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.

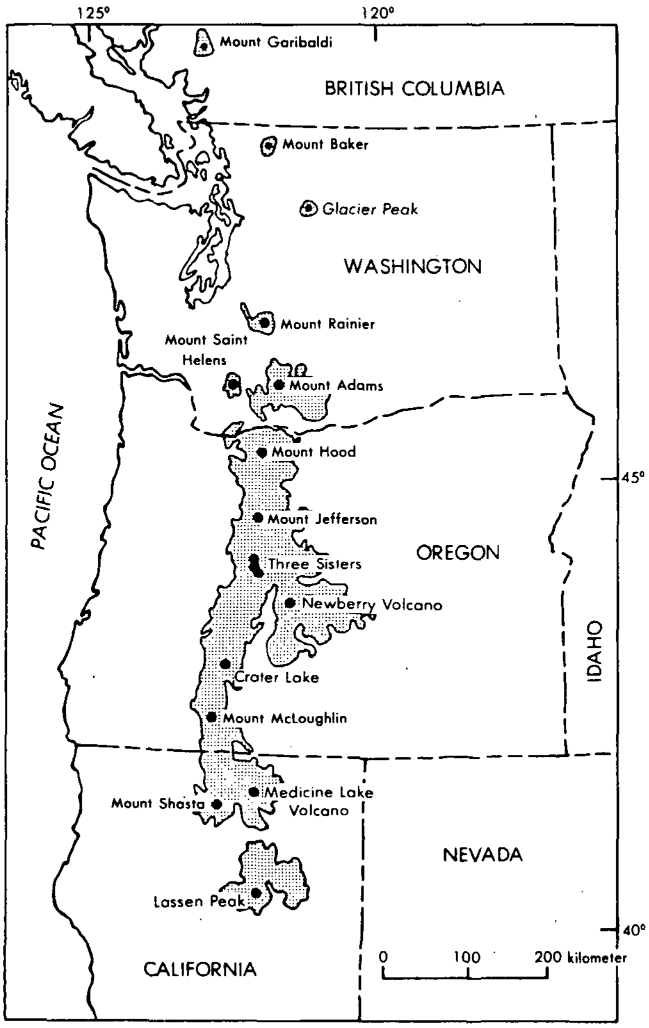

Figure 1. Major volcanic centers and areas of Quaternary volcanic rocks in the Cascade Range.

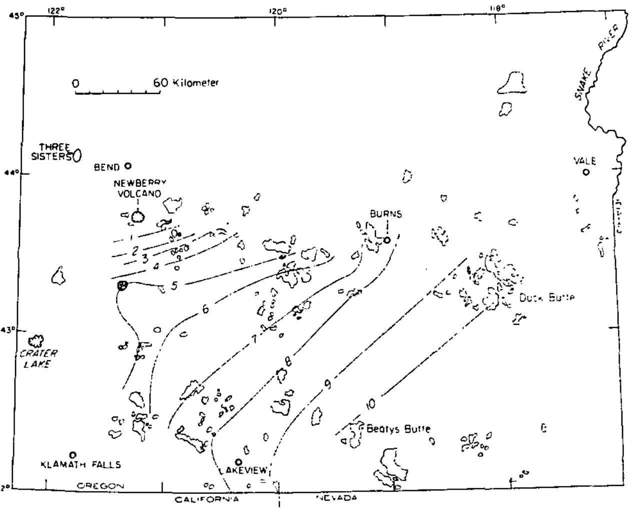

Figure 2. Age progression of silicic domal rocks (patterned) in southeast Oregon. Isochrons in increments of 1 million years. Modified from MacLeod and others (1976).

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

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* 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*

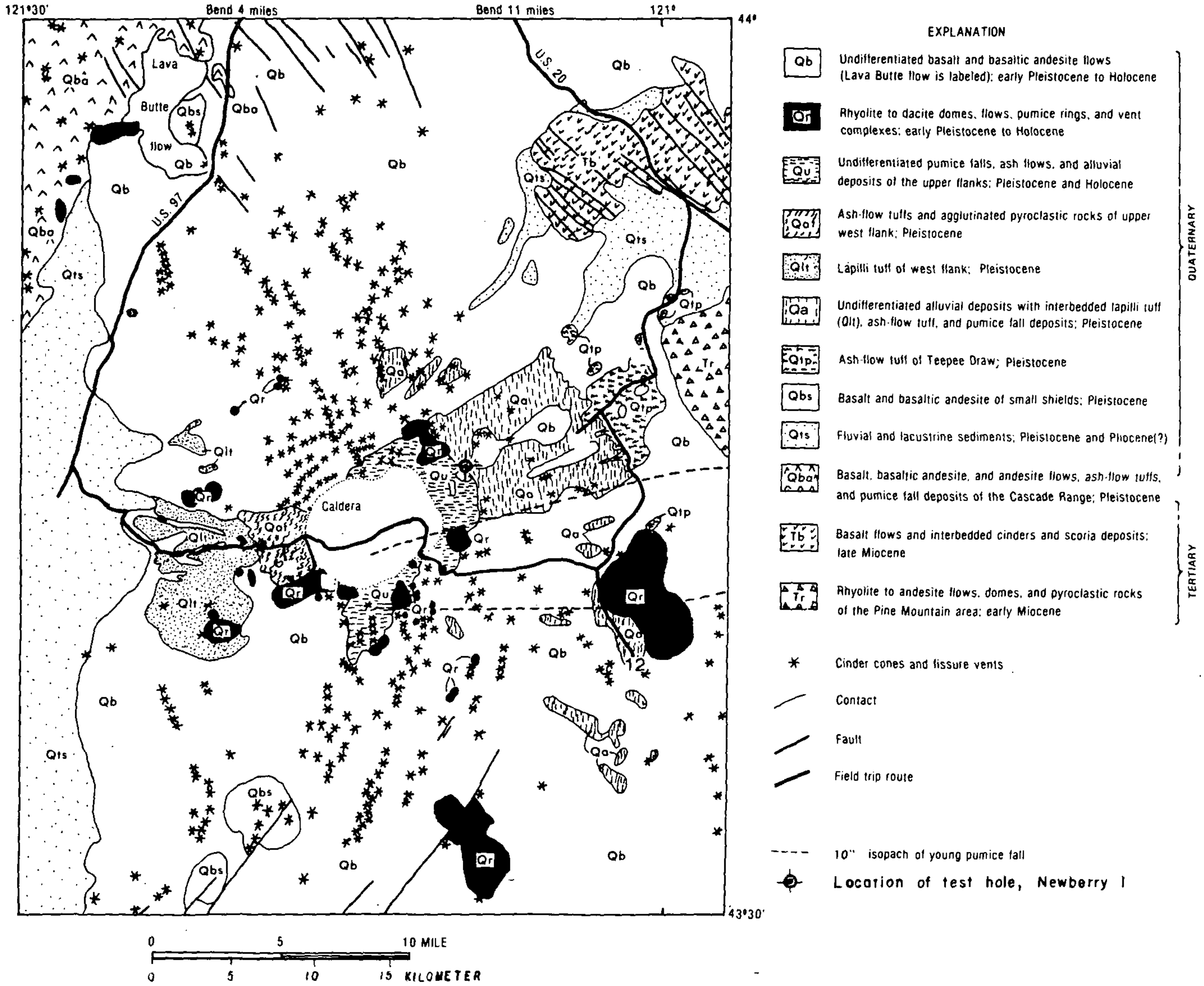


Figure 3. Geologic sketch map of Newberry Volcano. Geology of caldera is shown in Figure 4. Modified from MacLeod and others (1981).

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 km² 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 km³. Successively younger major pyroclastic units range from rhyodacite to andesite and basaltic andesite and have estimated volumes of less than 1 km³ to more than 40 km³. 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 km² 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.

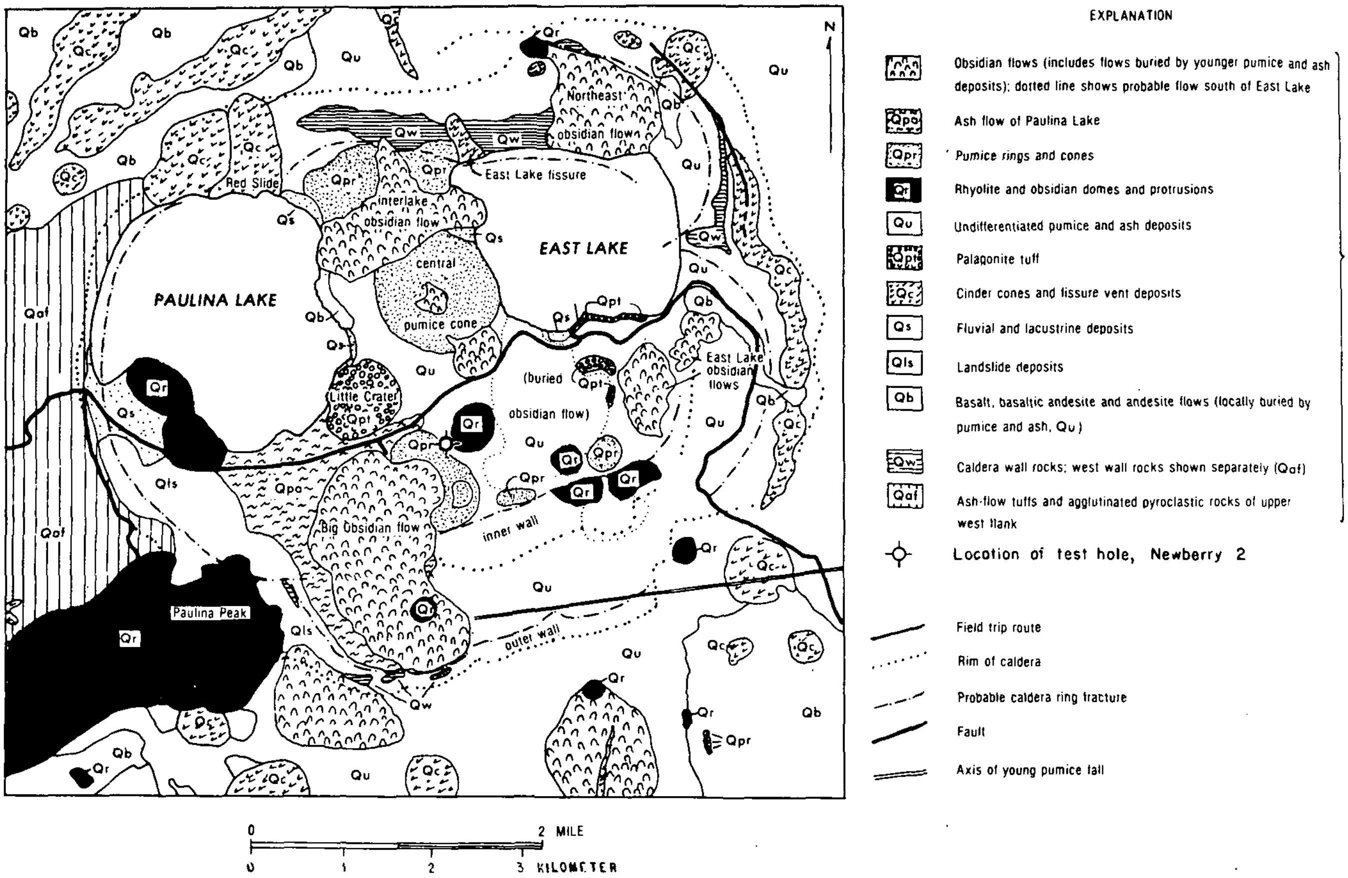


Figure 4. Geologic map of Newberry caldera. Modified from MacLeod and others (1981).

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 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.

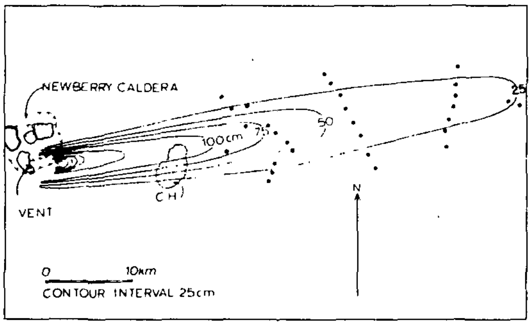


Figure 5. Isopach map of pumice fall from vent at Big Obsidian Flow. China Hat (C.H.) *lies at east base of Newberry Volcano.*

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

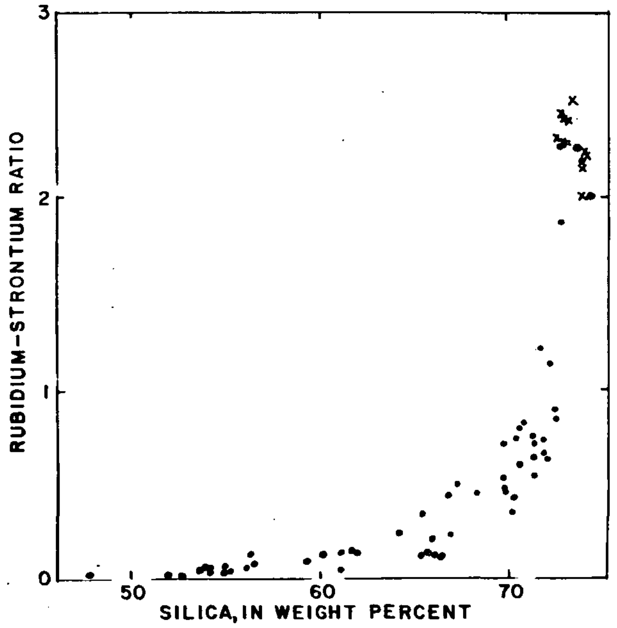


Figure 6. Relation of Rb-Sr ratio to SiO_2 for Newberry rocks. X = young rhyolites.

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

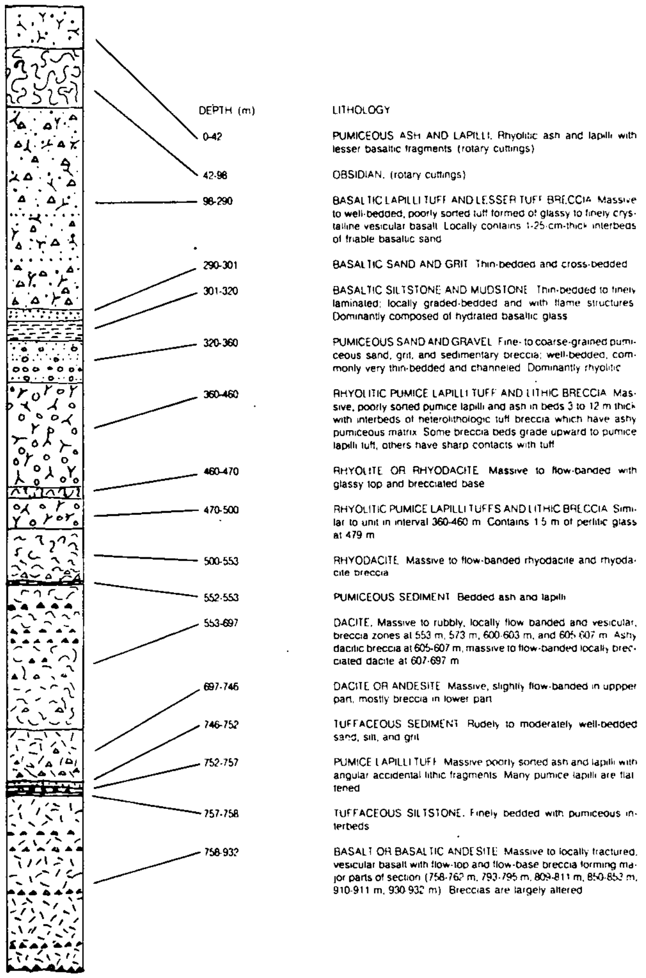
The basaltic tuff, tuff-breccia, and interbedded basaltic sand and gravel that occur between 98 and 290 m are dominantly formed of glassy fragments, suggesting that they may be of subaqueous origin. The underlying sediment in the interval from 301 to 320 m is lacustrine in origin. It consists of thin-bedded 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



DEPTH (m)	LITHOLOGY
0-42	PUMICEOUS ASH AND LAPILLI. Rhyolitic ash and lapilli with lesser basaltic fragments (rotary cuttings)
42-98	OBSIDIAN. (rotary cuttings)
98-290	BASALTIC LAPILLI TUFF AND LESSER TUFF BRECCIA. Massive to well-bedded, poorly sorted tuff formed of glassy to finely crystalline vesicular basalt. Locally contains 1-25-cm-thick interbeds of friable basaltic sand
290-301	BASALTIC SAND AND GRIT. Thin-bedded and cross-bedded
301-320	BASALTIC SILTSTONE AND MUDSTONE. Thin-bedded to finely laminated; locally graded-bedded and with flame structures. Dominantly composed of hydrated basaltic glass
320-360	PUMICEOUS SAND AND GRAVEL. Fine- to coarse-grained pumiceous sand, grit, and sedimentary breccia; well-bedded, commonly very thin-bedded and channeled. Dominantly rhyolitic
360-460	RHYOLITIC PUMICE LAPILLI TUFF AND LITHIC BRECCIA. Massive, poorly sorted pumice lapilli and ash in beds 3 to 12 m thick with interbeds of heterolithologic tuff breccia which have ashy pumiceous matrix. Some breccia beds grade upward to pumice lapilli tuff, others have sharp contacts with tuff
460-470	RHYOLITE OR RHYODACITE. Massive to flow-banded with glassy top and brecciated base
470-500	RHYOLITIC PUMICE LAPILLI TUFFS AND LITHIC BRECCIA. Similar to unit in interval 360-460 m. Contains 1.5 m of perlitic glass at 479 m
500-553	RHYODACITE. Massive to flow-banded rhyodacite and rhyodacite breccia
552-553	PUMICEOUS SEDIMENT. Bedded ash and lapilli
553-697	DACITE. Massive to rubbly, locally flow banded and vesicular, breccia zones at 553 m, 573 m, 600-603 m, and 605-607 m. Ashy dacitic breccia at 605-607 m, massive to flow-banded locally brecciated dacite at 607-697 m
697-746	DACITE OR ANDESITE. Massive, slightly flow-banded in uppper part, mostly breccia in lower part
746-752	TUFFACEOUS SEDIMENT. Rudely to moderately well-bedded sand, silt, and grit
752-757	PUMICE LAPILLI TUFF. Massive poorly sorted ash and lapilli with angular accidental lithic fragments. Many pumice lapilli are flattened
757-758	TUFFACEOUS SILTSTONE. Finely bedded with pumiceous interbeds
758-932	BASALT OR BASALTIC ANDESITE. Massive to locally fractured, vesicular basalt with flow-top and flow-base breccia forming major parts of section (758-762 m, 793-795 m, 809-811 m, 850-852 m, 910-911 m, 930-932 m). Breccias are largely altered

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

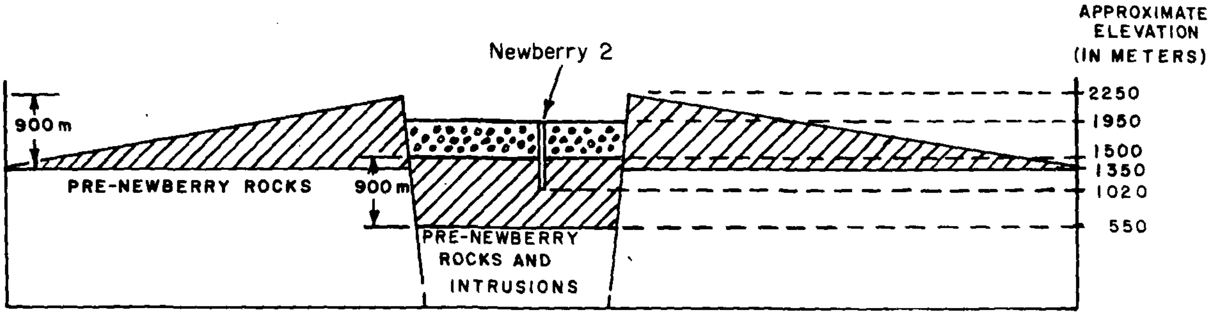


Figure 8. Schematic cross section of Newberry Volcano showing probable position of collapsed block.

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.

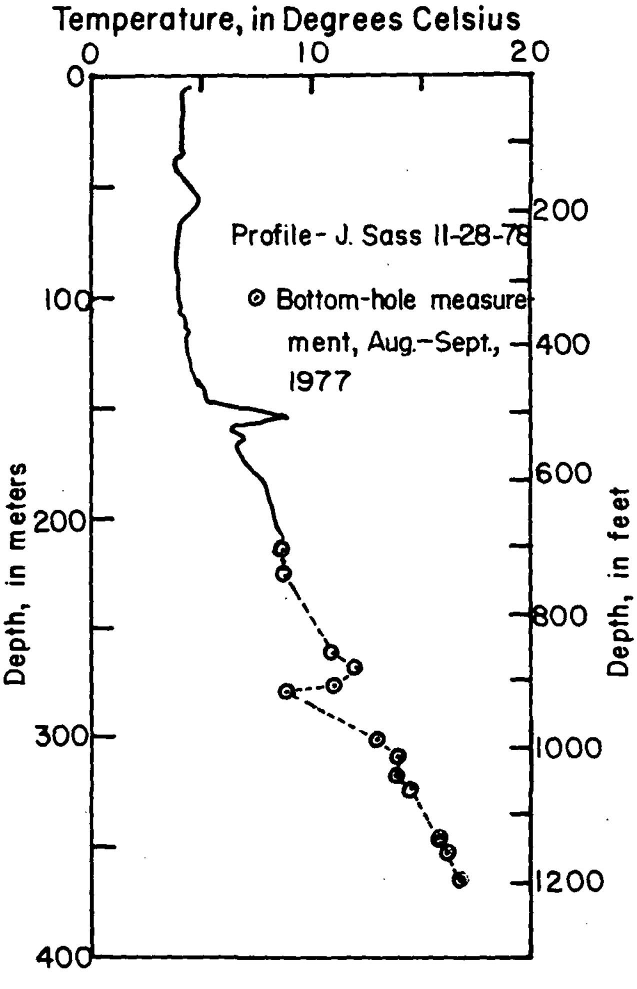


Figure 9. Temperatures measured in Newberry 1.

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

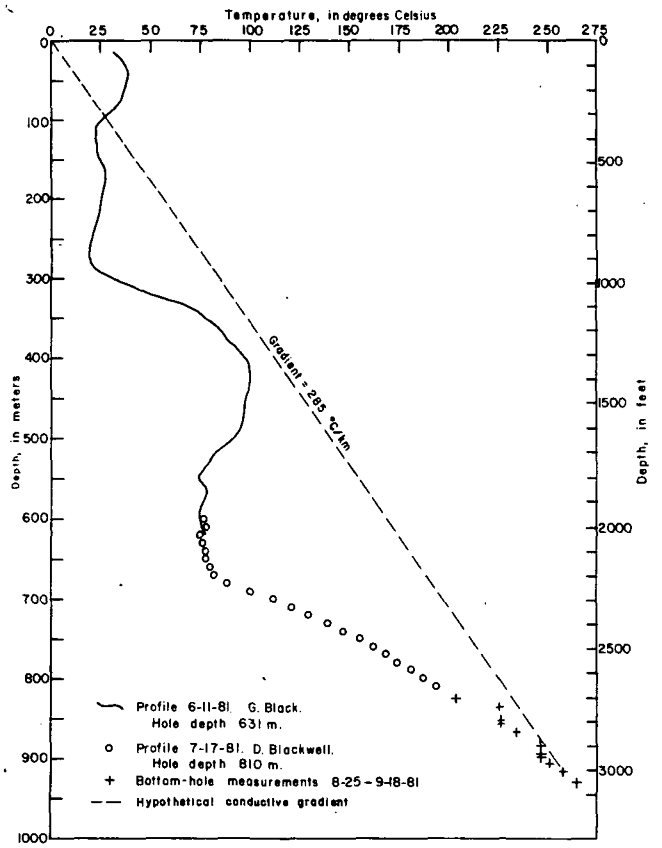


Figure 10. Temperatures measured in Newberry 2 and hypothetical conductive gradient projected from bottom of hole to land surface.

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.

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3. FREQUENCY OF ISSUE MONTHLY	A. NO. OF ISSUES PUBLISHED ANNUALLY 12	B. ANNUAL SUBSCRIPTION PRICE $6.00

4. COMPLETE MAILING ADDRESS OF KNOWN OFFICE OF PUBLICATION *(Street, City, County, State and ZIP Code) (Not printers)*

1005 State Office Building, Portland, OR 97201

5. COMPLETE MAILING ADDRESS OF THE HEADQUARTERS OR GENERAL BUSINESS OFFICES OF THE PUBLISHERS *(Not printers)*

1005 State Office Building, Portland, OR 97201

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Geothermal Resources Council, TRANSACTIONS Vol. 7, October 1983

THE SHALLOW HYDROTHERMAL SYSTEM AT NEWBERRY VOLCANO, OREGON: A CONCEPTUAL MODEL

Edward A. Sammel

U.S. Geological Survey

ABSTRACT

Investigations at Newberry Volcano, Oregon, have resulted in a satisfactory account of the shallow hydrothermal system, but have not indicated the nature of a possible geothermal reservoir. Hot springs in the caldera probably represent the return of circulating meteoric water, warmed at shallow depths by high conductive heat flow and by steam rising from greater depths. Ground-water recharge to the hydrothermal system is at most 250 liters per second, of which about 20 liters per second reappears in the hot springs. Analysis of temperature anomalies in a Geological Survey drillhole indicates that ground-water flow totaling about 125 liters per second could be moving laterally at depths of less than 650 m at the drill site. A small fraction of the total recharge may infiltrate to a deeper high-temperature reservoir whose existence has not yet been confirmed.

INTRODUCTION

Newberry Volcano, a large Quaternary structure located about 50 km east of the crest of the Cascade Range in west-central Oregon, has become well known in recent years for widespread Holocene silicic volcanism, a 6 km- to 8 km-wide caldera, several hot-spring areas, and a presumed geothermal potential. The structure and setting of the volcano have been described by MacLeod and others (1981), by MacLeod and Sammel (1982), and, most recently, in a detailed geologic map of the area, by MacLeod and others (1982).

Volcanic activity at Newberry began more than 600,000 years ago and continued until about 1350 years ago. Caldera collapse occurred episodically during this time along arcuate ring fractures that at places are concentric (fig. 1). The range of rock compositions (basalt to rhyolite), their age relationships, and the widespread occurrence of chemically similar young rocks suggest that a large magma chamber has been present beneath the volcano and that it has been resupplied with magma during the last 1/2 million years. The recency of silicic eruptions suggests that the upper part of the chamber could still be extremely hot.

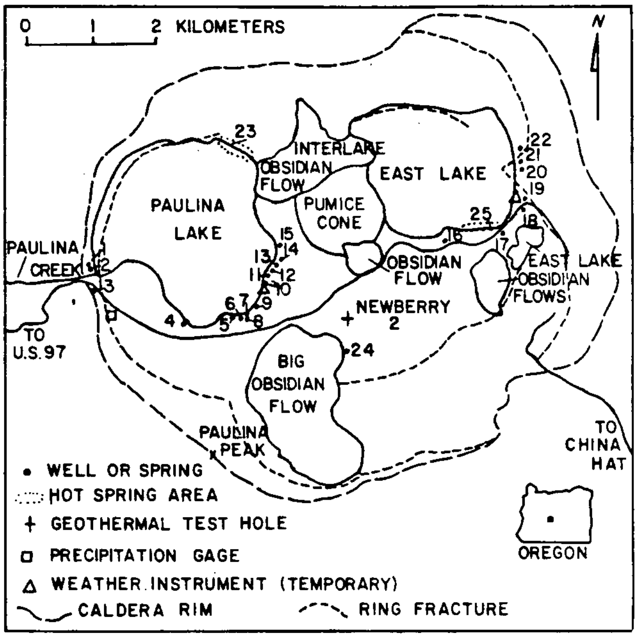

Figure 1. Index map of the caldera, Newberry Volcano.

A core hole, Newberry 2, completed by the Geological Survey in 1981, penetrated 932 m of caldera fill and underlying flow rocks and demonstrated that temperatures as high as 265°C exist at a depth of less than a kilometer beneath the caldera without producing any surficial high-temperature hydrothermal features. Data derived from the drilling have extended our knowledge of the volcano, but many questions regarding the geothermal potential remain unanswered. The purpose of this paper is to present data on the shallow hydrothermal system at Newberry and to examine these data for evidence of a geothermal resource.

The dominant features of the hydrologic regime in the caldera are two scenic lakes, East Lake and Paulina Lake, that occupy about half the low-lying caldera floor. Paulina Creek, the only stream in the caldera, drains water from Paulina Lake through a shallow cut in the west rim about 150 m from the lake shore (fig. 1). A study carried out by the Geological Survey during recent summers has defined many of the hydrologic relationships and has indicated the importance in the hydrologic regime of ground-water flow at shallow depths beneath the caldera floor (Sammel and Craig, 1983).

MAJOR-ION CHEMISTRY AND ISOTOPE RESULTS

Relationships between ground water and lakes are indicated by chemical analyses of water from 16 of the 22 shallow wells, two hot-spring areas, the lakes, and a gas vent in the caldera (table 1; locations shown in figure 1). Most of the wells are located near the lakes, and the known hot springs occur on the lake shores or in shallow water near the shores. The chemical data indicate that the shallow ground water is closely related to the lake water in each subbasin and that significant differences occur between the subbasins. The ground water appears to acquire generally higher concentrations of dissolved solids as it moves from east to west down the topographic gradient in the caldera.

The diagrams of figure 2 display concentrations of seven major ions in samples grouped by relative locations in the two subbasins. Samples 20 and 22 represent dilute ground water that has had only a short residence time in the shallow East Lake aquifer. Sample 3 demonstrates that an even more dilute water occurs at the western end of the caldera at some distance from Paulina Lake. The remainder of the diagrams show that magnesium, sodium, and potassium concentrations are higher in the Paulina Lake area than in the East Lake area, sulfate concentrations are lower, and chloride concentrations are similarly low in both areas. Calcium and bicarbonate concentrations, which are dominant in the eastern subbasin, increase only slightly in the western subbasin.

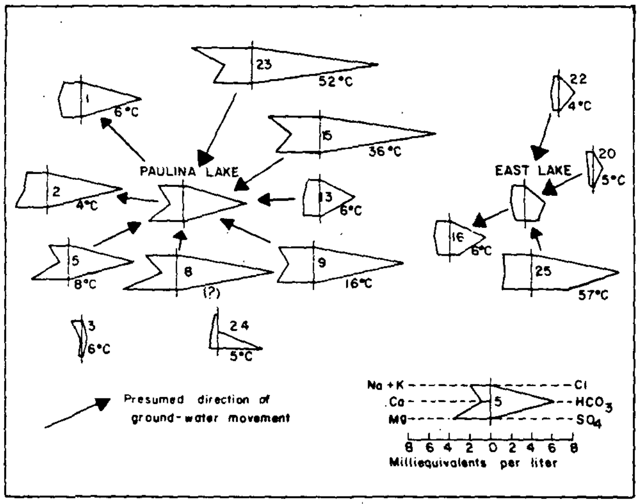

Figure 2. Chemical relations in ground and surface water, and presumed flow directions of ground water.

In the context of these general relations, the chemistry of the hot springs and warm wells provides some clues to the origin of the thermal water. In the Paulina Lake subbasin, the two warmest waters, Paulina Hot Springs (temperature 52°C) and well 15 (36°C), may be compared with Paulina Lake, which is assumed to be an indicator of ground-water quality in much of its subbasin. The chemical data show that concentrations of major ions in the thermal waters are roughly double the concentrations of the same ions in the lake water and in cooler ground waters near the lake (fig. 3). The single exception among the ionic constituents is sulfate, which is lower in the thermal waters than in the lake. In the East Lake subbasin, the hot spring (No. 25), which had a temperature of 62°C when measured in 1973 (Mariner and others, 1980), and 57°C in June, 1982 (table 1), has two to three times the concentrations of major ions, including sulfate, in nonthermal ground water (fig. 3).

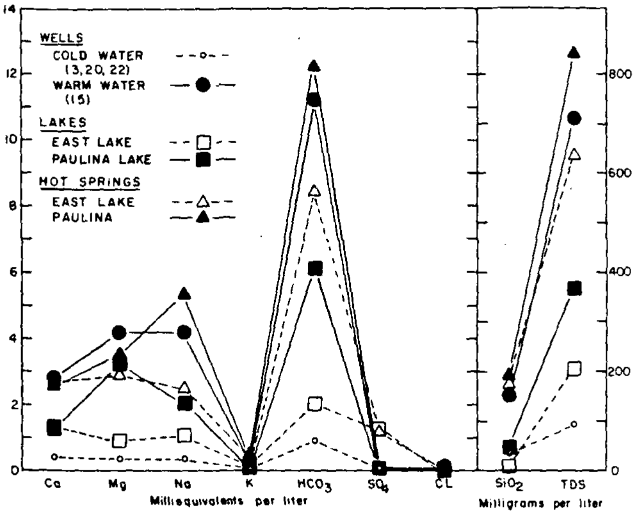

Figure 3. Concentrations of major ions in selected waters.

The difference in sulfate concentrations between East Lake and Paulina Lake waters is attributed to the presence of hydrogen sulfide gas in the East Lake area and its apparent absence in the Paulina Lake thermal waters (R.H. Mariner, written commun., 1983). The effect of hydrogen sulfide is clearly seen in the Obsidian Flow gas vent (24), which evolves abundant hydrogen sulfide and which is shown by the diagram in figure 2 to be a dilute cold water in which the sulfide from the gas has oxidized to sulfate. Chloride concentration in this water is several times background levels, and the pH has decreased to 3.4, well below the pH 6 to pH 7 values in other ground waters.

Silica concentrations in both hot springs are about 200 mg/L. In many other geothermal areas, concentrations of this magnitude indicate high temperatures of equilibration. At Newberry, however, concentrations of silica in all ground waters are high (30 to 160 mg/L) and they vary erratically, apparently in response to varying exposures to the glassy siliceous flow rocks and lapilli tuffs that underlie much of the caldera. Reservoir temperatures calculated by means of the silica geothermometer probably are not meaningful under these circumstances, although both the silica and the sodium-potassium-calcium geothermometers indicate equilibration of the hot-spring waters at temperatures of 175°C to 180°C. The silica geothermometer is suspect because of probable low-temperature silica dissolution, and the sodium-potassium-calcium geothermometer is invalid because of an extremely large magnesium correction. All of the chemical data suggest that the thermal waters equilibrated at shallow depths and low temperatures.

Concentrations of the stable isotopes, oxygen-18 and deuterium, support the foregoing conclusions and provide additional insight into relationships among the waters. The isotope diagram (fig. 4) shows that Paulina Lake, East Lake, and several well waters fall on a trend suggestive of low-temperature evaporation. Paulina Hot Springs is on the same trend and shows no evidence of a deep geothermal origin. East Lake Hot Springs and one sample from a warm well near Paulina Lake (15) have positions which suggest that these two waters have at least a small thermal component. The two analyses from well 15 differ considerably in deuterium concentration. Three chemical analyses of this water, obtained between 1974 and 1981, indicate a stable chemistry during this period and suggest that there may be a laboratory-related bias in deuterium concentrations that causes the Craig (1981) samples to differ from the Mariner samples (1981, 1982). The positions of the Craig samples in the diagram suggest that the reported deuterium concentrations may be too high.

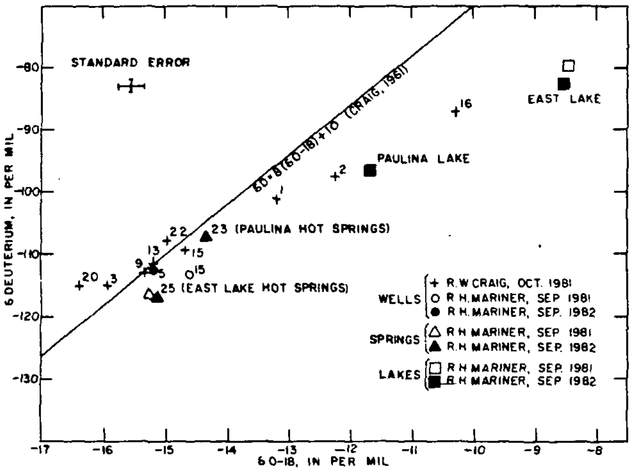

Figure 4. Concentrations of oxygen-18 and deuterium in ground and surface waters.

Sample 16, from a well at the East Lake campground, appears to be closely related to East Lake water (fig. 4), and the water level in the well, which is lower than the level of East Lake, suggests that the sample represents ground-water outflow from the lake. Samples 1 and 2, from wells on the west bank of Paulina Lake, similarly represent a probable connection with Paulina Lake.

The position of water from East Lake Hot Spring in the isotope diagram seems to preclude the possibility that this water is a mixture of hotter thermal water and East Lake water. Chemical mixing models also fail in applications to the samples from the East Lake area. The small shift toward higher oxygen-18 concentrations in the East Lake Hot Spring, together with the slightly increased chloride concentration, suggests that this water might be a mixture of shallow meteroic water and steam from a deep reservoir. The relatively high concentrations of bicarbonate and sulfate are readily explained by the presence of carbon dioxide and hydrogen sulfide gases in the water (Phillips and Van Denburgh, 1968).

The chemical and isotopic evidence thus points rather conclusively toward a near-surface, low-temperature origin for the thermal waters of the caldera. (For corroboration, see Keith and others, 1983). The heat source is likely to be conductive heat flow supplemented at places by steam and hot gas rising from a deep reservoir. The locations of the hot springs and gas vents suggest that the vertical conduits for these waters are largely restricted to areas near Holocene obsidian flows, the central pumice cone, and the caldera ring fractures.

HYDROLOGIC BUDGET AND POTENTIAL GEOTHERMAL RECHARGE

The water budget for the near surface hydrologic regime in the caldera is represented by the expression,

$$P - E - ET - OF = S,$$

where P is precipitation, E is evaporation from lake surfaces, ET is evapotranspiration from land surfaces, OF is stream flow leaving the caldera in Paulina Creek, and S is ground-water seepage out of the near-surface hydrologic system.

Estimates of the terms in this expression have been made on the basis of investigations carried out by the Geological Survey during the summers of 1980 and 1981 (Sammel and Craig, 1983) and a prior investigation of East Lake by Phillips and Van Denburgh (1968).

Annual precipitation in the caldera is estimated fairly reliably to be about 890 mm (35 in.); evaporation from lake surfaces is about 480 mm (19 in.) for Paulina Lake and 700 mm (28 in.) for East Lake; evapotranspiration from the densely forested land area is about 330 mm (13 in.) according to a calculation made for our study by J.E. Vaughn, U.S. Forest Service, Bend, Oregon; and streamflow is probably in the range 16×10^6 - 18×10^6 m^3/yr (18 - 20 ft^3/s). Applying these estimates to the 35 square kilometer land surface and the 9½ square kilometer lake area of the caldera, the residual term in the budget equation, assumed to be deep ground-water seepage, is estimated to be as much as 8×10^6 m^3/yr, or about 250 L/s. Consideration of probable errors in the budget estimates suggests that the seepage could be as little as half this amount but is not likely to be larger (Sammel and Craig, 1983).

A breakdown of the water-budget estimates by subbasins reveals that the East Lake subbasin has a large surplus of ground water each year, part of which must flow westward to make up an apparent deficit in the Paulina Lake subbasin. Perhaps as much as 70 L/s of this flow is attributable to seepage out of East Lake itself. The budget calculations for the Paulina Lake subbasin and the lack of observable ground-water discharge into Paulina Creek on the west flank of the volcano suggest that negligible amounts of ground-water seepage occur out of Paulina Lake. Nevertheless, the analysis of the ground-water flow, described in greater detail in Sammel and Craig (1983), makes it reasonable to suppose that excess ground water is available for deep recharge almost anywhere beneath the land surface in the south half of the caldera.

HYDROLOGIC EVIDENCE FROM TEST DRILLING

In the Geological Survey test hole, Newberry 2, located less than a kilometer south of the center of caldera (fig. 1), ground-water flows occurred in several sub-horizontal strata in the upper 650 m of the hole (MacLeod and Sammel, 1982). The temperature profile in the drill hole (fig. 5) suggests that large temperature perturbations in the profile probably result from the convective transfer of heat by moving ground water, and several of these perturbations can be correlated with observed flows. The 37°C bulge centered at a depth of about 40 m, for example, is probably caused by thermal water flowing above and within an obsidian flow below this depth. A temperature reversal below 175 m ends with a temperature of 20°C at a depth of about 275 m. The cause is probably the flow of cold water in a cavernous zone within strata of basaltic siltstone and mudstone. Between the depths of 550 m and 650 m drilling fluid was lost in dacitic breccias and pumiceous sediments, suggesting that ground-water flow could account for the temperature minima (about 75°C) in this zone also.

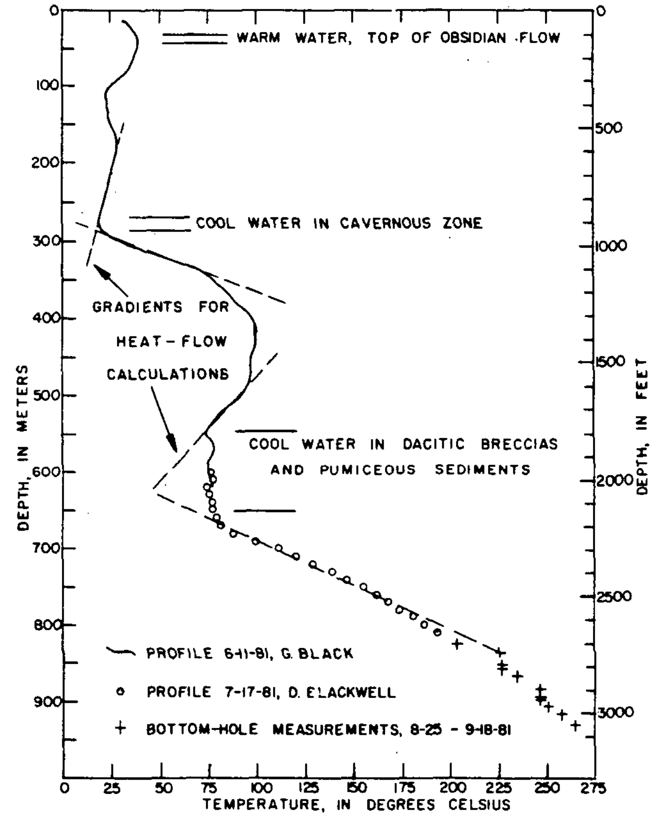

Figure 5. Temperature profile in test hole Newberry 2, showing inferred zones of cooling by ground water.

The thermal gradients above and below the flow zones are large, and the temperatures changed only 2 or 3 degrees over a period of more than a year despite episodes of drilling activity each summer. These facts tend to rule out disturbances due to drilling and convective flow in the borehole as significant influences on the temperature profile. If the temperature profile (fig. 5) represents the thermal regime in the rocks beneath the caldera, therefore, heat flow into the two principal cooling zones can be calculated on the basis of average conductive thermal gradients above and below these zones and the measured thermal conductivities of the rocks. The apparent conductive heat flow thus calculated for the two zones totals about 2 W/m^2 (50 Heat Flow Units).

The flow of cool water that is required to transfer the heat from these zones can be calculated and compared with the amount of water estimated to be available as seepage from the surface of the caldera. An analytical expression proposed by Bodvarsson (1969) affords a means of calculating the flow of a fluid at one temperature through a permeable zone bounded by two impermeable slabs having a different temperature. The observed temperature difference constrains the flow rate for any given period of time if it is assumed that the initial temperature profile was linear and conductive. The boundary conditions for Bodvarsson's expression are sufficiently similar to conditions known or deduced from the drilling data as to permit some qualitative conclusions from this approach.

Bodvarsson's expression (1969, p. 1989) is given as:

$$T = A \operatorname{erfc}[(\alpha X + y)/2(at)^{\frac{1}{2}}],$$

where T is the temperature at the boundary of the permeable zone (y = 0) at time t, A is the temperature of the injected water, erfc is the complementary error function, a is the thermal diffusivity of the rock-water mass in the impermeable slabs, x and y are spatial coordinates, and $\alpha = 2k/sq$ where k is the thermal conductivity of the slabs, s is the specific heat of the fluid, and q is the mass flow per unit length of the z coordinate. The mass flow rate calculated for ground water initially at a temperature of 20°C and for other conditions measured and assumed at a depth of 600 m in Newberry 2 ranges from 0.01 kg/s for 1,000 years to 0.007 kg/s for 1,500 years. At the depth of 275 m in the drill hole, the calculated flow rate of infiltrating ground water is 0.03 kg/s for 1,000 years and 0.02 kg/s per meter width for 1,500 years. The rates are calculated for a meter width of the permeable rock and for the 1100 m distance from the south caldera ring fracture to the drill hole.

If recharge has operated for 1,500 years, or roughly the time since the last major episode of eruption and caldera filling, a ground-water flow of about 0.03 kg/s per meter would be required in order to produce the profile observed in Newberry 2 from an originally linear conductive profile. This figure may be compared with the probable maximum available recharge beneath the drill site by assuming that one-half the recharge occurs through the land surface south of the lakes (a conservative assumption), and that it must occur in the approximately 4000 m-length of ring fracture bordering the south rim of the caldera. These crude assumptions result in a calculated recharge of 0.03 kg/s per meter, a figure fortuitously equal to the required flow at depth.

The values obtained by these methods are not quantitatively significant, but they suggest that meteoric water could supply the hydrothermal circulation system in the caldera fill and in the permeable flow rocks immediately below the fill. Core samples indicate that below 650 m horizontal permeabilities are extremely low and vertical permeability must be nearly zero (Keith and others, 1983). Only small amounts of water vapor and gas occurred in the rocks between 700 m and 930 m. The occurrence of formation water at 930 m remains a possibility which, at this time, cannot be confirmed or denied on the basis of chemical and isotopic data.

CONCEPTUAL MODEL

A model of the hydrothermal circulation system that fits most of the currently available data is one in which small amounts of steam and gas rise from a deep reservoir through poorly permeable fractures and faults (fig. 6). These heat sources were imposed, possibly within the last 1,300 years, on a conductive regime that had produced temperatures as high as 100°C at a depth of 400 m in the caldera. Some of the meteoric water that now infiltrates the caldera is warmed to temperatures that slightly exceed known spring temperatures (>62°C) and is chemically altered by the steam and gas. The thermal water returns to the surface at a few places that appear to be associated with ring fractures or vents for the Holocene flow rocks. Calculations based on observations of spring flow at the edges of the lakes and of temperatures in the lakes suggest that the total discharge of known thermal flows reaching the surface in the caldera is less than 20 L/s (Sammel and Craig, 1983). Some of the remaining surplus meteoric water may infiltrate deeper into the volcano, but most is probably dispersed to the flanks. Horizontal permeabilities probably are high enough to make it unlikely that a significant fraction of the recharge could reach a deep geothermal reservoir.

The conceptual model is currently being tested by the author in numerical simulation models based on a cooling pluton and ring-dike configuration proposed by Andrew Griscom (Written commun., 1983). At present, the location and nature of a geothermal reservoir are speculative. If the conductive gradient observed in the lower 70 m of Newberry 2 (505°C/km) continues to the base of the collapsed caldera block, temperatures would be about 500°C at a depth of about 1.4 km (MacLeod and Sammel, 1982). A small silicic magma chamber could be present at greater depth at the top of a large cooling pluton. Fracture permeability in adjacent volcanic rocks may provide a reservoir which could be supplied with water from deep regional groundwater flow.

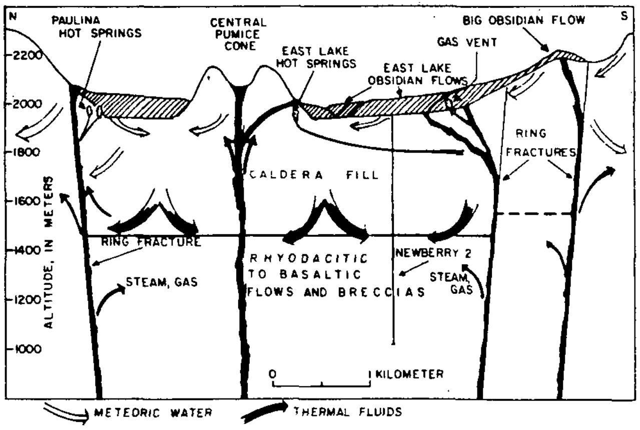

Figure 6. Sketch showing inferred relations among elements of the shallow hydrothermal regime.

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SAMMEL

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Table 1.-- Chemical analyses of ground and surface water [Concentrations in milligrams per liter unless otherwise indicated]

Sequence Number[1]	Owner/ name	Temp. (°C)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	SiO_2	As	B	Fe	Li	Mn	Dissolved solids[2]	Specific cond. (µmho/cm)	pH	Date sampled	Source[3]
												(µg/L)									
1	Paulina Lake Resort	5	35	24	28	6.1	315	5.0	2.8	0.3	29	1	460	120	13	11	286	400	6.95	10/07/81	A
		6.7	39	35	38	7.7	398	1.9	2.7	.4	33	2	700	180	--	1500	356	565	6.9	10/27/74	B
2	Paulina Lake Resort	4	44	39	44	6.4	450	6.0	3.1	.5	36	24	780	6700	88	2300	410	600	7.15	10/07/81	A
3	Paulina Guard Station (USFS)	6	3.3	2.6	6.5	1.8	27	5.0	.2	.7	46	3	20	23	17	<1	79	65	6.65	09/06/81	A
5	Mike Mathews (summer home)	8	18	41	41	5.0	376	2	2.6	---	90	--	--	--	--	--	--	(700[5])	6.97	06/30/82	E
8	Jack Hogg (summer home)	---	30	65	68	7.4	585	5.0	5.2	.8	110	39	1500	<10	120	2	581	900	6.15	09/06/81	A
9	Little Crater Picnic Area	16	42	44	64	8.3	535	5.0	4.6	.7	90	32	1600	180	100	30	532	710	6.80	10/07/81	A
13	Little Crater Camp Site 27	6	28	17	25	2.6	215	5.0	1.7	.3	46	16	570	43	29	10	232	360	7.10	10/07/81	A
15	Little Crater Camp Site 49	33	59	57	97	12	690	5.0	6.8	.5	156	<1	1800	360	140	270	733	900	6.21	09/06/81	A
		35.5	54	48	83	10	679	<1	5.1	.6	161	--	2500	4000	120	250	702	900	6.46	08/--/75	C
		36	56	51	96	12	691	2.5	4.5	.5	140	2	1000	5000	---	350	709	880	6.3	10/17/74	E
16	East Lake Campground well	6	33	15	26	6.0	200	43	2.8	.2	40	1	210	19	9	3	265	390	6.80	09/06/81	A
20	Cinder Hill Campground well	5	7.1	1.9	11	1.3	56	5.0	2.5	.4	30	5	10	27	8	5	87	110	6.70	09/06/81	A
22	Cinder Hill Camp Site 34	4	14	7.2	6.3	3.5	88	5.0	<.1	.1	34	<1	10	120	<4	57	113	140	7.20	10/06/81	A
23	Paulina Hot Springs	--	56	60	140	17	856	<1	6.0	.6	205	--	870	--	220	--	907	--	6.82	07/00/77	C
		50	51	43	120	16	699	4.0	4.7	.5	190	16	840	90	--	1700	776	960	6.9	10/26/74	B
		52	50	42	110	13	689	2	5.0	--	184	--	--	--	--	--	--	--	7.26	06/30/82	E
24	Lost Lake gas vent	5	13	8.2	7.9	1.1	0	200	1.1	0.0	31	1	180	15000	--	450	--	400	3.4	10/27/74	B
25	East Lake Hot Springs	49	70	34	53	--	547	28	.7	.2	199	--	1100	660	40	900	658	767	6.42	08/00/75	C
		55	77	39	59	9.7	581	20	1.3	.1	120	1	260	500	--	1400	614	840	6.7	10/26/74	B
		57	73	33	56	9.7	413	120	1.3	--	197	--	--	--	--	--	--	--	6.10	06/30/82	E
--	Paulina Lake[4]	--	26	39	47	5.2	352	3.8	2.8	.6	46	--	--	--	--	--	366	566	8.8	09/10/60	D
		6	28	38	47	5.0	402	4	2.4	--	--	--	--	--	--	--	--	--	8.38	06/30/82	E
--	East Lake[4]	--	27	13	27	4.5	120	64	.3	.2	10	--	640	20	--	--	206	334	7.8	00/00/73	E
			26	10	23	3.7	125	59	.2	.1	13	--	--	--	--	--	197	323	8.1	09/11/60	D
		10	25	11	24	3.7	123	64	<1	--	8.8	--	--	--	--	--	--	--	8.07	06/30/82	E

---

[1] Sequence No. ---- Identifying number used in tables and illustrations.

[5] Estimated.

[2] Estimated by summation of HCO_3 x 0.4917 and other ions listed (Hem, 1970).

[3] Source of data or collector (USGS): A: R. W. Craig; B: N. E. Voegtly; C: R. H. Mariner, and others (1980); D: K. N. Philips (1968); E: R. H. Mariner (unpub. data, 1981, 1982).

[4] Sample obtained at a depth of 45 feet near the center of the lake.

Key figures, Couch et al

Figure Captions

Figure 1. Regional geology of the Pacific Northwest. Rectangles outline the areas of gravity surveys in the Cascade Range of northern, central, and southern Oregon.

Figure 2. Topography of the Cascade Range in northern Oregon. Elevation contours occur at 1000-foot intervals. A-A' shows the location of the seismic refraction line reported by Wegener and others, 1980, and Hill and others, 1981. B-B' shows the trace of the northern Cascade Range geophysical cross section shown in Figure 20.

Figure 3. Free-air gravity anomalies of the Cascade Range of northern Oregon. Heavy contours occur at 50-mgal intervals.

Figure 4. Complete Bouguer gravity anomalies of the Cascade Range of northern Oregon. Heavy contours occur at 10-mgal intervals.

Figure 5. Topographic map of the Cascade Range in central Oregon.

Figure 6. Free-air gravity anomaly map of the Cascade Range in central Oregon. Heavy contours occur at 50-mgal intervals.

Figure 7. Complete Bouguer gravity anomalies of the Cascade Range in central Oregon. Heavy contours occur at 10-mgal intervals.

Figure 8. Topography of the Cascade Range in southern Oregon. Elevation contours occur at 1000-foot intervals. C-C' shows the trace of the geophysical cross section shown in Figure 21.

Figure 9. Free-air gravity anomalies of the Cascade Range in southern Oregon. Heavy contours occur at 50-mgal intervals.

Figure 10. Complete Bouguer gravity anomalies of the Cascade Range in southern Oregon. Heavy contours occur at 10 mgal intervals.

Figure 11. Regional gravity anomalies of the Cascade Range in Oregon. Reduction density is 2.43 gm/cm^3. Map shows anomalies with wavelengths greater than 90 km. Dotted lines outline gravity survey areas.

Figure 12. Topographic and gravity anomaly profiles along the axis of the Cascade Range in Oregon.

Figure 13. West-to-east topographic and gravity profiles of High Cascade Volcanoes.

Figure 14. Residual gravity anomaly map of the Cascade Range in northern Oregon. Heavy contours occur at 10-mgal intervals.

Figure 15. Residual gravity anomaly map of the Cascade Range in central Oregon. Heavy contours occur at 10-mgal intervals.

Figure 16. Residual gravity anomaly map of the Cascade Range in southern Oregon. Heavy contours occur at 10-mgal intervals.

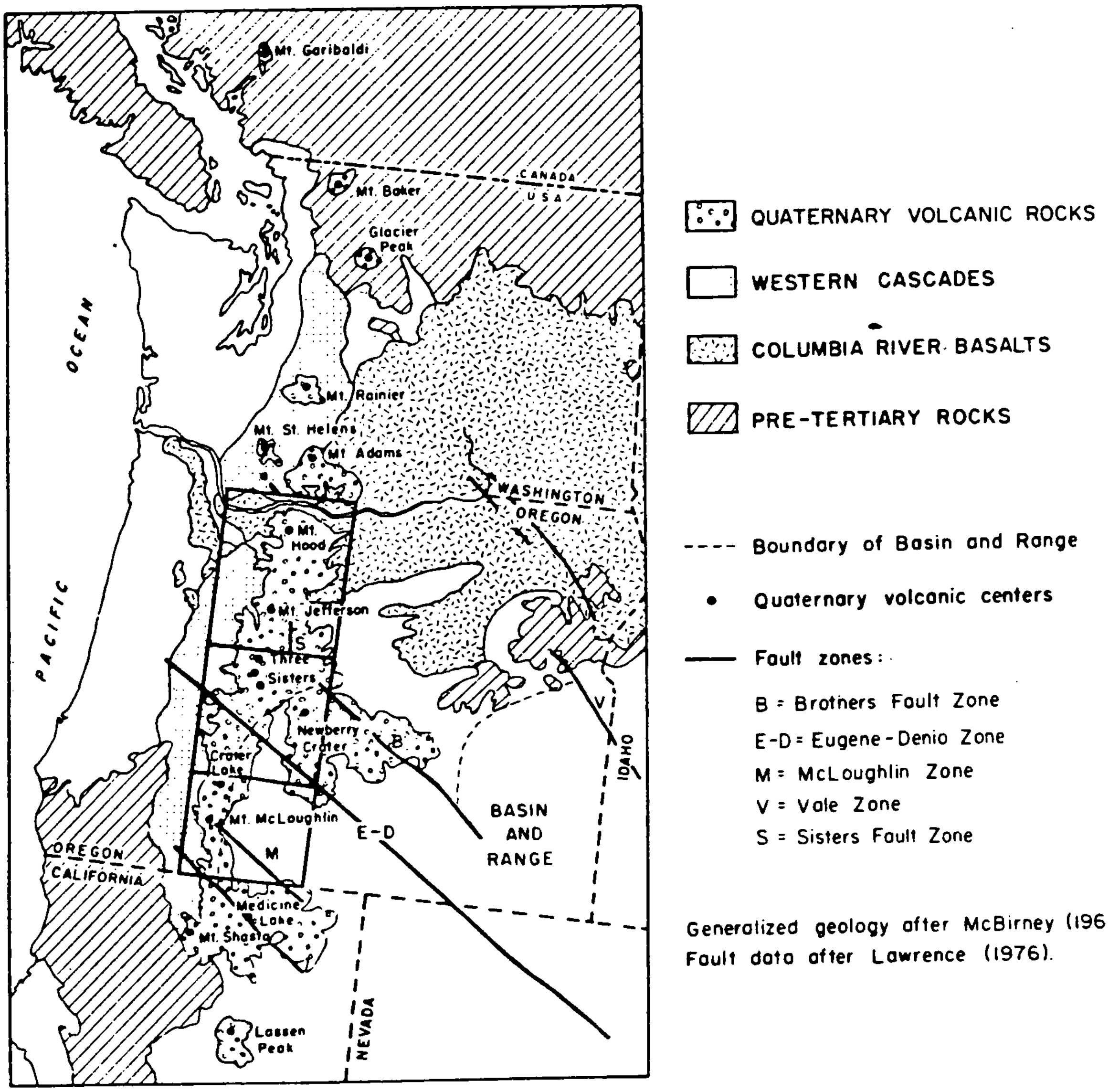
Figure 17. Gravity anomaly lineations in the Cascade Range of northern Oregon. Circles show the location of hot springs (Bowen and Peterson, 1970).

Figure 18. Gravity anomaly lineations in the Cascade Range of central Oregon. Circles show the location of hot springs (Bowen and Peterson, 1970).

Figure 19. Gravity anomaly lineations in the Cascade Range of southern Oregon. Circles show the location of hot springs (Bowen and Peterson, 1970).

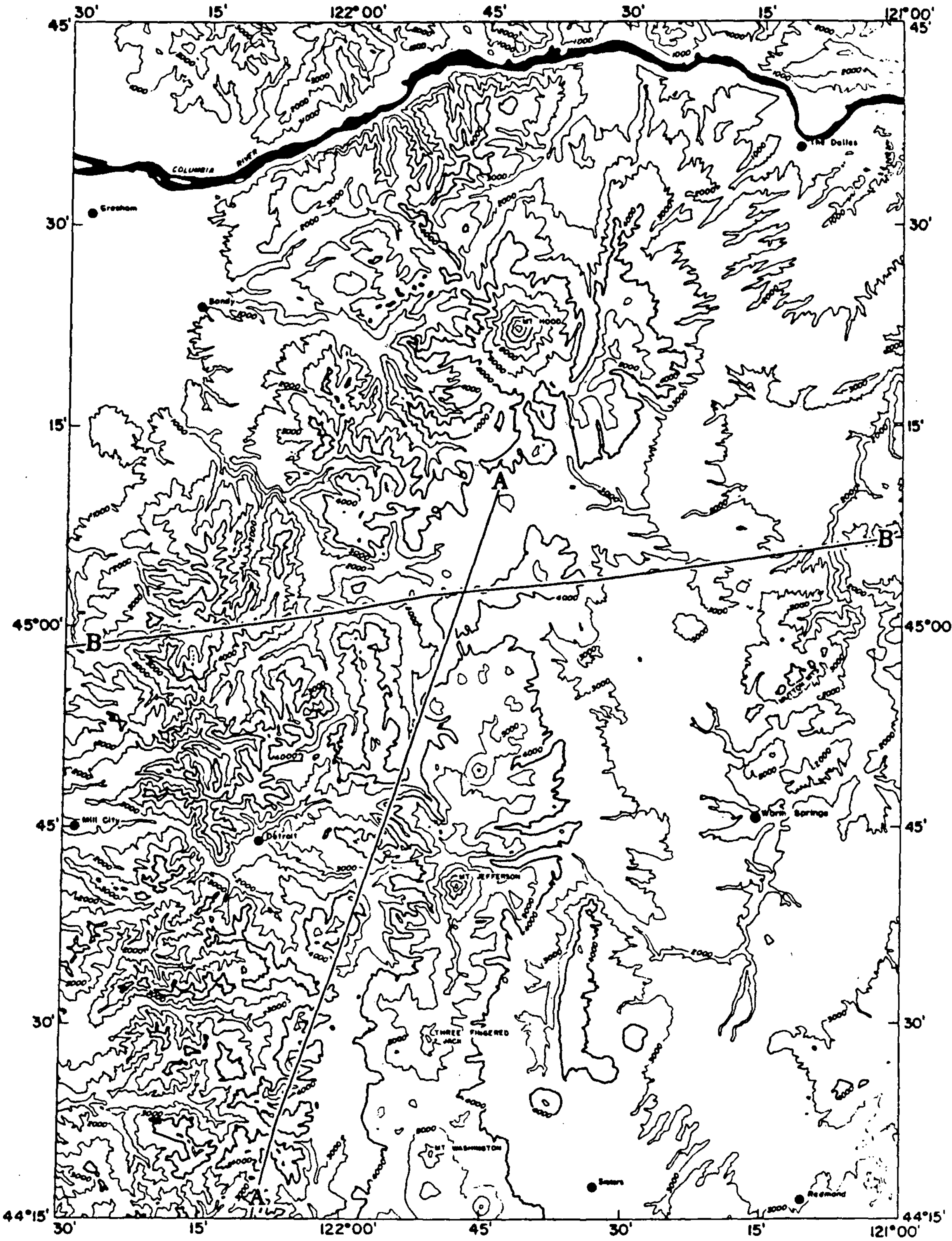
Figure 20. Geophysical cross section of the earth's crust through the Cascade Range in northern Oregon (B-B' Figure 2). The section extends westward offshore to Cascadia Abyssal Plain and easternward to Idaho.

Figure 21. Geophysical cross section of the earth's crust through the Cascade Range in southern Oregon (C-C' Figure 8). The section extends westward offshore to the Gorda Basin and eastward to Idaho.



Generalized geology after McBirney (1968).
Fault data after Lawrence (1976).

Figure 1.



TOPOGRAPHIC MAP

CASCADE MOUNTAIN RANGE, NORTHERN OREGON

MAP LOCATION

DATA FROM USGS 1:250,000 QUADRANGLE MAPS
BEND NL 10-12
SALEM NL 10-11
VANCOUVER NL 10-8
THE DALLES NL 10-9

KILOMETERS
0 5 10 15 20
0 5 10
MILES

TRANSVERSE MERCATOR PROJECTION
CONTOUR INTERVAL 1000 FEET

Figure 2.

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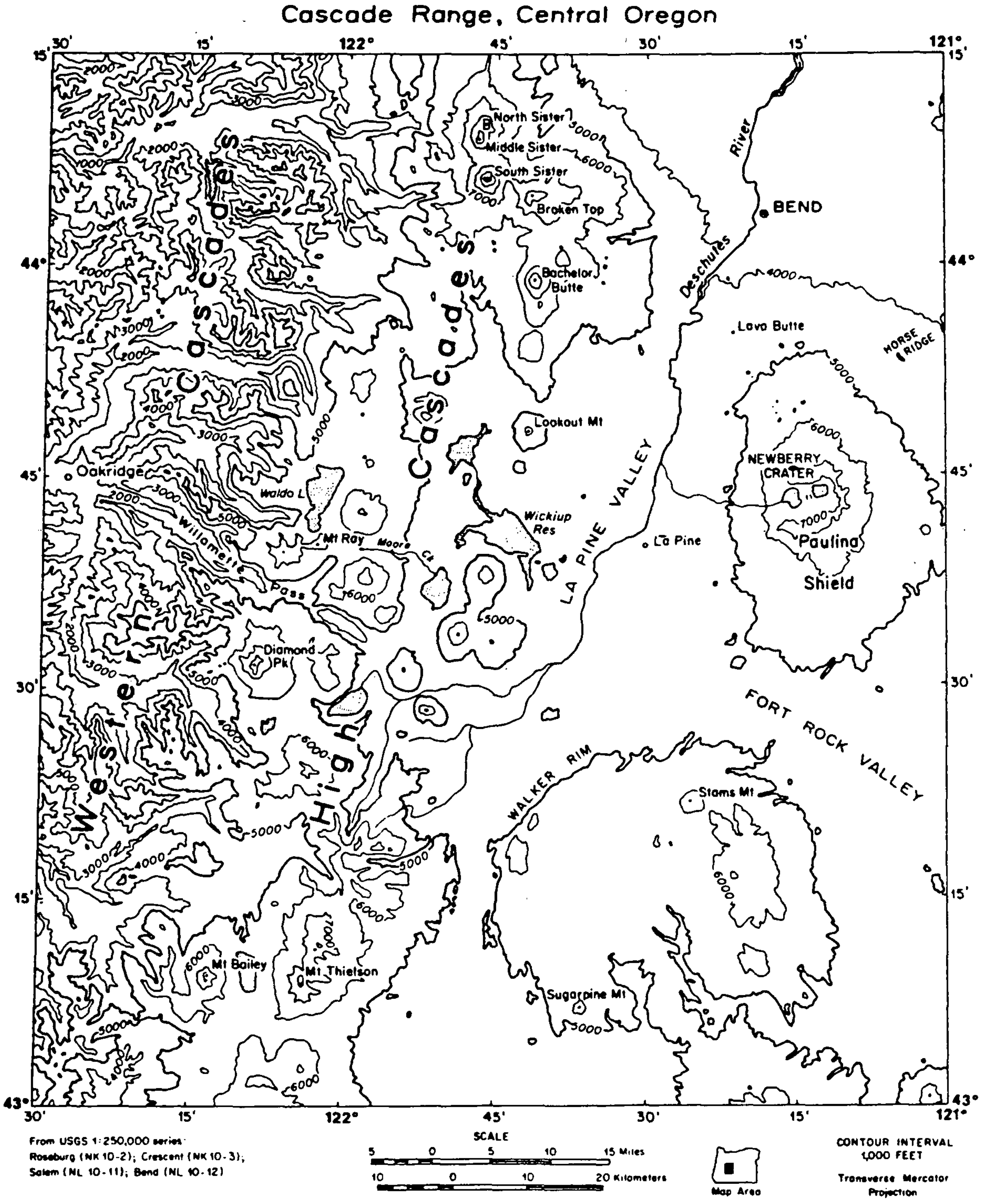
DECEMBER, 1980



From USGS 1:250,000 series:
Roseburg (NK 10-2); Crescent (NK 10-3);
Salem (NL 10-11); Bend (NL 10-12)

Figure 5.

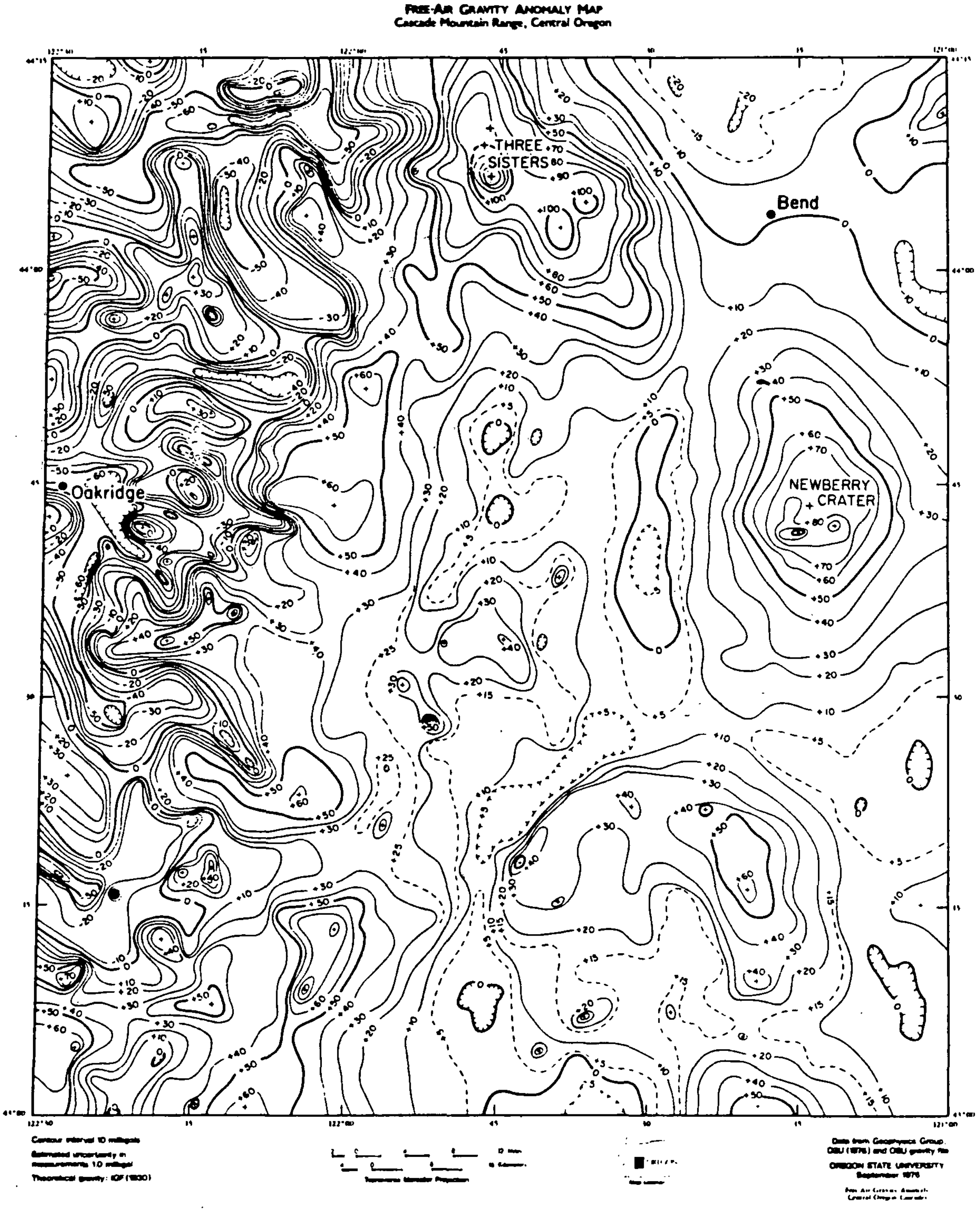

FREE-AIR GRAVITY ANOMALY MAP
Cascade Mountain Range, Central Oregon
THREE SISTERS
Bend
NEWBERRY CRATER
Oakridge
122°30
15
122°00
45
30
121°00
44°15
44°00
45
30
15
43°00
Contour interval 10 milligals
Estimated uncertainty in measurements 1.0 milligal
Theoretical gravity: IGF (1930)
Transverse Mercator Projection
Data from Geophysics Group, OSU (1976) and OSU gravity file
OREGON STATE UNIVERSITY
September 1976

Figure 6.

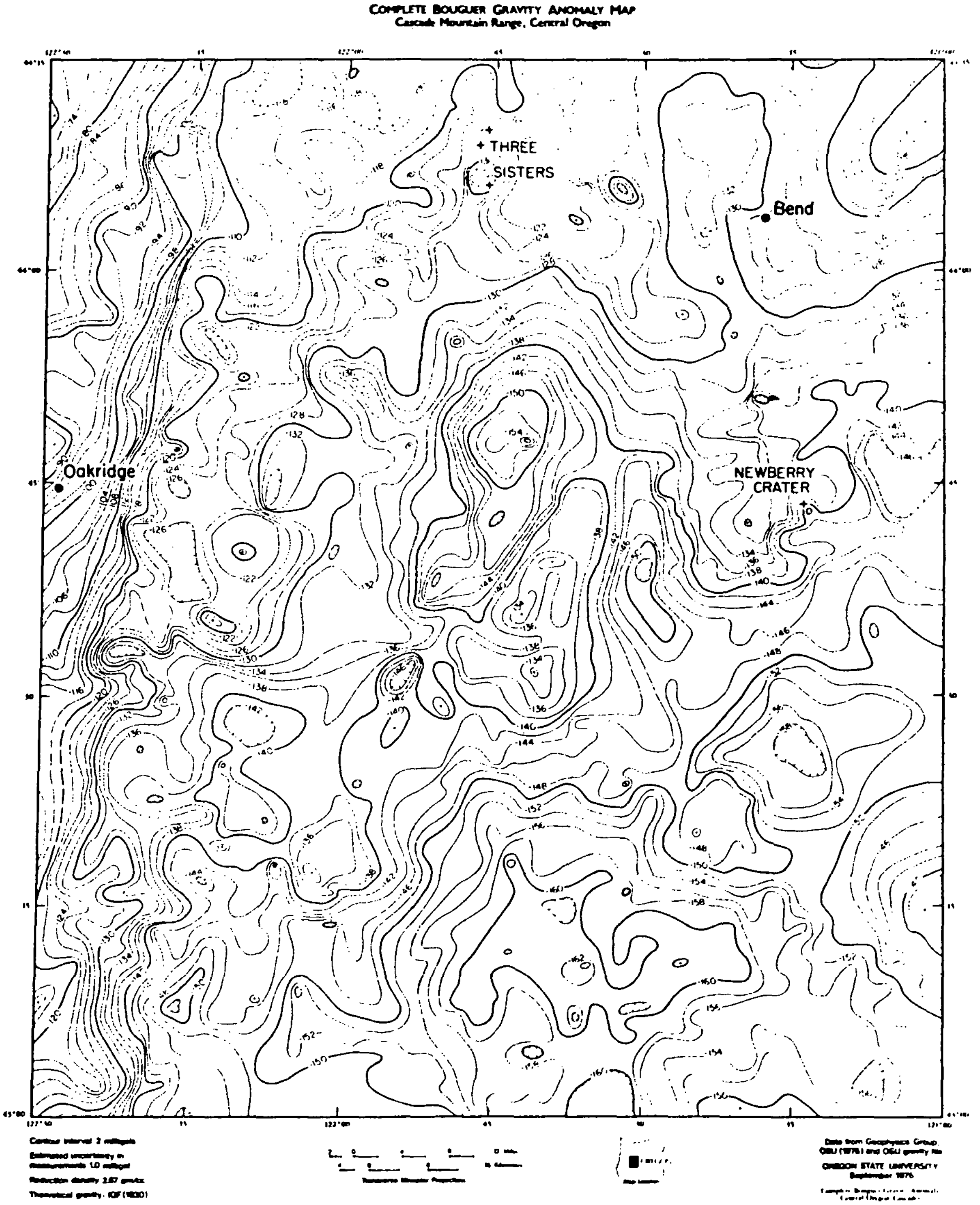
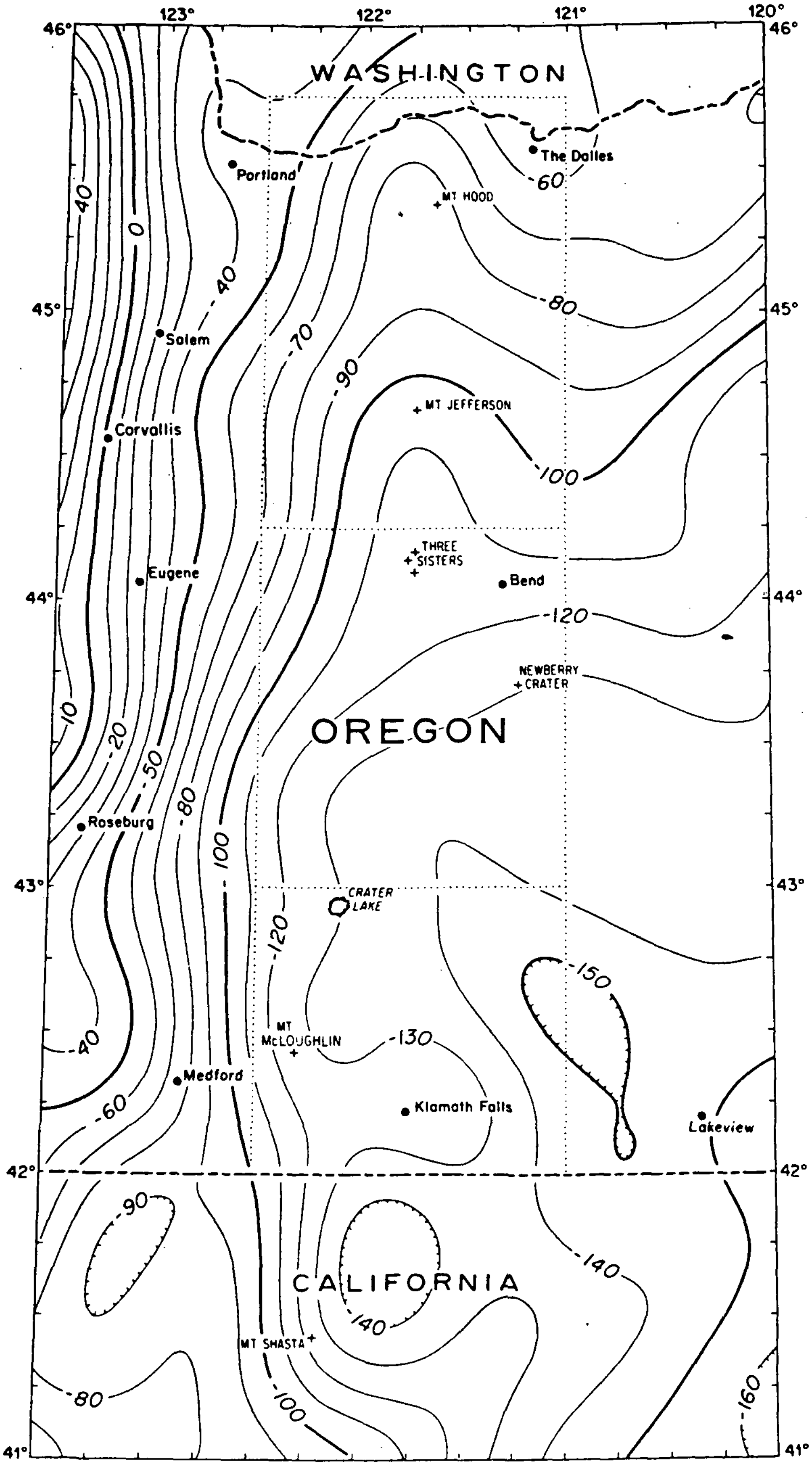

COMPLETE BOUGUER GRAVITY ANOMALY MAP
Cascade Mountain Range, Central Oregon
THREE SISTERS
Bend
Oakridge
NEWBERRY CRATER
122°00
121°00
44°00
Contour interval 2 milligals
Estimated uncertainty in measurements 1.0 milligal
Reduction density 2.67 gm/cc
Theoretical gravity: IGF (1930)
Transverse Mercator Projection
Map Location
Data from Geophysics Group, OSU (1976) and OSU gravity file
OREGON STATE UNIVERSITY
September 1976

Figure 7.



123°
122°
121°
120°
46°
45°
44°
43°
42°
41°
WASHINGTON
OREGON
CALIFORNIA
Portland
The Dalles
MT HOOD
Salem
MT JEFFERSON
Corvallis
THREE SISTERS
Eugene
Bend
NEWBERRY CRATER
Roseburg
CRATER LAKE
MT McLOUGHLIN
Medford
Klamath Falls
Lakeview
MT SHASTA
0
10
20
40
50
60
70
80
90
100
120
130
140
150
160

Figure 11.

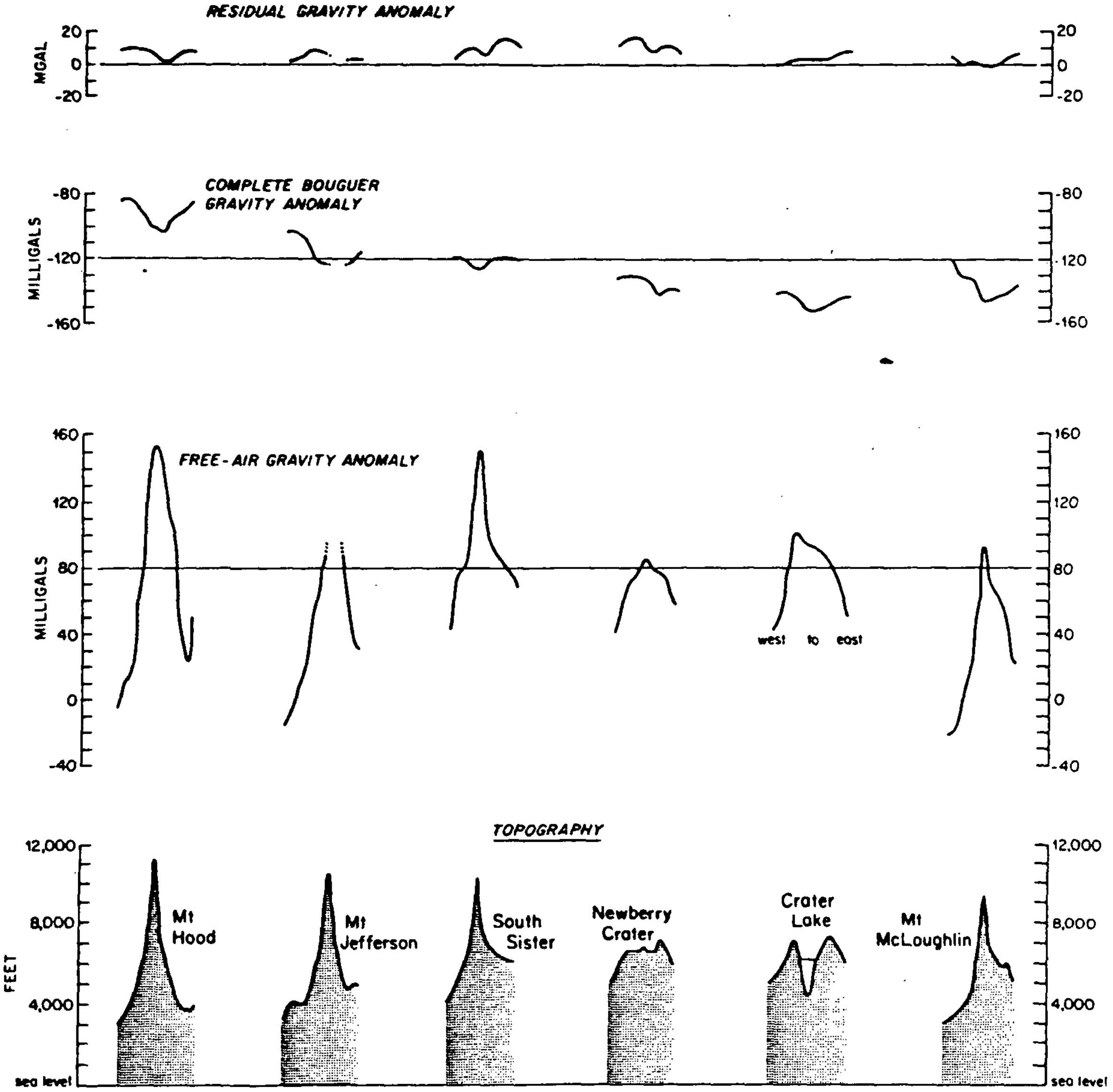
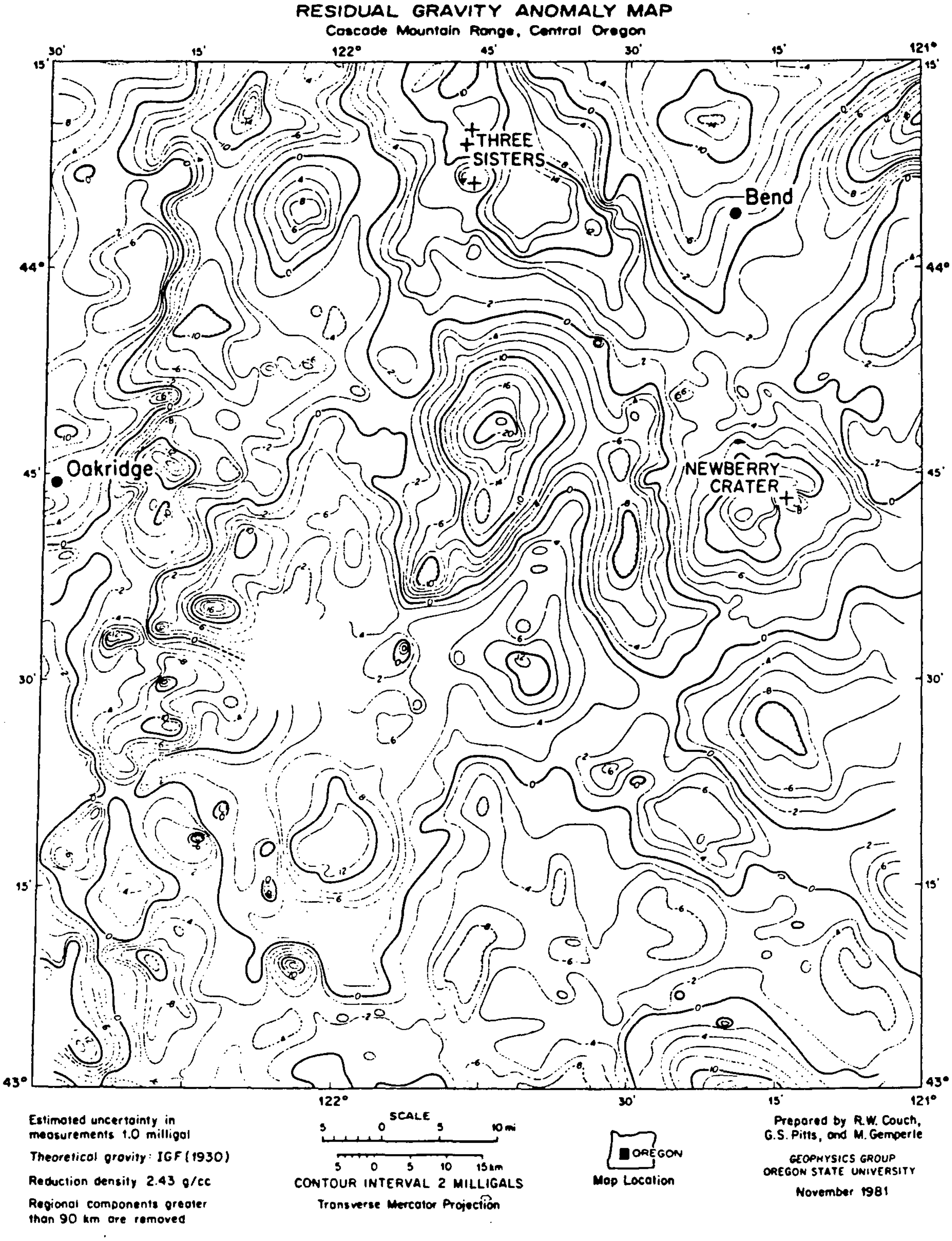

RESIDUAL GRAVITY ANOMALY
MGAL
20
0
-20
COMPLETE BOUGUER GRAVITY ANOMALY
MILLIGALS
-80
-120
-160
FREE-AIR GRAVITY ANOMALY
MILLIGALS
160
120
80
40
0
-40
west to east
TOPOGRAPHY
FEET
12,000
8,000
4,000
sea level
Mt Hood
Mt Jefferson
South Sister
Newberry Crater
Crater Lake
Mt McLoughlin

Figure 13.



RESIDUAL GRAVITY ANOMALY MAP

Cascade Mountain Range, Central Oregon

Estimated uncertainty in measurements 1.0 milligal

Theoretical gravity: IGF (1930)

Reduction density 2.43 g/cc

Regional components greater than 90 km are removed

CONTOUR INTERVAL 2 MILLIGALS

Transverse Mercator Projection

Prepared by R.W. Couch, G.S. Pitts, and M. Gemperle

GEOPHYSICS GROUP
OREGON STATE UNIVERSITY

November 1981

Figure 15.

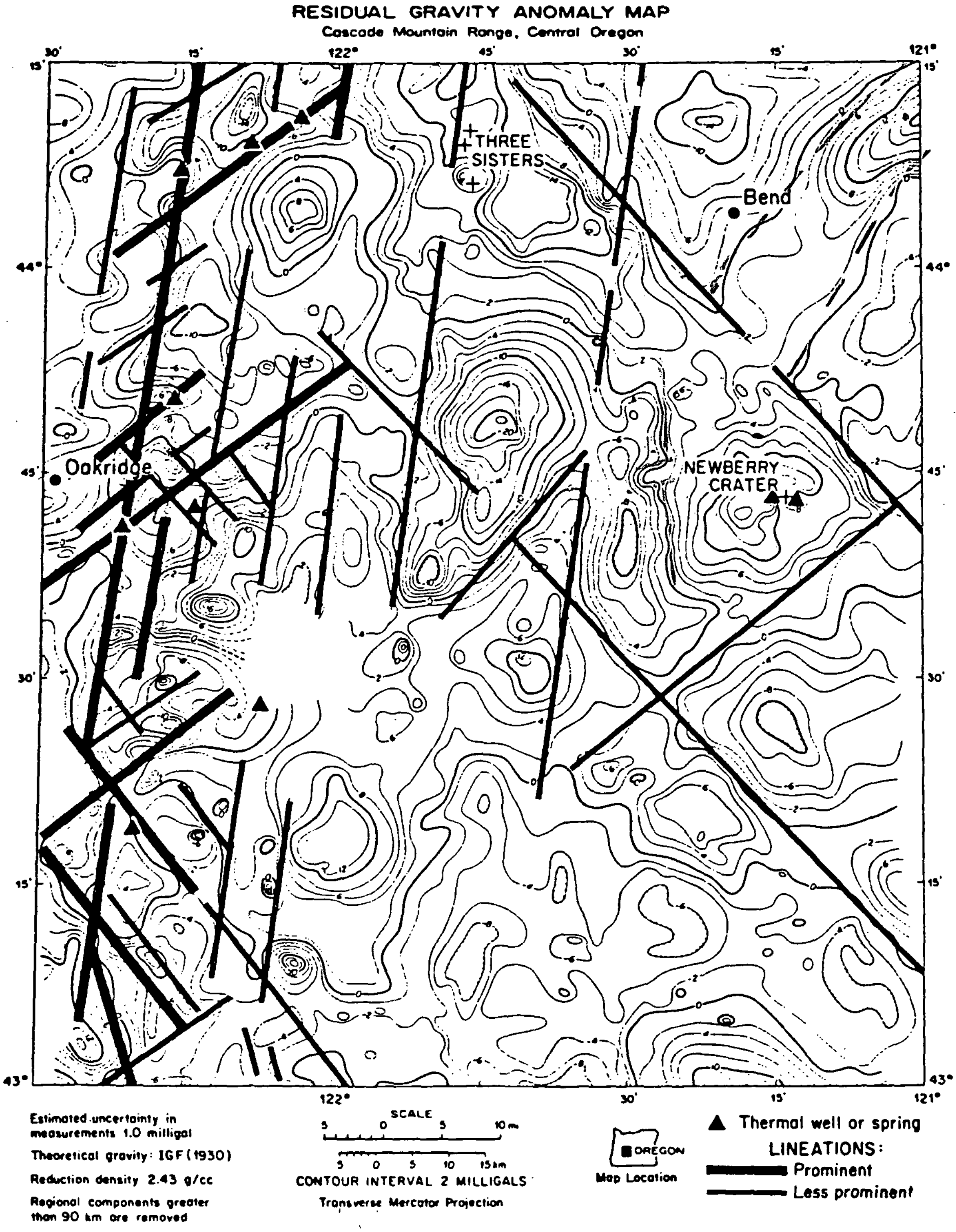
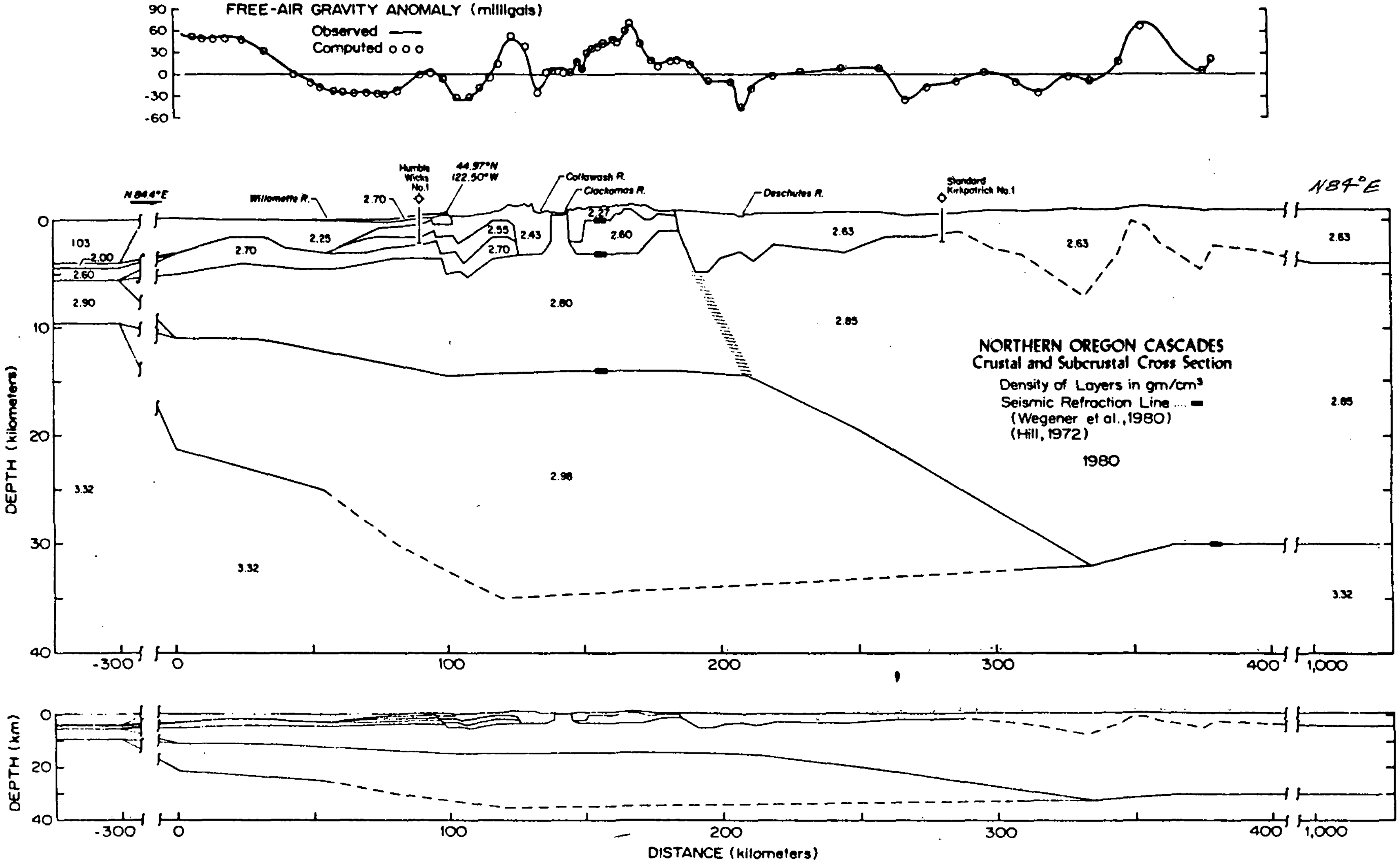

RESIDUAL GRAVITY ANOMALY MAP
Cascade Mountain Range, Central Oregon
30'
15'
122°
45'
30'
15'
121°
15'
44°
45'
30'
15'
43°
THREE SISTERS
Bend
Oakridge
NEWBERRY CRATER
Estimated uncertainty in measurements 1.0 milligal
Theoretical gravity: IGF (1930)
Reduction density 2.43 g/cc
Regional components greater than 90 km are removed
SCALE
5 0 5 10 mi
5 0 5 10 15 km
CONTOUR INTERVAL 2 MILLIGALS
Transverse Mercator Projection
OREGON
Map Location
▲ Thermal well or spring
LINEATIONS:
Prominent
Less prominent

Figure 18.

Figure 20.


FREE-AIR GRAVITY ANOMALY (milligals)
Observed ——
Computed o o o
90
60
30
0
-30
-60
N 84.4°E
Willamette R.
2.70
Humble Wicks No.1
44.97°N 122.50°W
Collawash R.
Clackamas R.
Deschutes R.
Standard Kirkpatrick No.1
N84°E
103
2.00
2.60
2.90
2.25
2.70
2.55
2.43
2.70
2.27
2.60
2.63
2.63
2.63
2.80
2.85
2.85
2.98
3.32
3.32
3.32
NORTHERN OREGON CASCADES
Crustal and Subcrustal Cross Section
Density of Layers in gm/cm³
Seismic Refraction Line .... ▬
(Wegener et al., 1980)
(Hill, 1972)
1980
DEPTH (kilometers)
0
10
20
30
40
-300
0
100
200
300
400
1,000
DEPTH (km)
0
20
40
-300
0
100
200
300
400
1,000
DISTANCE (kilometers)

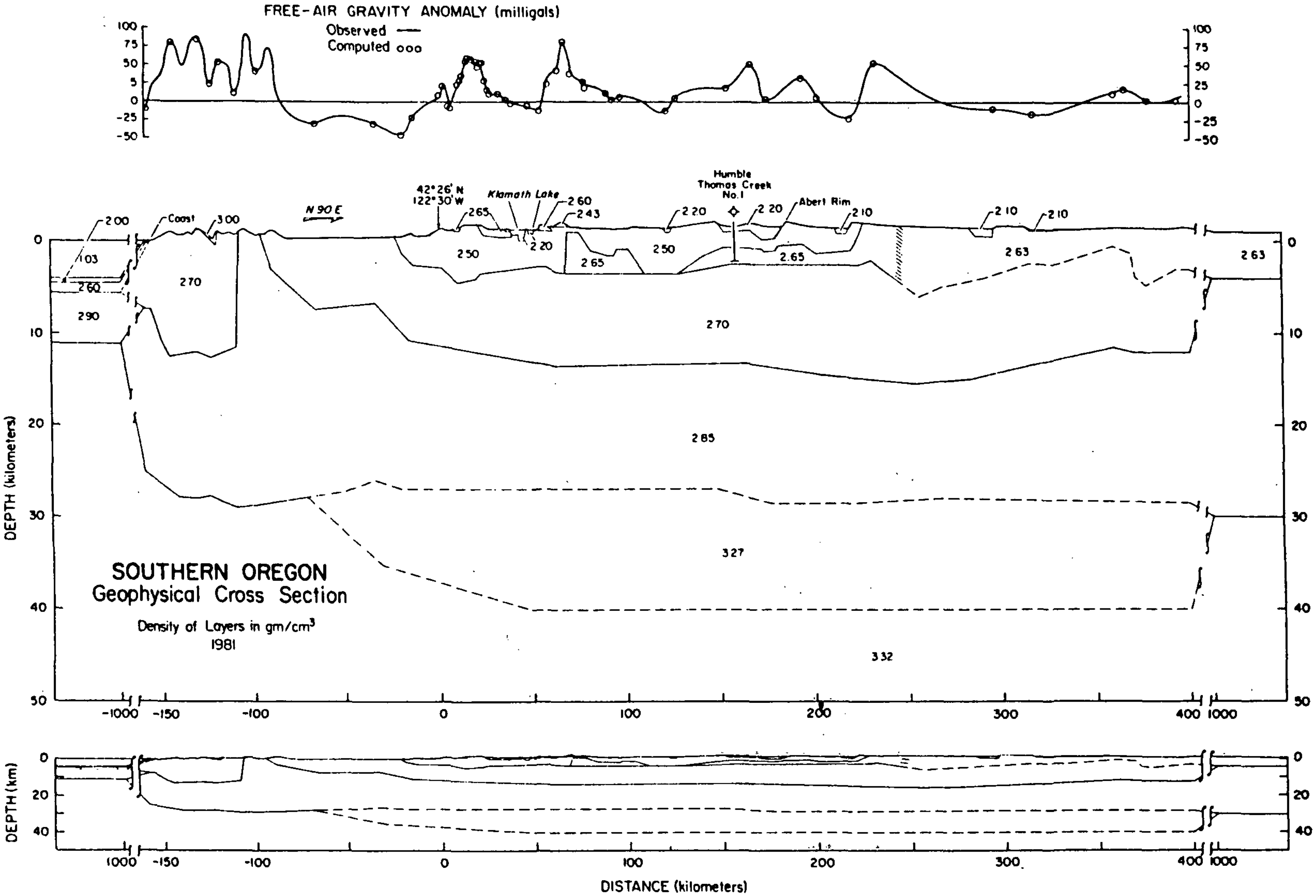
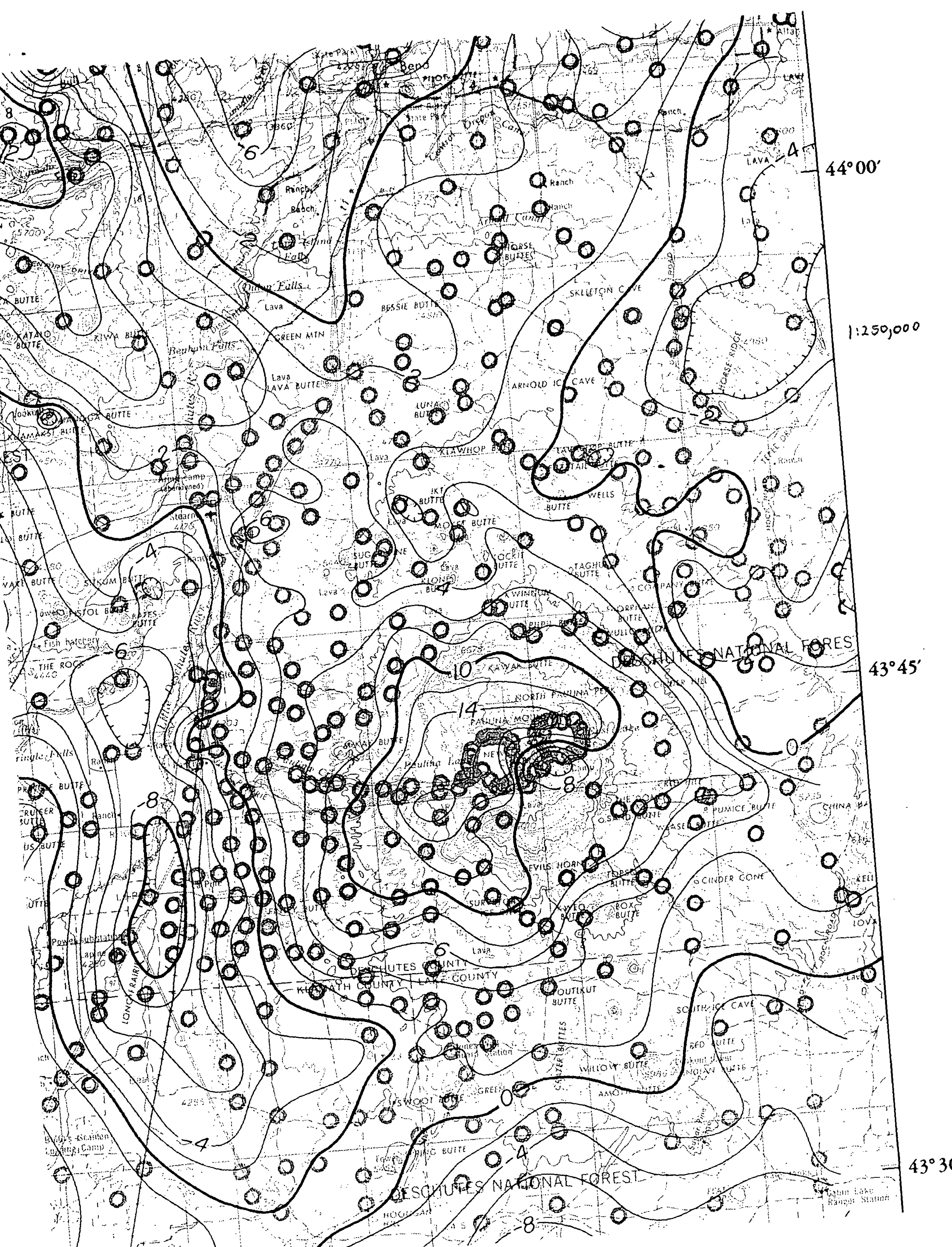
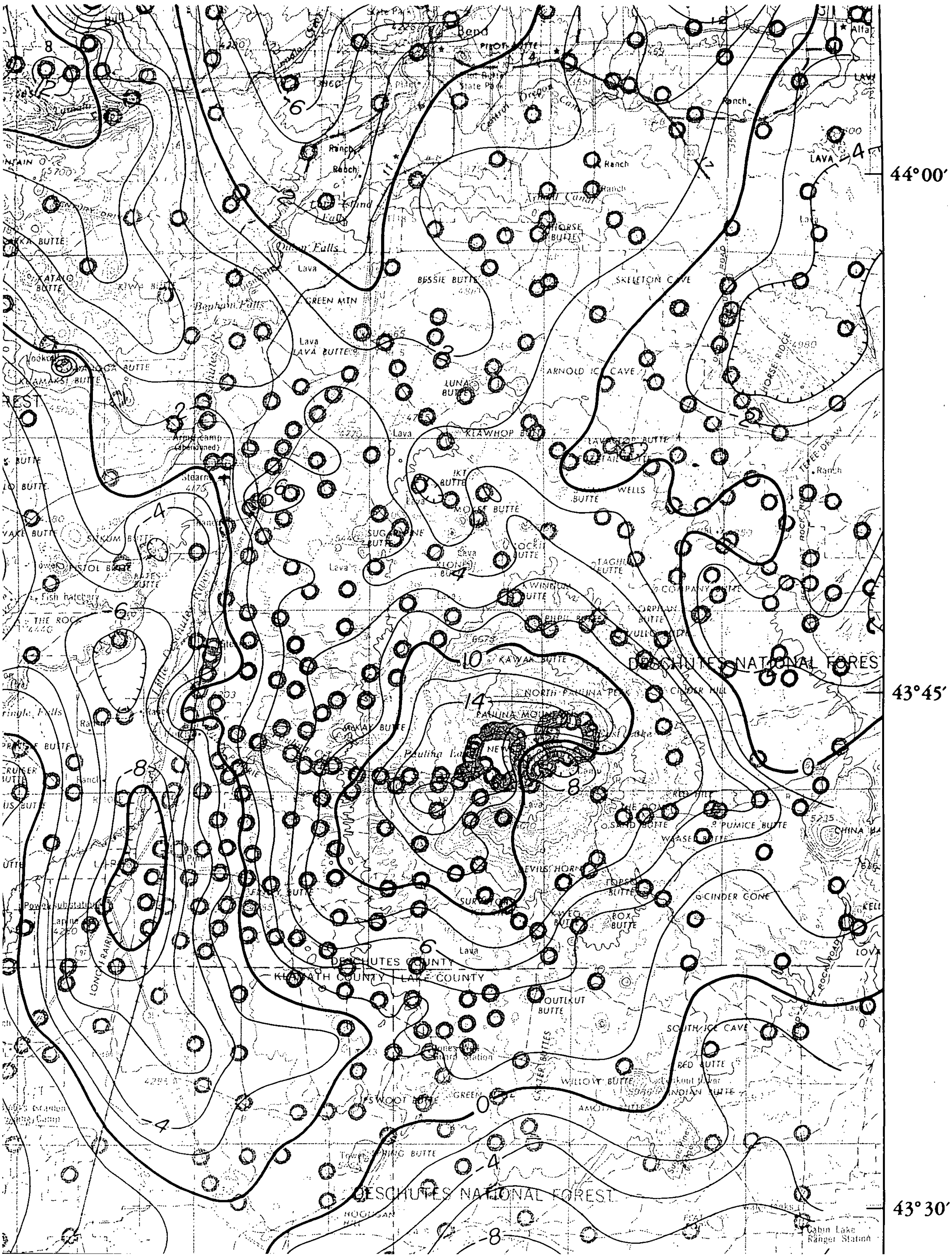

FREE-AIR GRAVITY ANOMALY (milligals)
Observed —
Computed ooo
100
75
50
25
0
-25
-50
42°26' N
122°30' W
Klamath Lake
Humble
Thomas Creek
No. 1
Abert Rim
N 90 E
Coast
2.00
3.00
2.65
2.60
2.43
2.20
2.20
2.20
2.10
2.10
2.10
1.03
2.60
2.90
2.70
2.50
2.50
2.65
2.65
2.63
2.63
2.70
2.85
3.27
3.32
SOUTHERN OREGON
Geophysical Cross Section
Density of Layers in gm/cm³
1981
DEPTH (kilometers)
0
10
20
30
40
50
-1000
-150
-100
0
100
200
300
400
1000
DEPTH (km)
0
20
40
DISTANCE (kilometers)

Figure 21.


Bend
Pilot Butte
State Park
Ranch
Arnold Canal
Horse Buttes
Skeleton Cave
Bessie Butte
Green Mtn
Lava Butte
Lava
Arnold Ice Cave
Horse Ridge
Luna Butte
Klawhop Butte
Wells
Kiwa Butte
Benham Falls
Dillon Falls
Lava Island Falls
Kataio Butte
Lookout
Klamaksi Butte
Stearns
Sugar Cone
Mokst Butte
Lava Rock Butte
Taghum Butte
Kweo Butte
Sitkum Butte
Pistol Butte
Bates Butte
Fish hatchery
The Rock
Pringle Falls
Spring Butte
Cruiser Butte
Kawak Butte
North Paulina Peak
Paulina Mountain
Paulina Lake
East Lake
Paulina Creek
Devils Horn
Pumice Butte
China Hat
Cinder Cone
Box Butte
Topso Butte
Surveyor
Lapine
Power substation
Deschutes County
Klamath County
Lake County
Outlkut Butte
South Ice Cave
Red Butte
Willow Butte
Indian Butte
Cabin Lake Ranger Station
Deschutes National Forest
Spring Butte
Long Prairie
Little Deschutes River
Deschutes River
44°00′
1:250,000
43°45′
43°30
4
2
0
-2
-4
-6
-8
6
8
10
14


44°00′
43°45′
43°30′
Bend
PILOT BUTTE
Central Oregon Canal
Arnold Canal
Lava Island Falls
Dillon Falls
Benham Falls
BESSIE BUTTE
GREEN MTN
LAVA BUTTE
SKELETON CAVE
HORSE BUTTES
HORSE RIDGE
ARNOLD ICE CAVE
LUNA BUTTE
KLAWHOP BUTTE
LAVA TOP BUTTE
IKT BUTTE
MOOSE BUTTE
WELLS BUTTE
SUGARPINE BUTTE
KLONE BUTTE
ROCKY BUTTE
TAGHUM BUTTE
COMPANY BUTTE
KWINUM BUTTE
KAWAK BUTTE
NORTH PAULINA PEAK
PAULINA MOUNTAINS
Paulina Lake
McKAY BUTTE
CINDER HILL
PUMICE BUTTE
CHINA HAT
DEVILS HORN
SURVEY BUTTE
BOX BUTTE
CINDER CONE
OUTLKUT BUTTE
SOUTH ICE CAVE
RED BUTTE
WILLOW BUTTE
INDIAN BUTTE
SWOOT BUTTE
HOOGAN HILL
Cabin Lake Ranger Station
DESCHUTES NATIONAL FOREST
DESCHUTES COUNTY
KLAMATH COUNTY
LAKE COUNTY
Army Camp (abandoned)
Pringle Falls
Fish hatchery
THE ROCK
PISTOL BUTTE
SITKUM BUTTE
KLAWAKSI BUTTE
Lookout
Power substation
La Pine
LONG PRAIRIE
Little Deschutes R
Deschutes R
Lava
Ranch
8
12
6
4
2
0
-2
-4
-6
-8
10
14

GEOTHERMAL RESOURCES COUNCIL
1983 ANNUAL MEETING

FIELD TRIP NO. 2

Medicine Lake Volcano, California
and
Newberry Volcano, Oregon

Saturday, 22 October - Monday, 24 October

Field Trip Leader: Eugene V. Ciancanelli

GEOTHERMAL RESOURCES COUNCIL
1983 ANNUAL MEETING

FIELD TRIP NO. 2

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GRC 1983 ANNUAL MEETING

FIELD TRIP #2

FIELD TRIP TO THE MEDICINE LAKE VOLCANO, CALIFORNIA AND NEWBERRY VOLCANO, OREGON

October 22-24, 1983

Medicine Lake volcano, California and Newberry volcano, Oregon are very similar large Quaternary bimodal shield volcanoes. Each volcano contains a caldera and both have been constructed during the last one million years. Considerable volcanism has also occurred during the last 2,000 years at each locality. Magma probably lies at relatively shallow depths beneath these volcanoes; offering large potential for the presence of geothermal resources. Most of the world's major geothermal fields and many hydrothermal ore deposits are associated with active or older volcanic centers of intermediate to silicic volcanism similar geologically to these two volcanoes.

Many researchers have contributed to an understanding of the petrology, structure and evolution of Medicine Lake and Newberry volcanoes. Excellent exposures, a wide diversity of well preserved volcanic features and ease of access provide the opportunity to observe a variety of volcanic features in a relatively brief time. The field trip will visit many of these volcanic features and type of deposits that are less conspicuous in other areas of geothermal resource and hydrothermal ore deposit exploration. Soil-mercury geochemical maps of both volcanoes will be available to compare the patterns of anomalous mercury with the geology in areas lacking obvious surface thermal manifestations or hydrothermal alteration.

Field trip participants are advised to bring a camera as both areas are very scenic.

ROAD LOG AND FIELD TRIP GUIDE TO MEDICINE LAKE VOLCANO, CALIFORNIA AND NEWBERRY VOLCANO, OREGON

October 22-24, 1983

Field Trip Leader:
EUGENE V. CIANCANELLI
CASCADIA EXPLORATION CORPORATION
3358 Apostol Road, Escondido, California 92025

GEOTHERMAL RESOURCES COUNCIL ANNUAL MEETING

Portions of the road log to Medicine Lake volcano modified after Donnelly-Nolan, J.M.; Ciancanelli, E.V.; Eichelberger, J.C.; Fink, J.H., and Heiken, G., 1981, Road log for field trip to Medicine Lake Highland: U.S. Geological Survey Circular 838, p. 141-149.

Portions of the road log to Newberry volcano modified after MacLeod, N.S.; Sherrod, D.; Chitwood, L.A., and McKee, E.H., 1981, Road log for Newberry volcano, Oregon: U.S. Geological Survey Circular 838, p. 93-103.

MEDICINE LAKE VOLCANO

MILES

0 Leave motel and head east on south 6th Street in Klamath Falls.

(3.1)*

3.1 At "Y" in road, keep right to avoid going toward Winnemucca. Continue south on Oregon Highway 39 toward Merrill.

The road passes through the southern part of the Klamath basin which has been a graben since at least the Pliocene. The oldest rocks exposed in the graben are Pliocene lacustrine and fluvial volcaniclastic sandstones, siltstones, diatomite and palagonite tuff with interbedded basalt flows and cinders known as the Yonna formation. The large hills and ridges within the Klamath basin contain exposures of Yonna formation rocks. The flat portions of the basin are underlain by Quaternary lacustrine sediments deposited in the large lake or lakes which have occupied the basin during Quaternary and possibly late Tertiary time. Upper and Lower Klamath Lakes and Tule Lake are the remnants of these large lakes. A summary of the geology of the Klamath basin is included with the papers that accompany this field trip guide.

(5.9)

9.0 The Klamath Hills are located to the west and southwest of Highway 39. The Klamath Hills are a northwest trending horst block within the Klamath graben. Virtually every large hill is a fault block bounded by northwest striking normal faults. Occassionally, northeast trending faults cross cut the northwest trending fault blocks. The Pliocene volcanic and sedimentary rocks of the Klamath Hills accumulated within lakes or on islands within a lake and along the margins of a lake basin. Rapid facies changes are a common characteristic of the Klamath basin rocks. In the Klamath Hills, individual rock units rapidly change lithology along strike. A summary of the geology of the Klamath Hills and the thermal area to the west is included with the papers that accompany this field trip guide.

(8.1)

17.1 The highway turns east at the town of Merrill. Pass through the town and continue east to Malone Road.

---

* interval milage in parentheses

MILES

(2.0)

19.1 Turn right on Malone Road and proceed south to State Line Road.

(1.9)

21.0 At State Line Road turn left and then immediately turn right at State Line Liquors and continue south toward the Fish and Wildlife Headquarters. Continue south along the fault scarp on the west side of Tule Lake.

(12.8)

33.8 Enter the north end of Lava Beds National Monument and turn right at the "T". The area to the east and south was the site of the Modoc War between the Modoc Indian Nation and the United States. Using the natural rock fortifications, 53 men and their families defended themselves against hundreds of soldiers during the winter and spring of 1872-1873. Waters (1981) has prepared a detailed summary of the significant role geology played in this war.

The road continues south through the Lava Beds Monument along the base of a north-south fault scarp known as Gillem's Bluff. The Pliocene lavas exposed in this fault scarp underlie the Quaternary Medicine Lake volcanic rocks. The fault scarp can be traced northward where these lavas appear to merge with the Yonna formation in the Klamath Basin. The road crosses the Devil's Homestead flow which is very young in appearance. The flow vented at Fleener Chimneys, a group of spatter cones located on the southward continuation of Gillem's Bluff fault scarp.

(8.4)

42.2 Turn right on the road to Mammoth Crater and Medicine Lake.

(2.6)

44.8 STOP 1. MAMMOTH CRATER

Mammoth Crater is a pit crater located at the summit of a broad low basaltic shield volcano. Mammoth Crater appears to be the source area for many of the basalt flows in the Lava Beds Monument. This relationship is very clearly evident on aerial photographs where flow structures on the lava flows and collapsed lava tubes show most flows vented in the vicinity of Mammoth Crater. The Mammoth Crater basalt flows are part of an outer ring of mafic lavas that surround Medicine Lake volcano.

From Mammoth Crater the road ascends the north flank of Medicine Lake volcano. The lower flank of the volcano is underlain by Anderson's older platy olivine andesite (Qopoa). At approximately 2 miles from Mammoth Crater the road enters the overlying platy andesite (Qpa) which forms the upper part of the volcano. The platy andesite and the older platy olivine andesite comprise two groups of andesite flows each having similar petrographic characteristics. The older platy olivine andesite lavas commonly contain olivine, pyroxene and plagioclase phenocrysts. The younger platy andesite lavas contain a few rare pyroxene and plagioclase phenocrysts. Other petrographic characteristics aid in distinguishing these two lava groups. The geology of Medicine Lake volcano is summarized in a paper which accompanies this field trip guide and in Anderson (1941).

STOP 2. TREE MOLDS

A series of basalt spatter cones and a small basalt flow were vented along a north trending fault. There are numerous tree molds in the area immediately north of the northern most spatter cone. The basalt was very fluid flowing around the trees and preserving them as molds.

(8.1)

52.9 Turn right on good graded road.

MILES

(1.0)

53.9 STOP 3. CRACKS, FAULTED CINDER CONE AND CRATER GLASS FLOW

Cracks

Hike northwest of the road about 200 feet to a narrow dirt road. Turn left and walk about half a mile into an area of recent cracks. These cracks are part of a broad belt of generally north to northeast trending fissures within the western half of the caldera and its immediate vicinity. The cracks are probably related to tumescence of the volcano during the most recent episode of silicic volcanism 1,300 to 200 years B.P. Open fractures such as these would be highly permeable zones for the movement of hydrothermal fluids within the volcano. Repeated cycles of volcanism with accompanying tumescence would produce many such fractures. Some of the exposed cracks are 30 to 40 feet deep. Most cracks appear to be open tension fractures, although some display offsets with the west side down.

Faulted Cinder Cone

Continue to follow the dirt road toward the northwest to a pumice-covered cinder cone. Climb up the cinder cone and observe the west facing fault scarp consisting of red cinders bare of pumice. The fault movement followed deposition of the white pumice which covers the red cinder cone everywhere except on the fault scarp. The white rhyolitic pumice was probably vented from the Crater Glass Flow vent prior to the eruption of the rhyolitic glass. The Crater Glass Flow appears to be contemporaneous with Glass Mountain and Little Glass Mountain, both of whose pumice fall deposits have been ^{14}C dated at 1065-1360 years B.P. The fault trends north-northeast and at each end it is covered by a recent rhyolite flow.

Crater Glass Flow

Proceed north along the fault to Crater Glass Flow, a very recent rhyolitic glass flow which is not covered by the 1065-1360 year old pumice fall deposits that mantle the upper flanks of Medicine Lake volcano. The eruptions of rhyolitic glass at Crater Glass Flow, Glass Mountain and Little Glass Mountain were preceeded by the eruption of pumice fall deposits. This is a common sequence observed at many other recent rhyolitic eruptions at other volcanoes. The surface of Crater Glass Flow is a highly convoluted assemblage of obsidian, rhyolitic pumice and breccia that has been complexly folded and fractured as the viscous rhyolitic lava flowed outward from a central vent. Fink (1983) discussed the surface structures at Little Glass Mountain on Medicine Lake volcano.

Return to the bus, turn around and head back to the Medicine Lake Road.

(1.0)

54.9 Turn right on Medicine Lake road and drive south to the caldera rim.

(0.3)

55.2 STOP 4. OVERVIEW OF MEDICINE LAKE CALDERA

This stop is on the north rim of the caldera. Mt. Hoffman, a young rhyodacite flow, is approximately 2 1/2 miles to the east. Glass Mountain, a recent rhyolitic glass flow, is 6 miles east-southeast on the caldera's east rim. The Medicine Lake dacite flow is the glassy flow with very few scattered trees on its surface immediately to the south. The Medicine Lake dacite flow rests directly on glacial morraine derived from the north rim of the caldera. Glacial striations, a common feature on the platy andesite outcrops around the caldera rim, show glacial movement from the caldera rim into the caldera and down the outer flanks of the volcano. Medicine Lake lies beyond the Medicine Lake dacite flow and is in the center of the caldera. The mountain south of Medicine Lake is Medicine Mountain and is located along the south rim of the caldera. The caldera rim is a constructional feature formed when andesite, rhyolite and basalt were vented along the

MILES

caldera ring fracture following the initial phase of caldera collapse. The west rim of the caldera lies along the basalt cinder cone of Little Mt. Hoffman.

Return to the bus and follow the road south into the caldera, passing the *Medicine Lake dacite flow. The floor of the caldera is glacial morraine resting* on platy andesite.

(2.1)

57.3 At the Ranger Station turn left at the "T" intersection and go east along the north side of Medicine Lake.

(1.0)

58.3 STOP 5. MEDICINE LAKE CAMPGROUND

This is a rest stop and lunch break. After lunch continue east and then south around the east end of Medicine Lake. The basalt flows along the north and east sides of Medicine Lake are a coarsely porphyritic basalt named "Lake basalt" by Anderson. The Lake basalt was vented on the east rim of the caldera and flowed westward into the caldera. Petrographically identical basalt flows, also vented on the east caldera rim, flowed eastward down the flank of Medicine Lake volcano (These flows were not mapped by Anderson, but are shown as Group 3 basalt in Figure 2 of the paper titled "Geology of Medicine Lake Volcano" which accompanies this report).

(3.3)

61.6 Proceed south to the road junction and turn left.

(0.5)

62.1 At the next main road intersection turn left.

(3.0)

65.1 Proceed for approximately two miles to the first main road junction to Arnica Sink. Take the right fork and proceed for approximately one mile to the second main road junction.

(1.5)

66.6 Turn left toward Glass Mountain and proceed for approximately 1.5 miles and pause for a view. The dome of Glass Mountain (the vent for the Glass Mountain rhyolitic obsidian flow) is to the northeast. A series of ^{14}C dates for the Glass Mountain flow range from 90 ± 200 to 390 ± 200 years B.P. The Mt. Hoffman rhyodacite dome to the northwest is the highest point on Medicine Lake volcano. Directly north of our present location is a bare spot on the ridge along the north edge of the glass flow. The bare spot, known as "the Hot Spot", is a fumarole where steam vapor is emitted and soil temperatures of 89°C (192°F) occur within 20 centimeters of the surface.

(2.0)

68.6 STOP 6. GLASS MOUNTAIN RHYOLITE FLOW

Continue east along the south edge of the glass flow for approximately 0.5 mile to a small parking space at the edge of the glass flow on the left. Walk a short distance back up the road to where a small bulldozer road goes up onto the glass flow. We will proceed out onto the glass flow to observe structures in the glass flow and various textural phases of the obsidian, rhyolitic pumice and rhyolite. CAUTION: OBSIDIAN IS VERY SHARP AND GLASS SPLINTERS FLY IN ALL DIRECTIONS WHEN IT IS STRUCK WITH A HAMMER.

MILES

(2.0)

70.6 Return to the road intersection at mileage 66.6 and turn left, proceeding south. The road crosses the Lake basalt flow and then Lyon Peak rhyodacite.

(1.4)

72.0 The large crater on the right (west) side of the road is an explosion crater and one of a series of phreatic eruptions that occurred along a northeast trending fault that extends 2.3 miles southwestward from Lyon Peak.

(0.1)

72.1 Turn right at main road intersection and proceed west.

(2.3)

74.4 Main road intersection (at mileage 62.1) proceed straight ahead on left fork to the west.

(0.5)

74.9 Main road intersection (at mileage 61.6) turn right and return to Klamath Falls by way of Lava Beds National Monument.

SECOND DAY

0 Leave motel and travel to Medicine Lake by the same route as the first day. Proceed to the road junction south of Medicine Lake.

(59.6)

59.6 Road junction south of Medicine Lake (mileage 61.6 on the previous day) turn right to paved road.

(0.4)

60.0 At paved road turn left and proceed south. The outcrops immediately south of the road junction are excellent examples of platy andesite from the lower flanks of Medicine Mountain. The road passes over the caldera's south rim and proceeds down the volcano's south flank.

(5.0)

65.0 STOP 7. GIANT CRATER LAVA FLOW

The first appearance of young pahoehoe basalt on the right side of the road is the Giant Crater Lava Flow, one of the largest and youngest basalt flows on the Medicine Lake volcano. Several large craters at the north end of the Giant Crater Lava flows produced an enormous volume of very fluid basalt which flowed for many miles due south. The flows exhibit many well preserved structures including: pahoehoe surfaces, lava toes, spatter cones, sag structures, and lava tubes. One lava tube has been traced for a length of 15.7 miles.

At the north end of the Giant Crater Lava Flow, turn right (west) and proceed to Grasshopper Flat. There are four main road intersections; at the first two bear left, at the third bear right, and at the fourth bear left.

(6.0)

71.0 Cross Grasshopper Flat, a large grassy field, to the main road intersection and turn right.

MILES

(2.2)

73.2 Travel north along the east edge of the Paint Pot basalt flow to the road intersection into Paint Pot Crater and turn left.

(0.2)

73.4 STOP 8. PAINT POT CRATER

Paint Pot Crater is a very young basalt cinder cone and lava flow. Shortly after the eruption of the cinder cone, the red cinders were covered with white rhyolitic pumice from Little Glass Mountain (1300 ± 135 years B.P.). Subsequent quarrying of the cinders exposed the spectacular color contrasts of Paint Pot Crater.

(0.2)

73.6 Return to main road intersection and turn left.

(1.6)

75.2 Travel north between Pumice Stone Mountain, a pumice covered cinder cone on the west, and Little Glass Mountain, a rhyolitic glass flow on the east. At the main road intersection turn right and drive along the north edge of Little Glass Mountain.

(1.0)

76.2 STOP 9. LITTLE GLASS MOUNTAIN

The north flow front of Little Glass Mountain is a steep rampart typical of the edges of viscous rhyolite lavas. Little Glass Mountain overlies a layer of pumice tephra (1300 ± 135 years B.P.) erupted from beneath the area now overlain by the glass flow (Heiken, 1978). Three different units make up the flow: (1) dense black obsidian, (2) brown to greenish gray coarsely vesicular pumice, and (3) whitish-gray finely vesicular pumice. Proceeding upward in the flow the apparent stratigraphic sequence is: tephra, coarsely vesicular pumice, obsidian, and finely vesicular pumice. At the base of the glass flow above the tephra layer and on the top surface of the flow are breccias comprised of the three units which make up the flow. On the top surface of the flow the obsidian and pumice can be seen to have been fractured and folded during flow (Fink, 1982).

Return to the bus and turn around back to the main road intersection.

(1.0)

77.2 At main road intersection turn right and follow pavement down the northwest flank of the volcano. The upper 1/4 of the volcano in this area is platy andesite and the lower 3/4 of the volcano is older platy olivine andesite. The andesite tuff, a thin ash flow unit, is exposed at many locations on the northwest quadrant of the volcano. Proceed north on paved road past cattle guard.

(9.7)

86.9 Turn right on next good dirt road north of cattle guard.

(0.9)

87.8 Follow road east and then south at junction and park at base of small ledge.

STOP 10. ANDESITE TUFF

Older platy olivine andesite is overlain by andesite tuff which probably vented from the caldera and flowed down the northwest flank of the volcano. Patches of andesite tuff are found at many locations on the volcano's northwest flank. All andesite tuff outcrops are relatively thin and generally only a few feet thick with a maximum thickness of about 20 feet. The tuff is nonwelded to only slightly welded. There are two color variations of the tuff; an unoxidized

MILES

buff-colored matrix with dark gray pumice fragments, and the more common reddish to reddish brown colored oxidized matrix.

Approximately 5 miles south of this stop near Dock Well the andesite tuff flowed across older platy olivine andesite and around two older rhyolite domes as the ash flow proceeded down the volcano's flank.

(0.9)

88.7 Turn around and proceed to the paved road. Turn right and follow paved road to Macdoel. At highway 97 proceed north to Klamath Falls and then north to Bend, Oregon. Highway 97 traverses the north half of the Klamath graben and many fault scarps along the east side of the graben will be visible in the quarries along the east side of Upper Klamath Lake.

NEWBERRY VOLCANO

THIRD DAY

MILES

0 Junction Highways 97 and 20 in Bend, Oregon head south on Highway 97.

(0.7)

0.7 High-alumina diktytaxitic olivine basalts exposed in the railroad underpass and in exposures along the highway for the next 11 miles to the south are typical of the lower flank flows of Newberry volcano. The flows are offset by northwest trending flows that extend down the northern flank of Newberry volcano into the Bend area. MacLeod et al. (1981) provides an analysis for a flank basalt flow in their Table #1 (a copy of this paper accompanies the field trip notes).

(3.2)

3.9 Road 1821 leads eastward to a series of lava tubes (Boyd Cave, 9 miles; Skeleton Cave, 12 miles; Wind Cave, 13 miles; and Arnold Ice Cave, 13 miles). Greeley (1971) describes each of these caves and several others in the Bend area.

(2.8)

6.7 Ash-flow tuff is exposed on the east side of Highway 97 near the draw. Ash-flow deposits are widespread around the Bend area and were derived from the Cascade Range to the west. Outcrops and float near the railroad west of Highway 97 show a wide range in pumice composition.

(3.3)

10.0 Cinders in the roadcut are from a tephra plume that extends northeast from Lava Butte. Charcoal from base of the cinders at this locality yielded ^{14}C age of 6,160 ± 65 years (Chitwood et al., 1977).

(0.7)

10.7 The northwest trending fault exposed on the east side of the highway offsets diktytaxitic olivine basalt. Note young "Gas Line" basaltic-andesite flow south of fault (^{14}C age 5,800 ± to 6,160 ± 65 years).

(0.5)

11.2 Turn right (west) to Lava Lands and drive across Lava Butte flow to the top of Lava Butte.

(1.8)

13.0 STOP 11. LAVA BUTTE

At the top of Lava Butte the basaltic-andesite flow that emerges from the south side of the butte extends northward for more than 5 miles and westward 3 miles to the Deschutes River. MacLeod et al. (1981) provides an analysis for the Lava Butte basaltic-andesite flow. The Lava Butte flow is one of many flows on the flanks of Newberry volcano that have radiocarbon ages of about 6,100 years. Several of these can be seen from this stop. The north and northwest flank of Newberry volcano is formed (at least at the surface) of basalt and basaltic andesite flows, vent areas and cinder cones, most of which are younger than the ash-flow units which will be observed at later stops. To the southeast, the north rim of Newberry caldera can be seen. To the west, a panorama of the Cascade Range includes from north to south, Mt. Jefferson, The Three Sisters, Broken Top, and Bachelor Butte. South of Lava Butte Pleistocene (and Pliocene?) lacustrine and fluvial sediments of the La Pine basin lie between Newberry volcano and the Cascade Range. Standing at Lava Butte, you are in the extreme northwest corner of the Basin and Range physiographic province in a subprovince known as the High Lava Plains. To the north are the Blue Mountains and Deschutes-Umatilla Plateau provinces and to the west the Cascade province.

MILES

Return to Highway 97.

(1.8)

14.8 Turn right (south) on Highway 97.

(1.2)

16.0 Road to east leads to Lava River Caves State Park which is open to the public. Lanterns can be rented to tour the mile long lava tube (Greeley, 1971).

(2.4)

18.4 Sun River Junction - the road east goes by Camp Abbot Cinder pit (3/4 mile) to Lava Cast Forest (9 1/2 miles). The cinder pit contains brilliant blue, green, gold, and red cinders. The Lava Cast Forest flow (^{14}C ages 6,380 ± 210 years) contains numerous well developed tree casts. A mile-long paved trail leads past many casts. Other young flows accessible by this road include Forest Road (5,960 ± 100 years), Mokst Butte, and Lava Cascade (5,800 ± 100 years).

(2.4)

20.8 Fall River Junction - road east leads to Sugarpine Butte flow (^{14}C age 5,870 ± 100 years).

(6.1)

26.9 Turn left (east) on Paulina Lake Road (U.S. Forest Service road 2129). The road crosses alluvial sediments covered with Mazama ash from the eruption of Crater Lake.

(3.0)

29.9 Outcrops of Newberry lava flows near the road. Farther along the road these flows are locally buried by lapilli tuffs.

(3.7)

33.6 Forest Service road 2045 provides access to three rhyolite domes on the volcano's west flank at McKay Butte (K-Ar age 0.6 ± 0.1 m.y.).

(2.9)

36.5 Lapilli tuff, exposed in a large scree-covered slope on the north side of the road, is one of the most widespread tephra units on Newberry volcano. The unit is rarely exposed but lapilli are distinctive so that it can be recognized in float. The lapilli tuff is deeply eroded but locally exceeds 200 feet thick, and the original volume was probably 5 to 10 cubic miles. The large volume permits speculation that eruption of this unit may have been accompanied by caldera collapse.

(1.0)

37.5 Contact of lapilli tuff and cinder cones. These vents probably fed flows exposed farther down the road that underlie the lapilli tuff. The cinder cones are buried on their east (caldera) sides by ash-flow tuffs.

(0.8)

38.3 Turn right (south) to U.S. Forest Service pit F-17, also known as "Mixture Butte".

(0.1)

38.4 STOP 12. MIXTURE BUTTE

Mixture Butte is a cinder cone with rhyolite and pumice inclusions. The pit is on the north side of a horseshoe-shaped cinder cone that is buried by ash-flow

MILES

tuffs on its east (caldera) side. Rhyolite and pumice, as well as basalt and andesite, occur as inclusions in the cinders and bombs as accidental fragments in the deposit. Some inclusions have been fused and have flowed. The pumice, blocks as large as 2 feet wide, commonly shows bands of different color and probably composition. A mile-long rhyolite dome crops out about 1 mile to the southwest, contains phenocrysts similar to those in the pumice and rhyolite inclusions and may extend at depth beneath the cinder cone. Possibly the pumice is derived from a buried pumice ring associated with the dome (this would be similar to the pumice tephra seen earlier near Little Glass Mountain at Medicine Lake volcano). Many cinder cones and flows on the upper flank of the volcano contain rhyolite inclusions. Rhyolite domes and flows crop out in many places and may be much more extensive at depth. Return to Paulina Lake road.

(0.1)

38.5 Turn right (east) on Paulina Lake road.

(1.6)

40.1 Turn left (north) into Paulina Falls parking lot.

(0.1)

40.2 STOP 13. PAULINA FALLS

Paulina Creek drains Paulina Lake less than one half mile to the east. The indurated rocks that form the cliffs of the falls are agglutinated andesitic pyroclastic deposits formed of many thin to thick units. Similar rocks occur along the caldera wall for about 1.5 miles north of the creek. They grade down the creek into ash flows and represent very near vent deposits, perhaps from a ring fracture bordering the west side of the caldera. Most of the deposit is probably co-ignimbrite lag, many units being entirely fall, others stubby agglutinated pyroclastic flows. MacLeod et al. (1981) provides a chemical analysis for this deposit. The less indurated rocks below the cliffs are formed of poorly sorted and rudely bedded ash, lapilli, and blocks with abundant accidental lithic fragments. Some beds low in the section contain accretionary and mud-armored lapilli. The contact is gradational between the lower and upper units. Probably the eruptions first deposited relatively cold material, perhaps from phreatic eruptions, and temperatures increased to the point where all fragments were agglutinated at time of deposition. Return to Paulina Lake road.

(0.1)

40.3 Turn left (east) on Paulina Lake road.

(0.3)

40.6 Turn right (south) on road 2160 to Paulina Peak.

(1.9)

42.5 View northward of gently sloping upper west flank formed mostly of ash-flow tuffs. Note rhyolite domes at and near McKay Butte (N60°W at 5.5 miles).

(1.1)

43.6 View of cinder cones and long narrow Surveyor basalt flow (^{14}C age 6080 ± 100 years) on the volcano's south flank.

(1.3)

44.9 STOP 14. PAULINA PEAK

Before looking at the caldera, walk to peak for view southward. Note fault-bounded Walker Mountain (S 42° W, 35 miles). Faults of the Walker Rim zone extend to Newberry's lower south flank. Some of the older rocks, such as the reversely polarized dacite flows on Indian-Amota Butte (S 30° E, 11 miles), are offset several hundred feet by northeast-trending faults; faults that cut the nearby basalt flows have vertical offsets of less than 100 feet and the faults disappear upslope below younger flows. Other distant features include:

(1) Bald Mountain (S 12° W, 28 miles), a rhyolite dome on the south side of a poorly preserved 4 or 5 million year old caldera with widespread ash-flow tuffs that crop out from Fort Rock Valley east of it, to Walker Mountain.

(2) Cascade Range. From south to north on a clear day you can see Mount Shasta, Mount Scott, Crater Lake, Mount Thielson, Diamond Peak, The Three Sisters, and nearby Bachelor Butte and Broken Top, Mount Washington, Three Fingered Jack, Mount Jefferson, Mount Hood, and Mount Adams.

(3) Fort Rock Valley southeast of Newberry with numerous palagonite tuff rings, cones, and maars. Included in these are Fort Rock in the middle of the valley, and beyond it about 39 miles from here is Table Rock.

(4) To the east are China Hat (N 85° E, 11 miles) and East Butte next to it. They are 0.8 and 0.9 m.y. old rhyolite domes on the west end of the belt of age transgressive rhyolite vents. Note the 5 m.y. old rhyolites of the Glass Buttes dome complex on the skyline (S 80° E, 60 miles). The High Lava Plains, a broad zone of Miocene to Quaternary basalts in addition to rhyolite domes and flows, extends from Newberry to beyond Glass Butte.

Now walk to the north along and beyond the fence bordering the cliffs of Paulina Peak to a viewpoint about 50 feet below the elevation of the parking lot. Please use caution in this area - the cliffs are 500 feet high. The generalized geologic map of the caldera (Figure 2, MacLeod et al. in the field trip guide) should be referred to for identifying features. From this location you can see the inner and outer (near pumice flats) walls of the south side of the caldera. The caldera wall rocks have been described by Higgins and Waters (1968) and Higgins (1973). The south wall near the Big Obsidian flow consists of platy rhyolite, basaltic andesite flows, scoria and cinder deposits, and an overlying obsidian flow. At the west end of the wall exposures is a thick sequence of near-vent pumice and ash deposits that have been fused near their contact with the obsidian flow. The north and east caldera walls contain rhyolite and basaltic andesite flows and pyroclastic rocks, as well as palagonite tuff; the east wall also contains near vent welded rhyolitic pumice deposits. Basaltic vents and flows occur on the north wall near Paulina Lake (Red Slide) and East Lake (East Lake fissure, Sheeps Rump), and a long fissure vent occurs near the top of the east wall. All of these vents and associated flows are pre-Mazama ash in age, except the East Lake Fissure. It is the southernmost vent of the northwest rift zone sequence of basalt flows and vents, about 6,100 years old, and contains abundant inclusions of obsidian, rhyolite, etc. (Higgins and Waters, 1970).

Young rhyolitic flows, pumice cones, rings, and other tephra deposits are widespread around East Lake. Hydration-rind dating by Friedman (1977) indicates that the East Lake obsidian flows are about 3,500 years old and that many of the other obsidian flows and pumice cones (Interlake flow, Game Hut flow, Central Pumice cone) are 4,500 to 6,700 years old.

The youngest period of volcanism was associated with the vent for the Big Obsidian flow. Eruptions began with a widespread pumice fall that now covers much of Newberry's east flank. Higgins (1969) obtained carbon from beneath the fall that has a ^{14}C age of 1,720 ± 250 years, and MacLeod et al. (1981) found carbon at another locality with an age of 1,550 ± 120 years. Isopachs of the pumice fall clearly show that it was erupted from at or very near the vent for the Big Obsidian flow (Sherrod and MacLeod, 1979). Later eruptions produced the Paulina Lake ash flow 1,300 to 1,400 years ago. The final event was the eruption of the Big Obsidian flow and the domal protrusion that marks its vent. Slight collapse occurred over a 1/2 mile wide area around the vent before the flow was erupted.

Paulina Peak dome extends about 3 miles southwest down the flank and is about 1 mile wide. It is marked by large rills parallel to its axis that formed

MILES

during expansion of the surface of the dome much as cracks form on french bread. The age of the dome is not yet known, but an obsidian flow that occurs on axis with the dome farther down the flank is 0.4 m.y. (E. H. McKee, unpub. data, 1979), and Paulina Peak dome may be similar in age. An analysis of rhyolite from the Paulina Peak dome is shown in Table 1 (MacLeod et al., 1981). Return to Paulina Lake Road.

(4.3)

49.2 Turn right (east) on Paulina Lake Road.

(0.4)

49.6 Roadcuts expose Mazama ash covered by a few inches of fine ash from Newberry eruptions. Holes dug through the Mazama ash show that it overlies sand and gravel deposits.

(0.5)

50.1 Road traverses south side of two rhyolite domes, overlain by Mazama ash and bordered on south by landslide deposits.

(0.3)

50.4 Roadcut exposes rudely bedded ash and pumice deposits, perhaps the remnant of a pumice ring associated with the rhyolite domes.

(0.1)

50.5 Western limit of Paulina Lake ash flow.

(0.2)

50.7 Paulina Lake ash flow. Concrete boxes on south side of road preserve collecting site for carbon in ash flow. Originally dated by Libby (1952) as 2,054 ± 230 ^{14}C years, subsequent dates indicate a younger age (1,270 ± 60 years, Pierson and others, 1966; and 1,390 ± 200, Meyer Reubin, *in* Friedman, 1977). The ash flow extends from the Big Obsidian flow to the shore of Paulina Lake. Ridges and furrows on the ash flow are apparently primary features, and their orientation suggests that the vent is located beneath the southern part of the Big Obsidian flow (Higgins, 1973). Although pumice is generally abundant, the ash flow in many places is composed almost entirely of ash. The absence of collapse and welding indicates the deposit had only a moderate temperature when emplaced, but sufficient for oxidation to give the deposit a slightly pinkish color. Continue eastward on road over ash flow.

(0.4)

51.1 Road on north leads to Little Crater Campground and interesting exposures along shoreline of palagonite tuff and silicified pumiceous, fossiliferous, lake deposits.

(0.4)

51.5 Turn right (south) into parking lot next to Big Obsidian flow.

STOP 15. BIG OBSIDIAN FLOW

Before walking to the flow, note that the pinkish Paulina Lake ash flow overlies weathered pumice deposits of a pumice ring on the east side of the parking lot. Lost Lake pumice ring is partly covered by the Big Obsidian flow, but its northern part can be seen from the trail ascending the obsidian flow. The trail provides interesting exposures of flow-banded obsidian, pumiceous obsidian, brown streaky obsidian that was formerly pumiceous before it collapsed, and various features indicating the flow behaved in both plastic and brittle manner during its emplacement. Laidley and McKay (1971) did extensive analytical work on the Big Obsidian flow and showed that it is essentially uniform in composition.

MILES

Their average of 66 chemical analyses is shown in Table 1 (MacLeod et al., 1981). Return to parking lot and to main road; note exposures of palagonite tuff of Little Crater north of road.

(0.1)

51.6 Continue eastward on paved road.

(0.4)

52.0 Dirt road to the right (south) leads to drill site of U.S. Geological Survey core hole. The hole drilled to a depth of 932 meters had a bottom hole temperature of 265°C (MacLeod and Sammel, 1982).

(0.5)

52.5 Game Hut obsidian flow is exposed on north side of road.

(0.5)

53.0 Pumiceous tephra deposits of the East Lake area. Roadcuts expose massive to rudely bedded pumice and ash with large accidental blocks, overlain by mud-armored pumice, accretionary lapilli, pumice, and ash beds. Bomb sags occur in the upper bedded part and indicate that the beds were probably wet and cohesive. A hole dug vertically through the deposits indicate that they are about 14 feet thick and overlie Mazama ash, which rests on obsidian. Tephra deposits, similar to the exposures here, occur over most of the eastern part of the caldera except where buried by younger units (East Lake obsidian flows, etc.). The vent or vents for the deposit are not known, and conceivably may lie in East Lake. The obsidian that underlies the deposit is part of an extensive obsidian flow that, mostly on the basis of topographic expression, probably extends to the south (inner) wall of the caldera, its vent apparently being an obsidian dome near the wall.

(1.0)

54.0 Turn left (north) into parking at the edge of East Lake.

(0.1)

54.1 Walk west along the south shore of East Lake to the headland.

STOP 16. HOT SPRINGS

The hot springs of East Lake occur along the south shore at the headland formed of palagonite tuff. Temperatures as high as 80°C have been measured, but the hot spring water is diluted by lake water. It is possible to feel these very high temperatures by placing your hand a few inches beneath the lake bottom gravel near the hot springs. If the lake level is low enough fumaroles with H_2S gas and sulfur deposits can be seen along the lake shore.

Leave the parking lot turn right (west) and return to Highway 97 on the Paulina Lake Road.

(16.2)

70.3 At Highway 97 turn right (north) and return to Bend. The bus will then continue to Portland.

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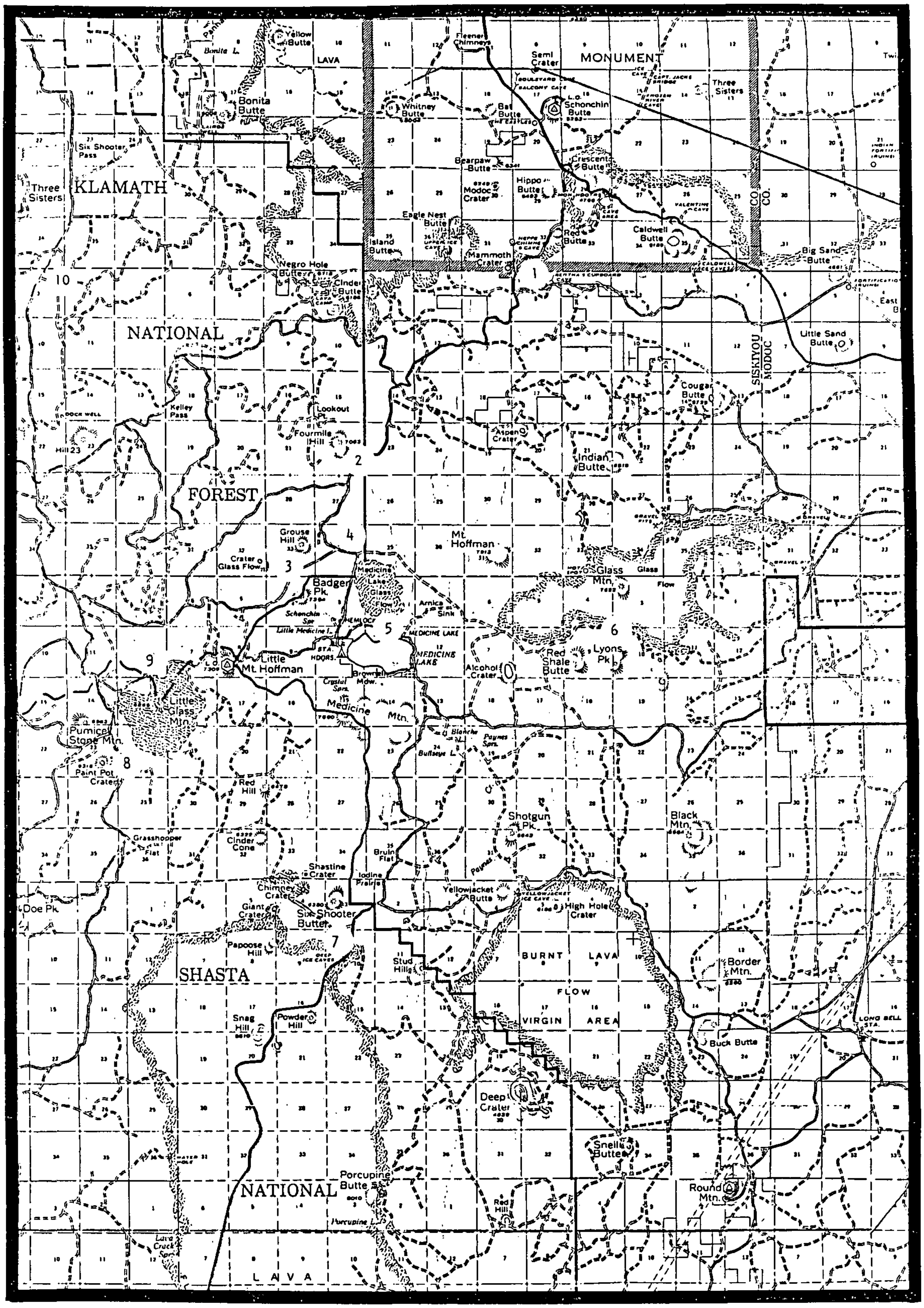


PLATE I LOCATION MAP FOR FIELD TRIP TO MEDICINE LAKE VOLCANO, CALIFORNIA

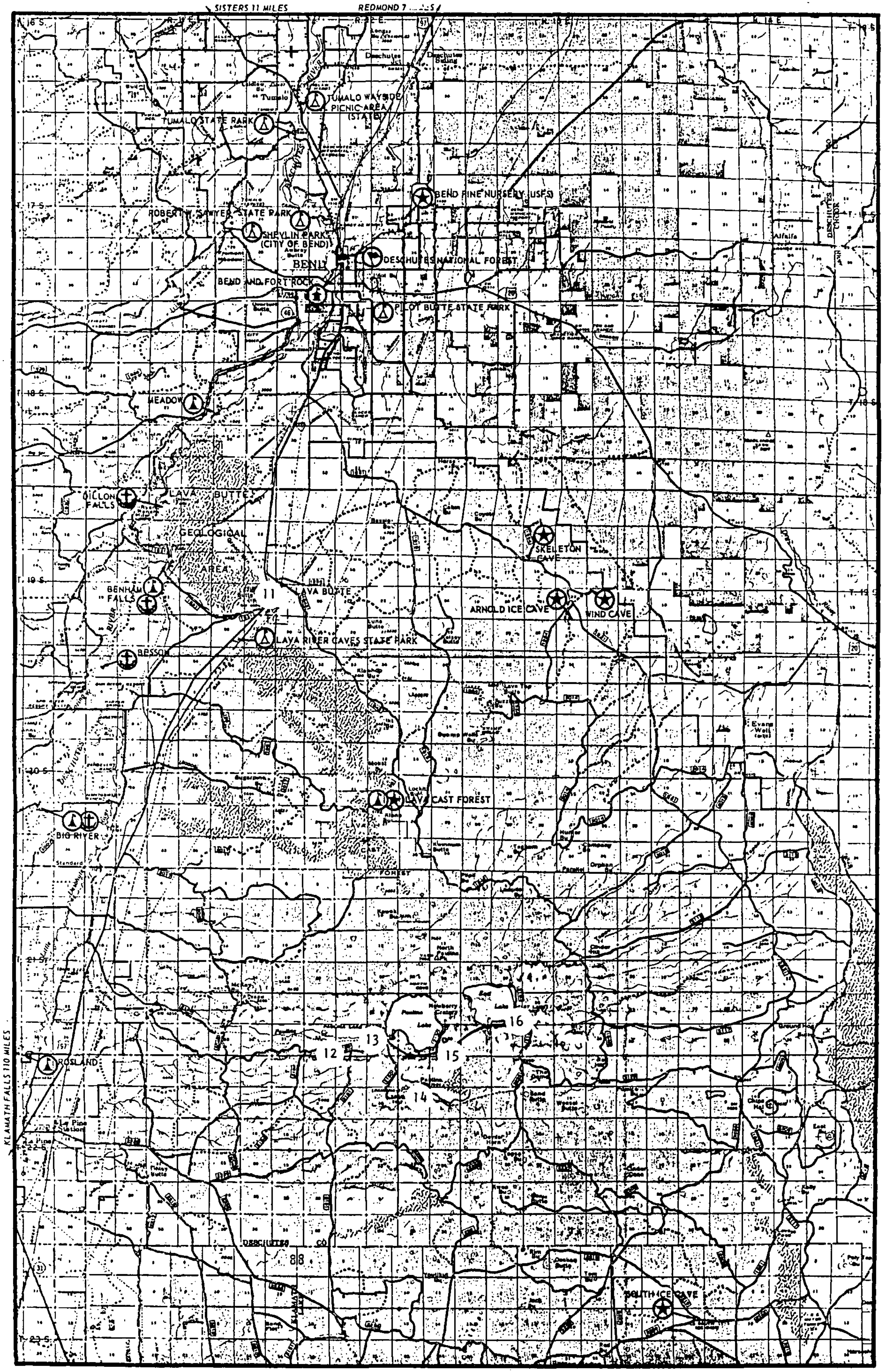
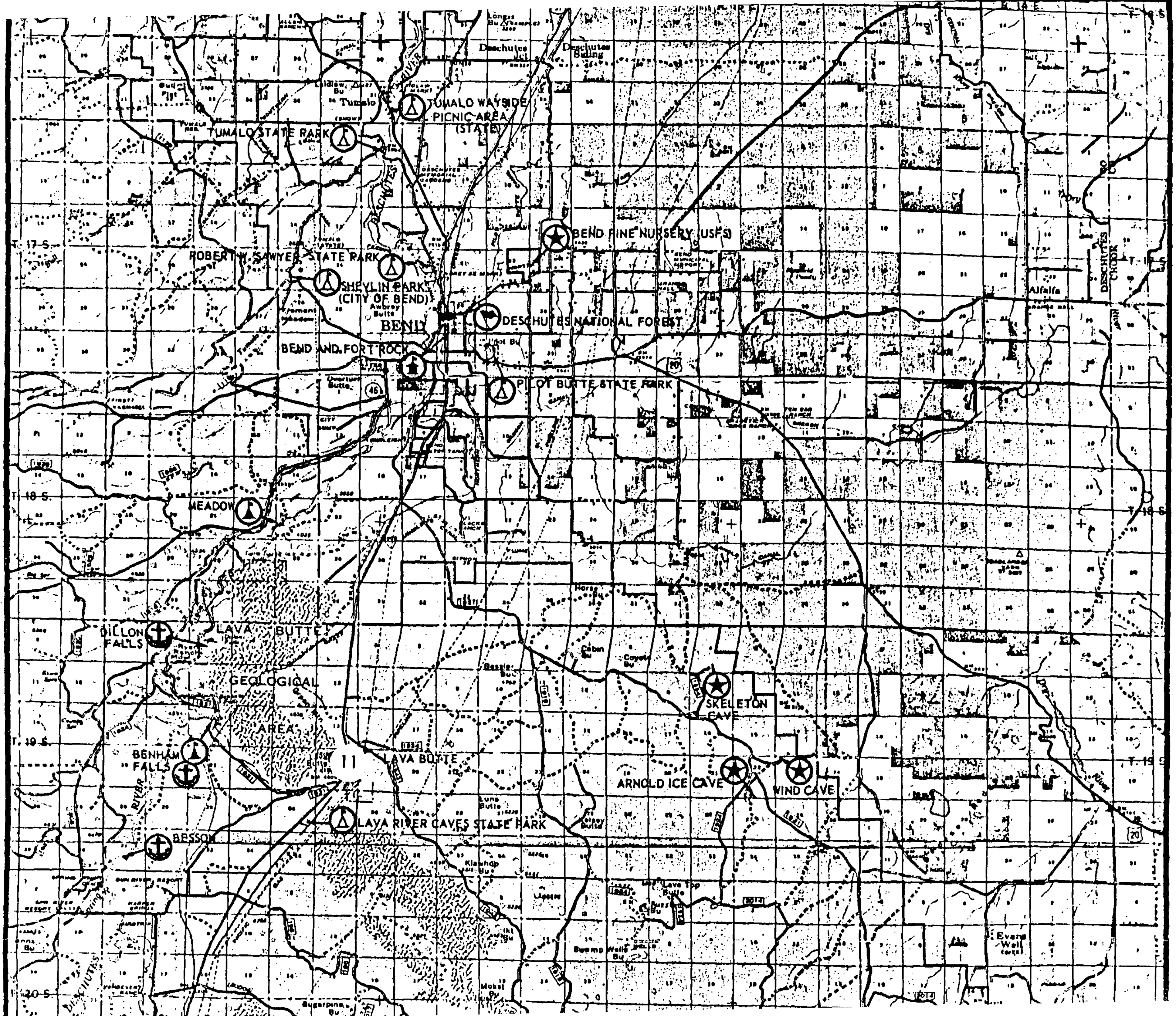
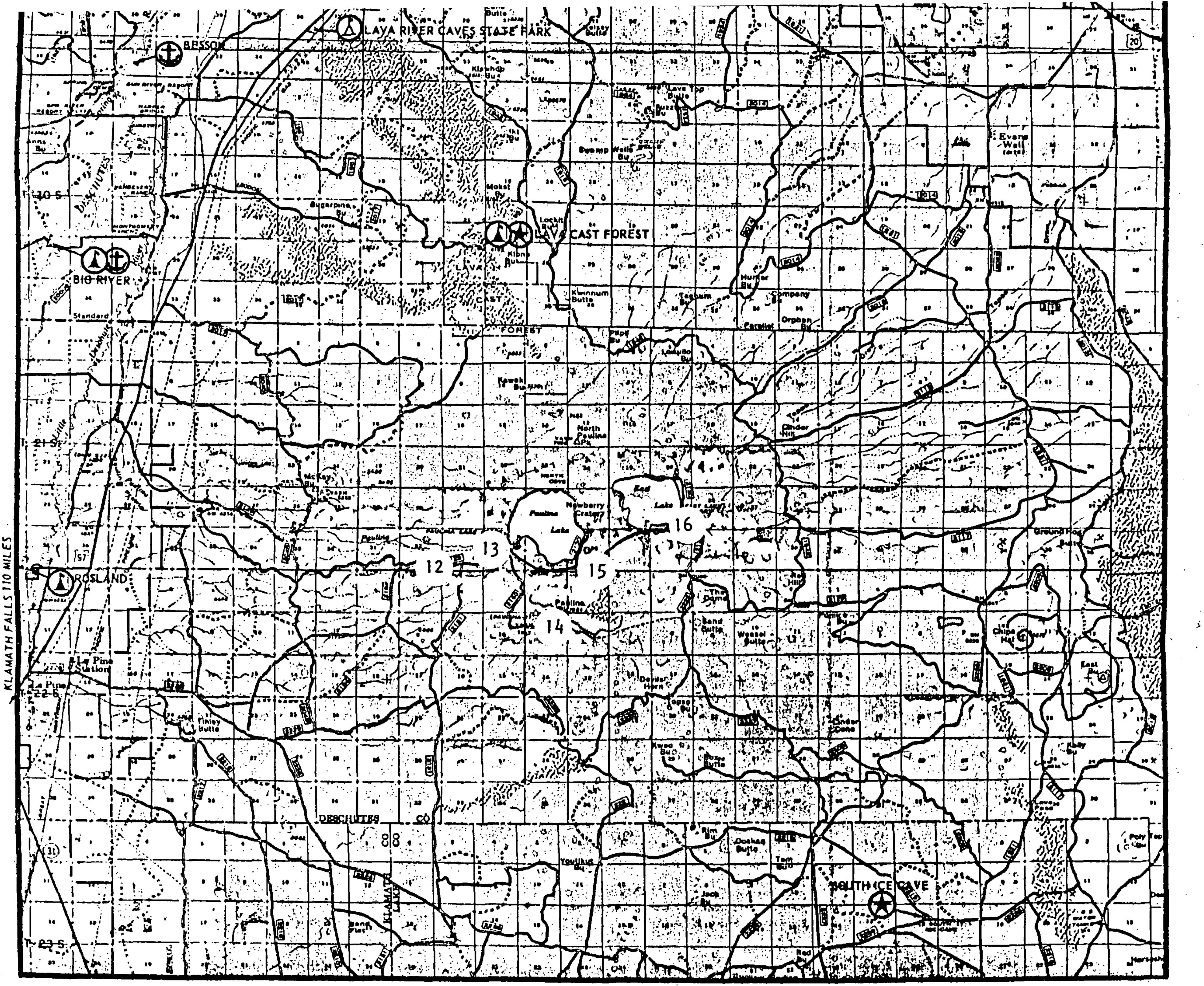


PLATE II LOCATION MAP FOR FIELD TRIP TO NEWBERRY VOLCANO, OREGON


T. 17 S.
T. 18 S.
T. 19 S.
T. 20 S.
Deschutes
Deschutes Siding
Tumalo
TUMALO WAYSIDE PICNIC AREA (STATE)
TUMALO STATE PARK
DESCHUTES RIVER
BEND PINE NURSERY (USFS)
ROBERT W. SAWYER STATE PARK
SHEVLIN PARK (CITY OF BEND)
Awbrey Butte
BEND
DESCHUTES NATIONAL FOREST
BEND AND FORT ROCK
Overturf Butte
46
PILOT BUTTE STATE PARK
20
Alfalfa
DESCHUTES CROOK
MEADOW
DILLON FALLS
LAVA BUTTE GEOLOGICAL AREA
Horse Bu
Cabin Bu
Coyote Bu
Bessie Bu
SKELETON CAVE
BENHAM FALLS
RIVER
11
LAVA BUTTE
ARNOLD ICE CAVE
WIND CAVE
LAVA RIVER CAVES STATE PARK
Luna Butte
BESSON
Klawhop Bu
Lava Top Butte
Swamp Wells Bu
Evans Well
Mokst Bu
Sugarpine Bu
DESCHUTES


LAVA RIVER CAVES STATE PARK
BENSON
LAVA CAST FOREST
LAVA CAST FOREST
BIG RIVER
Standard
ROSLAND
La Pine Station
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KLAMATH FALLS 110 MILES
T. 20 S.
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T. 22 S.
T. 23 S.
DESCHUTES
DESCHUTES CO
KLAMATH CO
Moksi Bu
Sugarpine Bu
Swamp Wells Bu
Lava Top Butte
Evans Well
Kwinnum Butte
Hunter Bu
Company Bu
Orphan Bu
Parallel
Kawak Bu
North Paulina Pk
McKay Bu
Cinder Hill
Newberry Crater
Paulina Lake
East Lake
Paulina Peak
The Dome
Sand Butte
Weasel Butte
Ground Hog Butte
Devils Horn
Finley Butte
Cinder Cone
Kelly Bu
East Bu
Jack Bu
Tom Bu
Red Bu
SOUTH ICE CAVE
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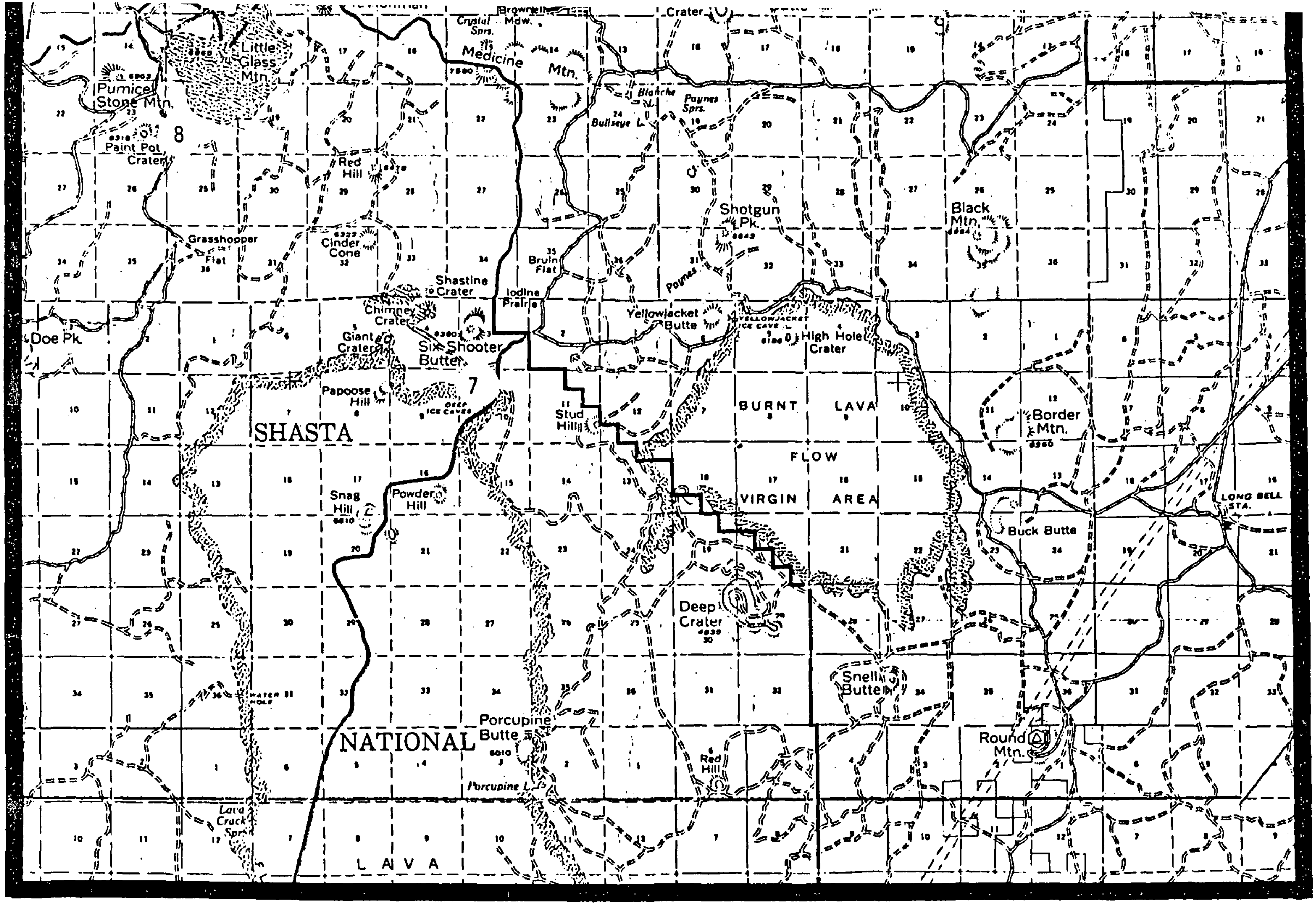
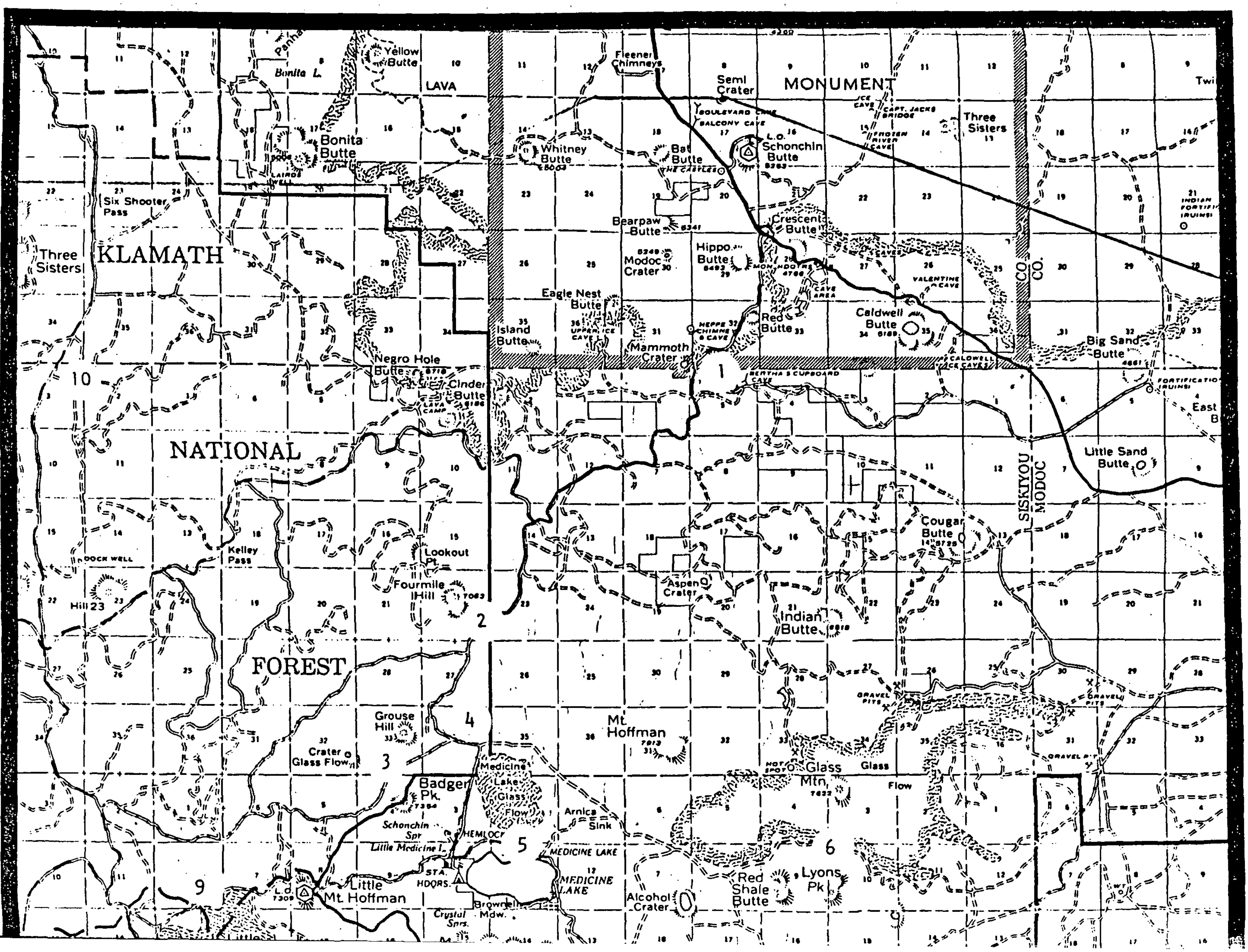


PLATE I LOCATION MAP FOR FIELD TRIP TO MEDICINE LAKE VOLCANO, CALIFORNIA



Yellow Butte
Bonita L.
LAVA
MONUMENT
Fleener Chimneys
Semi Crater
Boulevard Cave
Balcony Cave
Ice Cave
Capt. Jacks Bridge
Frozen River Cave
Three Sisters
Twi
Bonita Butte
Lairds Well
Whitney Butte 5004
Bat Butte
The Castles
L.O. Schonchin Butte 5253
Six Shooter Pass
Bearpaw Butte 5341
Crescent Butte
Three Sisters
KLAMATH
Modoc Crater 5249
Hippo Butte 5493
Mushpots Cave
Cave Area
Valentine Cave
CO.
CO.
Eagle Nest Butte
Upper Ice Cave
Island Butte
Mammoth Crater
Heppe Chimney & Cave
Red Butte
Caldwell Butte 5188
Big Sand Butte 4661
Indian Fortification (Ruins)
Negro Hole Butte 5710
Cinder Butte 5186
Lava Camp
Bertha's Cupboard Cave
Caldwell Ice Caves
Fortification (Ruins)
East B
10
1
NATIONAL
Little Sand Butte
SISKIYOU
MODOC
Cougar Butte 5725
Dock Well
Kelley Pass
Lookout Pt.
Fourmile Hill 7063
Aspen Crater
Hill 23
2
Indian Butte 6518
FOREST
Gravel Pits
Gravel Pits
Grouse Hill
4
Mt. Hoffman 7913
Crater Glass Flow
3
Medicine Lake Glass Flow
Gravel Pit
Hot Spot
Glass Mtn. 7622
Glass Flow
Badger Pk. 7394
Schonchin Spr
Hemlock
Arnica Sink
Little Medicine L.
5
Medicine Lake
6
Sta. Hdqrs.
Medicine Lake
Red Shale Butte
Lyons Pk
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L.O. 7309
Little Mt. Hoffman
Brownell Mdw.
Alcohol Crater
Crystal Sprs.

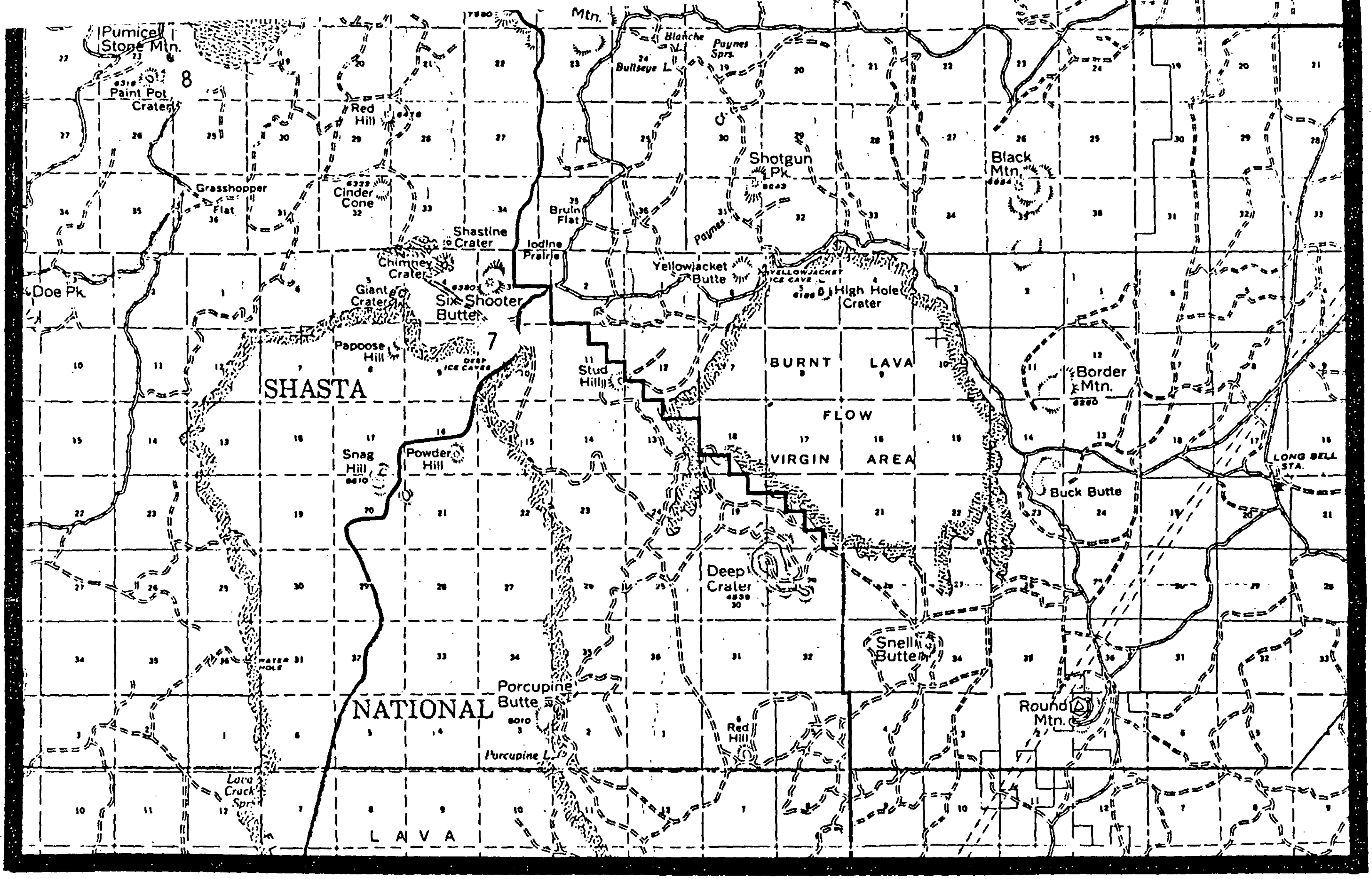

PLATE I LOCATION MAP FOR FIELD TRIP TO MEDICINE LAKE VOLCANO, CALIFORNIA

GEOLOGY OF NEWBERRY VOLCANO, OREGON

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ABSTRACT

Studies including geology, gravity, magnetics, soil-mercury geochemistry and a thermal gradient well have been completed at Newberry volcano. Silicic volcanism indicates magma was present beneath the caldera 1,350 years B.P. A thermal gradient well in the caldera has measured a temperature of 265°C. The shape of the gravity, magnetic and mercury anomalies and the distribution of rhyolite vents suggests the magma chamber is centered beneath the caldera and the volcano's southern and southeastern flanks.

INTRODUCTION

Newberry volcano is one of the largest Quaternary volcanoes in the conterminous United States (Figure 1). The volcano's petrology, high density of faulting, young age dates, and surface thermal manifestations are geologic features which it possesses in common with many of the world's high temperature geothermal reservoirs A 932 meter thermal gradient well in the center of Newberry caldera was completed by the U.S. Geological Survey (Sammel, 1981). Attainment of 265°C temperatures served to dramatically spark interest in the geothermal resource potential of Newberry volcano.

GEOLOGY OF NEWBERRY VOLCANO

Newberry volcano is one of a series of Quaternary bimodal volcanoes located to the east of the Cascade Range. Several of these bimodal volcanic centers are prime geothermal prospects. Newberry volcano also lies at the western end of the west-northwest trending Brothers Fault Zone. Cenozoic rhyolite domes along this fault zone become progressively younger to the west with the youngest located at Newberry volcano (Walker, 1974; MacLeod et al., 1975).

The oldest rocks exposed on Newberry volcano include ash-flow tuffs, pumice-fall tuffs, other types of pyroclastic deposits and mudflows. The composition of the individual ash-flow tuffs range from rhyolite to basaltic andesite. Some individual ash-flow units have volumes of more than 40km3 (MacLeod, 1982; MacLeod and Sammel, 1982).

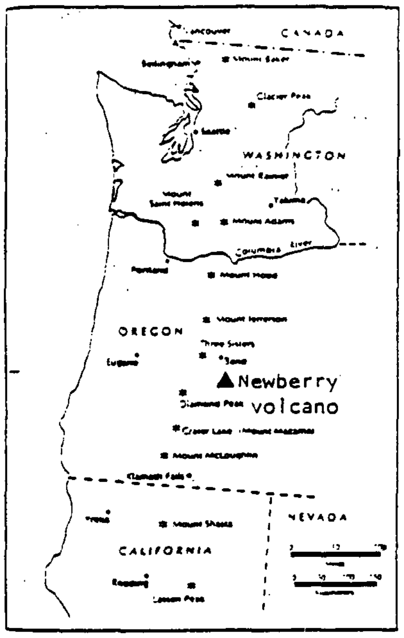

Figure 1. The major Quaternary volcanoes of the Cascade Range.

The volcano's upper flanks are composed of basalt flows, basaltic andesite flows and over 400 affiliated cinder cones and fissure vents (Figure 2). The basalt flows can be divided into two groups relative to the age of Mazama ash (C^{14} 6,900 yrs.). The youngest flows yield carbon-14 ages from 5,800 to 6,380 years. The pre-Mazama ash basalt flows are estimated to range in age from 7,000 to 10,000 years to possibly hundreds of thousands of years for the oldest flows. All flows sampled were normally polarized and are, therefore, younger than 700,000 years (MacLeod, 1982).

Silicic domes, pumice rings and flows are common on the volcano's flanks. Several larger domes have K-Ar ages of 100,000 to 600,000 years and some smaller silicic protrusions may be less than 10,000 years. The silicic domes have been separated into six groups on the basis of element and phenocryst compositions. Widely separated domes of the same group strongly suggest that a magma chamber underlay large areas of the volcano during extrusion of the domes (MacLeod, 1982).

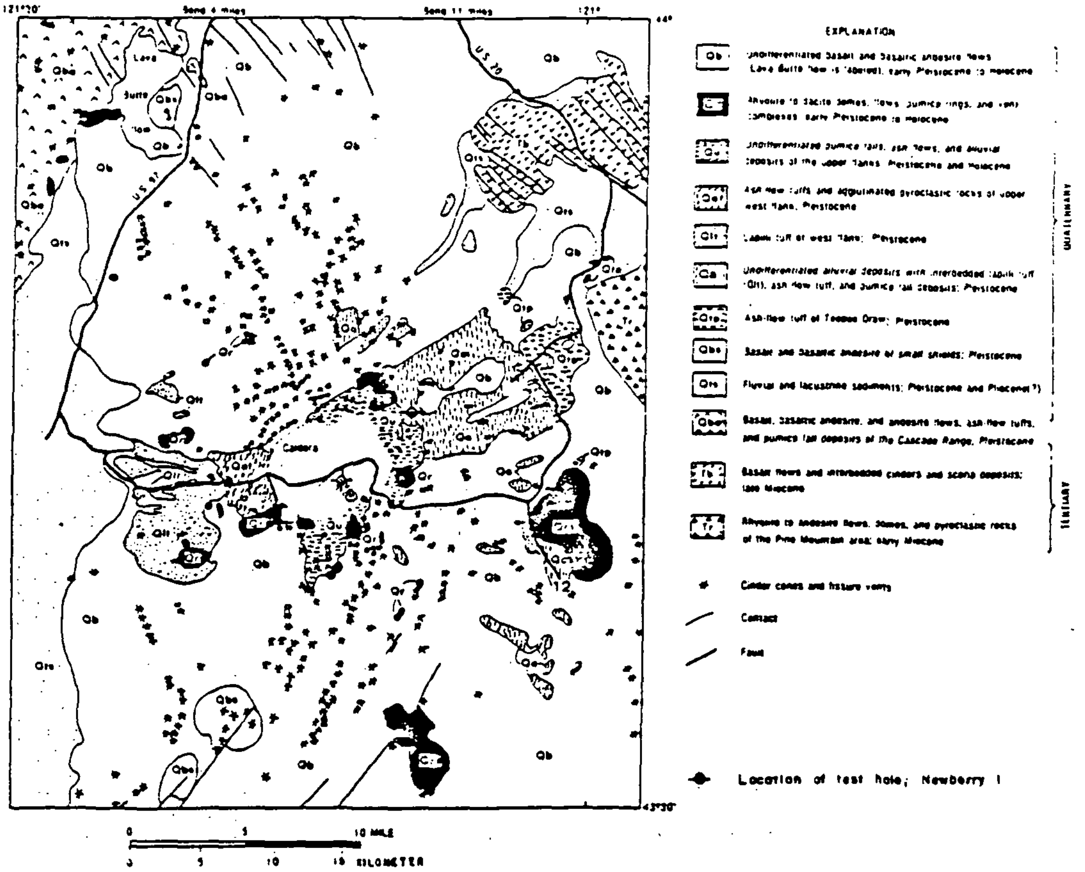

Figure 2. Geologic sketch map of Newberry volcano modified from MacLeod (1982). The geology of the caldera is shown in Figure 3.

MacLeod et al. (1981) interpret Newberry caldera to be a collapse structure formed in several collapse episodes as a result of a succession of eruptions of voluminous ash-flow tuffs. The floor of the caldera consists primarily of rhyolite domes, flows, ash-flow tuffs, pumice and explosion breccias that range from pre-Mazama age to 1,350 years (Figure 3). There are also some pre-Mazama mafic rocks and a single post-Mazama basalt within the caldera (MacLeod, 1982). The young inter-caldera rhyolites and a few small rhyolite protrusions on the upper southeast flank of the volcano have different chemical compositions and trace element concentrations than the older rhyolites (MacLeod, 1982). These younger rhyolites appear to have originated in a common magma chamber located beneath the caldera and the southeast flank of the volcano. The chamber contained magma 1,350 years ago and may still be partially molten.

The geologic map (MacLeod et al., 1982) shows three major zones of faulting crossing the Newberry shield. A northeast trending set of faults crosses the volcano's southern flank and can clearly be distinguished by faults and volcanic vent alignments (Figure 2). Similarly a northwest trending fault set on the northern flank is marked by faults and vent alignments. The northwest and the northeast trending fault sets both tend to shift to a more north-south orientation near the caldera. Thus, these fault sets appear to merge forming a single large broad arcuate pattern concave to the west. A third fault set, crossing the northeast flank of the volcano, trends in a northwest direction parallel to the Brothers Fault Zone. Radar imagery and vent alignments suggest less distinct fault trends. These include northeast striking faults across the northern flank, west-northwest striking faults on the southern flank, a northeast trending fault passing across the caldera along the northern base of Paulina Peak and arcuate features parallel to but outward from the northwest rim of the caldera.

GEOPHYSICS

GRAVITY

The residual gravity map of the Oregon Cascade Range (Couch et al., 1982b) shows a gravity high located over Newberry volcano. The gravity anomaly is centered over the western half of the caldera and forms a "horseshoe" shaped pattern with the open side facing to the southeast (Figure 4). Couch et al. (1982a) discuss two possible

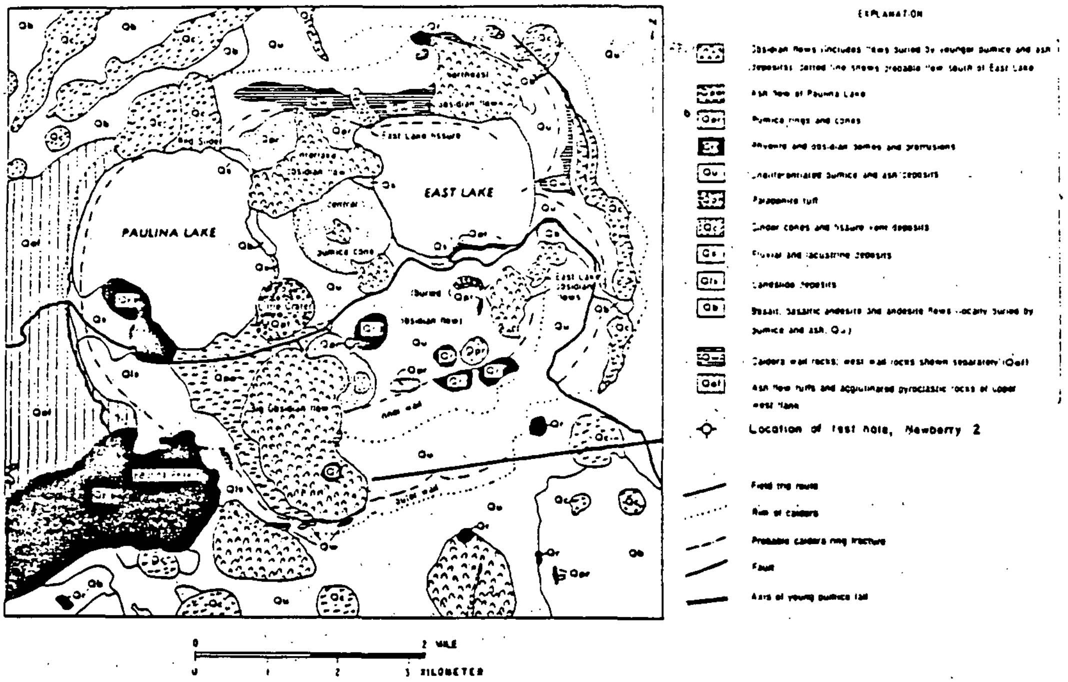

Figure 3. Geologic map of Newberry caldera (MacLeod, 1982).

causes for the gravity high: (1) uncompensated high density flows that increase in number and/or thickness toward the center of the volcano, and/or (2) a large intrusive body located at shallow depth beneath the volcano. Williams and Finn (1981) reinterpreted the Newberry gravity data and suggest a shallow large intrusive body about 3 km thick extends beyond the margins of the caldera.

MAGNETICS

The U.S. Geological Survey (1979) residual magnetic intensity map contains a cluster of circular magnetic highs and lows over the caldera. Additional highs and lows are scattered across the volcano's flanks. Many of the magnetic anomalies are associated with silicic and mafic vent areas located along the "horseshoe" shaped gravity pattern previously described. The gravity and magnetic patterns may reflect a ring structure beneath the caldera and the volcano's south and southeast flanks.

GEOCHEMISTRY

MERCURY GEOCHEMISTRY

A preliminary soil-mercury geochemical survey was completed across Newberry volcano (Hadden et al., 1982). The survey did not cover the outer flanks of Newberry volcano nor were large areas within the central portion of the volcano sampled. The soil samples were collected primarily from the Mazama ash layer. During eruption of Mt. Mazama the pumiceous ash would have been at very high temperature sufficient to volatilize all the original mercury in the ash. Since Mazama ash was deposited on Newberry volcano, mercury accumulated within the ash probably as a result of volatilization by an underlying magnetic heat source during the last 6,900 years. One mercury anomaly occurs within the caldera immediately north of Paulina and East Lakes (Figure 4).

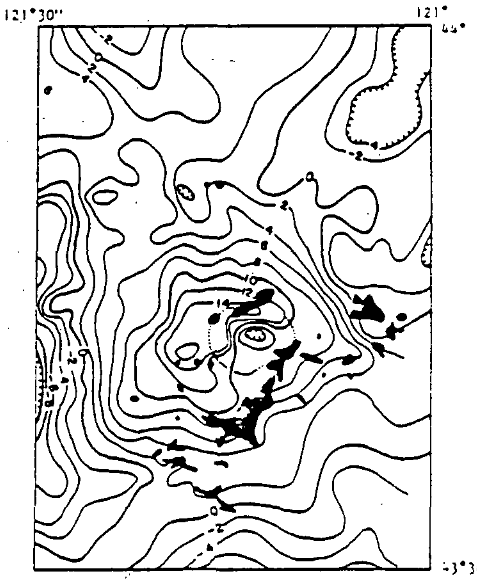

Figure 4. Residual gravity anomaly map of Newberry volcano (Couch et al., 1982b), contour interval 2 milligals. Dark areas are mercury anomalies in the central sampled area. The dotted line is the caldera rim.

A second group of anomalies form an arcuate band across the southern and southeast flanks of the volcano. The pattern of these mercury anomalies suggests a large arcuate structure, possibly a ring fracture on the southeast flank of the volcano. The mercury anomalies tend to occur in areas of silicic volcanism. One possible source of the mercury is from a hydrothermal system probably containing sulfides and located beneath the southeast flank of the volcano.

THERMAL GRADIENT WELL

The U.S. Geological Survey drilled Newberry #2 in the center of the caldera (Sammel, 1981). The hole penetrated fragmental volcanic rocks and lacustrine sediments to a depth of 500 m with flows and breccia below that depth. Hydrothermal alteration increases with depth. The alteration products include clay minerals, quartz, carbonates, chlorite, epidote and sulfides. The temperature profile (Figure 5) shows convective disturbance to 700 m. There are very few permeable zones below 700 m and the thermal gradient is a uniform 706°C/km to 932 m with a bottom hole temperature of 265°C.

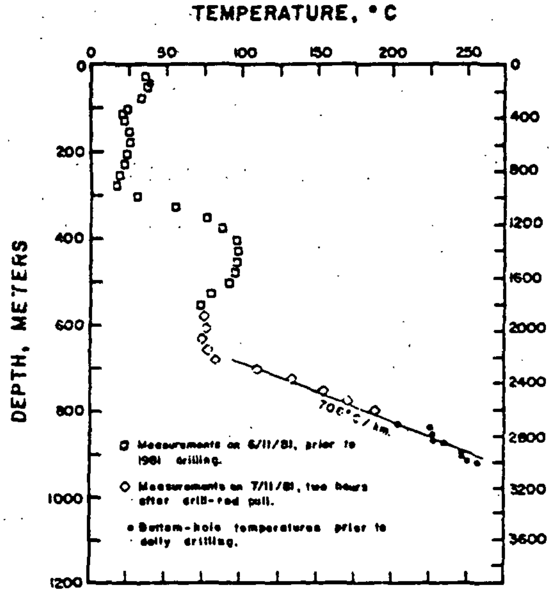

Figure 5. Composite temperature profile of Newberry 2 (Sammel, 1981).

CONCLUSIONS AND IMPLICATIONS REGARDING GEOTHERMAL RESOURCE POTENTIAL

Quaternary bimodal volcanism has produced a large shield volcano containing a caldera at the summit. Caldera collapse appears to have resulted primarily from the eruption of large silicic to andesitic ash-flow tuffs. Mafic flows and cinder cones, some as young as 5,800 years, erupted along numerous northwest and northeast trending faults on the volcano's flanks largely concealing the earlier ash-flow tuffs. Silicic domes and flows are prevalent within the caldera and on the volcano's southeast and upper flanks. Silicic volcanism during the last 7,000 years has been extensive within the caldera, culminating with the Big Obsidian Flow 1,350 years B.P. The age, composition and distribution of silicic volcanism suggest a still partially molten magma chamber of at least several kilometers diameter located at relatively shallow depth beneath the central and southeastern portion of Newberry volcano.

The thermal gradient hole Newberry #2 encountered a bottom hole temperature of 265°C and a uniform gradient of 706°C/km in the lower 232 m. The thermal data suggests the presence of a shallow intrusive at very high temperature, if not still partially molten. The hydrothermal alteration associated with high temperatures in the lower portion of Newberry #2 is proof of the presence of a hydrothermal system. Newberry #2 did not demonstrate the presence of a geothermal reservoir. A geothermal reservoir at Newberry volcano will probably consist of fracture permeability and permeability along flow breccia and pyroclastic zones within individual volcanic units.

The residual gravity high may be caused by a shallow intrusive body centered beneath the volcano. The residual magnetic intensity map contains a series of magnetic highs and lows many of which appear over volcanic vents. The distribution of magnetic anomalies and the overall shape of the gravity anomaly suggest that the intrusive body responsible for the Newberry lavas, domes and tephra is centered beneath the caldera and possibly extends beneath the southern and southeastern flanks of the volcano.

The soil-mercury geochemistry indicates volatilized mercury has been concentrated along leakage zones within the caldera and on the volcano's southern flank. The survey is preliminary and should be completed before conclusions are reached regarding the distribution of mercury on the volcano. The mercury anomalies suggest high temperatures are present beneath the volcano's caldera and southern flank.

The existing geologic, geophysical and geochemical data suggest an excellent potential for geothermal resources at Newberry volcano. Future exploration should include: (1) defining the fracture zones which may be potential reservoir structures, (2) extending the soil-mercury geochemical survey, (3) completing additional geochemical and geophysical surveys, (4) drilling a series of deep thermal gradient wells, and (5) eventually drilling several deep exploration wells to determine if a commercial reservoir is located beneath Newberry volcano.

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GEOLOGY OF MEDICINE LAKE VOLCANO, CALIFORNIA

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ABSTRACT

Medicine Lake volcano is a Quaternary bimodal shield volcano of the Cascade Range in California. The volcano possesses a shallow silicic magma chamber which during the last 1,300 years has erupted voluminous rhyolitic lavas over a broad area. Intense faulting on the volcano has produced numerous open fissures during the last several thousand years. The extensive fault network provides an excellent fracture reservoir potential. Geologic and geochemical studies have defined areas of intense faulting with associated volcanism and anomalous mercury concentrations which suggest the presence of high subsurface temperatures.

INTRODUCTION

Medicine Lake volcano is a Quaternary shield volcano located at the eastern edge of the Cascade Range in Siskiyou and Modoc Counties, California. The Glass Mountain KGRA lies on the upper portion of the volcano. The potential for the presence of a geothermal system associated with this volcano has elevated interest in Medicine Lake volcano to a high level.

The Vulcan Geothermal Group which possess geothermal leases around the KGRA began an exploration program in 1976. This paper represents a summary of the geologic data obtained during the exploration program.

GEOLOGY

STRUCTURE

The structural geology of Medicine Lake volcano is exceedingly complex. A generalized structure map is shown in Figure 1. The surface trace of many faults were mapped on the basis of scarps, sag depressions, fissures and vent alignments. In addition, high altitude infrared photography and radar imagery were very useful in defecting faults not recognized during field mapping.

Medicine Lake volcano rests on a base of faulted Pliocene basalt flows. The distribution of faults in the overlying Quaternary rocks follow the fault patterns present in the Pliocene. Many of the faults have remained active since the Pliocene and have offset Quaternary volcanic rocks. A very clear example of Recent faulting is related to a pumice fall associated with the Crater Glass Flow. The 1,100-1,300 year old pumice fall and underlying cinder cone are offset by a fault crossing the area. Another example of Recent faulting was described by Bennett et al. (1979). Bennett et al. noted displacement associated with the 1978 Stephens Pass earthquakes at the western edge of the Medicine Lake volcano.

North-south trending normal faults occur across the entire surface of the volcano. One group of north-south faults form a dense network approximately 19 km wide extending across the caldera from the east to west rims. The strike length of this fault belt can be traced across the entire volcano from the north to south and beyond. There are many open fissures associated with this fault set and these are especially common in the western half of the caldera. Along the south rim of the caldera in the vicinity of Paynes Springs, faults form a graben which is probably the hydrologic outlet for the caldera.

The open fissures and the recently active volcanic vents associated with them suggest tumescence of the volcano due to magma inflation in very recent time. Many of the fissures appear to have opened during the latest phase of rhyolitic volcanism which a series of carbon-14 dates place at 120 to 1,360 years B.P. (Chesterman, 1955; Ives et al., 1967; Heiken, 1978; Ciancanelli, unpublished data).

Northeast trending faults occur in many isolated areas on the volcano. There is a very prominent belt of northeast striking faults located between and including the vents of Little Glass Mountain and Garner Mountain. This fault set is part of a linear structure that can be traced from Mt. Shasta northeastward across the western and northern flanks of the Medicine Lake Highlands. The name Vulcan Lineament is proposed for this structure. The Vulcan Lineament is both a structural feature and a petrologic trend. All of the recent andesitic to silicic volcanism outside the caldera occurs along the Vulcan Lineament. Movement along the northeast fault set is probably normal, but west of Little Glass Mountain and south of Garner Mountain faults display "S" shaped traces,

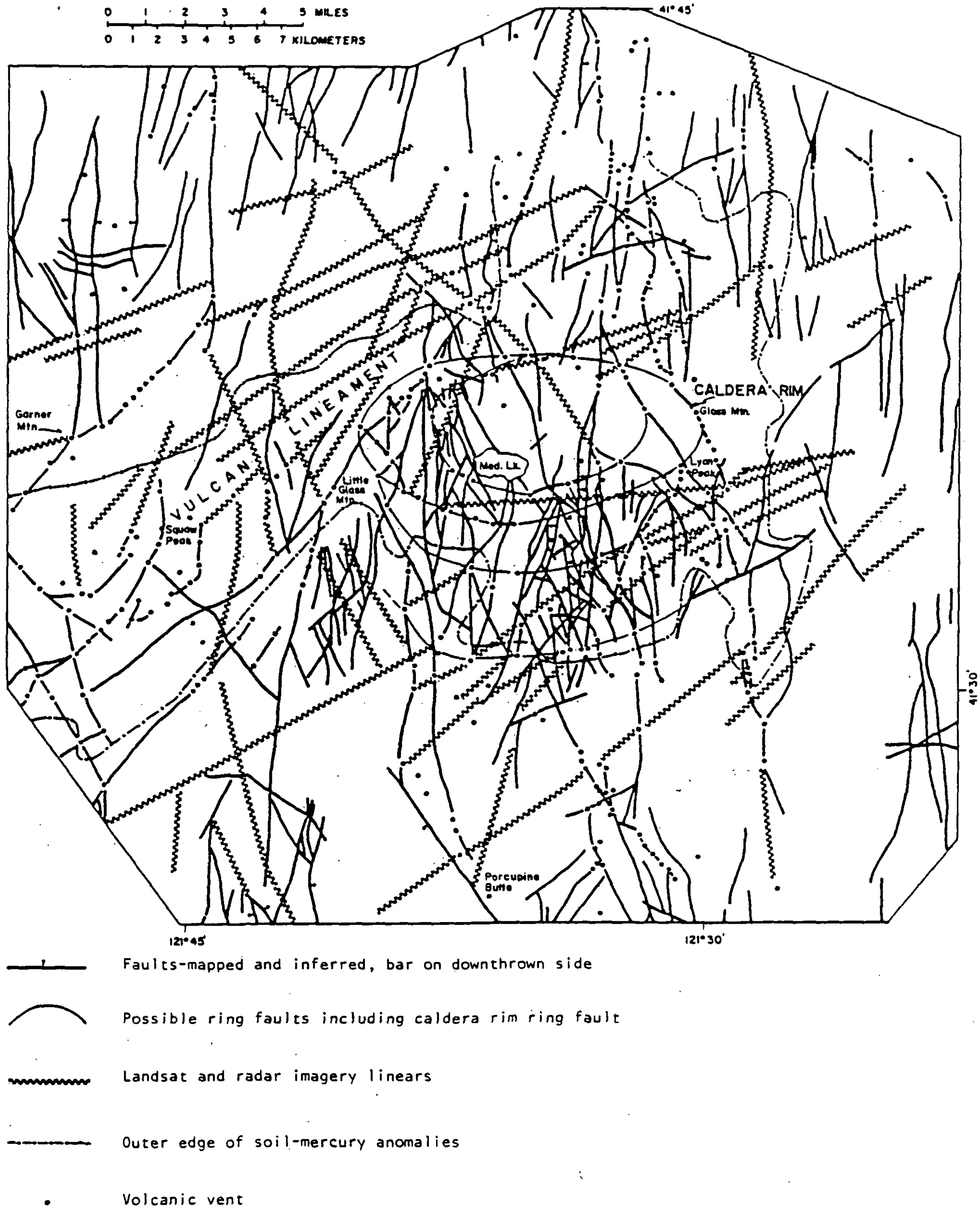
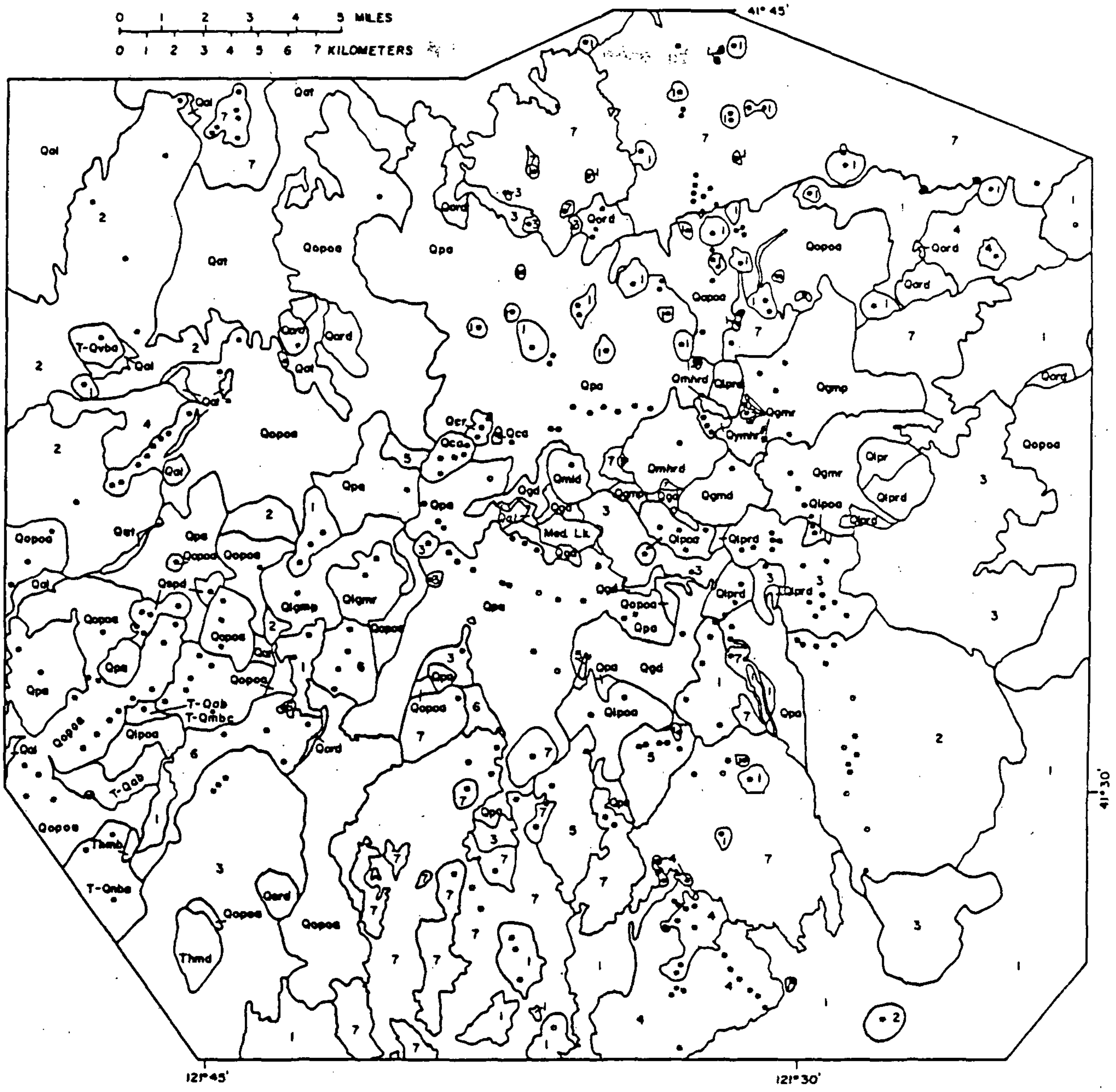


Figure 1. Medicine Lake volcano structure map showing faulting, linear features, volcanic vents and the outer edge of the area within which occur soil-mercury anomalies.



RHYOLITE AND DACITE

Qgmr	Glass Mt. rhyolite
Qymhr	Younger Mt. Hoffman rhyolite
Qcr	Crater rhyolite
Qlgmr	Little Glass Mt. rhyolite
Qgmp	Glass Mt. pumice
Qlgmp	Little Glass Mt. pumice
Qgmd	Glass Mt. dacite
Qmld	Medicine Lake dacite
Qmhrd	Mt. Hoffman rhyodacite
Qlpr	Lyon Peak rhyolite
Qlprd	Lyon Peak rhyodacite
Qspd	Squaw Peak dacite
Qord	Older rhyolite and dacite
T-Qmbc	Mt. Betty complex
Thmd	Harris Mtn. dacite

ANDESITE

Qca	Crater andesite
Qlpoa	Later platy olivine andesite
Qpa	Platy andesite
Qat	Andesite tuff
Qopoa	Older platy olivine andesite
T-Qvba	Van Bremmer andesite
T-Qnba	Nine Buck andesite

BASALT

Basalt	Groups 1-7, numbers do not imply stratigraphic order
T-Qab	Aspirin basalt

SEDIMENTS

Qal	Alluvium
Qgd	Glacial deposits
	Volcanic vent

Figure 2. Generalized geologic map of Medicine Lake volcano. Adapted from an unpublished geologic map by E.V. Ciancanelli.

suggesting left lateral movement along the Vulcan Lineament. In this area the distribution of volcanic vents seem to signify the presence of either a caldera or pull-apart graben.

Northwest trending faults are located primarily on the south half of the volcano. A few scattered northwest trending faults occur elsewhere on the volcano. There is a prominent fault scarp with a northwest strike on the volcano's south flank near Porcupine Butte.

Prominent linear features crossing the volcano are visible on Landsat and Radar imagery. Linear features not related to previously mapped structures include (1) a series of subparallel northeast trending features in a belt extending from the southeast rim of the caldera southward through the Burnt Lava flow and (2) a series of parallel northwest trending linear features crossing the west half of the volcano.

Medicine Lake caldera is a collapse feature with subsequent eruptions along the ring fracture constructing a volcanic rampart around the caldera. Alignment of basaltic vents on the volcano's southern flank suggests the presence of a second outer ring fracture. This second ring fracture extends south of the southern caldera rim but merges with both the east and west sides of the caldera rim.

LITHOLOGY

ANDESITE. Platy andesite group lavas are the predominate rocks of the volcano. Anderson (1941) divided the platy andesite lavas into (1) the older platy olivine andesites (Qopoa) which form the base of the volcano, (2) platy andesites (Qpa) which vented on the upper flanks and caldera rim and (3) later platy olivine andesites (Qlpoa) which occur as scattered flows around the eastern and southern caldera rims (Figure 2). An andesite ash-flow tuff (Qat) probably formed during the initial phase of the caldera collapse.

The various platy andesite lavas which have a very similar megascopic appearance are easily distinguished in thin section. Petrographic analysis of 332 thin sections compliment field and photogeologic studies in preparation of the geologic map (Figure 2).

Older platy olivine andesite flows (Qopoa) are the oldest of the andesite lavas. Mertzman (1981) dated a Qopoa flow at the northern base of the volcano at 0.21 ± 0.05 m.y. Porphyritic Qopoa lavas contain phenocrysts of plagioclase, olivine and pyroxene. The presence of phenocrysts, particularly olivine, aids in distinguishing Qopoa from the overlying platy andesite lavas (Qpa).

The platy andesite lavas (Qpa) were vented high on the volcano from vents near or along the caldera ring fracture and along the Vulcan Lineament. No Qpa lava vents have been recognized on the volcano's lower flanks. Two age dates of 0.09 ± 0.05 m.y. and 0.08 ± 0.04 have been reported for Qpa flows (Mertzman, 1981). In thin section the flows contain only trace amounts of plagioclase and even fewer olivine phenocrysts.

The later platy olivine andesite lavas (Qlpoa) were vented near the eastern and southern caldera rim and at one locality along the Vulcan Lineament. Qlpoa lavas are easily distinguished petrographically from the Qopoa and Qpa lavas. Numerous tiny phenocrysts of plagioclase, olivine and pyroxene give the Qlpoa a unique appearance in thin section.

RHYOLITE AND DACITE. The exposures of rhyolite and dacite on the volcano suggest at least three periods of silicic volcanic activity. Outcrops of older rhyolite and dacite (Qord) domes and flows occur around the lower flanks of Medicine Lake volcano. Mertzman (1981) presented three age dates for Qord ranging from 0.43 to 0.95 m.y. These dates suggest bimodal silicic and basaltic volcanism occurred at Medicine Lake volcano prior to eruption of the platy andesite lava group. At Harris Mountain on the volcano's southwest flank an unusual lava (Thmd) contains phenocrysts of quartz, olivine, plagioclase, K-feldspar, pyroxene and hornblende. This rock is possibly a product of magma mixing of silicic and mafic lavas. Field relationships suggest this is one of the oldest units on Medicine Lake volcano. Thmd may be related to the older period of silicic activity or may even pre-date this silicic period. Southwest of Little Glass Mountain, a series of poorly exposed silicic lavas (T-Qmbc) may similarly be related to the older period of silicic volcanism.

Near Lyon Peak on the east rim of the caldera a series of intermediate age rhyolite and dacite flows and domes (Qlpr and Qlprd) overlie platy andesite flows (Qpa) and are in turn overlain by Group 3 basalt and younger rhyolite (Qgmr). These intermediate age silicic rocks may be approximately contemporaneous with the dacite domes at Squaw Peak (Qspd) west of the caldera on the Vulcan Lineament.

The youngest silicic volcanic rocks at Medicine Lake are a series of Recent rhyolite and dacite glass flows, domes and pumice fall deposits vented around the caldera rim, within the caldera and along the Vulcan Lineament. These include Mount Hoffman rhyodacite (Qmhrd), Medicine Lake dacite (Qmld), younger Mount Hoffman rhyolite (Qymhr), Glass Mountain dacite (Qgmd), Glass Mountain pumice (Qgmp), Little Glass Mountain pumice (Qlgmp), Glass Mountain rhyolite (Qgmr), Crater rhyolite (Qcr), and Little Glass Mountain rhyolite (Qlgmr). A series of carbon-14 dates indicate these silicic rocks were erupted between 130 and 1,360 years B.P. (Chesterman, 1955; Heikin, 1978; Ives et al., 1967, Friedman, 1968; Ciancanelli, unpublished data).

BASALT. A total of 33 basalt units and approximately 200 cinder cones were mapped on the volcano. These have been placed into 7 basalt groups on the basis of similar petrographic characteristics. The individual basalt units within a single group may be widely separated in time and/or locality on the volcano. Very few age dates are available for the Medicine Lake basalts. Using field relationships most of the basalt flows on the volcano's middle and upper flanks are estimated to be about 50,000 to 200,000 years B.P. A Group 3 basalt flow which is one of the lava flows equivalent to Anderson's (1941) Lake Basalt was dated at 0.13 ± 0.10 m.y. (Luedke and Lanphere, 1980) and a Group 6 basalt was dated 0.15 m.y. (Brown and Mertzman, 1979). Several large Group 7 basalt flows are very recent. The Burnt Lava flow (Group 7) was dated at about 200 to 300 years B.P. (Ives et al., 1964).

Basalt flows and cinders are distributed across the volcano. However, a greater proportion of basalt has vented on the eastern and southern flanks of the volcano. The broad arc of basalt vents on the south flank of the volcano as previously noted suggests an outer ring fracture.

The distribution of silicic and mafic rocks is perhaps indicative of the shallow silicic magma chamber believed to be located 4 km beneath Medicine Lake volcano (Finn and Williams, 1982). Geologic evidence suggests magma is centered beneath the caldera and extends west and southwest of the caldera along the Vulcan Lineament. Basalt has vented around the outer edge of the silicic magma and in some instances basalt magma may have mixed with silicic magma (Eichelberger, 1981).

MERCURY GEOCHEMISTRY

A soil-mercury geochemical survey completed in cooperation with Republic Geothermal showed anomalous mercury concentrations across the caldera and along the Vulcan Lineament (Figure 1). Mercury appears to be transported along fracture zones after being volatilized by underlying heat. Mercury anomalies are also associated with a few isolated areas of surficially exposed hydrothermal alteration. The highest mercury values were collected in the vicinity of the fumarole known as The Hot Spot.

Anomalous mercury values approximately outline the general distribution of the younger andesite, dacite and rhyolite vent areas, and the areas of recently opened fault fissures. The general soil-mercury pattern is also largely coincident with the gravity anomaly associated with the volcano (Finn and Williams, 1982). This coincidence strongly suggests elevated temperatures and possibly shallow magma below the caldera and along the Vulcan Lineament.

SUMMARY

Medicine Lake volcano contains a summit caldera crossed by a strong north-south belt of active normal faults. The Vulcan Lineament, a northeast trending belt of faults and volcanic vents, crosses the volcano's western and northern flank. Silicic and andesitic volcanic vents are located along the caldera's rim and along the Vulcan Lineament. Extensive silicic volcanism has occurred very recently along these two structures. Basaltic volcanism is concentrated along the volcano's southern and eastern flanks and around the outer margins of the inferred magma chamber.

Volatilization of mercury by subsurface heat is believed to cause soil-mercury anomalies in the caldera and along the Vulcan Lineament.

The inferred shallow magma chamber appears to be located beneath the caldera and the Vulcan Lineament. Excellent potential for a fracture geothermal reservoir lies in the immediate vicinity of the caldera and along the Vulcan Lineament.

ACKNOWLEDGEMENTS

The author would like to thank the Vulcan Group for financing the field work and permission to publish the results. Appreciation is also extended to the Project Managers Norman D. Knowles and Jim Kirker. Keith Johnson, Kathy Theal and Betty Ciancanelli assisted with the preparation of the manuscript.

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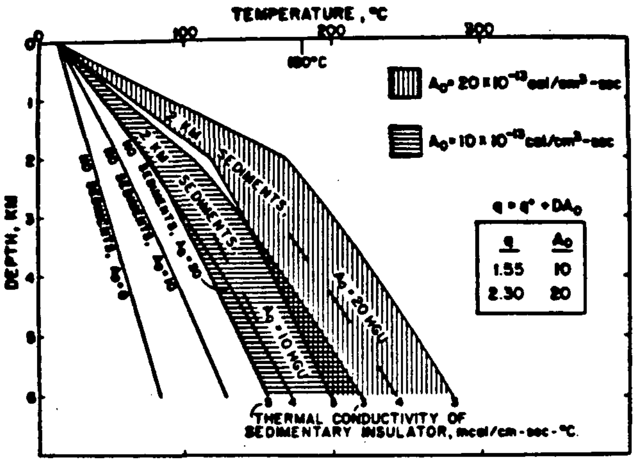

FIG. 2. Insulating effect of a sedimentary blanket.

the upper crust. The distribution of U and Th in the upper 10 km or so of the earth's crust is primarily responsible for lateral variations in surface heat flow in the eastern U.S. Most of the heat produced comes from U and Th; only about 10-15 percent comes from K. Optimum sites for the development of geothermal energy in the eastern U.S. are associated with the flat-lying, relatively unconsolidated sedimentary blanket beneath the Atlantic Coastal Plain that overlies heat-producing granitoids in the basement. At many locations, the overlying sediments yield large quantities of water that can be used for the effective transfer of heat to the surface.

One of the principal objectives of the geothermal program at VPI&SU has been to locate and study relatively young, (254-330 Ma.) unmetamorphosed heat-producing U- and Th-bearing granitoids such as those in the exposed basement rocks of the Piedmont province adjacent to the Atlantic coastal plain (Glover, 1979). Results of studies of the granite petrology were reported by Speer et al (1980) and Speer et al (in press).

The basement rocks are concealed to the southeast by the sediments of the Atlantic coastal plain which comprise the seaward-thickening sedimentary insulator. Sediment thickness is known to be about 3 km at Cape Hatteras, NC.

Figure 2 illustrates the effect on subsurface temperature where crystalline rocks are blanketed by a sedimentary insulator. The leftmost curve in Figure 2 is the temperature-depth profile in unblanketed basement crystalline rocks devoid of U and Th. As U and Th are added to produce 10 HGU (1 HGU = 1 heat generation unit = 10^{-13} cal/cm³) and 20 HGU, the subsurface temperature and geothermal gradient increase. Finally, if U- and Th-bearing granite is blanketed by sediments that have a relatively low thermal conductivity, the subsurface temperature is increased further.

The locations of our heat flow sites in the eastern U.S. were chosen on the basis of gravity data, magnetic data, thickness of coastal plain sediments, apparent thermal anomalies, available basement core data, suitable sites for the evaluation of the radiogenic pluton model, and proximity to energy markets.

Lambiase et al (1980) discussed the distribution and values of geothermal gradients obtained in the holes drilled on the northern Atlantic coastal plain. One promising area appears to be between Crisfield, Maryland and Oak Hall, Virginia, on the Eastern Shore. Higher gradients (48°C/Km) were found elsewhere, for example, on the west side of Chesapeake Bay within the large negative gravity anomaly in the vicinity of the bay, but the depth to basement there is less. A test hole was drilled on the Eastern Shore at Crisfield.

The temperature predicted at the base of the coastal plain sediments (1.42 km) at Crisfield was about 16 percent less than the actual temperature as a result of the uncertainty in predicting the thermal conductivity of coastal plain sediments at depths below the drill hole. Limited pump tests were made at Crisfield to estimate potential fluid production. Laczniak (1980) modeled the response of a leaky aquifer system to be a single dipole (pumping plus injection well) using the results from the Crisfield tests. The model was run for a simulated period of 15 years or until steady-state thermal and fluid flow were reached.

Important conclusions of Laczniak's study were: (a) direct injection back into the reservoir may be necessary to maintain sufficient fluid pressure at the production well for systems with a low permeability, (b) temperature distribution within the system is only slightly affected by changes in permeability in the range 10-100 md, (c) resting the system for periods of 6 months does not result in a significant recovery of heat at the production well, and (d) a doublet system with thermal and hydrologic conditions similar to those encountered at Crisfield, a well spacing of 1000 m, a permeability of 100 md, and a pumping-injection stress of 500 gpm (injection temperature 44° C) could produce 5.5 million Btu's per hour over a period greater than 15 years.

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Search for Geothermal Heat Sources in the Oregon Cascades by Means of Teleseismic P-Residual Technique GE.2

Doug

H. M. Iyer, A. Rite, Chevron International Oil Co.; and S. M. Green, U.S.G.S.

The geothermal potential of the Oregon Cascades is considered to be high in view of its tectonic setting, the presence of young volcanoes, and high heat flow. Geophysical techniques, however, have failed to provide unambiguous evidence for the presence of large crustal magma bodies, unlike at some other rhyolitic volcanic centers in the western United States. Teleseismic residual studies at Mount Hood and Newberry volcano show no evidence for crustal magma chambers of detectable size under these volcanoes; the same situation seems to prevail in the California Cascades as well. However, results of drilling at Newberry indicate that high-temperature water is present at a depth of 1 km and suggest that a magmatic heat source exists. Teleseismic-residual studies, using a 32-station seismic network encompassing the whole of the Oregon Cascades, give some clues as to the nature of the heat sources in the region. A velocity model derived from the teleseismic data shows a zone of relatively low velocity in the crust and upper mantle under the High Cascades, in comparison with higher velocities beneath the Western Cascades. We interpret these results as indicating the presence of low-density high-temperature rock to great depths. Intrusion of magma related to subduction of the Juan de Fuca plate is apparently responsible for this and results in the observed high heat flow. The presence of numerous small pockets of magma, as well as favorable hydrologic circulation patterns, may give rise to high-temperature water at shallow depths, such as at Newberry volcano.

It is generally believed that the Oregon Cascades have high geothermal potential. The tectonic setting of Oregon over the subducting Juan de Fuca plate, the abundance of Quaternary volcanism, the presence of numerous hot springs, and high measured heat flow suggest that an extensive geothermal resource may exist. However, unlike at many other geothermal areas in the Western United States where detectable low-velocity anomalies that can be interpreted as magma bodies seem to be present in the crust (Iyer, 1980), our efforts to detect such bodies in the Oregon Cascades have consistently met with negative results. The fact that magma is, indeed, locally present at shallow depths is evidenced by the recent eruption of Mount St. Helens and the building of a massive lava dome in the newly formed crater.

In this paper we present results of teleseismic P-residual measurements around Mount Hood and Newberry volcano in Oregon. In addition, we also present a three-dimensional *P*-wave-velocity model for the whole of the Oregon Cascades. These results, together with other available geophysical data, are interpreted to explain the geothermal enigma of the Oregon Cascades, namely, high apparent geothermal potential but the absence of detectable magma chambers.

Mount Hood

A detailed analysis of *P*-wave residuals from 55 teleseisms recorded by a 16-station seismic network around Mount Hood show a total regional variation of 0.7 sec (Figure 1a). There is no evidence, however, for a localized high or low-velocity anomaly (negative or positive relative residuals) that could be related to a magma chamber under the volcano (The teleseismic technique is capable of detecting magma bodies of 5 km or more in diameter.). Analysis of gravity data by Couch and Gemperle (1979), although showing regional structural trends and lateral and vertical variations in the density of pyroclastic flows, also shows no evidence for a magma chamber. Several drill holes around Mount Hood do not show any abnormally high bottom-hole temperatures or thermal gradients (Robinson et al, 1981; Ehni, 1981). Mount Hood, however, like other Quaternary volcanoes in the Oregon Cascades, is situated on a ridge of high heat flow that coincides with the High Cascades. Heat flow jumps by a factor of almost 2.5 from 40 mW/m² (1 HFU) in the Western Cascades to 105 mW/m² (2.5 HFU) in the High Cascades (Blackwell et al, 1978).

Newberry volcano

Newberry volcano, in west-central Oregon presents a more promising geothermal picture than the Mount Hood area. Test drilling by the U.S. Geological Survey near the center of New-

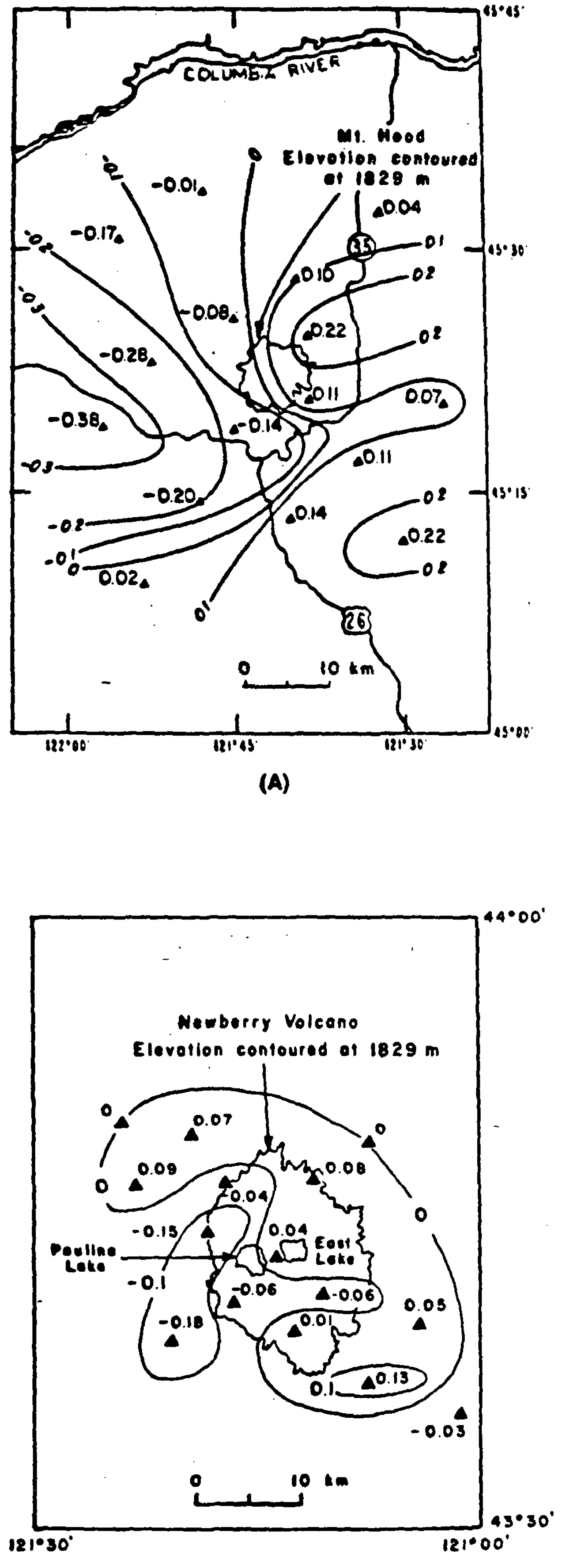

FIG. 1. Relative teleseismic residual contours. Units are in seconds. (A) Mount Hood (B) Newberry volcano.

berry caldera encountered high temperatures (265°C) at a depth of 930 m (Sammel, 1981). A teleseismic study by the U.S.G.S., however, showed no evidence for a low-velocity anomaly that could be interpreted as a magma body under the volcano. Teleseismic residuals were generally of low amplitude and independent of azimuth. The average relative residuals, contoured in Figure 1b, show only a negative residual anomaly of about 0.2 sec to the west of the caldera. This can be interpreted as a shallow high-velocity intrusion and is somewhat similar to an interpretation of gravity data by Williams and Finn (1981).

Oregon Cascades

Available evidence from several other cascade volcanoes, such as Mount St. Helens, Mount Shasta, and Lassen Peak (personal communication from various individuals), also seems to follow the pattern at Mount Hood and Newberry volcano, in that no detectable magma chambers of finite dimensions (diameter greater than 5 km) seem to be present in the crust or mantle. The obvious question, therefore, is: What is the nature of the geothermal heat source responsible for the elevated regional heat flow in the High Cascades (see Figure 2)?

The regional nature of the High Cascade heat source is corroborated by a teleseismic study using a 32-station seismic network being operated in Oregon by the U.S.G.S., under its Volcano Hazards Program. The teleseismic residuals show large azimuthally dependent variations with amplitudes of about 0.5 sec. The relative-residuals (average of 82 teleseisms) contoured in Figure 2 reveal the following features: (1) a ridge of positive residuals (indicating lower than normal velocities) over the High Cascades; (2) a sharp west-to-east transition from an average of −0.3 to +0.3 sec in the central area; and (3) a large regional delay (positive residuals) around Newberry volcano. The region of high heat flow (greater than 100 mW/m^2) is shaded in Figure 2 for comparison with the area of positive residuals.

We have used the inversion technique developed by Aki et al (1977) to obtain a 3-D velocity model of the area contoured in Figure 2. The block sizes used in the inversion are 50 km × 50 km horizontally and 20, 20, 75, 100, 100 km, vertically. The results (not shown here) indicate considerable complexity in structure of the northern Oregon Cascades within the top 20 km of the crust. In the central and southern cascades there is a change in velocity from higher to lower values by about a 10 percent from west to east. In the lower crust and upper mantle, the main feature throughout the model is this west-to-east change from high to low velocities. There is also some indication that this transition boundary migrates eastward with increasing depth. Figure 3 is a northwesterly cross-section of a highly idealized velocity model. Two important features of this model are relevant to volcanism in Oregon: (1) the inclined boundary between the high- and low-velocity zones suggests a subducting plate, and (2) the entire High Cascades region seems to be underlain by relatively low velocity material (Note that the cross-section is perpendicular to the direction of plate convergence and at 45 degrees to the axis of the volcanic chain.).

Regional-gravity data in Oregon also show this deficiency in mass under the High Cascades. Dehlinger et al (1968) and Thiruvathukal et al (1970) interpreted this phenomenon as due to a drastic increase in crustal thickness under the High Cascades. Crustal thickening would also result in a pattern of residuals similar to that shown in Figure 2. However, inversion of residual data computed using reasonable crustal-thickening models show that this effect alone cannot explain the results summarized in Figure 3. We conclude that the velocities in the crust and lower mantle are indeed lower in the High Cascades compared to the Western Cascades. We interpret this contrast as due to the presence of hot rock and pockets of magma.

Thus, our model for the deep structure of the High Cascades resembles that proposed by Karig (1971) for marginal basins behind island arcs. In such regions, above the underthrusting lithosphere, shear-heated material rises buoyantly and results in a wedge of low-density high-temperature upper mantle. A petrogenetic model, in which intrusion of calc-alkaline magmas occurs in the wedge-shaped region above a subducting plate, was postulated by Ringwood (1977). Further confirmation for the existence of such a structure under the High Cascades will require seismic-refraction surveys to constrain crustal effects and Q measurements on a regional scale. Magma pockets under the volcanoes may themselves be too small to be detectable by existing teleseismic techniques and other high-resolution seismic techniques will be needed to locate them.

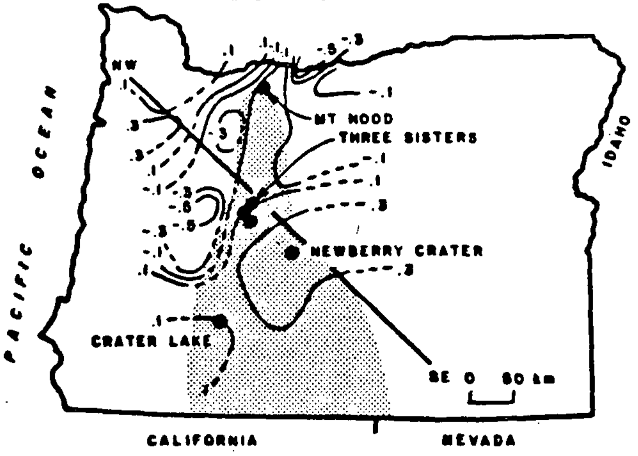

Fig. 2. Relative teleseismic residual contours in western Oregon. Units are in seconds. Stippling, area where heat flow exceeds 100 mW/m^2 (adapted from Blackwell et al, 1978). Dots denote selected volcanoes. Velocity cross-section shown in Figure 3 is along northwest-southeast line.

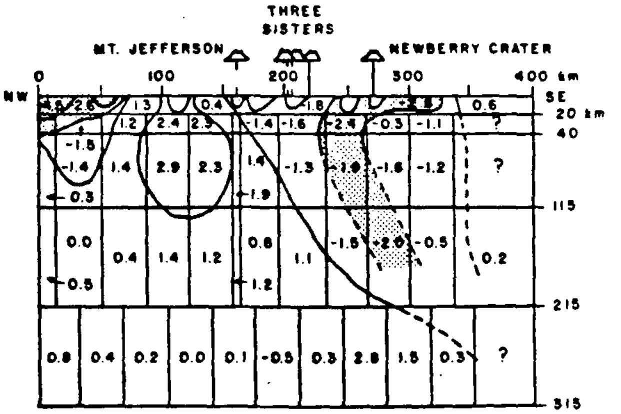

Fig. 3. Velocity cross-section along a northwest-southeast profile indicated in Figure 2. Numbers show relative velocity variation (in percent). Contour interval is 2 percent. Cells show block sizes used in inversion. Shaded area is where velocity decrease is greater than 2 percent.

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Compressional-Wave Velocity Structure of the Medicine Lake Volcano and Vicinity from Teleseismic Relative Traveltime Residuals GE.3

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Teleseismic *P*-wave relative traveltime residuals from an array spanning the Medicine Lake volcano, California, reveal high-velocity anomalies in the crust and upper mantle extending from very shallow depths to at least 100 km beneath the volcano. These preliminary data also suggest the presence of a shallow low-velocity feature beneath a young lava flow on the southeast flank of the volcano. This low-velocity feature may be associated with the source of the flow and is the most promising geothermal prospect seen from these preliminary data. The absence of any other significant low-velocity region, of even a mantle low-velocity source anomaly, suggests that any melt or partial-melt pockets forming prior to an eruption must either be very small, very short lived, or both. The high-velocity main anomaly contrasts sharply with those in other volcanic areas such as Yellowstone and The Geysers.

Method

Teleseismic *P*-wave relative traveltime residuals have been used in many areas to map the 2-D or 3-D compressional-velocity structure of the crust and upper mantle (for example, Iyer et al, 1981; Steeples and Iyer, 1976; Evans, 1982; Reasenberg et al, 1980; Oppenheimer and Herkenhoff, 1981). This technique can resolve features at least as small as a few kilometers across (Stauber, 1982) and has the unique ability to resolve complex structure to depths exceeding several hundred kilometers. In addition, resolution of the study volume is relatively uniform and is quantitatively described through a damped least-squares inversion technique (Aki et al, 1977).

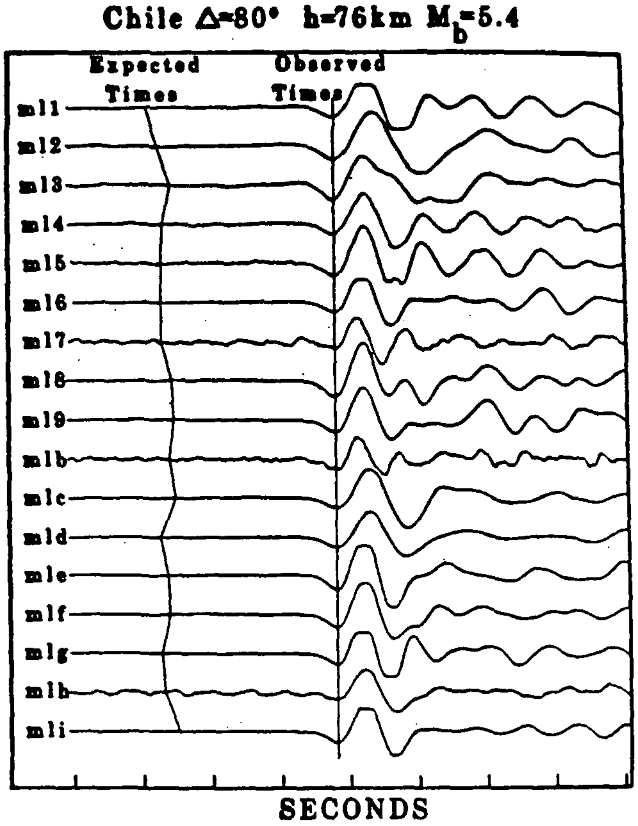

FIG. 1. An example of teleseismic data aligned by picks to show signal coherence across the array. The differences between these observed relative times and the expected arrival times (less the average difference for the event) are relative traveltime residuals. Picks were actually made in the first half cycle of narrow band-filtered copies of these traces.

Relative residuals are computed as follows:

(1) Accurate relative arrival times are determined for numerous teleseisms ($\Delta \geq 25$ degrees) at the stations in a 1-D or 2-D array. First peak, trough or zero-crossing times (Figure 1) of narrow band-filtered traces provide relative times usually accurate to ±0.05 sec.

(2) Theoretical arrival times based on a standard earth model (e.g., Herrin, 1968) and on hypocenters determined from worldwide networks (e.g., *Preliminary Determinations of Epicenters*, a regular publication of the U.S. Geological Survey) are subtracted from the observed times to produce traveltime residuals.

(3) Errors in hypocenters, departures from the standard earth model (including some large-scale structures near the array), and use of different earth models for locating the events and calculating expected arrival times all introduce large traveltime residuals. Since these effects are the same or nearly the same at all stations within a compact array, the average traveltime residual for each event is subtracted from each residual to give relative residuals.

Relative residuals contain information on relative-velocity structures smaller than the sampled volume under the array. Information on absolute velocities and on uniform structures spanning the sampled volume is lost when an event's average residual is removed, whereas information on velocity variations is retained.

OPEN-FILE REPORT (GEOLOGICAL SURVEY (U.S.))

GEOLOGIC MAP OF NEWBERRY VOLCANO, DESCHUTES, KLAMATH, AND LAKE COUNTIES, OREGON

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1982

UNITED STATES DEPARTMENT OF THE INTERIOR
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GEOLOGIC MAP OF NEWBERRY VOLCANO, DESCHUTES, KLAMATH, AND LAKE COUNTIES, OREGON

By

Norman S. MacLeod[1], David R. Sherrod[1], and Lawrence A. Chitwood[2]

Open-File Report

82-847

September 1982

This report is preliminary and has not been
reviewed for conformity with U. S. Geological
Survey editorial standards and stratigraphic
nomenclature.

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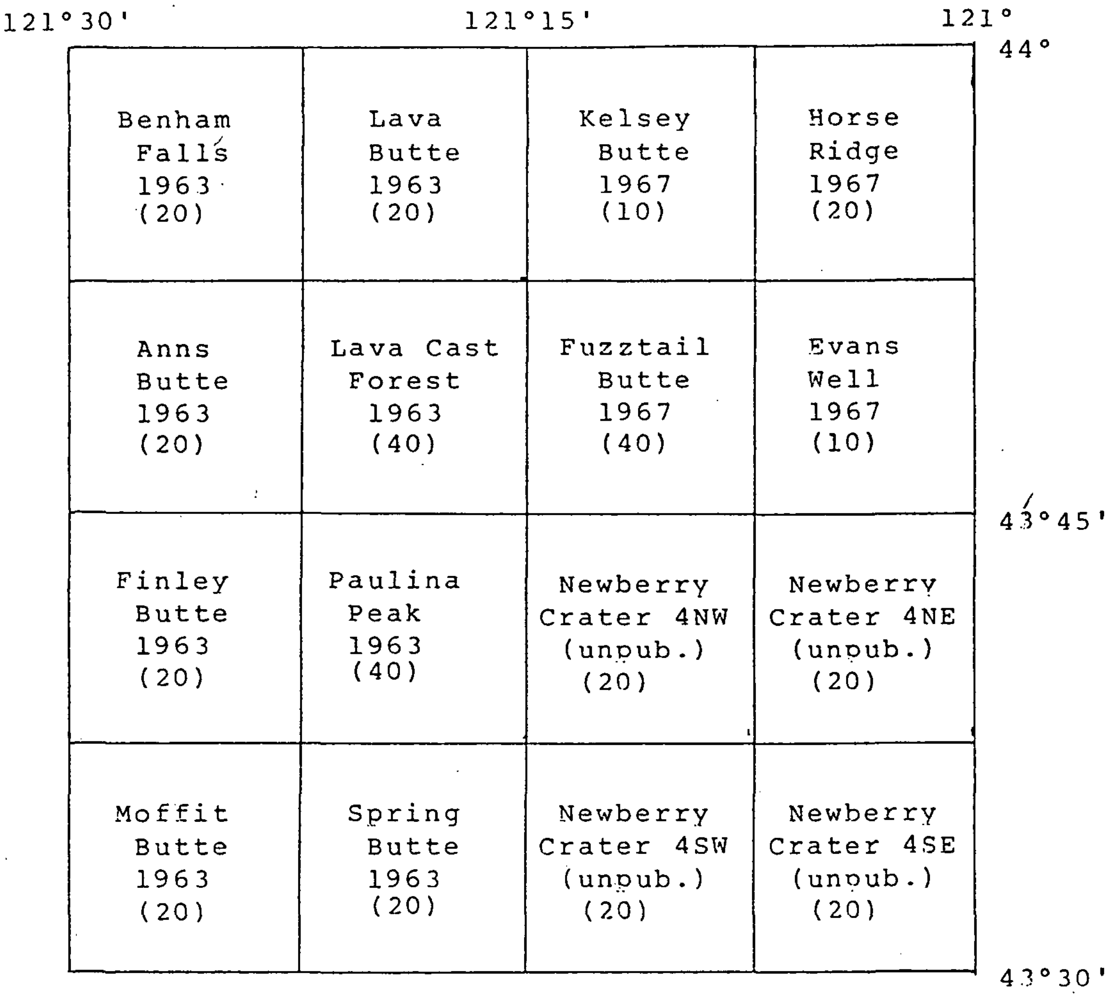
INTRODUCTION

Howel Williams (1935) provided the first comprehensive study of the geology of Newberry Volcano. It was based on fieldwork done in a brief period of time when roads and transportation were limited and before some volcanologic phenomena were well understood. Nevertheless it was a remarkable study. Subsequent investigations by Higgins (1969, 1973), Higgins and Waters (1968, 1970), Peterson and Groh (1969), Beyer (1973), Friedman (1977) and others have provided substantial new data and interpretations, but have concentrated on the summit caldera and young flank flows. Most of the flank rocks have a surface veneer of Mazama ash derived from Mt. Mazama (Crater Lake), lack significant erosion in many areas, and are locally buried by widespread tephra deposits from eruptions in the summit caldera. No prior geologic mapping of the entire volcano has been undertaken since the brief reconnaissance by Williams (1935, 1957).

The geologic map presented here is a product of an evaluation of the geothermal potential of Newberry Volcano conducted under the Geothermal Research Program of the U.S. Geological Survey. Fieldwork was done in the summers of 1976, 1977, and 1978, during which time we also mapped adjacent areas. The results of geothermal exploration drilling, which identified a shallow, high-temperature (265°C) zone beneath the caldera, are presented elsewhere (Sammel, 1981; MacLeod and Sammel, 1982). A guidebook to Newberry Volcano by MacLeod and others (1981) lists distinctive outcrop localities and summarizes the geologic evolution of the volcano and its summit caldera.

The base for the geologic map is a mosaic of sixteen 1:24,000-scale topographic maps (fig. 1) which has been reduced to 1:62,500. Owing to the scale reduction, letters and numbers on the base map are difficult to read; for clarification of names and elevations the reader is referred to the original 1:24,000-scale topographic maps. In addition, the four 1:24,000-scale maps of the southeast sector of the volcano are preliminary unpublished maps that have neither lettering nor numbers on them; the reader is referred to other maps for names of topographic features there. We refer to names of volcanic features in the summit caldera and of young flows on the flanks following the usage of other authors (Williams, 1935, 1957; Peterson and Groh, 1969; Higgins, 1973; Friedman, 1977).

In compiling this geologic map, we attempted to determine the distribution of rock units that lay buried beneath surficial fragmental rocks (largely tephra deposits). Many rock units have very limited exposure and the locations of some contacts shown on the map are based on topographic expression. In rare cases, rock units shown on the map do not crop out, but their location was suggested by geomorphic expression and they were identified by digging deep holes through the surface veneer



Benham Falls 1963 (20)	Lava Butte 1963 (20)	Kelsey Butte 1967 (10)	Horse Ridge 1967 (20)
Anns Butte 1963 (20)	Lava Cast Forest 1963 (40)	Fuzztail Butte 1967 (40)	Evans Well 1967 (10)
Finley Butte 1963 (20)	Paulina Peak 1963 (40)	Newberry Crater 4NW (unpub.) (20)	Newberry Crater 4NE (unpub.) (20)
Moffit Butte 1963 (20)	Spring Butte 1963 (20)	Newberry Crater 4SW (unpub.) (20)	Newberry Crater 4SE (unpub.) (20)

Figure 1. Index map showing names and dates of publication of 7-1/2', 1:24,000 scale topographic maps utilized to make base map. Contour intervals, in feet, are shown in brackets.

of fragmental rocks. The surficial tephra deposits in and near the caldera have a complicated stratigraphy, show little erosion, and were studied mostly in holes dug into them. We were unsuccessful in delineating most of the individual tephra units and were forced to show them as undifferentiated deposits derived from several vents of different ages; they warrant further work because they can provide data needed to decipher some of the later stages of volcanism and magma evolution.

Ages of Holocene rock units determined by ^{14}C methods are reported in ^{14}C years. Carbon that is 3,000 to 7,000 years old yields ^{14}C ages that are 100 to 700 years younger than the real age. Thus, rocks which have a ^{14}C age of 6,100 years have a real age of about 6,800 years (see Faure, 1977, Fig. 17.3). For rocks younger than 3000 years the deviation in age is less than 100 years. In contrast, the reported hydration-rind ages of obsidian flows should represent absolute ages. We divide Holocene rocks into two parts based on their age relations to Mazama ash. Bacon (1982) estimates Mazama ash to have a ^{14}C age of about $6{,}845 \pm 50$ years based on numerous new and published isotopic determinations. Rocks referred to the upper Holocene are younger than Mazama and those of the lower Holocene are older.

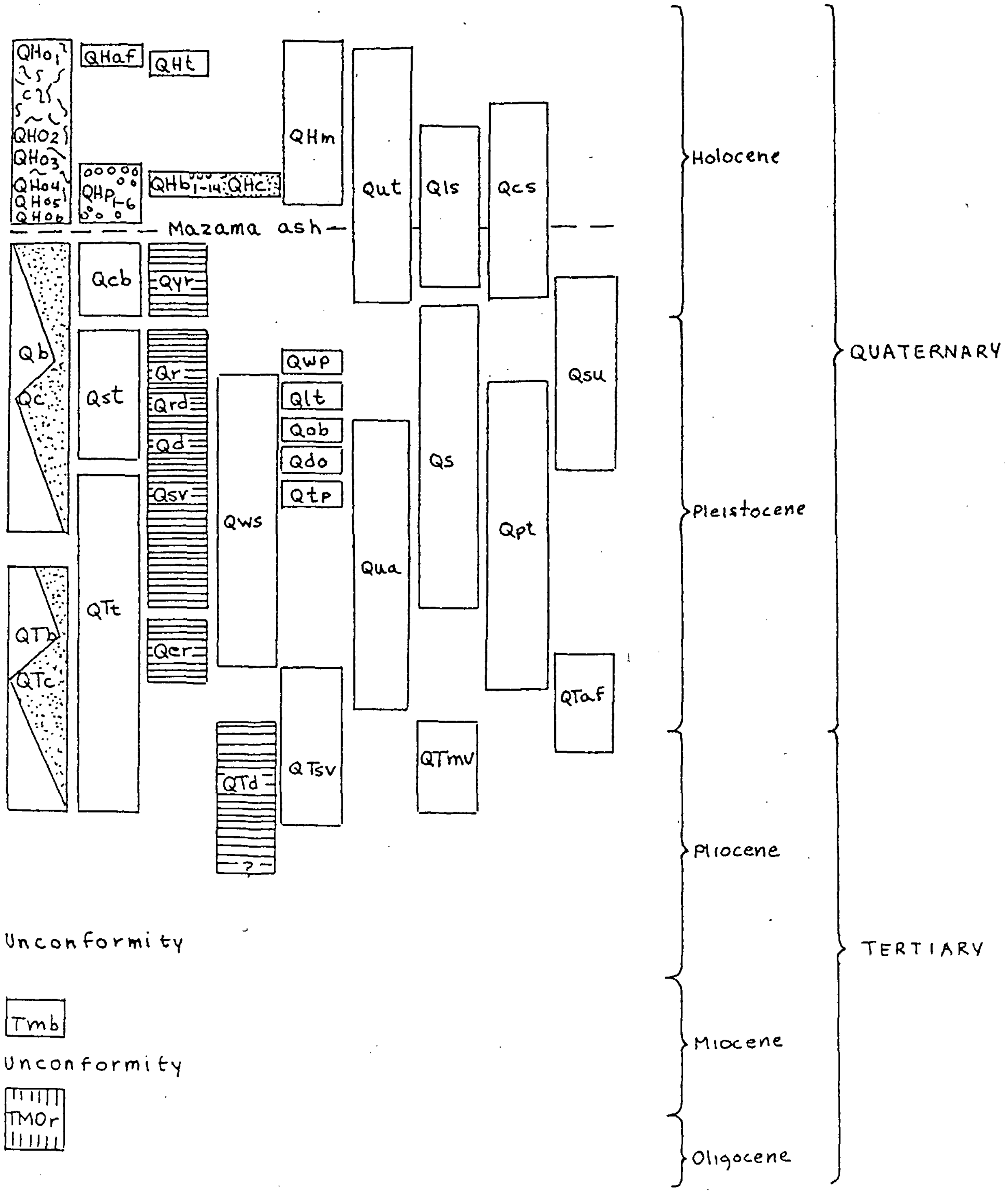
E. H. McKee has determined the K-Ar age of many of the rock units on and adjacent to Newberry Volcano. A complete list of these K-Ar ages and the locations of the samples is given in Fiebelkorn and others (1982). Some K-Ar ages, determined on whole rocks and on plagioclase, do not correspond to known geologic relations and some replicate age determinations on individual rock bodies are discordant. This apparently is caused by the combination of relatively youthful age, low potassium content, and large degree of contamination by atmospheric argon; also some anomalously old ages probably result from incorporation of radiogenic argon in the rocks when they formed. We refer in the rock descriptions below only to those K-Ar ages which we consider to be reliable or for which we have insufficient data to constrain the age.

A large number of Newberry rocks have been analyzed (see particularly Higgins, 1973, and Beyer, 1973) and we augmented these with numerous new analyses. In the rock descriptions below we refer principally to the SiO_2 content rounded to the nearest weight percent and based on analyses that have been recalculated water-free to 100 percent.

The volcanic rock names used in this report are based largely on chemical composition; rocks for which analyses are not available were compared petrographically to analyzed rocks. We classify the rocks in 5 percent increments of SiO_2 content as follows: basalt, less than 52; basaltic-andesite, 52-57; andesite, 57-62; dacite, 62-67; rhyodacite, 67-72; and rhyolite, 72 or more. Although rocks which crop out at Newberry Volcano form a bimodal assemblage in which basaltic-andesite with about 54 percent SiO_2 and rhyodacite and rhyolite with 72 percent dominate, analyzed rocks include every SiO_2 percent from 47 to 75.

———·······	CONTACT--Approximately located or inferred. Dotted where concealed (caldera only; concealed unit shown in bracket, surficial unit without bracket)
- - - - - - -	MARGIN OF INDIVIDUAL Qb FLOW--Based partly on interpretation of aerial photographs
┼┼┼┼┼┼┼┼┼┼	INFERRED POSITION OF SUBSURFACE FISSURE
——•——······	FAULT--Dotted where concealed; ball on apparent downthrown side
••••••••••••	INFERRED CALDERA RING FAULT--Ring faults are entirely concealed and lie near or inward from indicated position
—— 2 ——	ISOPACH OF QHt--Contour interval is 0.25 m.
× 172	THICKNESS OF QHt--numbers are in centimeters.
—·—·—	ISOPACH OF QHc CINDER FALL DEPOSITS--Contours are in centimeters; t = trace
X	LOCATION OF VENT FOR QHo, QHp and Qyr
⌖	U.S.G.S. GEOTHERMAL WELLS IN CALDERA AND ON NORTHEAST FLANK
×H.S. •F.	HOT SPRINGS (H.S.) AND FUMAROLE (F.) IN CALDERA

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

QHo$_{1-6}$ RHYOLITIC OBSIDIAN FLOWS IN CALDERA (upper Holocene)--Flows consist of banded, massive to vesicular or pumiceous, nearly aphyric obsidian. Most obsidian is dark gray or black; brown colored obsidian locally results from collapse of originally vesicular or pumiceous slightly oxidized obsidian. Surfaces of flows have concentric ridges and valleys formed of blocky dense to pumiceous obsidian and contain scattered small craters, possibly of phreatic origin. Flow fronts are generally steep and as high as 25 m. Vents for flows are shown by "X". Includes:

QHo$_1$ Big Obsidian flow--Age about 1,300 years based on ^{14}C age of underlying QHaf and hydration-rind age of obsidian. Flow is youngest volcanic unit on Newberry Volcano. 73 percent SiO_2.

QHo$_2$ East Lake obsidian flows--Hydration-rind age is 3,500 years. Probably fourth oldest unit; older than QHo$_1$, QHaf, and QHt. 73 percent SiO_2.

QHo$_3$ Central Pumice Cone obsidian flow--Hydration-rind age is 4,500 years. Reported age is younger than that of Central Pumice Cone (6,700 years); ages may both be 6,700 years if, as seems likely, the flow represents the remains of a ponded lava lake (see Qhp$_1$). 73 percent SiO_2

QHo$_4$ Game Hut obsidian flow--Hydration-rind age is 6,700 years. May be derived by draining of former lava lake interpreted to have partly filled Central Pumice Cone. 73 percent SiO_2.

QHo$_5$ interlake obsidian flow. Hydration-rind age is 6700 years. Younger than Central Pumice Cone. 73 percent SiO_2.

QHo$_6$ unnamed small pumiceous obsidian flow in pumice ring east of Big Obsidian flow. Undated: does not have obvious Mazama ash on its surface, but is covered by pumice fall deposit (QHT) and conceivably may be older than Mazama.

Hydration-rind ages reported above are by Friedman (1977). Numerous chemical analyses of flows by Williams (1935), Laidley and McKay (1971), Higgins (1973), Beyer (1973), and MacLeod (unpublished data) show that the obsidian flows differ only slightly in chemical composition. Laidley and McKay (1971) show that the Big Obsidian flow is homogeneous in chemical composition, based on 91 analyses. The flows and related tephra deposits (QHt, QHaf, QHp, Qut), as well as some slightly older rhyolites (Qyr), differ from most other rhyolitic rocks on Newberry Volcano in their much higher Rb/Sr ratio and to a lesser extent in their content of other trace elements. Chemical similarities suggest all the young relatively evolved rhyolites are derived from the same magma, even though erupted over an interval exceeding 6,000 years. Chemical differences, though slight, suggest the SiO_2 and K_2O content is systematically lower for progressively younger rocks and that systematic changes also occur for other major oxides and trace elements (Laidley and McKay, 1971; MacLeod, unpublished data). Also, even though most of the rocks are nearly aphyric, the younger ones have progressively fewer phenocrysts.

QHaf ASH-FLOW TUFF OF PAULINA LAKE (upper Holocene)--Extends west and north of Big Obsidian flow to Paulina Lake. Typically consists of a massive poorly sorted pinkish-brown deposit of ash shards and pumiceous ash, lapilli, and blocks and less common ash- and lapilli-size accidental lithic fragments. Pumice blocks are most abundant near top of unit. Lapilli and blocks are rounded. Deposits on slopes southwest of Big Obsidian flow are complex. Holes dug in these deposits expose many thin ash-rich units which may be ash-flow cloud deposits or parts of a pumice ring associated with the vent. Deposits at the northeast end of unit consist of pinkish ash with only rare pumice lapilli, are massive to well bedded, and are ash-flow cloud deposits and secondary flowage deposits derived from them. They extend as deposits less than 20 cm thick east beyond mapped contact beneath a thin cover of reworked pumice deposits and also also occur locally (included in Qut) farther south along east side of Big Obsidian flow. Deposits of pumiceous ash, lapilli, and blocks that occur at the north margin of the unit along the shoreline of Paulina Lake are well bedded and may be of phreatic origin due to interaction of hot tuffs and cool lake water. Age about 1,300 ^{14}C years based on ^{14}C ages of 1,270±60 (Pierson and others, 1966), 1,340±60 (S. W. Robinson, written commun., 1979), and 1,390±200 years (Meyer Reubin, *in* Friedman, 1977); older age (2,054±230 years) reported by Libby (1952). Except for Big Obsidian flow (QHo_1), which overlies southern part of deposit, this is youngest volcanic unit on Newberry Volcano. Pumice in deposit is nearly aphyric, has 73 percent SiO_2, and is chemically indistinguishable from Big Obsidian flow (QHo_1) and pumice fall deposit (QHt) that extends across east flank of volcano.

QHt RHYOLITIC PUMICE FALL DEPOSIT (upper Holocene)--Derived from the same vent as the Big Obsidian flow (QHo_1) and covers southern part of caldera and east flank of volcano (Sherrod and MacLeod, 1979). Outcrop area and thickness shown by isopachs; numbers on map show thickness of fall at individual localities. Consists of well sorted angular light-gray pumice lapilli and lesser lithic fragments (red cinders, basalt, obsidian, rhyolite, etc.) and ash. Contains breadcrusted obsidian blocks and accidental blocks to more than 1 m in diameter in area extending 2 km east from vent. Deposits within 2 km of vent consist of many thin units in upper part and lower part was not penetrated even in deep holes dug in deposit. Between 2 and 9 km east of vent, upper part of deposit contains 1 to 5 pumice lapilli beds separated by centimeter-thick ash beds and overlies a thick lower massive part which forms most of the deposit. Farther from vent deposit consists of single unit which is coarsest-grained in lower one-third. Median grain size decreases regularly eastward from a diameter of 1.1 cm at 3 km, 0.75 cm at 15 km, to 0.3 cm at 45 km. 25-cm-isopach extends beyond east edge of map to a distance of 60 km from vent with its axis oriented N 82° E. Age about 1,600 ^{14}C years based on reported ^{14}C ages of 1,720±250 (Higgins, 1969) and 1,550±120 years (S. W. Robinson, written commun. 1979). Although related to QHaf, and probably essentially the same age, ^{14}C ages suggest QHt may have been erupted about 300 years before QHaf. Pumice is essentially aphyric and is uniform in composition in vertical section. It has the same major- and trace-element composition as QHaf and the Big Obsidian flow.

QHm PUMICEOUS MUDFLOWS (upper Holocene)--Poorly sorted pumiceous ash, lapilli, and blocks with rare accidental lithic fragments in deposits which fill floors of ravines. Pumiceous mudflow deposits on upper south flank overlie and are typically much coarser grained and more poorly sorted than QHt and may have been produced during eruptions that formed QHaf. Deposit in small ravine northeast of Paulina Lake probably formed immediately after adjacent pumice cones (QHp$_3$) which are only slightly younger than Mazama ash.

QHp$_{1-6}$ PUMICE CONE AND PUMICE RING DEPOSITS OF THE CALDERA (upper Holocene)--Consists of poorly to well bedded and sorted deposits of pumiceous ash, lapilli, and blocks that dip away from central craters. Flanks of cones are as steep as 20 to 30 degrees, and crater walls are also steep-sided. Rings have lesser topographic expression and lower slopes. Contacts of cones and rings with adjacent tephra deposits are arbitrary and largely based on geomorphic expression. Includes:

QHp$_1$ Central Pumice Cone, between Paulina and East Lakes. Hydration-rind age is 6,700 years (Friedman, 1977). Contains massive and agglutinated obsidian plastered onto the innerwall midway from the top that may represent a "bathtub-ring" remnant of a former lava lake. The Game Hut obsidian flow (QHo$_4$) may have been produced by draining of this lava lake and the obsidian flow in the crater of the cone (QHo$_3$) may represent the remnants of the lake.

QHp$_2$ pumice deposits that surround the vent at north end of interlake obsidian flow. Probable age is about 6,700 years.

QHp$_3$ pumice cone complex west of interlake obsidian flow. Younger than Mazama ash and older than interlake obsidian flow.

QHp$_4$ large pumice ring partly filled by Big Obsidian flow. Contains small satellitic crater on southeast side. No Mazama ash was noted on this ring deposit, but it is locally covered by other tephra deposits, is weathered, and may be older than Mazama.

QHp$_5$ elongate small pumice ring along inner south wall. Overlain by QHt and probably younger than Mazama ash.

QHp$_6$ poorly developed pumice ring near inner caldera wall south of East Lake. Overlain by QHt and probably younger than Mazama ash.

Game Hut obsidian flow (QHo$_4$) may fill the broad crater of an unmapped poorly preserved pumice ring. Probable pumice ring deposits around the vent for the Big Obsidian flow are included in Qut. The pumice blowout vent of Higgins (1973), at the top of the inner south caldera wall south of East Lake, may be part of a pumice ring, but it is completely buried by QHt. Air-fall pumice lapilli and ash deposits related to QHp are included in Qut. SiO$_2$ content about 73 percent; nearly aphyric.

QHb$_{1-14}$ BASALTIC-ANDESITE FLOWS (upper Holocene)--Flows occur mostly on the northwest flank of volcano in a zone popularly referred to as the northwest rift system. Most flows are of aa or block type and have very fresh, young-appearing surfaces with only sparse vegetation, except where covered by cinders from related vents (QHc). Tree molds occur in many of the flows and are abundant in some areas, especially along flow margins. Flows on upper north flank (QHb$_{9-11}$) contain rhyolite and pumice inclusions. Includes:

QHb$_1$ Lava Butte flow, northwest flank. ^{14}C age 6,160±65 years. 55-57 percent SiO$_2$

QHb$_2$ Gas Line flow, northwest flank. ^{14}C age 5,800±150, 6,050±65, & 6,150±65 years

QHb$_3$ Mokst Butte flows, northwest flank. Younger than Mazama ash, probably same age as other flows in unit. 56-58 percent SiO$_2$

QHb$_4$ unnamed flow on middle north flank. Younger than Mazama ash, probably same age as other flows in unit

QHb$_5$ north Sugarpine Butte flow, northwest flank. ^{14}C age 5,870±100 years. 51 percent SiO$_2$

QHb$_6$ south Sugarpine Butte flow, northwest flank. Younger than Mazama ash, probably same age as other flows in unit. 53 percent SiO$_2$

QHb$_7$ Forest Road flow, northwest flank. ^{14}C age 5,960±100 years. 54 percent SiO$_2$

QHb$_8$ Lava Cast Forest flow, northwest flank. ^{14}C age 6,380±130 & 6,150±210 years. 54 percent SiO$_2$

QHb$_9$ Lava Cascade flow, northwest flank. ^{14}C age 5,800±100 years. 54-56 percent SiO$_2$

QHb$_{10}$ unnamed flow on upper north flank. Younger than Mazama ash, probably same age as other flows in unit.

QHb$_{11}$ north summit flows. ^{14}C age 6,090±65 years. Overlies pumice fall deposits related to QHp$_{1,2}$ or 3. 55-56 percent SiO$_2$

QHb$_{12}$ Surveyor flow, south flank. ^{14}C age 6,080±100 years. 54-56 percent SiO$_2$

QHb$_{13}$ unnamed flow on upper south flank. Overlain by pumice-fall deposit (QHt), but no Mazama ash observed on flow. 54 percent SiO$_2$

QHb$_{14}$ The Dome flow, upper southeast flank. Overlain by pumice fall deposit (QHt), but no Mazama ash observed on flow.

Ages referred to above are by Peterson and Groh (1969), Chitwood and others (1977), and S. W. Robinson (written commun., 1978). These flows are all about the same age and no mafic flows are known to be younger. Chemical analyses indicate most flows are basaltic-andesite; the analyzed rocks, however, include basalt and andesite (see SiO_2 contents listed above). The rocks are fresh, dark gray, sparsely porphyritic, and vesicular. Phenocrysts consist of plagioclase with microphenocrysts of augite and olivine.

QHc CINDER CONE AND FISSURE VENT DEPOSITS (upper Holocene)--Rudely bedded bombs, blocks, lapilli, and ash which form cones, and agglutinated spatter with interbedded blocks, bombs, lapilli, and ash adjacent to fissures. Fissure vent deposits on the upper north flank locally contain small steep-walled pit craters as deep as 10 m. Flows adjacent to fissures are commonly fountain-fed and contact with agglutinated spatter of vent deposits is arbitrary. Thin cinder fall deposits extend leeward from most cones and fissures. Isopachs of cinder fall deposits associated with Lava Butte, south Sugarpine Butte, and Mokst Butte on the northwest flank are shown on map; note that Mokst Butte is a vent complex and has a cinder fall older than some of its flows and another younger than them. Cones and fissure vent deposits on middle and upper flank commonly contain scattered inclusions of rhyolite and fused vesicular rhyolitic glass. East Lake fissure on the caldera wall north of East Lake contains abundant inclusions of rhyolite, fused rhyolite, obsidian, etc. (Williams, 1935; Higgins and Waters, 1970). Age of the cinder cones and fissure vent deposits is about 6,100 ^{14}C years. East Lake fissure, the only post-Mazama basaltic vent in the caldera, has not yielded carbon for dating, but it is along an extension of fissure that fed north summit flows (QHb_{11}) about 3 km to the north which yielded a ^{14}C age of 6,090±65 years, and they are almost certainly the same age. The East Lake fissure overlies pumice-fall deposits, probably from vents (QHp_{1-3}) on the north side of the caldera, and Mazama ash.

Qut UNDIFFERENTIATED YOUNG RHYOLITIC TEPHRA DEPOSITS (Holocene)--Consists of several units of different ages, most of which are younger than Mazama ash. Recognized subunits include: (1)Widespread and thick pumice deposit, informally called the East Lake tephra deposit for excellent exposures in roadcuts near the southwest side of East Lake. It extends eastward from approximately the longitude of Central Pumice Cone (QHp_1) and covers most of the east side of caldera and the upper east flank of volcano. Deposit is typically 4 to 5 m thick and consists of several subunits. Lower 3 m formed of massive to vaguely bedded poorly sorted pumiceous ash, lapilli, and blocks; upper 1 to 2 m consists of thin interbeds of mud-armored pumice lapilli, accretionary lapilli, and pumiceous ash and lapilli. Pumice is sparsely porphyritic. Some large pumice lapilli have breadcrusted obsidian rinds; the pumice cores of these lapilli have unusually low density. Contains scattered accidental fragments, especially of palagonite tuff. Character of unit does not change substantially even where exposed in holes dug through it on very steep slopes. Unit probably is largely of phreatomagmatic origin. Location of vent(s) is not known, but is in eastern part of caldera, and may lie beneath East Lake. It is younger than Mazama ash, older than East Lake obsidian flows (QHo_2), and apparently older than Game Hut and Interlake obsidian flows ($QHo_{4,5}$), but has not yielded carbon for dating. Chemically it is similar to all post-Mazama rhyolitic rocks in caldera and has a SiO_2 content of 74 percent. (2)Thin deposits of fine ash locally overlie East Lake tephra deposit near the southwest corner of East Lake. This ash, which is similar to ash that overlies Game Hut obsidian flow (QHo_4), is younger but its vent(s) is not known. (3)Post-Mazama age pumice-fall deposits derived from post-Mazama vents (QHp) in the caldera, especially on the upper north and east flanks of the volcano. (4)Pumice-ring and pumice-fall deposits around and east of the vent for the Big Obsidian flow (see QHt). (5)Pumice and lithic deposits related to and surrounding the vent for the East Lake obsidian flows (QHo_2). (6)Pre-Mazama-age pumice deposits were found in holes dug in Qut on the upper north and east flanks and locally in the east side of the caldera. Pre-Mazama pumiceous tephra deposits also occur at several localities along the west rim of the caldera and on Paulina Peak dome (Qrd), but their distribution is too poorly known to show on map. As a consequence of poor exposure owing to lack of significant erosion, Qut could not be subdivided. It was studied in holes, as much as 5 m deep, dug in it at scattered localities. However, significant data relevant to location, composition, and age of the products of relatively recent volcanism in the caldera could be generated by a more thorough study of these deposits. It would require digging many deep holes.

MAZAMA ASH (Holocene)--Pumiceous ash and lapilli fall deposit derived from the climactic eruption of Mount Mazama (Crater Lake) in the Cascade Range 100 km southwest of Newberry. Not shown on map. Forms a surficial deposit of variable thickness that covers most of Newberry Volcano, except where buried by younger units. Ranges from about 1.2 m thick in southwest part of map to a few centimeters thick in northeast part where it is largely reworked; deposit in caldera is typically 50 to 55 cm thick. Forms a very useful time horizon with which to distinguish relative ages of young rocks. However, it locally has been removed from surfaces of older deposits by wind and to a minor degree is wind-blown onto younger deposits. Grain-size decreases northward and eastward. Near southwest corner of map deposit consists mostly of small angular pumice lapilli and crystals; in caldera the deposit is formed mostly of coarse ash and crystals. Mazama ash on Newberry is a multiple fall unit which is coarsest at the top and contains a characteristic very fine brownish-colored ash layer near its base. Charcoal commonly occurs beneath deposit, probably the result of large lightning-caused forest fires associated with the eruption. Crystals of plagioclase, orthopyroxene, clinopyroxene, and hornblende are abundant. Easily distinguished from pumice- and ash-fall deposits derived from Newberry Volcano, especially by abundance of crystals and presence of hornblende which is rare in Newberry rocks. Numerous ^{14}C ages range mostly from 6,600 to 7,000 years; probable age about 6,845±50 ^{14}C years (Bacon, 1982).

Qls LANDSLIDE DEPOSITS (Holocene)--Mostly older than Mazama ash, but includes talus aprons younger than Mazama. Mapped only near Paulina Peak; smaller unmapped deposits also occur locally at the base of the caldera walls in other areas, especially on the east side of East Lake.

Qcs ALLUVIAL AND LACUSTRINE DEPOSITS OF THE CALDERA (Holocene)--Consists of silt, sand, and gravel marginal to Paulina and East Lakes. Unconsolidated to well cemented pumiceous gravel and sand on the east shore of Paulina Lake, which are younger than adjacent mafic rocks (Qb and Qpt), contain abundant wood and <u>Equisetum</u>, are locally silicified, and were deposited when the water level was several meters higher than at present. ^{14}C age of wood from the deposit is 4,300±100 years (S. W. Robinson, written. commun., 1977); Mazama ash occurs on the wave-cut terrace at the top of this deposit, however, indicating the deposit is older than Mazama. Holes dug through a surface veneer of Mazama ash southwest of Paulina Lake penetrated pumiceous sand and gravel, probably also deposited along a former higher stand of the lake. Subsequent downcutting by Paulina Creek at the outlet of Paulina Lake has lowered the lake to its present level. Unmapped gravel deposits southeast of Paulina Lake beneath QHaf and Mazama ash are higher in elevation than Qs along the shoreline; they may have been deposited along a former drainage connecting East Lake and Paulina Lake. Pumiceous gravels around East Lake are of both post- and pre-Mazama age. A post-Mazama lake level about 4 m above the present level is recorded by rounded pumice on rude terraces developed on the interlake obsidian flow (QHo_5).

Qyr YOUNG RHYOLITIC DOMES AND FLOWS OF THE CALDERA AND UPPER SOUTHEAST FLANK (lower Holocene?)--Includes: (1)Dome exposed near inner caldera wall south of East Lake and an associated obsidian flow that extends northward to East Lake. Flow is buried beneath Mazama ash and 4 to 5 m of pumiceous tephra deposits (Qut and, on south part, QHt), but was identified in deep holes dug through them; large blocks of obsidian along the south shoreline of East Lake are derived from it. (2)Small domes and pumice-ring(?) deposits on the upper southeast flank. No Mazama ash was observed on them, but they are thickly covered by pumice-fall deposit (QHt) and likely are somewhat older than Mazama ash. Rocks in this unit are chemically similar to rhyolitic rocks that are younger than Mazama ash (QHo, QHt, QHaf, QHp, and parts of Qut), but different than older silicic rocks (Qr and Qrd). SiO_2 content is 73-74 wt. percent; very sparsely porphyritic (plagioclase).

Qcb BASALTIC-ANDESITE FLOWS IN CALDERA (lower Holocene and Pleistocene?)--Includes three flows, all of which are overlain by thick pumice lapilli and ash deposits (Qut) and by Mazama ash. (1)Interlake basaltic-andesite flow of Higgins and Waters (1967) occurs along east shore of Paulina Lake and is older than adjacent strand line sediments (Qcs). Vent is presumably buried by Central Pumice Cone (QHp_1). SiO_2 content 53-54% percent. (2)Sheeps Rump basaltic-andesite flow extends to near the northeast shore of East Lake; only its steep leveed margin protrudes through Qut and Mazama ash, resulting in dike-like outcrops. SiO_2 content is 53 percent. (3)Resort flow (Higgins, 1973) occurs southeast of East Lake. It extends beneath a veneer of Qut, Mazama ash, and, locally, QHt, to the east rim fissure near the top of the caldera wall. Flow has highly variable phenocryst content and it and the east rim fissure (included in Qc) range from basaltic-andesite to rhyodacite (SiO_2 ranges from 56 to 68 percent); they may be products of mixed magmas. Small fountain-fed flows, locally associated with other pre-Mazama basaltic vents on the north caldera walls, are included in Qc.

Qb BASALTIC-ANDESITE, BASALT, AND MINOR ANDESITE FLOWS OF THE FLANKS (lower Holocene and Pleistocene)--Typical flows are 0.5 to 3 km wide and 4 to 8 km long. Many flows on the lower and middle flanks are buried progressively upslope by successively younger flows. Levees, pressure ridges, and tumuli are common, and lava tubes are developed in some flows (Greeley, 1971). Older flows on the lower northern and southern flanks cover much larger areas than flows higher on the flanks, and extend many kilometers beyond map area (see Peterson and others, 1976). Flows showing inverted topography occur locally on lower northeast flank. Well preserved flow margins shown by dashed lines are mapped on the basis of field observation and on interpretation of aerial photographs; however, numerous other unmapped flow boundaries with lesser topographic expression are locally obvious. Older than Mazama ash. All flows whose magnetic polarity was checked with a field fluxgate magnetometer are normally polarized, thus likely formed during the Brunhes Normal Epoch (younger than about 0.7 m.y.). Flows with very well preserved surface features that suggest a relatively young age, perhaps 8000 to 15000 years, are particularly abundant on the southeast, middle southwest, and northwest flanks. The bulk of the flows, however, are probably much older than 15,000 years and many have pumiceous tephra deposits, gravel, cinders, and loess, as well as Mazama ash, on their surfaces. Some of these older flows are interbedded between Qlt, Qsu, Qdo, and Qtp. Of 88 chemical analyses (Williams, 1935; Higgins, 1973; Beyer, 1973; MacLeod, unpublished data) of mafic to intermediate rocks (mostly Qb, but also including analyses of other units), 12 have 47 to 52 percent SiO_2, 64 have 52 to 57 percent, and 22 have 57 to 62 percent. Thus, the dominant analyzed mafic rock is basaltic-andesite. These analyses tend to be biased toward younger flows, and many voluminous older flows, especially those low on the flanks of the volcano, probably have less than 52 percent SiO_2. On the other hand, silicic andesite flows with 60-62 percent SiO_2 were found at only a few localities. Higgins (1973) and Beyer (1973) recognize two chemical types of the mafic and intermediate rocks, one calc-alkaline, the other high-iron tholeiite. The calc-alkaline flows greatly dominate. They contain 16 to 19 wt. percent Al_2O_3, 7 to 9.5 wt. percent total iron oxide, and are similar in their major and trace element composition to mafic flows that form the dominant part of the adjacent Cascade Range (see, for instance, analyses in Taylor, 1978). Some of these flows have diktytaxitic texture, especially the more mafic ones low on the flanks. The tholeiitic flows contain 15 to 16 wt. percent Al_2O_3, 10 to 13 wt. percent total iron oxides, and are characterized by much higher content of TiO_2 and P_2O_5 than the calc-alkaline flows. The tholeiitic flows have been identified by Higgins (1973) in the caldera walls (included in Qws), but also occur locally on the flanks (Beyer, 1973). Flows of both types commonly are plagioclase- and olivine-phyric and some also contain clinopyroxene phenocrysts; opaque oxides and apatite microphenocrysts are more common and abundant in tholeiitic flows. Vents for Qb are marked by cinder cones and fissure vent deposits (Qc).

Qc CINDER CONE AND FISSURE VENT DEPOSITS (lower Holocene and Pleistocene)--Related to Qb and Qcb flows. Cones are formed of mafic ash, lapilli, blocks, bombs, and agglutinated spatter which, where exposed in artificial cuts, are well bedded. Fissure vents are mostly formed of agglutinated spatter. The color of the deposits is variable, but is commonly red, dark gray, or black; cinders in some cones are brilliant metallic blue, green, and red. Cinder cones range from a few tens of meters to 140 m high and from 100 m to about 1 km across. Craters are common at the tops of cones. Crater rims are commonly asymmetric, being higher on leeward and lower on windward sides; rims are locally absent on sides where flows emerge (flows transported vent deposits "piggy-back" on their surfaces away from vent). Many older cones have no preserved craters. Cinder air-fall deposits extend several kilometers leeward of some younger cones, such as Pilpil Butte on the upper north flank. Cones commonly occur in linear arrays (shown by barred lines on map) that are interpreted to be fed by fissures at depth. Depressions locally occur on opposite rims of individual cones over inferred fissures. Fissure vents generally parallel inferred fissures. Several fissures on the northwest flank labled Qc? are inferred based on morphology of the flows and lineaments on them, but do not have obvious associated pyroclastic material. Most cone arrays on the south flank trend NNE and those on the north flank trend NW; faults low on the flanks have the same orientations. Cone arrays near the caldera commonly are concentric to it; possible cone arrays on the middle north and northeast flank (not shown, but note cone distribution) may also be concentric to the caldera rim. Many cones and fissure vents, especially those on the upper flanks, contain inclusions of pumice and fused rhyolite as well as inclusions of more mafic rocks. A well known example is "Mixture Butte" on the west flank (Williams, 1935); rhyolitic rocks crop out near it and likely occur below it. A fissure on the southeast flank that cuts a rhyolite dome (Qer) contains inclusions of rhyolite similar to the dome and also contains pumice that appears to be derived from fusing and frothing the rhyolitic rocks. Some pumice inclusions at other vents, however, may be derived from buried pumice deposits such as in pumice rings associated with domes, or from mixed magmas. The young (but pre-Mazama ash) fissure deposits along the east rim of the caldera and the associated flow (Qcb) in the caldera are highly variable in composition, both chemically and petrographically, and may be the product of magma mixing.

Qsu UNDIFFERENTIATED SEDIMENTS AND INTERBEDDED PYROCLASTIC ROCKS OF THE FLANKS (Pleistocene)--Occurs mainly on the northeastern flank, but also present on the other flanks where it commonly occurs as windows surrounded by younger mafic flows (Qb). Formed mostly of unconsolidated alluvial sand and gravel which is rarely well exposed owing to cover of Mazama ash and of pumiceous tephra deposits from the caldera. Judging largely by float derived from Qsu, it commonly contains cobbles and boulders high on the flanks, gravel with interbedded cobble beds on the middle flanks, and sand and gravel on the lower flanks. Boulders and cobbles occur as float on steep slopes in areas covered by thick deposits of Qut on the upper southern, eastern and northeastern flanks and at the top of the caldera walls above Qws, suggesting that Qsu locally extends buried to the caldera rim. A few holes dug through the tephra penetrated these sediments. Angular rhyolitic to dacitic pumice lapilli occur as float derived from probable air-fall deposits in Qsu in many areas. Thick pumice lapilli deposits are particularly obvious near and as far as 7 km southwest of China Hat on the lower east and southeast flanks. Unit represents deposits of several different ages and may be intercalated with other units, but its contacts are difficult to establish. In many areas on the middle and upper flanks Qsu contains very abundant dark colored lapilli identical to those in Qlt. Some areas mapped as Qsu likely are primary deposits of Qlt rather than being reworked from it. Qsu on the flanks is largely the result of one or more periods of substantial erosion of the volcano with intermittant periods of explosive volcanism during the late Pleistocene.

Qs FLUVIAL AND LACUSTRINE SEDIMENT (Pleistocene)--Occurs in the La Pine Basin west of Newberry and near Horse Ridge northeast of Newberry. Deposits nearest the flanks are mostly alluvial fans and they grade outward to interbedded fluvial and lacustrine deposits which locally contain thick diatomite beds. Partly correlative with Qsu. Commonly contains abundant detritus derived from Qlt. Also includes alluvial deposits in the eastern part of the Cascade Range in the northwest corner of the map; some of these may be fluvio-glacial deposits.

Qst NEAR VENT RHYODACITE TEPHRA DEPOSITS OF THE FLANKS AND CALDERA (Pleistocene)--Consists of three unrelated deposits: (1)Deposit on the southwest flank consists of thick units of rhyodacitic ash-flow tuff and pumice-fall deposits; the large size of the lapilli and blocks in the pumice-fall deposit suggests a near vent location. SiO_2 content is about 70 percent; unit differs in composition from nearby Paulina Peak dome (Qrd) and adjacent obsidian flow (Qr) at caldera wall. (2)Deposit on the upper northeast flank, which yielded a K-Ar age of .07±.12 m.y., consists of unconsolidated to agglutinated pumiceous rhyodacitic air-fall deposits, welded tuffs that may also be of air-fall origin, and obsidian; the latter may be densely welded tuff. Locally occurs as well bedded steeply dipping deposits that may be remnant of pumice ring. Similar weakly agglutinated pumice deposits of probable air-fall origin were found in holes on pumice-littered small hill 2-1/2 km to northeast. SiO_2 content also about 70 percent, but differs in other oxides from southwest flank deposits. Porphyritic with plagioclase, hypersthene, and opaque phenocrysts. Welded tuffs at the top of the caldera wall sequence in the east wall (see Qws) have chemical compositions (Higgins, 1973, table 4, cols. 17 and 18) similar to these upper northeast flank deposits, also appear to be largely of air-fall origin even though mostly densely welded, and may represent part of the same deposit. (3)Qst deposit in caldera consists of massive to bedded pumice lapilli and ash that occur adjacent to rhyodacite dome (Qrd) along Paulina Lake; may be remnant of pumice ring related to dome.

Qr RHYOLITIC OBSIDIAN FLOWS (Pleistocene)--Includes flow at top of south caldera wall east of Paulina Peak and flow at northeast side of East Lake which extends to vent near top of north caldera wall. Both flows are mostly buried by tephra deposits (Qut; south wall flow also by QHt) and are bounded by probable caldera ring faults (outer south caldera fault, and inner north caldera fault). Flows are indistinguishable in major oxide and trace element composition, and phenocryst (plagioclase, trace hypersthene) proportion and characteristics, suggesting they are comagmatic and coeval. SiO_2 content 72.4 percent. Similar to Qrd and Qd in trace element composition but different than Qer and all Holocene rhyolitic rocks.

Qrd RHYODACITE DOMES AND FLOWS (Pleistocene)--Some domes are mapped based on very sparse outcrops combined with geomorphic expression. Large flow on upper south flank 5 km due south of East Lake does not crop out and was identified by digging deep holes through overlying veneer of pumice lapilli tuff (QHt) and gravel deposits (Qsu). Two probable domes on upper east flank (east and northeast of QHb_{14}) are almost entirely buried by QHt and Qut. Includes Paulina Peak dome (K-Ar age .24±.07 and .58±.4 m.y.), two domes in caldera along shore of Paulina Lake (K-Ar age .56±.4 and .58±.4, but likely younger than Paulina Peak dome), dome on upper east flank (K-Ar age .20±.03 m.y.), dome on west flank (K-Ar age .40±.15 m.y.), and numerous other domes which have not been dated or which yielded ages considered to be unreliable. Locations of dated samples are listed in Fiebelkorn and others (1982). SiO_2 content 68-72 percent; phenocrysts are plagioclase, ± hypersthene, ± augite, ± opaques. Several domes in widely scattered localities have the same chemical composition and phenocryst assemblage suggesting some are comagmatic and coeval.

Qd DACITE DOMES AND FLOWS (Pleistocene)--Occurs on southwest and northeast flanks. SiO_2 content 64-66 percent; phenocrysts include plagioclase, hypersthene, augite, and opaques.

Qer	OLDER RHYOLITE DOMES AND FLOWS (Pleistocene)--Known or inferred to be older than Qr, Qrd, and Qd. Includes domes and associated flows at China Hat (K-Ar age .80±.2 m.y.; reversely magnetized) and East Butte (K-Ar age .87 ±.04 m.y.; reversely magnetized) at the base of the east flank, three domes at and adjacent to McKay Butte (K-Ar age .60±.10; magnetization not known) on west flank, and four small domes on southeast flank (ages probably comparable to McKay Butte domes). SiO_2 content 72 to 75 percent; characterized by high Rb/Sr. Somewhat similar in chemical composition to Holocene rhyolitic rocks (QHo, QHaf, QHt, QHp, Qut, and Qyr). Aphyric to porphyritic with plagioclase, hypersthene, ± augite, ± Fe-olivine phenocrysts in glassy to felsophyric matrix. China Hat and East Butte domes lie on west end of age-transgressive belt of rhyolitic rocks which extends across eastern Oregon (Walker, 1974; MacLeod and others, 1975). The other rhyolitic rocks in this group may also relate to this age progression inasmuch as they appear to occur in groups alined northeast approximately parallel to the isochrons of the age-transgressive rhyolites.
Qsv	RHYOLITE, RHYODACITE, AND DACITE DOMES AND FLOWS, UNDIFFERENTIATED (Pleistocene)--Similar to other silicic rock units on flanks, but have not been chemically analyzed.
Qwp	ANDESITIC TEPHRA DEPOSITS OF UPPER WEST FLANK (Pleistocene)--Forms the surface of the upper west flank extending to the caldera wall. Unit changes characteristics toward caldera. Westerly exposures consist of numerous interbedded lapilli air-fall deposits and ash-flow tuffs. Fall deposits occur as beds that are mostly less than 1 m thick, are commonly slightly agglutinated to densely welded, and are formed mostly of lapilli. Ash-flow tuffs are as much as 3 m thick, poorly sorted, and weakly consolidated to slightly welded (in basal parts). Near caldera rim, as at Paulina Falls, consists mostly of dense agglutinated deposits of probable near vent air-fall origin. Along caldera rim north of Paulina Creek unit consists of dense flow-like deposits which have a streaky appearance and contain scattered accidental fragments suggesting a pyroclastic origin. Lapilli, bombs, and blocks in unit are pumiceous to scoriaceous, commonly contain accidental felsophyric inclusions, and are very porphyritic with plagioclase, orthopyroxene, and opaque phenocrysts. Ashy matrix contains abundant accidental lithic fragments. Juvenile fragments in deposit are mostly andesitic to dacitic (SiO_2 ranges from 61 to 66 percent). The deposits at the caldera rim north of Paulina Creek are basaltic-andesite with SiO_2 content of 52-53 percent (Higgins, 1973, Table 4, cols. 22-23). Unit has not yielded meaningful K-Ar ages. Overlies Qlt, which is locally exposed beneath it in the bed of Paulina Creek, and is banked against and locally overlies cinder cones (Qc)

and related flows on its west side. Mafic flows (Qb) on north side are younger than Qwp; talus obscures contact with Paulina Peak dome (Qrd), but Qwp is probably younger. Normally polarized. Qwp is youngest major pyroclastic-flow unit on flanks of volcano. Unit is as much as 50 m thick.

Qlt BASALTIC-ANDESITE LAPILLI TUFF (Pleistocene)--Occurs on west flank, and locally on northeast flank. Poorly to moderately consolidated massive poorly sorted dark-gray lapilli tuff. Lapilli and less abundant bombs are dark-gray, finely vesicular to pumiceous, have cauliflowerlike surfaces, and contain ubiquitous angular rhyolitic to basaltic inclusions; some silicic inclusions are fused and frothed. The abundant inclusions, found in virtually all lapilli, and the characteristic shape and color allow lapilli from this unit to be readily recognized. Matrix consists of dark colored ash with abundant accidental lithic fragments. Lapilli and matrix have the same normal magnetic polarity as measured by field fluxgate magnetometer which suggests emplacement temperatures above the Curie point. Lapilli tuff was probably deposited dominantly as ash flows. In largest of three isolated outcrop areas north of McKay Butte on middle WNW flank, however, unit is well consolidated due to palagonitization and has characteristics suggesting mudflow origin. Unit is deeply eroded and everywhere poorly exposed except where it occurs as possible mudflows. Parts of unit on west flank are formed of alluvium derived from lapilli tuff, but exposures are too poor to delineate juvenile and reworked deposits. Areas on north and northeast flank mapped as Qsu locally contain abundant detritus from Qlt; some areas mapped as Qsu likely are juvenile deposits of Qlt, but exposures are available only in holes dug in deposits. Unit has not yielded meaningful K-Ar ages. On west flank overlies basaltic flows derived from vents midway on flank and some silicic domes and flows which have K-Ar ages of about .4 m.y. Underlies Qwp in bed of Paulina Creek on upper flank at scattered localities too small to show on map. Older than basaltic flows (Qb) which border it on north and south sides. On northeast flank younger than Qdo and overlain by or interbedded in Qsu. Chemical analyses of lapilli indicate a basaltic-andesite composition with a SiO_2 content of 54 - 55 percent; slightly porphyritic with plagioclase phenocrysts and microphenocryts. Maximum thickness is about 35 m; original thickness probably significantly greater. Alluvial sediments on all sides of volcano contain abundant detritus derived from Qlt indicating original volume of Qlt before erosion was substantial, probably several tens of cubic kilometers.

Qob ASH-FLOW TUFF OF ORPHAN BUTTE (Pleistocene)--Dark-gray to brown very pumiceous ash-flow tuff adjacent to and near cinder cone which forms Orphan Butte on middle northeast flank. Also crops out intermittantly farther to the south. Apparently interbedded in Qsu, and younger than Qdo. Normally polarized. Contains abundant small plagioclase and hypersthene phenocrysts. SiO_2 content 66%; chemically similar to but slightly more mafic than Qdo.

Qdo DACITIC PUMICEOUS ASH-FLOW TUFF (Pleistocene)--Occurs in walls of ravines on middle northeast flank where it is overlain by or is interbedded in Qsu; base is not exposed. Dark-gray or brown poorly sorted pumice blocks, lapilli, and ash with minor accidental lithic fragments; obsidian fragments which are probably cognate are a ubiquitous minor constituent. Pumice blocks and lapilli are locally collapsed. Pumice has SiO_2 content of 66.5 percent and is moderately porphyritic with plagioclase, augite, hypersthene and opaque phenocrysts and microphenocrysts; obsidian fragments in matrix have same phenocrysts in same relative proportion. Normally polarized. Older than Qlt and younger than Qtp. Base of unit is not exposed and top is eroded. Maximum exposed thickness is 20 m, but probably originally much thicker.

Qtp ASH-FLOW TUFF OF TEEPEE DRAW (Pleistocene)--Crops out on lower east and northeast flanks. Consists of poorly sorted pumiceous ash, lapilli, and blocks which range from weakly consolidated in most northeasterly exposures to moderately welded higher on flanks. In individual outcrops degree of welding increases upward with most densely welded part at eroded top. Fossil fumaroles are locally common. Angular pumice float at one locality is derived from between overlying and underlying exposures of ash-flow tuff suggesting unit may be formed of more than one flow unit with an interbed of pumice lapilli air-fall tuff. Bordered by younger mafic flows (Qb) and buried upslope by progressively thicker gravel and sand deposits (Qsu). Contact with Qsu is arbitrary and largely based on most westerly occurrence of abundant Qtp float. In largest area of exposure overlies and surrounds kipukas of older basalt. Base not exposed (except adjacent to kipukas) and upper surface eroded; maximum preserved thickness is about 20 m, but originally much thicker. Pumice in ash-flow tuff contains 70-71 percent SiO_2 and has much higher P_2O_5 content (.33 - .36 percent) than any other analyzed Newberry rock of similar SiO_2 content. Pumice is porphyritic with relatively abundant plagioclase, lesser augite and Fe-rich olivine, and rare hypersthene phenocrysts. Differences in color and phenocryst abundance suggest that pumices have varied composition. K-Ar ages are .51±.25 and .7±.7 m.y.; most likely age is about .5 m.y. Normally polarized. Probably oldest major tephra unit on flanks of volcano and most likely associated with first period of caldera collapse. May be present in subsurface on other flanks, in which case volume is likely several tens of cubic kilometers.

Qua UNDIFFERENTIATED ASH-FLOW TUFFS (Pleistocene?)--Includes several unrelated ash-flow tuffs: (1)Very poorly exposed tuff on west side of China Hat rhyolite dome (Qer) on easternmost flank that was identified by abundant float of large rounded pumice blocks and by digging holes into deposit. Appears to be plastered on west side of China Hat dome (K-Ar age 0.8±.2 m.y.) and thus is likely younger. SiO_2 content 72 percent. Chemically similar to Qtp, but pumice is much darker colored; petrographically and chemically different than QTt. (2)Lithic-rich pumiceous ash-flow tuff on upper south flank about 3 km south of Big Obsidian flow. Well exposed basal vitrophyre of tuff has an anomalously steep dip (45 to 70° northeast). Contacts of tuff with surrounding rocks are not exposed; may be isolated kipuka of pre-Newberry rock. (3)Scattered ash-flow tuffs interbedded in Qsu

Qpt PALAGONITE TUFF CONES AND RINGS (Pleistocene)--Includes the following: (1)Tuff cones and rings in caldera on the southwest side of Paulina Lake and on the south side of East Lake (Higgins, 1973). Both are complexes representing more than one vent. The palagonite tuff along the south shore of East Lake contains abundant mud-armored lapilli and accretionary lapilli and also includes accidental blocks of more altered palagonite tuff similar to that found in East Lake tephra deposits (included in Qut). (2)Palagonite tuff plastered on the north caldera wall above interlake obsidian flow (QHo_5). Vent for tuff is in the caldera, probably buried on the north side. (3)Palagonite tuff cones at Moffitt Butte on the southwesternmost flank. Qb flows mapped on it are related to it, flows adjacent to it are younger and derived from vents higher on the flanks. Probably relates to a series of palagonite tuff cones, rings and maars which extend east-southeast beyond the map area to Fort Rock Valley.

Qws CALDERA WALL ROCKS (Pleistocene)--Several caldera walls are present, locally occurring one inside the other. These probably are result of several periods of collapse of caldera. Detailed descriptions of rocks in wall sequence are given in Higgins and Waters (1968) and Higgins (1973). Rocks which extend from the walls onto the flanks, such as Paulina Peak rhyodacite dome, are shown as separate units (Qwp, Qrd, Qr). (1) South wall: Rocks in the south outer wall are exposed at three localities south and southwest of Big Obsidian Flow (QHo_1). The westernmost locality is a small ledge of basalt (Williams, 1935) surrounded by landslide and talus deposits. The second and largest exposure occurs below Qr near Big Obsidian flow. From base to top it consists of: platy rhyolite; unconformably overlain by basaltic-andesite flows, cinders, and agglutinate deposits with rhyolitic pumice fall interbed and cut by basaltic-andesite dike; overlain by massive to bedded mafic lapilli tuff with abundant silicic inclusions (similar to those in Qlt); overlain by rhyolitic pumice lapilli tuffs, probably part of pumice ring and locally densely collapsed and welded by overlying flow; and upper obsidian flow (mapped separately as Qr). The third exposure lies a short distance east and consists of dacitic(?) pumiceous ash-flow tuff and overlying basaltic-andesite flows and agglutinate deposits; the contact between the two units is not exposed. The remainder of the outer south wall has no exposures. The inner south wall has exposures only due south of East Lake where rhyodacite crops out. The rhyodacite is locally highly sheared and may be part of a dome cut by faults subsidiary to the caldera ring fault. (2)East wall: Rocks in the east caldera wall form bold outcrops at Cougar Point above the central east side of East Lake and are discontinuously exposed farther north. At Cougar Point the section consists of basaltic-andesite, an overlying unexposed area which contains float of lapilli tuff similar in appearance to Qwp, and at the top a sequence of welded rhyodacitic pumice lapilli tuffs. The latter tuffs extend a short distance southward where they are locally unwelded and the lapilli not collapsed, and they have characteristics suggesting very near vent air-fall rather than ash-flow origin. North of Cougar Point the tuffs are discontinuously exposed and densely welded. Contacts of the basal basaltic-andesite at Cougar Point with other wall rocks are not exposed. The basaltic-andesite is steeply flow-banded, crops out as a narrow and steep east-west-trending ridge, and has cinders and agglutinate at its top. It most likely is an exhumed shallow dike, but conceivably could be a flow that was originally in a narrow ravine (topography now inverted). Immediately north of the bold outcrops are discontinuous outcrops of palagonite tuff below the rhyodacite welded tuff. Antidune orientations in the palagonite tuff indicate the vent is to the northeast. (3)North wall: The north side of the caldera has two apparent walls. The outer wall extends north of East Lake and has no exposures in it, but has mafic cinder vents on it. Wall sequence rocks are exposed on the inner wall from East Lake westward to Paulina Lake. North of East Lake an obsidian flow (mapped separately as Qr), whose vent is near the outer caldera wall, extends to the shore of East Lake where it probably is cut by the inner caldera ring fault. Farther west discontinuous exposures of the wall sequence consist of platy rhyolite, overlain by basaltic-andesite flows, cinder deposits, agglutinated cinders and bombs, and palagonite tuff. The principal palagonite tuff unit occurs at the top of the sequence, but a second palagonite tuff is interbedded in the basaltic-andesite unit below. The upper half of the caldera wall is tephra covered, but locally has pumice float at some horizons, and rounded boulders at others suggesting a correlation with Qsu. (4) West wall: Wall sequence is Qwp which is mapped separately. Age of the caldera wall rocks is not well known. Rhyolite at base of caldera wall southeast of Paulina Peak has K-Ar age of .81±.23 m.y., but is normally polarized and thus likely less than .7 m.y. Rhyolite in lower part of north wall at "The Spire" (for location see Higgins and Waters, 1968, fig. 7) has K-Ar age of .12±.01; this rhyolite may intrude wall sequence rather than being in sequence. Paulina Peak dome, cut by south caldera ring fault, but included in Qrd, has K-Ar ages of .24±.07 and .58±.4 m.y.

QTt ASH-FLOW TUFF OF THE CHINA HAT AREA (Pleistocene?)--Poorly consolidated to welded very pumiceous lithic-rich ash-flow tuff. Color varies from dark-gray to tan, pink, and black. Locally contains concentrations of large dark-gray to black pumice blocks at top which are as much as 1 m in diameter. Overlain by Qsu and Qb; contacts with adjacent QTv not exposed. Northern part of mapped extent based partly on exposures in holes dug through thin deposits of Qsu. K-Ar age 2.75±.49 m.y. Most likely derived from Newberry Volcano in which case the K/Ar age is not correct, but a source other than Newberry cannot be discounted. Similar in appearance to some ash-flow tuffs in the Pliocene Peyerl Tuff (K-Ar age about 4.6 m.y.) which crop out south of Newberry, but also similar to some ash-flow tuffs (Qtp, Qdo, and Qob) derived from Newberry. SiO_2 content 70 percent; slightly porphyritic with small plagioclase and rare Fe-rich olivine(?) phenocrysts.

QTaf ASH-FLOW TUFFS AND PUMICE LAPILLI AIR-FALL DEPOSITS NEAR THE DESCHUTES RIVER AREA (Pleistocene and(or) Pliocene)--In map area consists of two units which have different sources and compositions. The lower unit is rhyolitic in composition and consists of a pumice lapilli fall deposit as much as 6 m thick and an overlying weakly consolidated to welded pumiceous ash-flow tuff locally more than 6 m thick. Crops out in northwest corner of map north of Benham Falls and east and west of the Deschutes River; crops out more extensively north of map and west of the Deschutes River (Mimura, 1977, unpublished geologic map; Taylor, 1981). Isopachs of the pumice fall and orientation of imbricated pumice in the ash-flow tuff indicate they were derived from a vent west of Newberry along the eastern side of the Cascade Range (Mimura and MacLeod, 1978). SiO_2 content is 73 to 75 wt. percent; chemically zoned in vertical sections. Sparsely porphyritic (plagioclase, rare hypersthene and augite). K-Ar ages of this unit are 2.1±2.1, 2.50±2.0, and 4.0±2.0 m.y.; both the pumice fall and ash-flow tuff overlie rhyodacite at Benham Falls (QTsv) which has a K-Ar age of 1.75±.8 m.y. This relationship suggests that the age of the fall, flow, and rhyodacite are probably about 2 to 2.5 m.y. Normally polarized. The upper unit, an andesitic to dacitic ash-flow tuff, crops out in northeast corner of map; readily accessible exposures occur along U.S. 97. The tuff has a pinkish-tan to black color, contains pumice lapilli of varied color and chemical composition (SiO_2 ranges from 59 to 65 wt. percent), and is crystal-rich (plagioclase, hypersthene, augite). Unit crops out in large areas west and north of the northwest part of the map (Taylor, 1981; MacLeod, unpublished geologic map; Mimura, unpublished geologic map). Distribution of unit and orientation of imbricated pumice within it indicate that it was derived from a vent in the highland area near Broken Top volcano (Mimura and MacLeod, 1978; Taylor, 1981). K/Ar age is 2.58±2.2; overlies the lower unit, but is probably also about 2 - 2.5 m.y. old. Normally polarized. Poorly exposed ash-flow tuff on lower WNW flank surrounded by basalt flows (Qb) may correlate with QTaf or may be derived from Newberry Volcano.

QTb BASALT AND BASALTIC-ANDESITE FLOWS OF THE EASTERN PART OF THE CASCADE RANGE (Pleistocene and Pliocene?)--Occurs west of the Deschutes River. Widespread very plagioclase-phyric basalt or basaltic-andesite flows west and north of Benham Falls are derived from a large vent complex (QTmv) near Kiwa Springs, only part of which is in the mapped area. Other flows are derived from scattered vents (QTc) within and west of the mapped area. Includes flows of a variety of ages; some flows are older than QTaf, others are younger.

QTc CINDER CONES OF THE EASTERN PART OF THE CASCADE RANGE (Pleistocene and Pliocene?)--Also includes cinder cones related to QTmv on northwest, south, and southeast flank of Newberry. Generally more eroded than cinder cones related to Newberry Volcano.

QTsv RHYOLITIC TO DACITIC DOMES AND FLOWS OF THE DESCHUTES RIVER AREA (Pleistocene or Pliocene)--Largest body is a rhyolite or rhyodacite dome at Benham Falls which has yielded a K-Ar age of 1.75±.8 m.y. and which is overlain locally by QTaf. Smaller poorly exposed domes or flows southwest of Benham Falls are dacitic.

QTmv MAFIC VENT COMPLEXES (Pleistocene or Pliocene)--Occurs on lower northwest, southwest, and southeast flanks. Shield-like polygenetic accumulations of basaltic flows, tuff, and breccia. Green Mountain and small unnamed hill northeast of Lava Butte, both on the northwest flank, are locally overlain by QTaf suggesting that they are pre-Pleistocene in age. Green and Spring Buttes on the southwest flank may be kipukas of older rocks or may relate to early stages of growth of Newberry Volcano. Vent complexes on the lower southeast flank were mapped as Quaternary or Tertiary in the adjacent area to the east (Walker and others, 1967).

QTd DACITE OF THE SOUTHEAST FLANK (Pleistocene or older)--Occurs on Indian and adjacent Amota Buttes and consists of massive to flow banded dacite; probably a dome or dome complex. Very porphyritic with plagioclase, hypersthene, and augite phenocrysts and microphenocrysts set in glassy to finely crystalline matrix. SiO_2 content 64 to 66 percent (Beyer, 1973). Reversely polarized; older than surrounding basaltic flows (Qb). Northeast-trending fault has a much higher scarp where it cuts QTd than where it offsets adjacent Newberry basaltic flows (Qb), suggesting that QTd is much older than the flows and that the fault has had recurrent movement.

TMb BASALT FLOWS OF THE HORSE RIDGE AREA (upper Miocene)--Occurs in northeast part of map area and is well exposed along U.S. 20 and along Dry River. Consists of thin basalt flows, flow breccias, and interbedded near vent deposits of basaltic cinders, blocks, and bombs. Probably derived from scattered eroded vents within mapped area and to northeast. Cut by faults which are part of the Brothers fault zone (see Walker and Nolf, 1981). K-Ar age 7.6±.1 m.y.

TMOr RHYOLITE OR RHYODACITE (lower Miocene or upper Oligocene)--Crops out only in very small area along eastern border of map near latitude 43° 49' N, midway between China Hat and Horse Ridge. Crops out much more extensively to east (Walker and others, 1967) on and near Pine Mountain where it consists of rhyolite, rhyodacite, dacite, and andesite flows, domes, and near vent tephra deposits. K-Ar age 22.0±.4 m.y. from rocks in unit east of map area. Probably correlates with upper part of the John Day Formation.

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HYDROLOGY OF THE NEWBERRY VOLCANO CALDERA, OREGON

U.S. GEOLOGICAL SURVEY, Water Resources Division

Water-Resources Investigations Report 83-4091

HYDROLOGY OF THE NEWBERRY VOLCANO CALDERA, OREGON

by Edward A. Sammel and Robert W. Craig

U.S. GEOLOGICAL SURVEY Water Resource Division

Water Resources Investigation Report 83-4091

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Menlo Park, California

1983

UNITED SATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

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CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch (in)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
acre-foot (acre-ft)	1,233	cubic meter (m^3)

Most temperatures are reported in degrees Celsius (°C); for conversion to degrees Fahrenheit (°F), use the formula, °F = 9/5 °C + 32.

HYDROLOGY OF THE NEWBERRY VOLCANO CALDERA, OREGON

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ABSTRACT

Precipitation in the Newberry caldera is nearly in balance with evaporation, evapotranspiration, and streamflow. A small surplus of water, estimated to be in the range 2,500 to 6,500 acre-feet, is available annually for recharge to deep aquifers beneath the caldera floor.

Precipitation in the caldera is estimated to be about 35 inches annually (31,900 acre-feet) on the basis of multiple-regression analyses of records from 5 weather stations in the region and intermittent records from a storage gage in the caldera. Paulina Creek, the only surface outlet from the caldera, discharges at least 13,000 acre-feet per year (18 cubic feet per second) from Paulina Lake. Annual evaporation from two lakes, Paulina and East, is about 19 inches and 28 inches (2,100 acre-feet and 2,300 acre-feet), respectively, and annual evapotranspiration from vegetated areas in the caldera is about 13 inches (8,000 acre-feet). Evaporation was estimated by means of an empirical expression on the basis of measurements at the lakes during the summer of 1981 and by correlation with annual records at high-altitude lakes in the western United States.

Nonthermal ground and surface water in the caldera has small concentrations of dissolved solids in which calcium, magnesium, and bicarbonate ions predominate. Thermal waters from springs and wells have dissolved solids concentrations of 900 milligrams per liter or more and are characterized by high concentrations of sodium and sulfate.

Maximum temperatures measured in the Paulina and East Lake Hot Springs are 52°C and 62°C, respectively. Attempts to account for the origin of the hot springs on the basis of mixing relations and isotopic analyses were inconclusive. The springs probably represent mixtures of thermal and nonthermal water that are altered by hydrogen sulfide and carbon dioxide gases rising from sources beneath the caldera floor.

Temperatures in the lakes are higher than normal in the vicinity of the hot springs and at other places, apparently due to inflows of thermal water through

the lake bottoms. The contributions of thermal water probably amount to no more than a few hundred acre-feet per year and are neglected in the hydrologic budget.

East Lake loses water by seepage to the shallow ground-water system at rates that vary seasonally in response to precipitation and ground-water inflow. Lake levels are self-regulating within fairly narrow limits. Paulina Lake probably loses little water by seepage and its surface outflow is maintained by ground-water inflow from the East Lake sub-basin.

Observations in a Geological Survey drill hole in the caldera suggest that part of the surplus water in the caldera flows to aquifers at depths as much as 1,900 feet beneath the caldera floor. Potential recharge from the caldera to a deep geothermal reservoir is likely to be small and is probably limited to permeable flow paths in faults and ring fractures.

INTRODUCTION

Newberry Volcano is one of many large volcanic structures built during Quaternary time in the Cascade Range of Oregon. Situated on the eastern margin of the Range in west central Oregon, Newberry is impressive more for its areal extent (about 500 square miles) than for its height (less than 4,000 feet above adjacent terrain). Newberry is characterized by a large collapsed summit caldera similiar to those of two other Cascade Range volcanos, the former Mount Mazama in Oregon, and Medicine Lake Volcano in California. The caldera contains two scenic lakes, Paulina and East, and has been set aside as a recreational area within the Deschutes National Forest.

Newberry has been studied by geologists since the early years of this century, and interest has increased during the past 10 years as a result of its potential as a source of geothermal energy. This interest has led to the drilling of two research core holes as a part of the Geothermal Studies Program of the U.S. Geological Survey (USGS) and has been the impetus for the hydrologic study described in this paper.

The discovery of high temperature and heat flow in the caldera (Sammel, 1981; MacLeod and Sammel, 1982) has encouraged the belief that a high-temperature geothermal resource may exist at Newberry, but has left many unanswered questions regarding the nature of the resource. One of these questions concerns the possible recharge of meteoric water to an underlying hydrothermal reservoir. This report gives tentative conclusions as to the magnitude and nature of recharge beneath the caldera.

A previous study by Phillips (1968) of three lakes in the Cascade Range of Oregon, including East Lake, provided valuable background information as well as preliminary estimates of the hydrologic terms evaluated in the present study. Phillips drew his conclusions largely on the basis of extrapolations of data from other areas, some of them distant from Newberry. Our estimate of possible ground-water recharge does not differ greatly from that of Phillips, and we commend his hydrologic acumen which led to apparently valid conclusions on the basis of minimal and uncertain evidence.

We also acknowledge the following agencies and individuals whose support was essential to our work; George I. Chesley, District Ranger, Fort Rock Ranger District, Deschutes National Forest, and his staff for friendly cooperation and support of our test drilling and hydrologic studies over a period of 4 years; J. E. Vaughn, Silviculturist of the Fort Rock Ranger District, for the estimate of evapotranspiration; Robert Pennington of the Oregon Department of Fish and Wildlife and Robert Main, Water Master, District 11, Oregon Water Resources Department, for aid in interpreting streamflow records; and Joe Kipp, owner of the Paulina Lake Resort, and Robert Saling and Al Nesbitt, former and present owners, respectively, of the East Lake Resort for aid and helpful interest during our work at Newberry.

SCOPE AND METHODS OF THE STUDY

The study was conducted during the summer and fall of 1981 and was confined to the approximately 17 square miles within the caldera (fig. 1). Prior reconnaissance had showed that no springs exist on the flanks of Newberry, that only a few wells are located on the lowermost flanks, and that surface discharge of water from the mountain normally occurs only in Paulina Creek, a westward-flowing stream draining Paulina Lake.

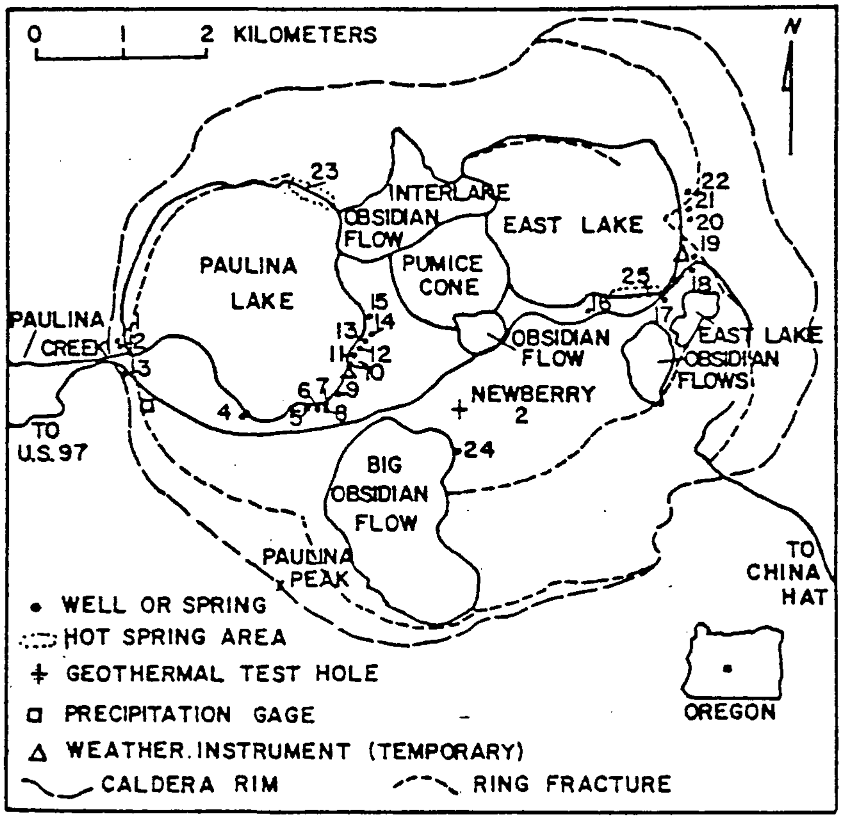

Figure 1. — Sketch map of the caldera at Newberry Volcano.

Information on ground water was collected from 22 water wells, two groups of warm springs, and two USGS drill holes. The hydrologic budget was estimated from data obtained both in the caldera and elsewhere in the region. The estimate of precipitation, based on multiple-regression analyses of records at Newberry and nearby stations, is thought to be the most reliable of the several estimates. All others involved a degree of subjective judgement that introduced large uncertainties into the estimates. Because the largest uncertainties pertain to the smallest terms in the budget equation, the results of the budget analysis are believed to be qualitatively correct and sufficiently accurate to justify the overall conclusions.

DESCRIPTION OF THE CALDERA

The physical characteristics of the caldera and its setting were described in detail by Phillips (1968), and the geology of the volcano was described in MacLeod and others (1981) and MacLeod and Sammel (1982). Only essential details are repeated here.

Newberry Volcano is a composite structure, made up of basalt and basaltic-andesite flows, andesitic to rhyolitic ash-flow and ash-fall tuffs and other pyroclastic deposits, dacite to rhyolite domes and flows, and alluvial sediments (MacLeod and others, 1981). The flows extend for tens of miles, principally toward the north and south. Massive tuffaceous deposits crop out on the flanks and probably underlie many of the younger basalt and basaltic-andesite flows.

The rim of the caldera lies at altitudes that range from 7,000 feet to 7,500 feet or more on the north, south, and east sides, but decrease to 6,330 feet on the west side at the outlet of Paulina Lake. The highest point on the rim, Paulina Peak, has an altitude of 7,985 feet, and is part of a large rhyolite dome.

The caldera is a steep-walled basin, about 5 miles long (east-west) and 4 miles wide. The rim of the caldera lies at altitudes that range from 6,330 feet on the west side to 7,985 feet at Paulina Peak on the south. Two lakes occupy much of the caldera floor. Paulina Lake has a surface altitude of about 6,333 feet, a maximum depth of 252 feet, and covers 1,345 acres. East Lake is smaller (980 acres) and shallower (170 feet depth) than Paulina Lake and lies at a higher altitude (about 6,375 feet). A large pumice cone and two obsidian flows separate the two lakes (fig. 1).

The caldera floor is a highly irregular surface formed largely of rhyolitic rocks, including domes, flows, and pumiceous tephra deposits. Basaltic-andesite and andesite flows and palagonite tuff rings occur in several places (MacLeod and others, 1981). Below these rocks, a few dacitic flows and thick sequences of alluvial and lacustrine sediments form the caldera fill which extends to a depth of at least 1,600 feet. Below the caldera fill are flow rocks that are similar in appearance and composition to the flank flows (MacLeod and Sammel, 1982).

Most of the caldera is densely forested with lodgepole pine, some yellow pine, fir, and alder, but nearly 20 percent of the land area is unvegetated rock, ash, or pumice. Depressions in the surface are mostly covered by pumice or other volcanic ejecta, fallen or washed in from adjacent slopes. Overland runoff from precipitation is nearly absent, even during heavy rainfalls. Ground-water flow probably occurs readily in the upper few tens of feet of permeable sediments, breccias, and the fractured tops of volcanic flows. Underlying flow rocks and tuffaceous deposits, exposed at the western end of the caldera, appear to have lower permeabilities and probably act as barriers to deep percolation.

CLIMATE

Summer daytime temperatures in the caldera reach 100°F at times, but nights are normally cool. Winter temperatures normally are below freezing, and subfreezing temperatures can occur in any month. The mean annual temperature is about 32°F. Prevailing windy conditions in the caldera cause high evapotranspiration during sunny periods and rapid cooling as storm fronts pass.

Precipitation patterns at Newberry are similar to those in most of the semi-arid region east of the Cascade Range in central Oregon, where most precipitation falls during the months of October through April. But orographic effects are significant at Newberry, and the volcano creates its own microclimate to a large degree. Rain or snow may fall in the caldera at times when the lower slopes and the adjacent valleys are in sunshine. The contrast between the climate at Newberry and that of the surrounding region is indicated by differences in the average annual precipitation at the three nearest weather stations. Annual precipitation at Newberry is about 35 inches, whereas that at Bend, 24 miles north, is 11.7 inches; at Fremont, 26 miles south, 10.9 inches; and at Wickiup Dam, 26 miles west, 20.5 inches. The nearby weather stations are at altitudes that range from 1,900 to 2,900 feet lower than the caldera.

THE HYDROLOGIC BUDGET

Estimation of Terms

The basic equation for the hydrologic budget of the caldera at Newberry Volcano is

$$P = OF + E + ET + S, \tag{1}$$

where P = precipitation in the caldera
OF = outflow to Paulina Creek
E = evaporation from lake surfaces
ET = evapotranspiration from land surfaces
S = seepage out of the near-surface hydrologic system.

The first four terms of the equation can be measured or estimated. The fifth term, S, is assumed to be equal to the residual needed to balance the equation.

In the absence of evidence for long-term trends in any of the terms, the seepage term, S, is assumed to be a long-term average seepage rate. As S is the residual in the equation, it contains all errors of measurement or estimation in other terms of the equation.

Precipitation

Records of precipitation at Newberry are available from a snow course and a precipitation storage gage. The snow course was maintained from 1955 to 1968 under the Cooperative Snow Surveys Program of the U.S. Department of Agriculture, Soil Conservation Service. Measurements were summarized in George and Haglund (1973). The precipitation storage gage, installed in 1965, is located south of Paulina Lake at an altitude of 6,400 feet (fig. 1). Records are published annually by the Oregon Water Resources Department. The average annual precipitation cannot be determined directly from the storage-gage data because of the difficulty of obtaining reliable winter measurements.

In order to estimate the average annual precipitation at Newberry Volcano the storage-gage measurements were supplemented by data from National Weather Service records at five stations in the region (table 1). Multiple-regression analysis of the data shows that two stations, Chemult and Wickiup Dam, have a significant correlation with reliable periods of record at Newberry despite being at lower altitudes (table 2, end of report).

The regression equation used to estimate precipitation at Newberry is

$$P = -0.137 + 0.246 (P_c) + 1.42 (P_w), \qquad (2)$$

where

P = average annual precipitation at Newberry, in inches

P_c = 30-year normal" (1959-1980) determined by the National Weather Service for the station at Chemult (25.6 inches per year)

P_w = "30-year normal" (1950-1980) at Wickiup Dam (20.49 inches per year).

The average annual precpitation at Newberry Volcano calculated from the regression equation is 35.3 inches. The coefficient of determination for the equation is 0.956. Reports from observers indicate that precipitation is virtually uniform over the caldera.

Phillips (1958) estimated the average annual precipitation at Newberry to be 35 inches on the basis of a comparison of the snow course records and National Weather Service records at Bend. J. E. Vaughn, Silviculturist with the Deschutes National Forest (written commun., 1982), estimated the annual precipitation at Newberry as 35.1 inches on the basis of records at six local stations, including the five used in this report, and unpublished U.S. Forest Service data. The precipitation estimate for Newberry is the most reliable of the terms in the hydrologic budget, with a probable error of less than 15 percent.

Surface-Water Outflow

Paulina Creek, which drains Paulina Lake on the west side of the caldera, is the only surface outlet from the caldera. The flow from the lake is partly controlled by a small concrete dam at the outlet except for periods during the winter and spring when lake levels exceed the spillway elevation of 6,332.8 feet. During the period April 1 to October 31, a sluice gate is used to maintain flow in order to satisfy water rights of a ranch located at the base of the mountain. During the late fall and winter, efforts are made to maintain a minimum flow of 2-3 cubic feet per second (ft^3/s) until the lake rises above the spillway (Robert Main, Water Master, Bend—written commun., 1982).

Table 1.-- National Weather Service stations in the vicinity of Newberry Volcano

Station	Location		Distance, direction from Newberry (miles)	Altitude (feet)	Average annual precipitation (inches)
	Latitude	Longitude			
Bend	44° 04'	121° 19'	24,N	3,599	11.7
Chemult	43° 14'	121° 47'	44,SW	4,760	25.6
Crater Lake	42° 54'	122° 08'	68,SW	6,475	67.4
Fremont	43° 20'	121° 10'	26,S	4,512	10.9
Wickiup Dam	43° 41'	121° 41'	26,W	4,358	20.5

Unpublished stream-flow records are available from 1966 to the present. Measurements were made by the Oregon Department of Fish and Wildlife between 1966 and 1974, and by the U.S. Forest Service from 1975 to the present. Flow estimates based on the measurements are shown in table 3. Most of the measurements were made in the months May through September and the estimates for this period given in table 3 are averages calculated after elimination of the high and low values for each month. These estimates are considered fairly reliable.

The data available for the winter months may be unreliable and misleading. A few lake-stage measurements indicate that flows during the winter can be as great as 30 or 35 ft^3/s, but reports from observers suggest that flows are normally below these values. Calculations show that a discharge rate of 30 ft^3/s for 5 winter months would lower the lake level 6.7 feet unless replaced by ground-water inflow. It is unlikely that winter ground-water discharge to the lake could replace the approximately 9,000 acre-feet of water that would be lost during so long a period of sustained high flow. Estimates for the period October through April in table 3 represent the calculated distribution of discharge on the basis of an average annual flow of $18^3/s$.

Table 3. -- Measured and estimated discharges, in cubic feet per second, from Paulina Lake to Paulina Creek

[Based on measurements by the Oregon Department of Fish and Wildlife (1967-1974) and the U.S. Forest Service (1975-1981). See text for explanation of estimated averages]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1967	---	---	---	---	22	---	---	---	---	---	---	---	
1970	49	---	---	21	22	20	16	15	15	---	---	25	
1971	---	---	34	32	38	---	---	---	15	---	---	22	
1972	---	---	---	---	23	25	---	---	---	---	8	18	
1973	---	34	---	---	---	10	13	---	---	---	16	20?	
1974	---	---	34	---	---	35	36	24	15	12	4	30?	
1975	---	---	---	---	29	40	30	22	21	12	---	26?	
1976	---	---	---	---	---	---	26	15	15	15	15	---	
1977	---	---	---	---	22	14	15	15	14	---	3	---	
1979	---	---	---	30	30	21	24	14	14	5	2	---	
1980	---	---	---	---	26	20	16	---	---	---	---	---	
1981	11	---	---	---	---	---	22	22	---	---	---	---	
Estimated monthly average	15	16	20	30	25	22	21	17	15	10	10	15	18

Phillips (1968) estimated the annual discharge as 20 ft^3/s on the basis of seven measurements made in summer months between 1903 and 1962. His distribution of monthly averages is similar to that in table 3. Personnel of the U.S. Forest Service and the Oregon Department of Fish and Wildlife who are familiar with the area agree that the annual figure probably is close to 20 ft^3/s, with a probable lower limit of 18 ft^3/s (J. E. Vaughn and Robert Pennington, personal commun., 1982).

Evaporation from Lake Surfaces

Evaporation from lake surfaces in the caldera has not been directly measured. Evaporation from nearby lakes at altitudes of about 4,000 feet was estimated to be 33 inches annually (Farnsworth and others, 1982). As the lakes at Newberry are at altitudes greater than 6,300 feet, they probably have lower evaporation rates, primarily because of cooler temperatures and greater humidity due to increased precipitation. Phillips (1968) estimated an annual evaporation rate of 28 inches partly on the basis of a comparison with Crater Lake, Odell Lake, Wickiup Dam, and Davis Lake, and partly by means of an adjustment for altitude to a rate of 34 inches determined by Kohler and others (1959) for lakes elsewhere in the western United States.

During July, August, and September, 1981, measurements of windspeed and direction, temperature, and relative humidity were made at each lake in order to estimate evaporation by means of a quasi-empirical mass-transfer expression (Harbeck, 1962):

$$E = Nu_z(e_o - e_a), \tag{3}$$

where E = evaporation from lake surface, inches per day (in/d),

N = Mass-transfer coefficient, constant for a specific lake (dimensionless),

u_z = windspeed at some height z above the water surface, miles per hour (mi/hr),

e_o = saturation vapor pressure in millibars (mb) calculated from temperature of the water surface, and

e_a = vapor pressure of the incoming air mass (mb).

Ideally N is calibrated by an energy budget study over a period of one or more years. If this is not possible, Harbeck suggests using the empirical relationship

$$N = \frac{0.00338}{A^{0.05}}, \qquad (4)$$

where A = surface area of the lake in acres. The windspeed, u_z, should be measured at a height of 2 meters above the lake surface at mid-lake. The saturation vapor pressure, e_o, preferably is calculated using daily water-surface temperatures at mid-lake. The vapor pressure of the air is taken from a station that best represents the incoming air mass unaffected by evaporation from the lake.

In this study, windspeed was measured at stations on the east banks of the lakes rather than at mid-lake. Water-surface temperatures are average monthly values for Paulina Lake obtained prior to 1981 by the Oregon Department of Fish and Wildlife. The measurements were assumed to be representative of East Lake also. The vapor pressure of the incoming air mass was calculated from daily minimum relative humidity and maximum-temperature measurements supplied by the U.S. Forest Service, Deschutes National Forest, for the Cabin Lake Guard Station at an elevation of 4,493 feet. The mass-transfer coefficient was calculated from equation (4), using a surface area of 980 acres for East Lake and 1,345 acres for Paulina Lake.

Measurements of windspeed and direction at Paulina Lake were made on the shore of the lake near Campsite No. 1 in Little Crater Campground. The East Lake site was on the east shore of the lake just north of the East Lake Resort boat ramp. Both sites were selected so that prevailing winds would be least affected by topography. Measurements were made by a single recording rotating-cup anemometer set approximately ten feet above lake level at each lake during alternate weeks.

During the 7 weeks of measurement at Paulina Lake, between 7:00 a.m. and 7:00 p.m. the winds were from the west, northwest, or north 83 percent of the time at an average speed of 5 1/2 miles per hour (mi/hr). From 7:00 p.m. to 7:00 a.m. the winds were from the east or southeast 80 percent of the time and averaged 1 1/2 mi/hr. During 6 weeks of measurements at East Lake, winds were from the west, northwest, or north 80 percent of the time during the day and from the east 65 percent of the time at night. Windspeeds during the day averaged about 7 mi/hr and at night about 4 mi/hr.

The daily average windspeed at Paulina Lake during periods of measurement was 3.9 mi/hr and at East Lake was 5.6 mi/hr. The ratio of these values, 0.70, was used to estimate average windspeed at each lake for weeks in which measurements were not obtained.

After substitution of the calculated value of the mass-transfer coefficient for East Lake, the equation of evaporation (3) becomes

$$E = 0.00240\ u\ (e_o - e_a),$$

where e_o = 17.77 mb for July, 19.19 mb for August, and 15.16 mb for September, and

u and e_a = daily measured values.

The equation for Paulina Lake is

$$E = 0.00236\ u\ (e_o - e_a),$$

with u, e_o, and e_a as above. The estimated total evaporation for July, August and September, 1981 is 13.3 inches at East Lake and 9.14 inches at Paulina Lake (table 4, end of report).

In order to relate the three-month total to an annual amount, evaporation measurements for 39 stations in California and Oregon were obtained from Blaney and Corey (1955) and Phillips (1968). Trials using multiple-regression analysis showed that total annual evaporation is reliably predicted by the three-month total if latitude and altitude are incorporated with data from stations at altitudes greater than 2,000 feet. Altitudes at 6 stations used ranged from 2,525 feet to 4,800 feet and latitudes ranged from approximately 35.0° to 43.6° north. The linear regression analysis indicated that 48 percent of the annual evaporation at Newberry occurs in the three-month period of actual measurement. The coefficient of determination for the regression was 0.60.

If it is assumed that the measurements in 1981 are typical of long-term conditions, the annual evaporation at Paulina Lake is 19 inches and at East Lake, 28 inches. The evaporation estimate for East Lake agrees with Phillips' (1968) estimate. The lower rate for Paulina Lake is due almost entirely to the lower average windspeed at Paulina Lake. Unknown windspeeds in the late fall and spring are a major cause of uncertainty in these estimates, and the measurement methods at the lakes also introduce large uncertainties. The resulting error of estimate is highly uncertain but probable compensating errors may place it in the range ± 20 percent.

Evapotranspiration

Evapotranspiration in the caldera was estimated J. E. Vaughn, U.S. Forest Service, on the basis of potential evaporation (PET) calculated by means of the equation (Hamon, 1961):

$$PET = 0.195 \; D \; P_t, \qquad (5)$$

where PET = potential evaporation (inches/month),

D = possible hours of daylight in units of 30 12-hour days, and

P_t = saturated absolute humidity (gm/m^3) at the mean monthly temperature.

Estimated annual PET is 13.6 inches (table 5). The actual evapotranspiration (AET) will be less than PET at any time during the year when adequate soil moisture is not available. The monthly soil-moisture balance calculated for the caldera (table 6) indicates that an average deficit of 0.06 inches occurs during August and 0.39 inches during September. Consequently, the annual evapotranspiration is estimated to be 13.1 inches.

Equation 5 is likely to underestimate evapotranspiration under the conditions that prevail at Newberry (Donald R. Satterlund, Washington State University, personal commun., 1982). Because of consistently high wind speeds in the caldera, evapotranspiration during summer months could be as much as 3 inches more than the estimate in table 6, and the budget term for evapotranspiration in table 8 may be low, therefore, by as much as 2,000 acre-feet.

Budget Calculation

In calculating the hydrologic budget, the value for precipitation was applied to the total caldera area and the evapotranspiration rate was applied only to the vegetated area (table 7). For the area without vegetation, all precipitation is assumed to result in recharge to shallow ground water. The calculations of the budget equation are shown in table 8 for each topographic basin and the total caldera. The apparent residual, 6,500 acre-feet annually for the caldera, is 20 percent of the total precipitation.

If the probable positive errors listed in table 8 were all additive, about 12,000 acre-feet of water would be available for seepage to the deep

Table 5.-- Calculation of potential evapotranspiration at Newberry caldera using the Hamon equation (Hamon, 1961)

[Calculated by J. E. Vaughn, Silviculturist, Deschutes National Forest. P_t = saturated absolute humidity, in grams per cubic meter; D = possible hours of daylight; PET = potential evapotranspiration]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Temperature, (°C)	-10.3	-6.6	-6.6	-1.6	+2.5	+5.4	+10.6	+9.5	+6.9	0.8	-3.3	-6.7	
P_t (gm/m^3)	2.13	2.85	2.86	4.30	5.72	6.91	9.71	9.12	7.62	5.10	3.71	2.81	
D (1 = 30 12-hour days of daylight)	.81	.82	1.02	1.13	1.27	1.29	1.30	1.20	1.04	.95	.80	.76	
PET (inches)	.34	.46	.57	.95	1.42	1.74	2.46	2.13	1.55	.94	.58	.42	13.56

Table 6.-- Calculation of soil-moisture balance at Newberry caldera

[For coarse soil with assumed maximum available soil moisture of 6 inches. Calculated by J. E. Vaughn, Silviculturist, Deschutes National Forest]

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Precipitation (inches)[1]	6.03	5.20	4.24	2.27	2.23	1.18	0.24	0.21	0.58	1.17	5.50	6.22	35.07
PET (inches)[2]	.34	.46	.57	.95	1.42	1.74	2.46	2.13	1.55	.94	.58	.42	13.56
AET (inches)[3]	.34	.46	.57	.95	1.42	1.74	2.46	2.07	1.16	.94	.58	.42	13.11
Change in soil moisture (inches)	0	0	0	0	0	-.56	-2.22	-1.86	-.58	.23	4.92	.07	----
Soil moisture (inches)	6.00	6.00	6.00	6.00	6.00	5.44	3.22	1.36	.78	1.01	5.93	6.00	----
Deficit (inches)	0	0	0	0	0	0	0	.06	.39	0	0	0	.45
Runoff (inches)[4]	5.69	4.74	3.67	1.32	.81	0	0	0	0	0	0	5.73	21.96

---

[1] Estimates by U. S. Forest Service based on records at 6 nearby weather stations.

[2] Potential evapotranspiration from table 5.

[3] Estimated actual evapotranspiration.

[4] Water available for ground-water recharge.

Table 7.-- Areas used in calculating the hydrologic budget

Area used	Paulina Lake topographic basin (acres)	East Lake topographic basin (acres)	Total caldera (acres)
Total	6,368	4,482	10,850
Vegetated	4,108	3,197	7,305
Nonvegetated	915	305	1,220
Lake surface	1,345	980	2,325

ground-water system. The summing of negative probable errors results in a negative seepage term and implies that there is an annual decrease of about 1,700 acre-feet of water in the lakes and the shallow ground-water system.

The thorough study by Phillips (1968) of levels of East Lake during the last 130 years shows rather conclusively that, although the lake has been at least 7 feet higher than at present during two abnormally wet periods, its mean level probably has not changed significantly in historic times. We assume, therefore, that the entire caldera is in a state of hydrologic balance, and that the long-term hydrologic budget must have at worst a zero net loss to deep ground-water percolation.

The apparent imbalance between the two basins probably is real, although it could be greater or smaller than the estimated one. If probable errors in estimates of evapotranspiration and the outflow to Paulina Creek are considered, it is likely that the Paulina Lake sub-basin has an annual deficit even if precipitation is 15 percent greater than the estimate. This deficit is presumably made up by ground-water inflow from the East Lake sub-basin, where there would be a surplus of water under almost any reasonable assumptions about probable errors in its budget. Westward movement of surplus ground water is virtually assured by the hydraulic gradient of at least 45 feet per mile between the two basins.

Table 8.-- Average annual hydrologic budget, Newberry caldera

[See text, "Budget Calculation" and "Discussion of Results", for an explanation of probable errors and most likely values]

	Paulina Lake basin (acre-feet)	East Lake basin (acre-feet)	Caldera (acre-feet)	Probable error (percent)
Precipitation [1]	(+)18,700	(+)13,200	(+)31,900	(+15,-10)
Evaporation from lakes [2]	(-) 2,100	(-) 2,300	(-) 4,400	(±20)
Evapotranspiration [3]	(-) 4,500	(-) 3,500	(-) 8,000	(+20,-0)
Outflow to Paulina Creek [4]	(-)13,000	----	(-)13,000	(+20,-0)
Residual [5]	(-) 900	(+) 7,400	(+) 6,500	(+45,-60)

[1] 35.3 inches

[2] Paulina Lake, 18.9 inches; East Lake, 27.8 inches

[3] 13.1 inches

[4] 18 ft^3/s

[5] Water assumed to be available for deep percolation.

During its residence and movement, a fraction of the ground water infiltrates the volcanic rocks beneath the surficial deposits and is removed from the shallow hydrologic system. Infiltration rates for the rhyolitic rocks in the caldera are probably high; those for the tuffaceous rocks may be low. A rate of 0.3 foot per year probably is a reasonable minimum value for the caldera, and this results in a lowest probable seepage estimate of about 2,500 acre-feet. This amount is about 10 percent of the annual precipitation on land surfaces.

An estimate of the highest probable value of the seepage term was calculated by assuming 15 percent greater precipitation, 20 percent less lake evaporation, 10 percent greater evapotranspiration, and 10 percent greater stream flow. The probable maximum amount of water available for deep percolation on this basis is about 10,000 acre-feet. (See below, "Discussion of Results", for a downward revision of this preliminary figure.)

CHEMISTRY OF SURFACE AND GROUND WATER

Major Ionic Constituents

Eleven of 22 wells in the caldera (table 9, end of report), three springs and gas vents (table 10, end of report), and the two lakes were sampled for chemical analysis. The results of the chemical analyses are shown in table 11. The identifying sequence numbers given in tables 9, 10, and 11 are used in the remainder of the report to refer either to the chemical analysis or to the well or spring from which the sample came.

Total concentrations of dissolved solids in the waters sampled range from 79 to 907 milligrams per liter (mg/L). Predictably, warm waters from wells and springs contain the higher concentrations. The lake waters are intermediate in concentration between these waters and the more dilute cold ground waters.

Water quality diagrams, modified from Stiff (1951), provide a convenient means for depicting relationships among the Newberry samples (fig. 2).

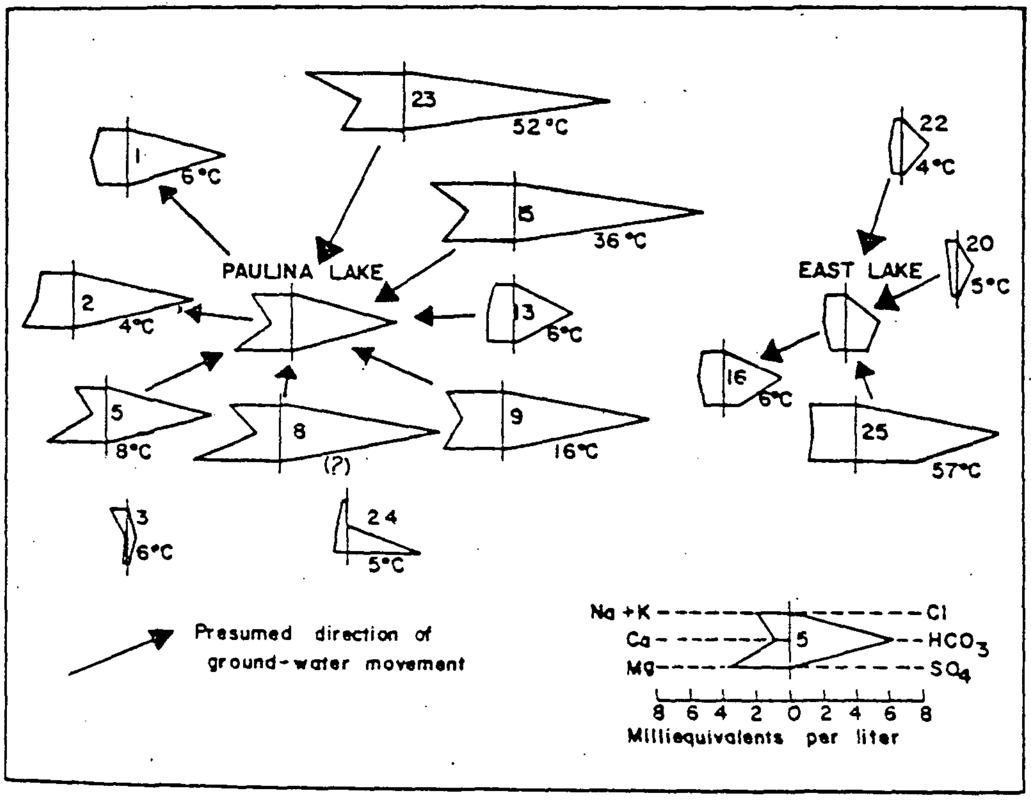

Figure 2. -- Stiff diagrams of the major chemical constituents in ground and surface water.

Table 11.-- Chemical analyses of ground and surface water

[Concentrations in milligrams per liter unless otherwise indicated. μg/L = micrograms per liter; μmho/cm = micromhos per centimeter]

Sequence Number[1]	Owner/ name	Temp. (°C)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	SiO_2	As	B	Fe	Li	Mn	Dis-solved solids[2]	Spec-ific cond. (μmho/cm)	pH	Date sam-pled	Source[3]
												(μg/L)									
1	Paulina Lake Resort	5-	35	24	28	6.1	315	5.0	2.8	0.3	29	1	460	120	13	11	286	400	6.95	10/07/81	A
		6.7	39	35	38	7.7	398	1.9	2.7	.4	33	2	700	180	--	1500	356	565	6.9	10/27/74	B
2	Paulina Lake Resort	4	44	39	44	6.4	450	6.0	3.1	.5	36	24	780	6700	88	2300	410	600	7.15	10/07/81	A
3	Paulina Guard Station (USFS)	6	3.3	2.6	6.5	1.8	27	5.0	.2	.7	46	3	20	23	17	<1	79	65	6.65	09/06/81	A
5	Mike Mathews (summer home)	8	18	41	41	5.0	376	2	2.6	---	90	--	--	--	--	—	--	(≈700[5])	6.97	06/30/82	E
8	Jack Hogg (summer home)	--	30	65	68	7.4	585	5.0	5.2	.8	110	39	1500	<10	120	2	581	900	6.15	09/06/81	A
9	Little Crater Picnic Area	16	42	44	64	8.3	535	5.0	4.6	.7	90	32	1600	180	100	30	532	710	6.80	10/07/81	A
13	Little Crater Camp Site 27	6	28	17	25	2.6	215	5.0	1.7	.3	46	16	570	43	29	10	232	360	7.10	10/07/81	A
15	Little Crater Camp Site 49	33	59	57	97	12	690	5.0	6.8	.5	156	<1	1800	360	140	270	733	900	6.21	09/06/81	A
		35.5	54	48	83	10	679	<1	5.1	.6	161	--	2500	4000	120	250	702	900	6.46	08/--/75	C
		36	56	51	96	12	691	2.5	4.5	.5	140	2	1000	5000	---	350	709	880	6.3	10/17/74	E
16	East Lake Campground well	6	33	15	26	6.0	200	43	2.8	.2	40	1	210	19	9	3	265	390	6.80	09/06/81	A
20	Cinder Hill Campground well	5	7.1	1.9	11	1.3	56	5.0	2.5	.4	30	5	10	27	8	5	87	110	6.70	09/06/81	A

Table 11.-- Chemical analyses of ground and surface water (Continued)

[Concentrations in milligrams per liter unless otherwise indicated. µg/L = micrograms per liter; µmho/cm = micromhos per centimeter]

Sequence Number[1]	Owner/ name	Temp. (°C)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	SiO_2	As	B	Fe	Li	Mn	Dissolved solids[2]	Specific cond. (µmho/cm)	pH	Date sampled	Source[3]
												(µg/L)									
22	Cinder Hill Camp Site 34	4	14	7.2	6.3	3.5	88	5.0	<.1	.1	34	<1	10	120	<4	57	113	140	7.20	10/06/81	A
23	Paulina Hot Springs	--	56	60	140	17	856	<1	6.0	.6	205	--	870	--	220	--	907	--	6.82	07/00/77	C
		50	51	43	120	16	699	4.0	4.7	.5	190	16	840	90	--	1700	776	960	6.9	10/26/74	B
		52	50	42	110	13	689	2	5.0	—	184	--	--	--	--	--	--	--	7.26	06/30/82	E
24	Lost Lake gas vent	5	13	8.2	7.9	1.1	0	200	1.1	0.0	31	1	180	15000	—	450	--	400	3.4	10/27/74	B
25	East Lake Hot Springs	49	70	34	53	--	547	28	.7	.2	199	--	1100	660	40	900	658	767	6.42	08/00/75	C
		55	77	39	59	9.7	581	20	1.3	.1	120	1	260	500	--	1400	614	840	6.7	10/26/74	B
		57	73	33	56	9.7	413	120	1.3	—	197	--	--	--	--	--	—	--	6.10	06/30/82	E
--	Paulina Lake[4]	--	26	39	47	5.2	352	3.8	2.8	.6	46	--	--	--	--	--	366	566	8.8	09/10/60	D
		6	28	38	47	5.0	402	4	2.4	—	--	--	--	--	--	--	--	--	8.38	06/30/82	E
--	East Lake[4]	--	27	13	27	4.5	120	64	.3	.2	10	--	640	20	--	--	206	334	7.8	00/00/73	E
			26	10	23	3.7	125	59	.2	.1	13	--	--	--	--	--	197	323	8.1	09/11/60	D
		10	25	11	24	3.7	123	64	<1	--	8.8	--	--	--	--	--	--	--	8.07	06/30/82	E

---

[1] Sequence No. ---- Identifying number used in tables and illustrations.

[2] Estimated by summation of HCO_3 x 0.4917 and other ions listed (Hem, 1970).

[3] Source of data or collector (USGS): A: R. W. Craig; B: N. E. Voegtly; C: R. H. Mariner, and others (1980); D: K. N. Philips (1968); E: R. H. Mariner (unpub. data, 1981, 1982).

[4] Sample (6/30/82) obtained at a depth of 45 feet near the center of the lake.

[5] Estimated.

The diagrams are arranged in a pattern roughly corresponding to the locations of wells and springs in relation to the two lakes. Waters with similar chemical compositions have similar shapes, and the arrows connecting the diagrams indicate presumed flow relationships in the shallow hydrologic system.

As shown in the sketch map, figure 1, the wells in Newberry caldera are clustered near the two lakes. The diagrams in figure 2 show that each lake water is similar to adjacent ground water and that most samples obtained in the Paulina Lake topographic sub-basin differ in character from waters in the East Lake sub-basin. In ground waters sampled near Paulina Lake, dissolved sodium, magnesium, and bicarbonate predominate. Concentrations of chloride and sulfate are low and silica concentrations range from 29 mg/L in cold well water (No. 1) to 205 mg/L in the Paulina Hot Spring (No. 23) (table 11).

In contrast to most samples from the western half of the caldera, samples from the East Lake sub-basin are characterized as calcium bicarbonate waters. Total concentrations of dissolved solids are lower than those in the western sub-basin. Chloride concentrations also are lower, and even the hot-spring water (No. 25) has a lower chloride concentration than most cold waters in the Paulina Lake area. Silica concentrations in the eastern ground waters have a range similar to that in the western waters (30 to 197 mg/L), but sulfate concentrations in East Lake, the East Lake hot springs, and a cold well (No. 16) are significantly higher than any concentrations in the Paulina Lake area. Silica concentrations in both lakes are unusually low in relation to other constituents, probably as the result of diatom scavenging.

East Lake itself probably is a definitive indicator of the ground-water character in its sub-basin because it has no surface outlet and it acts as a sink for ground-water flow from a large proportion of the sub-basin. Relying on East Lake as an indicator, therefore, we conclude that most ground water in the eastern part of the caldera is more dilute than ground waters in the western part. In East Lake itself, it might be expected that the higher evaporation rate relative to Paulina Lake would lead to greater concentrations of dissolved solids. The observed lower concentrations in East Lake probably result from dilute ground water inflow that effectively balances the ground-water outflow plus evaporation. This conclusion is discussed further in the final section of this report.

Relations among major ions indicate that the water in East Lake could be produced by mixing ground water similar to that in samples 20 or 22 with thermal water similar to that in sample 25 (East Lake Hot Spring). The mixing ratios range from 2.3 to about 9 to 1, depending on the sample and the ions used in the mixing calculation. The relatively high chloride concentration in sample 20 does not fit this mixing model, however, and suggests that the hot-spring water might be produced by mixing the ground water of sample 20 with lake water in a ratio of 1.25 to 1. Evidence from isotope analyses, discussed below, casts doubt on both of these simple mixing models, however, and further discussion of the origin of the waters is deferred to the following section of this report.

Subsurface discharge may occur from both lakes. Evidence for subsurface discharge from East Lake occurs in well 16, where both the water chemistry and the water level suggest that ground water moves from the lake to this location. In the Paulina Lake sub-basin, the chemistry of samples 1 and 2 show that these well waters probably originate in the lake and are slightly altered by residence in lake-shore sediments. Water levels in these wells are at least 5 feet below lake levels, whereas levels on the north, south, and east shores of the lake appear to be higher than lake levels.

Thermal water occurs in at least two wells in the Paulina Lake area. Concentrations of both chloride and silica in samples 9 and 15 are greater than those in other waters and the temperatures are higher. The temperature in well 8 is unknown, but the concentrations of silica and chloride, as well as the total concentration of dissolved solids, suggest a thermal component in this water also. These three waters have compositions similar to that of the Paulina Hot Spring water, possibly indicating that thermal waters occur widely near the center of the caldera and perhaps beneath the lake. Measurements of temperature in Paulina Lake, described in the next chapter, delineate several areas where thermal waters probably enter through the lake bottom.

In the East Lake sub-basin, thermal water is known to discharge only in the East Lake Hot Springs, although temperature measurements in the lake suggest that small amounts of thermal discharge also occur elsewhere. The East Lake Hot Spring water is similar to the Paulina Hot Spring water in many respects, but has higher concentrations of calcium and sulfate. The higher sulfate concentrations are probably caused by oxidation of hydrogen sulfide gas dissolved in the ground water. The gas was not detected in the Paulina Hot Springs (R. H. Mariner, USGS, unpublished data 1982), and sulfate concentrations in the Paulina Lake sub-basin waters are uniformly low.

The apparent causal relationship between hydrogen sulfide gas and dissolved sulfate in the ground water is supported by the analysis of water from the Obsidian Flow gas vent (sample 24). The water is extremely dilute, but has the highest concentration of sulfate known in the caldera (table 11). The concentration of hydrogen sulfide in gas from this vent also is the highest measured in the caldera (R. H. Mariner, USGS, unpublished data 1982).

Graphs of conservative constituents that are not related as dissociation pairs may be useful as indicators of origins and mixing trends among ground waters. (See, for example, Sammel, 1980; Sammel and Craig, 1981.) Figure 3a shows the relations between chloride and silica in the waters of the caldera. These constituents are expected to reflect, more or less independently, the effects of water-rock interactions and exposure to heat in a geothermal environment as well as the degree of mixing of differing waters.

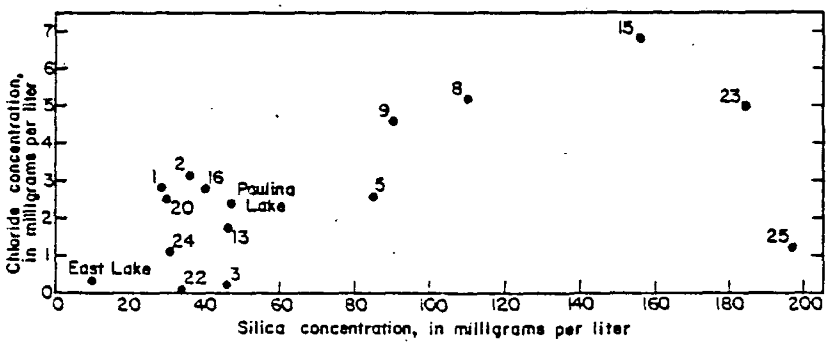

Figure 3a. — Relations between concentrations of selected chemical constituents: chloride versus silica.

Several possible trend lines are suggested by the data of figure 3a. One such trend includes samples 9 and 15 from wells near Paulina Lake, together with samples 1 and 2 from cold wells near the lake, and sample 8, a water of unknown temperature which probably has a thermal component. However, two other ground waters near the lake, 13 and 5, have chloride concentrations that place them below the upper trend line, and the hot-spring water (23) has less chloride than the low-temperature waters, 8, 9, and 15. The chloride concentration in East Lake Hot Spring (25) is exceptionally low but is in keeping with that of well 22 near East Lake and with East Lake itself. Two cold waters near East Lake, 16 and 20, have higher chloride concentrations than the East Lake Hot Springs. The chloride-silica relations, therefore, do not consistently distinguish thermal waters from nonthermal waters. The small number of samples, the extremely small range of chloride concentrations, and differing times of sampling contribute to uncertainties in the data that may be as great as the differences between most of the samples.

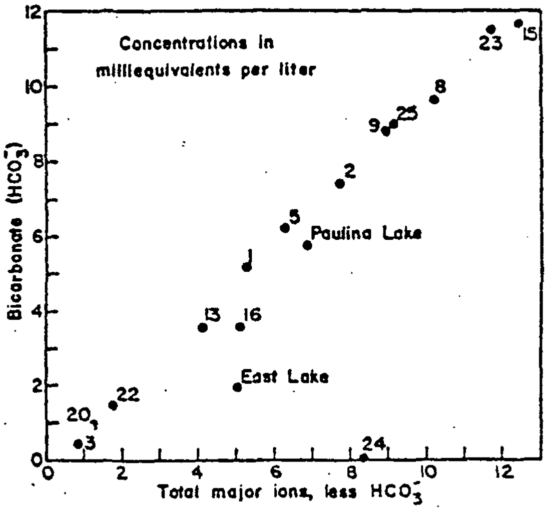

Figure 3b. — Relations between concentrations of selected chemical constituents: bicarbonate versus total major ions less bicarbonate.

Graphs of relations among other ionic species indicate that both thermal and nonthermal waters equilibrated in a low-temperature environment dominated by CO_2-HCO_3 reactions. One such graph is shown in figure 3b, where concentrations of bicarbonate, the dominant anion, are plotted versus the sum of concentrations of other major ionic species. The values occur in a nearly constant ratio through the range of total dissolved-solids concentrations. Departures from the linear trend occur only in well 16 and the Obsidian Flow gas vent (24), both of which have exceptional high sulfate concentrations, and in the two lakes, where carbonate reations probably differ from those in ground water. Ground waters in the caldera showed similar linear trends for all major ions except sulfate, thereby reinforcing the concept of a generally uniform chemical environment in which sulfate concentrations are controlled by an anomalous factor, presumably the contact with hydrogen sulfide gas.

Stable Isotopes in Surface and Ground Water

Concentrations of deuterium and oxygen-18 in meteoric water decrease with altitude and other factors in a relationship that is usually approximated by the expression, $\delta D = 8(\delta^{18}O) + 10$, where δD and $\delta^{18}O$ are ratios of these isotopes to ^{1}H and ^{16}O, respectively, expressed in parts per thousand (per mil) as departures from standard mean ocean water (SMOW) (Craig, 1961). The meteoric line resulting from the above expression is shown in figure 4, together with data from 14 samples. Results of the analyses are given in table 12.

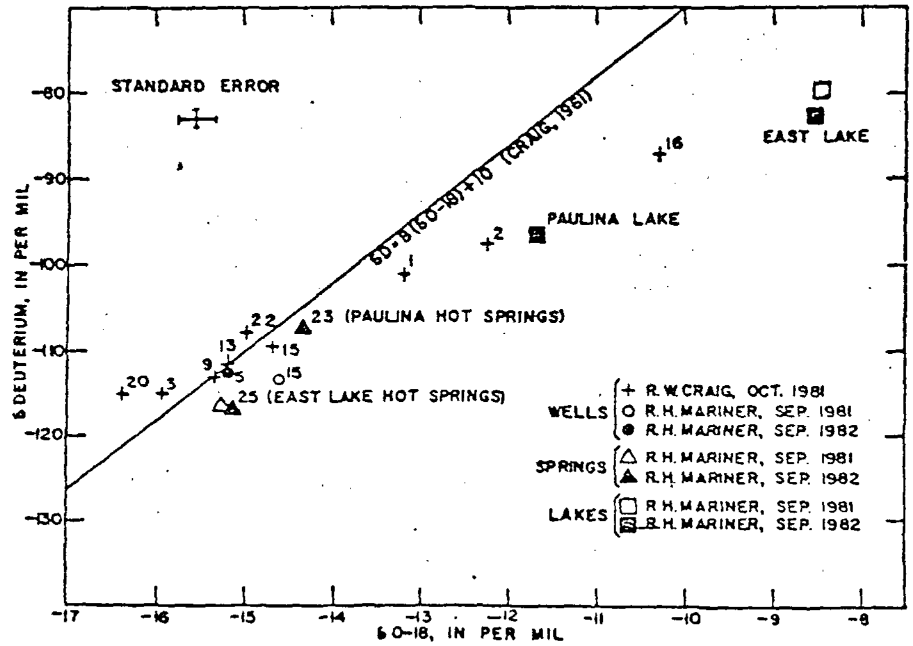

Figure 4. — Concentrations of oxygen-18 versus deuterium in ground and surface water.

Table 12.-- Concentrations of the isotopes oxygen-18 and deuterium in ground and surface water

[Concentrations of oxygen-18 and deuterium in parts per thousand as departures from standard mean ocean water (Craig, 1961)]

Sequence No.[1]	Name/ owner	Date sampled	Oxygen-18 (± 0.2)	Deuterium (± 1)	Temperature (°C)	Source[2]
1	Paulina Lake Resort	10/07/81	-13.20	-101.0	5	A
2	Paulina Lake Resort	10/07/81	-12.25	- 97.5	4	A
3	Paulina Guard Station (USFS)	10/07/81	-15.95	-115.0	6	A
5	Mike Mathews (summer home)	06/30/82	-15.18	-112.7	2	C
9	Little Crater picnic Area	10/07/81	-15.35	-113.0	16	A
13	Little Crater Camp Site 27	10/07/81	-15.20	-111.5	6	A
15	Little Crater Camp Site 49	10/07/81 08/00/75	-14.70 -14.60	-109.5 -113.4	33 35.5	A B
16	East Lake Campground well	10/07/81	-10.30	- 87.0	6	A
20	Cinder Hill campground well	10/06/81	-16.40	-115.0	5	A
22	Cinder Hill Camp Site 34	10/06/81	-15.00	-108.0	4	A
23	Paulina Lake Hot Springs	06/30/82 07/00/77	-14.33 ---	-107.3 -108.9	52 --	C B
25	East Lake Hot Springs	06/30/82 08/00/75	-15.12 -15.26	-116.9 -116.4	57 49	C C
--	Paulina Lake	06/30/82	-11.68	- 96.8	6	C
--	East Lake	06/30/82 00/00/73	- 8.54 - 8.44	- 82.8 - 79.7	10 --	C C

[1] Sequence number.-- Identifying number used in tables and illustrations.

[2] Source of data or collector: A: R. W. Craig (1981); B: R. H. Mariner and others (1980); C: R. H. Mariner (unpub. data, 1982).

The isotope results generally reinforce the relationships shown by the major-ion chemistry, but show additionally that both oxygen-18 and deuterium are concentrated in the two lakes as the expected result of surface evaporation. A line constructed through the Paulina Lake and East Lake sample points in figure 4 probably would represent this evaporative trend. Evaporation under low-temperature, nonequilibrium conditions should result in a trend with a slope of about 5 (Craig, 1961). The slope of the East Lake - Paulina Lake line is 4.6, which is reasonably close in view of the standard errors of estimate shown in figure 4.

The position of sample 16, a well water from the East Lake Campground, suggests that the sample contains a large proportion of evaporated water from East Lake. Similarly, samples 1 and 2 appear to have large proportions of Paulina Lake water. Both indications are in accord with the chemical analyses and water levels.

The isotope shift observed in the Paulina Hot Spring water (23) suggests that the spring water could be a mixture of thermal water such as samples 9, 13, or 15[1/] and Paulina Lake water. Temperatures of the waters as well as the major-ion chemistry make this simple mixing model unlikely however. In the East Lake Hot Spring water the isotope shift suggests that a mixing relation involving East Lake water would require a dilute end member having an isotopic composition with $\delta D < -127$ and $\delta^{18}O < -17$ and a volume fraction of at least 75 percent of the mixture. A water of this isotopic composition would probably have to originate at the high altitudes of the Cascades Range, if samples 20 and 3 represent the most nearly "meteoric" water in the caldera. It is unlikely that ground water from the Cascades could move through the intervening rocks and discharge from the Newberry geothermal system with the small concentrations of chloride, silica, and major cations observed in the East Lake hot springs. The small shift in oxygen-18 in the East Lake Hot Spring water seems most likely to

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[1/] The difference in deuterium concentrations between the sample obtained by Mariner and that obtained by Craig in well 15 is unexplained except as a possible effect of differing laboratory methods. The same explanation might account for the possibly anomalous deuterium concentrations in all samples collected by Craig in 1981. A decrease in deuterium of 2 to 4 per mil would place these samples in positions more consistent with the remainder of the isotope data as well as with the chemical analyses.

be caused by the injection of steam beneath the caldera. (See, for example Ellis and Mahon, 1977, for a discussion of this phenomenon.) The small chloride concentration in the spring water is consistent with this origin. The isotopic data are consistent with the major-ion chemistry in indicating that both thermal and nonthermal waters in the caldera are derived from local meteroic water and that thermal alterations occur at fairly shallow depths. The distinction between East Lake and Paulina Lake ground waters made on the basis of the major ionic constituents probably relates mainly to near-surface low-temperature phenomena rather than to deep-seated geothermal processes.

TEMPERATURES OF SURFACE AND GROUND WATER

Measured temperatures of shallow ground water in the caldera range from 4°C to 62°C. The highest temperatures (52°C and 62°C) were measured in the Paulina Lake and East Lake Hot Springs (Mariner and others, 1980; table 11, this report). Temperatures of well waters ranged from 2°C to 36°C; temperatures above 10°C occurred only near the east end of Paulina Lake. The range of seasonal fluctuations in ground-water temperatures is not known in the caldera, but because the average annual air temperature at Newberry is about 0°C, any ground-water temperature above 10°C probably implies the presence of a thermal component.

Temperatures of bottom water were measured in Paulina Lake and East Lake in an attempt to identify areas of high heat flow and possible inflows of thermal water (fig. 5). Additional measurements at a depth of 2 feet at each site indicated that near-surface temperatures were fairly uniform within each lake, but varied somewhat with daily metrological conditions. They are not shown in figure 5.

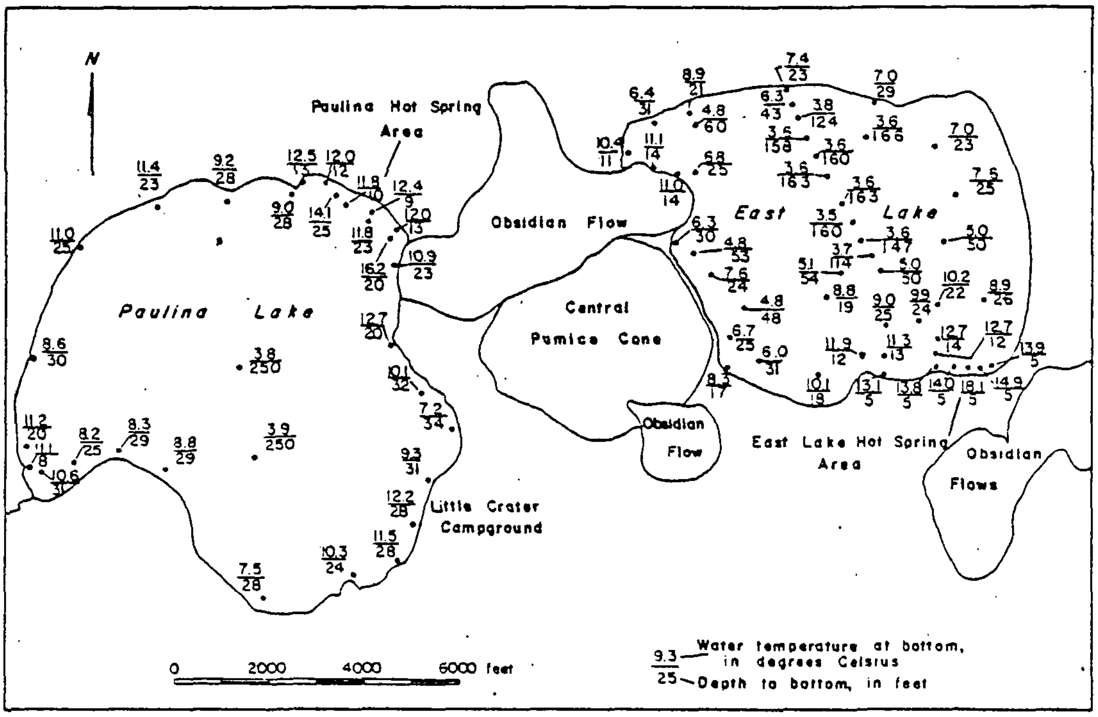

Figure 5. — Temperatures measured on the lake bottom in Paulina and East Lakes.

Offshore from both hot springs, there are sizeable areas in which temperatures are above normal and gas bubbles rise to the surface, indicating that spring activity is not confined to the shore. Temperature measurements along the east shore of Paulina Lake show that thermal water also enters the lake adjacent to Little Crater Campground. The low temperatures in most shallow wells in the Campground suggest that the thermal water does not flow laterally from the adjacent ground-water body but rather ascends vertically through the lake bottom.

Two additional areas, one in each lake, had temperatures that might indicate thermal inflow. The strongest possibility is in the northwest corner of Paulina Lake where temperatures of 11.0°C and 11.4°C were measured at depths of 25 and 23 feet respectively. In East Lake, temperatures of 11.0°C and 11.4°C were measured at a depth of 14 feet in the northwest part of the lake. In both cases, a more detailed investigation would be required to confirm a thermal influence.

The volume of thermal-water inflow to the lakes probably is small. Even if the amount of inflow were much greater than estimated, however, a deep geothermal origin is unlikely for most of the thermal water. The chemical and isotopic analyses indicate that a probable origin is the heating of meteoric water by rising steam. Thus, there may be only small additions of thermal fluid to the shallow ground-water system.

Two partly independent estimates of the inflow of warm water have been made as follows. Measurements in Paulina Lake show that about 25×10^6 ft^3 of lake water in the vicinity of the hot springs is warmed to an average 6°C above ambient temperature by the influx of thermal water[1/]. The average temperature of water contributed by hot springs and seeps on shore is about 40°C. Springs in the lake also are assumed to have an average temperature of 40°C. Calculations using a simple mixing model yield 0.23 as the fraction of thermal water in the affected volume of lake water. If the lake is assumed to turn over annually with complete mixing as a result, the inflow rate is about 11 ft^3/min or 130 acre-ft/yr.

[1/] Estimate based on temperature measurements made in 1977 by N. E. Voegtly and E. A. Sammel.

Along the Little Crater shore, there is no evidence of temperatures comparable to those near the Paulina Hot Springs, but the greater area involved leads to an estimate of inflow similar to the hot-spring area. Thus, the total thermal inflow in areas of Paulina Lake where temperatures have been measured is probably no more than 300 acre-ft/yr.

A partly independent estimate begins with discharge from the springs on shore which probably is no greater than 2 1/2 ft^3/min. Observations of gas vents offshore suggest that discharge in the lake could no more than double this figure. If the flows near the shore at Little Crater are again assumed to be comparable to those in the hot-spring area, the total inflow to the lake estimated in this way is similar to the previous estimate This amount would have no detectable effect on the large-scale temperature distribution in the lake.

The known areas of thermal discharge in East Lake are less extensive than those in Paulina Lake, and the total discharge is probably smaller. Even if a significant fraction of East Lake thermal water rises directly from a geothermal reservoir, the thermal water probably is a negligible addition to the groundwater influx. The hot springs in Paulina and East Lakes are the only ones known in the caldera and their apparently small contributions of thermal water have been ignored in the hydrologic budget.

DISCUSSION OF RESULTS

The summation of terms in the hydrologic budget for the caldera at Newberry Volcano shows an apparent annual surplus of water. The surplus, which is estimated to be at least 2,500 acre-feet and possibly as much as 10,000 acre-feet, is assumed to move downward to deep aquifers beneath the caldera floor.

Part of the recharge may move laterally out of the caldera and discharge through the flanks of the mountain. However, the absence of springs or surface flows other than Paulina Creek on the flanks of the volcano indicates that little ground water moves outward to the surface of the mountain, even though large amounts of recharge must occur on the upper flanks. Streamflow measurements by the Geological Survey in Paulina Creek in August, 1981, showed no gain in the stream between Paulina Lake and Paulina Prairie at the base of the mountain. Massive tuffaceous rocks exposed along Paulina Creek west of the caldera rim show no evidence of ground-water seepage, and only one small seep is known to occur below the outlet of Paulina Lake. A Geological Survey core hole (Newberry 1), located about 2 miles northeast of the caldera rim, encountered only minor flows of perched ground water at depths of about 200, 500, and 900 feet, and a temperature profile in the hole indicated that ground water recharge moves vertically downward through the upper 200 feet of rock at this site.

Within the caldera, data obtained in the Geological Survey's 3,057-foot core hole (Newberry 2) provide evidence of ground-water flow below the near-surface hydrologic regime. Small flows of ground water were detected in the core hole at depths ranging from 100 to 1,900 feet beneath the caldera floor (Sammel, 1981; and MacLeod and Sammel, 1982).

The ground water observed at depth probably originates in the caldera, but the present study does not indicate the areas from which it is derived. The presence of a surplus of water in the East Lake sub-basin (table 8) suggests that much recharge could occur there. However, the large hydraulic gradient between the two sub-basins undoubtedly causes much of the surplus water to flow from east to west across the caldera. Hydrologic studies in other volcanic areas of Oregon indicate that the topographic features of the present caldera floor would not be major obstacles to this near-surface ground-water flow (Sammel, 1980; Sammel and Craig, 1981) Thus the surplus of water from the East Lake sub-basin may be available for ground-water recharge anywhere in the caldera.

Waters sampled in the two sub-basins differ in their chemical characteristics, but the differences probably do not indicate separate hydrologic regimes. The occurrence of dilute waters such as those in samples 3, 20, and 22 (tables 9 and 11) in both sub-basins suggests that the chemical data may be biased by the preponderance of samples from the vicinity of the hot springs and the central pumice cone, which may represent only local chemical and thermal anomalies within the caldera.

A part of the ground-water contribution from the East Lake sub-basin to the Paulina Lake sub-basin probably originates as seepage from East Lake itself. Measurements of lake levels in East Lake during a 26-day period of no precipitation between August 11 and September 6, 1981 showed a decrease in stage of 0.45 feet. Evaporation from the lake surface during this period was estimated to be 0.32 feet. The seepage loss (ground-water inflow minus ground-water outflow), therefore, is 0.13 feet, from which is calculated a seepage rate of 2.5 ft^3/s, or about 5 acre-feet per day.

This figure is close to the estimate of 2.3 ft^3/s made by Phillips (1968, table 9) on the basis of fragmentary records for the period 1931 to 1961. Phillips concluded that annual seepage from East Lake is nearly constant and is fairly independent of lake levels. We conclude that the lake, at its historic and present levels, is largely self-regulating, and that seasonal or annual changes of ground-water inflow probably are balanced by similar increases or decreases in ground-water outflow. Thus, although our seepage estimate may be too high as the result of underestimating evaporation, the average annual rate should be higher than the figure obtained in the late summer at a time of low lake levels.

An average seepage rate from East Lake of 2.5 ft^3/s (1,800 acre-feet per year), exceeds the flow required to balance the estimated deficit in Paulina Lake (table 8). Observations of stages in Paulina Lake suggest, however, that the deficit may be higher than estimated. During the 26-day period, August 11 to September 6, 1981, the level of Paulina Lake declined 0.86 foot; estimated evaporation was 0.22 foot, and streamflow was equivalent to a decline of 0.84 foot. Therefore, if ground-water seepage out of the lake was small, about 0.2 foot of ground-water inflow entered the lake during this period. On the assumption that the estimated inflow rate for this period (5.2 ft^3/s) is close to the annual average, the net annual ground-water contribution to Paulina Lake is about 3,800 acre-feet.

An analysis of probable errors in these estimates leads to the following conclusions: (1) The streamflow estimate for the 26-day period has a small probable error due to the availability of precise flow measurements made by the USGS on August 20 and the generally uniform flow rate observed during the period; (2) estimated annual evaporation for Paulina Lake is extremely low, and the actual evaporation is likely to be higher than the estimate rather than lower; (3) ground-water inflow to the Paulina Lake sub-basin probably is several times greater than the deficit shown in table 8, and both evaporation from Paulina Lake and streamflow in Paulina Creek could be significantly greater than the estimated values without causing an actual deficit in the sub-basin. The subtraction of the required several thousand acre-feet per year from the budget of the East Lake sub-basin would still allow a surplus to remain in this area also. As a consequence of probable increases in evaporation and stream flow, however, the probable maximum amount of ground water available for deep recharge is reduced from 10,000 acre-feet to a figure close to the 6,500 acre-feet given in table 8.

Partly as a means of testing the general conclusions of this study, estimates of mean monthly values were made for all terms in the hydrologic budget. These estimates, and especially those for winter months, are not sufficiently reliable to warrant inclusion as a table in this report. However, seasonal aggregates of these figures seem to support the general conclusions and elucidate some aspects of the hydrologic regime.

At the end of a normal winter, for example, ground-water storage in the Paulina Lake sub-basin probably would have a deficit in the range 7,000 to 11,000 acre-feet, if not compensated by ground-water inflow from the East Lake sub-basin. In contrast, gains and losses in the East Lake sub-basin remain nearly in balance during winter months (assumed to be December through March).

During the period April through November, Paulina Lake sub-basin has an apparent surplus of about 3,000 acre-feet, all in ground-water storage. This surplus, carried over into the winter period, helps to support winter streamflows. However, observed lake levels and estimated streamflows could not be maintained through the winter in the absence of continued ground-water inflow from the East Lake sub-basin. The inflow probably reaches a peak in late spring or early summer and continues during the winter. Soil moisture, ground-water storage, and lake storage return to normal high levels during the winter and spring of most years.

Manipulation of the data in tables 7 and 8 shows that, of the 35 inches of precipitation that falls on land surfaces in the caldera, nearly 70 percent (24 inches) percolates below the evapotranspiration zone to recharge the shallow ground-water body. This percentage is exceptionally high when compared with more common volcanic terranes, but it is reasonable in view of the highly permeable land surface, which generally is either pumice- or ash-covered or consists of blocky, fractured obsidian or basaltic lava. Overland runoff is rarely observed except during brief periods of spring snowmelt.

Water that leaves the shallow ground-water flow system by infiltration to deeper zones beneath the caldera probably is in the range 0.3 to 0.7 foot annually, or 10 to 25 percent of precipitation on land surfaces. If the actual rate is near the upper end of the range, deep infiltration may occur uniformly over fairly large areas of the caldera floor. A value near the low end of the range, seemingly more likely in view of probable errors in the estimates, could imply that the conduits for deep recharge are restricted to major ring fractures and faults. The latter mode seems the more likely in view of the stratified aquifers and low vertical permeabilities observed in the caldera drill hole. These conclusions imply rather strongly that a deep hydrothermal convection system at Newberry could not be effectively recharged by vertical flow of meteoric water from the caldera. Sources of recharge for any such system probably must be sought in deep regional aquifers that intersect permeable zones beneath the mountain.

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Table 2.-- Precipitation recorded during selected periods at the Newberry Volcano, Chemult, and Wickiup Dam weather stations

Period	Newberry Volcano (inches)	Chemult (inches)	Wickiup Dam (inches)
11/23/65-05/31/66	18.65	14.63	10.37
06/01/66-07/26/66	2.25	2.04	1.86
08/12/66-11/14/66	4.75	5.17	3.38
11/15/66-06/18/67	26.55	21.04	14.54
06/19/67-10/15/67	2.75	2.73	2.29
10/16/67-01/31/68	8.20	7.89	6.55
02/01/68-04/14/68	6.95	4.96	3.10
04/15/68-06/17/68	3.90	2.02	1.92
06/18/68-10/06/68	1.85	2.91	2.12
10/07/68-01/07/69	12.00	11.50	7.16
01/08/69-04/08/69	15.10	7.71	6.37
09/08/69-10/09/69	1.60	0.87	1.75
10/10/69-01/21/70	25.00	14.53	10.17
04/07/70-06/04/70	1.10	0.66	0.67
06/05/70-07/15/70	1.80	1.71	1.49
10/10/70-03/09/71	32.30	25.78	18.96
03/10/71-09/28/71	10.65	9.36	6.79
09/29/71-10/19/71	1.85	0.68	0.73
10/20/71-05/04/72	31.50	28.02	18.70
11/02/72-02/22/73	13.05	13.48	7.76
02/23/73-06/13/73	5.75	3.43	2.01
07/17/75-09/01/75	2.00	0.75	0.60
11/21/75-07/01/76	24.70	14.75	12.49

Table 2.-- Precipitation recorded during selected periods at the Newberry Volcano, Chemult, and Wickiup Dam weather stations (Continued)

Period	Newberry Volcano (inches)	Chemult (inches)	Wickiup Dam (inches)
07/02/76-10/11/76	6.80	3.84	4.27
10/12/76-12/29/76	1.00	0.80	1.12
10/21/77-05/17/78	31.55	28.79	17.83
05/18/78-11/15/78	5.45	5.41	5.59
11/15/79-04/24/80	19.95	15.57	12.84

Table 4.--Estimated daily evaporation at Paulina Lake and East Lake for the period July 1 to September 30, 1981

[Includes data from which estimate is derived. Saturation vapor pressure at water-surface temperature used is 17.77 millibars for July, 19.19 millibars for August, and 15.16 millibars for September. See text for explanation]

Date	Vapor pressure of incoming air (mbar)	Average 24 h wind, Paulina Lake (mi/h)	Average 24 h wind, East Lake (mi/h)	Estimated evaporation, Paulina Lake (in/d)	Estimated evaporation, East Lake (in/d)
7-1	5.72	3.1	4.5[1]	0.088	0.130
7-2	7.01	2.3	3.3[1]	.058	.085
7-3	8.36	3.1	4.5[1]	.069	.102
7-4	7.01	2.8	4.0[1]	.071	.103
7-5	7.30	5.7	8.2[1]	.141	.206
7-6	7.58	8.9[1]	12.8	.214	.313
7-7	3.49	3.3[1]	4.8	.111	.113
7-8	9.07	3.3[1]	4.8	.068	.100
7-9	9.07	4.7[1]	6.7	.096	.140
7-10	8.67	3.3[1]	4.8	.071	.105
7-11	6.57	2.9[1]	4.2	.077	.113
7-12	6.57	7.1[1]	10.2	.187	.274
7-13	7.38	3.7	5.3[1]	.091	.132
7-14	5.86	2.8	4.0[1]	.079	.114
7-15	7.55	2.5	3.6[1]	.060	.008
7-16	7.55	3.4	4.9[1]	.082	.120
7-17	7.14	5.0	7.2[1]	.125	.184
7-18	5.52	3.5	5.0[1]	.101	.147
7-19	5.35	3.1	4.5[1]	.091	.134
7-20	4.81	3.0[1]	4.3	.092	.134

Table 4.-- Estimated daily evaporation at Paulina Lake and East Lake for the period July 1 to September 30, 1981 (Continued)

Date	Vapor pressure of incoming air (mbar)	Average 24 h wind, Paulina Lake (mi/h)	Average 24 h wind, East Lake (mi/h)	Estimated evaporation, Paulina Lake (in/d)	Estimated evaporation, East Lake (in/d)
7-21	4.64	3.3[1]	4.8	0.102	0.151
7-22	5.18	3.3[1]	4.8	.099	.145
7-23	3.93	3.6[1]	5.1	.117	.169
7-24	3.93	4.5[1]	6.4	.147	.213
7-25	5.82	3.5[1]	5.0	.099	.143
7-26	6.57	2.2[1]	4.6	.084	.124
7-27	7.82	2.9	4.2[1]	.064	.100
7-28	6.94	7.5	10.8[1]	.192	.281
7-29	4.98	4.2	6.0[1]	.127	.184
7-30	4.67	2.7	3.9[1]	.083	.123
7-31	3.69	3.6	5.2[1]	.120	.176
8-1	5.72	3.0	4.3[1]	.095	.139
8-2	6.80	5.6	8.0[1]	.164	.238
8-3	6.47	3.5[1]	5.0	.105	.153
8-4	6.47	3.1[1]	4.4	.093	.134
8-5	6.37	2.7[1]	3.9	.082	.120
8-6	6.26	2.4[1]	3.5	.073	.109
8-7	6.70	2.6[1]	3.8	.077	.114
8-8	9.71	3.3[1]	4.7	.074	.107
8-9	7.79	3.8[1]	5.5	.102	.150

Table 4.-- Estimated daily evaporation at Paulina Lake and East Lake for the period July 1 to September 30, 1981 (Continued)

Date	Vapor pressure of incoming air (mbar)	Average 24 h wind, Paulina Lake (mi/h)	Average 24 h wind, East Lake (mi/h)	Estimated evaporation, Paulina Lake (in/d)	Estimated evaporation, East Lake (in/d)
8-10	4.33	2.9	4.2[1/]	0.102	0.150
8-11	6.87	2.7	3.9[1/]	.078	.115
8-12	7.92	3.3	4.7[1/]	.088	.127
8-13	11.44	3.6	5.2[1/]	.066	.097
8-14	7.16	3.3	4.7[1/]	.094	.136
8-15	6.30	3.2	4.6[1/]	.097	.142
8-16	4.20	2.7	3.9[1/]	.095	.140
8-17	4.77	2.4[1/]	3.5	.076	.112
8-18	5.82	3.6[1/]	5.2	.113	.167
8-19	6.30	4.6[1/]	6.6	.140	.204
8-20	3.01	3.8[1/]	5.5	.145	.214
8-21	4.85	3.1[1/]	4.4	.105	.151
8-22	6.50	2.9[1/]	4.1	.087	.125
8-23	7.56	3.6[1/]	5.1	.099	.142
8-24	13.28	3.4[1/]	4.9	.047	.070
8-25	7.04	4.1	5.9[1/]	.117	.172
8-26	5.16	4.6	6.6[1/]	.152	.222
8-27	4.69	2.4	3.4[1/]	.082	.118
8-28	5.72	3.8	5.5[1/]	.121	.178
8-29	5.88	6.5	9.3[1/]	.204	.297

Table 4.-- Estimated daily evaporation at Paulina Lake and East Lake for the period July 1 to September 30, 1981 (Continued)

Date	Vapor pressure of incoming air (mbar)	Average 24 h wind, Paulina Lake (mi/h)	Average 24 h wind, East Lake (mi/h)	Estimated evaporation, Paulina Lake (in/d)	Estimated evaporation, East Lake (in/d)
8-30	8.05	5.3	7.6[1/]	0.139	0.203
8-31	6.36	3.3	4.7[1/]	.100	.145
9-1	5.72	5.4[1/]	7.7	.120	.174
9-2	7.02	2.5[1/]	3.6	.048	.070
9-3	8.37	3.8[1/]	5.4	.061	.088
9-4	4.54	3.8[1/]	5.4	.095	.138
9-5	4.54	3.3[1/]	4.7	.083	.120
9-6	6.03	2.7[1/]	3.9	.058	.085
9-7	5.55	2.4[1/]	3.4	.054	.078
9-8	8.87	2.1	3.0[1/]	.031	.045
9-9	6.47	2.2	3.2[1/]	.045	.067
9-10	6.50	2.3	3.3[1/]	.047	.069
9-11	6.09	2.2	3.2[1/]	.047	.070
9-12	9.55	3.6	5.2[1/]	.048	.070
9-13	6.50	5.7	8.2[1/]	.116	.170
9-14	6.70	4.4	6.3[1/]	.088	.128
9-15	6.94	3.0[1/]	4.3	.058	.085
9-16	5.82	2.6[1/]	3.8	.057	.085
9-17	7.85	2.4[1/]	3.5	.041	.061

Table 4.-- Estimated daily evaporation at Paulina Lake and East Lake for the period July 1 to September 30, 1981 (Continued)

Date	Vapor pressure of incoming air (mbar)	Average 24 h wind, Paulina Lake (mi/h)	Average 24 h wind, East Lake (mi/h)	Estimated evaporation, Paulina Lake (in/d)	Estimated evaporation, East Lake (in/d)
9-18	7.38	6.3[1]	9.1	0.116	0.170
9-19	7.07	6.5[1]	9.4	.124	.183
9-20	7.14	5.9[1]	8.5	.112	.164
9-21	5.45	9.2[1]	13.2	.211	.308
9-22	4.40	7.6	10.9[1]	.193	.282
9-23	3.35	4.0	5.7[1]	.111	.162
9-24	3.76	4.4	6.3[1]	.118	.172
9-25	4.50	7.3	10.5[1]	.183	.269
9-26	3.52	---	---	.460[2]	.670[2]
9-27	9.11	---	---	.460[2]	.670[2]
9-28	7.18	---	---	.460[2]	.670[2]
9-29	4.91	---	---	.460[2]	.670[2]
9-30	4.71	---	---	.460[2]	.670[2]
		Total Evaporation		9.14	13.32

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[1] Not measured; estimated from measurement at alternate lake. See text for explanation.

[2] Estimated.

Table 9.-- Data from wells in Newberry caldera

[µmho/cm = micromhos per centimeter at 25°C]

Sequence No.[1]	Owner/name	Latitude Longitude (deg)(min)	Date completed	Depth (ft)	Diameter (in)	Altitude[2] (ft)	Depth to water[3] (ft)	Temperature (°C)	Specific conductance (µmho/cm)	Date measured	Use[4]	Other data[5]
1	Paulina Lake Resort	43 42.90	1929	20	36	6,341.4	14.9	7	460	08/14/81	C,D	C,I(10/07/81)
		121 16.55					12.2	4	235	06/28/82		
2	Paulina Lake Resort	43 42.90	1980	65	8	6,340.1	15.1	4	600	10/07/81	C,D	C,I(10/07/81)
		121 16.55					11.0	5	550	06/28/82		
3	Paulina Guard Station (USFS)	43 42.70	----	45	6	6,356.3	30.7	9	90	09/03/81	D,R	C(09/06/81)
		121 16.60					28.3	4	80	06/30/82		I(10/07/81)
4	IOOF lodge	43 42.45	----	---	--	6,346.0	12.1	3	110	06/27/82	D	
		121 15.40										
5	Mike Mathews	43 42.45	1969	22	30	6,336.7	4.7	12	675	09/05/81	D	C,I(06/30/82)
		121 14.90					3.3	2	720	06/27/82		
6	Star (?)	43 42.45	----	5	24	6,334.2	.6	3	1,150	06/27/82	D	
		121 14.85										
7	Ulven	43 42.45	----	6	12	6,334.1	.1	2	650	06/27/82	D	
		121 14.85										
8	Jack Hogg	43 42.45	----	---	8	6,340	17.6	--	900	09/05/81	D	C(09/06/81)
		121 14.80										
9	Little Crater Picnic Area	43 42.50	----	12	6	6,342.1	10.5	16	710	10/07/81	U	C,I(10/07/81)
		121 14.70					8.8	13	530	06/28/82		
10	Little Crater Camp Site 4A	43 42.70	----	12	6	6,343.2	11.2	--	---	10/07/81	U	
		121 14.55					9.5	9.5	195	09/06/74		
11	Little Crater Camp Site 10	43 42.75	08/06/71	23	6	6,343.3	11.8	--	---	10/07/81	U	
		121 14.55					9.9	4	195	06/28/82		

Table 9.-- Data from wells in Newberry caldera (Continued)

[μmho/cm = micromhos per centimeter at 25°C]

Sequence No.[1]	Owner/name	Latitude Longitude (deg)(min)	Date completed	Depth (ft)	Diameter (in)	Altitude[2] (ft)	Depth to water[3] (ft)	Temperature (°C)	Specific conductance (μmho/cm)	Date measured	Use[4]	Other data[5]
12	Little Crater Camp Site 20	43 42.80 121 14.45	----	---	6	6,341.6	9.5 8.1	9 7	430 330	08/18/81 06/28/82	U	
13	Little Crater Camp Site 27	43 42.90 121 14.40	09/18/61	36	6	6,342.7	11.2 9.4	6 5	360 240	10/07/81 06/28/82	U	C,I(10/07/81)
14	Little Crater Campground well	43 43.00 121 14.35	----	---	8	6,344.8	---- ----	-- --	240 220	08/19/81 06/28/82	R	
15	Little Crater Camp site 49	43 43.05 121 14.35	09/16/61	50	6	6,343.8	12.3 10.3	30 32	900 960	10/07/81 06/28/82	U	C(09/06/81) I(10/07/81
16	East Lake Campground well	43 43.05 121 12.50	10/12/62	50	6	6,396.2	23.7 20.9	6 3	390 325	09/06/81 06/27/82	R	C(09/06/81 I(10/07/81)
17	Hot Springs Campground	43 43.10 121 11.90	----	---	6	6,389.8	14.4 11.0	-- 6	--- 120	10/07/81 06/30/82	U	
18	East Lake Resort R V park	43 43.40 121 11.55	----	---	8	6,407.2	27.4 24.8	10 3	85 90	08/19/81 06/28/82	C	
19	East Lake Resort	43 43.40 121 11.60	----	27.5	96	6,395	17.9	3	105	09/19/74	C,D	
20	Cinder Hill Campground well	43 43.80 121 11.70	10/17/63	76	6	6,393.7	20.1 18.2	5 5	110 90	09/06/81 06/27/82	R	C(09/06/81) I(10/06/81)
21	Cinder Hill Camp Site 27	43 43.90 121 11.70	----	---	6	6,392.8	19.1 17.2	-- --	--- ---	09/02/81 06/27/82	U	
22	Cinder Hill Camp Site 34	43 44.00 121 11.70	----	---	6	6,392.5	18.6 16.3	4 3	140 93	10/06/81 06/27/82	U	C,I(10/06/81)

Table 9.-- Data from wells in Newberry caldera (Continued)

[µmho/cm = micromhos per centimeter at 25°C]

Sequence No.[1]	Owner/name	Latitude Longitude (deg)(min)	Date completed	Depth (ft)	Diameter (in)	Altitude[2] (ft)	Depth to water[3] (ft)	Temperature (°C)	Specific conductance (µmho/cm)	Date measured	Use[4]	Other data[5]

---

[1] Sequence No. -- Identifying number used in tables and illustrations.

[2] Altitude -- Land surface at well, in feet above National Geodetic Vertical Datum of 1929.

[3] Depth to water -- Feet below land surface.

[4] Use -- C, commercial (resort); D, domestic; R, recreation; U, unused.

[5] Other data -- C, chemical analysis, table 11; I, isotope analysis, table 12.

Table 10.-- Data from springs and gas vents in Newberry caldera

[µmho/cm = micromhos per centimeter at 25°C]

Sequence No.[1]	Owner	Name	Latitude Longitude (deg)(min)	Altitude[2] (ft)	Probable water-bearing materials	Occurrence	Yield	Temperature (°C)	Specific conductance (µmho/cm)	Date	Other data [3]
23	U.S. Forest Service	Paulina Lake hot springs	43 43.85 121 14.95	6,334	Volcanic breccia	Thermal	Many small diffuse flows	52	960	10/26/74	C,I(06/30/82)
24	U.S. Forest Service	Lost Lake gas vents	43 42.25 121 13.65	6,390	Volcanics (Obsidian flow ?)	Gravity	Very small to none	5	400	10/27/74	C(10/27/74 Evident H_2S gas
25	U.S. Forest Service	East Lake hot springs	43 43.20 121 11.95	Follows lake level	Pumice, ash, and lacustrine sediments, at surface	Thermal	Many small diffuse flows	57	840	10/26/74	C,I(06/30/82)

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[1] Sequence No. -- Identifying number used in tables and illustrations.

[2] Altitude -- Land surface at spring, in feet above National Geodetic Vertical Datum of 1929. Paulina Lake Hot Spring and East Lake Hot Springs referenced to USGS benchmarks; altitude of Lost Lake gas vents estimated from Geological Survey topographic quadrangle map.

[3] Other data -- C, chemical analysis, table 11; I, Isotope analysis, table 12.

Geothermal Resources Council, TRANSACTIONS Vol. 7, October 1983

THE SHALLOW HYDROTHERMAL SYSTEM AT NEWBERRY VOLCANO, OREGON: A CONCEPTUAL MODEL

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ABSTRACT

Investigations at Newberry Volcano, Oregon, have resulted in a satisfactory account of the shallow hydrothermal system, but have not indicated the nature of a possible geothermal reservoir. Hot springs in the caldera probably represent the return of circulating meteoric water, warmed at shallow depths by high conductive heat flow and by steam rising from greater depths. Ground-water recharge to the hydrothermal system is at most 250 liters per second, of which about 20 liters per second reappears in the hot springs. Analysis of temperature anomalies in a Geological Survey drillhole indicates that ground-water flow totaling about 125 liters per second could be moving laterally at depths of less than 650 m at the drill site. A small fraction of the total recharge may infiltrate to a deeper high-temperature reservoir whose existence has not yet been confirmed.

INTRODUCTION

Newberry Volcano, a large Quaternary structure located about 50 km east of the crest of the Cascade Range in west-central Oregon, has become well known in recent years for widespread Holocene silicic volcanism, a 6 km- to 8 km-wide caldera, several hot-spring areas, and a presumed geothermal potential. The structure and setting of the volcano have been described by MacLeod and others (1981), by MacLeod and Sammel (1982), and, most recently, in a detailed geologic map of the area, by MacLeod and others (1982).

Volcanic activity at Newberry began more than 600,000 years ago and continued until about 1350 years ago. Caldera collapse occurred episodically during this time along arcuate ring fractures that at places are concentric (fig. 1). The range of rock compositions (basalt to rhyolite), their age relationships, and the widespread occurrence of chemically similar young rocks suggest that a large magma chamber has been present beneath the volcano and that it has been resupplied with magma during the last 1/2 million years. The recency of silicic eruptions suggests that the upper part of the chamber could still be extremely hot.

A core hole, Newberry 2, completed by the Geological Survey in 1981, penetrated 932 m of caldera fill and underlying flow rocks and demonstrated that temperatures as high as 265°C exist at a depth of less than a kilometer beneath the caldera without producing any surficial high-temperature hydrothermal features. Data derived from the drilling have extended our knowledge of the volcano, but many questions regarding the geothermal potential remain unanswered. The purpose of this paper is to present data on the shallow hydrothermal system at Newberry and to examine these data for evidence of a geothermal resource.

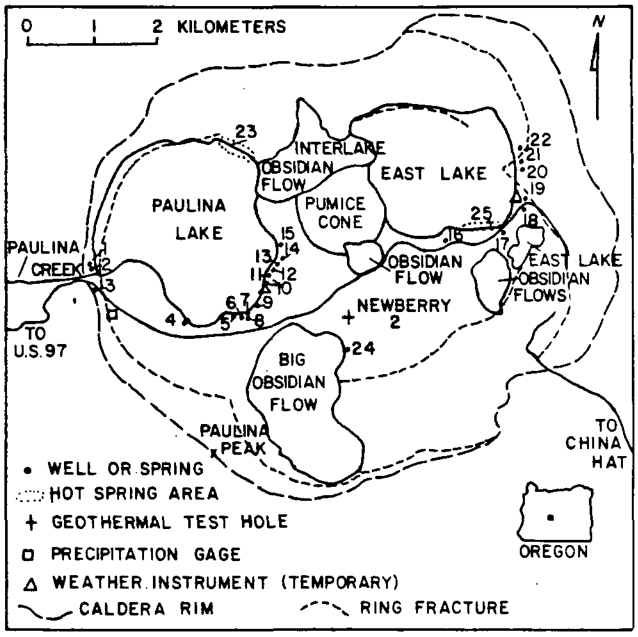

Figure 1. Index map of the caldera, Newberry Volcano.

The dominant features of the hydrologic regime in the caldera are two scenic lakes, East Lake and Paulina Lake, that occupy about half the low-lying caldera floor. Paulina Creek, the only stream in the caldera, drains water from Paulina Lake through a shallow cut in the west rim about 150 m from the lake shore (fig. 1). A study carried out by the Geological Survey during recent summers has defined many of the hydrologic relationships and has indicated the importance in the hydrologic regime of ground-water flow at shallow depths beneath the caldera floor (Sammel and Craig, 1983).

MAJOR-ION CHEMISTRY AND ISOTOPE RESULTS

Relationships between ground water and lakes are indicated by chemical analyses of water from 16 of the 22 shallow wells, two hot-spring areas, the lakes, and a gas vent in the caldera (table 1; locations shown in figure 1). Most of the wells are located near the lakes, and the known hot springs occur on the lake shores or in shallow water near the shores. The chemical data indicate that the shallow ground water is closely related to the lake water in each subbasin and that significant differences occur between the subbasins. The ground water appears to acquire generally higher concentrations of dissolved solids as it moves from east to west down the topographic gradient in the caldera.

The diagrams of figure 2 display concentrations of seven major ions in samples grouped by relative locations in the two subbasins. Samples 20 and 22 represent dilute ground water that has had only a short residence time in the shallow East Lake aquifer. Sample 3 demonstrates that an even more dilute water occurs at the western end of the caldera at some distance from Paulina Lake. The remainder of the diagrams show that magnesium, sodium, and potassium concentrations are higher in the Paulina Lake area than in the East Lake area, sulfate concentrations are lower, and chloride concentrations are similarly low in both areas. Calcium and bicarbonate concentrations, which are dominant in the eastern subbasin, increase only slightly in the western subbasin.

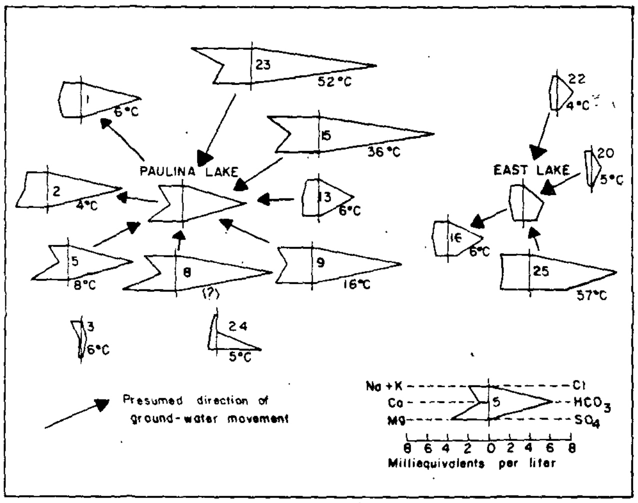

Figure 2. Chemical relations in ground and surface water, and presumed flow directions of ground water.

In the context of these general relations, the chemistry of the hot springs and warm wells provides some clues to the origin of the thermal water. In the Paulina Lake subbasin, the two warmest waters, Paulina Hot Springs (temperature 52°C) and well 15 (36°C), may be compared with Paulina Lake, which is assumed to be an indicator of ground-water quality in much of its subbasin. The chemical data show that concentrations of major ions in the thermal waters are roughly double the concentrations of the same ions in the lake water and in cooler ground waters near the lake (fig. 3). The single exception among the ionic constituents is sulfate, which is lower in the thermal waters than in the lake. In the East Lake subbasin, the hot spring (No. 25), which had a temperature of 62°C when measured in 1973 (Mariner and others, 1980), and 57°C in June, 1982 (table 1), has two to three times the concentrations of major ions, including sulfate, in nonthermal ground water (fig. 3).

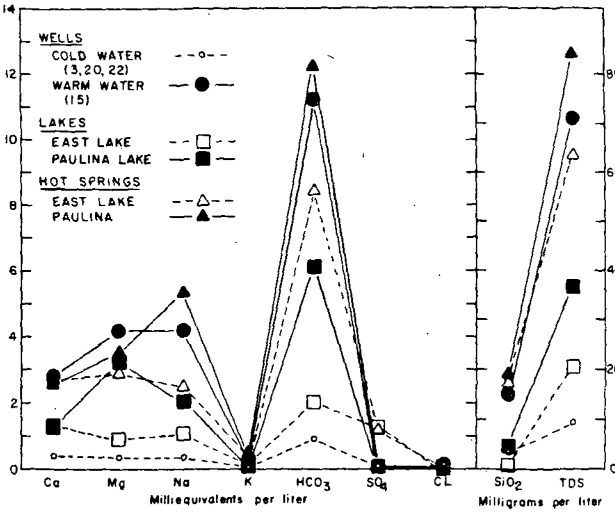

Figure 3. Concentrations of major ions in selected waters.

The difference in sulfate concentrations between East Lake and Paulina Lake waters is attributed to the presence of hydrogen sulfide gas in the East Lake area and its apparent absence in the Paulina Lake thermal waters (R.H. Mariner, written commun., 1983). The effect of hydrogen sulfide is clearly seen in the Obsidian Flow gas vent (24), which evolves abundant hydrogen sulfide and which is shown by the diagram in figure 2 to be a dilute cold water in which the sulfide from the gas has oxidized to sulfate. Chloride concentration in this water is several times background levels, and the pH has decreased to 3.4, well below the pH 6 to pH 7 values in other ground waters.

Silica concentrations in both hot springs are about 200 mg/L. In many other geothermal areas, concentrations of this magnitude indicate high temperatures of equilibration. At Newberry, however, concentrations of silica in all ground waters are high (30 to 160 mg/L) and they vary erratically, apparently in response to varying exposures to the glassy siliceous flow rocks and lapilli tuffs that underlie much of the caldera. Reservoir temperatures calculated by means of the silica geothermometer probably are not meaningful under these circumstances, although both the silica and the sodium-potassium-calcium geothermometers indicate equilibration of the hot-spring waters at temperatures of 175°C to 180°C. The silica geothermometer is suspect because of probable low-temperature silica dissolution, and the sodium-potassium-calcium geothermometer is invalid because of an extremely large magnesium correction. All of the chemical data suggest that the thermal waters equilibrated at shallow depths and low temperatures.

Concentrations of the stable isotopes, oxygen-18 and deuterium, support the foregoing conclusions and provide additional insight into relationships among the waters. The isotope diagram (fig. 4) shows that Paulina Lake, East Lake, and several well waters fall on a trend suggestive of low-temperature evaporation. Paulina Hot Springs is on the same trend and shows no evidence of a deep geothermal origin. East Lake Hot Springs and one sample from a warm well near Paulina Lake (15) have positions which suggest that these two waters have at least a small thermal component. The two analyses from well 15 differ considerably in deuterium concentration. Three chemical analyses of this water, obtained between 1974 and 1981, indicate a stable chemistry during this period and suggest that there may be a laboratory-related bias in deuterium concentrations that causes the Craig (1981) samples to differ from the Mariner samples (1981, 1982). The positions of the Craig samples in the diagram suggest that the reported deuterium concentrations may be too high.

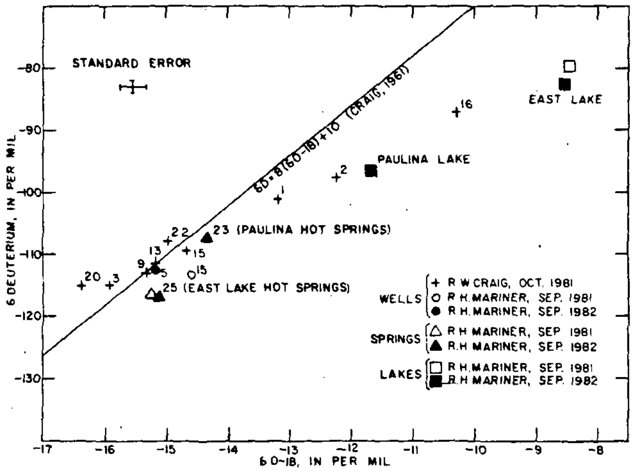

Figure 4. Concentrations of oxygen-18 and deuterium in ground and surface waters.

Sample 16, from a well at the East Lake campground, appears to be closely related to East Lake water (fig. 4), and the water level in the well, which is lower than the level of East Lake, suggests that the sample represents ground-water outflow from the lake. Samples 1 and 2, from wells on the west bank of Paulina Lake, similarly represent a probable connection with Paulina Lake.

The position of water from East Lake Hot Spring in the isotope diagram seems to preclude the possibility that this water is a mixture of hotter thermal water and East Lake water. Chemical mixing models also fail in applications to the samples from the East Lake area. The small shift toward higher oxygen-18 concentrations in the East Lake Hot Spring, together with the slightly increased chloride concentration, suggests that this water might be a mixture of shallow meteroic water and steam from a deep reservoir. The relatively high concentrations of bicarbonate and sulfate are readily explained by the presence of carbon dioxide and hydrogen sulfide gases in the water (Phillips and Van Denburgh, 1968).

The chemical and isotopic evidence thus points rather conclusively toward a near-surface, low-temperature origin for the thermal waters of the caldera. (For corroboration, see Keith and others, 1983). The heat source is likely to be conductive heat flow supplemented at places by steam and hot gas rising from a deep reservoir. The locations of the hot springs and gas vents suggest that the vertical conduits for these waters are largely restricted to areas near Holocene obsidian flows, the central pumice cone, and the caldera ring fractures.

HYDROLOGIC BUDGET AND POTENTIAL GEOTHERMAL RECHARGE

The water budget for the near surface hydrologic regime in the caldera is represented by the expression,

$$P - E - ET - OF = S,$$

where P is precipitation, E is evaporation from lake surfaces, ET is evapotranspiration from land surfaces, OF is stream flow leaving the caldera in Paulina Creek, and S is ground-water seepage out of the near-surface hydrologic system.

Estimates of the terms in this expression have been made on the basis of investigations carried out by the Geological Survey during the summers of 1980 and 1981 (Sammel and Craig, 1983) and a prior investigation of East Lake by Phillips and Van Denburgh (1968).

Annual precipitation in the caldera is estimated fairly reliably to be about 890 mm (35 in.); evaporation from lake surfaces is about 480 mm (19 in.) for Paulina Lake and 700 mm (28 in.) for East Lake; evapotranspiration from the densely forested land area is about 330 mm (13 in.) according to a calculation made for our study by J.E. Vaughn, U.S. Forest Service, Bend, Oregon; and streamflow is probably in the range 16×10^6 - 18×10^6 m^3/yr (18 - 20 ft^3/s). Applying these estimates to the 35 square kilometer land surface and the 9½ square kilometer lake area of the caldera, the residual term in the budget equation, assumed to be deep ground-water seepage, is estimated to be as much as 8×10^6 m^3/yr, or about 250 L/s. Consideration of probable errors in the budget estimates suggests that the seepage could be as little as half this amount but is not likely to be larger (Sammel and Craig, 1983).

A breakdown of the water-budget estimates by subbasins reveals that the East Lake subbasin has a large surplus of ground water each year, part of which must flow westward to make up an apparent deficit in the Paulina Lake subbasin. Perhaps as much as 70 L/s of this flow is attributable to seepage out of East Lake itself. The budget calculations for the Paulina Lake subbasin and the lack of observable ground-water discharge into Paulina Creek on the west flank of the volcano suggest that negligible amounts of ground-water seepage occur out of Paulina Lake. Nevertheless, the analysis of the ground-water flow, described in greater detail in Sammel and Craig (1983), makes it reasonable to suppose that excess ground water is available for deep recharge almost anywhere beneath the land surface in the south half of the caldera.

HYDROLOGIC EVIDENCE FROM TEST DRILLING

In the Geological Survey test hole, Newberry 2, located less than a kilometer south of the center of caldera (fig. 1), ground-water flows occurred in several sub-horizontal strata in the upper 650 m of the hole (MacLeod and Sammel, 1982). The temperature profile in the drill hole (fig. 5) suggests that large temperature perturbations in the profile probably result from the convective transfer of heat by moving ground water, and several of these perturbations can be correlated with observed flows. The 37°C bulge centered at a depth of about 40 m, for example, is probably caused by thermal water flowing above and within an obsidian flow below this depth. A temperature reversal below 175 m ends with a temperature of 20°C at a depth of about 275 m. The cause is probably the flow of cold water in a cavernous zone within strata of basaltic siltstone and mudstone. Between the depths of 550 m and 650 m drilling fluid was lost in dacitic breccias and pumiceous sediments, suggesting that ground-water flow could account for the temperature minima (about 75°C) in this zone also.

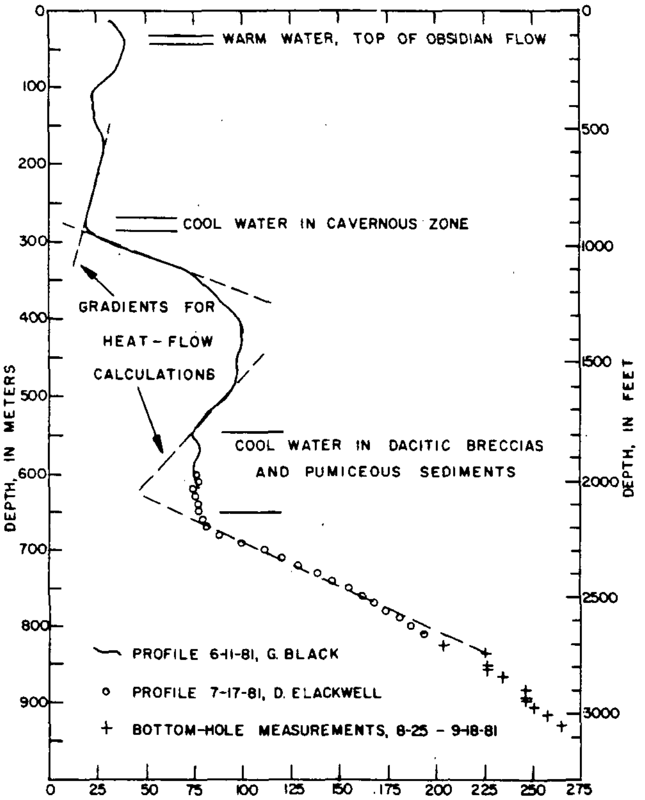

Figure 5. Temperature profile in test hole Newberry 2, showing inferred zones of cooling by ground water.

The thermal gradients above and below the flow zones are large, and the temperatures changed only 2 or 3 degrees over a period of more than a year despite episodes of drilling activity each summer. These facts tend to rule out disturbances due to drilling and convective flow in the borehole as significant influences on the temperature profile. If the temperature profile (fig. 5) represents the thermal regime in the rocks beneath the caldera, therefore, heat flow into the two principal cooling zones can be calculated on the basis of average conductive thermal gradients above and below these zones and the measured thermal conductivities of the rocks. The apparent conductive heat flow thus calculated for the two zones totals about 2 W/m^2 (50 Heat Flow Units).

The flow of cool water that is required to transfer the heat from these zones can be calculated and compared with the amount of water estimated to be available as seepage from the surface of the caldera. An analytical expression proposed by Bodvarsson (1969) affords a means of calculating the flow of a fluid at one temperature through a permeable zone bounded by two impermeable slabs having a different temperature. The observed temperature difference constrains the flow rate for any given period of time if it is assumed that the initial temperature profile was linear and conductive. The boundary conditions for Bodvarsson's expression are sufficiently similar to conditions known or deduced from the drilling data as to permit some qualitative conclusions from this approach.

Bodvarsson's expression (1969, p. 1989) is given as:

$$T = A \operatorname{erfc}[(\alpha X + y)/2(at)^{\frac{1}{2}}],$$

where T is the temperature at the boundary of the permeable zone ($y = 0$) at time t, A is the temperature of the injected water, erfc is the complementary error function, a is the thermal diffusivity of the rock-water mass in the impermeable slabs, x and y are spatial coordinates, and $\alpha = 2k/sq$ where k is the thermal conductivity of the slabs, s is the specific heat of the fluid, and q is the mass flow per unit length of the z coordinate. The mass flow rate calculated for ground water initially at a temperature of 20°C and for other conditions measured and assumed at a depth of 600 m in Newberry 2 ranges from 0.01 kg/s for 1,000 years to 0.007 kg/s for 1,500 years. At the depth of 275 m in the drill hole, the calculated flow rate of infiltrating ground water is 0.03 kg/s for 1,000 years and 0.02 kg/s per meter width for 1,500 years. The rates are calculated for a meter width of the permeable rock and for the 1100 m distance from the south caldera ring fracture to the drill hole.

If recharge has operated for 1,500 years, or roughly the time since the last major episode of eruption and caldera filling, a ground-water flow of about 0.03 kg/s per meter would be required in order to produce the profile observed in Newberry 2 from an originally linear conductive profile. This figure may be compared with the probable maximum available recharge beneath the drill site by assuming that one-half the recharge occurs through the land surface south of the lakes (a conservative assumption), and that it must occur in the approximately 4000 m-length of ring fracture bordering the south rim of the caldera. These crude assumptions result in a calculated recharge of 0.03 kg/s per meter, a figure fortuitously equal to the required flow at depth.

The values obtained by these methods are not quantitatively significant, but they suggest that meteoric water could supply the hydrothermal circulation system in the caldera fill and in the permeable flow rocks immediately below the fill. Core samples indicate that below 650 m horizontal permeabilities are extremely low and vertical permeability must be nearly zero (Keith and others, 1983). Only small amounts of water vapor and gas occurred in the rocks between 700 m and 930 m. The occurrence of formation water at 930 m remains a possibility which, at this time, cannot be confirmed or denied on the basis of chemical and isotopic data.

CONCEPTUAL MODEL

A model of the hydrothermal circulation system that fits most of the currently available data is one in which small amounts of steam and gas rise from a deep reservoir through poorly permeable fractures and faults (fig. 6). These heat sources were imposed, possibly within the last 1,300 years, on a conductive regime that had produced temperatures as high as 100°C at a depth of 400 m in the caldera. Some of the meteoric water that now infiltrates the caldera is warmed to temperatures that slightly exceed known spring temperatures (>62°C) and is chemically altered by the steam and gas. The thermal water returns to the surface at a few places that appear to be associated with ring fractures or vents for the Holocene flow rocks. Calculations based on observations of spring flow at the edges of the lakes and of temperatures in the lakes suggest that the total discharge of known thermal flows reaching the surface in the caldera is less than 20 L/s (Sammel and Craig, 1983). Some of the remaining surplus meteoric water may infiltrate deeper into the volcano, but most is probably dispersed to the flanks. Horizontal permeabilities probably are high enough to make it unlikely that a significant fraction of the recharge could reach a deep geothermal reservoir.

The conceptual model is currently being tested by the author in numerical simulation models based on a cooling pluton and ring-dike configuration proposed by Andrew Griscom (Written commun., 1983). At present, the location and nature of a geothermal reservoir are speculative. If the conductive gradient observed in the lower 70 m of Newberry 2 (505°C/km) continues to the base of the collapsed caldera block, temperatures would be about 500°C at a depth of about 1.4 km (MacLeod and Sammel, 1982). A small silicic magma chamber could be present at greater depth at the top of a large cooling pluton. Fracture permeability in adjacent volcanic rocks may provide a reservoir which could be supplied with water from deep regional ground-water flow.

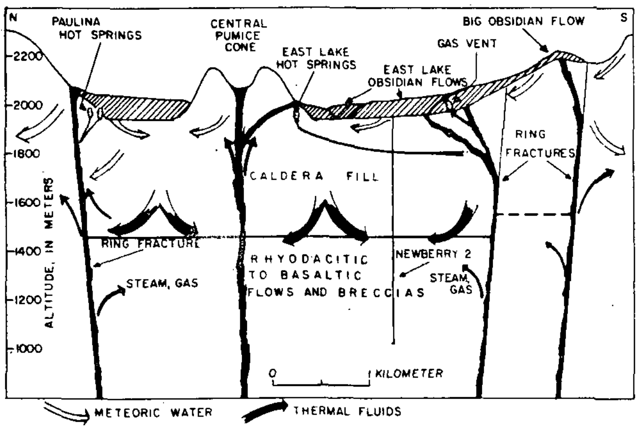

Figure 6. Sketch showing inferred relations among elements of the shallow hydrothermal regime.

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SAMMEL

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Table 1.-- Chemical analyses of ground and surface water [Concentrations in milligrams per liter unless otherwise indicated]

Sequence Number[1]	Owner/ name	Temp. (°C)	Ca	Mg	Na	K	HCO_3	SO_4	Cl	F	SiO_2	As	B	Fe	Li	Mn	Dissolved solids[2]	Specific cond. (µmho/cm)	pH	Date sampled	Source[3]
												(µg/L)									
1	Paulina Lake Resort	5	35	24	28	6.1	315	5.0	2.8	0.3	29	1	460	120	13	11	286	400	6.95	10/07/81	A
		6.7	39	35	38	7.7	398	1.9	2.7	.4	33	2	700	180	--	1500	356	565	6.9	10/27/74	B
2	Paulina Lake Resort	4	44	39	44	6.4	450	6.0	3.1	.5	36	24	780	6700	88	2300	410	600	7.15	10/07/81	A
3	Paulina Guard Station (USFS)	6	3.3	2.6	6.5	1.8	27	5.0	.2	.7	46	3	20	23	17	<1	79	65	6.65	09/06/81	A
5	Mike Mathews (summer home)	8	18	41	41	5.0	376	2	2.6	---	90	--	--	--	--	--	--	(700[5])	6.97	06/30/82	E
8	Jack Hogg (summer home)	--	30	65	68	7.4	585	5.0	5.2	.8	110	39	1500	<10	120	2	581	900	6.15	09/06/81	A
9	Little Crater Picnic Area	16	42	44	64	8.3	535	5.0	4.6	.7	90	32	1600	180	100	30	532	710	6.80	10/07/81	A
13	Little Crater Camp Site 27	6	28	17	25	2.6	215	5.0	1.7	.3	46	16	570	43	29	10	232	360	7.10	10/07/81	A
15	Little Crater Camp Site 49	33	59	57	97	12	690	5.0	6.8	.5	156	<1	1800	360	140	270	733	900	6.21	09/06/81	A
		35.5	54	48	83	10	679	<1	5.1	.6	161	--	2500	4000	120	250	702	900	6.46	08/--/75	C
		36	56	51	96	12	691	2.5	4.5	.5	140	2	1000	5000	---	350	709	880	6.3	10/17/74	E
16	East Lake Campground well	6	33	15	26	6.0	200	43	2.8	.2	40	1	210	19	9	3	265	390	6.80	09/06/81	A
20	Cinder Hill Campground well	5	7.1	1.9	11	1.3	56	5.0	2.5	.4	30	5	10	27	8	5	87	110	6.70	09/06/81	A
22	Cinder Hill Camp Site 34	4	14	7.2	6.3	3.5	88	5.0	<.1	.1	34	<1	10	120	<4	57	113	140	7.20	10/06/81	A
23	Paulina Hot Springs	--	56	60	140	17	856	<1	6.0	.6	205	--	870	--	220	--	907	--	6.82	07/00/77	C
		50	51	43	120	16	699	4.0	4.7	.5	190	16	840	90	--	1700	776	960	6.9	10/26/74	B
		52	50	42	110	13	689	2	5.0	--	184	--	--	--	--	--	--	--	7.26	06/30/82	E
24	Lost Lake gas vent	5	13	8.2	7.9	1.1	0	200	1.1	0.0	31	1	180	15000	--	450	--	400	3.4	10/27/74	B
25	East Lake Hot Springs	49	70	34	53	--	547	28	.7	.2	199	--	1100	660	40	900	658	767	6.42	08/00/75	C
		55	77	39	59	9.7	581	20	1.3	.1	120	1	260	500	--	1400	614	840	6.7	10/26/74	B
		57	73	33	56	9.7	413	120	1.3	--	197	--	--	--	--	--	--	--	6.10	06/30/82	E
--	Paulina Lake[4]	--	26	39	47	5.2	352	3.8	2.8	.6	46	--	--	--	--	--	366	566	8.8	09/10/60	D
		6	28	38	47	5.0	402	4	2.4	--	--	--	--	--	--	--	--	--	8.38	06/30/82	E
--	East Lake[4]	--	27	13	27	4.5	120	64	.3	.2	10	--	640	20	--	--	206	334	7.8	00/00/73	E
			26	10	23	3.7	125	59	.2	.1	13	--	--	--	--	--	197	323	8.1	09/11/60	D
		10	25	11	24	3.7	123	64	<1	--	8.8	--	--	--	--	--	--	--	8.07	06/30/82	E

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[1] Sequence No. ---- Identifying number used in tables and illustrations.

[5] Estimated.

[2] Estimated by summation of HCO_3 x 0.4917 and other ions listed (Hem, 1970).

[3] Source of data or collector (USGS): A: R. W. Craig; B: N. E. Voegtly; C: R. H. Mariner, and others (1980); D: K. N. Philips (1968); E: R. H. Mariner (unpub. data, 1981, 1982).

[4] Sample obtained at a depth of 45 feet near the center of the lake.