A-41

United States Department of the Interior

Geological Survey

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

by

J. H. Sass, Robert J. Munroe, and Claudia Stone[†]

U.S. Geological Survey Open-File Report 81-1089

1981

[†] State of Arizona, Bureau of Geology and Mineral Technology, Geological Survey Branch, Tucson, Arizona 85719

Contents

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

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.

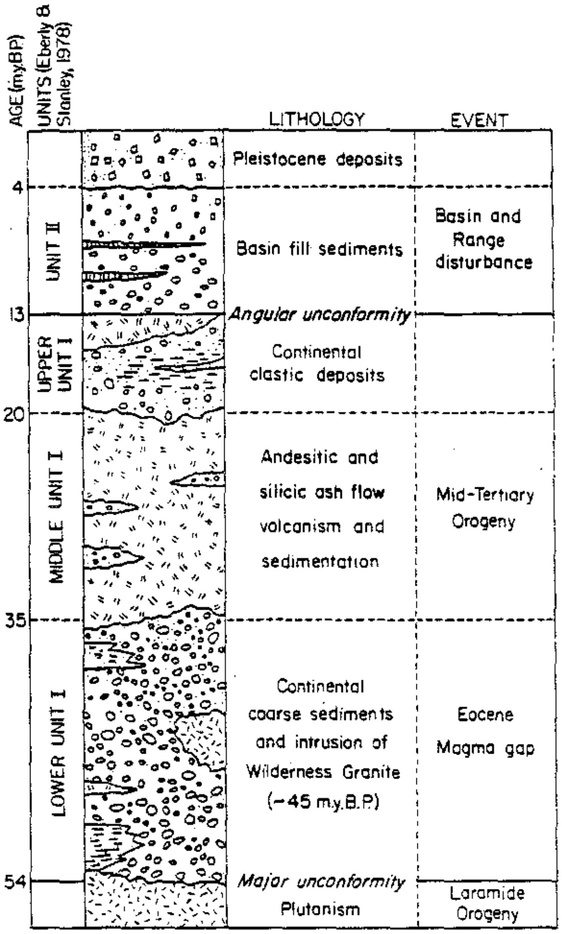

Figure 1b. Generalized stratigraphic column for west-central Arizona.

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

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.

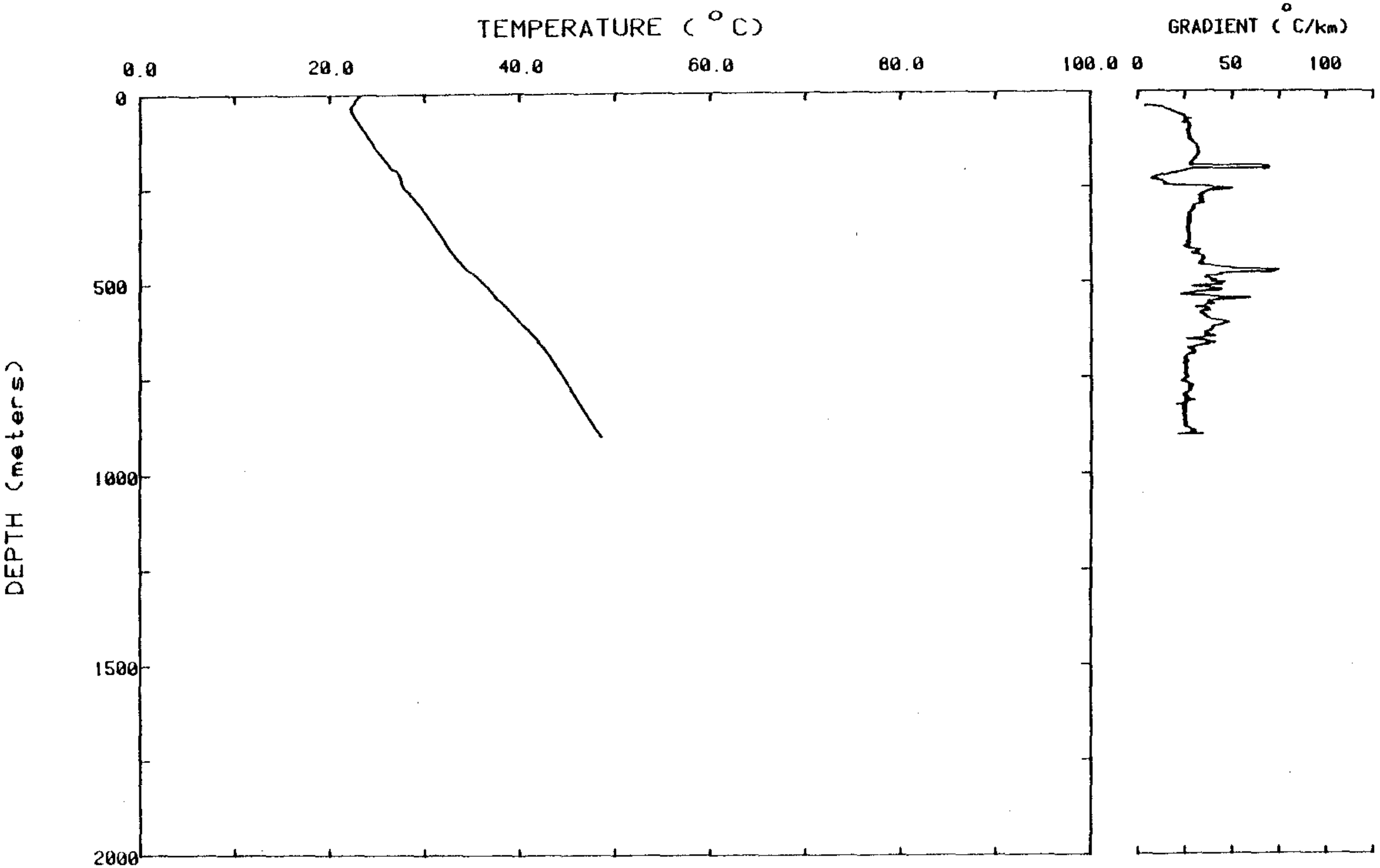

Figure 2. Temperatures and gradients (sliding average over 10 m), Hole PQ-1.

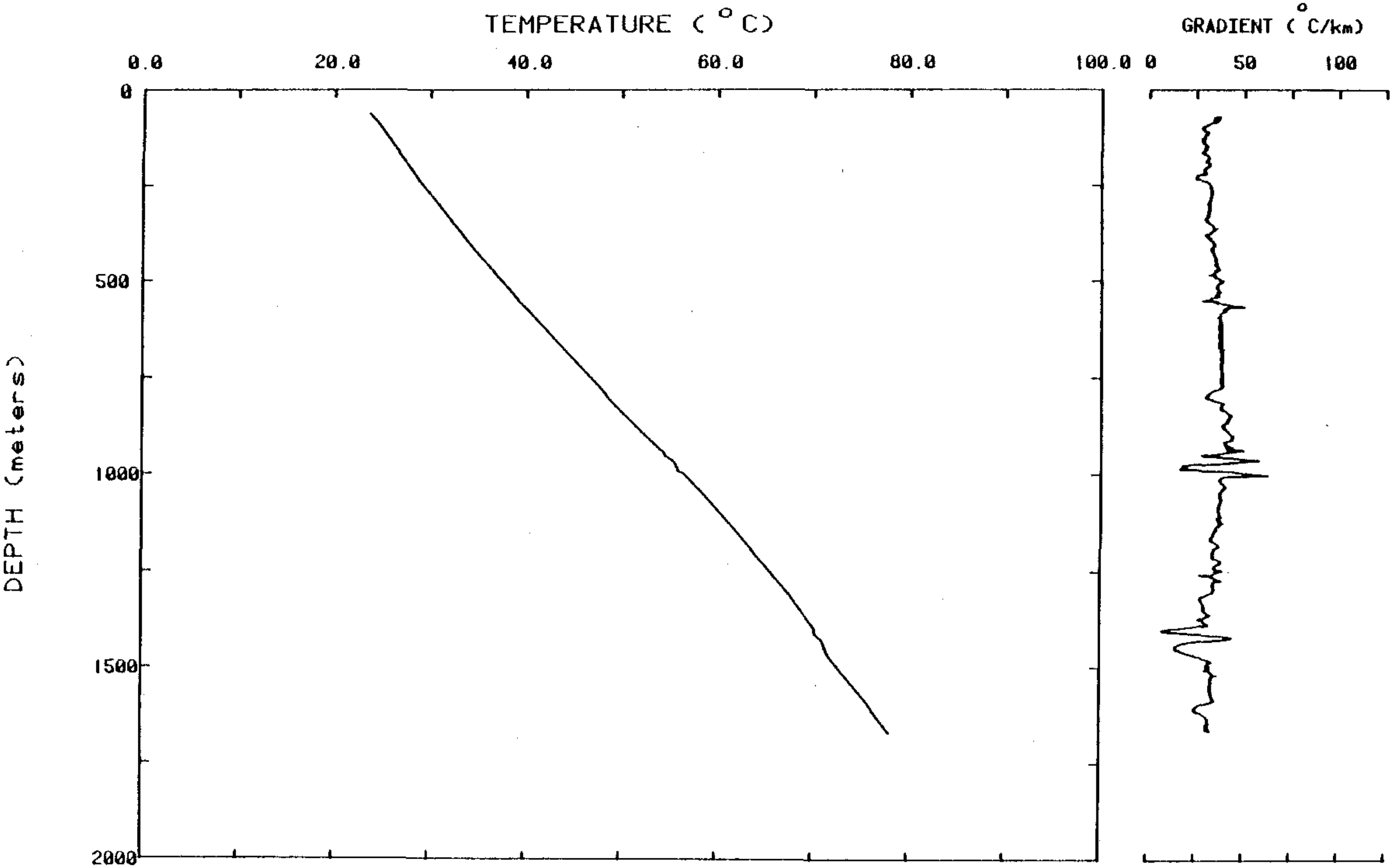

Figure 4. Temperatures and gradients (sliding average over 10 m), Hole PQ-4.

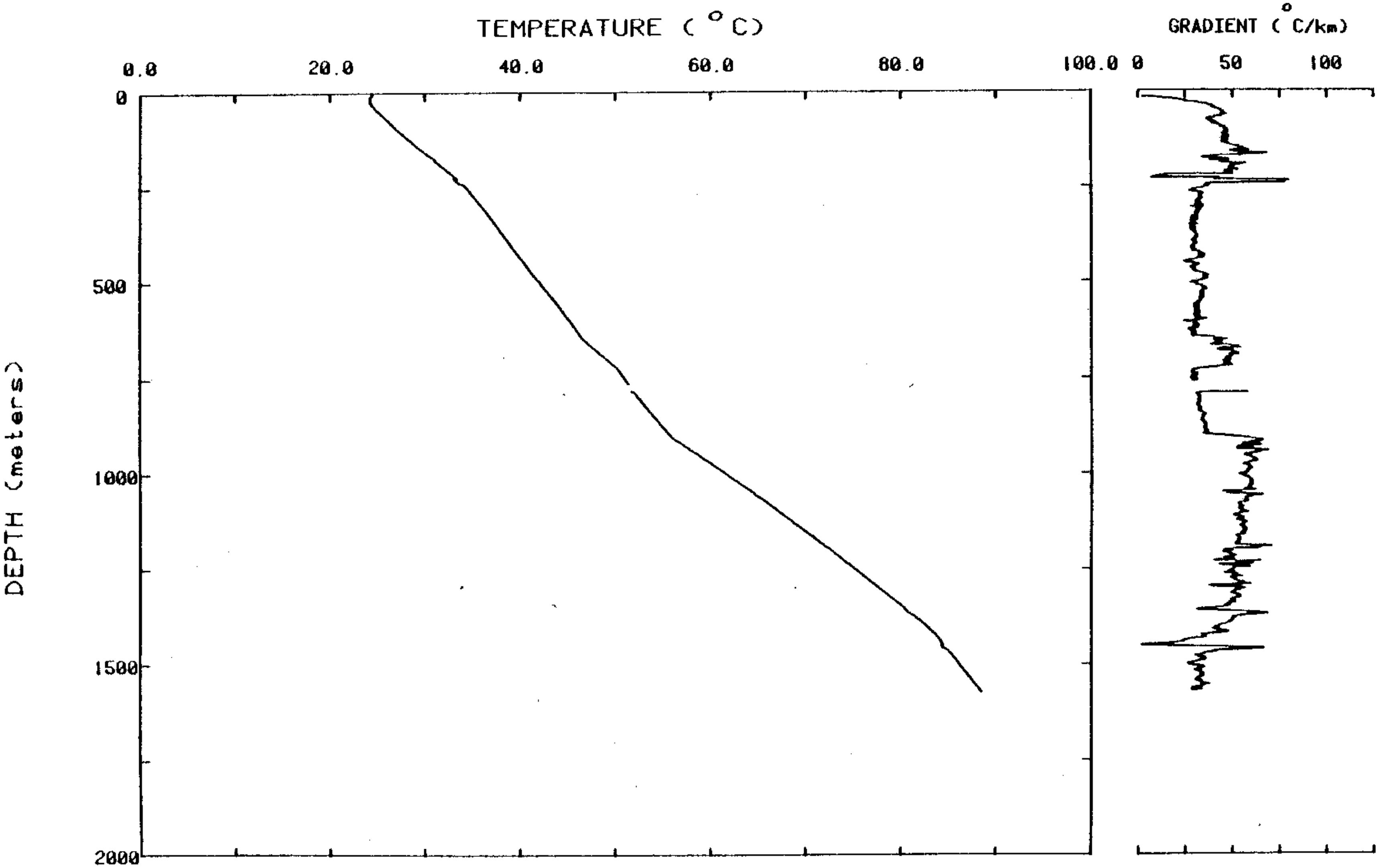

Figure 6. Temperatures and gradients (sliding average over 10 m), Hole PQ-9.

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 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	1.91	0.2
				20	4.94		
				25	4.57		
				30	4.22		
244-427	Sandstone	35.74±0.07	7	0	8.25±0.27	1.89	0.2
				20	5.79		
				25	5.30		
				30	4.85		
579-1097	Sandstone	33.25±0.01	19	0	8.11±0.16	1.90	0.2
				15	6.23		
				20	5.71		
				25	5.23		
1116-1131	Shale	41.6±0.3	3	0	5.79±0.26	1.95	0.2
				10	5.02		
				15	4.68		
				20	4.36		
1189-1317	Basalt/Andesite	36.39±0.03	10	0	5.61±0.11	1.90	0.1
				5	5.23		
				10	4.88		
			Weighted mean†			1.90±0.004	

*Number of samples.

†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.

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.

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.

Sass, J. H., Lachenbruch, A. H., Munroe, R. J., Greene, G. W., and Moses, T. H., Jr., 1971b, Heat flow in the western United States: Journal of Geophysical Research, v. 76, p. 6376-6413.

Scarborough, R., 1981, Radioactive occurrences and uranium production in Arizona: DOE Open-File Report GJBX-143(81), 297 p.

Scarborough, R. B., and Peirce, H. W., 1978, Late Cenozoic basins of Arizona: New Mexico Geological Society Guidebook No. 29, Land of Cochise, p. 253-259.

Scarborough, R., and Wilt, J. C., 1979, A study of uranium favorability of Cenozoic sedimentary rocks, Basin and Range province, Arizona: U.S. Geological Survey Open-File Report 79-1429, 101 p.

Shafiqullah, M., Damon, P. E., Lynch, D. J., Reynolds, S. J., Rehrig, W. A., and Raymond, R. H., 1980, K-ar geochronology and geologic history of southwestern Arizona and adjacent areas: Arizona Geological Society Digest, v. 12, Studies in Western Arizona, p. 201-260.

Shakelford, T. J., 1980, Tertiary tectonic denudation of a Mesozoic-early Tertiary(?) gneiss complex, Rawhide Mountains, western Arizona: Geology, v. 8, no. 4, p. 190-194.

Shearer, C. R., and Reiter, Marshall, 1981, Terrestrial heat flow in Arizona: Journal of Geophysical Research, v. 86, p. 6249-6260.

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 (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 (continued)

Depth range (m)	Rock	K*	
		tcu	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-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
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 (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 (continued)

Depth range (m)	Rock	K*	
		tcu	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
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.