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

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DISCUSSION

ABOUT THIS MAP

Newberry volcano, one of the largest Quaternary volcanoes in the conterminous United States, is a broad shieldlike landform with a summit caldera 7 km across. It comprises the products of thousands of eruptions, at least 25 of which occurred during the last 10,000 years (Holocene Epoch). Eruptions have occurred as recently as 1,300 years ago, but isotopic ages indicate that the volcano began its growth as early as 0.6 million years ago. Thus, its long history and recent activity indicate that Newberry volcano is likely to erupt in the future.

Many young volcanic features of Newberry volcano have become part of the newly formed Newberry National Volcanic Monument, which was created on November 5, 1990. Enabling legislation, Public Law 101-522, resulted from three years of intense work by a diverse group of central Oregon citizens, including those from environmental, geothermal, timber, and recreation groups. The monument is managed by the United States Forest Service, U.S. Department of Agriculture. It includes the caldera and extends along the northwest rift zone to the Deschutes River. About 30 percent of the area within the monument is covered by Holocene volcanic products erupted from Newberry volcano.

This geologic map is one product of an evaluation of Newberry volcano conducted for the Geothermal Research Program of the U.S. Geological Survey. As mapping progressed, the U.S Geological Survey started a drilling program to understand the volcano's hydrologic regime and geothermal potential (Sammel, 1981; MacLeod and Sammel, 1982). Numerous other studies, many of which were published in 1988, describe additional drilling and drill-core analysis, modeling of the caldera's hydrology and its hydrothermal flow system, analyzing gravity and aeromagnetic data, characterizing the volcano's electrical structure, determining the regional crustal velocity structure, and imaging of the local velocity structure below Newberry volcano using teleseismic and explosive sources (see Fitterman, 1988, for overview and additional references). Two field trip guides are available for Newberry volcano and surrounding area (MacLeod and others, 1981; Jensen, 1988).

This geologic map distinguishes rocks and deposits on the basis of their composition (for example, andesite versus rhyolite) and lithology (for example, lava flows mapped separately from pyroclastic-flow deposits). Most flank lavas, which are chiefly basalt and basaltic andesite, are grouped together but could be further subdivided by additional mapping and chemical analyses. The caldera pumice and ash deposits, also known as tephra, were studied only briefly. They are complexly interbedded, show little erosion, and warrant further work because they contain the most complete record of Holocene caldera eruptions. Most flank rocks are mantled by windblown ash deposits (Mazama ash bed) derived from distant eruptions at Crater Lake National Park and are locally buried by widespread pumice-fall deposits originating from vents in the summit caldera. Consequently, many rock units are poorly exposed. In some cases, contacts shown on the map are based partly on topographic expression.

The age of rock units has been determined by several techniques. Isotopic ages of some Holocene stratigraphic units were determined by carbon-14 (^{14}C) dating, a method useful for dating organic material younger than about 50,000 years in age. The ^{14}C time scale diverges from conventional calendar years, however, because the relative abundance of the ^{14}C isotope in the atmosphere has varied over time (for example, Faure, 1986). Organic materials 3,000-7,000 years old yield ^{14}C ages that are 100 to 900 years younger than the age as measured in calendar years (see table 1). For example, charcoal from beneath the Lava Cascade Flow (Qyb_9) has a ^{14}C age of 5,800±100 years before present (yr B.P.), which corresponds to a calendar age of 6,610±130 yr B.P. (table 1). For organic material younger than 3,000 ^{14}C yr B.P., the deviation from calendar age is less than 200 years.

The Mazama ash bed blankets all older rocks, thereby forming a useful stratigraphic marker for determining the relative ages of Holocene rocks and deposits. The ash has a carbon-14 age of about 6,845±50 ^{14}C yr B.P., which corresponds to a calendar age of 7,640±50 yr B.P. (table 1). Most lava flows younger than the Mazama ash bed are easy to recognize because their pristine surfaces contrast starkly with surrounding ash-blanketed units. On particularly rough-surfaced, pre-Mazama lava and obsidian flows, however, the ash has been washed from knobby protuberances into depresssions, as has subsequently deposited tephra. Our 2-m-deep excavations on some of those flows failed to penetrate the younger tephra deposits and to test for the presence of Mazama ash. Thus, the age of those flows relative to the Mazama ash bed remains uncertain.

Hydration-rind ages were obtained from many Holocene obsidian flows (Friedman, 1977; Friedman and Obradovich, 1981). This method of dating assumes that glass hydrates inward from a fresh surface as a function of time; the rate is dependent upon the ambient temperature and composition of the glass. Therefore, hydration-rind ages also would differ from calendar ages if, as is likely, atmospheric temperatures have had significant long-term variations. The hydration-rind ages (table 2) are discussed as calendar ages but have potentially large errors owing to uncertainties in temperature history.

Potassium-argon (K-Ar) dating has been applied to many of the older rocks in the map area. The ages are interpreted as the number of years (millions of years) since the rocks crystallized; for volcanic rocks this is the age of emplacement. The K-Ar method relies on the time-dependent decay of potassium to radiogenic isotopes of argon. To be accurately dated, the material sampled must have a sufficient concentration of potassium and must be old enough to have accumulated measurable amounts of radiogenic argon. At Newberry volcano, replicate age determinations on individual rock bodies have produced widely varying K-Ar ages, owing to a combination of relatively youthful age, low potassium content, and large degree of contamination by atmospheric argon. Some anomalously old ages may result from the initial incorporation of radiogenic argon into the magma. Many K-Ar ages obtained from rocks and drill core at Newberry volcano are inconsistent with stratigraphic relations. Therefore, we refer in the unit descriptions only to those K-Ar ages deemed consistent with stratigraphic relations or to those ages for which other data are insufficient to challenge the accuracy of the age.

We also rely on the magnetic polarity of rocks as a way to bracket the ages of some units. When volcanic rocks crystallize they develop a very weak magnetization parallel to the Earth's magnetic field. The strength of the field fluctuates, and the field orientation reverses itself periodically. Although irregular in duration, the ages of magnetic polarity reversals are well determined from studies worldwide. By convention, the modern orientation is called normal polarity, and it characterizes rocks erupted during the last 730,000 years, as well as other normal-polarity epochs in the geologic past. Rocks erupted between 0.73 and 0.90 million years ago possess reversed-polarity magnetization. The "north" end of a compass needle would point to the southern hemisphere during times of reversed-polarity magnetization.

On the basis of reconnaissance field magnetometer studies, all stratigraphic units on the volcano are normally polarized and thus likely younger than about 0.73 million years. Accepted K-Ar ages from rocks on the volcano are as old as about 0.6-0.5 million years. Older, reversely polarized domes and lava flows probably predate Newberry volcano. For example, reversely polarized domes at China Hat and East Butte have K-Ar ages of 0.80±0.21 and 0.87±0.05 million years, respectively. Undated rocks at Indian and Amota Buttes also are older than 0.73 million years, on the basis of their reversed-polarity magnetization.

Many geographic names have been popularized over the years, and some have become formal place names. The name "Mount Newberry" was first applied to the volcano by I.C. Russell in honor of Dr. John S. Newberry, a scientist with the Pacific Railroad surveys of the mid-1800s and one "who did much to make the geography, geology, and botany of the State [of Oregon] widely known" (Russell, 1905, p. 97). Mount Newberry never became established as a geographic name, but Newberry Crater commonly has been applied to the summit caldera of Newberry volcano. The name "Big Obsidian Flow" originated as an apt designation for one of the most prominent geographic features in the caldera; it was already in use in 1935 when Howel Williams did his pioneering study of the summit caldera (Williams, 1935). Several important features such as Paulina Lake and Paulina Peak were named after Chief Paulina of the Walapi tribe.

We capitalize those geographic names that are formally approved by the U.S. Board on Geographic Names, whereas informal names are uncapitalized. The East Lake Fissure, for example, is a formal geographic name applied to a feature on the north caldera wall and extending down to the shore of East Lake. In contrast, "east rim fissure" is an informal name we apply to a vent system that parallels the eastern caldera ring fault along the caldera rim. Some other names have been used repeatedly in the geologic literature and are at times treated as though they were formally approved, when in fact they remain informal—for example, "Mixture Butte" and "The Spire." To avoid confusion, those names are always shown in quotations when used in this report.

Similar conventions for capitalization apply to the naming of geologic units. For example, the widespread ash deposit from ancestral Mount Mazama, commonly referred to as "Mazama Ash," has never been formally defined. Therefore we refer to it informally as the "Mazama ash bed." Nearly every Holocene lava flow on Newberry volcano has been named, many of them by Norman V. Peterson and Edward A. Groh (for example, Peterson and Groh, 1965, 1969). Although the names are often capitalized as proper nouns (Lava Butte Flow, for example), we interpret this to indicate their use as geographic place names, not as formal stratigraphic names. In stratigraphic studies, several criteria are discussed when formally naming a volcanic stratum, including description of the unit, its composition, mineralogy, location of a reference or "type" section, and definition of boundaries. None of the Holocene lava flows have been so treated. Hopefully, the mention and clarification of these details doesn't detract from the enjoyment and use of the map.

REGIONAL GEOLOGIC SETTING

Newberry volcano lies at the boundary between the Cascade Range and the Basin and Range physiographic provinces (fig. 1). It is similar in age to many Quaternary volcanoes in the Cascade Range. Lava from Newberry volcano and the Cascade Range is chemically similar. Newberry volcano lies only 60 km east of the Cascade Range crest, a distance that includes back-arc volcanoes in other arc-related volcanic chains. The Newberry caldera is only slightly smaller than Crater Lake—best known of Cascade Range calderas—located 110 km to the southwest. A caldera may also lie buried east of Broken Top, 50 km northwest of Newberry volcano. Ash-flow tuff and tephra deposits (units Qtb and Qsh, northwest corner of map area), possibly derived from the caldera east of Broken Top (Hill, 1985; Hill and Taylor, 1990), lie adjacent to the northwest flank of Newberry volcano.

Newberry volcano also shares tectonic and compositional characteristics with the Basin and Range physiographic province. Newberry volcano lies at the northwest end of, and shares some characteristics with, a Basin and Range-related sequence of rhyolite domes and caldera-related ash-flow tuffs that show a well-defined monotonic age progression (fig. 1). The sequence includes rhyolite erupted 10 million years ago about 250 km to the east; the rhyolitic rocks become younger northwestward, culminating in rocks younger than 1 million years at Newberry volcano (Walker, 1974; MacLeod and others, 1976). The rhyolite domes of this progression are chemically evolved, with concentrations of large-ion lithophile elements higher than in most rhyolite and rhyodacite of the Cascade Range. Some of the older rhyolitic rocks (Qer) at Newberry volcano are similarly evolved; they form groups of domes and lava flows along northeast trends subparallel to the isochrons of the age progression shown in figure 1.

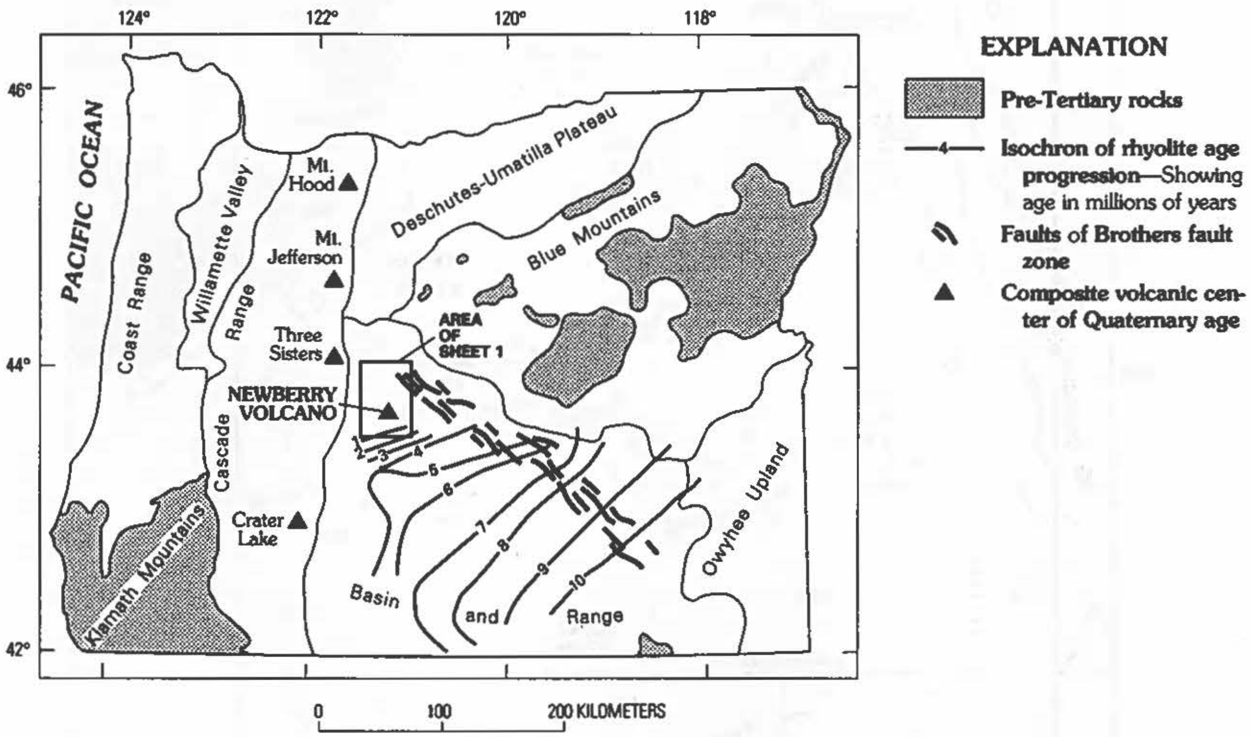

Figure 1. Physiographic provinces in Oregon (after Dicken, 1965) and location of map area. Rhyolitic age progression from MacLeod and others (1976).

SHAPE OF THE VOLCANO

The physiographic edifice of Newberry volcano is 60 km north-south and 30 km east-west (fig. 2). Its topographic base is at an elevation of about 1,350 m (4,400 ft), and its highest point, Paulina Peak, is 2,434 m (7,984 ft). Although only about 1,100 m high, the volcano covers an area of 1,600 km^2. The volume of the volcanic edifice is about 400-500 km^3, measured from the surrounding plains (1,350 m). The total volume of Newberry products may be twice as great, depending on the depth and configuration of the volcano's base in the subsurface and the volume of flows and tephra that extend beyond the map area or which are now eroded.

As shown by the geologic map (sheet 1), the elongate shape of Newberry volcano results from the distribution of vents and lava flows of basaltic andesite, basalt, and minor andesite along the length of the volcano. In contrast, dacitic to rhyolitic volcanism has been focused in the central part. Newberry-derived pyroclastic-flow deposits, which are mainly andesitic to rhyolitic in composition, are most widely exposed in the central sector of the volcano, as are nearly all the dacitic to rhyolitic domes and lava flows. The gentle 1°-3° slopes on the lower flanks of the volcano steepen abruptly at about the 1,800-m elevation (6,000 ft) to form the upper flanks, probably owing to the accumulation of stubby silicic lava flows and domes. Approximate limits of the central volcanic buildup are shown on cross sections *A-A'* and *B-B'* (sheet 1).

Basalt lava flows on the north flank of Newberry volcano spread across the broad plain of the Deschutes basin from Bend to beyond Redmond. They extend 45 km north of the map area, cover 700 km^2, range in thickness from 6 to 30 m, and account for an additional 4-20 km^3 of lava. The most northerly vents, however, are on the volcanic edifice in the map area. A broad low summit in an area known as the Badlands (northeast corner of sheet 1) is probably a rootless vent fed

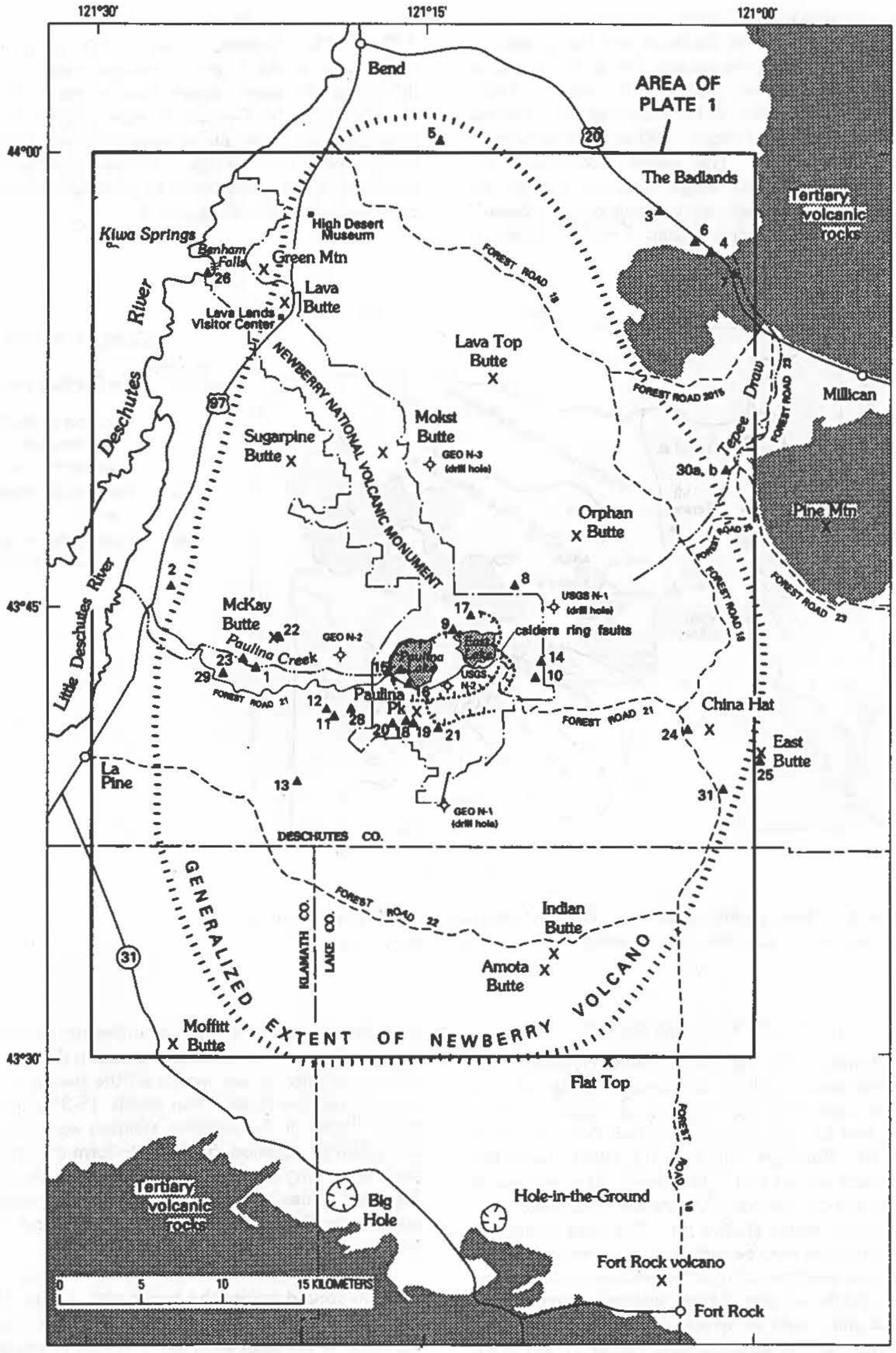

Figure 2. Geographic features in vicinity of map area. Potassium-argon sample locations (triangles) and map numbers shown for samples listed in table 3 except No. 27, which is located 13 km east of Pine Mountain summit. Stipple indicates rocks of known Tertiary age, generalized from Walker and others (1967), Swanson (1969), and MacLeod and Sherrod (1992).

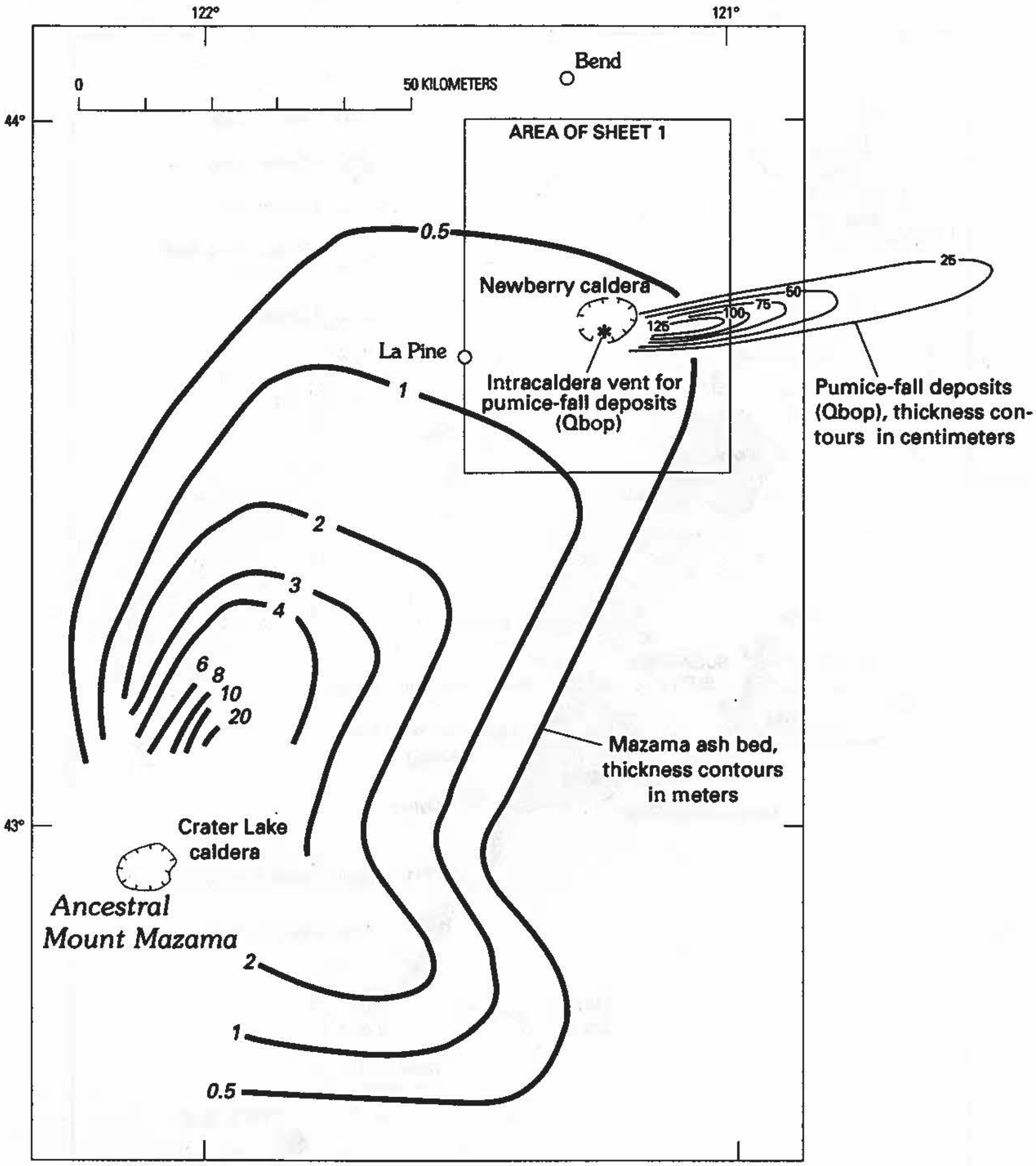

Figure 3. Distribution and thickness of the Mazama ash bed (erupted from Crater Lake caldera) and pumice-fall deposits (unit Qbop, erupted from Newberry caldera during the Big Obsidian eruptive period). Data from Sherrod (1991), MacLeod and Sherrod (1992), Sherrod and Pickthorn (1992), this map, and our unpublished work.

by lava tubes that originated upslope on Newberry volcano. The Badlands summit lacks near-vent cinder or spatter characteristic of primary vents.

Cross sections *A-A'* and *B-B'* (sheet 1) indicate that Newberry volcano sits astride a local downwarp with at least 500 m of relief. The downwarp is inferred from the distribution of rocks 3 million years or older at about the 1,400-m elevation (4,500 ft) south, east, and north of Newberry volcano, whereas equally old rocks have not been penetrated by even the deepest drill holes on the volcano's flanks. The downwarp may result from the weight of volcanic and shallow plutonic rocks that built the volcano. A downwarp of similar magnitude is known from Medicine Lake volcano (Calif.) (Dzurisin and others, 1991), a volcano remarkably similar to Newberry in its shape, eruptive style, and probably volume.

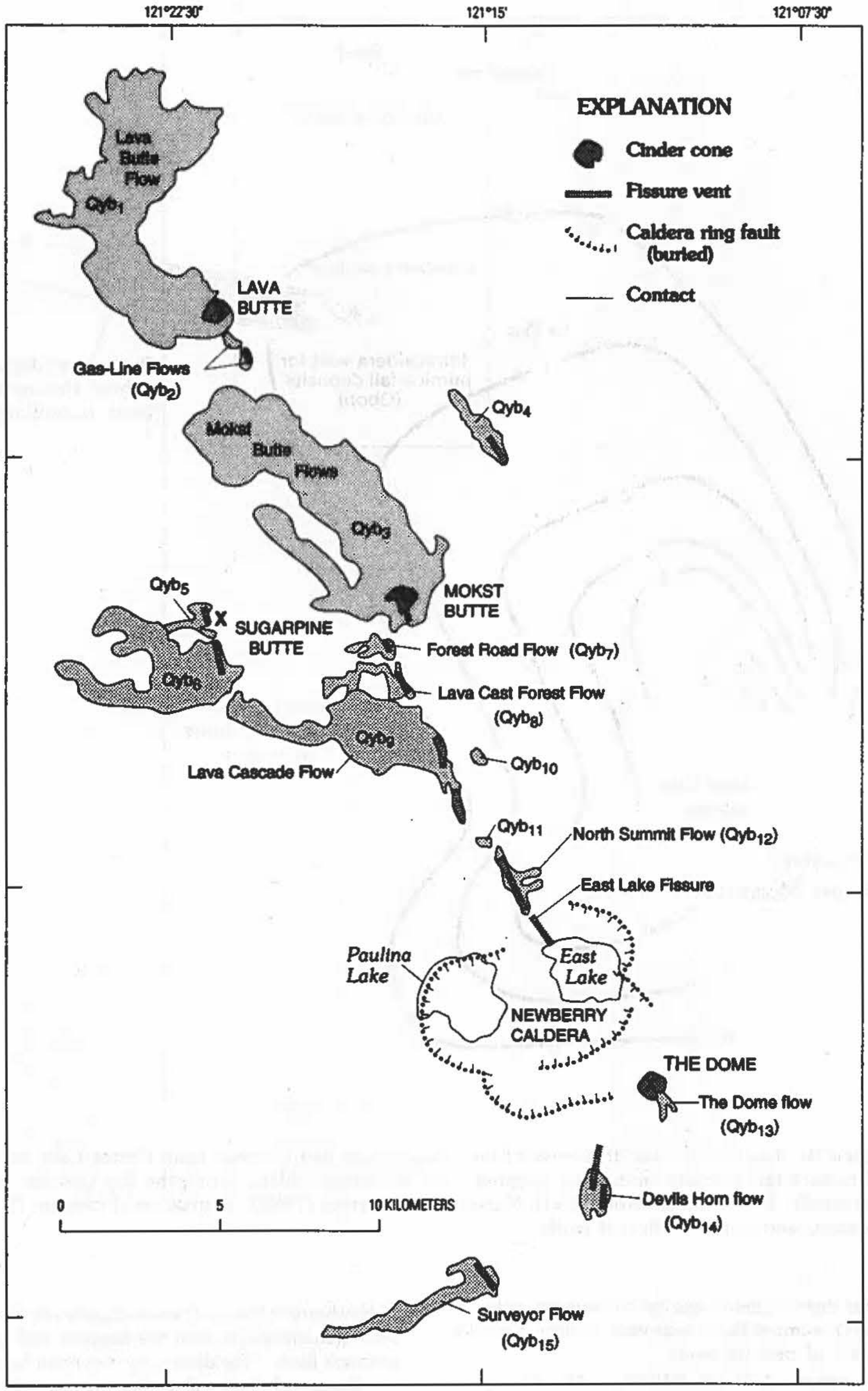

Figure 4. Holocene mafic lava flows (shaded) and geographic features of northwest rift zone and its south-flank continuation. The Dome flow and Devils Horn flow are informal names. See sheet 1 for explanation of map-unit symbols.

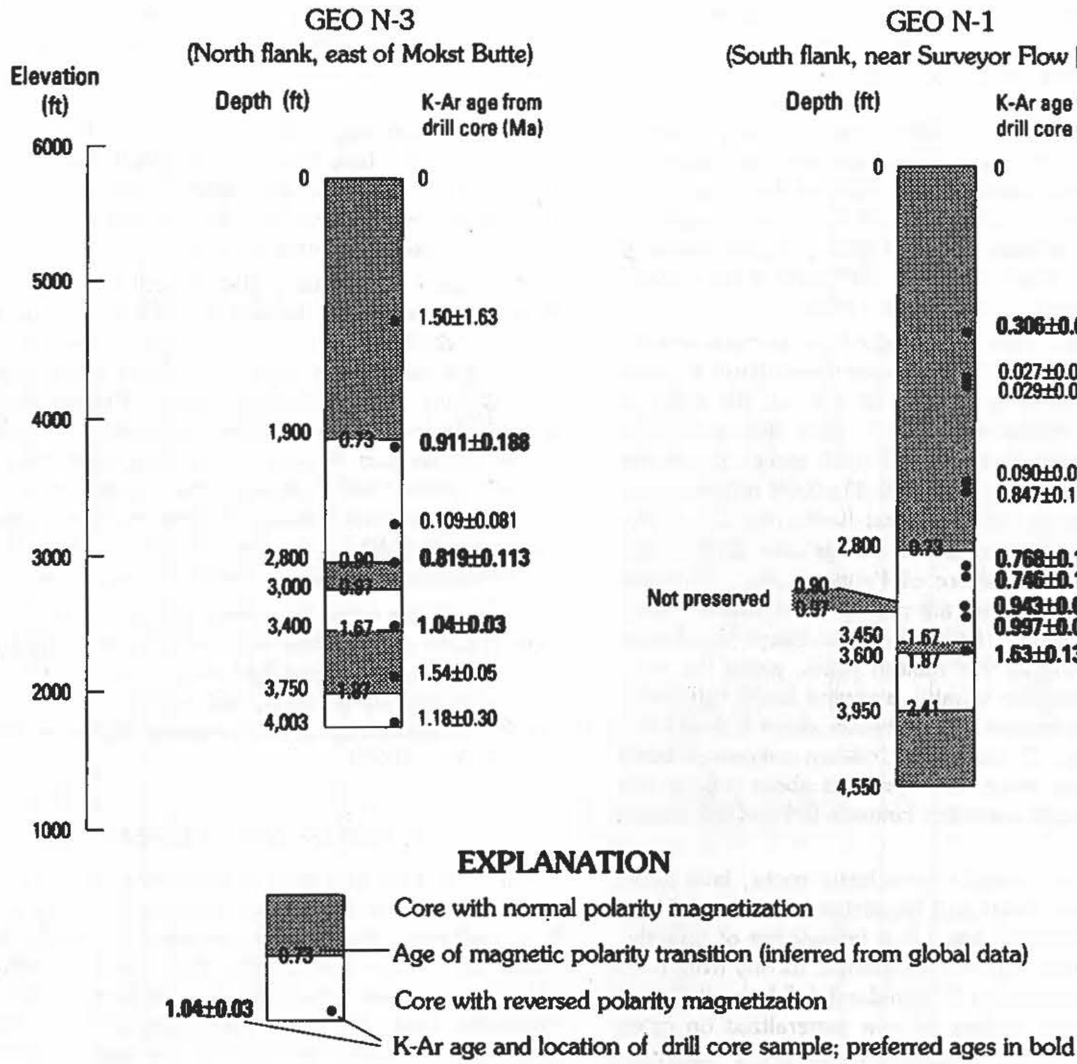

Figure 5. Drill core from GEO N-1 and GEO N-3, showing magnetic polarity transitions (Linneman, 1990) and K-Ar ages (Swanberg and others, 1988). Drill-core ages (right side of columns) in bold typeface are interpreted as accurate; other ages difficult to reconcile with magnetic polarity data. Ages of global magnetic polarity transitions from Mankinen and Dalrymple (1979). See figure 2 for location of drill sites.

For the cross sections, we have combined K-Ar ages from drill core (Swanberg and others, 1988) with magnetic polarity data (Linneman, 1990) to determine age-depth relations. The best fit for data from drill hole GEO N-1 (fig. 5) requires our assuming that the drill core does not record the Jaramillo Normal-Polarity Subchron (of the Matuyama Reversed-Polarity Chron) (0.97-0.90 million years ago). For GEO N-3, the K-Ar ages lack any internal consistency, so the magnetic polarity reversals were assigned to chronozone boundaries by assuming that every major reversal was sampled. If the assumptions are appropriate, then both holes penetrated rocks older than about 1.87 million years in their lowest parts. This interpretation of the drill-core data creates a symmetrical age-depth profile of the volcano (section *A-A'*).

Little is known about age-depth relations west of the volcano. Water wells in La Pine basin have penetrated as much as 400 m of alluvium, including lake deposits, before hitting lava flows (Couch and Foote, 1985). Thickest parts of the alluvial fill, which may be as thick as 0.7-1.0 km (Gettings and Griscom, 1988), probably coincide with a 10-mGal gravity anomaly located at the west edge of section *B-B'* (Couch and others, 1982). (Gravity anomalies commonly result where low-density sedimentary rocks accumulate to great thickness; the force of gravity measured at the Earth's surface is less in these areas owing to the density contrast.) In contrast to the alluvium of La Pine basin, lacustrine deposits are lacking in drill holes on the flanks of Newberry volcano, and the alluvial strata on the volcano are complexly interbedded with primary pyroclastic rocks. Thus it seems likely that the volcano has formed the eastern buttress to basin-filling sediment for a substantial period of time.

THE CALDERA

The summit caldera of Newberry volcano is about 7 km east-west by 5 km north-south. It is a collapse structure with several walls nested one inside the other, indicating more than one set of ring fractures. The multiple ring fractures may have formed during a single event as blocks collapsed piston-like or slumped along the margin of the caldera. More likely, however, is a collapse associated with each of the voluminous pumiceous eruptions that produced the major ash-flow tuffs of the flanks. The two largest ash-flow tuffs, the tuff of Tepee Draw (Qtp) and the basaltic andesite lapilli tuff (Qbt), probably produced caldera collapse. Each occupies a 50° sector of the volcano and has a volume in excess of 10 km^3.

Ages for the major pyroclastic-flow deposits remain poorly known. The tuff of Tepee Draw (Qtp) is most likely about 0.50 million years in age, on the basis of K-Ar age determinations (table 3, Nos. 30a and 30b). The basaltic andesite lapilli tuff (Qbt) lacks meaningful K-Ar ages. It is younger than 0.41±0.08 million years (age of a dome on the southwest flank, No. 13 on fig. 2) and older than intracaldera domes (unit Qrpl, sheet 2) on the southwest shore of Paulina Lake. The age of the intracaldera domes are poorly constrained by ages of 0.58±0.40 and 0.56±0.40 million years; the domes may be as young as 0.2 million years, given the relative error. Thus the basaltic andesite lapilli tuff probably was erupted some time between about 0.4 and 0.2 million years ago. To summarize, caldera collapse probably occurred at least twice, the first time about 0.5 million years ago and again sometime between 0.4 and 0.2 million years ago.

The caldera contains pyroclastic rocks, lava flows and domes, and fluvial and lacustrine deposits of Pleistocene and Holocene age. Our knowledge of underlying, caldera-filling deposits is obtained mostly from core samples of USGS N-2, a 932-m-deep drill hole sited near the center of the caldera (shown generalized on cross section *A-A'*, sheet 1) (MacLeod and Sammel, 1982; Keith and Bargar, 1988). Core from the upper 500 m consists of clastic rocks except for an obsidian flow at 42- to 98-m depth and a rhyodacite sill at 460-470 m. To a depth of 290 m, the rocks are basaltic and rhyolitic lapilli tuff, minor tuff breccia, and alluvium derived from the tuff. Lacustrine sediment from depths of 290-320 m indicate that the caldera was initially much deeper and that the central block subsided 500-800 m as measured from the caldera rim. Ash-flow deposits cored at depths of 320-500 m may be products of pyroclastic eruptions associated with caldera collapse, but they are chemically dissimilar to ash-flow deposits exposed on the flanks. In contrast to the clastic upper part, the core from 500 m to the base of the hole (932 m) consists mostly of lava flows, which are progressively more mafic downsection, from rhyodacite to dacite, andesite, and basalt. The flows between 500 m and the base of the hole at 932 m may be precaldera rocks of Newberry volcano (interpretation of cross section *A-A'*); alternatively, the lava flows may be caldera filling, in which case other major sequences of pyroclastic rocks, including lateral equivalents of the tuff of Tepee Draw (Qtp), exist at greater depth.

East and Paulina Lakes are the major lakes located in the caldera of Newberry volcano. (A minor intermittent pond, Lost Lake, is located near the Big Obsidian Flow.) East Lake occupies the northeast corner of the caldera floor. It is about 50 m deep at its deepest point, and much of the northern half is deeper than about 30 m (see bathymetry on sheet 2). Inflow to the lake is chiefly by subsurface flow and snowmelt; outflow is also by subsurface flow, some of which moves westward into the slightly larger Paulina Lake (Phillips and Van Denburgh, 1968; Johnson and others, 1985).

Paulina Lake is one of the deepest lakes in Oregon, about 80 m deep at its deepest point (Johnson and others, 1985). Like East Lake, Paulina Lake receives inflow by subsurface waters and snowmelt; unlike East Lake, it is drained by a stream, Paulina Creek. Paulina Lake lies about 15 m lower than East Lake, from which it is separated by lava flows and volcanic cones that have built up in late Pleistocene and Holocene time. Given the small difference in elevation between Paulina and East Lakes and the relative youth of rocks separating them, it seems likely that the lakes were a single body of water in past times.

Hot springs occur along the south and southeast shore of East Lake and the east and northeast shore of Paulina Lake. Additional thermal fluid seeps from the lake floors. Both lakes contain unusually high concentrations of major ions as a consequence of the hot-spring discharge (Johnson and others, 1985).

ABSENCE OF GLACIAL FEATURES

Evidence for glaciation at Newberry volcano is poorly substantiated, and it seems unlikely that the volcano sustained more than a few permanent snowfields at high elevations in late Pleistocene time. Perhaps small cirque-filling glaciers were located at the base of cliffs north of Paulina Peak. But earlier suggestions that the volcano's west flank is mantled by till or that the west rim of Paulina Lake is a terminal moraine (Russell, 1905) are now known to be incorrect. (Russell's early attempt to explain the caldera's landform was made without benefit of subsequent investigations into the mechanism of caldera collapse.) The absence of till has prevented the use of dating methods in which the age of volcanic deposits is inferred by their relation to glacial deposits of known age, a technique used elsewhere in the Cascade Range. Periglacial effects such as increased runoff and erosion during glacial wasting probably have modified older lava-flow surfaces; nevertheless, relative dating techniques such as comparative flow morphology proved difficult to apply as mapping tools because much of the volcano is thickly but variably blanketed by the Mazama ash bed. Also, precipitation (and consequently, rate of erosion) varies significantly across the volcano.

Glaciers were widespread in the Cascade Range during late Pleistocene time. Their apparent absence at Newberry probably resulted from the volcano's position in the rain shadow of the Cascade Range and perhaps from other effects of atmospheric circulation. Older volcanoes closer to the Cascade Range but east of the range crest, such as Black Butte (45 km northwest of Bend), are also known to have been spared from extensive glacial erosion.

HOLOCENE ERUPTIVE ACTIVITY

Holocene volcanic rocks and deposits are widespread at Newberry volcano. They include rhyolitic rocks centered around the east half of the caldera (for example, unit Qyo on sheet 1) and basaltic andesite flows of the flanks (Qyb_{1-15}). Lava flows younger than the Mazama ash bed are easy to recognize because of their stark, fresh surfaces. Pre-Mazama Holocene rocks are difficult to distinguish from Pleistocene units because they are poorly exposed.

We once interpreted as early Holocene an obsidian flow and dome (Qyrc) near the south caldera wall, the east rim fissure (part of unit Qc), and the basaltic andesite near East Lake Resort (unit Qbce, sheet 2) (MacLeod and Sherrod, 1988). This interpretation was based on the unweathered appearance of these units and their position beneath the Mazama ash bed. But carbon from beneath the east rim fissure recently yielded a ^{14}C age of 10,500±500 yr B.P. (Linneman, 1990), which corresponds to a calendar-year age of 10,970±500 yr B.P. (table 1), indicating that the rocks forming these geographic features are probably latest Pleistocene. Cinders from the east rim fissure overlie unweathered pumice deposits possibly erupted from the vent for the obsidian flow (Qyrc) near the south caldera wall. The other notable silicic deposits of uncertain age form the large pumice ring of Lost Lake (unit Qlp, sheet 2), at the northeast edge of the Big Obsidian Flow.

The first major post-Mazama eruptions were of rhyolitic composition and occurred within the caldera perhaps about 7,300 calendar yr B.P. The best known products of these eruptions are the Central Pumice Cone (unit Qicp, sheet 2), its obsidian flows (units Qicf and Qicg on sheet 2), and the Interlake Obsidian Flow (unit Qiif, sheet 2). Silicic tephra from some of these vents underlie basaltic andesite flows of the northwest rift zone (discussed next), which were emplaced between 6,600 and 7,200 yr B.P. Therefore, hydration-rind ages of about 6,700 yr B.P. from the Central Pumice Cone and associated obsidian flows are too young (table 2).

Also of this early, post-Mazama age is the East Lake tephra deposit of MacLeod and others (1982), which is a widespread thick phreatomagmatic pumiceous tephra deposit (part of unit Qyt) in the eastern and southeastern parts of the caldera. The East Lake tephra deposit has an age of 7,300±130 calendar yr B.P. (6,400±130 ^{14}C yr B.P., table 1). It was most likely erupted from a vent beneath the southwest corner of East Lake (vent symbol shown dotted on geologic map; see sheet 2 for bathymetry of proposed vent area). Other lesser known deposits produced at about the same time include pumice cones (units Qilp and Qiwp, sheet 2) at the base of the north caldera wall, small pumice rings and obsidian protrusions (units Qisp, Qipe, and Qisf, sheet 2) along the inner south wall, and possibly the young rhyolite of the upper southeast flank (Qyrf). None of them have been dated by isotopic or hydration-rind methods, and their tentative assignment to the first post-Mazama eruptive period is based on similar weathering profiles.

Holocene basaltic andesite forms cinder cones and fissure-vent deposits (Qyc) as well as extensive lava flows (Qyb_{1-15}) on the northwest, north, and south flanks of the volcano. No basaltic andesite erupted through the caldera floor, although basaltic andesite did erupt from the East Lake Fissure on the north caldera wall. The flows range from a few hundred meters to 9 km long and cover as much 25 km^2, although most are smaller than 1 km^2. Flows low on the flank are more extensive and voluminous than those high on the volcano. The suite of flows is chemically heterogeneous, and a few individual flows show as great a heterogeneity as the difference between all flows. Most of the flows are younger than the Mazama ash bed (younger than 6,845 ^{14}C yr B.P.), but the Devils Horn flow (Qyb_{14}) is known to be older, and The Dome flow (Qyb_{13}) is of uncertain age relative to Mazama ash. Ages of carbon found in or beneath the basaltic andesite range from 5,800 to 6,380 ^{14}C yr B.P. (table 1), and multiple age determinations from single flows have about as large a spread as the suite of ages. Thus the flows younger than Mazama ash may have been erupted in a brief time span. Paleomagnetic orientations of individual flows are similar, even though the flows formed at a time when magnetic secular variations were large. This lack of magnetic variation is consistent with a short eruptive episode (D.E. Champion, oral commun., 1991). The span of radiocarbon ages can be explained as resulting from the varying age of organic material engulfed or buried by the flows (heartwood of trees may yield ^{14}C ages hundreds of years older than layers near the bark).

Most vents for the Holocene basaltic andesite flows are aligned in a northwest-trending zone known as the northwest rift zone. The rift zone extends 23 km almost without interruption from its southeast end at the East Lake Fissure to Lava Butte at the northwest end (sheet 1). Its molten lava was fluid enough to encase trees in upright positions; the best known examples are in the Lava Cast Forest Flow (unit Qyb_8, sheet 1). Although the lava chilled quickly against the wood, the heat was intense and the trees were consumed in flames, leaving only hollow molds or wells as a record. Charcoal gathered from these tree wells or from the soil beneath the lava flows has been an important source of material for carbon-14 dating.

The edges of the Holocene lava flows in the northwest rift zone form a nearly continuous set of easily recognized landmarks leading to the caldera and thus provided a travel route used by prehistoric people. Caves associated with all the flank lava flows provided shelter, and several contained perennial ice that provided summer water in an otherwise arid terrane (for example, Cressman and Perry, 1938).

Rhyolitic eruptions have continued since the emplacement of the young basaltic andesite lava flows. The East Lake obsidian flows (sheet 2) were erupted about 3,500 years ago, as determined by hydration-rind dating methods. But the youngest and perhaps the best known volcanic deposits at Newberry volcano were emplaced about 1,300 yr B.P. from a vent beneath the Big Obsidian Flow. These deposits, which we assign to the Big Obsidian eruptive period, form the three-part volcanic sequence that characterizes many rhyolitic eruptions. The early, most explosive phase produced an eruptive column that was deflected by westerly winds to form a shower of pumice lapilli and ash in a narrow lobe on the east flank of the volcano. The resultant pumice-fall deposits (Qbop) are more than 3 m thick in the caldera and as much as 1 m thick at a distance of 15 km from the vent. Subsequent, less explosive eruptions created ground-hugging pyroclastic clouds that were confined mainly to the caldera as they surged downslope from the vent toward Paulina Lake. The road between Paulina and East Lakes today crosses these ash-flow deposits of Paulina Lake (Qboa) along the south shore of Paulina Lake and at Little Crater campground. The final stage of the eruption was relatively quiet as the degassed magma finally protruded to form the Big Obsidian Flow (unit Qbof, sheet 2). The vent for all three units emplaced during the Big Obsidian eruptive period is marked by a domal protuberance near the south edge of the Big Obsidian Flow.

Most likely the pumice-fall deposits were followed closely by pyroclastic flows, perhaps within days of each other. Surprisingly, however, a roughly 300-year difference separates ^{14}C ages from charcoal beneath the pumice-fall deposits (Qbop) and in the ash-flow deposits of Paulina Lake (Qboa) (table 1). The discrepant ages remain a problem in interpreting the history of the Big Obsidian eruptive period, but they may result merely from differences in material sampled for dating. Charcoal found beneath the pumice-fall deposits (Qbop) might be from woody material that had been on the forest floor for a substantial period of time, whereas charcoal in the ash-flow deposits most likely came from the branches of standing trees (the pumice-fall deposits had already mantled the ground) (W.E. Scott, written commun., 1991).

A rhyolitic magma chamber may persist beneath Newberry caldera. The evidence includes (1) relatively consistent composition of Holocene rhyolitic rocks, (2) distribution of rhyolitic Holocene vents in an area devoid of but surrounded by Holocene basaltic vents, (3) occurrence of mixed basaltic-rhyolitic Holocene rocks at the margin of this area, (4) similar duration of repose intervals between rhyolitic eruptions, and (5) a high conductive geothermal gradient that characterizes rocks in the lower 300 m of the caldera drill hole, USGS N-2 (MacLeod and Sherrod, 1988). The exclusion of basaltic vents from the area of silicic vents apparently is a shadow effect, such that dense basalt magma rising along dikes is unable to penetrate the overlying viscous, relatively light rhyolite magma. Presumably the distribution of Holocene basaltic vents (thus the shadow size) indicates the maximum area underlain by the silicic magma chamber. The limiting shallowest depth for the top of the chamber is about 2 km, the depth to dry partial melting of rhyolite, as inferred by extrapolating the geothermal gradient (600°C per km) and bottom-hole temperature (265°C) of the caldera drill hole. This extrapolation assumes that the geothermal gradient remains conductive below drilling depth and that thermal conductivities are similar to those in the lower part of the hole. The top of the chamber would be much deeper if, as is likely, convection characterizes the heat transfer below the drill hole. Although not conclusive, the five relations strongly support the presence throughout Holocene time of a magma chamber whose upper part did not crystallize, either between eruptions or since the last eruption about 1,300 yr B.P.

A low-velocity seismic anomaly about 3 km below the summit caldera was interpreted as a small magma chamber (Achauer and others, 1988). However, the anomaly corresponds to an area of average attenuation; whereas high attenuation of seismic waves would be expected from molten rock (Zucca and Evans, 1992). An alternative explanation for the zone of low velocity and average attenuation beneath the caldera is the presence of numerous dry cracks in a recently solidified, shallow, and still very hot pluton (Zucca and Evans, 1992).

The Holocene obsidian flows contain high-quality glass that attracted prehistoric inhabitants of the region. Historic ethnic groups such as the Tenino and Northern Paiute, and their direct ancestors or predecessors in the region, probably wintered at low elevations along the Deschutes River and ventured into the caldera during summer and fall (Connolly and others, 1991), when they quarried obsidian and produced bifacial quarry blanks (unfinished tools) for transport out of the caldera (Scott, 1985a; Flenniken, 1987; Flenniken and Ozbun, 1988). Although the Big Obsidian Flow (unit Qbof, sheet 2) was probably the main source for obsidian in the last 1,300 yrs, all major Holocene obsidian flows in the caldera were quarried for tool stone. Cultural flakes from south of East Lake are in soils developed beneath the Mazama ash bed on the young rhyolitic dome and flow of the caldera (Qyrc), indicating that this now-mostly buried obsidian flow was a source of lithic materials prior to 7,700 yrs ago (T.J. Connolly, written commun., 1991). On the flanks of Newberry volcano, McKay Butte is known to have been an important source of obsidian, especially prior to the emplacement of Holocene sources within the caldera (for example, Scott and others, 1986).

Holocene silicic tephra, especially the Mazama ash bed erupted at Crater Lake and pumice-fall deposits erupted as part of the Big Obsidian eruptive period in Newberry caldera, are important stratigraphic markers for archaeological studies in central Oregon. For example, the roughly 1,600-yr-old pumice-fall deposits provide a time horizon for bracketing the age of prehistoric occupation at Sand Spring, 27 km east of Newberry caldera. As noted by Scott (1985b), the archaeological setting at Sand Spring would be similar to other open-air sites on the High Lava Plains were it not for the presence of the young pumice-fall deposits (her "Newberry pumice") to separate artifacts younger than 1,600 yr from those that are older. Similarly, pumiceous tephra thought to correlate with Holocene eruptions at Newberry volcano overlies human artifacts in Fort Rock Cave, 38 km southeast of the caldera (Cressman and Williams, 1940). The tephra at Fort Rock Cave conceivably could be the 1,600-yr-old deposit, inasmuch as no other Holocene tephras from Newberry are known to blanket the southeast flank of the volcano.

GEOTHERMAL ACTIVITY

Much of the interest in Newberry volcano as a source of geothermal energy results from the abundance of young silicic rocks. Such rocks were probably derived from shallow crustal magma chambers that may retain some heat. The resulting thermal anomaly is superimposed on regionally high heat flow that characterizes the northern Basin and Range province. Throughout the Cascade Range in Oregon, only the area near Crater Lake National Park (ancestral Mount Mazama) compares with Newberry volcano in its abundance of young silicic rocks and high volcanic production rate (Sherrod and Smith, 1990).

Surface thermal features at Newberry volcano include hot springs at Paulina and East Lakes, hot water in wells adjacent to the lakes, and a drowned fumarole at Lost Lake, a small intermittently dry pond near the Big Obsidian Flow (sheets 1, 2). Gravel and sand in the caldera are silicified along the southeast shore of Paulina Lake, perhaps from silica-charged thermal waters effusing in past times. Measured temperatures from hot springs on the northeast shore of Paulina Lake are about 55°C; temperatures from East Lake hot springs (southeast shore of East Lake) are about 65°C (Mariner and others, 1980).

Exploratory geothermal drilling in Newberry caldera has produced some of the highest temperatures from the Cascade Range, but the reservoir temperature remains unknown. Bottom-hole temperatures in USGS N-2 were 265°C when measured at 932 m depth as drilling progressed. The high temperature most likely reflects a deeper convective anomaly. Cation thermometers, which rely on the concentration of sodium, potassium, and calcium cations in thermal fluids as a thermodynamic indicator of reservoir temperatures, range from 150 to 200°C (Mariner and others, 1980). The uppermost kilometer of the caldera's thermal system has never been significantly hotter than found today, according to the distribution of secondary minerals and isotope partitioning between water and minerals (Carothers and others, 1987; Keith and Bargar, 1988). Propitious temperatures and geothermal gradients have been found only within 5 km of the caldera, suggesting that the economically accessible thermal anomaly is areally restricted to the summit and upper flanks of the volcano.

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Table 1. *Carbon-14 ages from Newberry volcano*

Geologic unit (sheets 1 and 2)	Carbon-14 age[1] (^{14}C yr B.P.)	Weighted mean age (^{14}C yr B.P.)	Recalculated age[2] (calendar yr B.P.)	References
Silicic volcanic and volcaniclastic rocks and deposits				
Ash-flow deposits of Paulina Lake (Qboa)	1,270±60			Pearson and others (1966)
Do	1,340±60	1,310±40[3]	1,240±50	Robinson and Trimble (1983)
Do	1,390±200			Kelley and others (1978)
Do	2,054±230			Libby (1952)
Pumice-fall deposits (Qbop)	1,720±250	1,580±110	1,480±130	Spiker and others (1978)
Do	1,550±120			Robinson and Trimble (1983)
East Lake tephra deposit (Qyt, part)	6,220±200			Meyer Rubin and W.E. Scott, unpub. data, 1985
Do	6,500±300	6,400±130	7,300±130	Meyer Rubin, in Linneman (1990)
Do	6,550±300			Do.
Mazama ash bed		6,845±50[4]	7,640±50	Bacon (1983)
Sedimentary deposits				
East shore Paulina Lake	4,300±100[5]	----	4,860±120[5]	Robinson and Trimble (1983)
Mafic volcanic rocks				
Lava Butte Flow (Qyb$_1$)	6,160±70	----	7,070±110	Chitwood and others (1977); Robinson and Trimble (1981)
Gas-Line Flows (Qyb$_2$)	5,800±150			Do.
Do	6,150±65	6,100±60	7,020±130	Robinson (1977); Chitwood and others (1977)
Flow on west side of Sugarpine Butte (Qyb$_5$)	5,870±60	----	6,730±110	Robinson and Trimble (1981)
Forest Road Flow (Qyb$_7$)	5,960±100	----	6,800±100	Peterson and Groh (1969)
Lava Cast Forest Flow (Qyb$_8$)	6,150±210			Peterson and Groh (1969)
Do	6,380±130	6,320±110	7,240±70	Do.
Lava Cascade Flow (Qyb$_9$)	5,800±100	----	6,610±130	Peterson and Groh (1969)
North Summit Flow (Qyb$_{12}$)	6,090±60	----	7,000±150	Do.
Surveyor Flow (Qyb$_{15}$)	5,835±195			Swanberg and others (1988)
Do	6,080±100	6,030±90	6,950±190	Peterson and Groh (1969)
East rim fissure (Qc, part)	10,000±500	----	10,970[6]±500	Meyer Rubin, in Linneman (1990)

[1] Carbon-14 ages based on Libby half-life of 5,568 yrs. Years before present (yr B.P.) measured from 1950 A.D.

[2] Generalized from program in Stuiver and Reimer (1986) that computes intercepts and range (one confidence interval). Radiocarbon age curve not linear and may have multiple possible calendar ages (intercepts) for a given ^{14}C age. Recalculated age as reported here is midpoint between oldest and youngest intercepts, rounded to nearest ten years; reported error is range (one confidence interval) as calculated by the program. Note that age of east rim fissure (last age in table) was calculated by different method.

[3] Weighted mean age does not include Libby's (1952) determination of 2,054 yr B.P.

[4] Weighted mean age of four charcoal samples (Bacon, 1983).

[5] Age too young. Dated horizon underlies the Mazama ash bed, and age must be at least 6,845±50 ^{14}C yr B.P.

[6] Calculated using the formula "calendar yrs = (1.05) x (radiocarbon yrs) + 470" (Stuiver and others, 1986), which best approximates the limited data available.

Table 2. *Hydration-rind ages from Newberry volcano*

Geologic unit	Map symbol (sheet 2)	Age in calendar years[1] (yr B.P.)	Reference
Big Obsidian Flow	Qbof	1,400	Friedman (1977)[2]
East Lake obsidian flows	Qelf	3,500	Do.
Crater-filling obsidian flow of Central Pumice Cone	Qicf	4,500[3]	Do.
Game Hut Obsidian Flow	Qicg	6,700[3]	Do.
Central Pumice Cone—Volcanic bomb	Qicp	6,700[3]	Do.
Interlake Obsidian Flow	Qiif	6,700[3]	Do.

[1] No error range was reported, but it is probably tens of percent of the reported age. Friedman and Obradovich (1981) arbitrarily assigned error of ±20 percent for ages elsewhere in the western United States.

[2] Slightly younger ages were reported by Friedman and Obradovich (1981), who used slightly higher hydration rates.

[3] Ages too young; silicic tephra from the Central Pumice Cone and the vent for Interlake Obsidian Flow underlie basaltic andesite flows of the northwest rift zone, which were emplaced between 6,600 and 7,200 calendar yr B.P.

Table 3. *Potassium-argon ages from Newberry volcano and vicinity*

[Ages in boldface are consistent with stratigraphic relations or lack stratigraphic data that challenges their accuracy (at stated level of precision)]

Map No. (fig. 2)	Sample No.	Location		General geographic locale and map unit	Rock type	Material dated	K_2O (weight percent)	$^{40}Ar_{rad}$ $\times 10^{11}$ (moles/gm)	Percent $^{40}Ar_{rad}$	Calculated age[1] (million years)	References
		Latitude	Longitude								
					Mafic lava flows						
1	M9-24	43°42.95'	121°22.77'	Paulina Creek, Qba	Basalt	Whole rock	0.861	0.00249562	0.21	**0.02±0.10**	E.H. McKee and N.S. MacLeod, unpub. data, 1981.
2	M6-109	43°45.6'	121°26.5'	Lower west flank of Newberry volcano; Qba	Basalt	Whole rock	1.157	0.0078064	0.32	**0.05±0.07**	Fiebelkorn and others, 1983.
3	86-1	43°58.03'	121°04.13'	Badlands; Qba	Basalt	Whole rock	(0.482)[2]	(0.048)[2]		**0.7±0.1**	Hawkins and others, 1988.
							0.48	0.068	2.7		
							0.477	0.043	1.6		
								0.0350	1.3		
4	19/14E	43°56.8'	121°01.9'	Badlands; Qba	Basalt	Whole rock	0.680	0.082031	5.4	0.84±0.08	L.R. Squier Associates, Inc., 1984.
5	86-3	44°00.38'	121°14.38'	North flank of Newberry volcano; Qba	Basalt	Whole rock	(0.494)[2]	(0.190)[2]		2.7±0.3	Hawkins and others, 1988.
							0.518	0.0775	2.3		
							0.469	0.295	5.3		
							0.495	0.198	3.8		
6	86-2	43°57.03'	121°02.73'	Badlands; Qba	Basalt	Whole rock	(0.524)[2]	(0.22)[2]		2.9±0.3	Do.
							0.572	0.24	2.9		
							0.480	0.20	3.0		
							0.515				
							0.531				
7	M6-4	43°55.7'	121°00.8'	Horse Ridge; Tb	Basalt	Whole rock	0.992	1.08962	64.5	**7.61±0.08**	Fiebelkorn and others, 1983.
					Silicic domes						
8	M6-97	43°45.7'	121°10.7'	Northeast flank of Newberry volcano; Qrpn	Rhyolite	Obsidian	4.02	0.0413527	0.58	**0.07±0.12**	Do.
9	M6-36	43°44.2'	121°13.8'	North caldera wall; Qcw	Rhyolite	—	3.64	0.063703	4.69	0.12±0.01	Do.
10	M6-76	43°42.7'	121°09.8'	Upper east flank of Newberry volcano; Qru	—	Obsidian	3.46	0.10023	8.40	**0.20±0.03**	Do.
11	M6-67	43°41.4'	121°19.0'	West flank of Newberry volcano; Qrd	Rhyodacite	Feldspar	3.36	0.195582	1.45	**0.40±0.15**	Do.

Table 3. *Potassium-argon ages from Newberry volcano and vicinity—Continued*

Map No. (fig. 2)	Sample No.	Location Latitude	Location Longitude	General geographic locale and map unit	Rock type	Material dated	K_2O (weight percent)	$^{40}Ar_{rad}$ x10^{11} (moles/gm)	Percent $^{40}Ar_{rad}$	Calculated age[1] (million years)	References
12	M6-64	43°41.6'	121°19.4'	West flank of Newberry volcano; Qrd	Rhyodacite	Plagioclase	0.818	0.111510	6.17	0.95±0.20	Do.
13	M6-5	43°39.2'	121°20.7'	Southwest flank of Newberry volcano; Qrd	Rhyodacite	Whole rock	3.87	0.227196	6.96	**0.41±0.08**	Do.
14	M6-80	43°43.7'	121°09.6'	East flank of Newberry volcano; Qru	—	Whole rock	4.00	0.27051	9.59	**0.47±0.06**	Do.
15	M9-19	43°42.94'	121°16.04'	Southwest shore of Paulina Lake; Qrd (Qrpl on sheet 2)	Rhyodacite	Plagioclase	1.131	0.0908525	1.70	**0.56±0.40**	E.H. McKee and N.S. MacLeod, unpub. data, 1981.
16	M9-20	43°42.30'	121°15.66'	Paulina Lake road in caldera; Qrd (Qrpl on sheet 2)	Rhyodacite	Plagioclase	0.507	0.0425155	1.76	**0.58±0.40**	Do.
17	M6-23	43°44.8'	121°12.8'	North of East Lake; Qr	Rhyolite	Plagioclase	(0.604)[2] 0.608 0.600	0.2407012	9.7	2.8±0.4	Fiebelkorn and others, 1983.
18	M5-25	43°41.2'	121°15.6'	Paulina Peak dome; Qrd (Qrpp on sheet 2)	Rhyolite	Plagioclase	0.50	0.226224	1.06	3.14±3.0	Do.
19	M9-21	43°41.09'	121°15.29'	Paulina Peak dome; Qrd (Qrpp on sheet 2)	Rhyodacite		2.99	0.25039	1.24	**0.58±0.40**	E.H. McKee and N.S. MacLeod, unpub. data, 1981.
20	M9-22	43°41.04'	121°16.38'	Paulina Peak dome; Qrd (Qrpp on sheet 2)	Rhyodacite		3.19	0.109815	6.64	**0.24±0.07**	Do.
21	M6-31	43°41.0'	121°14.3'	South caldera wall; Qr	Rhyolite	—	3.94	0.459403	5.06	0.80±0.23	Fiebelkorn and others, 1983.
22	M4-16	43°44 2'	121°21.6'	McKay Butte domes; Qer	Rhyolite	Obsidian	4.01	0.34419	10.2	**0.60±0.10**	McKee and others, 1976.
23	M6-44	43°43.2'	121°23.3'	Dome or flow in lower Paulina Creek; Qer	Rhyodacite	Plagioclase	1.201	0.127209	10.96	**0.74±0.12**	Do.
24a	M3-53	43°40.8'	121°03.0'	China Hat dome; Qer	Rhyolite	Obsidian	3.69	0.42764	7.2	**0.80±0.21**	Do.
	M3-28	43°40.8'	121°03.0'	China Hat dome; Qer	Rhyolite						

Table 3. *Potassium-argon ages from Newberry volcano and vicinity—Continued*

Map No. (fig. 2)	Sample No.	Location		General geographic locale and map unit	Rock type	Material dated	K_2O (weight percent)	$^{40}Ar_{rad}$ x10^{11} (moles/gm)	Percent $^{40}Ar_{rad}$	Calculated age[1] (million years)	References
		Latitude	Longitude								
24b						(a) Obsidian	3.85	3.4870	1.2	6.3±1.1	Fiebelkorn and others, 1983.
24c						(b) Plagioclase	0.782	0.8315	3.3	7.4±0.8	Do.
25	M3-29	43°39.9'	120°59.6'	East Butte dome; Qer	Rhyolite	Obsidian	3.84	0.48229	22.8	**0.87±0.05**	McKee and others, 1976.
26	M5-18	43°55.8'	121°24.7'	Benham Falls dome; QTrd	—	Plagioclase	0.986	0.2488	3.25	**1.8±0.8**	Fiebelkorn and others, 1983.
27[3]	M4-72	43°48.0'	120°47.0'	Pine Mountain; Trp	Rhyodacite	Hornblende	0.285	0.906759	8.45	**22.0±4**	Do.
						Pyroclastic-flow deposits					
28	M9-25	43°41.74'	121°18.27'	Upper west flank of Newberry volcano; Qat	Ash-flow tuff	Plagioclase	0.31	0.247043	2.59	5.5±5.0	E.H. McKee and N.S. MacLeod, unpub. data, 1981.
29	M6-58	43°42.7'	121°24.1'	West flank of Newberry volcano; Qbt	Ash-flow tuff pumice	Plagioclase	0.311	0.234070	0.92	5.22±3.02	Fiebelkorn and others, 1983.
30a	M9-12	43°49.4'	121°00.9'	East flank of Newberry volcano; Qtp	Ash-flow tuff	Plagioclase	0.277	0.0198104	1.03	**0.50±0.25**	Do.
30b	M3-99	43°48.9'	121°00.9'	East flank of Newberry volcano; Qtp	Ash-flow tuff	Plagioclase	0.501	0.05476	0.05	**0.7±0.7**	McKee and others, 1976.
31	M6-47	43°38.8'	121°01.2'	Lower east flank of Newberry volcano; QTae	Ash-flow tuff	Plagioclase	0.325	0.128935	64.5	2.75±0.49	Fiebelkorn and others, 1983.

[1] K-Ar ages were calculated from data in references using the constants for the radioactive decay and abundance of ^{40}K recommended by the International Union of Geological Sciences Subcommission on Geochronology (Steiger and Jäger, 1977). These constants are: $\lambda_\varepsilon = 0.580 \times 10^{-10}\ yr^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10}\ yr^{-1}$, and $^{40}K/K_{total} = 1.167 \times 10^{-4}$ mol/mol.

[2] Value in parentheses is arithmetic mean used in age calculation.

[3] Sample location not shown on figure 2.

Table 4. *Location and total depth of drill holes shown on map*

Drill hole	Latitude N	Longitude W	Elevation (m)	Total depth (m)	Total depth (ft)	Drilled by, year	Bottom-hole temperature (°C)	Bottom-hole temperature (°F)	References for core data[1, 2]
PHILLIPS 3	43°50.3'	121°11.9'	1,690	18	60	Phillips Petroleum Co., 1976		—	Data and core not public
PHILLIPS 5	43°46.8'	121°13.5'	1,960	32	105	do, 1976		—	Do.
PHILLIPS 6	43°45.0'	121°09.0'	1,900	61	200	do, 1976		—	Do.
USGS N-1	43°45.0'	121°09.1'	1,900	386	1,266	U.S. Geological Survey, 1977	17	63	MacLeod and Sammel (1982)
USGS N-2	43°42.5'	121°13.5'	1,950	932	3,057	do, 1979	265	509	Keith and Bargar (1988)
USGS N-3	43°42.4'	121°13.5'	1,960	186	610	do, 1980			
RDO-1	43°42.3'	121°13.3'	1,970	424	1,390	Sandia National Laboratories, 1983	158	316[7]	Keith and others (1986)
UNION 82-9	43°42.0'	121°11.2'	2,100	610	2,000	Union Oil Co., 1982		—	Data and core not public
UNION 82-10	43°43.2'	121°07.8'	1,860	610	2,000	do, 1982		—	Do.
UNION 83-8	43°44.3'	121°18.2'	1,820	610	2,000	do, 1983		—	Do.
UNION 83-9	43°41.9'	121°17.8'	1,850	610	2,000	do, 1983		—	Do.
SF 72-03	43°42.1'	121°19.8'	1,990	1,372	4,501	Santa Fe-Occidental, 1984	154	310	Arestad and others (1988)
SF NC-01	43°43.6'	121°18.0'	1,860	1,220	4,000	do, 1984	171	339[3]	Do.
CE-NB-3	43°40.2'	121°11.2'	1,960	1,325	4,348	California Energy Co., 1986	93	200	Data unpublished[2]
CE-NB-4	43°46.7'	121°17.6'	1,750	1,225	4,020	do, 1986	77	170	Do.
GEO N-1	43°38.3'	121°14.5'	1,780	1,387	4,550	Geo-Newberry, Inc., 1985	71	160[4]	Swanberg and others (1988)
GEO N-2	43°43.6'	121°18.7'	1,780	1,336	4,387	do, 1986	164	328	Data unpublished[2]
GEO N-3	43°49.9'	121°14.7'	1,750	1,220	4,003	do, 1986	57	135[4]	Swanberg and others (1988)
GEO N-4	43°42.7'	121°08.2'	1,910	703	2,306	do, 1987	18	65[5]	Data unpublished[2]
GEO N-5	43°40.8'	121°18.6'	1,720	988	3,242	do, 1987	69	157[6]	Do.

[1] Location and elevation measured from Oregon Department of Geology and Mineral Industries (1988), which also reports total depth.
[2] Data for holes deeper than 2,000 ft become public information four years after hole is completed. Records are on file with Oregon Department of Geology and Mineral Industries.
[3] Temperature at 3,960-ft depth.
[4] Temperature at 4,000-ft depth.
[5] Temperature at 2,200-ft depth.
[6] Temperature at 3,200-ft depth.
[7] Temperature at 1,150-ft depth.

Table 5. *Representative analyses showing major- and trace-element concentrations in Quaternary rocks from the caldera and adjacent areas of Newberry volcano*

Map unit	Qbof	Qboa	Qbop	Qelf	Qicg	Qicf	Qiif	Qisf
Map No. (sheet 2)	A	B	C	D	E	F	G	H
Sample No.	M8-84	M8-83	M8-87	M9-10	48	M9-8	M9-7	N6-15
Reference	1	1	1	1	2	1	1	3
Major-element analyses (weight percent)								
SiO_2	71.8	71.8	71.0	72.32	72.8	72.75	72.82	73.48
Al_2O_3	14.5	14.1	14.0	13.82	14.6	13.83	13.74	15.05
Fe_2O_3	0.85	0.8	0.8	2.13	0.77	2.06	2.05	1.81
FeO	1.3	1.3	1.3	---	1.3	---	---	---
MgO	0.1	0.2	0.1	0.3	0.34	0.4	0.4	0.25
CaO	0.88	0.88	0.86	0.69	1.1	0.64	0.63	0.87
Na_2O	5.4	5.0	5.2	4.17	4.3	4.22	4.32	4.73
K_2O	3.83	3.78	3.78	4.15	4.0	4.18	4.21	4.39
H_2O^+	0.32	1.5	2.1	0.13	0.43	0.35	0.17	0.50
H_2O^-	0.29	0.51	0.78	0.11	0.00	0.03	0.05	—
TiO_2	0.23	0.22	0.22	0.21	0.24	0.19	0.19	0.25
P_2O_5	0.02	0.02	0.02	0.05	0.10	0.04	0.04	0.03
MnO	0.06	0.06	0.06	0.048	0.04	0.05	0.044	0.05
CO_2	0.02	0.03	0.03	<0.01	<0.05	<0.01	<0.01	---
F	0.06	0.06	0.06	0.03	---	0.03	0.02	—
Cl	0.1	0.096	0.098	0.07	—	0.08	0.09	---
Total	99.76	100.36	100.41	98.23	100.02	98.85	98.77	101.41
SiO_2, normalized to 100%, water-free	72.5	73.1	72.9	73.9	73.1	74.0	74.0	72.8
Trace-element analyses (parts per million)								
Rb	118.5	119.5	103	124	—	120	126	126
Sr	49	51	50	72	—	66	62*	62
Cs	4.45	4.5	4.6	5.2	—	5.3	5.1	---
Ba	897	841	842.5	944	—	925	925	905
La	31.5	80.7	31	32	—	31.5	31.5	---
Ce	61	62.0	60	62	—	62	63.5	—
Nd	27.5	36.3	26.5	27	—	27.5	28.5	—
Sm	6.25	27.8	6.15	5.9	—	5.9	5.8	—
Eu	0.755	8.5	0.70	0.735	—	0.71	0.72	—
Tb	1.12	12.8	1.065	1.05	—	1.025	1.03	—
Lu	19.7	18.2	0.725	0.68	—	0.665	0.675	—
Zr	304	357	348	304	—	296	368	262
Hf	8.25	8.25	8.2	7.5	—	7.4	7.2	7
Ta	1.61	1.63	1.62	1.44	—	1.46	1.44	—
Th	11.25	11.7	11.0	12.0	—	12.2	12.4	—
Sc	5.57	5.49	5.5	5.08	—	4.96	4.9	—
Cr	1.7	3.1	<4	1.1	—	1.3	0.7	—
Co	0.9	0.85	0.8	1.4	—	1.3	1.2	---

References

1: This map—Major-element analyses by X-ray fluoresence spectroscopy. Trace-element analyses by instrumental neutron activation analysis except Sr, which is by emission spectroscopy. Asterisk (*) indicates X-ray spectroscopy.

2: Higgins (1973)—Major-element analyses by X-ray fluoresence spectroscopy. Note that Higgins' sample locations are only approximately determined.

3: Linneman (1990)—Major-element analyses by induction-coupled plasma emission spectroscopy except Na_2O and K_2O, which were measured by atomic absorption. Trace-element analyses by X-ray fluoresence.

Table 5. *Representative analyses showing major- and trace-element concentrations in Quaternary rocks from the caldera and adjacent areas of Newberry volcano—Continued*

Map unit	Qyrf	Qyrc	Qbcp	Qbce	Qbce	Qr	Qr	Qru	Qrd
Map No. (sheet 2)	I	J	K	L	M	N	O	P	Q
Sample No.	M8-61	M7-32	34	36	37	M6-23	M9-34	H-26	M8-19
Reference	1	1	2	2	2	1	1	2	1
Major-element analyses (weight percent)									
SiO_2	73.5	72.13	53.10	55.4	63.41	70.91	70.85	69.88	67.4
Al_2O_3	13.5	13.96	17.68	16.4	16.63	14.44	14.21	14.96	15.1
Fe_2O_3	0.69	2.29	2.13	2.7	2.08	2.7	2.68	1.62	1.7
FeO	1.2	—	5.83	6.0	2.99	—	—	1.37	2.7
MgO	0.21	0.3	5.41	3.7	1.39	0.4	0.5	0.53	1.2
CaO	0.95	0.64	8.99	7.0	3.51	1.04	1.04	1.69	2.8
Na_2O	4.9	4.38	3.68	4.3	6.04	4.59	4.57	5.55	4.7
K_2O	4.1	4.13	1.09	1.5	1.78	3.48	3.48	3.12	2.9
H_2O^+	0.45	0.49	0.25	0.10	0.27	0.20	0.10	0.19	0.95
H_2O^-	0.28	0.07	0.03	0.15	0.11	0.03	0.01	0.02	0.56
TiO_2	0.23	0.22	1.18	1.5	1.04	0.33	0.32	0.36	0.74
P_2O_5	0.03	0.05	0.35	0.35	0.43	0.06	0.06	0.09	0.15
MnO	0.05	0.048	0.14	0.18	0.15	0.06	0.053	0.09	0.12
CO_2	0.01	<0.01	0.01	<0.05	0.00	<0.01	<0.01	0.06	0.01
F	0.06	0.02	—	—	—	0.03	0.03	—	0.05
Cl	0.068	0.05	—	—	—	0.07	<0.01	—	0.048
Total	100.228	98.778	99.87	99.28	99.83	98.34	97.903	99.53	101.128
SiO_2, normalized to 100%, water-free	74.0	73.5	53.3	55.9	63.8	72.3	72.5	70.4	67.7
Trace-element analyses (parts per million)									
Rb	138*	123	—	—	—	96	88	—	81*
Sr	63*	64*	—	—	—	113*	110	—	183*
Cs	—	5.2	—	—	—	4.3	2.4	—	—
Ba	817*	904	—	—	—	918	970	—	706*
La	—	32	—	—	—	29	28	—	—
Ce	—	65.6	—	—	—	58	55.5	—	—
Nd	—	32	—	—	—	27	28	—	—
Sm	—	7.05	—	—	—	6.25	6.3	—	—
Eu	—	0.825	—	—	—	1.075	1.09	—	—
Tb	—	1.285	—	—	—	1.12	1.105	—	—
Lu	—	0.81	—	—	—	0.685	0.675	—	—
Zr	—	358	—	—	—	341	344	—	—
Hf	—	8.8	—	—	—	7.8	7.7	—	—
Ta	—	1.52	—	—	—	1.27	1.17	—	—
Th	—	11.8	—	—	—	9.4	9.3	—	—
Sc	—	5.54	—	—	—	7.24	7.22	—	—
Cr	—	0.8	—	—	—	0.5	2.2	—	—
Co	—	1.3	—	—	—	1.6	1.7	—	—

Table 5. *Representative analyses showing major- and trace-element concentrations in Quaternary rocks from the caldera and adjacent areas of Newberry volcano—Continued*

Map unit	Qrd	Qrd	Qrpl	Qrps	Qrpn	Qat	Qat	Qat	Qrpp
Map No. (sheet 2)	R	S	T	U	V	W	X	Y	Z
Sample No.	M8-56	M6-103	33	M8-63	M8-45	M8-81	M8-75	22	M5-25
Reference	1	1	2	1	1	1	1	2	1
Major-element analyses (weight percent)									
SiO_2	71.0	68.89	69.7	68.4	69.8	65.8	60.6	51.65	70.32
Al_2O_3	14.4	14.96	15.2	15.1	14.6	15.8	15.8	17.05	14.68
Fe_2O_3	1.6	3.83	0.66	1.4	1.3	3.1	5.5	7.56	3.06
FeO	1.5	—	2.4	1.7	2.3	1.8	1.8	3.79	—
MgO	0.53	0.6	0.39	0.34	0.58	1	1.9	3.87	0.3
CaO	1.5	1.71	1.7	1.3	1.8	2.5	4.3	8.26	0.86
Na_2O	5.2	5.0	5.4	5	5.71	6.6	5.8	4.10	5.02
K_2O	3.5	3.06	3.1	3.1	3.1	1.7	1.3	0.66	2.98
H_2O^+	0.24	0.10	0.61	3.2	0.16	0.55	0.45	0.27	0.24
H_2O^-	0.28	0.04	0.07	1.1	0.20	0.17	0.41	0.07	0.04
TiO_2	0.49	0.52	0.36	0.39	0.52	0.86	1.4	2.09	0.27
P_2O_5	0.11	0.13	0.12	0.06	0.13	0.22	0.60	0.32	0.05
MnO	0.10	0.087	0.09	0.11	0.12	0.15	0.19	0.18	0.076
CO_2	0.01	<0.01	<0.05	0.02	0.01	0.03	0.04	0.01	<0.01
F	0.03	0.07	—	0.06	0.06	0.03	0.02	—	0.03
Cl	0.045	0.07	—	0.076	0.072	0.068	0.014	—	0.07
Total	100.54	99.067	99.80	101.356	100.462	100.4	100.12	99.88	97.996
SiO_2, normalized to 100%, water-free	71.0	69.7	70.3	70.6	69.8	66.1	61.1	51.9	72.0
Trace-element analyses (parts per million)									
Rb	101*	86	—	88*	82*	33*	16*	—	64*
Sr	134*	178	—	147*	177*	275*	401*	—	101*
Cs	—	—	—	—	—	—	—	—	2.7
Ba	736*	718	—	916*	726*	612*	536*	—	820*
La	—	—	—	—	—	—	—	—	29.5
Ce	—	—	—	—	—	—	—	—	59.5
Nd	—	—	—	—	—	—	—	—	31
Sm	—	—	—	—	—	—	—	—	7.6
Eu	—	—	—	—	—	—	—	—	1.32
Tb	—	—	—	—	—	—	—	—	1.17
Lu	—	—	—	—	—	—	—	—	0.76
Zr	—	310	—	—	—	—	—	—	344
Hf	—	—	—	—	—	—	—	—	8.3
Ta	—	—	—	—	—	—	—	—	1.17
Th	—	—	—	—	—	—	—	—	6.6
Sc	—	—	—	—	—	—	—	—	8.56
Cr	—	—	—	—	—	—	—	—	0.2
Co	—	—	—	—	—	—	—	—	0.8

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