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HEAT FLOW OF OREGON

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STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
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Mt. Bachelor, Oregon Cascade Range. (Oregon State Highway Division photo)

ABSTRACT

An extensive new heat flow and geothermal gradient data set for the State of Oregon is presented on a contour map of heat flow at a scale of 1:1,000,000 and is summarized in several figures and tables. The 1:1,000,000 scale heat flow map is contoured at 20 mW/m^2 (0.5 HFU) intervals. Also presented are maps of heat flow and temperature at a depth of 1 km averaged for 1° x 1° intervals. Histograms and averages of geothermal gradient and heat flow for the State of Oregon and for the various physiographic province within Oregon are also included.

The unweighted mean flow for Oregon is 81.3 ± 2.7 mW/m^2 (1.94 ± 0.06 HFU). The average unweighted geothermal gradient is 65.3 ± 2.5°C/km. The average heat flow value weighted on the basis of geographic area is 68 ± 5 mW/m^2 (1.63 ± 0.12 HFU) and the average weighted geothermal gradient is 55.0 ± 5°C/km.

On the basis of the data the State of Oregon can be divided into 4 heat flow provinces. The first of the heat flow provinces occupies the western third of the state and includes the Coast Range, Willamette Valley, Klamath Mountains and Western Cascade Range provinces. The mean heat flow for these provinces is 41.8 ± 1.3 mW/m^2 (1.00 ± 0.03 HFU) and the average gradient is 26.4 ± 1.0°C/km. Heat flow values within these provinces are relatively uniform, but low, with no evidence of extensive convective heat transfer.

The second group of provinces includes the Deschutes-Umatilla (Columbia) Plateau and Blue Mountains provinces in the northeastern third of the state. The mean heat flow for these two provinces 65.2 ± 2.6 mW/m^2 (1.56 ± 0.06 HFU) and the average gradient is 43.7 ± 2.5°C/km. This heat flow is considered anomalously high as the crust contributes very little to the surface heat flow and mantle heat flow value is 50-55 mW/m^2(1.2-1.3 HFU). There is ubiquitous water motion along flow contacts in the Columbia River Basalt. However, the water motion appears to be relatively slow and has only a minor effect on the measured heat flow values.

The third group of provinces occupies the southeastern third of the state and includes the High Lava Plains, Basin and Range, Owyhee Upland and Western Snake River Basin provinces. The mean heat flow is 98.4 ± 3.8 mW/m^2 (2.34 ± 0.08 HFU) and the mean gradient is 89.1 ± 3.4°C/km. The heat flow and geothermal gradient are extremely high and are related to the extensive volcanism and tectonism characteristic of these provinces within the past 15-20 m.y. Disruption of conductive heat transport both by regional ground water systems and by hydrothermal convection systems is common, resulting in large scatter in the observed heat flow values. Large scale crustal effects on the heat flow are also observed. Because of the high geothermal gradient and high heat flow this area of the state probably has the greatest potential for geothermal development for both high and moderate temperature geothermal systems.

The fourth area of the state includes the High Cascades Range. Reliable heat flow data are not available for the central and eastern parts of this area of extensive young volcanism; however, heat flow values along the northwestern boundary average 105.1 ± 8.5 mW/m^2 (2.51 ± 0.20 HFU) and the geothermal gradient averages 61.3 ± 3.4°C/km. More data are needed for the High Cascade Range in order to properly evaluate its heat flow and geothermal potential. However, based on the heat flow data along the northwestern boundary, the young volcanism, and the existence of many hot springs along the western boundary, the geothermal potential of this province is undoubtedly large.

Thus, the overall heat flow pattern in the state consists of subnormal heat flow values in the western one-third of the state separated from slightly high to very high heat flow values in the eastern two-thirds of the state by the High Cascade Range. The pattern is related to the effect of Cenozoic plate tectonic activity in the Pacific Northwest and to subduction of the Juan de Fuca plate beneath the Pacific Northwest during the past few tens of millions of years.

HEAT FLOW OF OREGON

INTRODUCTION

The purpose of this report is to describe the results of an eight-year project to investigate the geothermal features of Oregon, by publication of a 1:1,000,000 scale heat flow map and accompanying text. As a result of this study, the geothermal features of Oregon are probably better known than those of any equivalent-size area in a setting as geologically and tectonically complex as Oregon. This report completes the first phase of the study, because geothermal characteristics are now well-established for most of the physiographic provinces of Oregon. Study of the heat flow of Oregon is continuing, and future reports will deal with most of the provinces in a more detailed way than is attempted here, and further tighten the focus of studies to individual geologic features as well. The discussion of the heat flow data will be on a general and on a detailed level, but the map is intended to stand by itself as a description of the heat flow and geothermal character of Oregon as known at this stage of study.

When the first heat flow study specifically related to the Pacific Northwest of the United States was published (Blackwell, 1969), no heat flow values were available for the State of Oregon. In order to remedy this lack of data for purposes of a scientific understanding of the heat flow in Oregon, and for understanding of the heat flow pattern in order to evaluate the geothermal potential of Oregon, a systematic state-wide program of geothermal studies was initiated by the Oregon Department of Geology and Mineral Industries and by Southern Methodist University in 1971. Previous reports of this work include Bowen (1972); Bowen and Blackwell (1973, 1975); Bowen and others (1976, 1977); and Hull and others (1977b). This report is the most comprehensive and synthesizes the results from the reports previously published. Also available are a number of open-file data reports (Hull, 1975a, 1975b, 1976; Hull and others, 1976, 1977a, 1977c).

Temperatures measured in holes that penetrate the earth below the depth affected significantly by annual variations (about 20 meters), in general increase steadily with depth. This increase in temperature with depth indicates that the earth is losing heat; i.e., heat is flowing from the interior of the earth into space. The heat that is lost from the earth is primarily from the initial accretion and differentiation stages of the planet, augmented by the heat generated by long-lived radioactive elements, such as uranium, potassium and thorium.

Study of the heat lost by the earth has several important applications. The overall heat loss is a boundary condition for the interpretation of the state of the interior of the earth. The temperature, derivable from the heat flow, governs or bears directly on the relative rigidity, chemical phase, density, seismic velocity, electrical resistivity and, indeed, all the internal properties of the earth. Geographic variations of heat flow are directly related to, and in many cases cause, the tectonic activity which results in mountain belts, volcanoes, earthquakes and other features and phenomena of the earth's surface and shallow interior. Plate tectonics, the recently recognized unifying theory of the geological sciences, which interprets earthquakes, volcanoes, mid-ocean ridges, etc., as boundary interactions of large, relatively rigid, thin plates, or shells (60-150 km thick) of the earth's surface, is essentially a type of thermal convection. The material of the plates forms and rises from the interior of the earth at the mid-ocean ridges, moves laterally, and sinks into the interior of the earth at the trenches due to thermally related density contrasts. Finally, heat flow studies are the most useful geophysical technique for locating and evaluating geothermal resources.

Inside the earth the transfer of heat is by the mechanism of conduction, which is transfer of heat through a solid by lattice vibrations; or by convection, which is transfer of heat by mass movement (magma, for example). Near the surface of the earth (in the upper 5-10 km), heat transfer may be by thermal conduction, or thermal convection (via water motions), or by a combination of the two mechanisms. Conduction is predominant where rocks are relatively impermeable and the heat flow values are low to average (western Oregon). Where rocks are relatively permeable, and/or where heat flow values are above average, ground water convection may be an important and even dominant mechanism of heat transfer (southeastern Oregon). The water motions may be driven completely by thermal effects (differential heating); or by forced convection, where lateral water motions are caused by elevation differences in aquifers. The relative impacts of conduction and convection on the data shown on the heat flow map of Oregon (Plate 1) are discussed in subsequent sections. An existing study of some aspects of convective heat transfer in Oregon is represented by the map of thermal springs (Bowen and Peterson, 1970; Bowen and others, 1978).

A heat flow study measures the heat which originates within the earth and flows out to the surface of the earth. The units used are the quantities of energy (watts) per unit area (square meters). The world-wide average heat flow is about 60 mW/m^2 (60×10^{-3} watts per square meter, 1.5 HFU *). Typical low values of heat flow are 20-40 mW/m^2 (0.5-1.0 HFU), and typical high values of heat flow are 80-120 mW/m^2 (2-3 HFU). Values greater than 120 mW/m^2 (3 HFU) are not usually found except in geothermal areas.

The average value of heat flow is very small. For example, the energy from $1.7 \times 10^3 m^2$ (about 10,000 ft^2) would be required to light a 100-watt light bulb, assuming that the thermal energy could be converted directly to electrical energy (in fact, in commercial geothermal systems the maximum conversion efficiency of extracted heat to electrical energy is 10-15%). However, the total flow of heat over the surface of the earth is 1.1×10^{13} watts, a very large amount. The heat stored within the earth is virtually limitless, but mostly inaccessible. Geothermal energy can only be utilized where high temperatures near the surface (currently 3 km or less in depth) can be tapped in some fashion. These areas are anomalous because above-normal temperatures at a given depth are required according to present economics. Thus location and characterization of such geothermal anomalies, which may be due to any one of many causes, such as hot water flow along a fault zone, a magma chamber, etc., are the goals of geothermal exploration. Of all the different geophysical techniques applied to geothermal exploration, heat flow study is at present the most direct way in most cases to locate subsurface thermal anomalies, since heat flow directly measures the primary quantity desired — heat. The other required factor is a sufficient fluid flow for surface utilization. The utilization of geothermal resources for heating or generation of electric power is of increasing importance as the search for new energy sources expands. Oregon residents have been pioneers in the field, using hot water for space heating in Klamath Falls since prior to 1900. In view of the paucity of conventional energy sources in Oregon, and the large role played in the geologic history of Oregon by volcanism, geothermal energy utilization has an important potential impact on Oregon's future.

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* In previous publications, heat flow units (HFU), thermal conductivity units (TCU) and heat generation units (HGU) have been used. The currently recommended system of scientific units is the SI (Système Internationale) units. Conversions are:

1 HFU = 10^{-6} cal/cm^2-sec = 41.84×10^{-3} W/m^2 = 41.84 mW/m^2
1 TCU = 10^{-3} cal/cm-sec-°C = 0.4184 W/m K
1 HGU = 1×10^{-13} cal/cm^3-sec = $0.4184 \times 10^{-12} W/m^3$ = 0.4184 $\mu W/m^3$
1 mW/m^2 = 0.0239 HFU; 1 W/mK = 2.39 TCU; 1 $\mu W/m^2$ = 2.39 HGU

GEOLOGY OF THE PHYSIOGRAPHIC PROVINCES

Oregon is made up of several distinct geologic-physiographic provinces (Figure 1). These provinces will be briefly discussed in a general west-to-east order in this section. More detailed summaries may be found in Baldwin (1976). The various provinces are important geothermally, as the heat flow correlates well with the various geologic histories experienced by individual provinces or groups of provinces.

Coast Range

The Coast Range, extending from the Columbia River south to the Klamath Mountains, consists of basaltic lava that interfingers in a complex way with marine siltstone and sandstone. The oldest rocks known in the region are pillow lava and volcanic breccia of lower to middle Eocene age. During this time the region was apparently a series of volcanic islands with basins of sedimentation filled by volcanic debris from the highlands, and lesser amounts of fine-grained sediments eroded from the continental mass to the east. Volcanism of lessening intensity continued into the Miocene period, culminating with the intrusion of a sequence of gabbro sills in late Miocene time. There is no evidence of renewed volcanism or magmatism since late Miocene time.

Klamath Mountains

The Klamath Mountains lie in the southwest corner of Oregon between the Cascade Range on the east and the Coast Range on the north; they extend southward into northwestern California. The topography is rugged, with steep slopes and narrow deep canyons. Most of the rocks are pre-Cenozoic in age, but there are a few isolated remnants of Cenozoic sedimentary rocks, and a few bodies of Cenozoic intrusive rock (mostly dikes and sills of Oligocene and Miocene age) are present in the province. The oldest rocks are Paleozoic schists along the Oregon-California border west of Medford. Mesozoic metamorphic, igneous and sedimentary rocks make up the predominant rock units exposed in the region.

Willamette Valley

The Willamette Valley is a large structural trough that contains a thick sequence of early to middle Cenozoic marine mudstone and impure sandstone. Volcanism was local in this province. During the Miocene period basalt lava of the Columbia River Group, apparently originating east of the Cascades, flowed into the region near Portland and into the Salem area (Hodge, 1936). During Oligocene and Miocene time, several small intrusive masses were emplaced at the southern end of the Willamette Valley. At the northern end of the Willamette Valley an episode of volcanic activity occurred in the Portland region extending from middle Pliocene to Pleistocene. During this time possibly as many as one hundred basaltic volcanic centers were active in the Portland area. These volcanics are referred to as the Boring lavas.

Western Cascade Range

The Western Cascade Range is the wide, deeply dissected belt of volcanic rocks that lies between the High Cascade peaks on the east, the Willamette Valley on the west, and the Klamath Mountains on the south. The Western Cascade Range is made up largely of a series of mafic and andesitic volcanic centers with numerous tuffaceous interbeds, but in this case the deposits were largely subaerial rather than the submarine eruptions typical of the Coast Range. Contemporaneous with and following the volcanism, the region was subjected to numerous intrusions and extensive hydrothermal alteration within and at the

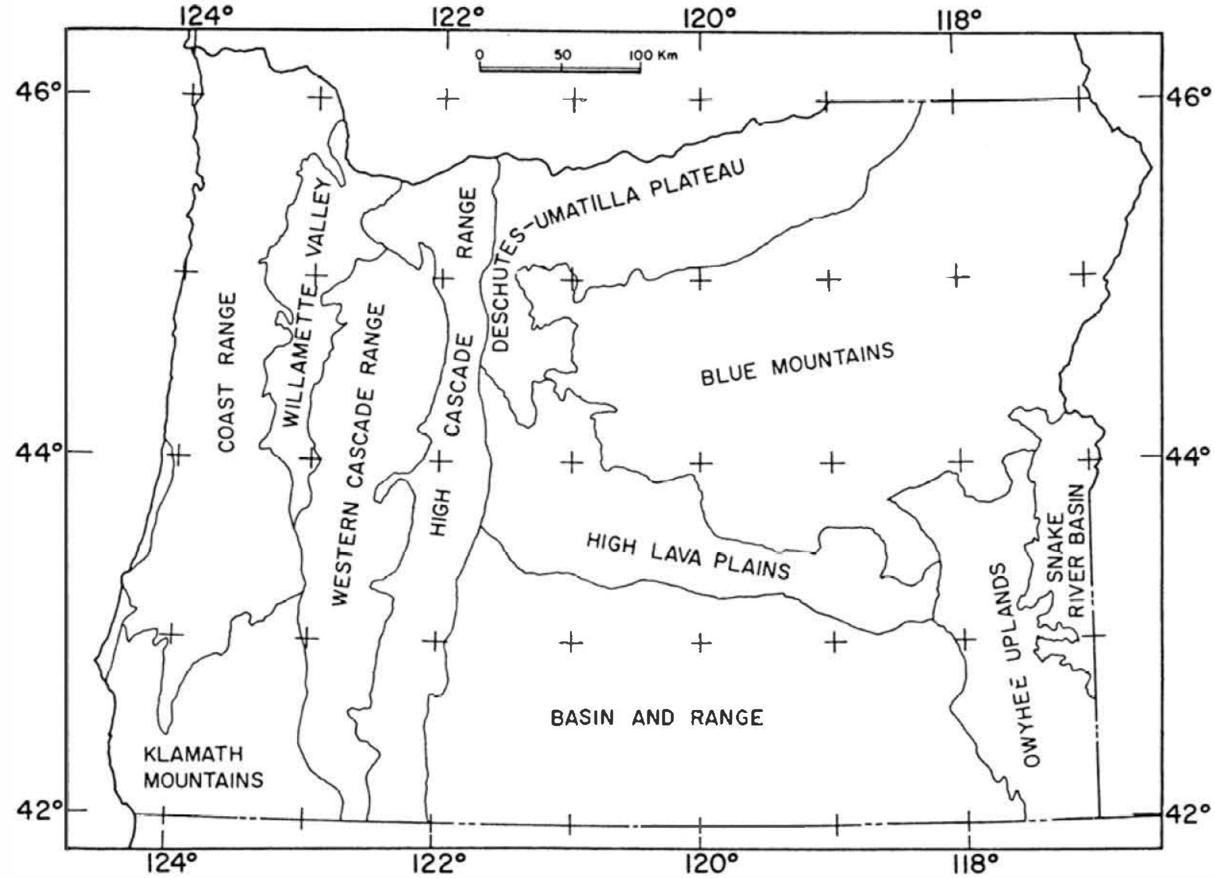

FIGURE 1: Physiographic provinces of Oregon after Baldwin (1976).

contacts of the intrusive rocks (Peck and others, 1964). At the northern end of the province, the Western Cascade Range terminates near Portland against the belt of the Pliocene-Pleistocene volcanic rocks extending westward from the High Cascade range.

High Cascade Range

The High Cascade Range province extends the width of the state and is dominated by large stratovolcanoes. Some authors consider the Newberry Volcano region of central Oregon to be part of the High Cascade Range, but in this report the Newberry Volcano is included in the High Lava Plains province. The stratovolcanoes are dominantly andesitic in composition, but interspersed among them are numerous smaller cinder cones, shield volcanoes, and eruptive centers of wide-ranging composition. Overall, however, basalt is the volumetrically dominant volcanic rock type within the province. Rocks more silicic than andesite, such as dacites and rhyolites, are generally rare except in the central portion of the High Cascade Range near the Three Sisters (Williams, 1957). The ages of the volcanic rocks range from Pliocene to Recent.

Over the years geologists have discussed the possibilities of fault control of the High Cascade Range for both the eruptive centers and for the definition of a large north-south trending graben controlling the overall lateral extent of the range (Allen, 1966). This concept is appealing because of the recognition of major faults along the eastern side and linear trends along the western side of the High Cascade Range. One of the strongest of these trends that may indicate faulting is the north-south alignment of hot springs extending over 200 km along the western boundary of the High Cascade Range. Possible further evidence of a bounding western structure is discussed in subsequent sections. Direct field evidence does not fully support the graben concept, as no fault of large magnitude has yet been mapped to define the western border of the proposed graben.

Recent studies of the magnetic polarity of the lavas from the High Cascade volcanoes indicate nearly all these lavas have normal polarity and are therefore younger than 690,000 yrs. B.P. Many of the volcanic features are obviously much younger than that, as they show little or no effects of weathering and glaciation. The most recent major eruptions in Oregon appear to have occurred on Mount Hood, where Crandell and Rubin (1977) report three major eruptive periods of 12,000, 1,600, and 220 (^{14}C) yrs. B.P. Newspaper accounts report that Mount Hood was in minor eruption in the period 1848 to 1865. Dating of volcanic activity in other parts of the High Cascade Range shows a great deal of activity in the range of 4,000 to 6,000 (^{14}C) yrs. B.P., with some of the flows as young as a few hundred years.

Deschutes-Umatilla Plateau

The Deschutes-Umatilla Plateau is a broad highland east of the High Cascade Range and bordering on the Columbia River. It is part of the broader Columbia Plateau province that is in Oregon. The regional slope is northward toward the center of the Columbia Basin. Rivers and streams have entrenched steep-walled canyons into the plateau in numerous places.

Basalt of the Columbia River Group (Miocene in age) is the dominant rock and thick flow-on-flow sequences can be seen in many of the canyons. Underlying those basalts are early to middle Cenozoic sedimentary, volcanoclastic and volcanic rocks of the John Day and Clarno Formations. Geothermal manifestations are sparse in this region, the only prominent one being the Kah-nee-Ta Hot Springs near the westernmost edge of the province. A few warm water wells are reported along the northern edge of this province. There is no evidence of volcanism younger that Pleistocene in this region, and no indication of voluminous volcanism after the extrusion of the Columbia River Basalt.

Blue Mountains

The Blue Mountains province is an area of high relief extending northeastward from the Deschutes-Umatilla Plateau into the northeast corner of the state. The province is composed of numerous individual mountain ranges with bedrock of pre-Cenozoic to early Cenozoic age. Rock types are diverse and structure is complex in this province. With the exception of a few cinder cones of probable Pliocene age, there are no known volcanic rocks younger than Miocene. However, there are several hot springs in the region with surface temperatures ranging as high as 82°C.

High Lava Plains

The High Lava Plains province extends in a west-east band about 50 km wide from the High Cascade Range to the Owyhee Uplands. The northern edge is the highlands of the Blue mountains, while to the south the province merges into the Basin and Range province. The bedrock of the province is a relatively undeformed sequence of silicic domes, young lava flows, ash flows, and cinder cones (Walker, 1969). The main structural feature is the west-northwest trending Brothers Fault Zone, a series of *en-echelon* normal faults that extend across the province. Several eruptive centers of both basaltic and rhyolitic volcanic rocks are concentrated along this zone of faulting and on nearby subsidiary fault zones. At the western edge of the High Lava Plains near where the Brothers Fault Zone merges into the High Cascade Range, a concentration of Holocene basaltic and rhyolitic eruptive centers has been shown by hydration dating (Friedman, 1977) to have been emplaced 1,400 yrs. B.P. MacLeod and others (1976) report a westward age migration of rhyolitic domes along the Brothers Fault Zone from approximately 10 m.y. on the east to less than 1 m.y. at the west end. At the eastern edge of the High Lava Plains is the Harney Basin, a large, semicircular depression suggested by Walker (1970) to be the source of many of the extensive ash flow tuffs in the region.

Basin and Range

The Basin and Range province is characterized by north-to-northwest trending mountain ranges and valleys, often fault-controlled. Basaltic lava flows are the dominant rock type, and in many areas, several thousand feet of basalt with interspersed tuffs and sedimentary lenses are exposed. Rhyolite is common in some regions, but overall makes up only a small portion of the rocks. Much more abundant are silicic ash flow tuffs, which in some cases cover several hundred square km and form the rim rock in the region. The high angle normal faults of large displacement typical of the Basin and Range province show decreasing displacement toward the borders of the province, where they merge into the relatively level region of the High Lava Plains and the High Cascade Range. The structural patterns of the Basin and Range province continue to the south and southwest into California and Nevada. With very few exceptions the rocks within this province in Oregon are all of Cenozoic age, but further south and southeast much older rocks are exposed by the faulting. Throughout the entire Basin and Range province there are scattered Pleistocene to Holocene volcanic rocks. There are hundreds of thermal springs in the Basin and Range province of the western United States, with probably a hundred within Oregon. The majority of these thermal springs are closely associated with the basin-bounding faults. Investigations of the geothermal resources have been made in some of the basins, such as the work by Sammel (1976) and Lienau (1978) in the Klamath Basin.

Owyhee Upland

The Owyhee Upland has rocks similar to the Basin and Range province, but lacks the prominent fault system. It is an isolated highland that extends eastward into Idaho and southward into northern Nevada. On its west side, it is bordered by the Blue Mountains, the High Lava Plains and the Basin and Range Provinces. To the north and east, the boundary is the Western Snake River Basin. The Owyhee Upland is essentially a volcanic upland developed from widespread centers of basaltic, andesitic and rhyolitic flows with associated pyroclastic and sedimentary rocks of middle to late Cenozoic age. There are numerous and widespread flows of Quaternary basalt and one basalt field of Holocene age (the Jordan Craters). Several thermal springs are found throughout the region, most occurring along the canyons of the Owyhee and Malheur Rivers.

Western Snake River Basin

The Snake River Basin extends a few miles into the eastern edge of Oregon, north of the Owyhee Uplands and south of the Blue Mountains. It is part of a large structural depression, the Snake River Plain, that extends from eastern Oregon across Idaho to Yellowstone National Park in Wyoming. The Western Snake River Basin is filled largely with fine-grained Cenozoic lacustrine and fluvial sediments and interbedded sequences of lava flows. The structure has been interpreted by some as a large complex graben bounded by normal faults. Within the province, fine-grained non-marine sediments up to 2 km thick overlie a widespread basalt formation which is mapped to the north as the Columbia River Basalt and to the south and west as Owyhee Basalt (Newton and Corcoran, 1963). There are numerous thermal springs associated with the Western Snake River Basin, most of them near the margins of the province.

TECHNIQUES OF HEAT FLOW MEASUREMENT

Temperature Gradients

To obtain a heat flow measurement, the geothermal gradient and thermal conductivity must be measured. Heat flow (Q) is then calculated as the product of the rate of change of temperature with depth (the geothermal gradient, dT/dx), and thermal conductivity (K):

$$Q = K \frac{dT}{dx}$$

The units of these parameters are discussed on page 2. The geothermal gradient is obtained by measuring temperature as a function of depth in a drill hole and then calculating the change in temperature for some given interval. On a plot of temperature versus depth, the slope of the straight line through the points is the geothermal gradient. Well locations are given in this report using the U.S. Geological Survey Water Resources Division convention; i.e., 14S/38E-21bba represents the NE 1/4, NW 1/4, NW 1/4 of Section 21, T14S, R38E.

The depth at which the annual surface temperature cycle ceases to affect the geothermal gradient depends primarily on the thermal conductivity of the rocks (Lachenbruch, 1959; Lovering and Goode, 1963). For rocks with thermal properties typical of those found in Oregon, the depth of penetration of significant effects of the annual surface temperature cycle is 10-20 meters. Thus, to obtain an unambiguous geothermal gradient with a single period of measurement, wells deeper than 10-20 m are needed. In this study we have not attempted to utilize holes shallower than 30 m, although results of the use of shallow holes (1-20m deep) in geothermal exploration are discussed in a previous report (Bowen and others, 1977).

Some examples of temperature-depth curves are shown in Figures 2 and 3. Ideally, the heat flow measurement will be based on temperature-depth data similar to that shown for hole 8S/ 5E-31cc. In this case, the temperature-depth curve is linear, except for a slight decrease in gradient above 80 m. Assuming conductive heat transfer, this gradient should continue through the crust, with changes due only to variations of thermal conductivity and the effects of radioactive heat sources in the crust. A typical gradient pattern which might be expected in a very deep hole is shown for hole 11S/15E-22cd. This hole shows a constant gradient over discrete intervals, with a tendency for geothermal gradient to decrease with depth. These discrete intervals of uniform gradient correspond to lithologic units; in this case, two units in the Clarno Formation (23-270 m and 270-664 m), and pre-Cenozoic sedimentary rocks (664-820 m). In general, more deeply buried rocks will have a higher thermal conductivity because of a loss in porosity, or because the basement rocks may be crystalline (no glass), or in some cases because of higher quartz content than the near-surface rocks. In particular, if gradients are measured in relatively poorly consolidated basin fill, gradients may decrease by a factor of 2-3 as the drill hole passes through the less consolidated clay and tuffaceous sands into low porosity volcanic and/or basement rocks at depth.

Temperature-depth curves commonly show curvature; i.e., increasing or decreasing gradient with depth. If the heat transfer is conductive, these smooth variations in gradient are most often due to topographic and microclimatological effects, and the gradients can be corrected for the observed effects (Blackwell and others, 1979).

In a large portion of Oregon, however, heat transfer may be conductive in one place and convective or some combination of conductive and convective in an adjacent location. In general, the subhorizontal lava flows characteristic of much of the state make very good aquifers, and water flow along and between these aquifers is common. If the water flow is relatively slow and the aquifers are confined, the effects on the gradient may not

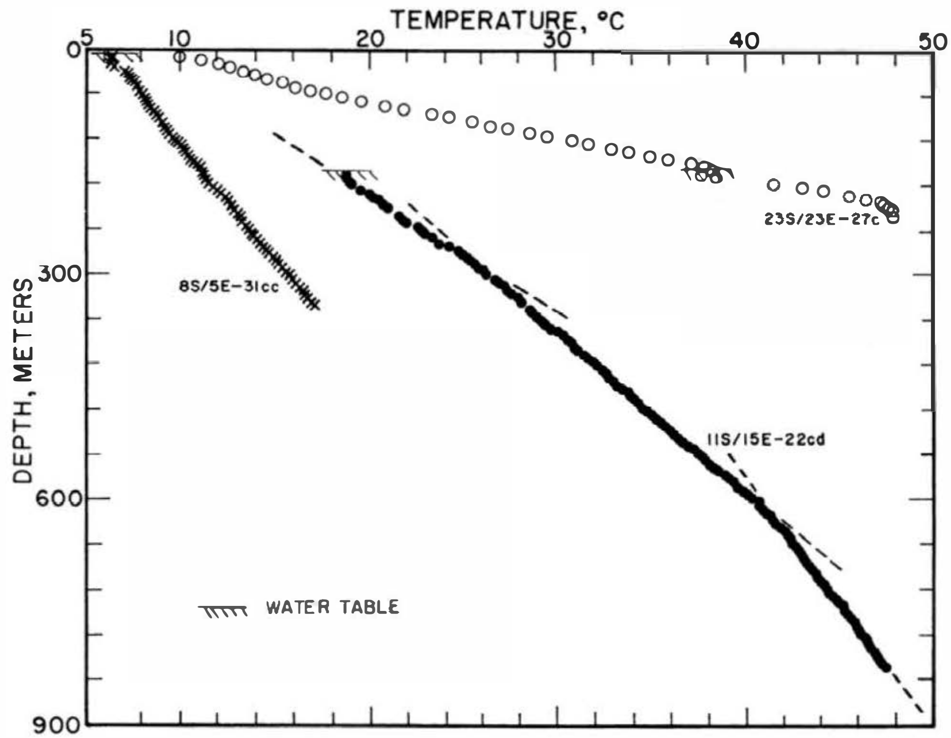

Figure 2: Temperature-depth curves for holes 8S/5E-31cc, 11S/15E-22cd, and 23S/23E-27c.

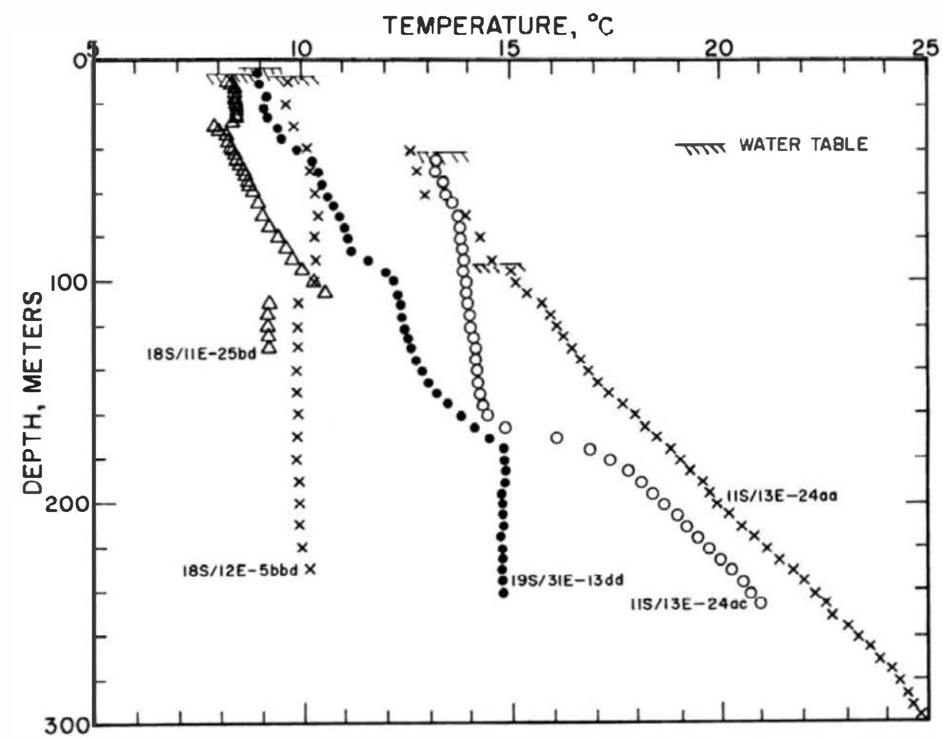

Figure 3: Temperature-depth curves for holes 11S/13E-24aa, 11S/13E-24ac, 18S/11E-25bd, 18S/12E-5bbd, and 19S/31E-13dd.

be appreciable until a hole is drilled which allows water to move from one aquifer to the next within the borehole. An example of this kind of anomaly is shown in hole 11S/13E-24ac. This hole is less than a kilometer from hole 11S/13E-24aa, and has essentially the same geothermal gradient except in the depth interval 70-180 m. From the characteristic shape of the temperature-depth curve, we infer that in hole 24ac, water enters at approximately 70 m (near the water table), and flows downward and out a fracture zone at approximately 160 m. The effect of the water at the appropriate rock temperature for 70 m lowers the temperature in the well to and below its exit point, to a total depth of approximately 180 m. Below 180 m a gradient similar to that observed in 11S/13E-24aa is found. If possible, holes that are drilled for heat flow studies are grouted, i.e., filled with cement or a similar material around a sealed tubing, so that water flow cannot occur within the hole to cause disturbances in the gradient.

The opposite case of the downflow situation is the upflow case which would give an exactly reverse type of curve. If the upflow reaches the surface, then the hole is artesian.

In layered rocks, where there may be many aquifers separated by zones of lower permeability, the temperature-depth curves may have a stairstep character from the intermingling of the different aquifers having different temperatures (hole 19S/31E-13dd, Figure 3). In many cases, although the general tendency for the temperature to increase with depth is clear, the best geothermal gradient to use for the hole is unclear.

In addition to circulation problems that are confined to a drill hole, however, large-scale aquifer flow may exist in many areas of volcanic rocks. These aquifers may have thicknesses in excess of a kilometer and dimensions of tens to perhaps hundreds of kilometers. A major volcanic aquifer exists in the Eastern Snake River Plain of Idaho (Brott and others, 1976) that is over 50 km wide and 200 km long. The volcanic rock aquifers in Oregon are not as well known, but may be quite large. For example, a very large area in the Deschutes River valley of central Oregon shows highly disturbed temperature-depth curves typical of major aquifer circulation. Two examples of these types of curves are shown in Figure 3 (holes 18S/11E-25bd and 18S/12E- 5bbd). Both holes show a shallow aquifer (above 100 m) with slightly warmer water than a deeper aquifer of colder water, with little change of temperature in the bottom parts of the holes. Obviously, heat flow interpretation in this setting is very difficult. Measured well locations where major aquifer effects appear to cause problems in data collection are shown by a separate symbol on Plate 1.

More subtle aquifer flow, difficult to recognize, may be characteristic of other areas. For example, a hole from Glass Buttes in central Oregon (23S/23E-27c, Figure 2) shows a basically linear, apparently conductive temperature-depth curve to 180 m, at which depth the gradient decreases by a factor of 5, in a major aquifer. Whether or not temperatures will again increase with depth (and at what depth) is unknown, because this well, as is the case with most water wells, was drilled only to the top of the first major aquifer. These results show the difficulties and uncertainties inherent in extrapolating to depth the gradient determined in shallow holes in some geologic settings, especially areas of young volcanic rocks.

Thermal Conductivity

Thermal conductivity is a material property which describes the ability of a rock to conduct heat. Thermal conductivity is primarily related to quartz content and porosity (increasing with increasing quartz content and decreasing porosity). Thermal conductivity measurements are usually made in the laboratory on core or cutting samples representative of the rocks penetrated by the well. The laboratory technique used in this study is the divided bar technique discussed by Birch (1950), Roy and others (1968a) and Sass and others (1971a). Heat flow is then calculated as the product of geothermal gradient times thermal conductivity.

Causes of Variations and Disturbances in Geothermal Gradients

Only in the ideal case is a temperature-depth curve exactly linear. Variations may reflect errors in measurement (usually very small), geological factors which affect the subsurface temperatures, or effects associated in some way with the hole or the drilling process. The causes of the non-uniformity of the geothermal gradient must be understood in order to obtain accurate heat flow values. The geothermal gradient is affected in a major way by geologic structure, because different rock units have different thermal conductivity values. If the rocks are horizontally layered, and the heat flow remains constant with depth, then the geothermal gradient and thermal conductivity in each rock type are inversely related to one another (see Figure 2, hole 11S/15E-22cd). If the rocks are not horizontally layered, or if the thermal conductivity varies in some way, complex heat flow patterns may be observed even if the underlying regional heat flow is constant. Therefore, the lithology penetrated by and adjacent to the well must be known, in addition to the geothermal gradient, for the heat flow to be calculated and interpreted.

Disturbances to the geothermal gradient may also arise from topographical features, microclimatic effects, circulation of water, or temporal changes in mean ground surface temperature. Terrain corrections have been calculated or estimated for all holes for which the effects appear to be greater than 5%. Terrain corrections have been made using a number of techniques, primarily the technique described by Birch (1950), and a technique which includes microclimatic effects (Blackwell and others, 1979). No significant systematic temporal changes in surface temperature are observed to affect the gradients in the holes discussed in this report, so no climatic corrections have been used. Local corrections for lateral variations in thermal conductivity have not been made. Regional effects may exist, as discussed in more detail below. Finally, and not uncommonly, the conductive temperatures may be disturbed by convective heat transfer. These disturbances may exist to depths of a few meters for shallow water table flow, or to depths of 5-10 km in the case of geothermal systems associated with magma chambers. These effects are discussed in more detail throughout the report.

Quality of Heat Flow Data

Field work for the heat flow studies has been carried out since 1971. Approximately 475 locations have yielded geothermal gradient data. Of these, approximately 100 holes were either too shallow or too disturbed for the data to be reliable. Of the remaining 375 points, heat flow values have been obtained for as many as possible by collection of thermal conductivity samples from the measured holes or from adjacent holes, or by estimation of thermal conductivity from measurements on rocks stratigraphically equivalent to those encountered in the drill hole. The resulting heat flow values have been ranked in three categories according to the estimated quality of the value. These categories are called A, B, and C. Heat flow values with an A or B quality rating have estimated errors of less than ± 5% and ± 10% respectively. Terrain corrections have been made, or are negligible. Measurements of thermal conductivity, or estimates of relatively high reliability, are available for each hole. In general, the segment of the temperature-depth curve representing at least the bottom 50 m of a drill hole 100 m or more deep must be linear for an A or B quality rating. Most of the holes used are between 100 m and 250 m deep, with the deepest hole being 820 m deep. In general, no holes have been included as A or B quality which show obvious circulation effects that cannot be considered of local (borehole) nature. Data from holes such as 18S/12E-5bbd have not been included in the analysis, although the locations of such holes are shown on Plate 1.

A number of heat flow values obtained are considered of C quality. These values may have large errors, perhaps as much as ± 50%, for individual measurements; although, taken as an overall set of data, the error is much smaller. These data have not been included on the heat flow map, except in cases where no other data are available near the site or important information is contained in the data in spite of their limitations.

Based on the error analysis of this data set, heat flow values for 286 holes are shown in Plate I. Of the 286 holes, approximately 70 have been drilled specifically for heat flow studies, and for these holes detailed thermal conductivity data and stratigraphic control are available. A total of 20 C category values have been included on Plate 1; the remainder are of A or B quality. The reliability of these data in terms of calculation of temperatures at depth can only be judged in the context of their local and regional setting. These uncertainties should be kept in mind when considering the data shown in Plate 1.

Of the heat flow values shown on the map, 47 have been published by other investigators. These data include 3 values in the Klamath Mountains in southwestern Oregon (Lachenbruch and Sass, 1973); 10 values in the Harney Basin-Catlow Valley area of central Oregon (Sass and others, 1976); and 25 values in the Klamath Falls area of southwestern Oregon (Sass and Sammel, 1976).

In general, data have not been excluded from the map if the temperature-depth curves satisfy the depth and linearity criteria discussed above, even if the values seem to be too low or too high to be "reasonable." To select data in this way would introduce a bias toward preconceived ideas. The approach here has been to obtain regional heat flow values by measuring as many heat flow values as possible and averaging. Thus, low heat flow areas may be characteristic of regional aquifer recharge areas, whereas high heat flow areas may be characteristic of the discharge areas of regional aquifers or of geothermal systems, and all values should be included in the averages to obtain a true regional heat flow and a realistic understanding of the thermal character of the upper few kilometers of the earth's surface in Oregon.

Conventional Heat Flow Interpretation

In many parts of the central and eastern United States and Canada, disturbances of heat flow due to large scale variation in crustal thermal conductivity and radioactivity can be avoided by making measurements in the center of large granitic bodies. Because these rocks are generally quite impermeable to water flow, regional aquifer motions generally do not exist, and disturbances of the conductive heat flow by convective transfer (except in sedimentary rocks overlying the granitic basement or in very localized areas), are generally not present.

For this large area of the continent, heat flow values observed at the surface are composed of two principal components. These components are the heat flow from the radioactive decay of uranium, thorium and potassium found in the uppermost 5-20 km of the earth; and a component of heat (the "reduced" heat flow, Roy and others, 1972) which comes from the interior of the earth below this surficial layer of radioactive heating. The "reduced" heat flow may have its origin in deeper-lying radioactivity, convective motions in the interior of the earth, or some other heat source mechanism. Thus, most studies of heat flow attempt to utilize measurements in basement rocks where the radioactivity at the surface may be related to the radioactivity at depth. It has been found that, when measurements are made in large granitic bodies, a linear correlation

$$Q = Q_o + bA$$

is found between the radioactive heat production of the rocks (A) and the surface heat flow (Q), (Birch and others, 1968; Roy and others, 1968a; Lachenbruch, 1968). This linear relationship has two parameters: a slope b and a constant Q_o. The slope can be related to the thickness of the radioactive layer, and Q_o can be related to the "reduced" heat flow from below the radioactive layer. Thus, reports of heat flow studies usually emphasize the results from granitic rocks.

Utilizing the correlation between radioactive heat generation and surface heat flow, various heat flow provinces can be identified. In general, the most significant parameter is Q_o, the heat flow from below the radioactive layer, or "reduced" heat flow. It appears that Q_o becomes systematically smaller as the age of intrusive and volcanic activity for a particular geological province becomes greater; for example, Q_o values for geologic provinces with ages greater than about 200 m.y. for the North American continent are 20-30 mW/m^2 (0.5-0.8 HFU). In areas of younger tectonism and volcanism, the Q_o values increase to over 80 mW/m^2 (2.0 HFU) because higher temperatures exist in the crust and upper mantle, associated with the thermal events causing (or related to) the tectonic and volcanic activity. In general, there is a systematic decrease in heat flow with increasing age of tectonism and volcanism for a particular area (Polyak and Smirnov, 1968; Chapman and Pollack, 1975), as the crust and upper mantle cool off following some period of activity. The time constant of the cooling is in the range of 100-500 m.y.

HEAT FLOW RESULTS

Difficulties in Regional Heat Flow Studies

The geology of Oregon does not fit the criteria previously discussed for conventional heat flow measurement and interpretation. Granitic or metamorphic basement exposures are rare, and often of minor extent. The only major outcrops of granitic or metamorphic basement rock are found in the Blue Mountains and the Klamath Mountains, provinces that occupy only a fraction of the total surface area of Oregon. The bedrock of the remainder of Oregon is composed of Cenozoic volcanic and volcanoclastic rocks, greatly disrupted in many areas by faulting. The rocks in general are very porous, water tables are often deep, and the hydrologic characteristics are virtually unknown. Intrusive rock outcrops, where they exist, do not exceed a few square miles in area. In areas of complex geology such as Oregon, the sort of confidence cannot be associated with a single measurement that can be assumed for a basement area in a stable geologic environment (the eastern United States, for example), where one heat flow measurement may be characteristic of a surrounding 500 to 1000 km^2, and disagreement of adjacent measurements rarely exceeds 10%. Therefore, conventional heat flow interpretation cannot be carried out, and new techniques must be devised.

In the typical geologic setting in Oregon, heat flow measurement and analysis must be carried out on at least three different geographic scales. In many cases extreme local variations (on the scale of 0.5-5 km) will be associated with geothermal systems, structural complexities, and local ground water flow systems. On a larger scale (5-50 km), variations may be associated with large scale structural features (basins and ranges, for example), with regional ground water systems, and with major volcanic and geothermal features. On the largest scale, heat flow variations will be related to provincial geologic features such as the Deschutes-Umatilla Plateau, or the High Lava Plains. Thus, almost two orders of magnitude more heat flow data are necessary for equivalent understanding of the heat flow pattern in Oregon than are necessary in basement rock terrains in the eastern United States, for example. In many places, individual heat flow values will average out to the correct regional values if enough uniformly distributed data are available, especially if convective heat losses (for example, volcanism and thermal springs) are included in the analysis (see Blackwell, 1978; Lachenbruch and Sass, 1977).

One factor which reduces the uncertainty associated with heat flow values not measured in basement rocks is the overall low radioactivity of the volcanic and intrusive rocks in Oregon. Heat generation for outcrop samples of the basalts, volcanoclastic rocks, andesites and trondhjemitic intrusive rocks typical of much of Oregon range from 0.4-0.8 $\mu W/m^3$ (1-3 HGU, Swanberg and Blackwell, 1973; Gosnold, 1976).

These surface units appear to be typical of the average crustal composition based on the results of geochemical studies (Armstrong and others, 1977). If rocks of this radioactivity comprise the 20-30 km thick crust, then at most only 8 ± 2 mW/m^2 (0.20 ± 0.05 HFU) can be attributed to such sources, and regional variations in heat flow attributable to variations in heat production should not exceed 4 mW/m^2 (0.1 HFU).

The technique used in this study was to make as many heat flow measurements in as wide a variety of geologic environments as possible. In this manner the factors affecting heat flow may be recognized in areas where enough data are available, making interpretation of the factors causing heat flow variation possible where only sparse data are available. For large scale interpretation, averaging techniques have been employed. Furthermore, a less biased picture of the heat flow will be obtained than if the regional heat flow studies concentrate on one rock type in a particular geologic setting (basement rocks in the ranges, for example).

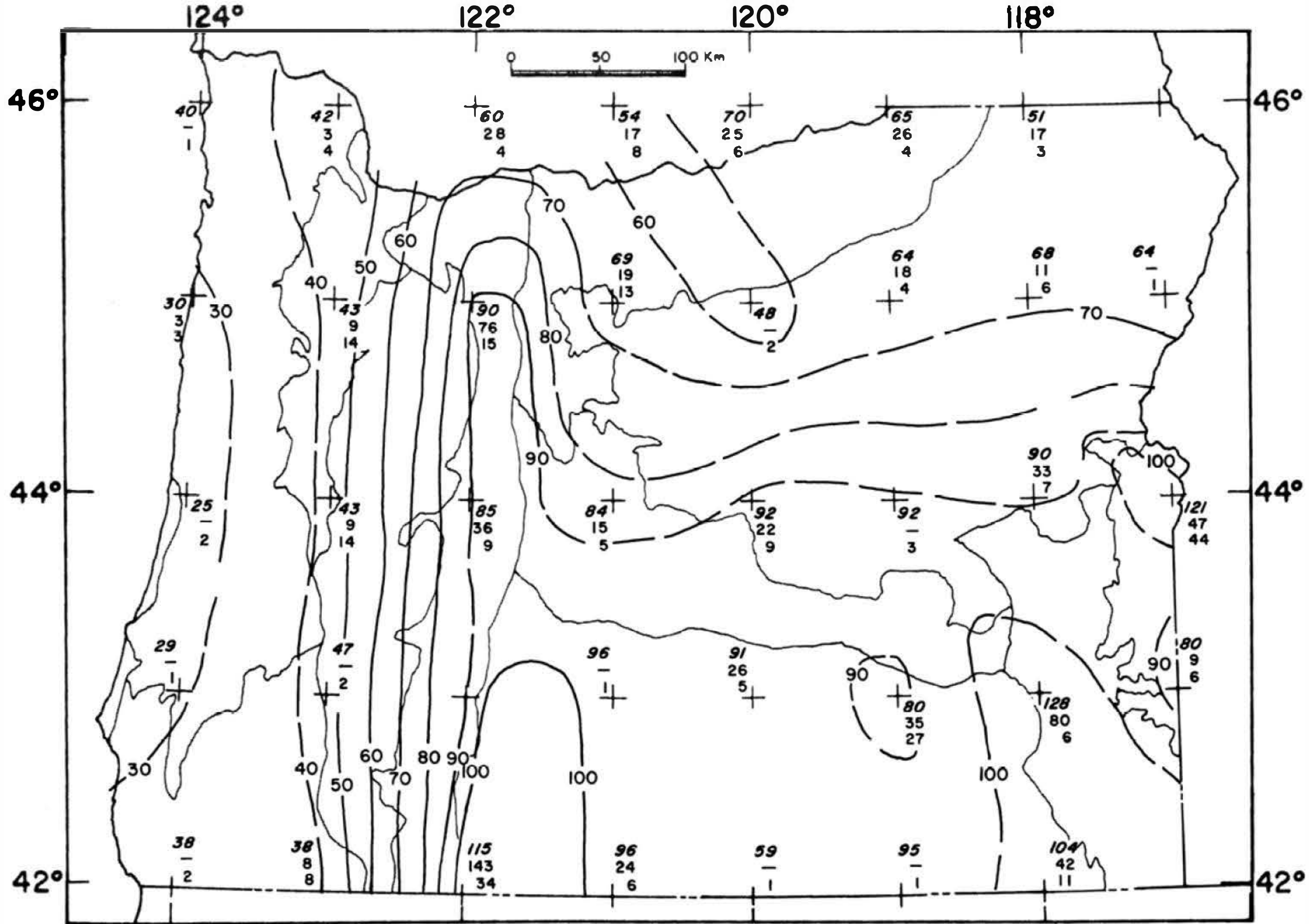

Figure 4: *Average heat flow map of Oregon. Average heat flow values (mW/m^2) for each 1° square block of Oregon are shown. The first figure below the heat flow value is the standard error of the heat flow average and the last figure is the number of data points included in each 1° block. The average values have been contoured at 10 mW/m^2 (0.25 HFU) intervals. Physiographic province boundaries are shown for reference.*

Such detailed studies could not have been made in the past; however, due to extensive drilling for water and mineral exploration in the past few years, and the interest in geothermal exploration, we have been able to obtain data from a total of 475 wells in Oregon, and heat flow values from 286 wells. This data set exceeds by a factor of two the densest published data set for any other state (New Mexico, with a total of approximately 150 heat flow measurements). Even so, although the data are adequate to outline rather well the broad-scale regional variations of heat flow in Oregon, they are still not adequate for a complete understanding of the heat flow at the detailed and intermediate scales; i.e., 0.5-50 km. Within each of the physiographic regions there are large areas with little or no heat flow data. Further measurements will outline significant geothermal features, but will probably cause little change in the regional average heat flow values reported here.

Some of the heat flow measurements have been made in holes drilled specifically for heat flow and geothermal studies. These drilling programs have been organized in order to investigate some of the major geologic features of Oregon. Thus, the data are better distributed for the investigation of particular areas of geothermal interest than if these data were strictly a random group of measurements in uncontrolled locations. Specific studies have focused on the Western Snake River Basin (Bowen and Blackwell, 1975; Bowen and others, 1977); the Western Cascade Range-High Cascade Range boundary (Hull and others, 1977c); the Catlow Valley-Harney Basin areas (Sass and others, 1976); and the Klamath Falls area (Sammel, 1976; Sass and Sammel, 1976; Lienau, 1978).

Overall Characteristics of Heat Flow

The principal result of this study, a heat flow map of the State of Oregon at the scale of 1:1,000,000, is shown on Plate 1. Locations and generalized heat flow values for 286 locations are shown on the map. The data have been contoured at 20 mW/m^2 (0.45 HFU) intervals. Additional data not shown are available in adjoining states to supply control for the contouring in areas near the state boundaries. These data are particularly critical along the Cascade Range trend and in the Western Snake River Basin. Considering that as recently as fifteen years ago, there was a published total of only approximately twenty heat flow measurements for the whole of the United States, this data set in Oregon represents a very large increase in our knowledge. Thus, this heat flow map represents a unique study into the variations and magnitude of heat flow in a large and complex part of the western United States.

Data are most abundant in the Deschutes-Umatilla Plateau, Willamette Valley, Western Cascade Range, High Lava Plains, and Western Snake River Basin. Data are sparse in the Blue Mountains, Basin and Range, Coast Range, Klamath Mountains, and High Cascade Range. Continuing studies are in progress to fill in data gaps and to investigate in more detail significant anomalies.

A striking feature of the data is the great variation of heat flow over relatively small distances within certain provinces. The scatter is greatest in the youngest geologic provinces: the High Cascade Range, High Lava Plains, Basin and Range, Owyhee Uplands, and Western Snake River Basin. Because of the extreme scatter of heat flow values and the uneven geographic coverage, the data can only be contoured *subjectively* at the 1:1,000,000 scale. In some cases (Harney Basin, High Cascade Range) the data have been contoured taking into account the location of hot springs, the trend of geologic structure, and geophysical data.

As a guide to interpreting the heat flow data and preparing the contour map, additional analyses have been carried out. Of particular interest are the average-heat-flow map (Figure 4), histograms of heat flow and geothermal gradient (Figures 5-6), and statistical data (Table 1) on the heat flow and geothermal gradients in the various provinces.

As one attempt to synthesize the data, heat flow values were averaged over 1° x 1° intervals (Figure 4). The average-heat-flow map is particularly useful in the areas of Oregon underlain by the youngest rocks. In these areas the scatter of data is so extreme as to render analysis on the state scale hopeless unless the data are smoothed. An example

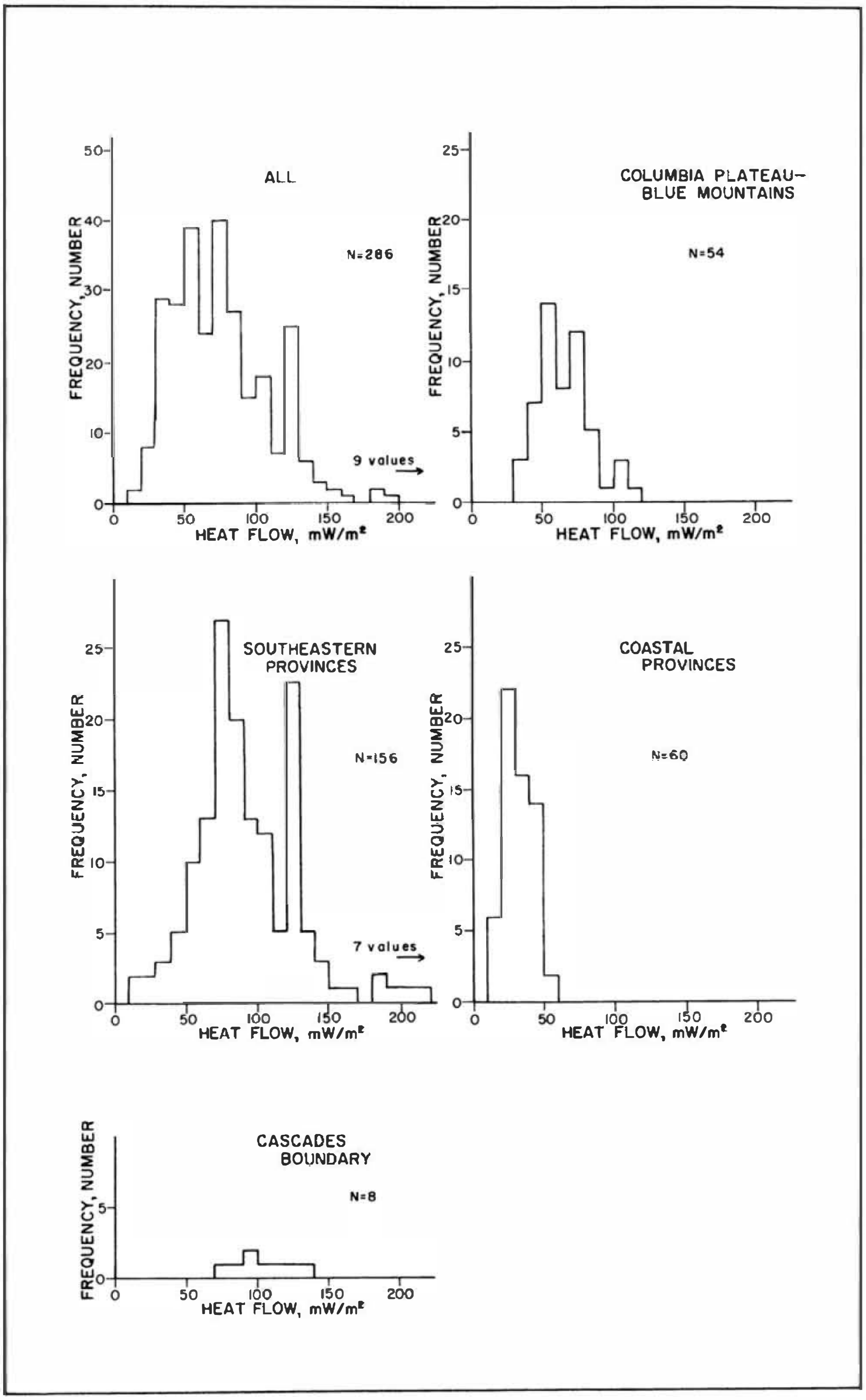

Figure 5: Histograms of heat flow. N is the total number of data points in each data set. Average values and standard errors are given Table 1.

of this is the Klamath Falls region where variations in geothermal gradient from 20°C/km to 500°C/km (measured in holes 100-200 m deep) may occur over a distance of less than 1 km.

To prepare Figure 4, the heat flow data shown on Plate 1 have been averaged over 1° squares, (about 1200 km^2), centered at 1° latitude and longitude intersections; for example, ± 1/2° about 121°00', 43°00'. Average-heat-flow at 0.5° interval maps were prepared; however, the data are too sparse in several areas to allow reliable half-degree averages.

Comparison of the heat flow maps in Figure 4 and Plate 1 shows that there are many overall similarities. The advantage of dealing with an averaged data set is that the extreme scatter of the data in the younger provinces is smoothed out. On the other hand, the averaging may smooth out actual sharp changes in the heat flow which may be well documented by detailed studies; for example, the sharp change in heat flow at the western edge of the High Cascade Range province shown in Plate 1 (see Figure 7). Furthermore, narrow anomalies, such as those along the Brothers Fault Zone and High Cascade Range may be somewhat diffused by the averaging process. Nevertheless, Figure 4 and Plate 1 taken in conjunction give an accurate picture of the regional heat flow of Oregon.

The average heat-flow and geothermal gradient values with their standard errors, state-wide, by physiographic province, and by groups of provinces, are given in Table 1. Histograms of heat flow and geothermal gradient are shown in Figures 5 and 6. The unweighted averages of all 286 heat flow values and 312 geothermal gradient values available for Oregon are 81 ± 3 mW/m^2 (1.94 ± 0.06 HFU) and 65 ± 3°C/km respectively (see Table 1). Area weighted averages for the two quantities are 68 ± 5 mW/m^2 (1.6 ± 0.1 HFU) and 55 ± 5°C/km. The area weighted averages were calculated by taking into account the province averages and the fractional area of Oregon occupied by each province. The continental averages of heat flow and geothermal gradient are about 60 mW/m^2 (1.43 HFU) and about 30°C/km respectively. Thus the average heat flow of Oregon is about 110% of the global average, while the average geothermal gradient is about twice the continental average. The high gradients are present because the average heat flow is higher and because in general, the thermal conductivity of Oregon rocks is relatively low, approximately half of the typical thermal conductivity of continental rocks.

There are significant economic advantages for the low conductivity/high geothermal gradient environment of Oregon compared to other regions of similar heat flow. For example, Sass and others (1971b) and Lachenbruch and Sass (1977) report average heat flow values of 105-120 mW/m^2 (2.5-2.9 HFU) for the Battle Mountain heat flow "high," an anomalous area in the Basin and Range province of Nevada immediately south of the area in the Oregon Basin and Range where heat flow values average 95-105 mW/m^2 (2.3-2.5 HFU). Reported thermal conductivity values range between 2.8 and 4.9 W/mK (6.8 and 11.7 TCU) for an average of 3.9 W/mK (9.3 TCU) for rocks in the Battle Mountain heat flow "high." As a result, the geothermal gradients average only 40°C/km. In southeast Oregon the rocks have an average thermal conductivity of 1.1 W/mK (2.6 TCU) and a geothermal gradient of 89.1°C/km. This comparison would indicate that the average depth to regional reservoirs of equivalent temperature in southeastern Oregon would be about half the depth in northern Nevada, even though the heat flow may be slightly higher in the Battle Mountain heat flow "high."

As pointed out above, heat flow on continents typically comes from two primary sources: crustal radioactivity and sources in the upper mantle. In much of Oregon, additional heat flow comes from crustal sources besides radioactivity, such as magma intrusion, hydrothermal convection systems, etc. Excluding the effect of crustal radioactivity, expected to be low because of the chemical composition of the crust in Oregon (see Armstrong and others, 1977), and here estimated as 8 mW/m^2 (0.2 HFU), the sum total of conductive heat flow from the mantle and crustal sources is approximately 30 mW/m^2 (0.75 HFU) for the coastal provinces, 55 ± 5 mW/m^2 (1.6 HFU) for the northeastern provinces, and 90 ± 10 mW/m^2 (2.2 HFU) for the southeastern provinces. These values are respectively equal to, above, and much above normal (25-35 mW/m^2; 0.6-0.8 HFU) for continents.

On the basis of regional heat flow, Oregon can be divided into four general areas. These four areas are 1) the Coast Range-Klamath Mountains-Willamette Valley-Western Cascade Range provinces, 2) the Deschutes-Umatilla (Columbia) Plateau and the Blue Mountains provinces, 3) the Western Snake River Basin-Owyhee Uplands-Basin and Range-High Lava

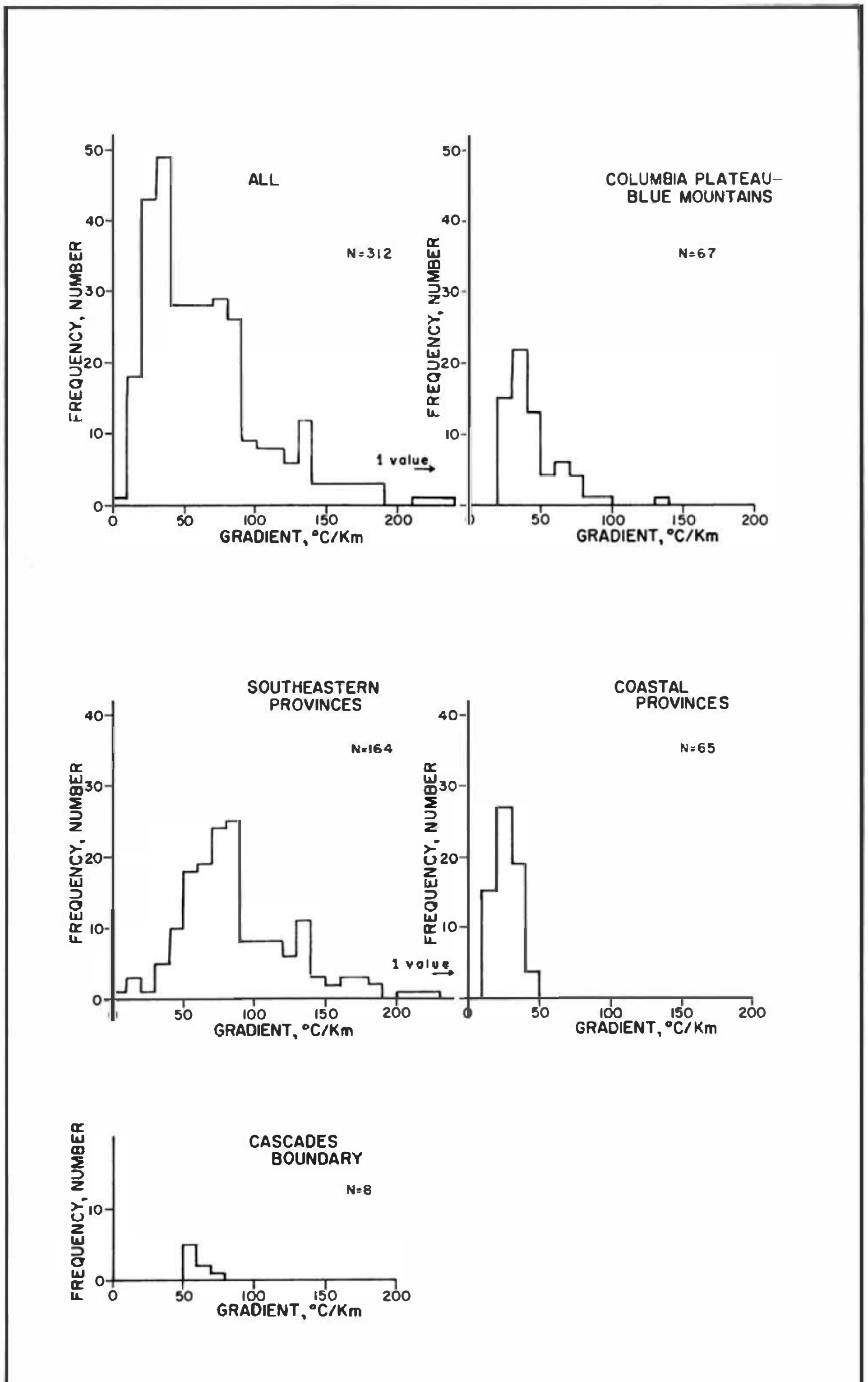

Figure 6: Histograms of geothermal gradient. N is the total number of samples. Average values and standard errors are given in Table 1.

Table 1: Average heat flow and geothermal gradient.
Mean values are shown with standard errors given below each mean value.

Province	Heat Flow mW/m^2	Heat Flow HFU	Heat Flow Number	Gradient °C/km	Gradient Number
Coast Range (1)	35.4 3.0	0.85 0.07	9	23.6 2.0	9
Willamette Valley (2)	40.6 2.1	0.97 0.05	13	28.0 1.8	13
Klamath Mountains (3)	36.8 3.5	0.88 0.08	7	14.8 2.7	7
Western Cascade Range (4)	45.3 2.0	1.08 0.05	31	28.8 1.4	36
Western Cascade-High Cascade Boundary (4a)	105.1 8.5	2.51 0.20	8	61.3 3.4	8
High Cascade Range (5)	(67.4) (14.3)	(1.61) (0.34)	5	(46.2) (5.8)	6
Deschutes-Umatilla (Columbia) Plateau (6)	61.9 3.7	1.48 0.09	33	43.6 2.8	38
Blue Mountains (7)	70.2 3.1	1.68 0.07	21	43.7 4.5	29
High Lava Plains (8)	90.8 4.8	2.17 0.11	36	82.2 5.6	37
Basin and Range (9)	86.3 6.6	2.06 0.16	61	91.5 6.4	64
Owyhee Upland (10)	105.8 13.3	2.53 0.32	15	73.6 9.1	18
Western Snake River Basin (11)	118.9 9.4	2.84	44	97.5 6.3	45
* Coastal Provinces	41.8 1.3	1.00 0.03	60	26.4 1.0	65
* Northeastern Provinces	65.2 2.6	1.56 0.06	54	43.7 2.5	67
* Southeastern Provinces	98.4 3.8	2.34 0.08	156	89.1 3.4	164
All Provinces (unweighted averages)	81.3 2.7	1.94 0.06	286	65.3 2.5	312
All Provinces (weighted averages)	68 5	1.63 0.12		55.0 5.0	

* Average of provinces 1-4 (Coastal), 6 & 7 (Northeastern) and 8-11 (Southeastern)

Plains provinces, and 4) the High Cascade Range. The boundary zone between the Western Cascade and High Cascade provinces is a zone of heat flow transition and will be discussed below. The coastal group of provinces occupies approximately the western one-quarter of the state. The High Cascade Range occupies a strip 50-100 km wide, extending north-south across the state, approximately two-thirds of the way from east to west. The Deschutes-Umatilla Plateau-Blue Mountains provinces occupy the northeastern quarter of the state, while the Basin and Range-Owyhee Uplands-Snake River-High Lava Plains provinces occupy the southeastern quarter of the state. These four groups of provinces will be discussed individually in the following sections.

Coast Range-Klamath Mountains-Willamette Valley-Western Cascade Range Provinces

Within this group of provinces, the heat flow data are most numerous in the Western Cascade Range. Overall, the heat flow and geothermal gradients are much lower and more uniform than in the rest of Oregon. The average heat flow is 41.8 ± 1.3 mW/m^2 (1.00 ± 0.03 HFU) and the average gradient is 26.4 ± 1.0°C/km (Figures 5 and 6, Table 1). Heat flow values measured at the Western Cascade Range-High Cascade Range province boundary are not included in this average and are discussed in detail below. This heat flow value is significantly below the global average, and thus, this area of Oregon is a major low heat flow anomaly. The geothermal gradient, however, is almost equal to the continental average, except in the Klamath Mountains. The gradient in the Klamath Mountains is the lowest in Oregon because of a combination of the low heat flow and rocks of high thermal conductivity (granitic and metamorphic rocks). The lack of scatter of heat flow values throughout these provinces (Figure 5) is in contrast to the large scatter observed elsewhere and is due to the fact that the heat transfer in these areas is dominantly conductive. No major aquifer systems appear to be present and no thermal springs occur, except in a portion of the Western Cascade Range as discussed below.

Deschutes-Umatilla Plateau-Blue Mountains Provinces

These two provinces are rather different geologically, but appear to be similar in thermal character. Data are abundant for the Deschutes-Umatilla Plateau, the part of the Columbia Plateau in Oregon, but relatively sparse for the Blue Mountains. The heat flow average for these two provinces is 65.2 ± 2.6 mW/m^2 (1.56 ± 0.06 HFU) and the average geothermal gradient is 43.7 ± 2.5°C/Km (Figure 6, Table 1). These values are respectively equal to the average world heat flow and about 50% above the average continental gradient. The heat flow is considered to be anomalously high, however, because the crust contributes very little to the surface heat flow, and the mantle heat flow must be 40-50 mW/m^2 (1.0-1.2 HFU) compared to a normal value of 25-35 mW/m^2 (0.6-0.8 HFU). The high mantle heat flow is related to the after-effects of early to mid-Cenozoic volcanic and tectonic activity. The data do not show as much variation as in southeastern Oregon, but more than in western Oregon. Evidence of water motion within holes between different flow contacts of the Columbia Plateau basalts is ubiquitous, although large-scale effects seem to be minor compared to the Bend area and the Snake Plain aquifer in Idaho (Brott and others, 1976). There is some evidence, however, for redistribution of the heat flow by aquifer flow (Bowen and others, 1977).

High Cascade Range

The average heat flow along the western boundary of the High Cascade Range is 105 ± 9 mW/m^2 (2.5 ± 0.2 HFU) and the average gradient is 61 ± 3°C/km (Table 1, Figures 5 and 6). These values are about twice the continental averages. No reliable heat flow values are available for the High Cascade Range area; the averages listed in Table 1 are from the area of Portland where the province boundary extends 30-50 km west of its northerly trend in the remainder of Oregon. Thus, these data are not considered to be characteristic of the province. Presently existing holes elsewhere in the High Cascade Range are shallow (< 100 m) due to the difficulties of drilling in the rubbly basalts typical of the surface units.

The high heat flow values found in the western transition zone may be characteristic of the High Cascade Range. The detailed heat flow pattern in the transition zone is discussed in a following section. Ultimately, understanding of the thermal characteristics of the High Cascade Range is vital in the location, understanding and evaluation of geothermal systems in Oregon. In the future, high temperature geothermal resources in the High Cascade Range could provide a significant energy resource for the State of Oregon.

Basin and Range-High Lava Plains-Owyhee Upland-Western Snake River Basin Provinces

The heat flow pattern within these provinces is extremely complicated, as might be expected in areas of abundant young tectonic and volcanic activity. Overall, the average heat flow is 98 ± 4 mW/m^2 (2.3 ± 0.1 HFU) and the average gradient is 89.1°C/km. These averages are much above normal, and indeed, the average gradient is almost three times the continental average. Data are relatively detailed for the High Lava Plains (Hull and others, 1976, 1977a) and for the Western Snake River Basin (Brott and others 1978; Bowen and Blackwell, 1975). Even within these areas, because of the complexity of the heat flow pattern, a complete picture has not yet been developed. This region has major geothermal potential and needs many times more data for a thorough understanding. However, in spite of the uncertainties, some systematic relationships appear. Averaged on a 1° x 1° scale, the heat flow is relatively uniform, ranging from about 80-100 mW/m^2 (1.4-2.4 HFU). Major thermal anomalies, both positive and negative, appear. For example, the Catlow Valley and the central part of the Harney Basin appear to have relatively low heat flow while the perimeter of the Harney Basin, extreme southeastern Oregon, and the Western Snake River Basin have relatively high heat flow. Local extreme values (both low and high) exist on a smaller scale (1-10 km). These anomalies are due to the effects of regional thermal variations, structural complications, regional and local ground water flow, and hydrothermal convection systems. The relative importance of these different effects is not known in detail at this time, but the way in which they might affect the heat flow data is discussed in more detail in a following section. The most obvious fact is that these regions have a large geothermal potential, but as yet the controlling features of the geothermal systems are not understood. Much additional study of these areas is vital to understanding the geothermal resources of Oregon.

Effects of Hydrothermal Convection

In several of the provinces (especially in the Basin and Range province just discussed) the conductive heat flow pattern is disturbed by the presence of numerous and extensive regional aquifer systems and hydrothermal convection systems. Without much additional data it is not clear whether the heat transferred in such systems is included in the data discussed here and summarized in Figures 5 and 6 and Table 1. In these averages all heat flow values less than 350 mW/m^2 (8.4 HFU) have been included. Removing values greater than 150 mW/m^2 (3.6 HFU), which can only occur in hydrothermal convection systems, would reduce the average heat flow for the four southeastern provinces by 10% (about 10 mW/m^2), and the average geothermal gradient by 10°C/km. On the other hand, calculation of the heat known to be lost in the hydrothermal convection systems (using the data of Bowen and Peterson, 1970; Bowen and others, 1978) suggests a minimum of 10 mW/m^2 (.24 HFU) averaged over the four southeastern provinces. This value is probably a conservative estimate by 50-100%. Therefore, the average total heat loss for the southeastern provinces from conduction and hydrothermal convection is estimated to be 100-110 mW/m^2 (2.4-2.6 HFU). The average shown on Table 1 is therefore a minimum value. The contouring of Plate 1 and Figure 4 reflects this estimate of the mean heat flow in the southeastern part of Oregon.

HEAT FLOW AND GEOTHERMAL SYSTEMS ALONG THE HIGH CASCADE RANGE-WESTERN CASCADE RANGE BOUNDARY

One of the major features discovered during the heat flow studies program has been a major change in heat flow near the boundary between the Western Cascade Range and the High Cascade Range provinces. There are a number of hot springs along major drainages in the Western Cascade Range that occur immediately to the west of the contact between the High Cascade Pliocene and Pleistocene volcanic rocks, and the older Western Cascade volcanic rocks (Waring, 1965; Bowen and Peterson, 1970; Bowen and others, 1978). Heat flow measurements in the Western Cascade rocks, from holes drilled specifically for heat flow and in water wells, document a major regional east-to-west change in heat flow that coincides in general with the locations of the hot springs.

The locations of the data are shown in Plate 1, and an east-west cross-section of the data between latitudes 43°15'N and 45°15'N is shown in Figure 7. This cross-section shows heat flow and geothermal gradient as functions of distance from a line approximately coinciding with the physiographic boundary between the Western Cascade Range and the High Cascade Range (Figure 1). The data have been grouped according to their position from north to south. Major data groups were obtained on the Clackamas River drainage in Townships 6S and 7S, the North Santiam River drainage in Township 9S, the McKenzie River in Townships 16S and 17S, and the Middle Fork of the Willamette River in Townships 21S and 22S. East of a north-south line approximately coinciding with the line of hot springs, heat flow values are systematically high. Although many of these determinations are within 5 km of the hot springs, very high values (greater than 150 mW/m^2; 3.6 HFU) characteristic of geothermal systems were generally not encountered, with the exception of two values near Austin Hot Springs on the Clackamas River. The other values indicate a rather uniform average heat flow of approximately 105 $\pm$ 9 mW/m^2 (2.5 $\pm$ 0.2 HFU) without a strong dependence on north-to-south position, and the results document a systematic east-to-west transition in heat flow all along the northern half of the High Cascade Range in Oregon. The corresponding average gradient is 61 $\pm$ 3°C/km. There is an extremely sharp transition to the west to low values of heat flow (40 mW/m^2; 1.0 HFU) over a distance of about 20 km (see Figure 7). Attempts to investigate the heat flow pattern further to the east, toward the axis of the High Cascade Range, where volcanism has been most continuous during the Quaternary, have not been successful so far because of drilling problems in the very rubbly basalts which cover the surface.

Also shown in Figure 7 are two Bouguer gravity cross-sections, one at 44°15'N and one at 43°15'N (Couch and Baker, 1977). These data indicate a regional change in Bouguer gravity anomaly associated with, but opposite in sign to, the heat flow data. This gravity change is of major magnitude and the short half-width implies that crustal density contrasts are the major cause of the anomaly. The gravity data can be explained by a large low density body (a magma chamber, or thermally expanded crust) in the upper part of the crust beneath the region of high heat flow. The coincidence of this gravity anomaly with the heat flow anomaly is evidence that the heat flow data are related to a regional crustal feature, and not to upper crustal groundwater circulation. Based on this hypothesis, a model of crustal temperature in the Western Cascade Range was calculated. In this model, heat flow values from a smooth curve fitted to the heat flow data (dashed curve in Figure 7) were taken as the input into a program which calculates temperatures at depth via the process of continuation (Brott, 1976). In the continuation calculation, steady-state heat flow conditions and uniform thermal conductivity are assumed, and subsurface isotherms are calculated based on the surface (shallow) heat flow data. The heat flow anomaly was extended at 100 mW/m^2 (2.4 HFU) to the east in order to accomplish the interpretation; although in fact, there are no data to support (or contradict) this extrapolation. The results show a rapid change in subsurface temperature at a distance of 10-20 km from the western boundary of the High Cascade Range. Beneath the eastern edge of the Western Cascade Range, temperatures may be in excess of 700°C at a depth of less than 10 km; whereas west of this boundary zone, temperatures are only on the order of 300°C at a depth of 10 km.

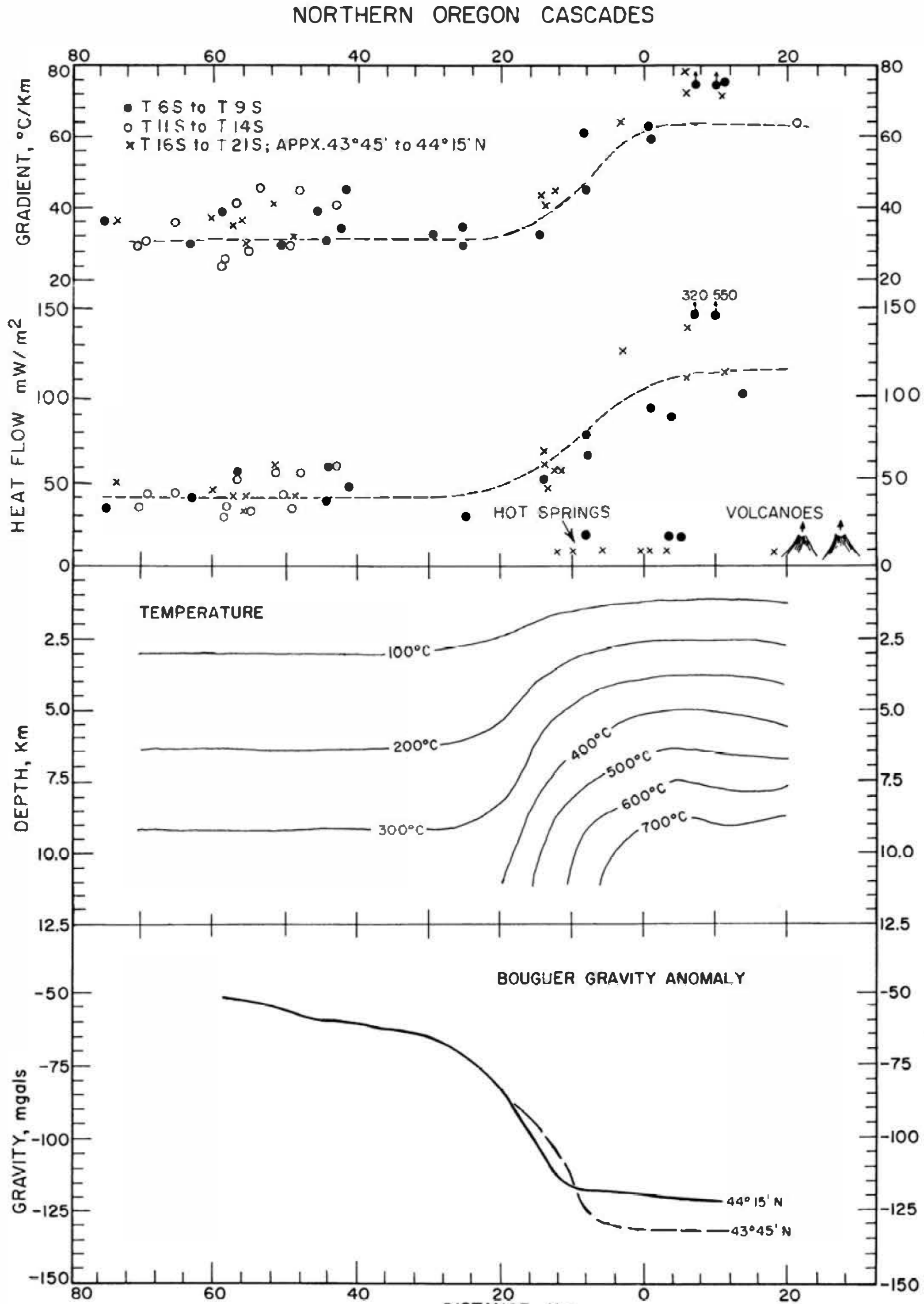

Figure 7: Geothermal gradient, heat flow, interpreted crustal temperatures, and regional Bouguer gravity anomalies for the western part of the northern Oregon Cascade Range (gravity data are from Couch and Baker, 1977). Heat flow data between latitudes 43°15'N and 45°15'N are projected to the profile. The zero distance reference is the mean location of the Western Cascade Range-High Cascade Range boundary (see Figure 1).

In spite of the geophysical contrasts, the cause of the abrupt west-to-east increase in heat flow and the heat source for hot springs is not readily apparent, as post-Pliocene volcanic centers have not been described in the immediate vicinity of the hot springs. Granitic rocks in the form of small stocks, dikes and sills are found in the Western Cascade Range province west of several of the hot springs, but available age determinations suggest ages in the range of 8-16 m.y. for the intrusive bodies (Bikerman, 1970; Sutter, 1978). Furthermore, no major faults have been mapped along the north-trending heat flow and gravity transition zone. However, on the basis of physiographic expression, several authors, including Thayer (1936), Baldwin (1976), and Allen (1966), have suggested that a fault zone forms the boundary between the Western and High Cascade Ranges.

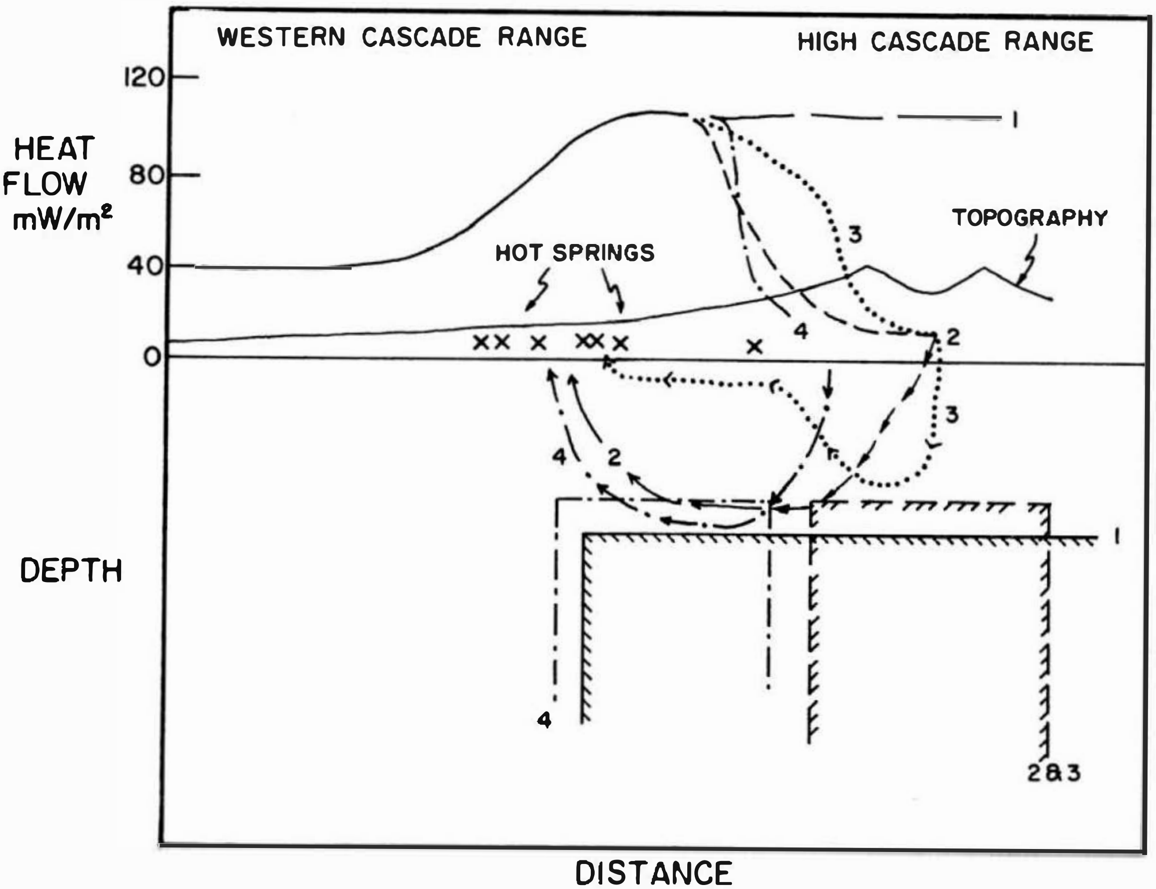

Figure 8: Several possible interpretations and conceptual models of the heat flow transition observed at the Western Cascade Range-High Cascade Range boundary. Four models are shown, with three different variations in the heat source at depth. Model 1 assumes that the observed anomaly (see Figure 7) is essentially conductive. In the other three models, the observed heat flow is interpreted in terms of regional water circulation (see text).

This interpretation of the heat flow data assumes that the heat flow measurements represent crustal heat flow variations, but there are other possible models. Shown in Figure 8 are several conceptual models for the hot spring systems and the heat flow anomaly at the Western Cascade Range-High Cascade Range province boundary. The first model was assumed in the interpretation shown in Figure 7; i.e., that the change in heat flow represents crustal sources, probably a central magma chamber underlying the axis of the High Cascade Rnage. Three other models assume hydrothermal circulation systems driven primarily by elevation differences between the High Cascade Range and the valleys in which the hot springs exist but differing in the interpretation of the location of the heat source. The water flow would be primarily from east to west, and the hot springs and high heat flow values would be related to large-scale regional flow of groundwater at depth. In the second case (the predicted heat flow is shown by curve 2 of Figure 8), the water would be circulating to great depths (greater than 3 km), then flowing laterally while at depth and coming up immediately under the hot springs. In the third case (curve 3 of Figure 8), the water could be circulating to depth directly beneath volcanoes, then coming up to relatively shallow depths and flowing laterally; for example, along tuff units (Hammond, 1976) until it reaches the surface at the hot spring locations. In a fourth possible model (curve 4 of Figure 8), the anomaly might be confined to a narrow band along the physiographic boundary. In this case, a shallow heat source, offset from the High Cascade Range axis, might control the hot spring locations; or the hot spring sites might be localized by fractured Miocene and older granitic rocks buried beneath the physiographic boundary; or the proposed boundary fault zone might localize hydrothermal circulation. In the fourth model, a zone of relatively high permeability could be the controlling factor. These different models have quite different geothermal implications, and it is important to differentiate amont them. Data presently available are not sufficient for this differentiation, however.

If heat flow values typical of the High Cascade Range are 100 mW/m^2 (2.4 HFU), and the regional gradients are 60 $\pm$ 10°C/km, then the conditions should certainly be favorable for the existence of geothermal systems of temperature high enough for electrical power generation, since in geothermal systems, water typically circulates to depths of 5-10 km. Water circulation to these depths should encounter rock temperatures well in excess of 300°C. However, the nature of the circulation systems and the nature of the localizing structures that might guide the groundwater circulation remain unknown at this time. Present geophysical data support the concept of a continuous "magma chamber" or thermally disrupted zone under the whole length and breadth of the High Cascade Range in northern Oregon, with the known geothermal systems occurring at the western margin of this hot zone. Heat flow data along the crest of the High Cascade Range are crucial to understanding the geothermal potential east of the province boundary, but these data do not yet exist.

In evaluating the observed heat flow pattern in the Western and High Cascade Ranges in Oregon, it is interesting to make a comparison with the available data for the Cascade Range in the State of Washington, where recent studies show a considerably different pattern (Schuster and others, 1978). Measurements in the Indian Heaven basalt field, midway between Mt. St. Helens and Mt. Adams in Skamania County, reveal typical gradients of 44-53°C/km and heat flow values of 56-74 mW/m^2 (1.33-1.79 HFU). Farther north in the Cascade Range in Washington, heat flow values obtained in early to mid-Cenozoic and pre-Cenozoic rocks range from 50-60 mW/m^2 (1.2-1.54 HFU) (Blackwell, 1974). Thus, there is apparently a major difference in the thermal structure of the crust in the Cascade Ranges in Oregon and in Washington, with higher heat flow values in the portion of the range in Oregon. The geologic reason for this thermal variation is not obvious, but may be due to a greater volume of young volcanism in the High Cascade Range of Oregon than in the Cascade Range in Washington.

CHARACTERISTICS OF HEAT FLOW PATTERNS IN THE BASIN AND RANGE PROVINCE

General Characteristics

The characteristic feature of heat flow in the Basin and Range province is the large variation in heat flow values over relatively short distances. These variations are typically so large, and occur over such short distances, that they are difficult to understand on the state scale. Therefore, we will discuss briefly some of the geologic and hydrologic characteristics of the Basin and Range province which cause such extreme fluctuations in heat flow, and some of the types of geothermal systems to be expected in the Basin and Range province. The conceptual heat flow and temperature model based on a typical structural situation in the Basin and Range province is shown in Figure 9. This figure shows a typical range-valley pair where a normal fault-bounded graben or valley exists in conjunction with a horst block, or range. The temperatures and heat flow shown were calculated by a finite difference heat conduction program. Two layers of different conductivity were chosen with values typical of those observed in southeastern Oregon. In the depth range from 1-3 km, the valley blocks are composed of volcanic rock, clay, and volcanoclastic sediment, whereas the ranges tend to be composed of a higher percentage of volcanic rock and possibly metamorphic and igneous basement rock. In general, a significant thermal conductivity variation exists, although obviously the model shown in Figure 9 is highly idealized. The ranges and the valleys may or may not include relatively permeable rocks, where the permeability exists due to fracturing or due to intrinsic permeability in the volcanoclastics and volcanic rocks typical of southeast Oregon.

Because of these differences in thermal conductivity, the heat flow from the deep interior (even if it is uniform over large areas) is refracted, i.e., follows the paths of lowest resistance to the surface, and is not uniform when measured in shallow holes (100-300 m). In the typical structural geometry of the Basin and Range province, this refraction implies heat flow variations of approximately 10-25% at places between the ranges and the valleys, with the lower values being found in the valleys and the higher values in the ranges. The actual magnitude of the difference is affected by the geologic history and by the geometry of the system, and only the simplest model, with homogeneous thermal conductivity within each block, is shown in Figure 9. Of course, thermal conductivity varies *within* each block as well as across the contact, leading to a much more complicated heat flow pattern than predicted by this simple model. The heat flow differences will approach the magnitude of the variation in thermal conductivity, which is 100% or more.

In addition, low values of heat flow in the valleys with respect to the ranges may be caused by the effects of erosion and sedimentation. Sediments are deposited in the valleys at the ambient surface temperature. As additional sediment is deposited, the sediment which is buried must now be heated up to the appropriate temperature by the heat flow from below. There is a time lag in this thermal heating, therefore in an area where valleys are actively forming, or have formed in the recent geologic past, the temperatures may be depressed due to this sedimentation. In the ranges, erosion of warmer rock and its subsequent exposure to colder surface temperatures causes exactly the opposite effect.

General hydrologic effects may also cause systematic variations in heat flow. The hydrology of the Oregon Basin and Range province is little known, and any such effects cannot be predicted at this time. In some cases, groundwater flow from the ranges to the valleys may lower heat flow in the range. In other cases, fluid flow within or between valleys may extensively modify the conductive heat flow (Sass and others, 1977; Lachenbruch and Sass, 1977).

Because of the very high geothermal gradients typical of southeastern Oregon (which are related to the high heat flow and low thermal conductivity of the rocks), relatively high temperatures may be reached at shallow depths without the presence of a major geothermal anomaly. Therefore, deeply buried aquifers (1.0 ± 0.5 km) may have temperatures high enough for utilization for space heating without the presence of unusually high heat flow. The highest temperatures will exist beneath the valleys, even though heat flow in the valleys may be slightly lower than in the ranges.

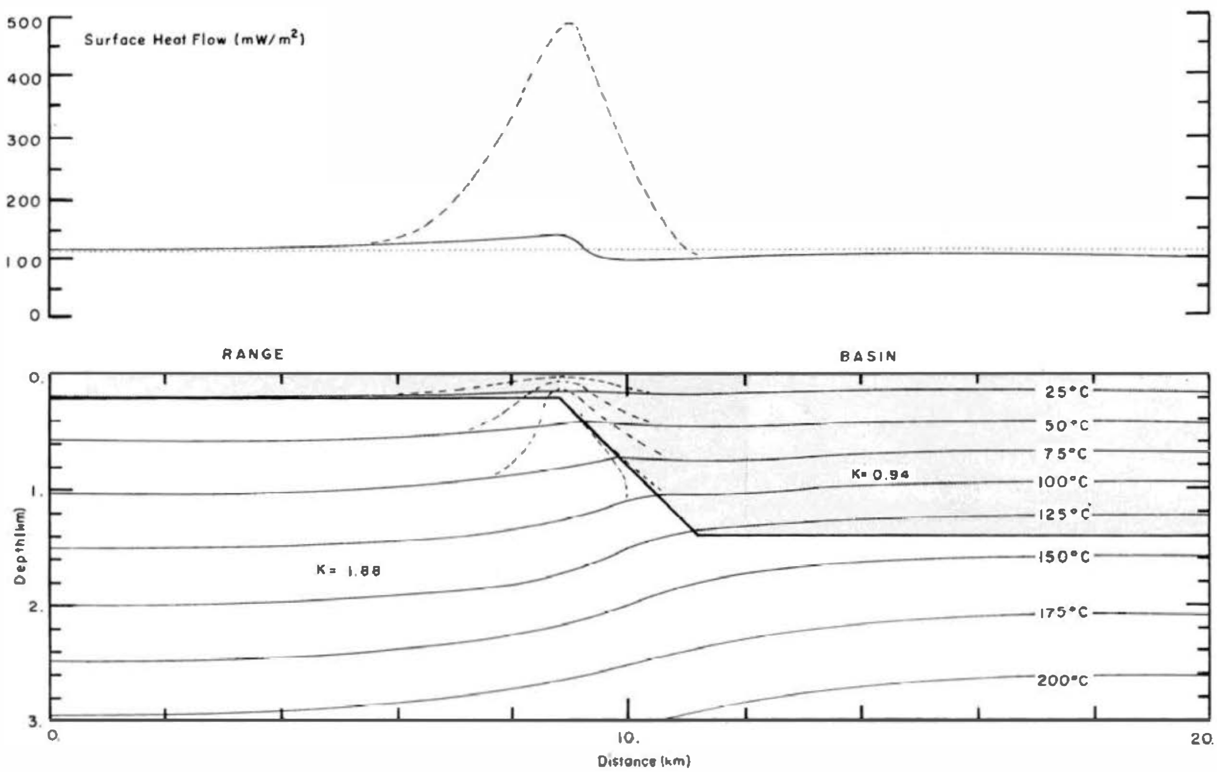

Figure 9: Idealized heat flow, structural, and temperature model for the Basin and Range province in Oregon. The background heat flow value assumed is 110 mW/m² (2.6 HFU). The thermal conductivities are assumed uniform in the range and in the basin and are assumed to be 1.9 W/mK (4.5 TCU) and .94 W/mK (2.25 TCU) for the range and basin blocks respectively. Solid lines show only the effects of thermal refraction between the range and valley. Dashed lines show the effects of water at 100°C circulating through the blocks and up along the bounding fault from a depth of approximately 1.0 km to 200 m.

Typical Geothermal Systems

The most common geothermal system associated with the Basin and Range province of Oregon is circulation of fluid up a major normal fault or fault zone. These normal faults may or may not be the range-bounding normal faults. The model shown in Figure 9 (dashed lines of heat flow and temperature), assumes relatively slow downward circulation so that the water heats up to the ambient temperature as it circulates to depth. As it intersects the fracture zone, the water moves very rapidly upward, maintaining almost a constant temperature until it approaches the surface.

Typically, this sort of circulation system can be identified by linear trends of hot springs along major faults, or by linear trends of heat flow anomalies which may or may not be associated with surface manifestations in the form of hot springs. As an example of some of these characteristics, heat flow and geothermal gradient values from the vicinity of Vale in the Western Snake River Basin are shown in Figure 10. In this example,

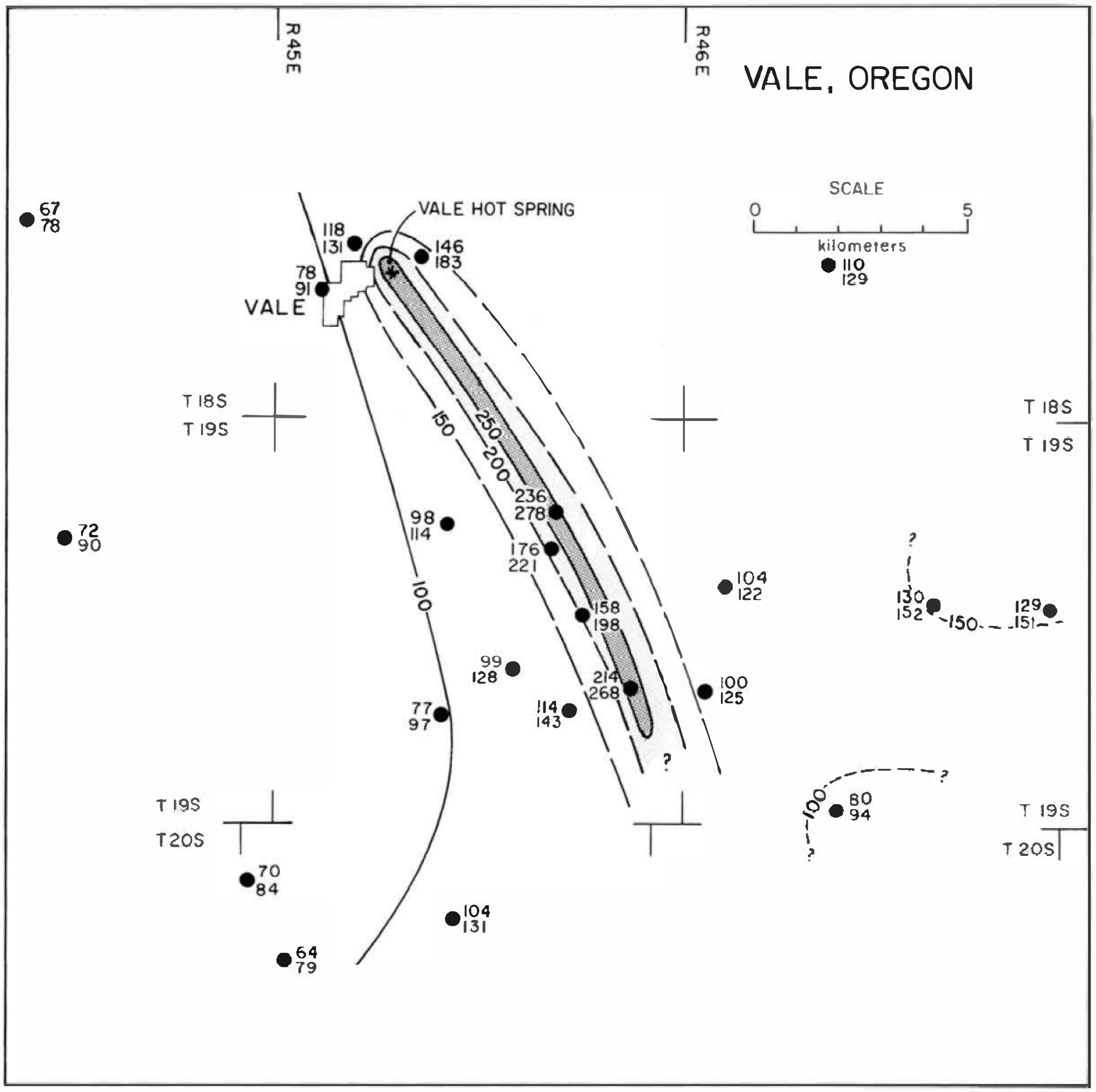

Figure 10: Heat flow and geothermal gradients for the Vale-Cow Hollow geothermal anomaly near Vale, Oregon. Gradients are shown in °C/Km and heat flow values are shown in mW/m². Heat flow is contoured at 50 mW/m² intervals.

there is a hot spring near the town of Vale at the north end of a major heat flow anomaly. The hot spring has an approximate flow of 75 liters/min, and an estimated geochemical reservoir temperature of about 160°C (Renner and others, 1975). Heat flow investigations in a number of holes drilled for other purposes, such as water and uranium exploration, have outlined a major geothermal anomaly which appears to be collinear with Vale Hot Spring. In this anomaly, heat flow values as high as 270 mW/m^2 (6.5 HFU) and gradients as high as 236°C/km exist along a linear zone approximately 15 km in length. The width of this geothermal anomaly is very narrow, however, on the order of only 2 km.

Heat flow values to the east of the geothermal anomaly average approximately 120 mW/m^2 (2.9 HFU), while those to the west average approximately 100 mW/m^2 (2.4 HFU). Geological and geophysical studies indicate that a major graben-horst pair occurs in the area, with the heat flow anomaly existing along a fault on which there may be slight up-to-the-east displacement internal to the horst block (Bowen and Blackwell, 1975). This sort of anomaly is similar to many others observed in the Basin and Range province, in that a relatively small thermal manifestation (hot spring) is associated with a heat flow anomaly many times larger in area than the thermal manifestation. In other cases, thermal manifestations may be scattered along the zone of anomalous heat flow; or, in some cases, there may be no thermal manifestations at all, and the anomaly can be detected only by heat flow studies or the measurement of unusually warm water in wells.

In this case, therefore, the variation in regional heat flow would be related to the major horst-graben structure underlying the area, while the very high individual heat flow values are related to a geothermal anomaly associated with a major fracture or fault zone.

Another typical occurrence is circulation along a fault intersection, which may be more equidimensional in surface plan than the sheet circulation illustrated in Figure 10. An example of this type of geothermal anomaly from the Basin and Range province of northern Nevada is shown in Figure 11 (Sass and others, 1977).

In most of the Basin and Range province of Oregon, the age of the last extensive volcanism and tectonism is younger than that in the Western Snake River Basin. In consequence, the rocks are much more permeable, and the conductive heat flow pattern is much more disturbed by water circulation. Within the Basin and Range province, the most detailed studies have been carried out in the Catlow Valley, Harney Basin, and the Klamath Falls area. Heat flow values in the valleys are typically on the order of 60-80 mW/m^2 (1.5-1.9 HFU). Geothermal anomalies similar to the Vale anomaly are characteristic of the margins of the valleys; for example, the Klamath Falls geothermal zone, the Coyote Buttes thermal anomaly, the Hines hot water artesian wells (northern Harney Basin) and the hot springs along the south flank of Harney Lake. Heat flow values in the associated ranges average 100 mW/m^2 (2.4 HFU) or more although there are very few determinations available.

In many areas, the rocks are sufficiently permeable that downward or lateral circulation in aquifers may be fast enough to result in very low or even zero heat flow values, in contrast to the Western Snake River Basin, where the relatively thick cap of claystone and siltstone retards rapid vertical water circulation. Thus in many parts of the Basin and Range province very low values (0-20 mW/m^2; 0-0.5 HFU) and high values (above 100 mW/m^2; 2.4 HFU) are juxtaposed.

An example of this situation occurs in the Klamath Basin (Sass and Sammel, 1976; Lienau, 1978). Figure 12 shows locations of anomalously high geothermal gradient (greater than 100°C/km) corresponding to heat flow values in excess of 80-100 mW/m^2 (1.9-2.4 HFU). Most of these zones are aligned along major normal faults which cut the Pliocene-Quaternary volcanics and sediments which make up the bedrock of the area. The area of Figure 12 is outlined on Plate 1. Actual values of heat flow within the high gradient zones range up to 500 mW/m^2 (12 HFU) or more, while values outside the high gradient areas range from 0-80 mW/m^2 (0-1.9 HFU). In places, for example at the northern end of the Klamath Falls anomaly, a full range of heat flow occurs over a distance of 2 km.

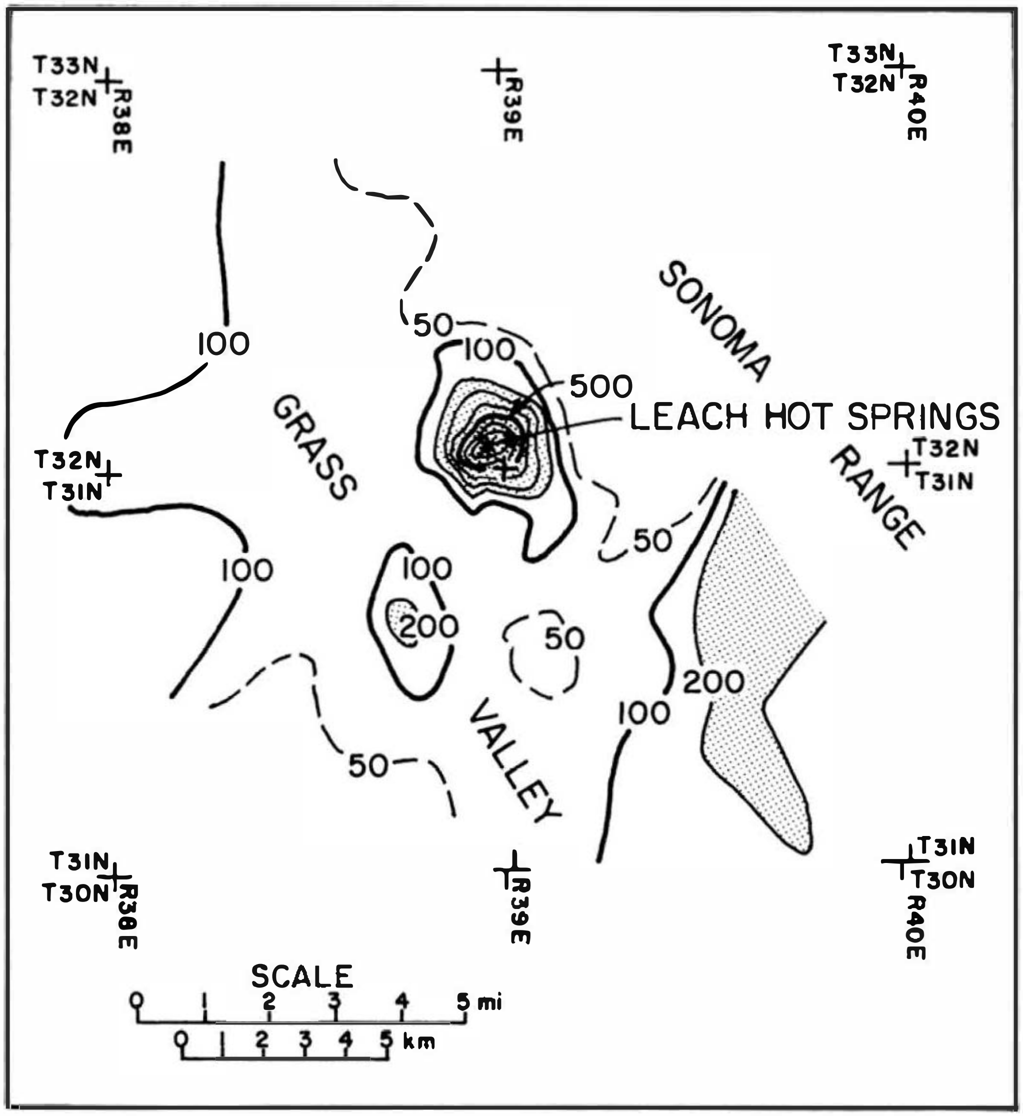

Figure 11: Heat flow anomaly at Leach Hot Springs, Nevada. (Sass and others, 1977). The contour interval is 100 mW/m² with supplementary dashed contours at intervals of 50 mW/m².

A summary of the available heat flow data for the Klamath Falls area is given in Table 2. Only data within the area of Figure 12 have been included in the table. The areas of anomalous gradient in Figure 12 are based on estimates of gradient from well temperatures measured or reported in over 200 water wells in the Klamath Falls area (Lienau, 1978). In contrast, temperature-depth data are available from less than 50 wells in the area and reliable heat flow values are available for only 33 wells. If all the data are considered, the average heat flow is 116.6 mW/m^2 (2.79 HFU). The extreme contrast in heat flow in such a tectonically jumbled area is indicated by the range

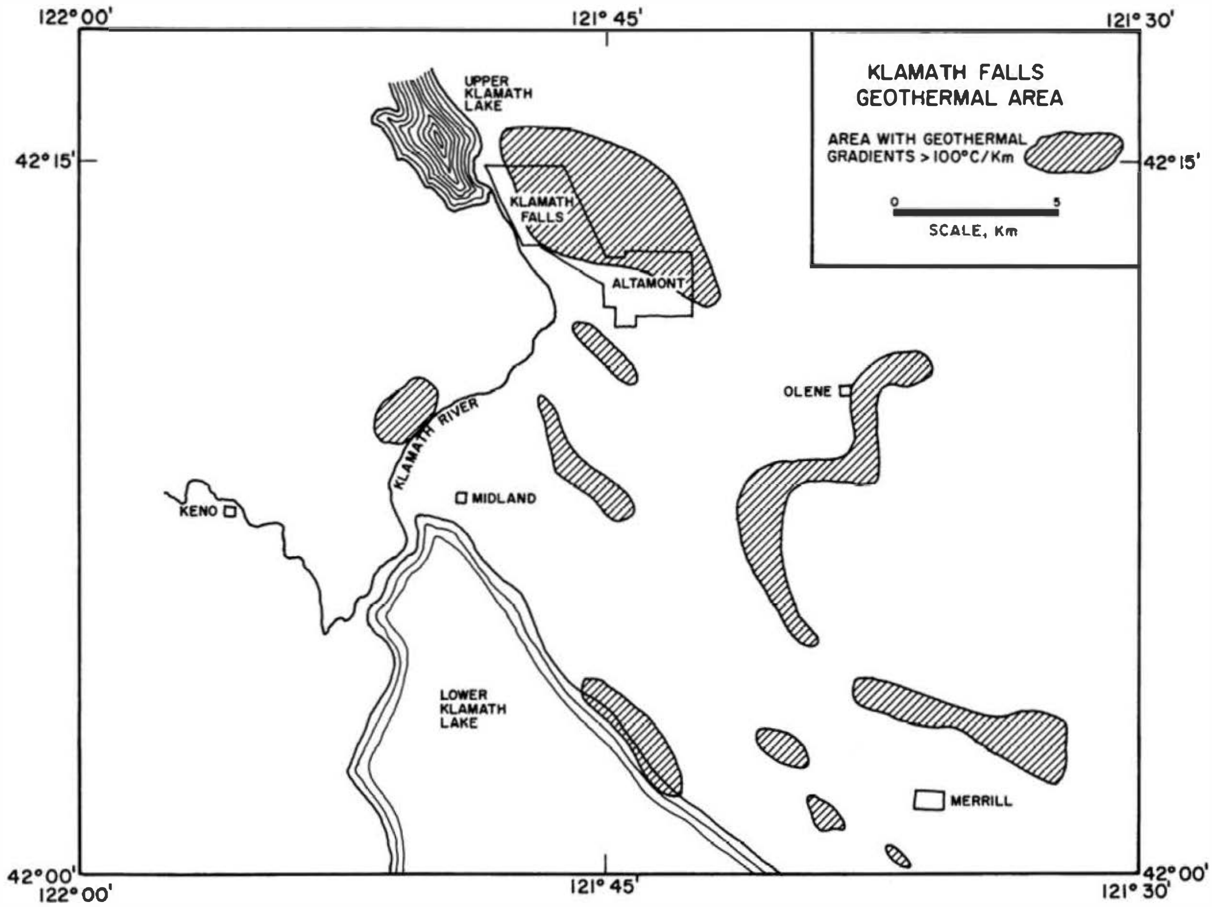

Figure 12: Generalized location of anomalously high geothermal gradients in the Klamath Falls area of southwestern Oregon (the area is outlined in Plate 1). Shaded areas correspond to locations with geothermal gradient greater than 100°C/km (after Lienau, 1978).

of observed values (12.6 to 716.0 mW/m^2; 0.3-17.1 HFU). If only the highest values of heat flow (from the Klamath Falls anomaly) are omitted, the average heat flow is 83.6 mW/m^2 (2.00 HFU), and if only data less than or equal to 150 mW/m^2 (3.6 HFU) are averaged, essentially excluding all data from the high heat flow anomalies, the average is 72.3 mW/m^2 (1.73 HFU). Sammel (1976) and Sass and Sammel (1976) concluded that the background heat flow for the area was 60-70 mW/m^2 (1.4-1.5 HFU) and that the background gradient was 30-40°C/km. We conclude that the average heat flow in the Klamath Falls area is between 84 and 117 mW/m^2 (2.0-2.8 HFU), that the average gradient in the lake beds ranges from 100-150°C/km, and that the average gradient in the basalts ranges from 50-100°C/km. The background heat flow and gradients proposed by Sass and Sammel (1976) and Sammel (1976) are much too low because only the non-geothermal areas were considered in determining background values.

Table 2: Heat flow and geothermal gradients in the vicinity of Klamath Falls (within the area shown in Figure 12). Q is heat flow. Standard errors are shown below average values.

	Heat Flow				Gradient		
Category	Average mW/m²	(HFU)	No.	Range mW/m² (HFU)	Average °C/km	No.	Range °C/km
All Data	116.2 26.0	(2.79)	33	12.6-716.0 (0.3-17.1)	153.6 34.4	33	16.8-950
$Q \leq 350$ mW/m² (8.4 HFU)	83.6 10.5	(2.00)	31	12.6-301.5 (0.3-7.2)	109.8 13.8	31	16.8-400
$Q \leq 150$ mW/m² (3.6 HFU)	72.3 7.3	(1.73)	28	12.6-138.2 (0.3-3.30)	94.6 9.4	28	16.8-180

SUMMARY AND DISCUSSION

The average heat flow value for the State of Oregon is over 10% higher than the average heat flow for continents, and the average geothermal gradient is about twice the average continental value. The state can be divided into four general heat flow regions, or provinces. The first region includes the Coast Range-Willamette Valley-Klamath Mountains-Western Cascade Range provinces, with an average gradient of 26.4°C/km and an average heat flow of 42 mW/m^2 (1.0 HFU). The second heat flow province includes the Deschutes-Umatilla (Columbia) Plateau-Blue Mountains provinces, where the heat flow is 65 mW/m^2 (1.5 HFU) and the average gradient is 44°C/km. The third area is in the southeastern part of the state, and includes the High Lava Plains-Basin and Range-Owyhee Upland and Western Snake River Basin provinces. The average heat flow for these provinces is 98 mW/m^2 (2.34 HFU), and the average gradient is 89°C/km. The fourth region consists of boundary areas between the High Cascade Range and the Western Cascade Range, with an average heat flow of 105 mW/m^2 (2.5 HFU), and an average gradient of 61°C/km.

The thermal character of the High Cascade Range is probably the least known of the major heat flow provinces of Oregon. Since the High Cascade Range is the area of most active and youngest volcanism in Oregon, the lack of heat flow data in this province represents a major block in attempts to completely characterize the heat flow of Oregon.

The correlation of the heat flow with these provinces is shown in two east-west cross-sections (Figure 13). These cross-sections show generalized heat flow along east-west lines at latitudes 42°30'N and 44°30'N. In the northern part of the state, the High Cascade Range stands out as an isolated area of high heat flow flanked by areas of lower heat flow, with the Western Snake River Basin appearing as a separate high heat flow region at the extreme eastern edge of the state. Further to the south, heat flow is low along the coast and very high everywhere east of the Western Cascade Range-High Cascade Range boundary.

In general, the boundaries between regions of different heat flow appear to coincide with several of the major geologic and physiographic province boundaries in Oregon, although not all of the province boundaries coincide with heat flow transitions. The important boundaries along which major heat flow transitions occur are the Western Cascade Range-High Cascade Range boundary, the High Cascade Range-Columbia Plateau boundary, and the High Lava Plains-Western Snake River Basin to Blue Mountains boundary.

The rapid change in heat flow from east to west along the Western Cascade Range-High Cascade Range boundary coincides with major changes in the earth's gravity field, and with a major north-south trending belt of hot springs that includes Austin, Bagby, Breitenbush, Belknap, Foley, McCredie, Kitson and Umpqua Springs. Certainly, this heat flow and physiographic transition represents a major feature of the upper part of the earth's crust.

The heat flow boundary between the southeastern and northeastern heat flow provinces coincides with the northern margin of the High Lava Plains and the Brothers Fault Zone. The Brothers Fault Zone has been considered by Lawrence (1976) to represent the northern terminus of late Cenozoic basin-and-range deformation.

Thus, the heat flow transitions occur along major crustal and upper mantle discontinuities in structure and geologic history. This relationship is typical of the western United States (see also Roy and others, 1972; Blackwell, 1971, 1978).

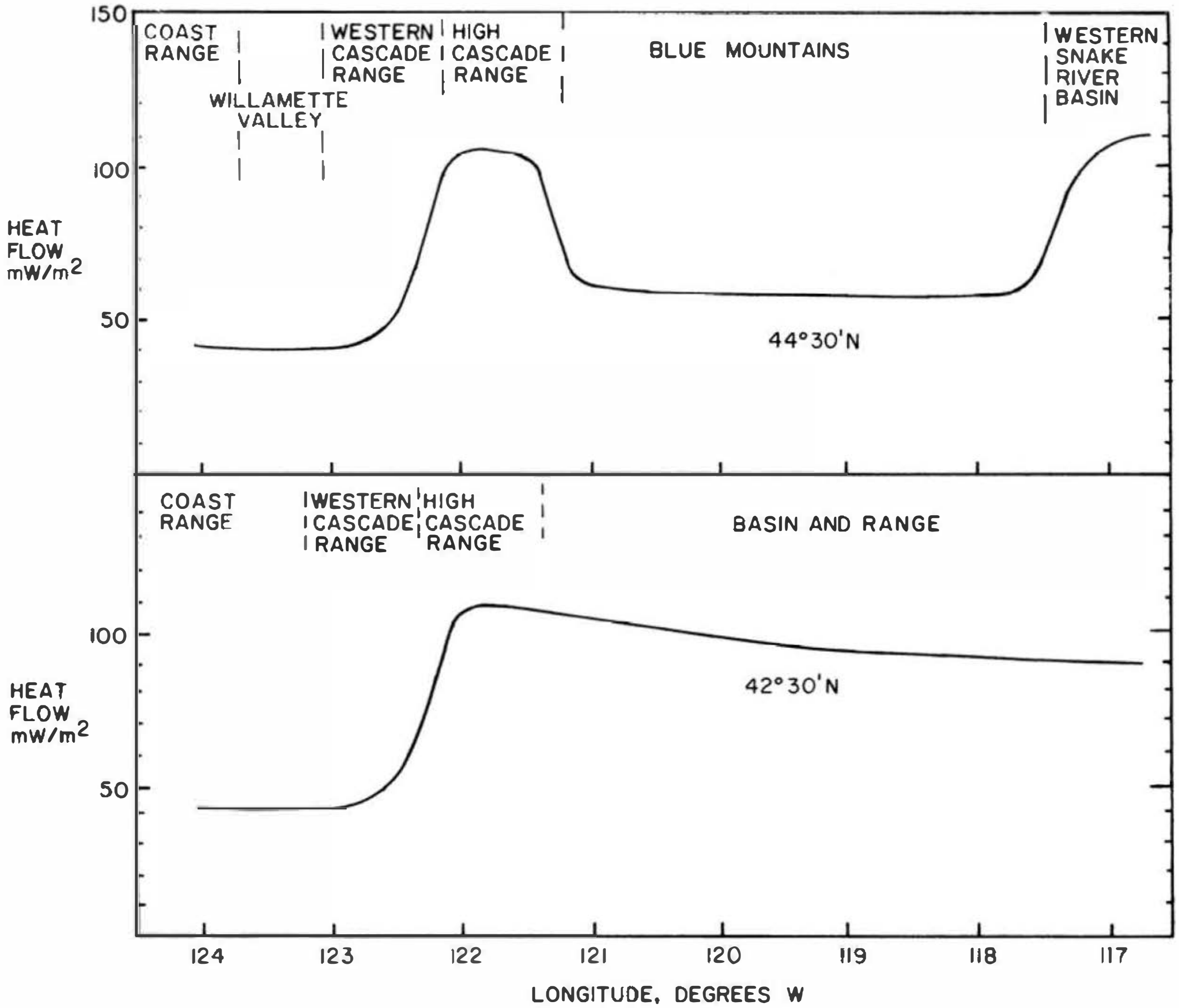

Figure 13: Generalized east-west heat flow profiles for bands of 1° latitude centered at latitudes 42°30'N. and 44°30'N.

Origin of Heat Flow Pattern

The overall pattern of heat flow in Oregon (Plate 1, Figure 4 and Figure 13) is related to the interaction of two large plates of the earth's surface over the past 10-20 m.y. During most of this time, a 100 km thick piece of crust and upper mantle (the lithosphere) of the Eastern Pacific Ocean, called the Juan de Fuca plate, has been slipping underneath North America. The plate initially starts to sink along an oceanic trench located just off the Oregon coast (Atwater, 1970). This material sinks to depths of 200-700 km into the mantle beneath the Pacific Northwest. As the plate of oceanic lithosphere sinks into the mantle, it initially is cold and absorbs heat from the overlying continental lithosphere. This absorption of heat is reflected by the subnormal heat flow values characteristic of the coastal provinces of Oregon. Such low heat flow zones are also typical of the coastal (outer arc) provinces around much of the circum-Pacific belt (Hasebe and others, 1970).

As the block sinks, it eventually begins to melt, and the volcanic rocks of the High Cascade Range reflect this melting. As the block continues to sink into the mantle, frictional heating supplies energy to the mantle overlying the sinking block. This energy, in a general way, causes the high heat flow characteristic of the eastern two-thirds of Oregon. At the latitude of Oregon, this belt of high heat flow extends from the High Cascade Range to the eastern edge of the Northern Rocky Mountains (Blackwell, 1969, 1971, 1978). The high heat flow zone extends north-south at least from western Canada (54°N) to the trans-Mexico volcanic belt, and has been called the Cordilleran Thermal Anomaly Zone (Blackwell, 1969) because it follows the Cordilleran mountain belt through most of North America. Within this belt of high heat flow, however, there are large variations in heat flow associated with particular volcanic and tectonic histories. Two subprovinces are clear from the data collected in Oregon, and a third probably exists. The combined Deschutes-Umatilla Plateau-Blue Mountains region is clearly quite different in heat flow from the Basin and Range-Snake River Plain-Owyhee Upland region. The High Cascade Range may have yet a different heat flow.

The origin of the thermal differences associated with these regions within the Cordilleran Thermal Anomaly Zone is related to their volcanic and tectonic history (Blackwell, 1978; Lachenbruch and Sass, 1978). The volcanism may reflect the motion of convection cells within the mantle, interaction of subduction heating with mantle hot spots, or local variations in the history of mantle and crustal melting and of tectonism. Blackwell (1978) has shown that, in general, areas within the Cordilleran Thermal Anomaly Zone that are characterized by volcanism younger than 17 m.y. old show very irregular but generally high heat flow values (greater than 80 mW/m^2; 2.0 HFU); whereas provinces in which volcanic activity has been older than 17 m.y. typically have heat flow values of approximately 60-80 mW/m^2 (1.5-1.9 HFU). This division is in reasonable agreement with the data collected in Oregon, in that the higher heat flow values are characteristic of the southeastern provinces, where extensive volcanism has taken place within the last 10-15 m.y.

A particular discrepancy in this pattern, however, is the relatively low heat flow characteristic of the Deschutes-Umatilla Plateau, where flood basalts were extruded approximately 12-14 m.y. ago; here, a somewhat higher heat flow might be expected. Further measurements should be carried out in the source area of the Columbia River Basalt near the common intersection of the states of Oregon, Washington and Idaho (Swanson and others, 1975), in order to see if there are significantly higher values associated with the source areas of the basalts.

Lachenbruch and Sass (1978) have related the high heat flow of the Basin and Range province to extension related to the normal faulting. In fact, both the volcanism and tectonism are involved in determining the thermal development of the lithosphere, and models of these phenomena are just now beginning to be evolved to explain the heat flow data.

The data imply interesting variations in the pattern of the sinking block of lithosphere. During the period from approximately 10-30 m.y. ago, the active andesite volcanoes characteristic of the present-day High Cascade Range appear to have been centered along the Western Cascade Range, and thus, during Oligocene and Miocene time, very high heat flow values characterized the Western Cascade Range. Between 5-10 m.y. ago, changes in the sinking block, or in the location of the melting point, caused a migration of the line of active volcanism to the east, to the present High Cascade Range. Subsequent to this migration, the sinking block has absorbed the heat from the Western Cascade block, resulting in subnormal heat flow values, even though approximately 10 m.y. ago, the heat flow must have been much above normal.

Convective Heat Transfer

As mentioned above, a summary of the locations of most known hydrothermal convection systems in Oregon is shown on the map of thermal springs by Bowen and Peterson (1970); Bowen and others (1978). Several probable hydrothermal convection systems without surface manifestations were also discovered during this study (the anomalies at Glass Buttes,

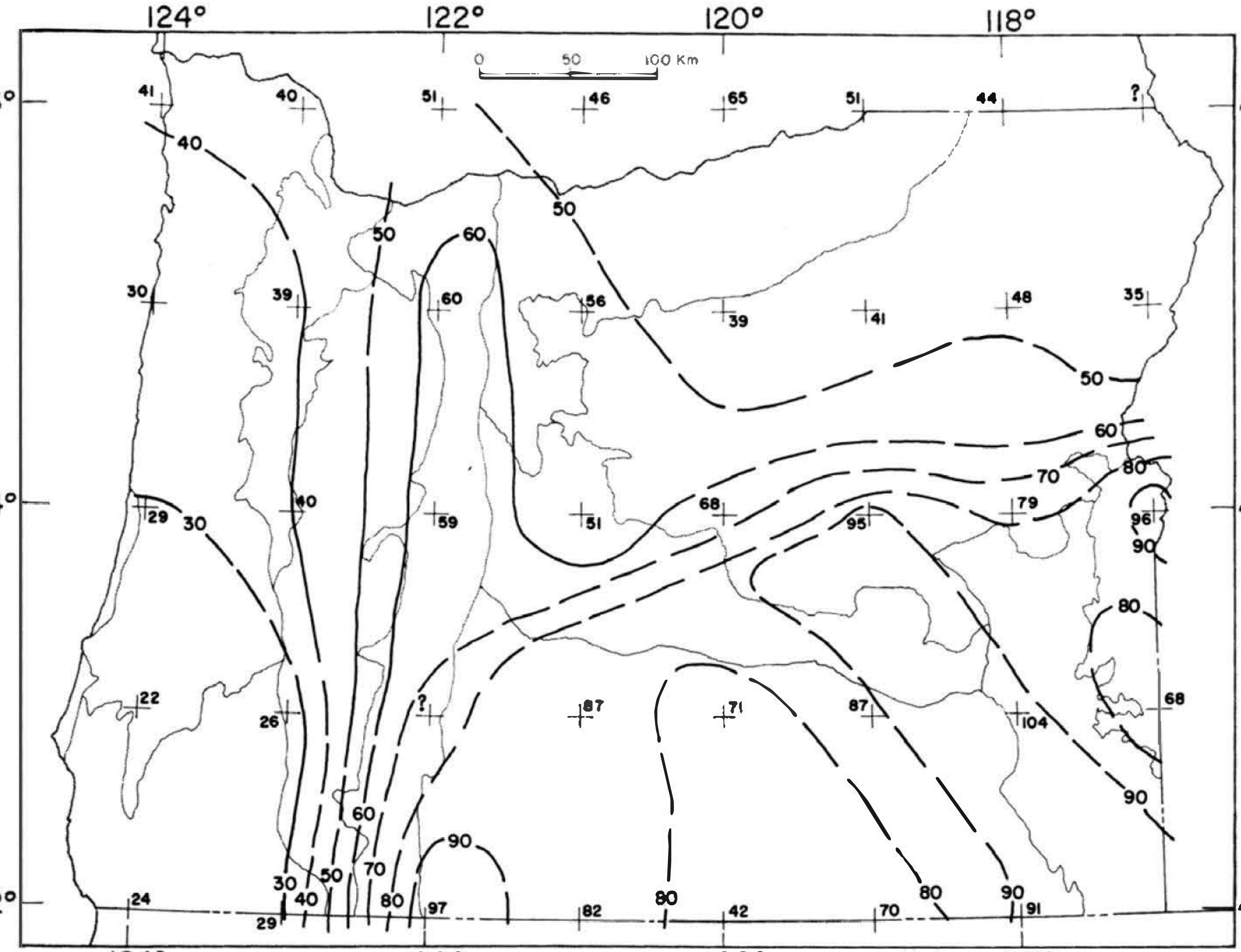

Figure 14: *Mean temperature at a depth of 1 km for 1° square areas of the State of Oregon. The temperature values were calculated by extrapolation of the observed gradient values, assuming a mean annual surface temperature of 10°C. In areas where the surface conductivity is less than 1.6 W/mK (4 TCU), temperature values form 500 m to 1 km were calculated using a gradient corresponding to a thermal conductivity of 1.6 W/mK (4 TCU). Data are contoured at 10°C intervals.*

Coyote Buttes, and Cow Hollow; Bowen and others, 1977). In some areas of the western United States, extensive regional aquifer systems destroy the conductive heat flow pattern over very large areas. The prime example of this phenomenon is the Snake Plain aquifer in eastern Idaho (Brott and others, 1976), where heat flow values are essentially zero over an area approximately 50 km wide and 200 km long. No such extensive aquifer systems have been recognized in Oregon at the present time; however, there are large areas where significant effects on the regional heat flow may be present due to aquifer systems, or due to large-scale hydrothermal convection systems. Examples where large areas of relatively low heat flow values have been observed are the Catlow Valley (Sass and others, 1976), the Harney Basin, and the area around Bend along the east side of the High Cascade Range. There also may be relatively slow regional aquifer motions which modify heat flow values associated with the Columbia Plateau Basalt. Relatively shallow drilling in the High Cascade Range so far indicates extensive groundwater flow in the young, porous volcanic rocks at the surface. However, except for the drill hole on the slopes of Mt. Hood, none of the holes drilled so far have penetrated below 150 m, so the extent and pervasiveness of aquifer motions are unknown.

Geothermal Energy Implications

Some of the geothermal implications of the heat flow data for the State of Oregon are relatively obvious, while others are somewhat more subtle. The heat flow maps (Plate 1, Figure 4) are directly related to the geothermal character of Oregon; however, a more obvious parameter is the temperature within the earth at a given depth. In order to analyze the subsurface temperatures in Oregon, an average Temperature at 1 km map was prepared (Figure 14). This map was made by contouring corrected geothermal gradients which had been averaged over 1° x 1° blocks (the data set was similar to but slightly more extensive than that used to prepare Figure 4). Temperatures at 1 km depth were calculated by extrapolation of the gradient, taking into account probable thermal conductivity changes in the depth range 0 to 1 km. The resulting temperatures were contoured at 10°C intervals. The assumed surface temperature was 10°C.

This map illustrates very clearly the contrasting thermal character, even at shallow crustal levels of the coastal low heat flow belt, the intermediate heat flow region in the northeast, and the high heat flow region in the High Cascade Range and in the southeast part of Oregon. In particular, *average* temperatures at a depth of 1 km are 80°C over almost one-third of the state, but are less than 30-40°C at this depth in the western one-third of the state.

Obviously, this map cannot be used to predict temperature at a specific point, because as discussed above, the actual heat flow at a given point (particularly in southeastern Oregon) is extremely variable on a local scale. Furthermore, large scale variations related especially to basins and ranges (see Figure 9) definitely exist. Nonetheless, this sort of map shows, in an intuitive way, the relative geothermal potential of the various areas within the state of Oregon.

The most obvious implication is that, from a regional point of view, the likelihood of high temperature geothermal systems (greater than 150°C) is greatest in the High Cascade Range and in the southeastern provinces of Oregon. The northeastern provinces have somewhat less likelihood of high temperature geothermal resources, while the coast provinces have little or no possibility of high temperature geothermal resources at currently explorable depths.

The low heat flow, low crustal temperature, lack of hot springs, and absence of post-Pliocene volcanic rocks in the Coast Range, Klamath Mountains, Willamette Valley and Western Cascade Range (exclusive of its eastern boundary) indicate a low potential for geothermal energy development. Uses of geothermal heat in the western part of Oregon will be restricted to those requiring relatively low temperature (less than 100°C), such as space heating or use of the mean annual ground temperature in heat pump applications. Existing deep holes or deep holes drilled in the future for other purposes and abandoned might be taken over for use as warm water sources.

Similarly, most of the northeastern part of Oregon will have few high temperature geothermal systems, because this area, although having high heat flow, has only slightly higher crustal temperature than the western one-third of Oregon. Several significant hot springs or groups of hot springs occur in the Blue Mountains, especially in the Baker-La Grande areas. Locally higher heat flow and significant geothermal potential may be present in these areas. At this time, the data are not sufficient in the vicinities of these areas to fully evaluate their geothermal potentials. No thermal anomalies have been found within the Deschutes-Umatilla Plateau in Oregon. However, just across the border in Washington, a well at 6N/34E- 7c has a temperature of 40°C at 400 m. This well has the highest gradient found so far in either the Washington or Oregon portions of the Columbia Plateau.

Most of the geothermal potential of Oregon for electrical power generation, and much of the geothermal potential for space and process heating, exists in the High Cascade Range-Western Cascade boundary area, along with the Western Snake River Basin, Owyhee Up-land, High Lava Plains and Basin and Range provinces. Even in these regions, not all areas will be suitable for geothermal development, although average heat flow values, geothermal gradients and crustal temperatures are very high. It is obvious that even in the areas of highest heat flow, regions of low heat flow do exist, and the presence of high temperature geothermal systems usually implies low temperature recharge areas as well. Therefore, location of geothermal resources will involve exploration to evaluate the actual geothermal gradient and heat flow in specific areas of interest. Exploration cannot be done simply by drilling production wells in a given area because of its average heat flow or because of apparent geologic potential. The data do verify, however, that at least one-third of the State of Oregon has as high or higher geothermal potential than any other area of equivalent size in the western United States, and that many possibilities for commercial geothermal power development exist.

So far, geothermal exploration is in its infancy in Oregon; through 1978 only four exploration tests have been drilled to depths greater than 1 km: one by Thermal Power Company near Klamath Falls; one by Gulf Oil Company near Lakeview; one by the San Juan Oil Company in the Warner Valley; and one by a combined state-federal-private consortium near Mt. Hood. The first three wells located temperatures greater than 100°C, but not high enough for production of electric power. In much of the area of Holocene volcanism where high temperature geothermal resources can be expected, exploration has been dis-couraged by lack of obvious surface manifestations. An example is the eastern slope of the High Cascade Range, a region where youthful volcanism is obvious, but in which there is nearly a complete lack of thermal springs. Throughout this region, the lack of thermal springs is probably associated with the carapace of the young volcanic rocks which allows the subsurface flow of groundwater to dissipate any indications of subsurface heat by dis-persion and mixing. It is obvious that there is geothermal potential in these regions of Oregon, and continued exploration will result in the location of important reservoirs of both high and low temperature geothermal energy.

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REFERENCES

Allen, J.E., 1966, The Cascade Range volcano-tectonic depression of Oregon, *in* Transactions of the Lunar Geological Field Conference, Bend, Oregon, August 1965: State of Oregon Dept. of Geol and Mineral Indus., 98 p.

Armstrong, R.L., Taubeneck, W.H., and Hales, P.O., 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington, and Idaho: Geol. Soc. American Bull., v. 88, p. 397-411.

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. America Bull., v. 81, p. 3513-3536.

Baldwin, W.M., 1976, K-Ar ages of Laurel Hill pluton and dike, Oregon: The Ore Bin, v. 32, p. 211-215.

Birch, F., 1950, Flow of heat in the Front Range, Colorado: Geol. Soc. America Bull, v. 61, p. 567-630.

Birch, F., Roy, R.F., and Decker, E.R., 1968, Heat flow and thermal history in New England and New York, *in* Studies of Appalachian geology: Northern and maritime, Zen, W., White W.S., Hadley, F.B., and Thompson, J.B., *eds.*: New York Interscience, p. 437-341.

Blackwell, D.D., 1969, Heat flow determinations in the northwestern United States: Journ. Geophys. Res., v. 74, p. 922-1007.

_________, 1971, The thermal structure of the continental crust, *in* The structure and physical properties of the earth's crust, Heacock, J.G., *ed.*: American Geophys. Union, Geophys. Mono. Series., v. 14, p. 169-184.

_________, 1974, Terrestrial heat flow and its implications on the location of geothermal reservoirs in Washington, *in* Energy resources of Washington: Washington Dept. of Natural Resources, Div. of Geol. and Earth Resources, Info. Circ. 50, p. 24-33.

_________, 1978, Heat flow and energy loss in the western United States, *in* Cenozoic tectonics and regional geophysics of the western Cordillera, Smith, R.B., and Eaton, G.P., *eds.*: Geol. Soc. of America, Memoir 152, p. 175-208.

Blackwell, D.D., Steele, J.L., and Brott, C.A., 1979, Terrain correction technique for terrestrial heat flow measurements, submitted to Jour. Geophys. Res.

Bowen, R.G., 1972, Geothermal gradient studies in Oregon: The Ore Bin, v. 34, p. 68-71.

Bowen, R.G., and Blackwell, D.D., 1973, Progress report on geothermal measurements in Oregon, The Ore Bin., v. 35, p. 6-7.

_____, 1975, The Cow Hollow geothermal anomaly, Malheur County, Oregon: The Ore Bin, v. 37, p. 109-201.

Bowen, R.G., and Peterson, N.V., 1970, Thermal springs and wells of Oregon: Oregon Dept. of Geol. and Mineral Indus., Misc. Paper 14.

Bowen, R.G., Blackwell, D.D., and Hull, D.A., 1977, Geothermal exploration studies in Oregon: Oregon Dept. Geol. and Mineral Indus., Misc. Paper 19, p. 50.

Bowen, R.G., Peterson, N.V., and Riccio, J.F., 1978, Low to intermediate temperature thermal springs and wells in Oregon: Oregon Dept. of Geol. and Mineral Indus., Geologic Map Series, No. 10.

Bowen, R.G., Blackwell, D.D., Hull, D.A., and Peterson, N.V., 1976, Progress report on heat-flow study of the Brothers fault zone, central Oregon: The Ore Bin, v. 38, p. 39-46.

Brott, C.A., 1976, Heat flow and tectonics of the Snake River Plain, Idaho (Ph.D. thesis): Dallas, Texas, Southern Methodist University, p. 197.

Brott, C.A., Blackwell, D.D., and Mitchell, J.C., 1976, Heat flow study of the Snake River Plain, Idaho: Idaho Dept. Water Resources Water Inf. Bull. 30, Pt. 8, 195 p.

_____, 1978, Tectonic implications of the heat flow of the western Snake River Plain, Idaho: Geol. Soc. America Bull., v. 89, p. 1697-1707.

Chapman, D.C., and Pollack, H.N., 1975, Global heat flow: A new look: Earth and Planetary Sci. Letters, v. 28, p. 23-32.

Couch, R., and Baker, B., 1977, Geophysical investigations of the Cascade Range in central Oregon: Final report, U.S. Geol. Survey, grant no. 14-08-0001-G-231, 55 p.

Crandell, D.R., and Rubin, M., 1977, Late-Glacial and Postglacial eruptions at Mt. Hood, Oregon (Abstract): Geol. Soc. America, Abstracts with Programs, v. 9, p. 406.
Friedman, I., 1977, Hydration dating of volcanism at Newberry Crater, Oregon: Journ. Res., U.S. Geol. Surv., v. 5, p. 337-342.
Gosnold, W.D., 1976, A model for uranium and thorium assimilation by intrusive magmas and crystallizing plutons through interactions with crustal fluids (Ph.D. thesis): Dallas, Texas, Southern Methodist University, p. 131.
Hammond, P.E., 1976, Geothermal model for the Cascade Range: Unpublished manuscript, 20 p.
Hasebe, K., Fujii, N., and Uyeda, S., 1970, Thermal processes under island arcs: Tectonophysics, v. 10, p. 335-355.
Hodge, E.T., 1936, Geology of the Lower Columbia River: Geol. Soc. America Bull., v. 49, p. 215-219.
Hull, D.A., 1975a, Geothermal studies in the Vale area, Malheur County, Oregon: The Ore Bin, v. 37, p. 104-106.
____, 1975b, Geothermal gradient data, Vale area, Malheur County, Oregon: Oregon Dept. Geol. and Mineral Indus., Open-File Report 0-75-4, p. 18.
____, 1976, Electrical resistivity survey and evaluation of the Glass Buttes geothermal anomaly: Oregon Dept. of Geol. and Mineral Indus., Open-File Report 0-76-1, 11 p.
Hull, D.A., Blackwell, D.D., Bowen, R.G., and Peterson, N.V., 1977a, Heat flow study of the Brothers fault zone, Oregon: Oregon Dept. of Geol. and Mineral Indus., Open-File Report 0-77-3, p. 24.
Hull, D.A., Bowen, R.G., Blackwell, D.D., and Peterson, N.V., 1976, Geothermal gradient data, Brothers fault zone, central Oregon: Oregon Dept. of Geol. and Mineral Indus., Open-File Report 0-76-2, p. 24.
Hull, D.A., Bowen, R.G., Blackwell, D.D., and Peterson, N.V., 1977b, Preliminary heat-flow map and evaluation of Oregon's geothermal energy potential: The Ore Bin, v. 39, p. 109-123.
Hull, D.A., Blackwell, D.D., Bowen, R.B., Peterson, N.V., and Black, G.L., 1977c, Geothermal gradient data: Oregon Dept. of Geol. and Mineral Indus., Open-File Report 0-77-2, p. 134.
Lachenbruch, A.H., 1959, Periodic heat flow in a stratified medium with application to permafrost problems, U.S. Geol. Surv. Bull. 1083-A, p. 36.
__________, 1968, Preliminary geothermal model of the Sierra Nevada: Jour. Geophys. Res., v. 73, p. 6977-6989.
Lachenbruch, A.H., and Sass, J.H., 1973, Thermo-mechanical aspects of the San Andreas fault: Stanford Univ. Pub., Geol. Sci., v. 13, p. 192-205.
__________, 1977, Heat flow in the United States and the thermal regime of the crust, *in* The earth's crust, its nature and physical properties, Heacock, J.G., *ed.*: American Geophys. Union Geophys. Mono. 20, p. 626-675.
__________, 1978, Models of extending lithosphere and heat flow in the Basin and Range province, *in* Cenozoic tectonics and regional geophysics of the western Cordillera, Smith, R.B., and Eaton, G.P., *eds.*: Geol. Soc. of America, Memoir 152, p. 209-250.
Lawrence, R.D., 1976, Strike-slip faulting terminates the Basin and Range province in Oregon: Geol. Soc. America Bull., v. 87, p. 846-850.
Lienau, P.J., 1978, Agribusiness geothermal energy utilizaton potential of Klamath and Western Snake River Basins, Oregon: DOE/DGE Final Technical Report IDO/1621-1, 180 p.
Lovering, T.S., and Goode, H.D., 1963, Measuring geothermal gradient in drill holes less than 60 feet deep, East Tintic District, Utah: U.S. Geol. Surv. Bull. 1172, 48 p.
MacLeod, N.S., Walker, G.W., and McKee, E.H., 1976, Geothermal significance of eastward increase in age of late Cenozoic rhyolite domes in southeastern Oregon, *in* Proc. 2nd United Nations symposium on the development and use of geothermal potential, v. 1: Washington, D.C., U.S. Govt. Printing Office, p. 465-474.
Newton, V.C., and Corcoran, R.E., 1963, Petroleum geology of the Western Snake River Basin: Oil and Gas Investigations No. 1, Oregon Dept. of Geol. and Mineral Indus., 67 p.
Peck, D.L., Griggs, A.B., Schlicker, H.G., and Dole, H.M., 1964, Geology of the central and northern parts of the Western Cascade Range in Oregon: U.S. Geol. Surv. Prof. Paper 449, 56 p.
Polyak, B.G., and Smirnov, Ya.B., 1968, Relationship between terrestrial heat flow and the tectonics of continents: Geotectonics, v. 4, p. 205-213.

Renner, J.H., White, D.E., and Williams, D.L., 1975, Hydrothermal convection systems, *in* Assessment of geothermal resources of the United States, White, D.E., and Williams, D.L., *eds.*: U.S. Geol. Surv. Circ. 726, p. 5-57.
Roy, R.F., Blackwell, D.D., and Birch, F., 1968a, Heat generation of plutonic rocks and continental heat flow provinces: Earth and Planetary Sci. Letters, v.5, p. 1-12.
Roy, R.F., Decker, E.R., Blackwell, D.D., and Birch, F., 1968b, Heat flow in the United States: Jour. Geophys. Res., v.73, p. 5207-5221.
Roy, R.F., Blackwell, D.D., and Decker, E.R., 1972, Continental heat flow *in* The nature of the solid earth, Robertson, E.C., *ed.*: New York, McGraw-Hill Book Co., p. 506-543.
Sammel, E.A., 1976, Hydrologic reconnaissance of the geothermal area near Klamath Falls, Oregon: U.S. Geol. Surv. Open-file Report WRI 76-127, p. 129.
Sass, J.H., and Sammel, E.A., 1976, Heat flow data and their relation to observed geothermal phenomena near Klamath Falls, Oregon: Jour. Geophys. Res., v. 81, p. 4863-4868.
Sass, J.H., Lachenbruch, A.H., and Monroe, R.J, 1971a, Thermal conductivity of rocks from measurements on fragments and its application to heat flow determinations: Jour. Geophys. Res., v. 76, p. 3391-3401.
Sass, J.H., Lachenbruch, A.H., Monroe, R.J., Green, G.W., and Moses, T.H., Jr., 1971b, Heat flow in the western United States: Jour. Geophys. Res., v. 76, p. 6356-6431.
Sass, J.H., Galanis, S.D., Jr., Monroe, R.J., and Urban, T.C., 1976, Heat flow data from southeastern Oregon: U.S. Geol. Surv. Open-file Report 76-217, p. 52.
Sass, J.H., Ziagos, J.P., Wollenberg, H.A., Monroe, R.J., di Somma, D.E., and Lachenbruch, A.H., 1977, Application of heat flow techniques to geothermal energy exploration, Leach Hot Springs area, Grass Valley, Nevada: U.S. Geol. Surv. Open-file Report 77-762, 125 p.
Schuster, J.E., Blackwell, D.D., Hammond, P.E., and Huntting, M.T., 1978, Heat flow studies in the Steamboat Mountain-Lemhi Rock area, Skamania County, Washington: Washington Dev. of Geol. and Earth Resources, Information Circ. 62, 56 p.
Sutter, J.F., 1978, K/Ar ages of Cenozoic volcanic rocks from the Oregon Cascades west of 121°30': Isochron/West, no. 21, p. 15-21.
Swanberg, C.A., and Blackwell, D.D., 1973, Areal distribution and geophysical significance of heat generation in the Idaho batholith and adjacent intrusions in eastern Oregon and western Montana: Geol. Soc. of America Bull., v. 83, p. 1261-1282.
Swanson, D.A., Wright, T.L., and Helz, R.T., 1975, Linear vent systems and estimated rates of magma production and eruption for the Yakima Basalt on the Columbia plateau: American Jour. Sci., v. 275, p. 877-905.
Thayer, T.P., 1936, Structure of the North Santiam River section of the Cascade Mountains in Oregon: Jour. Geol, v. 44, p. 701-716.
Walker, G.E., 1969, Geology of the High Lava Plains province: *in* Mineral and Water Resources of Oregon, Oregon Dept. of Geol. and Mineral Indus. Bull. 64, p. 77-79.
Walker, G.W., 1970, Cenozoic ash-flow tuffs of Oregon: The Ore Bin, v. 32, p. 97-115.
Waring, G.A., 1965, Thermal springs of the United States and other countries of the world-A summary: U.S. Geol. Surv. Prof. Paper 492, 383 p.
Williams, H. 1957, A reconnaissance geologic map of the central position of the High Cascade Mountains: Oregon Dept. of Geol. and Mineral Indus. Map.

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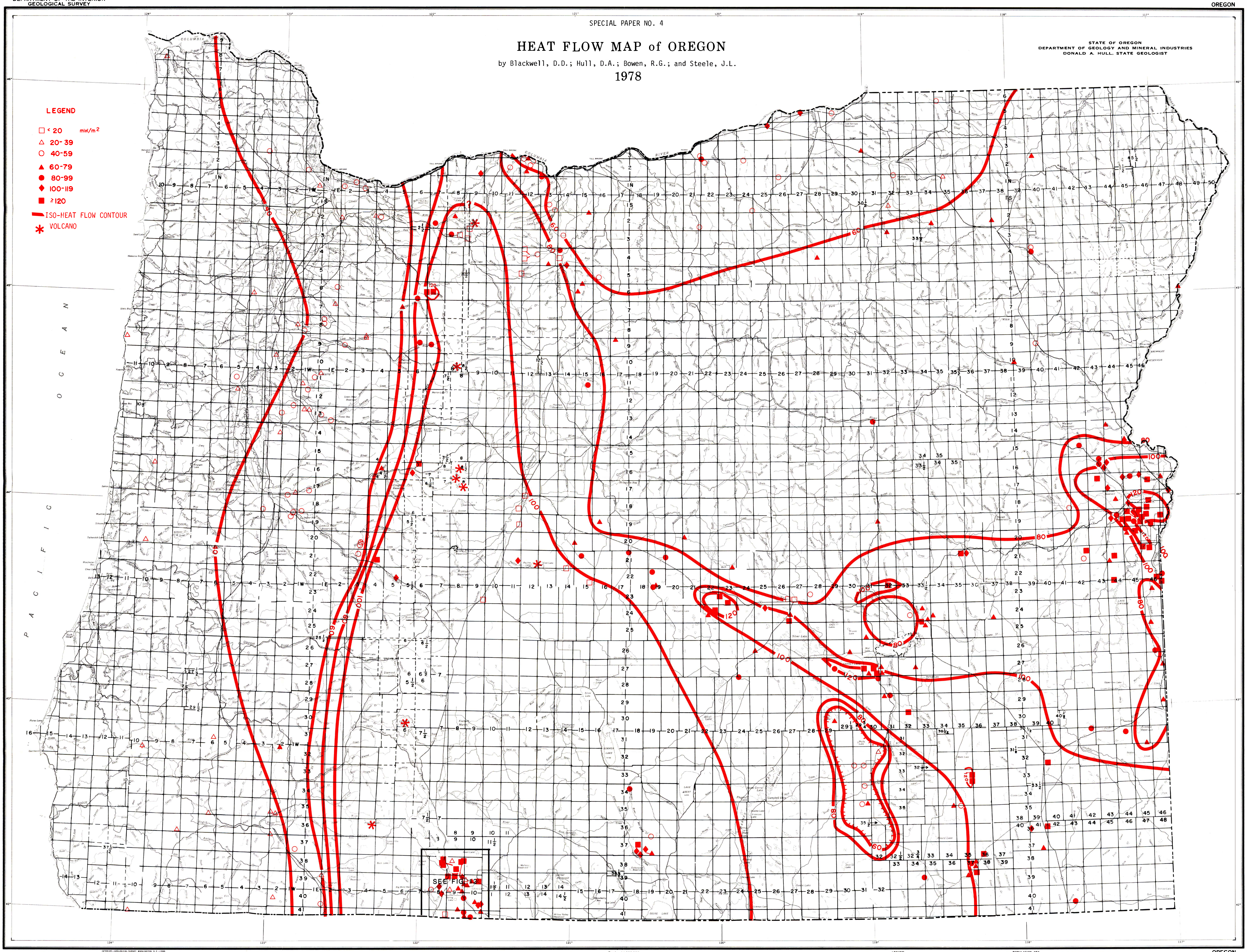

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