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SAN DIEGO GRANT PROSPECT

GEOTHERMEX

NOVEMBER, 1978

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INTERPRETATION OF GEOLOGY, GEOPHYSICS AND HYDROCHEMISTRY
FOR SELECTION OF GEOTHERMAL DRILLING SITES,
CAÑON DE SAN DIEGO GRANT, SANDOVAL COUNTY, NEW MEXICO

for

SUNOCO ENERGY DEVELOPMENT CO.
DALLAS, TEXAS

by

GeothermEx, Inc.

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November 1978

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CONCLUSIONS

1. The Cañon de San Diego Grant lies on the eastern slope of the Nacimiento Uplift, a tilted Precambrian block. Nowhere on the Grant is depth to Precambrian rock believed to be greater than 3,500 feet. Therefore, any deep geothermal test will be completed in Precambrian rock.
2. The Valles Caldera, northeast of the Grant's northeastern corner, is characterized by Quaternary magmatism, ring and radial fractures, and a commercially producible geothermal reservoir at depths of 1.5 to 2.5 km (5,000 to 8,000 feet). Production comes from the Quaternary Bandelier Tuff; flow tests have been run on underlying Quaternary-Tertiary lavas and sediments, Permian Abo redbeds, and possibly Pennsylvanian Madera Limestone. Field capacity is greater than 50 MW.
3. Precambrian has not been reached in drilling in the Valles Caldera to date. Union Oil Company plans a Precambrian test in the next one or two years.
4. Two principal structural directions are noted: nearly N-S and NE-SW. Producing wells and hydrothermal alteration in the Caldera align on a NE-SW fracture set that may be an extension of the Jemez Fault, which extends along the Jemez River Canyon on the Grant. Southwest of the Grant, this fault set intersects the N-S Nacimiento fracture and uplift trend. Many faults, especially the N-S set, do not cut the Quaternary volcanic cover.
5. Four types of thermal spring are present in the area:
 - a) acid sulfate springs associated with the hydrothermal system beneath the Caldera and created by steam heating of shallow meteoric groundwaters;
 - b) dilute warm springs created by shallow circulation of meteoric water into warm volcanic rocks in the ring-fracture zone;
 - c) mineralized Na-Cl hot springs in Jemez Canyon, which issue a mixture of meteoric recharge and thermal water that has flowed at depth from beneath the Caldera; and

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- d) mineralized cool to hot spring and well waters at the south and west sides of Sierra Nacimiento, which appear to issue mixtures of meteoric recharge with connate Na-Cl-SO₄-HCO₃ waters.
6. Water sampled from LASL GT-2 resembles the latter type and may be a mixture of Na-Cl thermal outflow from beneath the Caldera with connate fluid from the Madera Limestone. Samples from the 3,557-foot depth yielded SiO₂ temperature of 169°C (336°F). Bottom hole temperature was 197°C (387°F) at 9,700 feet, consistent with fluid mixing higher in the column.
 7. Mixing calculations suggest that water at Jemez and Soda Dam springs represents from 1:1 to 1:10 thermal to cool recharge. Silica geothermometry tentatively yields a thermal component at Soda Dam of about 100°C (212°F) and 160° to 195° (320° to 383°F) at Jemez Springs.
 8. Solfataric alteration and H₂S emissions in the Canyon west of Battleship Rock may represent boiling of a saline aquifer at depth, perhaps the same aquifer present within the Caldera. Alternatively, there is very shallow outflow of very high temperature water from the Caldera.
 9. Thermal outflow from the Caldera exists to some degree, via the Jemez Fault zone, through the highly porous Madera Limestone and possibly other units. Therefore, all temperature gradients and heat flows from holes completed within or above the Madera Limestone are elevated above purely conductive values. Despite this, there is a very impressive tongue of high heat flow and temperature gradients extending southwestward out of the Caldera, along the Jemez River Canyon.
 10. Another heat flow and gradient anomaly is present on the San Juan Mesa (eastern Grant border), separated from and lower in value than the Jemez River anomaly. It cannot be closed on its eastern side because of lack of data. Possibly it too is derived in part from thermal outflow from the Caldera. A local origin is more likely because of close correspondence with electrical resistivity and magnetotelluric lows, which are absent generally from the Jemez River Canyon.
 11. Several geoelectrical surveys have mapped a complex of resistivity and conductivity anomalies. The most impressive lies athwart the

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San Juan Mesa thermal anomaly. Again, a lack of data prevents closure on the eastern side. A small lobe extends into the Jemez Springs area; this may reflect thermal upwelling of mildly saline thermal water along the Jemez Fault.

12. Gravity and aeromagnetic positive trends and local highs appear to outline areas of denser and more magnetic rock within the Precambrian. An aeromagnetic minimum in the Grant's southeastern corner appears to delineate a thickening basin of Paleozoic and younger rocks. Similarly, the line of greatest change in gravity gradient from positive to negative may outline the shallow edge of the Precambrian massif and the adjacent deepening basins of younger rocks.
13. It is possible that resistivity lows and conductance highs of San Juan Mesa reflect principally a thickening of younger (more conductive) rocks atop the non-conductive crystalline basement. In this case, the thermal anomaly associated with the resistivity lows would be due only to thermal outflow from the Caldera via porous Paleozoic limestones. Arguing against this, the conductance anomaly may be 2 km (6,500 feet), or at least 1 km (3,200 feet), which would be well within the Precambrian section.
14. Sparse microseismic events are clustered south of the Grant, in an area of small resistivity lows. None of these anomalies is given much weight, as heat flow values in this area barely reach the regional average. Neither is any weight given to seismic noise anomalies because of the extreme difficulty of filtering background noise.
15. Thermal conductivities of rocks from LASL GT-1, GT-2 and EE-1, north of the Grant, increase markedly with depth and degree of crystallization. This corresponds to a decrease in temperature gradient with depth, such that overall gradient in 3 km (10,000 feet) deep holes is 3.0° to 3.5°F/100 feet in an area of 5 to 6 HFU, with gradient of 3.0°F/100 feet or lower in Precambrian rock.
16. The LASL area was selected specifically to avoid basement fractures and thus to avoid convective disturbances. Despite this, data can be projected with some confidence into the two thermal anomalies on the Grant because of similarities in rock type.
17. For a site near Battleship Rock, at the northeastern corner, with a depth of less than 500 feet to Precambrian, temperatures of

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perhaps 375°F would be found at 8,000 feet (2.5 km) and 425°F by 10,000 feet (3 km). At Jemez Springs, depth to Precambrian would be nearly twice as great but temperatures would be lower: perhaps 300°F at 8,000 feet, rising to about 350°F by 10,000 feet. These values compare closely with the 402°F at 10,053 feet in EE-1 and with the mixing-model geothermometer (320° to 383°F) for Jemez Springs.

18. At the San Juan Mesa thermal and electrical anomaly, temperatures are projected to be about 375°F at 8,000 feet and over 400°F by 10,000 feet. No independent means exist to verify this estimate.
19. If the thermal anomalies are due entirely to circulation of thermal water in Madera Limestone, temperatures within underlying Precambrian rock may not reach projected levels at depth.
20. Permeability in the Precambrian section is unknown but probably is highly variable. Jemez Fault zone offers the greatest potential for fracturing in Precambrian rock on the Grant, especially in the area of high gradients and heat flow in the Battleship Rock-Jemez Springs zone. Fracturing is unknown beneath the Quaternary volcanic cover of the San Juan Mesa.
21. The horseshoe-shaped zone of fracturing at the southern margin of the Grant may also have enhanced fracturing in the Precambrian section. However, heat flow and gradients are only normal in this area. Temperatures at 10,000 feet may not greatly exceed 250°F (120°C).
22. Water quality in a presumed geothermal system is likely to be mildly saline (7,000-10,000 ppm TDS, mostly NaCl). No clear evidence exists for a vapor-dominated regime beneath the Grant, despite reports of a vapor cap above the mildly saline reservoir encountered in the Caldera by Union Oil Company.
23. There is no firm evidence in support of a magmatic intrusion beneath the Cañon de San Diego Grant. All of the permissive evidence (arcuate faulting, gaseous thermal springs, high heat flow, microearthquakes, gravity and magnetic anomalies) can be explained without resorting to a magmatic hypothesis.
24. Heat flow, structural geology, geoelectrical surveys and the results of drilling by LASL and Union Oil Company support continued drilling on the Grant, either intermediate-depth gradient holes or deep exploratory holes or both.

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RECOMMENDATIONS

1. Attempts should be made to trade temperature-gradient data with Phillips Petroleum Co., for holes drilled by them east of the Grant. Such data might permit closure of the San Juan Mesa thermal anomaly.
2. Deep temperature-gradient holes should be considered as an intermediate step to drilling deep exploratory holes. Sites are nominated as:

- a) near Battleship Rock;
- b) near Jemez Springs;

each to about 1,000 feet (300 m). This would allow penetration through the presumed thermal aquifer of the Madera Limestone and into underlying Precambrian rock, to establish a new conductive gradient.

3. A less important site for a 1,000- or 1,500-foot deep hole would be within the arcuate fault set, just west of the Guadaloupe River. This, too, would penetrate Precambrian rock but in an area of lower heat flow and presumably lower temperatures at depth.
4. The minimum depth to Precambrian within the San Juan Mesa anomaly is about 2,700 feet within the nearly impassable Canon de la Canada; on the Mesa, minimum depth to Precambrian is at least 3,000 feet. Therefore, a deep exploratory test is recommended instead of further gradient drilling. A hole to 8,000 or possibly 10,000 feet is recommended, on the Mesa.
5. If warranted from the results of the deep gradient holes, or if agreed upon as a substitute for such a gradient hole, a deep geothermal test should be drilled near Battleship Rock. This test should have a minimum depth of 8,000 feet, and possibly 10,000 feet. Its objective would be highly fractured Precambrian rock within the Jemez Fault zone.
6. Deep geothermal holes should be planned elsewhere on the Grant only if results from the deep gradient holes are encouraging.
7. This drilling pattern would result in testing the most impressive thermal and electrical anomalies and the zone of presumed greatest

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fracturing. In each case a thermal aquifer may be present in the Madera Limestone; however, the objective will be fractured Precambrian rock at greater depth.

8. Consideration may be given to getting a partner for drilling, on the basis of impressive thermal and electrical anomalies, and proximity to a Quaternary caldera having within it a proven geothermal field. Companies that bid in earlier KGRA lease sales represent prospective partners.

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INTRODUCTION

Purpose and Scope

This project began in mid-1977 as an evaluation of the geology and hydrogeology of the Cañon de San Diego Grant for Sunoco Energy Development Co. (Sunedco) and evolved late in 1977, at Sunedco's direction, into a more comprehensive study of geophysical, geologic and hydrogeochemical data. This has been used to select sites for the possible drilling of deep geothermal wells.

Extensive use was made of previous contractor reports to Sunedco or allied companies by Senturion Sciences, Inc., Geonomics, Inc., Geothermal Services Incorporated, Geotronics Corporation, Earth Satellite Corporation and others, as well as published and open-file reports of the U.S. Geological Survey, the New Mexico Bureau of Mines and Mineral Resources, and Los Alamos Scientific Laboratories of the University of California. Several persons provided information privately, including Dr. G. R. Jiracek, Department of Geology, University of New Mexico; Richard Dondanville, Union Oil Company; and A. W. Laughlin, Los Alamos Scientific Laboratories. Additionally, GeothermEx, Inc. files were the source of much data on exploration in the Valles Caldera.

In addition to data compilation and personal inquiry, a detailed field reconnaissance was conducted across the entire Jemez-Nacimientito Uplift. Geologic reconnaissance and compilation was by James R. McIntyre. Dr. J. H. Beyer performed the geophysical evaluation. Hydrochemical studies were by Dr. C. W. Klein. J. B. Koenig supervised this and prepared the final syntheses, including selection of drill sites.

Including report preparation, some 50 man-days of effort were involved. Major plates and sections on conclusions and recommendations were submitted to Sunedco in April 1978. After minor revisions to the section on hydrogeochemistry, the final report was submitted in October 1978.

Location

This project concerns the Cañon de San Diego Grant, a tract of over 160 square miles in Sandoval County, New Mexico. The Grant is

Figure 1. Location map, Canon de San Diego Grant, New Mexico

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elongated north-south and occupies, from west to east, the eastern flank of the Sierra Nacimiento, the canyons of the Guadalupe and Jemez Rivers, and the southwest part of the Jemez Mountains. The northeastern corner of the Grant extends just into the Valles Caldera.

Topographically, the region is rugged, with access limited to roads following the Jemez River valley and to roads and trails along the flat crests of various mesas extending westward from the Jemez Mountains. There is very limited access into the Sierra Nacimiento.

After uniting, the Guadalupe and Jemez Rivers flow first north, and then southeast, into the Rio Grande about 20 miles north of Albuquerque. Each has numerous perennial and very many intermittent tributaries, of which Vallecito Creek, Rio Cebollo and Virgin Canyon may be the most important. Numerous springs feed these and other streams of the region.

Elevations range from a low of about 5,600 feet at the Grant's southern boundary, on the banks of the Jemez River, to over 9,000 feet near the crest of the Nacimiento Mountains. Most of the Grant is at elevations above 7,000 feet.

Precipitation is everywhere above 10 inches annually (Albuquerque is approximately 8 inches per year) and extends to about 30 inches annually at the higher elevations. Regional average for the entire Grant probably is 17 or 18 inches. Of this, nearly two-thirds falls as afternoon precipitation in the warmer season (April-September); the remainder (especially in the highlands) falls as winter snow and rain. Mean annual air temperature varies widely, from nearly 55°F (13°C) at the southern Grant boundary to perhaps under 45°F on higher slopes and crests. Summer climate is moderate to warm; winter climate is cool to cold.

Vegetation is principally ponderosa pine, with pinyon and juniper at lower elevations. Only the lowest part of Jemez River Valley exhibits desert grassland vegetation.

The Cañon de San Diego Grant is connected to Albuquerque, 50 miles to the south, by paved New Mexico Highways 4 and 44. Highway 4 continues northward and northeastward, across the southern edge of Valles Caldera, to Los Alamos and Santa Fe. Several hundred people live in small communities and on farms along the Jemez River, principally at the community of Jemez Springs. The upland parts of the Grant essentially are uninhabited.

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Summer tourism and recreation, logging (in the ponderosa- and spruce-forested uplands), and communal Indian life support the area economically. Jemez and Zia Indian pueblos border the Grant on the southeast, south and southwest. Lands of the Santa Fe National Forest form the northwest, north and northeast boundaries.

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GEOLOGY

Stratigraphy

Following is a general description of rock units from surface exposures or reported from wells in or near the project area. Particular attention has been paid to the factors which influence porosity and permeability.

In the Nacimiento Uplift itself, only Precambrian rocks appear to be present at depths required to reach significantly high temperatures. However, along the fault zone boundary between the eastern side of this uplift and the adjacent Española basin, Paleozoic or younger rocks have been downthrown into the zone of high gradients and covered by a blanket of Cenozoic sedimentary and volcanic rocks. In that setting, the reservoir potential of the Paleozoic and younger rock units may be significant to prospecting.

The regional stratigraphic section is shown in table 1; geology of the Grant and vicinity is shown on plates 1 and 2.

Precambrian

Rocks of Precambrian age are exposed over large areas of the Nacimiento and San Pedro Mountains to the west of the project area; in the western Sangre de Cristo Mountains, to the east of the Española basin; and in the Sandia Mountains, to the south. In addition, small, isolated outcrops occur in the floor of the Jemez River Canyon near Soda Dam and at Guadalupe Box on the Guadalupe River. Precambrian rocks also have been penetrated in several wells near the Cañon de San Diego Grant, including (plates 3 and 4) the Los Alamos Scientific Laboratories (LASL) hot dry rock tests GT-1 (SE/4 Sec. 1, T. 19 N., R. 2 E.), GT-2 and EE-1 (NE/4 Sec. 13, T. 19 N., R. 2 E.) but reportedly (R. Dondanville, oral communication, 1978) not in any of the Union Oil Company Baca Grant production wells. Of these, GT-1 penetrated 470 feet of Precambrian rocks, and the original hole at GT-2 penetrated 7,217 feet of these rocks.

In the Nacimiento Mountains, the Precambrian terrain is tripartite in character: a northern area of quartz monzonite to granodiorite gneiss; a central part of the range with pink, fine-to-medium-grained granite, which intrudes the gneiss; and a variety of rocks,

Table 1. Stratigraphic nomenclature in the Nacimientos Mountains, Espanola Basin area. (From Kelley et al., 1976.)

Era	System	Series	Group, formation member		Thickness (ft)	Lithology
CENOZOIC	Quaternary	Holocene and Pleistocene			0 to 300	<i>Terrace, valley, and slope alluvium; eolian sand; basalt flows of Cerras del Rio and Santa Ana Mesa.</i>
	Tertiary	Pliocene	Santa Fe Formation	Upper buff member	0 to 200	Sandstone (reddish, buff, purplish, gray, and white); mudstone (reddish, gray, and brownish); gravel. Contains lateral alluvial-fan facies of sedimentary, crystalline, and volcanic rocks; also eolian, playa, and fluvial facies. Group status is also applied and may include equivalents of Zia, Abiquiu, and Espinaso in local and adjoining areas. Also contains flows of basalt and andesite
		and		Middle red member	500 to 10,000	
		Miocene		Lower gray member	100 to 3,000	
		Oligocene	<i>Espinazo Volcanics and Carrillos Hills Intrusives</i>		0 to 3,000	<i>Rhyolite to basalt flows, sills and lacoliths.</i>
	Eocene - Paleocene	Galisteo, San Jose, and Baca Formations		0 to 3,000	Sandstone, mudstone, and conglomerate	
MESOZOIC	Cretaceous	Upper	Mesaverde Group		<i>750 +</i>	Sandstone, shale, coal
		Lower	Mancos Shale		<i>to 2,500</i>	Shale (black, olive drab)
			Dakota Sandstone		20 to 200	Sandstone (buff)
	Jurassic	Upper	Morrison Formation		<i>0 to 950</i>	Mudstone, sandstone, conglomerate (variegated)
			Todilto Formation		0 to 200	Gypsum, limestone
			Entrada Sandstone		0 to 150	Sandstone
	Triassic	Upper	Chinle Formation		1,500	Mudstone, sandstone, conglomerate (reddish brown)
PALEOZOIC	Permian	Guadalupian	San Andres Formation		0 to 150	Limestone, sandstone (Glorieta Ss)
		Leonardian	Yeso Formation		<i>250 to 700</i>	Sandstone, gypsum, limestone (tan brown)
			Abo Formation		800	Mudstone, sandstone, conglomerate (red brown)
		Wolfcampian				
	Pennsylvanian	Upper	Madera Formation		0 to 1,400	Limestone, shale, sandstone
		Middle	Sandia Formation		<i>50 to 250</i>	Sandstone, shale, limestone, conglomerate
			Osha Canyon formation		<i>0 to 70</i>	Limestone
		Lower	Log Springs Formation		<i>0 to 75</i>	Hematitic shale and sandstone
	Mississippian	Osagean	Arroyo Peñasco Formation		0 to 100	Limestone
	PRECAMBRIAN					

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including muscovite quartz schist, biotite quartz monzonite gneiss, quartz diorite gneiss and feldspathized quartz diorite gneiss, in the southern part of the range (Woodward, McLelland and Anderson, 1974). These rocks also have been intruded by the central-area granite. All have been cut by various dark-colored dike rocks. Farther to the east, Purtymun (1973) reported the presence of small amounts of amphibolite and mica schist (figure 2).

The most complete descriptions of the Precambrian rocks in the vicinity of the Cañon de San Diego Grant come from the cores of GT-2 and EE-1 (Laughlin and Eddy, 1977). The dominant rock type in these holes is leucocratic monzogranite gneiss, associated with minor amounts of amphibolite and hornblende-biotite-plagioclase schist, biotite granodiorite gneiss and biotite tonalite gneiss. These metamorphic rocks have been intruded by thin dikes or sills of pegmatite and leucocratic monzogranite, and by a larger intrusion of biotite granodiorite at the bottom of GT-2.

Mineral alteration is widespread in the cores, including conversion of biotite to chlorite, and plagioclase to sericite and calcite. Calcite produced during alteration seals the abundant fractures present in the rock, making the rock-mass impermeable. This alteration reflects one or more hydrothermal events of the past. No systematic work has been done on rock alteration, to determine if the effects seen in these cores are dependent on proximity to the igneous activity associated with the Valles Caldera. The particular significance of data from GT-2 is the indication that any pre-existing fracture reservoir at this locality has been sealed by hydrothermal alteration. Formation testing carried out in fractured intervals in GT-2 confirmed that the fractures were sealed and that porosity and permeability are extremely low (West, Kintzinger and Laughlin, 1975). Such a condition may be characteristic of the peripheral zone of a self-sealed fracture reservoir, such as that occurring in the Valles Caldera.

Numerous age determinations have been made by RB-Sr, K-Ar and fission-track methods on cores from GT-1, GT-2 and EE-1. These ages indicate that a metamorphic event at about 1.66 b.y. produced the gneisses and schists from older sedimentary and igneous rocks. The metamorphic rocks were then intruded by at least two different magmas at 1.3 to 1.4 b.y. during which argon loss occurred in the metamorphic assemblage, lowering the K-Ar ages to about 1.4 b.y. During the Pliocene-Pleistocene igneous event associated with the formation of the Valles Caldera, the local geothermal gradient appears to have increased to 50° to 60°C/km, producing fission-track annealing in

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apatite. However, when K-Ar and Rb-Sr ages are compared throughout the holes, it does not appear that argon loss is occurring in response to the present high geothermal gradient at this location. This lack of systematic argon loss, even at hole temperatures of 200°C, indicates that the present gradient is the highest felt by these rocks in the last 1.37 b.y. (Brookins et al., 1977). The fact that the temperature has risen through the thermal zone required to anneal apatite fractures but, though at 200°C, has not yet brought about argon loss, suggests to these authors that the temperature in the area is still rising.

The reservoir potential in these Precambrian rocks apparently is dependent on both (a) the existence of tectonic fracturing and (b) the post-fracturing history of hydrothermal alteration. Information on fracture distribution will be discussed in the section on Structure.

Paleozoic

A profound erosional unconformity separates Precambrian rocks from the overlying formations of Late Paleozoic age.

Mississippian

Thin remnants of Mississippian rocks have been found in the Jemez and Nacimiento Mountains, beneath an erosional unconformity which separates them from the overlying widespread Pennsylvanian sediments. Not enough data are available to construct an isopach map of the rocks of this system. However, they probably follow the thickness trends of the Pennsylvanian rocks and are absent over Late Paleozoic structural uplifts and present, at least in discontinuous belts, on the flanks of these uplifts. Mississippian rocks are the oldest Paleozoic strata reported in this part of New Mexico. One formation has been described in the Jemez-Nacimiento Mountains area.

Arroyo Peñasco Formation

Rocks assigned to this formation occur at two localities in the project area. At Soda Dam (NW/4 SW/4 Sec. 13, T. 18 N., R. 2 E., projected) the lenticular section is up to 37 feet thick, consisting

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of a thin green mudstone at the base, overlain by dense, cherty limestone. Here, erosional channeling is present at the top, and the unit is overlain by the Pennsylvanian Sandia Formation. At Guadalupe Box (NE/4 Sec. 6, T. 17 N., R. 2 E.) the maximum thickness is 25 feet. At this locality, it is overlain by the Early Pennsylvanian Log Springs Formation (Armstrong, 1967). The unit was absent in GT-1 and GT-2, immediately north of the Cañon de San Diego Grant.

There are no data available concerning the thickness and character of this unit to the east of the Jemez River Canyon. Far to the east, in the Sangre de Cristo Mountains, sink-holes and a collapse breccia occur in the upper part of this formation (Armstrong, 1974).

Where exposed, the unit is not thick enough to be of significance as a reservoir in geothermal prospecting. However, it may thicken eastward from the axis of the Nacimiento Uplift, beneath the Española Basin, and the reservoir potential might be of some significance if solution cavities were developed in it there.

Pennsylvanian

The thickness of rocks of Pennsylvanian age in the region is shown in the accompanying isopach map (figure 3) and locally on plate 4. The main feature of this map is the so-called Peñasco axis, located approximately on the present-day Nacimiento Mountains. Pennsylvanian rocks are absent over the crest of this uplift, because of non-deposition and post-depositional erosion. The section appears to thicken in all directions away from this axis. However, there is no control on the contours in the broad area of the Española Basin, between the Jemez River Canyon and the west side of the Sangre de Cristo Mountains.

There are four formations of Pennsylvanian age in the study area.

Log Springs Formation

This consists of a highly lenticular sequence of ferruginous deep-red shales and sandstones, resting on the Mississippian Arroyo Peñasco Formation along an erosional unconformity. It is much as 75 feet thick in the Nacimiento Mountains; however, only about 3 feet of

Figure 3. Isopach map of Pennsylvanian rocks in north-central New Mexico. (From Kottlowski, 1961).

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red sediments have been assigned to this formation at Guadalupe Box. It appears to be absent in the Jemez River Canyon sections.

The age of the formation is post-Meramecian (Mississippian) and pre-Morrowan (Pennsylvanian) (Armstrong, 1955).

Osha Canyon Formation

The maximum reported thickness of this formation is in its type area, at Guadalupe Box, where it is 71 feet thick. The lower part consists of bioclastic limestone and calcareous shale. The upper part is made up of light-grey shale. It contains a marine fauna of Morrowan (Early Pennsylvanian) age. It rests on the Log Springs Formation in Guadalupe Box and at several areas in the Nacimientos Mountains. Elsewhere, it rests directly on Precambrian rocks (Duchene, Kues and Woodward, 1977). It may be equivalent to the 55-foot-thick limestone included within the lower part of the Sandia Formation in GT-1 (Purtymun, 1973). It is uncertain whether it is present in GT-2.

Magdalena Group

This is the thickest and most widespread of the Pennsylvanian units. It is made up of two formations.

Sandia Formation. As the term is presently restricted, this unit consists of dark brown, grey and greenish sandstone, interbedded with impure limestone. It is 225 feet thick near Guadalupe Box and about 160 feet thick near Soda Dam and Jemez Springs. It thins to the north and west toward the crest of the Peñasco axis (Duchene, 1974). It is reported to be about 250 feet thick in both GT-1 and GT-2 but may include about 55 feet of the Osha Canyon Formation. The porosity and permeability potential of this unit is unknown, as no formation testing was carried out in the interval in either GT-1 or GT-2 (West, Kintzinger and Laughlin, 1975).

The Sandia Formation is considered to be Atokan (early Middle Pennsylvanian) age.

Madera Formation. The Madera Formation is exposed on the flanks of the Nacimientos Mountains and in the Guadalupe and Jemez River Valleys. It overlies the Sandia Formation at Guadalupe Box and Jemez Springs but elsewhere may rest on the Osha Canyon Formation or

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directly on Precambrian crystalline rocks. In the project area, it can be divided into a lower grey limestone member and an upper arkosic sandstone member. The lower member consists of grey cherty limestone interbedded with arkosic sandstone and shale. The upper arkosic member is gradational with both the underlying limestone unit and the overlying Abo Formation. It consists of arkosic grey limestone, pink arkose and grey shale (Duchene, 1974). The Madera Formation is about 740 feet thick at Guadalupe Box and 470 feet thick near Jemez Springs (Wood and Northrup, 1946). The subsurface section of Madera Formation is about 745 Feet thick in GT-1 and about 920 feet thick in GT-2.

Some indication of the porosity potential of the limestone in the Madera Formation is given by the drilling history of GT-2, where lost circulation was encountered at drilled depths of about 1,640 feet and in an interval about 60 feet thick between about 1,880 to 1,940 feet. The latter zone was cavernous, and 2,900 sacks of cement were pumped into the formation in this interval (West, Kintzinger and Laughlin, 1975; Laughlin, 1977, personal communication). From these and other data, it appears that large volumes of warm water are being carried outward from the Valles Caldera through the Madera Formation toward GT-2.

Warm springs in the Soda Dam area issue from the Madera Formation (Rennick, 1931). However, in this case, it is uncertain whether the porosity is due to solution channels in the limestone or to fracturing associated with nearby faults. At any rate, limestone of the Madera Formation offers the best potential for significant porosity and permeability in the Paleozoic section. The Madera Formation contains fossils of Atokan, Desmoinesian and Virgilian age.

Permian

A regional isopach of rocks of the Permian system is given in figure 4; local data are given in plates 1 and 2. Once again, the major feature in the project area is the Peñasco Axis, over which the sediments thin but do not disappear. There is a region of slightly thicker deposition to the east, between the Jemez and Sangre de Cristo Mountains. However, this eastward thickening beneath the Española Basin is poorly controlled and speculative.

Various subdivisions of the Permian section have been made in the Nacimiento and Jemez Mountains (Wood and Northrup, 1946; Baars, 1974): 3 formations generally are distinguished. Due to Late Mesozoic and Cenozoic uplift and erosion, the thickness of Permian strata preserved beneath the overlapping late Cenozoic volcanic rocks is

Figure 4. Isopachous map of Permian system. (From Barrs, 1961).

LEGEND

- WELL CONTROL
- ▭ SURFACE SECTION

CONTOUR INTERVAL = 200 & 1000 FEET

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variable. Complete or nearly complete sections of Permian rocks are present along the west side of the Nacimiento Mountains, at the south end of the mountains, and in the Guadalupe River Canyon near Gilman (Woodward and Martinez, 1977; Woodward and Ruetschilling, 1976).

The significance of Permian rocks to geothermal prospecting is twofold. For one, it is desirable to know their thickness in order to predict drilling depths to possible objectives beneath them. For another, in areas to the east of the Jemez River Canyon, porous sandstones may be preserved, downthrown toward the Española Basin and within a zone of geothermal gradients of interest in prospecting.

Abo Formation

The Abo Formation of Wolfcampian (Early Permian) age is typically an interbedded sequence of reddish-brown siltstone, shale, sandstone and arkosic sandstone. A complete section, 580 feet thick, is reported at Guadalupe Box. About 700 feet is present in Sec. 2, T. 19 N., R. 1 E., and adjacent sections. An incomplete section over 840 feet thick is reported in the Jemez Springs-Soda Dam area (Wood and Northrup, 1946). It is more than 910 feet thick in GT-1 and more than 800 feet thick in GT-2 (Purtymun, 1973; West, Kintzinger and Laughlin, 1975). The best detailed lithologic descriptions are from the logs of these wells. In these, most of the sandstones are described as fine grained. No lost circulation was reported nor were any formation tests made in this interval. To the southwest, in the Kaseman No. 2 well, located 9 miles due west of Jemex Pueblo (Sec. 6, T. 16 N., R. 1 E.), an undetermined amount of hot mineral water was produced from the Abo Formation (Rennick, 1931). Therefore, it appears that some parts of the Abo Formation may have reservoir potential.

Yeso Formation

Two major sub-units of the Yeso Formation have been distinguished in the project area. The lower is a massive, reddish, cross-bedded, cliff-forming sandstone. This member has been correlated with the De Chelly Sandstone of the Four Corners region (Baars, 1974). The upper unit, called the San Ysidro Member by Wood and Northrup (1946), consists of reddish-colored siltstone, shale and sandstone. The section also contains thin beds of limestone and gypsum.

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The thickness of the Yeso Formation varies considerably in the project region: it is reported to be about 500 feet thick in the Guadalupe Box and only about 260 feet a few miles away, in Rio de las Vacas (near Sec. 2, T. 19 N., R. 1 E.) (Wood and Northrup, 1946). The formation is absent in a considerable part of the Cañon de San Diego Grant, due to Cenozoic erosion. It is likely to be present in structurally low areas to the southeast and east of the Jemez River. The lower massive sandstone member might be of interest as a reservoir if it were deeply enough buried in a zone of high geothermal gradients.

The Yeso Formation in the project area is regionally related to marine rocks containing lower Leonardian (Middle Permian) fossils.

San Andres Formation

In the usage of Wood and Northrup (1946), this formation consists of two units, the lower of which is a light-colored cross-bedded cliff-forming sandstone, referred to as equivalent to the Glorieta Sandstone of other areas of New Mexico and west Texas. It thins to a feather edge in the central Nacimiento Mountains but is uniformly about 90 to 100 feet thick in the project area in localities in which it has been preserved from later erosion. This unit might have significant reservoir potential if it is buried deeply enough to be considered as an objective. The upper member of the San Andres Formation consists of 40 to 50 feet of reddish, fine-grained sandstone and siltstone.

The most complete sections of the San Andres Formation in the study area are in the Guadalupe Box and in canyons in the southeastern corner of the Cañon de San Diego Grant.

The San Andres Formation is Leonardian in age.

Mesozoic

Triassic and Jurassic rocks are relatively thin and are continental in origin. Cretaceous rocks of the region are thicker and represent the extension into the area of the so-called mesocordilleran seaway of Mid- to Late Cretaceous time. Of this section, Upper Triassic rocks outcrop in a small southeastern corner of the Cañon de San Grant, and both Triassic and Jurassic rocks are exposed at the south end of the Nacimiento Mountains, in the vicinity of the San Ysidro

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Pueblo. In most of the study area, Mesozoic rocks are likely to be absent beneath the strong erosional unconformity which separates the Late Cenozoic volcanics from the underlying section. However, if any grabens are buried under this volcanic section, some part of the Mesozoic section could be preserved there. More important, Triassic, Jurassic and Cretaceous rocks may be present beneath the Tertiary rocks of the Española Basin, to the east of the Grant boundary.

In that area, they may be buried at a sufficient depth to be of significance to prospecting in the basin-bounding fault zone. However, due to the very limited occurrence of these rocks in the Cañon de San Diego Grant, only a very brief description will be given here.

Triassic

One formation of Late Triassic age is present in this area.

Chinle Formation

A complete section is not exposed in the Cañon de San Diego Grant. Regionally, thicknesses range from about 400 to 1,300 feet. The Chinle Formation has been subdivided into several members, two of which, recognized in recent field mapping of the San Ysidro and Gilman quadrangles (Woodward and Ruetschilling, 1976; Woodward and Martinez, 1977), will be used here.

The Kaseman No. 1 (Sec. 7, T. 16 N., R. 1 E.) and No. 2 (Sec. 6, T. 16 N., R. 1 E.) wells had large flows of warm, brackish water from sandstones of the Chinle Formation (Rennick, 1931).

Agua Zarca Sandstone Member. The Agua Zarca Sandstone ranges from 150 to 250 feet in thickness in the southern Nacimiento and Jemez Mountains. It consists of white, buff and locally red, very thick-bedded, medium- to coarse-grained sandstone. The sandstone locally is interbedded with grit and conglomeratic sandstone.

Petrified Forest Member. The Agua Zarca Sandstone Member is overlain by about 1,000 feet of red-orange, brown, purple and greenish-grey shale and siltstone, reddish sandstone, brown limestone and small pebble conglomerate. The outcrops of this unit are mainly south and west of San Ysidro.

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Jurassic

All outcrops of Jurassic rocks in this region are in the southern end and western flank of the Nacimiento Mountains. Farther to the southeast, the presence of Triassic, Jurassic and Cretaceous rocks in the northeast end of the Sandia Mountains and at the southwest edge of the Sangre de Cristo Mountains suggests that they also may be present in the Española Basin. Several different subdivisions of the Jurassic section have been proposed, but the units used herein are derived from the recent mapping of Woodward and Ruetschilling (1976) and Woodward and Martinez (1977).

Entrada Sandstone

It appears that this unit was correlated tentatively with the Wingate(?) Sandstone by Wood and Northrup (1946). It consists of about 100 to 120 feet of massive-bedded, orange, tan or white, fine- to medium-grained sandstone. It is exposed along the west side of the Nacimiento Uplift and in mesas south of San Ysidro.

Todilto Formation

The thickness of this formation is fairly uniform and is approximately 100 feet. It consists of about five feet of limestone at the base, overlain by about 95 feet of massive gypsum.

Morrison Formation

As in the case of the other Jurassic formations, the closest outcrops of the Morrison Formation to the Cañon de San Diego Grant are to the south and west of the Grant boundary, along the west side of the Nacimiento Mountains and on the flanks of small anticlinal folds which are present southwest of San Ysidro. The total thickness of the Morrison in this area is about 750 to 920 feet. As a whole, the formation is made up of intertongued arkosic sandstone, variegated montmorillonitic mudstone and very minor amounts of dense limestone. There are no data available on the reservoir potential of the sandstones in this formation. Four members have been recognized in the area. The following descriptions have been taken from Woodward and Ruetschilling (1976), for the San Ysidro area.

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Lower Member (Recapture Shale of Flesch, 1974). About 375 feet of brown to maroon mudstone and interbedded fine sandstone are present.

Westwater Canyon Member. This unit is cliff-forming, thick-bedded arkosic sandstone and subordinate variegated mudstone, about 355 feet thick.

Brushy Basin Member. Variegated red and green mudstone with sandstone interbeds make up this unit. It is about 145 feet thick.

Upper Member ("Jackpile" Sandstone of Flesch, 1974). This uppermost member consists of about 45 feet of whitish, kaolinitic sandstone and minor green mudstone.

Cretaceous

Cretaceous rocks exposed along the west side of the Nacimiento Mountains, at the north end of the Sandia Mountains, and at the southwest edge of the Sangre de Cristo Mountains are representative of the major transgressive-regressive cycles of the Cretaceous period seen elsewhere in the southern Rocky Mountains. Many complexly intertonguing sandstone and shale units have been described in the area but only the largest stratigraphic units appear to be significant to this summary discussion.

The total thickness of Cretaceous rocks which might occur east of the project area beneath the Española Basin is unknown. A composite section from the Cerrillos-Galisteo area south of Santa Fe indicates that as much as 3,000 feet of these rocks could be preserved in structurally low areas (Disbrow and Stoll, 1957).

Three major stratigraphic units are present.

Dakota Sandstone

This sandstone is the basal transgressive unit of the advancing Cretaceous sea. It is made up of fine- to coarse-grained sandstone units separated by black carbonaceous shale. Its thickness varies from about 50 to 250 feet in the region. Porosity and permeability can be significant in the Dakota, but they vary greatly. There are no reservoir data available for the Española Basin area.

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Mancos Shale

In general, the Mancos Shale represents the deeper marine phase of the depositional cycle. However, there are minor cycles within it, and several thin sandstone, limestone and calcareous shale members have been designated. The total depositional thickness of the Mancos Shale appears to be from 2,000 to 2,500 feet.

Individual sandstones in the Mancos occasionally are porous and serve as hydrocarbon reservoirs. In general, the thick shale units represent an important barrier to fluid migration.

Mesaverde Group

This unit represents a regressive phase of Cretaceous deposition. It is made up of massive sandstone, carbonaceous siltstone, shale and coal beds. Due to post-Cretaceous erosion, its thickness is difficult to predict. Disbrow and Stoll (1957) reported from 0 to 765 feet of the unit in the Galisteo Creek-Cerrillos area. Some reservoir potential probably is present in this unit, but in the absence of deep well tests in the Española Basin there are no formation data on which to base an assessment of its magnitude.

In the San Juan basin, west of the Nacimiento Mountains, an additional transgressive shale and regressive sandstone overlie the Mesaverde Group. The sediments of this cycle have not been reported in the Galisteo Creek-Cerrillos area, and there are no data available to indicate whether they are present in the Española Basin.

Cenozoic

Cenozoic rocks of the Cañon de San Diego Grant are limited to a few hundred feet of Late Tertiary to Quaternary volcanic rocks. However, a short distance to the east of the Grant boundary, in the Española Basin, Cenozoic sedimentary and volcanic rocks are likely to reach a significant thickness. The precise location and character of the western boundary of this basin in the project area is unknown. Based on gravity data (plate 3) the axis of the basin appears to lie about 6 to 12 miles east of the Grant boundary. By analogy with other parts of the Rio Grande Rift system, the boundary zone is likely to be

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made up of one or more large normal faults, across which Cenozoic basin-fill materials thicken dramatically.

Cenozoic rocks reflect the complex structural and volcanic history of this region. They are subject to rapid thickness and facies changes. Local sections have been subdivided in various ways. A detailed discussion of this complex stratigraphy is not required for the purposes of this discussion, particularly since the available stratigraphic data are derived from localities which are relatively distant from the project area. Several major depositional intervals are recorded in the region.

Paleocene - Eocene

A thick accumulation of Early Tertiary sandstones and shales was deposited in the San Juan Basin and is exposed along the west side of the Nacimiento Mountains. Two units are present: the older Ojo Alamo Sandstone is a coarse-grained clastic sequence; it is overlain by the finer grained fluvial and lacustrine Nacimiento Formation. Total thickness of the two Paleocene units is in excess of 1,000 feet. They have not been reported from the limited outcrop areas around the edge of the Española basin and their presence within that basin is uncertain.

Eocene rocks are present in the eastern San Juan Basin and in the eastern border of the Española Basin, at Galisteo Creek. In the San Juan Basin, these rocks are assigned to the San Jose Formation, consisting of sandstone, shale and variegated shale. It is up to 2,400 feet thick in the eastern part of the Basin (Fassett, 1974). Along the eastern Española Basin margin, the Galisteo Formation ranges in outcrop thickness from 1,200 to 3,000 feet (Disbrow and Stoll, 1957). It consists of red-brown, orange and grey sandstone, mudstone and minor amounts of conglomerate. It is reported to have low permeability in the Santa Fe area (Spiegel and Baldwin, 1963). The Galisteo Formation may be in part of Oligocene age.

Eocene(?) - Oligocene

The intrusive-extrusive igneous complex of the Cerrillos Hills at the southeast end of the Española Basin include stocks, sills, laccoliths and dikes of probable Oligocene age (Stearns, 1953). The extrusive phase, called the Espinosa Volcanics, is made up of as much

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as 2,000 feet of latite tuffs, tuff breccias and flows, overlain by a limburgite flow and tuff. The intrusives are mainly monzonitic in composition (Disbrow and Stoll, 1957).

Miocene - Pliocene

Fault-bounded basins making up the Rio Grande Rift complex appear to have begun forming in mid-Miocene time. The Santo Domingo-Española Basin was filled with clastic sediments of the Santa Fe Group. The type section, near Santa Fe, is approximately 4,500 feet thick. It consists of interbedded lenses of sandstone, mudstone, conglomerate and volcanic ash (figure 5). The age-span of the Santa Fe Group, and therefore the period of active basin subsidence, is middle Miocene to middle Pliocene (Galusha, 1974).

Porosity and water yield from the Santa Fe Group in wells in the Santa Fe area generally are low but may be significant in some of the coarser clastic units. However, the principal significance of the units to geothermal prospecting is its potentially great thickness over older objectives along the west side of the rift zone and in its potential to function as a cap rock above fractured and faulted zones in these older rocks.

Cenozoic sediments bordering the south end of the Jemez Mountains are at least partly equivalent to the Santa Fe Group and are referred to here as the Zia Sand Formation of early to middle Miocene age. About 1,000 feet of these sediments are exposed in the San Ysidro quadrangle, but the total subsurface thickness doubtless is much greater. The section consists of mudstone, sandstone, conglomerate and tuffaceous beds. Farther north, along the east flank of the Jemez Mountains, a water well located in Guaje Canyon (well 19/7/4.444) penetrated 2,025 feet of Santa Fe Group beds without reaching the base (Griggs, 1964). These deposits appear to represent coarse fan and stream environments along the margin of the basin. They interfinger with fine-grained flood plain and playa materials in the axial parts of the graben.

Volcanic rocks are associated with the Rio Grande Rift zone in many places, although the volume of volcanic rocks appears to be small considering the proposed rift origin of the depression. However, the west side of the Española Basin and the adjacent uplifted Jemez-Nacimiento Mountain block are covered with a thick and extensive sequence of flows. A summary of this assemblage is shown in table 2

Figure 5. Composite stratigraphic section and chronostratigraphic correlations of the type locality of the Santa Fe Group. (From Galusha, 1974).

Table 2. Nomenclature of the volcanic and related rocks of the Jemez Mountains. (Adapted from Bailey and others, 1969). (From Kudo, 1974).

Age	Group	Formation and brief description	
Pleistocene	Teva Group	Valles Rhyolite	Banco Bonito Member (vitrophyre, flow) El Cajete Member (bedded air-fall deposits, rhyolite pumice blocks and lapilli) Battleship Rock Member (rhyolite ash-flow tuff) Valle Grande Member (porphyritic rhyolite domes, flows, and tuffs) Redondo Creek Member (quartz-poor rhyolite dome, dike, flow, tuffs) Dear Canyon Member (rhyolite dome-flows)
		Cerro Rubio Quartz Latite (biotite-hornblende quartz latite, intrusion dome)	Bandelier Tuff
		Cerro Toledo Rhyolite (quartz-poor, domes, tuffs)	
			Tshirege Member (ash-flow tuff, inclusions of hornblende-rich quartz-latite pumice; basal air-fall pumice, "Tsankawi Pumice Bed") Otowi Member (ash-flow tuff, lithic inclusions; basal air-fall pumice, "Guaje Pumice Bed")
Late Pliocene	Polvadera Group	El Rechuelos Rhyolite (pumice, perlite, obsidian; volcanic domes and cone) Tschicoma Formation (porphyritic dacite, rhyodacite, quartz latite; massive flows and domes) Lobato Basalt (olivine-augite basalt, flows)	Puye Formation (conglomerate, coarse sands, interlayered lithic lapilli tuff beds and lahar deposits; debris predominantly from contemporaneous erosion of the Tschicoma Formation; can have Precambrian debris and interlayered lake clays) Cochiti Formation (sand and gravel, poorly consolidated; debris predominantly from erosion of the Keres Group; granitic detritus increases southward)
Middle Pliocene	Keres Group	Bearhead Rhyolite-Peralta Tuff Member (rhyolite domes, intrusions, flows, and tuffs) Paliza Canyon Formation (basaltic andesite, andesites; flows, breccias, dikes; also porphyritic dacites to quartz latites) Canovas Canyon Rhyolite (domes, intrusions, flows, and tuffs) Basalt of Chamisa Mesa (olivine basalt flows)	
Early Pliocene			

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(from Kudo, 1974). Age-dates obtained from the Keres Group (a minimum of 8.5 m.y.) and at least part of the Polvadera Group (7.4 to 2.2 m.y.) indicate that these units are contemporaneous with part of the middle and upper Santa Fe Group sediments.

In addition to the Jemez Mountains volcanic complex, isolated basalt eruptive centers and associated flows are present in the Santo Domingo-Española Basin, such as the assemblage capping Santa Ana Mesa and the Cerros del Rio. The thickness of basalt varies greatly but is more than 1,300 feet at Chino Mesa, in Cerros del Rio (Griggs, 1964). A site near Jemez Dam (Sec. 32, T. 14 N., R. 4 E.) gave a K-Ar age-date of 2.6 ± 0.2 m.y. for basalt of Santa Ana Mesa (Armstrong et al., 1976).

Late Pliocene - Quaternary

In general, the area has been undergoing erosion during this period. Apart from the accumulation of volcanic rocks in the Jemez Mountains described in table 2, Quaternary materials consist of terrace deposits, landslide debris and the alluvium of active stream valleys. These sediments generally reach only a few tens of feet in thickness.

Structure

Four major periods of structural activity have left their imprints on the study area. All of these episodes contribute to the definition of possible geothermal prospects in the area (plates 1, 2 and 3).

Deformation during Precambrian time is responsible for much of the fracturing seen in the crystalline basement rocks. Late Paleozoic structural instability defined such regional positive elements as the ancestral Nacimiento Uplift (Penasco Axis) and controlled the distribution and character of Late Paleozoic sedimentary rocks. In Late Mesozoic to Early Tertiary time, the Laramide orogeny redefined the Nacimiento Uplift and gave rise to important faults and folds in the region. Finally, the Rio Grande Rift zone formed across the region, establishing new fault patterns and reactivating old ones as well as providing loci of the accompanying volcanism.

The main regional structural units of the project area are the result of Laramide deformation and mid-Cenozoic rifting. These are the

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Nacimientito Uplift and the Albuquerque-Santo Domingo and Española Basin segments of the adjacent Rio Grande Rift zone (figure 6). The Jemez Mountains volcanic field and the project area are located approximately at the intersection of major north-striking fault trends characteristic of the Albuquerque and Santo Domingo basins with the northeast-trending Española Basin (figures 6 and 7).

The important structures within each of these subdivisions will be outlined below with respect to their significance to geothermal prospecting in or near the Cañon de San Diego Grant.

Nacimientito Uplift

This uplifted block of Precambrian, Paleozoic and Mesozoic rocks trends northward through the project area for a distance of about 50 miles (figure 6) from its southern plunge near San Ysidro, northward to the east-trending San Pedro Mountains fault, near Gallina, which separates the Nacimientito Mountains Uplift from the adjacent Gallina-Archuleta arch (Kelley and Clinton, 1965).

The western boundary of the block is well-defined by the Nacimientito and Pajarito reverse faults, which separate the Uplift from the San Juan Basin to the west. The geometry of the Pajarito Fault is poorly known, but the Nacimientito Fault plane is reported to have an eastward dip of 60° at depth, flattening to about 45° at shallower horizons. The stratigraphic separation along the fault varies from a maximum of 4,000 feet in the north to about 100 feet in the south at Senorito Creek, where it dies out (Woodward, Kaufman and Anderson, 1972).

The Nacimientito Uplift block is tilted eastward and is cut by a number of normal faults. Some of these define subordinate horsts and grabens within the Uplift, whereas others are parts of a broad system which drops blocks progressively down to the east and southeast toward the flanking Santo Domingo and Española Basins. Some of these faults are covered or partly covered by the volcanics of the Jemez Mountains or by sedimentary rocks overlapping the uplift from the adjacent basins. Thus, the eastern edge of the Uplift block is difficult to define precisely. Based on gravity data for the Rio Grande Valley, the main trend of the eastern boundary appears to be northeastward from San Ysidro through the central part of the Jemez Mountains. This imparts a wedge shape to the south end of the Uplift. Major faults within the Uplift, as described below, parallel both the northeasterly

Figure 6. Index map showing major tectonic elements of central-northern New Mexico. (From Woodward, 1974).

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trend of the gravity gradient and the Española Basin axis, and the northerly trend of the Nacimiento Fault zone. Although the eastern edge of the Uplift is difficult to define, surface geological data indicate that the major downward displacement toward the basin axis is to the east of the easternmost outcrops of Triassic rocks, which occur east to the Jemez River, in Paliza Creek. Assuming that the steep gravity gradient seen on plate 3 marks the location of the main fault zone, the major faulting seems likely to be concentrated in a belt extending from Rio Guadalupe to Jemez Canyon.

Based on this interpretation, it appears that the Cañon de San Diego Grant and the adjacent acreage leased by competitive bidding are west of the main boundary fault zone between the Nacimiento Uplift and the Española Basin. Thus, the Grant may not provide the optimum location for prospecting the zone of high fracture potential. However, porous Paleozoic and Mesozoic rocks may be present beneath an impermeable cover of Cenozoic sediments at various places east and west of the inferred buried zone of maximum fracturing. The critical question is determining if such rocks are present at depths at which high temperatures might be reached.

There are a number of faults within the Uplift. The most important of these are described below.

San Ysidro, Sierrita and Associated Faults

The San Ysidro Fault extends from White Mesa, south of San Ysidro, along a northerly strike to the southern part of Sec. 13, T. 16 N., R. 1 E. Here, the strike changes to northwest and the fault appears to die out in the Precambrian terrain (Woodward and Ruetschling, 1976). North of Highway 4 and west of San Ysidro, the Cretaceous Dakota Sandstone is in fault contact with the upper part of the Triassic Chinle Formation. This indicates a stratigraphic separation of at least 1,200 feet, with the younger rocks downthrown to the east.

The Sierrita Fault branches off the San Ysidro Fault in the northern part of Sec. 11, T. 16 N., R. 1 E. This is one of the few features bounding the Rio Grande Rift that is well-enough exposed to study in detail. The strike of this fault is northerly at its southern end but curves to the northeast toward Guadalupe Box. It has been projected beneath Virgin Mesa, through the intensely fractured Precambrian outcrops at Soda Dam on the Jemez River, and on northeastward to the

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edge of the Valles Caldera, where it is buried beneath the recent Banco Bonito Rhyolite (Smith, Bailey and Ross, 1970). It may continue to the northeast through the numerous faults crossing the Redondo Peak resurgent dome, and it may be represented by the northeastward-trending lineament formed by the Valles and Toledo Calderas. In general, the eastern block has moved down toward the southeast.

The fault configuration and history of movement can be seen in considerable detail where it crosses the Guadalupe River, near Guadalupe Box (figure 8). A cross section of the fault at this locality shows that offset has taken place in at least two stages. Thus, the post-Triassic, pre-Quaternary offset amounts to about 2,200 feet. This may have taken place in Miocene to Pliocene time, related to the development of the Rio Grande depression. Offset at the base of the overlying Bandelier Tuff is approximately 45 feet. This evidence of Quaternary movement is important because refracturing of the rocks by repeated movement may maintain enough open fractures for the circulation of thermal fluids, where the system might otherwise have become completely blocked by mineral deposition.

The dip of the fault plane is nearly vertical in the Bandelier Tuff. At greater depths the dip flattens to about 50°. This flattening is interpreted to mean that the Rio Grande Rift formed by severe crustal extension (Woodward and Duchene, 1975). This view supports the hypothesis of Chapin (1971) that the Rift formed when the westward drift of the crust to the west of the Rift exceeded the rate of the segment to the east.

If the Sierrita Fault is one of the major structural features of the Rio Grande boundary, as proposed by Woodward and Duchene (1975), there are some aspects of its geometry which are puzzling. For one, persistence of the decreasing dip of the fault plane at depth would keep it from penetrating deeply enough to influence the upward movement of magma: how then to explain the Jemez volcanic field? Further, the relatively low dip of the fault plane, coupled with curvature of the surface trace of the fault in the segment between its junction with the San Ysidro Fault on the south and the Guadalupe Box on the north, suggests a relatively superficial feature, analogous to a huge slump block. Thus, although the fault is well exposed at this one locality, the significance to be drawn from it appears ambiguous.

Figure 6 Diagrammatic northwest-southeast structure section through Sierrita fault near Rio Guadalupe, New Mexico. Qbt = Bandalier Tuff (Quaternary), $\bar{A}$ = Triassic rocks, P = Permian rocks, M-P = Mississippian and Pennsylvanian rocks undivided, pC = Precambrian rocks.

(From Woodward and Duchene, 1975).

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Jemez Fault

This fault has been traced from NW/4 Sec. 31, T. 16 N., R. 2 E., northward to its intersection with the Sierrita Fault near Gilman. It is made up of a short, curving, southern segment which trends from north to northeast. The main part of the fault strikes nearly north-south. Although not well exposed, the northern segment trends to the northwest. The dip of the fault plane has not been described, but it has been interpreted to be steeper than the Sierrita Fault (Woodward and Martinez, 1977). This appears to be consistent with the generally straight surface trace through most of its length. Movement along the fault has been down to the east, with stratigraphic separation estimated to be from 1,000 to 1,500 feet in the central segment. It may be greater in the area north of San Ysidro, where it places Cenozoic rocks of the Rio Grande depression against rocks as old as the Permian Yeso Formation. It is possible that the Jemez Fault is a more deep-seated fracture and a more fundamental boundary element than is the Sierrita Fault. The latest movement on the Jemez Fault appears to be younger than the Miocene-Pliocene graben fill and older than collapse of the Valdes Caldera (Smith, Bailey and Ross, 1970).

Small Faults in the Meseta Blanca- Jemez-Mesa de Guadalupe Area

Several small inferred or approximately located faults have been mapped east of the Jemez River, near Jemez pueblo. Generally these strike slightly east or west of north and have maximum displacements of only a few hundred feet. Movement has been down to the east on most of them, but a few show movement down to the west. Together they form an area of small horsts and grabens. One or two of these faults have been mapped as curving strongly to the northwest to intersect the Jemez fault near Mesa de Guadalupe. The concentric curves formed by these features, and by the Sierrita fault to the north, are superficially suggestive of ring faulting around a circular collapse feature. However, the dips of several of the fault planes on the east side are toward the east, away from a concentric focal point (Smith, Bailey and Ross, 1970). Depending on the unknown relationships and configurations of faulting at depth, the structure may not be a clear-cut circular graben, as proposed by Earth Satellite Corporation (1976).

This area is on the plunging nose of a northeast-trending Bouguer gravity high, as well as on a closed high on the aeromagnetic

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map (plate 3). Although surface data alone are weak, the combination of surface, gravity and magnetic data indicates that a high-density magnetic body may occur here. The nature of such a body is uncertain. Precambrian rocks are relatively close to the surface here and, where exposed in the Nacimiento Mountains a few miles to the west, vary widely in composition. One interpretation of the geophysical data is that the anomaly may be due to compositional variations within the Precambrian. A second, more favorable, interpretation was presented by Earth Satellite Corporation (1976), in which they proposed that the anomaly is caused by a circular stock of Cenozoic age, intruded into the Precambrian along a major zone of weakness extending northeastward from this anomaly through the Valles and Toledo Calderas.

Faults Associated with the Valles Caldera

The concentric fault system presumed to have controlled caldera collapse is poorly exposed and of uncertain location. The main system of faults lies inside the topographic rim, beyond the northern edge of the Cañon de San Diego Grant. Although subtle ring fractures may have developed on the outer slopes of the northwestern rim, no evidence of such features has been reported along the southwest and western rim.

Fractures and Joints in Precambrian Rocks

There are numerous large- and small-scale fracture systems in the Precambrian rocks of the Nacimiento Uplift (figure 9). As these fractures have not been mapped in younger rocks, it is probable that they are of Precambrian age. Large-scale features made up a conjugate system with a dominant northwest component, a subordinate northeast component and occasional northerly trends. These trends are similar to faults which have developed in later periods of deformation (Kelley and Clinton, 1960). Detailed studies of the orientation and distribution of micro- and macro-fractures have not been made in outcrop areas. This is unfortunate because such fractures in Precambrian rocks represent the most likely reservoir in the section underlying the Cañon de San Diego Grant. Plans have been made by the geothermal study section of the Los Alamos Scientific Laboratory to carry out such studies at some undetermined future time (W. A. Laughlin, personal communication, 1977).

Figure 9. Faults, fractures and fold axes, San Juan Basin and Nacimiento uplift.
(From Kelley and Clinton, 1960).

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Some fracture analysis was done on cores of GT-2. As noted in the earlier discussion of the Precambrian rocks, these contained many small fractures, all of which were healed. The degree of rock alteration also commonly increases as the fractures are approached. Calcite is the most abundant cementing material, but epidote, chlorite, quartz, clays and/or sulfide minerals also have been observed (Laughlin and Eddy, 1977). Fractures occur in a variety of orientations but commonly are either horizontal, vertical or steeply inclined at about 60°. Commonly they are on the order of 8 cm apart, but occasionally they are as close together as 1 cm.

Santo Domingo-Española Basins

Various configurations have been proposed for these segments of the Rio Grande Rift. In general, the study area lies at the intersection of two main segments. The long Albuquerque-Belen Basin extends into the area from the south. Its trend is northerly and it is terminated at its junction with the Nacimiento-Jemez Uplift, near San Ysidro (figure 6). The rift axis changes trend here to northeasterly and is offset to the east, forming the Española Basin. The small subsidiary basin located at the offset is referred to as the Santo Domingo Basin.

Surface geologic evidence does not clearly define basin axes or the location of the flanks. However, gravity data suggest that the trend of the Española Basin axis is northeast, and that it is marked by a succession of gravity lows extending from Santo Domingo on the south, northeastward to the junction of the Rio Chama and Rio Grande. Problems involved in locating the northwestern flank of the basin have already been discussed. Some long faults on the east flank of the Jemez Mountains volcanic pile, extending northeast from the Cañada Ranger Station through Los Alamos, are roughly parallel to the axis of the basin.

There are many prominent north-trending faults in the transitional zone between the Albuquerque-Belen Basin and the Española Basin. These faults extend from beneath the Santa Ana Mesa basalt flows northward into the Jemez volcanic pile. They appear to intersect and cut across the southwest end of the Española Basin. Basalt vents in the Santa Ana Mesa volcanic field are aligned in this north-south direction, indicating that this fracture is an important deep-seated feature which has influenced magma movement here. Basalt eruptive centers to the northeast, in Cerros del Rio volcanic field, are arranged in north-northeast and northwest trends, more consistent with the axial trend of the Española Basin.

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GEOPHYSICAL SURVEYS

Unlike most geothermal areas, there are so many geophysical surveys available for the Cañon de San Diego area, at differing scales, with differing detail of coverage, and with differing conclusions, that a systematic synthesis and interpretation is necessary. In the following pages, each geophysical survey is discussed in terms of authorship, purpose, date, coverage, instrumentation (where known) and conclusions reached. After that is a section synthesizing all geophysical survey data for the region.

In addition to these survey results, it is known (Crowe et al., 1978) that several other geophysical projects are underway, in varying stages of completion. A 1:500,000-scale residual Bouguer gravity map of northern New Mexico was released by LASL (Aiken, Laughlin and West, 1977). Its value is limited to interpretation of regional structure. It shows dual patterns of north-south and northeast-southwest structural grain very clearly, the former slightly more intense than the latter. The eastern boundary of Nacimiento Uplift appears more north-south than described elsewhere (see Structure, above).

Heat-flow studies, dealing with reduced heat flow and convective effects on conductive heat flow, are continuing at Los Alamos also.

Two seismic-reflection surveys were run for LASL in the Barley Canyon area of the Jemez Mountains, extending across the northern boundary of the Grant. The report is not ready for release but should be of interest to the project when released. The principal LASL investigator was P. R. Kintzinger. Similarly, data still are under analysis from a high-explosive refraction survey, performed in Fall 1976 cooperatively by LASL, Union Oil Company and Massachusetts Institute of Technology. In this work, 4 seismometers were placed on a north-south line across the Valles Caldera. Preliminary results indicate travel-time delays comparable to those observed above a magma.

John Hermance, of Brown University, performed a magnetotelluric survey in Summer 1977, occupying 27 stations across an area of 20,000 square miles (50 by 40 mile rectangle), including the entire Grant within its reconnaissance boundaries. Only one station, Cañon, appears to be on the Grant, at its southern boundary. The study is funded by the U.S. Geological Survey and is continuing.

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Finally, down-hole geophysical logs are being studied for GT-1, GT-2 and EE-1 at LASL, as part of the continuing hot dry rock research effort.

Seismic Ground-Noise

Contractor: Senturion Sciences, Inc., Tulsa, Oklahoma

Client: Calvert Exploration Company

Survey Date: 7-30 September 1973 and 13 November 1973-1 January 1974

Area Covered: The eastern half of the Cañon de San Diego Land Grant, the Jemez Pueblo Grant, and the Jemez Indian Reservation, plus a few stations around the northeast corner of the Cañon de San Diego Grant, in and near the Valles Caldera.

Description of Survey: Seismic ground-noise was monitored at approximately 144 locations within an area of about 168 square miles. Contour maps were presented showing integrated power, mean frequency of the integrated power, predominant power, and frequency of the predominant power, plus a composite anomaly map.

No report was supplied to GeothermEx with these four contour maps; therefore, details of instrumentation, recording time at each station, and data-processing technique, along with comments and conclusions of the contractor, are not available.

Assessment of the Results: Great care must be taken in assessing these data, as field and laboratory data are not available and the contouring leaves much to be desired. Contour lines have been drawn far beyond the region containing data, and in some instances contours have been drawn which enclose areas containing no data. Furthermore, in several instances there are one-station anomalies.

Research since the date of this survey into the usefulness of ground-noise surveys in geothermal exploration has demonstrated that "typical [ground-noise] surveys suffer greatly when data are contaminated by non-seismic noise or by interfering seismic wave trains or by improper

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spatial sampling. These pervasive problems have combined to place the utility of noise analysis in a questionable area of subjective, qualitative geophysical methodology, and have limited its acceptance as an integral element in geothermal exploration" (Liaw and McEvilly, 1977).

Observation: Three ground-noise anomalies lie south of the Cañon de San Diego Grant along the Jemez River (plate 3, this report; also Senturion Sciences, unknown date *a*, figure 5). These probably represent noise of the river or noise amplified by the thin layer of alluvium adjacent to the river.

Microearthquake Surveys

Jemez I Microearthquake Investigation

Contractor: Senturion Sciences, Inc., Tulsa, Oklahoma

Client: Sun Oil Company

Report Date: Unknown

This report was not supplied to GeothermEx; the following two reports make reference to it. The location, seismometer array dimensions, and recording time are unknown. Only one observation is mentioned: on 4 April 1973, a swarm of 13 microearthquakes occurred near Jemez, New Mexico.

Cañon North Seismicity Investigations

Contractor: Senturion Sciences, Inc., Tulsa, Oklahoma

Client: Sun Oil Company

Report Date: None given

Seismometer Locations: A 5-kilometer-diameter array of 6 geophones was established on the Jemez Plateau in the northeast corner of the Cañon

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de San Diego Grant. This is adjacent to and south of the LASL GT-2 drill hole.

Description of Survey: During a 15-day recording period, from 16 August through 31 August 1974, 54 seismic events were recorded. Azimuths and distances were calculated for these events. In the opinion of the contractor, most of the events were cultural disturbances, as they occurred during the working day and could be correlated with mining areas.

Observations: Five events were local microearthquakes, of which three could be located (plate 3). One occurred northeast of Cuba. The second was located in the Jemez Canyon just north of the intersections of the Jemez River and Rio Guadalupe, near the north end of the activity swarm noted in the Jemez I survey. The third occurred within the Valles Caldera at a depth of $11,000 \pm 3,000$ feet.

Two regional earthquakes were recorded. The P-wave from one of these events traversed the seismometer array at 21,000 feet per second, a reasonable velocity, which is also in agreement with a seismic survey done for LASL with downhole seismometers in the GT-2 hole. For unexplained reasons, Senturion stated that this LASL survey is "of dubious reliability."

The second regional earthquake displayed a very low apparent velocity. This could be explained by a low velocity zone beneath the seismometer array, which would be in conflict with the LASL survey.

Conclusions of the Contractor: Mine blasts at Paguete to the southwest of the array yielded apparent velocities and apparent azimuths which could be explained by "a sharp boundary about 10 miles southwest of the array with an azimuth of roughly 160° separating media with velocities of 21 and 17 Kft/sec." The possibility of a low-velocity zone south of the array is encouraging because temperature increases and/or the presence of a gas (steam) under pressure in a porous media can reduce the velocity. This suggests the possibility of a small steam reservoir south of the array; however, such an explanation would be in conflict with downhole temperature data from the LASL GT-2 drill hole.

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Cañon I and Cañon II
Seismicity Investigations

Contractor: Senturion Sciences, Inc., Tulsa, Oklahoma

Client: Sun Oil Company

Report Date: 2 April 1975

Seismometer Locations: For the Cañon I survey, a 2-mile-diameter array of 6 seismometers was centered 1.5 miles northeast of the juncture of the Jemez and Guadalupe Rivers. For the Cañon II survey, with a 7-mile-diameter, a 6-seismometer array was centered 4.5 miles south of Jemez Springs.

Description of Survey: The first array was on location from 30 July through 13 August 1974, and the second array was operational from 20 December 1974 through 2 February 1975. Because of various problems with field instruments and the weather, only 18 days of data were considered to be worthy of analysis.

Observations: Only 3 local microearthquakes were recorded (plate 3). These occurred within a 4-minute time interval and were located near Jemez, 3.5 to 5 miles south of the Cañon II array, at a depth of 20,000 to 30,000 feet. These events correlate with the earthquake swarm recorded on 4 April 1973 by the Jemez I survey.

The next-nearest event was located in the Sierra Nacimiento, 12 miles west of the array. All other microearthquakes occurred at distant locations from the Cañon de San Diego Grant. One swarm of events was located near Cañon Tapia, about 40 miles southwest of the Cañon II array near the client's Cabezon exploration prospect.

Conclusions of the Contractor: Continuing, but infrequent, microearthquakes occur near Jemez, New Mexico, and a small-event swarm was recorded near Cabezon. These are the only areas of interest, based upon this survey. This level of seismic activity is very low when compared with microseismicity at The Geysers, California (10 to 50 events per day).

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Assessment of the Microearthquake Surveys: Microearthquake monitoring can be a very valuable component of a geothermal prospecting program: most non-basaltic geothermal systems exhibit high levels of microearthquake activity. It is this continued movement and refracturing that keeps rock formations permeable, permitting the flow of hydrothermal fluids.

During the total 33-day recording time of the Cañon North and the Cañon South I and II surveys, and the unknown duration of the Jemez I microearthquake investigation, only 19 microearthquakes were recorded in the immediate vicinity of the Cañon de San Diego Grant. Of these, 17 were located near Jemez, an area of mapped faulting just south of the Grant. While indicating that these faults are active, the rate of microearthquake events is far from dramatic, being significantly less than at The Geysers, California. Curiously, only one microearthquake occurred within the Valles Caldera during the seismic surveys.

The suggestion of a low-velocity zone southwest of the LASL GT-2 drill hole (see Senturion, Cañon North, figure 1) is based upon relatively little data and is in conflict with downhole measurements. If such a feature does exist, there is no assurance that it is related to a thermal anomaly.

Electrical Surveys

Geothermal Resistivity Survey
of the Jemez Pueblo Area,
Sandoval County, New Mexico

Contractor: Heinrichs Geoexploration Company, Tucson, Arizona

Client: Calvert Geothermal Resources, Inc.

Report Date: December 1973

Area Covered: The Jemez Pueblo Grant, an approximately 5-mile-square area immediately south of the Cañon de San Diego Grant.

Description of Survey: Electrical-resistivity measurements were made using an electrode array variously called roving dipole, dipole mapping

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or bipole-dipole. Two bipole transmitters, each about 8,000 feet in length, were located, respectively, in the southeastern and southwestern portions of the Jemez Pueblo Grant. A total of 102 receiving locations were occupied using the first bipole source, with an additional 59 locations for the second source. The station density in the areas covered was about 4 per square mile.

Observations: There are no striking resistivity anomalies. The most anomalous feature, which appears for the southwestern bipole source, is a 1- to 2-square-mile resistivity low, centered about 2 miles southeast of the northwest corner of the Jemez Pueblo Grant (see plate 3, present report; also Geonomics, 1974, plate III, anomaly 5). The apparent resistivity contrast with respect to the background is only about a factor of 2. There is also the slightest suggestion of a string of apparent resistivity lows trending eastward across the survey area from this anomaly. Data from the southwestern bipole source show a low-contrast resistivity low which correlates with this eastward trend (see Geonomics, 1975, plate IV, anomaly 4).

Conclusions of the Contractor: The electrical data appear to fit a simple 2-layer model consistent with the known geology: about 2,500 to 3,000 feet of Carboniferous, Permian and Miocene sediments overlying a Precambrian basement. The younger sediments appear to have a bulk resistivity of 10 to 15 ohm-meters, while the basement resistivity is probably 100 to 200 ohm-meters. Generally increasing conductance to the southwest suggests that the sedimentary section thickens in this direction.

The conductive anomaly near the northwestern corner of the survey is not thought to be highly significant in terms of a potential geothermal resource: the anomaly has a low apparent-resistivity contrast with respect to the background; it does not appear for both bipole sources; numerical modeling suggests that this anomaly pattern could result simply from the existence of more resistive rock to the northwest.

There is the possibility that the low-amplitude conductive anomalies trending east-west across the survey area halfway between Jemez and the northern border of the Jemez Pueblo Grant indicate a structural feature at depth.

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Deep Electrical Resistivity Investigations
Coupled with Dry Geothermal Reservoir
Experiments in New Mexico

Author: George R. Jiracek, Department of Geology, University of New Mexico, Albuquerque, New Mexico

Funding Agency: National Science Foundation (NSF)

Report Date: March 1975

Area Covered: An 8-square-mile area north of the Cañon de San Diego Grant in the vicinity of LASL GT-2 and the western rim of the Valles Caldera.

Description of Survey: Shallow Schlumberger and deep dipole-dipole resistivity soundings were conducted, centered upon the LASL GT-2 drill hole, and roving-dipole resistivity measurements were made at over 100 locations using a 1.3-mile-long bipole transmitter located 3.2 miles west-southwest of LASL GT-2.

Observations: Resistivity logging of the well displayed highly variable resistivity in the 466-foot-thick volcanic sequence (Bandelier Tuff), a resistivity of about 15 ohm-meters in the underlying 1,937-foot-thick wet sedimentary section, and resistivities in excess of 1,000 ohm-meters in the Precambrian granite, commencing at 2,403 feet. At a depth of 3,115 feet, water-filled fractures were encountered in the granite, with the result that the resistivity dropped to less than 100 ohm-meters.

The shallow Schlumberger sounding data are consistent with the well-log data, displaying a highly resistive (800 ohm-meters) surface layer to a depth of 16 feet, various layers with resistivities ranging as low as 3 ohm-meters to a depth of 269 feet, and then a 3,000 ohm-meter layer.

The deep dipole-dipole sounding data show evidence of the resistive (>1,000 ohm-meters) Precambrian basement.

The roving-dipole resistivity data are complex, displaying northeast-trending low resistivity anomalies through the well site, a north-south-trending resistivity high near the eastern edge of the survey, and a

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dramatic decrease in resistivity for locations within the Valles Caldera (Jiracek, 1975).

Conclusions of the Author: The low-resistivity region at the eastern edge of the survey area is interpreted as the ring-fracture system at the western edge of the Valles Caldera. If this fracture system is acting as a deep, hot-water plumbing system it could account for the electrical anomaly. This interpretation is supported by hot spring activity in the vicinity and by the successful geothermal wells drilled by Union Oil Company approximately 1.6 miles to the east. The low-resistivity anomaly suggests that the ring-fracture boundary is about 0.6 mile west of the Caldera margin as indicated by a row of dots on the geologic map by Smith, Bailey and Ross (1970).

The change from dry to water-saturated conditions in every rock type is characterized by a sharp decrease in apparent resistivity in each unit; for example, to 800 ohm-meters to 16 feet in the surface layer, thereupon dropping to less than one-tenth that value.

An Electrical Resistivity Survey of the
San Diego Grant Prospect,
Sandoval County, New Mexico

Contractor: Geonomics, Inc., Berkeley, California

Client: Sun Oil Company

Report Date: May 1975

Area Covered: The Cañon de San Diego Grant and adjacent areas to the northeast.

Description of the Survey: Three bipole sources were used to conduct a roving-dipole survey at a total of 342 receiver locations. The bipole sources, along with several other current transmitters, were used to make 10 resistivity soundings. This effort, when spread over an area the size of the Cañon de San Diego Grant, represents a reconnaissance survey for locating massive resistivity anomalies.

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Observations: In addition to the survey by Geonomics, the data acquired by Heinrichs (1973) and Jiracek (1975) were presented and utilized. Ten conductive anomalies are identified, and several faults are hypothesized; however, none of the anomalies has the size and contrast with background that is exhibited by the anomaly within the Valles Caldera near its western rim (plate 3, present report; also Geonomics, 1975, plate VII).

Conclusions of the Contractor: Only one anomaly defined by this survey,

. . . Anomaly 1 inside the Valles Caldera, is known to represent favorable geothermal conditions. All other anomalies are much less prominent and it is not possible at this time to conclude from the resistivity data alone, or with the aid of other (existing) geophysical data such as seismic noise and microearthquake locations obtained by Senturion, whether any represent economic geothermal systems. Anomaly 10, based on the total apparent conductance maps, was drilled by the AEC and high temperatures were encountered (197°C at 3 km). It is likely that the absence of prominent resistivity lows in the area indicates the absence of primary porosity. However, the San Diego Grant area is highly faulted and it is possible that small or narrow geothermal pockets exist along fracture zones and that they are not represented by prominent lows" (Geonomics, 1975, p. 19).

Assessment of the d.c. Resistivity Results: As a reconnaissance electrical exploration technique, the roving-dipole method can prove useful for locating large conductive anomalies. However, the method suffers from an inherent ambiguity with regard to the depth to an anomalous feature, and repeated receiver readings for multiple transmitter locations only partly help to resolve the ambiguity. For this reason, the method is of limited usefulness in defining small or complex structures. As stated in both the Heinrichs (1973) and Geonomics (1975) reports, the observed anomalies have low contrast and give no evidence of being of geothermal significance. Some of the anomalies may be associated with thin alluvium along the Jemez and Guadalupe Rivers and along Vallecito Creek, one mile northeast of Jemez.

The faults inferred by Geonomics (1975) from the roving-dipole data are based upon steep apparent-resistivity gradients and are conjectural. Lithology and topographic effects may account for some of these

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gradients, and one is due to inaccurate contouring (north of anomaly 3, Geonomics, 1975, plate IV). Several modified Schlumberger and monopole soundings were performed by Geonomics (1975). Based upon recent model studies (Beyer, 1977) monopole soundings cannot be trusted if lateral resistivity contrasts are crossed. However, these and the other resistivity soundings generally are in accord with the well logs and soundings discussed above (Jiracek, 1975). As with the roving-dipole data, the resistivity soundings do not reveal any anomalies which might be suspected of having geothermal significance.

Magnetotelluric Survey in the Jemez Springs
Vicinity of Central New Mexico

Contractor: Geotronics Corporation, Austin, Texas

Client: Sun Energy Development Co.

Report Date: January 1977

Area Covered: Approximately 16 square miles in the vicinity of Jemez Springs.

Description of the Survey: Magnetotelluric (MT) data were obtained at 16 locations in this area (see plate 3, present report; also Geotronics, 1977, plate 1.1). The data are analyzed and interpreted in this report; however, the same data are included in a subsequent report (see below), for which additional MT stations were occupied.

Magnetotelluric Survey in the Jemez
Springs Area of New Mexico

Contractor: Geotronics Corporation, Austin, Texas

Client: Sun Energy Development Co.

Report Date: February 1978

Area Covered: Approximately 64 square miles in the vicinity of the Cañon de San Diego and the eastern boundary of the Cañon de San Diego Grant.

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Description of Survey: MT data were obtained at 17 locations in addition to the 16 sites occupied in the previous survey. Tensor impedances were calculated for the data at each location, and the transverse electric (TE) and transverse magnetic (TM) mode data were each inverted using a horizontally layered model, to calculate resistivity as a function of depth. The inverted data from stations along 6 lines are presented as resistivity cross sections. The results of several other manipulations of the data are presented for the same cross sections, along with contour maps showing the depth to deep conductive material and the resistivity at a depth of 15,000 feet.

Conclusions of the Contractor: The survey indicates a major conductive anomaly in the southeastern portion of the survey area and a very resistive anomaly in the north-central portion. There may also be a conductive anomaly in the northwestern portion of the survey area (see plate 3, present report; also Geotronics, 1978, plate 7.1). The southern conductive anomaly appears to be fairly shallow. It plunges steeply to the west and north but is poorly defined in other directions.

A significant lateral contrast trends east-northeast, just north of Jemez Springs. More-conductive material lies at depth on the south side of this contrast.

"The data depict a conductive unit which thickens from a few hundred feet in the western portion of the survey area to several thousand feet on the east. This unit is correlatable with sandstone units of the Triassic and Permian age. The underlying resistive units correlate with the limestones of the Magdalena group and the very resistive Precambrian granite basement" (Geotronics, 1978).

There are significant differences between the inverted TE and TM resistivity sections, which demonstrate that much of the resistivity structure is 2- or 3-dimensional rather than flat-lying. "This survey and analysis develops several possible interpretive schemes. The possibilities of lateral sedimentary thickening, a hydrothermal feature located near the limestone-granite interface, a conductive geothermal anomaly shallowing near Site 2-8 or some other possibility or combination of these, are all worthy of consideration in a full scale geologic interpretation" (Geotronics, 1978).

Assessment of the Results: Depending upon geologic, cultural-noise and source-field conditions, high-quality MT data can be difficult and/or

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time-consuming to obtain; yet, in interpreting the data, it is essential to take the data quality into consideration. Geotronics recognizes this, as is evident from the section in their report entitled "Data Quality and Reliability." The information they provide, however, is rather scant for making this judgment. The most fundamental form in which the data is presented is resistivity as a function of depth (inversion of the data at each station, assuming horizontally layered structure already has been performed). It would be helpful to see the data for both TE and TM modes at each station presented as apparent resistivity as a function of frequency, along with a correlation of the respective orthogonal electric- and magnetic-field components as a function of frequency.

Data are presented as resistivity cross sections along profile lines, all but one of which are roughly parallel to topographic features (mesas and canyons). This profile form of presentation may be misleading, however, because the dip axis directions often change dramatically as a function of frequency and from one station to the next. This means, for example, that a TE-mode apparent resistivity (at a particular depth) from one station may be in a different direction from the TE resistivity at an adjacent station. This casts reasonable doubt on the validity of the correlation cross sections.

Geotronics also presents the ellipticity and skew of the MT data, which they relate to "uncoupled anomalies (a coincidence of two or more anomalies in different directions from each site as evidenced by elevated ellipticity and low skew)" and "coupled anomalies (the sensing of two or more anomalies in the same direction)." They go on to display an "anisotropy factor," the ratio of TM and TE resistivities, and an "anisotropy sense," a derivative of the anisotropy factor, which they relate to conductive and resistive anomalies. While these quantities undoubtedly are a function of the 1-, 2- and 3-dimensionality of the geologic structure, the relationships would have to be developed through extensive 2- and 3-dimensional modeling.

Recent unpublished work by Morrison (1977) has demonstrated that anything short of 3-dimensional modeling of long-period MT data may be of questionable validity for precise interpretation. Resistivity contrasts at great lateral distances from an MT station can significantly affect the data, while being interpreted as the result of deep structure. It has been demonstrated that if the 2-dimensional structure (suggested by the resistivity section obtained from 1-dimensional inversion performed along a line of stations) is used to calculate the

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magnetotelluric field that theoretically should have been measured, there is poor agreement between this and the field which was actually observed.

TE-mode electromagnetic fields do not respond abruptly to lateral resistivity contrasts, so that buried features which are small with respect to the skin depth of the MT field will not be detected. (The skin depth in meters is $S \approx 503 \sqrt{\rho/f}$, where ρ is the resistivity of the rock in ohm-meters and f is the frequency in hertz.) The TM response, on the other hand, can be more abrupt, displaying lower apparent resistivities than actually exist in the conductive side of a boundary and higher apparent resistivities than actually exist on the resistive side. Generally, it is the TE mode which is used for horizontally layered interpretation schemes (1-dimensional inversion) because for these data the electric-field vector is parallel to strike and, therefore, does not traverse resistivity contrasts. From numerical modeling of 2-dimensional structures, however, it appears that a qualitative "average" of TE and TM apparent resistivities is sometimes useful in estimating actual resistivities.

While it is easy to criticize some aspects of Geotronics' handling and presentation of the MT data, on balance it should be stated that the processing, modeling and interpretation of MT data is currently a major topic of geophysical research. It is apparent that the detailed interpretation of long-period MT data will depend upon extensive modeling but that state-of-the-art MT interpretation is advancing rapidly. While layered inversion of long-period data will not allow the interpreter to precisely locate deep lateral resistivity contrasts, or accurately determine depths to 3-dimensional conductive bodies, MT data are most certainly of value in determining trends and locating significant features in the resistivity structure. The Geotronics magnetotelluric data are quite successful in this regard.

The data reveal a massive conductive feature at depth in the southeastern portion of the survey area, as displayed in their plates 7.1 and 7.2 (Geotronics, 1978). It terminates abruptly to the north along a roughly east-west line near Jemez Springs and plunges to the west, becoming thinner and/or more resistive. From the vicinity of Jemez Springs there is a less significant conductive branch of the anomaly extending to the northwest toward site 1-7. The massive anomaly plunges and/or becomes somewhat more resistive to the south and east (MT sites 2-11, 2-15, 2-17 and 2-20); however, more data would be necessary to define the anomaly in these directions. Whether or not it extends to the northeast of site 2-4 is unclear: the data at that

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station are of low quality; and low resistivities observed for long periods (presumably at depth) at site 2-2 in the northeastern corner of the survey area are almost undoubtedly the result of conductive features within the Valles Caldera to the northeast.

The TE and TM magnetotelluric data show relatively good agreement in defining the conductive feature in the southeastern part of the survey area, and there is some correlation with a roving-dipole resistivity low observed on Cat Mesa, east of Cañon de San Diego (Geonemics, 1975). The shallowest depth to highly conductive material is interpreted to be 6,800 feet at site 2-8; this depth probably is not particularly accurate ($\pm 50\%$), but the location is significant.

Another conductive anomaly was observed in the northwestern part of the survey area, in the vicinity of site 1-2. It is considerably more resistive than the feature discussed above and is poorly defined by the station locations. There is the possibility that such an anomaly could lie within the region (Cañon North) that Senturion suggested might have low seismic velocity.

Gravity, Aeromagnetics and Airborne Imaging

Report on Geothermal Exploration Guide Maps
for Valles Caldera Area (Jemez
Mountains), New Mexico

Contractor: Earth Satellite Corporation, Berkeley, California

Clients: Sunoco Energy Development Co., Chevron Oil Co., and Phillips Petroleum Co.

Report Date: 23 June 1976

Area Covered: The Jemez Mountains, New Mexico

Description of the Survey: The report is an interpretation of the geothermal potential of the Valles Caldera area based upon publicly available (as of May 1976) geological, hydrological, geophysical and imagery data.

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Conclusions of the Contractor: It is suspected that intrusive rocks of the region may have a limited supply of water, so that the connate water of the Santa Fe Formation may be important to the producibility of the resource. For this reason, areas indicated (plates 1, 2 and 3, present report; also Earth Satellite, 1976, plate 8) as geothermal exploration targets include localities where the Jemez Mountains volcanic pile overlies the Santa Fe Formation. High permeability should also be present within alluvial-fan deposits within the Santa Fe Formation at the west edge of the Española Basin. Major fault zones within the heated pre-Tertiary rocks are potential drilling targets, but the proximity to the Santa Fe Formation may be crucial for supplying recharge.

The caldera boundary is located at the San Antonio River rather than at the ring dike. The boundary structures dip inward, providing better targets from within the caldera than from without.

The 8-mile-diameter area centered on the junction of the Jemez and Guadalupe Rivers is a potential target because of its well-defined structure, gravity anomaly and magnetic anomaly (U.S. Geological Survey, 1962).

Assessment of the Data: The horsts and grabens of the Rio Grande depression generally are evident in the gravity data (plates 1 and 3, present report; also Satellite, 1976, plate 2). The western edge of the Sierra Nacimiento horst displays a steep, linear gravity gradient down into the San Juan Basin. To the south this trend turns southwest to become the western boundary of the Lucero Uplift (Aiken, 1977).

The steep gradient which defines the eastern edge of the Nacimiento horst appears to correlate highly with the easternmost outcropping of pre-Tertiary rocks. Earth Satellite (1976, plate 4) has interpreted this as the eastern boundary of the Española Basin.

For the 6- to 8-mile-wide region of outcropping Bandelier Tuff northwest, west and southwest of the Valles Caldera (see Smith, Bailey and Ross, 1970) there is the likelihood that the Bouguer gravity values (Earth Satellite, 1976, plate 2) should be several milligals higher than contoured. This is most evident from the high gravity contours "drawn into" to the Cañon de San Diego to the northeast and results from the inadequacy of using a 2.67 gm/cm^3 Bouguer density correction over the Bandelier Tuff, which almost certainly has a lower density. If a density of 2.2 to 2.3 gm/cm^3 is assumed for the Bandelier Tuff, then where it is 300 to 600 feet thick the Bouguer value should be 1.5

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to 3.8 milligals higher. The significance of this is to broaden the Nacimiento Uplift 1 to 2 miles in an easterly direction and to suggest increased fault displacement along the western edge of the Española Basin as indicated by Earth Satellite (1976, plate 4).

Earth Satellite noted a "circular graben" located at the junction of the Jemez and Guadalupe Rivers (plate 1, this report; also Smith, Bailey and Ross, 1970), even though it is characterized by a "well defined gravity high that indicates more strongly the added higher density material at depth rather than the unfaulted pre-Tertiary sediments at the surface" (Earth Satellite, 1976, p. 24). Whether this is an isolated feature is unclear. The "circular graben" is located at the northeasternmost end of a limb of the Lucero Uplift as defined by gravity data (Aiken, Laughlin and West, 1968). At this location the gravity high turns to the north, over the Nacimiento Uplift.

The Jemez Fault, however, continues to the northeast through the Cañon de San Diego. Earth Satellite (1976) suggested that young intrusives lie along this fault zone at shallow depths and that these are responsible for hot springs at Soda Dam, Jemez Springs and Indian Springs (see Earth Satellite, 1976, figure II, locations 8.9 and 11, respectively). The conductive anomaly located south of Jemez Springs by the Geotronics (1978) magnetotelluric survey may lend support to this argument. However, Trainer (1974) and Swanberg (1975) believe that the waters at Soda Dam Springs and Jemez Springs are derived from the same source as hot-spring waters within the Caldera.

The eastern structural boundary of the Española Basin, southeast of the Valles Caldera, is defined by Earth Satellite (1976, plate 4) to lie along the Rio Grande. This is based upon Landsat imagery and gravity data. The gravity data alone, however, suggest that the eastern margin of the Española Basin lies along the steep gravity gradient which defines the western edge of the Sangre de Cristo Mountains (the north-south-trending steep gradient along the eastern edge of the Earth Satellite gravity map, plate 2).

Heat-Flow and Temperature-Gradient Surveys

Preliminary Report and Final Report,
San Diego Grant Prospect, New Mexico

Contractor: Geothermal Services, Inc., San Diego, California (GTS Jobs No. 9-76 and No. 3-77)

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Client: Sunoco Energy Development Co.

Report Dates: Preliminary report undated; final report dated 16 January 1978

Description of Surveys: Two sets of temperature-gradient holes were drilled on or very close to the Cañon de San Diego Grant beginning late in 1976. The first set of 12 holes (Job No. 9-76) went to depths of 43 to 500 feet. The second set of 16 holes (Job No. 3-77) went to depths of 57 to 500 feet. Four other holes, drilled by the U.S. Geological Survey near Battleship Rock, Guadalupe Box, Jemez Dump and Jemez Falls also were logged by Geothermal Services.

Thermal conductivities were measured on samples from 25 holes (plate 4); conductivities were estimated for the remainder. From the gradient and conductivity values, heat flow was calculated for each hole. Because of the steepness of local topography, terrain corrections were considered necessary. These were performed according to a formula given by Birch (1960), with resulting changes of -37% to +28%, for a maximum correction span of 65%.

Observations and Conclusions of the Contractor: Terrain-corrected heat flow above 5 HFU was observed across at least 25 square miles of the Grant (plate 4), principally along the eastern boundary and in the northeast corner. Data spacing was good in this area, being approximately 1 hole per 2 square miles. Elsewhere, station density dropped to fair (southeastern corner) and very poor (rugged western half of Grant). However, nothing in the data collected in the eastern half of the Grant suggested that hole density should be increased or that other areas should be explored.

A strongly bilateral high was recognized, the more intense lobe being the northern one, at the southwest corner of the Valles Caldera. Values in this lobe reached 22 and 26 HFU (undoubtedly disturbed by convective flow), with 7 holes being 6 HFU or above. In the southern lobe (San Juan Mesa and Jemez Springs), the highest value was 7.1 HFU. Only 3 values were above 6.0.

The contractor noted the close parallelism of much of the heat-flow anomaly with the Jemez River canyon. This feature they assumed to be fault-controlled, although most geologic maps show only small portions of the canyon to be fault-controlled. They further considered this

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fault-controlled canyon to be "a conduit for thermal leakages from a source hydrothermal system in the Valles Caldea to the northeast."

They referred also to unpublished plots made by them of heat flow versus total depth; heat flow versus maximum temperature; bottom-hole temperature versus total depth; extrapolated surface temperature versus distance from the caldera rim, etc. They concluded that all of these showed random scatter. This they interpreted to mean that there is a "fairly deep" source for the heat-flow anomaly. They did not choose between the two logical alternatives: local magmatic intrusion or deep outflow from the Caldera. They did note a third possibility: that the high heat flows represent a conductive edge-effect around the magmatic heat source within the Caldera. This might exist even without convective thermal circulation but would be enhanced (or at least disturbed) locally by the latter.

Finally, Geothermal Services, Inc. recommended at least 2 holes to 1,500 feet in depth prior to drilling a deep geothermal test. Sites were nominated on San Juan Mesa (projected Sec. 36, T. 18 N., R. 2 E.) and near Battleship Rock (projected Sec. 32, T. 19 N., R. 3 E.) on the west side of Jemez River.

Assessment of Geothermal Anomalies

Plate 3 shows the boundaries of the Cañon de San Diego Grant, mapped faults and the locations of geophysical anomalies as discussed above.

There is a striking correspondence of electrical and heat-flow anomalies on the east-central Grant boundary, centered on San Juan Mesa. This can be interpreted to suggest a significant geothermal resource. The anomaly is observed in both TE and TM magnetotelluric data (Geotronics, 1978), and there is good correlation with a roving-dipole resistivity low observed by Geonometrics (1975). It correlates very closely with the southern lobe of high heat flow and temperature gradient (Geothermal Services, 1978).

The southern part of this anomaly is associated with a gravity low which lies just east of the Cañon de San Diego (Earth Satellite, 1976, plate 2). As discussed above, a lower Bouguer density for the Bandolier Tuff would shift the north-south-trending gravity gradient 1 or 2 miles to the east of Jemez Springs; this would enhance the coincidence of gravity and resistivity lows.

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The southern portion of the conductive anomaly also is associated with an aeromagnetic low (U.S. Geological Survey, 1962). At this latitude, a relatively non-magnetic body causing the magnetic low would be found at the northern end of the low. North-south-trending faults extend south from the center of the magnetic low but do not cut the Late Cenozoic volcanic rocks overlying the conductive anomaly. Their presence beneath the volcanic cover is unresolved.

The magnetotelluric survey (Geotronics, 1978) revealed an increasing thickness of conductive material from west to east across the survey area and did not adequately define the eastern boundary of the conductive material. One explanation for the conductivity, gravity and magnetic anomalies is that there is an increasing thickness of low-density, water-saturated, probably calcareous (non-magnetic) Paleozoic rocks eastward from the Jemez River. The thermal anomaly may merely reflect the circulation of hot water through the Pennsylvanian Madera Limestone as downgradient outflow from the Valles Caldera.

However, the gravity low associated with the southern portion of the conductive anomaly is too small laterally to make this interpretation entirely adequate. When this is coupled with the near-circular form of the MT anomalies, the close coincidence of both the TM and TE phases, and the intensity and near-circular form of the thermal anomalies, the area becomes very interesting as a geothermal prospect.

The east-west-trending limb of the TM and TE conductive anomalies south of Jemez Springs is also interesting but is supported less strongly by other data. Earth Satellite (1976) suggested that there may be shallow intrusive bodies in the area along the Jemez Fault, but this is conjectural. A strong linear nose exists in both heat-flow and temperature-gradient data in this area, but this is considered to be part of the long, linear Jemez River thermal anomaly. The presence of mineralized hot water at Jemez Springs suggests that thermal upwelling along a fault controls both the conductance anomaly and the heat-flow nose.

There is a moderate correlation of geophysical anomalies in the vicinity of Jemez Pueblo, consisting of microearthquake activity, small anomalies of lower electrical resistivity, and seismic ground-noise anomalies. However, the ground-noise may well be associated with the Jemez River or with the thin alluvium along it. The resistivity anomalies are small, not very intense, and may also be associated with alluvium. Microearthquake activity apparently is less intense than at many known geothermal areas.

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Magnetotelluric data (Geotronics, 1978) suggest that there is a conductive anomaly at depth near the northeastern corner of the Cañon de San Diego Grant. However, the anomaly is poorly defined. There is a slight possibility that this feature correlates with a low-velocity seismic region interpreted by Senturion (1975) to lie some distance southwest of the northeast Grant corner. More important, a major linear high of temperature gradient extends southwestward from the Valles Caldera along, and just to the east of, the Jemez River. The degree of overlap between the thermal and conductive anomalies is not very great.

However, the intensity and linearity of the thermal anomalies suggest (a) fault control of the Jemez River canyon; (b) strong upwelling of thermal water along this fault zone; perhaps coupled with (c) outflow of thermal water from Valles Caldera, probably within the Pennsylvanian Madera Limestone.

The lack of an intense conductance anomaly may reflect merely the shallowness of Precambrian crystalline basement, compared to the San Juan Mesa section. Similarly, the lack of ground-noise or micro-earthquakes may reflect the absence of alluvium within the deep Jemez River canyon.

There is a significant bulge or bowing in the line of steep gravity gradient in the vicinity of Jemez Springs, as noted earlier. The direction of this bulge parallels the direction of the Jemez River fault zone and is marked by the presence of hot springs at Jemez Springs and Soda Dam. This is also the direction of trend of the Lucero Uplift, to the south. It apparently marks a deep-seated zone of displacement in the Precambrian basement, from northeast-southwest to north-south (the Nacimiento trend).

Exposures of Precambrian rock or areas of shallow depth to Precambrian are characterized commonly by aeromagnetic or/and gravity highs. The principal value of magnetic and gravity lows thus appears to be the identification of thicker sections of younger rocks. Even the potential geothermal anomaly of the San Juan Mesa is associated with such a thickening of Paleozoic and younger rocks.

The impressive arcuate pattern of faults at the southern Grant boundary is not reflected in thermal anomalies, either gradient or heat flow. Indeed, continuation of the Precambrian basement arch is suggested (gravity and magnetic highs), with the only thermal water leakage being Indain Springs, on the southwest margin of the fault arc.

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The numerous resistivity, microseismic and ground-noise anomalies centered near Jemez Pueblo are curious. They may reflect thermal activity at depth; however, as mentioned, this is not supported by data from thermal drilling, with heat-flow values for this area being the lowest regionally.

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HYDROLOGIC AND HYDROCHEMICAL REGIME

The hydrology and hydrochemistry of groundwaters in the region of the Cañon de San Diego Grant have been discussed and reviewed in numerous published and unpublished reports, including: Earth Satellite Corporation (1976), Rennick (1931), Purtymun et al. (1974a and 1974b), Summers (1965, 1976), Swanberg (1975) and Trainer (1974 and 1975). The following three paragraphs, adapted from Trainer (1974) introduce basic components of the area's subsurface hydrologic regime.

Groundwater Flow

The groundwater flow system can be considered in a preliminary way by noting sources of base runoff of the Jemez River (figure 10). In San Diego Canyon at the edge of the Valles Caldera, base runoff consists of (1) groundwater discharged from near-surface deposits (the crust of broken rock on rhyolite domes, and valley fill) in the caldera, immediately outside the Grant to the northeast; (2) flow from dilute warm springs that drain deeper aquifers within the caldera ring-fracture zone (San Antonio Hot Spring, Spence Spring, McCauley Spring); (3) discharge from perched aquifers that form groundwater mounds in volcanic and sedimentary rocks in interstream plateaus; and (4) flow of mineralized groundwater, from depth, through seeps in the floor of San Diego Canyon.

Preliminary estimates suggest that most of this groundwater runoff is derived from the near-surface deposits, a small part of it from the warm springs and interstream groundwater mounds, and only a small part from the deep sources.

Between the caldera rim and the confluence of the Jemez River and Rio Guadalupe (figure 10), the principal addition to base flow of the Jemez River is the discharge of warm springs at Soda Dam and Jemez Springs. Perched aquifers, that form groundwater mounds in the volcanic rocks on the plateaus flanking the canyon and in the underlying Abo Formation, are drained through springs along the canyon walls.

Base runoff of the Rio Guadalupe appears to come principally from perched aquifers that discharge on the canyon walls and from seeps in the canyon floors. Several springs flow from fault zones. So far as can be judged from chemical analyses of the stream water, little if any mineralized water similar to that of the springs at Soda Dam and Jemez Springs flows into the Rio Guadalupe.

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South of the Cañon de San Diego Grant are several springs which yield mineralized water, in some cases at higher concentrations of dissolved solids than at Soda Dam and Jemez Springs. These occur along the Jemez River (Indian Springs) and along the south and west fronts of the Sierra Nacimiento (springs west of San Ysidro, Phillips Springs). The most highly mineralized groundwater known in the region flows from the Kaseman No. 2 well (also known as Warm Springs), an abandoned gas-test drilled immediately west of the Nacimiento fault; this water is warm, flowing at 52°C. Total depth of the well is some 2,000 feet, but it first flowed at 425 feet (Summers, 1976).

Trainer (1974) noted that an important aspect of the shallow groundwater flow system is underflow through alluvium in the canyon bottoms. In San Diego Canyon, the canyon floor is formed of alluvium continuously below the caldera rim. Both the stream water and groundwater in the alluvium are slightly mineralized above Soda Dam. Below Soda Dam and Jemez Springs, both are more highly mineralized and contain appreciable concentrations of minor elements such as As, B, F and Li.

In addition to the dilute and mineralized thermal groundwaters mentioned above, there occurs within the Valles Caldera a group of acid sulfate springs known as Sulfur Springs and located on the northwest side of the resurgent dome (Redondo Peak) within an area of several square miles of locally altered ground and solfataras. The springs discharge small quantities of acidic sulfate water at up to 75°C, along with gas containing H₂S and CO₂; ground temperature at a few feet in depth has been reported to be as high as 93°C. Sulfur springs are the surface manifestations of a zone of boiling water at depth, which has been explored via the drilling of at least 12 wells in the Valles Caldera by Union Oil Co. and others (plates 4 and 5).

An additional area of solfataric activity occurs in San Diego Canyon, just inside the Grant, near Battleship Rock, about 2 miles west-northwest of McCauley Spring (figure 10). This is reported to consist of small areas of altered ground, some of which emit H₂S, which may be explained as above by hypothesizing the existence of boiling water at some depth, perhaps a part of the same hydrothermal system as lies beneath Sulfur and Redondo Creeks.

The distribution of thermal and cool mineral springs in San Diego Canyon and south of the Grant near San Ysidro coincides with patterns of fault zones which extend southwestward from the caldera.

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Trainer (1974, 1975) has suggested that these indicate a route for sub-surface drainage from the geothermal reservoir (or hydrothermal system) beneath the Caldera. Trainer (1974) reported a consistent decrease in head along the Jemez Fault zone, from the caldera rim to San Ysidro; and analyses of waters from several springs can be interpreted to be mixtures of water from a single deep, thermal source with different amounts of local groundwaters along the route of flow. Mineral waters at the west foot of the Sierra Nacimiento (as at Kaseman well) have a somewhat distinct gross chemical composition and different head relations. If they also originate in the Valles Caldera they must have followed a different flow path. Water chemistry is discussed below.

Thick limestone in the stratigraphic section cut by the Jemez Fault zone may facilitate the hypothesized flow of thermal water down the canyon wherever there has been solution enlargement of openings in the faulted rocks. Trainer (1974) reported that river water flows into limestone near the caldera rim; however, just outside of the rim, cool mineralized water issues from a spring in limestone and thus may contain a component of the river water. The difference in dissolved load in the waters of the springs at Soda Dam and Jemez Springs may similarly represent different mixing ratios of deep thermal water with river water which flows into the limestone at points along the river canyon, particularly where it is cut by faults. No warm mineral springs are known in San Diego Canyon below Jemez Springs, which is the southernmost exposure of limestone in the canyon bottom; however, all mineral springs as far south as San Ysidro yield water that chemically can be shown to have flowed through limestone.

Purtymun et al. (1974) reported that in the drilling of LASL GT-2, which lies just outside the northeast corner of the Grant (plate 5), perched water was encountered in the Cenozoic volcanics, the Abo Formation, and the upper limestone member of the Madera limestone. The zone of saturation was encountered in the lower limestone and shale member of the Madera and in the Sandia Formation. Underlying Precambrian rocks may contain small amounts of water in fractures.

Structure contours on the top of the Precambrian rocks (figure 11) show that groundwater in the saturation zone moves southeast to the Jemez Fault, which downdrops the less permeable sediments of the Abo Formation against the more permeable carbonate rocks in the zone of saturation to the west, thus forming a discharge boundary. The fault lies to the east of the river, intersecting it at Soda Dam, where the major point of discharge occurs. According to river gaging records of the U.S. Geological Survey, the total discharge from the zone of

Figure 11. Structure contours on top of Precambrian rocks showing direction of groundwater movement in overlying sediments (from Purtymun and others, 1974b, Fig. 3).

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saturation along the Jemez Fault from the confluence of San Antonio Creek and the East Fork of the Jemez to Soda Dam is small, about 5 cfs (143 l/s), indicating a water flow-velocity in the saturation zone of about 4,000 ft/yr.

Rennick (1931) reviewed groundwater capabilities of the various formations and rock types in Sandoval County. He listed the following as yielding abundant or generally abundant water of good to variable quality: alluvium and wind-blown sand; pediment and terrace gravels; Pliocene and Pleistocene basalt lava and cinders, and rhyolite lava and tuff; Santa Fe Formation; various Eocene sedimentary formations; Upper Cretaceous Mesaverde Formation.

Several generally older units were described as yielding moderate to abundant quantities of hard, saline, mineralized and sometimes good-quality water. These include: Upper Cretaceous Lewis Shale and Mancos Shale ("meager supplies of mineralized nonpotable water"); Dakota Sandstone (hard but otherwise good quality); Morrison Formation (hard but potable); Triassic-Jurassic units (probably hard, mineralized, occasionally strongly saline; meager supplies; thermal along young faults or near mountains); Abo Formation (hard, saline; thermal locally; abundant supply).

The Pennsylvanian Magdalena Group was described as yielding abundant supplies of hard and locally thermal water. Precambrian rocks were reported to yield minor amounts of water in shallow wells.

Therefore, all discussion of mineralization in thermal waters must consider provenance. Waters stored in or passing through Abo or younger Paleozoic and Lower Mesozoic rocks will likely be highly mineralized and perhaps saline. Water arising from the Pennsylvanian carbonates will be rich in CO_2 and HCO_3 .

Water Chemistry

Most of the thermal and mineral springs of the region have been analyzed numerous times in recent decades as part of both published and unpublished studies. Summers (1976) and Trainer (1978) made extensive compilations of publicly available data. Swanberg (1975) resampled and analyzed nearly all the thermal and/or mineral waters, plus a number of surface waters and cool, dilute springs. Table 3 shows a compilation by Trainer (1974) which includes the most important thermal and mineral waters; locations of the samples appear on figure 10. Plate 5 shows

Name or location, and water-bearing rock:

1. *Sulphur Springs; caldera fill.*
2. *Spring in Calaveras Canyon; Bandelier Tuff (rhyolite).*
3. *Spence Spring; Valles Rhyolite.*
4. *U.S. Geological Survey test well, canyon of Rio Guadalupe; limestone in Magdalena Group.*
5. *U.S. Geological Survey test well near village of Jemez Springs; sandstone in Abo Formation.*
6. *Spring at Soda Dam; probably from limestone in Magdalena Group.*
7. *Spring at Jemez Springs; probably from limestone in Magdalena Group, beneath alluvium.*
8. *Spring in San Diego Canyon near caldera rim; limestone in Magdalena Group.*
9. *Spring near mouth of Rio Guadalupe; probably from limestone in Magdalena Group, but water issues from fractured granite.*
10. *Spring near San Ysidro; sandstone in Chinle Formation.*
11. *"Warm Spring" (abandoned gas-test well), northwest of San Ysidro; probably from rocks of Magdalena Group, Abo Formation, and Chinle Formation.*
12. *Well near village of Jemez Springs; alluvium beside Jemez River.*

Table 3. Chemical analysis of selected ground-water samples from the southwestern Jemez Mountains, adapted from Trainer(1974). Locations of sample sites are shown on Figure 10.

Sample Number	1	2	3	4	5	6	7	8	9	10	11	12	13 Indian Spr.
Date of Collection	8-31-49	12-2-72	12-1-72	10-30-73	10-26-73	12-1-72	12-2-72	8-15-73	8-21-73	3-14-64	3-14-64	9-27-73	8-30-73
Silica (SiO ₂).....	216	40	100	16	17	50	79	42	44	15	31	59	68
Aluminum (Al).....	56	< 0.001	0.025	-	-	0.005	0.002	-	-	-	2.6	-	-
Iron (Fe).....	33	< .04	< .04	0.01	0.03	.04	< .04	0.06	0.14	0.00	3.9	0.03	.050
Manganese (Mn).....	3.3	< .01	< .01	.01	.06	.55	.175	.02	.08	-	.01	.000	1.30
Calcium (Ca).....	185	11	6.0	100	12	330	130	130	32	157	345	75	110.
Magnesium (Mg).....	52	1.3	1.7	11	10	24	4.8	12	5.7	70	56	13	21.
Sodium (Na).....	6.7	8.5	55	14	860	990	640	250	190	1,760	3,550	120	1300.
Potassium (K).....	24	2.4	1.8	5.8	8.5	200	82	35	8.2	71	87	19	73.
Arsenic (As).....	-	.006	.072	.000	-	1.5	.66	.000	.067	-	.60	.15	.069
Lithium (Li).....	-	< .04	.69	.06	-	13	8.7	3.6 ^{1/}	.43	6.4	6.9	1.4	6.7
Bicarbonate (HCO ₃).....	0	61.6	144	367	1,640	1,578	732	606	366	1,080	1,450	387	1440.
Carbonate (CO ₃).....	-	0	1.0	0	0	0.3	1.5	0	0	0	0	0	0
Sulfate (SO ₄).....	1,570	5.2	18	21	250	52	53	32	120	1,220	3,260	21	270.
Chloride (Cl).....	3.5	3.8	12	13	200	1,500	920	320	49	1,680	2,990	120	1200.
Fluoride (F).....	1.1	.4	.7	.3	2.4	3.3	4.8	2.3	7.6	2.9	2.8	1.6	4.0
Nitrate (NO ₃) plus nitrite (NO ₂), as N....	0	-	-	.56	.03	-	-	.11	.00	-	-	.76	-
Boron (B).....	-	.02	.07	.06	-	12.5	7.4	2.9	.38	6.8	4.8	1.2	8.2
Dissolved solids.....	2,160	126	224	365	2,170	3,740	3,500	1,120	638	5,510	11,000	625	3770.
Specific conductance (micromhos at 25°C)....	4,570	113	282	640	3,500	6,160	3,930	1,880	1,000	8,560	15,300	925	5694.
pH.....	1.9	7.0	8.0	7.3	7.4	6.1	6.3	6.8	7.6	7.6	7.3	7.3	8.0
Temperature (°C).....	65±	12.0	41.0	10.5	16.0	48.0	75.0	18.0	18.5	24.0	54	-	23.0

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selected sample sites in the region of the Grant, plus certain physical and chemical data for each. The compositions of samples from points on plate 5 are plotted on figure 11b.

The warm springs which drain deeper aquifers within the young volcanoes of the ring-fracture zone (McCauley Spring, Spence Spring and San Antonio Spring, Points C4, Ta3 and C15, plate 5) all are dilute. Their chemical character is consistent with rapid circulation of meteoric water into young, near-surface volcanic rocks, perhaps near feeder dikes or pipes in the Banco Bonita member (age = 100,000 years) of the Valles Rhyolite, where heat flow should be higher than in the somewhat older ash-flow tuffs (Bandelier Tuff, age = 1 m.y.) that rest on sedimentary rocks outside the caldera.

Silica in the springs is fairly high, giving quartz solubility temperatures of about 110° to 130°C (McCauley and Spence Springs). This could indicate mixing into a cold meteoric component of still-warmer dilute water, but more likely the silica levels represent dissolution of volcanic glass (amorphous silica) at only moderate temperatures. Trainer (1974, 1975) concluded that these warm springs do not contain any recognizable fraction of water from the geothermal system beneath the caldera; we agree.

Trainer (1974, 1975) discussed the water chemistry of thermal and mineralized cool waters of the Jemez Mountains and concluded that thermal springs along the Jemez Fault zone (Soda Dam, Jemez) issue water which has flowed downgradient from a thermal reservoir by hydrothermal system beneath the Valles Caldera and which has mixed with varying proportions of cool, dilute recharge before issuing at the hydrologic barrier created by the fault.

Several cool mineral springs associated with the fault zone also appear to issue mixed waters, which may or may not be of the same origin. Consideration of levels of F, Cl, Na, Ca and SiO₂ and the ratios Li/Na and B/Cl shows that the Soda Dam and Jemez thermal springs, and probably also water from an 18°C spring and an adjacent well in limestone near the caldera rim, contain solutes obtained from a volcanic-hydrothermal system (Trainer, 1974). For cool and thermal mineralized waters farther to the south (Indian Springs, Kaseman well or "warm spring"), such a conclusion is not clear.

On figure 11b it is seen that Soda Dam (Ta6), Jemez Springs (Ta7), the limestone spring near Battleship Rock (Tch32 and Ta8), and a well-water from alluvium near Jemez Springs (Ta12) all fall on an apparent

Figure 11b

Trilinear diagram of the chemical analysis of selected surface and groundwaters, Cañon de San Diego Grant and vicinity.

Sample numbers correspond to numbers on Plate 5.

(Sum of cations) $\times 10^2$

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mixing trend involving Na-Cl water from the caldera reservoir and Ca-HCO₃ water as end-members. Our single available analysis of the caldera reservoir fluid (table 4) shows very low bicarbonate, whereas bicarbonate is about equally concentrated as chloride in Soda Dam and Jemez Springs and is too high to have come from dilute meteoric recharge alone.

Principal sources of the bicarbonate are reaction of the reservoir fluid with limestone, and decomposition of volcanic rocks accelerated by a high concentration of CO₂ derived from limestone, during migration of the reservoir fluid from beneath the reservoir prior to mixing. Some of the bicarbonate also will have come from the cool component, but the composition of this cannot be fixed with certainty. It is most likely dilute and of a Ca-Na-HCO₃ composition, possibly produced by mixtures of Jemez River water (C3, C5, C12, C24) with Ca-HCO₃ water from limestone (such as C32, C38, C43, C44, Ta4), and Ca-Na-HCO₃ water from volcanic rocks, such as was sampled at points near Battleship Rock (Tch28, Tch29, Tch30, C4). Some of these latter waters have fairly high bicarbonate, again probably due to a high CO₂ content; and some have moderate sulfate, possibly derived from solfataric alteration zones in the caldera and near Battleship Rock; and chloride, perhaps from traces of thermal water or a connate source in the limestones.

The mixed mineralized waters at Soda Dam and Jemez all contain notably low sulfate. In contrast are the mineralized cool to hot groundwaters from the south and west sides of the Sierra Nacimiento, such as Kaseman well (R16), Phillips Springs (R13) and the mineral springs west of San Ysidro, which are quite uniform in composition, with moderately high sulfate relative to chloride. These appear totally unrelated to the caldera reservoir water and the Jemez-Soda Dam mixtures.

Water samples collected at different times during drilling of hole GT-2 contain relatively higher sulfate and bicarbonate than the Soda Dam-Jemez mixtures and are also distinct from the single available sample of the caldera reservoir (plate 5, sample TcN4).

GT-2 samples fall on a trend which suggests mixing of dilute Na-Ca-HCO₃ water with a mineralized water containing moderate sulfate, such as the waters from the south end of Sierra Nacimiento. This casts some doubt on whether GT-2 receives thermal water which has flowed laterally from beneath the caldera. At the least, it requires considerable reaction of this thermal water with different rocks or at different temperatures than in the caldera reservoir. It also suggests that

TABLE 4

FLUID COMPOSITION, VALLES CALDERA GEOTHERMAL RESERVOIR

<u>Liquid or Brine Phase (ppm)</u>	
Carbonate	0
Sulfide	4
Calcium	36
Sulfate	60
Bicarbonate	92
Potassium	506
Silica	716
Sodium	2,100
Chloride	3,900
Suspended solids	663
Total dissolved solids	7,313
Conductivity	10,895 μ mhos/cm
pH	6.7

<u>Steam Phase (Mole %)</u>	
H ₂ O (94-97% by weight)	
Noncondensibles (3-6%)	
Carbon dioxide	98.15
Hydrogen sulfide	1.27
Nitrogen	0.27
Hydrogen	0.21
Ethane	0.07
Methane	0.01
Propane	0.01
Ammonia	0.01
pH (condensate)	4.7

<u>Geothermometers</u>	
Quartz, conductive	287°C
adiabatic	253°C
Na-K-Ca	289°C

- Notes: (1) Unpublished analysis reported by Donald F. X. Finn, Geothermal Energy Institute, 10 December 1976, for deep well drilled by Union Oil Company.
- (2) Fluid temperature not reported with analysis. Summers (1976) reported a reservoir temperature of approximately 285°C, with some 7,000 mg/l TDS at well Baca #4.

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most of the thermal component in the Soda Dam-Jemez mixtures comes from beneath the caldera along a different flow route than does the thermal component in GT-2 waters. Probably there is a direct flow path through Jemez Fault zone to Jemez Springs, as was suggested by figure 11.

Sulfate in the thermal water of hole GT-2 probably comes from connate water or sulfate deposits in the Madera Limestone, which is the principal aquifer penetrated by the hole. Chlorided, mineralized waters from the Madera appear to be typically high in sulfate. Titus (1961), for example, reported that there are cool NaCl springs with moderately high sulfate and high TDS (15,000 to 34,000 mg/l) which issue from the Madera Limestone in Valencia County, New Mexico, south of Albuquerque.

It is less likely, therefore, that the waters issued by Soda Dam and Jemez Springs have had significant flow through the Madera Limestone, unless these rocks have been leached of their connate fluids. The deep thermal component at Soda Dam and Jemez Springs may have flowed downgradient within volcanic rocks in the caldera and within the Jemez Fault zone outside of it.

Because of the uncertain compositions of the deep thermal and cool components of the hypothesized Soda Dam and Jemez mixtures, mixing calculations can be carried out only very tentatively.

Trainer (1975) assumed that the deep thermal component of Soda Dam and Jemez Springs has a composition similar to fluid samples from GT-2 and that the cool, dilute component was similar to an analysis of water in Jemez River in San Diego Canyon. From this, he calculated apparent dilution factors for five different thermal and cool mineralized groundwaters along the fault zone. He considered only the concentrations of lithium, chloride, bromide and boron in each water; the results are shown here as table 5a.

The earlier discussion, however, showed that the GT-2 water may not be representative of the deep thermal component. At the least, if it originates by deep flow from the caldera, it has gained connate sulfate along with chloride and other solutes from Paleozoic sediments which appear not present at Soda Dam and Jemez Springs.

The caldera reservoir sample is obviously more representative of the deep component, but it in turn requires enrichment in bicarbonate, say by reaction with volcanic rocks at a high partial pressure of CO₂ or with carbonate rocks which lack connate fluids, either before or after mixing.

TABLE 5

CALCULATED DILUTION FACTORS FOR SELECTED MINERAL WATERS
IN THE SOUTHWESTERN JEMEZ MOUNTAINS¹

Sample Number ²	7(8)	8(6)	9(7)	10(9)	11(13)
Brief Name	Test well, limestone	Soda Dam	Jemez Springs	Spring, limestone- granite	Indian Spring

a) From Trainer (1975); based on deep component from hole GT-2

Dilution Factor, from:					
Lithium	8.5	0.5	1.3	46	2.0
Chloride ³	9.0	1.0	2.3	60	1.5
Bromide	12.6	1.2	2.8	74	2.0
Boron	9.4	1.0	2.4	65	2.0

b) This study; based on deep component from caldera reservoir

Dilution Factor, from:					
Chloride ⁴	12	1.6	3.2	79	2.3

¹Factor given is quantity of non-thermal groundwater believed to have mixed with one part of deep thermal groundwater to yield observed water.

²Sample numbers in parentheses are those of figure 10 and table 3, this report; samples 7(8) are from adjacent localities.

³Assumed to be 3,000 mg/l in deep component.

⁴Assumed to be 3,900 mg/l in deep component, nil in non-thermal.

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Table 5b shows the result of repeating Trainer's (1975) calculations employing Cl from the caldera reservoir, which should have been affected only minimally during the postulated enrichment of the deep component in bicarbonate. The results show that Soda Dam may contain about 1.5 parts cool to 1 part hot water and Jemez Springs, 3 parts cool to 1 part hot. A more complete analysis of the caldera reservoir water would be useful in attempting to confirm these ratios.

Application of the sodium-potassium calcium geothermometer to the Soda Dam and Jemez waters gives temperatures of about 200° to 230°C, lowered to about 170° to 180°C with application of a correction for magnesium, recently developed by Fournier and Potter (1978). If the cool component in the waters is dilute, it will not have a strong effect on the geothermometer, and the 170° to 180° range may be roughly representative of conditions at depth. A part of the Mg in the mixed thermal springs, however, certainly comes from the cool component. This suggests that the Mg-correction is very possibly too large and the 170° to 180° temperature range a minimum value.

Silica temperatures are lower (100° to 125°C). They could have been affected both by the mixing and low flow rates at each spring (flow rates on plate 5 are from Summers, 1976). Silica mixing calculations, along with the ratios given in table 5b, suggest that the deep component at Soda Dam may be only 100°C, whereas that at Jemez could be upwards of 160°C, in good agreement with the cation temperature.

Silica in GT-2 is at 170 mg/l (3,557-foot depth) much lower than its reported level of about 700 mg/l in the deep reservoir within the caldera (table 4). This suggests either cooling of the deep fluid with attendant loss of silica as it migrates outwards from the central reservoir or mixing with low SiO₂ connate waters. The temperature at the 3,557-foot depth in GT-2 was only 90°C, yet the reported 170 mg/l silica corresponds to quartz solubility at a minimum of 169°C (336°F). These observations may be taken to indicate considerable change in the thermal fluid as it migrates from the caldera reservoir towards GT-2. The same may happen with flow towards Soda Dam and Jemez Springs. However, the silica loss appears to lag behind enthalpy loss, so that the quartz temperatures for Soda Dam and Jemez may not be low.

The higher estimated cation temperature for the deep component at Soda Dam and Jemez may in contrast reflect failure of these ions to re-equilibrate during migration. Within the caldera (table 4), Na-K-Ca reservoir temperature of the fluid is 289°C (552°F). This is in good agreement with the quartz temperature of 287°C (549°F), based on 716

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mg/l SiO₂; and both geothermometers agree very well with the reported temperature of 285°C (545°F) from Union's Baca #4 (plate 4).

A final consideration of the suggested mixing ratios may be made in light of water temperature. Even in recognition of the low flow rates at both Soda Dam and Jemez Springs, which probably permit conductive cooling, the approximately 1:1.5 (hot:cold) mixing ratio for Soda Dam combined with a cool component at 15°C suggests a deep component at about 98°C and the suggested 1:3 ratio at Jemez Springs may reflect a deep component at about 195°C. These results suggest that if the deep component at each spring comes from the caldera reservoir, the Jemez Springs component has traveled with less cooling, and thus perhaps more quickly, than the Soda Dam component.

Hydrology, Geochemistry and the Thermal Regime

Hydrologic and hydrochemical data support the idea that thermal water from beneath Valles Caldera migrates southwestwards downgradient, probably within the Jemez Fault zone. Hydrologic data also support flow of thermal water from the vicinity of GT-2 southwards to the Jemez Fault zone, but hydrochemical data do not support this. Flow from the caldera mixes with dilute recharge and issues at Soda Dam and Jemez Springs, as well as at a cool spring in limestone near the caldera rim. The balance of evidence from temperature and mixing calculations suggests that the deep component at Jemez is hotter than at Soda Dam, possibly in the temperature range 160° to 195°C (320° to 383°F), compared to only 100°C (212°F) at Soda Dam. These estimates are highly tentative, within an upper limit of about 200° to 230°C (392° to 446°F) and a lower of perhaps 90° to 100°C (194° to 212°F). Temperature-gradient and heat-flow contours (plate 4) are consistent with the conclusion that the deep component at Jemez is hotter than at Soda Dam.

Thermal and cool mineralized waters from south of Jemez Springs are broadly similar to the above but appear more likely to represent connate waters from Paleozoic carbonate rocks or mixtures of these with dilute recharge.

Dilute warm springs in the ring-fracture zone surrounding the caldera are chemically consistent with rapid circulation of meteoric water into warm, young, near-surface volcanic rocks. There are no indications of mixing with deep thermal fluid.

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THERMAL REGIME

Valles Caldera

Several factors characterize the Valles Caldera as one of the major thermal areas of the western United States. To begin, volcanism was active through much of Late Tertiary time and almost the entire Quaternary period in this region, with caldera collapse occurring in middle Pleistocene epoch. Subsequent to that, there has been resurgence of highly silicic domes and eruption of silicic and basaltic lava, to several thousand years before the present. Along with Yellowstone, the Clear Lake Volcanics (The Geysers), Long Valley, Coso and the Medicine Lake Highlands, it is one of the principal Quaternary silicic centers of the United States.

It is quite possible that an active magma still exists beneath parts of the Caldera. Seismic travel-time studies in progress by LASL and others (see Geophysical Surveys, this report) may have detected delays consistent with a magma. Even if all magma has crystallized, subsurface temperatures are elevated significantly.

Thermal springs (see Hydrologic and Hydrochemical Regime, this report, for details) are very numerous and widespread, in 3 or 4 principal settings (plate 5). First are thermal springs along the Caldera rampart, such as San Antonio Hot Spring. These probably derive their heat from downward circulation of water along inward-dipping fractures that control the Caldera wall. However, these springs do not generally indicate very high temperatures of equilibration at depth, perhaps because of limited depth of penetration or mixing with cool meteoric water en route to the surface.

Second are thermal springs located in deep canyons draining outward from the Caldera, principally Jemez River canyon. Here, direct thermal outflow from the Caldera may be mixed with meteoric water, Jemez River water, vertically upwelling thermal water or some combination of the above. The probable complexity of the flow regime is indicated by the difficulty in obtaining a fully believable silica mixing model for waters from both Soda Dam Hot Springs and Jemez Springs (tables 3 and 5).

Third, and nearly in a class by itself, is Sulphur Springs, within the Caldera. It is characterized by higher temperatures, steaming ground, acid sulphate waters and intensive hydrothermal alteration

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of ground. It probably represents direct communication with the very high temperature regime underlying the Caldera. A solfatara in the Jemez River canyon west of Battleship Rock probably is of this second type and is the only representative of this type on the Grant.

A possible fourth type is represented by mildly thermal springs and well waters at the south end of the Nacimiento Uplift. These are chemically distinct from class two, above, and probably have a different origin, involving connate and meteoric waters.

Hydrothermal alteration is extensive within the caldera, especially on and near Redondo Peak, the major silicic resurgency within the Caldera. This is shown on plate 4. Of major interest is the alignment of hydrothermal alteration with the zone of northeast-trending fractures cutting the Caldera. These fractures are on trend with the Jemez Fault zone and may be an extension of the latter. This suggests that the Jemez Fault trend is of principal importance in controlling thermal circulation.

The great majority of productive wells drilled by Union Oil Company on its Baca Location No. 1 lease are along the same fault set. Union has confirmed (R. Dondanville, oral communication, 1978) that this fault set is the principal reservoir control on their lease, as shown by exploration to date. This stresses the importance of continuing exploration along the Jemez Fault on the Cañon de San Diego Grant.

Union and earlier companies have drilled at least 17 deep exploratory holes on the Baca Location lease (see plate 4). These have been to varying depths between 2,200 and 9,200 feet. Not all have encountered permeable zones or permeable zones at high enough temperatures to be of commercial interest for power generation. Production has been tested principally from the Bandolier Tuff and related Quaternary or latest Tertiary units, as well as from underlying Mesozoic and Paleozoic units. To date, no production tests have been made into Precambrian rock, although such tests are planned (R. Dondanville, oral communication, 1978).

Complex and intense faulting has created complicated subsurface geology, such that it is difficult to characterize the reservoir geologically. However, Union anticipates that commercial production, at least at first, will come from the Quaternary tuff series, which is significantly fractured in its deeper welded sections. Maximum depth of the Quaternary tuffs and latest Tertiary volcanic rocks is reported to be well in excess of 5,000 feet.

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It is informally reported that production trials were run on redbed sandstones underlying the Cenozoic volcanics (possibly the Abo Formation), and that this resulted in generation of a particulate-rich slurry, as formation began to break down under high flow pressures.

Hydrologically, the reservoir is hot water, at temperatures of 260°C (500°F) and higher at depths of 5,000 feet and deeper. A steam cap overlies the hot-water field locally, probably boil-off from the deeper water zone, and is confined apparently by impermeable Quaternary units above it. The deep fluid has an average chemical composition (table 4) of some 7,500 ppm total dissolved solids, principally Na and Cl, although this may represent post-flash brine concentrated slightly by steam separation. Waters of this composition are typical of geothermal fields in the youthful volcanic cordillera of North and Central America.

Capacity of the 6 or so production wells completed to date is about 4 MW per well. This represents an average steam consumption of about 80,000 pounds per hour, which at an assumed 25% steam separation would represent an average total mass yield of about 320,000 pounds per hour per well. This is not unusually great for hot water wells but is slightly above the average for hot water wells in Cerro Prieto, Mexico, and Ahuachapan, El Salvador.

Additional production wells are to be drilled in 1978-1979 for use in the planned 50 MW geothermal power plant. Total reserve capacity of the field may be well over 100 MW.

The Valles Caldera, therefore, represents an active hydrothermal system within a thick volcanic and sedimentary section, in close proximity to either an active magma or cooling intrusions at depth. Production of chlorided hot water is from moderate depths (despite the presence of a local, shallow steam cap), from a thick Quaternary and latest Tertiary section. This contrasts sharply with the Cañon de San Diego Grant, where an objective will be crystalline Precambrian rock, in the absence of an obvious cooling intrusion, and probably at depths on the order of 10,000 feet.

Fenton Hill Hot Dry Rock Experiment

LASL has conducted deep exploratory drilling for a hot dry rock system within Precambrian basement to the west of the Caldera, in rocks

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similar to those anticipated on the Grant. They have encountered temperatures to just over 200°C (400°F) at depths of 10,000 feet, in the total absence of a deep hydrothermal system. This is well above western regional gradient for deep holes (figure 12) and clearly shows the conductive heating effect of the plutons beneath the Caldera. A convective system would of course disturb this nearly linear gradient pattern. However, the actual effects cannot be predicted. For details of drilling and test results in LASL GT-1, GT-2 and EE-1, see Albright (1975), Kintzinger et al. (1977), Laughlin and Eddy (1977), Purtymun et al. (1974b) and West et al. (1975).

Regional Heat Flow

This part of the Rio Grande Rift is characterized by heat flow of 2.0 to over 3.0 (figure 13), according to data compiled by Reiter (1975). Values over 3.0 are associated with areas of geothermal exploration in Valles Caldera and elsewhere. To the west, on the Colorado Plateaus, values decline rapidly into the range 1.3 to 2.0 HFU. On the east side of the Rift, heat flow varies widely from less than 1.5 to locally over 2.5 HFU.

This asymmetrical pattern (figure 14) across the Rift has been attributed to crustal block movements, such that the east limb of the Rio Grande Rift is undergoing compression and the west limb, expansion. In a practical sense, it means that heat flow values on the Grant below 2.5 HFU may be considered as background and that values below 2.0 are anomalously low, perhaps in response to cool-water recharge from the Sierra Nacimiento.

Temperature Gradients and Heat Flow

Drillhole data are very abundant for the east half of the Grant, especially the northeast quadrant, and for a region north and east of the grant. These data include:

- a) temperature-gradient holes drilled for Sunedco;
- b) temperature-gradient holes drilled for LASL;
- c) geothermal exploration holes drilled within the Valles Caldera by Union Oil Company and others;

Equilibrium rock temperatures in GT-2.

Depth (m)	Equilibrium Rock Temperatures (°C)
1387	113.58
1475	117.78
1595	125.66
1670	128.35
1825	135.63
1877	138.57
1998	142.50
2040	146.20
2900	195.80
2928	197*

* Extrapolated and later measured.

Figure 12. Thermal gradient measured in GT-2 at Fenton Hill.

Figure 13. 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.

Figure 14. 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. (From Reiter, 1975)

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d) deep hot dry rock tests drilled for LASL.

In addition to these, but not available for this study, are temperature-gradient holes drilled by Phillips Petroleum Company and possibly by others.

When examined jointly, data from available sources (plate 4) show a coherent, consistent pattern. Most fundamentally, they show decrease in temperatures, temperature gradients and heat flow outward from the Caldera. More specifically, the decrease is more rapid to the south and southeast than to the southwest and west; and a long tongue of high gradients and heat flow extends southwest along the Jemez River. This tongue, and indeed the entire western Caldera perimeter, is marked by thermal springs (plates 4 and 5).

Taken together, this suggests hydrothermal circulation in rocks of the southwestern and western Caldera borders associated with a strong disturbance in the heat-flow regime. That is, although regional heat flow is high, calculated values do not reflect conductive conditions but probably show convection at relatively shallow depth.

As noted earlier, heat flow in this area largely is independent of hole depth; however, gradients do tend to decrease with depth because of the higher thermal conductivities of Paleozoic and Precambrian rocks, as compared with Cenozoic rocks. Where there is a convective disturbance in the shallow zone, the gradient-depth relationship is not always clear. However, the LASL test GT-1 (2,575 feet) was in impermeable rock for most of its course (table 6) and showed a clear gradient-thermal conductivity relationship at an assumed constant heat flow.

In LASL gradient holes A, B, C and D (plate 4 and figure 15), Abo Formation yielded apparent thermal conductivities of 4.3 to 5.6, which is quite consistent with data from GT-1. Geothermal Services (1978) reported conductivities of 4.6, 5.5, 5.8, 6.2 and 8.8 for Paleozoic sandstone, clay shale, silty shale and marly limestone from holes 77-6, 77-7, 77-12, 77-F1 and 77-F3. These conform to the values inferred from the LASL holes, with the exception of 8.8 for marly limestone. This may be a local phenomenon.

More surprisingly, Triassic sandstone and related rocks at the southern Grant margin yielded thermal conductivities of 7.6 and 8.7 (holes 77-18 and 77-20).

The apparent decrease in thermal conductivity in the Paleozoic section and the slightly lower values found generally in the northern

Figure 15. Gradient, thermal conductivity and heat flow, LASL holes A, B, C, D.

Hole A, temperature vs depth.

Hole B, temperature vs depth.

Figure 15, cont.

TABLE 6

DEPTH, TEMPERATURE GRADIENT, THERMAL
CONDUCTIVITY AND LITHOLOGY, GT-1¹

Depth, ft	Gradient, °F/100 ft	Thermal Conductivity	Formation
197-460	7.62	4.5	Abo Formation (Permian)
460-1,575	6.91	4.7	Abo Formation and Magdalena Group (Pennsylvanian)
1,575-2,100	5.24	6.6	Madera Limestone and Sandia Formation (Pennsylvanian)
2,100-2,362	2.59	11-13	Precambrian crystalline rock

¹Data largely from Reiter et al., 1976, and Purtymun, 1973; heat flow of 6 assumed.

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area may be explained in part by variations in formation facies or degree of cementation with silica and in part by the decrease that occurs in thermal conductivity with increase in temperature in any rock. This decrease is about 10% per 100°C increase in temperature.

Deep holes drilled in the thermally attractive parts of the Grant will penetrate into the Precambrian section. Declines in conductive gradient will be observed, perhaps comparable to those seen in GT-1 (figure 16) and GT-2 (figure 12), where the Precambrian section had an average gradient of 50° to 60°C per km (2.75° to 3.3°F per 100 feet). Using geologic data from cross sections A-A' (plate 2), figures 3 and 4 and table 6, the following synthetic gradient (table 7) can be constructed for an area not strongly disturbed by convective circulation.

A hole upslope from either canyon location would be characterized by lower heat flow, except possibly at the northeastern apex of the Grant, above La Cueva, or at the northern finger of San Juan Mesa some 3 miles northeast of Jemez Springs. Expect at these possible sites, lower heat flow would result in lower temperatures at depth despite the thicker section of low thermal conductivity rock. The La Cueva area, if accessible, might offer an attractive alternate site to Battleship Rock.

The assumed heat flow at Battleship Rock is higher than at LASL GT-2; Jemez Springs is comparable to GT-1. Therefore, temperature gradients and deep temperatures are calculated to be higher at Battleship Rock than at the other sites. Because the Paleozoic or younger section is so thin at either site, the gradient and temperature at depth basically will be a function of Precambrian rock conditions. Prejections yield temperatures of about 375°F at 8,000 feet at Battleship Rock and perhaps as much as 450°F at 10,000 feet. This compares favorably with 402°F at 10,053 feet in EE-1. At Jemez Springs, temperatures at comparable depths might be 300° and 350°F. This is in rough agreement with temperatures predicted by geochemical modeling: SiO₂ geothermometry predicts about 160°C (320°F).

A second thermal anomaly is observed in the heat-flow and temperature-gradient data on the San Juan Mesa, about 3 miles southeast of Jemez Springs, both within and outside of the Grant. Values from 4 holes (76-8, 77-3, 77-4 and 77-F30) describe an elliptical high oriented northeast-southwest, with apparently abrupt termination on all sides. A shallow neck of lower values connects the San Juan Mesa high

Figure 16. Gradient, thermal conductivity and heat flow, LASL GT-1

TABLE 7

SYNTHETIC CONDUCTIVE GRADIENT FOR DEEP GEOTHERMAL DRILL HOLES
AT BATTLESHIP ROCK, JEMEZ SPRINGS AND SAN JUAN MESA

Area	Stratigraphic Sequence	Thickness, ft	Thermal Conductivity, k	Temperature Gradient, °F/100 ft
Battleship Rock ¹	Permian		absent	
	Pennsylvanian	800	6.5	6.6
	Precambrian		11.0	4.0
Jemez Springs ²	Permian	500	5.0	6.6
	Pennsylvanian	1,000	6.5	5.0
	Precambrian		12.0	2.75
San Juan Mesa ³	Quaternary tuff	500	3.25	8.0
	Triassic	250	7.5	4.0
	Permian	1,600	5.0	5.5
	Pennsylvanian	950	6.5	4.25
	Precambrian		12.0	2.4

¹Assumed heat flow 8 HFU.

²Assumed heat flow 6 HFU.

³Assumed heat flow 5 HFU.

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to the Jemez Springs anomaly. However, geologically it appears that each feature is separate, aligned on regional structures. The San Juan Mesa high also may represent thermal outflow from the Banco Bonito rampart of the Caldera. There is no obvious fault or fracture set to control its existence, unlike the Jemez River thermal anomaly. Further, it does not correspond to any of the inferred intrusions (Earth Satellite, 1976) or to youthful eruptive centers.

Based on data from table 7, a temperature of 170°C (340°F) is projected at 8,000 feet, and about 200°C (395°F) is projected at 10,000 feet. This is based on fairly conservative estimates of thermal conductivity, heat flow, rock thickness and gradient and should not be regarded as optimistic.

The above assumes conductive heat-flow conditions. However, convection of thermal water is suspected strongly in the Paleozoic section, on the basis of thermal springs and presumed aquifer characteristics. The exact effect of this presumed convection on deep temperature patterns is unknown.

Thermal outflow from the Valles Caldera is thought likely. For example, Crowe et al. (1978) calculated that 1.8 HFU of a measured or estimated 5.5 HFU at the Fenton Hill hot dry rock site "is due to hydrologic effects from the Valles Caldera heat source"; that is, from hydrothermal outflow. They also noted that for GT-1, "Warm water moving outward from the ring fault through the permeable Madera Limestone is apparently disturbing the gradient in the overlying sedimentary and volcanic rocks." They concluded that "the conductive and hydrologic contributions of the Valles Caldera are roughly equivalent."

Because the San Juan Mesa is more than 1,000 feet higher in elevation than the Jemez River, there may be two (or more) thermal water aquifers. One could be in Precambrian crystalline rock, if sufficiently fractured (as along the Jemez River canyon); another is likely in Pennsylvanian Madera Limestone. Still others are possible in the Permian Abo Formation or in Cenozoic volcanic units (especially the Bandolier Tuff).

Nothing in the heat-flow data supports the concept of Quaternary or Late Tertiary intrusion (Earth Satellite, 1976) beneath the Cañon de San Diego Grant: the thermal highs do not correspond to presumed intrusive centers; lateral movement of thermal water can be shown from drill-hole and other data; contoured heat-flow and gradient data are in accord with a pattern of outflow from the Caldera at depth. From this, it

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would appear most attractive to site future geothermal holes in the northeast corner or along the eastern border of the Grant and not in the southern zone of postulated igneous intrusions.

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EXPLORATION STRATEGY

Data have been examined from many disciplines: geology, geophysics, hydrology, hydrochemistry, thermal drilling and deep exploration drilling, for both the Grant, the adjacent Valles Caldera, and intervening areas. Data proprietary to Sunedco have been integrated with data from public (LASL, U.S. Geological Survey) and other private (Union Oil Company, etc.) sources. From this, it is possible to define a program of continued exploration, with specific goals and objectives.

There appears to be an intrusive heat source beneath the Caldera. However, no intrusive source can be identified beneath the Grant, despite permissive evidence concerning circular fractures and sparse microearthquakes. Abnormally high heat flow and temperature gradients observed on the Grant and at other localities outside of the Caldera appear to originate: (a) by edge-effect conduction outward from the Caldera and (b) by hydrothermal outflow from the Caldera, via the Madera Limestone or other porous pre-Cenozoic units. By one estimate (LASL), each method contributes approximately equally to the high heat flow.

Hydrothermal disturbances to the conductive regime make it difficult to predict temperatures at great depth, despite temperature-gradient and heat-flow data from as deep as 500 feet on the Grant and as deep as 10,000 feet to the north. However, using conservative criteria for the conductive component of heat flow, synthetic gradients have been constructed for 3 localities on the Grant where significant geophysical, geological and/or thermal anomalies have been identified.

These 3 places are Battleship Rock, Jemez Springs and the San Juan Mesa (plate 4). Stratigraphic sections have been projected for these localities, based on lithology of gradient holes, nearby surface geology, measured thicknesses of various units and known or inferred structural breaks. These sections are shown on plate 4 and may be compared with regional cross sections in plate 2.

Temperatures at 8,000 and 10,000 feet for these locations are estimated in table 8.

The assumptions on which these numbers are based are discussed under Thermal Regime (see above). It must be stressed that these projections are tenuous and may be severely affected by unforeseen convective circulation of thermal fluid, unexpectedly high thermal conductivities of rocks *in situ*, surprising shallowness to Precambrian section

TABLE 8

ESTIMATED TEMPERATURES AT DEPTH,
BATTLESHIP ROCK, JEMEZ SPRINGS
AND SAN JUAN MESA

Location	Temperature, °F, at Depth, ft	
	8,000	10,000
Battleship Rock	375	450
Jemez Springs	300	350
San Juan Mesa	340	395

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and other factors. However, values for Battleship Rock and Jemez Springs are in basic agreement with data from other sources.

LASL EE-1, in a zone of somewhat lower heat flow (approximately 5.5 versus over 6 at Battleship Rock) had a temperature of 402°F at 10,053 feet, at a distance of about 4 miles nearly due north. Silica mixing models for water from Jemez Springs yields plausible temperatures comparable with those calculated by the synthetic gradient process for the Jemez Springs area (see Hydrologic and Hydrochemical Regime, above). However, there is no independent verification of the temperatures estimated for San Juan Mesa.

All of these temperature estimates are significantly below those encountered by Union Oil Company in its deep drilling within the Caldera.

Heat-flow and gradient values for the area of circular faults and microearthquakes near Jemez Pueblo are so low as not to warrant construction of synthetic gradients. Geologic sections for that area are given, however, on plate 4, if on some other consideration further examination is warranted.

It appears that further geologic or geophysical exploration is not necessary anywhere on the Grant, given the extreme steepness of topography and the degree of work already accomplished. Likewise, additional shallow temperature-gradient holes do not seem useful at this time: no important thermal anomalies were encountered at the margins of drilling activity, and gradient decreases sharply with distance south or west of the Caldera.

However, the prospect is too attractive to abandon or shelve. Therefore, drilling of intermediate-depth gradient holes and/or deep exploration tests is called for, especially in the thermal anomalies along the Jemez River and on San Juan Mesa. Because of apparent dependence on the magmatic heat source beneath the Caldera, at least one hole should be sited as close to the Caldera margin as land position and topography permit. The vicinity of Battleship Rock is recommended.

A second location is called for on San Juan Mesa. This may be on the Mesa surface, or topographically lower, in Cañon de la Canada. The advantage of the former site is to save drilling through some 500 feet of Quaternary section. However, it would require construction of a road into the narrow and difficult canyon to do so.

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A third location may be within the heat-flow and gradient high near Jemez Springs. Here, too, topography may limit site possibilities. In any case, it is desirable to avoid locating the drill site on top of the adjacent mesa, both because of the additional drilling required to reach objective and because of an anticipated lessening of fracture permeability with distance from the Jemez Fault zone.

In every case, Precambrian rock is the lithologic objective. It will be necessary to determine the gradient in the Precambrian section to determine if it is as favorable as that projected herein (table 8). If not, objective depth may be greater than suggested in this report. At Battleship Rock and Jemez Springs, holes to 1,500 feet would penetrate several hundred feet of Precambrian section and would be adequate as intermediate-depth gradient holes. On San Juan Mesa, over 3,000 feet of Phanerozoic section is foreseen (plate 4). This would be too deep for drilling with conventional temperature-gradient rigs and probably would require a formal deep test.

Should further gradient drilling be considered near Jemez Pueblo, to test the circular fault anomaly, sites are suggested on plate 4, where holes to 1,500 feet would penetrate the Precambrian section.

A Precambrian reservoir objective will depend upon presence of interconnected fracture permeability. Experience at LASL's Fenton Hill hot dry rock site suggests that the Precambrian is very impermeable in many places. Therefore, proximity to the Jemez Fault zone is highly desirable, to enhance the potential for fracturing. Conversely, distance from this fault zone may decrease the fracture potential.

To establish the nature and degree of fracturing within the Precambrian, coring of selected intervals is highly useful in all future holes on the Grant. Similarly, all holes should be logged for fractures by gamma ray-neutron methods. Again, if possible, formation fluid tests should be run, to determine flow quantities and composition of fluids.

Temperature-gradient holes drilled by Phillips Petroleum to the east of the San Juan Mesa anomaly may be useful in interpretation of that feature. Therefore, efforts should be made to obtain these data, by trade, purchase or pooling agreement.

Phillips or other companies active in exploration of the region may be interested in participation in further drilling on the Grant.

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This might take the form of a farm-in, pool or bottom-hole contribution. Prospective partners, other than Phillips, include Aminoil U.S.A., Inc., Chevron Resources, Inc. and all companies having bid in earlier KGRA sales of the region.

Ultimately, a target of such size and complexity as this will require more than one deep test to determine geothermal potential. It is recommended here that the first deep test be at Battleship Rock or vicinity (perhaps after a 1,500-foot gradient hole) and that the second be on San Juan Mesa. If either is successful, a program of continued drilling can be designed at that time. If neither is successful, the potential at Jemez Springs may warrant further consideration.

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REFERENCES

- Aiken, C. L. V., Laughlin, A. W. and West, F. G., 1977, Residual Bouguer gravity anomaly map of northern New Mexico: Los Alamos Scientific Laboratory LA-6737-M.
- Albright, J. N., 1975, Temperature measurements in the Precambrian section of Geothermal Test Hole No. 2: Los Alamos Scientific Laboratory LA-6022-MS.
- Anonymous, 1961, Structural problems of the Rio Grande trough in the Albuquerque country: New Mex. Geol. Soc. Guidebook, 12th Field Conference, p. 144-147.
- Armstrong, A. K., 1955, Preliminary observations on the Mississippian system of northern New Mexico: New Mex. Bur. Mines and Min. Res., Circ. 39.
- Armstrong, A. K., 1967, Biostratigraphy and carbonate facies of the Mississippian Arroyo Peñasco Formation, north-central New Mexico: New Mex. Bur. Mines and Min. Res., Mem. 20.
- Armstrong, A. K. and Mamet, B. L., 1974, Biostratigraphy of Arroyo Peñasco Group, north-central New Mexico: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 145-158.
- Armstrong, R. L., Speed, R. C., Graustein, W. C. and Young, A. Y., 1976, K-Ar dates from Arizona, Montana, Nevada, Utah, Wyoming: Isochron/ West, 16, p. 1-6.
- Baars, D. L., 1961, Permian strata of central New Mexico: New Mex. Geol. Soc. Guidebook, 12th Field Conference, p. 113-120.
- Baars, D. L., 1974, Permian rocks of north-central New Mexico: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 167-169.
- Bailey, R. A., Smith, R. L. and Ross, C. S., 1969, Volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geol. Surv. Bull. 1274-P.
- Baldwin, B. 1956, The Santa Fe Group of north-central New Mexico: New Mex. Geol. Soc. Guidebook, 7th Field Conference, p. 115-121.
- Beyer, J. H., 1977, Telluric and d.c. resistivity techniques applied to the geophysical exploration of Basin and Range geothermal systems: Univ. Calif. Lawrence Berkeley Laboratory, LBL-6325-2/3.

JAMES B. KOENIG (415) 524-9242
MURRAY C. GARDNER (503) 482-2605

- Blair, A. G., Tester, J. W. and Mortensen, J. J., 1976, LASL Hot Dry Rock Geothermal Project: 1 July 1975 - 30 June 1976: Los Alamos Scientific Laboratory LA-6525-PR.
- Brookins, D. G., Forbes, R. B., Turner, D. L., Laughlin, A. W. and Naesser, C. W., 1977, Rb-Sr, K-Ar and fission-track geochronological studies of samples from LASL drill holes GT-1, GT-2, and EE-1: Los Alamos Scientific Laboratory LA-6829-MS.
- Chapin, C. E., 1971, Asymmetry of the Rio Grande rift: Tectonic implications: Geol. Soc. Amer., Abs. with Programs, V. 3, No. 7, p. 765-767.
- Cordell, L., 1970, Gravity and aeromagnetic investigations of Rio Grande depression in northern New Mexico: New Mex. Geol. Soc. Guidebook, 21st Field Conference, p. 158.
- Cordell, L., 1972, Complete Bouguer gravity map of the Jemez area, New Mexico: U.S. Geol. Surv. Open-File Map.
- Cordell, L. and Kottowski, F. E., 1975, Geology of the Rio Grande graben: Geology, V. 3, p. 420-424.
- Dane, C. H. and Bachman, G. O., 1965, Geologic map of New Mexico: U.S. Geol. Survey.
- Disbrow, A. E. and Stoll, W. C., 1957, Geology of the Cerrillos area, Santa Fe County, New Mexico: New Mex. Bur. Mines and Min. Res., Bull. 48
- Duchene, H. R., 1974, Pennsylvanian rocks of north-central New Mexico: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 151-162.
- Duchene, H. R., Kues, B. S. and Woodward, L. A., 1977, Osha Canyon formation (Pennsylvanian), new Morrowan unit in north-central New Mexico: Amer. Assoc. Petrol. Geol. Bull., V. 61, p. 1513-1521.
- Earth Satellite Corporation, 1976, Report on geothermal exploration guide map for Valles Caldera area (Jemez Mountains), New Mexico: Earthsat Contract 1097, 23 June 1976, Berkeley, California.
- Energy Research and Development Administration, 1977, Hot Dry Rock geothermal energy: Status of exploration and assessment: Report 1 of the Hot Dry Rock Assessment Panel, ERDA 77-74.

JAMES B. KOENIG (415) 524-9242
MURRAY C. GARDNER (503) 482-2605

Exploration Associates, 1975, San Diego Grant area, Sandoval County, New Mexico - Report and recommendations: Unpub. report, 5 November 1975.

Exploration Associates, undated, Cañon de San Deigo Grant area, summary report and composite map, Sandoval County, New Mexico: Unpub. report.

Fasset, J. E., 1974, Cretaceous and Tertiary rocks of the eastern San Juan basin, New Mexico and Colorado: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 225-230.

Flesch, G. A., 1974, Stratigraphy and sedimentology of the Morrison Formation (Jurassic), Ojito Spring quadrangle, Sandoval County, New Mexico: A preliminary discussion: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 185-195.

Fournier, R. O. and Potter, R. W. II, 1978, A magnesium correction for the NaKCa chemical geothermometer: U.S. Geol. Survey Open File Report 78-986.

Galusha, T., 1974, Dating rocks of the Santa Fe Group: Programs and problems: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 283-286.

Geonomics, Inc., 1975, An electrical resistivity survey of the San Diego Grant prospect, Sandoval County, New Mexico: Report for Sun Oil Company, May 1975, Berkeley, California.

Geothermal Services, Incorporated, 1977, Preliminary temperature data, San Diego Grant prospect, New Mexico: Report for Sun Energy Development Co.

Geotronics Corporation, 1977, Magnetotelluric survey in the Jemez Springs vicinity of central New Mexico: Report for Sun Energy Development Co., January 1977, Austin, Texas.

Geotronics Corporation, 1978, Magnetotelluric survey in the Jemez Springs area of New Mexico: Report for Sun Energy Development Co., January 1978, Austin, Texas.

Griggs, R. L., 1964, Geology and ground-water resources of the Los Alamos area, New Mexico: U.S. Geol. Surv. Water-Supply Paper 1753.

JAMES B. KOENIG (415) 524-9242

MURRAY C. GARDNER (503) 482-2605

- Heinrichs Geoexploration Company, 1973, Geothermal resistivity survey of the Jemez Pueblo area, Sandoval County, New Mexico: Report for Calvert Geothermal Resources, December 1973, Tucson, Arizona.
- Hiss, W. L., Trainer, F. W., Black, B. A. and Posson, D. R., 1975, Chemical quality of ground-water in the northern part of the Albuquerque-Belen basin, Bernalillo and Sandoval Counties, New Mexico: New Mex. Geol. Soc. Guidebook, 26th Field Conference, p. 219-235.
- Jiracek, G. R., 1974, Geophysical studies in the Jemez Mountains region, New Mexico: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 137-144.
- Jiracek, G. R., 1975, Deep electrical resistivity investigations coupled with dry geothermal reservoir experiment in New Mexico: Technical Progress Report, prepared for the National Science Foundation.
- Joesting, H. E., Case, J. E. and Cordell, L. E., 1961, The Rio Grande trough near Albuquerque, New Mexico: New Mex. Geol. Soc. Guidebook, 12th Field Conference, p. 148-150.
- Kelley, V. C., 1952, Tectonics of the Rio Grande depression of central New Mexico: New Mex. Geol. Soc. Guidebook, 3rd Field Conference, p. 93-105.
- Kelley, V. C., 1954, Tectonic map of a part of the upper Rio Grande area, New Mexico: U.S. Geol. Surv. Oil and Gas Investigation Map OM 157.
- Kelley, V. C. and Clinton, N. J., 1960, Fracture systems and tectonic elements in the Colorado Plateau: Univ. New Mexico, Publications in Geology No. 6.
- Kelley, V. C., Woodward, L. A., Kudo, A. M. and Callender, J. F., 1976, Guidebook to Albuquerque basin of the Rio Grande rift, New Mexico: New Mex. Bur. Mines and Min. Res., Circ. 153.
- Kintzinger, P. R., 1976, Seismic signal location program for the Los Alamos Scientific Laboratory's Dry Hot Rock Geothermal Project: Los Alamos Scientific Laboratory LA-6274-MS.
- Kintzinger, P. R., West, F. G. and Aamodt, R. L., 1977, Downhole electrical detection of hydraulic fractures in GT-2 and EE-1: Los Alamos Scientific Laboratory LA-6890-MS.

JAMES B. KOENIG (415) 524-9242
MURRAY C. GARDNER (503) 482-2605

- Kottowski, F. E., 1961, Pennsylvanian rocks in north-central New Mexico: New Mex. Geol. Soc. Guidebook, 12th Field Conference, p. 97-104.
- Kudo, A. M., 1974, Outline of the igneous geology of the Jemez Mountains volcanic field: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 287-289.
- Laughlin, A. W. and Eddy, A., 1977, Petrography and geochemistry of Precambrian rocks from GT-2 and EE-1: Los Alamos Scientific Laboratory Informal Report LA-6930-MS.
- Liaw, A. L. and McEvilly, T. V., 1977, Microseisms in geothermal exploration; studies in Grass Valley, Nevada: Univ. Calif. Lawrence Berkeley Laboratory, LBL-6813.
- Manley, K., 1976, K-Ar age determinations on Pliocene basalts from the Española basin, New Mexico: Isochron/West, 16, p. 29-30.
- Manley, K. and Naesser, C. W., 1977, Fission-track ages for tephra layers in upper Cenozoic rocks, Española basin, New Mexico: Isochron/West, 18, p. 13-14.
- O'Sullivan, R. B., 1974, The upper Triassic Chinle Formation in north-central New Mexico: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 171-174.
- Purtymun, W. D., 1974, Geology of the Jemez Plateau west of Valles Caldera: Los Alamos Scientific Laboratory LA-5124-MS.
- Purtymun, W. D., West, F. G. and Adams, W. H., 1974a, Preliminary study of the quality of water in the drainage area of the Jemez River and Rio Guadalupe: Los Alamos Scientific Laboratory LA-5595-MS.
- Purtymun, W. D., West, F. G. and Pettitt, R. A., 1974b, Geology of geothermal test hole GT-2, Fenton Hill site, July 1974: Los Alamos Scientific Laboratory LA-5780-MS.
- Reed, R. K., 1971, Precambrian geology of the central Nacimiento Mountains, Sandoval County, New Mexico: Univ. New Mexico, unpublished Ph.D. thesis.
- 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. Amer. Bull., V. 86, p. 811-818.

JAMES B. KOENIG (415) 524-9242
MURRAY C. GARDNER (503) 482-2605

- Reiter, M., Weidman, C., Edwards, C. L. and Hartman, H., 1976, Subsurface temperature data in Jemez Mountains, New Mexico: New Mex. Bur. Mines and Min. Res., Circ. 151.
- Rennick, B. C., 1931, Geology and ground-water resources of western Sandoval County, New Mexico: U.S. Geol. Surv. Water-Supply Paper 620.
- Schempf, E. G., undated, Geothermal potential of the Jemez Mountains area: unpublished manuscript.
- Senturion Sciences Inc., undated, Seismic ground noise survey in the vicinity of the Cañon de San Diego; Tulsa, Oklahoma.
- Senturion Sciences Inc., undated, Jemez I microearthquake investigation; Tulsa, Oklahoma.
- Senturion Sciences Inc., undated, Cañon North seismicity investigation: Report for Sun Energy Development Co.
- Senturion Sciences Inc., 1975, Report in the Cañon I and II seismicity investigations at Cañon, Sandoval County, New Mexico: Report for Sun Energy Development Co.
- Smith, R. L., Bailey, R. A. and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geol. Surv. Misc. Geol. Inv. Map I-571.
- Spiegel, Z., 1961, Late Cenozoic sediments of the lower Jemez River region: New Mex. Geol. Soc. Guidebook, 12th Field Conference, p. 132-138.
- Spiegel, Z. and Baldwin, B. W., 1963, Geology and water-resources of the Santa Fe area, New Mexico: U.S. Geol. Surv. Water-Supply Paper 1525.
- Stearns, C. E., 1943, The Galisteo Formation of north-central New Mexico: Jour. Geol., V. 51, p. 301-319.
- Stearns, C. E., 1953, Tertiary geology of the Galisteo-Tonque area, New Mexico: Geol. Soc. Amer. Bull., V. 64, p. 459-508.
- Summers, W. K., 1965, Chemical characteristics of New Mexico's thermal waters--a critique: New Mex. Bur. Mines and Min. Res., Circ. 83.

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- Summers, W. K., 1976, Catalog of thermal waters in New Mexico: New Mex. Inst. Mining and Tech., Hydrologic Report 4.
- Swanburg, C. A., 1975, Geochemical study of the western portion of the Jemez Mountains: Report for Exploration Associates.
- Titus, F. B., 1961, Ground-water geology of the Rio Grande trough in north-central New Mexico, with sections on the Jemez Caldera and the Lucero Uplift: New Mex. Geol. Soc. Guidebook, 12th Field Conference, p. 186-192.
- Trainer, F. W., 1974, Groundwater in the southwestern part of Jemez Mountains volcanic region, New Mexico: New Mex. Geol. Soc. Guidebook, 25th Field Conference, p. 337-345.
- Trainer, F. W., 1975, Mixing of thermal and nonthermal waters in the margin of Rio Grande rift, Jemez Mountains, New Mexico: New Mex. Geol. Soc. Guidebook, 26th Field Conference, p. 213-218.
- Trainer, F. W. 1978, Geohydrologic data from the Jemez Mountains and vicinity, north-central New Mexico: U.S. Geologic Survey Water-Resources Investigations 77-131.
- U.S. Geological Survey, 1962, Aeromagnetic survey from 106° to 107° E longitude, and 35°30' to 36°15' W latitude: Open-File Report.
- West, F. G., 1973, Regional geology and geophysics of the Jemez Mountains: Los Alamos Scientific Laboratory LA-5362-MS.
- West, F. G., Kintzinger, P. R. and Laughlin, A. W., 1975, Geophysical logging in Los Alamos Scientific Laboratory Geothermal Test Hole No. 2: Los Alamos Scientific Laboratory LA-UR 75-1518.
- West, F. G. and Shankland, T. J., 1977, Exploration methods for hot dry rock: Los Alamos Scientific Laboratory Informal Report LA-6659-MS.
- West, S. W. and Broadhurst, W. L., 1975, Summary appraisals of the nation's ground-water resources--Rio Grande region: U.S. Geol. Surv. Prof. Paper 813-D.
- Wood, G. H. and Northrup, S. A., 1946, Geology of the Nacimiento Mountains, San Pedro Mountains and adjacent plateaus in parts of Sandoval and Rio Arriba Counties, New Mexico: U.S. Geol. Surv. Oil and Gas Investigations Preliminary Map 57.

JAMES B. KOENIG (415) 524-9242
MURRAY C. GARDNER (503) 482-2605

Woodward, L. A., 1975, Geometry of Sierrita fault and its bearing on tectonic development of the Rio Grande rift, New Mexico: Geology, V. 3, p. 114-116.

Woodward, L. A. et al., 1973, Geologic map and sections of San Pablo quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol. Map 26.

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

Woodward, L. A. and Duchene, H. R., 1974, Geologic map and sections of San Miguel Mountain quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol. Map 34.

Duchene Woodward, L. A., Duchen, H. R. and Martinez, R., 1977, Geology of Gilman quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol. Map 45.

Woodward, L. A., Kaufman, W. H. and Anderson, J. B., 1972, Nacimiento fault and related structures, northern New Mexico: Geol. Soc. Amer. Bull., V. 83, p. 2383-2396.

Woodward, L. A., Kaufman, W. H., Anderson, J. B. and Reed, R. K., 1972, Geologic map of the La Ventana N.W. quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol. Map 26.

Woodward, L. A., Kaufman, W. H. and Reed, R. K., 1973, Geologic map and sections of Rancho del Chaparral quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol. Map 27.

Woodward, L. A. and Martinez, R., 1974, Geologic map and sections of Holy Ghost Spring quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol. Map 33.

Woodward, L. A., McLelland, D., Anderson, J. B. and Kaufman, W. H., 1972, Geologic map of the Cuba quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol. Map 25.

Woodward, L. A., McLelland, D. and Anderson, J. B., 1974, Geologic map and sections of Nacimiento Peak quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol. Map 32.

JAMES B. KOENIG (415) 524-9242
MURRAY C. GARDNER (503) 482-2605

Woodward, L. A. and Ruetschilling R. L., 1976, Geology of San Ysidro
quadrangle, New Mexico: New Mex. Bur. Mines and Min. Res., Geol.
Map 37.