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Heat Flow and Thermal Hydrology of Beowawe KGRA, Nevada

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FIG. 6 Temperature-depth profiles with similar thermal gradients, Whirlwind Valley, showing inferred depths to water table and to top of thermal aquifer. Lithologic symbols given in Figure 5.

FIG. 7 Temperature-depth profiles along hydrologic cross section A-A', Whirlwind Valley. Lithologic symbols given in Figure 5.

FIG. 8 Generalized lithology, thermal gradients and conductivities, and computed heat flow, Chevron Resources Co. Ginn 1-13 geothermal test well, Whirlwind Valley. Lithologic symbols given in Figure 5.

FIG. 9 Map of shallow heat flow, with generalized, variable contour interval in $mW \cdot m^{-2}$. Discrepancies among neighboring values have been ignored. These differences may be due to the wide range of depths over which the thermal gradient is calculated.

FIG. 10 Map of water table elevation, contours in meters.

FIG. 11 Map of temperature at top of thermal aquifer, contours in °C.

FIG. 12 Map of elevation at top of thermal aquifer, contours in meters.

FIG. 13 Cross section A-A' showing water table thermal aquifer, depth to base of alluvium, and vertical hydraulic gradients.

Table 1. Estimates of heat loss in the Beowawe Geysers area: a) low estimate assuming no geysering action, b) high estimate assuming flow rate reported by Oesterling (1962), $1.5 \times 10^6\ \text{lb}\cdot\text{hr}^{-1}$.

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ABSTRACT

Forty 150 m deep thermal gradient holes have been drilled by industry in a 60 km^2 area surrounding the Beowawe Geysers as part of the Department of Energy/Division of Geothermal Energy's Northern Nevada Industry Coupled Case Studies Program. Temperature-depth profiles and measurements of thermal conductivity on chip samples from these holes and from Chevron Resource Company's Ginn 1-13 geothermal exploration hole (2917 m T.D.) have been used to produce maps of heat flow and of a shallow thermal aquifer in the Whirlwind Valley.

The anomalous surface heat loss above the shallow thermal aquifer is estimated to be between 8.6 and 10.4 MW, corresponding to a volume flow of water of 0.02-0.03 $m^3 \cdot sec^{-1}$. Thermal gradient and conductivity data from the deep well have a wide range of values (65-144°$C \cdot km^{-1}$, 1.59-5.79 $W \cdot m^{-1}K^{-1}$) but produce a relatively constant heat flow of 235 $mW \cdot m^{-2}$ above a depth of 1600 m. Near-isothermal conditions in fractured rock below 1600 m depth indicate the advective transport of heat.

The Dunphy Pass fault zone appears to form the eastern margin of the Beowawe hydrothermal system. If the average heat flow east of the Dunphy Pass fault zone, 110 $mW \cdot m^{-2}$ is representative of a local 'background' heat flow, the heat loss at Beowawe when The Geysers are dormant exceeds the total flux from a 100-200 km^2 area. Heat lost

through the action of The Geysers may increase this estimate by an order of magnitude.

Shallow temperature-depth profiles and open-file data from the U.S. Geological Survey, Water Resources Division, have been used to create water level maps and to compute vertical hydraulic gradients within the Whirlwind Valley. These basic hydrologic data show areas away from The Geysers where thermal water may rise from depth. Additional hydrologic data at the locations of several of the thermal gradient holes may locate viable exploration targets. The systematic acquisition of hydrologic data is recommended as a standard component of hydrothermal resource exploration programs.

INTRODUCTION

The geysering action of vandalized wells drilled in the late 1950s for geothermal exploration at Beowawe Known Geothermal Resource Area (KGRA) may have been the most spectacular hydrothermal phenomenon created by man in the United States. The blowing wells were spudded in a 1-km long opaline sinter terrace on the south flank of the Whirlwind Valley in Eureka and Lander counties, Nevada, approximately 50 km east of the town of Battle Mountain, as shown in Figure 1. At this time (spring 1981) The Geysers play intermittently.

In the 1970s, exploration for a hydrothermal resource capable of sustaining electrical power generation has been conducted by Chevron Resources Company and Getty Oil Company. Much of their geophysical data has been acquired and made available through the Department of Energy/Division of Geothermal Energy Industry Coupled Program, (Chevron Resources Co., 1979; Getty Oil Co., 1981). The data from 40 thermal gradient holes drilled to 150 m depth provide three-dimensional views of the flows of heat and water. These flows must be known in order to assess the area's potential for energy production. While heat flow studies have been incorporated into numerous geothermal exploration programs (Chapman and others, 1981), hydrogeologic investigations have been sorely neglected. This omission could be remedied if explorationists were to include piezometers in their shallow drilling plans. A piezometer is a small diameter pipe open to a water-bearing formation at one depth only, generally at the bottom, as schematically shown in Figure 2. The elevation at which water stands in the piezometer indicates the total hydraulic head at the point of measurement. The hydraulic head H is the sum of two components, the pressure head $p/\rho g$ and the elevation head z

$$H = z + \frac{p}{\rho g} \tag{1}$$

where z is the elevation above an arbitrary datum, usually sea level, p is the fluid pressure, ρ the fluid density, and g the acceleration due to gravity. Water always flows from areas of higher hydraulic head to areas of lower hydraulic head. Figure 2 sketches the relation given by equation 1. The elevations of standing water in a number of piezometers distributed over an area, as in Figures 3a and b, are used to produce maps of hydraulic head. The differences in water levels seen in plan view can be used to compute the horizontal component of hydraulic gradient and, in isotropic media, the direction of ground-water flow.

A cross section of hydraulic heads can be generated if water levels are measured in adjacent piezometers completed at different depths, illustrated by Figures 3c and d. The difference in elevation of standing water in adjacent piezometers can be used to compute the vertical hydraulic gradient. Since elevation is positive upward, a negative vertical hydraulic gradient implies that there is a downward component of ground-water flow at that location. A positive value is computed wherever water rises from depth.

In areas where water flow affects heat flow, standard ground-water hydrologic data should be able to delineate zones of upwelling hot water. Since hot water is the hydrothermal resource, water levels and vertical hydraulic gradient data should be gathered as part of any geothermal exploration program. Hydrologic data from the Whirlwind Valley demonstrate the utility of incorporating ground-water hydrology into thermal gradient surveys.

GEOLOGIC SETTING

Struhsacker (1980) gives the most thorough description of the stratigraphic and structural framework of the Beowawe area. Other recent geologic summaries are given in Zoback (1979) and Garside and Schilling (1979). Figure 4 is a generalized geologic map of the study area showing the locations of piezometers and thermal gradient holes.

The Beowawe Geysers lie along the Malpais fault zone at the base of the Malpais Rim. The steep fault-scarp slope faces northwest towards the Whirlwind Valley. Tertiary lava flows and tuffaceous sediments crop out on the Malpais dip slope. The Malpais scarp exposes an older normal fault system, the Dunphy Pass fault zone, that has a northwest trend. This Oligocene to Miocene fault zone forms the eastern margin of a major northwest-trending graben that is part of the southern extension of a 750 km-long linear aeromagnetic and structural feature called the Oregon-Nevada lineament (Stewart and others, 1975). The Tertiary volcanic section within the graben is approximately 1400 m thick; east of the Dunphy Pass fault zone it is only 100 m thick. The underlying Ordovician Valmy Formation is a shattered sequence of siliceous eugeosynclinal sediments that are part of the Roberts Mountains Thrust sheet. Carbonaceous siltstone, chert, and quartzite of the Valmy formation crop out along the Malpais east of the Dunphy Pass fault zone and are encountered by the deep geothermal test wells in the Whirlwind Valley. Tertiary diabase dikes that intrude both the Valmy and the volcanic rocks are thought to be the source for the pronounced aeromagnetic anomaly associated with the Oregon-Nevada Lineament and the feeders for the Tertiary volcanic sequence filing the graben (Robinson, 1970).

THERMAL CONDUCTIVITY

Two parameters must be measured in order to calculate heat flow: thermal gradient and thermal conductivity. Figure 5 summarizes the stratigraphy of the Beowawe area and presents the mean and standard deviations of the measured thermal conductivities for each of the major rock units. All thermal conductivity values were determined using a modified divided bar apparatus at the University of Utah (Chapman and others, 1981). Computations of the thermal conductivities of the 61 drill-chip samples were made using the cell technique of Sass and others (1971a) but were not corrected for in-situ porosity. Had in-situ porosity been known from bore-hole logs, a correction could have been made to the calculated values (Sass and others, 1971a). The porosity of the alluvial and tuffaceous materials may exceed 30%; if so, the conductivities measured for these sedimentary units may be 20-30% too large. The matrix porosity of the competent rocks probably averages less than 10%, and the required correction less than 15%. Uncertainty about the in-situ thermal conductivity contributes to the range in the estimates of anomalous surface heat loss.

The low thermal conductivities of the vitrophyric dacite flow and shard-rich tuffaceous sediments reflect their high glass content. The thermal conductivities of the volcanic flow and intrusive rocks cluster around 2 $W \cdot m^{-1} \cdot K^{-1}$, but argillization of some of the dacite flows reduces their conductivity significantly. The high thermal conductivity and standard deviation computed for the Valmy Formation reflects the preponderance of quartzite in the measured samples and a highly variable lithology.

TEMPERATURE DATA

Temperature-depth data from 40 thermal gradient holes are part of the open-file data package for Beowawe (Chevron Resources Co., 1979; Getty Oil Co., 1981). Most of the .12-.15 m diameter holes were drilled to 150 m. Schedule 40, 0.025 m black iron pipe plugged at the bottom joint was run to the total depth and filled with fresh water. The holes were then back-filled and grouted. Temperature-depth data were taken in the pipe after waiting a period of one to two months, more than sufficient time to allow the temperature of the water in the pipe to equilibrate with the surrounding rock. Selected temperature-depth profiles are shown in Figures 6 and 7 and the locations of the gradient holes in Figure 1.

The four profiles in Figure 6 have thermal gradients near 67°C·km^{-1}. Even though their gradients are similar, their thermal regimes are different. The coolest hole, B-54, is completed in alluvium and shows little disturbance by ground-water flow. This gradient may be one of the few in the Beowawe area that represents regional conductive heat flow; if so, the computed 'background' heat flow would be approximately 118 mW·m^{-2}.

Hole B-54 also serves as the reference for an arbitrary definition of 'cold' and 'thermal' for the Beowawe area: an aquifer that contains water at a temperature more than 7°C above the temperature in hole B-54 at the same depth is called a 'thermal aquifer'; water less than 7°C above the temperature in B-54 at the same depth is said to be 'cold.'

The remaining three profiles in Figure 6 all show temperature disturbances that can be attributed to the convective transport of heat by ground water. The abrupt inflections in the temperature-depth profiles are interpreted to indicate the depths to the tops of water-bearing zones. Holes B-11 and B-22 intersect a thermal aquifer in which the water is 36.3°C at 67 m and 39.6°C at 27 m, respectively. Hole B-29 appears to intersect cold water, 26.1°C at 34 m, within a layer of basalt, Tb.

The bottom of the thermal aquifer in hole B-11 corresponds to the contact between the alluvium, Qal, and volcanic rocks, Td. If the alluvium were highly permeable vertically, the temperature profile within the aquifer would be more nearly isothermal. The 67°C·km^{-1}

gradient within this thermal aquifer suggests that it has a low vertical hydraulic conductivity. It may contain numerous thin semi-confining layers. The convex upward curvature of the temperature-depth profile indicates a component of ground-water flow upward and a positive vertical hydraulic gradient (Sorey, 1971).

Similar hydrologic inferences have been made for all the temperature-depth profiles within the Whirlwind Valley. None of the profiles for holes in the Malpais Rim suggest that the rocks are saturated with either hot or cold water; these holes cannot be included in the hydrologic analysis. The profiles from the thermal gradient holes along section A-A' are shown in Figure 7. A relative temperature scale is used to avoid overlap, but inclusion of the measured temperature at the shallowest depth permits the reconstruction of actual temperature profiles. Included in Figure 7 are the temperatures at the top of the thermal aquifer and thermal gradients calculated for an interval above the thermal aquifer. Also shown in Figure 7 are shallow temperature disturbances that are inferred to represent the top of cold water-bearing zones. If the cold water in the Whirlwind Valley is unconfined, these distributions would show the depth to the water table.

An equilibrium temperature log of the Ginn 1-13 geothermal test well is shown in Figure 8 (Chevron Resources Co., 1979). The total depth of the hole is approximately 2900 m and the bottom-hole temperature 213°C. It is essentially isothermal below a depth of 2400 m within the Valmy Formation.

HEAT FLOW

Thermal gradients above 2400 m from the Ginn test hole, shown in Figure 8, range from 23 to 144°C·km^{-1} and thermal conductivities from 1.59 to 5.79 W·m^{-1}·K^{-1}. Above a depth of 1600 m there is a strong inverse relationship between the gradients and conductivities. When multiplied together, these wide ranges of values produce a nearly constant estimated heat flow averaging 235 mW·m^{-2} (5.6 HFU). Below 1600 m the temperature gradients decrease systematically; the hole is either penetrating a hot water-bearing structure or a permeable formation. Given the fractured character of the Valmy Formation (Evans and Theodore, 1978), it is likely that there is some sort of high-temperature hydrothermal reservoir below a depth of 1600 m.

The nearly constant conductive heat flow above the inferred deep reservoir indicates that the Tertiary volcanic section acts as a relatively impermeable cap. This points to the necessity for permeable structures at The Geysers and anywhere else that hot water is rising from depth. It also provides a control on the estimate of anomalous surface heat loss calculated from the shallow thermal gradient holes.

Figure 9 is a map of the interpreted values of heat flow along the Malpais Rim and above the shallow thermal aquifer in the Whirlwind Valley. In most of the area west of the Dunphy Pass fault zone, the heat flow exceeds the calculated value in the Ginn test hole; immediately west of The Geysers it exceeds 3350 mW·m^{-2} (80 HFU). The Whirlwind Valley and Malpais Rim apparently receive heat from both the deep reservoir and a shallower heat source that is presumably connected to the deep reservoir along permeable structures. The shallow thermal aquifer is a supplemental source of heat in the Whirlwind Valley.

If a thermal aquifer were to be a source of heat below the Malpais Rim, it must occur at depths greater than the 160 m reached by the thermal gradient holes. One plausible inference from Figure 9 is that a thermal aquifer may be found southeast of The Geysers. This area is one of three zones with heat flow above 251 $mW \cdot m^{-2}$ that radiate from the central area of highest heat flow. These three zones coincide with mapped faults that intersect at The Geysers, as indicated in Figure 4. While it is possible that these faults may be conduits for upwelling hot water from the deeper reservoir, hydraulic head data are required to resolve whether they allow hot water to flow away from The Geysers or channel hot water to The Geysers.

A different thermal regime is apparent east of the Dunphy Pass fault zone. Four of the values of heat flow along the Malpais Rim average 110 $mW \cdot m^{-2}$, near the 'background' value given by Sass and others (1971b) for this portion of the Basin and Range Province. The Dunphy Pass fault zone appears to form the eastern margin of the Beowawe hydrothermal system. The 110 $mW \cdot m^{-2}$ average value and the 118 $mW \cdot m^{-2}$ values from hole B-54, Figure 6, appear to be realistic values for 'background' heat flow.

The order of magnitude of the anomalous surface heat loss above the shallow thermal aquifer is calculated by integrating the heat flow that exceeds the assumed background, 110 $mW \cdot m^{-2}$, over the area of Figure 9. Details of the integration are given in Table 1. Two estimates are presented because the areas enclosed by the contours are arbitrary and the heat flow out of the sinter terrace is unknown. The low estimate, 8.6 MW, assumes an average heat flow out of the sinter terrace of 2500 $mW \cdot m^{-2}$ (60 HFU). The high estimate for heat loss above the aquifer, 10.4 MW, assumes a larger area of anomalous surface heat loss and an average heat flow out of the sinter terrace equal to the 3580 $mW \cdot m^{-2}$ (86 HFU) calculated at the nearest thermal gradient hole.

The anomalous heat loss calculated from Figure 9 is supported by the flow of water within the shallow thermal aquifer. Assuming that the water has an initial temperature Ti equal to 98°C and that it cools to the average ambient temperature Ta of 13°C, we can calculate the volume flow of water Q within the aquifer

$$Q = \frac{P}{\rho \; c_f \; (Ti - Ta)} \qquad (2)$$

where ρ is the density of the fluid, c_f its specific heat, and P the anomalous heat loss. The low estimate of 8.6 MW could be supported by a volume flow rate of 0.024 $m^3 \cdot sec^{-1}$ (380 $gal \cdot min^{-1}$) and the high estimate of 10.4 MW by a flow of 0.029 $m^3 \cdot sec^{-1}$ (460 $gal \cdot min^{-1}$).

If the 'background' heat flow were 110 $mW \cdot m^{-2}$, the estimates of anomalous heat loss at Beowawe correspond to the total heat flux from an 80-96 km^2 area. Since only a fraction of the total heat is likely to be transferred to deeply circulating water, the area over which the

Beowawe hydrothermal system gathers heat is likely to be approximately an order of magnitude larger, 1000 km^2.

These estimates of surface heat loss are insignificant compared to the estimate of the heat loss due to the action of The Geysers. Since The Geysers are now intermittent and since their discharge is poorly known, the heat loss due to fluid discharge is tenuous. Oesterling (1962) reported a discharge of at least $1.5 \cdot 10^6$ $lb \cdot hr^{-1}$. If this discharge were entirely saturated liquid at 110°C that cools to 13°C, the heat loss would be 75.8 MW. It is likely that a portion of the discharge would be steam and that the temperature would exceed 110°C; for this case, the heat loss due to fluid discharge would be significantly larger. The fluid discharge must be measured before a reliable assessment of the power production at Beowawe can be made.

THERMAL HYDROLOGY

Shallow, cold perturbations in the temperature-depth profiles from gradient holes in the Whirlwind Valley like those in Figures 6 and 7 have been inferred to correspond to the depths to the top of a zone saturated with cold water. Figure 10 illustrates that the elevations of these shallow temperature disturbances conform with the elevations of the cold water table in the USGS piezometers. For this reason, they are thought to indicate the depth to the water table.

The elevation of the water table in the Whirlwind Valley decreases systematically down the valley from west to east. At a playa lake beyond the eastern edge of Figure 10, all the ground water in the valley is presumably discharged by evapotranspiration.

In Figure 10, the area around The Geysers is shown to be an area where the water table is unusually high. This may be inaccurate; it is unclear whether the hot water there exists under artesian or water-table conditions. Additional piezometers near The Geysers would clarify this uncertainty.

As shown in Figure 7, most of the temperature-depth profiles in the Whirlwind Valley contain abrupt downward inflections. These inflections occur at a wide range of depths and at elevated temperatures and indicate zones where heat transport is dominated by advection. They have been used to infer the depth to the top of the thermal aquifer; the temperatures at the downward inflections in thermal gradients are shown in Figure 11 and their elevations in Figure 12. The marshy ground at the top of the sinter terrace defines the highest elevation where material is known to be saturated with hot water. The hot springs around the base of the terrace provide additional controls on the elevation of the thermal aquifer. The near-radial symmetry of the temperatures suggests that the area of The Geysers contains the principle source of hot water flowing into the alluvium of the Whirlwind Valley. This symmetry also suggests that the changes in thermal gradient picked from the temperature profiles represent the depths to a single, laterally continuous outflow system.

The map of the top of the thermal aquifer, Figure 12, displays a more complex pattern than the map of temperatures and does not reflect the west-to-east hydraulic gradient of the water table. The hot water flows away from The Geysers to the southwest, west, and north. Thermal water levels are higher within the outcrop west of The Geysers than they are in the adjacent alluvium. Within the alluvium, relatively high thermal water levels are sustained to the west of The Geysers. To the southwest or north of The Geysers, the thermal aquifer occurs below the water table. In these areas the aquifers may form effectively independent flow systems.

High water levels in Figure 12 indicate areas where hot water flows more freely, that is, portions of the thermal aquifer that are more permeable. The outcrop to the southwest and the buried extension of the Malpais Fault to the west of The Geysers appear to be more permeable than other areas of the Whirlwind Valley. A comparison of Figures 4 and 12 suggests that the structural zones that intersect at The Geysers maintain permeability away from The Geysers.

Figure 12 shows only the horizontal gradient of the top of the thermal flow system. The vertical hydraulic gradient, required to obtain a three-dimensional understanding of the hydrologic regime of the Whirlwind Valley, is shown along cross section A-A' of Figure 13. The cross section includes the land surface, geologic structure, the inferred elevations of the water table, the top of the thermal aquifer, and the calculated vertical hydraulic gradient values from USGS piezometers. The highest hot water level occurs below the outcrop southwest of The Geysers. North of the outcrop the water level decreases and the vertical hydraulic gradient of the cold water above it is large and directed down. There is a strong downward component of ground-water flow north of the western extension of the Malpais Fault.

Since vertical hydraulic gradient data are not available from the thermal gradient holes drilled in and near the outcrop, holes B-22, B-31, and B-37, we cannot decipher the hydrologic system that is responsible for these observations. One plausible hypothetical flow system limits the source of hot water to The Geysers and suggests that the thermal water within the outcrop is perched above relatively impermeable volcanic rock. The downward hydraulic gradient north of the Malpais fault would show that ground water cascades over the buried structure into the alluvium. This simple flow system may be appropriate for the outcrop but is incompatible with the inferred high thermal water levels further to the west along the extension of the Malpais fault.

The top of the thermal aquifer is nearer the surface along the trace of the western extension of the Malpais fault zone than it is to either the south or the north. This implies that warm water may flow to both the north and south away from the fault zone. The simplest flow system that accounts for this observation requires a source of warm water; the western extension of the Malpais fault zone may be leaking warm water into the alluvium of the Whirlwind Valley.

If the buried fault zone were a local source of hot ground water, the vertical hydraulic gradients computed from piezometer data along its trace would indicate an upward flow of water. Structures that allow water to rise from depth may prove to be viable geothermal exploration targets. Hydrologic analysis of thermal data from Beowawe suggests that the western extension of the Malpais fault zone and the outcrop southwest of The Geysers may be viable targets.

RECOMMENDATIONS

The hydraulic head of the shallow thermal flow system at Beowawe and any other hydrothermal exploration target with existing thermal gradient holes could be readily obtained by converting the existing thermal gradient holes to piezometers by perforating the casing below the top of the thermal aquifer. In addition, a shallower companion piezometer open below the water table would make it possible to compute the vertical hydraulic gradient at these locations. To obtain these hydrologic data it would be necessary to re-enter and perforate existing thermal gradient holes and to drill or auger shallow, 30 m companion piezometers. Even if conduits for upwelling hot water were not located, the hydrologic data would surely augment the existing thermal data and refine the conceptual model of the resource.

Converting thermal gradient holes to piezometers may not provide reliable hydraulic head values due to the difficulty of insuring that the perforated interval is open to only an isolated portion of the aquifer (Benson and others, 1980). However, it should be possible to obtain both hydrologic and thermal data from piezometers that are later converted to thermal gradient holes. In areas where shallow drilling is planned, holes that intersect an aquifer could be initially completed as piezometers. A screen and a wellpoint would be attached to the pipe and set at the bottom of the hole, the annulus filled with gravel to the top of the screen and grouted to the surface. After the static hydraulic head is obtained, the screen could be plugged with cement and the hole filled with water, converting it to a thermal gradient hole. Companion piezometers would be needed to obtain vertical hydraulic gradient data. This procedure is recommended as an integral part of future hydrothermal exploration programs.

At any geothermal prospect where drilling encounters water, the water is a source of data. The hydrologic-thermal field procedure recommended here requires repeated site visits and the drilling and completion of additional shallow, thin holes. This expanded exploration program is predicated on the assumption that it is worthwhile to gather as much meaningful data as possible at a reasonable price. The possibility of locating viable deep drilling targets with ground-water hydrology should encourage geothermal exploration managers to incorporate hydrologic data acquisition in all their exploration plans.

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a) Low Estimate

Contour Interval (mW·m^{-2})	Average Heat Flow (mW·m^{-2})	Area (km^2)	Heat Loss (MW)
1674<	2500	0.64	1.6
837-1674	1250	1.18	1.5
419- 837	625	7.23	4.5
251- 419	335	4.76	1.6
167- 251	210	8.55	1.8
		22.35	11.0
Background heat loss	110	22.35	2.4
Anomalous surface heat loss above thermal aquifer			8.6

b) High Estimate

Contour Interal ($mW \cdot m^{-2}$)	Average Heat Flow ($mW \cdot m^{-2}$)	Area (km^2)	Heat Loss (MW)
1674<	3580	0.64	2.3
837-1674	1250	1.18	1.5
419- 837	625	9.16	5.7
251- 419	335	4.97	1.7
167- 251	210	11.17	2.3
		28.58	13.5
Background heat loss	110	28.58	3.1
Anomalous surface heat loss above thermal aquifer			10.4
Contribution from fluid discharge = Mass flow × (enthalpy @ 110°C - enthalpy @ 15°C)			75.8
Total anomalous heat loss			89.3

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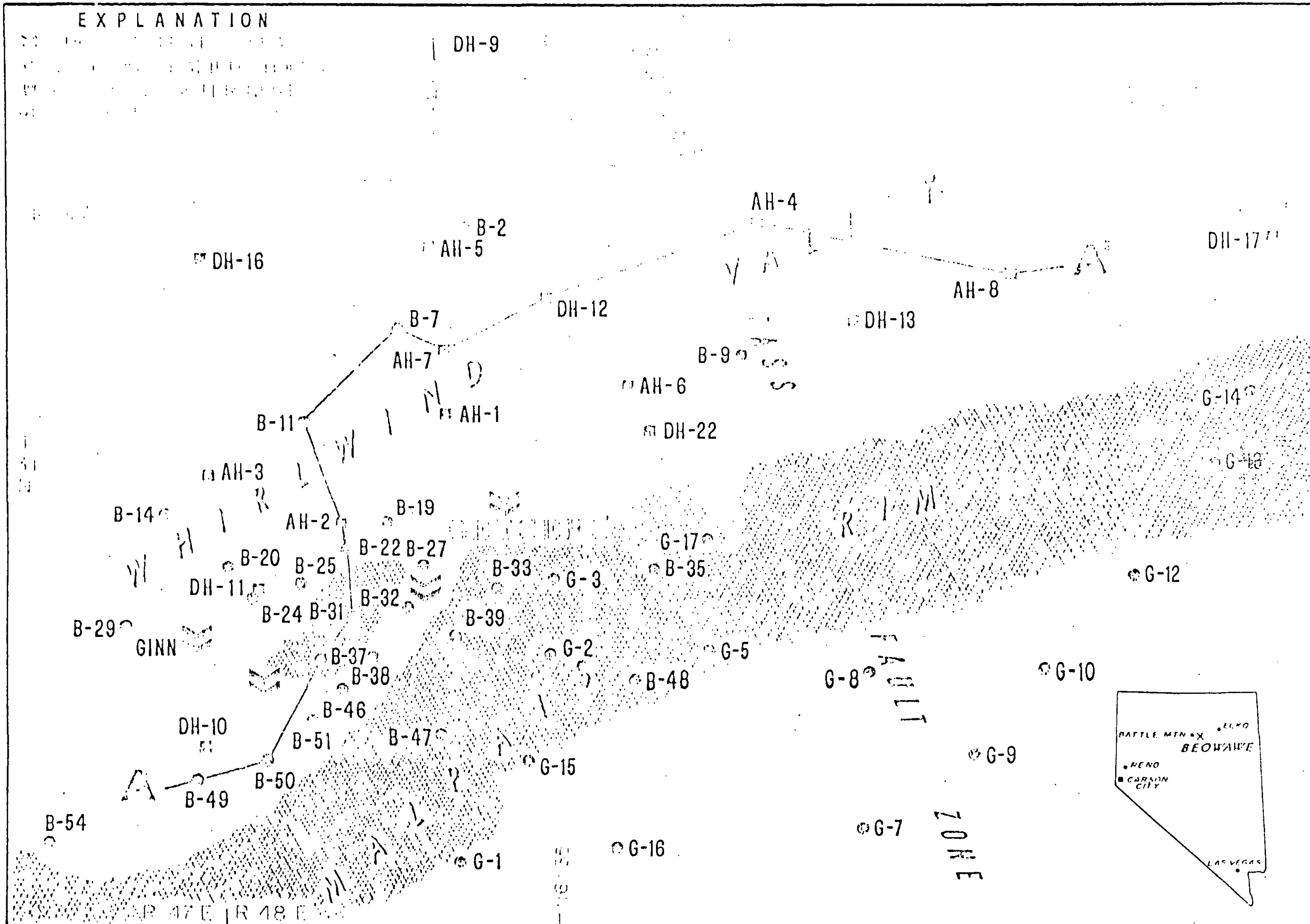
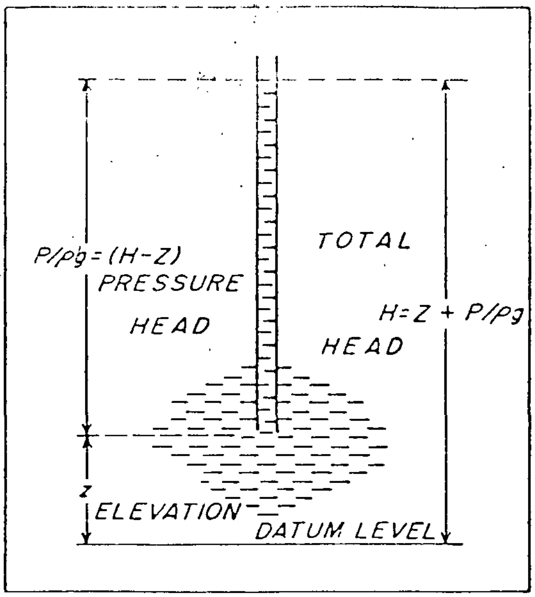
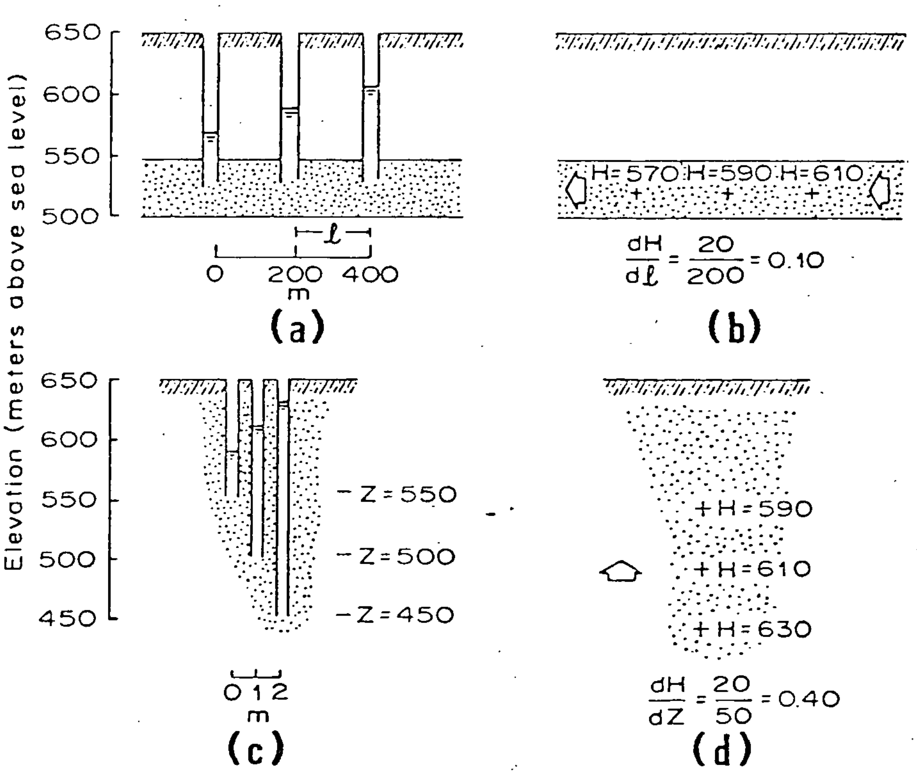


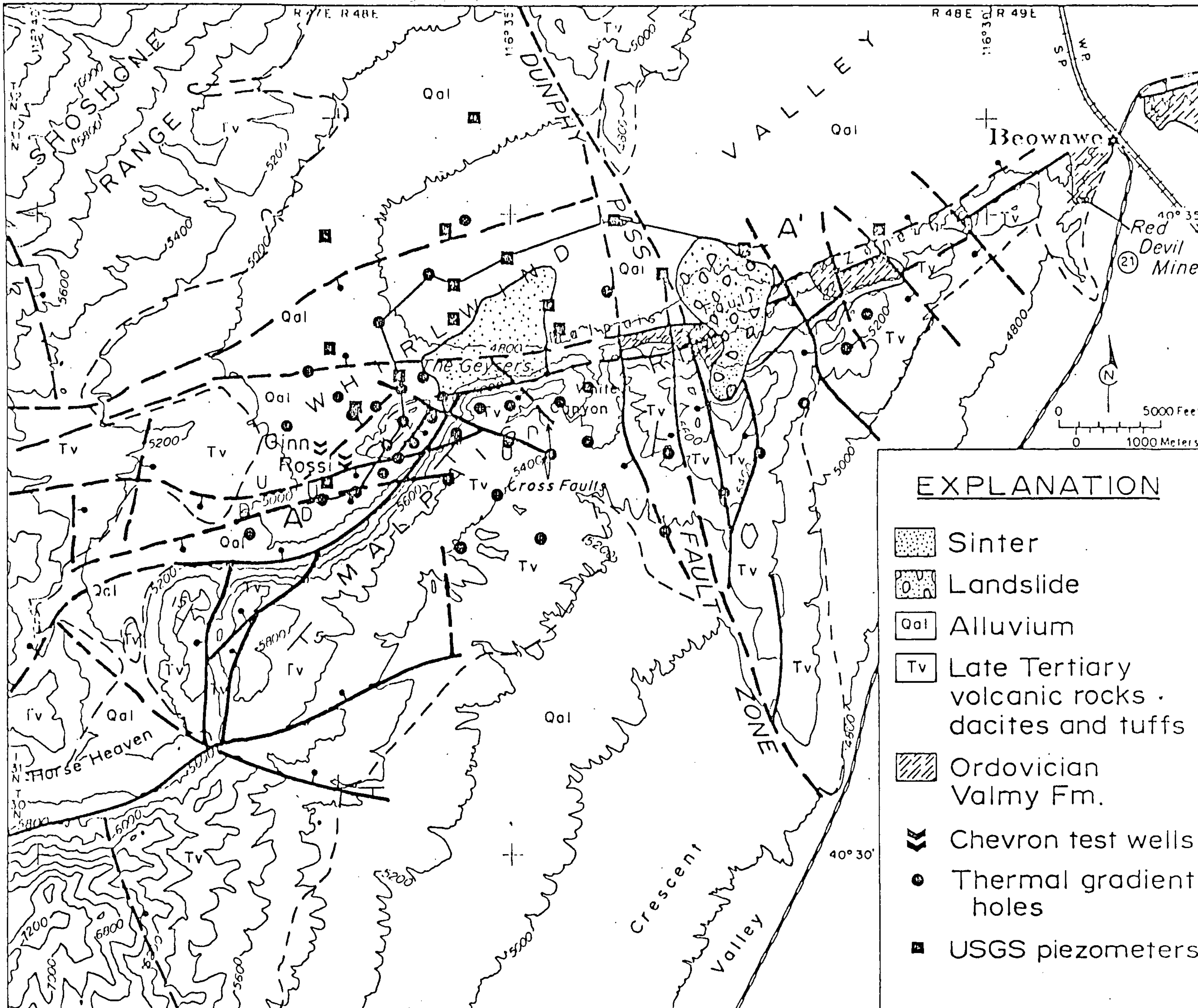
EXPLANATION
DH-9
AH-4
B-2
AH-5
DH-16
DH-17
AH-8
A'
DH-12
B-7
DH-13
AH-7
B-9
AH-6
AH-1
B-11
DH-22
G-14
AH-3
B-14
AH-2
B-19
G-17
B-22
B-27
B-20
B-25
B-33
G-3
B-35
G-12
DH-11
B-32
B-24
B-31
B-39
B-29
GINN
B-37
G-2
G-5
G-10
B-38
B-48
G-8
B-46
DH-10
B-51
B-47
G-9
G-15
A
B-50
B-49
B-54
G-7
G-16
G-1
R 47 E
R 48 E
BATTLE MTN
ELKO
BEOWAWE
RENO
CARSON CITY
LAS VEGAS



P/ρg = (H-Z)
PRESSURE
HEAD
TOTAL
HEAD
H=Z + P/ρg
Z
ELEVATION
DATUM LEVEL

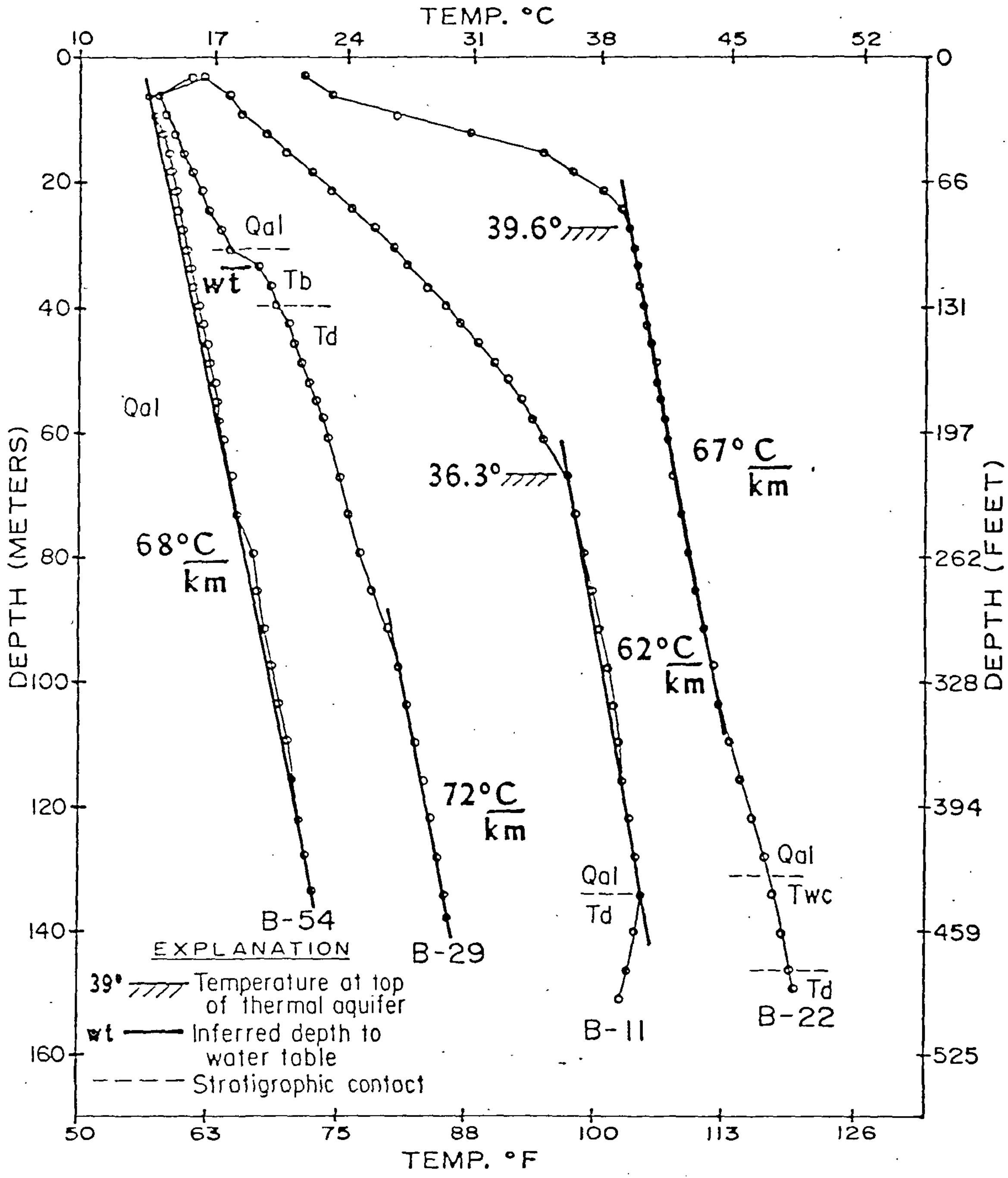


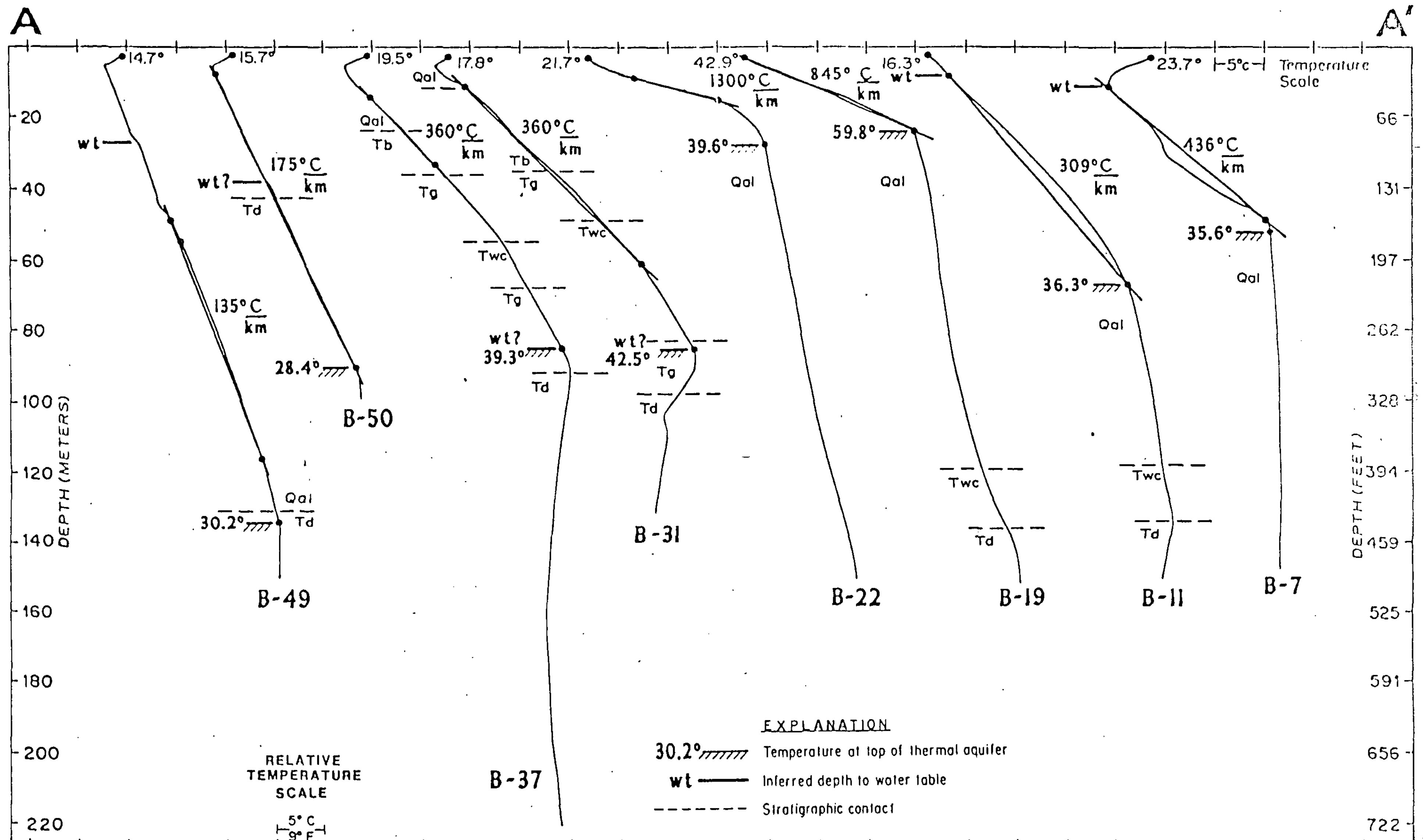
Elevation (meters above sea level)
650
600
550
500
450
ℓ
0
200
400
m
(a)
H=570
H=590
H=610
dH/dℓ = 20/200 = 0.10
(b)
Z=550
Z=500
Z=450
0 1 2
m
(c)
H=590
H=610
H=630
dH/dZ = 20/50 = 0.40
(d)



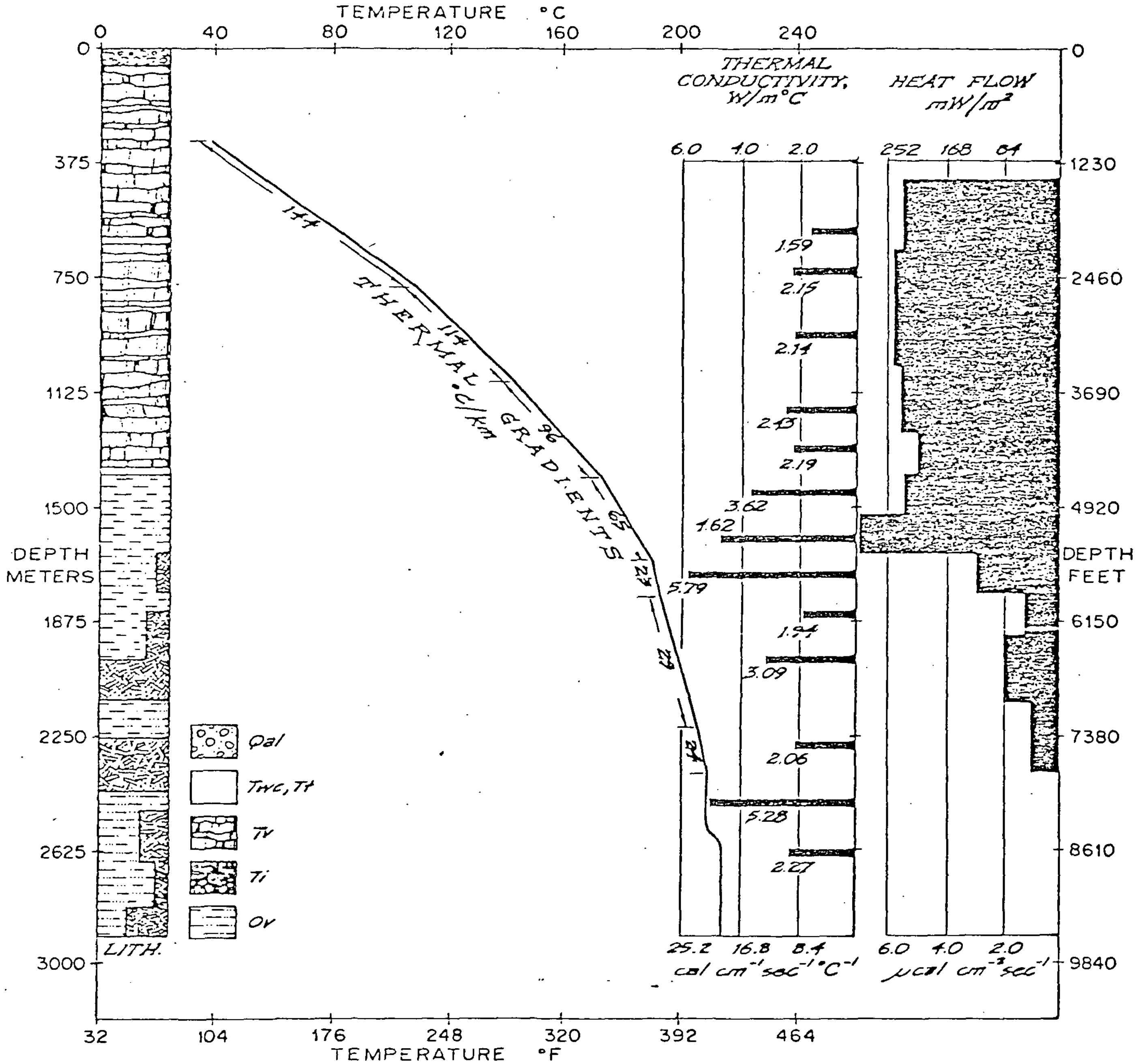
SHOSHONE RANGE
VALLEY
DUNPHY PASS FAULT ZONE
WHIRLWIND
MALPAIS
Beowawe
Red Devil Mine
The Geysers
White Canyon
Cross Faults
Ginn
Rossi
Horse Heaven
Crescent Valley
A
A'
Qal
Tv
R 47E R 48E
R 48E R 49E
40°35'
40°30'
0 5000 Feet
0 1000 Meters
EXPLANATION
Sinter
Landslide
Alluvium
Late Tertiary volcanic rocks · dacites and tuffs
Ordovician Valmy Fm.
Chevron test wells
Thermal gradient holes
USGS piezometers

MAP CODE		LITHOLOGIC UNIT	THERMAL CONDUCTIVITY Mean ± Std. Dev. ($W \cdot m^{-1} K^{-1}$)	NUMBER SAMPLES
Qs		Opaline Sinter	———	———
Qls		Landslide	———	———
Qal		Alluvium	1.68 ± 0.11	8
Tv	Tg	Coarse Gravel	1.60	1
	Tb	Basalt	1.60	2
	Twc	Tuffaceous Sediment of White Canyon		
		glassy	1.33 ± 0.12	3
		silty	1.65 ± 0.08	9
	Td	Dacite		
		porphyritic	2.02 ± 0.13	9
		vitrophyric	1.20	2
		argillized	1.67 ± 0.22	4
	Tba	Basaltic Andesite	2.26 ± 0.06	5
	Tts	Early tuffaceous material	1.58 ± 0.01	4
	Tha	Hornblende Andesite	1.90 ± 0.17	5
	Ti	Diabase dikes	2.09 ± 0.17	3
Ov		Valmy Formation	4.44 ± 1.01	6

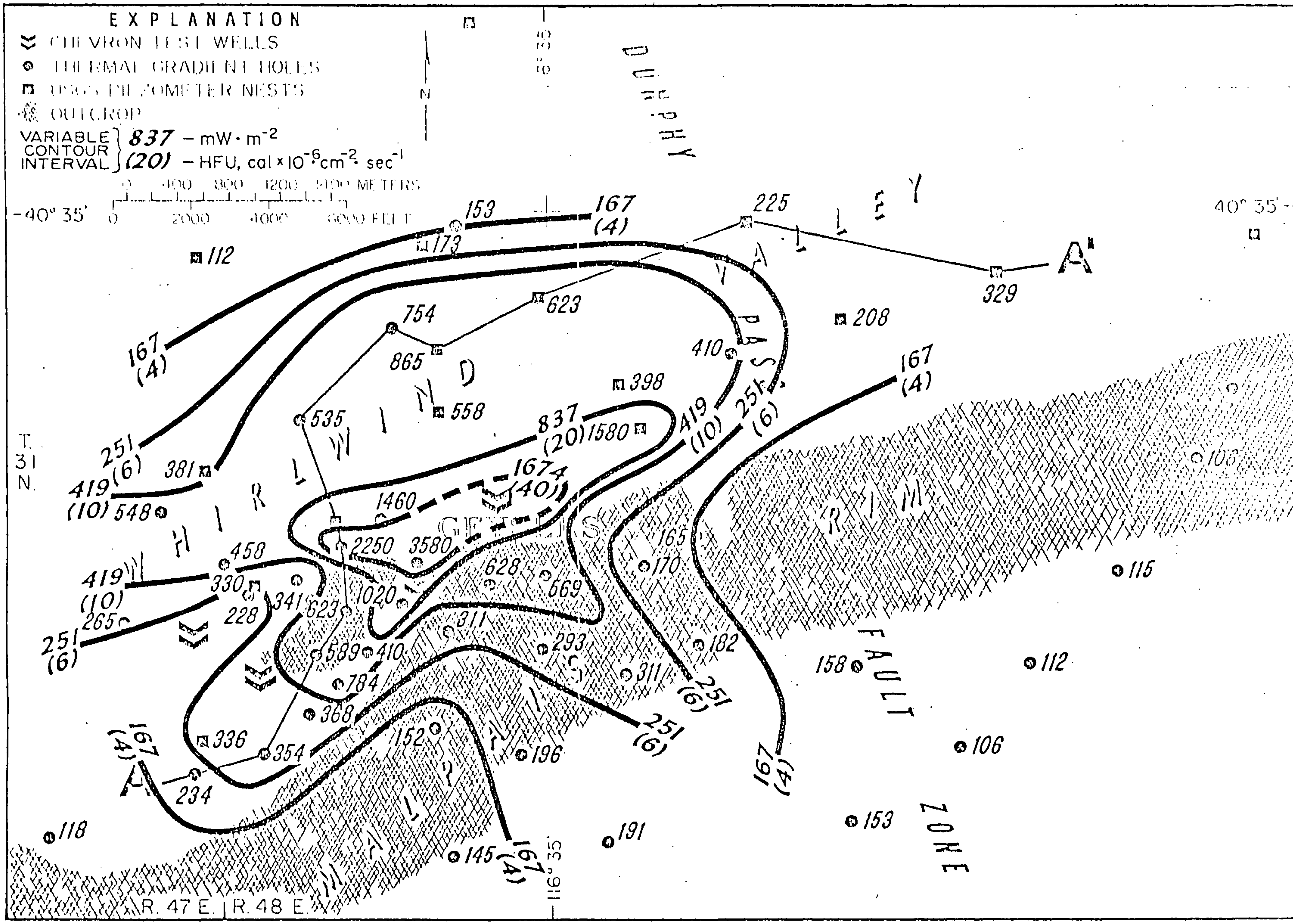

TEMP. °C
10 17 24 31 38 45 52
TEMP. °F
50 63 75 88 100 113 126
DEPTH (METERS)
0 20 40 60 80 100 120 140 160
DEPTH (FEET)
0 66 131 197 262 328 394 459 525
39.6°
36.3°
68°C/km
72°C/km
62°C/km
67°C/km
Qal
wt
Tb
Td
Twc
B-54
B-29
B-11
B-22
EXPLANATION
39° Temperature at top of thermal aquifer
wt Inferred depth to water table
Stratigraphic contact



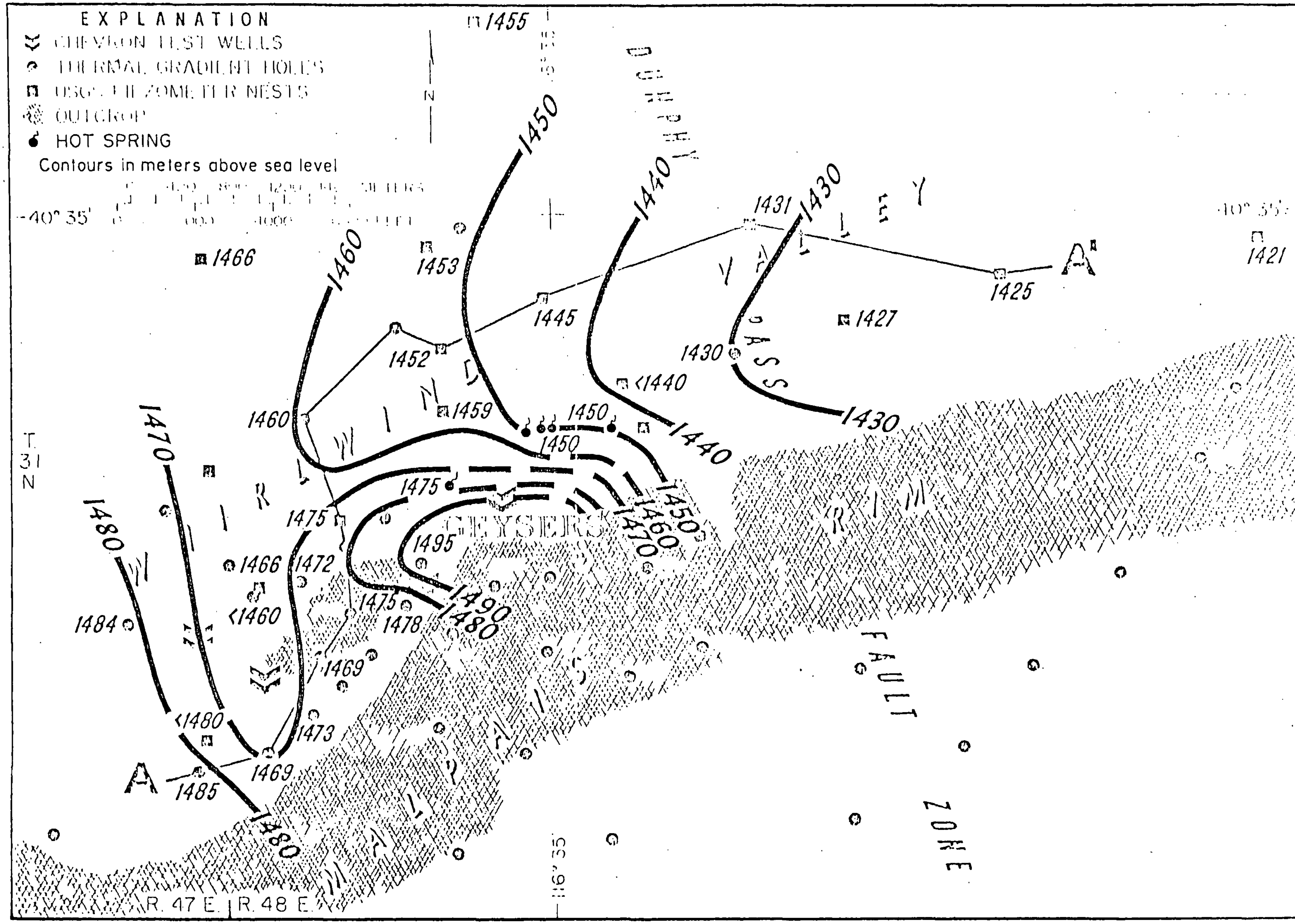
A
A'
14.7°
15.7°
19.5°
17.8°
21.7°
42.9°
16.3°
23.7°
5°C
Temperature Scale
wt
wt?
wt?
wt?
wt
wt
Qal
Qal
Tb
Tb
Tg
Tg
Td
Twc
175°C/km
360°C/km
360°C/km
1300°C/km
845°C/km
309°C/km
436°C/km
135°C/km
39.6°
59.8°
35.6°
36.3°
28.4°
39.3°
42.5°
30.2°
B-50
B-49
B-37
B-31
B-22
B-19
B-11
B-7
DEPTH (METERS)
DEPTH (FEET)
RELATIVE TEMPERATURE SCALE
5° C
9° F
EXPLANATION
30.2° Temperature at top of thermal aquifer
wt Inferred depth to water table
Stratigraphic contact

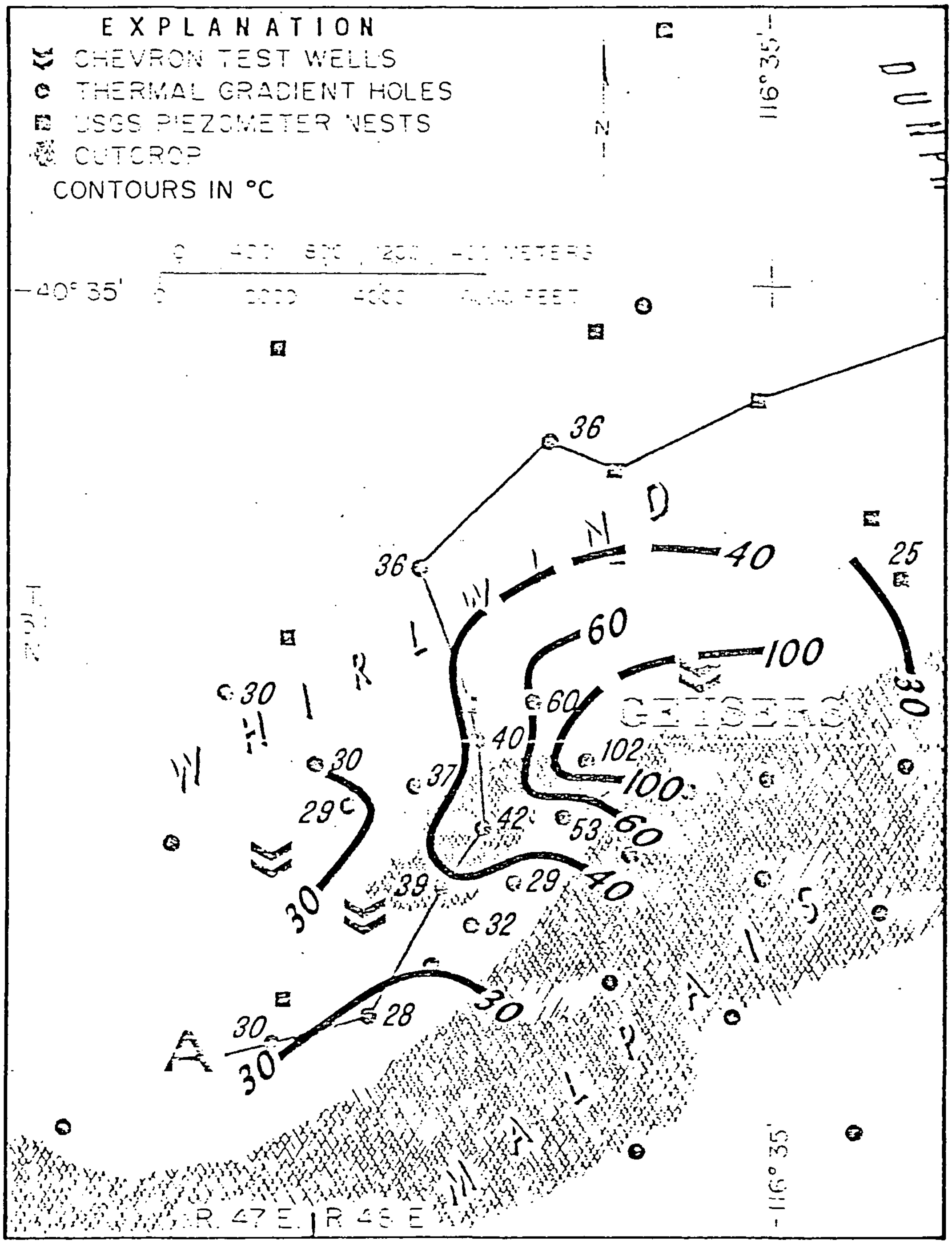


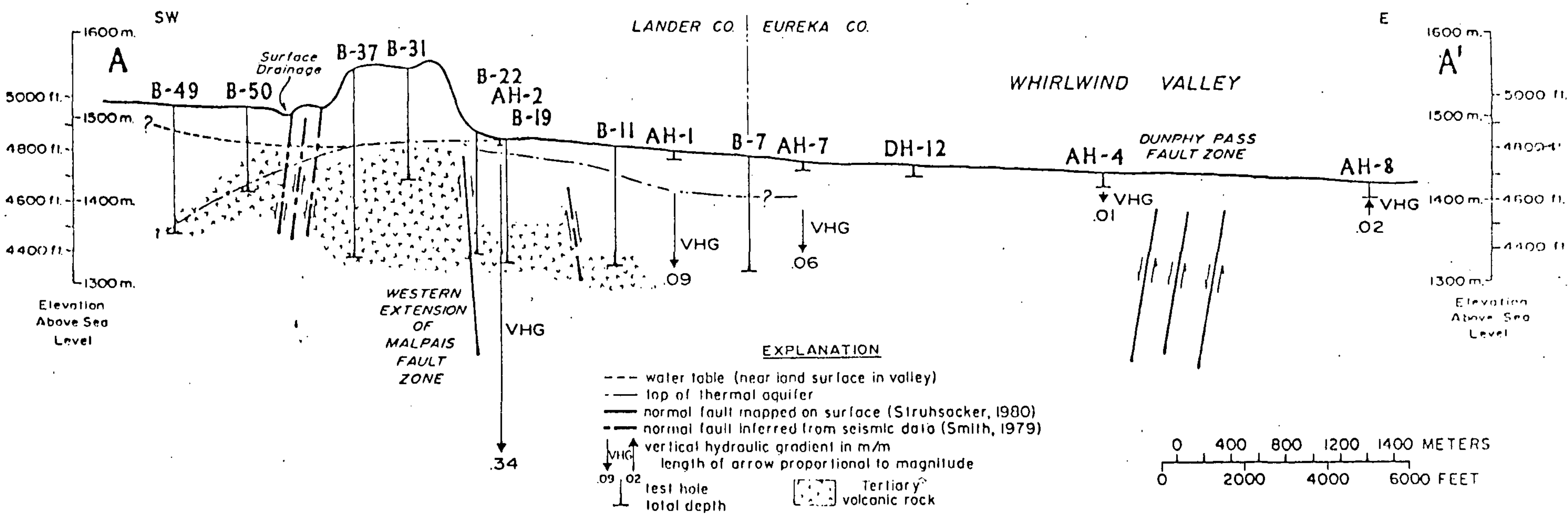
TEMPERATURE °C
0 40 80 120 160 200 240
THERMAL CONDUCTIVITY, W/m°C
HEAT FLOW mW/m²
6.0 4.0 2.0
252 168 84
THERMAL GRADIENTS °C/km
174 114 96 65 127 77 24
1.59 2.15 2.14 2.13 2.19 3.62 4.62 5.79 1.94 3.09 2.06 5.28 2.27
DEPTH METERS
0 375 750 1125 1500 1875 2250 2625 3000
DEPTH FEET
0 1230 2460 3690 4920 6150 7380 8610 9840
Qal
Twc, Tt
Tv
Ti
Ov
LITH.
25.2 16.8 8.4
cal cm⁻¹ sec⁻¹ °C⁻¹
6.0 4.0 2.0
μcal cm⁻² sec⁻¹
32 104 176 248 320 392 464
TEMPERATURE °F



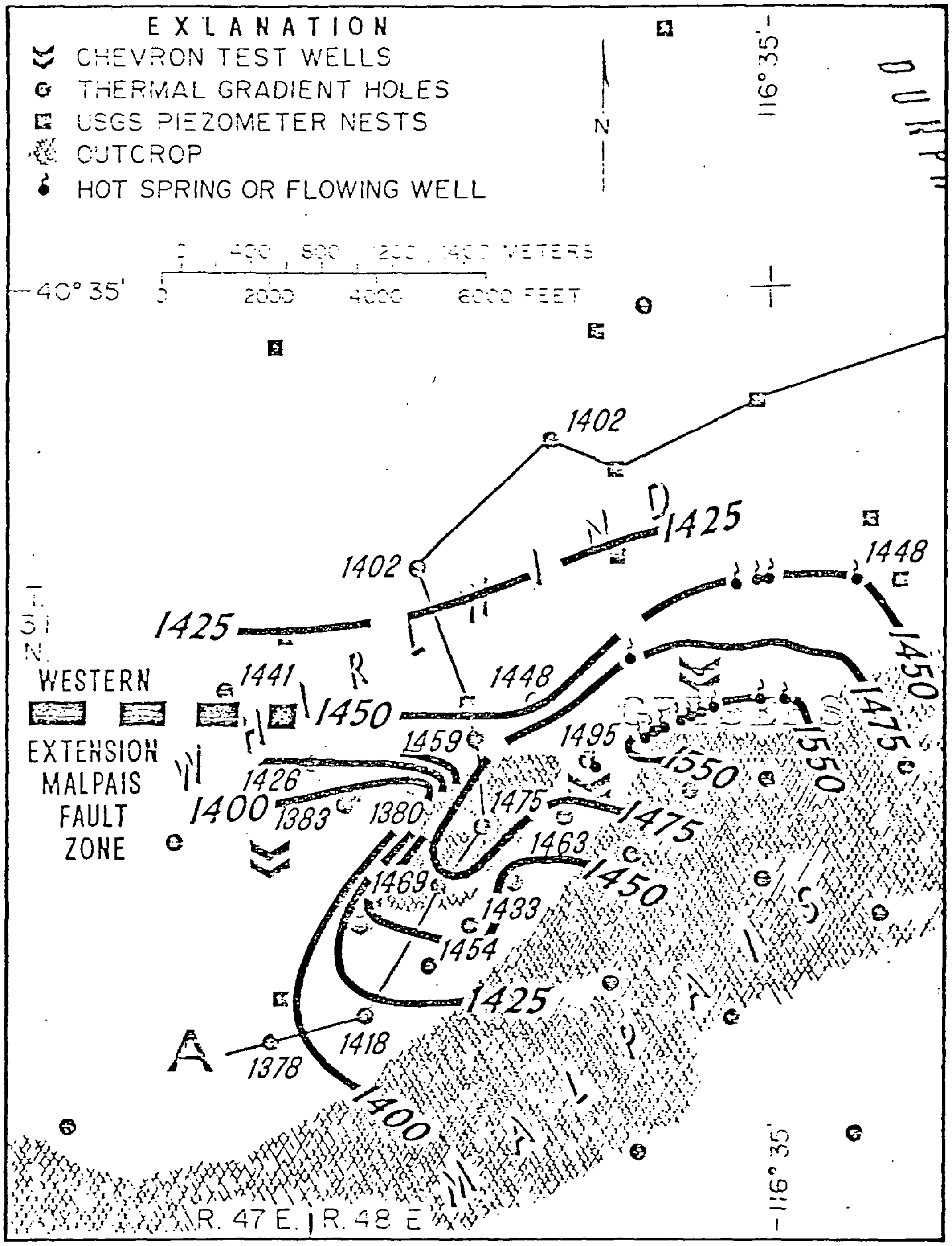
EXPLANATION
CHEVRON TEST WELLS
THERMAL GRADIENT HOLES
USGS PIEZOMETER NESTS
OUTCROP
VARIABLE CONTOUR INTERVAL
837 – mW · m^-2
(20) – HFU, cal × 10^-6 cm^-2 sec^-1
0 400 800 1200 1600 METERS
0 2000 4000 6000 FEET
N
40° 35'
40° 35'
T. 31 N.
R. 47 E.
R. 48 E.
116° 35'
DUN PHY
VALLEY
DESERT PASS
WHIRLWIND
GEYSERS
RIM
FAULT ZONE
A
A'
167 (4)
251 (6)
419 (10)
837 (20)
1674 (40)
153
173
112
225
329
208
623
754
865
558
398
410
535
1580
381
548
1460
2250
3580
458
330
228
341
623
1020
628
569
165
170
265
589
410
311
293
182
158
112
115
106
784
368
311
152
196
336
354
234
118
145
191
153


EXPLANATION
CHEVRON TEST WELLS
THERMAL GRADIENT HOLES
USGS PIEZOMETER NESTS
OUTCROP
HOT SPRING
Contours in meters above sea level
40° 35'
N
1455
1466
1453
1450
1440
1431
1430
1460
1445
1452
1425
1427
1421
A'
1459
<1440
1475
1495
GEYSERS
1470
1480
1490
1466
1472
<1460
1484
1478
1469
<1480
1473
1485
A
T. 31 N
R. 47 E.
R. 48 E.
116° 35'
FAULT ZONE
PASS


EXPLANATION
CHEVRON TEST WELLS
THERMAL GRADIENT HOLES
USGS PIEZOMETER NESTS
OUTCROP
CONTOURS IN °C
40° 35'
116° 35'
N
R. 47 E.
R. 48 E.



SW
A
1600 m.
5000 ft.
1500 m.
4800 ft.
4600 ft.
1400 m.
4400 ft.
1300 m.
Elevation Above Sea Level
B-49
B-50
Surface Drainage
B-37
B-31
B-22
AH-2
B-19
B-11
AH-1
LANDER CO.
EUREKA CO.
B-7
AH-7
DH-12
WHIRLWIND VALLEY
DUNPHY PASS FAULT ZONE
AH-4
AH-8
E
A'
WESTERN EXTENSION OF MALPAIS FAULT ZONE
VHG
.34
.09
.06
.01
.02
EXPLANATION
water table (near land surface in valley)
top of thermal aquifer
normal fault mapped on surface (Struhsacker, 1980)
normal fault inferred from seismic data (Smith, 1979)
vertical hydraulic gradient in m/m
length of arrow proportional to magnitude
test hole total depth
Tertiary volcanic rock
0 400 800 1200 1400 METERS
0 2000 4000 6000 FEET



EXLANATION
CHEVRON TEST WELLS
THERMAL GRADIENT HOLES
USGS PIEZOMETER NESTS
OUTCROP
HOT SPRING OR FLOWING WELL
N
116°35'
40°35'
2000
4000
6000 FEET
WESTERN
EXTENSION
MALPAIS
FAULT
ZONE
1402
1402
1425
1425
1448
1448
1441
1450
1459
1426
1400
1383
1380
1495
1550
1550
1475
1475
1475
1463
1450
1450
1469
1433
1454
1425
1418
1378
1400
A
116°35'
R. 47 E.
R. 48 E.

Society of Exploration Geophysicists

ANNUAL MEETING

AUTHOR'S ABSTRACT

Paper No. ____________

Please type, double-spaced. Send 2 copies to:
Society of Exploration Geophysicists, P.O. Box 3098, Tulsa, Oklahoma 74101

TITLE OF PAPER Heat Flow and Thermal Hydrology of Beowawe KGRA, Nevada

AUTHORS Christian Smith

(Indicate with an asterisk * the author who will present paper at SEG Annual Meeting.)

The Beowawe Geysers lie near the base of a Basin and Range fault scarp near Battle Mountain, Nevada. They have attracted exploration for geothermal electric power generation. The high-temperature (200+^{o}C) hydrothermal system appears to be controlled by the intersection of fault sets that tap deeply circulating water in an area with high regional heat flow (>100 mW·m^{-2}, 2.5 HFU).

Forty 150 m thermal gradient holes have been drilled in a 60 km^{2} area surrounding the Beowawe Geysers as part of the DOE/Division of Geothermal Energy's Northern Nevada Industry Coupled Case Studies Program. Thermal gradients have been calculated and corrected for topography for these holes. Measurements of thermal conductivity were made on chip samples from these holes and from Chevron Resources Company's Ginn 1-13 geothermal well (2917 m T.D.). These data have been used to produce maps of heat flow and of the shallow thermal aquifer.

Thermal gradient and conductivity data from the deep well have a wide range of values (51-141^{o}C·km^{-1}, 1.59-4.62 W·m^{-1}·^{o}C^{-1}) but produce a constant conductive heat flow of 234 mW·m^{-2} (5.6 HFU) above a depth of 1600 m. Low (30^{o}C·km^{-1}) gradients below 1600 m indicate advective heat transport in the fractured rock. If extrapolation of this gradient is accurate, the maximum temperatures predicted by geothermometry (250+^{o}C) would be encountered at depths of 3.75+ km. Thus, the zone of advective heat transport may be 2.0+ km thick.

The detailed heat flow map defines a 12 km^{2} area with heat flow above 234 mW·m^{-2}, the value from the deep hole. Using the 12 km^{2} area predicted from heat flow and the 2 km thickness predicted from thermal gradient and geothermometer data, one can predict a volume of advective heat transport of 24 km^{3}.