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Terrestrial Heat Flow in Eastern Arizona,

A First Report

by

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Abstract

Twelve heat flow measurements are presented for eastern Arizona and neighboring areas. From these measurements the following geothermal conditions within the region are suggested: (1) in the Safford Valley, complex hydrothermal phenomena at depth interact with faults to the surface to produce the observed hot spring activity, (2) in the mountains to the north of the Safford Valley the heat flow is estimated to be 1.9 HFU, (3) high heat flows (≥ 2.5 HFU) are observed 100 km into the southern Colorado Plateau, within the Mogollon Slope, and seem to relate to the sources of extensive Quaternary volcanics, (4) the heat flow for the Black Mesa Basin which encompasses much of the southwestern Colorado Plateau is estimated between 1.7 HFU and 1.8 HFU and therefore suggests relatively hot crustal and mantle temperatures.

Introduction

Arizona is divided between two major geologic provinces, the Colorado Plateau in the northeastern half of the state and the Basin and Range in the southwestern half. Wilson and Moore (1959) suggest a Transition Zone between the two provinces running from southeast to northwest. This Transition Zone varies in width, narrowing to the northwest so that near Kingman, Arizona, the boundary between the Colorado Plateau and the Basin and Range becomes very sharp.

The Colorado Plateau is an elevated crustal block with large structural basins and broad uplifts separated by monoclinal flexures. As compared to the Basin and Range, the Colorado Plateau appears to demonstrate large scale lithologic continuity; however, a number of igneous dikes and laccolithic intrusives are noted (Eardley, 1962). Roller (1965) determines a crustal thickness of 43 km and a P_n velocity of 7.8 km/sec in northeast Arizona near Chinle. Warren (1969) reports a flat M-discontinuity at 40 km depth under the Mogollon Slope in the southern Colorado Plateau with a P_n velocity of 7.85 km/sec. Published heat flow values for the Colorado Plateau (Roy and others, 1968; Decker, 1969; Sass and others, 1971; Costain and Wright, 1973; Reiter and others, 1975) indicate that most reliable data are greater than 1.5 HFU. Reiter and others (1975) suggest variations in heat flow between major basins and uplifts within the Colorado Plateau.

In contrast to the Colorado Plateau the Basin and Range is structurally complex, locally faulted and fractured with alternating individual mountain ranges and valleys. These ranges are defined by high-angle faults (Eardley, 1962) and in general trend northerly in southeast Arizona and northwesterly in central and southwest Arizona. The Basin and Range has been subjected to widespread and almost continuous volcanic activity in mid-Tertiary and Quaternary times. Warren (1969) reports a steady increase in the depth to the M-discontinuity, from 21 km to 40 km, along a line northeast from Gila Bend, Arizona, to the Mogollon Rim. The P_n velocity along this profile is 7.85 km/sec (Warren, 1969). The Basin and Range is generally considered a region of high heat flow although heat flow values vary greatly (Roy and others, 1968; Warren and others, 1969; Sass and others, 1971).

The Transition Zone, as suggested by Wilson and Moore (1959), includes the extensive Tertiary White Mountains volcanic field in east-central Arizona which adjoins the immense Tertiary Datil volcanic field in west-central New Mexico (Figure 1). These two volcanic fields cover approximately 50,000 sq km (Ratté and others, 1969). The volume of the Datil field alone is about 10,000 cu km and is spread over an area of about 18,000 sq km (Elston and others, 1970).

Figure 1 shows new heat flow sites for this study located on a generalized geologic map of eastern Arizona and western New Mexico. Table I presents basic heat flow data from 15 new test sites, 12 of which yield A or B estimates of the heat flow. Heat flow estimates graded A, B, or C are believed representative to ±10%, ±20%, or greater than ±20%. The experimental procedure for these heat flow measurements and the evaluation criteria for the heat flow estimates are described in Reiter and others (1975).

Discussion

Safford Valley-Gila Mountains, Southeastern Arizona

Of the new heat flow values presented in this study, seven are located along or near the northeast boundary of the Safford Basin, southeastern Arizona (Table I, Figure I). The Safford Basin is a northwest-southeast trending structural trough within the Basin and Range Province, bounded on the northeast by the Gila and Peloncillo Mountains and on the southwest by the Pinaleno, Santa Teresa and Turnbull Mountains. Five heat flow sites are on the southwest flank of the Gila Mountains. These five values have an average heat flow of 1.8 HFU; the two best values are both 1.9 HFU. The sixth site, at the north end of the Peloncillo Mountains, has a heat flow of 2.1 HFU. A seventh site at Morenci, northeast of the Gila Mountains, has a heat flow value of 1.7 HFU.

Robinson and Cook (1966) suggest that the Gila Mountains have been subjected to basin-and-range faulting with possible displacements of 600 m. Lindgren (1905) describes the complex faulting of the Clifton-Morenci area, noting vertical throws of as much as 600 m. About 10 km south of Clifton, the Gillard Hot Springs has a reported temperature of 82°C while the Clifton Mineral Hot Springs Co. well in Clifton has a reported temperature of 54°C (Hem, 1950). Silica geotemperatures of 136°C and 97°C to 153°C are reported for the two areas respectively (Swanberg and others, 1977). Hem (1950) notes for the Clifton site that the high temperature and high mineralization of the water indicates the water comes from deep subsurface regions, moving along fault zones and entering the alluvium at the bottom of the San Francisco Canyon.

The heat flow value at Morenci (1.7 HFU) is somewhat below the Basin and Range average, and it would seem unreasonable to expect that this value is being increased by warm ground water. The values along the Gila Mountains average 1.8 HFU; the value at the north end of the Peloncillo Mountains is 2.1 HFU. The relative tightness of this data group from sites widely spread along the mountains northeast of the Safford Valley (1.8 HFU ±0.3 HFU) and the occurrence of hot springs in the area suggest that ground water is warmed at depth and moves upward along fracture zones producing only very local anomalies that our site locations appear to have avoided. However, the regional effects of ground water moving vertically may, as in most areas, influence geothermal gradients and create variations in the heat flow data.

The hydrothermal environment in the Safford Basin is as complicated as in the area to the northeast. Figure 2 shows the temperature log measured in a drill hole about 16 km east of Safford. The measured diffusive heat flow of 5.0 HFU above the zone of inverted gradient is in marked contrast to the measured diffusive heat flow of 1.2 HFU below the inversion. Although neither of these two values may be considered the diffusive heat flow for the area, the character of the temperature profile demonstrates the potential problems in measuring the diffusive heat flow in the basin.

Gerlach and others (1975) tabulate those wells and springs in the Safford Basin having temperatures of 32°C or greater. Most of these temperatures are reported between 32°C and 40°C. However, the Mack well, approximately 20 km northwest of Safford, has a reported water temperature of 59°C, and a series of springs about 27 km northwest of Safford has reported temperatures of 50°C. Hem (1950) suggests that the hot springs and wells in the area result from ground-water movement along faults in the Tertiary and Pleistocene valley fill deposits. Swanberg and others (1977) report silica geotemperatures as high as 116°C for waters in the Safford area.

Hem (1950) also reports that the Mack well was flowing at a rate of 1350 gpm in April 1942, when a temperature of 59°C was recorded for the flowing water, and that the total depth of the well was 1148 m. He records a mean annual air temperature of 17°C at nearby Thatcher, Arizona. From this information and the assumptions that the 59°C ground water came from the 1148 m depth and the well water flowed isothermally to the surface, it is possible to estimate a temperature gradient of about 36°C/km. This gradient combined with a thermal conductivity of 6.0 mcal/cm-sec-°C (based on the Mack well stratigraphic log; Gerlach and others, 1975) allows a heat flow estimate of about 2.2 HFU. The gradient of 36°C/km places a source for the water having a silica geotemperature of 116°C (Swanberg and others, 1977) at about 2.8 km depth.

However, the uncertainties in estimating heat flow and geothermal gradients in this area are well demonstrated by the temperature profile in Sol-5 (Figure 2). The high gradient in the upper part of the well, indicating high heat flow in the near surface, is inconsistent with a considerably lower gradient in the bottom of the well. The gradient inversion and the incompatibility of upper and lower heat flows suggest a complicated hydrothermal regime at depth in the area. Horizontal influx of heated water just above the negative gradient interval may or may not interact with a vertical convective ground-water regime at depth to yield the complicated temperature profile in the bottom half of the well and the elevated gradient in the upper half of the well.

South-Central Colorado Plateau

Seven new measurements within the Colorado Plateau are presented (Table 1, Figure 1). High heat flow values on the Mogollon Slope near Sanders, Arizona (2.6 HFU, 3.8 HFU), and Red Hill, New Mexico (2.5 HFU), contrast with lower values in and around the Black Mesa Basin (1.5 HFU, 1.7 HFU, 1.8 HFU) and at Page, Arizona (1.3 HFU).

The Mogollon Slope forms the southernmost region of the Colorado Plateau. It is bounded on the north by the Black Mesa Basin and the Defiance Uplift, on the east by the Zuni Uplift and the Zuni volcanic field, and on the south by the widespread volcanics of the White Mountains and Datil fields (Kelley, 1958). The primary characteristic of the Mogollon Slope is the gentle broad dip to the northeast, which is however disrupted by the high-angle Atarque fault, approximately 65 km in length and demonstrating 600 m of throw (Kelley, 1958). Large areas of the Mogollon Slope have experienced considerable Tertiary and Quaternary volcanic activity. Extensive basalt flows on the northeast part of the

Mogollon Slope are thought to be of Quaternary age (Hunt, 1956). To the south, the Datil eruptive cycles occurred throughout the Oligocene (Elston and others, 1970). The volcanics in the southwest part of the White Mountains and Datil volcanic fields are also principally Oligocene (Ratté and others, 1969). Kelley (1955) notes that during Pliocene time volcanic eruptions continued in the White Mountains and Datil fields along the margin of the Colorado Plateau. West of Springerville, Arizona, Quaternary basalts cover another large area of the Mogollon Slope (Wilson and others, 1960). The Red Hill heat flow site is within an area of extensive Quaternary basalt flows (Wilson and others, 1960; Willard and Weber, 1958) and volcanic eruptions of Pleistocene time are located 24 km north of the Red Hill site at the Zuni Salt Lake maar (Bradbury, 1971). Byerly and Stolt (1977) show a relatively shallow depth to the Curie point isotherm for the Mogollon Slope.

Heat flow data (this paper; Reiter and others, 1975) indicate a high heat flow region encompassing the eastern part of the Mogollon Slope. It seems likely that the high heat flow of this region is caused by the sources of the widespread Quaternary volcanic activity.

Three heat flow measurements are presented for sites in or near the Black Mesa Basin, a nearly circular downwarp some 145 km in diameter and characterized by low regional dips and shallow structural relief (Kelley, 1958). The

Basin is generally about 1800 m to 2100 m deep (Am. Assoc. Pet. Geol., 1967). Pliocene, low temperature, phreatic eruptions have occurred over an area of 2000 sq km in the southern part of the basin whereas no volcanic activity is observed elsewhere in the basin (Hack, 1942; Williams, 1936). The Black Mesa-Kaiparowitz synclinorium is the major structural feature of the southwestern Colorado Plateau.

Heat flows of 1.5 HFU, 1.8 HFU, and 1.7 HFU are estimated respectively in the southern part of the Black Mesa Basin (within a diatreme) and in the central and northern parts of the basin. The values of 1.7 HFU and 1.8 HFU are believed more representative of the Basin than the value of 1.5 HFU. The higher heat flow sites are deeper and present markedly different temperature gradients at different depth intervals which interface with measured and estimated thermal conductivity values to yield similar heat flow between different depth intervals. As always, deep measurements (several km) will be necessary to have a high confidence in the data.

The value at Page, Arizona, is believed unrepresentative of the area because ground-water movement is thought to be observed in the lower part of the well.

Conclusions

Temperature measurements in the Safford Valley (Sol-5) indicate complex hydrothermal phenomena. Although the true diffusive heat flow is unmeasurable in the depth intervals available, the appreciation obtained for the hydrological problems in the area is very important. The temperature profile in Sol-5 may demonstrate cellular convection below 850 m. Heated ground water moving horizontally from a distant thermal source may be present. Water moving vertically from depth along faults in the valley seems the probable explanation for the hot spring activity in the area. Deep measurements are necessary to further appreciate the geothermal phenomena in the area.

The heat flow values in the Gila Mountains, in the north end of the Peloncillo Mountains, and at Morenci, form a relatively tight data group and are near the average heat flow for the Basin and Range. The variance in the data suggests that the thermal gradients at these new sites are not being influenced very differently from site to site by warm ground-water movement along faults thought to produce the thermal springs in the area. Consequently the phenomena creating the thermal springs may have a very local effect. It is probable that the variations observed in the data are primarily controlled by ground-water movement not involved in the thermal springs systems. A heat flow of 1.9 HFU is estimated for this area; however, deeper measurements would permit a better evaluation of the heat flow with depth. The biasing of heat flow sites away from thermal anomalies in the area is quite possible.

High heat flow values (2.5 to 3.8 HFU) within the Mogollon Slope appear to be related to the sources of the Quaternary volcanics. The area of high heat flow extends into the Colorado Plateau for about 100 km. Unless upper crustal radioactivity is very high in the region, the heat flows observed imply partial melting in the crust. Helium production in the Sanders area may imply a high radiogenic heat production in the upper crust. It is always possible that temperature gradients will decrease at deeper depths as at site Sol-5.

Heat flow for the Black Mesa Basin is estimated at 1.7 to 1.8 HFU. Upper crustal radioactive heat generation must be measured before good estimates of crustal and mantle temperatures are possible; however, it appears that crustal and upper mantle temperatures for this area are similar to the average temperatures estimated for the crust and upper mantle of the Basin and Range when similar heat flows are measured (Lachenbruch, 1970; Roy and others, 1972).

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Captions for Figures

Figure 1. New heat flow sites in eastern Arizona and western New Mexico (◆from Reiter and others, 1975). "X" indicates sites where measured geothermal gradients are believed to be disturbed by regional or borehole water movement.

Figure 2. Temperature vs. depth profile for site Sol-5.

Caption for Table

Table 1. Basic heat flow data for sites presented in present study. Fragment samples corrected for porosity estimates. "+" means thermal conductivity value measured for the same formation from a well in the immediate vicinity; "*" means thermal conductivity value measured for the same formation but from a well at considerable distance (1 indicates thermal conductivity for the Wingate sandstone from Costain and Wright, 1973); "**" means thermal conductivity value estimated from consideration of lithologic description.

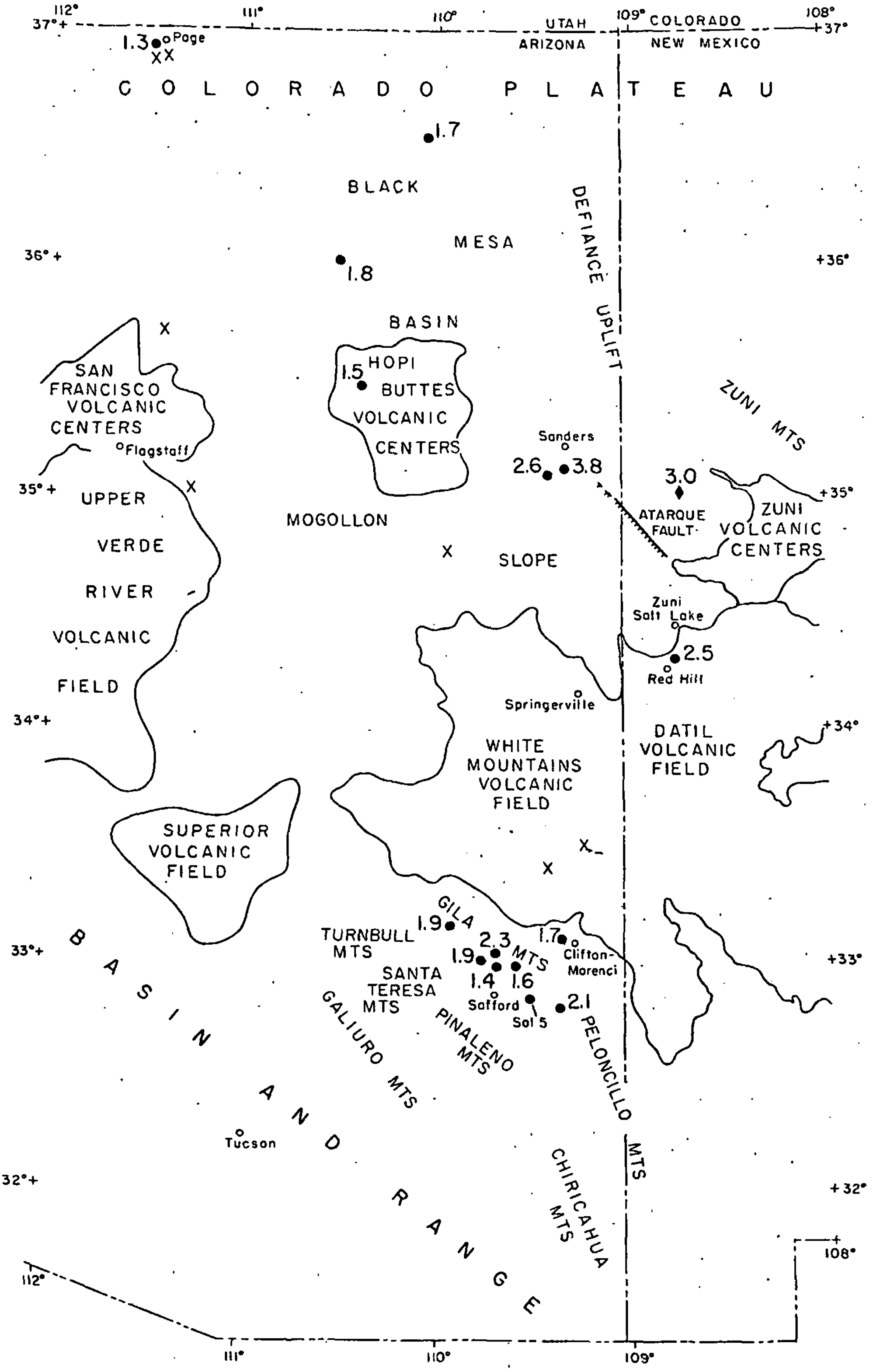
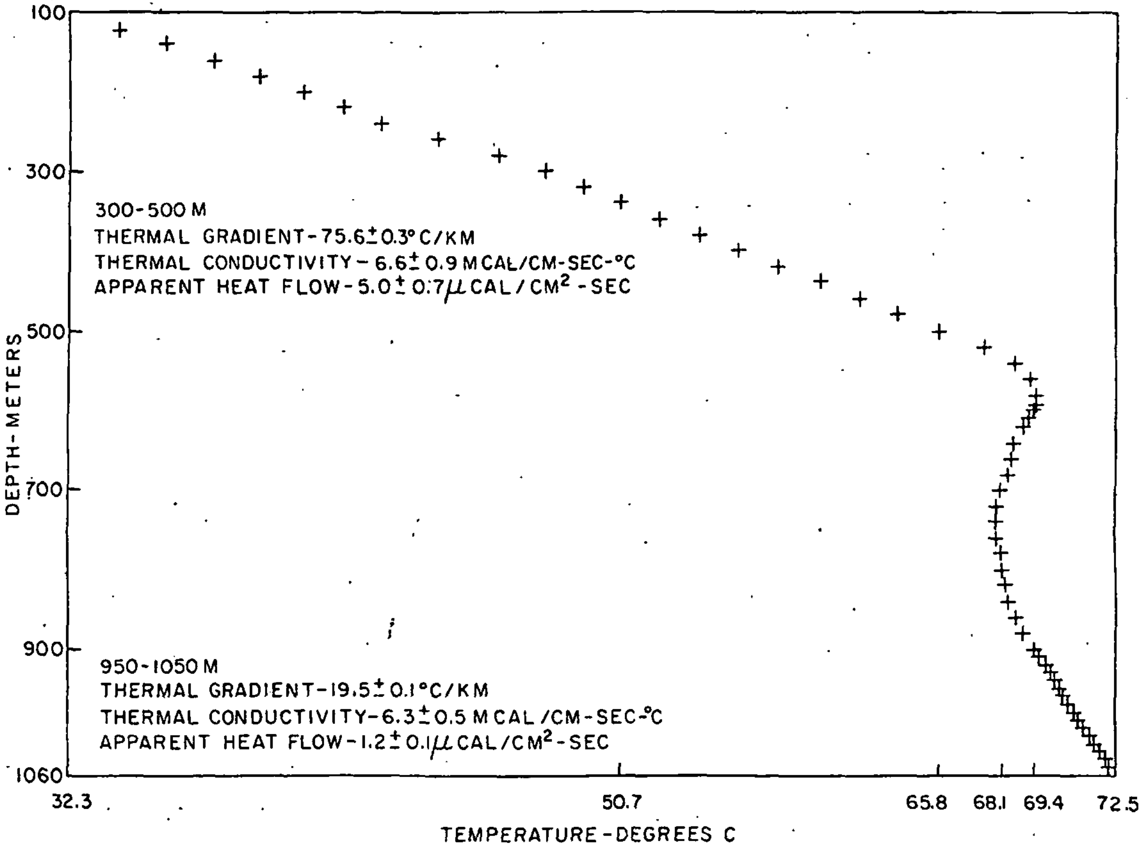

112°
111°
110°
109°
108°
37°
UTAH
ARIZONA
COLORADO
NEW MEXICO
1.3
Page
COLORADO PLATEAU
1.7
BLACK
MESA
BASIN
DEFIANCE UPLIFT
36°
1.8
SAN FRANCISCO VOLCANIC CENTERS
Flagstaff
1.5
HOPI BUTTES VOLCANIC CENTERS
ZUNI MTS
Sanders
2.6
3.8
3.0
35°
UPPER VERDE RIVER VOLCANIC FIELD
MOGOLLON
SLOPE
ATARQUE FAULT
ZUNI VOLCANIC CENTERS
Zuni Salt Lake
2.5
Red Hill
Springerville
34°
WHITE MOUNTAINS VOLCANIC FIELD
DATIL VOLCANIC FIELD
SUPERIOR VOLCANIC FIELD
GILA
1.9
TURNBULL MTS
2.3
1.9
MTS
1.7
Clifton-Morenci
33°
SANTA TERESA MTS
1.4
1.6
Safford
Sol 5
2.1
GALIURO MTS
PINALENO MTS
PELONCILLO MTS
BASIN AND RANGE
Tucson
32°
CHIRICAHUA MTS
108°
112°
111°
110°
109°

FIGURE 1

FIGURE 2


100
300
500
700
900
1060
DEPTH-METERS
300-500 M
THERMAL GRADIENT-75.6±0.3°C/KM
THERMAL CONDUCTIVITY-6.6±0.9 MCAL/CM-SEC-°C
APPARENT HEAT FLOW-5.0±0.7μCAL/CM² -SEC
950-1050 M
THERMAL GRADIENT-19.5±0.1°C/KM
THERMAL CONDUCTIVITY-6.3±0.5 MCAL/CM-SEC-°C
APPARENT HEAT FLOW-1.2±0.1μCAL/CM²-SEC
32.3
50.7
65.8
68.1
69.4
72.5
TEMPERATURE-DEGREES C

Locality	N. lat.	W. long.	Elev(m)	Depth Interval(m)	Thermal Gradient °C/km	No. of Samples	Type of Samples	Thermal Conductivity m cal/cm-sec-°C	Heat Flow µ cal/cm²-sec	Best Heat Flow µ cal/cm²-sec.	Quality of value
Cedar Springs	35°30'	110°24'	1854	90-150	23.4 ± 0.2		Fragments	6.6 *	1.5	1.5	B
				170-230	22.1 ± 0.2			6.6 *	1.5		
Chilchinbito	36°36'	110°09'	1825	180-210	15.2 ± 0.1		Fragments	10. *	1.5	1.7	B
				240-320	17.5 ± 0.1			10. *	1.8		
				330-360	30.1 ± 0.2			6. **	1.8		
				420-460	14.1 ± 0.2			12. *1	1.7		
Gadiahi Mission	36°02'	110°31'	1825	170-250	38.2 ± 0.3		Fragments	5. *	1.9	1.8	B
				270-320	17.1 ± 0.1			10. **	1.7		
				320-420	18.8 ± 0.1			10. **	1.9		
Gila Mts. #1	32°58'	109°36'	1512	290-350	39.9 ± 0.6	7	Fragments	4.1 ± 0.1	1.6	1.6	B
				350-410	30.4 ± 0.2	5	Fragments	4.9 ± 0.2	1.5		
Gila Mts. #2	33°00'	109°42'	1390	40-90	33.9 ± 0.2	4	Fragments	6.5 ± 0.2	2.2	2.3	B
				90-140	35.2 ± 0.2	2	Fragments	6.5 ± 0.4	2.3		
Gila Mts. #3	32°58'	109°42'	1195	510-650	31.0 ± 0.2	5	Fragments	4.6 ± 0.2	1.4	1.4	C
				650-750	25.2 ± 0.1	4	Fragments	5.6 ± 0.3	1.4		
Gila Mts. #4	32°59'	109°47'	1097	200-360	40.7 ± 0.1	4	Fragments	4.2 ± 0.3	1.7	1.9	A
				380-440	37.5 ± 0.4	3	Core & Frag	4.7 ± 0.4	1.8		
				440-560	33.2 ± 0.2	7	Core	5.7 ± 0.3	1.9		
Gila Mts. #5	33°08'	109°55'	1350	260-540	34.9 ± 0.1	9	Core	5.6 ± 0.2	2.0	1.9	A
				560-640	33.2 ± 0.2	6	Core	5.6 ± 0.2	1.9		
				640-700	30.3 ± 0.1	5	Core	6.0 ± 0.1	1.8		
Slick Rock	32°47'	109°23'	1230	100-180	49.7 ± 0.5	1	Fragments	4.3	2.1	2.1	B
				180-240	48.0 ± 0.6	1	Fragments	4.6	2.2		
				240-360	45.1 ± 0.2	1	Core	4.1	1.8		
				360-450	37.3 ± 0.4	2	Core & Frag	6.0 ± 1.5	2.2		
Morenci	33°05'	109°22'	1296	340-580	22.7 ± 0.1	7	Core	6.1 ± 0.2	1.4	1.7	B
				600-660	22.2 ± 0.6	4	Core	7.7 ± 0.9	1.7		
Navajo	35°06'	109°26'	1796	120-170	48.7 ± 1.2	2	Fragments	5.0 ± 0.6 +	2.4	2.6	B
				210-240	50.9 ± 1.8	2	Fragments	5.1 ± 0.6 +	2.6		
				270-310	61.1 ± 0.5	3	Fragments	5.0 ± 0.4 +	3.1		
				340-370	46.9 ± 0.2	1	Fragments	5.3 +	2.5		
Page #1	36°57'	111°29'	1194	60-160	13.3 ± 0.1	3	Core	10.0 ± 0.1	1.3	1.3	C
Red Hill	34°17'	108°47'	2125	20-60	51.1 ± 0.3	4	Fragments	5.3 ± 0.5 *	2.7	2.5	B
				80-100	35.4 ± 0.8	3	Fragments	6.5 ± 0.6 *	2.3		
Sanders	35°07'	109°21'	1829	100-230	57.0 ± 0.4	8	Fragments	6.6 ± 0.3 +	3.8	3.8	B
				240-270	60.8 ± 1.4						
				290-320	56.5 ± 2.0						
Sol-5	32°49'	109°31'	1067	300-500	75.6 ± 0.3	5	Core	6.6 ± 0.9	5.0		
				950-1050	19.5 ± 0.1	7	Core	6.3 ± 0.5	1.2		

Table 1