GEOTHERMAL POTENTIAL OF DIVERSE VOLCANOTECTONIC SETTINGS OF THE CASCADE RANGE, USA

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ABSTRACT

Late Quaternary volcanic centers in the U.S. Cascade Range comprise four categories that correlate with geothermal potential. (1) ***Stratovolcanoes:*** Hydrothermal activity (often transitory) occurs primarily near narrow volcanic conduits, although deep cryptic hydrothermal systems at the more silicic volcanoes cannot be ruled out. (2) ***Composite centers:*** Stratovolcanoes with silicic domefields and related young intrusions can support high-temperature hydrothermal systems. (3) ***Explosive caldera:*** A caldera at Crater Lake formed at 7700 ka by explosive eruption of –50 km^3 of andesite and dacite. Viable heat sources may still remain as the unerupted part of the large magma chamber at 7.5–15 km and as small shallow intrusive bodies associated with pre-caldera magmatism. (4) ***Shield complexes:*** Medicine Lake and Newberry volcanoes occur where Basin-and-Range extension impinges on the Cascade Range. Young basalt and rhyolite in shallow intrusive plexuses comprise favorable heat sources. Surface thermal manifestations are very sparse, but promising high-temperature systems have been identified at both volcanoes. Undiscovered hydrothermal resources of the U.S. Cascade Range appear to be significantly less than previously estimated.

1. INTRODUCTION

In the 1978 assessment of geothermal resources of the United States, the U.S. Geological Survey estimated that the Cascade Range of the United States contains significant undiscovered geothermal resources (Brook *et al.*, 1979). In the years since that assessment, the Cascade Range has been the focus of considerable geologic, hydrologic, geochemical, and geophysical research aimed at elucidating magmatic processes and crustal thermal regimes in the range and at refining estimates of its geothermal resources. In this paper, we highlight some results pertinent to a conceptual magmatic-hydrothermal model that is the foundation of an new assessment of the region's geothermal resources (Muffler and Guffanti, in preparation), and we offer some qualitative conclusions about geothermal potential of the U.S. Cascade Range (see also Muffler and Guffanti, 1995).

2. VOLCANOTECTONIC SETTING

The Cascade Range, an elongate volcanic arc extending ≈1000 km from northeastern California, USA, into British Columbia, Canada, is the surface expression of deep magmagenesis related to Cenozoic subduction of the Juan de Fuca plate system beneath the North American plate (Muffler and Tamanyu, 1995). The Cascade volcanic arc is active, with several well-documented historic eruptions as recently as 1914–1917 at Lassen Peak, California, and 1980–1986 at Mount St. Helens, Washington. About a dozen visually prominent Quaternary volcanic centers such as Mount Rainier and Mount Shasta represent sites of focused intrusion of magma into the upper crust (Figure 1). Eruptive volumes of the large centers range from tens to hundreds of km^3, and their life spans may reach several 100 ka. Dacite and rhyolite are found in the Cascades mainly at some of these large volcanoes (Sherrod and Smith, 1989; Smith, 1993). In addition to the large centers, a myriad of smaller, short-lived volcanoes have produced mostly basaltic to andesitic magmas, particularly in Oregon and California.

Quaternary extrusion rates of volcanic rocks vary significantly along the length of the Cascade Range (Sherrod and Smith, 1990). The extrusion rate north of Mount Rainier in the northernmost Cascades is low, ≈0.21 km^3 per km of arc length per million years (km^3 km^{-1} $m.y.^{-1}$), whereas the rate in southern Washington and northern Oregon is ≈1.6 km^3 km^{-1} $m.y.^{-1}$. The highest extrusion rate, 3-6 km^3 km^{-1} $m.y.^{-1}$, is in central Oregon. In northeastern California, the extrusion rate is ≈3 km^3 km^{-1} $m.y.^{-1}$.

The high extrusion rates (≥3 km^3 km^{-1} $m.y.^{-1}$) occur south of Mount Hood, Oregon, in the part of the Cascade Range adjacent to the actively extending Basin and Range province. The widespread volcanism and high extrusion rates, along with normal faulting and linear vents trends, in the central and southern Cascades are evidence of regional extension within the volcanic arc. Consequently, various investigators have suggested a tectonic link between the two provinces, with the Basin and Range province having some attributes of a back-arc environment (Priest *et al.*, 1983; Guffanti and Weaver, 1988; Guffanti *et al.*, 1990). North of Mount Hood, extensional zones in the Cascade Range are more localized (Smith, 1993; Weaver *et al.*, 1987), and volcanism is concentrated at stratovolcanoes.

On a regional scale, the Cascade Range is characterized by a positive heat-flow anomaly (Blackwell and Steele, 1992). This anomaly has been investigated in detail in central Oregon, where the regional 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). A gravity gradient is roughly coincident with the heat-flow gradient (Blakely and Jachens, 1990). Blackwell *et al.* (1982, 1990a, 1990b) interpret the coincidence of the heat-flow and gravity gradients in central Oregon to indicate a partly molten heat source at 10±2 km extending –30 km west from the range axis. Blakely (1994), however, has shown by ideal-body analysis that the gravity gradient must be caused by density variations in the upper 2.5 km of the crust, thus precluding interpretation of the gravity and heat-flow gradients as caused by the same hot mid-crustal mass. Ingebritsen *et al.* (1992) argue that the high heat-flow values west of the Cascade crest are due to lateral outflow of water heated by discrete igneous centers along the Cascade crest.

The major Cascade volcanic centers are of four main types: (1) Stratovolcanoes are the most common type and range 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 largest, having an extruded volume of 400 km^3, and most silicic, being composed of silicic andesite to dacite with some rhyolite. (2) Composite centers are andesitic stratovolcanoes combined with silicic domefields and are exemplified by the Lassen volcanic center and the Three Sisters volcanic center. During the late Quaternary, these two centers have erupted significant volumes of silicic magma in domefields. (3) The only instance of a young explosive caldera is at Crater Lake, Oregon, where a catastrophic eruption of ≈50 km3 of andesitic to dacitic magma occurred at Mount Mazama 7700 years ago (Bacon, 1983; Bacon and Druitt, 1988). (4) The large shield complexes of 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 central and southern 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.

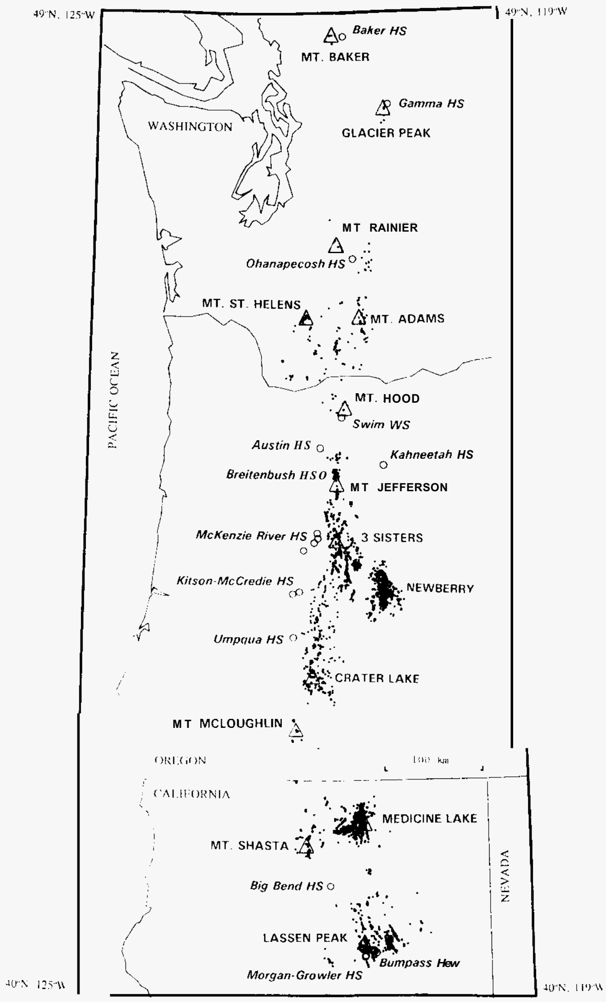

Figure 1. ***Volcanic setting of the Cascade Range, USA. Large triangles are major Quaternary volcanic centers. Small dots are individual volcanic vents younger than 730,000 years. Vent locations in Washington and Oregon were digitized from Sherrod and Smith (1989) and Smith (1993). Open circles are hot springs associated with known hydrothermal systems having subsurface temperatures ≥90°C.***

3. MAGMATIC HEAT SOURCES

The young, widespread volcanism of the Cascade Range was a major factor in the large estimate of undiscovered geothermal resources made by Brook *et al.* (1979) for the region (Muffler and Guffanti, 1995). The volcanic history of the Cascades indicates that substantial amounts of magma have been transmitted through the crust, suggesting the potential for igneous heat sources that could support overlying hydrothermal systems. According to the geothermal model of Smith and Shaw (1975) however, volcanic vigor alone is not a sufficient indicator of geothermal favorability. Young, still-hot, partially molten intrusions must lodge in the upper crust at depths less than 10 km in order to effectively provide heat for associated hydrothermal systems; magma that rises to the surface in small batches through narrow conduits contributes little stored heat to the upper crust. The model of Smith and Shaw (1975) emphasizes that silicic (dacitic and rhyolitic) magmas are more likely to form high-level storage chambers than mafic (basaltic and andesitic) magmas.

Thus, knowledge about the composition, depth, and configuration of magmatic heat sources in the Cascades also must be factored into the evaluation of the region's geothermal potential. The body of geologic and geophysical evidence obtained through a sustained research program in the Cascades now indicates that, although overall magmatic **flux** through the crust is indeed high in the Cascades, large silicic upper-crustal intrusions capable of supporting major high-temperature hydrothermal systems are not common.

At most of the stratovolcanoes, upper-crustal storage of magma appears to be limited to a narrow conduit that connects to a small magma reservoir in the middle to lower crust. The magmatic system of Mount St. Helens is especially well-defined from a variety of data provided by its 1980–1986 eruptions (Pallister *et al.*, 1992). A cylindrical magma reservoir 7–11 km deep and ≈1.5 km in diameter has a volume of 5–7 km^3 and temperature of ≈920°C; a narrow conduit 30–60 m in diameter connects the reservoir to the surface. This general configuration probably is representative of the magmatic systems at the other andesitic to dacitic stratovolcanoes (Mount Hood, Mount Rainier, and Glacier Peak). At the more mafic (basaltic to andesitic) stratovolcanoes, Mount Baker and Mount Adams, magmatic transport also appears to be through a relatively fixed central conduit system, with magma storage zones lodged deeper (>20 km) in the crust. Only at Mount Shasta, a very large and dominantly silicic stratovolcano, might storage of a substantial volume of silicic magma in the upper crust be considered (although a specific magma body has not been delineated geophysically).

At the Lassen composite center, where silicic rocks comprise more than half of the eruptive volume, seismic-refraction and teleseismic investigations have failed to identify a large, coherent magma chamber in the shallow crust (Berge and Monfort, 1986; Berge and Stauber, 1987). Upper-crustal (<5 km) magma storage is likely to be in the form of smaller discrete still-hot intrusions related to the dacitic domefield that has erupted episodically during the past 250,000 years and as recently as 1917 at Lassen Peak (Clynne, 1990). Such intrusions are not easily discernible with seismic methods. At Three Sisters center, eruption of silicic domes occurred as recently as 1900 years ago on the flanks of South Sister (Scott, 1987), and intrusive equivalents of those domes likely reside in the shallow crust there also.

At the shield complexes of Newberry and Medicine Lake volcanoes, several geophysical techniques have been employed to characterize the structure and physical state of the upper crust (Achauer *et al.*, 1988; Donnelly-Nolan, 1988; Fitterman, 1988; Dzurisin *et al.*, 1991; Zucca and Evans, 1992). These techniques have not identified a large shallow magma body at either center. Rather, the combined geological and geophysical evidence suggests that magma ranging in composition from basalt to rhyolite is stored in the upper few kilometers of the crust as a branching plexus of recently solidified, still-hot dikes, sills, and small magma pods, most of which are too small to be individually recognized by present geophysical methods.

A large silicic crustal magmatic system is thought to have fed the caldera-forming eruption at Mount Mazama (Crater Lake) 7,700 years ago (Bacon and Druitt, 1988). However, the configuration and composition of that magmatic system now is significantly different than just before that eruption. The top of the pre-caldera reservoir was at a depth of at least 5 km. During the caldera-forming event, most of the silicic part of this reservoir, ≈50 km^3, was erupted and its thermal energy dissipated to the atmosphere. Bacon and Nathenson (in preparation) estimate that roughly 40% of the total heat added to the crust by the Mazama magmatic system was lost by eruption. The top of magma chamber probably is now at a depth of at least 7.5 km, and the composition of the unerupted magma is primarily andesitic. The substantial amount of magmatic heat still remaining in the crust, $\approx 370\times10^{18}$ J, is stored fairly deep at 7.5–15 km. In addition to the recent caldera-forming eruption, extrusion of silicic magma at Crater Lake has occurred as several dacitic dome eruptions beginning about 70,000 years ago, before development of the Mazama magma chamber.

At the hundreds of smaller, short-lived, mafic volcanoes in the Cascades, only modest volumes of magma are stored in the upper crust at any time as dike and sill intrusions.

In summary, the model of a large, partially molten, silicic magma chamber cooling in the shallow crust and providing heat for major hydrothermal activity is not generally applicable in the Cascade Range. Shallow storage of silicic magma is more likely as smaller discrete intrusions related to eruption of dome complexes. In much of the Cascades, mafic magma is stored deeper than 10 km and is transported to the surface by narrow conduits.

TABLE 1. ***Known Hydrothermal Systems in the Cascade Range, USA, with Subsurface Temperatures ≥90°C.***
Subsurface temperatures from Mariner ***et al.*** (1990) unless otherwise noted; type of chemical or isotopic geothermometer in parentheses.

System	Description	Subsurface Temperature (°C)
WASHINGTON		
Mt. Baker Area	Summit fumaroles: heat flux of ≈11 MW_t at Sherman Crater and Dorr Fumarole Field; enhanced fumarolic emission and phreatic ash ejection 1975–1976.	---
	Baker HS: ≈10 km E of summit; discharges 1.4 L s^{-1} at 44°C.	140 (quartz)
Glacier Peak Area	Gamma HS: ≈6 km NE of summit within Glacier Peak Wilderness Area. Na-Cl-HCO_3 water discharging at 65°C.	157 (quartz)
	(Kennedy HS and Sulphur HS are low-temperature systems.)	
Mt. Rainier Area	Summit fumaroles: near boiling with heat flux of 9 MW_t; other thermal areas (low-temperature) on flanks.	---
	Ohanapecosh HS: =20 km SE of summit in Mt. Rainier National Park; ≈14 L s^{-1} of Na-Cl water at up to 50°C.	110 (sulfate)
	(Longmire HS is low-temperature system.)	
OREGON		
Mt. Hood Area	Summit fumaroles: 71–91°C with heat flux of ≈10 MW_t.	---
	Swim Warm Springs: at ≈1220 m elevation on S flank; discharge 6.4 L s^{-1}L s^{-1} at 26°C.	110 (sulfate)
	Parkdale thermal well: =17 km NE of summit; 24°C measured at 50 m.	95 (Mg-corrected); unpublished estimate of M. Nathenson
Kahneetah HS	Located east of Cascade crest; Na-HCO_3 water different from Western Cascades waters; spring temperatures to 52°C	137 (Na-K-Ca)
Austin HS	Between Mt. Jefferson and Mt. Hood; discharging at 84°C.	186 (sulfate)
Breitenbush HS	NW of Mt. Jefferson; discharging at 86°C.	178 (sulfate)
McKenzie River Group	W of 3 Sisters; includes Belknap-Bigelow HS, Foley HS, Terwilliger HS.	up to 150 (sulfate)
Kitson/McCredie HS	Several springs to 73°C.	96 (chalcedony), 1 18 (sulfate)
Umpqua HS	Several springs to 46°C; CO_2-rich water; geothermometers may be unreliable.	131? (chalcedony)
Newberry Volcano	East Lake HS and Paulina HS: dilute CO_2-charged water; gas seeps, weak fumaroles.	---
	Drill hole USGS N-2, within caldera.	265 (measured at 932 m)
Crater Lake Area	Drill hole MZI-11A: industry exploration hole along eastern border of Crater Lake National Park.	130 (measured at 1067 m)
CALIFORNIA		
Medicine Lake	Hot Spot: within caldera, weak steam discharge contaminated with air.	---
	Industry drill holes with proprietary temperature logs.	175–325 (inferred from fluid inclusions and hydrothermal mineralization in drill core)
Mt. Shasta Area	A few small fumaroles and acid-sulfate springs at summit.	---
Big Bend HS	Between Mt. Shasta and Lassen Peak, 6 springs up to 82°C.	120 (quartz)
Lassen System	Bumpass Hell: major upflow zone of vapor-dominated reservoir; within Lassen Volcanic National Park.	235 (gas geochemistry; Muffler ***et al.***, 1982)
	Morgan-Growler HS: lateral outflow from deep hot-water part of system.	220–240 (Na-K-Ca; quartz; sulfate; Muffler ***et al.***, 1982)

4. HYDROTHERMAL SYSTEMS

The distribution of hydrothermal manifestations in the Cascade Range is sparse (Figure 1). Sixteen hydrothermal systems having estimated subsurface reservoir temperatures ≥90°C are known (Table 1). Some of these systems are manifested by thermal springs at low elevations around large Quaternary stratovolcanoes. In Oregon, a belt of hot springs occurs west of the Quaternary arc in volcanic rocks >7 Ma (Ingebritsen ***et al.***, 1994). The only Cascade system having vigorous high-temperature surface hydrothermal activity is within and adjacent to Lassen Volcanic National Park. Interestingly, the most promising geothermal targets in the range (Medicine Lake and Newberry volcanoes) have negligible surface hydrothermal features.

Hydrothermal activity at Cascade stratovolcanoes commonly includes summit fumarolic activity that discharges ≈10 MW_t (Friedman and Frank, 1980; Friedman *et al.*, 1982; Frank, 1985) and low- to moderate-temperature springs that issue at lower elevations on the flanks or beyond the bases of the volcanic edifices. At Mount Hood for example, fumaroles occur near the summit, low-temperature springs occur on the southeast flank, and thermal water occurs in a drill hole 15 km northeast of the summit. At Glacier Peak, no thermal features occur on the volcano, but three thermal springs discharge from older rocks 6–17 km from the summit. At Mount Rainier, fumaroles are present at the summit and upper flanks, two clusters of slightly thermal springs occur on the lower flank of the volcano, and two Cl-rich thermal springs issue from older rocks beyond the edifice of Mount Rainier. In a model proposed by Frank (1995), a shallow steam-heated aquifer occurs within the upper kilometer of the Mount Rainier edifice; secondary boiling of this water feeds fumaroles at the summit and on the upper flanks. Lateral flow and mixing with cold shallow groundwater feeds the springs on the lower flanks. The more distant Cl-rich springs can be interpreted as originating in a deep (>2 km) hydrothermal zone under Mount Rainier with lateral transport over 10–20 km. The general aspects of parts of this model — summit fumarolic activity centered around the magmatic conduit that feeds stratovolcano eruptions, lateral transport of thermal fluids away from the cone, and substantial mixing with cold groundwater flowing within the volcanic edifice — probably pertain to most Cascade stratovolcanoes.

Hydrothermal activity at Mount St. Helens has some exceptional characteristics. Two groups of hot springs developed there after the 1980 eruption. These new hydrothermal features appear to be shallow-rooted, transient, and localized within deposits of the 1980 eruptions (Shevenell and Goff, 1993). One group of springs could contain about 10% magmatic water, derived from the crater dome and magmatic conduit beneath it. The other group of springs does not exhibit any influence of the dome and conduit; the major source of heat and chemical species is cooling of the pyroclastic flow and debris-avalanche deposits of 1980. For both groups of springs, temperatures declined tens of degrees from 1985 to 1989. No convincing evidence is available of a deeper hydrothermal system beneath the volcano.

At Mount Hood, where temperature data from several drillholes are available, heat-flow modeling suggests that a deeper hydrothermal system may exist in addition to the small, localized systems seen at the volcano's summit and on its flanks. Nathenson and Tilling (1993) compare the observed heat-flow pattern at Mount Hood to a calculated pattern based on conductive heat loss from a postulated isothermal magma body. They find that matching the observed pattern requires an unreasonably large (113 km^3) or too shallow (top at 4 km) magma chamber. To resolve this discrepancy, they infer that hydrothermal circulation may occur at depths >2 km around a magma body of reasonable volume for a stratovolcano ($\approx$ 14 km^3). However, the heat-flow modeling does not constrain temperature or size of the postulated hydrothermal system, and drilling to depths greater than 2 km is needed to confirm its existence.

Important new data on hydrothermal activity at Crater Lake are now available, although an integrated picture of the regional hydrothermal-circulation regime remains elusive. Collier *et al.* (1991) found pools of warm, slightly saline water on the floor of Crater Lake; temperatures of up to 19°C were measured in bacterial mats also found on the lake bottom. These observations indicate that low- to moderate-temperature thermal water discharges from the floor of Crater Lake. Another area of hydrothermal discharge is 25–35 km south of Crater Lake at the Wood River group of springs, a set of low-temperature mixed waters with an unknown thermal end-member that may be different from the thermal fluid feeding into Crater Lake (Nathenson, 1990; Nathenson *et al.*, 1994). Hydrothermal activity having no surface expression was located by an industry hole drilled east of Crater Lake. The maximum temperature measured in hole MZI-11A is 129.6°C at 1067 m (Priest *et al.*, 1987; Blackwell, 1994), well above what is attributable to the regional conductive gradient. How hydrothermal circulation in that drill hole is related to lake-bottom hydrothermal discharge and or the Wood River group of springs is unclear. Crater Lake lies within Crater Lake National Park, and by US Federal law development of any geothermal reservoirs within the Park is prohibited. Also by Federal law, development of any reservoirs occurring outside the Park would be conditional upon determination that thermal features within the Park would not be adversely affected.

The Lassen hydrothermal system consists of a central vapor-dominated reservoir at a temperature of $\approx$235°C underlain by a reservoir of hot water presumed to be at a similar temperature (Muffler *et al.*, 1982; Ingebritsen and Sorey, 1985). The focus of hydrothermal upflow is at Bumpass Hell, along a contact between young silicic volcanic domes and an older andesitic stratocone. Discharge from the deep hot-water part of the Lassen hydrothermal system occurs at Morgan Hot Springs and Growler Hot Spring, both located nearly 1000 m lower than Bumpass Hell and $\approx$7 km to the south. Part of the hot water also flows laterally to the southeast, where it was encountered in well Walker "O" No. 1 at Terminal Geyser. The Lassen geothermal system is centered within Lassen Volcanic National Park; as at Crater Lake, power development within the Park is prohibited by Federal law, and development in outflow zones adjacent to the Park is likely to be highly restricted.

The principal commercial geothermal prospects in the U.S. Cascade Range are at Medicine Lake volcano, California, and Newberry volcano, Oregon, notwithstanding the fact that surface hydrothermal manifestations are insignificant at both volcanoes (weak steam discharge at Medicine Lake; two small warm springs and gas seeps at Newberry). More than 20 exploration holes have been drilled by industry on Medicine Lake volcano, but nearly all the data on subsurface temperatures and fluid compositions remain proprietary. Fluid-inclusion studies on samples of drill core provide strong support for a geothermal reservoir of at least 180°C (Bargar and Keith, 1993), and hydrothermal alteration patterns in drill core suggest subsurface temperatures reached and perhaps still are $\approx$260°C or higher (T.E.C. Keith, written communication). At Newberry volcano, government-supported research drilling has provided publicly available temperature data and has established two important facts: (1) high temperatures exist at accessible depths; 265°C was measured at 932 m in drill hole USGS N-2 (Sammel *et al.*, 1988), and (2) an isothermal zone of cool water, or "rain curtain," can reach depths of 1 km and mask underlying high temperatures in a hydrothermal reservoir (Swanberg *et al.*, 1988).

Evaluation of the full magnitude of hydrothermal resources throughout the Cascades is complicated by the widespread occurrence of cool, hydrologically disturbed zones such as the one documented at Newbemy volcano. Downward and lateral flow of cold groundwater in permeable volcanic rocks results in low-to-zero near-surface heat flow over broad areas, particularly in Oregon (Blackwell *et al.*, 1982, 1990a; Ingebritsen *et nl.*, 1992, 1994) and northeastern California (Mase *et al.*, 1982). Unfortunately, given the uneven distribution of sufficiently deep research and exploration drilling in the Cascades, the three-dimensional extent of the "rain curtain" throughout the range cannot be delineated.

In north-central Oregon, a large area of near-zero heat flow occurs in the near surface in young volcanic rocks. In contrast, anomalously high advective and conductive heat flow has been measured west of the Cascade crest in older (>7 Ma) rocks at lower elevations, where hot springs occur in deeply incised river valleys. Ingebritsen *et al.* (1992) numerically simulate groundwater flow and heat transport through geologic cross-sections that include two hot spring groups, Breitenbush and McKenzie River. Both hot-spring groups are several kilometers west of young rhyolitic and dacitic domes in the vicinity of Mount Jefferson and South Sister. Subsurface temperatures of the thermal fluids may reach $\approx$150°C in the McKenzie River group and $\approx$180°C at Breitenbush Hot Springs (Mariner *et al.*, 1993). Ingebritsen *et al.* (1992) conclude that the springs are recharged in the Quaternary arc and that gravitationally driven thermal-fluid circulation transports heat from the Quaternary arc into older Cascade volcanic rocks on the western flanks of the range. The numerical simulations (based on measured temperature profiles, hot-spring discharge rates, and geochemical data) constrain the regional permeability structure, for which few measured data are available. Bulk permeability of older rocks is thought to be low due to hydrothermal alteration; reservoir-like permeabilities ($\approx 10^{-14}$ m^2) are assigned to thin zones (tens of meters) in only a very small fraction of the heated rock volume. An important implication of the modeling for resource assessment is that, although these springs are significant surface hydrothermal features in the Cascades, producible reservoirs are likely to be of small volume in restricted zones of localized high permeability.

In order to evaluate the intensity of hydrothermal activity range-wide, minimum rates of fluid and heat discharge for hydrothermal areas have been determined by Mariner *et al.* (1990) using the chloride-inventory method, which takes into account not only thermal waters discharging from visible springs but also thermal water discharging directly into streams (Not included in the inventory are springs at Mount St. Helens and Crater Lake.). The measured minimum fluid-discharge rate of 340 L s^{-1} convectively transports about 82 MW, (8.2×10^4 kJ s^{-1}) of heat to the land surface. Mariner *et al.* (1990) note that these rates of fluid and heat discharge in the Cascades are quite low compared to other volcanic arcs. Austin-Rreitenbush Hot Springs and Kahneetah Hot Springs in northern Oregon discharge nearly two-thirds of the total convective heat.

A difficulty in determining total convective heat discharge by thermal fluids in the Cascades lies in dealing with barely thermal springs having low concentrations of chloride. Such springs occur around Mount Shasta and south of Crater Lake at the Wood River group of springs. Nathenson *et al.* (1994) combine data from the chloride inventory of Mariner *et al.* (1990) with other chemical and physical data from the springs to calculate convective heat flux of at least 87 MW, for the Wood River group. Total convective heat flux into Crater Lake itself is 15–30 MW_t (Collier *et al.*, 1991). Thus, most of the hydrothermal heat discharge occurs on the flanks of the volcanic system rather than into Crater Lake. A similar analysis of Mount Shasta (M. Nathenson, written communication, 1994) suggests that the convective discharge from barely thermal springs at low elevations on the volcano is ≈20 MW,.

The preceding summary of Cascades hydrothernial activity indicates some significant difficulties in quantifying geothermal resources of the range: (1) Downward and lateral flow of cold groundwater obscures evidence of hydrothermal activity in the upper 1–2 km of the crust; except at a few locations, drilling has been either too sparse or too shallow to see through this "rain curtain." (2) Thermal waters can flow laterally tens of kilometers from their heat source, mixing extensively with cooler groundwater before appearing as surface springs. The subsurface reservoir associated with such a lateral-flow system may be an areally extensive but thin aquifer of localized high permeability whose overall volume, temperature, and producibility are difficult to determine. (3) Unseen hydrothermal systems may exist at depths greater than 2 km in areas unexplored by drilling; reservoir temperatures and volumes of such undiscovered geothermal resources, however, are not known.

5. GEOTHERMAL POTENTIAL

Geothermal potential in the Cascades generally correlates with the crustal magmatic system and tectonic setting of the four types of major late Quaternary volcanic centers. At stratovolcanoes, small magmatic heat sources have developed in localized zones of crustal extension. Hydrothermal activity occurs in the vicinity of the narrow. still-warm magmatic conduit within the volcanic cone; lateral transport of thermal fluids away from the cone involves substantial mixing with cold groundwater flowing within the volcanic edifice. Overall, geothermal potential at these stratovolcanoes appears to be modest. Mount Shasta, however, may be transitional to the next category. Its huge size, dominantly dacitic character, and location in a regional extensional setting allow for the possibility of substantial upper-crustal magma storage and deep undiscovered hydrothermal resources. At composite centers, intrusions in the shallow crust related to young silicic dome eruptions appear to be effective heat sources for hydrothermal circulation. For example, the vigorous high-temperature Lassen hydrothermal system is sited in a dacitic dome field. Three Sisters volcanic center, although having no significant thermal features on the main volcanic edifices, is the likely heat source for the McKenzie River hot springs, 15–30 km to the west. At Crater Lake caldera, eruption of the shallowest and most silicic part of the magma chamber 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. Discrete intrusive bodies associated with pre-caldera dome eruptions also may act as effective shallow heat sources; the 130°C hydrothermal system discovered by drilling just east of Crater Lake National Park may be related to intrusive equivalents of dacitic domes erupted about 70,000 years ago near the east rim of the young caldera. 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.

Thus, 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 Mount Jefferson and Three Sisters. These sites are in extensional settings where the southern Cascades adjoins the Basin and Range province. Federal land-use restrictions eliminate the Lassen hydrothermal system and any hydrothermal reservoirs within the Three Sisters and Mount Jefferson Wilderness Areas from potential development, so Newberry and Medicine Lake volcanoes remain the main geothermal targets in the Cascades. Crater Lake caldera appears to support only low- to intermediate-temperature hydrothermal systems and is subject to restrictions on development within and adjacent to National Parks. The several dominantly andesitic stratovolcanoes in the Cascade Range support small hydrothermal systems related to the volcanic conduits. Most of the area of the U.S. Cascade Range comprises basaltic andesites and has little likelihood for sizable high-level intrusions and, thus, low potential for associated major high-temperature hydrothermal systems. The range does have potential for localized low- to intermediate-temperature hydrothermal systems. Deep (>2 km) cryptic hydrothermal systems are conceivable at the major volcanic centers, but their reservoir characteristics and resource potential cannot be evaluated at this time. Overall, undiscovered hydrothermal resources of the Cascade Range of the United States appear to be significantly less than previously estimated.

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