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VOL. 81, NO. 26 JOURNAL OF GEOPHYSICAL RESEARCH SEPTEMBER 10, 1976

Heat Flow Data and Their Relation to Observed Geothermal Phenomena Near Klamath Falls, Oregon

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Two holes were drilled to depths of about 180 m in the Lower Klamath Lake basin south of Klamath Falls, Oregon, to obtain heat flow data and to provide estimates of the thermal conductivity of the valley fill. Twenty-nine thermal conductivity determinations on eight cores give a mean conductivity of 1.82 mcal/cm s °C (0.75 W/m °K). Curvature in the upper 50 m of both temperature profiles indicates a decrease in surface temperature of about 1.8°C, presumably resulting from reclamation of what was marshland in the early part of this century. A surprisingly low heat flow of 0.3 HFU (1 HFU = 10^{-6} cal/cm^2 s = 41.8 mW/m^2) was measured at site LS near the center of the basin. At site OC-1, 7 km east of LS and 2 km from the Klamath Hills geothermal zone, the heat flow was 1.44 HFU, also a low value in this setting. Temperature profiles in 15 unused water wells in the area had linear gradients ranging from 47° to 170°C/km. The corresponding lower limits of heat flow (conductivities measured at the two heat flow sites being used) range from 0.8 to 3.1 HFU. These variations in heat flow evidently are caused by temperature variations in a convecting system within the near-surface volcanic rocks and do not provide firm constraints on the nature of heat sources at depth.

INTRODUCTION

There is considerable interest in the geothermal potential of the Klamath Falls area in southern Oregon (see inset, Figure 1). Klamath Falls is situated in the western Basin and Range province near its boundary with the Cascade province in an area cut by numerous faults that produce NW-SE trending horst and graben structures [*Peterson and McIntyre*, 1970]. Volcanic activity has occurred intermittently in the area and in surrounding regions since early Tertiary time, the most recent events being the extrusion of lavas in the southern part of the Lower Klamath Lake basin in California and the explosive eruption 6600 years ago [*Newcomb and Hart*, 1958] of Mount Mazama (now Crater Lake), about 50 km north of Upper Klamath Lake. With the exception of the eruptive rocks of Mount Mazama, most Pliocene and younger volcanic rocks are of andesitic or basaltic composition. Silicic volcanic rocks, which elsewhere are most often associated with geothermal reservoirs, are not present in the Klamath Falls area, the nearest examples being Black Hills and Yamsay Mountain, which are 4–5 m.y. old [*MacLeod et al.*, 1975].

The geothermal resources in the Klamath Falls area have been used for space heating and agriculture for some time [*Lund et al.*, 1975], but no systematic appraisal of the geothermal energy potential of the region has as yet been completed. The U.S. Geological Survey (USGS) is currently engaged in a multidisciplinary study of the geology, hydrology, and hydrothermal phenomena in the area. In addition, the Geo-Heat Utilization Center of the Oregon Institute of Technology has recently begun a study of hot wells in the urban area of Klamath Falls.

Peterson and Groh [1967] studied surface geology and well data and suggested that the near-surface hydrothermal regime results from the heating of shallow groundwater by steam arising from a deeper geothermal zone. They suggested that the Plio-Pleistocene sedimentary-pyroclastic rocks might form an impervious cap on the deeper system.

In the present work, temperatures were measured in about 40 wells within an area of about 1000 km^2 to examine the near-surface hydrothermal regime. Temperature measurements were made in a variety of ways, but they were obtained primarily with a commercial thermistor probe having a digital readout and an overall accuracy of ±0.05°C between 0° and 100°C. This apparatus was in turn calibrated against the more precise (~±0.01°C) USGS temperature-logging system [see *Sass et al.*, 1971*b*] used for most other measurements. Measurement intervals ranged from 3 m for most wells to 0.3 for the USGS 'continuous' logging mode used for most of the deeper (>150 m) wells. Maximum thermometer readings obtained by *Van Orstrand* [1938] were used for well KFO (Figure 2).

Many of the wells penetrated about 100 m of Quaternary lake sediments having fairly uniform physical properties. In order to relate temperature gradients in these wells to the geothermal flux and to obtain independent estimates of heat flow, two 180-m wells were drilled at locations about 7 km apart in the southern part of the Lower Klamath Lake valley (LS and OC-1, Figure 1). Eight 1.5-m cores were obtained between depths of 30 and 180 m in an effort to characterize the mean thermal conductivity and its variation with depth.

OBSERVATIONS

Figure 1 shows the locations of the heat flow holes (LS and OC-1) and other thermal observation wells in relation to the major geologic features of the area. In Figures 2 and 3, temperature profiles from the heat flow holes and from about 40 unused water wells illustrate the gross patterns of temperature variation. Individual profiles discussed in the text are labeled in Figures 2 and 3. In common with observations made by *Lachenbruch et al.* [1976] within the Long Valley caldera, three distinct types of profiles were observed: (1) nearly isothermal profiles with temperatures in the range 10°–12°C, which we interpret as indicating hydrologic recharge, (2) quasi-conductive profiles, which extrapolate upward to surface temperatures in the range 10°–13°C and are fairly linear but in some instances have small easily identifiable hydrologic disturbances over short lengths, and (3) convex upward profiles with elevated temperatures, which represent discharging parts of the hydrothermal system. A fourth group includes profiles exhibiting various types of curvature, indicating a combination of upward and downward flow, some depth intervals apparently

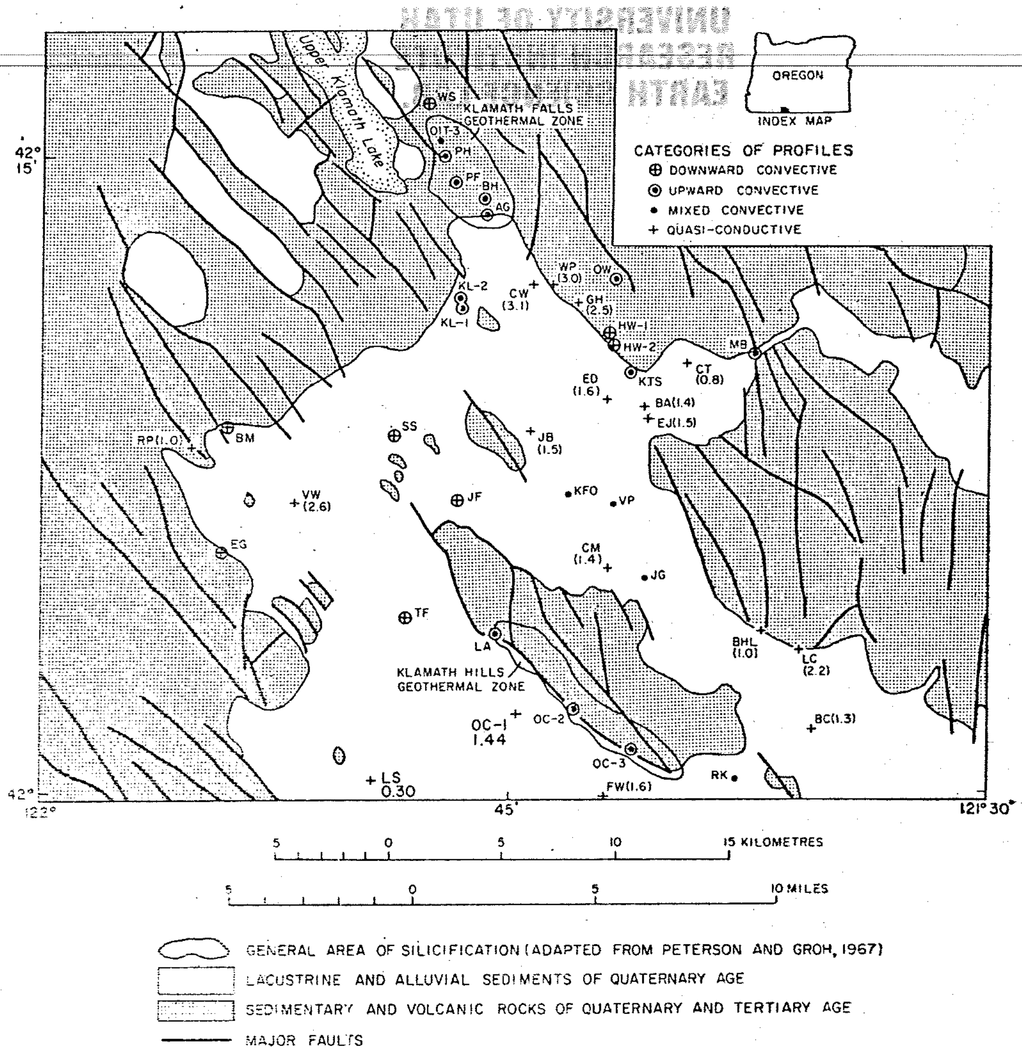

Fig. 1. Geologic sketch map of the Klamath Falls area [after *Peterson and McIntyre,* 1970] showing locations and categories of wells studied. For wells with quasi-conductive (linear) profiles, the lower limit of heat flow (q_{min}, based on an assumed thermal conductivity of 1.8 mcal/cm s °C) is shown in parentheses. Heat flow determinations at LS and OC-1 are also shown. The inset gives the outline of Oregon showing location of the map area.

having no water movement. The distribution of the four types of profile is shown in Figure 1.

Wells in the first category, relatively cold isothermal profiles, are located mainly in the central areas of the valley floor. Measurements of hydraulic head in these and similar wells indicate that the heads decline with depth and that a downward hydraulic gradient exists over much of the lowland area (unshaded area, Figure 1). Because most of these wells are accessible to vertical water movement through large sections of the valley fill (slotted casing, uncemented casing, or no casing), downward flow undoubtedly occurs in the wells between permeable zones. The extent to which the nearly isothermal profiles also reflect downward movement in the formations depends on the vertical permeability, for which we have no data. For wells of this type it is impossible to distinguish intrabore flow from water flow in the formation from the temperature profile alone. Temperature measurements on water pumped from some of the wells suggest, however, that the aquifers are hotter than we would infer from temperature profiles obtained before pumping, and we conclude that downward water flow within the well accounts for at least some of the near-isothermal profiles.

The convex upward profiles may also be influenced by upward flow within the wells. This can be seen in PH (Figure 2*a*), where the profile may be compared with bottom-hole temperatures obtained during drilling of another well about 140 m distant (pluses, Figure 2*a*). The bottom-hole temperatures indicate that a nearly linear thermal gradient exists in the interval in which the profile from PH has its maximum upward curvature [see also *Sammel,* 1976].

Temperature profiles indicating upward-flowing warm-to-hot water were found in the Klamath Falls geothermal zone (Klamath Falls–Altamont area) and the Klamath Hills geothermal zone on the southwest flank of Klamath Hills (Figure 1). The highest temperatures measured in this study (80°–93°C) were in Klamath Falls (PH, PF, BH, and AG, Figures 1 and 2), but near-boiling temperatures have also been observed from at least two wells in the Klamath Hills geothermal zone [*Peterson and Groh,* 1967].

HEAT FLOW DETERMINATIONS

One heat flow hole (LS) was sited near the center of the Lower Klamath Lake valley, and the other (OC-1) about 2 km west of the southwest-bounding fault of the Klamath Hills horst [*Peterson and McIntyre,* 1970]. The holes were drilled with a rotary rig, and 1.5-m cores were obtained at intervals of 30–90 m. The cores were placed in plastic tubes and sealed until thermal conductivity measurements were performed

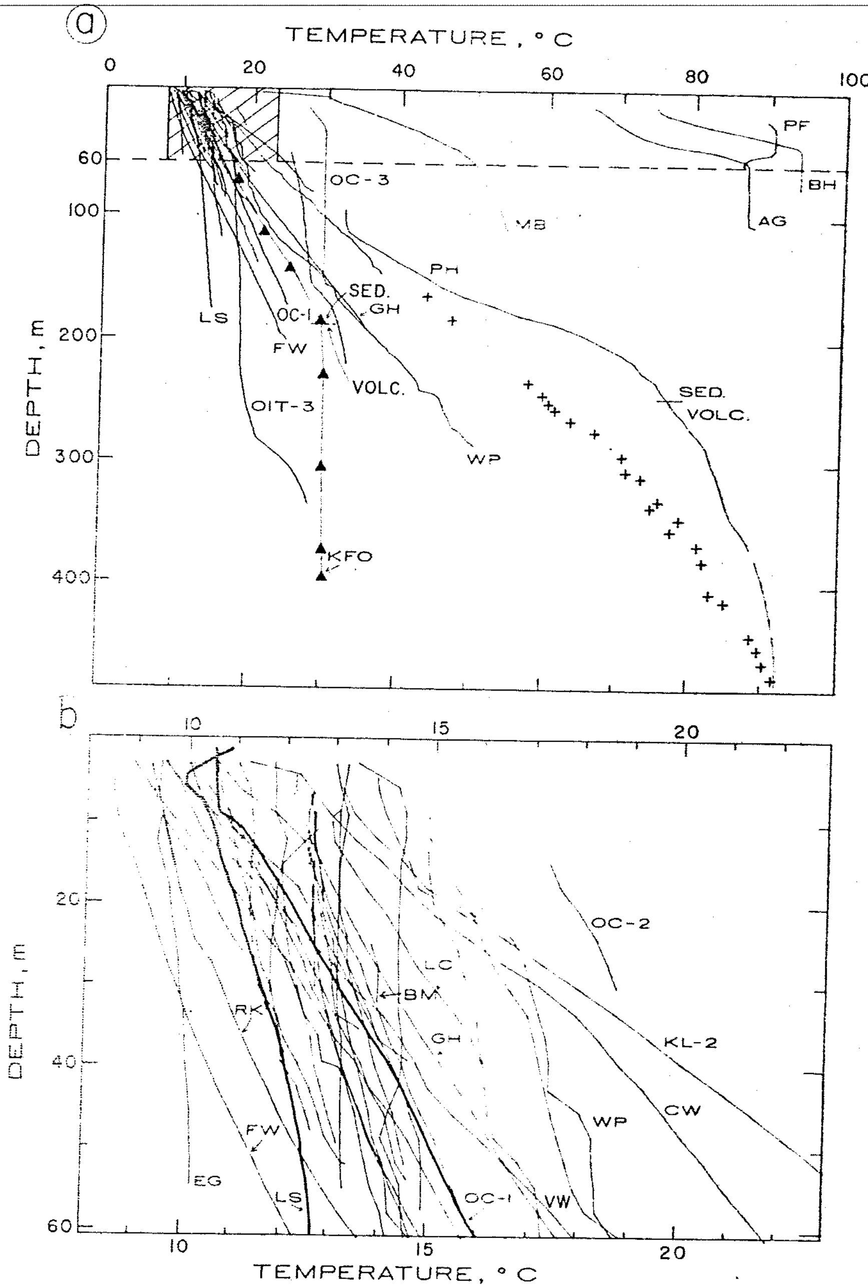

Fig. 2. (*a*) Temperature profiles for all wells measured in the Klamath Falls area. Triangles are temperature measurements in KFO [*Van Orstrand*, 1938]. Pluses are bottom-hole temperatures in a well near PH. (*b*) Detail of hatched part of Figure 2*a*.

within a week or so of drilling. Upon completion of drilling, 3.8-cm-ID plastic pipe was grouted in place to permit later temperature observations. We emphasize here that although the grouting operation is time consuming and expensive, it is a necessary part of any heat flow study that seeks to differentiate between fluid flow within the formation and fluid flow in the hole.

Temperatures and thermal conductivities in the heat flow holes are shown in Figure 4. The greater temperature gradient in the upper 50 m of both holes cannot plausibly be ascribed to layering in the sediments because (1) drill cuttings were uniform in appearance over the entire length of both holes, (2) conductivity measurements were made on samples from depths of 30 m in both holes, and these conductivities were the same as those determined at greater depths, and (3) both gradients are greater than the deeper one by the same amount (~30°/km) rather than by the same fraction, as we would expect from layering.

The history of marsh drainage and conversion to agriculture between 1900 and 1920 suggests that a drop in surface temperature is responsible for the curvature in the temperature profiles. Below the zone of annual variation (~10 m) the shallow parts of the temperature profiles extrapolate to about the same surface temperature (~9.7°C, Figure 4), which we should expect, since the surface settings of the two sites are now identical. By contrast, the deeper gradients (solid lines, Figure 4) extrapolate to surface temperatures of 11.2° and 11.7°C for OC-1 and LS, respectively. Surface temperature differences of this magnitude are reconciled easily in terms of the variations in surface conditions which must have existed prior to the conversion of these lowlands from natural marsh to agricultural land.

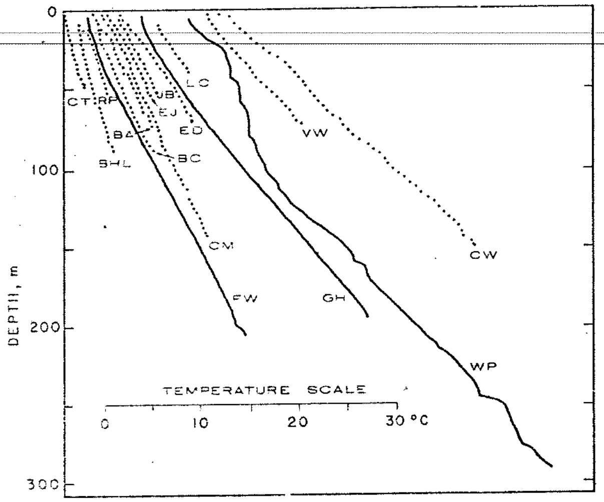

Fig. 3. Temperature profiles with arbitrary temperature origin for wells used to estimate minimum heat flows (q_{min}, Table 2). Individual points are shown for the most common measurement interval (3 m). Temperatures measured at ~0.3-m intervals ('continuous mode') are shown as solid lines.

The dashed curves in Figure 4 represent the theoretical present-day temperature profiles for a sudden lowering of the surface temperature to a mean value of about 9.7°C fifty years ago in a material of thermal diffusivity of 0.003 cm²/s [*Carslaw and Jaeger*, 1959, equation 2, p. 63]. For longer times or higher diffusivities the depth of penetration of the disturbance would be greater than that indicated in the temperature profiles.

Thermal conductivities were measured on the eight cores from the two heat flow holes by means of the needle probe system described by *Lachenbruch and Marshall* [1966]. Both holes penetrated relatively uniform silty clays with minor amounts of fine sand. Twenty-nine values of conductivity ranged from 1.47 to 2.14 mcal/cm s °C (Figure 4). The low mean conductivity of this water-saturated material (1.82 ± 0.04) can be attributed to a combination of high porosity, the predominance of low-density (~2.3 g/cm³) clay minerals, and the presence of some organic material. Variable amounts of plagioclase feldspar ranging generally from 5 to 15% with one example of ~25% (OC-1, 91 m, Figure 4) were observed (B. J. Anderson, written communication, 1975). The samples showed evidence of contamination by drilling mud, and for this reason, no porosity or permeability measurements were attempted. In general, we have found that thermal conductivity of poorly consolidated sediments is easier to measure than most other possibly correlative physical properties (e.g., density, seismic velocity, porosity, or permeability). Thermal conductivity measurements on cores are straightforward [see, e.g., *Sass et al.*, 1971*b*], and measurements of the conductivity of the solid component of sedimentary rocks from drill cuttings can be combined with rough estimates of porosity to provide reasonable values of bulk conductivity [*Sass et al.*, 1971*a*]. The values of conductivity shown in Figure 4 are consistent with those measured in lake sediments of volcanic origin in other parts of southern Oregon and northwestern Nevada [*Sass et al.*, 1976; U.S. Geological Survey, unpublished data, 1975, 1976]. Furthermore, they are consistent with the low thermal diffusivity required to explain the curvature in the upper 70 m of both holes.

The principal elements of the heat flow calculations, including geographic coordinates and elevation, are summarized in Table 1. Because there is no variation in thermal conductivity, the striking contrast in temperature gradients (Figure 4) between sites located only 7 km apart is directly reflected in the

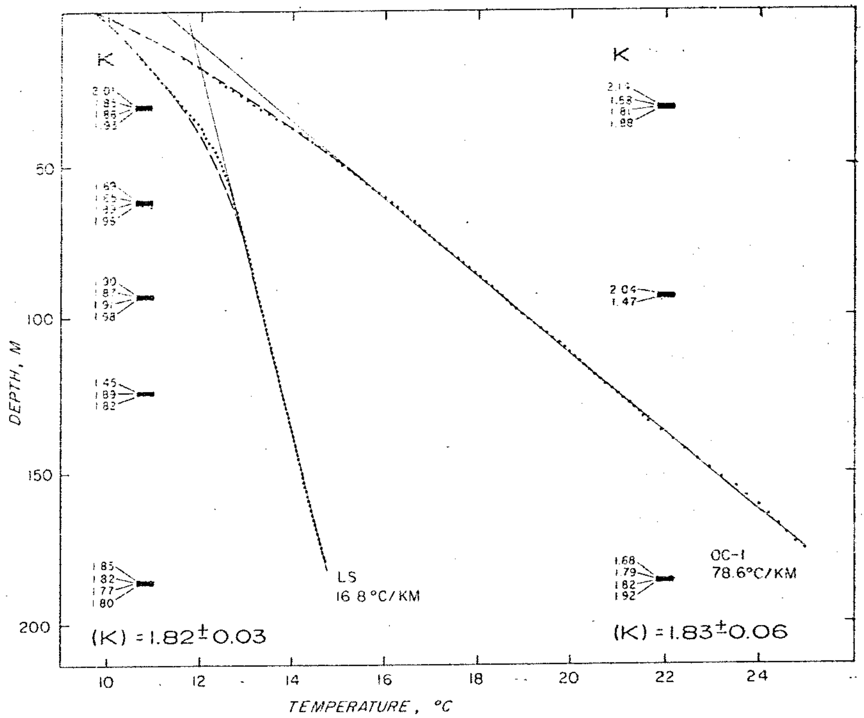

Fig. 4. Temperature profiles in the two heat flow holes. Points are individual temperature measurements, and solid lines define least squares temperature gradients used to determine heat flow. Dashed curves represent theoretical departures from the least squares relations (solid lines) resulting from a sudden temperature disturbance (step change) occurring 50 years before measurement. A thermal diffusivity of 0.003 cm²/s is assumed. Disturbance is 1.5°C for OC-1 and 2.0°C for LS. Individual thermal conductivities within cored intervals (solid bars) and harmonic mean conductivities $<K>$ are also shown.

heat flow values. Were it not for the low conductivity values, the contrast could perhaps be explained in terms of an anomaly associated with the observed upwelling of hot water along the southwest flank of the Klamath Hills; however, the heat flow of 1.44 HFU at OC-1 represents a lower limit for the regional background heat flow that one could reasonably expect in this tectonic setting [*Roy et al.*, 1968; *Blackwell*, 1969; *Sass et al.*, 1971*b*]. The value of 0.3 HFU calculated for LS is lower than any heat flow that plausibly can be ascribed to a steady state within the earth's deep interior, even in cratonic regions like the Canadian Shield.

It thus appears that the heat flows observed in the two specially drilled wells do not provide information on heat sources at depth. This conclusion is supported by examination of temperatures in other wells within the Lower Klamath Lake basin [*Sammel*, 1976]. The best example is seen in well KFO (Figures 1 and 2), an oil test hole drilled by the Klamath Falls Oil Company in the early 1920's. Although no driller's log is available, the well is assumed to have penetrated lake sediments and is reported to have penetrated basalt at a depth of about 200 m. Temperatures were measured by *Van Orstrand* [1938]. A gradient of about 90°C/km, consistent with a heat flow of about 2 HFU, was observed in the upper zone of the well; however, very close to the presumed surface of the volcanic rocks at a depth of ~200 m there is a sharp downturn in the temperature profile (Figure 2). This might be explained on the basis of convection in the volcanic rocks, but it also could be the result of downward flow in the well itself.

ESTIMATES OF MINIMUM HEAT FLUX FROM LINEAR TEMPERATURE PROFILES

Despite our preliminary conclusion that linear temperature profiles in the Quaternary lake deposits do not reflect regional heat flow but rather the temperature at the boundary between basin sediments and more permeable formations beneath them, we believe that the exercise of making formal calculations of heat flow is useful in evaluating the observed thermal gradients objectively, particularly in the context of geothermal energy potential. One of the common misconceptions in this relatively new area of energy-related geophysical exploration is that a high temperature gradient, say, 100°C/km, is automatically an indicator of a geothermal resource. The present study provides examples of high temperature gradients resulting from a combination of very low thermal conductivities and moderately high fluid temperatures in permeable rock formations at relatively shallow depths. For a more detailed discussion of examples of this type, see *White* [1973].

Liquid water has a thermal conductivity K of about 1.4 mcal/cm s °C at 20°C, and all inorganic mineral constituents of sedimentary rocks have conductivities at least twice as high. Thus the average conductivity ($\langle K \rangle \simeq 1.8$) in the heat flow wells represents a very plausible lower limit. This is particularly true for the lacustrine sediments in these wells, where a significant mineralogical constituent is plagioclase feldspar. From studies in many valleys in the western United States, mean thermal conductivities of valley fill can range from about 1.8 to 4.0 mcal/cm s °C for unconsolidated sediments containing large amounts of crystalline quartz ($K \simeq 15$). Because quartz is scarce in this area, it is unlikely that the porous valley fill anywhere in the basin has conductivities higher than 2.5-3 mcal/cm s °C.

Recognizing that there is an uncertainty in thermal conductivity, we have estimated lower limits for the conductive heat flux within the study area on the basis of the minimum thermal conductivity of 1.8. Temperature gradients and the lower-limit heat flow $q_{\min}$ are listed in Table 2 for all temperature profiles judged predominantly conductive (Figure 3). Values of $q_{\min}$ are also shown in parentheses in Figure 1. The rather large range in $q_{\min}$ (0.8-3.1 HFU) reinforces our preliminary conclusion that heat flows in this restricted area do not reflect deep-seated geologic processes. Wells exhibiting the highest conductive gradients (140°-170°C/km) and thus the highest values of $q_{\min}$ (2.5-3 HFU) are concentrated in the northernmost part of the study area. They are just south of the urban hot wells and are flanked by other wells that indicate upward or lateral movement of warm water.

Driller's logs of wells BH and AG (Figures 1 and 2) indicate that 'black lava' is encountered in layers 2-6 m thick intercalated among lacustrine clays for depths below 30 m at BH and below 50 m at AG. Casings in these wells are perforated opposite the black lava horizons. The temperature profiles and driller's logs suggest that hot water in this area moves laterally through layered basalts in a predominantly southeasterly direction. Water levels and temperatures measured in the wells south and east of Klamath Falls (Figure 1) indicate that the area is a sink for much of the thermal water originating in the Klamath Falls geothermal zone [*Sammel*, 1976]. On the basis of the data available from the deepest well (WP) measured in this area (Figures 1-3) it is apparent that the convective system near Wiard Park (WP) is deeper than 300 m and hotter than 50°C.

TABLE 1. Heat Flow Determinations From Two Sites in the Quaternary Sedimentary Rocks of the Lower Klamath Lake Basin

	Liskey (LS)	O'Connor (OC-1)
North latitude	42°00.3′	42°01.8′
West longitude	121°49.3′	121°44.8′
Elevation, m	1244	1244
Depth range, m	51-179	53-176
Temperature gradient, °C/km	16.76 ± 0.09	78.6 ± 0.3
Number of conductivity determinations	19	10
Harmonic mean conductivity, mcal/cm s °C	1.82 ± 0.03	1.83 ± 0.06
Heat flow q, HFU	0.30 ± 0.01	1.44 ± 0.05

TABLE 2. Temperature Gradients and Estimates of Minimum Heat Flow for Linear Temperature Profiles, Klamath Falls Region

Hole	Depth Interval, m	Temperature Gradient, °C/km	$q_{\min}$,* HFU
WP	30-290	165	3.0
GH	80-150	138	2.5
RP	15-52	55	1.0
LC	20-38	120	2.2
BHL	60-89	58	1.0
BC	25-87	74	1.3
CW	25-150	170	3.1
ED	40-70	90	1.6
JB	10-50	86	1.5
EJ	20-54	82	1.5
VW	20-72	146	2.6
CM	12-140	77	1.4
BA	20-73	80	1.4
CT	10-48	47	0.8
FW	60-200	90	1.6

*Minimum heat flow $q_{\min}$ is based on a lower-limit thermal conductivity of 1.8 mcal/cm s °C.

We interpret the heat flow of 0.3 HFU at LS as reflecting lateral and/or downward movement of relatively cool water in the volcanic rocks below the basin. Low values of q_{min} in other parts of the basin probably also represent areas of recharge. Thus the q_{min} of 1.0 HFU at RP is consistent with the apparent recharge at BM and EG on the extreme west side of the valley (Figure 1). The high conductive heat flow at VW (Figure 1) may represent a local upwelling in what otherwise seems to be a zone of recharge. East of this zone and south of Klamath Falls, values of q_{min} close to the value at OC-1 (1.3–1.6 HFU) seem to predominate within the Quaternary lake sediments. The difference between values of q_{min} at BHL and LC may be the result of a corresponding difference in thermal conductivities. No lithologic logs were available, but both wells were collared in the Yonna formation [*Newcomb and Hart*, 1958], which consists largely of layered sedimentary and pyroclastic rocks of variable mineralogic composition, density, and porosity and includes thin basalt flows. So variable is this material that we did not even attempt to measure thermal conductivities of outcrop samples.

SUMMARY AND DISCUSSION

Heat flow estimates over some 1000 km² in the Klamath Falls area range from 0.3 to more than 3 HFU. Estimates for the minimum heat flow q_{min} near the south end of the Klamath Falls geothermal zone are in the range 2.5–3 HFU. Farther south, q_{min} in lake sediments is generally in the range 1.3–1.6 HFU, which agrees with a determination of 1.44 HFU at OC-1 (Figure 1), but some lower values, including a determination of 0.3 HFU at LS, lead us to speculate that all of the observed heat fluxes represent temperature boundaries at the base of the basin sediments at depths of a few hundred meters and hence do not provide information on thermal activity at depth. Striking confirmation of this speculation is provided by the temperature profile from well KFO (Figure 2), which is consistent with other quasi-conductive profiles in the basin down to the base of the lake sediments at about 200 m. Within the volcanic rocks below the basin this profile is nearly isothermal, an indication of vertical movement of water at a temperature of about 30°C over a depth of at least 200 m.

On the basis of geologic considerations, both regional and local, some workers [*Newcomb and Hart*, 1958; *Peterson and Groh*, 1967; *Peterson and McIntyre*, 1970] suggest that a magma chamber exists or has existed until very recently beneath the major structure known as the Klamath graben. However, temperature gradients and heat flows in the upper few hundred meters of this volcanic terrane do not provide meaningful constraints on the size, shape, or depth of the heat source responsible for the observed geothermal phenomena, nor do they require the presence of a magma chamber within the crust.

Acknowledgments. We are indebted to Nickolas E. Voegtly, who obtained most of the field data, and to Paul A. Twichell, who supervised drilling of the heat flow holes. Robert J. Munroe and Eugene P. Smith made the thermal conductivity measurements, and S. Peter Galanis, Jr., assisted greatly in the reduction of field data. Arthur H. Lachenbruch, Norman S. MacLeod, and Donald E. White reviewed and offered valuable comments on an earlier version of the manuscript.

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(Received January 12, 1976;
revised April 6, 1976;
accepted April 22, 1976.)