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# Geothermal Abundance in the Cascade Range (Washington/Oregon/ N. California)

**Adam Jones**

LAIKA LLC, Portland, Oregon, USA

adam@jonz.org

**Abstract.** Arc volcanism is typically associated with high geothermal potential and the Cascade Range of North America is no different. As an active continental arc, the Cascades have an abundance of mid-to-upper crustal heat sources. Yet the region has a scarcity of active hydrothermal systems that is typical in geologically similar areas. What is different about the Cascades? Elevated geothermal heat flow and few hydrothermal occurrences convey that heat from magmatic influence is mostly dissipating conductively. The region has low internal deformation with few extensional structures that would facilitate hydrothermal convection. The area is seismically quiet despite evidence of active subduction and frequent volcanism. A staccato extrusive history and a regional layer-cake of basalts and altered volcanoclastic deposits lack vertical permeability. This restricts the structures needed for the circulation of fluids from the underlying hot rock upward to the surface, limiting the development of hydrothermal systems. Hydrothermal systems that do exist have relatively small volumes and low-to-intermediate temperature, and are associated with esoteric structural features or recent near-surface volcanics.

## 1. Introduction

The building blocks of the Pacific Northwest are an assemblage of accreted terrains whose accumulation describes a long history of subduction and volcanism on this margin. Active for 150 my, more than 100 my before Cascade Range volcanism, the region has added marine and igneous provinces to the western edge of the North American plate. More recently, activity persists as a subduction related arc volcanic chain. This chain interlaces with the Western Cordillera, a nearly unbroken series of volcanic arcs that extends along the eastern edge of the Pacific Ocean south across the globe [6].

The Cascade Range is a geothermal contradiction. Elevated geothermal heat flow is expected in continental arc volcanic chains and the Cascades have widespread high heat flow throughout the Range. Geothermal temperature gradients are commonly above 45°C/km near volcanic centers yet the prevalence of hydrothermal features are quite rare, features that are more abundant in similar volcanic terrains. Geothermal systems in volcanic arcs are the result of fluid circulation in areas of high heat flow. Convection drives heated fluids through available fractures or dilated structures and then ascends towards the surface. Often these emerge as hydrothermal systems. The US portion of the Cascades has 17 identified persistent hydrothermal systems with near surface water temperatures greater than 90°C (see Figure 1). Measurements of heat flow in the chain shows elevated temperature that suggests the combined effects of mid-crustal intrusive bodies is conductively elevating geothermal gradients.



Understanding this, the Cascade Range shows an irregular distribution of magmatic influx. There are notable gaps of high heat flow in Northern Washington and British Columbia and higher heat flow in Oregon and Southern Washington. Areas of higher heat flow relate, not surprisingly, to a greater concentration of hydrothermal and extrusive features.

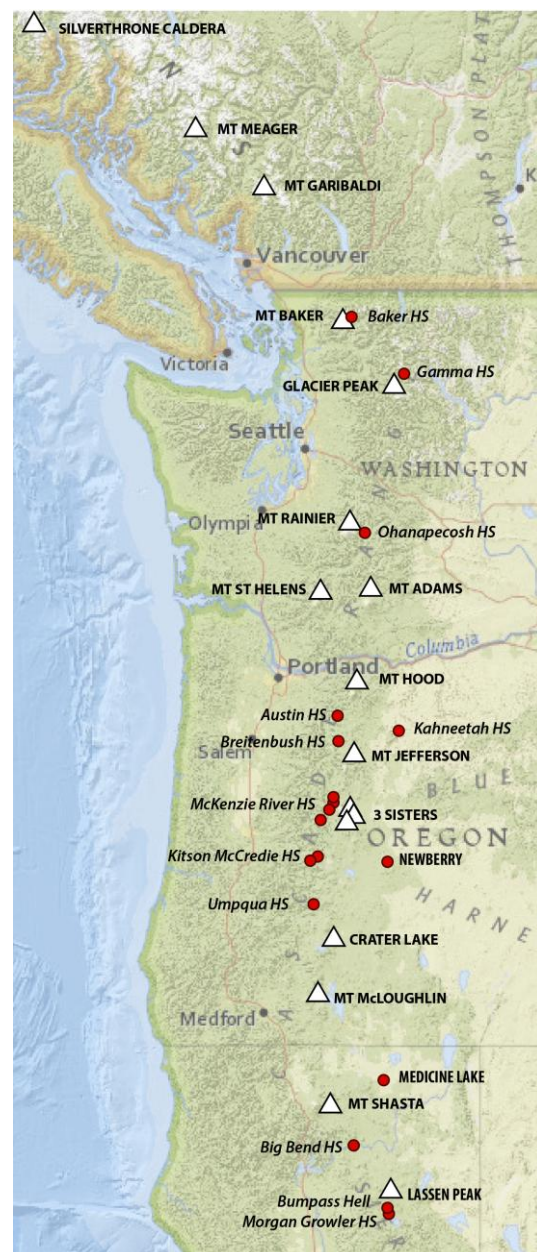
Seismicity is uncommon in the Cascade Range. Deep earthquake activity is concentrated at the northern and southern extremes of the arc and is very sparse in between. This is also echoed in the frequency and density of faulting found throughout the arc. Few structural trends are apparent throughout the arc and those that do exist typically show little offset and are not well organized. This lack of tectonic activity does not promote breakage through stratigraphic boundaries and inhibits vertical structural permeability. This has an effect on the formation of convective hydrothermal systems limiting their occurrence because fluid is not freely moving up or down throughout the subsurface.

## 2. Geological Setting

The Cascade Range is a continental arc volcanic chain on the west coast of North America. They are a result of northwest oblique subduction of the smaller Gorda, Juan de Fuca, and the Explorer plates underneath the much larger North American plate. Subsequent volcanism creates a 1300 km string of Cascades volcanoes that stretch from the South near Lassen Peak in Northern California and extends north to the Silver throne caldera in the Canadian province of British Columbia. Major stratovolcanoes are spaced around 75-100 km apart throughout the chain with slightly denser clusters in Oregon and Southern Washington. Composite volcanoes and volcanic complexes are constructed of basaltic, andesitic, and in some edifice, dacitic lavas. Thousands of discrete individual volcanoes and cinder cones also interstitially dot the chain. These smaller eruptive centers primarily produce basaltic andesite and are mostly the result of a single event, or at most a few events over a period of centuries.

Cascade Range volcanism has occurred on this axis for at least the last 42 my, however the focus of volcanism for the last 10 my has been on the eastern portion among the larger, mostly andesitic, stratovolcanoes of the High Cascades (Duncan and Klum). The Northern section of the arc shows somewhat isolated volcanism. Mostly large stratovolcanoes dominate the Northern Washington and British Columbia Cascades and fewer small volcanoes are present than to the south of Mt. Rainier. These northern structures intrude into and build upon older volcanic terrains and metamorphosed belts of previous orogenies [6].

Earlier volcanism of Oligocene to Miocene age is well exposed to the west of the High Cascades volcanic axis. These Western Cascades are deposits



**Figure 1:** Regional occurrence of Cascade Range hydrothermal systems with near surface temperature  $>90^{\circ}\text{C}$  (red circles) and many of the major stratovolcanoes (White triangles)

of primarily basalts (by volume), dacitic tuffs, and volcanoclastic deposits from an earlier period of arc volcanism [18]. Two large essentially bimodal, basalt/rhyolitic volcanoes, (Newberry, in central Oregon, and Medicine lake, in northern California) lie just east of the High Cascades and have long sustained volcanic histories with eruptions occurring many times in the last 10,000 years [15,16].

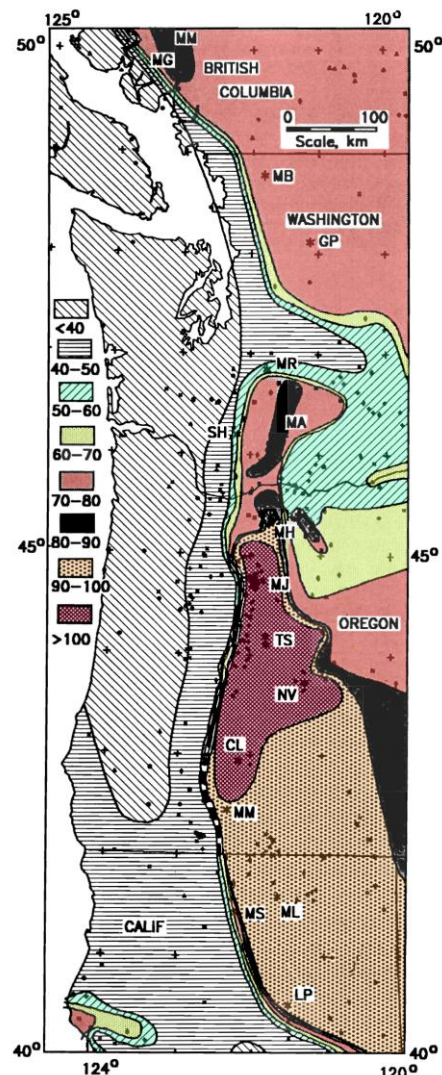
The peaks in the High Cascades have experienced repeated periods of Quaternary glaciation and even recently active areas often show deeply eroded summits. Older, now inactive, Pleistocene centers are typically eroded to some softened edifice, or to spires of coherent materials and volcanic plugs.

Prevailing winds are from the west off the Pacific Ocean and precipitation varies greatly across the divide. There is abundant rainfall on the western slopes of the Cascade Range from 114 cm/yr to more than 300 cm/yr at higher elevations. Several deep river drainages cut deeply into older volcanic structures and are typically west flowing until merging with rivers in the north-south trending Willamette valley, which is a deeply sedimented fore-arc basin. A rain shadow extends east of the Cascades crest with only about twenty percent of the annual precipitation that falls on the western slopes. Groundwater is abundant and hydraulic conductivity varies greatly with local stratigraphy. Shallow permeability is generally high and perennial springs are common. Permeability often transitions abruptly at depth as alteration increasingly weathers basalts and volcanoclastic deposits [5].

### 3. Heat sources beneath the Cascade Range and their association with hydrothermal systems

Heat flow measurement in the Cascade Range show elevated anomalies along almost all of the arc axis (see Figure 2). Zones of geothermal heat flow measure as high as  $100 \pm 9$  mW/m<sup>2</sup> in pockets of the High Cascades, which suggests a large volume of partially molten or still-hot intrusive bodies exist at depth. Conductive modeling infers that this source of heat is intrusive plutonism present at a depth of  $10 \pm 2$  km. The lateral extent of these intrusive bodies in Oregon and Southern Washington could be as much as 30 km west and 10 km east from the Cascades axis (Blackwell et al 1982, 1990a, 1990b). Subsurface heat flow is observed generally in arc-parallel isotherms but show a sudden drop off to the west with contact to the, evidently, now cold and inactive Western Cascades. A less dramatic fall in geothermal heat flow is measured to the east (See Figure 2).

Estimates of magma production in the Cascade Range for the last 2 my differ from north to south. Volumes north of Mt. Rainier are approximately  $0.21 \text{ km}^3/\text{km arc-length/ma}$  and increase to  $3\text{-}6 \text{ km}^3/\text{km arc-length/main}$  the Oregon Cascade

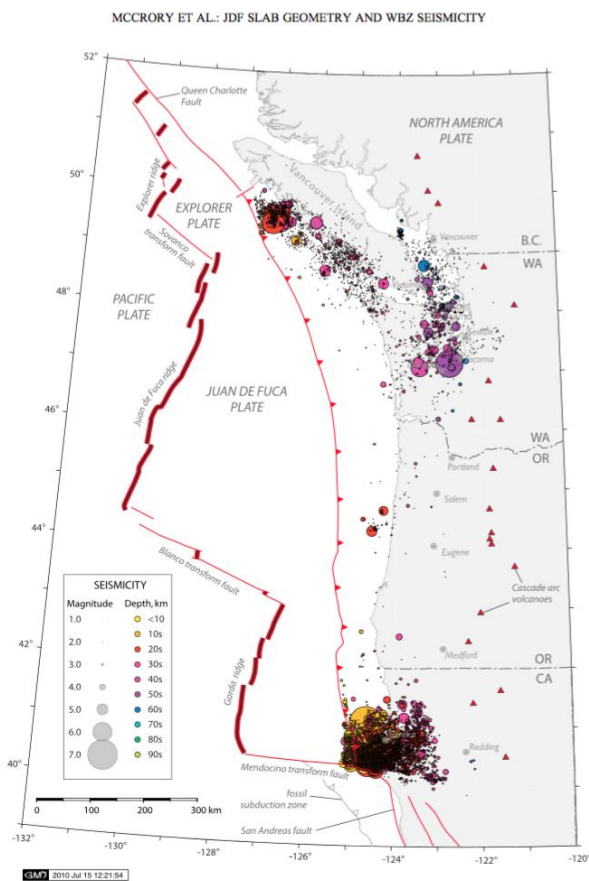


**Figure 2:** Summary heat flow map of the Cascade Range. Modified from Figure 10 from Blackwell et al 1990b, Large Asterisks are major volcanic centers (identified by two letter abbreviations) Data points are for location only. The volcanoes from north to south are, MM, Meager Mountain; MG, Mount Garibaldi; MB, Mount Baker; GP, Glacier Peak; MR, Mount Rainier; SH, Mount Saint Helens; MA, Mount Adams; MH, Mount Hood; MJ, Mount Jefferson; TS, Three Sisters; NV, Newberry Volcano; CL, Crater Lake; MM, Mount McLoughlin; MS, Mount Shasta; ML, Medicine Lake; LP, Lassen Peak.

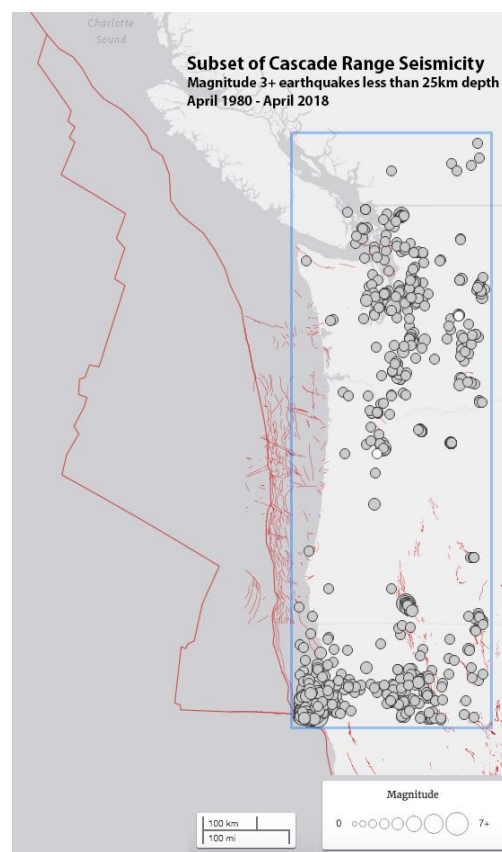
Range [22]. Extrusive activity also echoes this respective variation. Volcanism is sparse and isolated in Washington and British Columbia and is localized at a few major, mostly andesitic, stratovolcanoes. Activity increases to the south but eruptions are dominated by pulses of more primitive lavas in short and volumetrically small events [15,16].

Crustal pooling of highly evolved magmas is uncommon in the Cascades. Silicic magmas typically do not reside long in the upper crust and this lack of intrusive high-level storage does not allow for significant heat to dwell near the surface. Even potentially favorable conditions at the youngest explosive caldera in the arc, Crater Lake, only support low-to-intermediate temperature hydrothermal systems. Lassen Peak hosts perhaps the largest accessible geothermal feature in the range. With an eruption at Lassen Peak as recent as 1917, the subsurface is still hot. Although fluid outflow varies seasonally with rainfall, Lassen Volcanic National Park has the Cascade Range clearest evidence of persistent near surface hydrothermal circulation [15,16].

Active volcanoes in the Cascade Range may potentially host a modest hydrothermal system that includes shallow groundwater percolation through the still warm subvolcanic rock underlying the volcanic cone. In some cases some energetic boiling summit fumaroles may develop (e.g. Mt. Hood/Mt. Rainier). Other occurrences of geothermal waters are mostly down slope from the



**Figure 3:** Location map showing uneven distribution of epicenters interpreted to be Wadati-Benioff Zone earthquakes beneath the Cascades arc subduction boundary colored by depth range. Compiled from ANSS (1975–2009) and CNSN (1985–2009). Modified from Figure 1 [14].



**Figure 4:** Subset of earthquakes Magnitude 3+ epicenters with less than 25km depth for section within blue line. Strong red lines are plate boundaries and thin red lines are mapped Quaternary faults. (1500 largest earthquakes, April 1980–April 2018 from <http://earthquake.usgs.gov>)

topographical highs. Some are along the lateral edge of fractures or boundaries between the High Cascades with the Western Cascades. This interface with the Western Cascades shows some association with structures that allow fluid paths to communicate to deeper zones of heat. Each instance is apparently structurally unique to its individual hydrothermal occurrence.

#### **4. Regionally low seismicity of the Pacific Northwest**

Subduction has accreted several exotic terrains to the western edge of the North American plate building a cluster of well-sutured crustal blocks (Duncan and Klum). The specifics of these blocks are not yet well understood. However, observation of the eastern migration of volcanic focus in the central and southern sections of the Cascade Range and investigations by global positioning system (GPS) surveys have revealed a clockwise rotation of the Cascade Range, and much of the Pacific Northwest. [24]. Subduction of around 30mm/yr for the southern section and up to 45mm/yr in the northern section of the arc is observed [14]. Slab rollback in the subduction zone is measured at a rate of 35mm/yr [19]. Jarrod classifies the Cascade Range as a neutral or (locally) weakly extensional (Class 4a) subduction, indicating a neutral strain environment with little crustal thickening. Also, no shear or extension along the Cascades arc has revealed itself (in millimeters of movement per year) throughout the past few decades. This suggests that differential strain in the Cascades is primarily accommodated by crustal block rotation [13].

Deep focus earthquakes along the interface of the Cascades subduction zone and the North American plate occur with most frequency in the northern third of the arc and near the southern boundary with the Mendocino transform fault. Both of these localities suggest that Wadati-Benioff zone (WBZ) seismicity is most prevalent near areas of subduction where slab flexing results in warping during subduction [14]. Where the portion of subducting slab is dipping nearly perpendicular to the trench under Oregon, there is an overall drop in shallow seismicity (Figure 4) and a precipitous drop in deep slab focused WBZ earthquakes (Figure 3). Very large deep earthquakes have likely occurred as recently as 1700 AD (Atwater et al; [25]) and shallow crustal events as large as M7 have occurred near the Puget Sound. But large earthquakes are historically rare in the Cascade Range itself. There are few exposed quaternary fault structures (Figure 4) and those that do exist are not well organized and rarely show significant offset. Small earthquakes are observed infrequently in small clusters in and around volcanic vents but decrease away from those centers. Aside from very rare subduction zone earthquakes, other large earthquakes are only incrementally more frequent. Overall, the region is very quiet seismically.

#### **5. Comparison of the Cascade Range to the Tohoku arc in the Northern Japan**

The Cascade Range bears some resemblance to the Tohoku subduction zone in Northern Japan but there are some differences. The Pacific plate at that boundary is significantly older and cooler than the Juan de Fuca plate. The age of the Juan de Fuca plate at subduction is 0-11 ma compared to 120-145ma for the Pacific plate under the Tohoku Arc (Nakanishi et al). Also the rate of subduction in Tohoku is nearly 100 mm/yr, more than twice that of the Cascades subduction zone. Correspondingly, volcanic and seismic activity is more abundant along the Tohoku arc. While there have been at most 7 historical eruptive centers in the Cascade Range (~1,500bp), 25 are presently associated with Tohoku and some of those volcanoes have had multiple events in this period. Greater hydration from a thicker, cooler slab and faster subduction likely increase volatile influx in the mantle wedge above the Pacific plate, resulting in more magmatic activity. Aramaki and Ui estimate magma production is likely greater than 2.2 km<sup>3</sup>/km arc-length/ma for the length of the Tohoku arc. Superficially, this is a lot less than in some sections of the Cascades arc. But this difference is misleading in the sense that much of the volcanism in the Cascade Range are outpourings of basalts which tend to have little geothermal significance [9]. Volcanoes in Japan are considerably more andesitic and dacitic in character therefore magmas have longer residence in the upper crust and more opportunity to interact with groundwater.

A difference between Tohoku and the Cascades is very apparent with respect to deep WBZ seismicity. Considering Severinghaus' and Atwater's estimates for the time it takes a subducting slab to warm-up and become effectively aseismic, approx 0.1x the age of plate at subduction. The Juan de



discharge from the Cascades are ~82 MW(thermal) compared to an estimated heat energy of ~1513 MW(thermal) for the Tohoku arc, a nearly eighteen-fold difference. Although the chloride derived estimates of the Cascades may not completely account for convective heat loss from thermal waters or the dewatering of marine sediments in the Western Cascades; Yet, it is quite clear empirically, the overall number and fluid volumes of identified hydrothermal systems in Tohoku dwarfs what is present in the Cascades. (See Figure 6)

## 6. Discussion

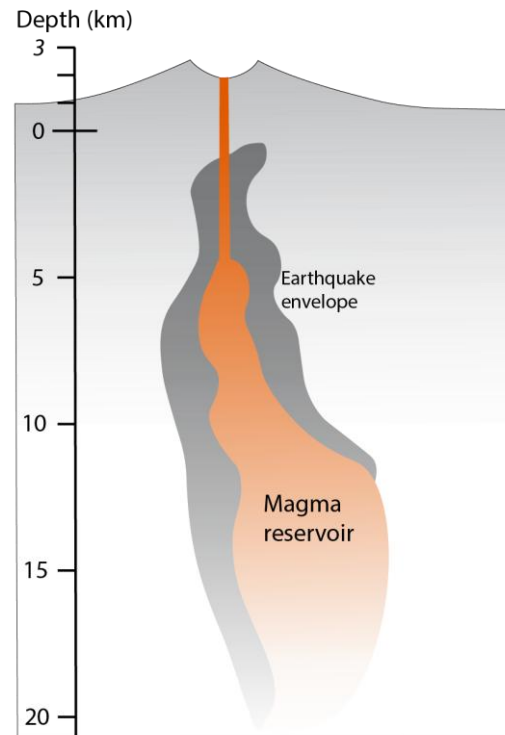
The accreted igneous terrains of Western Washington and Oregon are coherent, relatively aseismic, and well attached to the locally stable North American Plate. Large-scale crustal forces are neutral to weakly extensional with some normal faulting [11]. With little differential strain and sparse seismicity there is limited development of vertical permeability and dilated structures for fluid flow, up or down. Layered and anisotropic stratigraphies result in abrupt transitions between zones of high fluid flow and high permeability to zones of low permeability and stalled fluid flow. Therefore, at depth, circulation is limited except along favorable stratigraphic units or along fractures and faulting. Dominant rock types, (brecciated basalts/volcanoclastic rocks) are far from equilibrium at the surface and a humid climate rapidly alters and erodes these features. This assures that permeability is further restricted by sedimentation or clay alteration-matrix.

The Cascade Range is an irregularly developed volcanic arc. Subduction of a young slab and a lack of high level, evolved magmas do not create persistent heat sources near the surface. Consistently high geothermal gradients are observed below zones of shallow ground water circulation and a regional staging of mid-crustal magmas is apparent at depth. Yet its presence has a mostly conductive influence and only isolated effects on hydrothermal systems. Heat flow, even by areas that are not recently active, are elevated and appear to have persisted for several million years [4], [5]. The source is likely a cluster of plutons confined to near the Cascade arc axis and to the west. Consequently, so are most of the geothermal features. There are about twenty known significant hydrothermal features throughout the nearly 1300 km chain (see Figure 1). This is a remarkably low number for an active volcanic arc. If hydrothermal activity in Japan and other volcanic arcs are useful to compare, as they are also typical subduction zones, the Cascade Range is anomalously low.

The potential for developing geothermal circulation at stratovolcanoes is modest. Despite being the most obvious locations of magmatic influx, much of this still hot material is at depths of 10 km or more (see Figure 7). The surface edifices are composed of mostly pyroclastic materials and are rarely long lived or have near surface structures to circulate fluid around intrusions. Hydrothermal systems that do form are usually confined to narrow conduits in the volcanic edifice.

## 7. Conclusion

There is a challenge to identify geothermal systems without an extensive study of deep drilling data and the majority of the promising volcanic zones in the proximity of the Cascade Range have land-use limitations. Only two bodies, at this time, have the potential for significant commercial geothermal



**Figure 7:** Postulated magma reservoir cross-section with envelope of earthquake hypocenters beneath Mt St Helens after the eruption in May 1980. Modified from Schmincke, Fig 10.28, pp 175



development: Newberry Volcano and Medicine Lake. These volcanoes are large enough with adequate resources and only have partially protected land-use restrictions. Newberry Volcano, for example, is a Phase 1 site for the Department of Energy's Frontier Observatory for Research in Geothermal Energy (FORGE) aimed to develop technologies for Enhanced Geothermal Systems (EGS). It was selected for its success with deep wells encountering high temperatures and a promising hydrothermal system. As of this writing, research and development still continues at Newberry Volcano. Other targets (Breitenbush hot springs (<120°C) in Oregon and the Wind river systems (<100°C) in Southern Washington) are more accessible and have had some interest for economic development, recreation included. It is unlikely, however, that they will become viable targets for more than a small local power source or similar scale direct-use application.

The low abundance of geothermal systems in the Cascades deserves a closer investigation. The study of known resources may better illuminate why they are unique throughout the region, although accessibility remains an issue. A combination of poor permeability, low seismicity, and a lack of structural vertical permeability prevents fluid circulation. Heat is present at depth and it is a matter of technology and investment that may allow for utilization of these resources for either commercial power generation or other uses.

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