Newberry Volcano, Oregon: A Cascade Range geothermal prospect *

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INTRODUCTION

Temperatures as high as 265° C in a 932-m-deep drill hole in the caldera of Newberry Volcano (Figure 1) marked the culmination of a series of geologic and geothermal studies in central Oregon undertaken by the U.S. Geological Survey (USGS) in its Geothermal Research Program. These temperatures, easily the highest recorded in the Pacific Northwest, as well as the large volume and wide areal distribution of young silicic volcanic rocks, suggest that a large heat source underlies the volcano and that it may have a potential for electric power generation.

Many of the electric-power-producing geothermal reservoirs in the world occur in or near young silicic volcanic fields. Magma chambers that feed rhyolitic volcanism are commonly large and located in the upper crust; if the rhyolitic bodies have not cooled substantially, they offer a heat source within the range of modern drilling technology (Smith and Shaw, 1975). Basalt fields fed by narrow dikes extending from great depth are less favorable geothermal targets, although in some places such as Iceland and Hawaii they form important geothermal systems.

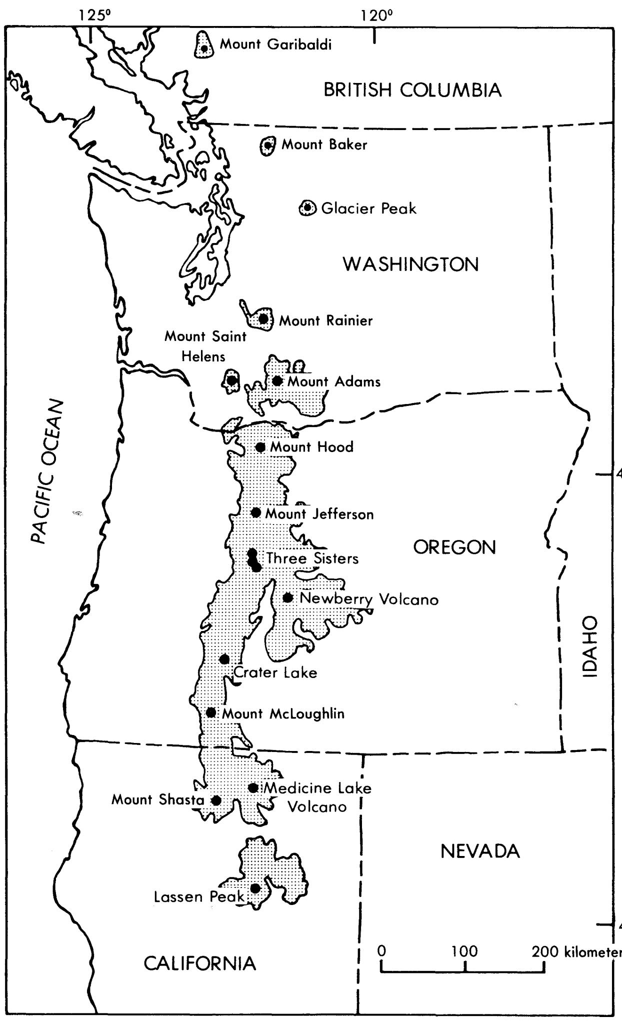

Figure 1. Major volcanic centers and areas of Quaternary volcanic rocks in the Cascade Range.

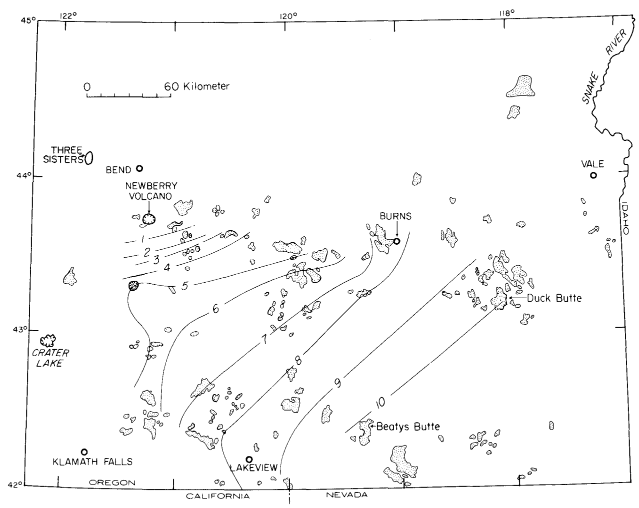

Figure 2. Age progression of silicic domal rocks (patterned) in southeast Oregon. Isochrons in increments of 1 million years. Modified from MacLeod and others (1976).

The USGS geothermal project in Oregon began with studies of young rhyolitic rocks that occur in a broad zone that extends about 320 km eastward from the Cascade Range (Figure 2). Field work by G.W. Walker suggested that the rhyolitic rocks were progressively younger toward the Cascade Range. Extensive potassium-argon (K-Ar) dating of the rhyolites by E.H. McKee confirmed this progression and showed that the rhyolites have a monotonic decrease in age from about 10 million years (m.y.) in southeastern Oregon to less than 1 m.y. near the Cascade Range in the vicinity of Newberry Volcano (Walker, 1974; MacLeod and others, 1976). This age progression suggested that geothermal resources related to young rhyolitic volcanism are most likely to occur at the west end of the rhyolite belt near Newberry. The occurrence of hot springs, fumaroles, and young obsidian flows and pumice deposits in the caldera at Newberry's summit further suggested it as a target for additional geologic and geophysical studies.

Williams (1935, 1957) and Higgins (1973) considered Newberry Volcano to be a basaltic shield with rhyolites mainly restricted to the caldera. Later mapping of the volcano, however, showed that rhyolitic domes and flows and andesitic to

* Because of similarities between Newberry Volcano in Oregon and the Medicine Lake region in California, the editors of *California Geology* solicited this article from the authors and are publishing it in the November issue of their magazine. We are printing it in *Oregon Geology* because we believe it will provide useful and interesting information to our readers as well. —*Editor*

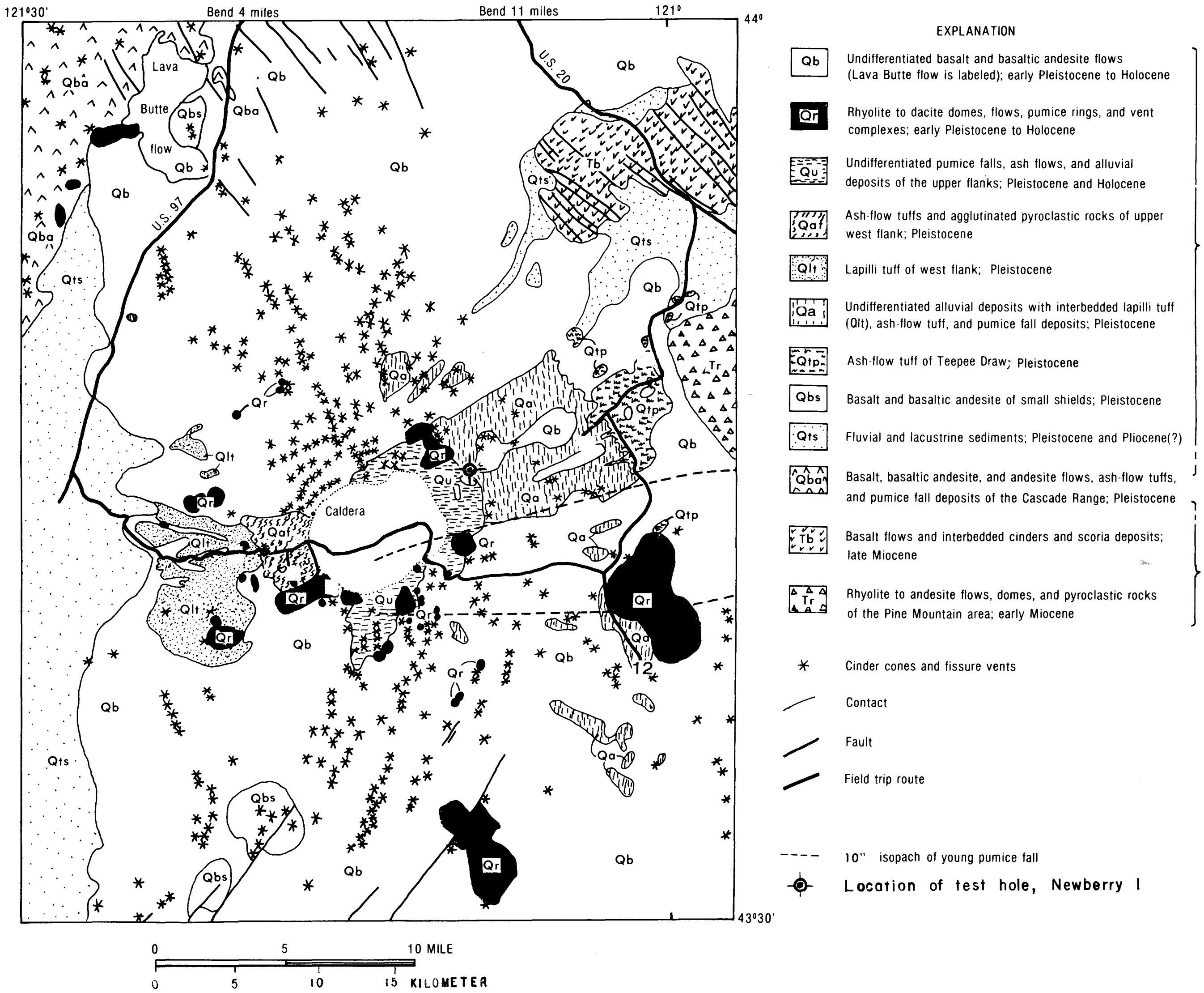

Figure 3. Geologic sketch map of Newberry Volcano. Geology of caldera is shown in Figure 4. Modified from MacLeod and others (1981).

rhyolitic ash-flow tuffs are widespread on the flanks and that the volcano has a long and complex history of volcanism that ranged from basaltic to rhyolitic (MacLeod, 1978). These encouraging indications of geothermal potential resulted in the focusing of geologic, geophysical, and water-resources investigations on the volcano and ultimately led to the drilling of two exploratory holes.

GEOLOGY

Newbery Volcano lies 60 km east of the crest of the Cascade Range in central Oregon (Figure 1) and is among the largest Quaternary volcanoes in the conterminous United States. It covers an area in excess of 1,200 km^2 and rises about 1,100 m above the surrounding terrain. The gently sloping flanks, studded with more than 400 cinder cones, consist of basalt and basaltic-andesite flows, andesitic to rhyolitic ash-flow and air-fall tuffs, dacite to rhyolite domes and flows, and alluvial sediments produced during periods of erosion of the volcano (MacLeod and others, 1981). The 6- to 8-km-wide caldera at Newberry's summit, which contains scenic Paulina and East Lakes, has been the site of numerous Holocene eruptions, the most recent of which occurred about 1,350 years ago.

Among the older rocks on the flanks of the volcano are ash-flow tuffs and associated pumice-fall tuffs, mudflows, and other pyroclastic deposits (Figure 3). They occur predominately on the east and west flanks of the volcano but probably extend completely around it and are buried by basaltic flows on the north and south flanks. Although many of the pyroclastic flows may be shoestring-type deposits that occur at only a few locations, at least four are major sheetlike deposits with considerable volume. The oldest ash-flow tuff is rhyolitic in composition and is at least 20 m thick even at places where the top is eroded and the base not exposed. Its original volume may have been more than 40 km^3. Successively younger major pyroclastic units range from rhyodacite to andesite and basaltic andesite and have estimated volumes of less than 1 km^3 to more than 40 km^3. Gravel deposits peripheral to the volcano commonly are largely composed of clasts derived from the deeply eroded pyroclastic rock sequence.

Basalt and basaltic-andesite flows and associated vents veneer the north and south flanks of the volcano. Individual flows are a few meters to 30 m thick and cover areas of less than 1 km^2 to many tens of square kilometers. The flows can be divided readily into two groups on the basis of their age relative to Mazama ash (carbon-14 age about 6,900 years) derived from Mount Mazama, 120 km to the southwest. The youngest flows, which overlie Mazama ash, have carbon-14 ages that range from 5,800 to 6,380 years. Indicated carbon-14 ages of this magnitude are generally about 800 years younger than actual ages. These youngest flows may have erupted during a much shorter period of time than the age spread indicates, inasmuch as the spread of replicate dates from individual flows is nearly as large as the spread of dates from all flows. Some of the flows that are covered by Mazama ash have surface features that suggest a rather young age, perhaps 7,000 to 10,000 years. Other flows are probably several tens or hundreds of thousands of years old. All flows sampled are normally polarized; thus none are probably older than 700,000 years.

More than 400 cinder cones and fissure vents have been identified on the flanks of Newberry; few other volcanoes contain so many. The cones and fissures are concentrated in three zones. The northwestern zone of vents is collinear with a zone of faults on the lowermost flank that extends to Green Ridge in the Cascade Range; a southwestern zone is collinear with the Walker Rim fault zone that extends south-southwest from the south flank of Newberry; and an eastern zone is a continuation of the High Lava Plains zone of basaltic vents and parallels the Brothers fault zone. Most fissures and aligned cinder cones parallel the belts in which they occur. Some aligned cinder cones and fissure vents near the summit caldera occur in arcuate zones parallel to the caldera rim and probably lie along ring fractures.

Rhyolitic domes, pumice rings, flows, and small protrusions also are common on the flanks. The larger domes are 30 to 180 m high and as much as 1,200 m across; the largest forms Paulina Peak, the highest point on the volcano, and extends 5 km southwestward from the caldera walls. Several of the larger domes have yielded K-Ar ages of 100,000 to 600,000 years. Some small protrusions on the upper southeast flank may be less than 10,000 years old.

Petrochemical and petrographic studies of the flank rhyolites have distinguished at least six groups of rhyolites on the basis of major- and minor-element compositions and proportions as well as compositions of phenocryst phases. Within each group, represented by two or more domes, compositions are virtually identical, although they occur at sites as much as 18 km apart. As it is likely that individual groups are products of extrusion at the same time from the same magma chamber, the chamber(s) at one time may have underlain large areas below the volcano.

The caldera at the summit of the volcano was formerly thought to result from drainage of the underlying magma reservoir by subterranean migration of magma or copious eruptions of basalt from flank fissures (Williams, 1957) or by tectonic volcanic collapse along fault zones that intersected at the summit (Higgins, 1973). Ash-flow tuffs and other tephra units, however, are now known to be common and voluminous on the flanks. Thus, the caldera seems much more likely to be the result of collapse following voluminous tephra eruptions of silicic to intermediate composition from one or more magma chambers below the summit. The several major tephra eruptions may be associated with several episodes of caldera collapse, each one involving areas smaller than that of the present caldera. Evidence for sequential collapse is also found in the configuration of the caldera walls which, rather than forming a single circular wall, consist of several walls, in places one inside the other, which in aggregate form an ellipse with an east-west axis. The oldest voluminous ash-flow tuff has a K-Ar age of 510,000 years, indicating a similar age for the earliest caldera. The youngest voluminous tephra unit has not yielded meaningful K-Ar dates, so the age of the most recent collapse is not known. This tephra deposit, however, is deeply eroded and may be many tens of thousands of years old.

The walls of the caldera are mostly covered by younger deposits (talus, pumice falls, etc.), and the wall rocks are only locally exposed. The caldera walls were described in detail by Williams (1935) and Higgins (1973) and consist mostly of platy rhyolite at the base overlain by basaltic-andesite flows, palagonite tuff, cinders, and agglutinated spatter deposits. In a few places the walls also contain welded tuff, pumice falls, obsidian flows, and domes.

The caldera floor (Figure 4) is formed mainly of rhyolitic rocks (domes, flows, ash flows, pumice falls, and explosion breccias). The few mafic rocks that occur in the caldera are older than Mazama ash, except for those along the East Lake fissure which cuts the north caldera wall and which may extend onto the floor beneath East Lake. The fissure has not been dated, but the summit basaltic-andesite flows on the same fissure 2 km to the north were determined to be about 6,090 years old by carbon-14 dating and almost certainly are the same age as the East Lake fissure. Rhyolitic rocks of pre-Mazama age include two domes along the south shore of Paulina Lake, a large obsidian flow in the northeast corner of the caldera, an obsidian dome and an associated buried obsidian flow that extends from the caldera wall northward to East Lake, and a poorly exposed dome(?) south of the central pumice cone. In addition, rhyolitic pumice falls and lacustrine, fluviatile, and landslide deposits locally underlie Mazama ash.

Rhyolitic deposits of post-Mazama age blanket the eastern two-thirds of the caldera (Figure 4). These deposits include obsidian flows, pumice rings and cones, ash flows, pumice falls, and other pumiceous tephra deposits. Isotopic (carbon-14) and hydration-rind dates indicate that they range in age from about 6,700 years to 1,350 years (Friedman, 1977).

The youngest period of volcanism within the caldera was associated with the vent for the Big Obsidian Flow (Figure 5). Initial eruptions produced a widespread pumice fall that covers the southern part of the caldera and eastern flank of the volcano (Sherrod and MacLeod, 1979). Isotopic ages of 1,720±60 (Higgins, 1969) and 1,550±120 years (S.W. Robinson, written communication, 1978) were obtained on carbon collected beneath the fall. The axis of the fall trends N. 80° E. away from the vent for the Big Obsidian Flow; at 9 km from the vent the fall is 4 m thick and at 60 km about 25 cm thick. The pumice fall was followed by eruptions that produced an ash flow that extends over a broad area between the Big Obsidian Flow and Paulina Lake. Three carbon-14 ages cluster at about 1,350 years, suggesting that about 200 years may have elapsed between the pumice fall and ash flow. The final event was the eruption of the Big Obsidian Flow which extends from the south caldera wall 2½ km northward toward Paulina Lake. The pumice fall, ash flow, and obsidian flow are indistinguishable in their trace- and major-element composition, and all are essentially aphyric.

The young rhyolites in the caldera and a few young, but possibly pre-Mazama, rhyolite protrusions on the upper southeast flank differ in chemical composition from older caldera rhyolites and from most older domes and flows on the flanks. Particularly obvious are marked differences in some trace elements such as rubidium (Rb) and strontium (Sr), but the silica content of the young rhyolites also is slightly higher (Figure 6). All of these young rhyolites may be derived from the same magma chamber inasmuch as they are chemically closely similar and all are aphyric or nearly so. If so, parts of the chamber must have been at or above the liquidus as recently as 1,350 years ago and thus are probably still hot.

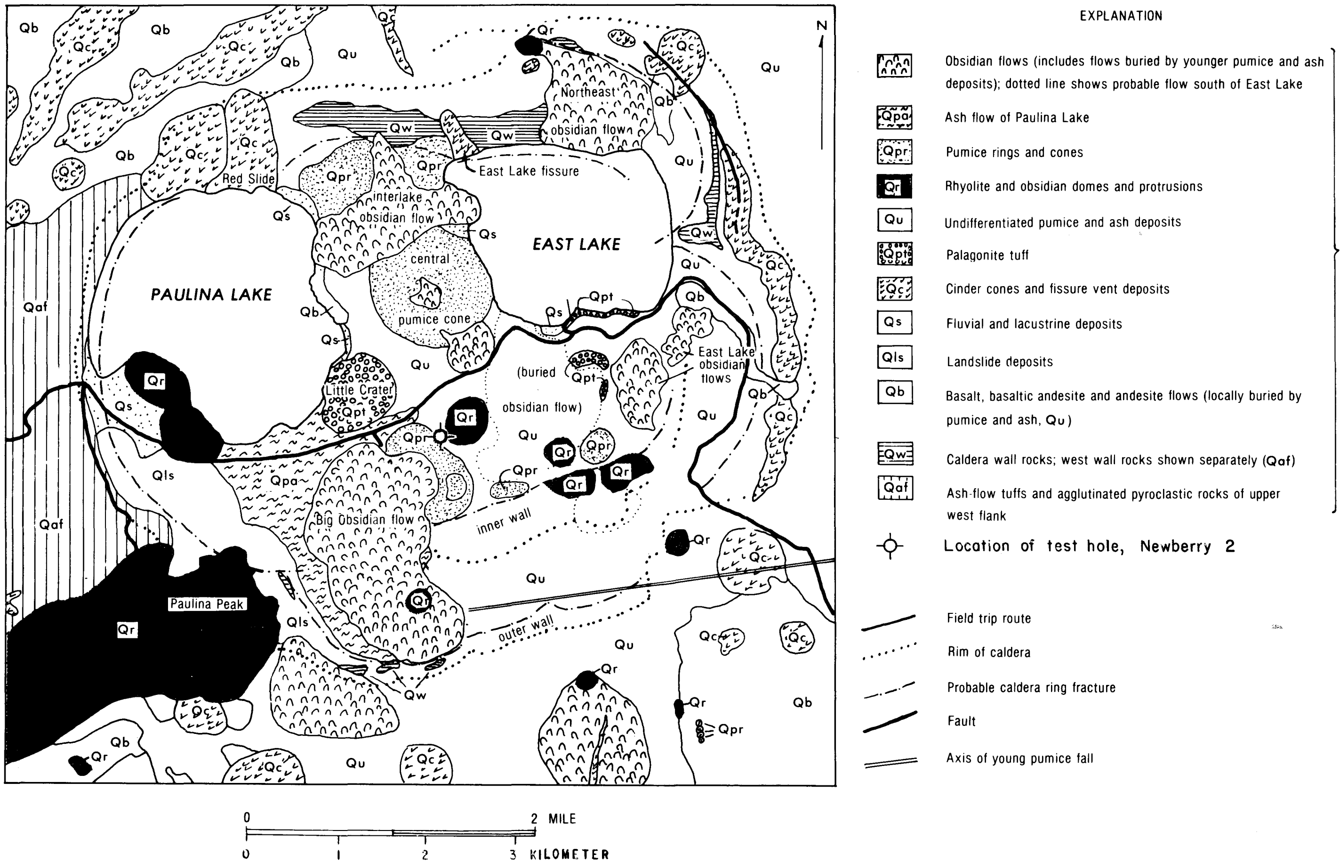

Figure 4. Geologic map of Newberry caldera. Modified from MacLeod and others (1981).

RESULTS OF DRILLING

General

Two exploratory holes were drilled on Newberry Volcano as part of the geothermal and volcanologic studies. Both were drilled by wireline methods so as to provide continuous cores of the rocks that constitute the volcano. The first hole, Newberry 1, was completed in September 1977 on the upper northeast flank of the volcano (Figure 3) to a depth of 386 m. Core recovery was excellent in massive rocks but poor in unconsolidated deposits. The second hole, Newberry 2, was drilled in the central part of the caldera near the locus of vents for rhyolitic rocks that are younger than 6,900 carbon-14 years (Figure 4). The caldera is a scenic recreation area with few roads; consequently, selection of the drill site was dictated partly by environmental and access considerations. In 1978, the first 312 m of the hole was drilled by the mud-rotary

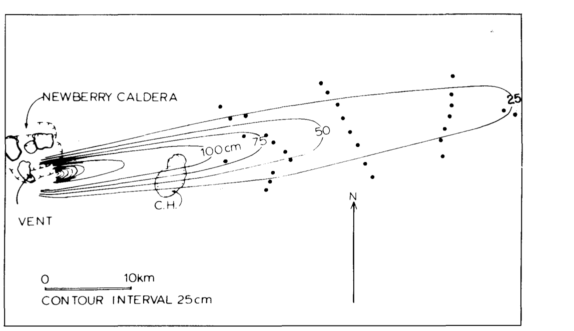

Figure 5. Isopach map of pumice fall from vent at Big Obsidian Flow. China Hat (C.H.) *lies at east base of Newberry Volcano.*

method in order to allow for maximum reductions in diameter during later core drilling. During the summers of 1979 and 1981, as funds became available, the hole was deepened by wireline core drilling to a final depth of 932 m in September 1981. In addition, an offset hole was drilled to provide core in parts of the upper section previously drilled by rotary drill. Core recovery ranged from as little as 40 percent in parts of the upper 300 m to more than 90 percent in most of the lower 600 m; only drill cuttings are available for the upper 98 m.

Lithology

Newberry 1 penetrated flows of basaltic to rhyolitic composition with interbedded cinders, breccia, volcaniclastic sand and gravel, pumice-fall deposits, and ash-flow tuff. The total thickness of tephra deposits and volcanic sediments at this site was unexpectedly large, comprising about 55 percent of the section. Flows are generally thin, with a median thickness of about 6 m. Only two flows exceeded 10 m in thickness: a 70-m-thick dacite flow encountered at a depth of 183 m and a 43-m-thick basaltic-andesite flow encountered at 337 m. Analyzed flows include basalt, basaltic andesite, andesite, dacite, and rhyodacite; no one rock type predominates, and the section is not bimodal (basalt-rhyolite) as is generally the case for surface rocks at Newberry.

Small amounts of perched water were found in Newberry 1, notably at 154 and 280 m, but the rocks appeared to be generally unsaturated. Drilling fluids were lost into the formations during most of the drilling.

Newberry 2, in the caldera, penetrated dominantly fragmental rocks to a depth of 500 m and flows and associated breccia below that depth (Figure 7). From 98 to 320 m the rocks are basaltic in composition; from 320 to 746 m they

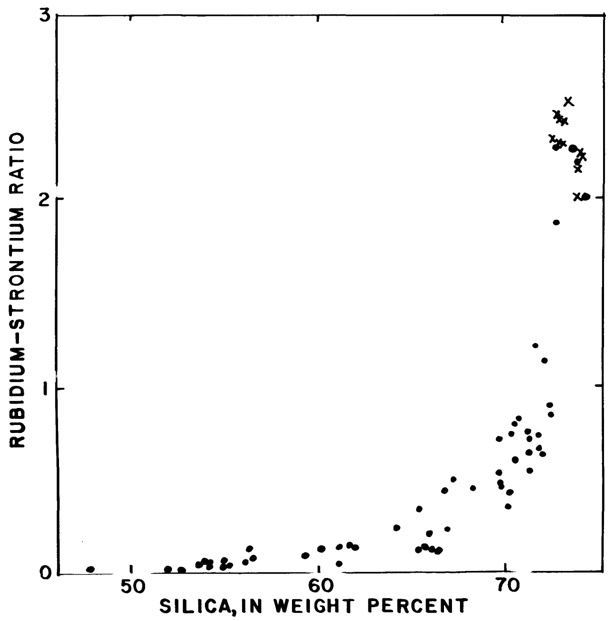

Figure 6. Relation of Rb-Sr ratio to SiO_2 for Newberry rocks. X = *young rhyolites.*

grade downward from rhyolitic to andesitic composition; below 758 m the section consists of basalt or basaltic andesite.

The basaltic tuff, tuff-breccia, and interbedded basaltic sand and gravel that occur between 98 and 290 m are dominantly formed of glassy fragments, suggesting that they may be of subaqueous origin. The underlying sediment in the interval from 301 to 320 m is lacustrine in origin. It consists of thin-bedded to finely laminated claystone to fine sandstone and shows graded bedding, flame structures, and zones of penecontemporaneous deformation. The fine grains that constitute the deposit are mostly hydrated basaltic glass; where cemented locally by carbonate, the glass is fresh. Well-bedded pumiceous ashy sand and gravel of either lacustrine or fluviatile origin occur between 320 and 360 m. They differ from sediments above in that they are coarser grained and dominantly formed of fragments with rhyolitic composition.

Pumice lapilli tuff occurs between 360 and 500 m. It consists of numerous units 3 to 12 m thick, is poorly sorted, and contains interbedded lithic breccia with ashy matrix. Individual units of the tuff range from massive to doubly graded with larger light pumice lapilli at the top and dense lithic fragments at the base. Some lithic breccias appear to grade upward into pumice lapilli tuff, whereas others form discrete units with sharp boundaries. Pumice lapilli show no flattening, but the lapilli tuffs are probably ash-flow tuffs on the basis of their poor sorting and grading. The lithic breccias are probably ash-flow lag breccias and explosion breccias. A rhyolite sill occurs in this section at 460 to 470 m, and a 1½-m-thick unit of perlitic glass (welded tuff?) occurs at 479 m.

Flows form most of the section from 500 m to the bottom of the hole. Most flows are massive or fractured; however, thick units of breccia also occur in the sequence, and most massive flows have brecciated tops and bottoms. The flow sequence appears to be divided into two units separated by a zone of tuffaceous pumiceous sand and silt and ash-flow tuff(?) that occurs between 746 and 758 m. Above these sediments the flows are rhyolitic to dacitic and andesitic in composition, whereas below that depth they are basaltic andesite and basalt.

Alteration in the core is highly variable but generally more intense lower in the hole. Fragmental rocks that initially were glassy are locally altered to clay minerals. Massive rocks commonly contain sulfides (marcasite, pyrrhotite, and pyrite), carbonates (calcite and siderite), and quartz along fractures. Many breccias in the lower part of the hole have a bleached appearance and are altered to clay minerals, quartz, carbonates, epidote, chlorite, and sulfides.

Some preliminary inferences and conclusions can be made, based on lithology of the cores, even though they have not yet been studied in detail. First, the lacustrine sediments that occur at a depth of about 300 m indicate that the caldera was once much deeper and may have been physiographically similar to the Crater Lake caldera. These sediments lie about 790 m below the present highest point on the caldera rim, a depth comparable to that from the rim above Crater Lake to its base. The fragmental rocks of sedimentary and pyroclastic origin that form the upper 300 m of the core appear to represent a discontinuous filling of a once much deeper caldera. Second, the 130 m of pumice lapilli tuff and associated breccia that occur below the lake sediments are probably ash flows and may relate to one or more periods of collapse of the caldera. It is not obvious from preliminary studies that these tuffs correlate with ash flows on the flanks; they are most like the oldest rhyolitic ash-flow tuff, but unlike it in that they are not welded. Third, the flows in the lower part of the hole are

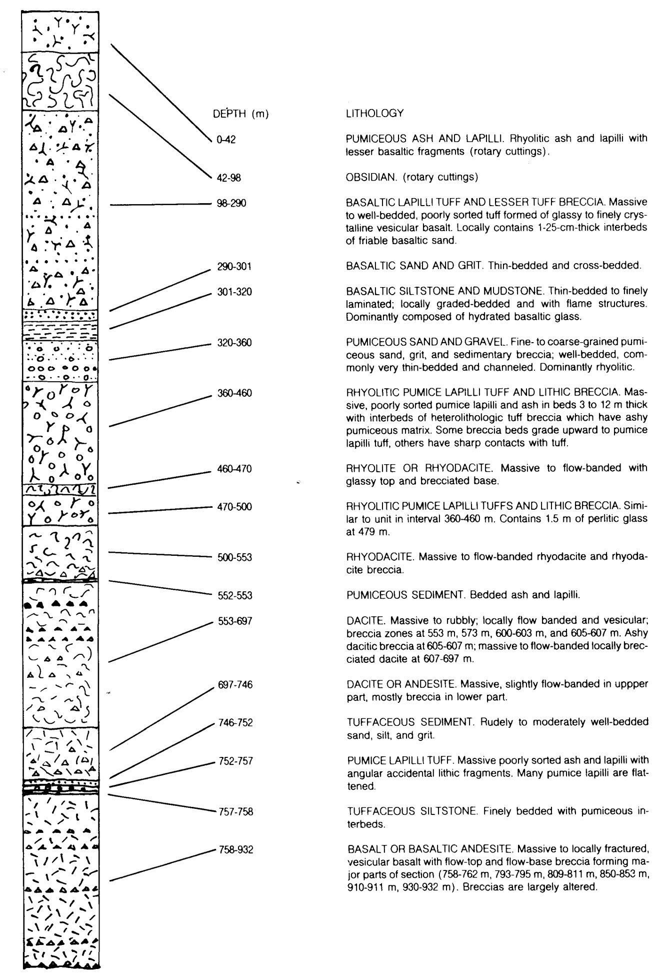

Figure 7. Preliminary generalized lithologic log of Newberry 2. Rock names are based on visual examinations and have not been confirmed by chemical analyses.

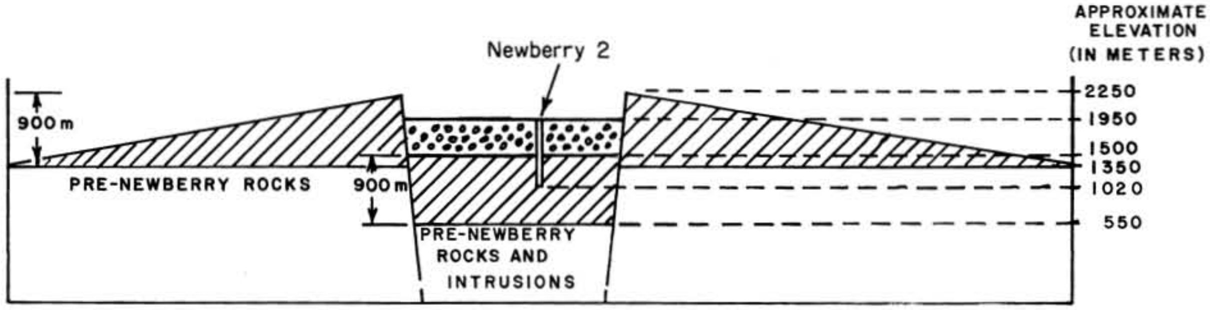

Figure 8. Schematic cross section of Newberry Volcano showing probable position of collapsed block.

similar to flows on the flanks of the volcano and may be the former upper part of the volcano that collapsed to form the caldera.

We do not know the shape of the old surface upon which Newberry Volcano is built or the original shape of the volcano before collapse. Thus, we can only crudely estimate the amount of collapse and the possible elevation of the base of the collapse block. The difference in elevation between the lowest flank flows and the caldera rim is about 900 m, and this difference may approximate the thickness of volcanic rock adjacent to the caldera. As the former summit was undoubtedly at a higher elevation than the present rim, this figure represents a minimum thickness of the collapse block. If the top of the section of flow rocks in the hole at an elevation of about 1,500 m represents the top of the collapsed block, then its base lies at about 550-m elevation. Thus the base of Newberry rocks in the caldera is roughly 800 m or more lower than the base of the volcano outside the caldera and is 500 m or more below the bottom of the hole. These crude estimates are shown diagrammatically in Figure 8, in which a single rather than multiple-collapse block is illustrated.

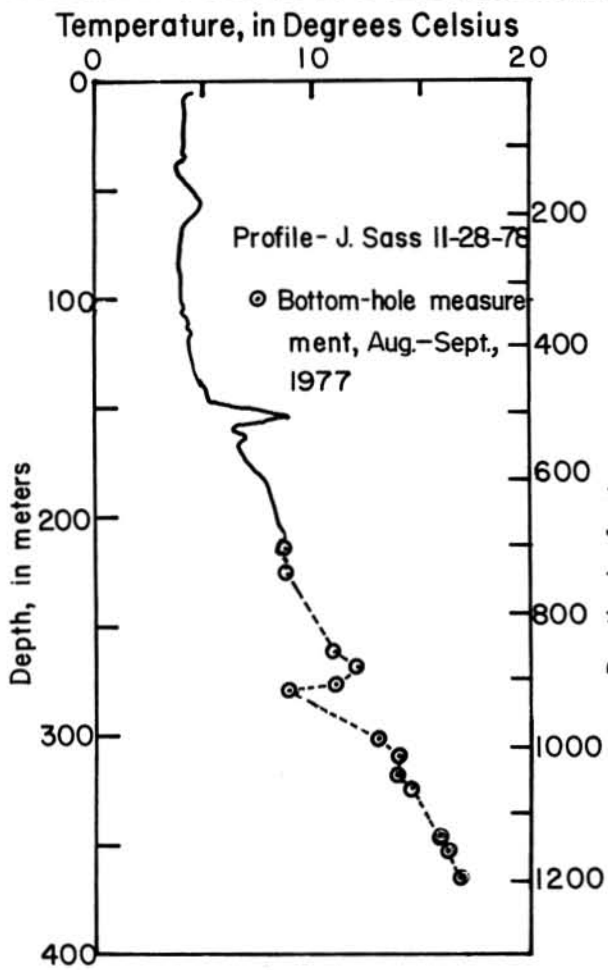

Figure 9. Temperatures measured in Newberry 1.

Temperature and heat flow

The temperature profile obtained in Newberry 1 (Figure 9) on the flank of the volcano indicates that heat flow is suppressed in the upper 90 m of rock, presumably by the vertical flow of cool water in the permeable sediments that predominate in this zone. Below 90 m, the thermal regime is predominately conductive, although perturbations in the profile indicate minor flows of both cooler and warmer water. For example, the peak in the profile at 155 m is probably due to the flow of warm water in a permeable zone at the scoriaceous base of a dacitic flow and the rubbly top of an andesitic flow; in the interval 270-280 m, ground-water flow of differing temperatures may occur in beds of cinders, grit, and scoria that overlie the rubbly top of an andesitic flow.

The smoothed thermal gradient in the lower 260 m of the hole is approximately 50° C/km, which is significantly lower than the mean gradient of 65° C/km estimated for the region (Blackwell and others, 1978). On the basis of measured values in rocks at Newberry 2, the mean thermal conductivity in the lower 260 m of Newberry 1 is estimated to be less than 1.3 $W°C^{-1}m^{-1}$. The conductive heat flux is estimated to be no greater than about 60 mW/m^2, or a little more than one-half the expected value for the High Cascade region (Blackwell and others, 1978; Couch and others, 1981). In the light of the high heat flux discovered later beneath the caldera, the low values found in Newberry 1 are believed to result from flow of cool water at depths below 386 m (the base of the hole) which depresses the thermal gradient and transfers heat radially away from the caldera.

Representative profiles and bottom-hole measurements obtained in Newberry 2 (Figure 10) show a quasi-linear conductive gradient in the lower 230 m of the hole and large convective anomalies in the upper 700 m. Repeated logging in the hole as drilling progressed demonstrated that, over periods of time on the order of a year, the profiles represent stable thermal regimes in the rocks at the drill site. It seems probable, however, that over longer periods of time the temperatures and heat flows would be observed to be in a transient state.

The major displacements in the temperature profile generally coincide with higher than average permeabilities in the core samples and flows of formation water observed in the borehole. For example, the temperature minimum at 280-m to 290-m depths is probably due to the flow of cool water observed in a cavernous zone within beds of basaltic sand and grit. A temperature maximum at depths between 350 m and 450 m is associated with permeable sand, gravel, and lithic

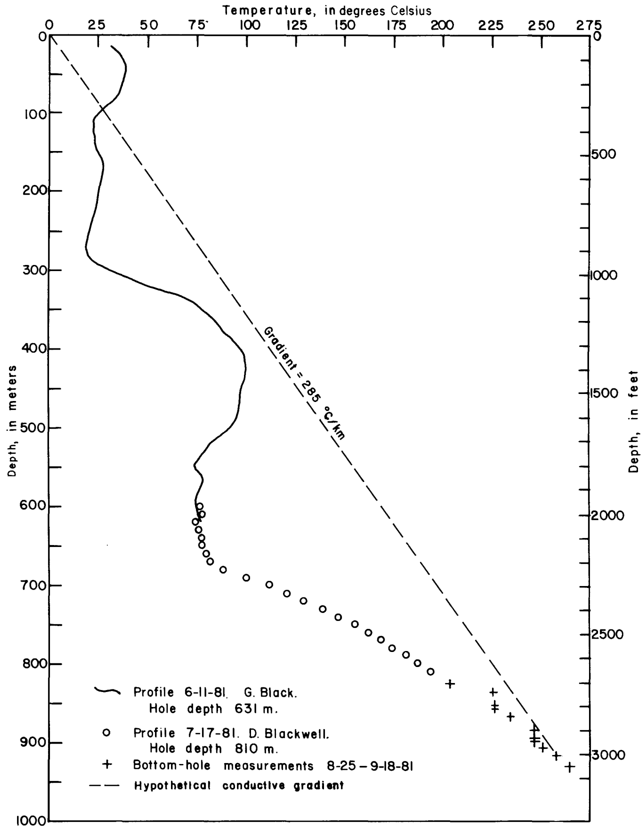

Figure 10. Temperatures measured in Newberry 2 and hypothetical conductive gradient projected from bottom of hole to land surface.

breccias in which flows of warmer water diluted the drilling mud. A significant water flow in brecciated dacite encountered between 555 m and 564 m probably accounts for much of the temperature minimum observed between 550 m and 610 m. The stronger flows produced up to one-half liter per second in the well bore, and many weaker flows probably went undetected. Mud circulation was completely lost in strata of rhyodacite, pumiceous sediment, and dacite in the interval from 515 to 610 m.

Below 758 m, permeable zones were few, and although gas was encountered in many hydrothermally altered strata, there was no evidence of water or steam. Fluid recovered from the bottom 2 m of the hole during a 20-hour flow test (Sammel, 1981) is now believed likely to have consisted largely of drilling fluids injected into the formation combined with dry gas already present in the formation.

Available evidence indicates, therefore, that vertical permeabilities are generally low in the caldera fill as well as in the collapsed caldera block. The vertical flow of both geothermal fluids and meteoric recharge water is probably restricted to faults, ring fractures, or brecciated intrusion conduits. Lateral flow may be confined to those permeable strata that have good hydraulic connections with water-bearing vertical fracture zones.

Surface expression of discharge from the hydrothermal system occurs at only three places in the caldera and is entirely absent on the flanks, so far as is known. Small springs of moderate temperature rise along the northeast margin of Paulina Lake and the southwest margin of East Lake. Several fumaroles occur along the northeast margin of the Big Obsidian Flow. The total heat flux from these sources is unknown but is thought to be small.

The vertical component of the heat flux in the lower 180 m of Newberry 2 can be estimated on the basis of the more reliable temperatures by calculating the mean thermal gradient (approximately 600° C/km) and estimating the mean thermal conductivity from four measured values (about 1.9 $W°C^{-1}m^{-1}$). The conductive heat flux calculated from these estimates is 1.1 W/m^2, which is more than 10 times the regional average. This large heat flux reflects in part the rate of convective heat transfer in the interval from 550 to 670 m. If heat were not being removed in this zone, temperatures in the rocks above the linear profile would presumably be higher than those observed, and both the gradient and the heat flux would be lower than those now observed.

Convective effects above a depth of 700 m cause the total heat flux at the drill site to be greater than the 1.1 W/m^2 calculated for the lower 170 m. Fluid flowing laterally in the intervals from 550 to 670 m and 100 to 280 m absorbs heat from warmer zones above and below and presumably transports this heat away from the site. Using linear approximations of temperature gradients above and below these intervals and estimating corresponding thermal conductivities, we obtained an estimate of 2.5 W/m^2 for the total heat flux into these intervals. Assuming a conductive heat flux in the top 20 m of dry caldera fill and a land-surface temperature equal to the mean annual air temperature of 0° C in the caldera, we estimate an additional flux of 0.5 W/m^2 conducted to the land surface. Thus, the total lateral and vertical heat flux at the drill site above a depth of 930 m may be at least 3 W/m^2.

This heat flux is considerably larger than the conductive flux of 0.3 W/m^2 that hypothetically would exist on the basis of a linear temperature gradient (285° C/km) between the measured temperature at the bottom of the hole and a land-surface temperature of 0° C (Figure 10) and a harmonic mean thermal conductivity for the entire section, based on 47 measured values, of 1.1 $W°C^{-1}m^{-1}$. This hypothetical conductive heat flux is itself anomalously large, possibly because of convective effects occurring below the bottom of the drill hole.

The high rate of heat flow in the vicinity of the drill site may not be typical of heat flow over the entire 30 km^2 of the caldera floor. Flows of cooler water, apparently interstratified with flows of warmer water, produce the anomalies in the temperature profile that have been described above. These anomalies suggest that lateral flows of water beneath the caldera floor have separate origins and complex flow paths. It is likely, therefore, that the distribution of thermal discharge in the caldera is highly variable, both spatially and temporally, in response to varying conditions in the hydrologic regime.

SOURCE OF GEOTHERMAL HEAT

The highest observed temperature (265° C), large heat flux, and recency of volcanism at Newberry strongly suggest that the heat source is of magmatic origin. The widespread occurrence of rhyolitic rocks of similar compositions that have been erupted during at least the last 7,000 years and as recently as 1,350 years ago suggests that the magma chamber may be several kilometers wide and that temperatures could still be partly in the magmatic range.

Geophysical studies by USGS workers and others have elucidated some of the large-scale characteristics of the crustal rocks beneath Newberry, but the studies do not conclusively indicate either the presence or absence of shallow crustal magma chambers. From their reduction of gravity data obtained by Andrew Griscom, Williams and Finn (1981) inferred the existence of a large, dense stock at a depth less than 2 km beneath the volcano. Although there are differing views among the geophysicists regarding the size and shape of the subvolcanic stock, there is general agreement that a stock exists. This interpretation is supported by teleseismic data that suggest that there is a large compressional-wave velocity contrast in the area, with higher velocities localized under the caldera (Mahadeva Iyer, oral communication, 1981). The teleseismic data fail to show evidence for a molten mass; the limit of lateral resolution for the data, however, may be about 3 km. Magnetotelluric soundings at Newberry (Stanley, 1981) are inconclusive but suggest that a body having low to intermediate resistivity may occur at a depth of about 1½ km.

Heat-flow data derived from the measurements at Newberry 2 do not provide a firm basis for limiting the size, depth, or temperature of a magmatic heat source. Preliminary analysis of the data suggests, however, that if the total heat flux estimated in Newberry 2 represents a widespread and long-lasting thermal regime beneath the caldera, a magmatic source would be likely to have a diameter of several kilometers and to have been continuously supplied with magma for a period of thousands of years prior to the most recent eruption. If the apparent heat flux at Newberry 2 represents only a local anomaly within the caldera, the source of heat could be significantly smaller.

The results of such analyses are sensitive to assumptions regarding the transient state of the temperature profile in Newberry 2 and the applicability of the estimated heat flux to other parts of the caldera. Calculations based on several conceptual models show, for example, that if the heat flux estimated in Newberry 2 represents the flux over the caldera during the 1,350 years since the last eruption and if there has been no new input, much of the magma in a 3-km-wide chamber could have solidified and the temperatures could have decreased below the solidus temperature.

A possible limiting case for temperatures below the drill hole can be derived on the basis of the assumption that heat flow in the basaltic-andesite flow rocks of the collapse block is predominately conductive. The following specific assumptions are used: (1) the nearly linear gradient observed between 860 and 930 m (505° C/km) represents a conductive regime in the basaltic and basaltic-andesite rocks near the base of the volcano; (2) this gradient continues in rocks of low vertical permeability to the base of the collapsed caldera block at a depth of 1.4 km beneath the caldera floor (Figure 8). The temperatures at the base under these conditions would be about 500° C. Below the base, possible effects of intrusive activity in the pre-Newberry rocks make the presence of hydrothermal convection seem more probable, and continued extrapolation of the temperature gradient is not justified.

CONCLUSIONS AND REGIONAL IMPLICATIONS

Evidence of a high potential for the development of geothermal energy at Newberry is compelling, but the nature and magnitude of the resource currently is poorly defined. The flow test conducted in Newberry 2 suggests that if a hot hydrothermal reservoir exists at Newberry, it is tightly confined by overlying rocks of low thermal and hydraulic conductivity. The paucity and small size of geothermal emanations in the caldera also attest to the probable low vertical permeability of the caldera rocks. Many strata in the upper 670 m of the hole appear to have moderately high permeabilities, but the stratification of the warm and cool zones in the rocks demonstrates that the horizontal permeability greatly exceeds the vertical at the drill site.

Because the more permeable rocks in the lower part of the hole are the brecciated tops and bottoms of flows, it is reasonable to suppose that similar breccia zones may occur at greater depths. Marked changes in permeability and porosity may occur below the base of the collapsed caldera block in pre-Newberry rocks that are fractured and faulted by magmatic intrusion. If late intrusions of magma have not penetrated the collapsed block, the largest reservoir of high-temperature fluids seems most likely to occur below the block in the pre-Newberry rocks. Careful testing by additional and probably deeper drill holes will be required in order to evaluate these possibilities and the magnitude of the geothermal resource at Newberry.

Geological and geophysical studies at Newberry have shown that this large composite volcano differs significantly from most other volcanoes in the Cascade Range. Unlike most of the well-known stratovolcanoes, but in common with Mount Mazama in Oregon and Medicine Lake Volcano in California, Newberry has a summit caldera and has experienced large eruptions from silicic magma chambers. Large volumes of mafic magma probably have resided for long periods of time in the crust at these three locations in order to have produced the voluminous silicic magmas (Hildreth, 1981; Bacon, 1981). Newberry appears to be unique, however, in its position at the end of a 10-million-year progression of silicic volcanism across the northern edge of the Basin and Range Province. There is at present no evidence that the progression continues into the High Cascades, where a possible extension might culminate in the vicinity of the Three Sisters.

The geological parallels between Newberry Volcano in Oregon and Medicine Lake Volcano in California permit some inferences concerning the geothermal potential at the latter site. The geology of the Medicine Lake area is currently being studied by Julie Donnelly-Nolan under the USGS Geothermal Research Program, and a number of geophysical studies have been made in the area (see Hill and others, 1981; Williams and Finn, 1981; Christopherson and Hoover, 1981; and Stanley, 1981). The results of these studies show that although surface indications of geothermal activity are sparse, large volumes of silicic rocks have been erupted at Medicine Lake during the last several thousand years and the caldera is underlain at shallow depths by dense rocks of high seismic velocity and low to moderate resistivity. The results of the Newberry drilling thus present an encouraging indication of the potential for geothermal resources at Medicine Lake.

Certain implications of the results at Newberry may have a wider regional significance. The probable existence of a magmatic heat source at Newberry suggests that other magmatic heat sources of significant magnitude may exist at fairly shallow depths within the Cascade region. Geothermal anomalies associated with these heat sources are likely to be masked by rocks of low vertical permeability and by the lateral flow of ground water in the same way that the anomaly is hidden at Newberry. Recharge to deep hydrothermal systems may be impeded by low vertical permeabilities as at Newberry, and the amounts of recharge may be significantly less than would be expected on the basis of local precipitation rates. On the other hand, deep regional ground-water flow systems may occur in older rocks beneath the Quaternary volcanics; where these rocks are fractured and faulted, as they may be in the vicinity of subvolcanic intrusions, permeable geothermal reservoirs may occur.

Crucial questions for exploration in the Cascade region are whether or not surface geophysical methods and shallow test drilling will be able to delineate areas underlain by shallow magma chambers or hot intrusive rocks and whether or not strata having moderately high permeability and significant lateral extent occur in the vicinity of such heat sources.

The numerous thermal springs that rise in the Cascade region may be of little help in locating magmatic sources because, with few exceptions, the springs are not closely related to the major Quaternary volcanic centers. Some of these springs may be the surface expression of lateral flow that originates in geothermal reservoirs at some distance from the surface outlet. Others may be the result of local deep circulation in faults and fracture zones at the boundary between rocks of the High Cascades and the older rocks of the Western Cascades. In either case, they may not reliably indicate the location of geothermal reservoirs associated with young intrusive rocks.

The development of geothermal energy in the Cascades will probably depend on the exploitation of hydrothermal convection systems that concentrate the heat from deeper sources and transport it to shallow depths where the energy can be economically extracted. Hydrothermal systems that function in this way also tend to accelerate the decay of temperatures in the heat sources and shorten the useful lives of the systems. Nevertheless, the positive indicators of geothermal potential in the Cascade region, high heat flows and shallow silicic intrusive rocks, encourage the belief that economical sources of geothermal energy may be found in the region. Deep drilling will probably be required in order to determine favorable locations and to ascertain the extent and nature of the geothermal reservoirs.

REFERENCES CITED

Bacon, C.R., 1981, Geology and geophysics in the Cascade Range [abs.]: Society of Exploration Geophysicists, 51st Annual International Meeting, Los Angeles, Calif., 1981, Geothermal Special Session 3, Technical Program Abstracts, G3.1.

Blackwell, D.D., Hull, D.A., Bowen, R.G., and Steele, J.L., 1978, Heat flow of Oregon: Oregon Department of Geology and Mineral Industries Special Paper 4, 42 p.

Christopherson, K.R., and Hoover, D.B., 1981, Reconnaissance resistivity mapping of geothermal regions using multicoil airborne electromagnetic systems [abs.]: Society of Exploration Geophysicists, 51st Annual International Meeting, Los Angeles, Calif., 1981, Geothermal Special Session 3, Technical Program Abstracts, G3.6.

Couch, R.W., Gemperle, M., Connard, G.G., and Pitts, G.S., 1981, Structural and thermal implications of gravity and aeromagnetic measurements made in the Cascade volcanic arc [abs.]: Society of Exploration Geophysicists, 51st Annual International Meeting, Los Angeles, Calif., 1981, Geothermal Special Session 3, Technical Program Abstracts, G3.3.

Friedman, I., 1977, Hydration dating of volcanism at Newberry Crater, Oregon: U.S. Geological Survey Journal of Research, v. 5, no. 3, p. 337-342.

Higgins, M.W., 1969, Airfall ash and pumice lapilli deposits from Central Pumice Cone, Newberry Caldera, Oregon, *in* Geological Survey Research 1969: U.S. Geological Survey Professional Paper 650-D, p. D26-D32.

——— 1973, Petrology of Newberry Volcano, central Oregon: Geological Society of America Bulletin, v. 84, no. 2, p. 455-487.

Hildreth, W., 1981, Gradients in silicic magma chambers: Implications for lithospheric magmatism: Journal of Geophysical Research, v. 86, no. B11, p. 10153-10192.

Hill, D.P., Mooney, W.D., Fuis, G.S., and Healy, J.H., 1981, Evidence on the structure and tectonic environment of the volcanoes in the Cascade Range, Oregon and Washington, from seismic-refraction/reflection measurements [abs.]: Society of Exploration Geophysicists, 51st Annual International Meeting, Los Angeles, Calif., 1981, Geothermal Special Session 3, Technical Program Abstracts, G3.2.

MacLeod, N.S., 1978, Newberry Volcano, Oregon: Preliminary results of new field investigations [abs.]: Geological Society of America Abstracts with Programs, v. 10, no. 3, p. 115.

MacLeod, N.S., Sherrod, D.R., Chitwood, L.A., and McKee, E.H., 1981, Newberry Volcano, Oregon, *in* Johnston, D.A., and Donnelly-Nolan, J., eds., Guide to some volcanic terranes in Washington, Idaho, Oregon, and northern California: U.S. Geological Survey Circular 838, p. 85-103.

MacLeod, N.S., Walker, G.W., and McKee, E.H., 1976, Geothermal significance of eastward increase in age of upper Cenozoic rhyolitic domes in southeast Oregon: Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, Calif., 1975, Proceedings: Washington, D.C., U.S. Government Printing Office, v. 1, p. 465-474.

Sammel, E.A., 1981, Results of test drilling at Newberry Volcano, Oregon—and some implications for geothermal prospects in the Cascades: Geothermal Resources Council Bulletin, v. 10, no. 11, p. 3-8.

Sherrod, D.R., and MacLeod, N.S., 1979, The last eruptions at Newberry Volcano, central Oregon [abs.]: Geological Society of America Abstracts with Programs, v. 11, no. 3, p. 127.

Smith, R.L., and Shaw, H.R., 1975, Igneous-related geothermal systems, *in* White, D.F., and Williams, D.L., eds., Assessment of geothermal resources of the United States—1975: U.S. Geological Survey Circular 726, p. 58-83.

Stanley, W.D., 1981, Magnetotelluric survey of the Cascade volcanoes region, Pacific Northwest [abs.]: Society of Exploration Geophysicists, 51st Annual International Meeting, Los Angeles, Calif., 1981, Geothermal Special Session 3, Technical Program Abstracts, G3.7.

Walker, G.W., 1974, Some implications of late Cenozoic volcanism to geothermal potential in the High Lava Plains of south-central Oregon: Oregon Department of Geology and Mineral Industries, Ore Bin, v. 36, no. 7, p. 109-119.

Williams, D.L., and Finn, C., 1981, Evidence from gravity data on the location and size of subvolcanic intrusions [abs.]: Society of Exploration Geophysicists, 51st Annual International Meeting, Los Angeles, Calif., 1981, Geothermal Special Session 3, Technical Program Abstracts, G3.5.

Williams, H., 1935, Newberry volcano of central Oregon: Geological Society of America Bulletin, v. 46, no. 2, p. 253-304.

——— 1957, A geologic map of the Bend quadrangle, Oregon, and a reconnaissance geologic map of the central portion of the High Cascade Mountains: Oregon Department of Geology and Mineral Industries, 1 sheet, scales 1:125,000 and 1:250,000. □

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COVER PHOTO

View to the northeast of the caldera of Newberry Volcano. The paper beginning on next page discusses the geothermal potential of this Quaternary volcano. Features visible in this photo include Big Obsidian Flow in the foreground; Paulina Lake on the left; East Lake on the right; Little Crater, central pumice cone, and interlake obsidian flow in the middle; and north wall of the caldera behind. In the background are some of the 400 cinder cones and fissure vents that dot the flanks of Newberry.

OIL AND GAS NEWS

Columbia County

Reichhold Energy Corporation drilled Adams 34-28 to a total depth of 2,572 ft. The well, in sec. 28, T. 7 N., R. 5 W., was abandoned as a dry hole in September.

The company will soon spud Libel 12-14 in the Mist gas field. The proposed 2,900-ft well is to be located in sec. 14, T. 6 N., R. 5 W.. The location is half a mile from the recently completed redrill of Columbia County 4.

Clatsop County

Oregon Natural Gas Development Company's Patton 32-9 in sec. 9, T. 7 N., R. 5 W., is idle pending the decision whether to redrill.

Douglas County

Florida Exploration Company has abandoned the 1-4 well near Drain. It is not known whether the company will drill other locations.

Yamhill County

Nahama and Weagant Energy Company recently drilled Klohs 1 in sec. 6, T. 3 S., R. 2 W. The well was abandoned as a dry hole.

Recent permits

Permit no.	Operator and well name	Location	Status and depth TD = total depth (ft) RD = redrill (ft)
219	Reichhold Energy Corp.; Werner 14-21	SW¼ sec. 21 T. 5 S., R. 2 W. Marion County	Abandoned; dry hole; TD: 3,354.
220	Reichhold Energy Corp.; Crown Zellerbach 31-33	NE¼ sec. 33 T. 6 N., R. 4 W. Columbia County	Permit issued.
221	Reichhold Energy Corp.; Crown Zellerbach 44-23	SE¼ sec. 23 T. 5 N., R. 4 W. Columbia County	Permit issued.
222	Reichhold Energy Corp.; Siegenthaler 42-13	NE¼ sec. 13 T. 6 N., R. 5 W. Columbia County	Permit issued.
223	Reichhold Energy Corp.; Crown Zellerbach 14-36	SW¼ sec. 36 T. 7 N., R. 5 W. Columbia County	Permit issued.
224	Reichhold Energy Corp.; Libel 12-14	NW¼ sec. 14 T. 6 N., R. 5 W. Columbia County	Permit issued.

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