HEAT FLOW AND THE THERMAL REGIME IN THE CLIFTON, ARIZONA AREA

by

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Useful Conversions

HFU = 1 heat flow unit = 1×10^{-6} cal/cm^{2}sec = 41.84×10^{-3} W/m^2

TCU = 1 thermal conductivity unit = 1×10^{-3} cal/cm sec $^{\circ}$C = 0.4184 W/mk

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Introduction

Four heat flow measurements in the Clifton, Arizona area are available for interpretation. Three of the heat flow measurements are detailed in this report. Reiter and Shearer (1979) reported the additional heat flow measurement. Analysis of the data shows significant movement of groundwater in the area, which masks the regional heat flow. Near-surface heat-flow measurements in the drill holes less than 350 m deep have values ranging between 0.4 HFU and 2.3 HFU. The Clifton area regional heat flow is believed to be 2.25 HFU.

Hot springs in the area, with discharge temperatures up to 82°C, are surface manifestations of local geothermal convection system(s). Low measured-heat-flow values, compared to the regional heat flow, result from lateral or downward flow of water in the Clifton area, or from a combination of both; the water flow may recharge the hot spring-geothermal convection system(s). Available data suggest that the convective systems are heated by regional heat flow although a hypothetical magmatic heat source masked by water flow is not disproven.

Regional Setting

The Clifton area lies on the northern margin of the Basin and Range province near the transition zone with the Colorado Plateau province (Figure 1). The confluence of the San Francisco

River with the Gila River is just south of Clifton. In the northern part of the area, topographic relief is great because high mountains (greater than 1800 m) are cut by deep canyons. In the southern part, the elevations (1060 m) are lower and the land surface is also cut by smaller canyons related to entrenchment of the Gila and San Francisco rivers. The entrenchment of the rivers is post-Pliocene and may be due to regional uplift, to acquisition of drainage outside of the Clifton area, or to climatic change (Morrison, 1965, Harbour, 1967). All of these factors may influence local and regional heat flow.

Rainfall and the mean annual temperature are quite varied in the area. In the mountains, weather stations at Granville and Grey Peak average 50.6 cm (20 inches) of rain per year and have mean annual temperatures around 11°C to 12°C (Sellers and Hill, 1974). At lower elevations such as at Clifton, average annual rainfall is 15.4 cm (10 inches) or less and the mean annual temperatures range up to 19°C (Sellers and Hill, 1974). As a result of the climatic contrasts, the vegetative cover changes radically from low elevations to high elevations. Sparse creosote vegetation changes to dense forests of pinon, cedar, oak, manzanita, and ponderosa pine with increasing elevation. The areally variable climate and vegetative cover enchance complex hydrologic conditions. Lateral and vertical flow of water, which can profoundly change the thermal regime, may result from complex hydrologic conditions.

Geology

The geologic history of the Clifton area is complex, as evidenced by an extremely varied suite of lithologies and ages and styles of tectonic deformation (Figure 2). Crystalline rocks of Precambrian and Late Cretaceous-early Tertiary ages are exposed in the Clifton area. Granite, granodiorite, and diorite comprise the bulk of these rocks. Outcrops of Precambrian schist and metaquartzite are identified north of Clifton (Lindgren, 1905).

Paleozoic rocks unconformably overlie the Precambrian rocks and depict a time of relative tectonic quietude. A basal arkosic sandstone is overlain by interbedded shales and carbonate rocks; the carbonate rocks become dominant higher in the Paleozoic section (younger in age). Sediments from all Paleozoic periods except Silurian and Permian are exposed (Lindgren, 1905). Silurian rocks are not found in Arizona, having never been deposited or having been stripped away by erosion during Late Silurian or early Devonian (McKee, 1951). Permian rocks are not exposed in the Clifton area and are probably absent due to Mesozoic and Cenozoic erosion. North of Clifton, Permian rocks are probably present in structural lows where they were protected from erosion and are now buried beneath Mesozoic and Cenozoic sediments and volcanics. Deeply eroded Pennsylvanian carbonate rocks crop out north of Clifton along Highway 666 in the vicinity of Mitchell Peak (Ross, 1973). Prior to Mesozoic tectonism, up to 1300 m of Paleozoic rocks are believed to have overlain the Clifton area (Pierce, 1976).

The Clifton area was greatly disturbed by Mesozoic and Cenozoic tectonic events. No Triassic or Jurassic strata are observed in the area; either they were removed by erosion during the Cretaceous Burro-Graham uplift or they were never deposited. Erosion following the Burro-Graham uplift stripped off all of the Paleozoic rocks, exposing Precambrian rocks in the region south of Clifton (Elston, 1958; Turner, 1962). Late Cretaceous fine-grained clastic rocks deposited in shallow marine and terrestrial environments unconformably overlie lower Paleozoic rocks at Clifton (Lindgren, 1905).

Late Cretaceous-early Tertiary (Laramide Orogeny) magmatic intrusion and faulting created an extensive hydrothermal system that emplaced low-grade copper mineralization into the area (Moolick and Durek, 1966; Langton, 1973).

Mid-Tertiary volcanism buried the area under thick piles of andesite and basaltic andesite that contain volumetrically minor and discontinuous silicic ash flow tuff (Lindgren, 1905; Berry, 1976). Silicic intrusions of rhyolite are observed in a northwest-striking zone north of Clifton. The rhyolites were intruded contemporaneously with the last mid-Tertiary eruptions of basaltic andesite (Berry, 1976). Major late-Tertiary faulting has uplifted the northern part of the area into a horst or upthrown crustal block (Clifton-Morenci horst) that is itself broken into two blocks by the northeast-trending San Francisco fault (Lindgren, 1905; Langton, 1973). More than 600 m of late-Tertiary vertical displacement along the San Francisco fault is believed to separate the upthrown intrahorst Morenci block on the west from the downthrown intrahorst Clifton block on the east. The Clifton-Morenci horst is bordered on the south by the Ward Canyon fault (Lindgren, 1905; Langton, 1973). The downthrown block south of the Ward Canyon fault comprises the basement of the Duncan basin. Late-Tertiary sedimentation has filled the Duncan basin with a thick sequence of clastic sediments derived mostly from volcanic rocks. The southern boundary of the Duncan basin is defined by the Peloncillo Mountains, a thick pile of mostly basaltic andesite volcanics of probably middle Tertiary age. A major fault is inferred to separate the mountains and the basin.

The Ward Canyon fault is inferred to have Quaternary to Recent movement. Analysis of U-2 air photos reveals a poorly defined scarp along the inferred and continued trace of the mapped portion of the fault. The inferred young movement has not been field checked to confirm the air photo interpretation.

Hot Springs

Clifton area hot springs, surface manifestations of local geothermal convective systems, discharge the hottest groundwater naturally flowing at the surface in Arizona (Figure 1). The maximum spring temperatures range from 66°C for the Clifton Hot Springs to 82°C for the Gillard Hot Springs.

Chemical geothermometry on these springs indicates subsurface reservoir temperatures over 130°C (Swanberg and others, 1977). The highest geothermometer temperatures are calculated from chemical analysis of the Clifton Hot Springs north of Clifton. Chemical and isotopic evidence suggests that mixing with cold near-surface groundwater is occurring (Mariner and others, 1977; Witcher, 1979). Mixing model calculations suggest temperatures up to 180°C for the quartz geothermometer and agree well with the Na/K/Ca geothermometers (Witcher, 1979).

The Clifton Hot Springs occur as small seeps and limited flows on the banks of the San Francisco River. However, temperature, salinity, and increased flow of the river down stream from the hot springs indicate that a significant amount of hot water flows into the San Francisco River through the river bed (Hem, 1950; Swanberg and others, 1977). The system's total discharge is substantial and is greater than 3785 liters per minute (Hem, 1950).

The Clifton Hot Springs and Gillard Hot Springs appear to be controlled by structure and topography. Both spring systems occur near major fault zones and in the bottoms of canyons formed by the Gila and San Francisco rivers.

Heat Flow - General Discussion

Many factors influence the temperature distribution within the upper crust of the earth. Heat flow from the earth's interior is the most important factor. Daily and annual solar heating has only minor importance and affects only the uppermost few meters. Temperature differences caused by pressure changes with depth (adiabatic temperature) are insignificant and of no importance in shallow crustal studies because of the incompressibility of crustal rocks.

Heat flow is predominantly influenced by deep subsurface temperature, thermal conductivity of rock, and by groundwater flow (convection). Additional factors are also important, such as radiogenic and chemical heat production, and time (i.e., time since emplacement of a magma body or initiation of convection). Topography may also influence subsurface temperature distribution.

Conductive heat flow measurements are the easiest and most straightforward method to study the temperature distribution of the crust. Conductive heat flow depends mostly upon the rock thermal conductivity and the subsurface temperature. The equation for vertical conductive heat flow, assuming no radiogenic heat production, groundwater convection, or inhomogeneity in crustal rock is: $q= K \frac{\partial T}{\partial Z}$ (1)

where

q is heat flow
K is the rock thermal conductivity
$\frac{\partial T}{\partial Z}$ is the temperature gradient

Temperature at depth may be extrapoltated to greater depth in a region of conductive heat flow if reasonable assumptions about rock thermal conductivity can be made. For this reason, regional heat flow studies seek drill holes that are located in nonpermeable, isotropic rock such as granite.

The objective of geothermal exploration is to locate and explore hydrothermal convection systems, at economically drillable depths. Since convective transport of heat from great to shallow (economic) depths occurs in convection systems, geothermal studies are concerned with convective heat-flow measurements in addition to conductive heat-flow measurements. Also, convective heat flow contains information concerning the movement of goundwater that may be useful for indirect estimation of flow rates, rock permeability, and heat budgets within the system. The equation for vertical heat flow with convection, but no heat production, is:

$$q= K \frac{\partial T}{\partial Z} + \rho C v \partial T \qquad (2)$$

where

ρ is the density of water,
C is the heat capacity of water,
∂T is change in temperature through interval of the heat flow measurement
v is the vertical component of water velocity,
and other terms as in Equation (1)

The velocity of convective water flow is dependent upon the pressure (head), permeability, and fluid viscosity according to Darcy's Law.

Clifton Heat Flow Data

Rotary-mud drilling commenced at the Clifton-1 drill site on 9 September, 1979 by Cowley Pump Company of Phoenix, Arizona. Funding agent for the drilling operation was the U.S. Bureau of Reclamation (Water and Power Resources Service), Boulder City, Nevada. Lost circulation due to caving and high formation permeability resulted in temporary cessation of drilling so 17.8 cm (seven inch) OD casing could be emplaced to 44 m. Drilling stopped at 305 m and the hole was completed with a 5.1 cm (two-inch) iron pipe cemented in place at the top and bottom by ten sacks of cement. The iron pipe was filled with water.

The water table at Clifton 1 is approximately 50 m deep, which approximates the level of the Gila River one-half mile away.

Figure 3 shows the lithology of the Clifton-1 drill hole. Basin-fill sediment derived mostly from volcanic rocks is penetrated by the hole. The lower 130 m appears to be a boulder fanglomerate consisting of basaltic andesite clasts. Drill chips are rounded and slightly weathered on one side as if originally part of a large cobble or boulder. Also, the cuttings contain substantial quantities of "fines", but these "fines" could be contamination or sluff from the upper parts of the drill hole.

The other heat-flow holes, HF1 and HF2, are "free" holes that Phelps Dodge Corporation, Morenci, Arizona, kindly gave permission to log and provided rock samples for thermal conductivity measurements. Figure 3 shows the lithology of these holes. HF1 is in granite and monzonite porphyry of Paleocene (?) age. HF2 is in the lower Paleozoic section exposed in the Clifton area. The upper 60 m is in the Ordovician El Paso Limestone (Longfellow Limestone of Lindgren, 1905), a sandy dolomite-to-dolomitic sandstone. The lower 70 m is in the Cambrian Coronado Sandstone, a tightly cemented arkose to orthoquartzite.

Temperature measurements at five-meter intervals were taken in HF1, HF2, and Clifton-1 with a calibrated thermister logging unit. Calibration accuracy of the temperatures is $\pm .001^{\circ}C$. The temperature data from the drill holes are shown in Figure 4.

HF1 has a straight temperature-depth profile, possibly indicative of a lithology with conductive heat flow and little change in rock thermal conductivity. HF2 has a curved temperature profile and a very low overall temperature gradient. High and variable rock thermal conductivity or water flow can explain the temperature log of HF2.

Clifton-1 temperatures were obtained a few days after drilling had stopped. The anomalous temperatures at the top and bottom of the hole on 9/29/79 represent the heating effects of newly poured cement holding the 5.1 cm (two-inch) casing in place. (As cement solidifies it generates heat). The 11/19/79 temperature log of Clifton-1 shows the hole had equilibrated to ambient rock temperature. The temperature gradient in this hole is very low. The temperature-depth profile reveals a subtle concave-upward curvature. Downward or lateral flow of water can create the Clifton-1 temperature profile.

Heat-flow determinations are listed in Table 1, with pertinant supporting information. Rock thermal conductivities of representative drill cuttings were obtained with a divided bar apparatus, using the chip method of Sass, Lachenbruch and Munroe (1971). Measurements were made in the laboratory of Dr. Robert F. Roy, University of Texas, El Paso. Thermal conductivities are also listed in Table 1.

Reiter and Shearer (1979) published heat-flow data in the Clifton area on a hole drilled deeper than 600 m. The data are summarized in Table 1. The temperature-depth profile of their hole is concave upward, also suggesting downward water seepage or progressively decreasing rock thermal conductivity (Figure 4). The low, 1.4 HFU, value from the thickest depth interval of their hole is significantly below the 2.0 HFU average Basin and Range province heat flow, and tends to substantiate modification of the thermal regime of this hole by water flow.

Heat Flow, Interpretation and Conclusions

HF1 probably represents a regional heat flow of 2.25 HFU for the Clifton area. However, this interpretation could be in error because the thermal regime may not result strictly from conductive heat flow as the straight temperature profile would initially suggest (Figure 4). The rock thermal conductivities probably are accurate because they are consistent with the subsurface lithology. However, the heat flow values change from over 2.0 HFU to less than 1.50 HFU (Figure 5). The inconsistent section of the hole is associated with a section of monzonite porphyry between 189-293 m. The lowest heat-flow value is calculated at the middle of the monzonite interval. We believe the monzonite porphyry is an almost vertical dike that is an apophysis of a local northeast-striking monzonite intrusive(s) which is related in turn to the Paleocene magmatic activity that emplaced copper mineralization at Morenci (Langton, 1973). We hypothesize downward seepage of cold water in the dike that "washes out" the conductive heat flow in the dike. Also, the monzonite dike may not be sufficiently wide to change the temperature profile in the hole even though the monzonite has different thermal conductivity (Paul Morgan, personal commun., 1980). Figure 5 summarizes the pertinant data on HF1.

HF2 temperature gradients are very low. Figure 6 is a Temperature versus Temperature Gradient profile of the HF2 heat-flow hole. At least two conditions are influencing the temperature distribution in this hole. First, very high thermal conductivities are contributing to very low temperature gradients, shown by the fact that gradients less than 12°C/km have conductivities greater than 9 TCU and gradients greater than 16°C/km have conductivities less than 7 TCU. Second, groundwater flow at depth seems likely since the heat flow values for the hole are internally consistent but the 1.0

HFU value is far below the average basin-and-range value of 2.0 HFU.

Clifton-1 also has very low heat flow. The Temperature versus Temperature-Gradient profile (Figure 7) between 130-350 m is nearly linear, suggesting a uniform vertical flow of water that would transport heat. The Heat Flow versus Depth plot (Figure 8) shows that the heat flow increases with depth, which confirms that vertical water flow is occuring in a downward direction. Where vertical water flow exists, the heat flow contributed or removed by this convective component (Δq) can be calculated by subtracting the component of heat flow contributed by conduction.

$$\Delta q = \rho C v \partial T = (\text{Eqn. } 2 - \text{Eqn. } 1) \quad (3)$$

For Clifton-1, Δq is - 0.22 HFU* and is obtained by subtracting the heat flow at 250 m from the heat flow at 130 m. Assuming a heat capacity (C) of 1.0 cal/gm°C and a density (ρ) of 1.0 gm/cm^3 for water, a one-cm^3 volume of water would require a downward velocity (v) of about 4.6 cm/year to lower the heat flow through a one-cm^2 area at the top of the 130-250 m interval by 0.22 HFU.

A column of water moving downward each year (4.6 cm/year) is 18 percent of the annual rainfall (26 cm/year). This percentage of annual rainfall recharging subsurface aquifers may be too high for an arid region because Rantz and Eakin (1971) report

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* A negative sign indicates reduction of heat flow by loss of heat to downward flowing water. A positive sign indicates increased heat flow by addition of heat by upward flowing water.

recharge percentages of annual rainfall less than 7 percent in an arid and cooler region in Nevada. Therefore flow of water resulting from rainfall recharge may not account for the observed heat loss at Clifton-1. However, lateral water flow associated with a sloping water table could account for the vertical water velocities and heat loss observed by heat-flow measurements at Clifton-1. With a sloping water table in an isotropic aquifer, the lateral water flow would have a downward component of flow at shallow depths.

If the water flow is laminar and the water table is the piezometric surface for the 130 m to 250 m depth interval (unconfined), it is possible to approximate the average permeability of the sediments in the 130-250 m interval. In order to do this, the volumetric velocity calculated using convective heat flow has to be converted to the true or darcian velocity if the same volume of water flows through a porous medium. The vertical darcian velocity was calculated by dividing 4.6 cm/year (volumetric velocity) by the effective porosity or specific yield of the rock between 130 m and 250 m. Since core samples were not taken from this zone it was necessary to estimate the effective porosity from lithology logs of cuttings. Using .25 for the effective porosity, a vertical darcian velocity of 18.4 cm/year was calculated.

Assuming that the water table gradient is roughly the same as the elevation drop of the Gila River with linear map distance, a lateral velocity may be approximated by dividing the darcian vertical velocity (18.4 cm/year) by the water-table gradient (.27 percent). The approximate lateral darccian water velocity is 6815 cm/year. Using this lateral darcian velocity the permeability of the sediments in Clifton 1 was calculated to be 1.0396×10^3 darcys by applying Darcy's Law.

$$k = \frac{v_d \mu}{\rho g \frac{\partial H}{\partial l}} \qquad (4)$$

where

v_d = darcian water velocity, 6815 cm/year or 1.161×10^{-4} cm/sec

μ = viscosity of water, 0.1 gm/cm sec

ρ = density of water, 1,0 gm/cm^3

g = gravity, 780 cm/sec^2

$\frac{\partial H}{\partial l}$ = water table gradient, .0027 or 14 feet/mile

k = permeability, 1.026×10^{-5} cm^2 or $1{,}0396 \times 10^3$ darcys

1 darcy = 9.87×10^{-9} cm^2

The permeability estimated from the heat flow data indicates that a very good aquifer exists between 130 m and 250 m.

All of the measured heat-flow values in the Clifton area except HF1 are significantly influenced by local or regional water flow. The low heat-flow values indicate lateral and downward water flow in permeable recharge areas. In order to conserve energy, the heat losses due to groundwater recharge are balanced by heat gains in discharge areas. Discharge may occur by lateral-subsurface flow out of the area, or by springs discharging at the surface or into through-flowing rivers. Conservation of mass is required too. Water that is recharging aquifers or flowing into the subsurface must exit somewhere.

The hot springs around Clifton are part of the conservation-of-mass-and-energy processes in the area.

The convective heat loss at Clifton Hot Springs is calculated using equation 5. A spring discharge temperature of 50°C is used to give a conservative figure.

$$Q = C\dot{m}\Delta T \quad \text{(Kilty and others, 1979)} \quad (5)$$

where

Q = convective heat loss, cal/sec

C = heat capacity of water, 1.0 cal/gm°C

$\dot{m}$ = mass discharge rate, 63 l/sec (Hem, 1950)

ΔT = difference of spring discharge and mean annual temperature 50°C - 19°C = 31°C, (Hem, 1950; Swanberg, other, 1977; Witcher, 1979; Sellers, and Hill, 1974)

The minimum convective heat loss is 1.95×10^6 cal/sec or 8 megawatts. Additional conductive heat loss associated with hot springs may range up to 30 percent of the convective heat loss (Kilty and others, 1979). If the 2.25 HFU observed in HF1 is used as the regional heat flow, a recharge area of 85 km^2 is required to balance the convective heat loss by the springs. However, since downward-flowing water accounts for (removes) only about 50 percent of the heat (average heat flow of 1.0 HFU versus 2.25 HFU regional value), a minimum recharge area of 170 km^2 is required to conserve heat. Therefore, the low measured-heat-flow values probably reflect part of the recharge for the geothermal systems in the area. The highly variable topography, precipitation, and permeable rock in the Clifton area result in forced convective systems that circulate water to great depth and heat it by regional heat flow.

Where the piezometric surface, topography, and vertically permeable zones coincide, these systems are visible as hot springs.

Additional heat flow, geologic and hydrologic studies are needed to adequately understand the systems in the area and determine the exact reservoir locations and heat contents. Also, radiogenic heat production data on the granite is needed to determine the source of heat for the regional heat flow.

Additional heat-flow holes should be drilled in three different geologic settings. First, shallow (30 m) holes should be drilled to profile heat flow in the hot-spring areas. Second, one or two deeper (100-300 m) holes should be drilled into Precambrian granite to confirm the 2.25 HFU regional value. Third, one or two heat-flow holes (300-500 m) should be drilled into the volcanic sequence north of Clifton to quantify regional water flow and heat loss due to recharge in the extensive volcanic sequence. These data are absolutely necessary prior to siting and drilling a production or test well in the inferred high-temperature reservoir in the Clifton area. These heat flow data will show the heat contents of the systems, provide data for estimates of potential production rates from geothermal wells, and the best locations for shallow production wells.

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Table 1 Heat Flow Data in the Clifton, Arizona Area

Heat Flow Hole	Morenci(1)	HF1	HF2	Clifton 1
Latitude Degrees	33° 05'	33° 5.9'	33° 2.7'	32° 56.7'
Longitude Degrees	109° 22'	109° 21.1'	109° 22.0'	109° 13.8'
Township section, township, range	sec. 16 T. 4S., R. 29E	NW¼, SE¼ sec. 10, T. 4S., R. 29E.	NE¼, NW¼, sec. 33, T. 4S., R. 29E.	NE¼, NE¼, sec. 1, T. 6S., R. 30E.
Elevation Meters	1296	1445	1341	1097
Mean Annual* Temperature °C	17.4	16.0	16.6	19.0
Thermal Gradient °C/km (Depth Interval)	22.7 ± 0.1 (340-580m) 22.2 ± 0.6 (600-660m)	25.8 (70-185 m) 23.0 (300-365 m)	9.4 (60-100 m) 16.1 (105-140 m)	12 (135-140m) 20.0 (250-255m)
Thermal Conductivity 10^{-3}cal/cm-sec-°C (Depth Interval)	6.1 ± 0.2 (340-580m) 7.7 ± 0.9 (600-660m)	8.73 ± .47 (70-185m) 9.93 ± 1.7 (300-365m)	10.4 (60-100 m) 6.5 (105-140 m)	4.3 (135-140m) 4.5 (250-255m)
Heat Flow 10^{-6}cal/cm^2-sec (Depth Interval)	1.4 (340-580m) 1.7 (600-660m)	2.25 (70-185 m) 2.28 (300-365 m)	0.98 (60-100 m) 1.05 (105-140 m)	0.51 (135-140 m) 0.98 (250-255 m)
Type Sample	Core	Fragments	Fragments	Fragments
Lithology	granite ?	granite	orthoquartzite, dolomitic sandstone, granite	Coarse clastic sediment derived mostly from intermediate volcanics.

(1) Data from Reiter and Shearer, 1979.

*Obtained by interpolating mean annual temperatures from drill hole elevations using local weather station elevations and average temperatures.

Figure 1

CLIFTON AREA ARIZONA

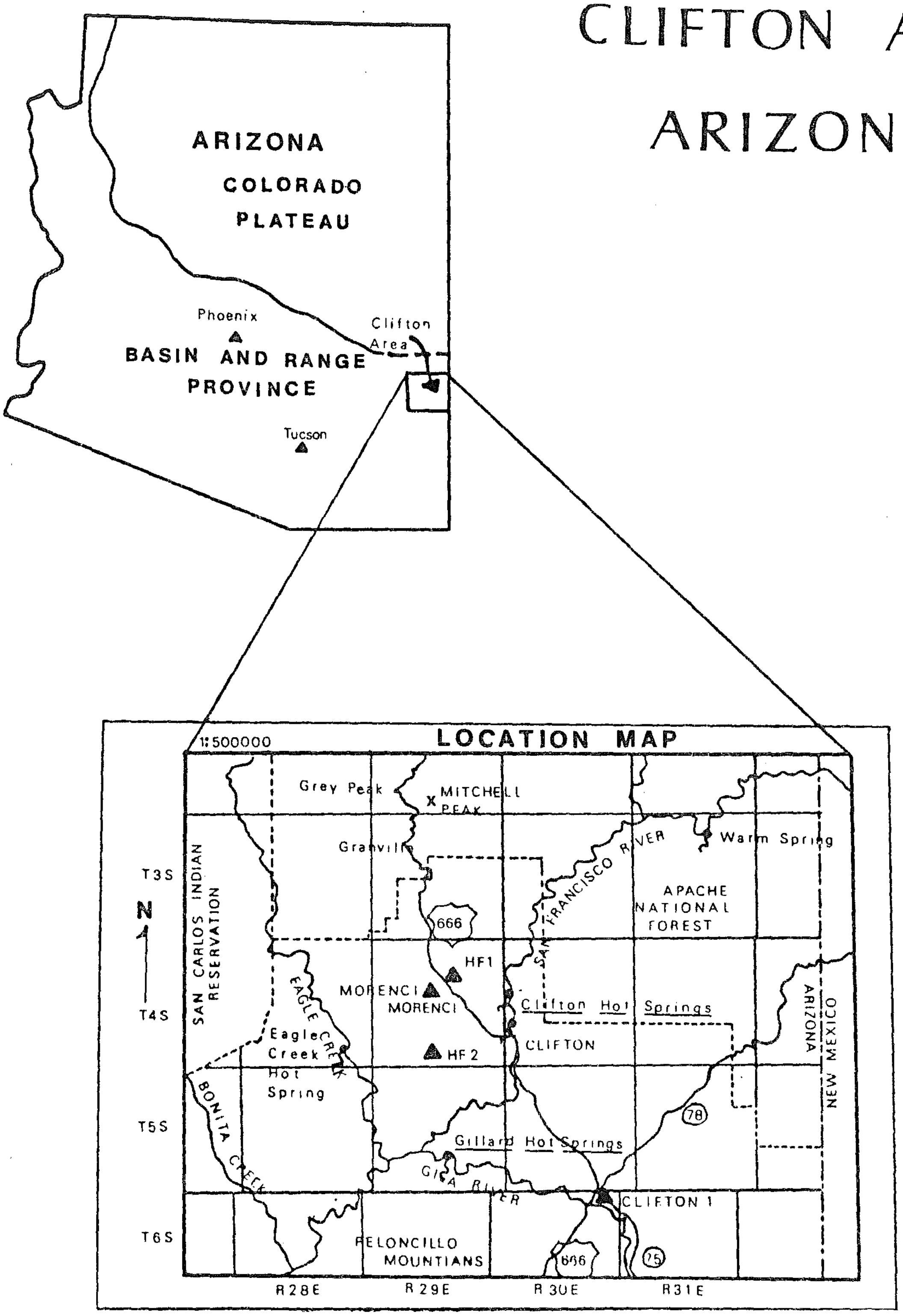
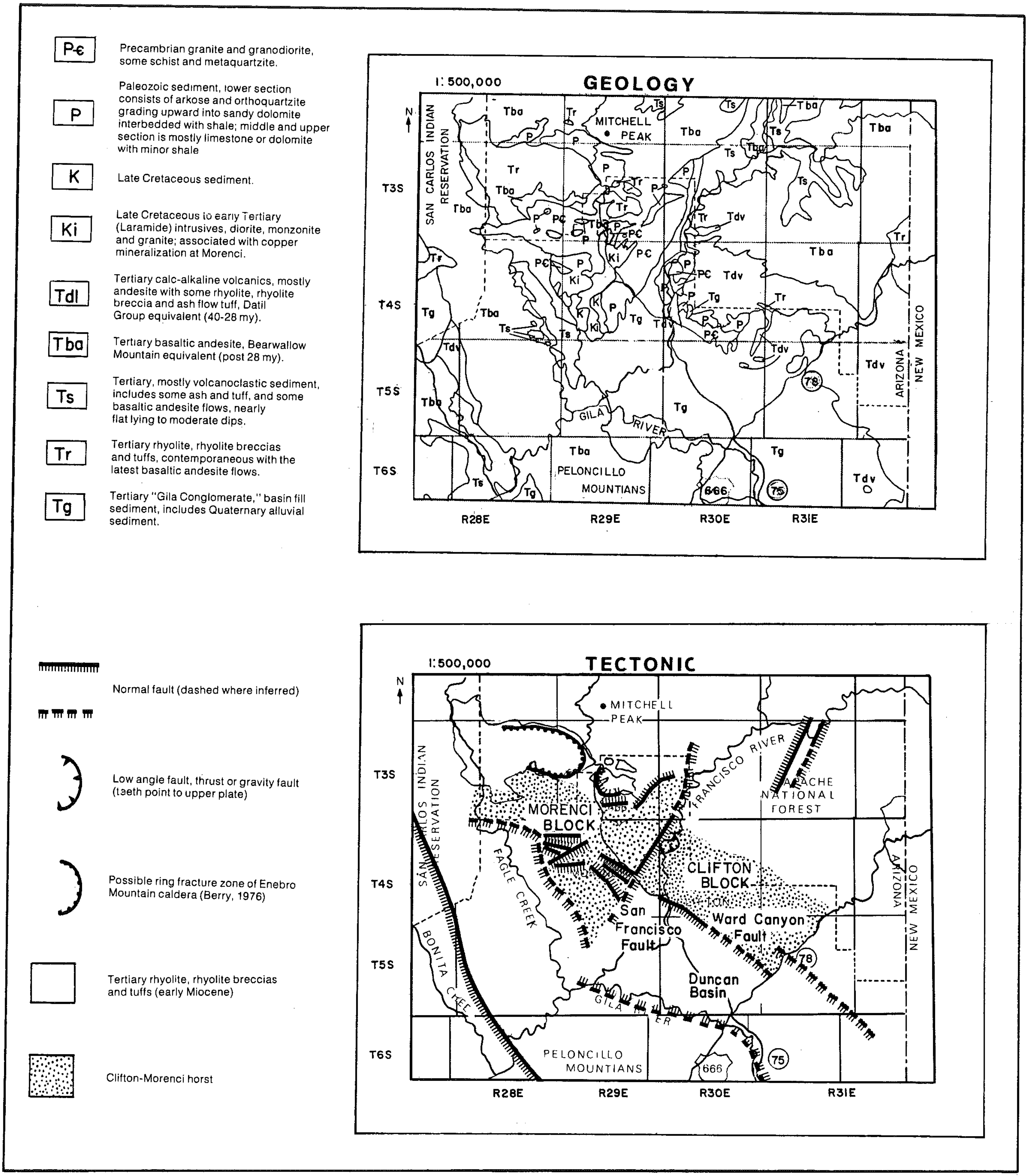


Figure 2



P-€	Precambrian granite and granodiorite, some schist and metaquartzite.
P	Paleozoic sediment, lower section consists of arkose and orthoquartzite grading upward into sandy dolomite interbedded with shale; middle and upper section is mostly limestone or dolomite with minor shale
K	Late Cretaceous sediment.
Ki	Late Cretaceous to early Tertiary (Laramide) intrusives, diorite, monzonite and granite; associated with copper mineralization at Morenci.
Tdl	Tertiary calc-alkaline volcanics, mostly andesite with some rhyolite, rhyolite breccia and ash flow tuff, Datil Group equivalent (40-28 my).
Tba	Tertiary basaltic andesite, Bearwallow Mountain equivalent (post 28 my).
Ts	Tertiary, mostly volcanoclastic sediment, includes some ash and tuff, and some basaltic andesite flows, nearly flat lying to moderate dips.
Tr	Tertiary rhyolite, rhyolite breccias and tuffs, contemporaneous with the latest basaltic andesite flows.
Tg	Tertiary "Gila Conglomerate," basin fill sediment, includes Quaternary alluvial sediment.

Normal fault (dashed where inferred)

Low angle fault, thrust or gravity fault (teeth point to upper plate)

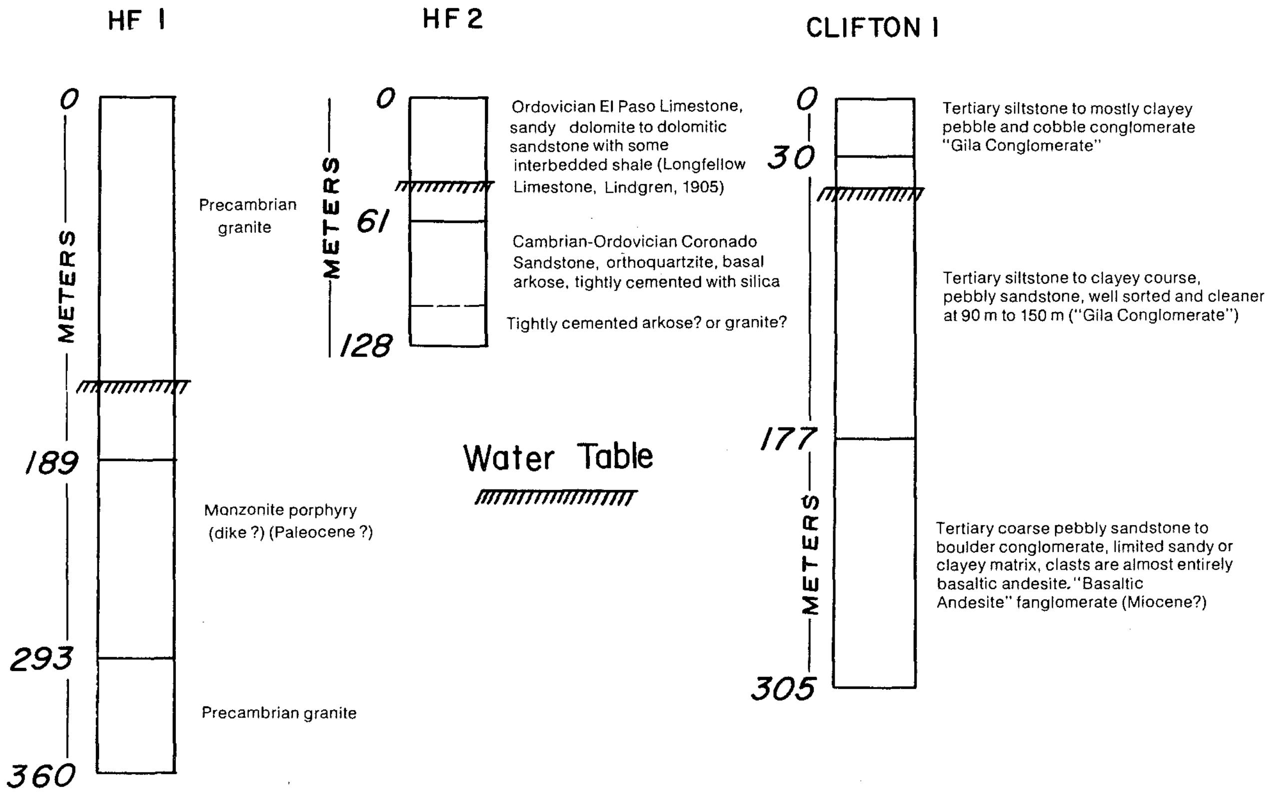
Possible ring fracture zone of Enebro Mountain caldera (Berry, 1976)

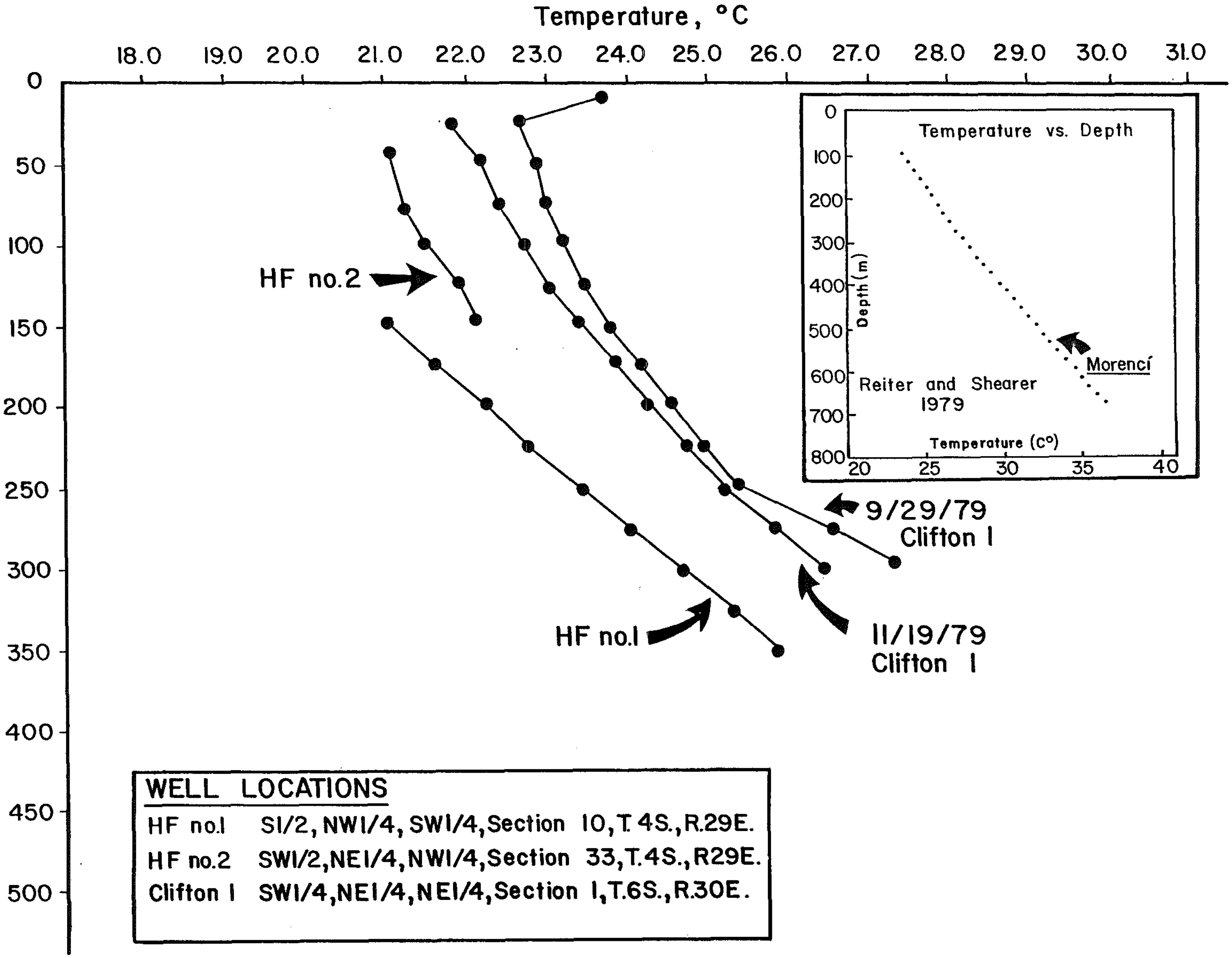
Tertiary rhyolite, rhyolite breccias and tuffs (early Miocene)

Clifton-Morenci horst

Figure 3

LITHOLOGY OF HEAT FLOW HOLES





WELL LOCATIONS

HF no.1	S1/2, NW1/4, SW1/4, Section 10, T.4S., R.29E.
HF no.2	SW1/2, NE1/4, NW1/4, Section 33, T.4S., R29E.
Clifton I	SW1/4, NE1/4, NE1/4, Section 1, T.6S., R.30E.

Temperature logs of drill holes in the Clifton, Arizona area.

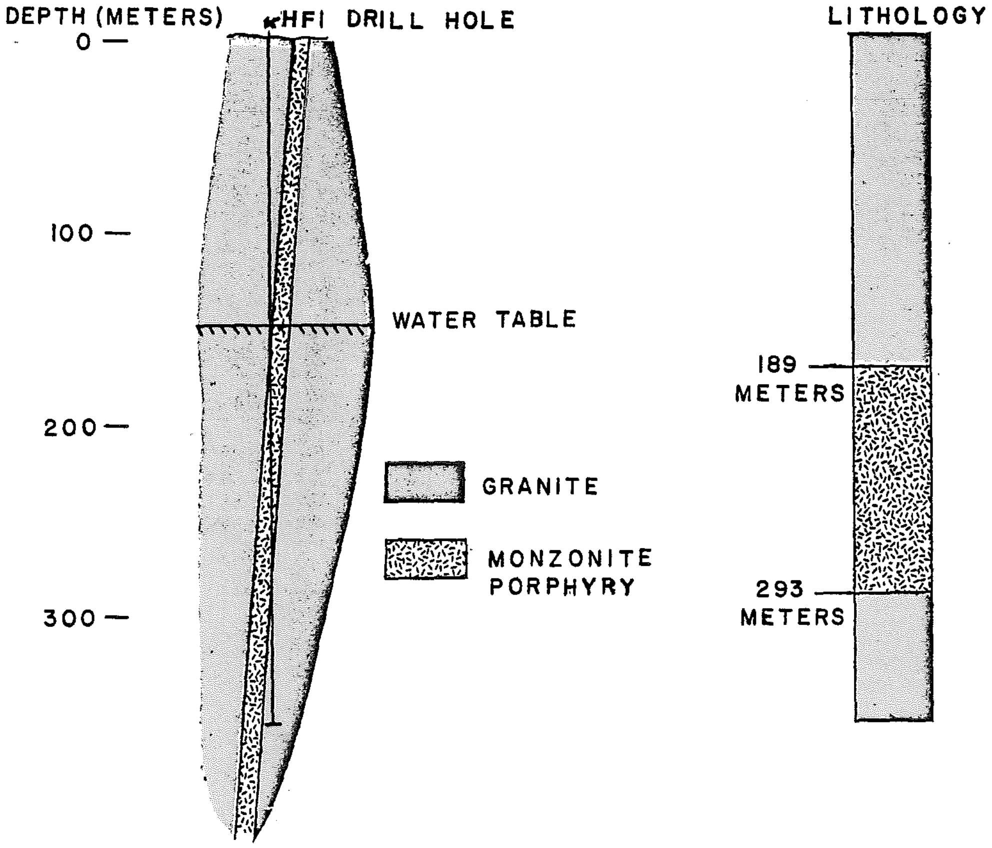
Figure 4

Figure 5

Heat Flow Data for HF1 Drill Hole

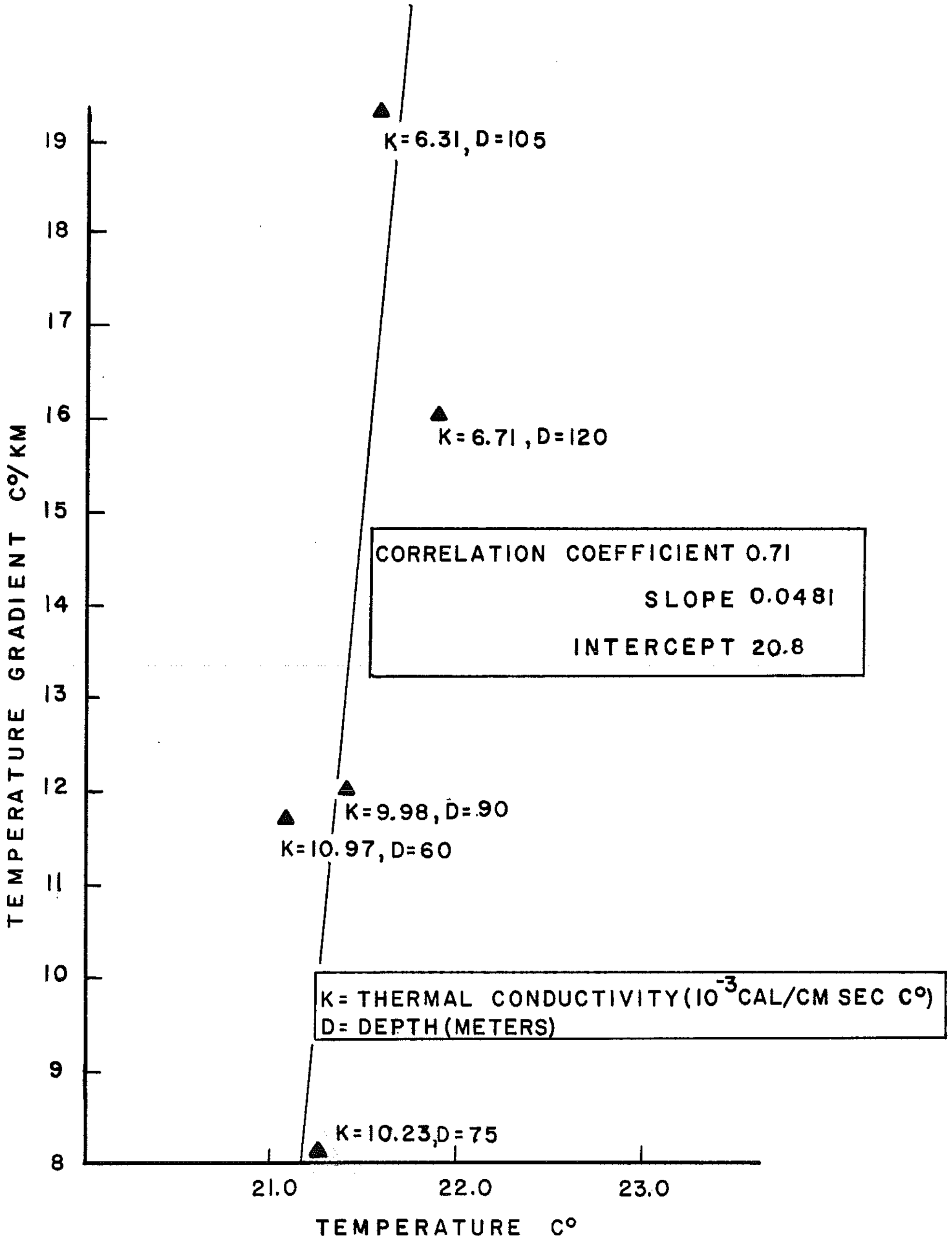
Depth Meters	Temperature Gradient °C/km	Temperature °C	Thermal Conductivity 10^{-3}cal/cm-sec-°C	Heat Flow 10^{-6}cal/cm^2-sec
75	28.7	19.07	8.74	2.10
105	24.0	19.80	8.26	1.98
180	25.7	21.78	7.48	1.92
220	22.7	22.62	8.24	1.87
240	24.3	23.09	5.92	1.44
280	25.3	24.18	7.04	1.78
290	24.7	24.43	6.52	1.61
320	23.7	25.19	8.72	2.06
355	20.0	25.89	11.13	2.23

Cross section of Hypothesized Geology in HF1



Note: The HF1 heat flow data in Table 4 are mean values for conductivities and temperature gradients calculated over the reported depth intervals. The heat flows in this figure are slightly different because they were calculated for each depth interval without averaging the data.

Figure 6



TEMPERATURE VERSUS TEMPERATURE GRADIENT
HF 2

Figure 7

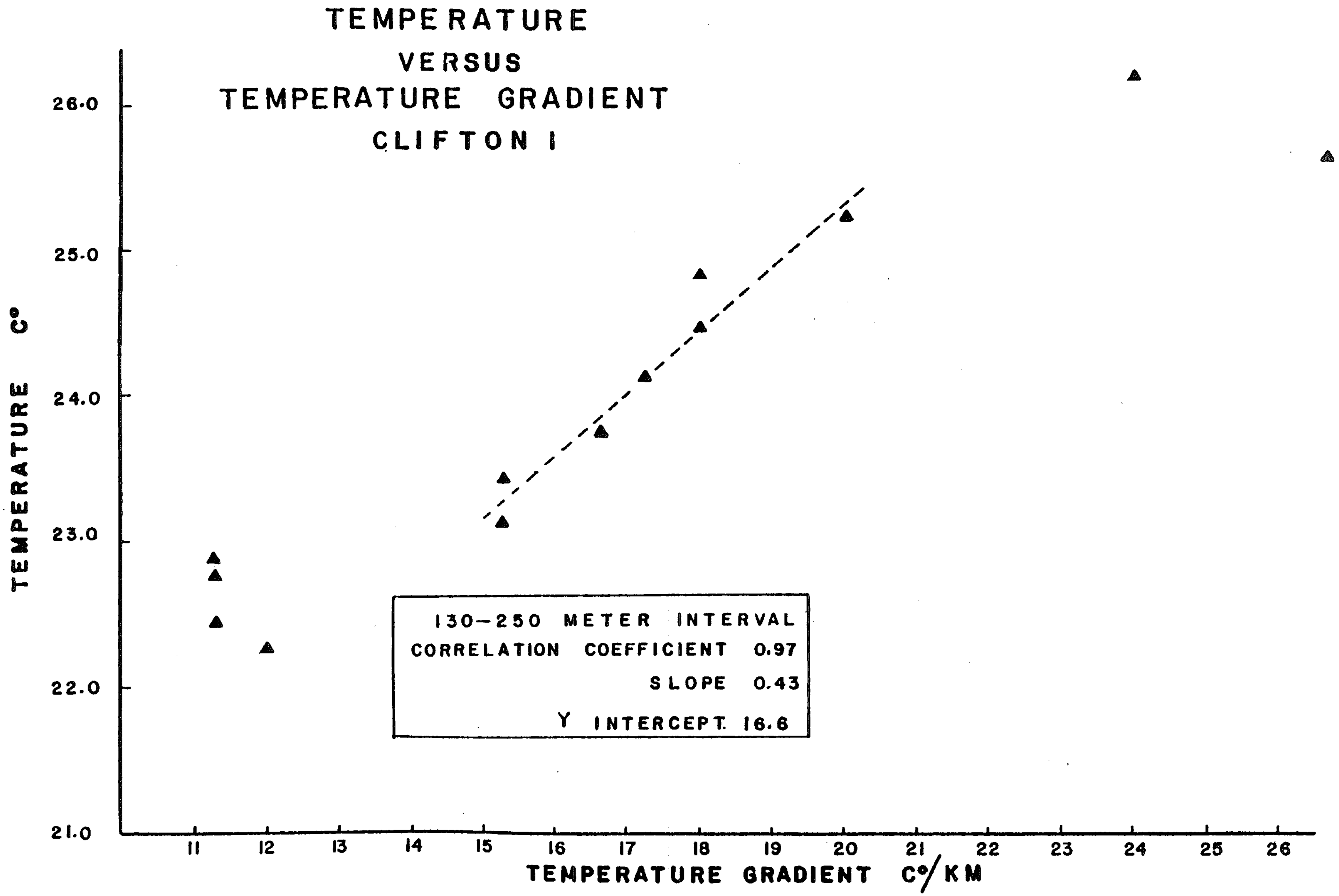
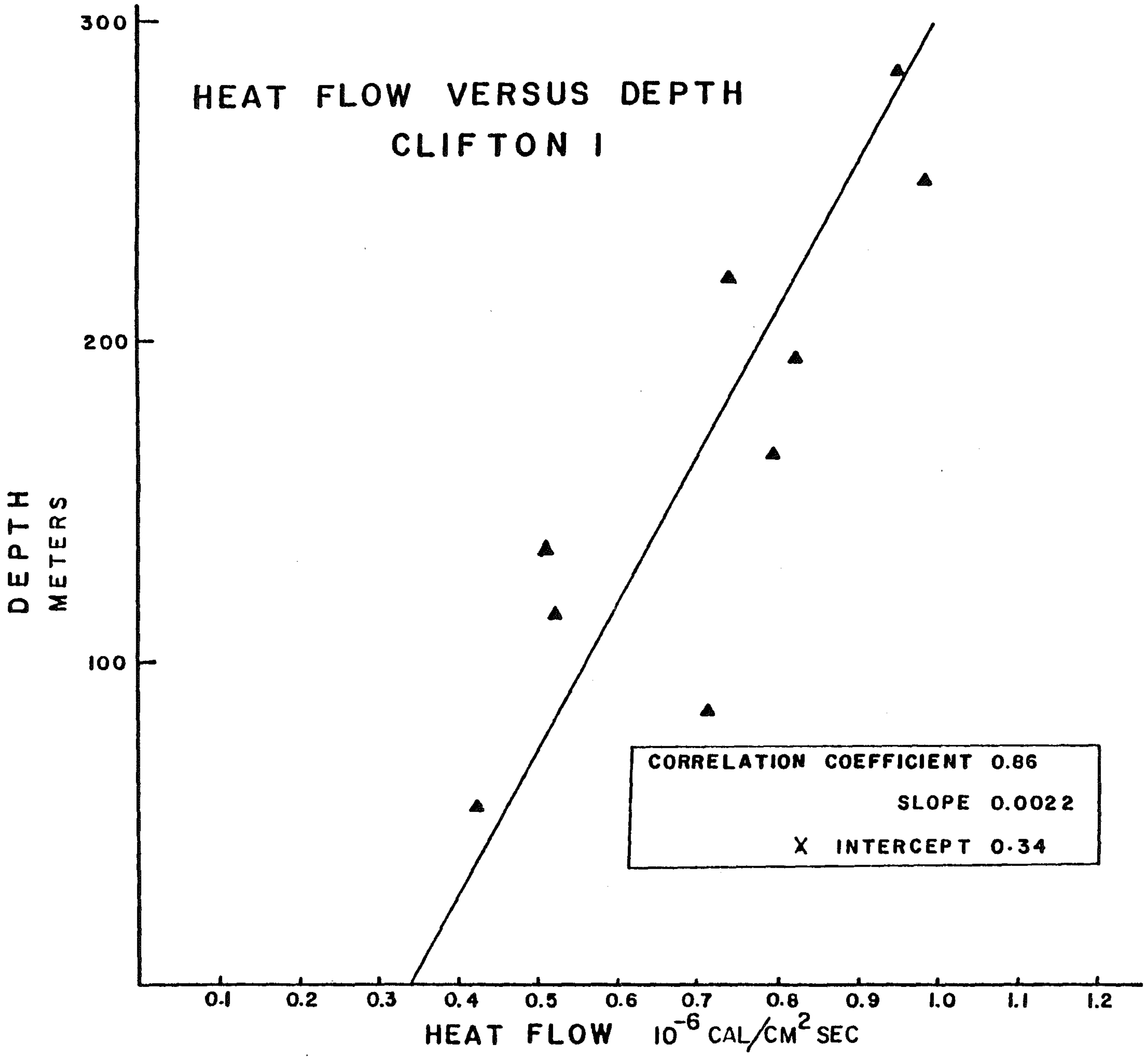

TEMPERATURE
VERSUS
TEMPERATURE GRADIENT
CLIFTON I
TEMPERATURE C°
26.0
25.0
24.0
23.0
22.0
21.0
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
TEMPERATURE GRADIENT C°/KM
130-250 METER INTERVAL
CORRELATION COEFFICIENT 0.97
SLOPE 0.43
Y INTERCEPT 16.6

Figure 8


HEAT FLOW VERSUS DEPTH
CLIFTON I
DEPTH
METERS
300
200
100
CORRELATION COEFFICIENT 0.86
SLOPE 0.0022
X INTERCEPT 0·34
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
HEAT FLOW 10⁻⁶ CAL/CM² SEC