindaraju (1994). Between 30 and 55 data points were gathered for each working curve; various elemental interferences were also taken into account, e.g., SrK_β on Zr, RbK_β on Y, etc. The Rh Compton peak was utilized for a mass absorption correction. Slope and intercept values, together with correction factors for the various wavelength interferences, were calculated and then stored on a computer. A Philips 2404 X-ray fluorescence vacuum spectrometer equipped with a 102-position sample changer and a 4-Kw Rh X-ray tube was used for automated data acquisition and reduction.

The amount of ferrous iron was titrated using a modified Reichen and Fahey (1962) method, and loss on ignition was determined by heating an exact aliquot of the sample at 950°C for one hour. The X-ray procedure determined total Fe content as Fe_2O_3T.

K-AR RESULTS

Table 1 contains the K-Ar results for nearly 180 samples organized by the 1:24,000 quadrangle from which the sample was collected, the quadrangles listed in alphabetic order and with exact UTM coordinates. Those samples from the State of Oregon come first in Table 1, followed by those from California. Also, sufficient analytical data are given for each sample to satisfy those readers who are geochronologists. Several samples were analyzed in duplicate, several years apart, to provide insight into the analytical precision of the methodology.

Table 2 contains a major- and trace-element whole-rock chemical analysis for each of the samples listed in Table 1. These data, too, are organized by state and quadrangle.

The data set is divided into two latitudinal groups, a northern contingent containing the samples from the southern boundary of Crater Lake National Park to Oregon Route 66, which connects Klamath Falls to Keno and Ashland, and a southern contingent of samples from south of this line to the headwaters of the Little Shasta River west of Macdoel, Calif. (see dotted line in Figure 1). On the basis of the geologic time boundaries of Stanley (1999), all the samples reported in this study are Neogene in age, that is, <24.0 million years old. The absolute time boundaries between the early, middle, and late Miocene, the Pliocene, and the Pleistocene epochs are 16, 11, 5.3, and 1.8 million years (Ma), respectively. Following Priest (1990) for correlation of volcanic episodes and absolute geologic time, I use the following differentiation: 35–17 Ma, early Western Cascade volcanism; 16.9–7.5 Ma, late Western Cascade volcanism; 7.4–4.0 Ma, early High Cascade volcanism; and 3.9–0 Ma, late High Cascade volcanism.

Figure 2a shows plots of silica versus age, with data from the northern portion of the study area depicted in the left diagram and data from the southern portion in the right. The northern (left-hand) plot shows an age gap of approximately 10 million years in the rock record to the north (17 to 7 Ma), whereas no such gap is apparent in the southern dataset. Noticeable is also the paucity of samples more silica-rich than andesite: Two dacitic samples appear in the northern segment of the dataset and a few more dacite to rhyolite samples farther south, but, on the whole, the data set is overwhelmingly dominated by basalts and andesites. Also evident in Figure 2a for the southern data segment is a more pronounced relationship between declining silica content and lower radiometric age. For ages older than 10 Ma, the extruded igneous rocks range from basalt through rhyolite, but for vol-

canic rocks <10 Ma the compositional range is much narrower, only basalt through andesite. It is also noteworthy that basalts and andesites were extruded in both regions over the entire period of time from the early Miocene through the late Pleistocene; only the more siliceous compositions dwindle in relative importance with decreasing age and only in the southern study area. Lastly, it is worth noting that most of the pyroclastic units mapped are from the southern region and are >17 Ma in age.

Figure 2b plots K_2O versus age.

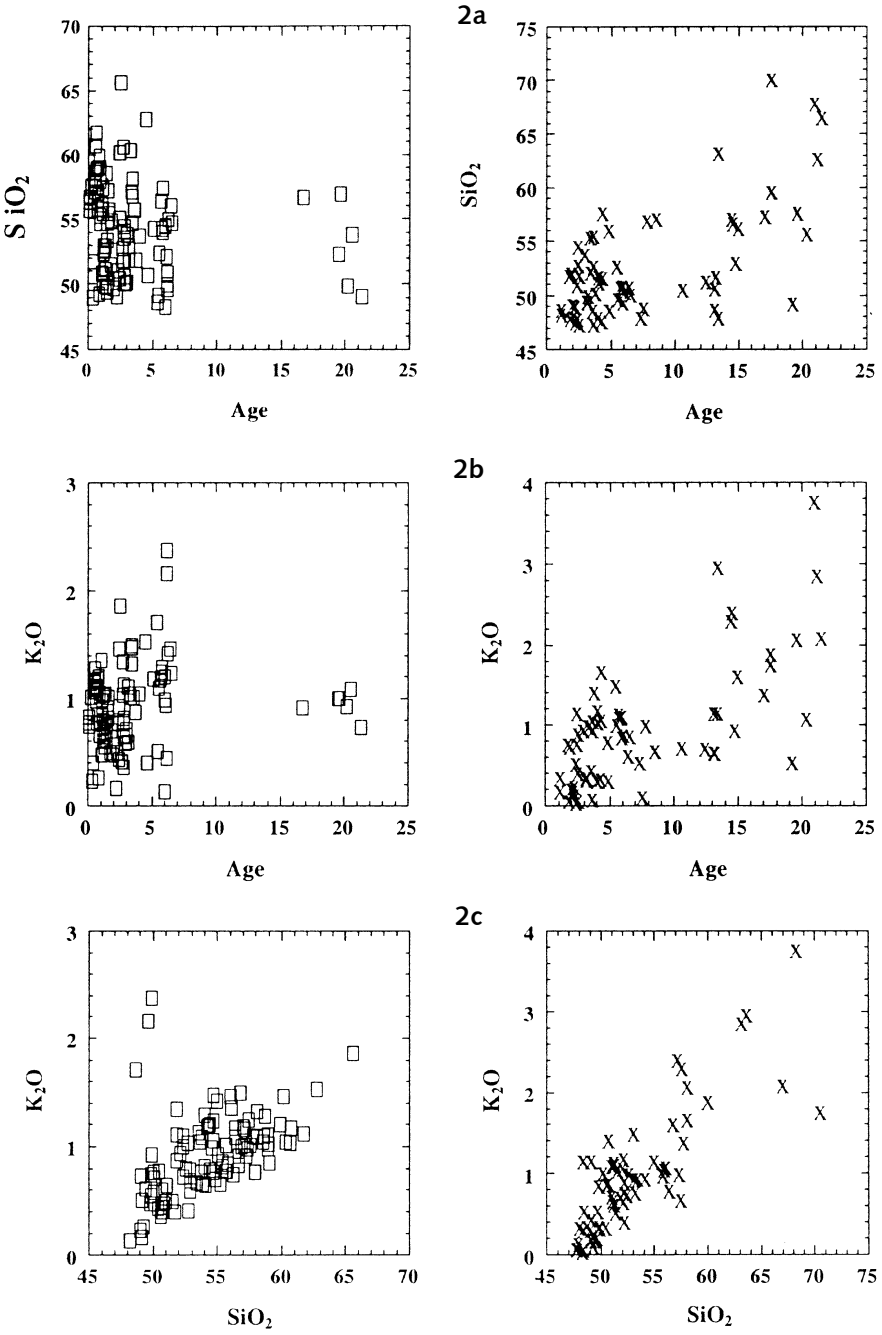

Figure 2. Plots of silica (SiO_2) and potash (K_2O) versus age and each other, with samples from the north of Oregon Route 66 in the left-hand diagrams and samples from the south of that line in the right-hand diagrams. Values are weight percent for chemical content and million years for age.

(Potassium can serve as an indicator for other large ionic lithophile [LIL] elements, too.) Notable results of the plot are that (1) the K_2O content of the samples older than 7.4 Ma decreases, both north and south, with decreasing age and (2) all southern samples with $K_2O > 2$ per cent are mid-Miocene in age or older.

In Figure 2c, which depicts the K_2O-SiO_2 relationship of the samples, there are two idiosyncratic groupings in the northern area: the high-K_2O/low-silica samples that are LIL-enriched mafic basalts marking the renewal of volcanism between 7 and 6 million years ago, and a large group of samples that originate from one small area south of Lake of the Woods in Oregon. The data points from the southern region are much more contiguous except at the high-silica end, where they are more scattered. Cursory examination of the two diagrams in Figure 2c in the silica range of 50–60 per cent provides two insights: First, the data points can be thought of as constituting two parallel lines each, offset from one another with some scatter and with K_2O increasing as SiO_2 increases. One interpretation of the lines showing higher K_2O content is that they represent batches of magma that had greater crustal residence times and therefore more time for assimilation to occur, before they were extruded onto the Earth's surface. Second, the slopes of the trends depicted are different for the two regions, indicating that the K_2O values at 55 per cent SiO_2 may reflect significantly thicker or less dense continental crust and/or a more steeply inclined subduction zone in the southern region—which perhaps implies the existence of a major tear fault in the subducted plate in the vicinity of the arbitrarily selected boundary between the two regions described in this study.

Nearly a decade ago, Guffanti and Weaver (1988) proposed a division of the Cascade volcanic arc into five segments defined on the basis

(Continued on page 107)

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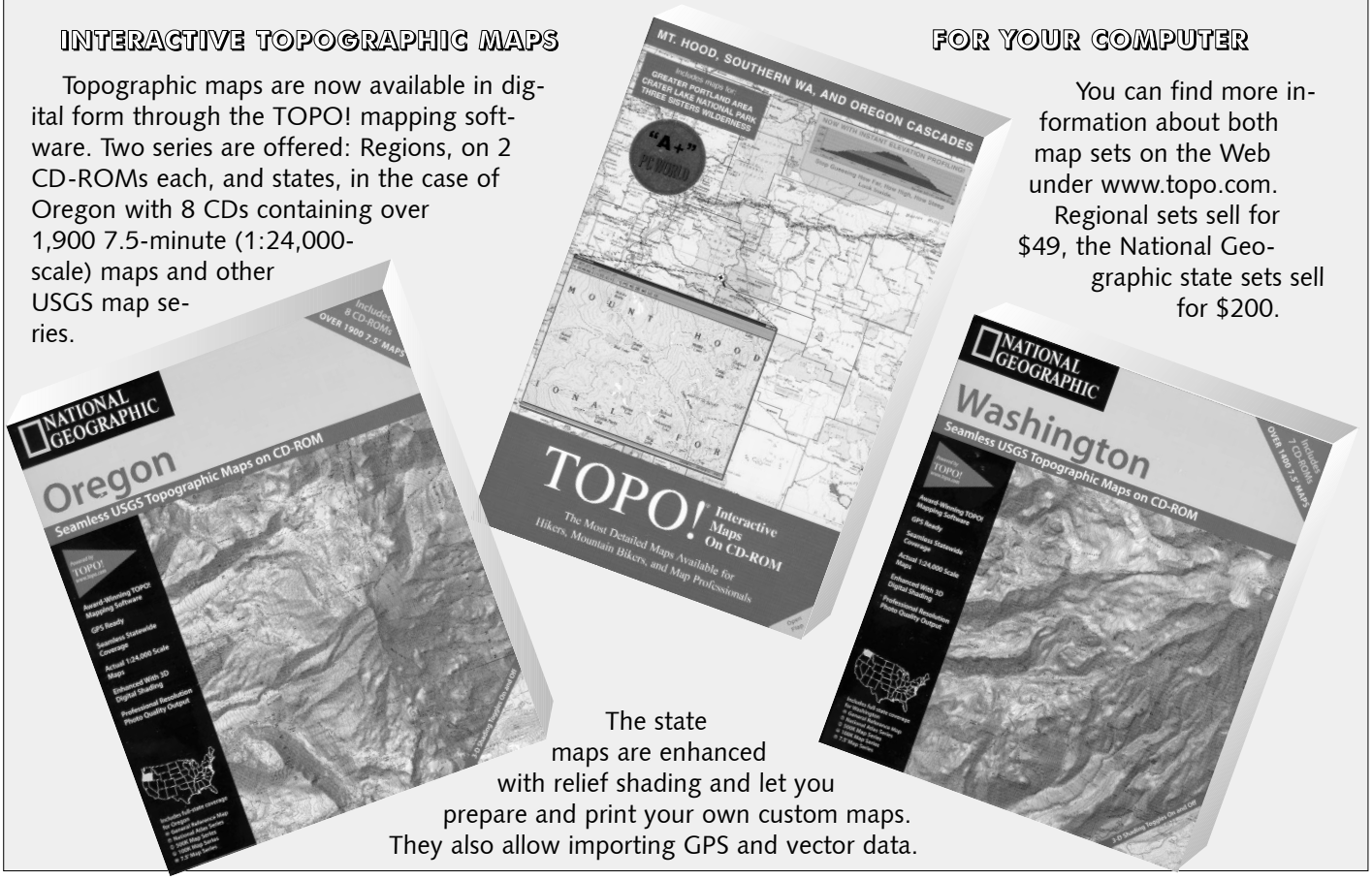

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(Continued from page 102)

of spatial, temporal, and compositional distribution of the constituent volcanoes. The boundary between their segments three and four was essentially the state boundary between Oregon and California. In a later gravity study, Blakely and Jachens (1990) found their gravity data consistent with much of the interpretation by Guffanti and Weaver (1988). However, they located the structural boundary equivalent to the boundary between segments three and four of Guffanti and Weaver (1988) farther north by approximately 30 km. That location is nearly coincident with the regional boundary employed in this study.

Blakely and Jachens pointed out that the Guffanti-Weaver segment boundary in question was, according to Guffanti's own judgment, the least constrained of all their boundaries; it was based on a change in the ratio between andesitic and basaltic vents but not on published chemical analyses, which appeared in 1989 (Blakely and Jachens, 1990, p. 19,447 to -48). The detailed and plentiful geochemistry presented in the present paper supports the structural boundary suggested by the isostatic residual gravity data of Blakely and Jachens (1990). In further discussions by Blakely and others (1997), the authors go on to effectively argue from a geophysical perspective that the northeast-trending gravity anomalies are most likely caused by upper crustal structures that predate the early Miocene through Pleistocene volcanism discussed in this paper. These crustal structures reflected in the gravity data control to some degree the locations of Cascade volcanism. Thus, Cascade segmentation may be influenced by similar effects.

During the earliest phase of renewed volcanism in the northern segment between 7 and 6 million years ago, many varieties of volcanic rocks were extruded, particularly basalts. They are best exposed in the vicinity of Robinson Butte, particularly in the small canyons cut by both the North and South Fork Little Butte Creeks. Initial igneous activity after a 10-million year hiatus runs the gamut from nepheline-normative trachybasalt (Figure 3), which contains >1 weight percent P_2O_5 and 2,000 ppm Sr, to low-K_2O, high-alumina olivine tholeiite basalts, to several basalts that are quartz normative. In addition, a thick andesite lava flow that contains, in textural equilibrium, a phenocryst mineral assemblage of

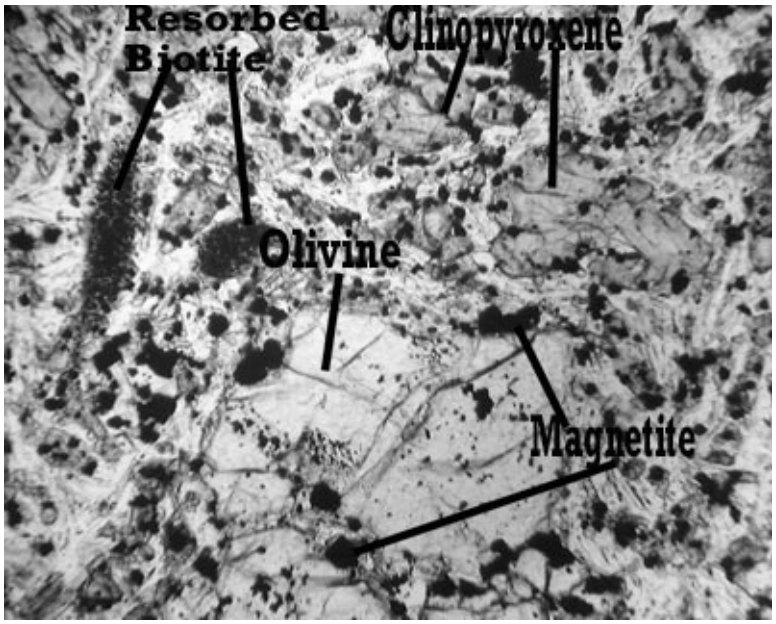

Figure 3. Thin section photomicrograph of a 6-m.y.-old trachybasalt. Image is 3mm × 2mm.

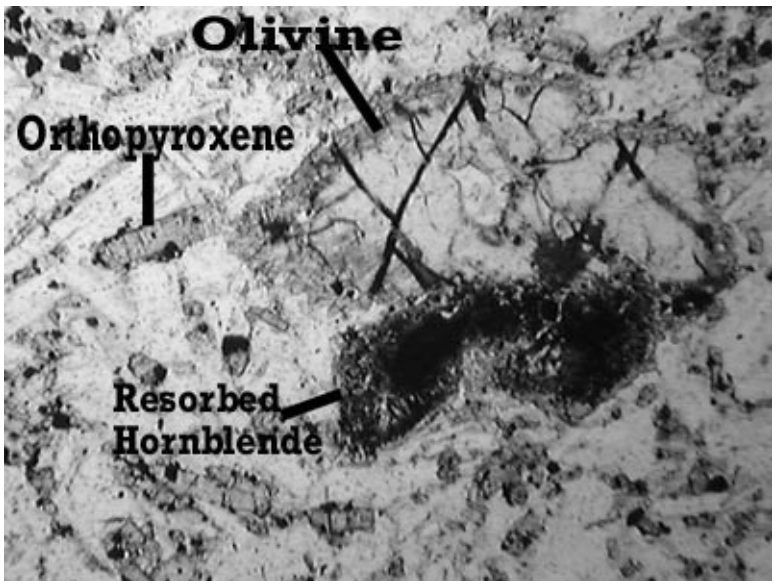

Figure 4. Thin section photomicrograph of hornblende-olivine textural relationship in a 5.6-m.y.-old andesite flow. Image is 3mm × 2mm.

hornblende and olivine is presently exposed in an abandoned trap-rock quarry 3.3 mi southwest of Mount McLoughlin. This unusual mineral assemblage is depicted in Figure 4 and suggests a crystallization depth of 30–40 km for the olivine and the co-precipitating hornblende at elevated P_{H_2O}. Why such a wide variety of extrusive igneous rocks, especially the LIL-enriched basalts, in this relatively small area in southern Oregon at this period of geologic time? I fully realize that "correlation is not causality," but one has to wonder about the coincidence of this unusually diverse occurrence of volcanic rocks and the segmentation boundary proposed by Blakely and Jachens (1990). Perhaps these contact zones

(Continued on page 120)

Table 1. K-Ar analytical results from volcanic rocks of the southern Oregon and northern California Cascades. Samples are listed by their quadrangle location, with quadrangles in alphabetic order and divided into Oregon and California quadrangles. Ar* = radiogenic Ar. E = ×10.

Sample number	T. (S.)[1]	R. (E.)[1]	Sec.	UTM	Lithology[2]	Percent K_2O	$^{40}Ar^*$/gm	Percent $^{40}Ar^*$	Age (Ma)
Oregon									
Aspen Lake									
92-81	37	6	10	573890E4690150N	2 pyr. And.	1.17	9.539E-13	17.07	0.57 ± 0.10
92-82	37	6	10	574430E4690890N	2 pyr., ol. B.A.	0.98	1.60E-12	16.22	1.13 ± 0.02
92-83	37	6	10	574770E4691390N	2 pyr. And.	1.04	2.029E-12	35.92	1.36 ± 0.04
92-27	37	6	26	575290E4685000N	ol., 2 pyr. B.A.	1.16	7.773E-13	6.72	0.47 ± 0.04
92-47	37	6	21	573320E4687210N	2 pyr. And.	0.85	9.449E-13	14.85	0.77 ± 0.04
92-48	37	6	22	574130E4687980N	ol. B.A.	1.06	1.305E-12	9.95	0.86 ± 0.02
Brown Mtn.									
91-69	37	4	16	553580E4689280N	ol., cpx B.A.	1.49	7.34E-12	61.21	3.42 ± 0.06
91-68	37	4	24	558540E4687570N	ol., 2 pyr. B.A.	1.32	6.43E-12	48.74	3.38 ± 0.06
91-76	37	5	30	560480E4685340N	ol-phyric B.	0.77	3.06E-12	35.28	2.77 ± 0.05
91-39	38	5	6	560440E4683270N	ol-phyric B.	0.58	2.44E-12	39.53	2.92 ± 0.07
91-63	37	4	26	555750E4685200N	ol, cpx B.	0.66	2.81E-12	35.65	2.96 ± 0.06
91-43	38	4	4	552830E4682560N	cpx, ol B.A.	1.29	1.08E-11	54.37	5.82 ± 0.17
91-44	38	4	4	552800E4682690N	cpx, ol B.	0.4	2.65E-12	22.3	4.60 ± 0.34
91-46	37	4	32	552140E4684400N	ol, cpx B.A.	1.18	8.64E-12	66.33	5.08 ± 0.13
91-84	38	5	19	560630E4677920N	hbl, 2 pyr. And.	1.25	1.04E-11	72.40	5.77 ± 0.09
91-85	38	5	19	559340E4677760N	2 pyr, ol B.	0.65	2.61E-12	45.11	2.78 ± 0.10
94-16	38	4	23	556180E4677690N	ol,cpx B.	0.47	1.34E-12	5.52	1.97 ± 0.08
94-20	38	4	11	555670E4680720N	ol, cpx-phyric B.A.	1.11	5.06E-12	41.82	3.16 ± 0.12
94-21A	38	4	10	554850E4681630N	ol, cpx B.	0.71	3.03E-12	43.17	2.96 ± 0.11
AL94-51	38	4	12	557520E4681380N	ol B.	0.41	1.55E-12	14.29	2.63 ± 0.32
RSP-131	37	4	20	551600E4686870N	ol, cpx B.	2.39	2.12E-11	80.02	6.14 ± 0.15
84-16	37	4	8	552220E4689980N	ol, cpx B.	0.4	2.12E-13	1.07	0.40 ± 0.30
Chicken Hills									
95-16	40	6	35	576170E4654930N	ol., cpx B.	0.42	6.867E-13	10.67	1.14 ± 0.19
95-20	41	6	10	575010E4652620N	ol B.	0.93	8.853E-12	56.68	6.6 ± 0.19
95-21	40	6	12	577580E4662100N	ol., cpx B.	1.25	NA	47.20	4.10 ± 0.1
95-22	40	6	12	577380E4661950N	ol B.	0.37	2.655E-12	42.44	4.98 ± 0.18
95-25	40	6	23	576370E4659010N	2 pyr., ol. B.A.	1.74	1.10E-11	28.58	4.39 ± 0.24
95-28	40	6	10	574020E4661780N	ol. B.	1.01	5.37E-12	50.11	3.69 ± 0.11
95-48	40	7	6	578540E4663180N	ol. B.	0.81	2.232E-13	10.11	1.91 ± 0.34
95-50	40	6	12	578050E4662260N	ol., cpx B.	0.59	NA	27.90	2.4 ± 0.1
95-59	40	6	14	576760E4660040N	ol. B.	0.37	2.171E-12	29.19	4.07 ± 0.22
95-61	40	6	1	578590E4663130N	ol. B.	0.96	3.507E-12	36.61	2.54 ± 0.11
95-70	40	7	32	580260E4655690N	ol. B.	0.17	1.871E-12	2.27	7.6 ± 6.6
95-71	40	6	23	575620E4659070N	ol. B.A.	1.06	5.845E-12	20.26	3.83 ± 0.32
95-74	41	7	4	582180E4653380N	ol. B.	0.95	8.429E-12	60.49	6.15 ± 0.17
96-10	41	6	4	573380E4653900N	ol., cpx B.	1.16	9.85E-12	43.19	5.9 ± 0.2
AG95-87	40	6	13	576960E4659740N	ol. B.	1.12	7.05E-12	19.01	4.37 ± 0.39
SR-64	40	6	26	576310E4657150N	ol. B.	0.11	NA	8.90	2.4 ± 0.5
SR-106	40	6	28	572760E4656510N	ol. B.	0.92	7.90E-12	60.27	5.95 ± 0.16
97-51	40	6	16	573130E4659960N	ol. B.A.	1	5.30E-12	49.29	3.7 ± 0.1
MH95-33	40	7	31	579780E4655720N	ol. B.	0.25	4.106E-13	4.73	1.14 ± 0.30
Devils Peak									
96-20	34	6	6	568960E4722780N	2 pyr., ol. And.	1.28	1.047E-12	18.78	0.57 ± 0.05
96-22	34	6	6	568520E4722540N	2 pyr., hbl And.	1.12	9.688E-13	19.98	0.60 ± 0.05

[1] All sample locations in California differ in Township and Range notation from those in Oregon and, therefore, are marked accordingly.
[2] B. = Basalt; TrB. = Trachybasalt; B.A. = Basaltic Andesite; And. = Andesite; D. = Dacite; T. = Tuff; ol = olivine; pyr = pyroxene; hbl = hornblende; cpx = clinopyroxene

Table 1. (Continued)

Sample number	T. (S.)[1]	R. (E.)[1]	Sec.	UTM	Lithology[2]	Percent K_2O	$^{40}Ar^*$/gm	Percent $^{40}Ar^*$	Age (Ma)
Hamaker Mtn.									
95-3	40	7	22	584770E4658360N	2 pyr., ol. B.A.	1.01	4.314E-12	20.62	2.96 ± 0.24
95-4	40	7	16	583260E4660560N	2 pyr., B.A.	1.22	4.408E-12	53.28	2.51 ± 0.07
MH95-39	40	7	33	583260E4655080N	2 pyr., ol. B.A.	1.74	7.227E-12	27.33	2.88 ± 0.17
Lake of the Woods North									
BS92-77	36	5	4	563120E4702350N	ol. B.	0.48	7.74E-13	15.61	1.12 ± 0.05
CG-100	35	5	35	565480E4703360N	ol. B.	0.55	1.05E-12	26.67	1.32 ± 0.06
92-75	35	5	34	564830E4702680N	2 pyr., ol. B.A.	1.36	2.00E-12	4.74	1.02 ± 0.09
86-62	36	5	1	568050E4701820N	opx, ol. And.	1.01	3.1E-13	0.48	0.21 ± 0.18
92-73	36	5	24	567880E4697710N	ol. B.	0.47	7.82E-13	7.25	1.16 ± 0.05
92-77	36	5	14	566320E4697920N	ol. B.	1.03	1.81E-12	29.30	1.22 ± 0.04
MG91-63	36	5	15	564430E4698840N	ol. B.	0.36	1.44E-12	18.84	2.78 ± 0.09
MG91-22	36	5	16	563040E4699310N	ol. B.	0.16	5.03E-13	13.59	2.19 ± 0.14
MG91-56	36	5	16	562800E4698160N	ol., cpx B.A.	1.01	2.29E-12	28.07	1.58 ± 0.03
92-86	36	5	34	565180E4693850N	ol., cpx B.	0.74	1.52E-12	14.77	1.42 ± 0.05
84-52	37	5	4	563070E4692550N	ol. B.	0.61	1.30E-12	11.05	1.48 ± 0.04
92-85	36	6	30	569820E4694820N	ol. B.	0.72	1.18E-12	10.91	1.14 ± 0.10
Lake of the Woods South									
91-3	38	5	3	565210E4681780N	ol. B.	0.26	3.07E-13	3.78	0.82 ± 0.08
91-79	37	5	28	563170E4686240N	2 pyr. And.	1.04	4.87E-12	47.69	3.25 ± 0.05
92-53	37	5	33	562150E4683500N	2 pyr., ol. B.A.	0.7	1.807E-12	38.19	1.79 ± 0.04
RB92-21	37	5	34	564480E4684490N	2 pyr. D.	1.86	6.625E-12	48.73	2.47 ± 0.04
92-43	37	6	29	570310E4686410N	2 pyr., hbl And.	0.98	8.90E-13	8.29	0.63 ± 0.05
92-44	37	6	17	570790E4689480N	2 pyr. And.	1.02	1.355E-12	19.77	0.92 ± 0.02
92-62	37	6	4	570860E4690060N	2 pyr. And.	1.21	1.40E-12	17.87	0.80 ± 0.03
92-63	37	6	8	571750E4691170N	2 pyr. And.	1.11	1.135E-12	12.75	0.71 ± 0.06
92-84	37	6	31	569150E4684120N	2 pyr., ol. B.A.	0.66	8.591E-13	9.68	0.90 ± 0.05
94-5	38	5	2	565520E4682080N	2 pyr. And.	1.46	5.153E-12	50.98	2.45 ± 0.08
92-87	37	5	11	565700E4689880N	ol., 2 pyr. B.A.	1.09	1.059E-12	12.24	0.68 ± 0.09
DH94-50	38	5	12	567080E4681540N	2 pyr., ol. B.A.	0.86	1.333E-12	30.85	1.08 ± 0.05
DH94-106	38	5	2	566970E4682040N	2 pyr. And.	1.03	3.978E-12	36.14	2.68 ± 0.11
JP92-2	37	5	14	566040E4688820N	2 pyr. And.	0.92	2.058E-12	43.81	1.55 ± 0.04
94AH-96	37	5	21	563170E4687310N	2 pyr. And.	1.01	4.83E-12	20.59	3.32 ± 0.27
Little Chinquapin Mtn.									
BS94-53	38	5	30	559590E4675860N	2 pyr., ol. B.	0.78	2.68E-12	13.66	2.39 ± 0.31
94-14	38	4	26	556500E4676720N	ol. B.	0.65	2.081E-11	30.29	2.22 ± 0.12
Mares Egg Spring									
96-28	33	6	28	57194E472649N	2 pyr., ol. And.	0.77	9.841E-13	21.80	0.89 ± 0.07
Mount McLoughlin									
84-62	36	5	32	561680E4693150N	cpx, ol. B.	0.59	2.66E-12	22.52	3.14 ± 0.07
84-50	36	5	17	560790E5697980N	cpx, ol. B.A.	0.93	3.24E-12	23.27	2.42 ± 0.15
84-48	36	4	13	558480E4698420N	cpx, ol. B.A.	0.78	1.03E-14	2.31	0.08 ± 0.03
84-21	36	4	27	554880E4694980N	2 pyr., ol. B.A.	1.21	1.04E-11	39.02	5.97 ± 0.36
84-38	36	4	14	556350E4699160N	2 pyr., ol. B.A.	0.78	6.27E-14	~0.0	<0.15
91-89	36	4	20	551420E4697090N	hbl, ol., 2 pyr. And.	1.16	9.39E-12	63.2	5.62 ± 0.09
M91-85	36	4	16	552530E4698290N	2 pyr., ol. And.	1.46	1.35E-11	65.97	6.43 ± 0.10
HC-44	37	4	4	553930E4692520N	cpx, ol B.A.	1.04	5.94E-12	23.5	3.97 ± 0.08
HC-49	37	4	2	556480E4692740N	2 pyr., ol. And.	0.91	2.18E-12	24.75	1.67 ± 0.03
HC-67	37	4	2	556420E4692120N	2 pyr., ol. B.A.	1.01	5.18E-12	50.95	3.56 ± 0.06
91-49	36	4	15	555350E4698770N	2 pyr., ol. B.A.	0.83	6.37E-14	0.73	0.05 ± 0.03
91-52	36	4	10	554860E4699940N	2 pyr., ol. B.A.	0.74	8.93E-14	2.27	0.08 ± 0.03
14-K-1	36	4	35	555810E4694330N	ol., cpx B.A.	1.47	7.26E-12	65.37	3.43 ± 0.06
92-66	35	5	31	559230E4703520N	ol. B.	0.5	1.26E-12	7.43	1.76 ± 0.08

Table 1. (Continued)

Sample number	T. (S.)[1]	R. (E.)[1]	Sec.	UTM	Lithology[2]	Percent K_2O	$^{40}Ar^*$/gm	Percent $^{40}Ar^*$	Age (Ma)
Mule Hill									
95-29	40	6	8	570930E4661380N	ol., 2 pyr. B.A.	1.42	1.277E-11	61.08	6.24 ± 0.17
95-30	40	5	23	565660E4658700N	ol. B.	0.47	1.742E-12	18.56	2.57 ± 0.24
95-33	40	5	24	567930E4658280N	ol., cpx B.	0.21	6.839E-13	15.34	2.26 ± 0.26
95-75	40	6	30	569830E4657290N	ol., cpx B.	0.31	1.013E-12	16.56	2.27 ± 0.24
95-77	40	5	2	565610E4662470N	2 pyr., ol. B.A.	1.05	5.20E-12	43.81	3.44 ± 0.12
95-26	41	6	9	572380E4652500N	ol. B.	0.61	6.523E-12	64.80	7.41 ± 0.19
96-1	41	6	8	571560E4652560N	cpx, ol. B.	1.18	1.016E-11	40.02	5.97 ± 0.23
96-2	41	6	8	571180E4652610N	ol., cpx B.	0.42	1.956E-12	21.15	3.23 ± 0.25
96-3	41	6	5	570980E4652750N	ol. B.	1.07	8.559E-12	47.27	5.55 ± 0.18
96-5	41	6	6	569800E4653890N	ol. B.	1.2	1.00E-11	41.58	5.80 ± 0.2
96-6	40	5	36	568380E4655340N	ol. B.	1.22	2.375E-11	53.53	13.5 ± 0.4
96-7	40	5	36	568380E4655340N	cpx And.	2.36	4.936E-11	47.50	14.5 ± 0.5
96-8	40	6	31	569060E4655170N	ol. B.	1.22	2.33E-11	77.86	13.2 ± 0.3
96-9	41	6	5	570980E4653080N	cpx, ol. B.	0.13	4.86E-13	11.29	2.6 ± 0.4
97-22	40	5	3	565230E4663570N	ol. B.	0.43	1.51E-12	20.17	2.4 ± 0.2
97-35	41	6	5	570560E4652730N	ol., cpx B.	0.41	1.40E-11	32.71	3.26 ± 0.16
97-37	41	6	7	570340E4652200N	D.	2.15	6.71E-11	71.42	21.6 ± 0.5
97-46	41	5	1	567880E4652630N	ol., cpx B.	0.39	1.78E-12	26.75	3.2 ± 0.2
97-47	41	5	1	567850E4652800N	cpx, ol. B	0.13	3.62E-12	6.44	1.9 ± 0.3
97-54	41	6	9	572380E4652500N	hbl-bearing D.	2.46	4.78E-11	42.89	13.5 ± 0.5
97-55	41	6	7	570340E4652200N	Rhyolite	1.82	4.644E-11	26.67	17.6 ± 0.7
CW6-5	40	5	35	565540E4654340N	ol., cpx B.	0.28	8.38E-13	6.49	2.1 ± 0.3
CW6-9	40	5	36	566950E4654320N	cpx And.	1.68	3.64E-11	82.88	15.0 ± 0.4
CW9-13B	40	5	11	566160E4661520N	ol., cpx B.	0.14	7.373E-13	25.03	3.66 ± 0.24
S97-21	40	6	31	568800E4654930N	ol., cpx And.	2.47	5.192E-11	24.95	14.6 ± 0.9
S97-62	40	5	13	568410E4660800N	cpx, ol. B.A.	1.57	1.24E-11	39.07	5.5 ± 0.2
S97-87	40	5	1	567350E4663000N	ol., 2 pyr B.	1.48	8.091E-12	66.02	3.79 ± 0.10
97-54Z	41	6	9	572380E4652500N	And. T.	1.45	3.592E-11	33.89	17.1 ± 0.8
JM97-27D	48	3	14	567960E4650440N	ol. B.	1.16	9.75E-12	63.07	5.83 ± 0.15
Parker Mtn.									
95-34	40	5	7	559730E4661480N	ol. B.A.	0.83	2.968E-12	5.39	2.48 ± 0.50
97-2	41	5	5	561420E4654000N	cpx, ol. B.	0.25	8.03E-13	8.16	2.2 ± 0.3
97-16	40	4	36	558690E4654810N	ol., cpx B.	0.69	6.49E-12	42.74	6.5 ± 0.2
97-41	40	5	8	560470E4660720N	ol. B.	0.84	2.22E-12	9.69	1.8 ± 0.2
86-85	48N	4W	19	554350E4650280N	ol., cpx B.	0.51	2.672E-12	16.64	3.64 ± 0.38
Pelican Bay									
92-74	36	6	34	574070E4694640N	ol. B.A.	0.84	1.363E-12	10.09	1.13 ± 0.09
92-89	36	6	10	573240E4699800N	ol. B.	0.6	1.034E-12	11.24	1.20 ± 0.04
92-80	36	6	3	573430E4702260N	2 pyr., ol. And.	1.09	7.086E-13	10.94	0.45 ± 0.04
AG92-75	36	6	27	573970E4695170N	2 pyr. B.A.	0.76	1.608E-12	16.85	1.47 ± 0.04
Pelican Butte									
86-59	35	6	20	570270E4706940N	ol, 2 pyr And.	1.1	8.48E-13	4.26	0.54 ± 0.05
92-91	35	6	20	571500E4705900N	2 pyr And.	1.1	8.62E-13	13.60	0.54 ± 0.05
96-11	35	5	2	565610E4711220N	ol B.	0.69	1.225E-12	25.04	1.23 ± 0.08
96-13	34	6	30	569830E4714120N	ol B.	0.79	1.506E-12	25.91	1.32 ± 0.08
96-17	34	6	18	568960E4717660N	ol B. A.	0.82	1.94E-12	3.01	1.64 ± 0.40

Table 1. (Continued)

Sample number	T. (S.)[1]	R. (E.)[1]	Sec.	UTM	Lithology[2]	Percent K_2O	$^{40}Ar^*$/gm	Percent $^{40}Ar^*$	Age (Ma)
Robinson Butte									
91-61	37	4	7	549310E4690380N	2 pyr. And.	1	2.84E-11	87.29	19.6 ± 0.3
92-21	37	4	19	549130E4687930N	ol., cpx TrB.	2.16	1.907E-11	66.11	6.13 ± 0.10
92-24	37	3	13	549060E4688670N	ol., 2 pyr. B.A.	1.09	3.234E-11	88.48	20.5 ± 0.3
JB91-56	37	4	18	550220E4688230N	ol., cpx TrB.	1.71	1.318E-11	75.03	5.35 ± 0.09
92-26	37	3	14	546460E4688530N	ol., B.	0.93	2.725E-11	74.76	20.2 ± 0.3
92-41	37	3	23	546830E4688050N	ol., 2 pyr. B.A.	1	2.826E-11	53.15	19.5 ± 0.3
94-40	37	3	35	546830E4684510N	ol. B.	0.51	3.99E-12	46.08	5.43 ± 0.18
RSP-94	37	4	20	551370E4686920N	ol., 2 pyr. B.A.	1.19	9.835E-12	67.42	5.73 ± 0.15
94-42	37	4	31	549980E4683960N	ol., 2 pyr. B.A.	1.1	8.777E-12	63.64	5.54 ± 0.15
Rustler Peak									
86-47	35	4	14	556560E4707940N	ol. B.A.	0.67	1.365E-12	25.46	1.42 ± 0.09
86-48	34	4	16	553570E4718550N	hbl. And.	1.53	9.767E-12	45.37	4.43 ± 0.15
Spencer Creek									
95-68	39	7	20	580350E4667530N	ol. B.	0.8	1.375E-12	17.72	1.19 ± 0.11
95-69	39	7	29	581460E4666740N	ol. B.	0.13	3.703E-13	6.00	2.0 ± 0.3
Surveyor Mountain									
95-46	39	6	19	570060E4668640N	ol., 2 pyr. B.A.	0.82	3.25E-12	27.26	2.76 ± 0.16
91-21	38	5	35	567030E4674140N	ol. B.	0.76	2.06E-12	14.82	1.88 ± 0.22
94-36	38	5	28	562740E4676280N	cpx, ol. B.A.	1.13	4.52E-12	41.82	2.78 ± 0.10
91-15	38	5	21	562460E4676880N	ol. B.	0.5	1.67E-12	34.00	2.32 ± 0.11
97-28	39	5	35	565680E4664840N	cpx, ol. B.	0.87	4.60E-12	10.51	3.7 ± 0.3
94-4	38	5	34	565150E4674700N	ol., 2 pyr. B.A.	0.79	3.20E-12	30.62	2.81 ± 0.14
Willow Lake									
84-26	36	4	18	549660E4699130N	ol. B.A.	0.99	8.57E-11	48.32	6.01 ± 0.30
91-60	37	4	6	550340E4692860N	ol. B.	0.94	8.21E-11	67.63	6.06 ± 0.10
JB91-41	37	4	6	549550E4692920N	ol. B.	0.44	3.875E-12	42.50	6.11 ± 0.21
91-89	36	4	20	551420E4697090N	hbl., ol., 2 pyr. B.A.	1.16	9.39E-12	63.20	5.62 ± 0.09
KWW33-91	36	4	18	549760E4698310N	ol., 2 pyr. B.A.	1.24	1.16E-11	62.19	6.48 ± 0.10
KWW25-91	36	4	8	551140E4699920N	ol., 2 pyr. B.A.	0.78	7.39E-13	13.08	0.66 ± 0.02
California									
Copco									
86-88	48N	4W	29	554910E4648520N	ol. B.	1.1	6.508E-12	15.86	4.11 ± 0.45
86-92	48N	4W	30	553530E4648620N	hbl. And.	0.75	9.289E-12	14.87	8.59 ± 0.59
Panther Rock									
97-66	46N	3W	14	568690E4630910N	hbl. And.	1.15	3.40E-11	65.56	20.4 ± 0.5
Secret Spring									
B'3	48N	2W	30	571540E4647080N	2 pyr., ol. B.A.	1.01	2.18E-11	54.46	15.0 ± 0.4
B'317	48N	2W	30	571540E4647080N	2 pyr., ol. B.A.	0.32	2.00E-12	19.00	4.35 ± 0.39
B'3	48N	2W	30	569910E4649580N	ol. B.	1.01	2.12E-11	61.54	14.5 ± 0.4
Anders-1	48N	3W	22	567100E4647890N	Dacite T.	3.85	1.17E-10	74.99	21.0 ± 0.5
K97-78	48N	2W	20	572320E4648530N	cpx, ol. B.	0.78	1.41E-11	27.39	12.5 ± 0.5
97-68	48N	3W	32	563520E4636540N	ol. B.A.	1.12	5.99E-12	62.52	3.7 ± 0.1
A24	48N	3W	25	569070E4647020N	ol. B.	0.61	1.70E-11	63.29	19.25 ± 0.51
A73	48N	3W	23	567600E4648290N	pyr. D.	2.92	8.95E-11	66.65	21.17 ± 0.54
K97-43	48N	2W	30	570610E4647510N	ol. B.	0.73	1.39E-11	24.37	13.19 ± 0.80
L-24	47N	3W	1	569540E4644070N	ol., 2 pyr. B.A.	0.86	6.12E-12	39.30	4.94 ± 0.19
97-53	48N	3W	26	567890E4646770N	2 pyr. And.	2.14	6.06E-11	47.29	19.6 ± 0.6
L-42	48N	3W	27	566610E4646570N	2 pyr. And.	1.06	1.21E-11	32.64	7.9 ± 0.4
K97-24	48N	2W	30	571850E4647060N	cpx, ol. B.	0.72	1.38E-11	62.70	13.3 ± 0.4
JM97-16	48N	3W	24	570170E4649320N	pyr., And. T.	1.95	4.96E-11	45.69	17.6 ± 0.6
K97-23[3]	48N	2W	30	571710E4647080N	cpx, ol. B.	0.79	1.22E-11	53.93	10.7 ± 0.3

[3] Sample from neck of Secret Spring volcano exposed by a large landslide. Age listed is a minimum age.

Table 2. Major- and trace-element whole-rock chemical analyses for each of the samples for which a K-Ar age . . . ⇨

Quad./sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3T	Rb	Sr	Y	Zr	V
Oregon																			
Aspen Lake																			
92-81	60.70	0.67	17.81	2.98	2.49	0.09	3.09	6.31	3.78	1.17	0.15	0.55	99.79	5.75	16.7	982	15	63	125
92-82	57.34	0.60	19.10	1.87	3.89	0.09	3.90	7.55	3.60	0.98	0.10	1.04	100.06	6.19	14.4	800	13.2	44	136
92-83	58.54	0.65	18.84	2.89	2.75	0.08	3.05	7.11	3.86	1.04	0.12	0.80	99.73	5.95	18.3	788	15.1	55	134
92-27	57.10	0.87	17.55	1.88	5.04	0.12	4.22	7.36	3.45	1.16	0.27	1.05	100.07	7.48	19.5	614	21.5	113	154
92-47	59.02	0.68	18.48	2.47	3.38	0.10	3.69	7.17	3.88	0.85	0.13	0.29	100.14	6.23	13	1,215	14.2	50	131
92-48	54.69	1.01	17.44	3.25	4.54	0.14	4.60	7.30	3.86	1.05	0.39	0.92	99.19	8.30	17.1	606	26.8	140	167
Brown Mtn.																			
91-69	56.77	1.01	17.15	3.30	4.10	0.12	4.02	6.96	4.01	1.49	0.26	0.58	99.77	7.86	24.8	599	34	132	181
91-68	58.07	0.84	17.54	3.02	3.82	0.12	3.40	6.56	4.67	1.32	0.18	0.86	100.40	7.27	23.6	640	26.6	98	158
91-76	50.04	0.95	14.97	3.63	5.01	0.15	10.63	9.82	2.67	0.77	0.33	0.72	99.69	9.20	8.3	981	21.1	74	201
91-39	50.01	0.99	16.07	2.64	6.07	0.15	9.38	9.88	2.95	0.58	0.31	0.39	99.42	9.39	5.1	737	23.8	80	198
91-63	53.83	0.73	17.36	3.10	4.22	0.12	6.41	9.41	3.38	0.66	0.16	0.55	99.93	7.79	7.4	905	14.6	35	210
91-43	54.01	1.14	17.10	5.60	3.68	0.12	3.50	7.26	3.85	1.29	0.50	1.57	99.62	9.69	12.1	811	37.4	130	192
91-44	50.70	0.68	16.10	2.40	5.90	0.15	9.11	10.68	2.49	0.40	0.15	0.91	99.67	8.96	5.3	566	16.3	32	247
91-46	54.20	1.15	17.75	3.52	4.50	0.14	4.38	7.87	4.10	1.18	0.50	0.76	100.05	8.52	11.1	920	33.5	118	194
91-84	57.41	0.78	17.50	4.27	2.49	0.08	3.08	6.46	4.13	1.25	0.25	1.82	99.52	7.04	9.7	1,014	23.3	72	144
91-85	54.08	0.91	17.16	3.06	5.09	0.14	6.28	8.41	3.39	0.65	0.21	0.41	99.79	8.72	11.4	557	21.4	67	194
94-16	49.71	1.20	18.09	1.39	7.79	0.16	6.74	10.25	3.20	0.47	0.20	1.26	100.46	10.05	6.8	469	30	68	229
94-20	51.86	1.04	16.76	5.30	3.08	0.13	6.85	9.16	3.92	1.11	0.44	0.49	100.14	8.72	11.9	1,283	17	104	225
94-21A	50.09	0.88	16.70	4.08	4.97	0.15	8.21	10.02	3.23	0.71	0.33	1.18	100.55	9.60	8.5	875	18.3	64	233
AL94-51	52.75	0.93	18.08	2.30	5.81	0.14	5.37	8.13	3.68	0.41	0.25	1.60	99.45	8.76	3.8	683	19.2	78	175
RSP94-131	49.77	1.07	15.56	5.41	3.10	0.14	7.49	9.70	3.35	2.39	0.64	0.74	99.36	8.86	22.4	2,246	19.2	140	210
84-16	51.70	0.95	18.05	2.33	5.88	0.14	6.84	9.98	3.19	0.40	0.13	0.88	100.47	8.86	4.9	811	21.1	53	210
Chicken Hills																			
95-16	48.77	1.46	16.91	2.54	7.75	0.17	8.19	9.68	2.97	0.42	0.27	0.97	100.10	11.15	4.8	444	26.6	112	247
95-20	50.63	1.46	17.97	5.65	4.84	0.16	5.16	7.96	4.02	0.93	0.51	0.95	100.24	11.03	7.8	747	25.4	112	195
95-21	52.17	1.19	17.11	4.66	3.99	0.14	5.61	8.73	3.72	1.25	0.39	1.02	99.98	9.09	12.9	1,052	19.7	117	205
95-22	49.06	1.04	18.35	4.45	4.59	0.15	6.63	9.69	3.40	0.37	0.28	1.59	99.60	9.55	2	793	17.1	55	249
95-25	58.15	1.13	17.12	3.06	4.06	0.11	2.60	6.28	4.34	1.74	0.31	0.95	99.85	7.57	28.9	677	20	147	210
95-28	53.23	1.27	17.25	2.47	6.24	0.15	5.53	8.46	3.62	1.01	0.39	0.85	100.47	9.40	13.8	663	26	125	225
95-48	52.50	1.04	17.94	2.24	6.34	0.14	6.35	8.36	3.41	0.81	0.30	0.79	100.22	9.29	9.6	663	20	114	185
95-50	51.46	1.23	17.39	3.05	6.63	0.16	6.59	8.63	3.53	0.59	0.28	0.66	100.20	10.42	7.2	551	21.1	91	191
95-59	48.45	1.31	17.28	4.01	6.58	0.17	7.53	10.40	2.91	0.37	0.21	0.94	100.16	11.32	5	465	22.4	71	245
95-61	52.32	1.17	18.25	3.52	4.86	0.16	5.00	8.37	3.73	0.96	0.38	1.51	100.23	8.92	6.1	854	21.4	145	192
95-70	49.34	1.23	17.16	2.98	6.44	0.16	7.70	11.15	2.93	0.17	0.23	0.67	100.16	10.14	2.4	730	18.8	67	270
95-71	52.68	1.32	17.34	2.70	6.28	0.15	5.34	8.38	3.60	1.06	0.40	1.00	100.25	9.68	13.7	724	20.9	130	199
95-74	50.77	1.33	17.19	4.82	5.31	0.17	6.32	8.36	3.67	0.95	0.52	1.01	100.42	10.72	9.7	650	27.5	120	218
96-10	51.11	1.30	17.62	3.25	6.42	0.17	5.24	8.21	3.76	1.16	0.57	0.62	99.43	10.38	9.7	768	29	139	208
AG95-87	52.12	1.17	16.93	1.08	7.19	0.14	6.46	8.88	3.45	1.13	0.40	1.30	100.25	9.07	10.5	1,062	19	116	200
SR-64	48.34	0.96	17.37	1.55	7.84	0.16	9.11	11.48	2.53	0.11	0.06	0.92	100.43	10.26	2.1	261	22.6	47	226
SR-106	49.85	1.28	17.28	4.94	5.46	0.17	6.46	8.85	3.47	0.92	0.46	0.72	99.86	11.01	10.1	749	29.9	108	182
97-51	53.21	1.25	17.41	2.79	5.92	0.15	5.30	8.25	3.82	1.00	0.40	0.86	100.36	9.37	10.8	692	27	127	220
MH95-33	49.20	1.34	17.10	3.06	6.73	0.16	7.51	10.89	2.92	0.25	0.22	0.43	99.81	10.54	2.8	676	21.4	83	220
Devils Peak																			
96-20	58.66	0.74	17.63	1.95	4.18	0.14	3.88	6.57	3.94	1.28	0.23	0.52	99.72	6.60	18.7	720	19	157	128
96-22	61.66	0.54	18.11	2.35	2.60	0.09	2.68	5.78	4.27	1.12	0.12	0.56	99.88	5.24	15	830	12	80	103
Hamaker Mtn.																			
95-3	54.21	0.96	18.65	2.61	5.21	0.14	4.46	8.02	3.72	1.01	0.33	1.15	100.47	8.40	10.7	776	21.5	148	172
95-4	55.01	1.12	18.09	2.23	5.62	0.14	3.90	7.87	3.92	1.22	0.31	0.97	100.40	8.48	18.6	742	22.1	144	188
MH95-39	53.07	1.13	18.06	4.31	3.94	0.14	4.50	7.91	3.69	1.74	0.51	0.61	99.61	8.69	16.7	1,284	22.8	180	198

. . . is reported. Major-element data are in weight percent; trace-element data are in parts per million (ppm).

Ni	Cr	Nb	Ga	Cu	Zn	Co	Ba	La	Ce	U	Th	Pb	Be	Sc	Yb	Age (Ma)	Hf	Ta	Nd	Sm	Eu	Tb	Lu
77	31	3.9	21.1	45	49	19	439	13	27	1.5	5	6.3	1.3	14	1.3	0.57±0.10	–	–	–	–	–	–	–
36	43	2.9	20.8	62	57	21	303	9	16	0.7	3.4	5	1	17	0.8	1.13±0.02	–	–	–	–	–	–	–
24	16	2	19.1	65	44	20	376	9	20	1.4	4.1	5.9	1.3	17	1.3	1.36±0.04	–	–	–	–	–	–	–
39	49	7.2	21.1	58	72	24	528	17	36	1.7	4.2	8.2	1.6	19	1.9	0.47±0.04	–	–	–	–	–	–	–
21	37	3.2	22.3	24	57	20	316	13	27	1.2	3	4	1	15	0.9	0.77±0.04	–	–	–	–	–	–	–
69	102	8.2	20.7	67	84	28	494	23	43	0.6	3.5	7.1	1.3	21	2.1	0.86±0.02	–	–	–	–	–	–	–
38	91	5.3	21.2	90	73	22	478	15	33	1.7	4.8	6.1	1.5	23	1.8	3.42±0.06	–	–	–	–	–	–	–
17	48	4.2	21.6	57	69	23	455	16	31	2.4	3.4	7.2	1.7	17	1.9	3.38±0.06	–	–	–	–	–	–	–
184	529	4.4	18.2	59	70	42	369	16	34	0.8	3.5	5.4	1.3	29	1.7	2.77±0.05	2.4	0.3	18	3.6	1.15	0.5	0.26
151	356	3.4	18.5	48	69	42	277	15	33	1.8	2.1	3.8	1.4	30	1.9	2.92±0.07	–	–	–	–	–	–	–
28	216	3	20.9	91	65	30	224	9	21	0.7	3.7	4.3	1.3	23	1	2.96±0.06	–	–	–	–	–	–	–
25	63	7.7	21.8	34	79	26	513	23	49	1.6	3.2	5.7	1.7	19	2.3	5.82±0.17	–	–	–	–	–	–	–
127	482	2.6	18.2	70	64	39	181	6	13	1.5	4	3.6	1.3	32	1.2	4.6±0.34	–	–	–	–	–	–	–
27	64	8	22.7	36	71	21	497	22	49	1.7	4.1	4.9	1.8	21	2.9	5.08±0.13	–	–	–	–	–	–	–
25	30	3.7	22.9	87	53	22	404	14	28	0.3	4.1	4.6	1.6	15	1.6	5.77±0.09	–	–	–	–	–	–	–
82	178	4.1	20.8	75	69	32	316	10	24	0.8	4.5	4.6	1.4	23	1.7	2.78±0.10	–	–	–	–	–	–	–
57	166	3.1	20.4	66	69	31	246	12	27	2.5	3.8	3.8	1.2	32	2.7	1.97±0.08	–	–	–	–	–	–	–
54	192	8.3	23.6	80	94	23	476	25.6	50.3	1.8	6.5	4.1	1.7	19	1.7	3.16±0.12	–	–	–	–	–	–	–
76	341	6.9	21.4	78	80	27	305	17	40	1.7	6	3.5	1.4	28	2	2.96±0.11	–	–	–	–	–	–	–
73	153	5.5	20.5	69	73	25	401	13.7	31.9	0.9	2.1	8.9	1	23	1.8	2.63±0.32	–	–	–	–	–	–	–
115	231	2.8	18.4	101	78	33	1925	41.3	103.7	4.5	8.2	7.4	1.5	36	1.8	6.14±0.15	–	–	–	–	–	–	–
48	146	2.6	20.4	67	58	33	167	12	23	0.5	3	3.2	1	26	1.7	0.40±0.30	–	–	–	–	–	–	–
140	284	8.2	19	72	79	39	258	12	29.4	0.8	1.2	6	–	31	2.61	1.14±0.19	2.4	<0.3	15	3.75	1.34	0.8	0.4
63	70	7.4	20.2	56	86	30	531	17	32.3	0.7	0.8	6.6	–	23	2.21	6.6±0.19	2.5	<0.3	20	4.68	1.53	0.7	0.35
69	104	6.6	20.6	73	80	28	592	19.2	47.2	0.8	2.7	6.2	2.7	23	1.72	4.1±0.1	0.6	23	4.74	1.47	0.6	0.27	–
107	128	4.4	19.7	79	81	31	353	8.8	30.6	0.2	0.9	5.4	–	28	–	4.98±0.18	–	–	–	–	–	–	–
11	24	6.9	20.8	43	72	17	581	15.9	41.2	1.8	4.1	10.3	–	20	–	4.39±0.24	–	–	–	–	–	–	–
56	100	9.1	20.6	78	83	26	449	16	43.7	1.1	1.6	8.3	–	25	–	3.69±0.11	–	–	–	–	–	–	–
123	181	6.8	19.9	66	79	28	382	15.7	38.7	0.6	1.3	7.9	<.3	24	2.01	1.91±0.34	2.4	19	3.78	1.32	0.6	0.27	–
98	170	5.2	19.3	72	76	30	286	9.7	30.1	0.4	0.8	7.7	2.2	24	2.15	2.4±0.1	<.3	13	3.43	1.14	0.6	0.32	–
117	181	5.1	18.9	88	76	41	245	10.1	19.1	0.3	0.7	6.5	–	30	–	4.07±0.22	–	–	–	–	–	–	–
52	87	7.7	21.8	73	84	23	668	24.9	54.8	0.3	3.2	8.2	–	23	–	2.54±0.11	–	–	–	–	–	–	–
79	207	5.3	19	65	66	30	177	9.5	30.4	0.2	1.8	6.1	–	32	–	7.6±6.6	–	–	–	–	–	–	–
53	94	8.7	21.5	50	81	26	471	15.7	48.9	0.3	2	8.8	3	23	2.15	3.83±0.32	<.3	21	4.61	1.41	0.6	0.33	–
84	202	8.2	18.1	42	99	33	502	16.8	39.2	1.2	0.6	4.9	2.7	25	2.49	6.15±0.17	<.3	23	4.88	1.54	0.7	0.37	–
68	106	9	22.2	77	83	34	561	24	50	1.8	3.3	5.8	–	24	–	5.9±0.2	–	–	–	–	–	–	–
126	180	6.5	20.4	83	86	32	519	16.9	49.3	1.6	2.6	6	2.8	23	1.95	4.37±0.39	0.3	24	4.55	1.51	0.6	0.25	–
156	228	3.6	16.3	75	62	39	68	3.5	8	0.2	1	5.3	1.2	33	2.32	2.4±0.5	<.3	7	2.1	0.87	0.6	0.32	–
99	173	7.3	19.8	292	82	32	459	18.1	35.5	0.9	0.9	4.8	–	25	–	5.95±0.16	–	–	–	–	–	–	–
51	98	7.3	22.5	84	75	28	560	25	49	1.5	4.3	3.3	–	27	–	3.7±0.1	–	–	–	–	–	–	–
80	199	5.4	18.3	60	70	32	140	10	30.8	0.8	1.1	6	2	32	2.35	1.14±0.30	0.5	14	3.24	1.2	0.7	0.34	–
51	93	6.5	21.3	51	70	19	610	20	46	1.7	4.5	6.5	–	17	–	0.57±0.05	–	–	–	–	–	–	–
21	24	3	21.5	37	50	14	432	15	36	1.7	5.3	6.3	–	10	–	0.60±0.05	–	–	–	–	–	–	–
34	37	7.7	21.3	76	79	21.5	628	20.3	50.1	1.4	2.8	9.5	–	21	–	2.96±0.24	–	–	–	–	–	–	–
18	40	7.3	21.7	91	75	18.2	576	18.8	37.3	1.3	1.9	9.8	3.1	23	2.06	2.51±0.07	<.3	19	4.23	1.34	0.7	0.29	
66	59	6.4	20.5	79	86	23	1013	25	63.6	2.1	3	9.8	–	22	–	2.88±0.17	–	–	–	–	–	–	–

(Continued on next page

Table 2. *(Continued)*

Quad./sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3T	Rb	Sr	Y	Zr	V
Lake of the Woods North																			
BS92-77	50.08	0.96	17.21	2.18	6.46	0.14	9.34	8.53	3.29	0.48	0.19	0.32	99.18	9.36	2.8	636	16.5	67	199
CG91-100	49.83	1.19	17.13	2.69	7.60	0.15	7.23	9.06	3.34	0.55	0.29	0.60	99.66	11.14	7.7	509	26.2	101	206
92-75	56.11	1.01	17.15	2.37	5.29	0.13	4.36	7.65	3.36	1.36	0.39	0.95	100.13	8.25	19.4	612	24.8	155	172
86-62	57.58	0.84	17.67	2.35	4.09	0.11	4.08	7.25	3.44	1.01	0.20	1.35	99.97	6.90	13.8	701	22.2	108	156
92-73	50.83	1.11	18.67	2.08	6.53	0.15	6.37	8.77	3.71	0.47	0.20	0.50	99.39	9.34	3.9	608	17.1	76	176
92-77	52.66	1.03	16.61	3.36	4.78	0.13	7.24	8.92	3.23	1.03	0.34	0.61	99.94	8.67	11.4	968	20.3	93	207
MG-91-63	50.60	0.73	15.37	2.43	6.35	0.15	10.60	9.57	2.73	0.36	0.11	0.58	99.58	9.49	5.8	469	13.5	49	188
MG-91-22	49.08	0.89	17.07	1.29	7.20	0.15	9.62	11.15	2.31	0.16	0.10	0.87	99.89	9.29	3.2	426	24.7	35	222
MG-91-56	55.65	0.93	18.39	1.47	5.53	0.12	4.62	8.12	3.61	1.01	0.23	0.73	100.41	7.62	16	669	21.8	105	183
92-86	49.80	1.22	16.92	3.41	5.90	0.15	7.25	9.75	3.11	0.74	0.34	0.87	99.46	9.97	12.5	669	25.2	106	249
84-52	49.38	1.17	16.57	5.25	4.22	0.15	7.95	9.31	3.22	0.61	0.34	1.09	99.26	9.94	10	623	20.2	96	193
92-85	52.34	1.10	17.48	3.84	4.83	0.14	6.08	8.40	3.66	0.72	0.24	0.53	99.36	9.21	10.7	613	22.8	78	204
Lake of the Woods South																			
91-3	49.24	1.05	17.46	3.14	5.89	0.15	7.58	10.59	2.86	0.26	0.10	1.25	99.57	9.69	3.2	492	27.1	55	214
91-79	60.28	0.59	18.38	2.68	2.82	0.09	2.91	6.22	3.98	1.04	0.13	0.82	99.94	5.81	11.9	780	13.2	68	106
92-53	54.86	0.77	17.94	2.57	4.52	0.12	5.76	7.27	3.44	0.70	0.14	1.53	99.62	7.59	6.1	805	20.9	60	159
RB92-21	65.61	0.86	16.01	2.88	2.19	0.08	0.91	3.24	5.12	1.86	0.22	1.19	100.17	5.31	26	446	25	156	67
92-43	58.88	0.71	17.86	2.57	3.28	0.10	3.62	6.91	3.57	0.98	0.20	0.66	99.34	6.22	15.8	1,161	13.7	71	140
92-44	58.96	0.69	17.72	3.00	2.74	0.09	3.83	6.66	3.89	1.02	0.15	0.43	99.18	6.05	13.1	1,038	14	66	134
92-62	59.89	0.66	18.17	3.07	2.70	0.09	3.19	6.37	4.27	1.21	0.16	0.62	100.40	6.07	16.7	980	14.8	65	125
92-63	58.91	0.67	17.34	1.64	3.77	0.09	3.90	6.69	4.10	1.11	0.14	1.36	99.72	5.83	14.1	1,031	13.7	62	130
92-84	55.26	0.87	18.75	4.17	2.77	0.11	4.31	8.32	3.93	0.66	0.20	0.59	99.94	7.25	6.6	1,199	16.2	47	180
94-5	60.18	0.64	17.72	3.18	2.41	0.09	2.74	5.71	4.29	1.46	0.16	1.08	99.66	5.86	23.2	598	16.4	109	119
92-87	56.41	0.89	17.34	2.92	4.30	0.11	4.81	6.31	3.33	1.09	0.27	2.35	100.13	7.70	17	748	20.1	105	157
DH94-50	55.39	0.86	17.48	2.47	4.25	0.11	5.87	8.00	3.87	0.86	0.21	0.70	100.07	7.19	10.2	1,098	12	88	147
DH94-106	60.61	0.60	18.47	3.28	2.00	0.08	2.73	6.02	4.29	1.03	0.14	1.40	100.65	5.50	9.7	885	8.6	73	108
JP92-2	57.23	0.78	18.59	2.25	4.19	0.10	4.18	7.58	3.87	0.92	0.26	0.24	100.19	6.91	12.3	1,292	18.4	93	126
AH94-96	57.10	0.87	18.47	2.86	3.88	0.10	4.19	7.08	3.87	1.01	0.22	0.96	100.61	7.17	11.3	1,182	20	69	167
Little Chinquapin Mtn.																			
BS94-53	50.41	1.43	17.43	3.38	7.43	0.18	5.15	9.83	2.76	0.78	0.29	1.31	100.38	11.64	7	616	24	86	190
94-14	51.06	1.03	17.56	4.70	4.52	0.15	6.82	9.55	3.41	0.65	0.24	0.76	100.45	9.72	8.6	686	23	76	212
Mares Egg Spring																			
96-28	57.91	0.78	18.54	2.13	3.84	0.10	3.79	7.21	4.01	0.77	0.16	0.57	99.81	6.40	8.9	990	12	70	144
Mount McLoughlin																			
84-62	52.87	0.91	18.09	4.27	3.83	0.13	5.26	8.80	3.45	0.59	0.18	1.04	99.42	8.53	5.8	723	26.7	57	209
84-50	55.06	0.86	18.56	1.87	5.22	0.11	4.65	7.57	4.27	0.93	0.24	0.55	99.89	7.67	12.4	792	17.6	81	178
84-48	55.65	0.78	19.21	2.30	4.50	0.10	4.08	8.00	4.11	0.78	0.13	0.45	100.09	7.30	7.8	852	15.5	50	179
91-89	56.41	0.80	18.11	2.95	3.87	0.11	4.02	6.99	4.05	1.17	0.26	1.27	100.01	7.25	9.7	861	16.1	74	163
M91-85A	56.00	1.02	17.92	3.30	4.50	0.12	3.68	7.01	3.97	1.46	0.51	0.88	100.37	8.30	13.2	937	23.1	123	158
84-21	54.45	1.06	18.31	2.91	5.21	0.14	3.81	7.69	4.24	1.21	0.51	0.63	100.17	8.70	11.7	840	24.4	114	196
HC-91-44	53.67	1.09	18.15	2.78	5.86	0.14	5.14	7.85	3.89	1.04	0.25	0.83	100.69	9.29	13.8	858	36.2	65	214
HC-91-49A	56.66	0.79	18.33	2.68	3.49	0.10	4.19	7.52	3.54	0.91	0.24	0.91	99.36	6.56	11.7	1,276	16.6	82	151
HC-91-67	55.67	0.75	18.10	2.80	4.06	0.11	4.04	7.00	3.95	1.01	0.16	1.62	99.27	7.31	12.3	768	23.1	66	144
91-49	56.65	0.78	18.88	2.01	4.48	0.11	3.55	7.80	3.73	0.83	0.13	0.80	99.75	6.99	8.5	870	15.5	51	172
91-52	56.27	0.78	18.66	2.51	4.06	0.10	4.02	8.12	3.76	0.74	0.13	0.37	99.52	7.02	7	865	14.4	45	182
14K-91	54.68	1.01	16.10	3.61	3.71	0.13	5.35	8.69	3.96	1.47	0.48	0.38	99.57	7.73	18.9	1,137	227	139	202
84-38	55.69	0.76	18.85	3.04	3.83	0.10	4.55	7.78	4.13	0.78	0.12	0.34	99.97	7.30	7.7	877	7.3	48	164
92-66	51.48	0.99	17.05	3.78	4.90	0.14	7.05	9.34	3.19	0.50	0.18	0.78	99.38	9.23	4.8	690	21.8	77	228

Ni	Cr	Nb	Ga	Cu	Zn	Co	Ba	La	Ce	U	Th	Pb	Be	Sc	Yb	Age (Ma)	Hf	Ta	Nd	Sm	Eu	Tb	Lu
251	241	4.4	20	90	75	44	181	4.1	16.5	0.8	3	3.7	–	27	–	1.12±0.05	–	–	–	–	–	–	–
107	160	4.4	18.3	49	77	39	290	17	32	1.4	1.6	–	1.6	29	2.4	1.32±0.06	–	–	–	–	–	–	–
34	49	8.6	21.3	68	75	26	541	21	45	1.3	4	8.5	1.7	22	2	1.02±0.09	–	–	–	–	–	–	–
32	43	5.7	21.6	51	72	22	470	16	32	1.5	0.4	7.4	1.5	19	1.8	0.21±0.18	–	–	–	–	–	–	–
92	133	3.1	21.7	61	69	29	283	7.4	24.6	0.4	1.7	4.5	1.4	25	1.8	1.16±0.05	–	–	–	–	–	–	–
80	203	6	21.7	71	77	35	414	19	37	1.3	5	6	1.6	23	1.6	1.22±0.04	–	–	–	–	–	–	–
175	605	3.3	13.6	59	65	38	150	4.2	10.8	0	0	4.9	1.2	28	1.1	2.78±0.09	–	–	–	–	–	–	–
128	311	1.7	17.3	87	61	42	72	3.4	8.2	1.2	3.4	2.1	2.2	37	2.1	2.19±0.14	1.4	0.3	7	2.1	0.83	0.5	0.38
21	93	5	21.4	48	68	22	386	12	24	1.4	3.3	9.6	1.3	23	1.3	1.58±0.03	2.3	0.3	12	3	1.04	0.6	
55	194	6.5	21.4	59	83	37	341	21	44	1.6	3.2	3.9	1.5	29	1.7	1.42±0.05	–	–	–	–	–	–	–
126	363	6.8	20.4	64	81	31	299	18.6	45	1.5	3.9	4.4	1.5	26	1.8	1.48±0.04	–	–	–	–	–	–	–
76	95	4.4	21.1	110	79	34	326	11	26	1.2	4	5.4	1.3	24	1.5	1.14±0.10	–	–	–	–	–	–	–
91	239	1.1	17.6	83	62	41	113	4.3	13	1.3	3.7	5.1	1.1	34	2.31	0.82±0.08	1.5	<.3	9	2.45	0.98	0.6	0.32
6	15	3.2	22.3	65	54	18	308	8	16	1.4	3.2	4.7	1.1	12	0.9	3.25±0.05	–	–	–	–	–	–	–
70	165	2.4	21.2	27	61	32	209	12	20	1.7	3.1	3.5	0.9	19	1.5	1.79±0.04	–	–	–	–	–	–	–
3	4	6.2	19.2	20	74	7.1	590	16	36	2.3	4.9	9	1.7	13	2.82	2.47±0.04	3.9	<.3	25	4.85	1.45	0.9	0.42
18	31	3.7	22.9	28	59	21	376	15	34	1.6	1.5	6.9	1.4	12	1.2	0.63±0.05	–	–	–	–	–	–	–
41	54	4	22	50	58	22	377	14	25	2.6	5.3	8.2	1.2	14	1	0.92±0.02	–	–	–	–	–	–	–
17	35	3.8	21.1	47	52	18	439	13	27	1.5	5.3	6.5	1.1	13	0.9	0.80±0.03	–	–	–	–	–	–	–
37	44	3.5	20.9	56	61	20	379	13	26	2.3	2.8	6.3	1.2	15	0.9	0.71±0.06	–	–	–	–	–	–	–
14	25	3.3	23.2	42	58	25	213	12	29	0.5	4.1	3.2	1.2	18	0.9	0.90±0.05	–	–	–	–	–	–	–
24	51	4.6	21	36	53	12	553	15	31	2.1	5.7	6.6	1.4	14	2	2.45±0.08	–	–	–	–	–	–	–
65	106	2.9	21.6	83	66	26	508	16	34	2	3.8	5.4	1.5	15	1.4	0.68±0.09	–	–	–	–	–	–	–
79	163	3.9	17.8	43	58	20	331	12.3	2.4	1	1.2	4	1	17	1.2	1.08±0.05	–	–	–	–	–	–	–
25	46	2.9	18.9	29	56	14	272	13	30.1	0.5	1.5	9.5	0.9	13	1.2	2.68±0.11	–	–	–	–	–	–	–
29	21	1.5	21.4	28	59	–	390	20	40	1.6	5.3	–	–	–	–	1.55±0.04	–	–	–	–	–	–	–
51	87	2.3	19.8	75	68	–	–	–	–	0.9	1	–	–	–	–	3.32±0.27	–	–	–	–	–	–	–
91	74	4	19	68	73	34	420	12	24	1	1	–	1	24	2.2	2.39±0.31	–	–	–	–	–	–	–
89	295	4.4	20.2	57	72	33	302	12.8	36	1.3	5.1	4	1.3	26	2.6	2.22±0.12	–	–	–	–	–	–	–
34	32	2.7	22	31	53	20	304	14	34	0.8	4.7	2.4	–	17	–	0.89±0.07	–	–	–	–	–	–	–
51	124	3.3	20.9	60	69	32	284	15	28	1.6	3.5	4.4	1.3	24	1.7	3.14±0.07	–	–	–	–	–	–	–
42	77	4.7	23	63	65	24	328	13.2	28.1	1	4.4	4.8	1.4	19	1.48	2.42±0.15	2.49	0.24	15.18	3.23	1.19	0.62	0.2
17.6	26	2.4	22.5	99	59	22	224	7	14	1.4	3.5	4.7	1.1	20	0.8	0.08±0.03	1.82	0.36	11.42	2.25	0.83	0.55	0.16
27	89	4.1	22.9	148	63	22	344	10	23	1.3	4.6	5.1	1.4	17	0.9	5.62±0.09	–	–	–	–	–	–	–
16.4	50	8.2	23.2	44	73	23	638	22	46	1	3.6	5.2	1.7	18	1.7	6.43±0.10	–	–	–	–	–	–	–
10	32	7.4	23.3	60	65	24	528	20	42	0.7	3.8	6	1.7	17	1.7	5.97±0.36	–	–	–	–	–	–	–
49	58	3.8	22.2	105	78	33	399	14	26	1.3	4.1	5.3	1.7	23	2.2	3.97±0.08	2.1	0.5	16	4	1.35	0.7	0.37
25	60	3.4	23.3	57	65	25	432	21	46	2.2	3.5	4.4	1.3	17	1	1.67±0.03	–	–	–	–	–	–	–
32	78	3.7	21.3	39	56	23	424	15	24	1.6	4.6	7.2	1.4	18	1.4	3.56±0.06	2.3	0.3	16	3.6	1.19	0.6	0.25
21	24	3	22.3	52	62	21	237	9	19	1.1	4.5	3.7	1.5	18	1.2	0.05±0.03	–	–	–	–	–	–	–
26	45	2.5	22.3	19	56	22	234	8	19	1.3	3.3	2.4	1.6	20	1.1	0.08±0.03	–	–	–	–	–	–	–
34	100	9.7	23.7	36	76	27	581	34	59	1.9	8.8	5.5	1.7	20	1.25	3.43±0.06	3.8	0.6	25	5	1.4	0.6	0.2
40	28	2.4	22.6	50	57	23	224	7	14	1.3	4.4	3.9	1	17	1	<0.15	1.79	0.14	13.45	2.63	1.01	0.57	0.19
68	156	4.1	21	77	68	36	269	12	25	1.9	3.7	5.1	1.3	26	1.4	1.76±0.08	–	–	–	–	–	–	–

(Continued on next page

Table 2. *(Continued)*

Quad./sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3T	Rb	Sr	Y	Zr	V
Mule Hill																			
95-29	54.96	1.12	17.86	4.16	4.14	0.14	3.45	7.29	4.10	1.42	0.61	0.58	99.83	8.76	14.3	649	30.5	180	189
95-30	52.32	0.79	17.59	2.73	5.17	0.14	6.61	10.63	3.10	0.47	0.14	0.64	100.33	8.48	6.8	678	14.1	47	224
95-33	48.00	1.11	17.66	4.25	5.95	0.17	7.87	11.10	3.03	0.21	0.18	0.96	100.49	10.86	2.7	377	23.8	67	222
95-75	49.38	1.07	18.53	5.55	4.23	0.16	6.38	10.04	3.11	0.31	0.16	1.06	99.98	10.25	2.7	510	25.6	64	205
95-77	55.90	1.05	17.70	3.55	4.12	0.13	3.80	7.66	4.09	1.05	0.29	0.83	100.17	8.13	13.7	770	28.3	106	177
95-26	48.47	1.32	17.00	2.54	8.00	0.17	7.46	9.97	2.87	0.61	0.35	1.06	99.82	11.43	7.1	439	24.3	83	263
96-1	51.39	1.32	17.34	3.12	6.66	0.17	5.55	7.99	3.81	1.18	0.59	0.86	99.98	10.52	12.3	752	27	141	205
96-2	49.90	1.02	18.16	2.28	6.92	0.15	7.17	9.77	3.32	0.42	0.15	0.56	99.82	9.97	4.9	548	20	63	227
96-3	50.23	1.24	17.30	5.54	4.53	0.16	5.79	8.56	3.75	1.07	0.46	0.95	99.58	10.57	9.8	924	25	102	226
96-5	51.29	1.33	18.20	7.47	2.94	0.17	3.65	7.72	4.04	1.20	0.75	1.08	99.84	10.74	5.9	818	30	163	196
96-6	48.45	1.79	15.45	4.88	6.29	0.16	7.80	8.27	3.25	1.22	0.59	1.50	99.65	11.87	17.8	637	42	148	242
96-7	57.61	1.33	16.86	5.94	2.22	0.13	2.17	5.31	3.93	2.36	0.45	1.85	100.16	8.41	40	500	44	266	176
96-8	49.16	1.82	16.14	4.61	6.41	0.16	6.49	8.54	3.40	1.22	0.57	0.74	99.26	11.73	16.8	667	29	149	251
96-9	47.85	0.90	17.74	2.47	6.63	0.16	9.24	11.22	2.57	0.13	0.07	1.03	100.01	9.84	1.4	271	23	47	203
97-22	50.40	1.11	17.80	3.33	6.11	0.17	7.45	9.35	3.51	0.43	0.25	0.53	100.44	10.12	0.9	517	23	82	210
97-35	50.55	0.99	18.38	3.35	5.77	0.15	6.69	9.83	3.43	0.41	0.15	0.81	100.51	9.76	2.7	581	18	58	214
97-37	67.08	0.81	15.82	2.30	1.04	0.06	0.56	2.48	5.70	2.15	0.20	2.08	100.28	3.46	29.5	353	39	263	49
97-46	49.94	1.08	18.02	2.96	6.66	0.16	7.22	9.97	3.36	0.39	0.15	0.53	100.44	10.36	2.3	566	20	58	242
97-47	48.38	0.74	17.53	3.20	5.78	0.16	9.44	11.08	2.33	0.13	0.11	1.49	100.37	9.62	0.9	386	19	47	215
97-54	63.72	0.69	14.86	3.41	1.36	0.12	1.14	2.64	2.91	3.02	0.19	6.46	100.52	4.92	43.9	266	33	262	63
97-55	70.54	0.70	13.00	3.69	0.21	0.06	0.50	2.30	4.26	1.82	0.22	2.99	100.29	3.92	24.2	297	28.4	208	45
CW9-13B	47.85	1.08	17.21	1.94	8.06	0.17	9.16	11.33	2.60	0.14	0.12	0.87	100.53	10.90	0	327	22	59	262
CW6-5	49.99	0.74	18.16	3.52	5.15	0.16	7.36	11.69	2.70	0.28	0.11	0.80	100.66	9.24	1	437	18	49	240
CW6-9	56.37	1.73	15.97	4.95	4.57	0.16	2.36	5.55	4.77	1.67	0.78	1.40	100.28	10.03	23.4	526	146	157	212
S97-21	57.20	1.29	16.37	4.72	3.00	0.12	2.49	5.51	3.66	2.47	0.46	2.33	99.62	8.05	42.9	519	40	273	172
S97-62	53.16	1.13	17.56	3.80	4.99	0.16	4.52	7.53	3.59	1.57	0.69	0.80	99.50	9.35	13.8	652	33.3	179	171
S97-87	50.74	1.11	16.46	2.05	6.15	0.14	6.77	9.94	3.12	1.48	0.53	0.83	99.32	8.88	22.4	1,325	23.3	153	224
97-54Z	57.82	1.09	15.64	4.41	2.04	0.14	2.56	5.08	2.84	1.45	0.48	7.10	100.65	6.68	23.3	462	27.7	162	108
JM97-27D	50.98	1.26	17.35	2.74	6.73	0.17	5.23	8.30	3.61	1.16	0.62	1.01	99.16	10.22	10.3	747	23.1	131	201
Parker Mtn.																			
95-34	53.28	1.10	18.34	4.31	4.46	0.14	4.86	8.00	3.96	0.83	0.34	0.65	100.27	9.27	11.2	700	17.8	90	188
97-2	49.51	0.74	18.03	2.88	5.68	0.16	8.09	11.51	2.53	0.25	0.11	1.01	100.50	9.19	1	416	19	51	224
97-16	51.24	0.93	17.94	4.32	4.29	0.15	6.16	10.35	3.24	0.69	0.39	0.72	100.42	9.19	3.5	736	19	72	245
97-41	52.29	1.12	18.50	1.99	6.55	0.15	5.37	8.69	3.83	0.84	0.32	0.67	100.32	9.27	8.8	665	21	92	204
86-85	49.14	1.62	16.58	2.60	8.37	0.18	7.12	9.38	3.16	0.51	0.34	0.72	99.72	11.90	7.5	404	30	114	257
Pelican Bay																			
92-74	55.80	1.12	17.07	3.69	5.08	0.14	3.98	7.66	3.92	0.84	0.18	0.49	99.97	9.34	10.4	700	20.8	59	263
92-89	50.74	0.88	17.18	3.07	5.73	0.14	8.92	8.56	2.82	0.60	0.18	0.70	99.52	9.44	8.6	614	17.7	60	175
92-80	58.04	0.81	17.13	2.81	3.92	0.11	4.47	7.16	3.64	1.09	0.21	0.75	100.14	7.17	15	727	20.4	108	148
AG92-75	54.72	0.90	18.55	3.49	4.32	0.12	4.84	8.05	3.56	0.76	0.15	0.61	100.07	8.29	8.2	772	12.5	57	186
Pelican Butte																			
86-59	58.61	0.79	17.47	1.81	4.25	0.10	3.75	6.94	3.90	1.10	0.17	1.07	99.96	6.53	17.4	681	18	106	153
92-91	57.75	0.78	18.00	2.19	3.99	0.10	3.76	7.07	3.98	1.10	0.17	0.55	99.44	6.62	16.6	844	17.5	94	159
96-11	52.90	0.95	18.81	3.31	5.25	0.14	5.12	8.00	3.62	0.69	0.22	0.87	99.88	9.14	7.7	609	19	78	181
96-13	52.86	0.96	18.04	4.94	3.22	0.13	5.87	8.68	3.53	0.79	0.21	0.43	99.66	8.52	11.8	691	20	98	197
96-17	55.42	0.76	18.44	2.22	4.66	0.12	5.00	8.04	3.52	0.82	0.16	0.64	99.80	7.40	14.3	615	16	88	165

Ni	Cr	Nb	Ga	Cu	Zn	Co	Ba	La	Ce	U	Th	Pb	Be	Sc	Yb	Age (Ma)	Hf	Ta	Nd	Sm	Eu	Tb	Lu
23	41	12.1	20.6	70	93	19	583	28.7	60.8	0.2	1.1	11.2	–	22	–	6.24±0.17	–	–	–	–	–	–	–
48	155	4	18.5	35	66	27	195	8.5	25.5	0.9	1.3	5.1	–	29	–	2.57±0.24	–	–	–	–	–	–	–
159	221	4.2	16.7	102	72	41	166	2	7.2	0.9	0.6	5	–	31	–	2.26±0.26	–	–	–	–	–	–	–
133	176	4.7	18.3	73	75	38	312	13.8	25.8	0.5	1.2	5.8	–	29	–	2.27±0.24	–	–	–	–	–	–	–
26	63	7.2	21.9	34	73	17	454	18.2	34.7	1.5	2.3	6.4	–	22	–	3.44±0.12	–	–	–	–	–	–	–
131	247	6.8	18.4	91	88	38	307	11.6	23.3	0.3	0.8	6.5	–	32	–	7.41±0.19	–	–	–	–	–	–	–
64	110	9.3	23.1	94	81	33	582	23	51	1.8	3.7	7.3	–	22	–	5.97±0.23	–	–	–	–	–	–	–
113	133	2.9	21.7	91	66	38	254	9	28	1.3	3.2	2.5	–	24	–	3.23±0.25	–	–	–	–	–	–	–
90	135	6.3	21.9	85	77	29	535	17	44	2.3	6.3	4.7	–	22	–	5.55±0.18	–	–	–	–	–	–	–
55	98	11.2	23.1	45	99	30	763	28	62	1.1	4.5	7.5	–	21	–	5.8±0.2	–	–	–	–	–	–	–
178	370	10.4	22.3	64	106	49	530	24	47	2.3	3.8	5.7	–	25	–	13.5±0.4	–	–	–	–	–	–	–
30	41	10.4	22.3	60	90	18	787	28	57	1.9	7.5	8.4	–	20	–	14.5±0.5	–	–	–	–	–	–	–
115	213	11.6	21.7	59	101	41	556	19	50	1.1	5.6	4.9	–	26	–	13.2±0.3	–	–	–	–	–	–	–
163	224	1.4	17.7	97	58	45	103	4	11	1.6	4	1.8	–	32	–	2.6±0.4	–	–	–	–	–	–	–
109	222	3.9	17.1	75	69	41	264	13	33	0.9	<0.5	–	–	–	–	2.4±0.2	–	–	–	–	–	–	–
115	124	3	21.6	100	67	43	244	7	24	1.5	4.3	3.3	–	27	–	3.26±0.16	–	–	–	–	–	–	–
4	11	11.5	20.5	8	93	4	760	30	59	2.8	7.8	9.9	–	13	–	21.6±0.5	–	–	–	–	–	–	–
102	131	2.7	21.2	115	65	37	248	9	27	1.7	3.5	2.8	–	26	–	3.2±0.2	–	–	–	–	–	–	–
199	413	2.5	17.5	83	59	44	386	10	28	0.9	3.5	2.5	–	33	–	1.9±0.3	–	–	–	–	–	–	–
16	29	10.9	19.4	19	70	12	782	27	55	2.9	8.4	9.9	–	16	–	13.5±0.5	–	–	–	–	–	–	–
4.6	21	10.5	17.9	16.9	72	4.5	633	23.4	49.3	1.6	5.1	11.6	–	13	–	17.6±0.7	–	–	–	–	–	–	–
134	272	1.6	19.6	104	64	43	81	4	19	1.1	3.7	2.1	–	33	–	2.1±0.3	–	–	–	–	–	–	–
80	207	2.4	18.5	82	60	37	196	6	18	0.7	2.7	2.3	–	32	–	15.0±0.4	–	–	–	–	–	–	–
5	15	4.3	23.8	33	93	15	725	56	58	1.2	5.7	8.4	–	26	–	3.66±0.24	–	–	–	–	–	–	–
18.8	36	12.3	20.6	66	93	11.7	769	33.8	57.9	1.3	5.2	13.4	–	20	–	14.6±0.9	–	–	–	–	–	–	–
40.7	64	12.8	20.5	75	88	22.3	590	25.4	65.2	0.5	1.8	9.9	–	19	–	5.5±0.2	–	–	–	–	–	–	–
79.2	166	6.9	20.1	79.4	72.1	28.5	1067	32.3	70.3	1.5	3.2	6.4	–	24	–	3.79±0.10	–	–	–	–	–	–	–
6	26	9.1	19	23.1	88	10.5	704	22.3	50.8	1.1	3.5	9.7	–	20	–	17.1±0.8	–	–	–	–	–	–	–
56	102	9.5	20.6	75	91	28.4	550	19.1	57.5	0.6	2.1	8.8	–	25	–	5.83±0.15	–	–	–	–	–	–	–
48	68	5.7	20.8	58	78	26	400	11.9	28.5	0.6	1	7.5	–	21	–	2.48±0.50	–	–	–	–	–	–	–
111	285	2.7	18.7	69	54	38	148	7	22	0.6	3.7	2.3	–	32	–	2.2±0.3	–	–	–	–	–	–	–
43	145	5.3	19.9	79	68	29	387	18	46	1.1	4.2	4.8	–	28	–	6.5±0.2	–	–	–	–	–	–	–
45	89	5.3	22	78	74	30	460	12	36	1.2	4.5	5.2	–	22	–	1.8±0.2	–	–	–	–	–	–	–
104	208	6.6	21.7	79	80	37	358	10	26	1.1	3.9	3.7	–	25	–	3.64±0.38	–	–	–	–	–	–	–
7	21	3.3	22.9	105	78	27	355	10	22	1.5	4.7	4.9	1.6	26	1.6	1.13±0.09	–	–	–	–	–	–	–
248	309	4	19.8	65	79	46	261	8	21	1.1	4.4	3.8	1.2	23	1.5	1.20±0.04	–	–	–	–	–	–	–
57	101	4.6	18.8	53	68	25	444	16	29	0.8	1.8	8.5	1.4	18	1.8	0.45±0.04	–	–	–	–	–	–	–
39	101	3.4	20.3	43	71	23	286	5.3	24.1	1.5	2.7	5.1	1.4	21	1.4	1.47±0.04	–	–	–	–	–	–	–
31	51	5.4	21.3	49	66	22	401	14	33	2.4	4.8	5.4	1.3	19	–	0.54±0.05	–	–	–	–	–	–	–
25	28	4.8	22.5	62	65	22	393	15	33	2.1	5.4	6.3	1.3	18	1	0.54±0.05	–	–	–	–	–	–	–
60	85	4	21.6	57	75	29	357	13	32	1.1	3.5	5.5	–	23	–	1.23±0.08	–	–	–	–	–	–	–
74	128	4.4	20.7	49	72	33	376	11	34	1.6	4.2	5.4	–	25	–	1.32±0.08	–	–	–	–	–	–	–
80	82	3.8	21.5	53	64	30	375	16	37	1.2	4.5	5.5	–	20	–	1.64±0.40	–	–	–	–	–	–	–

(Continued on next page

Table 2. ***(Continued)***

Quad./sample no.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI	Total	Fe_2O_3T	Rb	Sr	Y	Zr	V
Robinson Butte																			
91-61	56.89	0.64	19.11	3.30	3.21	0.10	3.17	7.62	3.57	1.00	0.16	1.68	100.45	6.87	10.6	844	13	59	132
92-21	49.62	1.06	15.41	5.58	3.11	0.13	7.83	9.25	3.33	2.16	0.63	1.56	99.67	9.04	21.3	2,187	22.6	65	183
92-24	53.79	0.89	17.27	3.19	4.93	0.13	5.54	7.97	3.58	1.09	0.30	1.11	99.79	8.67	23.4	643	24.8	120	181
JB91-56	48.60	1.36	14.56	5.19	4.14	0.13	8.37	9.28	3.99	1.71	1.11	1.16	99.60	9.79	15.4	1,718	21.6	105	220
92-26	49.88	1.39	16.64	6.33	3.71	0.14	5.82	9.32	3.37	0.93	0.48	1.38	99.39	10.45	13.8	653	29	122	236
92-41	52.29	0.91	18.11	3.96	4.30	0.13	5.28	8.97	3.12	1.00	0.24	1.21	99.52	8.74	11	859	21.4	73	212
94-40	49.10	0.66	13.45	2.81	6.52	0.14	15.59	8.21	2.28	0.51	0.12	0.83	100.22	10.06	4.8	804	13.7	30	182
RSP94-94	53.71	1.16	17.38	3.23	4.92	0.15	4.83	8.00	3.96	1.19	0.48	0.91	99.92	8.70	10.4	968	24.5	132	170
94-42	51.82	1.05	17.54	6.75	2.28	0.14	5.88	7.98	3.78	1.10	0.35	1.65	100.32	9.28	9	1,392	19	56	158
Rustler Peak																			
86-47	53.37	0.85	18.17	2.54	5.33	0.13	5.77	8.71	3.42	0.67	0.17	1.00	100.13	8.46	8.7	627	27	81	194
86-48	62.76	0.48	18.28	2.28	2.37	0.10	1.56	4.57	4.46	1.53	0.20	0.91	99.50	4.91	15.9	859	10	98	71
Spencer Creek																			
95-68	52.52	0.87	19.35	2.08	5.46	0.12	5.63	8.91	3.39	0.80	0.17	0.87	100.17	8.15	9.1	709	15	70	788
95-69	48.21	0.93	17.45	2.94	6.46	0.17	9.13	11.64	2.50	0.13	0.12	0.77	100.45	10.12	2.4	270	22.8	48	225
Surveyor Mtn.																			
95-46	54.02	1.02	17.95	2.38	5.99	0.14	5.13	8.11	3.72	0.82	0.29	0.55	100.12	9.04	12.1	689	16.7	86	177
91-21	53.71	1.05	17.88	3.27	5.00	0.14	5.24	7.93	3.89	0.76	0.27	0.81	99.95	8.83	10.7	592	24.5	97	171
94-36	53.52	1.05	17.69	2.95	5.07	0.13	5.63	8.04	3.83	1.13	0.36	0.83	100.23	8.58	11.5	1,118	22.7	110	192
91-15	51.01	0.91	17.64	2.31	5.92	0.13	7.70	8.72	3.18	0.50	0.16	1.27	99.45	8.89	3.6	876	15.9	44	221
97-28	51.83	1.00	18.04	2.66	5.69	0.15	6.23	9.59	3.49	0.87	0.36	0.47	100.38	8.98	7.6	738	19	95	214
94-4	54.40	0.83	18.20	2.51	5.15	0.12	5.12	8.47	3.74	0.79	0.15	0.98	100.46	8.23	11.3	723	17.1	58	204
Willow Lake																			
84-26	54.53	0.87	18.55	4.44	3.27	0.12	4.41	7.13	4.50	0.99	0.20	1.02	100.03	8.07	8.4	1,133	14.1	25	168
91-60	52.12	1.20	17.27	3.53	6.05	0.16	5.14	7.75	3.99	0.94	0.51	1.31	99.97	10.25	7.8	817	23.4	66	185
JB91-41	50.80	0.70	16.20	3.42	5.68	0.15	9.01	9.85	2.98	0.44	0.16	0.62	100.01	9.73	4.2	636	14.7	15	193
91-89	56.41	0.80	18.11	2.95	3.87	0.11	4.02	6.99	4.05	1.17	0.26	1.27	100.01	7.25	9.7	861	16.1	74	163
KWW-91-33	54.72	1.09	17.90	3.15	4.77	0.13	4.02	7.24	3.82	1.24	0.47	1.68	100.23	8.45	9.8	877	34.7	105	182
KWW-91-25	55.74	0.78	18.67	2.16	4.47	0.10	4.38	8.18	3.89	0.78	0.13	0.40	99.68	7.13	7.1	851	14.8	55	106
California																			
Copco																			
86-88	51.65	1.04	16.85	4.03	4.10	0.13	6.76	8.95	3.23	1.10	0.36	1.62	99.82	8.59	14.3	879	21	107	204
86-92	57.56	0.65	18.70	3.74	2.47	0.09	3.27	7.44	3.61	0.75	0.17	1.21	99.66	6.49	3.7	1,036	12	50	123
Panther Rock																			
97-66	56.14	0.65	18.17	3.60	3.15	0.10	4.11	7.76	3.34	1.15	0.22	1.50	99.89	7.10	9.6	976	16.4	89	144
Secret Spring																			
B'3	53.55	0.89	17.26	3.59	5.38	0.13	5.49	8.40	3.40	1.01	0.30	0.79	100.19	9.57	9.6	773	16.5	97	182
B'317	48.09	1.31	15.53	4.60	6.30	0.18	9.60	10.64	2.45	0.41	0.25	0.79	100.15	11.60	5.3	459	25.6	86	269
B'3	53.55	0.89	17.26	3.59	5.38	0.13	5.49	8.40	3.40	1.01	0.30	0.79	100.19	9.57	9.6	773	16.5	97	182
Anders-1	68.31	0.71	15.04	3.45	0.48	0.05	0.49	1.89	4.58	3.83	0.15	1.04	100.02	3.98	97	223	31	404	32
K97-78	51.83	0.94	17.35	4.67	3.95	0.13	7.78	8.84	3.04	0.78	0.27	0.86	100.44	9.06	9.3	765	11	69	179
97-68	56.00	1.00	17.46	3.27	4.48	0.13	4.22	7.53	4.01	1.12	0.36	0.58	100.16	8.25	10.1	800	20	142	170
A24	49.77	1.11	15.99	8.33	–	0.15	8.56	8.95	2.85	0.61	0.25	1.88	98.45	8.33	8.9	466	16.4	84	209
A73	63.16	1.23	15.41	6.09	–	0.10	0.58	3.05	4.49	2.92	0.40	2.21	99.64	6.09	74.5	369	41	344	91
K97-43	51.15	0.83	18.53	4.34	3.97	0.12	7.08	9.25	3.09	0.73	0.22	0.54	99.85	8.75	7.9	875	8.2	56	186
L-24	56.26	0.71	17.84	2.62	4.55	0.12	4.25	7.29	3.84	0.85	0.18	1.11	99.62	7.68	10.9	728	9.1	50	132
97-53	58.14	1.13	16.46	1.70	4.68	0.14	3.10	6.47	3.58	2.14	0.36	2.33	100.23	6.90	50.1	551	28.1	232	151
L-42	57.38	0.53	19.40	3.82	1.50	0.06	2.45	7.67	3.83	1.06	0.19	1.79	99.68	5.49	7.8	1,102	4.7	45	65
K97-24	52.22	0.73	17.43	2.72	4.76	0.12	8.06	9.32	3.05	0.72	0.20	0.56	99.89	8.01	9.6	763	8.5	57	170
JM97-16	60.08	0.76	15.72	4.01	0.78	0.12	1.79	3.52	2.63	1.95	0.23	8.94	100.53	4.88	44.5	359	37	220	55
K97-23	51.09	0.52	18.52	4.76	2.50	0.12	7.71	10.24	2.52	0.79	0.17	1.50	100.44	7.54	12.5	890	6	47	147

Ni	Cr	Nb	Ga	Cu	Zn	Co	Ba	La	Ce	U	Th	Pb	Be	Sc	Yb	Age (Ma)	Hf	Ta	Nd	Sm	Eu	Tb	Lu
6	25	3.5	23.1	59	51	17	286	8	15	1	4	4.6	1.2	13	0.8	19.6±0.3	2.2	0.4	10	2.2	0.82	0.3	0.16
81	168	5.1	20.7	104	74	34.5	1749	43.8	92	2.4	7.9	9	–	18	1.3	6.13±0.10	2.9	<.3	50	8.87	2.36	0.8	0.2
67	161	4.5	20.6	29	76	20	619	26.7	62.1	2	6	6.3	–	20	–	20.5±0.3	–	–	–	–	–	–	–
97	242	16.7	24.5	86	118	36	905	55.4	93	2.1	8.2	5.4	2.3	21	1.3	5.35±0.09	3.4	0.6	49	6.47	1.93	0.6	0.2
158	287	8	17.9	61	102	35	467	24	42	0.3	3.3	6.3	1.3	28	2.3	20.2±0.3	–	–	–	–	–	–	–
53	133	5	22.2	72	76	33	365	17	26	0.7	3.3	7.7	1.2	23	1.4	19.5±0.3	–	–	–	–	–	–	–
263	879	1.3	15.5	69	71	47	138	9	21	–	–	–	0.8	29	1.7	5.43±0.18	–	–	–	–	–	–	–
34	74	7.8	21.7	37	70	25	523	19	43.9	0.9	1.2	5	1.2	20	2.4	5.73±0.15	–	–	–	–	–	–	–
135	194	4.7	23.2	43	76	18	506	15.2	39.3	1.8	6.5	3.9	1.3	19	2.2	5.54±0.15	–	–	–	–	–	–	–
61	125	4.1	20.5	79	70	32	302	11	33	1.7	4.8	4.5	–	26	–	1.42±0.09	–	–	–	–	–	–	–
5	26	4.4	17.1	22	60	7	494	13	37	1.2	3.3	2.4	–	33	–	4.43±0.15	–	–	–	–	–	–	–
78	84	4.3	19.5	71	73	26	270	8.6	20	0.4	2	4.6	–	24	–	1.19±0.11	–	–	–	–	–	–	–
171	234	3.3	16	91	67	41	60	5.6	7.8	0.5	1	5.5	–	39	–	2.0±0.3	–	–	–	–	–	–	–
53	88	5.5	20.5	40	75	24	408	12.7	31.4	0.6	1.2	8.8	–	24		2.76±0.16	–	–	–	–	–	–	–
61	118	4.3	18.7	70	73	28	368	14	31	1	4.7	5.9	1.5	22	2.4	1.88±0.22	–	–	–	–	–	–	–
76	134	5.5	22.8	90	74	17	527	21.1	45.8	1	3.3	5.8	1.6	24	2.5	2.78±0.10	–	–	–	–	–	–	–
106	306	2.9	20.5	79	69	34	215	9	22	1.1	3.5	3	1.3	25	1.1	2.32±0.11	–	–	–	–	–	–	–
54	118	6.9	19	94	72	29	592	16	43	<0.5	2.7	–	–	–	–	3.7±0.3	–	–	–	–	–	–	–
42	75	3.5	22.6	170	64	24	319	9	19	1.3	4.3	4.3	1.3	22	1.7	2.81±0.14	–	–	–	–	–	–	–
51	108	2.1	20.2	52	69	28	493	11	21	–	0.8	–	1.3	17	0.8	6.01±0.30	–	–	–	–	–	–	–
48	101	5.7	21.7	51	75	33	551	15	31	2.1	3.5	5.1	1.3	22	1.8	6.06±0.10	–	–	–	–	–	–	–
148	656	2.4	18.3	84	70	44	278	4.8	12	1.4	3.2	3.9	1.3	28	1.1	6.11±0.21	0.9	<.3	8	1.97	0.76	0.3	0.16
27	89	4.3	23.2	148	63	22	344	10	23	0.7	4.1	4.4	1.4	17	0.9	5.62±0.09	–	–	–	–	–	–	–
33	71	5	20.4	85	81	27	578	29	52	1.9	1.3	–	1.6	18	2.5	6.48±0.10	–	–	–	–	–	–	–
16	15	1	20.2	39.5	66	18	224	8	16	0.7	3.3	–	1.1	10	0.9	0.66±0.02	–	–	–	–	–	–	–
138	238	6.2	20.5	72	85	32	692	25	59	2.2	5.4	4.8	–	24	–	4.11±0.45	–	–	–	–	–	–	–
25	46	2.5	21.8	51	63	21	213	9	27	2	4.8	2.8	–	17	–	8.59±0.59	–	–	–	–	–	–	–
45	77	3.5	20.4	38.2	65	18.6	238	9.9	30.2	1.1	2.1	3.5	–	17	–	20.4±0.5	–	–	–	–	–	–	–
142	196	5.1	21.1	76	70	26	345	12.7	31.5	2.8	1.1	6.1	–	17	–	15.0±0.4	–	–	–	–	–	–	–
217	298	6.1	17.1	103	92	44	246	10.4	20.5	1.1	2.2	5.8	–	32	–	4.35±0.39	–	–	–	–	–	–	–
142	196	5.1	21.1	76	70	26	345	12.7	31.5	2.8	1.1	6.1	–	17	–	14.5±0.4	–	–	–	–	–	–	–
3.5	12	15.5	19	7	56	6	940	31	52	3.2	11.9	13	–	10	–	21.0±0.5	–	–	–	–	–	–	–
128	299	4.7	17.8	57	70	21	267	12.7	34	0.7	2.5	7.2	–	23	–	12.5±0.5	–	–	–	–	–	–	–
37	62	7.9	21.7	53	79	26	453	20	49	2.1	4.8	2.3	–	20	–	3.7±0.1	–	–	–	–	–	–	–
207	416	6.4	17.7	53	82	34.6	258	8.4	17.7	1	0.7	6.2	–	27	–	19.25±0.51	–	–	–	–	–	–	–
1.3	6.3	14.7	19.9	9.3	88	6.7	857	33.1	65	2.9	7.5	12.9	–	22	–	21.17±0.54	–	–	–	–	–	–	–
115	198	3.6	18.3	122	67.4	30.4	195	7	24.2	0.6	1.6	7.6	1.1	23	1.66	13.19±0.80	0.22	13.4	2.51	0.78	0.34	0.15	–
44	148	3.2	21.1	37	73.7	20.6	393	8.4	26.8	1.2	2.7	13.2	–	19	–	4.94±0.19	–	–	–	–	–	–	–
27.8	49	12.4	19.4	42	85	17.5	577	23.1	56.7	0.9	5.4	10.8	–	21	–	19.6±0.6	–	–	–	–	–	–	–
12.7	58	2	20.4	25.2	60	10.7	366	6.5	35.8	0.6	1.9	17.6	–	14	–	7.9±0.4	–	–	–	–	–	–	–
105	304	3.4	17.5	64	69	34	244	8.7	31.2	0.6	1.5	8.1	–	23	–	13.3±0.4	–	–	–	–	–	–	–
12.8	41	11.2	17.9	22	66	8.5	863	29.9	59.8	1.8	6.2	11.3	–	16	–	17.6±0.6	–	–	–	–	–	–	–
72	230	2.2	17.9	58	60	28	273	9.1	25.7	1.6	2.7	6.6	0.9	23	1.85	10.7±0.3	0.12	12.9	2.57	0.92	0.26	0.16	–

(Continued from page 107)

between crustal blocks of differing densities, as they propose, provide an easier path to the surface for magmas generated at various levels within the lithosphere and upper reaches of the asthenosphere.

GEOCHEMICAL RESULTS

For a broad view of regional petrogenesis, Figure 5 shows three MgO-major element variation diagrams, while Figure 6 shows three MgO-trace element variation diagrams. Both sets of diagrams provide a large-scale context in which to begin a general discussion of the regional petrology and geochemistry. The MgO-SiO_2 relationship, interpreted in light of detailed thin-section petrography, suggests olivine phenocryst fractionation with poikilitically enclosed Cr-spinel grains, which has a significant role to play in mafic mineral evolution. This conclusion is substantiated by the Ni-MgO diagram (Figure 6a) which depicts a rapidly declining whole-rock Ni content as a function of decreasing MgO. Both Cr and Co follow a very similar pattern. The Al_2O_3 trend (Figure 5b) suggests that plagioclase crystal fractionation plays a rather minor role until MgO decreases to values ≤4 weight percent, because the Al_2O_3 concentration increases as a function of decreasing MgO. This conclusion is corroborated by the Sr-MgO diagram (Figure 6b), which depicts an increasing Sr whole-rock content as MgO declines. The Fe_2O_3T trend (Figure 5c) decreases at MgO values ≤5 weight percent, which approximately coincides with the petrographic occurrence of titanomagnetite as a significant microphenocryst to phenocryst phase. Given the density of titanomagnetite compared to the magma that surrounds it, titanomagnetite crystals are likely participants in any gravity-driven magmatic differentiation process. As one might surmise, both V and Ti follow a very similar geochemical pattern. In distinct contrast

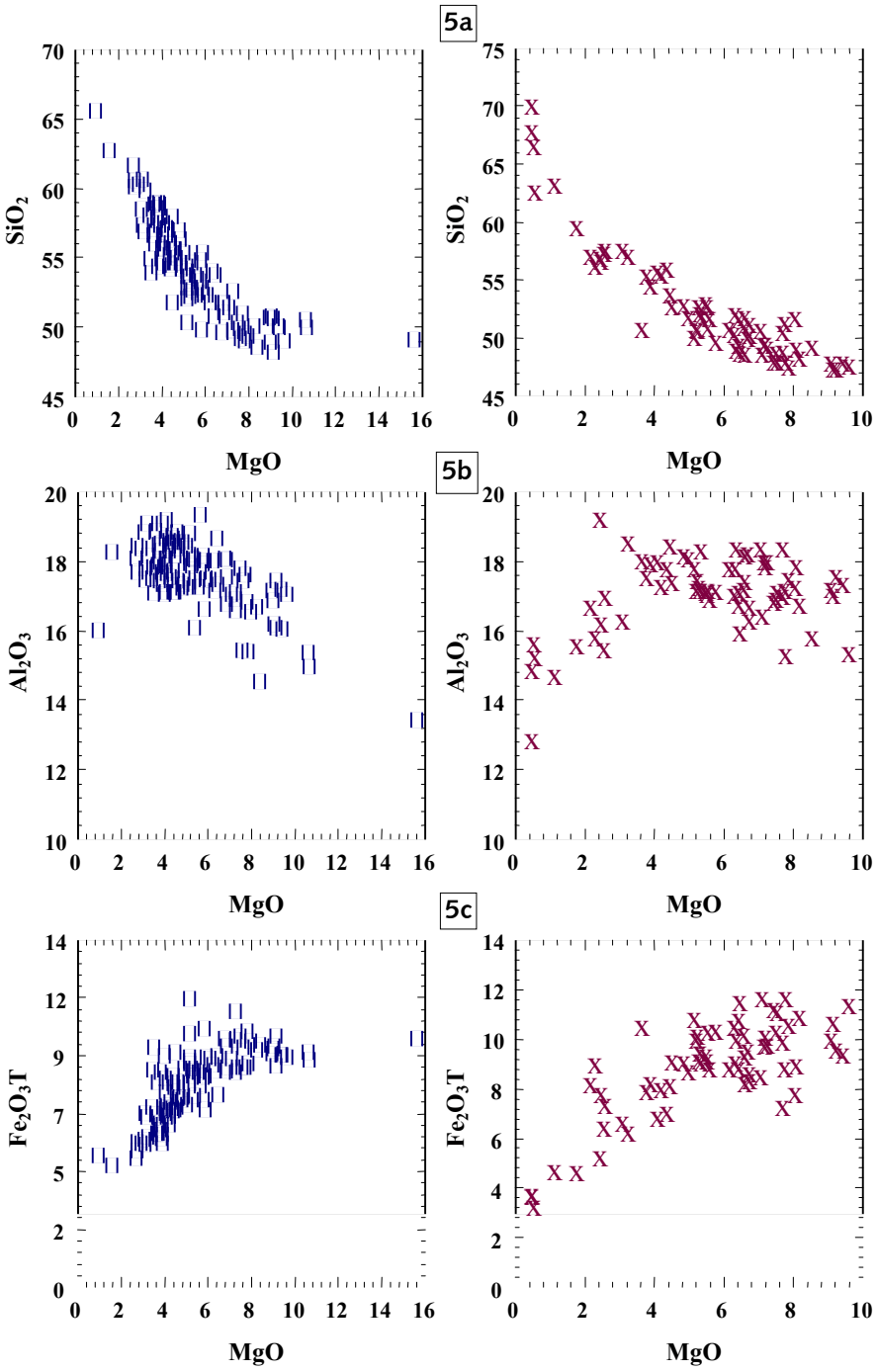

Figure 5. Plots of MgO versus three major elements, with samples from the north of Oregon Route 66 in the left-hand diagrams and samples from the south of that line in the right-hand diagrams. Values are in weight percent.

to many of these declining elemental patterns as MgO decreases, Ba (Figure 6c) behaves as an incompatible element, depicting a behavior more extreme than that of either Al_2O_3 or Sr. This is to be expected because petrographic data indicate that in no case did the K_2O content of those magmas currently represented as lavas sampled in this study reach a concentration level that would have potassium feldspar, most likely sanidine, crystallize as a liquidus phase. Since Ba^{+2} proxies for K^{+1} in numerous minerals due to ionic size similarities, these two elements tend to behave similarly in terms of geochemistry. Invariably, K_2O appears in

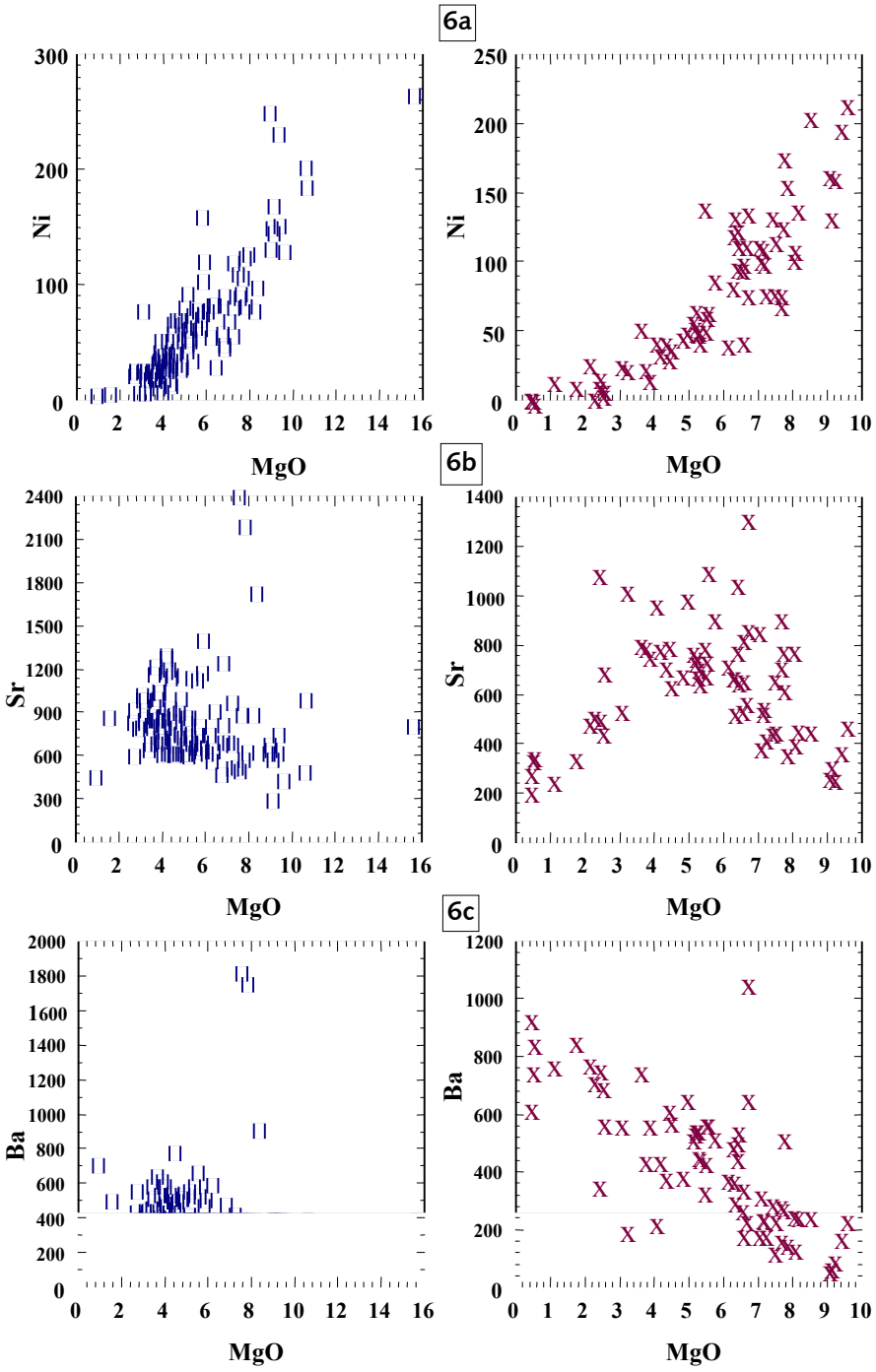

Figure 6. Plots of MgO versus three trace elements, with samples from the north of Oregon Route 66 in the left-hand diagrams and samples from the south of that line in the right-hand diagrams. MgO values are in weight percent; trace-element values in parts per million (ppm).

the groundmass feldspar phase, confirming potassium feldspar's role as a near-solidus phase. The only exception can be found in some latest Miocene-earliest Pliocene mafic trachybasalt lavas found in the drainage of the South Fork Little Butte Creek in both the Robinson Butte and Brown Mountain quadrangles. In these lavas, small (0.4-1.2 mm) phenocrysts of magnesian biotite, which is also a potassium-rich mineral, occur together with olivine and clinopyroxene. Many biotite crystals show strong evidence of dehydration and oxidation reactions, which most likely occurred during transit to the Earth's surface. Potassium feldspar is still confined to groundmass status in these lavas, too.

CONCLUSION

Detailed K-Ar geochronology is a necessary tool for all field geologists who are attempting to work out the geologic history of specific volcanic regions. Since individual lava flows extruded in volcanic regions where compressive stress is strong tend to be less voluminous than their counterparts extruded in volcanic regions undergoing extension, seldom is an area completely covered by a blanket of lava as in the case of some of the Columbia River basalt flows. Consequently, accurate volcanic stratigraphy is frequently difficult to determine due to the lack of convincing layer-on-layer deposition. Hence the need for a tool determining absolute age such as the K-Ar method, which makes more exact comparisons and a more defined stratigraphic column possible.

What are the large-scale unanswered questions with regard to the regional volcanic geology? Ascertaining whether or not the 10-million-year hiatus in volcanism documented here for the region to the west and southwest of Mount McLoughlin exists over a larger area is a good place to begin. What was the ultimate cause of the cessation of volcanism approximately 17 million years ago and what set it off again six to eight million years ago? What was the nature of the initial volcanic eruptions that put an end to the gap in volcanic activity? Are the initially extruded lavas consistently trace-element-enriched trachybasalts as identified in this study? Why is there a relatively quick changeover to a more typical orogenic suite of volcanic rocks soon after the renewal of volcanism?

From a more petrological point of view: Would studying the strontium, neodymium, and lead radiogenic iso-

topic systems and the oxygen nonradiogenic system as function of sample age provide valuable insights into the origin of these lavas within the Earth's lower crust and/or upper mantle? For instance, the late Quaternary, very fine grained two-pyroxene andesites extruded from Brown Mountain have an $^{87}Sr/^{86}Sr$ mean ratio of 0.70367 ± 1, while the time-correlative, quite porphyritic two-pyroxene basaltic andesite lavas from Mount McLoughlin have a mean value of 0.70324 ± 1 (Mertzman, unpublished data). These two large volcanic edifices are nearest neighbors in the Cascades of southern Oregon. The data speak to the strontium-isotopic heterogeneity of the crust/mantle region beneath this one small region. What other isotopic variations exist, when the entire spectrum of bulk compositions is examined? Further, do the isotopic signatures for nearly primary, little fractionated basalts vary over time and if so, how? What do such data tell us about regional magma generation?

The data reported in this paper provide a substantial time-stratigraphic framework upon which a number of more detailed studies can be based. Many unanswered questions with regard to the volcanic geology of southern Oregon and northern California remain, a sufficient number to keep interested geologists busy for decades.

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(Continued from page 86)

many. We visited, and some time after my inquiries, the Baker Regional Geologist, Mark Ferns, wrote and asked me if I might be interested in applying for membership on the Board."

Seymour's interest in DOGAMI's work has many facets. She says about herself: "In college, I had many friends who were interested in geography and geology and I went on field trips with them. I am interested in landslides from experience along Oceanside coastline; in oil and gas since drafting the oil and gas severance tax bill; in water, underground water channels, and geothermal resources from ranch and legislative experience and drafting legislation; in gravel excavation also from ranch and legislative experience; in gold mining in Baker County; and in geologic mapping for purposes of information needed for environment and energy conservation and to prevent injury and property damage. I am interested in natural resource conservation but believe that economic development can be continued compatibly with some resource development. I am also interested in funding issues related to compatible conservation and development, as well as disaster preparation and prevention issues." □

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Klaus K. Neuendorf, Editor

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Released August 3, 2000:

Earthquake-induced slope instability: Relative hazard map, western portion of the Salem Hills, Marion County, Oregon, by R.J. Hofmeister, Y. Wang, and D.K. Keefer. Interpretive Map Series IMS–17, scale 1:24,000, $12.

Earthquake-induced slope instability: Relative hazard map, eastern portion of the Eola Hills, Polk County, Oregon, by R.J. Hofmeister and Y. Wang. Interpretive Map Series IMS–18, scale 1:24,000, $12.

Earthquake-induced slope instability: Methodology of relative hazard mapping, western portion of the Salem Hills, Marion County, Oregon, by R.J. Hofmeister, Y. Wang, and D.K. Keefer. Special Paper 30, 73 p., $15.

Released August 24, 2000:

Tsunami hazard map of the Gold Beach area, Curry County, Oregon, by G.R. Priest, Myers, E., Baptista, A., and Kamphaus, R.A. Interpretive Map Series IMS–13, 3 p. text, map scale 1:12,000.

Released August 24, 2000:

Penrose Conference 2000, Great Cascadia Earthquake Tricentennial. Program summary and abstracts, compiled by J.J. Clague, B.F. Atwater, K. Wang, Y. Wang, and I. Wong. Special Paper 33, 156 p., $15. □

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Numbers refer to issue and first page of entry. Subject entries cross-referenced to author entries (in parentheses).

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Places to see—Recommended by the Oregon Department of Geology and Mineral Industries:

Moccasin Lake in the Eagle Cap Wilderness of the Wallowa Mountains, with Eagle Cap in the background.

This tarn lake, filling an ice-gouged rock basin, lies in the center of the Wallowas at an elevation of nearly 7,500 ft. It is one of the many marks left from the carving done by Pleistocene ice, which covered a large portion of these "Oregon Alps." Nine large glaciers radiated out from here during the ice age between two million and 10,000 years ago. The rock at the core of the Wallowa Mountains is the Wallowa batholith, granite from a magma upwelling in Late Jurassic and Early Cretaceous time (between 160 million and 120 million years ago) that also cemented together a great diversity of still older, "exotic" terranes—blocks of the Earth's crust that traversed the Pacific Ocean and attached themselves to the (then) edge of the North American continent.

Access: One road leads to within about 7 mi of this area: from State Route 82 south along the Lostine River. Trails converge here from several directions, including a trailhead near the south end of Wallowa Lake. This is not only a wilderness area but the most precious inner core of it, protected by special regulations. Before any visit one should definitely consult with the U.S. Forest Service Visitor Center in Enterprise, (541) 426-4978. A map of the Eagle Cap Wilderness Area is available from DOGAMI's Nature of the Northwest Information Center (see page 103).