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ARE THERE SIGNIFICANT HYDROTHERMAL RESOURCES IN THE U.S. PART OF THE CASCADE RANGE?

L.J. Patrick Muffler[1] and Marianne Guffanti[2]

[1]US Geological Survey, MS 910, Menlo Park, CA 94025
[2]US Geological Survey, MS 922, Reston, VA 22092

ABSTRACT

The Cascade Range is a geothermal dichotomy. On the one hand, it is an active volcanic arc above a subducting plate and is demonstrably an area of high heat flow. On the other hand, the distribution of hydrothermal manifestations compared to other volcanic arcs is sparse, and the hydrothermal outflow calculated from stream chemistry is low.

Several large estimates of undiscovered geothermal resources in the U.S. part of the Cascade Range prepared in the 1970s and early 1980s were based fundamentally on two models of the upper crust. One model assumed that large, partly molten, intrusive bodies exist in the upper 10 km beneath major volcanic centers and serve as the thermal engines driving overlying hydrothermal systems. The other model interpreted the coincident heat-flow and gravity gradients west of the Cascade crest in central Oregon to indicate a partly molten heat source at 10 ± 2 km depth extending ≈ 30 km west from the axis of the range. Investigations of the past ten years have called both models into question.

Large long-lived high-temperature hydrothermal systems at depths <3 km in the U.S. part of the Cascade Range appear to be restricted to silicic domefields at the Lassen volcanic center, Medicine Lake volcano, Newberry volcano, and possibly the Three Sisters. Federal land-use restrictions further reduce this list to Medicine Lake and Newberry. Dominantly andesitic stratocones appear to support only small transitory hydrothermal systems related to small intrusive bodies along the volcanic conduits. The only young caldera, at Crater Lake, supports only low- to intermediate-temperature hydrothermal systems. Most of the Cascade Range comprises basaltic andesites and has little likelihood for high-level silicic intrusions and virtually no potential for resultant large high-temperature hydrothermal systems. Undiscovered hydrothermal resources of the Cascade Range of the United States are substantially lower than previous estimates. The range does have potential for intermediate-temperature hot dry rock and localized low- to intermediate-temperature hydrothermal systems.

INTRODUCTION

This paper presents preliminary conclusions from a multi-year effort of the U.S. Geological Survey to evaluate the geothermal potential of the Cascade Range. A detailed assessment will be published as a Bulletin of the U.S. Geological Survey (Muffler and Guffanti, in preparation). Here we draw heavily on a manuscript (Guffanti and Muffler, 1995) submitted to the May 1995 World Geothermal Congress in Florence, Italy, as well as several recent publications of our USGS colleagues, particularly Ingebritsen *et al.* (1989, 1992, 1994), Mariner *et al.* (1990), and Blakely (1994).

TECTONIC AND VOLCANIC SETTING

The Cascade volcanic arc lies above the Cascadia subduction zone along which the small Gorda, Juan de Fuca, and Explorer plates are being subducted eastward under the large North American plate. The Cascade volcanic arc consists of two physiographic and geologic provinces (Peck *et al.*, 1964; Duncan and Kulm, 1989): the 42–10 Ma Western Cascades, and the 10–0 Ma High Cascades. Just east of the High Cascades are two large, essentially bimodal, basalt-rhyolite volcanoes: Newberry volcano in Oregon, and Medicine Lake volcano in northern California.

Major composite volcanoes that have erupted andesites, dacites, and even rhyolites occur at intervals of ≈ 100 km along the Cascade Range (Figure 1). In addition, there are several thousand smaller, discrete volcanoes that over the past five million years have erupted only once, or at most a few times, producing primarily basaltic andesite (see Guffanti and Weaver, 1988).

Sherrod and Smith (1990) estimated the following extrusion rates since 2 Ma in km^3 per km of arc length per million years:

- north of Mount Rainier: 0.21
- southern Washington and northern Oregon: 1.6
- central Oregon: 3–6
- northern California: 3.2.

The high extrusion rates for Oregon and northern California are determined in great part by the large volumes of basaltic andesite in Oregon and in the Lassen region of California (See Figure 3 of Sherrod and Smith, 1990).

The major Cascade volcanic centers are of four main types (Guffanti and Muffler, 1995):

> Stratovolcanoes. These comprise the most common type, ranging in composition from predominantly andesitic (Mount Baker, Mount Adams, Mount Rainier, and Mount Hood) to more dacitic (Glacier Peak, Mount St. Helens, and Mount Shasta). Of these, Mount Shasta is the largest, having an extruded volume of 400 km^3, and the most silicic.

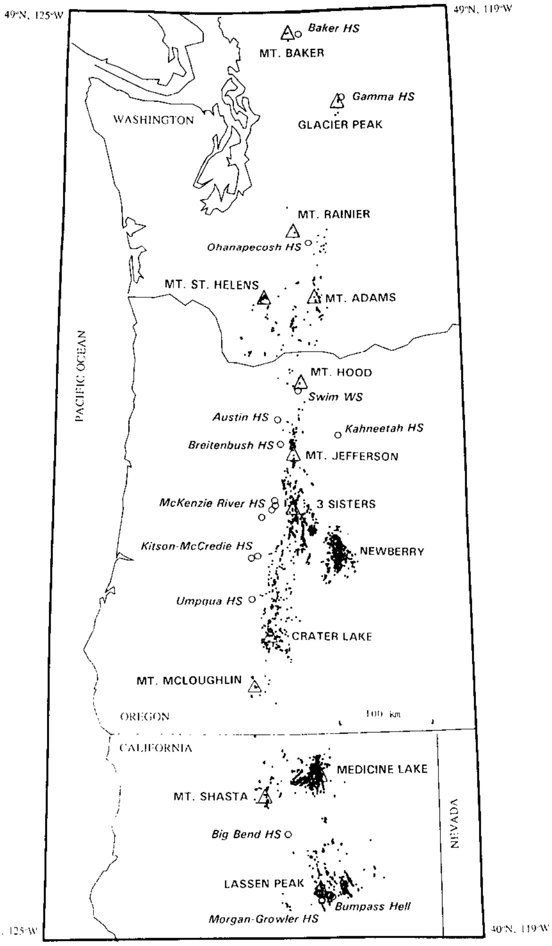

Figure 1. Volcanic setting of the Cascade Range, USA. Large triangles are major Quaternary volcanic centers. Small dots are individual volcanic vents younger than 730,000 years. Open circles are hot springs associated with known hydrothermal systems having subsurface temperatures ≥90°C. From Guffanti and Muffler (1995).

> Composite centers. These are andesitic stratovolcanoes combined with silicic domefields and are exemplified by the Lassen volcanic center and the Three Sisters volcanic center.

> Shield complexes. Two large shield complexes, Newberry volcano and Medicine Lake volcano, have developed on the east side of the Cascade Range where extensional tectonism of the back-arc-like Basin and Range province impinges on the Cascade Range. Both volcanoes are dominantly mafic, with silicic domes and flows of dacitic to rhyolitic composition typically found on the higher parts of the volcanic edifices. Both volcanoes have erupted numerous times during the past 10,000 years (MacLeod and Sherrod, 1988; Donnelly-Nolan, 1988).

> Collapse caldera. The only large young collapse caldera is at Crater Lake, Oregon, where a catastrophic eruption of ≈50 km^3 of andesitic to dacitic magma occurred at Mount Mazama 7700 years ago (Bacon and Druitt, 1988).

The Cascade Range is characterized by a positive, conductive heat-flow anomaly (Blackwell and Steele, 1992). This anomaly has been investigated in detail in central Oregon, where the regional conductive heat flow of 100 mW m^{-2} of the Cascade Range is more than twice that of the Willamette Valley and Coast Range to the west; an abrupt heat-flow gradient separates the two regions (Blackwell *et al.*, 1990a).

Mariner *et al.* (1990), using a chloride-inventory method that detects both thermal water discharged in springs and thermal water discharged into streams, estimated that the total discharge of thermal springs in the Cascade Range of California, Oregon, and Washington was 340 L s^{-1}, corresponding to ≈82 MW$_t$. This value is approximately 5% of that estimated from Sumi (1980) for the minimum discharge of hot springs of the Tohoku volcanic arc (Muffler and Tamanyu, 1995). This difference in hydrothermal discharge between the two arcs also correlates qualitatively with the far greater number of thermal springs in the Tohoku arc (compare Sumi, 1975, with Figure 1a of Mariner *et al.*, 1990).

PREVIOUS GEOTHERMAL RESOURCE ASSESSMENTS OF THE CASCADE RANGE

Identified Geothermal Resources

Brook *et al.* (1979) identified seventeen geothermal systems ≥90°C in the Cascade Range (as used here to include Newberry, Kahneetah, Klamath Falls, and Klamath Hills). The sum of the individual energy figures given by Brook *et al.* (1979) for these systems is 118×10^{18} J (Table 1), with most of the energy residing in three major systems (Lassen at 42×10^{18} J, Newberry at 27×10^{18} J, and Klamath Falls at 30×10^{18} J).

Resources (identified thermal energy that can be extracted legally and used at some future time under reasonable economics) are even less. Laws and regulations prohibit geothermal development in National Parks and Wilderness Areas, where some of the most attractive targets exist. Accordingly, Brook *et al.* (1979) did not calculate geothermal resources in Lassen Volcanic National Park or at Ohanapecosh Hot Springs (in Mount Rainier National Park). Recoverable thermal energy from identified >150°C reservoirs totaled 8.3×10^{18} J, equivalent to 880 MW_e for 30 years. Of this, 740 MW_e was from Newberry and 116 MW_e from Morgan-Growler (probably southerly outflow from the large geothermal system centered in Lassen Volcanic National Park). Recoverable thermal energy from identified 90°–150°C reservoirs totaled 10.4×10^{18} J, with beneficial heat of 2600 MW_t for 30 years. These figures are dominated by Klamath Falls (resource = 7.4×10^{18} J; beneficial heat = 1890 MW_t for 30 years).

Reed *et al.* (1983) estimated reservoir energy for 36 low-temperature (<90°C) spring systems in the Cascade Range and calculated the mean resource (using a recovery factor of 0.25) and beneficial heat. The total reservoir energy of these systems is 3.5×10^{18} J (Mariner *et al.*, 1983, Table 5), and the total beneficial heat is 390 MW_t for 30 years

Wright (1991, 1992) estimated that the Cascades region may be capable of producing 750 MW_e of electrical power from geothermal generation in the next two decades, with most of this coming from Medicine Lake. No data were given to back up this estimate.

Undiscovered Geothermal Resources

The range of estimates of undiscovered geothermal resources in the Cascade Range (Table 1) is great, reflecting in great part the sparsity of drillhole information. An additional factor, however, is a profound geothermal dichotomy—*i.e.*, the existence of Quaternary volcanism and high regional heat flow opposed to the sparsity of hot springs and identified hydrothermal reservoirs of geothermal energy. Many workers have suggested that substantial quantities of geothermal energy are masked by cool, near-surface groundwater. This interpretation was encouraged by the discovery of 265°C temperatures at 930 m depth beneath Newberry volcano (Sammel, 1981), effectively masked by a surficial zone greater than 300 m thick at less than 100°C (Swanberg *et al.*, 1988). Optimism for the High Cascades, however, was balanced by Benoit (1983), who concluded that several geological, geochemical, and geophysical factors severely limit the chances of discovering and developing high-temperature geothermal reservoirs in the High Cascades of Oregon (excluding Newberry volcano).

Brook *et al.* (1979), on the basis of the favorable volcano-tectonic setting, multiplied the identified reservoir energy of the Cascade Range (including National Parks and Wilderness Areas) by a subjective factor of 20 to give an estimate of 1140×10^{18} J for the undiscovered accessible resource base to a depth of 3 km. Newberry volcano and Kahneetah were considered by Brook *et al.* (1979) to be part of the Oregon Plateaus geologic province, and Klamath Falls and Klamath Hills to be part of the northwestern Basin and Range province; in both these provinces, the undiscovered accessible resource base was estimated to be five times the identified. Thus the total undiscovered accessible geothermal resource base for the Cascade Range (as considered in this paper) can be estimated from the figures and assumptions of Brook *et al.* (1979) to be 1440×10^{18} J.

Mariner *et al.* (1983) estimated that the undiscovered accessible resource base <90°C was 10.5×10^{18} J, three times the thermal energy in identified low-temperature reservoirs. Corresponding figures for the resource and the beneficial heat would be 2.5×10^{18} J and 1170 MW_t for 30 years.

Black *et al.* (1983) calculated an accessible resource base for the Oregon Cascade Range of 105×10^{18} J to $16{,}000\times10^{18}$ J, with the corresponding range in electrical energy being 2500–370,000 MW_e for 30 years (excluding National Parks, etc.). The high figure assumed that most of the range is underlain at 1.75–3.0 km by a hydrothermal reservoir at 190°C. The low figure assumed permeability only in 100-m-wide fracture zones between 1.75 and 3.0 km depth. Black *et al.* (1983) stated that these estimates "***are based solely upon the conductive heat-flow anomaly underlying the Cascade Range east of the transition zone. Estimates for known (e.g., Austin and Breitenbush Hot Springs) or undiscovered hydrothermal systems masked by cool groundwater are not included, nor are estimates of residual heat remaining in igneous related systems ***."

Another large estimate of undiscovered geothermal resources in the Cascade Range was given by Bloomquist *et al.* (1985) for the Cascade Range in Oregon and Washington. Basing their calculations on the temperature-depth model of Blackwell *et al.* (1982), Bloomquist *et al.* (1985) inferred a geothermal reservoir 40–60 km wide with a reservoir thickness of 1.25 km in the southern part and 0.5 km in the northern part. Mean reservoir temperature in the southern part was estimated to be 190°C, and in the northern part, 165°C. Bloomquist *et al.* (1985) used these volumes in the accepted volumetric heat equation (Brook *et al.*, 1979, equation 1) to give a stored reservoir thermal energy between the 150°C isotherm and at depth of 3 km of $11{,}800$–$17{,}600\times10^{18}$ J.

Bloomquist *et al.* (1985) also calculated thermal energy for individual geothermal systems in the Cascade Range. The total of these estimates (2400×10^{18} J) is heavily weighted by Mount McLoughlin and Crater Lake (500×10^{18} J and 1630×10^{18} J, respectively). Reservoir thicknesses and temperatures for these regions were based on the modeled crustal temperatures of Blackwell *et al.* (1982), and the areas were taken from associated Curie Point isotherm anomalies.

Table 1: *Estimates of geothermal energy in Cascade Range of USA. Numbers rounded to 2 significant figures.*

Temperature range (°C)	Accessible resource base (10^{18} J)	Resource (10^{18} J)	Electrical Energy (MW_e for 30 y)	Beneficial Heat (MW_t for 30 y)
Brook *et al.* (1979) identified (including Newberry, Kahneetah, Klamath Falls, & Klamath Hills)				
>150		8.3	880	
90–150		10.4		2600
≥90	118	18.7		
Reed *et al.* (1983) identified <90°C (all of Cascade Range				
	3.5	0.84		390
Wright (1992) (all of Cascade Range)				
			750 MW_e[a]	
Brook *et al.* (1979) undiscovered ≥90°C (including Newberry, Kahneetah, Klamath Falls, & Klamath Hills)				
>150	550–890[b]	138–220[b]	14,000–22,000[b]	
90–150	550–890[b]	138–220[b]		35,000–56,000[b]
≥90	1440	360		
Reed *et al.* (1983) undiscovered <90°C (all of Cascade Range)				
	10.5	2.5		1170
Black *et al.* (1983) (Cascade Range in Oregon; conductive regimes only)				
	105–16,000		2500–370,000	
Bloomquist *et al.* (1985) (Cascade Range in Oregon and Washington)				
	11,800–17,600		185,000–280,000	
Black (1994) (Cascade Range in Oregon, including Newberry; conductive regimes only)				
	2900		580–5800	

[a] Electrical capacity (time not specified)

[b] Range depends on whether one assumes constant reservoir volume *vs.* temperature or whether one assumes increase of reservoir volume with temperature of the line in figure 13 of Brook *et al.* (1979)

The large amounts of thermal energy calculated by Bloomquist *et al.* (1985) and by Black *et al.* (1983) at depths <3 km do not necessarily imply a large amount of recoverable geothermal energy. Much of the calculated thermal energy may be tied up in rock of low porosity and permeability ("hot dry rock") and thus be unavailable for conventional recovery as from a hydrothermal reservoir. Specifically, the recovery factor of 0.25 is far too high, perhaps by several orders of magnitude, for use throughout a geological province. Accordingly, the figures given by Bloomquist *et al.* (1985, p. 75) are probably two orders of magnitude too high.

Black (1994) presented an estimate of the geothermal power potential of the Cascade Range in Oregon, including Newberry volcano, based on a systematic calculation of thermal energy in each township at depths between the 150°C isotherm and a depth of 3 km, assuming a totally conductive thermal regime. Electrical energy for each block was calculated using a utilization factor of 0.4 and a range of recovery factors. The results were corrected to include only the part of each block not in a National Park or a Wilderness Area. The summary ranges (Table 1) reflect recovery factors of 0.25 and 0.025 for Newberry volcano and 0.025 and 0.0025 for the rest of the Cascade Range in Oregon, under the assumption that recovery factors for Newberry volcano are likely to be higher than for the rest of the Cascade Range in Oregon (Black, 1994, p. 9).

The implications of this analysis are not clear, primarily because of the lack of any specific criteria for choosing among the 10^3 range of recovery factors presented. Given that this analysis is based solely on conductive heat transfer (hydrothermal systems are specifically excluded), the analysis falls under the broad category of "hot dry rock", with any recovery factor being based upon the specific technology and economics anticipated.

UNDERLYING EARTH-SCIENCE MODELS

The optimism of the geothermal-resource assessments described above was predicated primarily on three factors: (1) the minimal amount of exploration and deep drilling carried out in the Cascade Range, (2) the large amounts of thermal energy estimated by Smith and Shaw (1975, 1979) to be in igneous-related systems to a depth of 10 km, and (3) the heat-flow interpretation of Blackwell *et al.* (1982) and Blackwell and Steele (1983, 1985) that invoked an extensive upper-crustal heat source underlying both the Quaternary rock and adjacent older rocks. The first factor has not changed very much—geothermal exploration in the Cascade Range (with the exception of Newberry and Medicine Lake volcanoes) has been minimal, and there still are few deep drill holes. Factors 2 and 3, however, are amenable to re-analysis in the light of geological, geophysical, and geochemical data accumulated over the past two decades.

Geothermal resources related to crustal magmatism

The association of volcanic rocks with high- and intermediate-temperature geothermal systems has been noted for over three decades (e.g., Muffler, 1976). Accordingly, identification of the Cascade Range as a geothermal target was hardly surprising. The fact that High Cascade volcanism has persisted for ≈10 m.y. and is still continuing indicates that substantial mass and heat have been transmitted from the mantle through the crust, providing the potential for igneous heat sources that could support substantial overlying hydrothermal systems.

For such igneous activity to support a hydrothermal system, however, igneous rock must lodge in the upper crust at depths of 3–10 km. Smith and Shaw (1975) emphasized that "***basic rocks (basalts, andesite, and comparable magmas) are formed in the mantle and/or lower crust and rise to the surface through narrow pipes and fissures; the individual magma pulses are volumetrically small, and such systems contribute little stored heat to the upper crust until magma chambers begin to form at high levels. With the exception of large oceanic volcanoes, basic magmas do not form high-level storage chambers out of context with derivative silicic magmas (dacites, rhyolites, and comparable derivative magmas). On the other hand, we think that silicic magmas are always erupted from high-level storage chambers, probably in the upper 10 km of the crust".

The significance of the estimates of Smith and Shaw (1975, 1979) for "igneous-related geothermal systems" is in the role that young, still hot, silicic intrusions can play in supporting overlying hydrothermal systems in the upper crust. If the volume of young magma chambers (whether still molten or already partially cooled) in the upper crust is substantial, there ought to be substantial overlying hydrothermal systems. But if the volume of young intrusive material in the upper crust is small, the heat sources to support overlying convection of meteoric water are doomed to be few and impotent.

The tables of Smith and Shaw (1975, 1979) presented estimates of thermal energy still remaining in silicic intrusions and adjacent country rock, calculated by conductive cooling models using estimates of the size and age of intrusions (these estimates are critically dependent on the volumes assumed). Smith and Shaw (1979) estimated that roughly $3{,}900 \times 10^{18}$ J remain today to depths of 10 km in eleven igneous-related systems in the Cascade Range (including Medicine Lake and Newberry volcanoes) for which data available in 1978 allowed such calculations. They further noted that additional igneous-related energy resides in systems not evaluated because of insufficient data. They gave no estimate specific to the Cascade Range, but for the entire United States they estimated that the unevaluated geothermal energy in igneous-related geothermal systems is perhaps 10 times that which could be evaluated in 1978. If this ratio applies to the Cascade Range, the implication is that greater than $40{,}000 \times 10^{18}$ J remain today in volcanic areas of the Cascade Range, to a depth of 10 km. It is this figure that had major influence upon the estimate of Brook et *al.* (1979) that the undiscovered hydrothermal resource to depths of 3 km beneath the Cascade Range was 20 times the identified resource. It did not appear unreasonable that the hydrothermal resource at depths <3 km could be ≈4% of the igneous-related thermal energy.

Extensive mid-crustal heat source beneath the Cascade Range

High heat flow measured in the Cascade Range has also been used to suggest a substantial volume of molten or still high-temperature igneous rock at depths of 10±2 km beneath the Cascade Range (Blackwell *et al.*, 1982, 1990b). Heat flow in the Cascade Range is undeniably high, ≈100 mW m^{-2}, contrasting with heat flow of 40–50 mW m^{-2} to the west (Blackwell *et al.*, 1982, 1990a, 1990b; Blackwell and Steele, 1992). Blackwell *et al.* (1982, figure 8) converted the heat-flow data in central Oregon to a set of isotherms in the crust. The solution is not unique—any one of these isotherms can explain the heat-flow data. The choice that Blackwell *et al.* (1982) made among the isotherms was based on comparison with regional Bouguer gravity data, under the fundamental assumption that the change in Bouguer gravity along this cross section "is directly associated with the same phenomenon which causes the change in heat flow" (Blackwell *et al.*, 1982, p. 8,749). They argued that the observed gravity anomaly is much too great to be explained by simple thermal expansion of rock at any of the subsolidus temperatures of their Figure 8. Accordingly, they concluded that partial melting is required, with partial melting at a depth of 6 to 10 km giving the best correspondence to the observed gravity data. Although Blackwell *et al.* (1982, Figure 10) presented several other models to explain the heat-flow data, they preferred "the model that relates the gravity and heat flow data to a (large) zone of hot, low-density (partially molten) material in the upper part of the crust (10±2 km) beneath the High Cascade Range and extending about 10 km west of the High Cascade Range boundary." (p. 8750 of Blackwell *et al.*, 1982; see also Blackwell and Steele, 1985, Figure 3, and Blackwell *et al.*, 1990a, 1990b).

Blackwell *et al.* (1982) projected the thermal and gravity cross sections to the north and to the south from central Oregon, based upon the uniformity of the heat-flow and Bouguer gravity transition zones. The resultant geometry—a uniform heat source 40-60 km wide (Blackwell and Steele, 1983) at temperatures of 600–800°C extending under the entire Cascade Range—became the philosophical basis for the estimates of Black *et al.* (1983), Bloomquist *et al.* (1985), and Black (1994).

Blakely (1994), however, has used ideal-body analysis to show that the gravity gradient must be caused by density variations in the upper 2.5 km of the crust, most likely a relict boundary between a pre-Oligocene extensional trough to the east and oceanic crust to the west. Blakely's conclusion precludes interpretation of the gravity and heat-flow gradients as caused by the same hot mid-crustal mass. Consequently, the gravity data can not be used to choose between the thermal models presented by Blackwell *et al.* (1982, Figure 10).

In addition, Blakely (1994, figure 9) compared the observed heat flow in central Oregon (from Blackwell, 1982) with the conductive heat flow expected above semi-infinite heat sources located at various depths (from Lachenbruch *et al.*, 1976). This comparison demonstrates that the heat-flow gradient is too abrupt to be explained by conductive heat sources deeper than 5 km.

Ingebritsen *et al.* (1989, 1992, 1994) recontoured the heat-flow data in central Oregon and presented a map displaying significant complexity, in contrast to the simple, linear north-south contours of Blackwell *et al.* (1982, 1990b) and Blackwell and Steele (1993). On the basis of this map, isotopic studies, and hydrologic modeling, Ingebritsen *et al.* (1989, 1992, 1994) argued that high heat-flow values west of the Cascade crest are due to lateral outflow of water heated by discrete igneous centers along a relatively narrow zone of magmatism along the Cascade crest.

LOCALIZED MAGMATIC HEAT SOURCES

The composition, depth, and configuration of possible magmatic heat sources in the US part of the Cascade Range were analyzed by Guffanti and Muffler (1995) and by Muffler and Guffanti (in preparation), on the basis of extensive investigations of the USGS in the Cascade Range during the past two decades. They concluded that large, silicic, upper-crustal intrusions capable of supporting major, high-temperature, hydrothermal systems occur only in some of the major volcanic centers. At the thousands of smaller short-lived mafic volcanoes of the Cascade Range in Oregon and northern California, mafic magma is stored deeper than 10 km and is transported to the surface quickly in only narrow conduits. Only small volumes of magma are stored in the upper crust at any time, there is little likelihood for sizable high-level intrusions, and resultant long-lived, high-temperature hydrothermal systems are unlikely. Furthermore, even the major volcanic centers display widely differing hydrothermal potential (Guffanti and Muffler, 1995; Muffler and Guffanti, in preparation). At predominantly andesitic stratovolcanoes (Mount Baker, Mount Adams, Mount Rainier, and Mount Hood), hydrothermal activity occurs primarily in the vicinity of the narrow, still-warm magmatic conduit within the volcanic cone and is transitory, as shown by Shevenell (1990) and Shevenell and Goff (1993) at Mount St. Helens. In addition, lateral transport of thermal fluids away from the cone involves substantial mixing with cold groundwater flowing within the volcanic edifice. Geothermal potential at stratovolcanoes appears to be modest, although deep undiscovered hydrothermal resources can not be precluded, particularly at the more dacitic stratocones (Mount Shasta, Mount St. Helens, and Glacier Peak). At composite centers (Lassen; Three Sisters), shallow intrusions related to young silicic domes appear to be effective heat sources for hydrothermal circulation. At the only young explosive caldera (Crater Lake), a catastrophic eruption of the shallowest and most silicic part of the magma chamber 7700 years ago removed a potent heat source from the upper crust. A viable heat source may remain, however, as the deeper (>7.5 km) andesitic portion of the magma chamber, and discrete intrusive bodies associated with pre-caldera dome eruptions may act as effective shallow heat sources for hydrothermal systems of modest temperature. Indeed, the chemistry of the large-volume, 5–10°C, Wood River group of springs south of Crater Lake has been interpreted by Nathenson *et al.* (1994) to indicate a heat discharge of 87 MW_t. Finally, the shield complexes of Newberry volcano and Medicine Lake volcano, along the boundary with the Basin and Range province, have high geothermal potential. The shallow intrusive plexuses of sills and dikes that underlie the centers apparently provide favorably configured heat sources for hydrothermal circulation, although no single mafic or silicic intrusion is large.

Known high-temperature hydrothermal systems in the U.S. Cascade Range are associated with silicic domefields at Medicine Lake volcano, Newberry volcano, Lassen volcanic center, and perhaps in north-central Oregon in the vicinity of Mt. Jefferson and Three Sisters. It appears significant that these sites are in extensional settings where the southern Cascades adjoins the Basin and Range province.

LAND-USE CONSIDERATIONS

Any evaluation of hydrothermal potential of the Cascade Range must take into account the spatial relationship between volcanic centers likely to have upper-crustal intrusions capable of supporting major high-temperature hydrothermal systems and areas subject to land-use restrictions. For example, hydrothermal systems in National Parks (most conspicuously the Lassen hydrothermal system) are not available for any geothermal development. Similar restrictions apply to hydrothermal systems in Wilderness Areas, thus eliminating virtually all of the volcanic centers in the High Cascades. Development of hydrothermal systems adjacent to a National Park (e.g., Crater Lake caldera) is likely only if it can be convincingly demonstrated that there will be no adverse effect on hydrothermal phenomena or other protected aspects of the Park.

CONCLUSIONS

Newberry and Medicine Lake volcanoes are the main (and possibly the only) high-temperature geothermal targets in the Cascade Range. Newberry was included in identified resources by Brook *et al.* (1979), whereas Medicine Lake was included with undiscovered resources by Brook *et al.* (1979) but certainly now should be considered an identified resource. Klamath Falls remains the major identified intermediate-temperature hydrothermal system. The Cascade Range does have significant additional potential for localized low- to intermediate-temperature hydrothermal systems and for intermediate-temperature hot dry rock. Deep (>2 km) cryptic high-temperature hydrothermal systems at the major volcanic centers cannot be precluded, but their reservoir characteristics and resource potential cannot be evaluated without deep drilling data. Overall, undiscovered hydrothermal resources of the Cascade Range of the United States appear to be substantially less than published numerical estimates, a conclusion presaged by Benoit (1983).

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