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ANALYSIS OF HEAT FLOW AND GEOTHERMAL GRADIENTS AT A GEOTHERMAL PROSPECT IN BEAVER COUNTY, UTAH

by

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Summary

Heat flow and geothermal gradient data from thirteen drill holes outline a geothermal anomaly with gradients as high as 28°F/100' in basement rock and heat flow values 10-15 times the background value. The geothermal anomaly is associated with a Basin and Range normal fault between the Mineral Range on the east and the Escalante Valley on the west. The zone of geothermal fluid circulation extends to depths of 6-10,000 feet. The volume of prospectively productive ground less than 10,000 feet deep is at least 40 mi^3. The inferred geochemical temperature of the reservoir is in excess of 400°F. Deep drilling west of the fault should encounter a productive reservoir along and adjacent to the fault zone in both basin and range rocks. Production from the basement block beneath the fault depends on the degree of fracture porosity and permeability present. This second area might be the best for possible steam discovery. Additional exploration studies are recommended in order to extend the possible productive area known, obtain more information on reservoir conditions and to investigate the potential of the Mineral Range.

Introduction

This report concerns analysis of the temperature gradients and heat flow in 13 exploration drill holes in a geothermal prospect in R 9 W, T 26 and 27 S, Beaver County, Utah. Thermal manifestations (hot springs and hot spring deposits) occur along a linear band about 5 miles long within the prospect area. Geochemical temperatures from Roosevelt Hot Springs range from 400 to over 500°F (see Peterson, 1973, and a preliminary report, Blackwell, 1973). The prospect lies between the Mineral Mountains to the east and the Escalante Valley to the west. On the basis of regional gravity data (Peterson, 1972) the Escalante Valley is a faulted basin on the order of 5000 feet deep (the relative gravity anomaly is -30 mgal). The drill holes were put down to investigate the size, intensity, and nature of the geothermal anomaly associated with the surface manifestations.

Temperature Gradients

Data for this analysis were available from 13 holes in the prospect. The average gradients for different portions of the drill holes are shown in Table 1. The temperature-depth data are plotted in Figures 1 through 4. Most of the holes were drilled in relatively unconsolidated alluvial fill; however, on the basis of the drilling reports it appears that holes 7, 8, 9, and possibly 6 bottomed in the basement rocks of the Mineral Range. The lowest gradient observed is 3°F/100' (from 410'-TD) in DH-3 and (from 160'-TD) in DH-13. The highest gradients are found in DH-7 in section 16. There the gradient in the lower interval in the drill hole (probably in basement rock) is 27.5°F/100'.

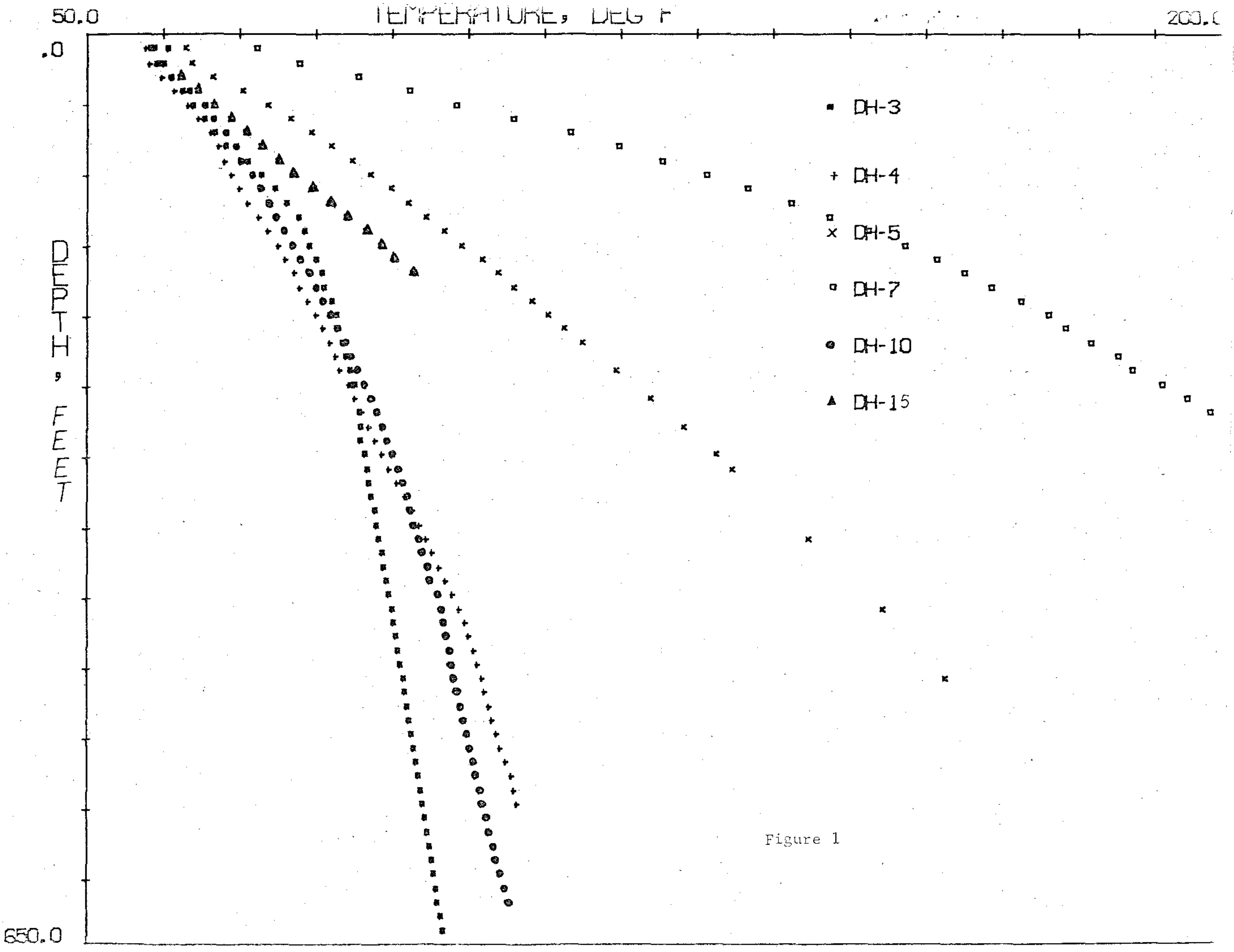
The temperature-depth curves shown in Figures 1-4 have been divided into a series of different intervals based on variations in gradient (Table 1). Some of these gradients intervals may indicate distinct lithologic units; however, most of the contacts are gradational and represent relatively smooth variations in lithology or porosity of the alluvial material. Few of the contacts are sharp, except the contact between the intervals of very high gradient observed in the upper part of some of the drill holes (for example, in 3, 4, 10, and 13) and the lower gradients in units below. This contact might represent the water table in these drill holes. Almost all of the temperature-depth curves are convex upward. The explanation for this convexity is that the porosity decreases and the thermal conductivity increases with depth in most of the drill holes.

Table 1 Geothermal gradients and heat flow values. The figure beneath the geothermal gradient for each depth interval is the standard deviation. Inferred values are in parentheses.

Drill Hole	Depth Interval Feet	Geothermal Gradient °F/100'	Thermal Conductivity 10^{-3}cal/cm sec°C	Heat Flow 10^{-6}cal/cm^{2}sec
2	40-110	4.9 0.9	(2.2)	2.0
3	40-120	16.3 3.5		
	120-250	7.1 2.0	(2.2)	2.8
	250-410	3.5 1.7	(3.3)	2.1
	410-640	3.0 0.7	5.0	$\frac{2.7}{2.5}$
4	40-70	15.7 1.5		
	70-200	10.9 2.0	(2.2)	4.4
	200-435	8.5 1.5	(3.3)	5.1
	435-550	5.3 1.1	4.7	$\frac{4.5}{4.7}$
5	40-60	32.0 1.4		
	60-110	26.2 0.8		
	110-300	22.6 1.2	(2.2)	8.9
	300-460	18.7 2.0	(3.3)	$\frac{11.1}{10.2}$
6	40-90	11.0 1.2		
	90-160	8.9 0.7	(2.2)	3.6
	160-250	5.8 2.0	(3.3)	4.0
	250-310	4.3 1.2	4.2	$\frac{3.3}{3.6}$
7	40-120	62.8 8.5		
	120-150	49.3 1.2	(2.2)	20
	150-230	35.1 5.9	(3.3)	21
	230-280	27.5 5.8	4.0-5.7	$\frac{20\text{-}29.5}{20}$

Table 1 continued

Drill Hole	Depth Interval Feet	Geothermal Gradient °F/100'	Thermal Conductivity	Heat Flow
8	30-50	60.0 1.4		(19)
9	60-80	13.5 2.1		
	80-180	10.7 1.8	(2.2)	4.3
	180-240	7.7 1.5	(3.3)	4.3 4.3
10	50-100	15.8 3.1		
	100-250	10.0 1.1	(2.2)	4.0
	250-350	6.4 1.5	(3.3)	3.6
	350-590	4.3 1.5	4.7	3.7 3.8
	590-620	6.0		
11	40-150	28.1 9.3	(2.2)	11.3
	150-190	23.3 1.9	(2.2-3.3)	9.3-14.0 11.5
12	40-420	9.8 1.2	(3.3)	5.9
	420-480	6.3 1.0	(4.7)	5.4 5.7
15	40-100	20.8 0.8		
	100-140	24.0 0.8	(2.2)	9.6
	140-170	20.7 4.7	(2.2-3.3)	8.3-12.4 (10)
13	40-160	15.4 1.3		
	160-475	3.2 0.5	(5.0)	2.9


50.0
TEMPERATURE, DEG F
200.0
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650.0
■ DH-3
+ DH-4
× DH-5
□ DH-7
● DH-10
▲ DH-15

Figure 1

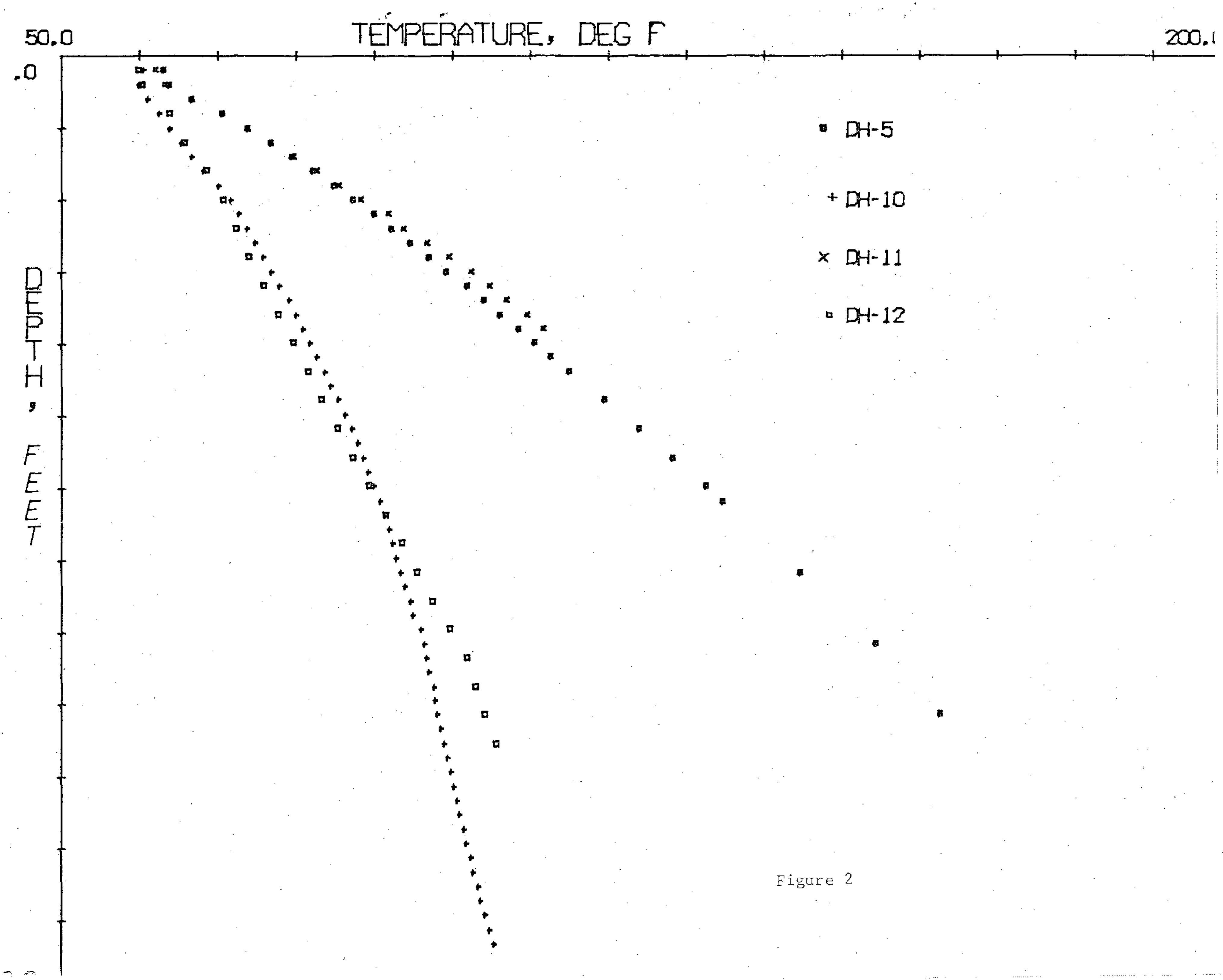

Figure 2

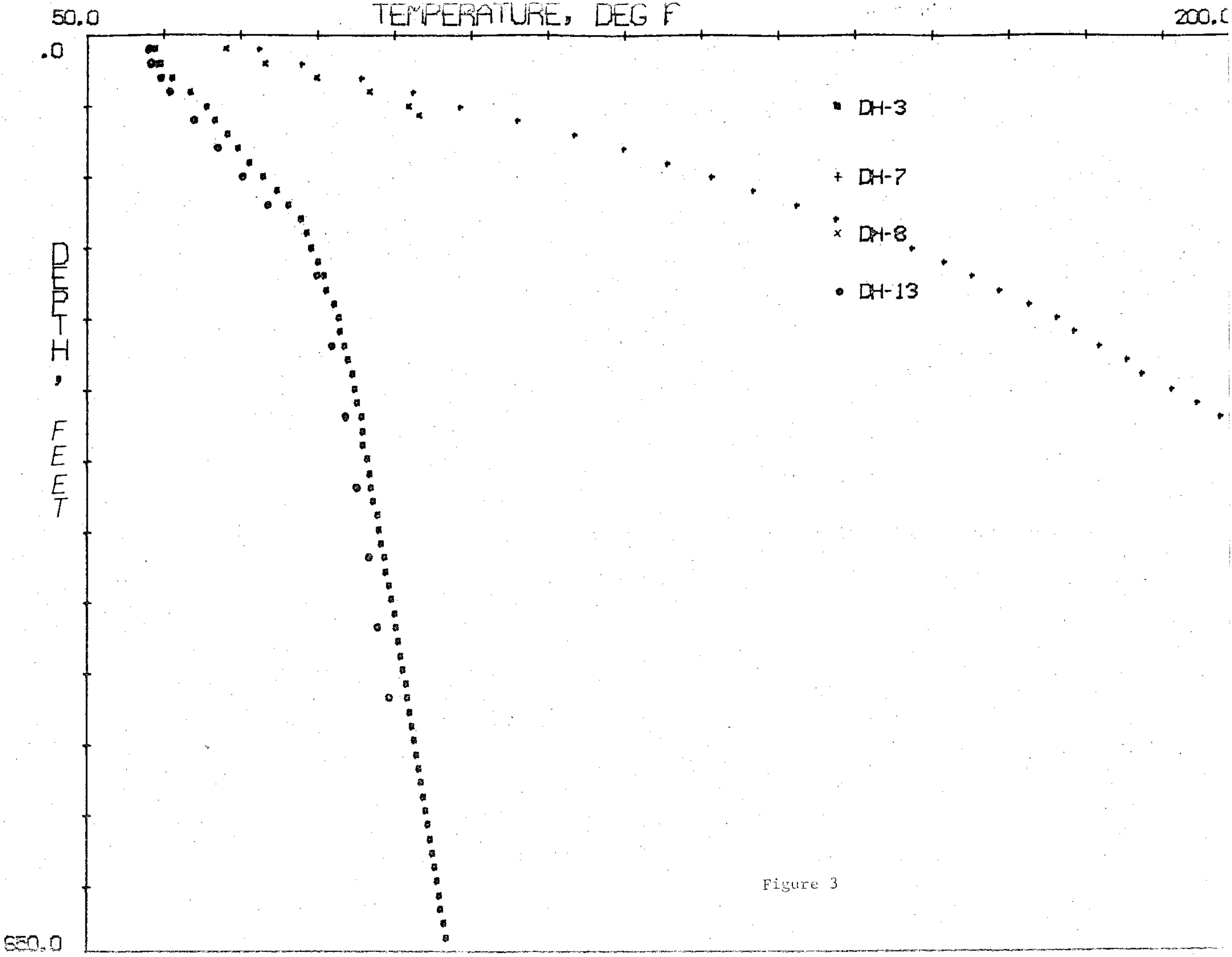

Figure 3

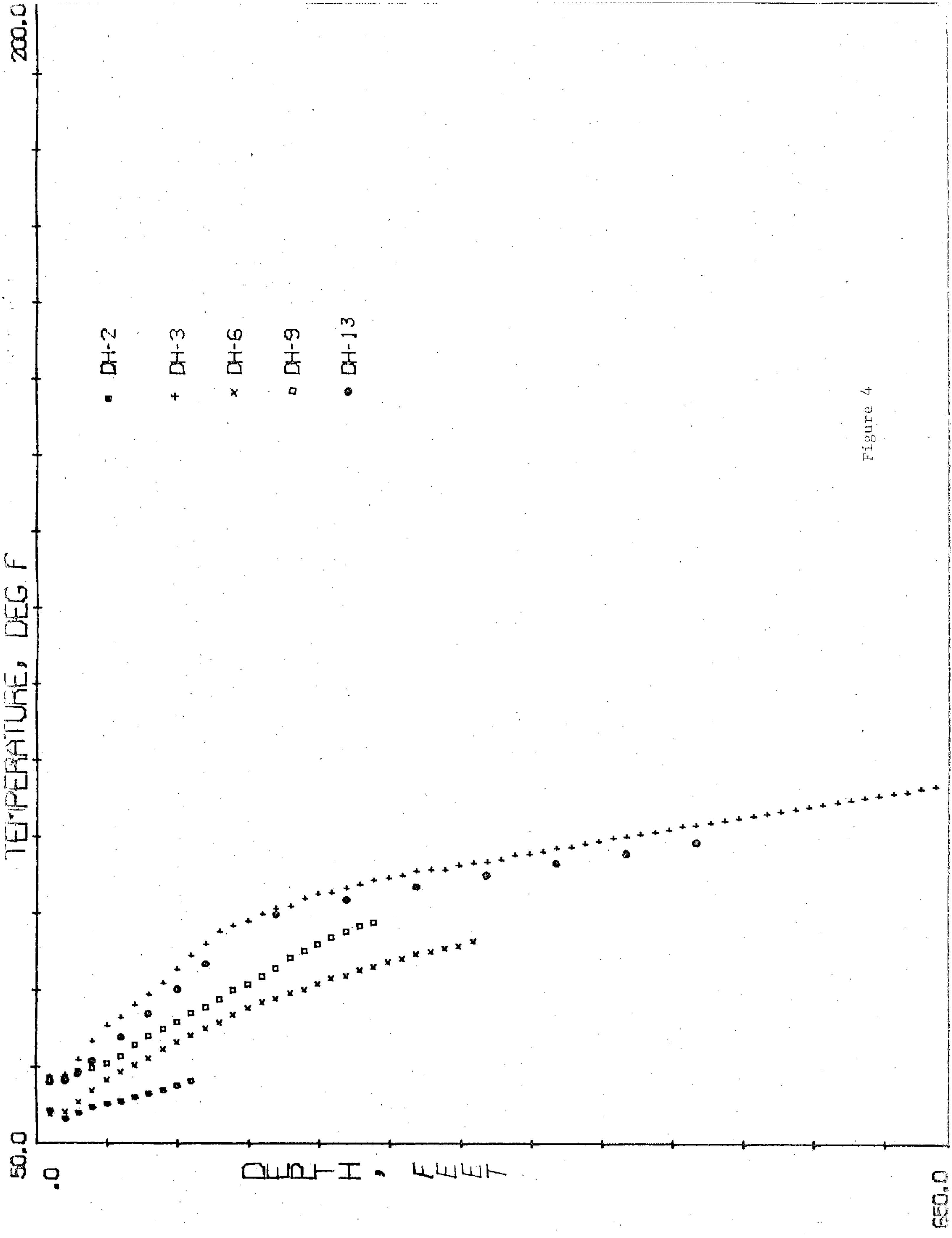
TEMPERATURE, DEG F
50.0
200.0
DEPTH, FEET
.0
650.0
■ DH-2
+ DH-3
× DH-6
□ DH-9
● DH-13

Figure 4

Thermal Conductivity

Thermal conductivity measurements were made on 8 samples of cuttings collected from drill holes 3, 4, 6, and 7. The results of these measurements are shown in Table 2. The intrinsic conductivity (column 3) is the conductivity of the rock fragments making up the cutting samples. This value would be the conductivity if the sediments had zero porosity. However, the porosity is significant and undoubtedly changes with depth (from an estimated value at the surface of 40 ± 10% in these unconsolidated materials to perhaps 25 ± 5% at depth). The calculated conductivity for porosity values of 40 ± 10% and 25 ± 5% are shown in the final two columns of the table. These values were calculated assuming that the rocks are saturated with water. Above the water table, thermal conductivity may be significantly lower than the values listed here due to the presence of air (which acts as an insulator) in the pores of the rock in place of water.

The increase in the intrinsic thermal conductivity with depth in the holes is related to the decrease in the percentage of volcanic glass in the cutting. Volcanic glass probably has an intrinsic thermal conductivity of approximately 3.5 x 10^{-3}cal/cm sec°C whereas the granite of the Mineral Range pluton would probably have thermal conductivity between 6 and 8, similar to that observed in the deeper parts of the drill holes. The intrinsic thermal conductivity is low in the bottom part of DH-7 because the basement rock cut there is more mafic (biotite schist). For the segments of the drill holes which cut basement the intrinsic conductivity would be the value to use. Thus the conductivity used for the bottom interval of DH-7 is the intrinsic conductivity whereas the thermal conductivities in most of the remainder of the drill holes are reduced by a factor appropriate

Table 2 Thermal conductivity of cutting samples. The intrinsic conductivity is that of the constituent rock fragments. The conductivity is also shown for water saturated sediments with porosities indicated. The units of thermal conductivity are 10^{-3}cal/cmsec°C.

Hole Number	Depth Feet	Thermal Conductivity		
		Intrinsic	25±5% Porosity	40±10% Porosity
3	60-75	5.34	3.8±0.3	3.1±0.5
	390-405	6.87	4.6±0.4	3.6±0.7
	630-645	7.65	5.0±0.5	3.9±0.7
4	60-75	5.35	3.8±0.3	3.1±0.5
	510-525	6.97	4.7±0.4	3.7±0.6
6	300-316	6.11	4.2±0.3	3.4±0.5
7	180-195	7.04	4.7±0.4	3.7±0.6
	270-280	5.73	4.0±0.3	3.3±0.5

for effect of the porosity. The primary uncertainty in the determination of the heat flow is the porosity. It is difficult to evaluate this parameter without data from some other logging technique useful for estimating variations in porosity.

The results from DH-3 and DH-4 are very consistent and indicate that the intrinsic thermal conductivity of the rock material increases with depth. This result is consistent with the general decrease in geothermal gradient with depth, but the thermal conductivity ratio is lower than the gradient ratio. For example the geothermal gradient in 410-640' interval is only 50% of that between 120-250' in DH-3. At the equivalent horizons in DH-4 (70-200' and 435-550') the difference is the same. The maximum that can be explained on the basis of thermal conductivity is approximately 35% if the porosity remains constant. Therefore, it is likely that porosity is decreasing with depth from 40 ± 10% at the surface to 25 ± 5% at depths of several hundred feet.

Heat Flow

Heat flow values were calculated for all the drill holes. Of course the data are most reliable for the drill holes for which samples are available. The results of calculations are shown in Table 1 and are plotted on the map in Fig. 5. Metric units are used for the section on thermal conductivity and heat flow in order to facilitate comparison of the data with the published literature. In addition the English units appropriate are rather awkward to use. The conversion factors are $1^{\circ}F/100' \approx 18^{\circ}C/km$, $1 \times 10^{-6} cal/cm^2 sec = 3.58 \times 10^{-6} BTU/ft^2 sec$. Heat flow is calculated as the product of the geothermal gradient times the thermal conductivity, $Q=K\frac{dT}{dx}$, The reason for emphasizing heat flow values rather than gradient alone are demonstrated well in this area. Gradient variations of a factor of two are caused by variations in porosity and intrinsic rock thermal conductivity. Without knowing the cause of the gradient variations one would not know which one to use in downward extrapolations of temperature. Also lateral variations in thermal conductivity might cause lateral variations in geothermal gradient even though the heat flow was the same.

The heat flow values are rather variable within a single drill hole; however, low significance is attached to these variations as they undoubtedly do not reflect real variations of heat flow. Thermal conductivity was estimated for holes for which no samples were measured. In view of the similar character of the temperature-depth curves in most of the wells and the proximity of one well to another, it seems unlikely that these estimates can be off by much. The greatest uncertainty is the thermal conductivity used for drill holes 6 and 9 as both of these drill holes may have bottomed in basement rock. It is assumed that the sections of gradient were not in basement but were still in the alluvial part of the sequence. If the interval between 250' and 310' in DH-6 and between 180' and 240'in DH-9 is in fresh or slightly weathered basement rock, then the heat flow values will be higher than estimated in Table 1 and the contours of the heat flow will be extended to the south and east. The porosity will probably continue to decrease with depth and it appears unlikely that the intrinsic thermal conductivity will change drastically; the best temperature gradients to use in downward extrapolation would be those observed in the lower parts of the drill holes.

The heat flow data are plotted in Figure 5. The elongation of the heat flow contours parallel to the surface evidence of hydrothermal activity beginning in section 16 and extending to Roosevelt hot springs is striking. It seems quite clear that the heat flow anomaly must be related to the thermal manifestations. A regional background heat flow in this area is approximately

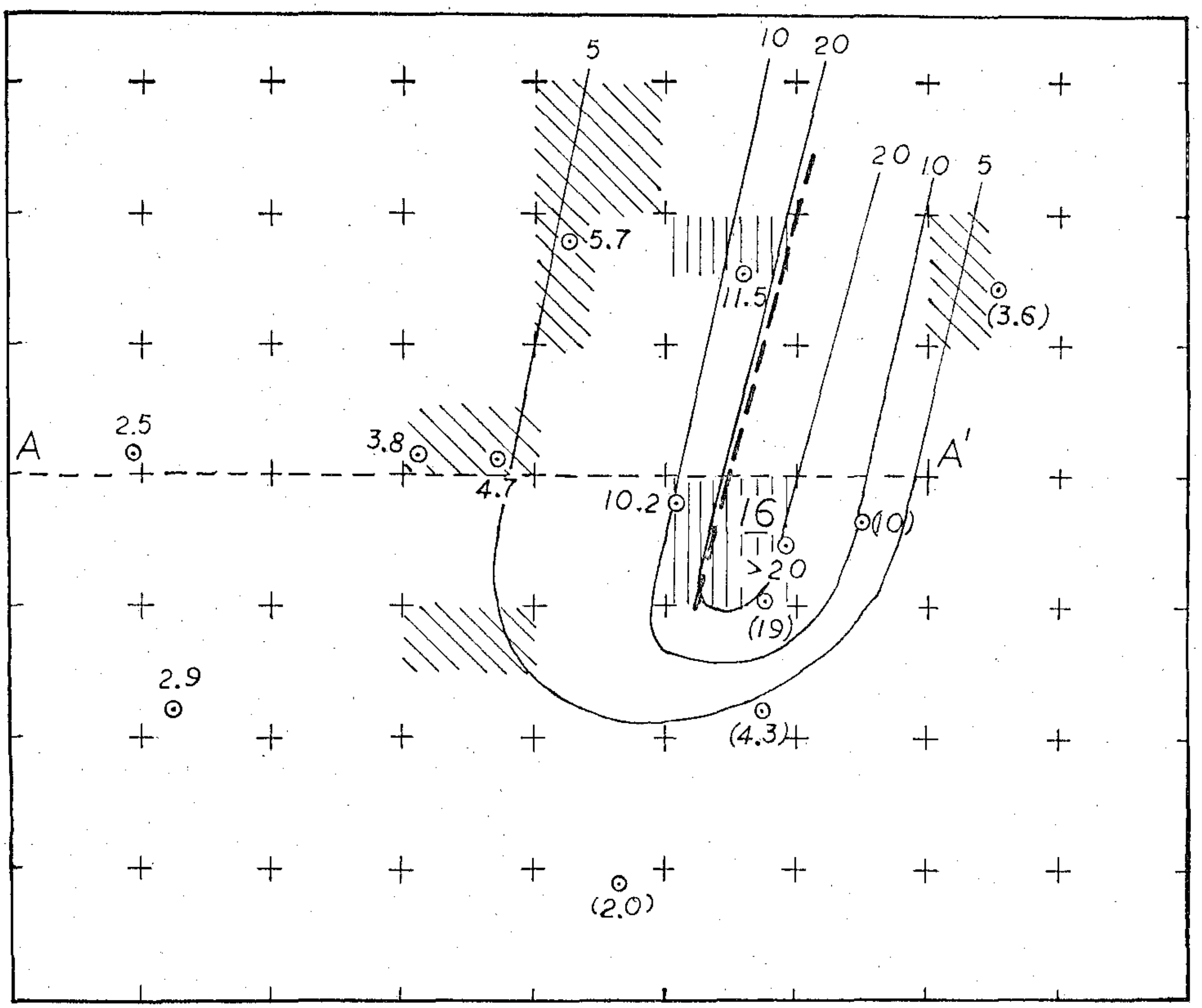

Figure 5 Heat flow values and contours (units are 10^{-6}cal/cm^{2}sec). The location of the thermal manefestations is indicated by the heavy dashed line. Areas with high temperature at shallow depth (less than 5000 feet) are indicated by the vertical line pattern. Areas with deeper potential (5-10,000 feet) are indicated by the diagonal pattern.

2.2 μcal/cm^{2}sec (Roy et al., 1968, Sass et al., 1971). The minimum values in the prospect are not statistically different (DH-3 and DH-2). Thus it appears that the source of heat for the fluid causing the anomaly along the fault is not in the valley directly to the west. If the 3°F/100' gradient in the bottom of DH-3 is extrapolated, the temperatures in the valley sediments (probably 3000-6000 feet thick) remain too low to explain the predicted base temperature (geochemical) from the Roosevelt spring water. These results are discussed in more detail in the next section.

Discussion

A cross section of temperature and heat flow is shown in Figure 6. This cross section (AA' in Figure 5) extends east-west from the southwest corner of section 10 T27S, R10W east to the southeast corner of section 10 T27S, R9W. Heat flow data from drill holes 3, 4, 10, 5, 7 and 15 are projected onto the profile and isotherms have been constructed beneath a topographic profile. This cross section is probably typical of the whole north-south extent of the thermal anomaly zone (see Figures 2 and 5).

The fault apparently acting as the conduit for thermal fluids is also the range-bounding fault. The range-bounding faults in the Basin and Range province invariably dip basinward at 45-90° and may have displacements of 1000's of feet. They may also flatten with depth. The possible range of likely dips for the fault in section 16 is shown in Figure 6. If the gradient in DH-5 is projected downward to intersect the fault (as extrapolated from the apparent surface exposure), the temperature at the fault might range between 400 and 500°F. Thus the heat flow data are consistent with the high temperature indicated by the chemical data.

A theorectical heat flow curve is also shown in Figure 6. The curve was calculated assuming that there is 400°F fluid along a fault dipping at 45° to the west and extending to a vertical depth of about 6000'. A fit could also be obtained for fault zones with dips between 45 and 60°, vertical extents of 6000 - 10,000' and temperatures above 400°F. From this evidence it seems quite clear that the fault zone as a conduit explains most of the observed anomaly. The only exception is that the peak of the

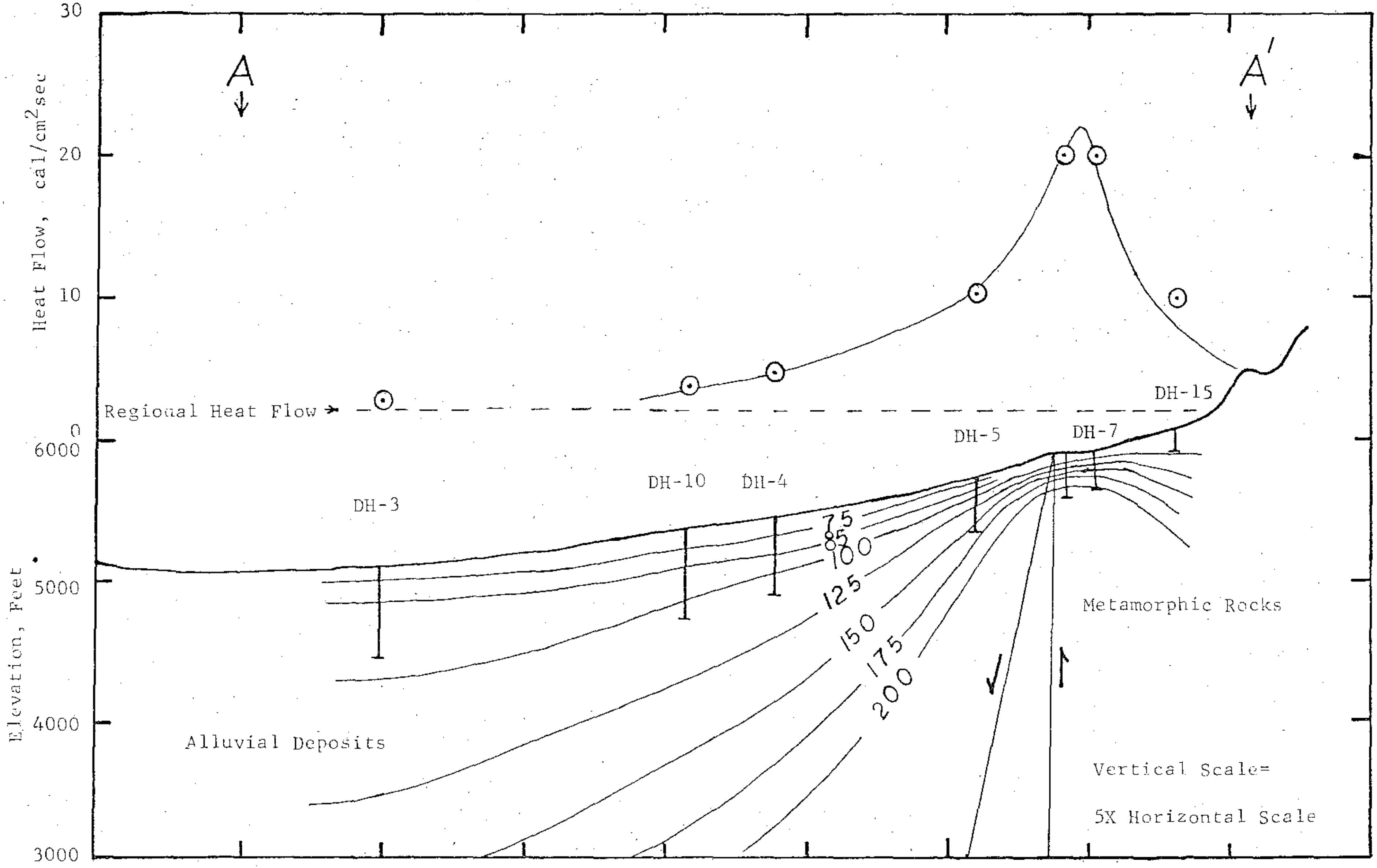

Figure 6 Cross section AA'. Measured and theoretical heat flow, topography, and isotherms (in °F). The location of the drill holes is shown. The dip of the fault probably lies between the limits shown (45°-90°). The Davies well is also included on the section.

anomaly is slightly broader than is predicted and the heat flow, to the east in the range, is somewhat higher than predicted.

If the main structure of interest in the prospect is the fault contact between the range and the basin then the most important unknowns for assessing the geothermal potential are the thickness, extent, permeability, and dip of the fault zone (or zones). The permeable zone must be 10's to 1000's of feet wide. A deep drill hole to the west of the surface manifestations (near the site of DH-5 for example) will hit the fault where the projected temperature would be on the order of 400°F (at 2000-3000'). The thickness of the producing interval would depend on the degree of fracturing accompanying the faulting. A drill hole at the site of DH-7 might hit a maximum temperature of approximately 400°C at about 1000'. Whether or not sufficient permeability and porosity exist in the east half of section 16 depends on the nature of the faulting and shattering accompanying the range-bounding fault. If the permeability is low, but not negligible, then this block may be the most favorable area in the prospect for the occurrence of dry steam.

Thus on the basis of available data the west 1/2 of section 16 and the north 1/4 of section 4 appear to have temperature and probably permeability and porosity necessary for geothermal production at relatively shallow depths (2-4000'). The east 1/2 of section 16 evidently has the necessary temperature, but the presence of sufficient permeability and porosity is not proven.

The heat flow evidence is consistent with a vertical extent of the reservoir zone to depths of 6-10,000'. Thus much of the land in sections 32, 5, 7, and 19 (diagonal pattern, Figure 5) should have production potential at depths of 5-10,000'. The west 1/2 of section 2 might also have potential, but as is the case with the east 1/2 of section 16, the porosity and permeability are unknown.

These results are illustrated in a diagramatic cross section also corresponding to the line AA' (Figure 7). This section has no vertical exaggeration so the horizontal and vertical scales are equal. The various geologic and thermal zones are illustrated. The range-bounding fault is shown as is an inferred fault of the same type, but of smaller displacement, to the east of DH-7. This fault is included partly to explain the breadth of the high heat flow. The most promising production areas would be between these two faults in fractured and shattered metamorphic rocks and just to the east of the main fault in porous basin margin facies rocks. The area of high temperatures is shown.

One of the main uncertainties remaining in the evaluation of the prospect is the source of the heated fluids. A hypothetical heat source is shown in Figure 7 beneath the fault zone and extending into the range. I believe that the evidence is consistent with such a model. The implications of this location for the source of the heat will be discussed briefly in the concluding section.

The width of the zone which is considered definitely to have economic possibility is shown by the dashed line in the upper part of Figure 7. The minimum width of the zone is about 2½ miles. The length of the anomolous zone is at least 5 miles (from section 16 to Roosevelt Hot Springs). Thus the total surface area is 12.5 mi^2. The reservoir temperatures appear to be between 400°F and 500°F (geochemical). Based on the curves of

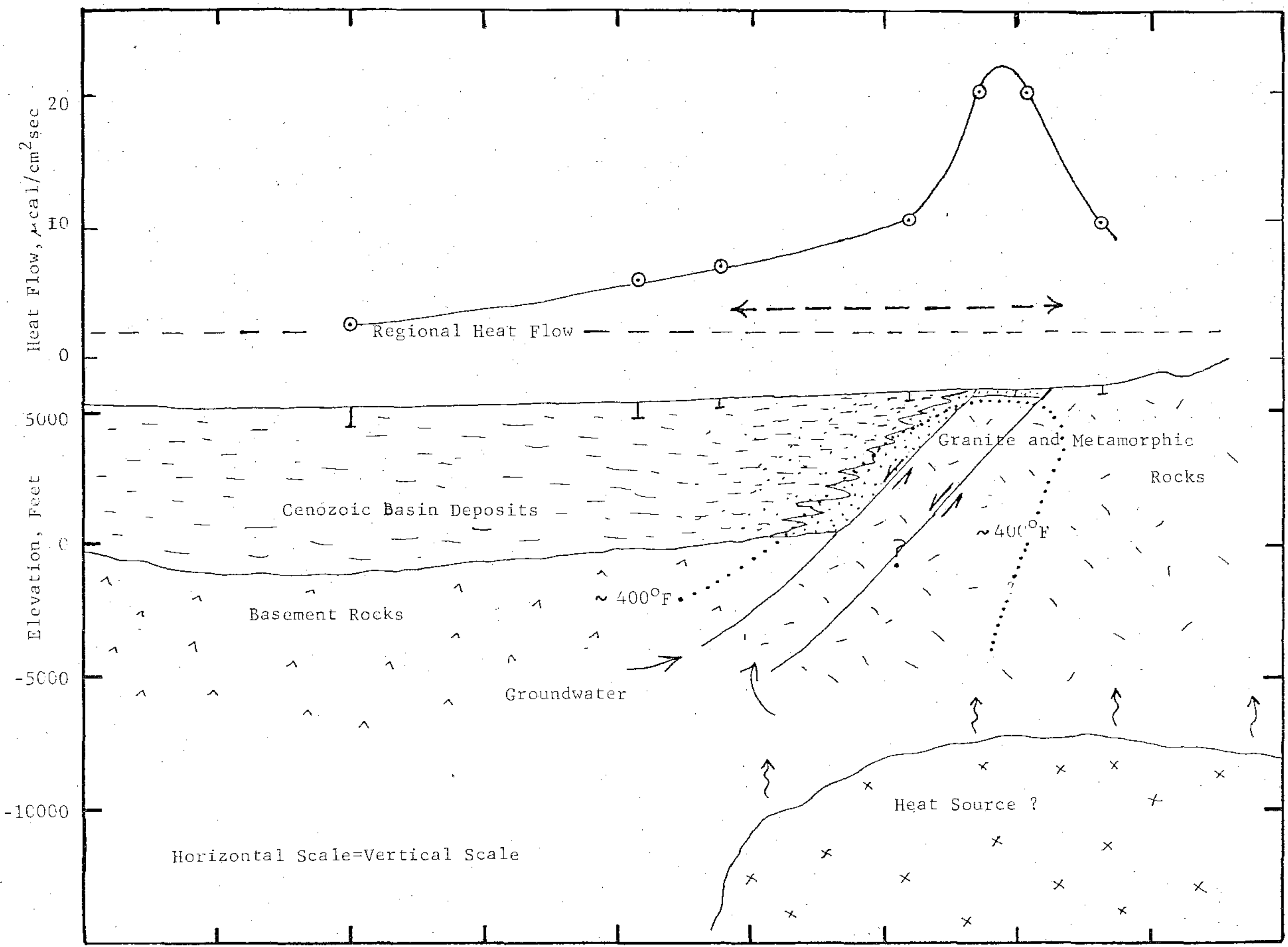

Figure 7 Interpretive cross section AA'. The depth of the valley is approximate.

Banwell (1963) a conservative estimate for the power potential of this anomoly is 400 MW for 20 years. This estimate could be significantly enlarged if deeper potential is present at the western margin of the area. Also if the heat source is beneath the range then the areas of potential economic interest could be many times that known at the present.

Additional Surveys

Geologic Mapping. An adequate map is a necessity for complete analysis or even planning of geophysical surveys. Mapping should be on a scale of 1:24,000' or smaller. In particular the aerial photos of this area indicate many lineations, structures, etc., which may be important to the interpretation of the geophysical data. The development of such a map for the prospect area should be a first priority item at this time! Geological analysis of the cuttings from the wells should also be included in the study. Geochemical analysis of any waters which can obtained should also be a priority item. The main evidence for the high temperatures is geochemical and additional data developed specifically for the exploration project would be extremely useful.

If the heat source is related to the volcanics exposed in the Mineral Range, then the range itself should be mapped as quickly as possible. Such a project is probably not yet needed, but contingency plans should be prepared in the event that the range and its east boundary look promising.

Drilling. The situation with respect to deep production drilling has been outlined in the previous section. Additional shallow heat flow and gradient drilling would also be helpful, but not absolutely necessary. Additional drill holes should be located at the west boundary of section 2, the NE and NW corners of section 4, in the SE ¼ of section 32 and in the NE corner of section 19. The depth of these holes could be on the order of 300'.

Several (2-4) additional shallow holes are strongly recommended in the Mineral Range itself. The source of the heat escaping in the prospect has not yet been identified. The size of the prospect at the present seems quite well identified, but the presence of a heat source beneath the range could enlarge the prospective valuable area by a factor of 10 or more! The presence of volcanics and a gravity anomaly in the range may be evidence that such a source exists. The heat flow should be the first study for the range block. If high heat flow values are observed ($> 4 \mu$cal/cm^{2}sec) then the other regional studies proposed for the range elsewhere in this report would be called for to locate promising smaller areas for more detailed studies.

Gravity. A detailed W to E cross section approximately coinciding with AA' will be shortly available. A regional type map (scale 1:250,000') is already available (Peterson, 1972). The gravity data are useful for the general structure of the area. With the completion of the detailed survey, no additional gravity data should be needed for the prospect itself. As will be described in a separate report, the regional gravity data seem to indicate an anomaly underlying the granite of the Mineral Range east of the prospect area. If this negative gravity anomaly is associated with the heat source for the geothermal anomaly in the prospect area, then the regional gravity data should be augmented on the east side of the range in order to obtain a complete picture of the gravity anomaly. The available gravity data will be considered more fully in a subsequent report.

Electrical Resistivity. Two important questions remain in the evaluation of the prospect area: the depth to the basement rocks under the valley; and the porosity and permeability of the basement block east of the fault running through section 16. An electrical resitivity survey designed to penetrate to resistive basement in the valley and to determine the resistivity of the block east of the fault could supply data on these two unknown parameters. However, if the material in the valley is very conductive, then it may be difficult to get penetrations to the depth necessary (5000 feet at least).

Again, if the range appears to be a possible exploration target, then a broad scale electrical resistivity survey might be appropriate. Such a survey would concentrate on detailing the structures outlined by geologic mapping as favorable for fluid circulation and as reservoir situations. The faults mapped and inferred in the range and the bounding fault on the east side of the range would deserve special emphasis.

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