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HEAT FLOW FROM FIVE URANIUM TEST WELLS IN WEST-CENTRAL ARIZONA

by

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This report is preliminary and has not been reviewed for conformity
with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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INTRODUCTION

The Department of Energy's National Uranium Resource Evaluation (NURE) resulted in the drilling of many exploratory wells in selected sedimentary basins in the southwestern United States. Through the cooperation of DOE and Bendix Field Engineering Corporation, we (USGS and State of Arizona, Bureau of Geology and Mineral Technology) were able to preserve for measurements of equilibrium temperature five of these wells (Figure 1a, Table 1), ranging in depth from about 750 to nearly 1700 meters. From thermal conductivity measurements on drill cuttings and a few cores, combined with porosity estimates and lithologic logs, we also were able to characterize thermal conductivities with sufficient precision to make meaningful estimates of heat flow.

The holes were drilled between June and September 1979, and temperature measurements were completed in December 1979 (Table 1). In the deepest hole (PQ-4), an obstruction was encountered in the casing at 320 meters during this set of temperature logs. On April 16, 1980, the casing was flushed out, and a log was obtained to nearly total depth on May 6.

In this report, we describe the measurements and the interpretive procedures followed in determining heat flows. The regional significance of these results has been touched on briefly by Lachenbruch and Sass (1981) and is the subject of continuing research.

The following symbols and units are used in the remainder of the report:

Temperature,	°C
Γ,	Temperature gradient, °C km^{-1}
K,	Thermal conductivity, 1 TCU = 1 mcal cm^{-1} s^{-1} °C^{-1} = 2.39 Wm^{-1} k^{-1}
Heat flow,	1 HFU = 10^{-6} cal cm^{-2} s^{-1} = 41.8 kW km^{-2}
Heat production,	1 HGU = 10^{-13} cal cm^{-3} s^{-1} = 2.39 kW km^{-3}

Acknowledgments. We are grateful to John P. Ellis, Department of Energy, and L. W. Lease, Bendix Field Engineering Corporation for their cooperation in preserving the holes. Tom Moses, Jack Porter, and Fred Grubb, USGS, rendered valuable help in organizing casing and obtaining temperature measurements. Funding for the project was provided by the Division of Geothermal Energy, Department of Energy.

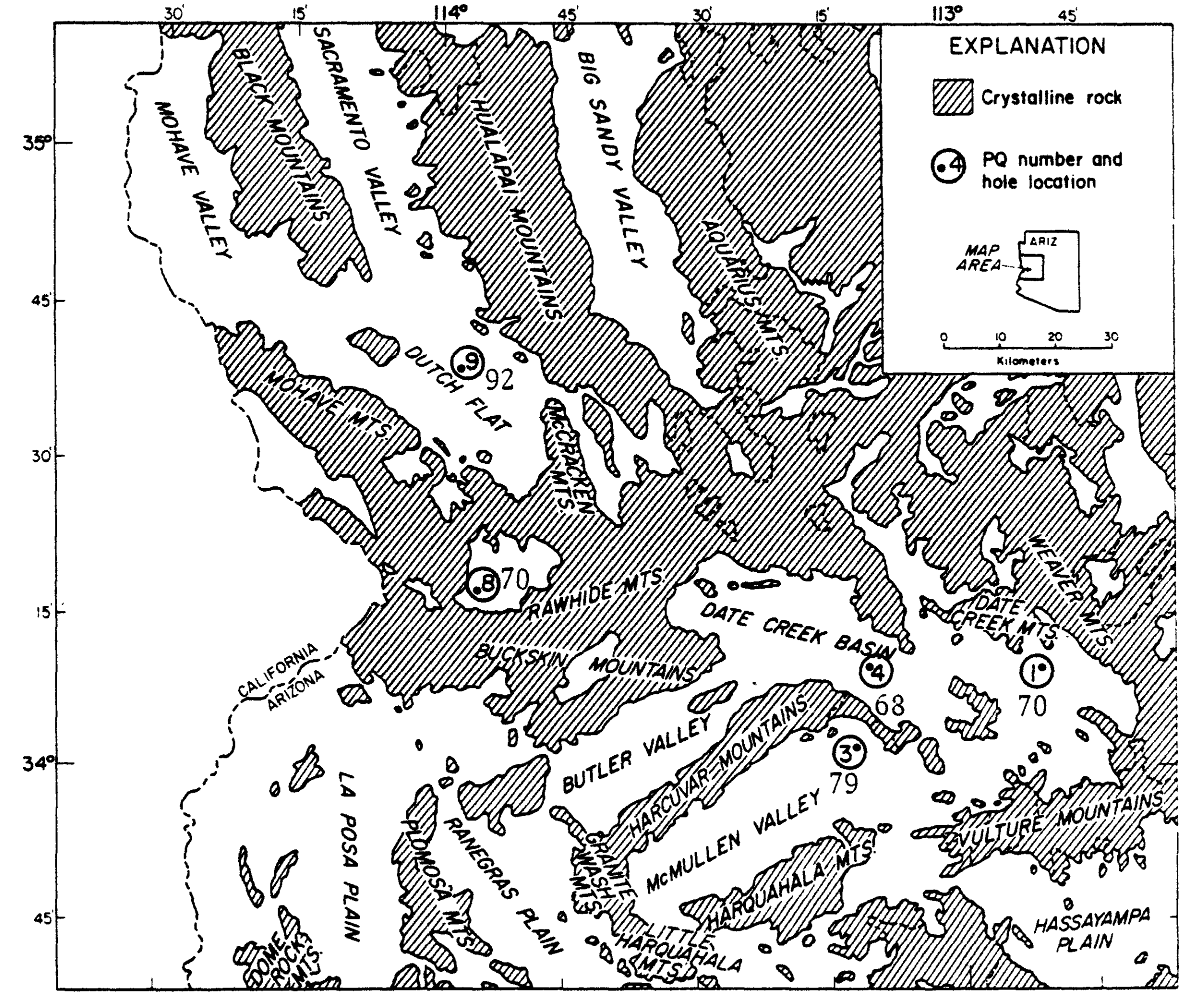

Figure 1a. Sketch map of study area showing major physiographic features, locations of boreholes, and heat-flow values (in kw km^{-2}).

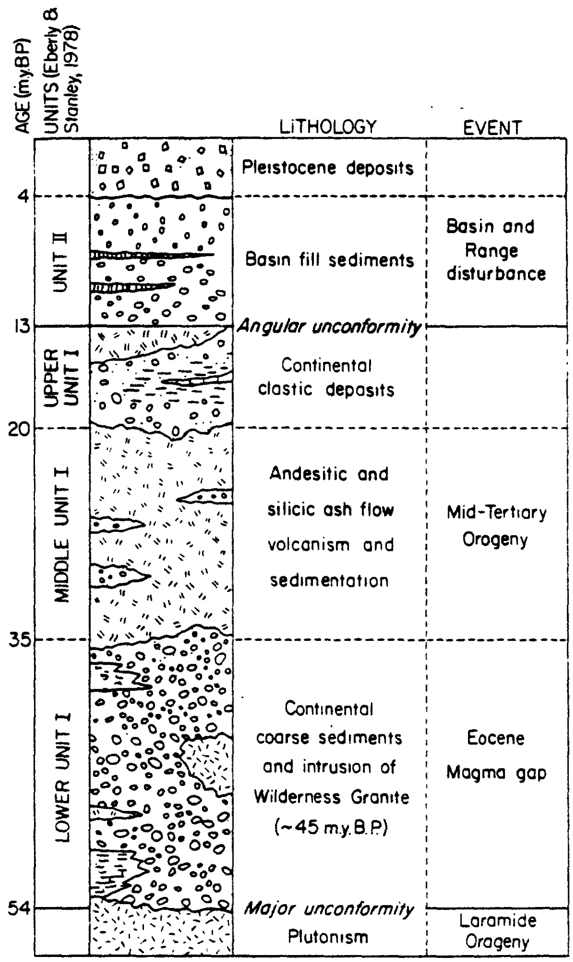

Figure 1b. Generalized stratigraphic column for west-central Arizona.

TABLE 1. Summary of heat-flow data from NURE holes, Arizona

Hole	N. Lat.	W. Long.	Elev m	Depth, m		Dates drilled		Date logged	Heat flow		Heat production*	
				Drilled	Logged	From	To		HFU	kw km^{-2}	HGU	kw km^{-3}
PQ-1	34° 07.8'	112° 51.5'	891	899(?)	905	6-29-79	7-17-79	12-3-79	1.68	70	5.84	2.44
PQ-3	34° 00.3'	113° 13.1'	662	1321	1317	6-10-79	6-22-79	12-2-79	1.90	79	3.44	1.42
PQ-4	34° 09.4'	113° 10.6'	759	1674	1671	7-20-79	8-15-79	5-6-80†	1.62	68		
PQ-8	34° 17.0'	113° 56.6'	267	747	625	9-1-79	9-11-79	12-1-79	1.68	70	10.2	4.26
PQ-9	34° 38.5'	113° 58.6'	683	1586	1574	7-26-79	8-27-79	11-29-79	2.19	92	18.4	7.69

*Single determinations on basement core when basement penetrated.

†Ran 1" tubing inside of casing and circulated for 2 hours on 4-16-80 to clear obstruction.

GEOLOGIC SETTING

The geologic and tectonic history of west-central Arizona is complex and at best incompletely understood. Only recently have investigators presented major geologic, geochronologic, and tectonic syntheses of southwestern Arizona in general (Eberly and Stanley, 1978; Scarborough and Peirce, 1978; Shafiqullah and others, 1980) and west-central Arizona in particular (Reynolds, 1980).

Although rocks of all eras are represented in west-central Arizona, those of Precambrian age are most abundant, followed by 30- to 13-m.y.-old alkali-calcic volcanic rocks. Eberly and Stanley (1978) divided the Cenozoic stratigraphy of southwestern Arizona into two main units: the older Unit I, Eocene to late Miocene, and the younger Unit II, late Miocene to Holocene. A major unconformity separates Unit I and Unit II (see Figure 1b).

During Eocene and early-Oligocene time, coarse clastic continental sediments were transported short distances and deposited under oxidizing conditions in shallow basins. These sediments, named Lower Unit I by Eberly and Stanley (1978), were deposited directly on a widely recognized unconformity surface that separates them from pre-Eocene bedrock, which is Precambrian to Paleocene in age. Lower Unit I is composed of a wide variety of fine- and coarse-grained clastic sediments including limestones and, in certain areas, extensive fanglomerates.

By the end of the Oligocene (26 m.y.B.P.) volcanism was again widespread and intense. Damon and others (1964) named this magmatic pulse the mid-Tertiary orogeny. Subduction-related andesites and silicic ash-flow sheets were erupted. Some sediments are intercalated with these volcanic rocks, and unconformities are common. A major unconformity marks the end of this episode and separates these highly deformed Middle Unit I rocks of Eberly and Stanley (1978) from the less deformed overlying rocks of Upper Unit I.

Upper Unit I began about 20 to 17 m.y. ago as the mid-Tertiary orogeny started to ebb. The rocks of this unit consist of continental deposits of poorly indurated sandstones, fanglomerates, mudstones, and beds of water-laid tuff and are regionally overlain by the first of the true basalts that relate to initiation of the Basin and Range disturbance. The Artillery and Chapin Wash formations, which are typical of the middle-Miocene deposits, were recognized in the Date Creek Basin and adjacent ranges by Otton and Wynn (1978). These formations are characterized by silicified root casts, imprints of palm fronds, and locally abundant lignites. The lignitic-rich facies in Upper Unit I are the host rocks for the uranium deposits in the area of the Anderson Mine.

Evidence is accumulating (Scarborough, 1981, personal communication) that listric-style faulting and northeast-trending arches seen in the crystalline and metamorphic rocks of west-central Arizona affected structures and layered rocks as young as 15 m.y. old and were in turn affected by Basin and Range faulting. Thus a period of low-angle tectonic transport and superposed arching of these ranges was sandwiched between 15 and 12 m.y.B.P. Upper Unit I rocks (including the Artillery and Chapin Wash formations) were affected by these events and are therefore, to some unknown extent, allochthonous.

As motion along the North American-Pacific plate boundary changed from convergent to transform, the intense volcanism and shallow listric-normal faulting (associated with ductile strain during the mid-Tertiary orogeny) gradually changed to high-angle, normal block faulting, subsidence, and erosion (characteristic of the Basin and Range disturbance). The major unconformity separating Unit I and Unit II marks this profound change in plate motions.

In Arizona, active Basin and Range faulting began after 13 m.y.B.P. and had virtually ceased by 4 m.y.B.P. Sediments that accumulated in these foundering grabens constitute the younger Unit II of Eberly and Stanley (1978). These deposits, termed "basin fill" by Scarborough and Peirce (1978), are mostly coarse grained along the basin margins and fine grained to clayey in the basin centers.

The Basin and Range disturbance disrupted earlier drainage networks and paleobasins and created new depocenters for material eroded from nearby ranges. The presence of some NaCl salts in at least one drillhole in the Date Creek Basin suggests the existence of closed playa drainage in the area during at least part of the time. These salt occurrences appear to be minor (and by extrapolation, the duration of internal drainage, short) compared with the thick (thousands of feet) bedded evaporite deposits found in some basins in other parts of Arizona (Peirce, 1976).

Thin veneers of Pleistocene clastic sediments cover all valley areas today, except where they have been locally dissected by active stream down-cutting.

HOLE PRESERVATION

At the conclusion of drilling, 32 mm (1¼") nominal I.D. black iron pipe was run into each hole as nearly as possible to total depth (compare columns 5 and 6, Table 1). The mud within this casing was then displaced by pumping a wiping plug down to the latching collar at the bottom of the casing string (Moses and Sass, 1979) using clear water. An ~3 m cement plug was emplaced around the collar, and a standard USGS locking cap assembly was installed.

TEMPERATURE MEASUREMENTS

After sufficient time (~3 to 4 months) had elapsed to allow dissipation of the thermal transients introduced by the drilling process, temperature measurements were made using the USGS continuous-temperature-logging system. This system has been evolved from the well-logging mode described by Sass and others (1971b) from which it differs primarily in that a sophisticated digital data-acquisition system has replaced the Wheatstone bridge, allowing continuous logging at a line speed of about 0.1 m/s. In this study, temperatures were sampled at intervals of 2 feet (~0.6 m), which allowed us to etch out some very small scale anomalies. Individual temperature profiles are presented in Figures 2 through 6. The gradient profiles shown in these figures represent sliding averages over about 10 m.

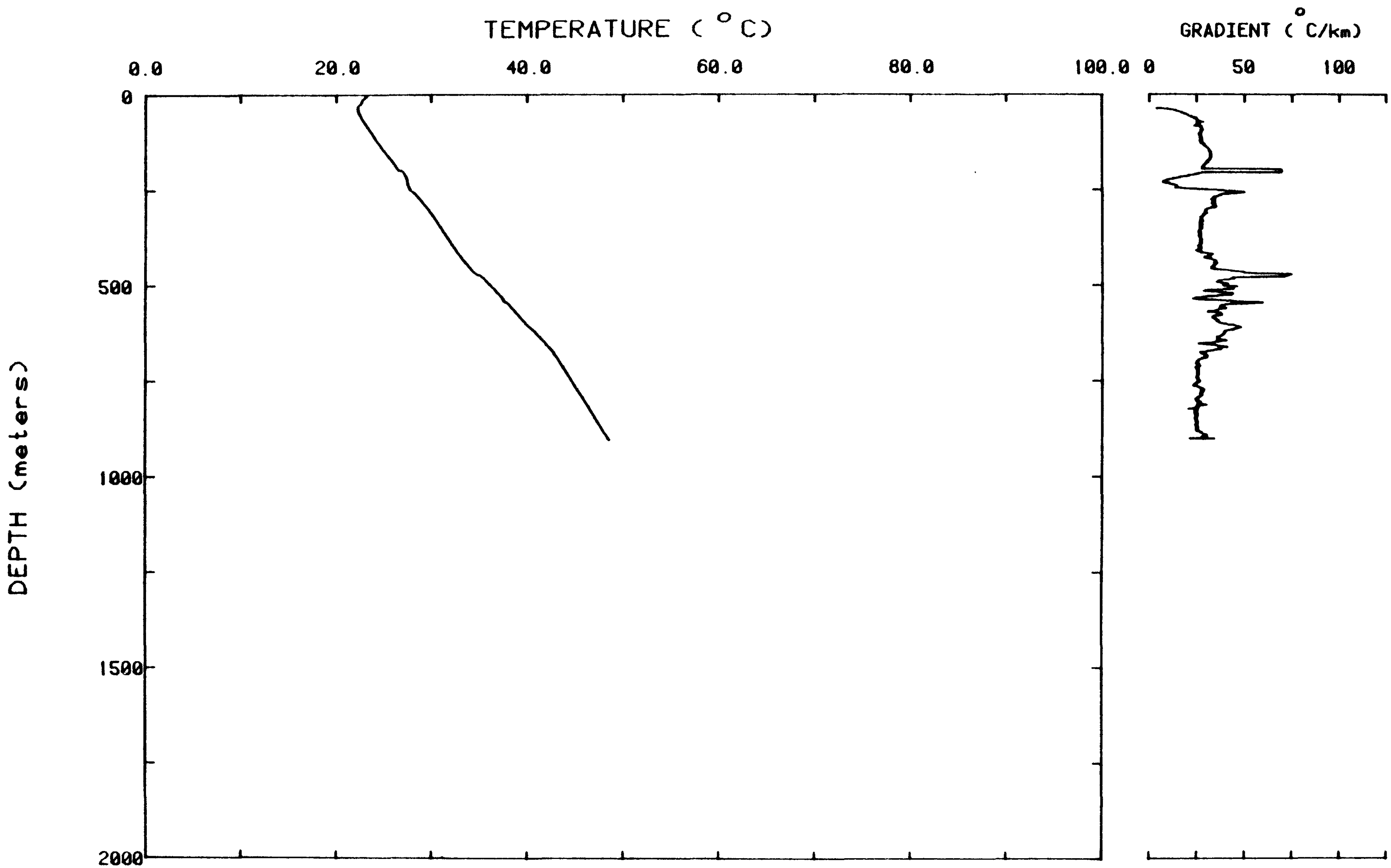

Figure 2. Temperatures and gradients (sliding average over 10 m), Hole PQ-1.

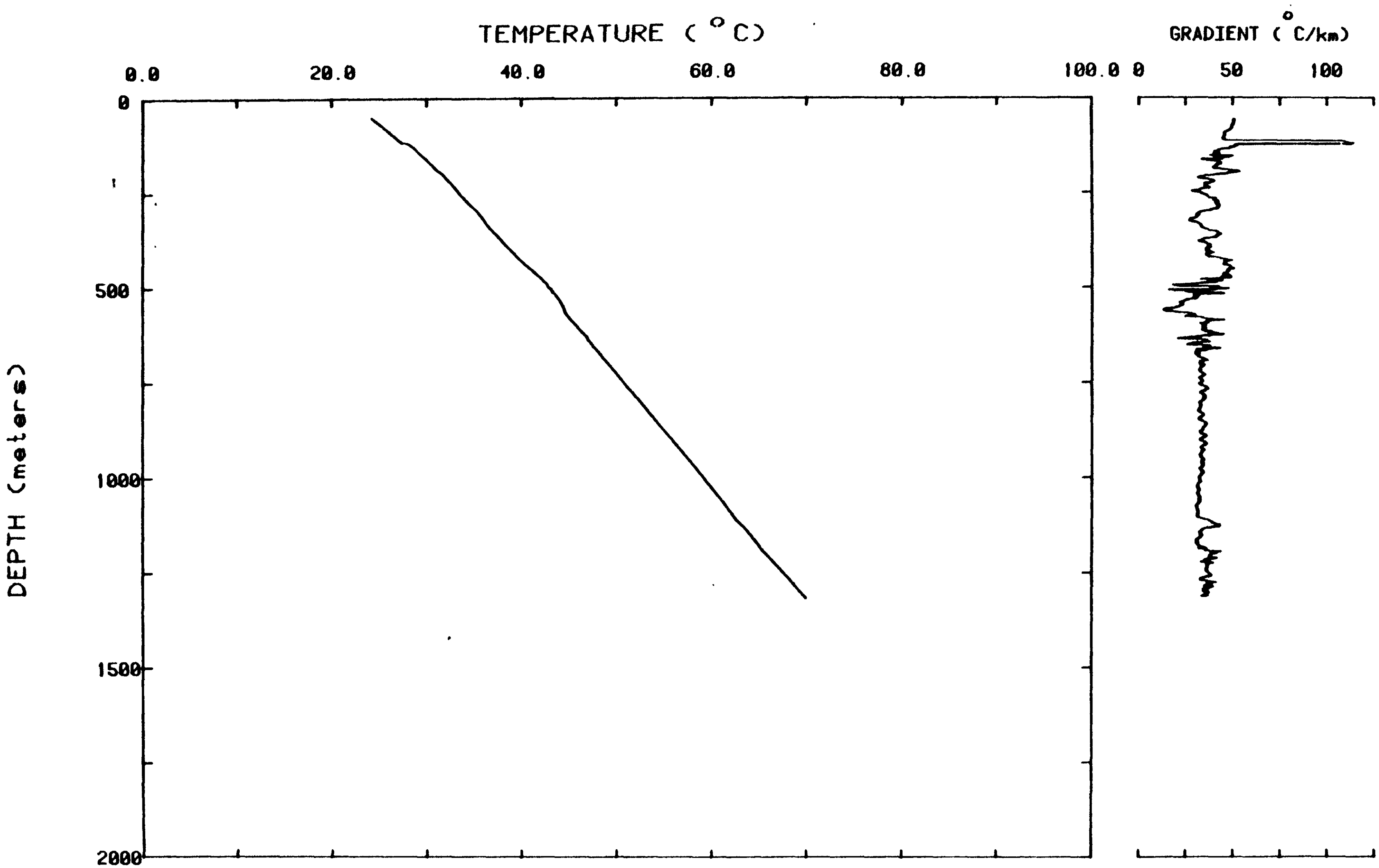

Figure 3. Temperatures and gradients (sliding average over 10 m), Hole PQ-3.

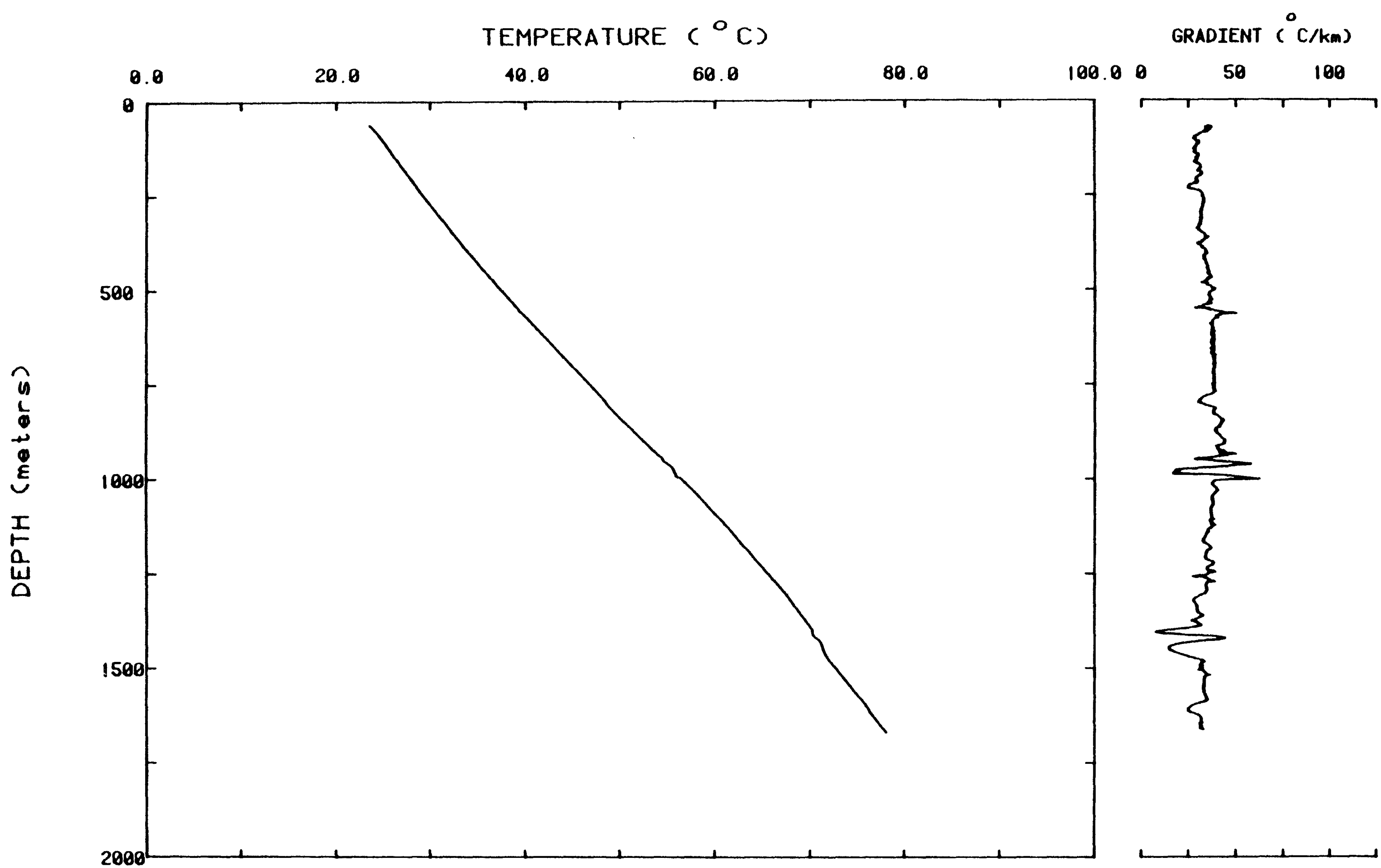

Figure 4. Temperatures and gradients (sliding average over 10 m), Hole PQ-4.

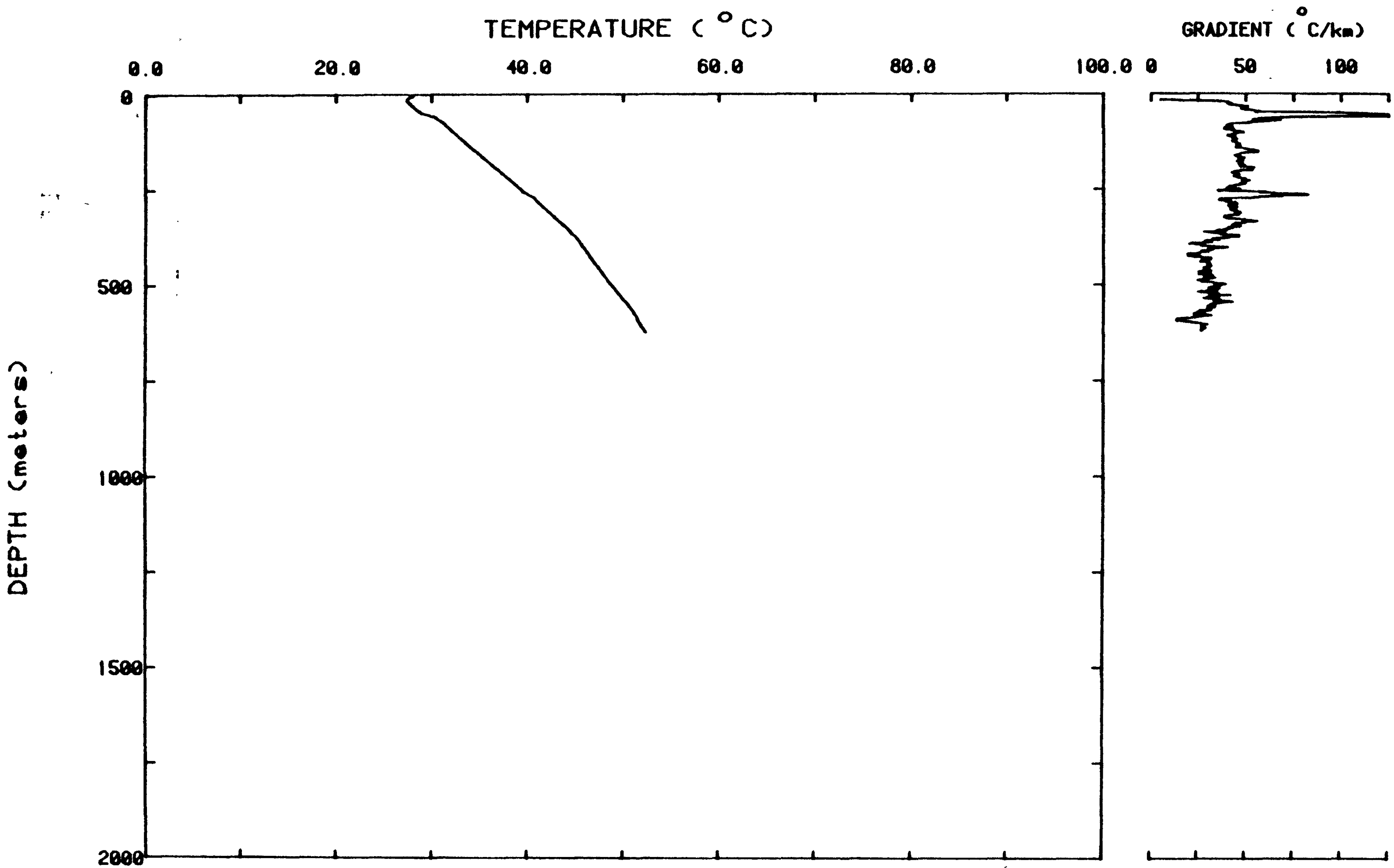

Figure 5. Temperatures and gradients (sliding average over 10 m), Hole PQ-8.

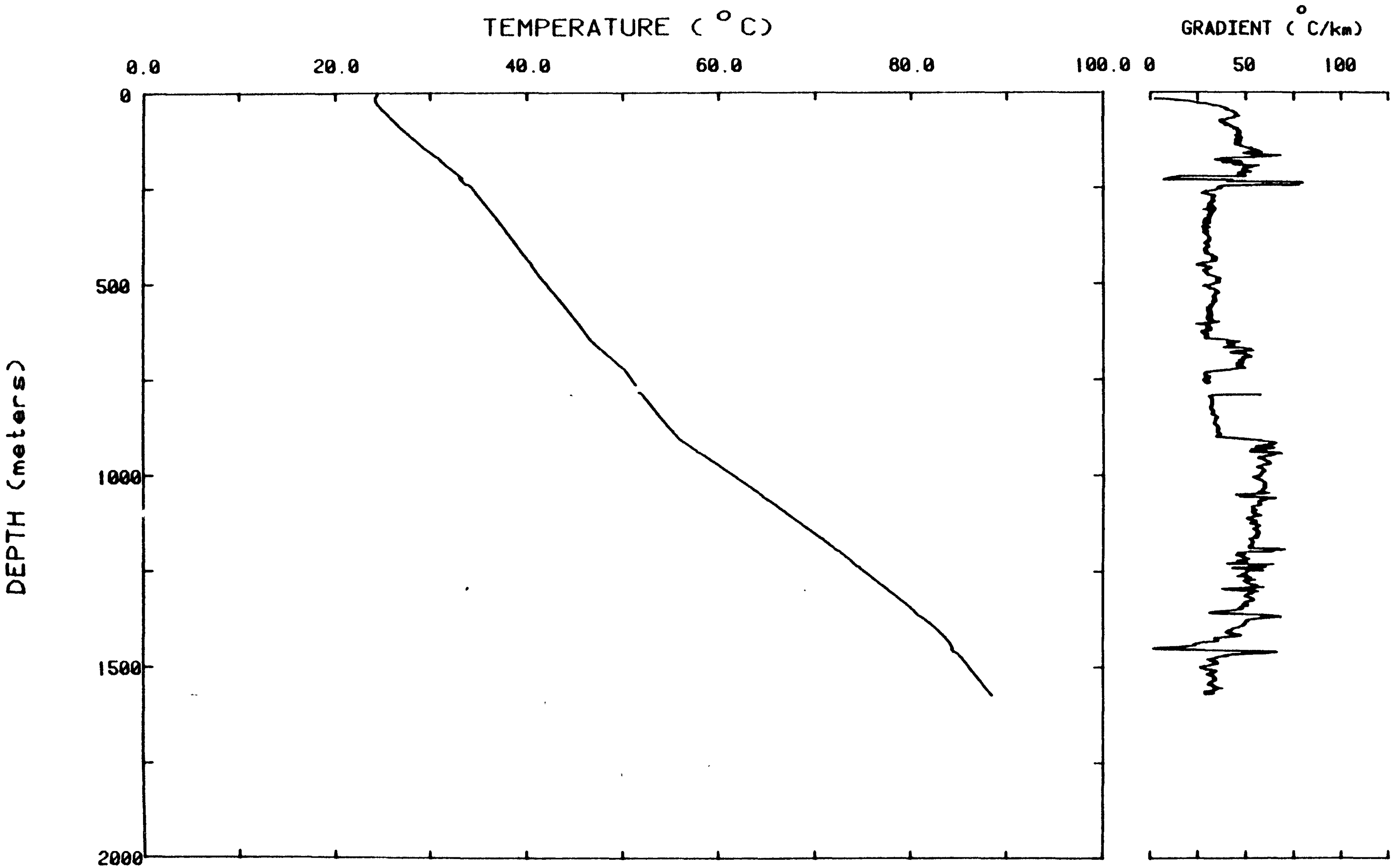

Figure 6. Temperatures and gradients (sliding average over 10 m), Hole PQ-9.

THERMAL CONDUCTIVITIES

Drill cuttings were collected at 10-foot (∿3 m) intervals for virtually the entire depth of all holes. In addition, one or two cores were obtained in each hole. After examining the temperature logs, we selected intervals with coherent temperature gradients (Figures 2 through 6) and sampled drill cuttings at intervals that allowed a statistically significant number of conductivity measurements (typically 5 to 10) over each "flux plate." We also sampled all available cores from which we prepared disks for divided-bar determinations of conductivity (see Sass and others, 1971b) and estimates of porosity.

Most thermal conductivity measurements were made on drill cuttings using the chip method described by Sass and others (1971a). These data together with measurements on core are documented in the Appendix (Tables A-2 through A-6). The datum obtained from a measurement on chips is the thermal conductivity of the solid component (K_s) of the rock. Where porosity is negligibly small, this is the conductivity value required for determination of heat flow. For the sedimentary and volcanic rocks sampled in this study, this generally is not the case, and we must seek an independent means of estimating porosity. To this end, we estimated porosities from all available core specimens (see Appendix, Table A-1). We also examined lithologic logs, drilling rates, and larger-than-average specimens of cuttings (∿1 cm). We were fortunate in that we were able to generalize porosities from one hole to the next on the basis of initial estimates from measurements on core (Table A-1) and internally consistent heat flows in individual holes (see discussion of heat-flow calculations and the Appendix).

HEAT FLOW

For the heat-flow determinations, intervals along each temperature profile having coherent, linear segments (Figures 2 through 6) were chosen. Least-squares temperature gradients were calculated and harmonic mean conductivities were combined with porosities (determined from a combination of the results of Table A-1, examination of cuttings, drilling rates, and, in the case of sandstones and siltstones, internal consistency between contiguous flux plates) using the geometric mean (see Sass and others, 1971a). The results are summarized in Tables 2 through 6. Conductivities are shown for the porosity values adopted and for plausible limiting values of porosity, to illustrate the sensitivity of the heat-flow determinations to formation porosity. The estimated uncertainty reflects a combination of the scatter in zero-porosity values and the uncertainty introduced by the porosity estimate. Finally, a mean heat flow was calculated by weighting according to the thickness of rock represented by each individual determination. Considering the various uncertainties, there is a remarkable internal consistency among component heat flows in each well. The mean heat flows (Table 1) are within the range previously published for the region (Shearer and Reiter, 1981; Sass and others, 1981; Lachenbruch and Sass, 1981).

TABLE 2. Heat-flow summary, Hole PQ-1

Depth range m	Rock type(s)	Gradient °C/km	N*	Assumed porosity %	K (TCU)	Heat flow (HFU)	Estimated uncertainty (HFU)
122-206	Sandstone, minor siltstone	31.9±0.2	11	0	9.05±0.22		
				20	6.23		
				25	5.68	1.81	0.2
				30	5.17		
274-296	Volcanic rocks	33.6±0.1	6	0	5.52±0.44		
				5	5.15	1.73	0.15
				10	4.81		
457-482	Siltstone	57.6±1.5	8	0	4.13±0.32		
				20	3.33		
				25	3.15	1.81	0.2
				30	2.99		
488-655	Volcanic rocks	38.0±0.1	6	0	4.53±0.14		
				5	4.27	1.62	0.15
				10	4.03		
671-905	Granite wash	25.3±0.01		0	7.17±0.18		
				5	6.61	1.67	0.15
				10	6.09		
			Weighted mean†			1.68±0.03	

*Number of specimens.

†Weighted according to thickness of section.

TABLE 3. Heat-flow summary, Hole PQ-3

Depth range m	Rock type(s)	Gradient °C/km	N*	Assumed porosity %	K (TCU)	Heat flow (HFU)	Estimated uncertainty (HFU)
122-244	Alluvium	41.7±0.1	4	0	6.77±0.03		
				20	4.94		
				25	4.57	1.91	0.2
				30	4.22		
244-427	Sandstone	35.74±0.07	7	0	8.25±0.27		
				20	5.79		
				25	5.30	1.89	0.2
				30	4.85		
579-1097	Sandstone	33.25±0.01	19	0	8.11±0.16		
				15	6.23		
				20	5.71	1.90	0.2
				25	5.23		
1116-1131	Shale	41.6±0.3	3	0	5.79±0.26		
				10	5.02		
				15	4.68	1.95	0.2
				20	4.36		
1189-1317	Basalt/Andesite	36.39±0.03	10	0	5.61±0.11		
				5	5.23	1.90	0.1
				10	4.88		
			Weighted mean†			1.90±0.004	

*Number of samples.

†Weighted according to thickness of section.

TABLE 4. Heat-flow summary, Hole PQ-4

Depth range m	Rock type(s)	Gradient °C/km	N*	Assumed porosity %	K (TCU)	Heat flow (HFU)	Estimated uncertainty (HFU)
244-335	Volcanic rocks	31.84±0.04	7	0	5.21±0.12		
				5	4.88	1.55	0.15
				10	4.57		
579-762	Volcanic rocks	37.68±0.02	7	0	4.44±0.12		
				5	4.19	1.58	0.15
				10	3.96		
808-930	Volcanic rocks	40.88±0.05	4	0	4.27±0.15		
				5	4.04	1.65	0.15
				10	3.82		
1006-1143	Volcanic rocks	37.23±0.34	6	0	4.55±0.17		
				5	4.29	1.60	0.15
				10	4.04		
1158-1250	Volcanic rocks	35.02±0.05	4	0	5.17±0.34		
				5	4.84	1.69	0.15
				10	4.54		
1494-1646	65% volcanic rocks	31.62±0.05	6	0	6.19±0.23		
	35% sand and siltstone			12†	5.18	1.64	
				20	4.60		
			Weighted mean††			1.62±0.02	

*Number of specimens.

†0.65×5% + 0.35×25%.

††Weighted according to thickness of section.

TABLE 5. Heat-flow summary, Hole PQ-8

Depth range m	Rock type(s)	Gradient °C/km	N*	Assumed porosity %	K (TCU)	Heat flow (HFU)	Estimated uncertainty (HFU)
274-366	Welded tuff	44.1±0.1	6	0	4.58±0.10		
				5	4.32		
				7.5	4.19	1.85	0.2
				10	4.07		
396-579	Conglomerate	30.83±0.07	12	0	8.01±0.10		
				20	5.65		
				25	5.18	1.60	0.2
				30	4.75		
594-625	Conglomerate	26.97±0.15	3	0	9.57±0.41		
				20	6.52		
				25	5.92	1.60	0.2
				30	5.38		
			Weighted mean†			1.68±0.08	

*Number of specimens.

†Weighted according to thickness of section.

TABLE 6. Heat-flow summary, Hole PQ-9

Depth range m	Rock type(s)	Gradient °C/km	N*	Assumed porosity %	K (TCU)	Heat flow (HFU)	Estimated uncertainty (HFU)
244-457	Sandstone	30.26±0.03	7	0	9.82±0.22		
				20	6.68		
				25	6.06	1.87	0.2
				30	5.58		
475-640	Granite wash	31.83±0.04	11	0	8.82±0.28		
				5	8.04		
				7.5	7.68	2.44	0.2
				10	7.34		
646-719	Tuff	47.08±0.12	9	0	6.23±0.39		
				5	5.79		
				7.5	5.58	2.63	0.3
				10	5.37		
747-899	70% Granite wash 30% Sandstone	33.08±0.06	9	0	8.25±0.15		
				8	7.16		
				12	6.67	2.21	0.25
				16	6.21		
914-1280	Tuff	55.28±0.05	12	0	4.30±0.10		
				5	4.07		
				7.5	3.95	2.18	0.25
				10	3.84		
1280-1402	Volcanic rocks	49.6±0.1	4	0	4.16±0.05		
				5	3.94	1.95	0.2
				10	3.73		
1463-1574	Granite, Granite wash	32.14±0.05	9	0	6.74±0.22		
				2.5	6.48	2.08	0.2
				5	6.23		
			Weighted mean†			2.19±0.08	

*Number of specimens.

†Weighted according to thickness of section.

BASEMENT RADIOACTIVITY

Holes PQ-3 and PQ-4 did not penetrate basement rocks. The other holes cut basement in the form of intrusive or metamorphic rocks, and we obtained radioactivity data from them (Table 1). Since we have only one sample from each hole, it is impossible to calculate a representative heat production. The only statement we can make is that the results from PQ-1 are within the range found typically for heat-flow - heat-production pairs in a "normal" Basin and Range setting (Lachenbruch and Sass, 1977). For PQ-8 and PQ-9, the single determinations of radioactivity seem anomalously high.

The Black Mountains and the Hualapai Mountains (Figure 1a) comprise Precambrian rocks of granitic, quartz monzonitic, and granitic gneiss, which have been shown to have relatively high counts in thorium and uranium (Malan and Sterling, 1969). It is probable that the granitic rock at the bottom of PQ-9 is the same as that found in the Black and Hualapai ranges, accounting for the abnormally high heat production measured in that hole (Table 1).

The high heat production measured in PQ-8 is not as easily explained. Recently Shakelford (1980) has shown that the Rawhide Mountains, southeast of PQ-8, are composed predominantly of Mesozoic-early Tertiary(?) mylonitic gneisses and are part of a much larger structural terrane covering parts of western Arizona and southeastern California. This metamorphic complex grades from middle greenschist to lower amphibolite facies. It is structurally overlain by an allochthonous assemblage of Precambrian through Miocene upper-plate rocks, which were tectonically emplaced in the interval 16 to 13-10 m.y.B.P. (Scarborough and Wilt, 1979).

Coney and Reynolds (1980) reported that exposed rocks of these metamorphic complexes in Arizona overall do not appear to be anomalously radioactive, except for (1) an anomaly associated with an upper bounding low-angle fault in the general Tucson area, and (2) a fault-related anomaly (the Blue Smoke claim) mentioned below.

Surface evidence of anomalously radioactive crystalline rocks in the region of PQ-8 is found at several former uranium mines. One mine that shipped a small amount of uranium ore is located about 22 km east of PQ-8. The Cheryl M #1 mine has a maximum radioactivity 20 times background. The mine produced 29 tons of uranium ore (0.01% U_3O_8) in 1958. Scarborough (1981, p. 205) reported that the "ore was apparently in granite or schist. Radioactive hematized quartz veins reportedly intrude foliated granite-gneiss." About 4 km north-northeast of that mine, the Blue Smoke claim has a maximum radioactivity 10 times background. "Radioactivity (is) associated with a klippe of Jurassic or Precambrian granite above a low-angle east-dipping fault or detachment zone" (Scarborough, 1981, p. 203). Ten kilometers west of PQ-8 at the Triple H claims, "uraninite is disseminated in Precambrian gneiss" (Scarborough, 1981, p. 214). Maximum radioactivity at the Triple H claims was not reported, but analyses indicate ore grades of 0.85% e U_3O_8 and 0.77% U_3O_8.

We suggest that the chlorite schist found at the bottom of PQ-8 may be related in some way to these areas of anomalous radioactivity, or the schist may have been in part derived from the radioactive Precambrian granitic rocks found in this region.

R. Scarborough (personal communication, 1981) suggested that radioactive Miocene sediments could be located beneath stacked Precambrian schist in the region of PQ-8, adding to the anomalous heat production measured in that hole. He also stated that the high heat production could be Laramide in age rather than Precambrian. Laramide vein systems with anomalous uranium are known at the Bagdad mine and Mineral Park mine areas, Yavapai County.

SUMMARY AND CONCLUSIONS

Five holes drilled in the sedimentary basins of west-central Arizona for the evaluation of their uranium potential all have primarily conductive thermal regimes as evidenced by the equilibrium temperature profiles (Figures 2 through 6). With some minor perturbations over short vertical distances, variations in temperature gradients correlate very well with lithologic changes and hence, variations in thermal conductivity.

Thermal conductivity measurements were made mostly on samples of drill cuttings. Plausible ranges of in situ porosity were estimated from measurements on a limited number of core samples (Table A-1). The conductivity of the solid component was combined with porosity estimates of varying uncertainties (depending on the lithology) to provide reasonably well-constrained values of thermal conductivity (Tables 2 through 6) for each lithologic unit. These conductivities were, in turn, combined with the appropriate least-squares thermal gradients to produce estimates of heat flow. Component heat flows within individual holes generally were in good agreement, confirming that the thermal regimes are indeed conductive. The range of heat flows (1.6 to 2.2 HFU) measured within this area in these deep wells generally coincides with the range of values from a larger group (∿25) of shallower (∿100-200 m) wells in the same region (cf., Figure 1a, this paper, and Figure 1, Lachenbruch and Sass, 1981). This is a gratifying result in that it lends confidence to our shallow heat-flow measurements.

Three of the wells penetrated basement rocks. Unfortunately, with only one sample from each, our rather fragmentary data on radiogenic heat production are inconclusive.

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APPENDIX: Individual Determinations of Porosity and Thermal Conductivity

Laboratory determinations of apparent porosity and thermal conductivity are presented in the following tables. Inasmuch as we have not had the opportunity to make more than a cursory examination of the samples, we have followed the nomenclature of the wellsite geologists.

Porosity. The determinations of apparent porosity listed in Table A-1 were made on cylindrical core specimens. In cgs units, they are determined simply as

$$\frac{\text{saturated weight - dry weight}}{\text{volume}} \times 100$$

Unfortunately, no core samples were available for the most abundant lithologic unit, the sandstone-siltstone intervals, and no cuttings samples of size sufficient to estimate porosity were available. Our primary source of information on porosities of sandstone and alluvium was based on assuming conductive heat flow in hole PQ-3 (Table 3 and Figure 3) and "backing out" porosities for sandstone, shale, and alluvium, based on the well constrained heat flow of 1.90 from the basalt/andesite section in the lowermost part of the hole, and the conductive assumption. The value of 20% to 25% so derived yielded plausible and consistent estimates of heat flow in sandstone or siltstone intervals from the other four holes. It was difficult to estimate porosity for conglomerates because of the large size of lithic fragments contained in them; however, their mineralogy was similar to the sandstones, and the texture of fine-grained cuttings samples and drilling rates support the value of 25% adopted for their porosity.

Thermal conductivity. Conductivity values are listed individually in Tables A-2 through A-6. All measurements were made on a Birch (1950)-type divided-bar apparatus (see Sass and others, 1971b). The primary measurement is that on chips following Sass and others (1971a). Where suitable specimens could be prepared from the cores, disks were prepared and conductivity measurements were made, thus obviating the necessity for estimates of porosity. The latter measurements are flagged by a superscript "s" in the tables. In general, they are in good agreement with the chip measurements when porosity is taken into account.

TABLE A-1. Apparent porosities of core samples from NURE holes

Hole	Depth (m)	Rock	Apparent porosity, %
PQ-1	712.3	Granite wash	10.7
	712.5	Granite wash	2.2
	713.0	Granite wash	7.6
	713.2	Granite wash	6.8
	713.7	Granite wash	7.9
	713.9	Granite wash	8.1
	714.4	Granite wash	8.9
	714.6	Granite wash	10.6
	714.8	Granite wash	8.9
	714.9	Granite wash	7.0
	715.1	Granite wash	11.4
	715.2	Granite wash	12.6
	715.4	Granite wash	13.7
	715.4	Granite wash	1.1
	897.9	Plutonic rock	0.1
PQ-3	1200	Basalt	4.8
	1201	Basalt	5.0
	1319	Andesite	1.9
	1320	Andesite	0.4
PQ-8	741	Greenschist	0.2
	744	Greenschist	0.5
PQ-9	1292.4	Welded tuff	9.7
	1294	Welded tuff	5.5
	1582	Granite	0.7

TABLE A-2. Thermal conductivities from Hole PQ-1

Depth range (m)	Rock	K* tcu	K* SI
76.2- 79.2	Sandstone	10.52	4.40
88.3- 91.4	Sandstone	9.52	3.98
100.6- 103.6	Sandstone	7.69	3.22
112.8- 115.8	Sandstone	8.80	3.68
121.9- 125.0	Sandstone	8.98	3.76
137.2- 140.2	Siltstone with some sandstone	8.95	3.75
149.4- 152.4	Siltstone with some sandstone	8.90	3.72
161.5- 164.6	Sandstone	8.93	3.74
173.7- 176.8	Sandstone	9.68	4.05
185.9- 189.0	Sandstone	9.54	3.99
198.1- 201.2	Sandstone	8.63	3.61
274.3- 277.4	Volcanics	4.73	1.98
277.4- 280.4	Volcanics	4.93	2.06
280.4- 283.5	Volcanics	4.84	2.02
283.5- 286.5	Volcanics	5.22	2.19
289.6- 292.6	Volcanics	7.03	2.94
292.6- 295.7	Volcanics with some sandstone	7.64	3.20
457.2- 460.2	Siltstone	3.11	1.30
460.2- 463.3	Siltstone	3.44	1.44
463.3- 466.3	Siltstone	3.72	1.56
466.3- 469.4	Siltstone	3.77	1.58
469.4- 472.4	Siltstone	4.33	1.81
472.4- 475.5	Siltstone	5.17	2.16

TABLE A-2. Thermal conductivities from Hole PQ-1 (continued)

Depth range (m)	Rock	K*	
		tcu	SI
475.5- 478.5	Siltstone	5.92	2.48
478.5- 481.9	Siltstone	5.06	2.12
487.7- 490.7	Volcanics	4.29	1.80
521.2- 524.3	Volcanics	4.13	1.73
548.6- 551.7	Volcanics	4.41	1.84
579.1- 582.2	Volcanics	5.16	2.16
612.6- 615.7	Volcanics	4.60	1.92
640.1- 643.1	Volcanics	4.73	1.98
673.6- 676.7	Granite wash	6.94	2.90
701.0- 704.1	Granite wash	7.55	3.16
712.6	Granite wash	6.48	2.71
713.2	Granite wash	7.32	3.06
714.9	Granite wash	6.77	2.84
715.4	Granite wash	7.59	3.18^s
715.4	Granite wash	7.68	3.21
715.4	Granite wash	6.70	2.80^s
734.6- 737.6	Granite wash with some volcanics	7.46	3.12
762.0- 765.0	Granite wash with some volcanics	6.23	2.61
792.5- 795.5	Granite wash	7.53	3.15
823.0- 826.0	Granite wash with some volcanics	7.71	3.23
853.4- 856.5	Granite wash	7.73	3.24
887.0- 890.0	Granite wash	7.01	2.94

*Values with superscript s determined from discs prepared from core.

TABLE A-3. Thermal conductivities from Hole PQ-3

Depth range (m)	Rock	K* tcu	K* SI
128.0- 131.1	Alluvium	6.70	2.81
152.4- 155.4	Alluvium	6.84	2.86
195.1- 198.1	Alluvium	6.75	2.83
216.4- 219.5	Alluvium	6.81	2.85
246.9- 249.9	Sandstone	8.68	3.64
277.4- 280.4	Sandstone	7.03	2.94
304.8- 307.8	Sandstone	8.03	3.36
368.8- 371.9	Sandstone	8.54	3.58
371.9- 374.9	Sandstone	9.15	3.83
402.3- 405.4	Sandstone	8.26	3.46
432.8- 435.9	Sandstone	8.39	3.51
463.3	Sandstone	8.43	3.53
493.8	Sandstone	8.34	3.49
515.1- 518.2	Sandstone	8.66	3.62
554.7	Sandstone	8.63	3.61
585.2	Sandstone	8.75	3.66
615.7- 618.7	Sandstone	8.77	3.67
630.9- 634.0	Siltstone	8.37	3.50
646.2- 649.2	Siltstone	9.02	3.77
676.7- 679.7	Sandstone	9.11	3.81
707.1- 710.2	Sandstone	8.77	3.67
728.5- 731.5	Sandstone	7.82	3.27
762.0- 765.0	Sandstone	8.38	3.51

TABLE A-3. Thermal conductivities from Hole PQ-3 (continued)

Depth range (m)	Rock	K* tcu	K* SI
792.5- 795.5	Sandstone	6.66	2.79
826.0- 829.1	Sandstone	7.78	3.26
853.4- 856.5	Sandstone	7.57	3.17
883.9- 887.0	Sandstone	8.35	3.50
914.4- 917.4	Sandstone	7.71	3.23
947.9- 951.0	Sandstone	8.47	3.55
975.4- 978.4	Sandstone	8.08	3.38
1005.8-1008.9	Sandstone	8.39	3.51
1036.3-1039.4	Sandstone	8.30	3.48
1066.8-1069.8	Sandstone	7.08	2.96
1097.3-1100.3	Sandstone	7.63	3.19
1109.5-1112.5	Siltstone	7.08	2.96
1115.6-1118.6	Shale	6.21	2.60
1121.7-1124.7	Shale	5.89	2.47
1127.8-1130.8	Shale	5.33	2.23
1136.9-1140.0	Siltstone with some sandstone	6.81	2.85
1194.8-1197.9	Chert with some basalt	7.13	2.98
1199.1-1200.3	Chert with some basalt	4.29	1.80^s
1201.2-1201.5	Basalt	4.43	1.86^s
1200.9-1204.0	Basalt	5.66	2.37
1219.2-1222.2	Basalt	5.44	2.28
1231.4-1234.4	Basalt	5.82	2.44

TABLE A-3. Thermal conductivities from Hole PQ-3 (continued)

Depth range (m)	Rock	K*	
		tcu	SI
1240.5-1243.6	Basalt	5.17	2.16
1252.7-1255.8	Basalt	5.96	2.49
1264.9-1268.0	Basalt	5.06	2.12
1280.2-1283.2	Basalt	6.13	2.57
1292.4-1295.4	Basalt	5.83	2.44
1304.5-1307.6	Basalt	5.57	2.33
1316.7-1320.7	Basalt	5.68	2.38
1318.6-1319.5	Basalt	5.05	2.11^{s}
1319.5-1320.7	Basalt	4.92	2.06^{s}

*Values with superscript s determined from discs prepared from core.

TABLE A-4. Thermal conductivities from Hole PQ-4

Depth range (m)	Rock	K* tcu	K* SI
228.6- 231.6	Sandstone	8.45	3.54
240.8- 243.8	Volcanics with some sandstone	6.68	2.80
253.0- 256.0	Volcanics	5.33	2.23
265.2- 268.2	Volcanics	5.66	2.37
277.4- 280.4	Volcanics	4.95	2.07
289.6- 292.6	Volcanics	4.96	2.08
301.8- 304.8	Volcanics	4.84	2.02
313.9- 317.0	Volcanics	5.40	2.26
341.4- 344.4	Sandstone with some volcanics	5.45	2.28
371.9- 374.9	Sandstone with some volcanics	5.56	2.33
402.3- 405.4	Volcanics	4.30	1.80
432.8- 435.9	Volcanics	4.51	1.89
463.3- 466.3	Volcanics	4.12	1.72
490.7- 493.8	Volcanics with some sandstone	4.45	1.86
524.3- 527.3	Sandstone with some volcanics	4.96	2.08
554.7- 557.8	Sandstone with some volcanics	4.33	1.81
585.2- 588.3	Volcanics with some sandstone and claystone	5.05	2.11
615.7- 618.7	Volcanics with some sandstone and claystone	4.12	1.72

TABLE A-4. Thermal conductivities from Hole PQ-4 (continued)

Depth range (m)	Rock	K*	
		tcu	SI
646.2- 649.2	Volcanics	4.18	1.75
676.7- 679.7	Volcanics	4.43	1.85
707.1- 710.2	Volcanics	4.34	1.82
737.6- 740.7	Volcanics	4.42	1.85
768.1- 771.1	Volcanics	4.72	1.98
798.6- 801.6	Volcanics	6.20	2.59
829.1- 832.1	Volcanics	4.58	1.92
859.5- 862.6	Volcanics	4.45	1.86
890.0- 893.1	Volcanics	3.93	1.64
920.5- 923.5	Volcanics	4.19	1.75
951.0- 954.0	Volcanics	4.19	1.75
981.5- 984.5	Volcanics	4.28	1.79
1042.4-1045.5	Volcanics	4.54	1.90
1072.9-1075.9	Volcanics	4.52	1.89
1103.4-1106.4	Volcanics	4.45	1.86
1133.9-1136.9	Volcanics with some claystone	5.53	2.31
1164.3-1167.4	Claystone	5.29	2.21
1194.8-1197.9	Volcanics with some claystone	4.34	1.82
1225.3-1228.3	Claystone with some volcanics	5.59	2.34
1255.8-1258.8	Volcanics with some claystone	5.70	2.39
1286.3-1289.3	Volcanics	5.35	2.24

TABLE A-4. Thermal conductivities from Hole PQ-4 (continued)

Depth range (m)	Rock	K* tcu	K* SI
1316.7-1319.8	Volcanics	5.59	2.34
1377.7-1380.7	Volcanics	6.11	2.56
1408.2-1411.2	Volcanics	6.20	2.60
1438.7-1441.7	Granite wash	7.98	3.34
1499.6-1502.7	Volcanics	5.62	2.35
1560.6-1563.6	Volcanics	5.85	2.45
1578.9	Volcanics with some metamorphism	7.40	3.10
1585.0-1588.0	Volcanics with some metamorphism	6.17	2.58
1621.5-1624.6	Volcanics	6.22	2.60
1652.0-1655.1	Volcanics	6.17	2.58

TABLE A-5. Thermal conductivities from hole PQ-8

Depth range (m)	Rock	K* tcu	K* SI
85.3- 88.4	Conglomerate	7.25	3.03
97.5- 100.6	Conglomerate	7.59	3.18
109.7- 112.8	Conglomerate	7.67	3.21
121.9- 125.0	Conglomerate	7.92	3.32
134.1- 137.2	Conglomerate	7.57	3.17
146.3- 149.4	Conglomerate with some sandstone	7.74	3.24
158.5- 161.5	Sandstone	8.02	3.36
170.6- 173.7	Sandstone	7.78	3.26
182.9- 185.9	Sandstone with some conglomerate	7.77	3.25
195.1- 198.1	Conglomerate with some sandstone	8.01	3.36
320.0- 323.1	Welded tuff	4.89	2.05
335.3- 338.3	Welded tuff	4.78	2.00
347.5- 350.5	Welded tuff	4.47	1.87
359.7- 362.7	Welded tuff	4.51	1.89
371.9- 374.9	Welded tuff	4.24	1.78
384.0- 387.1	Welded tuff	4.66	1.95
396.2- 399.3	Conglomerate	8.30	3.47
411.5- 414.5	Conglomerate	7.65	3.20
426.7- 429.8	Conglomerate	8.01	3.35
442.0- 445.0	Conglomerate	8.42	3.52
457.2- 460.2	Conglomerate	8.56	3.58
472.4- 475.5	Conglomerate	7.98	3.34

TABLE A-5. Thermal conductivities from Hole PQ-8 (continued)

Depth range (m)	Rock	K*	
		tcu	SI
487.7- 490.7	Conglomerate	8.58	3.59
518.2- 521.2	Conglomerate	7.96	3.33
533.4- 536.4	Conglomerate	7.57	3.17
548.6- 551.7	Conglomerate	7.76	3.25
563.9- 566.9	Conglomerate	7.91	3.31
579.1- 582.2	Conglomerate	7.65	3.20
594.4- 597.4	Conglomerate	9.64	4.03
609.6- 612.6	Conglomerate	10.30	4.31
624.8- 627.9	Greenschist	8.88	3.72
711.4	Greenschist	5.78	2.42[s]
731.5- 734.6	Greenschist	7.90	3.31
734.4- 744.3	Greenschist	5.80	2.43[s]

*Values with superscript s determined from discs prepared from core.

TABLE A-6. Thermal conductivities from Hole PQ-9

Depth range (m)	Rock	K* tcu	K* SI
70.1- 73.1	Sandstone	9.23	3.86
97.5- 100.6	Sandstone	9.87	4.13
125.0- 128.0	Sandstone	9.82	4.11
158.5- 161.5	Sandstone	9.80	4.10
182.9- 185.9	Sandstone	9.88	4.14
219.4- 222.5	Sandstone	10.80	4.52
246.9- 250.0	Sandstone	9.99	4.10
277.4- 280.4	Sandstone	10.49	4.39
304.8- 307.8	Sandstone	10.10	4.23
335.3- 338.3	Sandstone	10.35	4.33
365.8- 368.8	Sandstone	8.90	3.73
399.3- 402.3	Sandstone	9.29	3.89
429.8- 432.8	Sandstone	9.80	4.10
460.2- 463.3	Granite wash	9.43	3.95
487.7- 490.7	Granite wash	9.06	3.79
518.2- 521.2	Sandstone	8.95	3.75
548.6- 551.7	Granite wash	9.39	3.93
582.2- 585.2	Granite wash	9.45	3.95
603.5- 606.6	Granite wash	9.05	3.79
604.7- 605.6	Granite wash	7.63	3.19
605.6- 606.6	Granite wash	7.04	2.95
606.6- 609.6	Granite wash	8.92	3.73
618.7- 621.8	Tuff	9.58	4.01

TABLE A-6. Thermal conductivities from Hole PQ-9 (continued)

Depth range (m)	Rock	K* tcu	K* SI
640.1- 643.1	Granite wash	9.42	3.94
649.2- 652.3	Tuff	5.99	2.51
658.4- 661.4	Tuff	5.91	2.47
667.5- 670.6	Volcanics with some tuff	6.54	2.74
676.7- 679.7	Welded tuff	6.34	2.65
685.8- 688.8	Welded tuff	4.93	2.06
691.9- 694.9	Welded tuff	8.81	3.69
694.9- 698.0	Welded tuff	5.93	2.48
704.1- 707.1	Sandstone	8.58	3.59
713.2- 716.3	Welded tuff	5.13	2.15
731.5- 734.6	Granite wash	8.01	3.35
740.7- 743.7	Granite wash	8.36	3.50
749.8- 752.9	Granite wash	7.93	3.32
765.0- 768.1	Granite wash	8.20	3.43
792.5- 795.5	Granite wash with some sandstone	8.73	3.65
823.0- 826.0	Granite wash with some sandstone	8.72	3.65
853.4- 856.5	Granite wash with some sandstone	8.66	3.62
887.0- 890.0	Granite wash with some sandstone	8.41	3.52
897.9	Granite wash with some sandstone	7.41	3.10[s]
944.9- 947.9	Welded tuff	5.34	2.23

TABLE A-6. Thermal conductivities from Hole PQ-9 (continued)

Depth range (m)	Rock	K* tcu	K* SI
978.4- 981.5	Tuff	4.42	1.85
1008.9-1011.9	Tuff	4.22	1.77
1039.4-1042.4	Tuff	4.36	1.83
1069.8-1072.9	Tuff	3.93	1.64
1100.3-1103.4	Tuff	4.33	1.81
1136.9-1140.0	Tuff	3.95	1.65
1161.3-1164.3	Tuff	4.67	1.95
1191.8-1194.8	Tuff	3.94	1.65
1222.2-1225.3	Tuff	4.15	1.74
1252.7-1255.8	Tuff	4.38	1.83
1283.2-1286.3	Volcanic flow	4.27	1.79
1292.4	Pyroclastic flow	3.44	1.44^s
1293.9	Pyroclastic flow	3.71	1.55^s
1313.7-1316.7	Volcanic flow	4.04	1.69
1344.2-1347.2	Volcanic flow	4.11	1.72
1374.6-1377.7	Volcanic flow	4.25	1.78
1405.1-1408.2	Volcanic flow	4.26	1.78
1435.6-1438.7	Sandstone with some volcanic flow	8.02	3.36
1466.1-1469.1	Granite wash	6.11	2.56
1475.2-1478.3	Granite wash	6.14	2.57
1484.4-1487.4	Granite wash	6.17	2.58
1493.5-1496.6	Granite wash	6.46	2.70
1505.7-1508.8	Granite wash with some volcanic flow	6.82	2.86

TABLE A-6. Thermal conductivities from Hole PQ-9 (continued)

Depth range (m)	Rock	K* tcu	K* SI
1514.9-1517.9	Granite wash	6.53	2.74
1527.1-1530.1	Granite wash	7.13	2.98
1581.0-1584.0	Granite	7.86	3.29^{s}

*Values with superscript s determined from discs prepared from core.