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Christian S. Smith

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GEOPHYSICS, GEOLOGY AND GEOTHERMAL LEASING STATUS OF THE LIGHTNING DOCK KGRA, ANIMAS VALLEY, NEW MEXICO

CHRISTIAN SMITH
University of Utah Research Institute
Earth Science Laboratory
Salt Lake City, Utah

INTRODUCTION

Four stock wells drilled in sec. 7, T.25S., R.19W., Animas Valley, New Mexico in 1948 hit steam and boiling water at depths of less than 30 m. The wells tapped water and steam at 101.5°C from a zone of alluvium 5-10 m thick which overlies a lithic rhyolitic tuff. These wells are referred to as "hot wells." There are no other surface manifestations of an active hydrothermal system in the Animas Valley.

The hot wells have prompted the geothermal industry to file both competitive and noncompetitive lease applications for rights to the geothermal resource in the Animas Valley. The Geothermal Steam Act of 1970 specifies that where areas of sections included within more than one lease application overlap by more than 50 percent, the overlapped area is designated a Known Geothermal Resource Area (KGRA) (fig. 1). This area has been denoted the Lightning Dock KG RA; Lightning Dock Mountain is a nearby peak in the Pyramid Mountains.

This article presents geophysical and geologic data collected in the area and attemptes to show that geologic features caused by superimposed but unrelated tectonic events control the occurrence of hot water. It also briefly discusses the interest and activity of the geothermal industry in the area.

GEOLOGIC SETTING

The Animas Valley is an elongated north-south graben within the Basin and Range province. At the site of the hot wells, the valley is about 18 km wide and is flanked by the Peloncillo Mountains on the west and the Pyramid Mountains on the east (fig. 1).

The Peloncillo Mountains consist of Precambrian granite, Paleozoic and early Cretaceous sedimentary rocks, Tertiary intrusive rocks, and late Cretaceous and Tertiary volcanic rocks (Gillerman, 1958). The Basin and Range system of faults which bounds the Peloncillo Mountains horst block can be observed south of the area shown in Figure 2 (Gillerman, 1958).

The Pyramid Mountains are a complex pile of volcanic and intrusive rocks. Flege (1959) shows the part of the range indicated in Figure 2 to be Cretaceous to late Tertiary volcanic rock, and some of the silicic volcanic rocks to be younger than Basin and Range faulting. Flege completed his work well before Smith and Bailey (1968) explained their concept of resurgent cauldrons. Deal and Elston (1978a) mapped the geology of the Pyramid Mountains and found evidence for a cauldron. Their results show no volcanic rocks younger than Oligocene in the Pyramid Mountains and none younger than Basin and Range faulting.

According to Deal and Elston (1978a), the Pyramid Mountains contain a thick accumulation of ash-flow tuff within an inner cauldron. This inner cauldron is bordered by three arcuate zones of ring-fracture domes, flows, chaotic breccias and moat deposits. Figure 2 schematically shows the approximate locations of the mappable limits of the inner cauldron wall one the outer ring-fracture zone. While much of the inner cauldror is thought to be exposed in the Pyramid Mountains, only the northeastern third of the ring-fracture zones can be seen. Evidently northwest-trending Basin and Range faults have transected the cauldron, dropping its western half below the present Animas Valley. Deal and Elston (1978a) have named this cauldron the Muir cauldron (see Deal and others, this guidebook).

Basin and Range faults along the Pyramid Mountain front are sites of hydrothermal manganese and fluorite veins dated at Miocene or younger (Elston, 1965). The veins are near the present surface and extend intermittently from south of the international border to Caprock Mountain, 70 km north of the Lightning Dock KGRA. Fluorspar-bearing veins at the foot of Lightning Dock Mountain are only 5 km east of the hot wells.

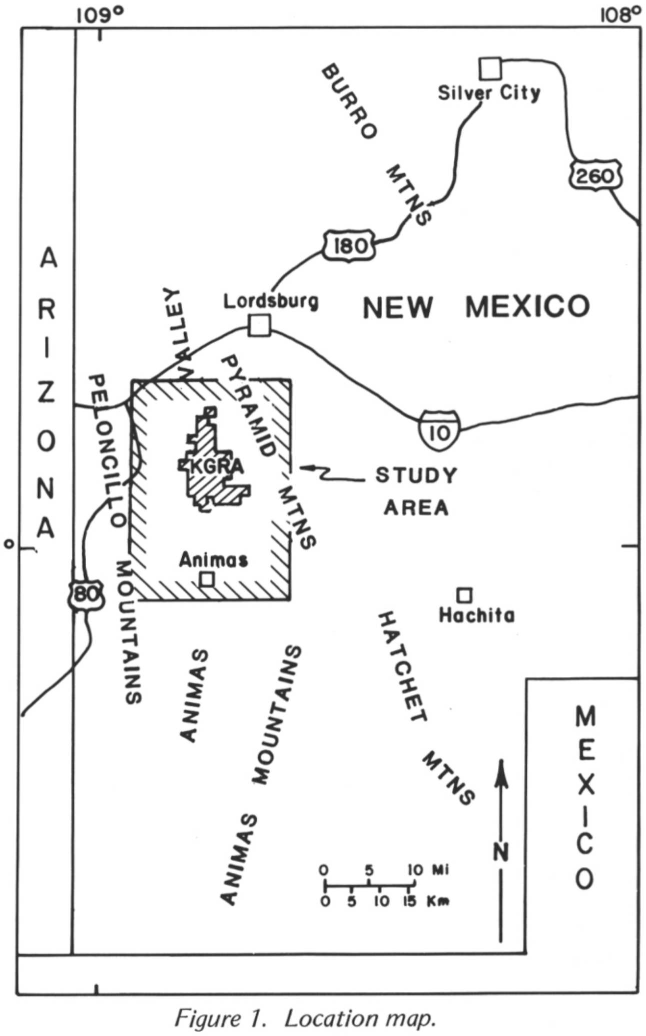
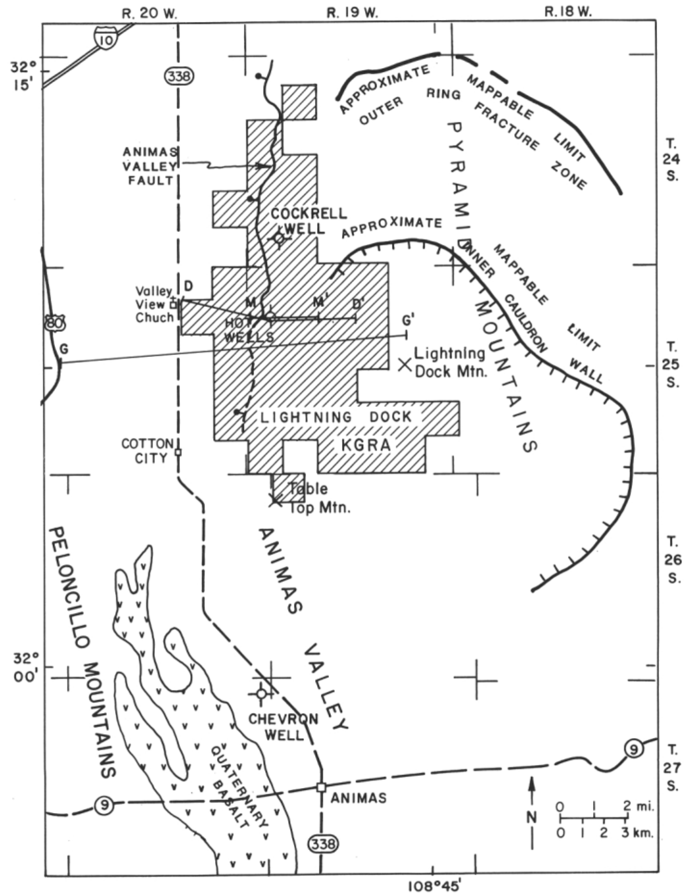


Figure 1. Location map.



Location of Quaternary Basalt from Reeder, 1957. Location of Animas Valley Fault and limits of Muir Cauldron from Deal and Elston, 1978.

Figure 2. Lightning Dock Known Geothermal Resource Area (KGRA), locations of sections and some generalized geology.

The hot water pumped by the hot wells contains about 1,100 milligrams per liter (mg/L) total dissolved solids but as much as 13 mg/L fluoride (Preslar, 1978). The high fluoride content of the water and its proximity to Neogene fluorspar veins suggests that the hot wells may tap a remnant of a larger and largely extinct hydrothermal system.

Table 1 is a log of the Cockrell Corporation No. 1 Federal Pyramid oil test well drilled about 3 km north of the hot wells (fig. 2). Rock units encountered were valley fill, Tertiary volcanic rock, Paleozoic sedimentary rocks and Precambrian rock. Possible reservoir rocks for the hot water include Paleozoic limestones and perhaps permeable tuffs within the 1,200 m-thick volcanic sequence. The well log of a heat-flow hole 300+ m deep drilled by Chevron Resources Company in sec. 1, T.27S., R.20W. (fig. 2) indicates the well was drilled entirely in clayey and gravelly sands. Neither hot water nor anomalous thermal gradients were reported for this well.

A late Quaternary basalt crops out south of the town of Animas (fig. 2). There is no direct evidence that relates this basalt to the occurrence of hot water.

Reeder (1957) was the first to discuss the recent fault near the hot wells (fig. 2). This fault is subparallel to the front of the Pyramid Mountains and displaces late Pleistocene to early Holocene surfaces and probably represents only the most

Table 1. Descriptive log of the Cockrell Corporation No. 1 Federal Pyramid oil test well, 24S.19W.31.230 (after Summers, 1976).

Depth (m)	Description
0-576	Valley fill
576 1,766	Volcanic rock
1,766 2,173	Paleozoic rock
2,173 – 2,254	Precambrian rock

recent episode of continuing Basin and Range faulting. S. G. Wells, in Deal and Elston (1978a), has informally named this fault the Animas Valley fault, the name which will be used in this article. Reeder (1957) was also the first to suggest that the fault near the hot wells may provide a structural control for the ascent of steam and hot water. Many of the geophysical investigations within the valley have attempted to assess this hypothesis.

GEOPHYSICAL SETTING

Prior to Reeder's (1957) hydrologic study, Kintzinger (1956) conducted a shallow temperature and temperature-gradient survey in the area surrounding the hot wells. Kintzinger (1956) showed an isolated eye of highest temperature near the southern hot well and a fanlike pattern of slightly lower temperatures spreading 3 km to the north. Thermal radiation associated with the hot water was detected by an airborne infrared profile (Strangway and Holmer, 1966). The infrared profile is shown together with a cross section of Kintzinger's map in Figure 3.

The bottom profile in Figure 3 (M-M' of fig. 2) is one of five residual magnetic anomaly profiles discussed by Preslar (1978). Each of these magnetic profiles reveals a magnetic high about 1 km east of the hot wells. Preslar (1978) suggested that the magnetic anomaly may be caused by a westward dipping dike within a north-south trending fault zone. He also suggested that faults that controlled the emplacement of a dike may also control the occurrence of the hot water. Since the magnetic anomaly does not coincide with the thermal anomaly measured by Kintzinger (1956) and Strangway and Holmer (1966), the inferred dike cannot be the heat source for the hot water.

The complete Bouguer gravity anomaly map of Preslar (1978) is shown in Figure 4. This map shows data for the Animas Valley and parts of adjoining mountain ranges. The gravity map reveals the general shape of basement rock below valley fill. Gravity values north and south of Valley View Church are lowest where low-density valley fill is interpreted to be thickest. Values increase toward the Peloncillo and Pyramid Mountain fronts that flank the valley.

The steep gravity gradients west of Valley View Church and north of Lightning Dock Mountain are typical of the Basin and Range province. High-angle normal faults probably form the Animas Valley graben. The high gravity values surrounding and south of Table Top Mountain are atypical. The northwest-trending gradients that define the eastern edge of this gravity high swing to the northeast near Cotton City and pass through the vicinity of the hot wells. This arcuate zone of steep gravity gradients defines an area south and east of the hot wells and Cotton City where rocks more dense than valley fill must be present at a relatively shallow depth. North and south of

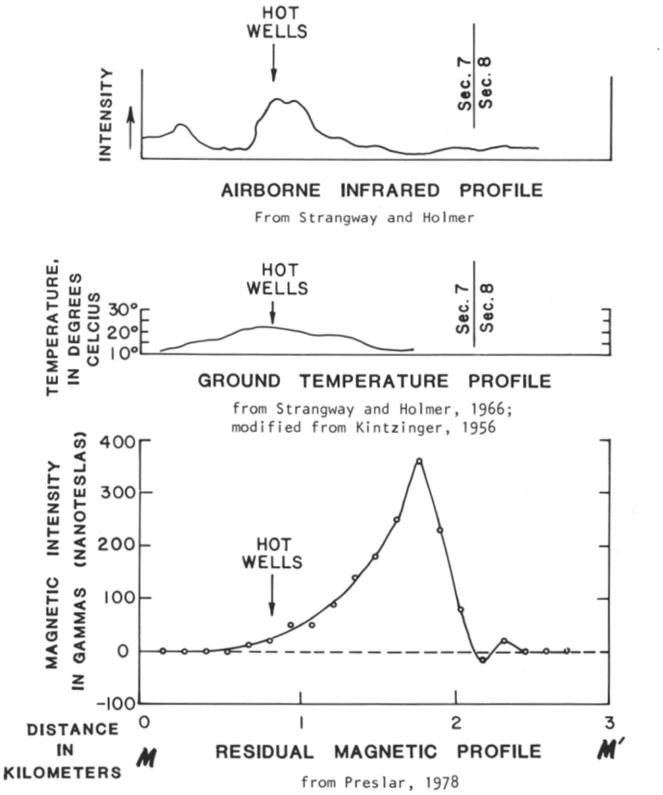


Figure 3. Profiles of infrared intensity, ground temperature and residual magnetic intensity.

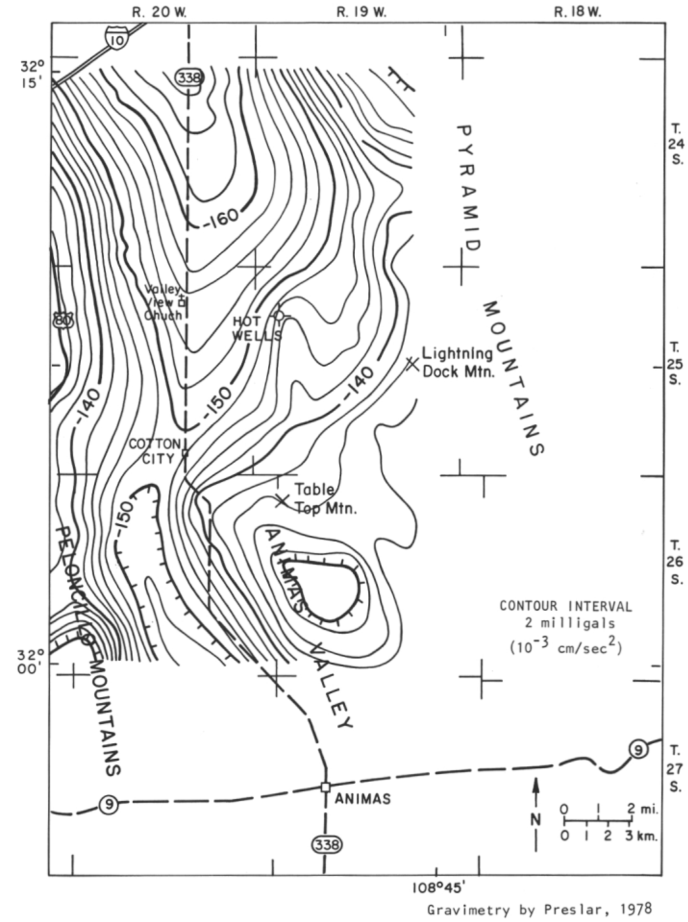


Figure 4. Complete Bouguer gravity.

Valley View Church, more than 700 m of fill can be expected, whereas less than 160 m can be expected southeast of Cotton City. The gravity gradients resume their typical northwesterly trend north of Lightning Dock Mountain.

At the hot wells, a north-trending ridge of higher gravity interrupts the arcuate anomaly pattern. This gravity ridge parallels the magnetic anomaly described by Preslar (1978) shown in cross section in Figure 3. The combination of gravity and magnetic highs means that this local anomaly cannot be mineralization deposited by hot water (Preslar, 1978). The gravity anomaly, but not the magnetic anomaly, is probably associated with lithic rhyolitic tuff found during drilling of the hot wells. To evaluate this possibility, a distribution of estimated rock densities in grams per cubic centimeter (g/cm^3) can be assumed and mathematically fit to the observed data. The valley fill is assumed to possess no internal density contrasts. The observed Bouguer gravity from data along a line about 1.5 km south of the hot wells (G-G' of fig. 2) is shown by the solid line of Figure 5; the dashed line is the theoretical gravity from the three-dimensional model shown in cross section in Figure 6. Figures 5 and 6 were prepared by Arthur L. Lange of Amax Exploration, Inc.

Figure 6 shows bedrock on the west to possess a density contrast of 0.6 g/cm^3 and to rise in a series of steps simulating Basin and Range normal faults. A similar faulted pattern is not evident in the model or to the east of the hot wells. Rather, rock with a density contrast of 0.4 g/cm^3 reaches within 30 m of the surface about 1 km east of the hot wells (Lange, 1978, written commun.). Other gravity cross sections reveal shallow bedrock forming a north-trending ridge (Lange, 1978, written commun.; Preslar, 1978, oral commun.). On the east, rock associated with the Pyramid Mountains may possess a density contrast of 0.55 g/cm^3.

Electrical resistivity is frequently used in geothermal areas to locate rocks that may contain hot water. The dipole-dipole method incorporates colinear current and potential electrodes, and produces an electrical section that can be mathematically modeled. Figure 7 is a theoretical two-dimensional geoelectric model below the hot wells calculated by H. T. Holcombe of the University of New Mexico from data presented by Jiracek and Smith (1976). Bedrock with a resistivity of 30 ohm-meters (ohm-m) is shown at a depth of about 1 km. The valley fill above possesses resistivities of 20, 10, 4 and 1 ohm-m. The lower values probably reveal areas of high clay content within the valley fill. Below the hot wells the bedrock is interpreted to be much closer to the surface than it is either to the west or the east. Within this high resistivity ridge and to the west of the hot wells there is a vertical conduit with a resistivity of 4 ohm-m. This low resistivity vertical feature is the conduit discussed by Smith (1977) and may represent a fracture or fault system along which the hot water could rise to the aquifer tapped by the hot wells. The geometry of this inferred conduit has not been defined.

A quadripole resistivity map is shown in Figure 8. This map was calculated from a pair of conventional resistivity maps discussed in detail by Smith (1977). Since the bipole transmit-

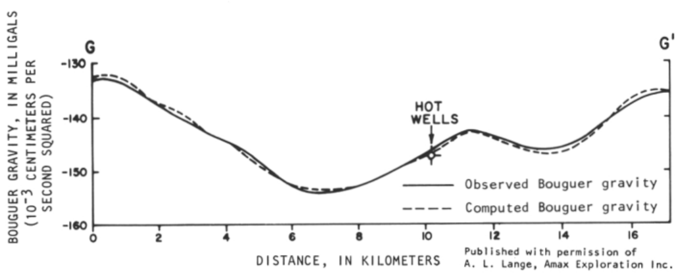


Figure 5. Profile of observed and calculated complete Bouguer gravity.

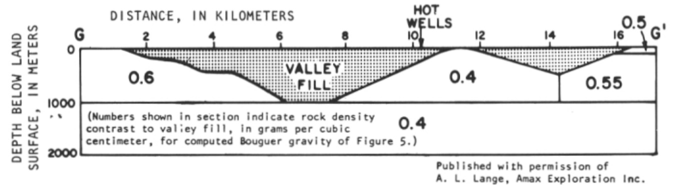


Figure 6. Section of theoretical two-dimensional density contrast model.

ters are not crossed, the quadripole resistivities of Figure 8 do not satisfy the mathematical simplicity specified by Doicin (1976). Nevertheless, Figure 8 is a single qualitative map of the lateral variation in resistivity. The uniform low resistivity values in the center of the valley are thought to indicate areas of the greatest thickness of conductive valley fill. The sharp resistivity gradients that flank the valley coincide with the areas of inferred Basin and Range faults. Passing through the vicinity of the hot wells is a series of high resistivity anomalies that extend from near Cotton City into the Pyramid Mountains. These anomalies lie just north of the arcuate gravity anomaly of Figure 4 and appear to define a series of discrete bedrock features, not a continuous ridge. The hot wells are located where the Animas Valley fault (fig. 2) intersects the resistivity and gravity anomalies.

The strength of the earth's natural magnetic and electric fields at frequences in the range of 10 to 10^{-3} hertz (hz) can be related to the distribution of resistivities within the earth. This is the basis for the telluric and magnetotelluric methods. A combined telluric and magnetotelluric interpretive section was prepared by A. T. Mazzella of Terraphysics for Amax Exploration, Inc. and is reproduced in Figure 9. These data also show a highly resistive feature below the hot wells. On the west, highly resistive ground may be related to the Peloncillo Mountains. The anomaly below the hot wells appears to become more resistive with depth to a depth of 6 km. Other magnetotelluric data suggest that a region of lower resistivity underlies the resistive anomaly at depths greater than 6 km (Jiracek and others, 1977). The low resistivity zones flanking the resistive anomaly may represent underflow of the hot water within the valley fill (Lange, 1978, written commun.).

In map and cross-sectional view, geophysical data show a high resistivity and high density anomaly below the hot wells. Associated with the local resistivity and density anomalies are high thermal radiation and a strongly magnetic dike. The local anomaly interrupts a valley-wide arcuate anomaly of high gravity south of the hot wells and east of Cotton City. The hot wells appear to be on the western flank of this local anomaly.

While it is likely, as Reeder (1957) first suggested, that the Animas Valley fault is in part responsible for the occurrence of the hot water, this youngest of Basin and Range faults in this area cannot in itself cause all the valley-wide and local geophysical anomalies. On the other hand, the reevaluated geology of the Pyramid Mountains (Deal and Elston, in press) may explain these geophysical anomalies.

GEOLOGIC AND GEOPHYSICAL INTERPRETATION

Deal and Elston (1978b) have interpreted the arcuate outcrop patterns in the Pyramid Mountains as the mappable limits of the inner wall and the outer ring-fracture zones of an Oligocene ash-flow cauldron they have named the Muir cauldron. If these arcuate patterns (fig. 2) are extended into the Animas Valley, they encompass the series of high resistivity anomalies shown in Figure 8; the resistivity anomalies may be the locations of several ring-fracture domes. Ash-flow tuff has a greater density than valley fill; the arcuate zone of anomalously higher gravity shown in Figure 4 lies entirely within the inner-cauldron wall and may reveal the location of a thick accumulation of inner-cauldron ash-flow tuffs.

This interpretation suggests that the hot wells are located where the Animas Valley fault intersects the ring-fracture zone of the Muir cauldron. The superposition of the Animas Valley fault upon the ring-fracture zone may have enhanced its permeability and formed a conduit for the up-flow of deeply circulating ground water or the upward migration of steam. This conduit is schematically shown by the electrical cross section of Figure 7. Further, the high resistivity and high density feature of Figures 4 through 9 may be a ring-fracture dome. A localized conduit within the ring-fracture zones may explain thermal anomalies of Kintzinger (1956) and Strangway and Holmer (1966) (fig. 3).

With this interpretation, the most promising area for the discovery of up-flowing hot water or rising steam would be along the Animas Valley fault north of the gravity anomaly of Figure 4 and south of the outer ring-fracture zone of Figure 2. This area lies within T.24 and 25S., the western part of R.19W., and the easternmost part of R.20W. This is also the area of most intensive exploration, drilling and leasing activity by the geothermal industry in the Animas Valley.

GEOTHERMAL INDUSTRY AT THE LIGHTNING DOCK KGRA

Figure 10 shows the currently active geothermal leases on Federal and State lands within the Animas Valley. Most of the land not leased is either private or under the Stockraising Homestead Act. Some of the private lands may be leased and most of the remaining State lands and all the Homestead lands will be put up for lease the summer of 1978 (Jim Querry and

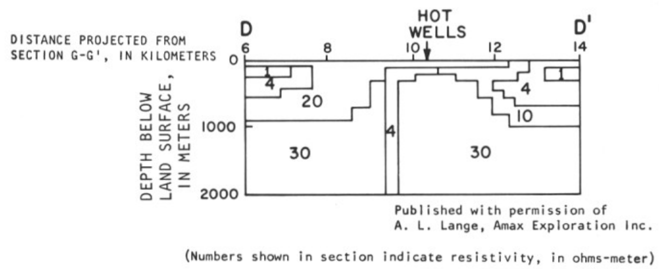


Figure 7. Section of theoretical two-dimensional resistivity model.

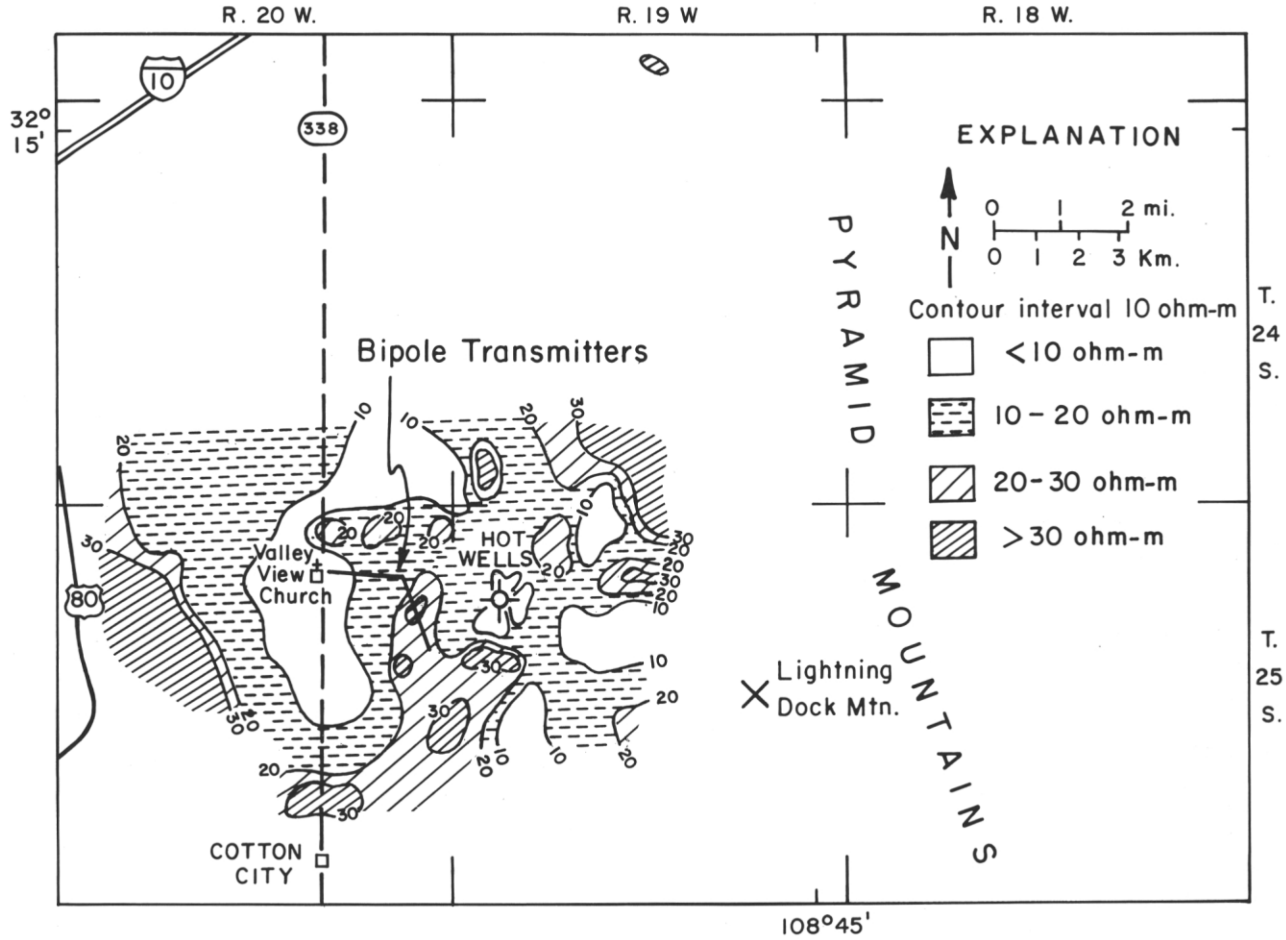


Figure 8. Quadripole apparent resistivity.

Chris Garcia, 1978, oral commun.). Many of the leases in Figure 10 are joint ventures; the majority holder is the leasee shown. Aminoil and Amax are the most active. Most of the lands held by subsidiaries of the U.S. Geothermal Corp. and by Chevron have been terminated.

The geothermal industry is looking for a reservoir of steam or water above 200°C. Reported estimates for the maximum water temperature at depth in the Animas Valley fall below this value (Renner and others, 1975; Preslar, 1978). More than two dozen holes have been drilled in the Animas Valley for heat flow and thermal gradient measurements. Because of the pending lease sales, little information about these measurements is available. Lange (1977) reported heat flows ranging from 2 to 21 heat flow units (HFU, microcalories per square centimeter per second). Background heat flow values are about 2.5 HFU. Because of the low temperature estimates and the near normal thermal gradients, some industry representatives have termed the area a "marginal prospect" and a "high-risk area." It appears that while geophysics and geology may have combined to find why the hot water occurs, not enough of it at a high enough temperature has been found to warrant a commitment from the geothermal industry at this time.

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Those who contributed time, data and effort to this article include Tony Preslar (Micromagnetics, Inc.), Arthur L. Lange

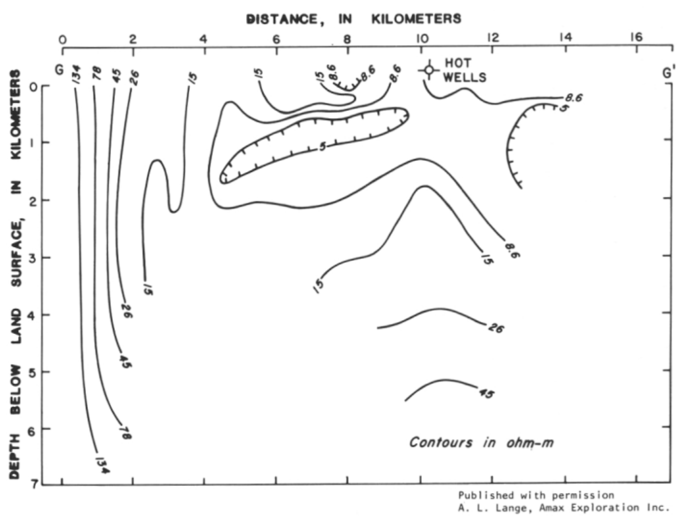

Figure 9. Pseudosection of combined telluric-magnetotelluric resistivity.

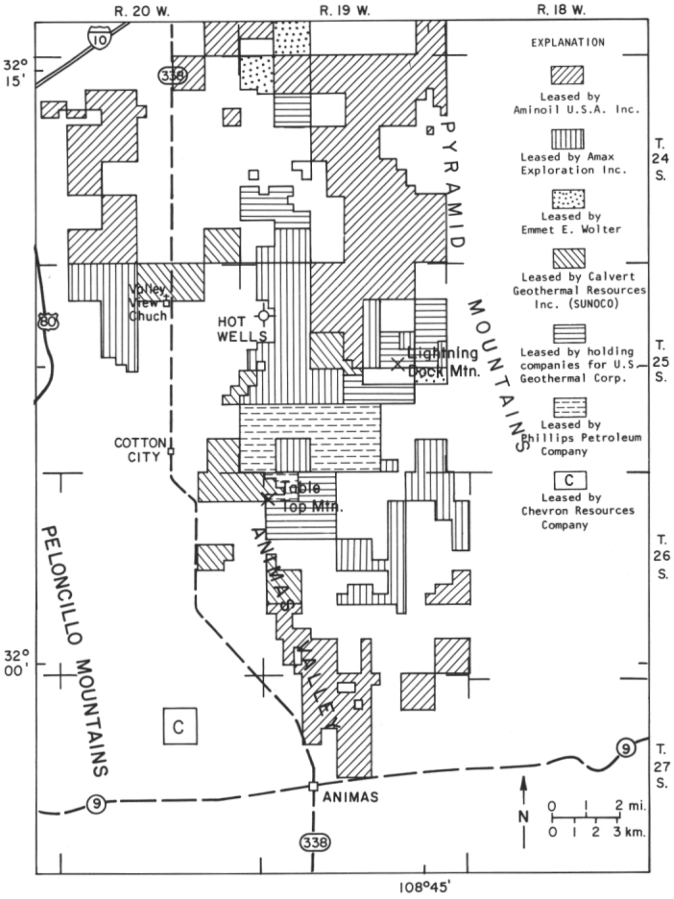

Figure 10. Active geothermal leases by leasee.

(Amax Exploration, Inc.), Aldo T. Mazzella (Terraphyics), Edmond G. Deal (Eastern Kentucky University), Wolfgang E. Elston, H. Truman Holcombe and George R. Jiracek (University of New Mexico), Chris Garcia (New Mexico State Land Office), and Jim Querry and Martha Kline (Bureau of Land Management).

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