HEAT FLOW RESEARCH AND EXPLORATION FOR GEOTHERMAL POWER BLACK ROCK DESERT, NEVADA

E. R. DECKER JUNE 1971

DISCLAIMER

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CORDERO MINING COMPANY — INTER-OFFICE CORRESPONDENCE

DATE: June 23, 1971

SUBJECT: GEOTHERMAL PROJECT BLACK ROCK DESERT, NEVADA

FROM: G. W. Berry

TO: Mr. J. E. Gilbert
Palo Alto

I forward three (3) copies of "Heat Flow Research and Exploration for Geothermal Power in the Black Rock Desert, Nevada" handed me this date by Dr. Edward R. Decker, Department of Geology, University of Wyoming.

Dr. Decker is highly knowledgeable in crustal geophysics, particularly heat flow. I engaged him in 1970 as a consultant on our Black Rock Desert prospects, to review the available data and recommend research and exploration for evaluating and developing the area, or areas. Dr. Decker and I made field observations together in July 1970 and we have conferred frequently at Laramie and Boulder. I enthusiastically endorse his excellent report.

In the first seven pages Dr. Decker summarizes, with tables and figures, up-to-date information on heat flow determinations on land: techniques, calculations, corrections, averages. He then reviews the Hadsell, Grose, and Berry report "Thermal Data of the Black Rock Desert Area" (Sun Oil Co. Rept., Boulder, April 10, 1967, 22 p.). Although kind to us, he makes clear that "Their data indicate that each area is thermally anomalous, but do not lead to reliable subsurface temperature information." He makes "Recommendation for Future Research" (p. 10) in general discussion and then specifically for Pinto Mountains, Fly Ranch, Gerlach, and Soldier Meadows.

Although Dr. Decker's report is mainly on heat flow, he urges a coordinated geological, geophysical, geochemical, hydrological research and exploration program. In other geophysics he favors gravity and is particularly impressed with the deep electrical resistivity work of Dr. George V. Keller (Group Seven).

Some have argued Cordero should simply drill the Nevada geothermal prospects now and "see if we got steam." I consider our plays on good samples of Basin and Range terrain, prefer to think big, oppose fragmented "black box" exploration, and recommend a geological-geophysical-geochemical exploration team of educated, experienced, and enthusiastic men. Cordero has considerable spade work done. We can, I think, work very effectively with Dr. Decker and Dr. Keller. I am strongly in favor. I suggest a figure of $100,000, but we could start with $50,000.

G. W. Berry

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Heat Flow Research

and

Exploration for Geothermal Power

in the

Black Rock Desert, Nevada

A Report Submitted

to

Dr. George W. Berry, Cordero Mining Company

by

Edward R. Decker
Assistant Professor
Dept. of Geology
University of Wyoming

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Introduction

Measurements of heat flow near the earth's surface provide the most reliable boundary conditions to be employed in the calculation of models of subsurface temperatures and the spatial distribution of crustal sources of heat. The subsurface temperature and heat source distributions, in turn, have many broad implications in the explanation of several geologically-observed phenomena and must be considered in exploration for geothermal power. In this report, several aspects of modern heat flow research are briefly summarized and reviewed. These comments are then used as a basis for a heat flow research project that would provide more definite data on the geothermal power potential of the Black Rock Desert area in northwestern Nevada.

Notation and Units

Table 1 summarizes the notation and units that are used in this report. More complete discussions of the thermal parameters and conventions may be found in Roy, Decker, Blackwell and Birch (1968) and Decker (1969).

Heat Flow Determinations on Land

Determinations of heat flow require the measurement of temperatures at known positions in underground openings (boreholes, tunnels, mine shafts, etc.) and the measurement, usually in the laboratory, of the thermal conductivity of representative samples of rock from the same openings. Temperatures are frequently measured with thermistor probes in combination with cables and three-and four-

Table 1. Summary of notation and units

Depth - vertical depth in meters (m) or feet (ft) below the surface of the ground. 1 meter $\cong$ 3.28 feet.

Temperature - ^{o}C and ^{o}F

Gradient - ^{o}C/km. The least-squares gradient refers to the slope of a least-squares straight line fitted to observed temperatures and depths. The numbers in parentheses denote the depth intervals used.

Thermal Conductivity, K - millical/cm sec ^{o}C = 10^{-3} cal/cm sec ^{o}C. The numbers in parentheses indicate the number of samples determining average conductivity.

Thermal Resistivity, R - cm sec ^{o}C/cal. For isotropic media R = 1/K. The numbers in parentheses indicate the number of samples determining average resistivity.

Thermal Diffusivity, k - cm^2/sec. $k = K/Cp \cdot \rho$ where K is conductivity, Cp is specific heat, and ρ is density. This parameter determines the changes of temperature with time and distance in a body and is used in time-dependent (transient) heat conduction calculations.

Heat Flow or Heat Flux - 1.0 HFU (Heat Flow Unit) = 1.0 microcal/cm^2sec = 1.0×10^{-6} cal/cm^2sec. In geology, the terms heat flow and heat flux are used interchangibly. In the theory of heat conduction, heat flow refers to the transfer of heat per unit time, whereas heat flux refers to the transfer of heat per unit area and in unit time.

Precision Indices - Standard errors are used as measures of the internal consistency of the data. The errors are for 95% confidence limits including a "Students t" multiplier for (n-1) degrees of freedom.

lead compensated DC bridges and null-detectors (see Roy, Decker, Blackwell and Birch, 1968). Thermal conductivities are normally measured using divided-bar systems (Birch, 1950). With these systems and techniques, temperatures may be measured to within ±.001°C, and thermal conductivities of individual samples can be reproduced to within ±2%.

The observed temperatures provide a measure of the uncorrected gradient. Uncorrected values of heat flow combine the observed temperatures and conductivities and are usually calculated by one of three methods. If the gradient profile is linear, the heat flow may be calculated as the product of mean conductivity multiplied by the least-squares gradient (GK); otherwise, the flux should be calculated from the resistance integral (RI) (after Bullard, 1939, p. 481), or as the mean value of several heat flows determined over several separate intervals of depth (I). The results obtained after these methods were applied to geothermal data collected in four different drill holes are summarized in Table 2. The temperature-depth profiles for these holes are shown in Figures 1 through 4. The gradient is very uniform in DDH#CH3 at Cerrillos, New Mexico (Fig. 1); therefore, heat flow was calculated as the simple product of least-squares gradient times mean conductivity. At DDH#1 and DDH#2 near Santa Rita, New Mexico and DDH#N-55 near White Pine, Michigan, however, the gradients significantly varied with depth and heat flows were calculated using the interval and the resistance integral methods, respectively (see Figures 2, 3 and 4; also Table 2). The high precision (standard errors $\leq \pm 5\%$) of the calculations

Table 2. Methods for heat flow calculations.

GK Method

Q_z = Gradient • K

Cerrillos, N. Mex.
DDH CH#3

Gradient: (90-280m)
24.4±2°C/km

Conductivity:
$5.0\pm2(42)^{*}10^{-3}\frac{cal}{cm\ sec\ ^\circ C}$

Heat Flow:
1.22±.06 HFU

RI Method

$$Q_z \int_{Z_1}^{Z_2} R_z d_z = \int_{T_1}^{T_2} dT$$

White Pine, Mich.
DDH#N-55

Depth (m)	R_{ave} ($\frac{cm\ sec\ ^\circ C}{cal}$)	T (°C)
91.4	132(7)	7.65
121.9	154(6)	8.08
152.4	159(7)	8.58
182.9	164(3)	9.08
213.4	152(3)	9.57
243.8	139(5)	10.02
274.3	123(7)	10.44
304.8	135(6)	10.84
335.3	135(7)	11.26
365.8	130(5)	11.67
396.2	127(5)	12.09
426.7	145(5)	12.50
457.2	185(6)	12.96
487.7	179(5)	13.54
518.2	179(5)	14.14
548.6	189(8)	15.30
579.1	175(6)	15.88
609.6	185(8)	16.51
640.1	172(3)	16.78
655.3	103(6)	17.02
678.2		

Heat Flow = 1.040 ± .003 HFU

* (after R.F. Roy, unpublished)

Table 2 continued

I Method

$$Q_z = \left\{\frac{T_2 - T_1}{Z_2 - Z_1}\right\}\left\{\frac{Z_2 - Z_1}{\sum_{i=1}^{n} \frac{Z_i}{K_i}}\right\}$$

Santa Rita, N. Mex.

DDH #1

Depth (m)	Gradient ($^{\circ}C$/km)	Average Conductivity (10^{-3} cal/cm sec $^{\circ}C$)	Heat Flow (HFU)
225	26	7.0(2)	1.8
230	22	7.3(3)	1.6
235	20	7.1(3)	1.4
240	24	6.9(2)	1.7
245	22	6.8(3)	1.5
250	20	7.4(3)	1.5
255	28	7.2(2)	2.0
260	22	7.5(2)	1.7
265	22	7.5(2)	1.7
270	22	7.4(4)	1.6
275	22	7.7(2)	1.7
280			

Heat Flow = 1.7±.1 HFU

Corrected Heat Flow = 1.8±.1 HFU

DDH #2

Depth (m)	Gradient ($^{\circ}C$/km)	Average Conductivity (10^{-3} cal/cm sec $^{\circ}C$)	Heat Flow (HFU)
180	34	5.4(3)	1.8
190	42	4.3(3)	1.8
200	46	4.0(3)	1.8
210	51	3.9(8)	2.0
220	56	3.5(4)	2.0
230	58	2.9(4)	1.7
240			

Heat Flow = 1.90.02 HFU

Corrected Heat Flow = 2.00±.02 HFU

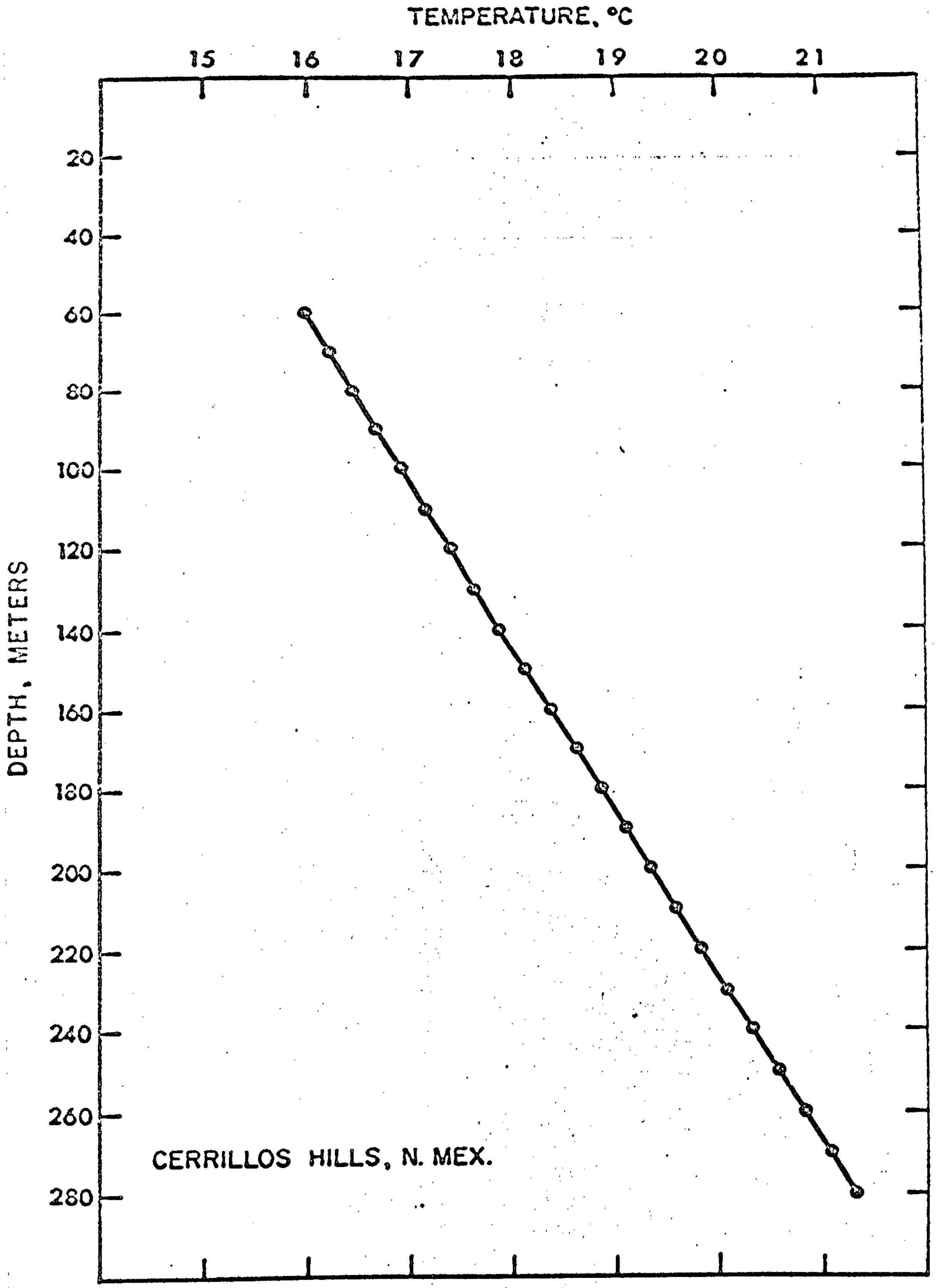


Figure 1. Temperature vs. depth in drill hole CH-3, Cerrillos, New Mexico (Decker, unpublished).

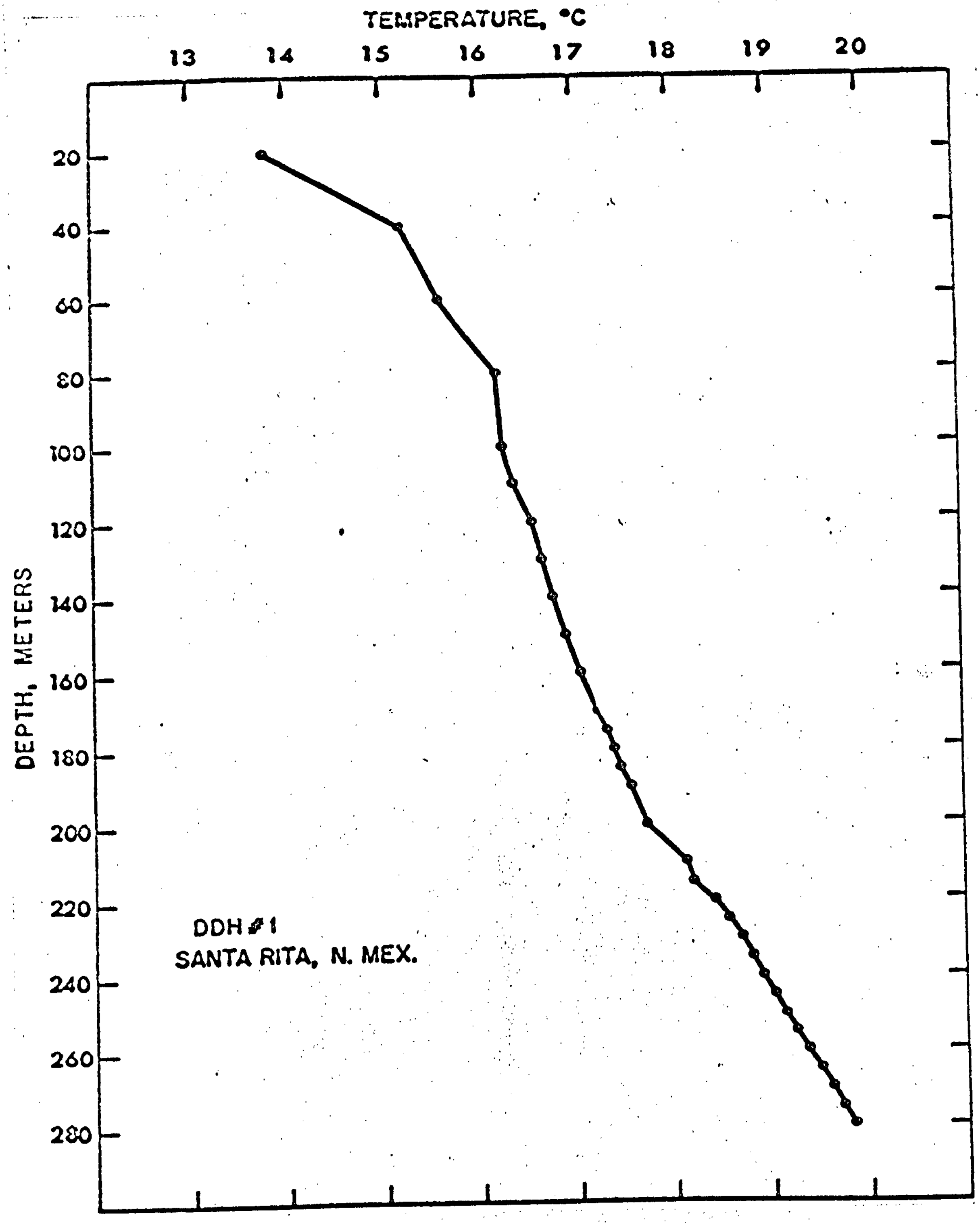


Figure 2. Temperature vs. depth in drill hole #1, Santa Rita, New Mexico (Decker, unpublished).

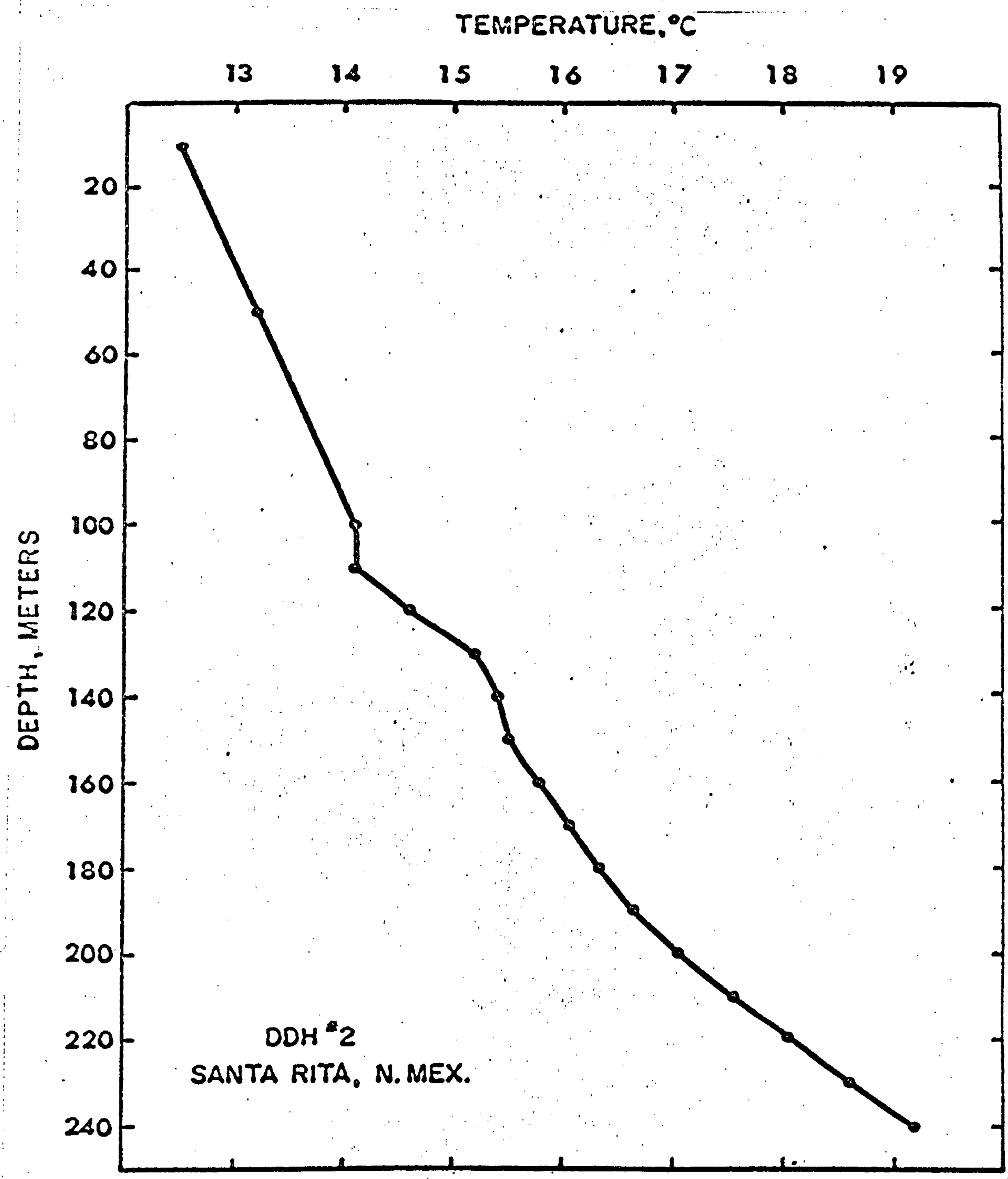


Figure 3. Temperature vs. depth in drill hole #2, Santa Rita, New Mexico (Decker, unpublished).

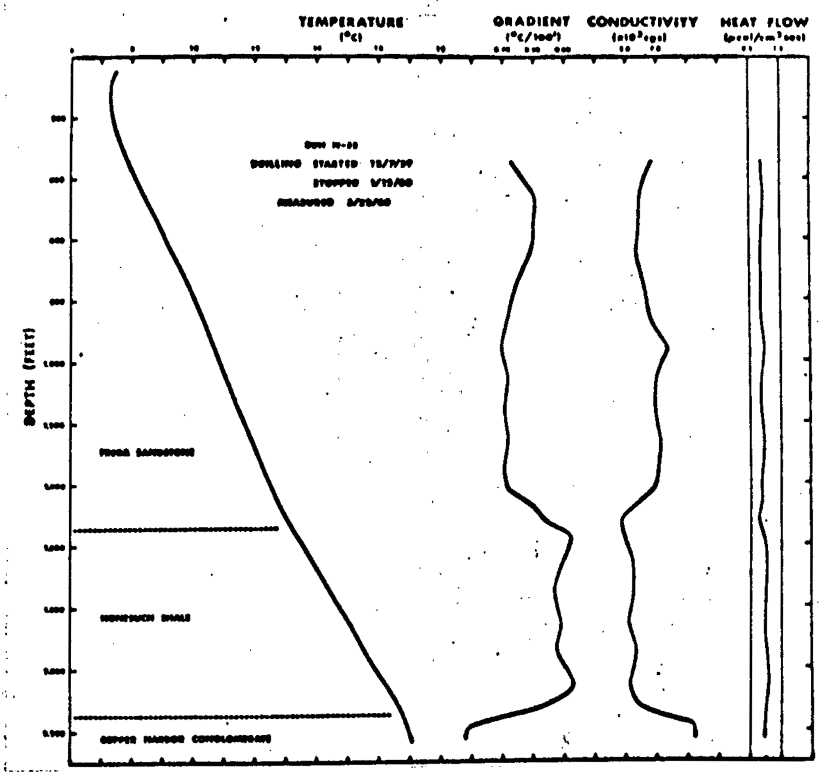


Figure 4. Temperature, gradient, conductivity, and heat flow vs. depth in drill hole N-55, White Pine, Michigan (R.F. Roy, unpublished).

demonstrates that the temperature and conductivity data are internally consistent at all four sites and clearly illustrates the need for different calculation methods in the analyses of geothermal measurements at different localities.

The geothermal data from Santa Rita, New Mexico also illustrate the value of heat flow in the determination of deep temperature and heat source distributions. In particular, the gradient in DDH#2 systematically increases (34-58°C/km) with depth below 180 meters, but the conductivity varies inversely such that the vertical component of flux is uniform (2.00±.02 HFU) throughout the 180-to 240-meter interval (see Figure 3; also, Table 2). The gradient is significantly lower (22.7±.2°C/km) in DDH#1 about two miles distant, but the "topographically corrected" flux at this site is 1.80±.1 HFU, a value close to that obtained in DDH#2. The good agreement between the heat flows obtained in the two different drill holes shows that high and uniform regional flux is characteristic of the Santa Rita area. If the regional flux were not known to be uniform in the Santa Rita area, and if the inverse correlation between temperatures and conductivity had not been observed in DDH#2, it would have been reasonable to speculate that the increasing and higher gradients in DDH#2 provided evidence for anomalous heat sources (hot waters, etc.) closer to the surface near this site.

Although modern techniques allow very precise (±10%) determinations of flux over short intervals of depth (20-50 meters) in drill holes, the experience of much logging has shown that various disturbances (climatic changes, culture, ground water circulation, etc.) are likely to affect temperatures in the first few tens of meters beneath the earth's surface. As a result, values of thermal gradient representative of the heat flow from below are usually not obtainable at depths of less than 100 meters. For example, the highly irregular gradients in the upper portions of DDH#2 at Santa Rita, New Mexico (Figure 3) and the drill holes near Hesperus and Colorado Springs, Colorado (Figures 5 and 6) represent the disturbing effects of circulating waters that are entering the holes at various locations. The heat flows calculated in these zones are significantly different (±10 to ±100%, Decker, 1966 and 1971, unpublished) from those obtained in the lower, undisturbed intervals. The effect of circulating water is more regular at the site near Colorado Springs, Colorado (Figure 6), but the flux also is variable and inaccurate for a distance of 800 feet above the point (~2300 feet) where water enters the hole.

Figure 7 illustrates the effect of transient changes of culture and climate on near-surface temperatures. The linear portions of the deep (below 100 meters, or so) temperature curves represent thermal equilibrium established when the surface temperature was different (higher and lower) throughout the areas. The curvature in the shallower profiles, however, represents the adjustment of near-surface temperatures to recent changes of mean surface temperatures associated with climatic variation and changes of vegetation or construction (see, for examples, Lachenbruch and Marshall, 1969; Roy, Blackwell, and Decker, 1971, in press). If the magnitudes and durations of the surface temperature fluctuations

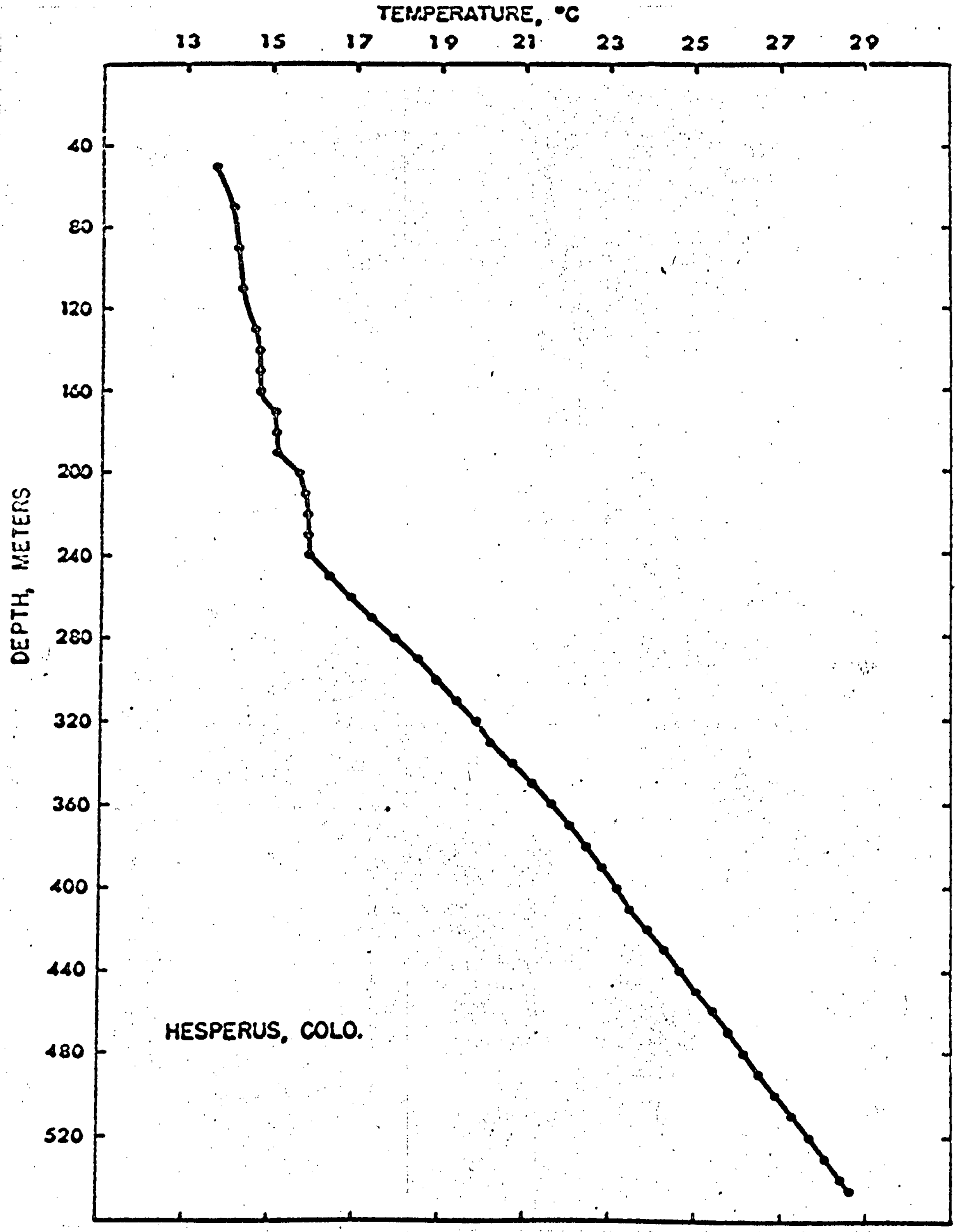


Figure 5. Temperature vs. depth in a drill hole near Hesperus, Colorado (Decker, unpublished).

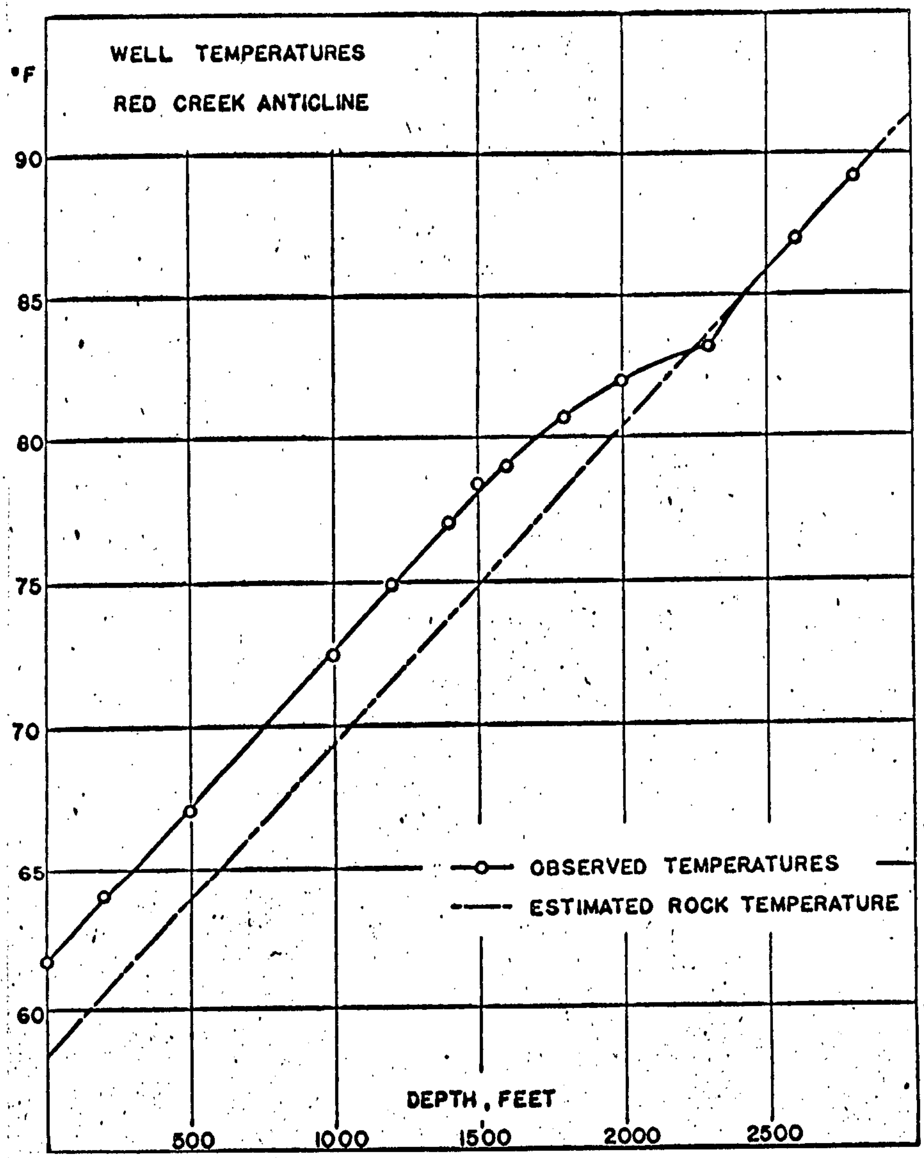
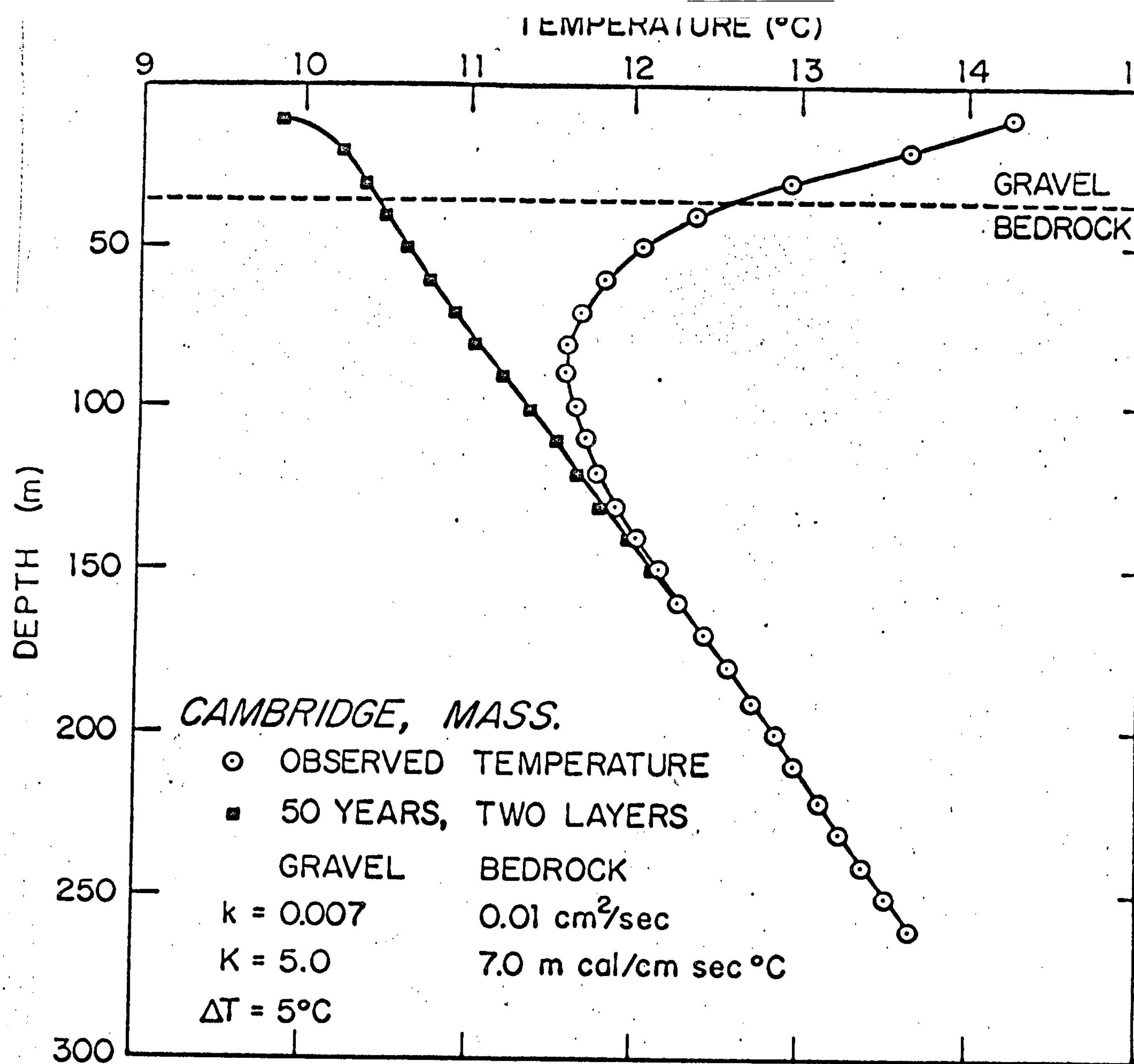
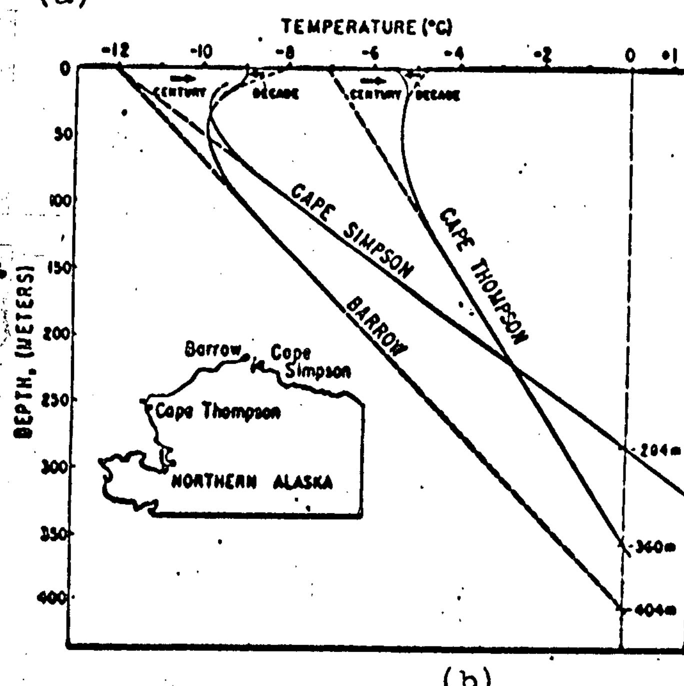


Figure 6. Temperature vs. depth in a drill hole near Colorado Springs, Colorado (after Birch, 1947).



(a)



(b)

Figure 7. Effect of culture and climatic change on subsurface gradients. (a) Effect of nearby buildings at site in Cambridge, Mass. (from Roy, Blackwell and Decker, 1971, in press). Open circles are observed temperatures. Solid squares represent temperatures obtained after correction for shown diffusivities and conductivities. (b) Effect of climatic change at three sites in the Alaskan Arctic (after Lachenbruch and Marshall, 1969).

are known in a quantitative sense, corrections (after Birch, 1948; Roy, Blackwell, and Decker, 1971; also, Figure 7a) may be applied to the near-surface temperatures to obtain corrected values for the geothermal gradient; otherwise, as is usually the case, any attempts to use uncorrected nonlinear near-surface temperature profiles would obviously lead to unreliable estimates for the heat flow from below, or the true regional flux.

The disturbing affect of circulating ground water can be of the transient type and, at drill sites where it is economically feasible, may be greatly reduced or alleviated by grouting (AM-9, or cement) casing in place at the termination of drilling. This technique has been used with good success in drill holes in the New York-New England area (see, for example, Figure 8). Grouting also could have been used to alleviate the water disturbance shown in Figure 6. Although grouting does not remove climatically or culturally induced disturbances, it does reduce those related to circulating water and should be done at all sites drilled specifically for heat flow research.

Like measurements of gravity at the earth's surface, observations of underground temperature obtain their full significance only after certain kinds of topographic reduction. In general, the temperatures follow the topography such that the isothermal surfaces are more widely separated beneath peaks than under valleys. As a result, more heat is conducted out through the valley floors than through the sides of adjacent hills or mountains.

Birch (1950) (see also Bullard, 1938; Jeffreys, 1938; Carslaw

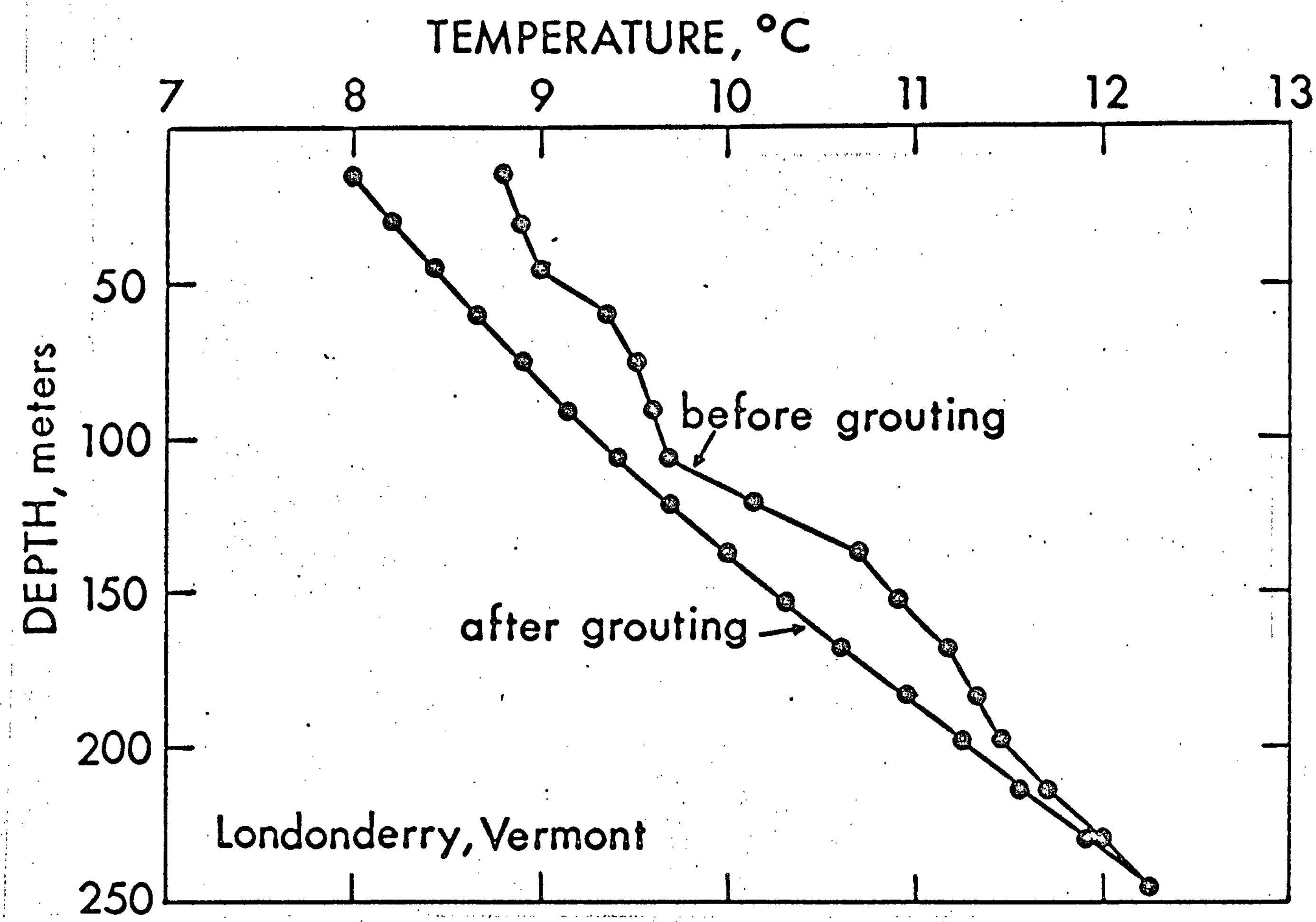


Figure 8. Temperatures vs. depth before and after grouting in drill hole at Londonderry, Vermont (from Roy, Blackwell and Decker, 1971, in press).

and Jaeger, 1959; Jaeger, 1965) has developed a method for calculating the first order effects of two-and three-dimensional topography. His results, together with those of others (Roy, Decker, Blackwell, and Birch, 1968, Table 5; Decker, 1969; Blackwell, 1969), clearly demonstrate that uncorrected heat flows in deep (100-1000 meters) drill holes or tunnels may be 10-40% different from those obtained after correction for steady-state topography. The terrain correction may be ±50-200% at localities where the depth of measurement (shallow drill holes) is small relative to the distance to moderate relief (Lachenbruch, 1969). Thus the distorting effects of local topography must be considered at each temperature station, if regional heat flow surveys are to provide reliable quantitative information on the subsurface temperature and heat source regimes.

Results of Recent Continental Heat Flow Studies

Recent studies (Birch, Roy and Decker, 1968; Roy, Blackwell and Birch, 1968; Lachenbruch, 1968; Roy, Blackwell and Decker, 1971, in press) suggest that the earth's thermal field may be subdivided into "heat flow provinces," within which there are linear relationships between heat flow and heat production from local basement radioactivity (U, Th, K). These lines are of the form

$$Q_S = Q_O + A_S H$$

where Q_S is the flux where radioactive heat generation is A_S, Q_O is the heat flow where $A_S = 0$, and H, with the dimension of thickness, is the slope of the line. The intercept Q is considered to provide a measure of the heat from the lower crust and/or upper mantle, and it can be analytically shown that the steady-state heat from a layer with vertically uniform heat production A_s and thickness H would be the excess flux ($Q_s - Q_o = A_s H$) at a given site.

A list of well-determined "heat flow provinces" and the parameters of their respective heat flow - heat production lines is given in Table 3. The similar slopes (total range 5 to 10 km) of the lines imply that crustal radioactivity has undergone extreme upward differentiation and readily accounts for 1.0 to 1.5 HFU variations of heat flow at the surface. The significantly different Q_o values (.4 to 1.4 HFU), on the other hand, provide the first reliable demonstration that heat flows from the lower crust and upper mantle are the characteristic thermal parameters of the provinces. Moreover, the intercepts (Q_o) appear to be uniform throughout each province. Thus the average high surface flux (1.9-2.1 HFU) in the Basin and Range province and Southern Rocky Mountains is probably due to heat sources and temperature anomalies at depth ($>$H) beneath each region. The very high values of flux ($>$3.0 HFU) observed in these areas suggest that anomalous heat sources and temperatures are locally closer to the surface.

Heat Flow Research Near Cordero Mining Company's Hot Springs In Northwestern Nevada

Previous Results. Hadsell, Grose and Berry (1967) summarized flow rates and mean water temperatures for the hot springs at Soldier Meadows, Fly Ranch, Gerlach and the Pinto Mountains (Table 4), and calculated heat flows in seven shallow (65-385 ft. deep) drill holes at the Pinto Mountain Prospect (Figures 9-15). Their data

Table 3. Summary of heat flow provinces

Data after Roy, Blackwell and Birch (1968), Roy, Blackwell and Decker (1971, in press), and Jaeger (1970).

Province	Slope (km)	Intercept (10^{-6} cal/cm^{2}sec)	Average Flux (10^{-6} cal/cm^{2}sec)	Range of Flux (10^{-6} cal/cm^{2}sec)	Range of Radioactivity (10^{-13} cal/cm^{3}sec)
Continental U.S.					
Basin and Range Province	9.4	1.4	1.9-2.1	1.6-3.7	3.0-10.0
Eastern U.S.	7.5	.8	1.2	.81-2.3	.4-21.2
Sierra Nevada	10.1	.4	.96	.6-1.3	1.8-9.6
Southern Rocky Mtns.	10	1.2	1.9-2.1	1.5-3.7	3.0-16.0
Australia					
Western	4.5	.6	1.6	.7-2.3	1.2-21.9

Table 4. Summary of flow rates and mean temperatures of not springs in northwestern Nevada (from Hadsell, Grose and Berry, 1967).

Locality	Flow Rate gal/min	Temperature °F
Soldier Meadows	2842	110
Fly Ranch	1472	138
Gerlach	253	175
Pinto Mountains	142	189

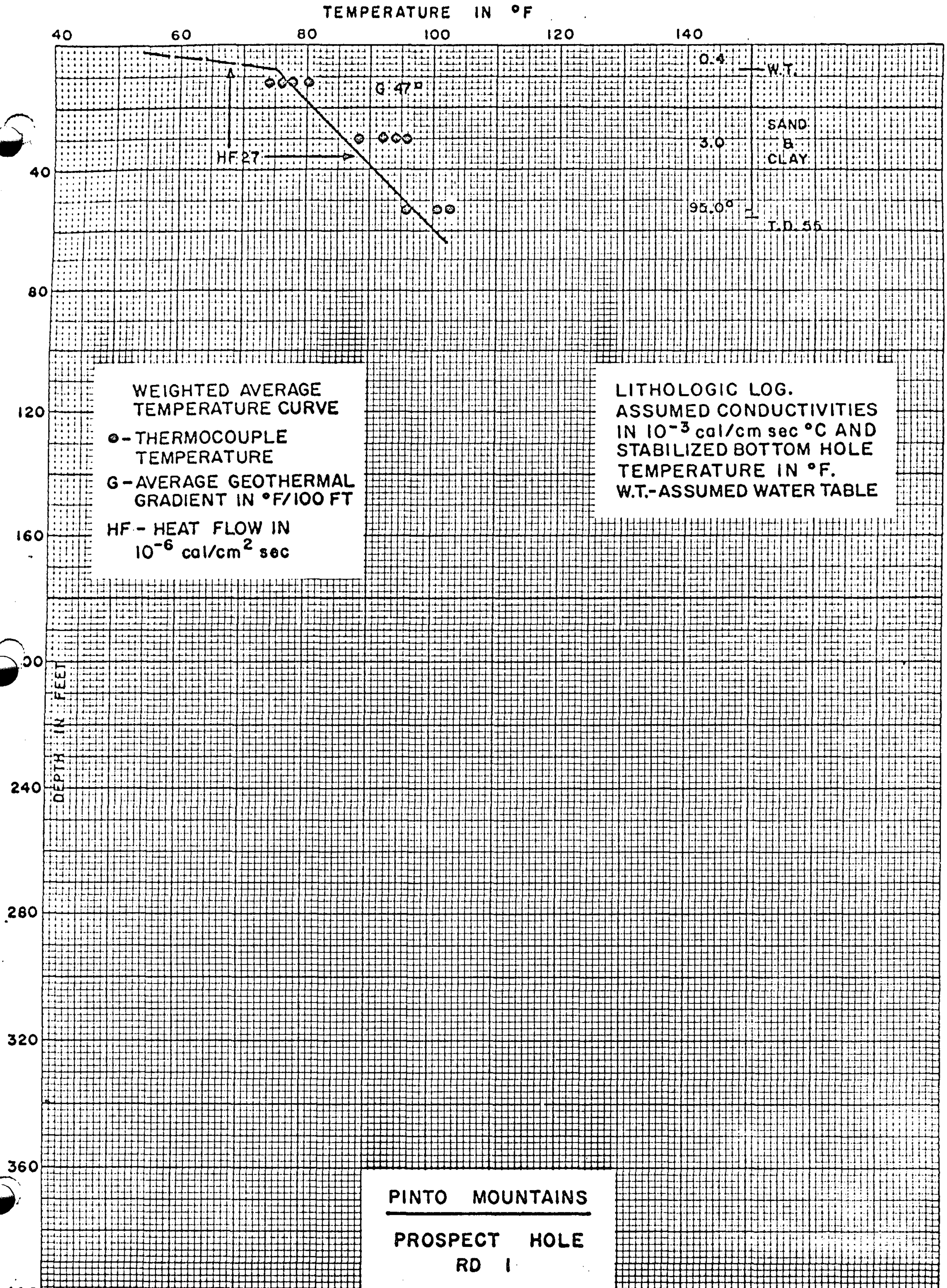


Figure 9. Geothermal data from rotary drill hole in the Pinto Mountains (from Hadsell, Grose and Berry, 1967).

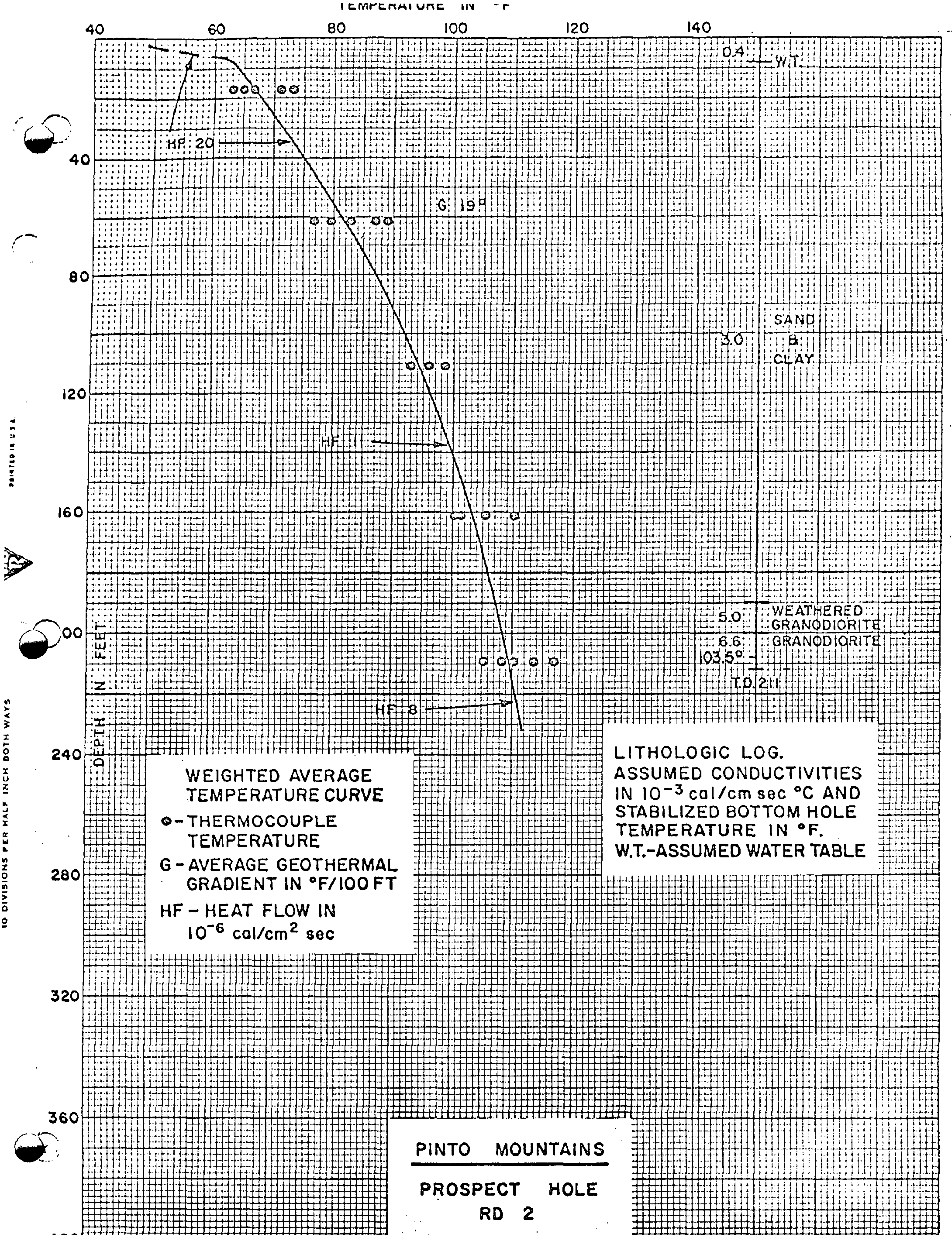


Figure 10. Geothermal data from rotary drill hole in the Pinto Mountains (from Hadsell, Grose and Berry, 1967).

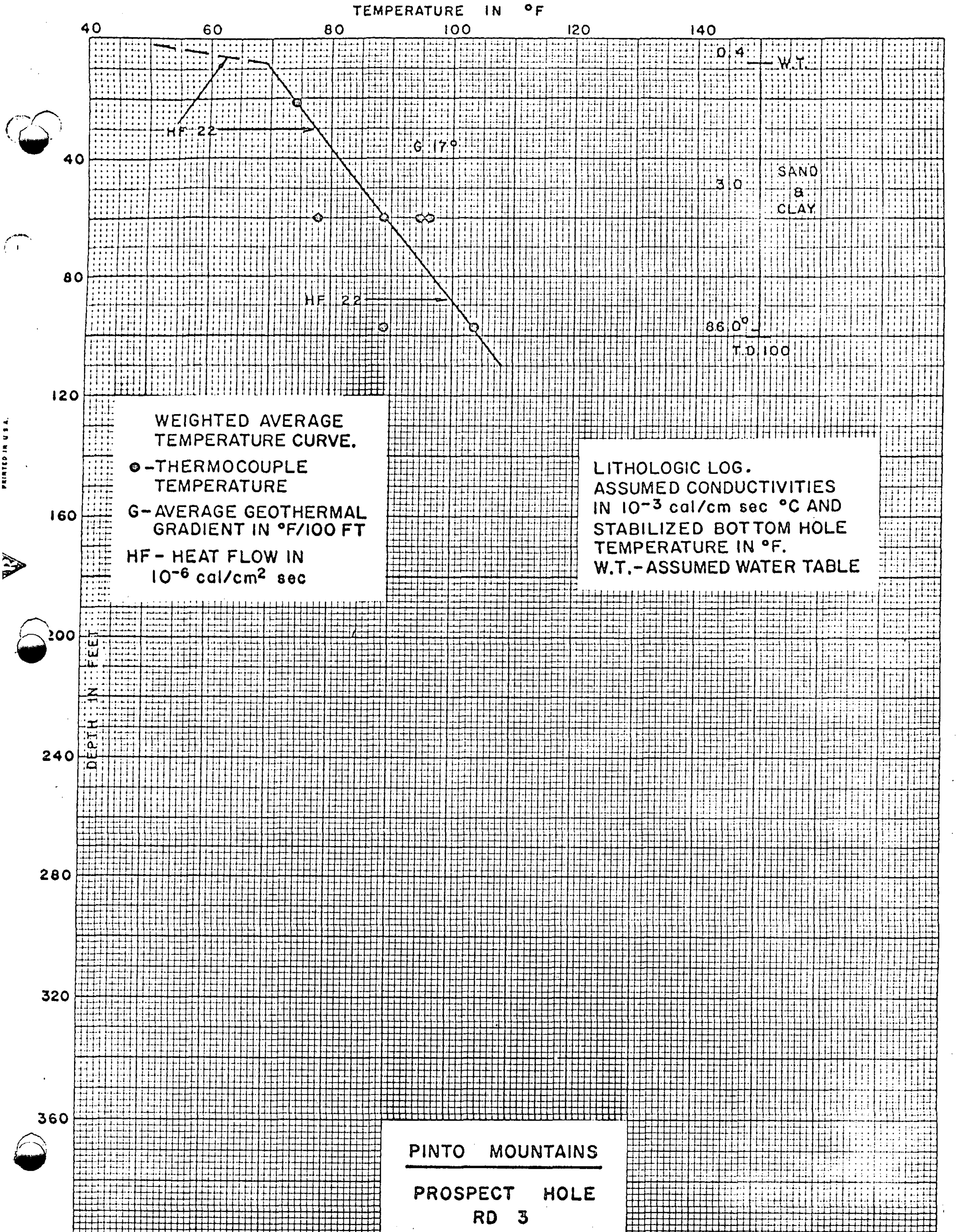


Figure 11. Geothermal data from rotary drill hole in the Pinto Mountains. (from Hadsell, Grose and Berry, 1967).

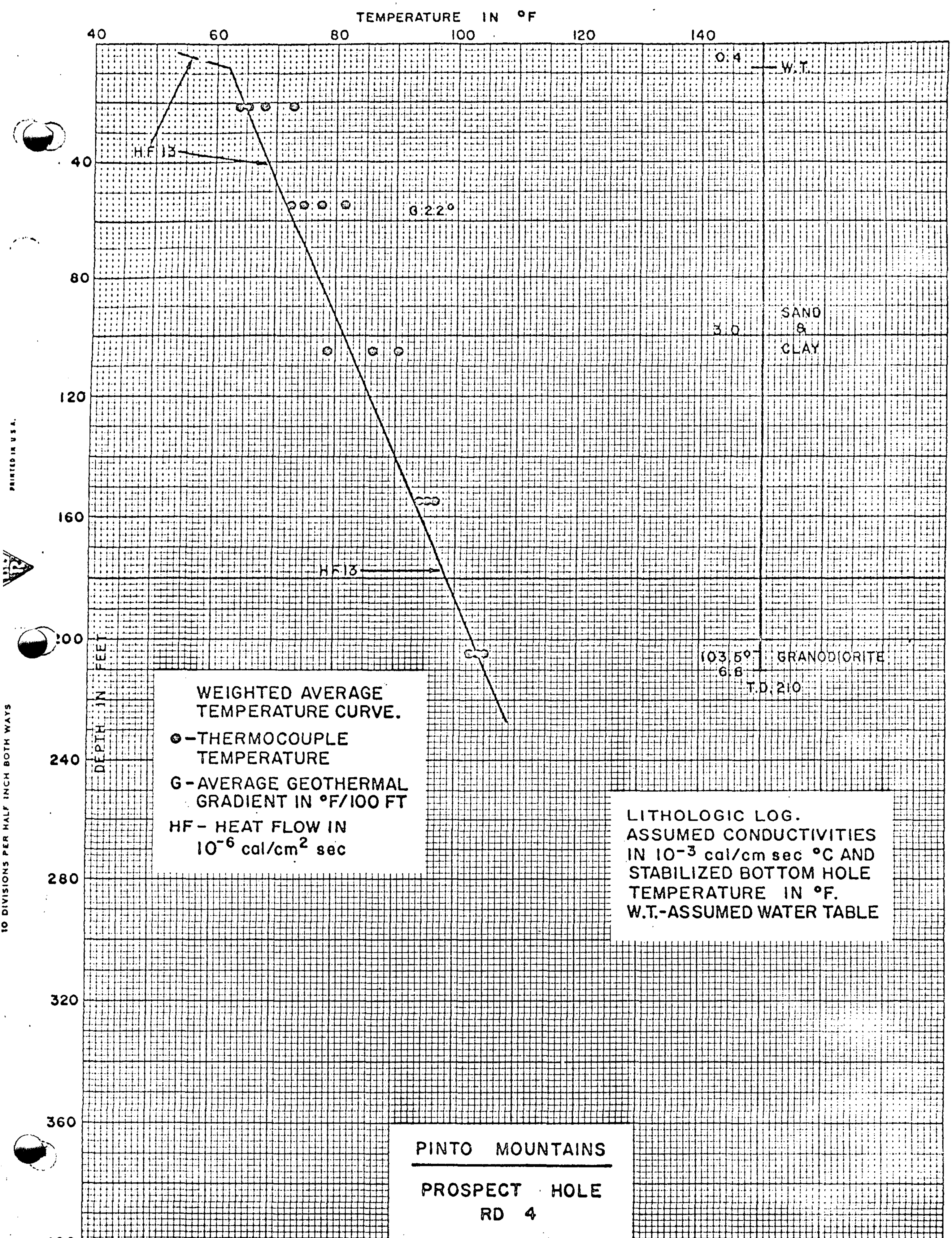


Figure 12. Geothermal data from rotary drill hole in the Pinto Mountains. (from Hadsell, Grose and Berry, 1967).

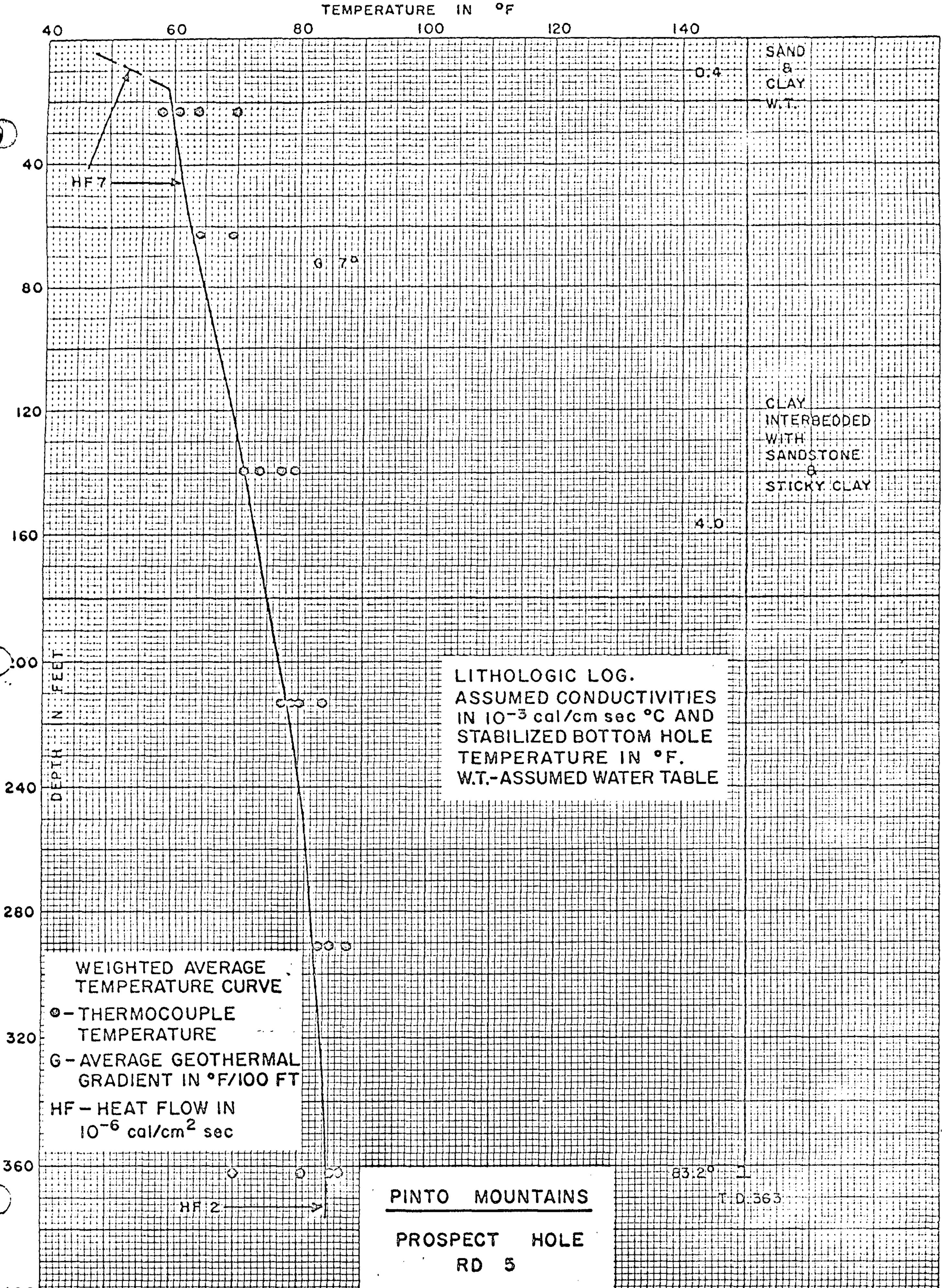


Figure 13. Geothermal data from rotary drill hole in the Pinto Mountains (from Hadsell, Grose and Berry, 1967).

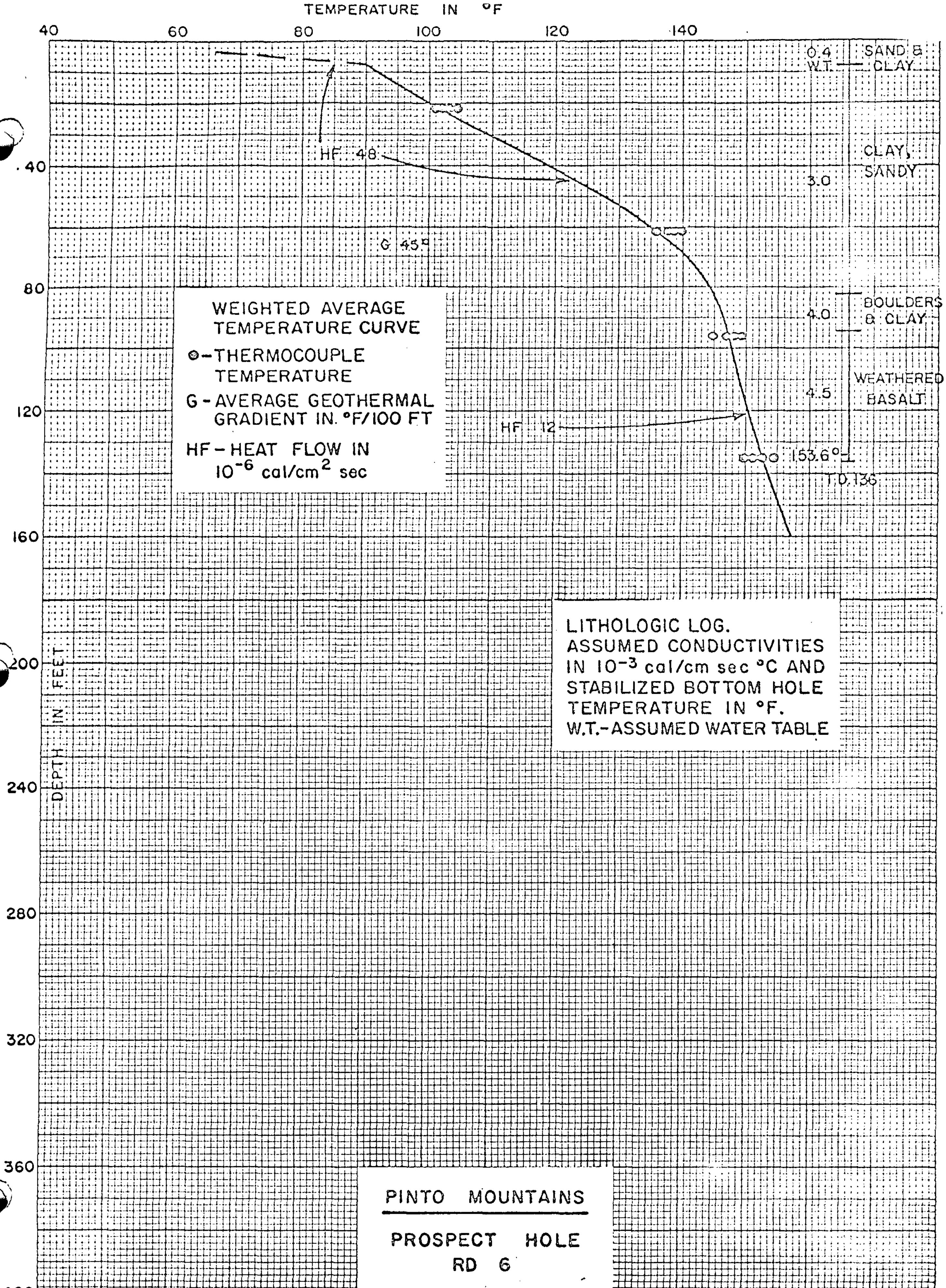


Figure 14. Geothermal data from rotary drill hole in the Pinto Mountains (from Hadsell, Grose and Berry, 1967).

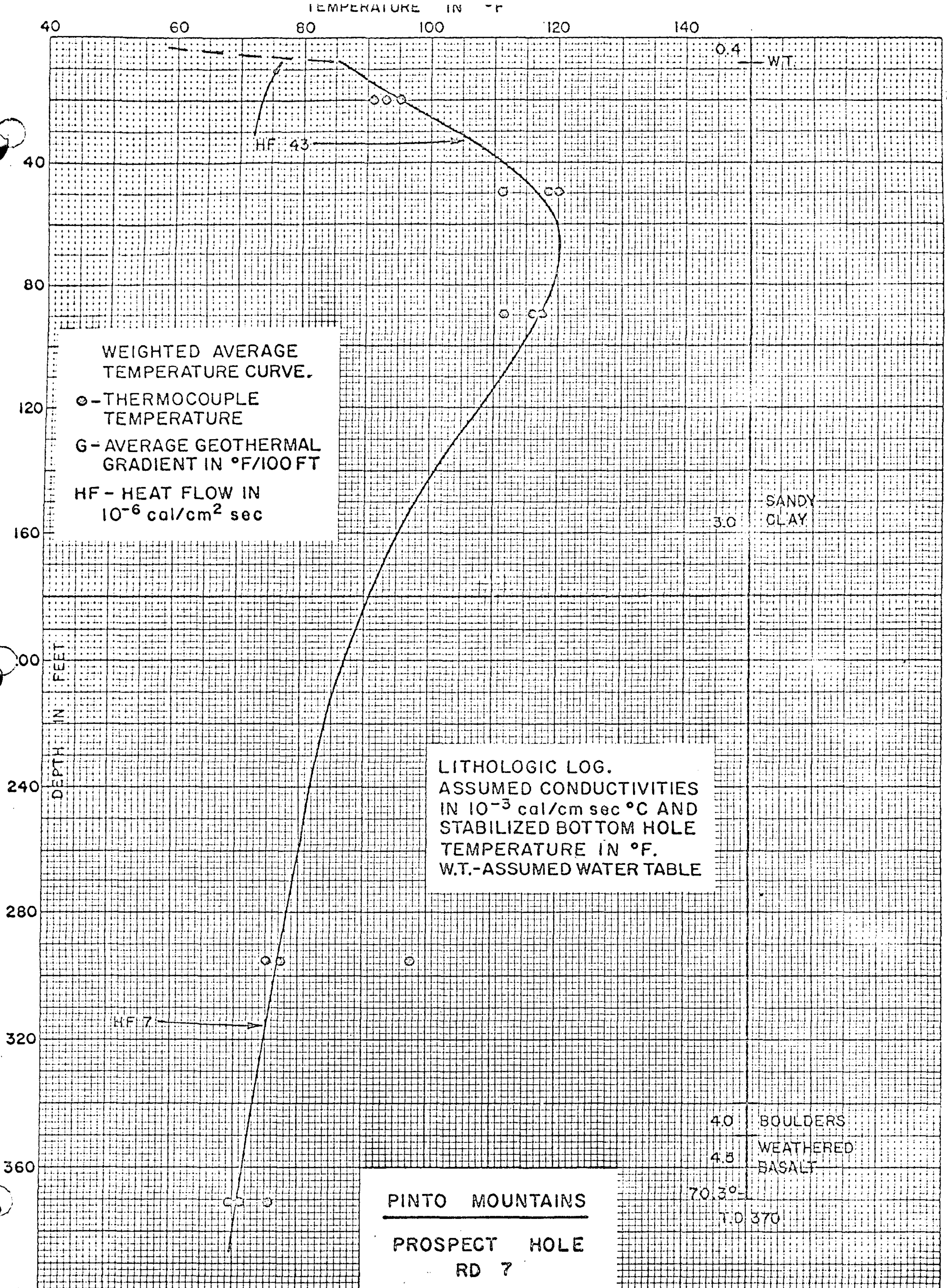


Figure 15. Geothermal data from rotary drill hole in the Pinto Mountains (from Hadsell, Grose and Berry, 1967.)

indicate that each area is thermally anomalous, but do not lead to reliable subsurface temperature information. The reasons for this are discussed below.

1) The unweighted temperature gradients in all of the deeper holes (100-to 385-ft. deep) decrease with depth, with no inverse correlation with thermal conductivity (see Figures 9-15). Therefore the temperature and assumed conductivity data are not internally consistent and the calculated components of flux do not provide measures of the heat flow from below. This is particularly true in drill hole RD-7 (Figure 15), in which the temperatures actually decrease below 50 ft; therefore, the heat flow is negative in the 50-to 370-ft. interval, not +7 HFU as reported by Hadsell, Grose and Berry (1967).

Three possible explantions for the curvature to lower gradients in the Pinto Mountain holes are:

i) The Sand and Clay - Granodiorite and the Sand and Clay - weathered Basalt contacts are zones of circulating water.

ii) The Sand and Clay units are saturated and permeable enough such that, when the adiabatic gradient is exceeded, hot water circulates toward the surface by normal and penetrative convection. This mechanism would account for the high gradients near the surface and the lower gradients below.

iii) The high near-surface gradients reflect anomalous temperature phenomena that are frequently observed, but not easily explained, in the initial 100-to 150-meters of many drill holes.

In either case, the geothermal data from the Sand and Clay unit are unreliable for regional heat flow studies and clearly do not yield good estimates for the true thermal anomaly in this portion of these mountains.

2) Table 5 lists heat flow data for the hot spring areas that were calculated using Whites' (1968) concept of "base temperature," or the temperature at the depth below which temperatures increase little with depth. For the Gerlach, Fly Ranch and Soldier Meadows springs, the flow rates and base temperatures were assumed to be the values listed in Table 4. The flow rate for the Pinto Mountains is from Table 4, whereas the three different base temperatures are the average bottom hole temperatures from holes RD 1 through 4, RD 6 (Figures 9-15), and the mean temperature for the hot springs (Table 4). For all areas, the calculated heat flows are much greater than the normal continental flux (1.5 HFU) or the average value (2.0 HFU) for the Basin and Range province, indicating that each area is truly anomalous. Moreover, the values for Soldier Meadows probably represent minimums because the surface area of the entire region, not just the springs, was approximated. However, the information for all areas do not provide reliable data on the underlying deep temperature regimes because the base temperature method does not account for the depth at which the temperature becomes uniform; thus the geothermal gradients are not accurately

Table 5. Base temperature heat flux at hot springs in northwestern Nevada. Method after White (1968)

Heat Flux = $T_f/A = (F/A) \cdot x \cdot d \cdot Cp \cdot (B_t - S_t)$ where T_f = heat flow (cal/sec), A is area, x = 63.1 $\frac{cm^3 min}{gal\ sec}$, F = flow rate (gal/min), d = density (1.0 $\frac{gm}{cm^3}$), cp = specific heat (1.0 $\frac{cal}{gm ^oC}$), V_t= base temperature (°C), and S_t= surface temperature (°C).

Locality	Flow Rate gal/min	B_t °C	S_t* °C	Surface** Area km²	Total Heat Flow 10^5cal/sec	Heat Flux 10^{-5}cal/cm²sec	Ratio of Calculated Flux to Normal Continental and Basin and Range Flux.+ Normal	Basin & Range
Pinto Mountains	142	48.9	12.2	1.08	3.3	3.1	20.3	15.0
	142	71.1	12.2	1.08	5.3	4.9	32.6	24.5
	142	87.2	12.2	1.08	6.7	6.2	41.0	31.0
Fly Ranch	1472	58.9	12.2	.94	43.4	46.4	309	232
Gerlach	253	79.4	12.2	.02	10.7	535	3343	2675
Soldier Meadows	2842	43.3	12.2	43.7	55.8	1.3	8.7	6.5

* After Hadsell, Grose and Berry (1967).
** Estimated from maps by Berry and Downs (1966a,b,c, 1969)
\+ Normal Continental Flux = 1.5×10^{-6}cal/cm²sec;
Average Basin and Range Flux = 2.0×10^{-6}cal/cm²sec.

known and the surface temperatures can not be reliably continued downward.

Recommendation for Future Research. Future evaluation of Cordero's geothermal prospects should be directed toward the acquisition of reliable heat flow data and a better knowledge of the deep subsurface temperature regimes at each area. A few recommendations for future research are outlined below.

1) Since most of the springs crop out near or along obvious or postulated faults or fault systems, the temperatures measured near and in them undoubtedly represent the end result of a complex history of heat transfer between host rock and circulating fluids migrating upward and along fault planes or fractures. The actual amount of heat transfer will depend upon the undisturbed regional gradient, the flow rate of the fluids, the thermal diffusivities of the host rocks, and the orientation of the fault planes or systems, but the general effect is that hot waters from depth lose heat to the lower temperature surroundings and the temperatures measured in springs at the surface do provide direct measures of the true magnitude of the underlying thermal anomaly.[1] Moreover, if the above mentioned parameters are

1. See, for example, Figure 6. Water enters the hole between 2300 and 2400 feet and flows to the surface. The flow rate (1 gal/min) is low enough such that the water loses heat to the rock during upward migration. If a fast flow occurred, the water temperature could be 83°F all of the way to the surface. The temperature at the surface is 20°F lower for the low flow rate.

known, the reduction of water temperature can be analytically determined by approximating the springs and fault planes as line, cylindrical or plane sources of heat (see Birch, 1947; Carslaw and Jaeger, 1959, Chandrasekhar, 1961; Levich, 1962; Jakob, 1957). Therefore additional exploration near the hot spring areas should include more extensive gravity and magnetic surveys to determine the subsurface geology and the extent and orientation of folding and faulting at depth. Considered with direct observations of regional flux, thermal conductivity, and presently available water-flow rates (Table 4; and Berry, personal communication, 1970 and 1971), detailed analyses for the thermal effects of the local geology could lead to better estimates for the highest subsurface temperatures and the depths at which large quantities of dry steam might be produced.

2) The thermal affects of local geology can be significant, but many studies of hot springs indicate that the flows at the surface consist largely of meteoric water (Toulmin and Clark, 1967; White, 1967). As a result, the temperatures measured in hot springs at the surface also may be abnormally low due to mixing with lower temperature ground water. Thus future exploration should: a) obtain reliable knowledge of each regional ground water regime; b) arrive at estimates for the age and volumes, etc. of meteoric and primary waters; and c) use background heat flow data to obtain estimates for the temperatures of meteoric waters before mixing with hotter waters from below. The thermal consequences of a

mixing of meteoric and primary waters are complex, but may be treated analytically if local hydrology, water ages, and regional heat flow are known in a quantitative sense. Studies of this type could be especially pertinent in Soldier Meadows where the low temperatures of the springs (Table 4) suggest quenching by colder near-surface waters.

This research would require chemical analyses and additional geologic mapping. It would be desirable also to conduct deep electrical surveys (> 1000', DC resistivity and EM) in each area since changes in resistivity can reflect the degree of saturation in subsurface rock (Keller and Frischkneckt, 1966; Grant and West, 1965). Moreover, electrical surveys provide information on subsurface structure and subsurface temperature anomalies (Keller and Pritchard, 1966). Thus the electrical surveys could yield data on regional hydrology, geologic structure, and subsurface temperature models that could be compared with those based on heat flow studies to arrive at additional estimates for the depths at which high temperatures might occur.

3) Deep rotary and core drilling to determine reliable values of heat flow near the hot springs. The holes should be at least 200 meters deep, penetrate competent rock units (not just alluvium) in the bottoms of the holes, and be continuously cored (NX or BX size) for the bottom 30 to 50 meters. The holes should be cased and left accessible for subsequent temperature loggings. The casing should be grouted

in place with cement or chemical grout (Am-9, American Cyanamide Co.) to alleviate disturbances associated with circulating water. Because the primary objective is to use the heat flow measurements to determine the deep temperature regimes and estimate the depths appropriate for the production of dry steam, the holes should not be drilled near individual hot springs; temperatures close to the springs obviously would be anomalous and provide little information on the flux at depth.

Although the final selection of hole locations would require further consultations with Cordero's Geologists, existing maps (Berry and Downs, 1966a, b, c, 1969) and a brief visit to each property in July, 1970 suggest the following numbers and distribution of sites:

A. Pinto Mountain Hot Springs. Two drill holes would be needed. One should be drilled in the granodiorite about half way between West and East Spring. The other should be 3000-to 4000-feet west of the West Spring. Because the granodiorite appears to be compositionally and texturally uniform, excellent background heat flow should be obtained at this site. The other site would provide data away from the springs and detect deep temperature anomalies associated with circulating waters, etc. along the north-south trending fault very near West Spring. Since there is 300 to 400 feet of relief in the area, terrain corrections would be needed at all sites. The Tertiary volcanics and sediments near the surface also should be sampled for studies of their thermal properties, and to determine if refraction models should be calculated. Although only two spring systems are evident at the Pinto Mountain prospect, the relatively simple geology and exposures, the high temperatures of the springs (Table 4), and the earlier shallow drilling (Figures 9-15) make it an excellent test area.

B. Fly Ranch Hot Springs. Two holes should be drilled in the high resistivity layer (35 ohm-meters) that Keller and Pritchard (1966) mapped with electromagnetic and DC resistivity surveys. This unit should provide the best deep geothermal data because it appears to have low porosity and reduced water content; thus there should be fewer transient disturbances due to circulating water. It would be desirable to have data on the downthrown side of the fault bordering the east side of the spring system, but a heat flow site in this area should not be selected without better estimates for the depth to basement.

C. Gerlach Hot Springs. One drill hole in the granodiorite croping out to the north and west of Mud and Great Boiling Springs, respectively, should provide an excellent value for the undisturbed flux. A terrain correction would be needed at this site. A site 2000-to 3000-feet east of Great Boiling Springs should provide data on the underlying, deep temperature anomaly. Drilling in the alluvial valley should be delayed until geophysical techniques are employed to determine the subsurface geology.

D. Soldier Meadows. Because of the large areal extent, the large total flow rate (Table 4), and the low temperatures of the springs (Table 4), thorough research should be conducted to determine the deep flux in this area. A very comprehensive survey would require the drilling of five holes at the following rough locations (see Berry and Downs, 1969): the western boundary of S27, T40N, R24E; the northwest quarter of S25, T40N, R24E; the central portion of S13, T40N, R24E; the northwest quarter of S19, T40N, R25E; and the eastern portions of S17 or S6 (Slum Gullion Creek), T40N, R25E. A less thorough survey would require four drill holes, with the site in S13, T40N, R24E being deleted, and the location on S19, T40N, R25E being substituted for by a site roughly halfway between Springs E and F and B and C. In either case, the sites off the eastern and western boundaries of the Meadows should provide heat flow data for the areas away from the springs. Those in the Meadows should lead to accurate estimates for the magnitudes of the underlying thermal anomaly. A study of the half-widths, etc. of the heat flow anomaly across the meadows would provide data on the depths to anomalously high subsurface temperatures.

Cost for Future Research. The approximate expense for gravity and deep electrical surveys in each area are summarized in the excellent report by Keller and Pritchard (1966, p. 12-13). With the exception of the proposed shallow drilling, it is my opinion that their proposals have great merit and could be of special value at the Gerlach and Soldier Meadows prospects, where more subsurface control (geologic, hydrologic, and temperature) is needed. I also believe that the final evaluation of all of the hot spring areas should include a comparison of subsurface temperature models arrived at from heat flow and resistivity surveys.

Heat flow measurements would involve expenses for contract drilling, casing and grouting, preparation of thermal conductivity samples, field support for temperature logging, and costs for data reduction and interpretation. The average expenses that would be incurred if the work were done using equipment and personnel at the University of Wyoming as summarized below:

Drilling, Casing and Grouting. Rotary and core drilling is estimated at $7 to $8 per linear foot of drill hole, whereas experience shows that casing (with 1¼" black iron pipe) and grouting costs about $.75 per foot of hole, including materials and rig-time. Therefore a 200 meter hole would cost $4900 to $5600. A lower cost might be incurred at Soldier Meadows, if four to five holes were drilled.

Thermal Conductivity. Commercial grinding and edging of conductivity samples averages about $3.00 to $3.50 per sample. Approximately 150 to 200 samples would be needed at a total cost of $525 to $750. A cost for laboratory measurements is not included, because our laboratory could handle 20-to 30-additional samples per day without interrupting the usual routine.

Field Support for Temperature Measurements. A 200 meter hole may be readily logged in two hours using portable equipment. Therefore one day, including travel from the nearest base, would be required to measure temperatures at any prospect. Two loggings on different days, separated by a month, or so, would be needed. Excluding costs for air travel, etc. to and from the nearest base, temperature logging would cost about $100/day plus a $15-$16 per diem per man (one or two). If temperatures were logged with equipment already in existence, no cost for equipment would be incurred; new equipment would cost $2000 to $2500 for cable, (teflon insulated), thermistors, construction and calibration of probes, and DC circuitry for resistance measurements at the surface (bridges and null-detectors).

Interpretation. This would involve data reduction and interpretation, and the preparation of reports. Since most of the necessary computer programs are in existence, only 6 to 7 man-days would be needed for rather complete interpretations in each area. The maximum cost for interpretation at each prospect is estimated to be $800, including computer time.

The above discussion demonstrates that heat flow measurements at Cordero's Geothermal Power prospects would be costly. For example, the proposed research at all four prospects would cost $60,000 to $70,000. However, without reliable heat flow data, and hence more reliable subsurface temperature models, drilling for geothermal power in these areas would be very speculative, as is strongly suggested by the deep (1000-5000 ft.), non-producing holes near the anomalous springs at Beowaivé and Bradie Hot Springs, Nevada.

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