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Terrestrial Heat Flow along the Rio Grande Rift, New Mexico and Southern Colorado

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ABSTRACT

From heat-flow data obtained in New Mexico and southern Colorado, we recognize (1) a major geothermal anomaly with heat-flow values greater than 2.5 HFU (heat-flow unit, μcal/cm²-sec) coincident with the western part of the Rio Grande rift; (2) a complex heat-flow pattern in the eastern Colorado Plateau with values of 1.5 HFU and less, apparently associated with major structural basins, and values of 2.0 HFU and greater, apparently associated with some intrusions and perhaps major uplifts, (3) a regional increase in heat-flow values from 1.5 to 2.0 HFU to values greater than 2.5 HFU in southwestern New Mexico, which may be coincident with the north-trending geothermal transition zone between the Colorado Plateau and the Basin and Range provinces.

INTRODUCTION

A definition of the terrestrial heat-flow pattern within the southwestern United States will probably require heat-flow measurements on the order of 50 km apart. To appreciate the geothermal character of the crust and upper mantle in regions where the heat-flow pattern is complex, or is demonstrating a transition, it may be necessary to acquire heat-flow measurements on the order of 10 km apart. This study attempts to geographically define regional geothermal trends associated with the Rio Grande rift and neighboring geologic provinces. We have made 175 temperature logs, from which 103 heat-flow measurements, representing 100 sites, are presented and tabulated (Fig. 1). Measurements taken 2 km or more apart are considered distinct, whereas two or more measurements less than 2 km apart have been averaged to represent one location.

GEOPHYSICAL SETTING

In New Mexico and southern Colorado, four geologic provinces with very different characteristics exist in juxtaposition with the Rio Grande depression, a major continental rift extending 1,000 km between Leadville, Colorado, and El Paso, Texas (Chapin, 1971). The northern part of the Rio Grande rift bisects the high ranges of the southern Rocky Mountains and has intermittent contact with the Colorado Plateau to the west. The southern part of the rift is bordered on the west by the Colorado Plateau, the Datil-Mogollon volcanic field, and perhaps the Basin and Range province, if one wishes to distinguish the southern part of the rift from the Basin and Range province. The Great Plains lie to the east of the mountains bordering the Rio Grande rift. Bedrock relief along the rift varies from 100 m in some of the smaller basins to 11,000 m in the San Luis valley (Chapin, 1971). Christiansen and Lipman (1972) and Bruning and Chapin (1974) have cited evidence that suggests rifting may have begun as early as 24 to 28 m.y. ago.

Most of the volcanism concurrent with rifting occurs along the middle and western parts of the Rio Grande rift. Summers (1965) demonstrated that present hot-spring activity generally coincides with these volcanic areas. Lipman (1969) reported that in northern New Mexico and southern Colorado, alkalic, crustally contaminated basalt is present to the east and to the west of the Rio Grande rift, whereas primitive, tholeiitic basalt is present within the grabens. Lipman postulated that the tholeiitic basalt comes from a shallow depth under the rift, suggesting that a thermal anomaly may be associated with the depression. Various other studies suggest that high heat flows are associated with the Rio Grande rift (Warren and others, 1969; Smithson and Decker, 1972; Hartman and Reiter, 1972; Edwards and others, 1973; Reiter and others, 1973). Decker (1969) suggested that the southern Rocky Mountains regionally possess high heat flow. Roy and others (1972) interpreted seven reduced heat-flow measurements within the southern Rocky Mountains as evidence that this province has a regional geothermal character similar to that of the Basin and Range province.

Near Socorro, New Mexico, a sharp discontinuity, possibly underlain by material of very low rigidity, has been detected at a depth of 18 km (Sanford and others, 1973). This discontinuity dips to a 30-km depth 60 km north of Socorro. Sanford (1963) and Sanford and Holmes (1962) indicated that the majority of earthquakes in New Mexico occur as swarms along a narrow seismic zone coincident with the Rio Grande valley. Sanford (1968) showed by gravity studies that Bouguer anomalies locally exhibit minimum negative values within the Rio Grande rift near Socorro. Smithson and Decker (1972) also suggested gravity highs associated with the southern part of the Rio Grande rift near Orogrande and El Paso.

The Colorado Plateau occupies most of northwestern New Mexico and western Colorado. Although the plateau is a seemingly stable, elevated platform, numerous diatremes, laccolithic masses, and dike systems do appear within the province. Several authors have cautioned against generally characterizing the Colorado Plateau as a province of regionally low heat flow on the basis of sparse earlier data (Costain and Wright, 1973; Edwards and others, 1973; Reiter and others, 1973). Roy and others (1972) also indicated the sparse and ambiguous data on crustal radioactive heat generation within the Colorado Plateau. The Mohorovičić discontinuity is approximately 40 to 45 km under the Colorado Plateau, and P_n velocities are reported as between 7.8 km/sec and 8.1 km/sec (Pakiser, 1963; Archambeau and others, 1969; Healy and Warren, 1969; Herrin, 1969; Bucher and Smith, 1971).

The Basin and Range province is present in southwestern New Mexico. The physiography of this province is characterized by a series of mountain ranges with intermontane valleys. The Basin and Range is considered a regional geothermal high, although heat-flow values vary greatly (Warren and others, 1969; Sass and others, 1971a). Reduced heat-flow values for the Basin and Range are reported as 1.4 ± 0.2 HFU (Roy and others, 1972). The Mohorovičić discontinuity under the Basin and Range lies at a depth of approximately 20 to 30 km, and the P_n velocity under this

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province is generally considered to be 7.8 km/sec (Pakiser, 1963; Healy and Warren, 1969; Archambeau and others, 1969; Herrin, 1969; Bucher and Smith, 1971).

ANALYSIS OF THE DATA

The fundamentals of our heat-flow data are given in Table 1. Most of the heat-flow values were obtained by multiplying the linear thermal gradients measured in drill holes by the corresponding average thermal conductivity values. A best heat-flow value was chosen for each well site by considering such factors as possible ground-water movement, thermal conductivity control, depth of the drill hole, linearity of the thermal gradients, drilling history of the well, and rock conditions encountered while drilling. Unfortunately, heat-flow data are both ambiguous and normally suspect. The temperature logs indicate to us that the movement of subsurface water has the most significant influence on the diffusion geothermal gradient. Sass and others (1971a) indicated the potential influence of regional ground-water flow on subsurface temperature gradients in an area near Las Vegas, Nevada. They imply the importance of temperature measurements at great depths

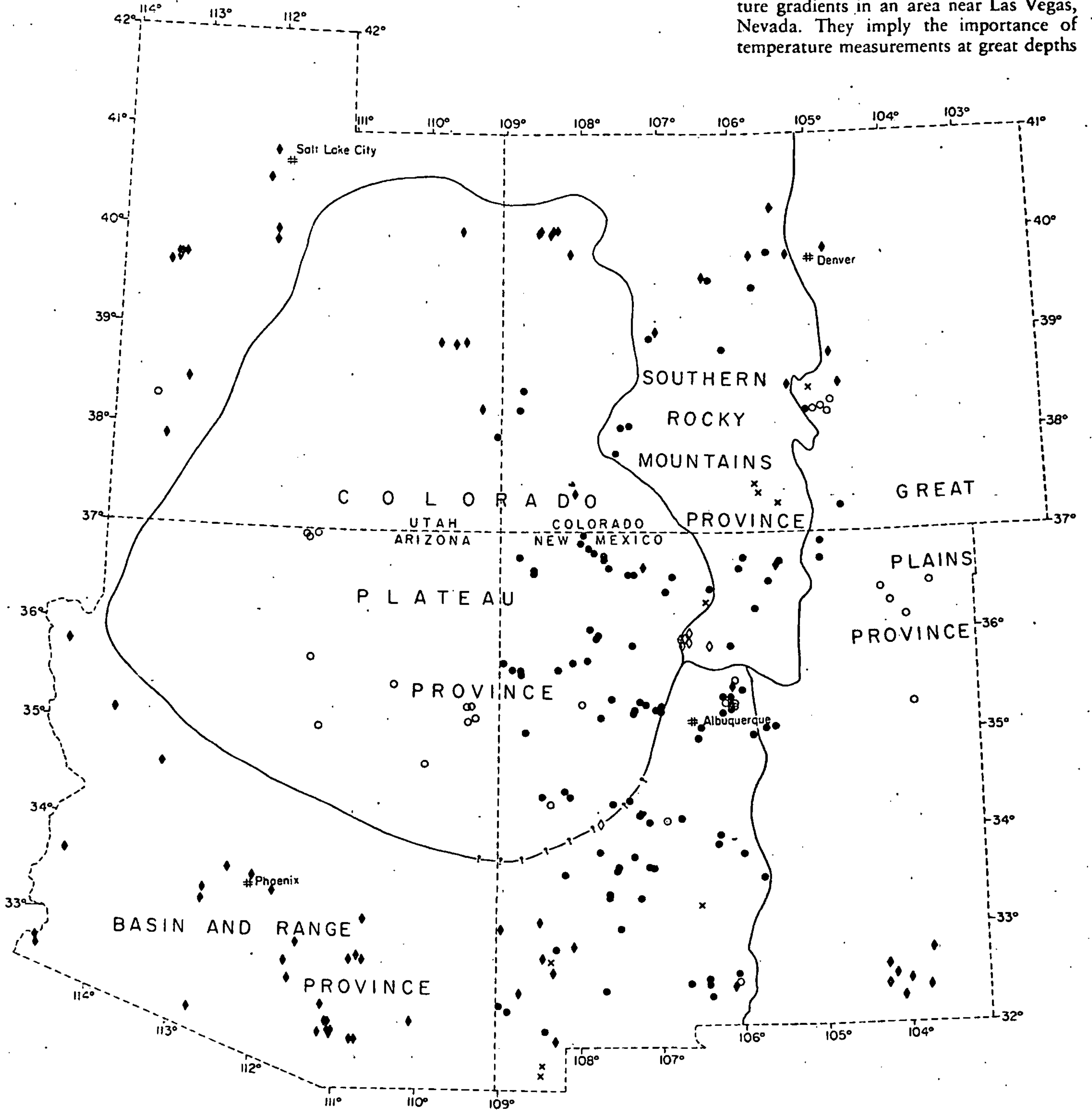

Figure 1. Heat-flow stations in southwestern United States. Solid diamonds indicate published data by other investigators (Birch, 1947, 1950; Lovering, 1948; Herrin and Clark, 1956; Spicer, 1964; Warren and others, 1969; Decker, 1969; Sass and others, 1971a; Costain and Wright, 1973). Open diamonds indicate heat-flow sites being cooperatively studied by M. Chessman and others (in prep.) and M. Reiter and others (in prep.). Open circles indicate flow sites being studied by A. Sanford and others (in prep.), C. Edwards and others (in prep.), and M. Reiter and others (in prep.). Solid circles indicate heat-flow data sites as presented and tabulated in text. Xs indicate sites demonstrating severe ground-water disturbance in temperature log.

to better define the geothermal gradients within the area.

Ground-water movement may be recognized by nonlinear behavior in the temperature log and (or) an incompatibility between heat-flow values in different zones of the drill hole. When these characteristics are observed at several sites within a region, one must attempt to investigate regional hydrologic conditions, such as thickness and continuity of aquifers, recharge and discharge areas, permeability variations within aquifers, and subsurface flow rates. Unfortunately, the hydrologic setting is rarely known well enough to apply quantitative corrections for ground-water movement (Bredehoeft and Papadopulos, 1965). Normally one can only hope to avoid the influence of regional ground-water movement by measuring the geothermal gradient at sites and depths where ground-water movement is minimal.

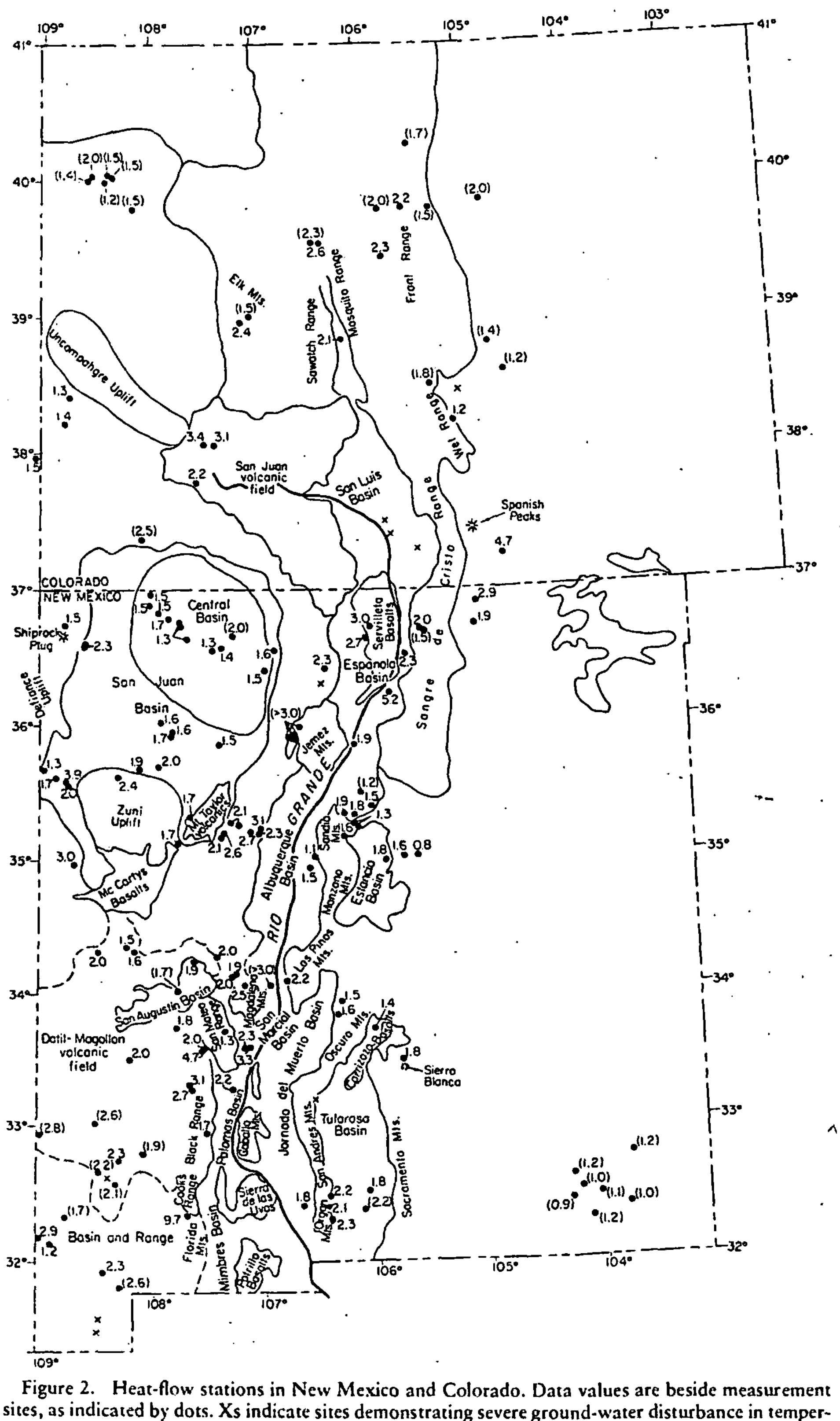

Figure 2. Heat-flow stations in New Mexico and Colorado. Data values are beside measurement sites, as indicated by dots. Xs indicate sites demonstrating severe ground-water disturbance in temperature log. Data in parentheses are from Birch (1947, 1950), Herrin and Clark (1956), Roy and others (1968), Warren and others (1969), Decker (1969), Sass and others (1971a), M. Chessman and others (in prep.), A. Sanford and others (in prep.), and M. Reiter and others (in prep.).

Heat-flow values presented in Table 1 have not been corrected for the effects of topographic relief. Terrain corrections (Birch, 1950) were initially applied at several sites where the effects of topography should have been large in comparison to most sites in the study. These corrections were only a few percent of the measured thermal gradients; consequently, we decided that in light of the other uncertainties in most of our heat-flow data, terrain corrections typically were not warranted.

Each heat-flow measurement was evaluated with respect to the probability of it being representative within a 2-km radius. We employed the following criteria, similar to that of Sass and others (1971a), in evaluating the data: if we believed the measured heat flow at a site was accurate to ± 10 percent, it was evaluated as an A measurement; if ± 20 percent, as a B measurement; and if greater than 20 percent, as a C measurement. Although A measurements can be made in 100- to 200-m drill holes, A measurements typically are taken in boreholes 300 m and deeper in which good thermal conductivity control is possible and in areas where ground-water flow is thought to be minimal. We generally interpret A measurements from zones of linear gradients 100 m and longer. B measurements are normally interpreted from shorter (40 to 90 m) zones of linear temperature gradients. The classification of a heat-flow measurement depends on whether or not heat-flow fluctuations within the drill hole can be explained and a most representative flux value can be chosen. If the calculated heat flows in several zones of the drill test vary by 10 to 20 percent, we evaluate the data as a B measurement. C measurements have qualitative importance in the regional heat-flow pattern; for example, the heat flow in a specific area is probably greater than 2.5 HFU.

Heat-flow data in New Mexico, southern Colorado, and bordering areas are illustrated in Figure 2. Using the available data, we have constructed a geothermal map of New Mexico and southern Colorado (Fig. 3) with contours based on the magnitude, quality, and compatibility of heat-flow measurements within a region. Question marks indicate those areas where considerable ambiguity exists in the character and location of the contours.

When evaluating the geophysical significance of geothermal data, one must consider the scatter of data values within an

TABLE I SUMMARY OF HEAT FLOW DATA

LOCALITY	NORTH LAT	WEST LONG	ELEV METERS	DEPTH INTERVAL METERS	THERMAL GRADIENT DEG.C/KM	N	TYPE OF SAMPLE	THERMAL CONDUCTIVITY MCAL/CM-SEC-DEG.C	HEAT FLOW HFU[a]	BEST HEAT FLOW ESTIMATE HFU[a]	QUALITY OF HEAT FLOW VALUE
ALBUQUERQUE (NM)	35 03	106 31	1650	140-180	19.71±0.96	10	FRAGMENTS*	5.47±0.32	1.08±0.12	1.08	C
ALBUQUERQUE/SE #1 (NM)	34 56	106 33	1820	20-130	19.70±0.0	13	FRAGMENTS*	7.91±0.0	1.56±0.0	1.56***	C
ALBUQUERQUE/SE #2 (NM)	34 56	106 33	1820	30-130	17.50±0.0	11	FRAGMENTS*	8.15±0.0	1.43±0.0	1.43***	C
ANIMAS PEAK (NM)	32 58	107 32	1670	120-180	29.99±0.25	6	CORE	5.45±0.37	1.63±0.13	1.70	A
				180-290	32.02±0.07	9	CORE	5.54±0.45	1.77±0.15		
ATKLUSON MESA (C)	38 12	108 49	1970	90-160	27.30±0.31	6	FRAGMENTS*	5.05±0.14	1.38±0.05	1.38	B
				150-190	21.24±0.92	4	FRAGMENTS*	6.46±0.44	1.37±0.16		
AZTEC/NORTH (NM)	36 54	108 01	1870	80-380	29.09±0.25	15	FRAGMENTS*	4.46±0.56	1.30±0.18	1.46	A
				380-650	35.35±0.33	12	FRAGMENTS*	4.57±0.66	1.62±0.25		
AZTEC/NE (NM)	36 50	107 55	1850	50-500	28.88±0.14	24	FRAGMENTS*	4.72±0.57	1.36±0.17	1.47	A
				500-710	39.58±0.40	8	FRAGMENTS*	3.98±0.31	1.58±0.14		
BIBO/NORTH (NM)	35 13	107 19	1870	90-150	30.38±0.92	5	FRAGMENTS*	7.54±1.55	2.29±0.55	2.58	C
				210-260	50.52±1.53	5	FRAGMENTS*	6.79±0.89	3.43±0.57		
				250-300	45.64±0.88	9	FRAGMENTS*	6.02±0.40	2.75±0.24		
				290-340	30.90±2.48	8	FRAGMENTS*	6.12±0.76	1.89±0.41		
BIBO/SOUTH (NM)	35 12	107 19	1910	90-140	28.34±1.11	5	FRAGMENTS*	7.54±1.55	2.14±0.54	2.14	B
BIG RED CANYON (NM)	33 44	107 21	1760	80-120	28.54±1.03	13	CORE**	4.47±1.32	1.28±0.44	1.28	C
BINGHAM/NE (NM)	33 57	106 17	1770	30-110	22.09±1.09	6	FRAGMENTS*	6.59±0.95	1.46±0.29	1.46	B
BINGHAM/SOUTH (NM)	33 53	106 21	1730	80-130	27.86±0.28	5	FRAGMENTS*	5.52±0.28	1.54±0.09	1.56	A
				130-180	29.82±0.91	5	FRAGMENTS*	5.29±0.45	1.58±0.19		
BLANCO/NORTH (NM)	36 47	107 50	1840	220-520	29.01±0.42	12	FRAGMENTS*	5.94±0.91	1.72±0.29	1.72	B
BLANCO/EAST #1 (NM)	36 45	107 43	1950	260-380	26.89±0.28	5	FRAGMENTS*	4.45±0.08	1.20±0.03	1.31	A
				380-450	29.19±0.65	2	FRAGMENTS*	4.86±0.21	1.42±0.09		
BLANCO/EAST #2 (NM)	36 42	107 43	1960	230-450	28.94±0.12	7	FRAGMENTS*	4.59±0.24	1.33±0.08	1.33	A
BUCKMAN (NM)	35 52	106 09	1810	30-90	34.17±0.49	4	FRAGMENTS*	5.06±0.41	1.73±0.17	1.91	B
				150-300	40.27±0.17	7	FRAGMENTS*	5.32±0.49	2.14±0.21		
				300-450	30.24±0.45	8	FRAGMENTS*	5.52±0.48	1.67±0.17		
BUENA VISTA (C)	38 47	106 10	2500	60-110	30.93±0.41	5	FRAGMENTS*	6.03±0.52	1.87±0.19	2.13	B
				120-180	37.71±1.08	3	FRAGMENTS*	6.08±0.10	2.29±0.10		
				260-295	39.92±0.86	4	FRAGMENTS*	4.92±0.51	1.96±0.25		
CARRIZO CREEK (NM)	36 39	107 40	1890	100-650	27.31±0.19	49	FRAGMENTS*	4.63±0.57	1.26±0.17	1.26	B
CARRIZOZO/NW (NM)	33 44	106 02	1700	80-220	26.54±0.15	10	FRAGMENTS*	5.36±0.89	1.42±0.25	1.44	B
				290-320#	22.44±1.10	4	FRAGMENTS*	4.94±0.62	1.11±0.20		
				330-360	20.98±0.13	5	FRAGMENTS*	6.90±0.96	1.45±0.21		
CEDAR HILL/WEST (NM)	37 57	107 59	2000	50-700	35.06±0.25	21	FRAGMENTS*	4.30±0.28	1.51±0.11	1.51	A
CENTRAL CITY (C)	39 48	105 35	2650	30-160	28.58±0.22	8	CORE	7.69±0.66	2.20±0.21	2.20	A
CHACO CANYON (NM)	36 02	107 54	1880	40-90#	36.89±0.40	3	FRAGMENTS*	3.37±0.0	1.24±0.01	1.56	B
				100-150	36.16±0.29	2	FRAGMENTS*	4.17±0.29	1.51±0.12		
				140-170	41.59±0.58	3	FRAGMENTS*	2.82±0.37	1.59±0.18		
CHACO SLOPE (NM)	35 51	107 24	2020	380-540	32.96±2.15	7	FRAGMENTS*	4.50±0.62	1.48±0.31	1.49	A
				600-830	34.15±0.34	8	FRAGMENTS*	4.36±0.74	1.49±0.27		
CHACO WASH (NM)	35 56	107 48	1970	40-100	37.41±0.22	5	CORE	4.36±0.75	1.63±0.29	1.63	B
CHLORIDE #1 (NM)	33 19	107 42	2080	45-71	34.99±0.85	3	CORE	6.86±0.47	2.40±0.23	2.73	B
				71-143	42.96±0.53	5	CORE	7.60±2.17	3.26±0.98		
				143-160	49.05±2.90	3	CORE	5.17±0.32	2.54±0.32		
CHLORIDE #2 (NM)	33 19	107 42	2050	26-67	45.23±1.80	3	CORE	6.80±0.34	3.08±0.28	3.11	A
				86-162	42.37±0.49	6	CORE	7.38±2.62	3.13±1.16		
CHUPADERA MESA (NM)	34 06	106 48	1533	70-130	33.47±0.67	4	FRAGMENTS*	6.69±0.47	2.24±0.21	2.20	A
				130-160	42.61±1.94	2	FRAGMENTS*	5.06±0.56	2.16±0.35		
CLINES CORNERS (NM)	35 00	105 37	1980	60-150	12.13±0.70	40	FRAGMENTS*	6.76±1.16	0.82±0.20	0.82	C
CRESTED BUTTE (C)	38 55	107 07	3640	300-580	29.18±0.06	15	CORE	7.63±0.70	2.23±0.21	2.40	A
				580-740	32.56±0.20	8	CORE	7.90±0.76	2.57±0.26		
CROWN POINT (NM)	35 40	108 08	2650	180-260	27.91±0.46	6	FRAGMENTS*	5.73±0.78	1.60±0.22	1.91	B
				300-380	47.04±0.88	3	FRAGMENTS*	4.70±0.32	2.21±0.19		
CROWN POINT/EAST (NM)	35 42	107 56	2020	50-150	31.40±1.24	4	FRAGMENTS*	6.15±0.47	1.93±0.23	2.04	B
				170-210	29.12±0.70	5	FRAGMENTS*	7.39±0.71	2.15±0.26		
DIXON (NM)	36 13	105 48	2270	70-100	42.72±0.53	7	CORE	12.70±1.97	5.43±0.92	5.25	B
				90-140	38.05±0.33	12	CORE	13.30±1.53	5.06±0.63		
EL VADO/SW (NM)	36 32	106 51	2120	190-270#	58.49±2.40	5	FRAGMENTS*	4.73±0.24	2.77±0.26	1.60	B
				270-330	32.20±0.60	3	FRAGMENTS*	4.94±0.40	1.59±0.16		
				330-470	37.45±0.46	7	FRAGMENTS*	4.30±0.35	1.61±0.19		
FT CRAIG #1 (NM)	33 37	107 08	1440	20-90	65.66±2.24	7	FRAGMENTS*	5.03±0.40	3.30±0.38	3.30	C
FT CRAIG #2 (NM)	33 37	107 08	1440	20-90	46.17±1.41	6	FRAGMENTS*	5.03±0.40	2.32±0.26	2.32	C
GALISTEO (NM)	35 25	106 00	1870	40-200	30.94±0.34	10	CORE**	4.78±0.43	1.48±0.15	1.48	A
GALLUP/WEST #1 (NM)	35 33	108 46	1980	20-100	32.34±0.38	2	FRAGMENTS*	6.24±0.24	2.02±0.10	2.02	C
GALLUP/WEST #2 (NM)	35 35	108 51	2030	40-80	30.76±1.68	3	FRAGMENTS*	5.40±0.42	1.66±0.17	1.66	C
GALLUP/WEST #3 (NM)	35 38	109 02	2070	30-80	22.05±0.26	8	FRAGMENTS*	5.77±1.03	1.27±0.24	1.27	C
GALLUP/WEST #4 (NM)	35 33	108 46	1980	70-150	61.82±3.94	2	FRAGMENTS*	6.24±0.24	3.86±0.40	3.86	C
GAVILAN/EAST (NM)	36 22	106 54	2180	100-200	23.91±0.53	3	FRAGMENTS*	6.54±2.02	1.56±0.53	1.51	B
				300-420	27.35±0.74	4	FRAGMENTS*	4.76±0.32	1.30±0.13		
				420-820	32.19±0.39	13	FRAGMENTS*	4.73±0.76	1.52±0.27		
				800-920	38.84±0.48	4	FRAGMENTS*	4.71±0.39	1.83±0.18		
				900-1300	29.43±0.17	14	FRAGMENTS*	4.54±0.48	1.34±0.15		
GOBERNADOR/SOUTH (NM)	36 36	107 21	2000	210-280	32.85±0.20	2	FRAGMENTS*	3.90±0.15	1.28±0.06	1.35	A
				280-400	30.22±0.22	4	FRAGMENTS*	4.68±0.32	1.41±0.11		
GRANITE GAP (NM)	32 07	108 56	1300	90-120	21.10±0.18	3	FRAGMENTS*	5.79±0.51	1.22±0.12	1.22	C
GRANTS (NM)	35 07	107 46	2030	80-220	30.05±0.31	8	FRAGMENTS*	6.59±0.93	1.98±0.30	1.68	C
				220-260	19.45±0.30	4	FRAGMENTS*	7.08±0.45	1.38±0.11		
HOLWEG (NM)	35 09	106 16	2090	60-140	23.33±0.37	40	FRAGMENTS*	6.76±1.16	1.58±0.30	1.58	C
HORSE RANGE MESA (U)	37 59	109 03	2120	150-190	22.83±1.13	1	FRAGMENTS*	6.41±0.07	1.46±0.09	1.46	B
INDIANS SPRINGS (NM)	34 18	107 26	2080	20-90	31.93±0.36	9	FRAGMENTS*	6.10±0.50	1.95±0.18	1.95	B
LITTLE HATCHET MTN (NM)	31 54	108 26	1580	90-175	40.14±1.17	3	FRAGMENTS*	5.72±0.11	2.30±0.11	2.30	B
MAGDALENA/NW (NM)	34 09	107 18	2000	90-190	43.99±0.21	2	CORE	4.31±0.60	1.90±0.27	1.91	A
				170-300	40.44±0.15	9	CORE	4.73±0.61	1.91±0.25		
MAGDALENA/WEST (NM)	34 07	107 17	2020	20-90#	22.68±0.63	7	CORE	4.51±0.26	1.02±0.09	2.01	B
				120-180	38.93±1.19	4	CORE	5.17±0.02	2.01±0.07		
MARIANO LAKE (NM)	35 38	108 19	2150	40-80	50.95±1.40	3	FRAGMENTS*	4.56±0.57	2.32±0.36	2.35	B
				90-150	54.07±0.49	2	FRAGMENTS*	4.38±0.58	2.37±0.34		
MARQUEZ (NM)	35 17	107 15	2120	70-130	51.98±1.70	6	FRAGMENTS*	4.11±0.37	2.14±0.27	2.14	B
MARQUEZ/SE (NM)	35 15	107 13	1570	100-130#	21.12±0.47	3	FRAGMENTS*	8.40±0.70	1.77±0.19	2.11	B
				130-180#	33.91±0.54	3	FRAGMENTS*	5.49±0.35	1.86±0.15		
				160-300	32.34±0.50	6	FRAGMENTS*	6.51±0.87	2.11±0.32		
MARY ALICE CR (C)	38 03	107 30	3660	140-190	89.11±3.44	5	CORE	3.86±0.18	3.44±0.30	3.44	B
MIRAGE (NM)	32 22	107 40	1370	30-320	83.64±0.31	11	CORE	11.57±0.55	9.68±0.50	9.68	B
MONTICELLO CAN #1 (NM)	33 34	107 36	1750	70-120#	23.86±1.37	3	CORE	4.77±0.03	1.14±0.07	1.98	B
				100-230	41.58±0.59	7	CORE	4.75±0.08	1.98±0.06		

area. Some areas have little scatter in heat-flow values — for example, the region of 1.5 HFU and less in the central San Juan basin, and the area of 2.0 to 2.5 HFU near the eastern side of the Organ Mountains (Fig. 2). Alternatively, other areas have considerable discrepancy in measured heat flow — for example, the Elk Mountains, the western San Juan Mountains, and west of the Zuni uplift (Fig. 2). The most "quiet" areas have a probable noise level of 0.1 to 0.2 HFU; "noisy" areas have variations of 1.0 HFU and greater. It is, therefore, tenuous to place geophysical significance on trends of less than 0.2 HFU unless a large number of high-quality measurements are available. Consequently, trends on the order of 0.5 HFU are a conservative consideration in mapping the geothermal field. In addition, regional trends are more certain than local trends because disturbances in the data caused by phenomena such as local ground-water movement and hydrothermal activity tend to average out.

The most obvious feature of the geothermal map in Figure 3 is the zone of high heat flow (≥2.5 HFU) coincident with the western part of the Rio Grande rift. The peaking of heat flow near the western part of the rift is shown in the profiles in Figure 4. Data of southern Colorado indicate the possibility that the San Juan volcanic field may be within the Rio Grande zone of high heat flow (Fig. 2).

Heat-flow data may be biased within the belt of high heat flow toward mining regions and areas of hydrothermal activity. As more data are obtained near the zone of high heat flow, the zone may fragment into

TABLE I SUMMARY OF HEAT FLOW DATA (CONTINUED)

LOCALITY	NORTH LAT	WEST LONG	ELEV METERS	DEPTH INTERVAL METERS	THERMAL GRADIENT DEG.C/KM	N	TYPE OF SAMPLE	THERMAL CONDUCTIVITY MCAL/CM-SEC-DEG.C	HEAT FLOW HFU@	BEST HEAT FLOW ESTIMATE HFU@	QUALITY OF HEAT FLOW VALUE
MONTICELLO CAN #2 (NM)	33 34	107 36	1910	110-190	79.25±1.22	8	CORE	7.09±2.41	5.62±2.03	4.73	B
				200-250	81.92±0.90	9	CORE	5.77±0.24	4.73±0.25		
MORIARTY/EAST (NM)	35 00	105 54	1980	60-115	26.98±0.34		FRAGMENTS*	6.76±1.16	1.82±0.34	1.82	C
MUNOZ CREEK (NM)	36 36	107 25	1980	100-460	25.30±0.16	9	FRAGMENTS*	4.79±0.57	1.21±0.15	1.29	A
				460-820	29.32±0.13	8	FRAGMENTS*	4.65±0.62	1.36±0.19		
NELLIE CREEK (C)	38 04	107 23	3660	30-160	66.22±0.40	10	CORE	4.64±0.21	3.07±0.16	3.07	B
NO AGUA (NM)	36 46	105 58	2620	30-100	100.90±1.49	3	FRAGMENTS*	3.24±0.09	3.27±0.14	3.02	B
				100-140	74.32±1.64	5	FRAGMENTS*	4.84±0.79	3.60±0.68		
				160-220	64.27±0.69	6	FRAGMENTS*	4.28±1.01	2.75±0.69		
NORTH BALOY (NM)	34 02	107 13	2590	90-170#	24.70±1.10	3	CORE	5.00±0.61	1.23±0.21	2.48	C
				150-210	33.86±0.94	4	CORE	5.86±0.88	1.98±0.36		
				230-280	44.69±2.09	3	CORE	6.66±0.23	2.98±0.25		
NORTH LAKE (NM)	34 14	107 38	2130	61-122#	37.07±1.51	8	CORE**	4.37±0.79	1.62±0.37	1.91	B
				198-244	43.59±0.52	8	CORE**	4.37±0.79	1.90±0.37		
				274-305	43.65±1.65	8	CORE**	4.37±0.79	1.91±0.43		
ORGAN (NM)	32 24	106 39	1360	120-150	30.60±1.06	7	FRAGMENTS*	5.76±0.24	1.76±0.14	1.76	C
OROGRANDE/NORTH (NM)	32 30	106 06	1370	20-50	32.54±0.45	4	CORE	5.74±0.65	1.87±0.24	1.75	A
				70-150	28.37±0.23	20	CORE	6.53±1.28	1.85±0.28		
				140-300	30.54±0.08	18	CORE	5.74±1.14	1.75±0.35		
				270-370	32.28±0.22	19	CORE	5.04±0.10	1.63±0.04		
ORTIZ MTN. (NM)	35 20	106 11	2560	230-350	27.90±0.0	12	CORE	6.18±0.0	1.72±0.0	1.76***	B
PIETOWN/NORTH (NM)	34 19	108 07	2320	70-220	35.07±0.43	7	CORE**	4.42±1.29	1.55±0.48	1.55	B
PIETOWN/NW (NM)	34 23	108 13	2300	50-150	48.13±0.51	6	CORE**	3.04±0.28	1.46±0.15	1.46	B
QUEMADO/SOUTH (NM)	34 20	108 30	1980	20-90	39.90±0.68	4	CORE**	4.95±0.60	1.98±0.28	1.98	C
QUESTA/EAST (NM)	36 42	105 28	2620	180-360#	22.76±0.10	8	FRAGMENTS*	7.93±0.49	1.80±0.12	2.04	A
				330-440	24.19±0.17	7	FRAGMENTS*	8.23±0.43	1.99±0.12		
				440-480	26.85±0.50	3	FRAGMENTS*	7.78±0.24	2.09±0.10		
RAILROAD CAN/NORTH (NM)	33 45	107 49	2320	20-350	54.40±0.87	7	CORE**	3.21±0.89	1.75±0.52	1.75	B
RAILROAD CAN/SOUTH (NM)	33 31	108 11	2130	20-150	61.77±1.09	7	CORE**	3.21±0.89	1.98±0.59	1.98	B
RATTLESNAKE (NM)	36 45	108 48	1620	80-100	31.74±1.76	5	FRAGMENTS*	4.28±0.28	1.36±0.17	1.46	B
				130-160	41.99±1.63	3	FRAGMENTS*	3.69±0.09	1.55±0.10		
REDCLIFF (C)	39 31	106 22	2900	40-90	41.84±3.37	9	CORE	6.32±1.91	2.64±1.08	2.64	C
				100-120#	49.94±8.11	4	CORE	7.35±0.91	3.67±1.12		
RED MOUNTAIN (NM)	35 55	107 49	1980	90-140	39.04±1.55	5	CORE	4.36±0.75	1.70±0.32	1.70	B
RIO PUERCO #1 (NM)	35 13	107 01	1740	60-120	37.39±0.28	5	FRAGMENTS*	5.51±0.25	2.06±0.11	3.08	C
				140-180	56.18±1.93	3	FRAGMENTS*	5.57±0.32	3.13±0.29		
				180-210	75.23±1.34	2	FRAGMENTS*	5.38±0.0	4.05±0.07		
RIO PUERCO #2 (NM)	35 12	107 01	1750	60-140	30.83±0.81	4	FRAGMENTS*	5.67±0.28	1.75±0.13	2.27	C
				160-190	55.78±2.65	2	FRAGMENTS*	5.01±0.12	2.79±0.20		
RIO PUERCO #3 (NM)	35 12	107 05	1830	60-120	35.66±0.22	3	FRAGMENTS*	5.70±0.39	2.03±0.15	2.66	C
				120-150	49.12±0.57	1	FRAGMENTS*	5.60±0.0	2.75±0.03		
				150-170	60.01±0.78	1	FRAGMENTS*	5.34±0.0	3.20±0.04		
SAN FELIPE/EAST (NM)	35 18	106 15	1920	70-120#	22.33±0.34	5	FRAGMENTS*	5.73±0.55	1.28±0.14	1.86	B
				120-180	31.48±1.56	3	FRAGMENTS*	5.43±0.33	1.71±0.19		
				170-260	36.58±0.78	4	FRAGMENTS*	5.51±0.18	2.02±0.11		
SAN MATEO MESA (NM)	35 20	107 37	2530	100-280	28.30±0.35	9	CORE**	5.47±0.53	1.55±0.17	1.66	B
				280-400	32.16±0.32	9	CORE**	5.47±0.53	1.76±0.19		
SAN PEDRO #1 (NM)	35 15	106 11	2160	30-160	19.04±0.10	9	CORE	7.04±1.06	1.34±0.21	1.34	B
SAN PEDRO #3 (NM)	35 15	106 11	2160	40-80	15.84±0.33	3	CORE	6.50±0.33	1.03±0.07	1.29	A
				80-160	23.05±0.14	4	CORE	5.60±0.26	1.29±0.07		
				180-270	21.57±0.16	7	CORE	6.23±1.76	1.34±0.39		
				310-490	19.92±0.12	13	CORE	6.26±1.56	1.25±0.32		
SIERRA BLANCA (NM)	33 28	105 47	2440	20-140	34.44±0.21	6	FRAGMENTS*	5.39±0.51	1.86±0.19	1.77	A
				130-250	30.36±0.13	10	FRAGMENTS*	5.49±0.75	1.67±0.24		
SILVER CITY (NM)	34 47	108 16	1830	70-200	20.68±0.17	16	CORE	9.89±1.88	2.05±0.41	2.33	A
				200-260	31.60±2.70	9	CORE	7.93±1.91	2.51±0.87		
				260-350	25.42±0.07	20	CORE	9.51±2.02	2.42±0.52		
SILVERTON (C)	37 48	107 37	3350	160-260	36.40±0.22	8	CORE	6.18±0.25	2.25±0.11	2.22	A
				300-400	36.77±0.14	4	CORE	5.94±0.30	2.18±0.12		
SOUTH PARK (C)	39 28	105 47	3050	100-280	29.15±0.07	5	CORE**	8.00±0.93	2.33±0.28	2.33	B
STEINS (NM)	32 10	109 02	1290	100-310	47.31±0.17	21	FRAGMENTS*	6.17±0.41	2.92±0.21	2.92	A
TABLE MESA #1 (NM)	36 37	108 37	1690	170-230#	22.12±0.14	6	FRAGMENTS*	5.34±0.50	1.18±0.12	2.30	B
				270-390	52.24±0.39	7	FRAGMENTS*	4.41±0.31	2.30±0.18		
TABLE MESA #2 (NM)	36 37	108 37	1690	120-180	37.86±1.42	4	FRAGMENTS*	5.99±0.26	2.27±0.19	2.29	B
				180-240#	20.95±0.24	5	FRAGMENTS*	5.06±0.26	1.06±0.07		
				280-420	52.41±0.62	11	FRAGMENTS*	4.40±0.34	2.31±0.21		
TAOS #1 (NM)	36 27	105 35	2130	60-110	37.41±0.54	7	FRAGMENTS*	5.94±0.13	2.22±0.08	2.29	B
				110-140	41.68±0.27	3	FRAGMENTS*	5.66±0.15	2.36±0.08		
TIERA AMARILLA #2 (NM)	36 23	106 23	2130	40-80	31.69±0.75	5	FRAGMENTS*	7.38±0.58	2.34±0.24	2.34	C
T OR C NORTH (NM)	33 17	107 16	1650	20-160	42.99±1.36	12	FRAGMENTS*	5.12±0.32	2.20±0.21	2.20	B
TRES PIEDRAS (NM)	36 39	105 59	2590	60-130	50.88±0.69	10	FRAGMENTS*	5.23±0.61	2.66±0.35	2.66	B
TRINIDAD #1 (C)	37 13	104 43	2160	50-380	57.65±0.24	8	CORE**	8.13±1.63	4.69±0.96	4.69	B
VERMAJO PARK (NM)	36 54	104 55	2320	30-85	55.45±1.70	3	FRAGMENTS*	5.16±0.29	2.86±0.25	2.86	C
VERMAJO RIVER (NM)	36 45	104 53	2260	30-1350	47.07±0.17	53	FRAGMENTS*	4.11±0.57	1.93±0.28	1.93	A
WAGON WHEEL (NM)	35 00	105 43	1980	30-100	23.76±0.24	40	FRAGMENTS*	6.76±1.16	1.61±0.29	1.61	B
WETMORE #1 (C)	38 14	105 05	1860	70-580	26.77±0.07	15	FRAGMENTS*	4.60±0.18	1.23±0.05	1.23	A
WHITE SANDS #2 (NM)	32 17	106 24	1230	120-150	41.44±2.65	12	FRAGMENTS*	5.51±0.23	2.28±0.25	2.28	B
WHITE SANDS #3 (NM)	32 26	106 27	1220	90-130	37.84±6.83	12	FRAGMENTS*	5.51±0.23	2.08±0.48	2.08	C
WHITE SANDS #4 (NM)	32 32	106 25	1220	190-230#	23.30±1.44	12	FRAGMENTS*	5.52±0.22	1.29±0.13	2.18	B
				240-290	39.48±0.82	12	FRAGMENTS*	5.51±0.25	2.18±0.15		
WILD STEER MESA (C)	38 26	108 46	1830	50-90#	14.06±0.11	3	FRAGMENTS*	5.49±0.26	0.77±0.04	1.33	B
				90-140#	20.96±0.20	8	FRAGMENTS*	4.33±0.41	0.91±0.10		
				150-170	22.05±0.38	7	FRAGMENTS*	6.04±0.91	1.33±0.23		
ZUNI PIA MESA (NM)	34 58	108 45	2130	50-150#	24.87±0.30	3	CORE**	7.40±0.11	1.84±0.05	2.96	B
				200-240	50.61±0.90	3	CORE**	5.89±0.77	2.98±0.45		
				240-290	71.59±1.60	2	CORE**	4.09±0.86	2.93±0.69		

N IS NUMBER OF THERMAL CONDUCTIVITY SAMPLES
@ 1 HFU = 1 UCAL/CM*CM-SEC
* CONDUCTIVITIES OF FRAGMENT SAMPLES HAVE BEEN CORRECTED FOR POROSITY
** CORE TAKEN FROM OUTCROP SAMPLES
*** HEAT FLOW DETERMINED BY BULLARD TECHNIQUE
\# THIS DEPTH INTERVAL NOT USED IN DETERMINING BEST HEAT FLOW ESTIMATE
± INDICATES THE STANDARD DEVIATION
(C), SITE IN COLORADO; (NM), SITE IN NEW MEXICO; (U), SITE IN UTAH
ELEVATIONS ARE ± 20 METERS

a series of localized anomalies. Alternatively, ground-water movement in the basins of the rift structure may be lowering actual geothermal gradients and consequently affecting our interpretation of the extent of the zone of high heat flow.

Eastward from the zone of high heat flow, the geothermal flux decreases to values of 1.5 HFU and less, characteristic of the stable interior (Fig. 2). Currently available data make the continuity of the heat-flow bands shown in Figure 3 uncertain. From heat-flow measurements in the Front Range, we suggest a regional heat flow of 2.0 to 2.5 HFU for the area (Fig. 2). In southern Colorado and northern New Mexico, the boundary between the southern Rocky Mountains and the Great Plains (Fig. 2) is within or nearly coincident with the 1.5- to 2.0-HFU band. In southern New Mexico the boundary between the Rio Grande rift and the Great Plains also is within or near the 1.5- to 2.0-HFU band. Anomalously high heat-flow measurements within this belt are present near the Spanish Peaks, the Sangre de Cristo Range, and the Organ Mountains (Fig. 2). We suggest that ground-water movement could cause the lowering of true geothermal gradients in the Palomas, Jornado del Muerto, and Tularosa basins (Fig. 2).

From heat-flow data just west of the zone of high heat flow associated with the Rio Grande rift, we interpret a 2.0- to 2.5-HFU step throughout the length of New Mexico and southern Colorado (Figs. 2, 3). In northwestern New Mexico, the central San Juan basin is characterized by heat-flow values of 1.5 HFU and less (Fig. 2). In western Colorado and easternmost Utah, there are additional areas of 1.5 HFU and less. In west-central New Mexico we define a broad area with heat-flow measurements typically between 2.0 and 2.5 HFU. Data in extreme southwestern New Mexico suggest a large area characterized by heat flow above 2.5 HFU. Figure 4 illustrates the heat-flow profile along long. 108° W.

On the basis of the available heat-flow data, we propose the following geothermal trends: a coincidence of high heat-flow values in New Mexico and Colorado with the western part of the Rio Grande rift, an increase in heat flow southwestward from the central San Juan basin toward the Zuni uplift and the McCartys basalts or northeastward from the central San Juan basin toward the San Juan volcanic field, and an area of high heat flow in southwestern New Mexico. Additional data sites will be needed before other possible heat-flow patterns can be substantiated — for example, a rapid decrease in heat flow west of the Zuni uplift, a large thermal anomaly near the Spanish Peaks, joining of the Rio Grande zone of high heat flow with an area of high heat flow in southwestern New Mexico, heat-flow patterns in the basins of south-central New Mexico, and continuity of high heat flow in the San Juan volcanic field (Fig. 2).

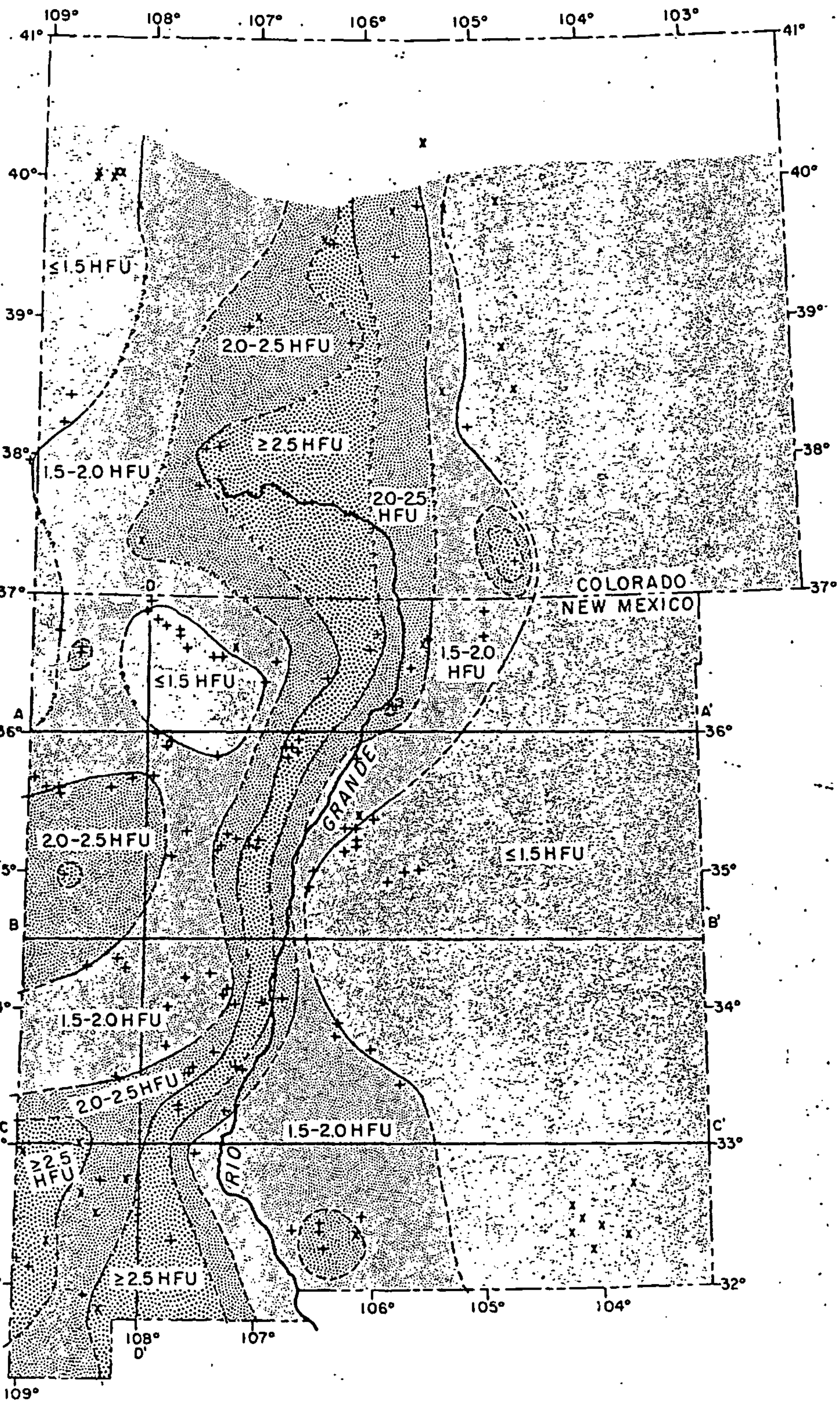

Figure 3. Terrestrial heat-flow contour map of New Mexico and southern Colorado. Contour interval, 0.5 HFU. Plus signs indicate control sites measured by New Mexico Institute of Mining and Technology; Xs indicate control sites of other investigators.

DISCUSSION

The ribbon of high heat flow along the western side of the Rio Grande rift is probably a reflection of a thermal source associated with the depression. The anomaly may overlie deep crustal fractures, penetrating the mantle, through which magmatic fluids approach the surface, perhaps forming in some instances magma chambers of considerable extent, as suggested by Sanford and others (1973). Such a fracture system could be associated with major crustal weaknesses between the Rio Grande rift and the Colorado Plateau and Basin and Range provinces. Recent volcanic activity and thermal springs, coincident with the location of the zone of high heat flow, may imply that extensional tectonic activity has been primarily concentrated along the western side of the Rio Grande rift.

Chapin (1971) proposed a thinning of the crust under the Rio Grande rift and an upward bulge in the mantle. He stated that faults along the eastern edge of the rift may be tight and therefore not conducive to magma transport, whereas faults along the western edge of the rift may be less tight because of a westward drift of the Colorado Plateau away from the mantle-bulge under the rift.

Additional heat-flow data may allow one to distinguish between a continuous mantle upwarp and a normal mantle depth along the Rio Grande rift. A series of high heat-flow areas and low heat-flow areas along the rift should imply a thermal source involving crustal fractures and magmatic movement into the crust from a mantle whose depth would be that of the Colorado Plateau or the Basin and Range province — that is, a normal mantle depth. Continuity in the zone of high heat flow along the rift may imply a continuous mantle upwarp; however, the fracturing and magmatic intrusion of the crust may be so extensive as to make a mantle upwarp thermally indistinguishable from an extensively fractured and magmatically intruded crust. Measurements of heat flow at great depth within and near the rift, insuring the absence of ground-water disturbances, will be needed to substantiate the extent and character of the thermal anomaly along the Rio Grande rift. On the basis of heat-flow data from northwestern New Mexico and western Colorado, we suggest a complex geothermal character associated with the eastern Colorado Plateau. Heat-flow measurements of about 1.5 HFU and less are typically associated with major structural basins. For example, our data within the central San Juan basin are normally 1.5 HFU and less (Fig. 2). Our heat-flow values in southwestern Colorado near the Blanding basin are 1.5 HFU and less. Heat-flow measurements by other investigators in northwestern Colorado within the Piceance basin are normally 1.5 HFU and less. On the basis of these data, we suggest variations in the crust and upper mantle of the Colorado Plateau which are associated with major structural basins — for example, mantle undulations, variations in crustal radioactivity, or large-scale crustal tectonic variations. Alternatively, the relatively low heat flow may result from disturbances such as ground-water movement or deep refraction of isotherms. Measurements at great depth within the basins are needed if we are to be more confident of this heat-flow pattern. Present data indicate a decrease in heat flow toward the center of the central San Juan basin. Measurements of radioactive heat generation in the crust are also needed to clarify the significance of these heat-flow values.

Heat-flow values between 2.0 and 2.5 HFU have been measured within the Colorado Plateau near laccoliths (Hesperus, near the La Plata Mountains — see Decker, 1969) and near some other intrusions (Table Mesa, near the Shiprock plug and dike system, Fig. 2; Gobernador, near the north-trending dike system east of Gobernador — see Sass and others, 1971a). Heat-flow values seem to increase to 2.0 to 2.5 HFU near the Zuni uplift (Fig. 2). Higher heat-flow values in the Colorado Plateau are apparently associated with some intrusions and perhaps major uplifts, and lower values are associated with major structural basins. Heat-flow values in the Colorado Plateau in areas other than these are normally 1.5 to 1.7 HFU.

Heat-flow values in western New Mexico generally increase southward from the central San Juan basin to the Basin and Range province (Fig. 4). This smooth regional trend is interrupted by a broad area of 2.0 to 2.5 HFU in west-central New Mexico near the Zuni uplift and the McCartys basalts (Fig. 3). In southwestern New Mexico, a major north-south heat-flow transition occurs between lat 34° and 33° N. This latter geothermal transition may be associated with a transition between the Colorado Plateau and the Basin and Range province. In southwestern New Mexico, a ripple in the thermal structure west of the central zone of high heat flow may result from variations of crustal fracturing and magmatic intrusion, variations in crustal radioactivity, or variations in the ground-water regime within the Basin and Range province.

EXPERIMENTAL PROCEDURE

Terrestrial heat-flow measurements were made by multiplying measured geothermal gradients from drill holes by the thermal conductivity of the rocks penetrated by the drill holes. Heat-flow sites were drill holes, sponsored by other organizations, for oil and mineral tests and fluid-level observation wells. This method of obtaining heat-flow sites may provide data that are perhaps less than random; it is, however, the most practical technique of acquiring heat-flow measurements. If sufficient data coverage can be obtained, biasing is less probable.

Geothermal gradients were calculated from temperatures measured at discrete vertical intervals in drill holes. Platinum resistance elements and thermistors, in conjunction with Mueller-type resistance bridges, were used to measure temperature. The absolute accuracy of measurement is probably ±0.05°C; the relative accuracy between two points 10 m apart in a well is probably an order of magnitude more accurate. Temperature-sensing systems were periodically calibrated at 0°C, with the use of a distilled-water circulating bath. Over several years the reproducibility of the ice point has been within ±0.05°C for all systems. Several times each year, compatibility between thermistor and platinum sensors was checked at other water temperatures in the circulating bath.

Temperature data were plotted as a function of depth, and the geothermal gradients believed representative of the site were analyzed. Disturbing effects caused by such phenomena as ground-water movement, climate, and vegetation changes were, we hope, noted and the associated data removed from the analyses. To determine the geothermal gradient, a least mean squares technique was applied to temperature data in linear thermal-gradient zones. If thermal fluxes were equivalent between several zones of a drill test, it was assumed that the determined heat flow was probably representative of the site. Vertical changes in the thermal conductivity at some sites were so frequent that it was necessary to correlate each segment of the temperature log with the respective thermal conductivity.

Thermal conductivity of both core and fragments was measured. Core samples consisted of wafers 1 to 2 cm long whose surfaces were lapped flat and parallel within ±0.005 cm. Core diameters normally ranged from 2.5 to 5.5 cm. The technique we used to measure the thermal conductivity of fragments is similar to that of Sass and others (1971b). The thermal-conductivity apparatus was regularly calibrated with fused and crystalline quartz and several intermediate well-known samples. The apparatus was also calibrated with fused quartz and other secondary standards in fragment form to ensure the reliability of fragment measurements. The accuracy of core measurements was ±5 percent.

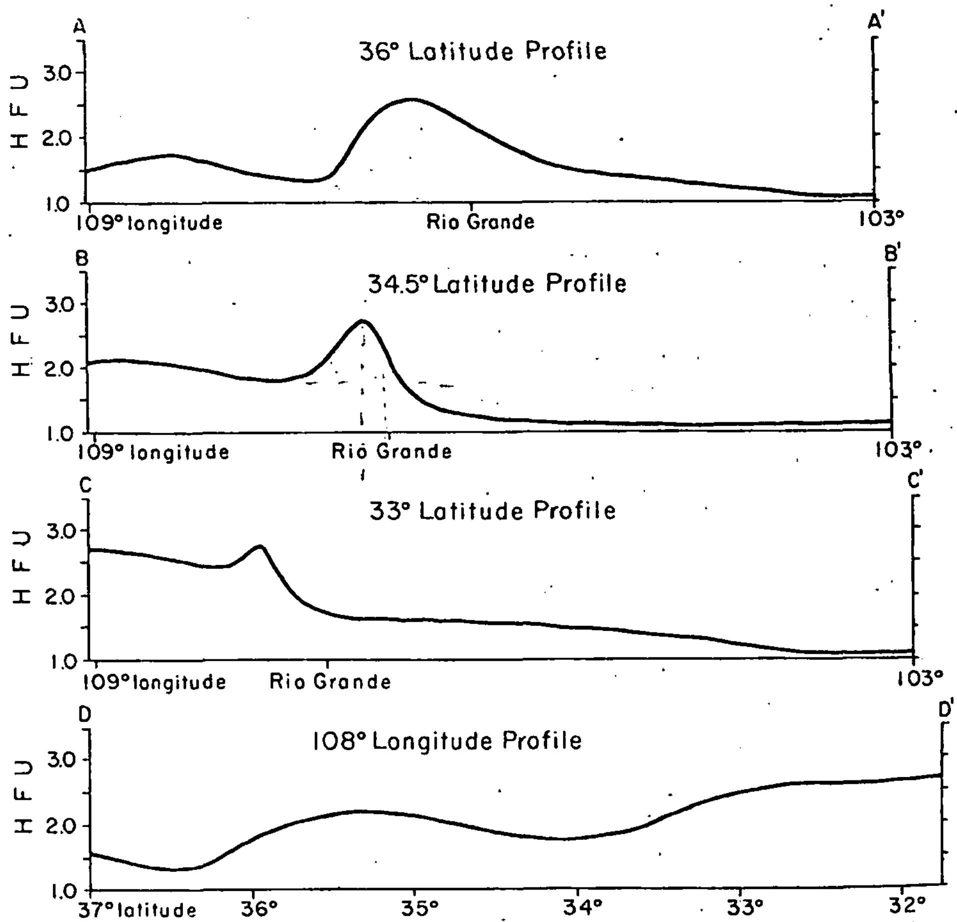

Figure 4. Terrestrial heat-flow profiles across New Mexico. Profiles are shown in Figure 3.

The accuracy of fragment measurements was ±10 to 15 percent if the porosity of the rock was known.

After correlating geothermal gradients with thermal-conductivity values, a best value of heat flow was chosen. We hope that the data are representative to ±20 percent; however, data with larger errors are applied in qualitative geothermal considerations of various areas.

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