GEOTHERMAL SYSTEMS OF THE CASCADE RANGE

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Abstract In the central and southern Cascade Range, plate convergence is oblique, and Quaternary volcanism produces mostly basalt and mafic andesite; large andesite-dacite composite volcanoes and silicic dome fields occur in restricted areas of long-lived igneous activity. To the north, plate convergence is normal, producing widely spaced centers in which mafic lavas are minor. Most Cascade volcanoes are short-lived and unlikely to be underlain at shallow levels by large magma bodies that could support high-temperature geothermal systems. Such systems are known, however, near Meager Mountain, at Newberry Volcano, and near Lassen Peak. Persistent fumaroles occur on several major composite volcanoes, but drilling to date has been insufficient to determine whether exploitable geothermal reservoirs occur at depth. Thermal springs away from the major volcanic centers are few and generally inconspicuous. However, significant geothermal systems along and west of the Cascade Range may well be masked by abundant cold ground water.

Tectonics and volcanism

Quaternary volcanoes of the Cascade Range form a chain of stratocones, shields, cinder cones, and domes that lies approximately parallel to the Pacific coast (figure 1). Tertiary volcanic rocks underlie much of the range (McBirney, 1978), and pre-Tertiary rocks are known to be present only north of Mount Rainier and south of Crater Lake. The ends of the Quaternary chain coincide with the onshore projections of the northern and southern edges of the Juan de Fuca plate, which is evidently being subducted in a northeast direction beneath the North American plate (Riddihough, 1978). Consequently, the ultimate source of magma in the Cascades is thought to be related to subduction of the Juan de Fuca plate. The regional crustal stress field, which affects the character of volcanism, is determined largely by the interaction between the much larger North American and Pacific plates. Earthquake focal mechanisms, north-south-trending normal faults, Quaternary dike orientations, northwest-southeast-trending right-lateral strike-slip faults within the Cascade Range, and east-west-trending fold axes east of the range indicate that crustal tectonics are dominated by north-south horizontal maximum principal compressive stress. This regional stress field influences the formation of fractures and the flow of fluids so that vent alignments and the dikes that fed them have a north-south preferred orientation (cf. Nakamura, 1977).

A growing body of evidence points to the asthenospheric wedge above subduction zones as the primary source of basaltic magma for arc volcanism. Basalt intrudes the crust at a distance behind the plate boundary where horizontal compression owing to plate convergence is no longer the dominant component of the stress field. Perhaps none of this magma escapes the crust unmodified, though basaltic lava has been erupted throughout the length of the Cascades in the Quaternary. Basalt is seen as the principal carrier of heat and a significant contributor of mass to the more differentiated magmas that are erupted (see Hildreth, 1981). Long-lived igneous sytems are evidently compositionally zoned, open systems that are repeatedly tapped at the top and resupplied in the roots (Smith, 1979). The residence time of magma in the crust governs the degree of magmatic differentiation and interaction with crustal rocks and fluids, and thus the average composition of magmas that reach the surface.

From Glacier Peak northward, in the region where the direction of plate convergence is roughly normal to the plate boundary and trend of the Cascade volcanic chain, volcanic centers are areally restricted and have relatively differentiated average compositions. The roughly equal spacing of volcanic centers and paucity of basaltic lava are typical features of volcanism related to ocean-continent convergence. South of Mount Rainier, where plate convergence is oblique to the plate boundary, the volcanic chain is broader, vents are less concentrated, and the Cascade Range contains a higher volume and proportion of mafic rocks. Presumably this is because basaltic magma finds it easier to reach the surface here where the component of horizontal compression normal to the volcanic chain is probably smaller, though there is no reason to believe that the rate of magma production is everywhere the same.

Large stratocones like Mount Shasta (Christiansen

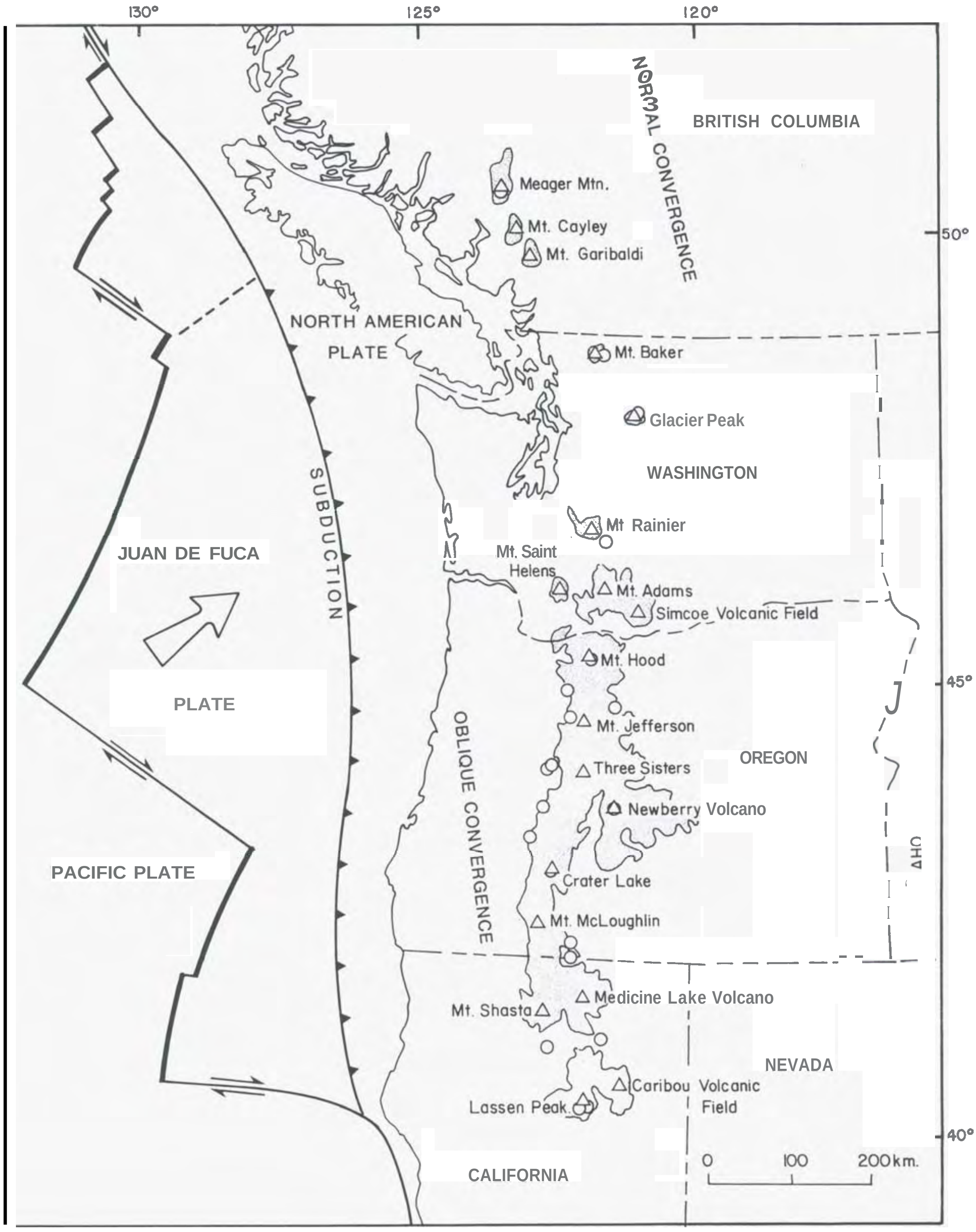

Figure 1.--Map showing plate-tectonic setting of the Cascade Range. Large arrow indicates direction of convergence of Juan de Fuca plate and North American plate. Pattern indicates Pliocene and Quaternary volcanic rocks. Triangles indicate major volcanoes. Circles indicate geothermal systems.

and Miller, 1976) and silicic rocks, as at Crater Lake (Bacon, 1982) and the Lassen dome field (Muffler and others, 1982), occur where volcanism has taken place for comparatively long periods. Major centers may mark large-scale structural discontinuities that tend to focus magmatic activity. Between them, in the region of oblique convergence, are smaller stratocones, mafic shields, and cinder cones where magma has not been intruded so continuously or resided in the crust for long. The Simcoe Volcanic Field, Newberry Volcano, Medicine Lake Volcano, and the Caribou Volcanic Field (figure 1) mark areas where Quaternary volcanism extends to the east of the Cascades crest, merging into the Columbia Plateau and Basin and Range provinces; these centers are here discussed as part of the Cascade Range. Holocene silicic volcanic rocks are conspicuous at South Sister, Newberry, Crater Lake, Medicine Lake, Shasta, and Lassen Peak. High-temperature geothermal systems are most likely to be found in such areas, where youthful silicic volcanism suggests the presence of relatively voluminous and long-lived crustal magma reservoirs (Smith and Shaw, 1975).

Known geothermal systems

High-temperature geothermal systems have been identified at three of the major Quaternary volcanic centers: Meager Mountain (British Columbia), Newberry Volcano (Oregon), and Lassen Volcanic National Park (California). In addition, several of the andesite-dacite composite volcanoes of the Cascade Range display persistent fumaroles and/or hot springs. Among these are Mount Cayley (Souther, 1980), Mount Baker (Frank and others, 1977; Hyde and Crandell, 1978; Malone, 19791, Mount Rainier (Fiske and others, 1963; Crandell and Mullineaux, 1967), Mount St. Helens (Crandell and Mullineaux, 1978; Lipman and Mullineaux, 1982), Mount Hood (Crandell, 19801, Mount Mazama (Crater Lake; Williams and Von Herzen, 1982; Bacon, 1982), and Mount Shasta (Christiansen and others, 1977; Wharton and Vinyard, 1979). With the exception of Mount Hood, none of the latter has been drilled to any significant depth. Each of these volcanoes, however, has had a history of frequent eruption throughout the late Quaternary and has the potential to support a geothermal system of significant size. The climactic eruption of Mount Mazama 6,850 yr B.P. produced almost 50 km^3 of silicic magma, and the resulting caldera attests to the recent presence of a substantial magma body in the upper crust.

Lassen region Lassen Volcanic National Park (LVNP), located in northeastern California, contains the most conspicuous geothermal .system in the Cascade Range. Geological, geochemical, and geophysical observations in the Lassen region all fit a model, originally suggested by D. E. White, of a single large geothermal system with a central vapor-dominated reservoir underlain by a zone of hot water discharging at lower elevations (Muffler and others, 1982). The focus and major thermal upflow of the Lassen geothermal system is at Bumpass Hell along the contact between a 0.5-m.y.-old andesitic composite cone and a field of dacite domes that were emplaced during the past 0.25 m.y. The outflow of hot water is detected at Morgan and Growler Hot Springs in the valley of Mill Creek 8 km to the south of LVNP, and at depth in the geothermal well Walker "O" No. 1 at Terminal Geyser in the southeast corner of LVNP. Na-K-Ca, sulfate-water isotope, and mixing-model geothermometers indicate that the deep thermal water feeding Morgan and Growler Hot Springs has a temperature of 220-240°C (Muffler and others, 1982). Temperatures in the Walker "O" No. 1 well at Terminal Geyser reach a maximum of 176°C between 603 and 640 m and then decrease gradually to 124°C in an isothermal zone 18 m thick at the bottom of the hole at 1,222 m (Beall, 1981). Significant contents of Na, K, and Cl in the fluids produced from Walker "O" No. 1 (Beall, 1981) indicate unequivocally that the well is drawing upon a hot-water reservoir, whereas the reversal in temperature with depth indicates that the water flows to the well laterally (presumably from the northwest) rather than vertically from below.

Most of the Lassen geothermal system is located in LVNP and is thus protected from geothermal development. Walker "O" No. 1 was drilled on private land within LVNP, but title to this land has subsequently been acquired by the U.S. government, and the geothermal energy under that land will not be developed. Morgan and Growler Hot Springs are on private land, bordered to the east and west by National Forest land subject to geothermal leasing. However, Federal lease stipulations require that any geothermal production in this National Forest land will have to be carried out without any detrimental effect to the thermal features in LVNP. It remains to be seen to what extent this part of the Lassen geothermal system can be developed for commercial use.

Newberry Volcano Newberry Volcano is a Quaternary volcanic center covering over 1200 km^2 at the west end of the High Lava Plains, 60 km east of the crest of the Cascade Range (MacLeod and others, 1976). The flanks of the volcano consist of basalt and mafic andesite flows and cinder cones, andesitic to rhyolitic ash-flow and air-fall tuffs, and dacite to rhyolite domes; there are over 400 separate vents (MacLeod and others, 1981). At the summit of the volcano is a composite caldera 6-8 km in diameter within which are several rhyolitic flows and pumice cones, the youngest of which is only 1,400 yr old (MacLeod and others, 1981). Surface hydrothermal activity is limited to a few warm springs within the caldera (Sammel, 1981).

Two holes have been drilled on Newberry Volcano by the U.S. Geological Survey for stratigraphic, heat flow, and hydrologic information. The first was drilled to 386 m at a location approximately 4 km northeast of the caldera to a maximum temperature of 9°C (Sammel, 1981). The second well, located just northeast of the 1,400-yr-old obsidian flow, was drilled in 1978 and 1979 to 631 m; the temperature-depth curve is shown in the upper part of figure 2. In 1981, this hole was deepened to 930 m, and the temperature-depth curve shown in the lower part of figure 2 was measured (Sammel, 1981). The well was flowed for 20 hours, with flow rate declining from 1.5 kg s^{-1} to 0.7 kg s^{-1} after 20 hours. Chemistry of the reservoir fluid is uncertain, since fluids recovered in the production test appear to be mostly drilling fluid.

The high temperatures at depths greater than 700 m in the well are masked by the flow of cooler ground water at shallow depths (Sammel, 1981). This situation may be common in much of the Cascade Range. In particular, a nearly identical situation may exist at Medicine Lake Volcano, northern California, a volcanic center whose size, age, geologic evolution, and position east of the High Cascades are very similar to Newberry Volcano.

Meager Mountain Meager Mountain is located in the extreme northern part of the Cascade Range, approximately 190 km north of Vancouver, British Columbia, Canada. Meager Mountain is a composite andesite-rhyodacite dome complex with a volume of about 15 km3 (Read, 1977; Souther, 1981). Volcanic activity has migrated progressively to the north over time during the last 2 m.y., with the most recent activity being the eruption of silicic pumice from the northern edge of the complex 2,500 years ago (Read, 1979; Souther, 1981). Warm springs occur in the valleys just northeast and just south of the volcanic complex.

Several shallow diamond-drill holes near the warm springs at Meager Creek showed temperatures as high as 205°C at a depth of 600 m (Fairbank and others,. 1981). Deep exploration drilling was carried out in 1981-82. The first deep hole had a temperature of greater than 200°C at 2.5 km, whereas the second reached 260°C at 3 km (J. G. Souther, written communication, 1982). Reservoir rocks are fractured granodiorite and metamorphic rocks of pre-Tertiary age. Test data from the wells are not yet available, although the first well sustained flashing steam in a 20-cm pipe for 1 hour (J. G. Souther, oral communication, 1982). A third deep well had reached 3,430 m in August 1982.

Mount Hood Of the Quaternary composite cones displaying fumarolic activity, only Mount Hood has been subjected to significant drilling. Mount Hood is a Quaternary andesite-dacite composite cone that had major eruptive periods at 12,000-15,000 yr B.P., 1,500-1,800 yr B.P., and 200-300 yr B.P.; minor air-fall pumice erupted in the 1850's and 1860's (Crandell, 1980). There are fumaroles high on the cone, particularly at Crater Rock, a dacite dome emplaced 200-300 years ago.

A number of holes have been drilled for heat-flow and hydrologic purposes on the flanks of Mount Hood (Hull, 1979), and some deeper exploration drilling has been carried out at Old Maid Flat (8 km northwest of the summit of the volcano) and in the Timberline Lodge area (5 km south of the summit). Well No. 1/2 at Old Maid Flat recorded 82°C at 1,220 m (Blackwell and Steele, 1979), whereas well 7A, also at Old Maid Flat, reached 113°C at 1,837 m. However, neither well encountered significant permeability.

The USGS has drilled a number of wells for hydrologic testing around Mount Hood. Among these, the Pucci well, just south of the main cone, was drilled to 1,220 m, where temperatures of 75-80°C were recorded. One flow test gave as much as 415 L min^{-1}, but a subsequent test gave only 8-10 L min^{-1}, probably owing to caving in the hole.

Despite the size and youth of Mount Hood, geothermal exploration to date has been disappointing. High-temperature reservoirs have not been identified, and the low- and intermediate-temperature rock found on the northwest of the volcano is too impermeable to be exploited. However, most of the 188 km^2 of the volcano has not been drilled and may possibly contain geothermal resources.

Other geothermal areas Geothermal resources in the Cascade Range are not restricted to the major volcanic centers. Substantial resources, particularly for direct use, occur at lower elevations on both sides of the Cascade Range. In Oregon, hot springs appear to be concentrated along a fault zone separating the the High Cascades from the western Cascades. This fault zone is interpreted by (Taylor, 1981) to be the western margin of a major north-trending graben 30 km wide filled by Quaternary volcanic rocks of the High Cascades. Deep exploration drilling has taken place at Breitenbush Hot Springs along the west edge of the graben, but the results are not public.

Just east of the Cascade Range at Klamath Falls, a 120°C reservoir has long been exploited for heating homes and businesses. Much of the Oregon Institute of Technology is heated by geothermal fluids, and a district heating system is being constructed in the central part of the city (Lund, 1982). The source of heat for this large geothermal system is unknown. The system is located just east of the Cascade range and may therefore be related to igneous activity beneath the range. On the other hand, the geothermal system may be due simply to deep circulation of meteoric water along the conspicuous, northwest-southeast-trending normal faults that cut the area.

Geothermal Potential

The Cascade Range has long been recognized as a region of geothermal potential. Brook and others (1979) calculated the identified accessible resource base of geothermal energy in the Cascade Range to be 57 x 10^{18} J. In addition, based

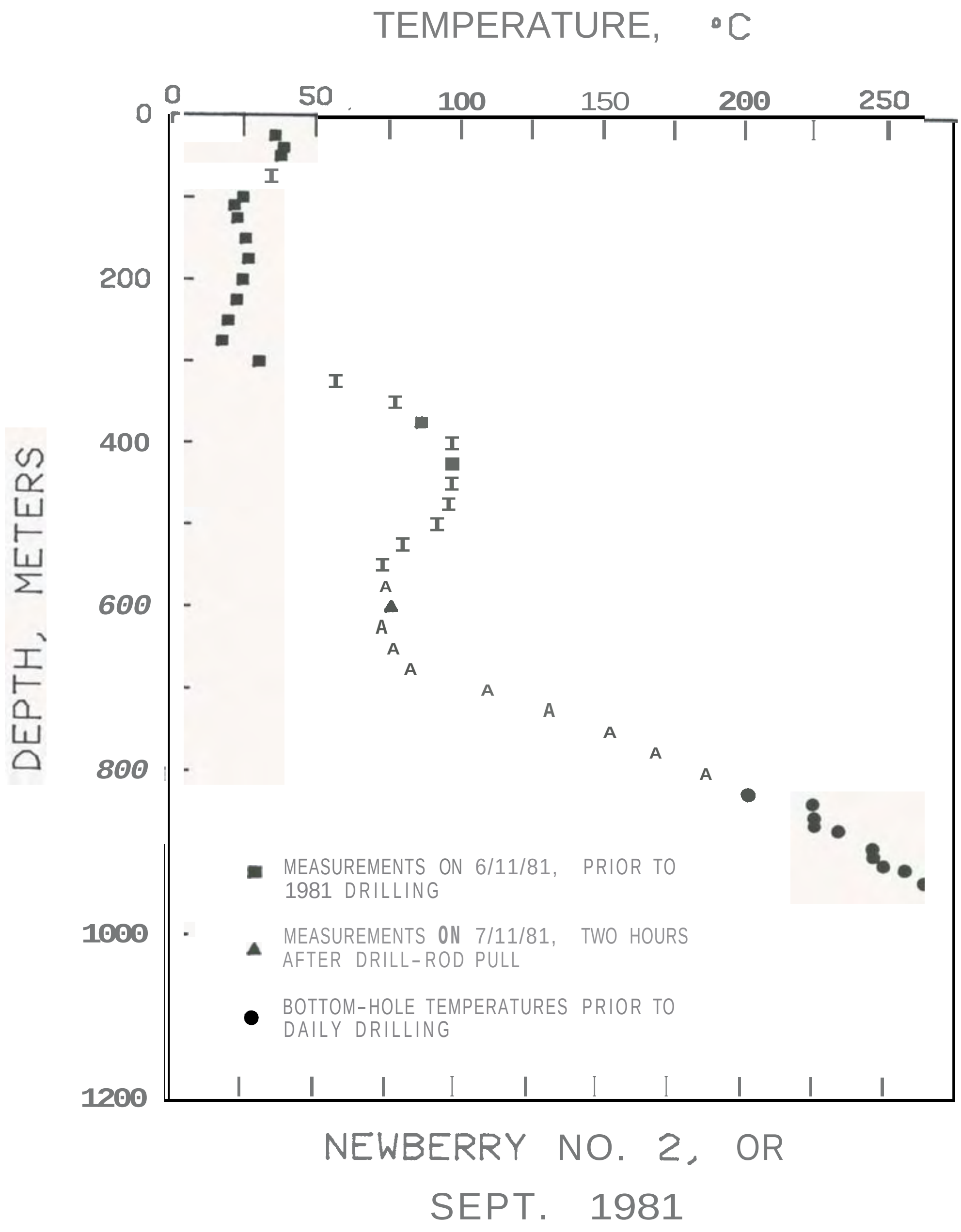

Figure 2.--Composite temperature profile of Newberry 2 drill hole (from Sammel, 1981, Figure 4).

primarily on the favorable geologic setting, they estimated the undiscovered accessible resource base to be 1,140 x 10^{18} J. If this estimate proves to be correct, the geothermal resources could make a substantial contribution to the energy requirements of the Pacific Northwest.

However, despite the high heat flow and the presence of Quaternary volcanic rocks throughout the range, geothermal exploration in the Cascade Range has not yet been extensive. This low level of exploration is due to four main reasons:

1. The paucity of of thermal manifestations, especially away from the major volcanic centers.
2. The fact that much of the land potentially valuable for geothermal resources is withdrawn as National Parks or lies in National Forests that until recently were not available for leasing.
3. The abundance and low cost of petroleum in the United States, which discourages high-risk exploration ventures in energy sources such as geothermal.
4. The persistent high interest rates in the United States, which mitigate against exploration ventures with only long-term, somewhat uncertain payoff.

The first reason is geologically fundamental and provides the major challenge for geothermal research in the Cascade Range. Various authors (e.g. Brook and others, 1979, p. 33) have suggested that the paucity of thermal springs in the Cascades may be due to masking of hydrothermal convection systems by overlying cold ground water in the permeable volcanic rocks, this effect being enhanced by the high precipitation throughout much of the region. Indeed, this interpretation is supported by the results of the Newberry drillhole given above, where high temperatures were found at depth beneath a zone of circulating cold water approximately 700 m thick in an area with only weak hydrothermal activity at the surface (Sammel, 1981). The precipitation in the Cascade Range proper is significantly greater than at Newberry, and accordingly one would expect a stronger masking effect. Masking of high-temperature geothermal systems by overlying cold water is also compatible with the data from Meager Creek, where a geothermal system of 250-300°C at depth is expressed at the surface only by springs of 58-60°C (Souther, 1981). On the other hand, there are many volcanic belts throughout the world where precipitation is high and yet there are very significant geothermal systems expressed at the surface (e.g., Japan, the Philippines, New Zealand). Furthermore, the geothermal system at Lassen Peak, an area of very heavy snowfall, finds conspicuous surface expression.

In summary, the available data suggest that high-temperature geothermal reservoirs may be associated with the major volcanic centers of the Cascade Range. With the exception of the Lassen system, however, the surface expression of these systems is weak. Furthermore, available production data from the two high-temperature systems defined only by drilling (Meager Creek and Newberry) are not yet sufficient to confirm large geothermal reservoirs of high productivity. Perhaps most of the high-temperature geothermal systems at depth beneath the Cascades are small and circulate relatively small volumes of thermal water. Such systems could easily be swamped by overlying cold ground water. This question can be resolved only after several of these promising areas are drilled and their productivity or lack thereof is demonstrated.

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