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# GEOTHERMAL SIGNIFICANCE OF EASTWARD INCREASE IN AGE OF UPPER CENOZOIC RHYOLITIC DOMES IN SOUTHEASTERN OREGON

By

Norman S. MacLeod, George W. Walker, 1921-
and Edwin H. McKee, 1935-

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# GEOTHERMAL SIGNIFICANCE OF EASTWARD INCREASE IN AGE OF UPPER CENOZOIC RHYOLITIC DOMES IN SOUTHEASTERN OREGON

By Norman S. MacLeod, George W. Walker,
and Edwin H. McKee
U.S. Geological Survey, Menlo Park, Calif. 94025

## ABSTRACT

Rhyolitic domes, flows, and ash-flow tuffs of Miocene to Holocene age form an important part of the thick sequence of Cenozoic volcanic rocks that cover southeastern Oregon east of the Cascade Range. Rhyolitic domes 11-17 m.y. old are widespread, particularly in the easternmost part of the state and in adjacent parts of Idaho and Nevada. Domes younger than 11 m.y. occur principally in two 250-km-long belts that trend N. 75° W. On the basis of 47 K/Ar radiometric dates, the rhyolitic domes in and between these belts show a remarkably well defined monotonic age progression from less than 1 m.y. old in the west to about 10 m.y. old on the east. The progression in age of the domes is sufficiently well defined that the ages of the domes can be smoothly contoured and the age of most undated domes can be estimated to within 1 m.y. The age contours are oblique to the trend of the two belts; domes younger than 4 m.y. occur only in and near the northern belt. The rate of progression is about 1 cm/yr for domes younger than about 5 m.y. and 3 cm/yr for domes 5-10 m.y. old. The change in rate of progression about 5 m.y. ago is accompanied by a change in orientation of the age contours and in area of outcrop. Inferred vents for dated rhyolitic ash-flow tuffs younger than 10 m.y. are located in areas where domes are approximately the same age as the tuffs and thus also fit the age progression.

Most electric-power-producing geothermal fields in the world occur in or proximal to areas of young silicic volcanic rocks. On the basis of the well-defined age progression of rhyolitic domes in southeastern Oregon, silicic intrusive bodies sufficiently young to be heat sources for geothermal systems are likely only in the vicinity of Newberry Volcano at the west end of the northern belt of domes.

## INTRODUCTION

Southeastern Oregon is underlain largely by volcanic rocks that range in age from Eocene to Holocene. Upper Cenozoic volcanic rocks are widespread and form a bimodal basalt-rhyolite association. Walker recognized that upper Cenozoic rhyolitic rocks in this region are progressively older toward the east, and he documented this with K/Ar dates on a few rhyolitic domes and ash-flow tuffs (Walker, 1974; Walker and others, 1974). Thirty-four new and 13 published K/Ar dates on rhyolite domes substantiate a very well defined monotonic age progression.

This study of the upper Cenozoic rhyolites of southeastern Oregon was undertaken as part of a regional evaluation of geothermal potential designed to provide data and concepts useful for geothermal exploration. Our isotopic, petrologic, and field investigations are not yet complete, and this preliminary report is intended only to summarize the available data and its geothermal implications. Most power-producing geothermal areas in the world are underlain by late Cenozoic silicic volcanic rocks (for example, Wairakei, New Zealand; Matsukawa, Japan; Namafjall, Iceland; Pauzhetka, U.S.S.R.; Monte Amiata, Italy) or occur in proximity to young silicic volcanic fields (The Geysers, U.S.A.; Larderello, Italy). Thus knowledge of the distribution and age of young silicic volcanic rocks can be an important guide to areas of favorable geothermal potential (Smith and Shaw, 1973).

## GEOLOGIC SETTING

Southeastern Oregon, as used here, includes the High Lava Plains, the Basin and Range, and part of the Owyhee Uplands provinces (figs. 1 and 2). The geology of this area of about 90,000 $km^2$ is shown on 1:250,000-scale reconnaissance geologic maps by Walker (1963), Walker and Repenning (1965, 1966), Walker and others (1967), Peterson and McIntyre (1970), and Greene and others (1972), and on the recently published 1:500,000-scale geologic map of eastern Oregon (Walker, 1973).

All of southeastern Oregon is underlain by Cenozoic volcanic and sedimentary rocks, with the exception of a small window of Mesozoic and older rocks on the east flank of the Pueblo Mountains adjacent to the Nevada border and an even smaller area a few kilometres to the east.

Volcanic and volcaniclastic rocks of late Miocene[1] to Quaternary age are particularly abundant in the High Lava Plains, where they almost entirely veneer middle Miocene and older volcanic rocks. Basalt flows and their associated vent deposits predominate, but exogenous and endogenous rhyolitic domes and ash-flow tuffs are abundant, and andesite and dacite occur locally. These upper Cenozoic volcanic rocks form a bimodal basalt-rhyolite association similar to other basalt-rhyolite sequences that occur peripheral to the circum-Pacific calcalkaline belt in Central and South America, Kamchatka, and Japan.

North-trending faults with escarpments as high as 1-2 km displace the volcanic rocks south of lat 43° N. (fig. 1). They become less pronounced northward into the High Lava Plains province. Numerous northwest-trending, en echelon faults defining the Brothers fault zone offset the volcanic rocks of the High Lava Plains; faults of similar orientation, but less abundance, also occur farther south. Gravity data (Thiruvathukal and others, 1970) suggest a change in crustal structure between the High Lava Plains and the Blue Mountains province to the north.

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[1]Ages of epoch boundaries used in this report are from Berggren (1972). They are younger than those traditionally used in reports on eastern Oregon, which are based on radiometric ages of mammalian stages (Evernden and others, 1964).

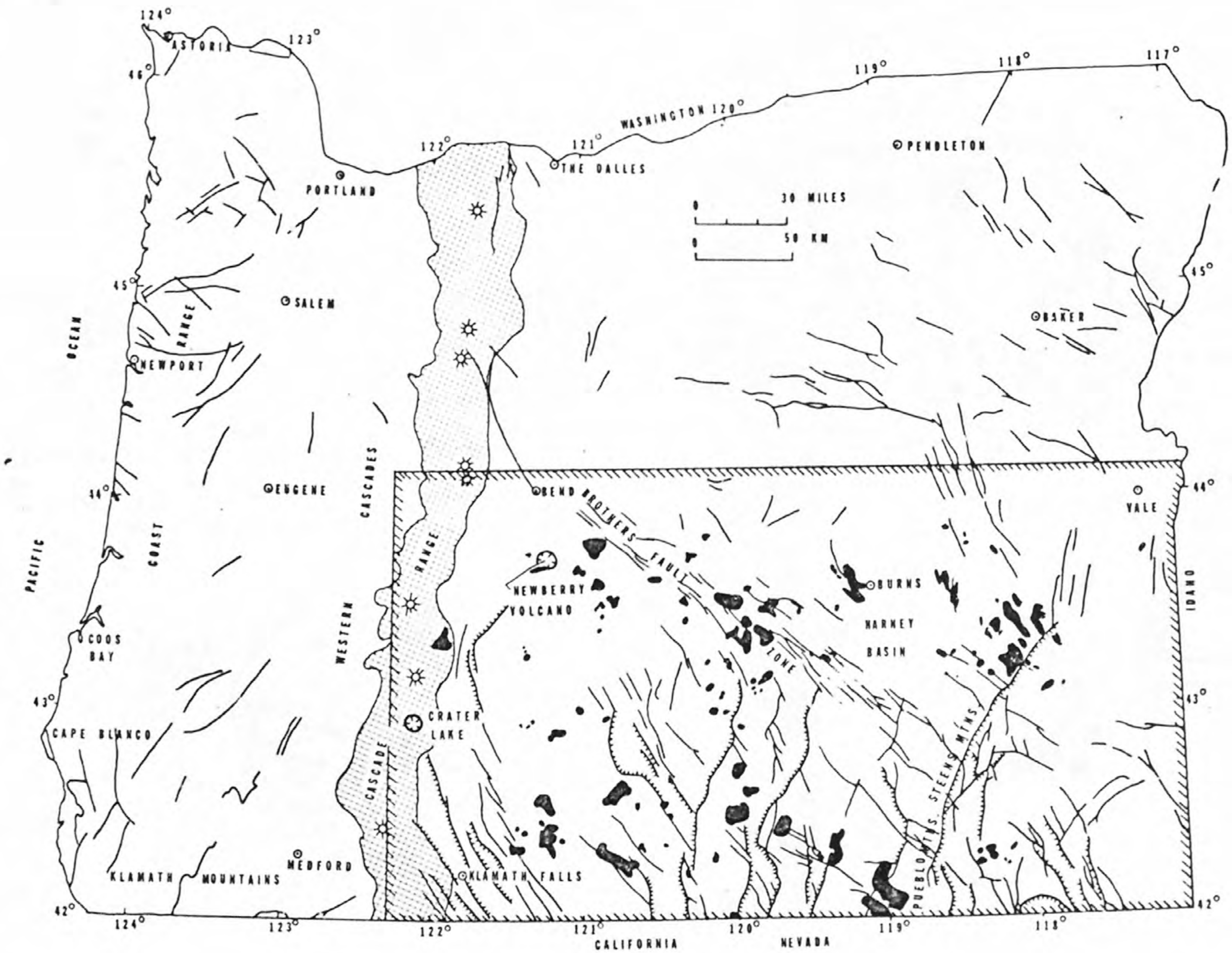


Figure 1. Map of Oregon showing the location of the rhyolitic domes in the southeastern part of the state (black). Major faults shown are from Walker and King (1969); hachures are shown on the downthrown side of the larger faults of the Basin and Range Province. The area shown in figures 2 and 4 is outlined.

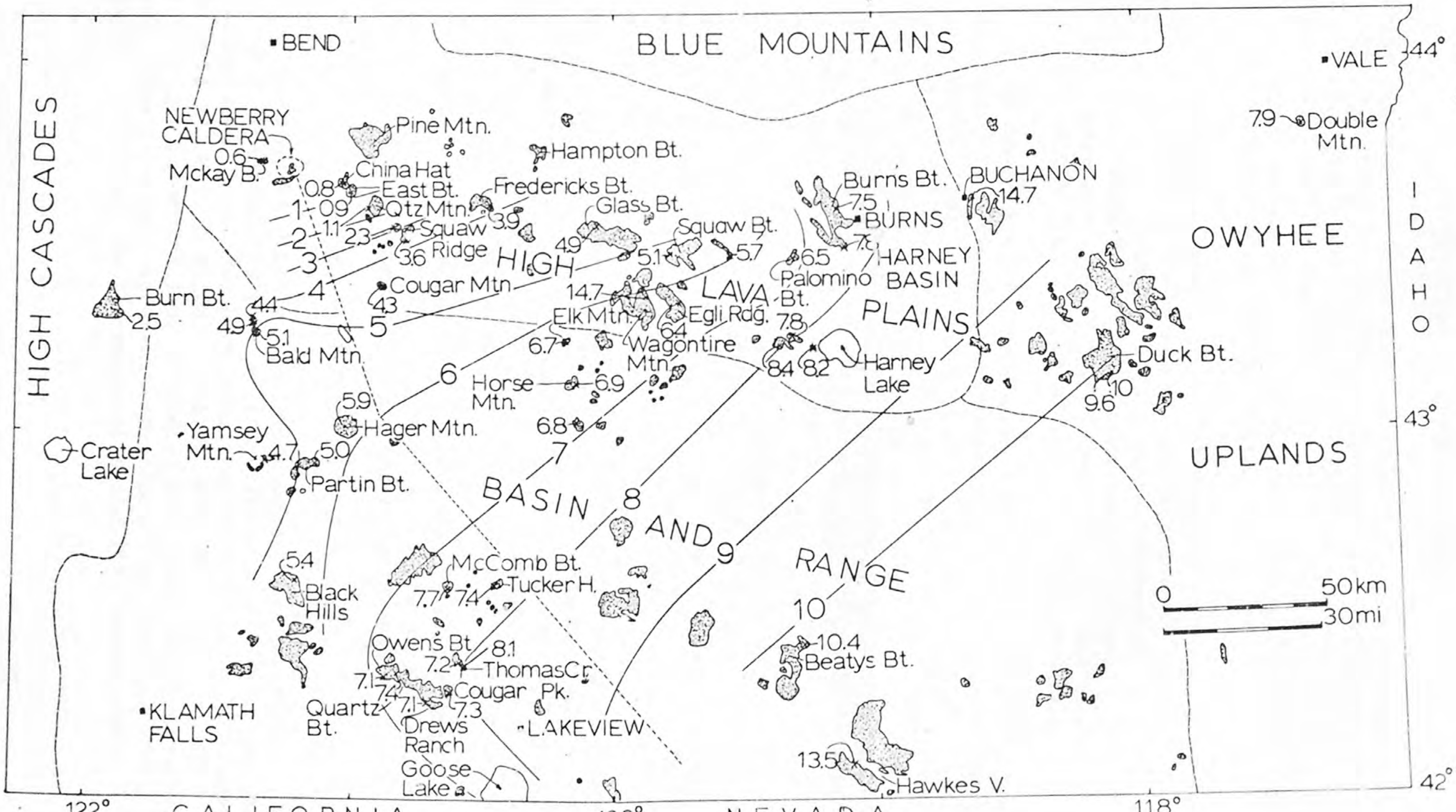


Figure 2.--Map of southeastern Oregon showing radiometric ages of domal rocks. Isochrons separating ages of domes in 1 m.y. increments are approximate, particularly in the eastern part of the area. Dashed line is an approximate normal to the 0 to 6 and 6 to 10 m.y. isochrons to which ages were projected for construction of figure 3A. Physiographic provinces are from Dicken (1950). Locations of domes are from Walker (1973) except the area west of longitude 121 W., which is from Williams (1957) and Peterson and McIntyre (1970).

## DISTRIBUTION OF RHYOLITIC DOMES

Rhyolitic domes and flows form many of the higher mountains and ridges in the High Lava Plains, Owyhee Uplands, and Basin and Range provinces (figs. 1 and 2). The domes occur principally in two broad belts that trend about N. 75°-80° W. One belt lies in the High Lava Plains and Owyhee Uplands, the other in the Basin and Range province; a few domes occur between the western parts of the two belts.

The northern belt of about 100 rhyolitic domes extends from near Newberry Volcano south of the town of Bend eastward to Duck Butte southeast of Harney Basin. Several clusters of isolated domes such as near Duck Butte may represent extrusions from single large intrusive bodies at depth. On the other hand, several of the larger domes, for instance Pine Mountain, may consist of several contiguous domes of slightly different age.

Many of the domes are exogenous with a carapace of obsidian and rhyolite flows and flow breccia that extend a short distance from the dome margins; a few domes, such as at Wagontire Mountain, have vented ash-flow tuffs (Walker and Swanson, 1968). The domes and their associated flows range in shape from equant to highly elongate; the long axes of most elongate domes trend parallel to or somewhat more northerly than the orientation of the belt in which they occur. The larger domal masses are 10 to over 20 km in longest dimension.

The only large area within the northern belt that is devoid of domes is in the Harney Basin, where Quaternary basalt flows and sedimentary rocks form the surface outcrops. Because this structural depression is the probable vent area for several very large sheets of ash-flow tuff, however, rhyolitic vent complexes are likely present there at depth.

The southern belt of rhyolitic domes and associated flows extends from the Black Hills-Yamsey Mountain area northeast of Klamath Falls to or beyond Beatys Butte, 50 km east of Lakeview. This broad belt of domes approximately parallels the northern belt. It contains only about half as many domes, although many are as large as those farther north.

Domes between the northern and southern belts are abundant only in the west half of the area and include domes and vents at and near Bald Mountain, Connley Hills, Hager Mountain, and Horse Mountain.

## AGE OF RHYOLITIC DOMES

Thirty-four rhyolitic or rhyodacitic endogenous or exogenous domes were dated by K/Ar methods as part of this study, and 13 K/Ar ages of domes or associated flows have been published previously. These ages are listed in table 1a, and locations of dated domes are shown in figure 2. Duplicate K/Ar age determinations on individual domes, and radiometric ages of proximal domes that may represent extrusions from a single intrusive mass, generally agree within the range of analytical uncertainty.

Table 1a.--*New and published K/Ar radiometric ages of rocks from silicic domes in southeastern Oregon*

| Col. No. | Location | Latitude | Longitude | Age (m.y.)[1] | Col. No. | Location | Latitude | Longitude | Age (m.y.)[1] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | E. McKay Butte | 43°43.8' | 121°21.6' | 0.58±0.10 | 24 | Egli Ridge | 43°22.8' | 119°51.0' | 6.42±0.19 |
| 2 | China Hat | 43°40.8' | 121° 3.0' | 0.78±0.20 | 25 | Elk Mtn. | 43°15.0' | 120°10.5' | 6.67±0.18 |
| 3 | East Butte | 43°39.9' | 120°59.6' | 0.85±0.05 | 26 | S. of Horse Mtn. | 43° 2.8' | 120° 8.6' | 6.84±0.22 |
| 4 | Quartz Mtn. | 43°37.5' | 120°53.3' | 1.11±0.05 | 27 | Horse Mtn. | 43° 9.1' | 120° 7.7' | 6.92±0.14 |
| 5 | Long Butte | 43°33.5' | 120°49.8' | 2.30±0.32 | 28 | Owens Butte | 42°19.7' | 120°51.9' | 7.11±0.94 |
| 6 | Burn Butte | 43°19.2' | 121°53.3' | 2.45±0.94 | 29 | Drews Ranch | 42°16.1' | 120°43.8' | 7.14±0.34 |
| 7 | Squaw Ridge | 43°31.8' | 120°46.8' | 3.59±0.07 | 30 | Thomas Creek | 42°23.8' | 120°36.0' | 7.19±0.32 |
| 8 | Frederick Butte | 43°37.5' | 120°27.6' | 3.90±0.40* | 31 | Cougar Peak | 42°18.3' | 120°37.9' | 7.28±0.50 |
| 9 | Cougar Mtn. | 43°24.0' | 120°53.0' | 4.31±0.34 | 32 | Tucker Hill | 42°36.0' | 120°25.3' | 7.42±0.19 |
| 10 | Bald Mtn. area | 43°20.1' | 121°22.8' | 4.43±0.18 | 33 | Burns Butte | 43°34.1' | 119° 8.2' | 7.55±0.10 |
| 11 | Yamsey Mtn. area | 42°56.6' | 121°19.5' | 4.68±0.17 | 34 | Quartz Butte | 42°20.6' | 120°47.7' | 7.60±0.40[2] |
| 12 | Bald Mtn. area | 43°19.2' | 121°22.5' | 4.88±0.59 | 35 | McComb Butte | 42°34.6' | 120°37.1' | 7.71±0.09 |
| 13 | Glass Buttes | 43°33.3' | 120° 0.4' | 4.91±0.73 | 36 | Burns Butte | 43°30.8' | 119° 8.3' | 7.80±0.30* |
| 14 | Partin Butte | 42°54.9' | 121° 8.5' | 5.02±0.20 | 37 | Harney Lake area | 43°17.0' | 119°18.8' | 7.80±0.50* |
| 15 | Squaw Butte | 43°30.0' | 119°46.7' | 5.12±0.08 | 38 | Double Mtn. | 43°49.8' | 117°20.4' | 7.86±0.21 |
| 16 | Bald Mtn. | 43°16.5' | 121°21.3' | 5.07±0.64 | 39 | Thomas Creek | 42°19.8' | 120°34.8' | 8.10±0.50[2] |
| 17 | Black Hills | 42°35.6' | 121°13.4' | 5.38±0.54 | 40 | Harney Lake area | 43°14.3' | 119°13.5' | 8.20±0.20* |
| 18 | Palomino Buttes | 43°30.3' | 119°18.0' | 5.60±0.40* | 41 | Harney Lake area | 43°13.5' | 119°21.2' | 8.40±1.30* |
| 19 | E. of Squaw Butte | 43°29.0' | 119°32.1' | 5.70±0.67 | 42 | Duck Butte | 43°12.2' | 118° 7.5' | 9.60±0.60* |
| 20 | Hager Mtn. | 43° 0.6' | 121° 1.2' | 5.90±0.09 | 43 | Duck Butte | 43°12.2' | 118° 7.5' | 10.00±0.40* |
| 21 | Palomino Buttes | 43°28.8' | 119°18.0' | 6.10±0.20* | 44 | Beatys Butte | 42°25.5' | 119°18.8' | 10.37±0.53 |
| 22 | Palomino Buttes | 43°30.3' | 119°18.0' | 6.40±0.20* | 45 | Hawkes Valley | 42° 6.8' | 119° 7.5' | 13.48±0.23 |
| 23 | Palomino Buttes | 43°28.8' | 119°18.0' | 6.50±0.30* | 46 | Buchanan | 43°38.9' | 118°37.3' | 14.74±0.50 |
| | | | | | 47 | Wagontire Mtn. | 43°22.5' | 119°52.2' | 14.71±1.10 |

Table 1b.--*New K/Ar radiometric ages of ash-flow tuffs in southeastern Oregon*

| Col. No. | Location | Latitude | Longitude | Age (m.y.) |
|---|---|---|---|---|
| 1 | N. of China Hat | 43°49.4' | 121° 1.1' | 0.70±0.70 |
| 2 | W. of Fort Rock | 43°22.5' | 121°17.3' | 3.35±0.44 |
| 3 | W. of Fort Rock | 43°21.7' | 121°12.1' | 4.47±0.84 |
| 4 | S. of Silver Lake | 43° 1.6' | 121° 6.9' | 6.77±1.10 |
| 5 | W. of Silver Lake | 43° 5.2' | 121°11.2' | 7.18±1.54 |

[1]Asterisk after ages refer to previously published ages listed in Walker and others (1974).
[2]Peterson and McIntyre (1970).

The dated domes and their associated eruptive products show a remarkably well defined progression in age, successively older toward the east (fig. 3). The youngest rhyolitic rocks are those of Newberry Volcano at the west end of the northern belt. Newberry is a 20-by-40-km basaltic shield volcano with a summit caldera in which both basaltic and rhyolitic rocks have been erupted (Williams, 1957; Higgins, 1973). Many ash- and pumice-flow tuffs, air-fall tuffs, and obsidian flows in the caldera are only 2,000-7,000 years old (Oregon Dept. Geology and Mineral Industries, 1965; Peterson and Groh, 1969; Higgins, 1969, 1973).

One of three small rhyolite domes at McKay Butte on the west flank of Newberry Volcano yielded a radiometric age of 0.58±0.10 m.y. Progressing southeastward from Newberry, the dome at China Hat is 0.78±0.20 m.y.; East Butte, 0.85±0.05; Quartz Mountain, 1.11±0.05; Long Butte, 2.30±0.32; Squaw Ridge, 3.59±0.07; and Frederick Butte is 3.9±0.4 m.y. On the basis of the available ages, domes east of the Cascade Range younger than 4 m.y. (± analytical uncertainty) are known to crop out only within 70 km of Newberry Volcano at the west end of the northern belt. A large exogenous dome or exhumed vent complex at Burn Butte on the eastern flank of the Cascade Range about 70 km southwest of Newberry (figs. 2 and 3) has a radiometric age of 2.45±0.94 m.y. and may be related to the young domes of southeastern Oregon.

Rhyolitic bodies in the range 4-5 m.y. (± analytical uncertainty) occur in a band that includes domes both in and between the northern and southern belts. Glass Buttes has a radiometric age of 4.91±0.73 m.y.; three domes near Bald Mountain are 4.43±0.18; 4.88±0.59, and 5.07±0.64 m.y.; a dome on the east flank of the large andesitic volcano at Yamsey Mountain is 4.68±0.17 m.y.; and Partin Butte is 5.02±0.20. Progressively older rhyolitic rocks occur in successively more southeastward bands at least as far east as Beatys Butte and Duck Butte, which are both about 10 m.y. old.

The progression in age of the domes is sufficiently well defined and enough domes have been dated so that the ages can be contoured (fig. 2). The resulting age contours for domes younger than about 5 m.y. trend about N. 70° E. and for older domes about N. 45°-50°E. The change in orientation of the age contours corresponds approximately in time to a change in rate of age progression of the domes (fig. 3A). The rate of westward decrease in age is about 1 cm/yr for domes younger than about 5 m.y. and about 3 cm/yr for domes between 5 and 10 m.y. (measured normal to the age contours). Domes younger than 1 or 2 m.y. occupy a relatively broad area, suggesting a recent (<2 m.y.) increase in rate of progression. The main trends of the age contours are oblique to the trend of the northern and southern belts of domes, to the Brothers fault zone, and to Basin and Range faults of southeastern Oregon (fig. 1).

The age contours change orientation at their extremities. This change is particularly pronounced for the south end of the 5- and 6-m.y. contours but also applies to the 7- and 8-m.y. contours because numerous domes in the Warner Mountains of California, near the Oregon border

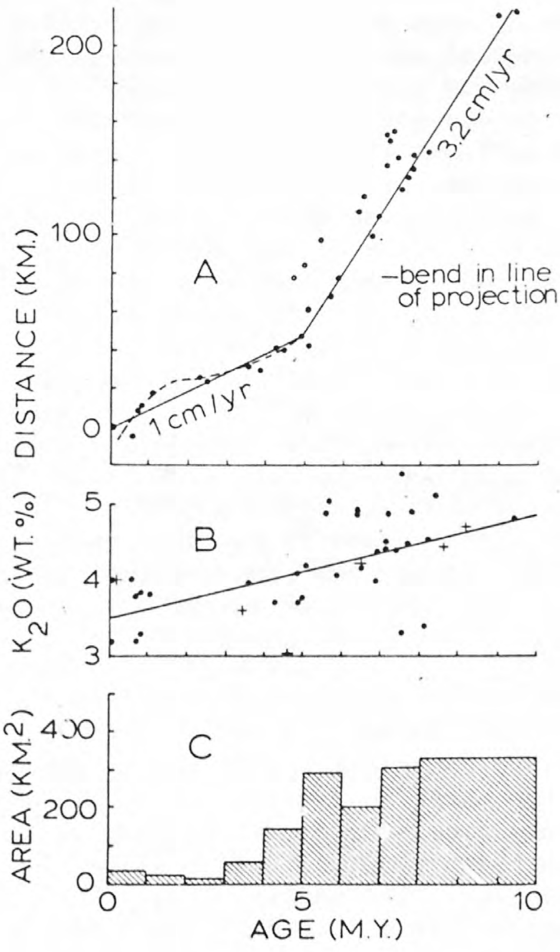


Figure 3. A, Age-distance relations of radiometrically dated domes. Distance is measured along dashed line extending from an arbitrary zero point at Newberry caldera as shown in figure 2. Circled points between 4 and 6 m.y. are of domes in the southwestern part of area where isochrons show a marked change in orientation. Dashed line between 0 and 5 m.y. is a curved, rather than straight line fit to the younger dates and suggests a recent increase in rate of progression. B, Relation of age to $K_2O$ content of domes (points) and ash-flow tuffs (crosses). K2O data are from table 2 and from K O determined on whole rocks (mostly obsidian) dated by K/Ar methods. C, Relation of age to area of outcrop of domes. Includes area of outcrop of all dated and undated domes between isochrons of figure 2. Vents for major ash-flow tuffs inferred to be buried beneath younger rocks in the Harney Basin would add to the 6-7, 8-9, and 9-11 blocks if exposed. Few domes in the 8-11 m.y. range have been dated, so the areas of domes in this age range have been grouped together.

southeast of Goose Lake, are 7-8 m.y. old (W. A. Duffield and E. H. McKee, unpub. data). A northerly deflection of the north end of the 7-m.y. contour is suggested by one date there.

Ages of most of the undated domes in the region can probably be estimated to the nearest 1 m.y. on the basis of their geographic location. We know of no undated domes west of Beatys Butte and Duck Butte whose contact relations with rocks of known age indicate an age younger than that inferred from their geographic position. Some undated domes, however, may be older than the predicted age. A rhyodacite flow on the northwest flank of Wagontire Mountain, for instance, yielded a radiometric age of 14.7±1.0 m.y., whereas nearby domes are about 5-7 m.y. old. Probably two units of rhyolitic rocks crop out at Wagontire Mountain, one about 6 m.y. associated with Pliocene(?) ash-flow tuffs that crop out on the southern flank of the mountain (Walker and Swanson, 1968), the other about 15 m.y. Rhyodacite from an exogenous dome near Buchanan (east of Burns) yielded a K/Ar age of 14.74±0.50 m.y., much older than the age inferred by its location. This dome is on the north edge of the northern belt and may be unrelated to rocks of the belt. Other silicic rocks north of the belt are dated at 12-15 m.y. (Walker and others, 1974). Old rhyolite and rhyodacite domes occur farther east at Lake Owyhee (Corcoran and others, 1962; Kittleman and others, 1965), where they are overlain unconformably by basalt that is about 13.5 m.y. (Watkins and Baksi, 1974), and domes about 15.6 m.y. old crop out near Silver City, Idaho, just east of the Oregon border astride lat 43° N. (Pansze, 1972). A dome at Hawkes Valley near the Nevada border yielded a 13.48±0.23 m.y. age, and rhyolitic intrusive rocks and ash-flow tuffs in southeasternmost Oregon and adjacent northwestern Nevada are mostly 15-17 m.y. (Evernden and James, 1964; Noble and others, 1970; McKee and Marvin, 1974; Kittleman in Laursen and Hammond, 1974; McKee and others, 1975).

Emplacement of rhyolitic rocks east of the Oregon Cascade Range 10-18 m.y. ago thus appears to have been widespread but mostly confined to easternmost Oregon and adjacent parts of Idaho and Nevada. Younger rhyolitic domes in Oregon were emplaced almost exclusively within or between the two belts shown on figure 2. The only dated dome that is younger than about 10 m.y. and well outside either belt is at Double Mountain, 20 km southwest of Vale, and has a 7.86±0.21 m.y. radiometric age.

## DISTRIBUTION AND AGE OF ASH-FLOW TUFFS

Late Cenozoic rhyolitic ash-flow tuffs form widespread and voluminous units in southeastern Oregon (Walker, 1970) and are apparently related in origin to the domes. The generalized distribution of these ash-flow sheets are shown in figure 4 and new K/Ar ages are listed on table 1b.

The 2,000- to 7,000-year-old ash-flow and air-fall tuffs of Newberry Volcano (Higgins, 1973) are the youngest known silicic tuffs in southeastern Oregon. They were erupted from within Newberry caldera and are associated with obsidian flows and near vent pumice deposits, and basaltic flows, cinder cones, and volcano-phreatic deposits. A thick welded ash-flow tuff

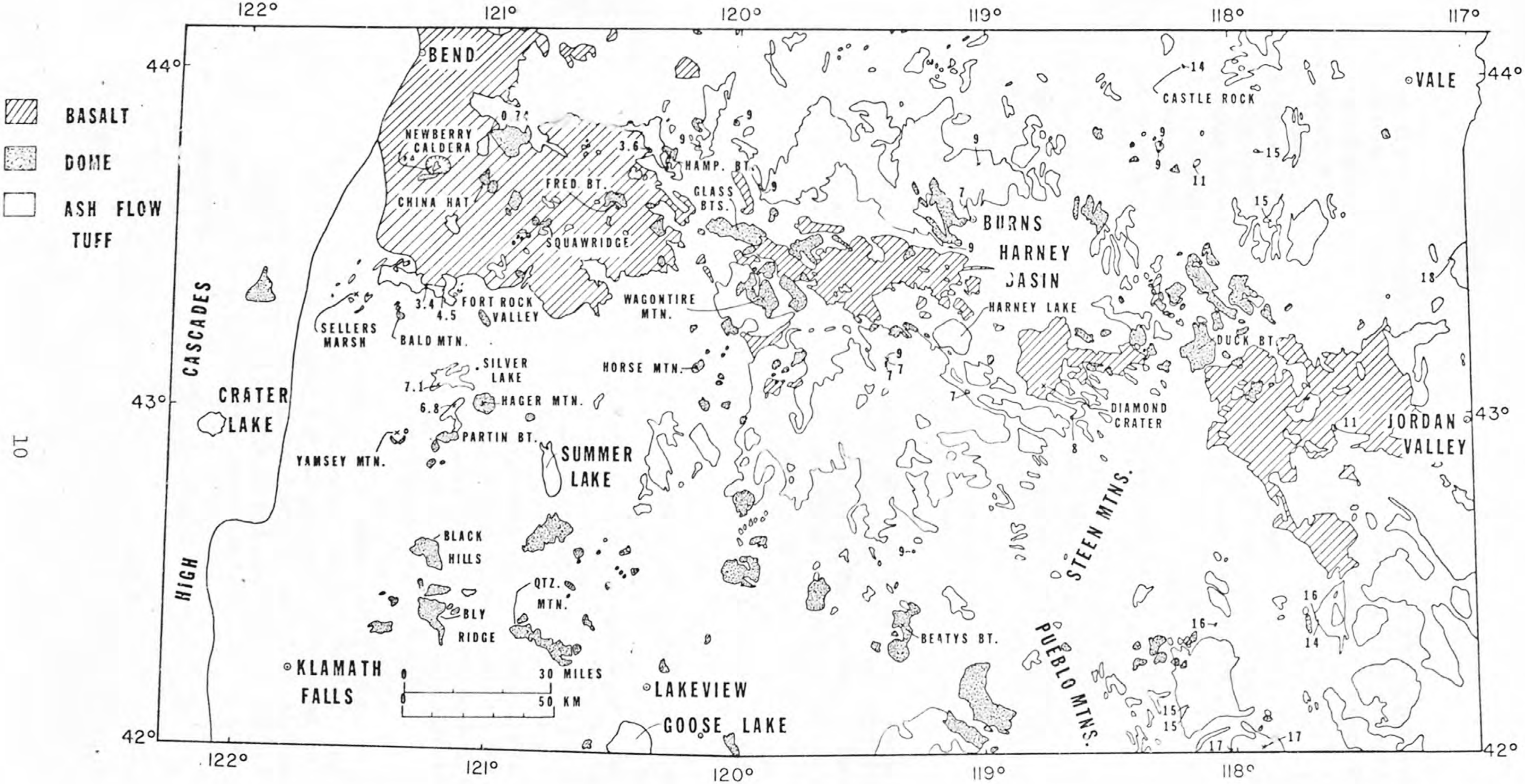


Figure 4.--Map of southeastern Oregon showing distribution of major ash-flow tuffs (dotted pattern) and Quaternary and latest Pliocene basalt flows (from Walker, 1973). Some late Cenozoic basalt flows east and northeast of Klamath Falls (Peterson and McIntyre, 1970) may be as young as some of the basalt flows shown here. Ages of newly dated ash-flow tuffs are listed in Table 1a; other ages, rounded to the nearest 1 m.y., are from the compilation of Walker, Dalrymple, and Lanphere (1974).

older than the 6,700-year-old Mazama ash occurs on the upper east wall of the caldera. Highly pumiceous ash-flow tuff is also exposed below a veneer of basalt in a 50-$km^2$ area on the northeast flank of Newberry Volcano about 30 km from the caldera; plagioclase from pumice lumps in this ash flow yielded an age of 0.7±0.7 m.y. (table 1b, col. 1). This ash flow either may have originated from Newberry Volcano, in which case it is probably much younger than 0.7 m.y., or it may be related to the exogenous rhyolitic dome of nearby China Hat (0.8±0.2 m.y. old; table 1a, no. 2). Several ash-flow tuffs of late Pliocene or Pleistocene age crop out northwest of Newberry along the east side of the Cascade Range but were probably derived from Cascade vents (Williams, 1957; Walker, 1970).

The Peyerl Tuff, a sequence as much as 150 m thick of ash-flow tuffs and interbedded sedimentary rocks, crops out along the west side of Fort Rock Valley, southeast of Newberry Volcano (Hampton, 1964; Peterson and McIntyre, 1970). Our preliminary geologic mapping indicates that these tuffs extend about 40 km westward and southwestward from Fort Rock Valley to Sellers Marsh and beyond (fig. 4). Radiometric ages of 4.47± 0.84 m.y. were determined on plagioclase separated from pumice lumps in one ash-flow tuff in the Peyerl and 3.35±0.44 on frothed and collapsed obsidian in the densely welded part of another ash-flow tuff (table 1b, nos. 2 and 3). The source of the ash-flow tuffs appears to be a 7- to 10-km-wide probable caldera near Bald Mountain, now partly filled with younger basalt and andesite flows. Small rhyolitic domes and flows on the margin, including the dome at Bald Mountain, and in the center of the probable caldera have radiometric ages of 4.43±0.18, 4.88±0.59, and 5.07±0.64 m.y.

An unnamed sequence of ash-flow tuffs near Silver Lake (Peterson and McIntyre, 1970) yielded radiometric ages of 7.18±1.54 and 6.77±1.10 (table 1b, nos. 4 and 5). The ages are older than nearby domal rocks such as at Partin Butte (5.02±0.20 m.y.), a dome on the east flank of Yamsey Mountain (4.68±0.17 m.y.), and one atop Hager Mountain (5.90±0.09 m.y.), and it seems more likely that these tuffs issued from 7-m.y.-old vents farther east or southeast. Late Cenozoic ash-flow tuffs are also reported farther south near Sprague River southwest of the Black Hills and over a large area northwest of Lakeview (Peterson and McIntyre, 1970), but as they are not distinguished from other volcanic and sedimentary units on published maps, they are not shown on figure 4.

Ash-flow tuffs about 3.6 m.y. old (Walker and others, 1974) crop out near Hampton Butte, midway between Bend and Harney Basin. The dome at Hampton Butte has not been dated but is probably unrelated to the ash flows, as it is more mafic. Rhyolite domes 20-40 km to the south and southwest at Frederick Butte (3.9±0.4 m.y.) and Squaw Ridge (3.59±0.07 m.y.) are about the same age as the ash-flow tuff, and either could be related to the tuff.

An ash-flow tuff sheet of probable Pliocene age south and west of Wagontire Mountain was erupted from vents on the southwest side of the mountain (Walker and Swanson, 1968). Rhyolite on the northwest flank of Wagontire has a radiometric age of 14.71±1.10 m.y., suggesting that the mountain may include rocks of both Miocene and Pliocene age.

Three extensive sheets of ash-flow tuff and several smaller, more restricted sheets crop out over a large area peripheral to Harney Basin. The youngest major sheet covers an area of 10,000 $km^2$, mostly northwest, west, and south of central Harney Basin, and has an estimated volume of about 185 $km^3$ (Walker, 1970). It has variously been called the welded tuff of Double O Ranch (Greene and others, 1972), ignimbrite member of the Rattlesnake Formation of Merriam (1901), and tuff breccia member of the Danforth Formation of Piper, Robinson, and Park (1939). Published K/Ar dates on this ash-flow tuff listed in Walker, Dalrymple, and Lanphere (1974) indicate an age of about 6.4 m.y. The ash-flow tuff apparently vented from a caldera in Harney Basin, an area that is now veneered by later Cenozoic sedimentary deposits and basalt flows (Walker, 1970). Rhyolitic domes and flows near the west end of Harney Lake, dated at 7.8 and 8.4 m.y. by Parker and Armstrong (1972), are about 2 m.y. older than the tuff, but rhyolite domes of about the same age as the tuff occur only a short distance west of Harney Basin (Palomino Butte is 5.6-6.5 m.y. and Egli Ridge about 6.4 m.y.). The vent for the tuff may be located between the domes about 30 km west-northwest of Harney Lake. A large negative anomaly on aeromagnetic maps of this area (U.S. Geol. Survey, 1972) may be caused by nonmagnetic fill in a buried caldera or by vent rocks with the same reversed polarization as the tuff.

The welded tuff of Prater Creek underlies the welded tuff of Double O Ranch on the north side of Harney Basin and has been dated at 8.6±0.2 m.y. (Parker and Armstrong, 1972). The vent for this tuff probably lies buried beneath Quaternary sediments of Harney Basin east or southeast of Burns. Rhyolitic flows and domes at Burns Butte near Burns are 7.55±0.1 to 7.8±0.3 m.y., about 1 m.y. younger than the tuff.

The welded tuff of Devine Canyon, the oldest of the three major ash-flow tuffs, crops out over a wide area surrounding Harney Basin. It originally covered about 18,000 $km^2$ and had a volume of over 200 $km^3$ (Greene, 1973). It is about 9 m.y. old on the basis of eight K/Ar dates listed in Walker, Dalrymple, and Lanphere (1974), and its distribution and thickness suggest that it was erupted from a buried caldera in the Harney Basin near or southeast of Burns (Walker, 1970; Greene, 1973).

Miocene ash-flow tuffs older than 10 m.y. are widespread in eastern Oregon and adjacent parts of Idaho and Nevada and show no clear relation to the time transgressive belts of rhyolitic domes. For instance, the Dinner Creek Welded Tuff, about 14.5 m.y. old, crops out over a large area northeast of Harney Basin and may have issued from fissure zones now occupied by rhyolite dikes in the Castle Rock area (Haddock, 1965) and possibly also from domal masses at and near Black Butte north of the northern belt of domes. Isolated outcrops of Miocene or Pliocene ash-flow tuff occur even farther north in the Durkee and Sparta quadrangles east of Baker (Prostka, 1962, 1967) and in the Juntura area east of Harney Basin (Bowen and others, 1963).

Ash-flow tuffs in southeastern Oregon adjacent to Nevada and Idaho are mostly 13-18 m.y. old (fig. 4). Ash-flow tuffs between Duck Butte and the Idaho border have radiometric ages of 15.1 (Evernden and James, 1964) 15.4, and 18.5 m.y. (Kittleman in Laursen and Hammond, 1974). The sources of these tuffs are unknown, but rhyolite flows of the same age occur near the Idaho border, and domes occur at Owyhee Dam and near Silver City, Idaho. Volcanic rocks, including ash-flow tuffs, from the McDermitt caldera astride the Oregon-Nevada border at long. 118° W. are about 15-17.5 m.y. old (McKee and others, 1975). Other ash-flow tuffs in Oregon near the Nevada border may correlate with extensive tuffs in northwestern Nevada that are about 15.5 m.y. One of these ash flows, the Soldier Meadow Tuff, was erupted from a series of vents in Nevada at 41°28' N., 119°10' W. (Noble and others, 1970), approximately on trend with the southern belt of domes in Oregon.

To summarize, the inferred vents of ash-flow tuffs east of the Oregon Cascade Range that are younger than about 10 m.y. are apparently restricted almost entirely to the area in which rhyolitic domes are 10 m.y. and younger. Ash-flow tuffs older than 10 m.y. erupted from areas east, north, and south of these domes.

## AGE RELATED COMPOSITIONAL AND VOLUMETRIC VARIATIONS OF SILICIC VOLCANIC ROCKS

Sufficient data are available to indicate the principal chemical characteristics of the silicic volcanic rocks and to show that the age progression of the domes and the ash-flow tuffs that appear to relate to them is accompanied by minor but significant changes in chemical composition. Chemical analyses of rhyolitic domes and associated flows and ash-flow tuffs are listed in table 2; additional $K_2O$ values are available for the dated rocks.

Most of the analyzed rocks are peraluminous, and the generally high $SiO_2$ content (average 73.7) and Na/K, and relatively low CaO of many of the rhyolites and obsidians are typical of those of bimodal basalt-rhyolite associations (Christiansen and Lipman, 1972). The analyzed ash-flow tuff generally have lower content of $Al_2O_3$ and CaO and higher $SiO_2$ than rhyolite domes and associated flows, perhaps partly as the result of crystal settling before, or sorting after, eruption.

The most obvious variation in chemical composition with age, and hence location, is in the $K_2O$ content (fig. 3B). Although considerable scatter is shown, the younger rocks generally have 3-4 percent $K_2O$ and older rocks have 4-5½ percent. The older rocks also generally have higher $K_2O$ content in analyzed phenocrystic plagioclase, and sanidine-anorthoclase

Table 2.--*Chemical analyses of rocks from silicic domes, flows, and ash-flow tuff sheets younger than 10 m.y. in southeastern Oregon*

| Col. No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Age (m.y.) | <0.1 | <0.1 | <1(?) | 0.8 | 0.9 | 3.6 | 4.9 | 6.4 | 6.5 |
| $SiO_2$ | 72.7 | 70.6 | 70.5 | 69.5 | 71.2 | 71.5 | 75.7 | 76.0 | 78.2 |
| $Al_2O_3$ | 14.4 | 13.9 | 14.9 | 15.8 | 14.9 | 13.3 | 13.4 | 12.9 | 12.4 |
| $Fe_2O_3$ | 0.38 | 0.53 | 1.3 | 1.7 | 2.3 | 1.4 | 0.26 | 0.75 | 0.57 |
| FeO | 1.6 | 1.7 | 1.7 | 0.72 | 0.44 | 1.6 | 0.56 | | |
| MgO | 0.20 | 0.26 | 0.35 | 0.13 | 0.20 | 0.08 | 0.09 | 0.4 | 0.24 |
| CaO | 1.0 | 1.4 | 1.5 | 1.0 | 1.0 | 1.4 | 0.90 | 1.6 | 0.15 |
| $Na_2O$ | 4.8 | 4.5 | 5.4 | 3.9 | 4.2 | 4.5 | 3.8 | 3.4 | 3.7 |
| $K_2O$ | 4.0 | 4.0 | 3.2 | 3.2 | 3.3 | 3.0 | 3.7 | 4.9 | 4.2 |
| $H_2O^-$ | 0.41 | 2.2 | 0.29 | 2.1 | 1.2 | 2.5 | 0.39 | --- | --- |
| $H_2O^-$ | 0.05 | 0.24 | 0.11 | 1.2 | 0.82 | 0.16 | 0.04 | --- | --- |
| $TiO_2$ | 0.21 | 0.38 | 0.32 | 0.17 | 0.20 | 0.24 | 0.10 | 0.08 | 0.23 |
| $P_2O_5$ | 0.05 | 0.09 | 0.03 | 0.10 | 0.09 | 0.04 | --- | --- | 0.01 |
| MnO | 0.04 | 0.09 | 0.06 | 0.07 | 0.08 | 0.11 | 0.06 | --- | 0.19 |

| Col. No. | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|
| Age (m.y.) | 6.9 | 7.1 | 7.2 | 7.6 | 8.1 | 8.6 | 9.2 | 5-15 |
| $SiO_2$ | 76.5 | 73.1 | 76.7 | 70.2 | 76.2 | 74.2 | 74.5 | 75.8 |
| $Al_2O_3$ | 11.0 | 14.1 | 13.3 | 14.4 | 13.3 | 12.1 | 11.2 | 12.1 |
| $Fe_2O_3$ | 2.6 | 1.5 | 0.29 | 1.3 | 0.80 | 3.0 | 2.2 | 1.6 |
| FeO | 0.26 | 0.31 | 0.08 | | | | 0.61 | 0.88 |
| MgO | 0.07 | 0.22 | 0.04 | 0.91 | 0.30 | 0.24 | 0.25 | 0.01 |
| CaO | 0.29 | 1.1 | 0.64 | 1.9 | 0.75 | 0.43 | 0.42 | 0.30 |
| $Na_2O$ | 4.2 | 3.5 | 3.3 | 3.2 | 3.8 | 4.6 | 3.9 | 4.3 |
| $K_2O$ | 4.0 | 4.5 | 4.9 | 3.3 | 3.4 | 4.4 | 4.7 | 4.2 |
| $H_2O^-$ | 0.36 | 1.0 | 1.1 | 3.2 | 1 ? | --- | 1.1 | 0.44 |
| $H_2O^-$ | 0.04 | | | | | --- | 0.51 | 0.15 |
| $TiO_2$ | 0.18 | 0.19 | 0.06 | 0.08 | 0.07 | 0.15 | 0.20 | 0.06 |
| $P_2O_5$ | | 0.04 | 0.01 | --- | --- | --- | 0.05 | 0.02 |
| MnO | 0.08 | 0.10 | 0.06 | 0.11 | 0.13 | --- | 0.05 | --- |

| Col. | Location |
|---|---|
| 1 | Newberry Volcano, Big obsidian flow, average of four analyses (Higgins, 1973, p. 483) |
| 2 | Newberry Volcano, Paulina Lake ash flows (Higgins, 1973, p. 474) |
| 3 | Newberry Volcano, Paulina Peak rhyolites, average of six analyses (Higgins, 1973, p. 469) |
| 4 | China Hat, dome (Higgins, 1973) |
| 5 | East Butte, dome, average of two analyses (Higgins, 1973) |
| 6 | Hampton Butte area, ash-flow tuff |
| 7 | Glass Butte, dome |
| 8 | Palomino Butte, dome (Parker and Armstrong, 1972) |
| 9 | Ignimbrite tongue of Rattlesnake Formation, average of four analyses (Enlows, 1973, p. 26) |
| 10 | Horse Mountain, dome |
| 11 | Owens Butte, dome |
| 12 | Thomas Creek, dome |
| 13 | Quartz Butte, dome (Peterson and McIntyre, 1970) |
| 14 | Thomas Creek, dome (Peterson and McIntyre, 1970) |
| 15 | "Prater Creek member of the Danforth Formation" of Parker and Armstrong (1972, p. 7, 10) |
| 16 | Welded tuff of Devine Canyon, average of 14 analyses (Greene, 1973) |
| 17 | Ash-flow tuff southeast Wagontire Mountain (Walker and Swanson, 1968) |

Columns 6, 7, 10, 11, and 12 were analyzed using methods similar to those described in U.S.G.S. Bull. 1036-C and 1144A, by P. Elmore, I. Barlow, S. Botts, G. Chloe, and L. Artis.

phenocrysts are more common than in younger rocks. The available chemical data also suggest that $SiO_2$ tends to be higher and $Al_2O_3$ lower in older rocks.

Volume-age relations cannot be directly determined because the shape of the domal masses at depth are not known. Assuming the areas are approximately proportional to volumes, a decline in rhyolitic volcanism is indicated at about 5 m.y. ago (fig. 3C). The decline corresponds approximately in time to the change in orientation of the age contours from N. 45° E. to N. 70° E., and to a decrease in rate of westward age progression from about 3 to 1 cm/yr.

## DISTRIBUTION OF AGE OF LATE CENOZOIC BASALT FLOWS

Late Cenozoic basalt flows and basaltic (palagonitic) sediments in southeastern Oregon have a greater volume than do the rhyolitic domes, associated flows, and ash-flow tuffs. Most exposed intrusive contacts of rhyolitic domes are with basaltic rocks and basalt flows lap onto many domes. In addition, many ash-flow tuffs occur between basalt flows, indicating that basalt eruptions both preceded and followed rhyolitic volcanism in many areas. The exact age of basaltic volcanism is poorly known because few basalt flows younger than 10 m.y. have been dated. From the scattered data available, however, the basalt flows do not show the same monotonic age increase toward the east as do the rhyolite domes.

Uppermost Pliocene and Quaternary basalt flows and vents are abundant in the general area of the northern belt of domes (fig. 4). Upper Pleistocene and Holocene flows and vents occur at Newberry, at Diamond Craters on the southeast side of Harney Basin, and west of Jordan Valley near the Idaho border (Walker, 1973). Uppermost Pliocene or Pleistocene flows occur in a large area extending from Newberry eastward to Glass Butte, on the west and southeast sides of Harney Basin, and west of Jordan Valley. These young basalt flows form a belt that largely coincides with the northern belt of domes, suggesting a similar structural control despite differences in ages. If any age progression is shown by Miocene and Pliocene basalts, it is obscured by the younger basaltic volcanism.

## SIGNIFICANCE OF RHYOLITE AGE PROGRESSION TO GEOTHERMAL EXPLORATION

Oregon is one of several western states considered to have a high potential for development and utilization of geothermal energy. This is based on the abundance of thermal springs and late Cenozoic volcanic rocks and on high temperature gradients measured in several areas.

Of about 150 thermal-spring areas in Oregon listed in a compilation by Bowen and Peterson (1970), 75 percent occur in southeastern Oregon between lat 42° and 44° N., east of the Cascade Range. Thermal springs are five to six times more abundant per unit area in southeastern Oregon than in the remainder of the state. Most of the thermal springs in southeastern Oregon have temperatures of less than 50°C, but 18 are in excess of 70°C, and several have surface temperatures near or at the boiling point of water for their elevation. Chemical analyses of 32 of the hotter thermal springs show that nine have cation concentrations indicating minimum reservoir temperatures in excess of 140°C (Mariner and others, 1974). The thermal water of many of the cooler springs may be contaminated by cool near-surface water.

Temperature gradients of more than 80°C/km in sedimentary rocks and 60°C/km or more in basaltic rocks have been measured in several areas; considering probable conductivities, they suggest heat flows of 2-4 $\mu cal/cm^2$ sec or higher (Bowen, 1972; Sass and Munroe, 1973). These limited data suggest that heat flow in southeastern Oregon is relatively high and comparable to that of the Basin and Range Province of Nevada.

Few thermal springs in southeastern Oregon occur in areas where Quaternary volcanic rocks crop out. Most springs lie along or near large faults, and considering the possible relatively high heat flux, most thermal springs probably result from upward circulation of relatively hot, low-density meteoric water from substantial depths along fracture zones. Few of these thermal-spring areas are likely to be developed as electric power-generating fields in the near future, but some may be exploitable for space heating and industrial and agricultural uses. Thermal springs and shallow thermal water near Klamath Falls, Lakeview, Burns, and Vale have long been used for these purposes, and their full potential has yet to be realized.

We know of only two thermal springs east of the Cascade Range that can reasonably be assumed to have cooling intrusive bodies as their heat source. Both lie in Newberry caldera, an area subjected to voluminous Holocene basaltic and rhyolitic volcanism. The springs at Newberry are the only recorded thermal springs at the western end of the northern belt of silicic domes, the only known area where silicic volcanism is of Quaternary age. In this region the paucity of both hot and cold springs may be partly due to zones of high porosity and permeability associated with laterally extensive interbeds of tuff and flow breccia, as well as to unconsolidated ash-fall tuff and windblown ash and pumice that veneers much of the surface. Many thermal anomalies in this area may, therefore, have no surficial hydrologic expression.

Most electric power-producing geothermal fields in the world occur in or near young silicic volcanic fields, and southeastern Oregon, with its abundant young rhyolitic rocks, offers a likely geologic setting for magmatic heat reservoirs. Rhyolitic bodies, because of their generally large size and equant shape in the shallow part of the crust, may if sufficiently young have heat potential within the range of modern drilling technology. Basalts that reach the earth's surface through small dike systems extending from great depth are much less likely targets for sustained geothermal heat production. No maximum age can be assigned to rhyolitic intrusive bodies of geothermal interest without knowing the volumes and shapes of the bodies at depth. Some additional factors that affect the cooling rate include the original temperature regime of the country rock, circulation of fluids in both the country rock and the intrusive body, and depth of burial of the body. Calculations by Lachenbruch and others (1975) on the Long Valley caldera of eastern California indicate that any large rhyolite body there older than 2 m.y. would have cooled to near ambient temperatures by now. An intrusive body with the cross sectional area of the Long Valley caldera is probably much larger than any intrusive silicic body at the west end of the northern belt, the only known area east of the Oregon Cascade Range where silicic rocks as young as 2 m.y. occur.

Newberry Volcano appears to have the highest potential for geothermal power production in southeastern Oregon because of its very young age, large volume of both silicic and basaltic lavas, and presence of thermal springs. Exploration and development there must be weighed against recreational uses of the caldera area. Domes at McKay Butte, China Hat, East Butte, and Quartz Mountain, near or on the lower flanks of Newberry, are 1 m.y. old or younger and, if substantially larger at depth than their surface outcrop suggests, may still retain sufficient magmatic heat to be geothermal energy sources. The hydrologic regime around these domes, however, may or may not be amenable to production of hot water or steam. Some young rhyolitic intrusive bodies in the Newberry area may have no surface expression and if present will probably be found only by using geophysical techniques. Considering the age progression, the west flank of Newberry may be a particularly important area for geophysical exploration.

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