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William J. Stone } New Mexico Energy Resources, 75

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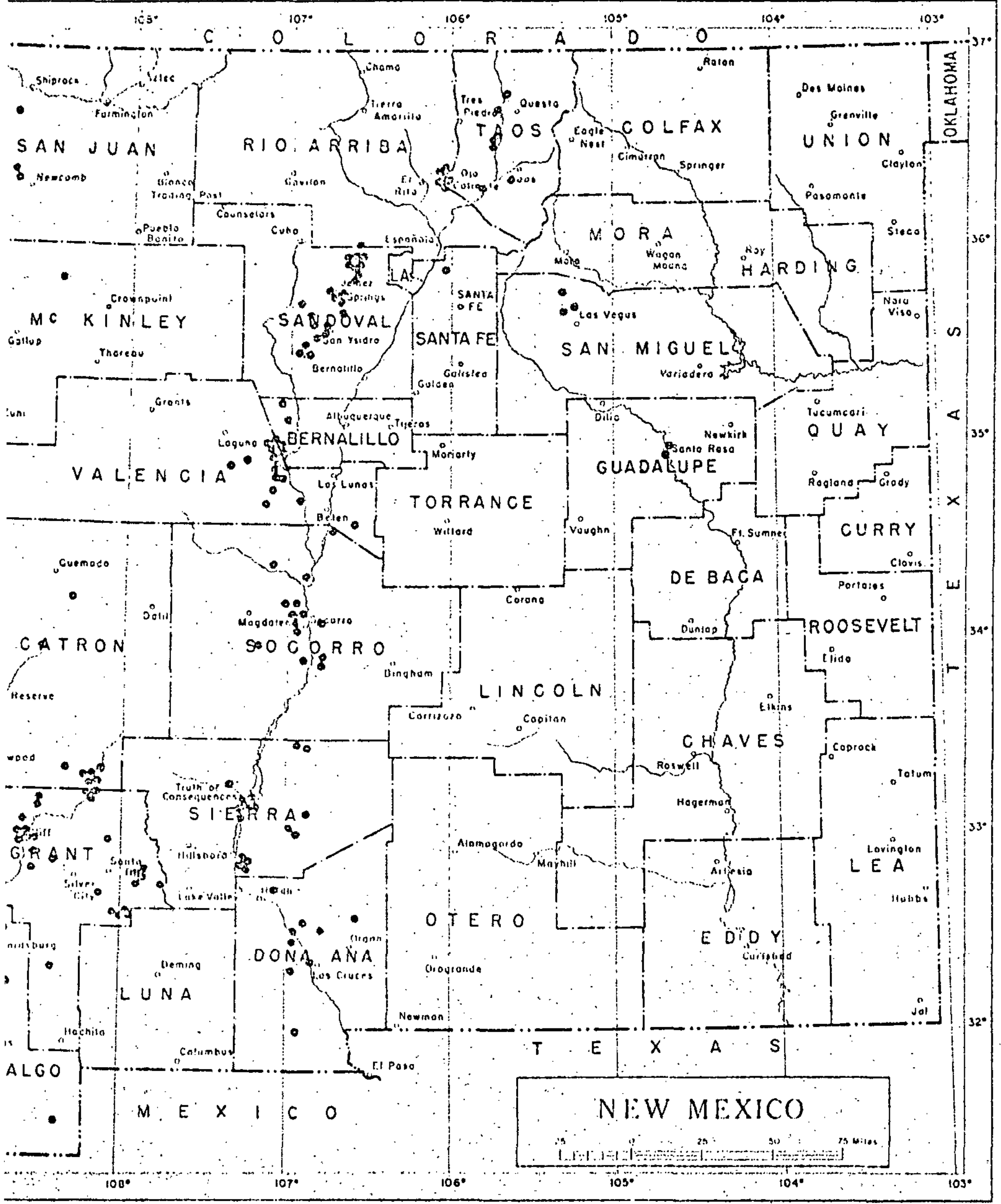
Geothermal—
A little known resource having interesting potential

NM Bur Mines ~~Circular~~ Bull. 107



URE 16–LOCATION OF THERMAL SPRINGS AND WELLS HAVING TEMPERATURES GREATER THAN 5°F.

OCCURRENCES

Geothermal reservoirs are complex and difficult to evaluate. Furthermore, the are local phenomena, therefore difficult to find. Based on recent studies, tw regions in New Mexico have geothermal potential: the region encompassing th Rio Grande valley and adjoining mountains, and the region encompassing th west-central and southwest part of the state.

The Rio Grande region is characterized by: mountain masses bordering, an uplifted above, the valley floor; with numerous hot springs having temperature greater than 65°F (fig. 16, Summers, 1965b); with heat flow values approximatel twice that of normal values for geologically stable areas (fig. 17, Reiter, an others, 1975); with intense tectonic and volcanic activity (Chapin, 1971); and wit locally intense seismic activity (Sanford, 1963).

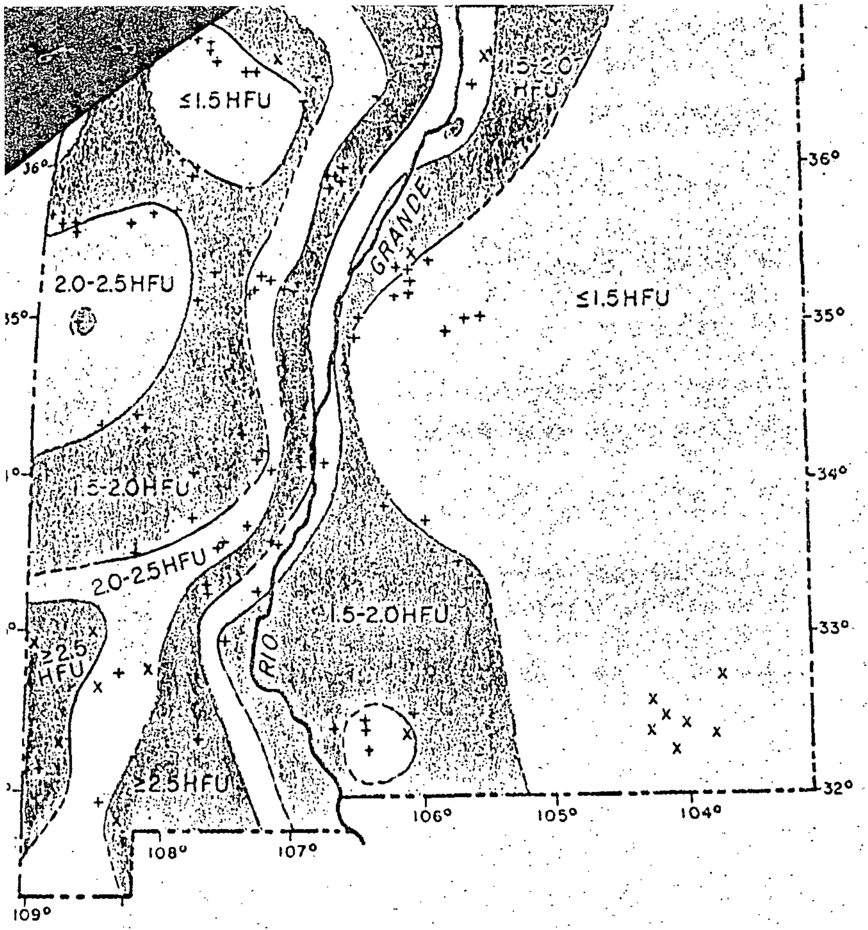
The west-central and southwest region is characterized by local areas of ho springs, by sites of approximately twice normal heat flow, by large ancien volcanoes (Elston and others, 1975), and by immense masses of volcanic rocks.

Chemical analysis of thermal spring waters, determination of terrestrial hea flow, monitoring of seismicity, measurement of earth resistivity, and geologi analysis of volcanic provinces are the major methods for evaluating regional an local geothermal potential. Numerous hot springs suggest the presence o significant geothermal waters. Chemical analyses of waters in hot springs ma provide possible geothermal reservoir temperatures and may be used to locat areas of high geothermal potential (Swanberg, 1975). Heat-flow values of twic normal suggest areas of regional geothermal potential, whereas heat-flow value of 5 to 10 times normal suggest areas of significant local geothermal potential Regions of high seismicity may relate to major tectonic and volcanic activity High seismicity may be related in some areas to geothermal phenomena. Th passage of electrical currents through the earth's near-surface crust is enhance (resistivity is reduced) in hot rock (Jiracek, 1974). Recent large-scale volcanism i often correlated with high subsurface temperatures.

UTILIZATION

NEW MEXICO

Presently the only use of New Mexico's geothermal energy is associated wit hot springs, many of which have been developed as small mineral baths or spa The most significant industrial activity is that being conducted by Union O Company in the Valles Caldera, an ancient volcano in the Jemez Mountains. Th wells drilled by Union Oil Company's Geothermal Division range in depth fro 6,000 to 9,000 ft, and cost from $500,000 to $1,000,000 per well. Of the 16 tes drilled, 6 are reported to have produced hot water and/or wet steam, wit temperatures around 200°F. The water has a brine content of about one-quart that of sea water, including much silica as well as carbonates and sulfates. T



URE 17—TERRESTRIAL HEAT-FLOW CONTOUR MAP. Contour interval, 0.5 HFU: +, sites measured
y New Mexico Institute of Mining and Technology; X, sites of other investigators. (*Source:* Reiter
nd others, 1975).

act a 55-megawatt electric generating complex, Union would need to prove a
year energy resource capacity from their wells (*Enchantment*, 1975). Ex-
imental stimulation of a geothermal reservoir is being carried out by Los
mos Scientific Laboratory on the west margin of Valles Caldera.

)ther interests in geothermal energy in New Mexico are reflected by the active
ing program. The valuable land areas are shown on fig. 18. Specific locations
tate geothermal leases may be obtained from the Commissioner of Public
ids in Santa Fe, and of federal leases from the U.S. Bureau of Land
nagement in Santa Fe.

'he greatest geothermal potential in New Mexico appears to be along the Rio
inde valley, coinciding with a geologic structure called the Rio Grande rift.
as of high heat flow and/or hot waters near or above 100°F are the Valles
dera, Socorro Mountain, Radium Springs, and Ojo Caliente. The greatest
sity of population also occurs along the Rio Grande valley. The future
trical and heating needs of some of this population might be served by

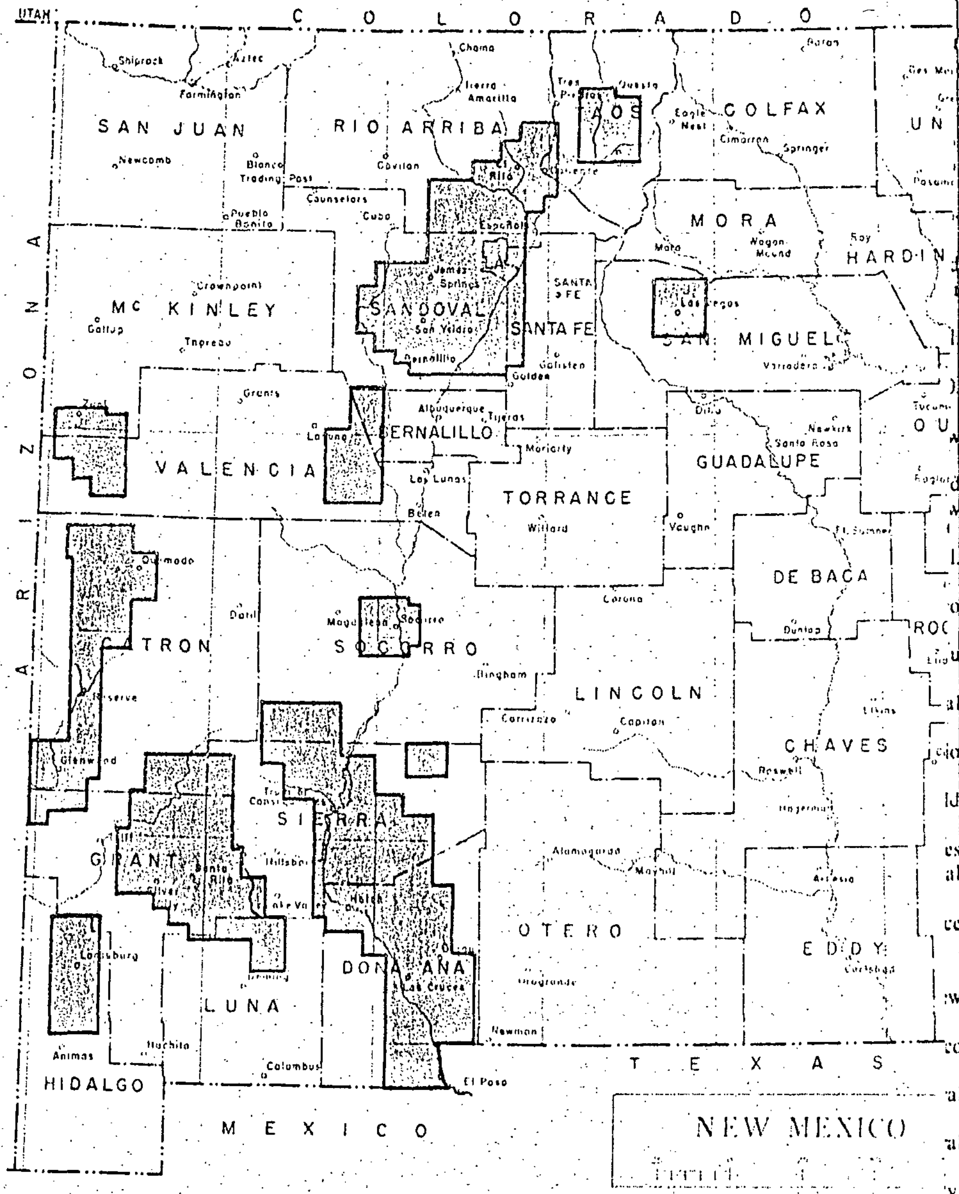


FIGURE 18—LOCATION OF GEOTHERMAL-RESOURCE LANDS (*Source:* State Land Office).

Other areas of very hot waters are located in southwest
Gila Hot Springs, Mimbres, and the Animas "Hot Spot"
ock area) southwest of Lordsburg.

work is needed before such energy resources can be accurately located
eloped. State, industrial, and federal groups working cooperatively on
studies as well as local detailed investigations to obtain hydrogeologic,
ical, and geochemical data could determine likely geothermal targets.
vironmental impact of exploitation and development for each area
careful evaluation. The results of present studies in the Valles Caldera
will be useful in forecasting development of geothermal energy for
ion of electric power in New Mexico. Use of thermal waters for space
in the near future should also be evaluated. Some of the many scientific
tions on geothermal energy in New Mexico are listed among the selected
ces at the back of this bulletin.

AREAS

ıse of geothermal energy to power energy plants is fairly recent in the
States. The first commercial geothermal power plant (now developed to
gawatts) was built in 1960 in The Geysers area in California, north of San
co. The first large geothermal power plant (now 340 megawatts) was
cted at Larderello, Italy in 1904. In the 1950's the geothermal fields of
aland were initially developed. Japan, Mexico, and Russia have built and
rating power plants using geothermal energy.

hree types of geothermal fields are hot water, dry steam, and dry rock.
water fields may be further divided into superheated water (wet steam)
se of lower temperatures (Berman, 1975):

Area	*Type*
Larderello, Italy	Dry steam
The Geysers, California	Dry steam
Wairakei, New Zealand	Wet steam
Cerro-Prieto, Mexico	(Superheated water)
Patho, Mexico	(Superheated water)

ıse of natural steam or superheated water that flashes to steam provides a
t source where the steam is passed through a screen to remove instream
s, then introduced into a turbine. A plant using this source requires no
plant, fueling facilities, or smokestack. The discharged waters, however,
ossibly introduce pollution problems. The Valles Caldera area being
d by Union Oil Company in New Mexico produces wet steam, only about
ent as efficient as the dry steam produced at The Geysers.

Selected References

Atwood, G., 1975, The strip mining of western coal: Scientific American, v. 233, no. 6, p. 23-29.

Berman, E. R., 1975, Geothermal Energy: Parkridge, New Jersey, Hayes Data Corporation.

Bieberman, R. A., Weber, R. H., Summers, W. K., Shomaker, J. W., and Kottlowski, F. E., 1975, Energy reserves and resources in New Mexico, *in* Annual Report July 1, 1973 to June 30, 1974: New Mexico Bureau Mines Mineral Resources, p. 22-26.

Brookins, D. G., 1975, Uranium and thorium resources, *in* Report of the committee on nuclea energy: Governor's Task Force, Santa Fe, New Mexico.

Chapin, C. E., 1971, The Rio Grande rift, Pt. 1: modifications and additions: New Mexico Geol. Soc., Guidebook 22nd Field Conf., p. 191-201.

Elston, W. E., Seager, W. R., and Clemons, R. E., 1975, Emory cauldron, Black Range, New Mexico source of the Kneeling Nun Tuff: New Mexico Geol. Soc., Guidebook 26th Field Conf., p. 283-292.

Enchantment, 1975, Geothermal exploration: New Mexico Rural Electrification Cooperative Association, Inc., v. 26, no. 3, July, p. 3-4.

Fassett, J. E., and Hinds, J. S., 1971, Geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico and Colorado: U.S. Geol. Survey, Prof. Paper 676, 76 p.

Finch, W. I., Butler, A. P., Armstrong, F. C., and Weissenborn, A. E., 1973, Uranium: U.S. Geol. Survey, Prof. Paper 820, p. 456-467.

Foster, R. W., 1975, Petroleum developments for 1974, *in* Annual Report July 1, 1974 to June 30, 1975: New Mexico Bureau Mines Mineral Resources, p. 22-23.

Foster, R. W. and Grant, P. R., 1974, The future of New Mexico's oil and gas resources: New Mexico Bureau Mines Mineral Resources, Resource Map 3.

Hilpert, L. S., 1963, Regional and local stratigraphy of uranium-bearing rocks, *in* Geology and technology of the Grants uranium region, compiled by the Society of Economic Geologists: New Mexico Bureau Mines Mineral Resources, Mem. 15, p. 6-18.

———, 1965, Uranium *in* Mineral and water resources of New Mexico, prepared by U.S. Geol. Survey: New Mexico Bureau Mines Mineral Resources, Bull. 87, p. 209-225.

Jiracek, G. R., 1974, Geophysical studies in the Jemez Mountains region, New Mexico: New Mexico Geol. Soc., Guidebook 25th Field Conf., p. 137-144.

Kelley, V. C., 1963, Geology and technology of the Grants uranium region: New Mexico Bureau Mines Mineral Resources, Mem. 15, 277 p.

Kottlowski, F. E., Beaumont, E. C., and Shomaker, J. W., 1975, New Mexico, *in* 1975 Keystone Coal Industry Manual: McGraw-Hill, Inc., New York, p. 585-593.

Reiter, M., Edwards, C. L., Hartman, H., and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado: Geol. Soc. America, Bull., v. 86, p. 811-818.

Sanford, A. R., 1963, Seismic activity near Socorro: New Mexico Geol. Soc., Guidebook, 14th Field Conf., p. 146-151.

Shomaker, J. W., Beaumont, E. C., and Kottlowski, F. E., 1971, Strippable low-sulfur coal resources of the San Juan Basin in New Mexico and Colorado: New Mexico Bureau Mines Mineral Resources, Mem. 25, 189 p.

Smith, M. C., Brown, D. W., and Pettitt, R. A., 1975, Los Alamos dry geothermal source demonstration project: Los Alamos Sci. Lab., Mini-Review 75-1, 4 p.

Staatz, M. H., and Olson, J. C., 1973, Thorium: U.S. Geol. Survey, Prof. Paper 820, p. 468-476.

Summers, W. K., 1965a, A preliminary report on New Mexico's geothermal energy resources: New Mexico Bureau Mines Mineral Resources, Circ. 80, 41 p.

———, 1965b, Chemical characteristics of New Mexico's thermal waters—a critique: New Mexico Bureau Mines Mineral Resources, Circ. 83, 27 p.

———, 1968, Geothermics—New Mexico's untapped resource: New Mexico Bureau Mines Mineral Resources, Circ. 98, 9 p.

———, in press, Catalog of thermal waters in New Mexico: New Mexico Bureau Mines Mineral Resources, Hydrologic Rept. 4.

Swanberg, C. A., 1975, Detection of geothermal components in ground waters of Doña Ana County, southern Rio Grande rift, New Mexico: New Mexico Geol. Soc., Guidebook 26th Field Conf., p. 175-180.

Trainer, F. W., 1975, Mixing of thermal and nonthermal waters in the margin of the Rio Grande rift, Jemez Mountains, New Mexico: New Mexico Geol. Soc., Guidebook 26th Field Conf., p. 213-218.

U.S. Bureau of Mines, 1974, The mineral industry in New Mexico in 1974, Mineral Industry Surveys, Annual Preliminary Report.

continued

Geothermal anomalies along the Rio Grande rift in New Mexico

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ABSTRACT

Heat-flow data suggest that there are regions along the Rio Grande rift where crustal temperatures are above those in neighboring areas. Magma bodies at 15 to 30 km, as predicted by several investigators, seem to provide reasonable sources of heat that could increase heat-flow values from 1.8 to about 2.5 HFU and somewhat higher. However, heat-flow values of 6.0 to 16.0 HFU occur at four locations along the Rio Grande rift; these values occur within geologic environments such as recent volcanic centers and the intersections of cauldron boundaries with large normal faults where upward heat transport by magmatic and/or ground-water movement is plausible. Test drillings of several kilometres are necessary to confirm the continuity with depth of these very high geothermal gradients and to relate them to their possible sources in the upper crust.

INTRODUCTION

The Rio Grande rift is a series of deeply filled en echelon grabens that trend south from Leadville, Colorado, past El Paso, Texas. The rift structure began to form about 24 to 29 m.y. ago along zones whose position was apparently influenced by late Paleozoic and Laramide uplifts (Chapin and Seager, 1975). Numerous studies suggest that the rift is a tectonically and volcanically active zone of deep-seated crustal weaknesses (Chapin and Seager, 1975; Cordell and Kottlowski, 1975; Cordell, 1976). Studies by Decker and Smithson (1975) and Reiter and others (1975) have shown that the Rio Grande rift is a high heat-flow region. From heat-production data, Edwards and others (1978) concluded that the high heat flow along the Rio Grande rift is not the result of anomalously high crustal radioactivity.

Table 1 presents basic subsurface temperature data from 17 new drill tests along the Rio Grande rift; from 11 of these drill tests, data are used to estimate the heat flow. Data are presented to three significant figures for calculation purposes; however, heat-flow values should be considered meaningful to only two significant figures. The experimental procedure for these heat-flow measurements and the evaluation criteria for the heat-flow estimates are given in Reiter and others (1975). Figure 1 shows heat-flow observation sites from several investigations of the Rio Grande rift in New Mexico.

GEOTHERMAL CHARACTERIZATION OF THE RIO GRANDE RIFT IN NEW MEXICO

Heat-flow data indicate a zone of high heat flow along the Rio Grande rift; this zone may be thought of as an envelope of heat-flow values greater than 2.5 HFU, although there are values less than 2.5 HFU within the envelope (Fig. 1). From the Colorado–New Mexico border south to about lat 35.5°N, the zone of high heat flow appears to coincide generally with the rift structure. From about lat 35.5°N to about lat 33.0°N, the zone appears to follow along the western part of the rift; south of lat 33.0°N, the zone seems to broaden. At four locations within the zone of high heat flow there are hot spots having heat flows in excess of 6.0 HFU (see Fig. 1).

It is likely that the geothermal environment within the zone of high heat flow along the Rio Grande rift is more dynamic than within areas bordering the rift structure. Heat-flow values within the high heat-flow zone are extremely variable, whereas values within areas bordering the zone are more consistent (Fig. 1). Large differences in heat flow over relatively small distances imply relatively shallow thermal sources—for example, in the Jemez Mountains and near Socorro.

Many of the critical characteristics of the high heat-flow zone are not known at present. It is possible that the high heat-flow zone is divided into segments (Sass and others, 1976), and in many places the width of the zone is uncertain. In the southern part of the rift structure the variability of the data, with many values less than 2.5 HFU, suggests that the zone is more complex than the ribbonlike trend to the north.

GEOLOGIC ENVIRONMENT NEAR DATA SITES

Sites having high heat flow (>2.5 HFU) along the Rio Grande rift are often located in geologic environments of a structural and volcanic nature that suggests the presence of magmatic heat sources relatively close to the Earth's surface (Fig. 1). On the other hand, many measurements of less than 2.5 HFU, primarily in the southern part of the rift, are in similar geologic

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TABLE 1. DATA FROM NEW TEMPERATURE MEASUREMENT SITES IN NEW MEXICO

Locality	Lat (N)	Long (W)	Elev (m)	Depth interval (m)	Thermal gradient ± st. dev. (°C/km)	No. of thermal conductivity samples	Type of thermal conductivity sample	Interval thermal conductivity ± st. dev. (mcal/cm·s·°C)	Interval heat flow ± st. dev. (μcal/cm²·s)	Quality of heat-flow value
Aden Hills	32° 09'	107° 03'	1325	150-230	46.6 ± 0.2	..	..	..	..	
Black Range 1	33° 17'	107° 43'	2098	180-230	43.8 ± 0.4	5	Core	5.37 ± 0.44	2.36 ± 0.21	B
Black Range 2	33° 17'	107° 43'	2065	80-200	39.7 ± 0.1	14	Core	5.86 ± 0.60	2.33 ± 0.24	B
Caballo	32° 53'	107° 15'	1451	30-221	26.5 ± 0.3	8	Cuttings	7.39 ± 1.33	1.96 ± 0.37	B
Jornado	32° 58'	107° 06'	1515	50-80	22.6 ± 0.4	..	..	..	..	
				90-140	30.5 ± 0.4					
Las Cruces N. E.	32° 22'	106° 40'	1366	130-350	40.1 ± 0.1	..	..	..	..	
Las Cruces S. W.	32° 08'	106° 51'	1280	150-210	20.6 ± 0.5	..	..	..	..	
				230-290	15.3 ± 0.3					
				300-360	48.3 ± 1.6					
				360-490	30.1 ± 0.2					
Monticello	33° 25'	107° 25'	1756	50-90	53.5 ± 3.6					
				90-135	44.8 ± 1.5	2	Core	8.11	3.64	B
Pecos 1	35° 45'	105° 39'	2463	80-101	14.1 ± 0.2					
				101-130	17.2 ± 0.3					
				130-170	24.3 ± 0.1	6	Core	8.74 ± 1.32	2.13 ± 0.34	B
Pecos 2	35° 45'	105° 39'	2470	30-60	46.9 ± 0.1					
				70-170	31.0 ± 0.2	7	Core	8.23 ± 1.47	2.56 ± 0.48	B
Pt. of Rocks 1	32° 48'	106° 52'	1356	170-230	53.3 ± 1.0	..	..	..	..	
				240-270	158. ± 4.					
				280-300	66.5 ± 0.5					
Pt. of Rocks 2	32° 48'	106° 54'	1334	180-200	29.9 ± 2.6	..	..	..	..	
				200-240	100. ± 5.					
				240-270	140. ± 1.					
				280-300	76.3 ± 5.2					
Organ N. 1	32° 27'	106° 36'	1530	80-310	29.5 ± 0.1	8	Core	10.1 ± 0.9	3.00 ± 0.28	
				310-840	36.7 ± 0.1	43	Core	8.81 ± 1.86	3.24 ± 0.68	B
Organ N. 2	32° 27'	106° 36'	1530	500-910	35.8 ± 0.1	25	Core	6.92 ± 0.65	2.48 ± 0.23	A
Orogrande S.	32° 25'	106° 07'	1378	100-600	34.5 ± 0.1	7	Core	6.36 ± 0.82	2.20 ± 0.28	A
San Diego Mt. 1	32° 37'	106° 58'	1303	30-60	190. ± 3.	8	Cuttings	7.20 ± 1.09	13.7 ± 2.3	
				80-140	205. ± 1.	8	Cuttings	7.87 ± 0.82	16.1 ± 1.8	B
San Diego Mt. 2	32° 37'	106° 58'	1353	41-61	209. ± 2.					
				61-140	218. ± 1.	6	Cuttings	6.99 ± 1.35	15.3 ± 3.0	B

environments. Therefore, it is generally necessary to consider convective heat transfer by ground-water movement as an additional and highly variable factor in the near-surface geothermal gradients at sites along the Rio Grande rift. Data at Monticello Canyon No. 1 (2.0 HFU) and Monticello Canyon No. 2 (4.7 HFU) (Reiter and others, 1975), only several hundred metres apart, indicate the potential for local abstraction of near-surface heat flow and exemplify the problems in interpreting near-surface heat flow in a structurally and hydrologically complex environment.

Heat-flow values greater than 6.0 HFU were measured within the high heat-flow zone (Fig. 1) of the Jemez Mountains (three sites; Reiter and others, 1976), Socorro Peak (Reiter and Smith, 1977), San Diego Mountain (two sites, this paper), and Mirage (Reiter and others, 1975). Heat flows of 5.3 and 4.7 HFU were measured at Dixon and Monticello Canyon No. 2 (Reiter and others, 1975). The San Diego Mountain and Socorro Peak sites are both on intersections of large normal faults with cauldron boundaries of Oligocene age (Seager, 1973; Chapin and Seager, 1975; Chapin and Chamberlin, 1976). The Jemez Mountains sites are within several kilometres of the Valles caldera, active in Pleistocene and Holocene time (Doell and others, 1968). The Mirage site is within several kilometres of a large normal fault, as are the sites at Dixon and Monticello Canyon No. 2. It should be noted, however, that heat-flow values less than 2.5 were estimated at Caballo (2.0 HFU, this paper) and at Big Red Canyon (1.3 HFU; Reiter and others, 1975) within geologic environments that are similar to those at San Diego Mountain and Socorro Peak.

Elevated geothermal gradients continue to a depth of several kilometres in the Jemez Mountains, as demonstrated by the commercial steam wells in the Valles caldera (Stone and Mizell, 1977). From the history of Quaternary eruptions (Doell and others, 1968) and the very high geothermal gradients, it is probable that the heat source in the Jemez Mountains is magmatic and is within the upper crust. However, the continuation with depth of the very high near-surface geothermal gradients at Socorro Peak, San Diego Mountain, and Mirage is not certain. Temperatures at these sites have not been measured at depth, and the cauldron structures at Socorro Peak and San Diego Mountain are much older than the Valles caldera (Seager, 1973; Chapin and Seager, 1975; Chapin and Chamberlin, 1976). Consequently, one must consider several alternative explanations for the very high near-surface geothermal gradients at Socorro Peak, San Diego Mountain, and Mirage. First, it is possible that elevated temperature gradients near the surface are caused by warm ground water moving upward along the fracture zones associated with these sites. Ground water could be warmed under the influence of (1) near-normal geothermal gradients in deeper levels of the fracture zones or (2) somewhat above-normal temperature gradients associated with magmatic intrusion into the lower crust. Alternatively, high near-surface temperature gradients may be caused primarily by magmatic intrusion into the upper crust, with or without associated vertical convective heat transfer by ground water. The importance of vertical heat convection by ground water within geothermal areas has been discussed by many workers (for example, Helgeson, 1968; Renner and others, 1975).

DISCUSSION

Several studies have related to the possibilities of magma bodies existing within the upper crust in the Western United States (Blackwell and Baag, 1973; Lachenbruch and others, 1976; Shuleski and others, 1977). If temperature gradients of about 200 °C/km (for example, San Diego Mountain) were to continue with depth, it would be reasonable to suppose that molten rock would be encountered within 5 to 6 km of the surface. The rapid lateral decrease in heat flow at Socorro and the Jemez Mountains supports the concept of relatively shallow thermal sources at these high heat-flow sites. A one-dimensional heat-conduction calculation shows that it is unlikely that magmatic bodies at depth could be directly responsible for very high near-surface temperature gradients. If an initial average temperature gradient in the crust of 30 °C/km and heat transfer only by conduction are assumed, a steady-state, continuous heat source such as magma at 15-km depth, which remains 100 to 500 °C hotter than the in situ rock, could only increase the geothermal gradient by a maximum of 6.7 to 33 °C/km (solidus curves in the presence of excess water in Wyllie, 1971; and Lambert and Wyllie, 1972). Therefore, if the background heat flow is 1.8 HFU, assuming a near-surface thermal conductivity of 6 mcal/(cm•s•°C), then the observed heat flows greater than 6 HFU

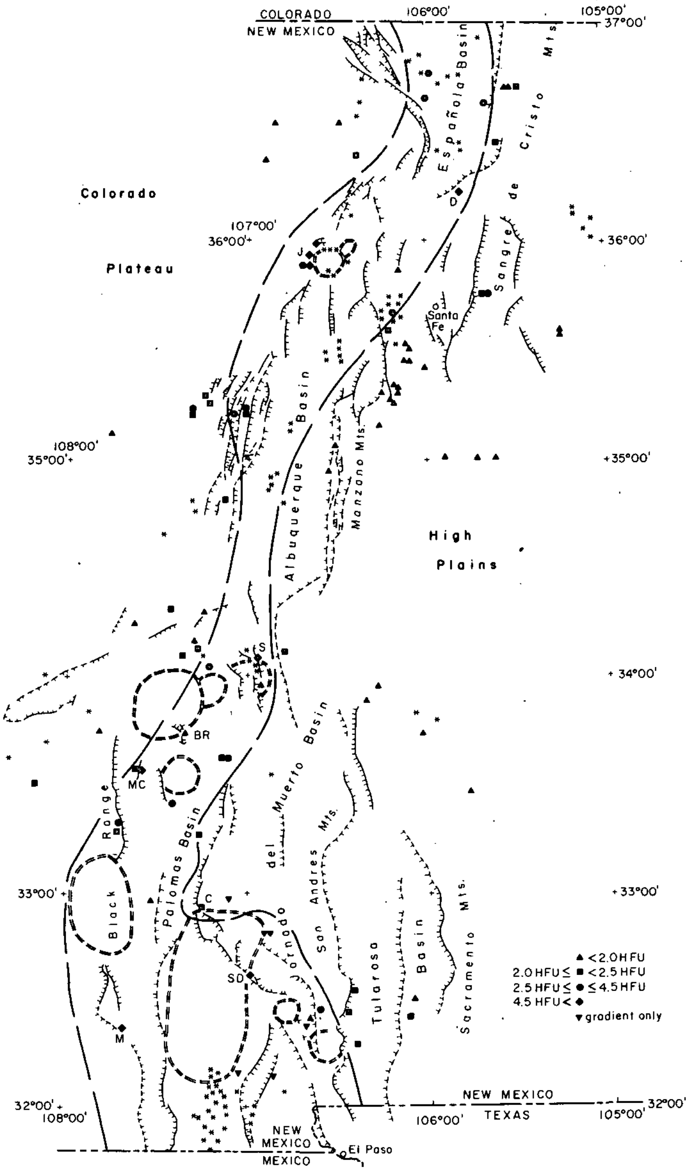

Figure 1. Heat-flow data and geologic features along the Rio Grande rift, New Mexico. Heat-flow sites from Reiter and others (1975), Edwards and others (1978), Reiter and others (1976), Reiter and Smith (1977), and this paper. Geologic features along the Rio Grande rift after Woodward and others (1975), Socorro Peak cauldron boundary by Chapin and Chamberlin (1976). From north to south, sites labeled are D, Dixon; J, Jemez Mountains; S, Socorro Peak; BR, Big Red Canyon; MC, Monticello Canyon 1 and Monticello Canyon 2; C, Caballo; SD, San Diego Mountain; and M, Mirage. Hachured lines indicate normal faults, hachures on downthrown side; solid line through points at Monticello Canyon indicates a high-angle fault; asterisks indicate volcanic centers; double broken lines encircle cauldron boundaries; heavy broken lines indicate the high heat-flow envelope.

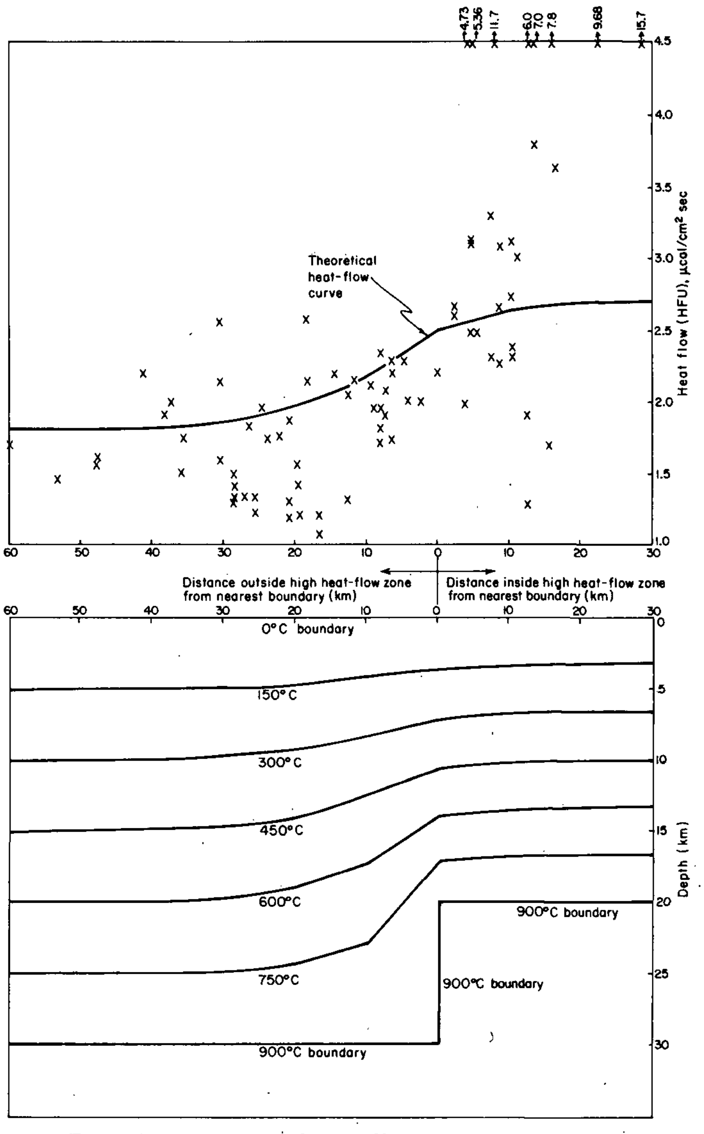

Figure 2. A steady-state finite-difference numerical model (below) of isotherms that would result from a 300 °C temperature increase (from 600 °C to 900 °C) at 20-km depth under the Rio Grande rift. An initial temperature gradient of 30 °C/km and a near-surface thermal conductivity of 6 mcal/cm•s•°C are assumed. A resulting theoretical heat-flow curve is shown above on a plot of measured data within and near the high heat-flow zone. (Dixon and San Diego Mountain sites are average values.)

that are due to direct conduction must result from thermal anomalies that are significantly shallower than 15 km. Nevertheless, it is probable that ground water transports heat vertically by convection at most sites characterized by high heat flow, and this convective thermal regime can make the interpretation of shallow thermal measurements ambiguous. Whether very high geothermal gradients at most of the high heat-flow sites are induced directly or secondarily by magmatic sources relatively close to the Earth's surface or primarily by nonmagmatic hydrological phenomena in deep fracture systems may require tests in boreholes several kilometres deep.

Several studies predict magma bodies within the crust under the Rio Grande rift at 15 to 30 km (Lipman, 1969; Sanford and others, 1973; Decker and Smithson, 1975). Within the heat-flow anomaly in the Rio Grande rift, about twice as many heat-flow values are above 2.5 HFU as are below. This may imply that our data are biased toward areas with high heat flow or, alternatively, that background crustal temperatures are indeed hotter along the Rio Grande rift than in neighboring areas. A straightforward calculation suggests that the heat-flow values of about 2.5 HFU may be due to magmatic bodies at 15 km or more, in contrast to sources for the local high heat-flow anomalies. If initial geothermal gradients are assumed to have been 30 °C/km and initial heat flows to have been 1.8 HFU, then an increase of about 12 °C/km in the geothermal gradient would be required to raise the regional heat flow to 2.5 HFU. Although there is considerable uncertainty in estimating the thermal regime of a deep magma body and its surroundings through time, as well as the temperature differential between the magma and host rock, it would appear reasonable to believe (using the calculation method of the preceding paragraph) that heat flows of about 2.5 HFU and somewhat greater could be induced by the introduction of magma sources of sufficient thermal capacity (volume) at 15 to 30 km. The projected half-width of the thermal anomaly along the Rio Grande rift at many locations (15 to 35 km) supports this conclusion (Reiter and others, 1975).

Figure 2 shows a steady-state model of isotherms in a thermal regime developed in the Rio Grande rift with an initial temperature gradient of 30 °C/km (heat flow of 1.8 HFU), which is subjected to a 300 °C temperature increase at a depth of 20 km. A theoretical heat-flow curve based on the described model is shown on a plot of heat-flow data measured along the rift. The average heat flow outside the high heat-flow zone as tentatively indicated in Figure 2 is 1.77 ± 0.38 HFU. The unadjusted average heat flow inside this zone is 4.20 ± 3.25 HFU. However, if we were to include only values between 2.25 and 3.50 HFU inside the high heat-flow zone, the average heat flow is 2.73 ± 0.35 HFU. Measurements within these limits are less scattered than the higher and lower heat-flow values, and it is reasonable to assume that these measurements are indicators of background heat flow of 2.7 HFU for many regions along the Rio Grande rift. Values outside of the high and low limits probably are caused by magmatic intrusion close to the surface and/or near-surface hydrothermal circulation. Deep ground-water circulation can result in a variety of temperature distributions at depth, but this aspect of the thermal regime in the Rio Grande rift has yet to be adequately explored.

REFERENCES CITED

Blackwell, D. D., and Baag, C. G., 1973, Heat flow in a "blind" geothermal area near Marysville, Montana: Geophysics, v. 38, p. 941-956.

Chapin, C. E., and Chamberlin, R. M., 1976, Geologic road log of the Socorro-Magdalena area, New Mexico: Guidebook for Field Trip No. 4, Ann. Mtg., Rocky Mtn. Section, Geol. Soc. America, Albuquerque, N.M.

Chapin, C. E., and Seager, W. R., 1975, Evolution of the Rio Grande rift in the Socorro and Las Cruces areas, 26th Field Conf., 1975: New Mexico Geol. Soc., p. 297-321.

Cordell, L., 1976, Aeromagnetic and gravity studies of the Rio Grande graben in New Mexico between Belen and Pilar: New Mexico Geol. Soc. Spec. Pub. 6, p. 62-70.

Cordell, L., and Kottlowski, F. E., 1975, Geology of the Rio Grande graben, Penrose Conference Report: Geology, v. 3, p. 420-421.

Decker, E. R., and Smithson, S. B., 1975, Heat flow and gravity interpretation across the Rio Grande rift in southern New Mexico and West Texas: Jour. Geophys. Research, v. 80, p. 2542-2552.

Doell, R. R., Dalrymple, G. B., Smith, R. L., and Bailey, R. A., 1968, Paleomagnetism, potassium-argon ages, and geology of the rhyolites and associated rocks of the Valles caldera, New Mexico: Geol. Soc. America Mem. 116, p. 211-248.

Edwards, C. L., Reiter, M., Shearer, C., and Young, W., 1978, Terrestrial heat flow and crustal radioactivity in northeastern New Mexico and southeastern Colorado: Geol. Soc. America Bull. (in press).

Helgeson, H. C., 1968, Geologic and thermodynamic characteristics of the Salton Sea geothermal system: Am. Jour. Sci., v. 266, p. 129-166.

Lachenbruch, A. H., Sass, J. H., Munroe, R. J., and Moses, T. H., Jr., 1976, Geothermal setting and simple heat conduction models for the Long Valley caldera: Jour. Geophys. Research, v. 81, p.769-784.

Lambert, I. B., and Wyllie, P. J., 1972, Melting of gabbro (quartz eclogite) with excess water to 35 kilobars, with geological applications: Jour. Geology, v. 80, p. 693-708.

Lipman, P. W., 1969, Alkalic and tholeiitic basaltic volcanism related to the Rio Grande depression, southern Colorado and northern New Mexico: Geol. Soc. America Bull., v. 80, p. 1343-1353.

Reiter, M., and Smith, R., 1977, Subsurface temperature data in the Socorro Peak KGRA, New Mexico: Geothermal Energy Mag., v. 5, p. 37-41.

Reiter, M., Edwards, C. L., Hartman, H., and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande rift, New Mexico and southern Colorado: Geol. Soc. America Bull., v. 86, p. 811-818.

Reiter, M., Weidman, C., Edwards, C. L., and Hartman, H., 1976, Subsurface temperature data in Jemez Mountains, New Mexico: New Mexico Bur. Mines and Mineral Resources Circ. 151, 16 p.

Renner, J. L., White, D. E., and Williams, D. L., 1975, Hydrothermal convection systems: U.S. Geol. Survey Circ. 726, p. 5-57.

Sanford, A. R., Alptekin, O. S., and Toppozada, T. R., 1973, Use of reflection phases on microearthquake seismograms to map an unusual discontinuity beneath the Rio Grande rift: Seismol. Soc. America Bull., v. 63, p. 2021-2034.

Sass, J. H., Diment, W. H., Lachenbruch, A. H., Marshall, B. V., Munroe, R. J., Moses, T. H., Jr., and Urban, T. C., 1976, A new heat flow contour map of conterminous United States: U.S. Geol. Survey Open-File Rept. 76-756, 24 p.

Seager, W. R., 1973, Resurgent volcano-tectonic depression of Oligocene age, south-central New Mexico: Geol. Soc. America Bull., v. 84, p. 3611-3626.

Shuleski, P. J., Carabella, F. J., Rinehart, E. J., Sanford, A. R., Wallace, T. C., and Ward, R. M., 1977, Seismic studies of shallow magma bodies beneath the Rio Grande rift in the vicinity of Socorro, New Mexico: Geol. Soc. America Abs. with Programs, v. 9, p. 73.

Stone, W. J., and Mizel, N. H., 1977, Geothermal resources of New Mexico: A survey of work to date: New Mexico Bur. Mines and Mineral Resources Open-File Rept. 73, p. 20.

Woodward, L. A., Callender, J. F., Gries, J., Seager, W. R., Chapin, C. E., Shaffer, W. L., and Zilinski, R. E., 1975, Tectonic map of the Rio Grande region, Colorado-New Mexico border to Presidio, Texas, 26th Field Conf., 1975: New Mexico Geol. Soc., in pocket.

Wyllie, P. J., 1971, Experimental limits for melting in the Earth's crust and upper mantle, *in* Heacock, J. G., ed., The structure and physical properties of the Earth's crust: Am. Geophys. Union Geophys. Mon. 14, p. 279-301.

ACKNOWLEDGMENTS

Reviewed by Charles E. Chapin, Lindrith Cordell, and John H. Sass. The following organizations gave permission to make heat-flow measurements in wells under their supervision and to present data in Table 1: ASARCO Inc., Conoco Minerals, Exxon Minerals, Louisiana Land and Exploration, Parnasse, Perry-Knox and Kaufman, Rocky Mountain Energy, and the U.S. Geological Survey. The cooperation of many other organizations has been cited in previous works where the data were initially tabulated (Fig. 1) This study was supported in part by National Science Foundation Grant GI 32482, New Mexico Energy Resources Board, and New Mexico Bureau of Mines and Mineral Resources.

MANUSCRIPT RECEIVED JULY 7, 1977

MANUSCRIPT ACCEPTED NOVEMBER 17, 1977