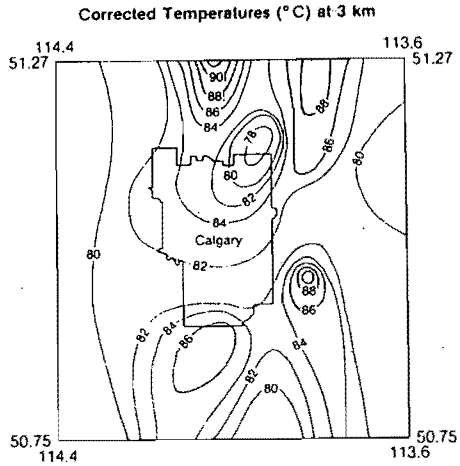


Fig. 4(a) Temperatures at 3km depth in the Calgary area.

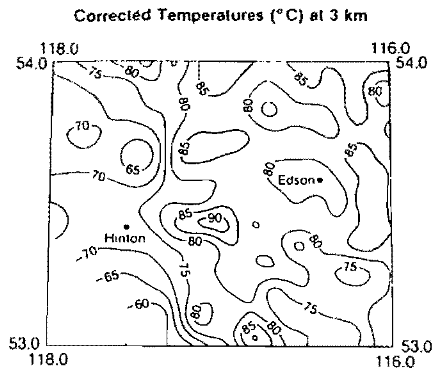


Fig. 4(b) Temperatures at 3km depth in the Hinton-Edson area.

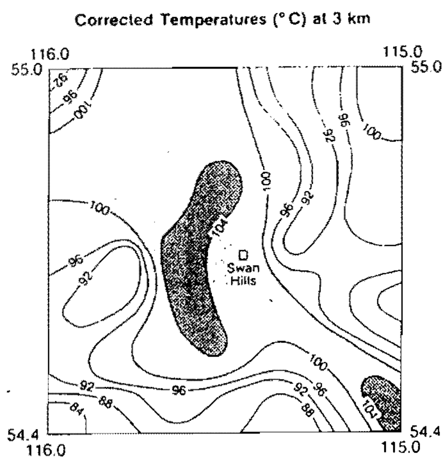


Fig. 4(c) Temperatures at 3km depth in the Swan Hills area.

INTEGRATION OF EARTH-SCIENCE DATA SETS TO ESTIMATE UNDISCOVERED GEOTHERMAL RESOURCES IN THE CASCADE RANGE, USA

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The Cascade Range is a Tertiary and Quaternary volcanic arc that extends north from northeastern California through Oregon and Washington into British Columbia (Canada). The arc lies above an easterly dipping active subduction zone along which the Juan de Fuca, North Gorda, South Gorda, and Explorer microplates are thrust beneath the North American plate (Riddihough, 1984). The volcanic arc is active, with historic eruptions at Lassen Peak (1914-17) and Mount St. Helens (mid 1800's; 1980-86), and possibly at Mt. Shasta (1786), Mt. Hood (mid 1800's), Mt. Baker (mid 1800's), and Cinder Cone (east of Lassen Peak; 1851?). In addition to the major composite volcanoes that have erupted andesite, dacite, and even rhyolite, there are a myriad of smaller, discrete volcanoes that erupted only once, or at most a few times, producing primarily calc-akaline basalt and mafic andesite (Guffanti and Weaver, 1988; Luedke and Smith, 1981, 1982; McBirney, 1978).

Geothermal potential in the Cascade Range is indicated not only by the young volcanism, but also by a regional, positive, conductive heat-flow anomaly (Blackwell et al., 1982; Blackwell and Steele, 1983, 1985). For example, the regional conductive heat flow of 100 $mW/m^2$ of the Cascade Range in Oregon is more than twice that of the Willamette Valley, immediately adjacent to the west (Black et al., 1983). In young, porous rocks of the High Cascades, however, conductive heat flow in holes up to several hundred m deep is generally near zero, owing to hydrologic disturbances (Blackwell et al., 1982; Mase et al., 1982).

The elevated regional heat flow is also expressed by sporadic thermal springs along the Cascade Range. Sorey (1985) has classified these thermal springs into three groups: (1) summit-crater systems, (2) caldera systems, and (3) lateral-flow systems.

The geothermal resource base identified to date in hydrothermal convection systems of the Cascade Range is modest. Fourteen hydrothermal systems in the Cascades were estimated by Brook et al. (1979) to contain 84 x $10^{18}$ J, with most of this energy in two major systems (Lassen at 42 x $10^{18}$ J and Newberry at 27 x $10^{18}$ J). Since 1979, exploratory drilling at Medicine Lake volcano in northeastern California apparently has identified a substantial resource, but the data are still held proprietary by the private companies exploring the area. In addition, exploratory drilling at Breitenbush in Oregon has confirmed temperatures of >141°C at 2500 m, and drilling east of Crater Lake, Oregon, reached temperatures of 107°C at 405 m (Priest et al., 1986; Blackwell and Steele, 1987).

The identified geothermal resource (identified thermal energy that can be extracted legally and used at some future time under reasonable economics) is further restricted by laws and government regulations that prohibit geothermal development in National Parks or in Wilderness Areas (where some of the most attractive targets exist); Lassen Volcanic National Park is the most conspicuous example. Furthermore, geothermal development adjacent to a National Park is likely to encounter vigorous opposition if there is any likelihood of a significant effect on thermal or other features in the Park.

The geothermal dichotomy in the Cascade Range is thus the existence of Quaternary volcanism and high regional heat flow opposed to the sparsity of hot springs and identified hydrothermal reservoirs of geothermal energy (Muffler, 1987). The young volcanism and high regional heat flow suggest the presence of substantial geothermal energy, yet the geothermal resource defined to date is modest. The fundamental geothermal question is what geothermal resources yet remain to be discovered in the Cascade Range. Many workers have suggested that substantial quantities of geothermal energy are masked by cool, near-surface groundwater. This interpretation was supported by the discovery of temperatures of 265°C beneath Newberry volcano (Sammel, 1981), effectively masked by a zone nearly 700 m thick at less than 100°C.

The range of estimates of undiscovered geothermal resources in the Cascade Range is great. Brook et al. (1979), based on the favorable volcano-tectonic setting, multiplied the identified reservoir energy of the Cascade Range (excluding Newberry and Medicine Lake, but including National Parks and Wilderness Areas) by a subjective factor of 20 to give an estimate of 1140 x $10^{18}$ J for the undiscovered accessible resource base to a depth of 3 km. Newberry volcano was considered with the Oregon Plateaus geologic province, and Klamath Falls (30 x $10^{18}$ J) with the northwestern Basin and Range province; in both these provinces, the undiscovered accessible resource base was estimated to be 5 times the identified. All these estimates, however, should be considered as no better than educated guesses because the assmued multipliers cannot be defended rigorously.

A much higher estimate of undiscovered geothermal resources in the Cascade Range was given by Bloomquist et al. (1985) for the part of 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 to 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 above 150°C to a depth of 3 km of 11,750 to 17,620 x $10^{18}$ J.

The estimate of Bloomquist et al. (1985) is critically dependent upon the interpretation of the regional heat-flow data of Blackwell et al. (1982). These heat-flow data are converted by Blackwell et al. (1982) to a set of isotherms in the crust using the method of continuation of thermal data (Brott et al., 1981). Any one of the isotherms shown on Figure 8 of Blackwell et al. (1982) can explain the heat-flow data. Their choice 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 that causes the change in heat flow" (Blackwell et al., 1982, p. 8749). They noted 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 prefered "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 $\pm$ 2 km) beneath the High Cascade Range and extending about 10 km west of the High Cascade Range boundary" (see Blackwell and Steele, 1985, Figure 3).

The thermal and gravity cross sections of Blackwell et al. (1982) are in central Oregon between 43°45' and 45°05', and the results were projected to the north and to the south based upon the uniformity of the heat-flow and gravity transition zones from north to south. Bloomquist et al. (1985) thus applied the conclusions of Blackwell et al. (1982) for central Oregon to the entire Cascade Range in Oregon and Washington, albeit with a less intense heat source in the northern part. The temperature and size of the thermal source preferred by Blackwell et al. (1982) were thus the critical input parameters to the thermal energy calculations of Bloomquist et al. (1985).

Bloomquist et al. (1985) also calculated thermal energies for individual geothermal systems in the Cascade Range. The total of these estimates (2415 x $10^{18}$ J) is heavily weighted by two areas: Mt. McLoughlin and Crater Lake (638 x $10^{18}$ and 1640 x $10^{18}$ J respectively). Reservoir thicknesses and temperatures for these regions were based on the modeled crustal temperatures of Blackwell et al. (1982), whereas the areas were taken from associated Curie Point isotherm anomalies (Connard et al., 1983).

The thermal energies calculated by Bloomquist et al. (1985) for the shallow crust (<3 km) represent an innovative attempt to use regional geophysical data to determine the thermal structure of a major geological province. Although the thermal structure, if valid, implies a very large amount of thermal energy in the upper crust, it does 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 25%, used for hydrothermal convection systems by Brook et al. (1979), is far too high, perhaps by several orders of magnitude, for use throughout a geological province. Accordingly, the figure of 184,948 to 277,420 $MW_e$ for 30 years given by Bloomquist et al. (1985, p. 75) is probably two orders of magnitude too high, even if the thermal structure inferred from the geophysical models is correct.

Resolution of the wide ranging resource estimates as well as the fundamental geothermal dichotomy of the Cascade Range can be addressed in two ways: (1) drilling, and (b) integrated interpretation of regional earth-science data sets. Drilling, the ultimate test for any earth-science model, is essential in the Cascade Range. In the ideal world, speculation about the thermal or geologic structure at drillable depths would quickly be tested by drilling. In the Cascade Range, however, economic, institutional, and other pressures have precluded such a direct approach. Commercial geothermal drilling has been limited, primarily because of the short-term energy glut in the United States and the resultant absence of economic incentive to explore for alternative energy sources. Commercial drilling, however, has been supplemented by support from the Department of Energy (Swanberg and Combs, 1986; Blackwell and Steele, 1987). Efforts to implement a program of dedicated scientific drilling in the Cascade Range (Priest, 1986) have yet to bear fruit.

A complement to drilling, however, is the integrated interpretation of regional earth-science data sets. In this light, a number of emerging data sets may be relevant to estimation of undiscovered geothermal resources of the Cascade Range.

It is becoming clear from tectonic data that the Cascade Range can not be considered as a province uniform thermally and structurally south to north from California to British Columbia (Weaver, 1985; Weaver and Michaelson, 1985). Recent analysis of seismicity and the distribution of volcanic vents in space and time (Guffanti and Weaver, 1988) has emphasized this segmentation of the Cascade Range and suggests that each major segment should be considered separately in the estimation of geothermal resources.

The past few years also have seen a systematic compilation of the geology of the Cascade

Range (Smith, 1987; Sherrod, 1987). A byproduct of this compilation will be a refined estimate of the rate of volcanic production per unit of arc length (e.g., $km^3/Ma/km$). Comparison of volcanic production between the Cascade Range and other volcanic arcs with identified geothermal resources provides a potentially powerful tool in estimating the geothermal potential of the Cascade Range.

Hydrology clearly plays an important role in evaluating the three-dimensional thermal budget of the Cascade Range. In the early 1970's, R.L. Smith and H.R. Shaw (oral communication, 1973) recognized that the many of the thermal springs of the Western Cascades cluster to the west of young silicic volcanic areas on the Cascade crest. They proposed that heat sources under the silicic centers of the High Cascades generate large hydrothermal plumes that move west and emerge at the boundary between the High Cascades and the Western Cascade Range. Based on a heat budget approach, Ingebritsen et al. (1988) show that enough heat is swept out of the High Cascades by this groundwater circulation to account for the anomalous convective and conductive heat discharge in adjacent pre-late Pliocene volcanic rocks. This model implies that the anomalous heat flow measured in the Western Cascade Range is a shallow-rooted phenomenon and casts serious question upon the concept of a partially molten zone tens of km wide extending the length of the Cascade Range.

Finally, other geophysical techniques such as gravity (Finn and Williams, 1982; Williams et al., 1988), magnetic (Blakely et al., 1985), magnetotelluric (Stanley et al, 1987), electrical (Fitterman et al., 1988), and seismic (Achauer et al., 1988; Evans and Zucca, 1988), provide additional data to constrain geothermal models. For example, the correspondence of the Bouguer gravity and thermal profiles is key to the model of Blackwell et al. (1982) in the Oregon Cascades.

These and other regional earth-science data sets will be the subject of a workshop on the geological, geophysical, and tectonic setting of the Cascade Range, to be held in Monterey, California, December 1-4, 1988, under the auspices of the Geothermal Research Program of the U.S. Geological Survey. The workshop has three major themes: (1) variations in tectonism, geophysical signature, and magmatism along the length of the Cascade volcanic arc, (2) relationship of the Cascade Range to the subduction tectonics to the west and the continental tectonics to the east, and (3) controls on the location, composition, and rates of magmatism in the Cascade Range. The workshop will be multidisciplinary, with invited contributions on volcanology, heat flow, gravity, magnetics, electromagnetics, hydrology, geochemistry, and seismology. The ultimate goal of the workshop is the integration of data sets, ideas, and perspectives into a comprehensive understanding of the Cascade Range. This understanding will then serve as the basis for an estimate of the undiscovered geothermal resource of the Cascade Range, and will provide mature, documented models that can be tested in an efficient, cost-effective manner by commercial and scientific drilling.

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