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GEOPHYSICAL STUDIES IN THE JEMEZ MOUNTAINS REGION NEW MEXICO

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INTRODUCTION

Noninstrumental geophysical information regarding the Jemez Mountains region of New Mexico began accumulating long before the increased activities of the past decade. The information was in the form of reports and observations collected from persons experiencing earthquakes in the vicinity. Data of this kind has been traced back to 1849 by S. A. Northrop (1947; 1961), presently Professor Emeritus at the University of New Mexico. Instrumental seismicity studies in New Mexico began in 1960 and unique shock locations (epicenters), requiring three recording stations, were mapped beginning in 1962 (Sanford, 1965). Considerably more detailed seismic information of the Jemez Mountains region is currently being gathered by the six station seismic network installed by Los Alamos Scientific Laboratory (LASL) in 1972-73.

Other geophysical techniques were used to study the Jemez Mountains region beginning in 11962 when the U.S. Geological Survey (USGS) initiated gravity and aeromagnetic surveys to support their geologic mapping and water resource investigations. Geophysical studies in the region have become increasingly more important due to the geothermal energy potential and relationship of the volcanism to the Rio Grande rift.

The association of the Rio Grande rift with other Basin-and-Range structures of the western United States is crucial in understanding the phenomena of internal rifting in continental plates. Most recent geophysical measurements have resulted in the interpretation that the Rio Grande rift is possibly underlain by a hot "pillow" in the upper mantle (Decker and Smithson, 1973) or by an upwarp of the earth's mantle (Edwards and others, 1973; Ramberg and others, 1974). Either situation could easily have controlled the thermal and volcanic history of the Jemez Mountains region.

The establishment of the Jemez Mountains region as a major Known Geothermal Resource Area (KGRA) was officially made in 1970 (Godwin and others, 1971). This designation was given to the Baca Location No. 1 which comprises about 100,000 acres of the Valles Caldera. The Baca has been the scene of considerable exploratory drilling by Union Oil Company of California who are acting as operators for a joint venture comprising Union, Dunigan Enterprises, and the Baca Land and Cattle Company, Abilene, Texas. The eleventh well has been reported (Albuquerque Tribune, January 23, 1974) to have a tested flow of geothermal fluids with a power capacity of 6500 kilowatts per hour. A twelfth well is currently being drilled and unconfirmed reports indicate that it too is a successful geothermal well. It is known that Union has had geophysical surveys run on the Baca Location, in particular, a resistivity survey; however, until adjacent lands are leased, the geophysical data is considered proprietary (C. Otte, personal communication, May, 1973). Additional proprietary geophysical exploration including seismic noise and micro-earthquake measurements is in the process of being done on the Callon de San Diego land grant south of the Baca Location (J. R. Bailey, Senturian Sciences, Inc., personal communication, October, 1973).

The decision by LASL to make the world's first hot, dry-rock geothermal feasibility tests in the Jemez Mountains has resulted in a surge of geophysical studies. Heat flow measurements have been made by New Mexico Institute of Mining and Technology (NMIMT) (M. Reiter, personal communication, May, 1973; Potter, 1973) and several geophysical measurements are being made in conjunction with the drilling and fracturing tests. These include deep electrical resistivity investigations by researchers from the University of New Mexico (UNM), surface seismic and tilt-meter tests, and a variety of downhole geophysical measurements by LASL. The downhole measurements include caliper, temperature, gamma-ray, neutron, sonic, resistivity, and self-potential logs together with borehole televiewer logging.

SEISMIC STUDIES

Seismicity or the geography of earthquake activity in the Jemez Mountains region based on noninstrumental reports may be misleading due to the low population density of the area. However, the instrumental studies reported since 1962 by Sanford (1965), Sanford and Cash (1969), Toppozoda and Sanford (1972), Sanford and others (1972), K. H. Olsen (personal communication, July, 1974) and S. A. Northrop (personal communication, July, 1974) have confirmed the surprisingly low seismicity in the Jemez Mountains region. Shocks originating in the Dulce area to the north, the Cimarron area to the northeast, and the Rio Grande rift to the south (particularly the Albuquerque to Socorro segment) have been felt in the Jemez Mountains but very few epicenters have occurred in the region. Sanford's data listing shocks above magnitude* 2.5 does not yield a single event from the Valles Caldera. An earthquake of magnitude 4.0 was, however, felt by everyone in Los Alamos on August 17, 1952 (S. A. Northrop, personal communication, July, 1974). The focus of this shock has been estimated to be directly below Los Alamos. Most earthquakes recorded recently in the Jemez Mountains region are associated with continuing activity beginning on December 6, 1971, 25 to 35 km north of Los Alamos near Abiquiu. A number of shocks exceeding magnitude 3.0 have been recorded; on March 17, 1973 a magnitude 3.4-4.5 event with smaller aftershocks

*Earthquake magnitudes reported in this paper are local magnitudes (M_L) based on the seismic phase, often direct S, having the largest amplitude on the seismograph. For the magnitudes $2.7 \leq M_L \leq 4.2$, the local magnitude is about 0.7 less than body wave magnitude (Toppozoda and Sanford, 1972).

was strongly felt by Los Alamos residents (K. H. Olsen, personal communication, July, 1974). The activity near Abiquiu may be related to the October 13, 1973 earthquake which occurred about 5 km deep on the Pajarito fault beneath Los Alamos. This shock was too small for detection by people but the measurement is an example of the increased sensitivity now available using the new LASL seismic array.

The new LASL six station seismic network was installed by J-Division to estimate the seismic risk in the Los Alamos area and for geothermal investigations in the vicinity. The present network is shown in Figure 1 along with the proposed expanded array. The three letter codes are international designators assigned by the National Earthquake Data Center, Boulder, Colorado. Stations LOA and FCN are located in technical areas at LASL. Stations LCV, SPD, CLP, and TSP are at La Cueva, St. Peters Dome Lookout, Clara Peak Lookout, and Tesuque Peak, respectively. All seismometers at the stations have a natural resonant frequency of 1 Hz with a band pass of 0.5 to 100 Hz. They are especially useful for low detection thresholds necessary to record local and regional earthquakes. Stations LOA, LCV, and CLP contain three component seismometers, whereas the remaining stations have vertical component instruments only. Detection limit within the boundaries of the present network is better than 0.5 magnitude. All data is telemetered either by telephone lines or VHF radios to the main recording center in the LASL Administration Building. Installation of the sixth station at Tesuque Peak was completed in October, 1973 and a seventh station is near-operational at Seven Springs about 5.5 km northwest of LCV (Fig. 1). During the first quarter of 1974, at least 5 seismic events have been recorded and associated with the Pajarito Fault complex which runs approximately NS through Los Alamos and Abiquiu (Fig. 1). Magnitudes of the shocks varied from 0.2 to 1.9 (K. H. Olsen, personal communication, July, 1974). Further activity measured during this period originated from near the Nacimiento fault, the Puerco-Mt. Taylor area, and the DuIce area. Explosions from the Nevada test site and from local quarries and mines have also been recorded. These latter sources result in seismic signals which have been recorded after traveling beneath the Valles Caldera, thus some inferences regarding a deep magma chamber can be made. Such a molten or semimolten zone would delay P wave arrivals and would severely attenuate or eliminate S waves. A preliminary study of the S and P wave amplitudes and the corresponding seismic ray paths does not indicate any significant liquid regions, at least for those depths beneath the caldera sampled by the observed seismic events. Various station anomalies are noted but it appears that these can be explained by local, near-surface geological variations (K. H. Olsen, personal communication, July, 1974).

Considerable geophysical investigation, including seismology, is currently being made in conjunction with the LASL Dry Geothermal Source Demonstration Project. The project objective is to investigate and develop methods of extracting geothermal energy economically from hot-rock in the earth's crust. The region selected for the large-scale field tests is in the Jemez Mountains west of the Valles Caldera (Fig. 2). Four test holes (A, B, C, D, of Fig. 2) ranging from 500 to 750 ft (152 to 229 m) were drilled in this area in April, 1972. A deeper test probe into Precambrian granite reached a depth of 2575 ft (785 m) and was completed in June, 1972 (Granite Test 1 of

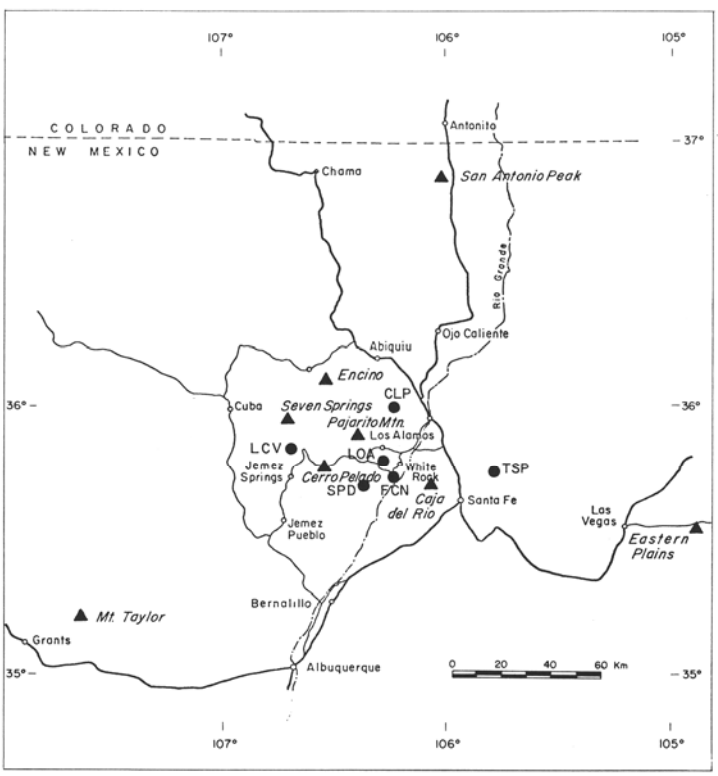

Figure 1. Locations of present LASL regional seismometer array (circles) and proposed sites (triangles). (Map courtesy of K. H. Olsen.)

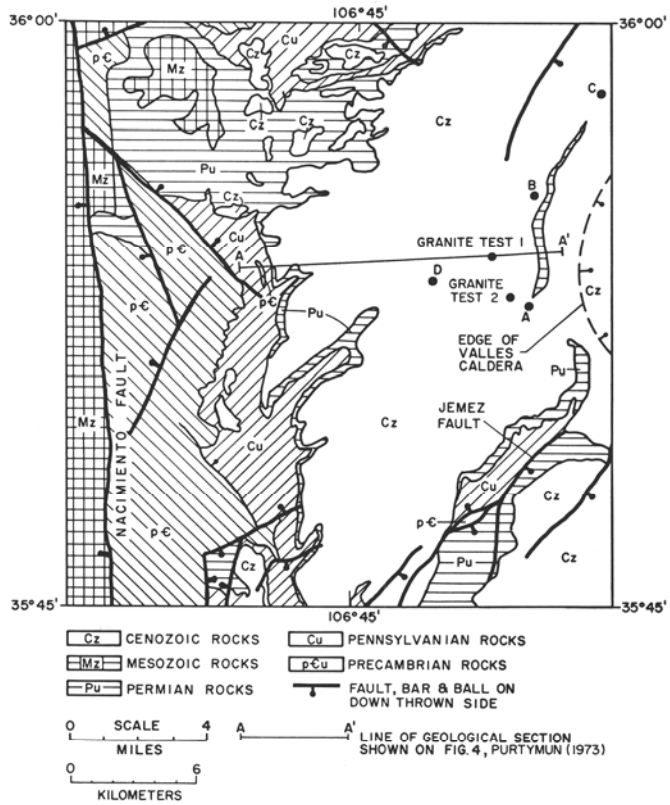

Figure 2. Location map of LASL geothermal test holes A, B, C, D, and Granite Tests 1 and 2 together with generalized geology west of the Valles Caldera. (After Purtymun, 1973).

Fig. 2). Upon consideration of the geological and temperature data obtained from these holes, Granite Test 2 (GT-2) was begun in January, 1974 (Fig. 2). The hole was completed to a depth of 6350 ft (1935.5 m) in early July, 1974 and at this writing, it is being prepared for hydraulic fracturing tests. Seismometer sites have been set up around GT-2 in an effort to monitor natural seismic events in the vicinity and to measure seismic first motions, polarizations, and source mechanisms produced by the hydraulic fracturing. Figure 3 shows the distribution of the seismic array. Locations indicated by circles and coded by a Q prefix were emplaced by Q-22 Division of LASL, whereas the stations marked by squares were installed by J-Division. All stations except 13 have either three component or vertical component seismometers identical to those described for the six station regional array. Station 13 has a marine hydrophone in a 180 m hole which has a higher frequency response (50-300 Hz) than the seismometers. Q-22 Division has also located four sensitive tilt-meters within 155 m of GT-2. Fracturing tests are to take place during August, 1974.

LASL has contracted additional seismic studies in conjunction with the GT-2 site. A conventional seismic reflection survey, with limited refraction measurements, was made near GT-2 out to distances exceeding 1 km. Preliminary analysis of the records indicate reflections from and within the Precambrian section which is at depth of 2404 ft (733 m) at GT-2. Reflection and refraction information was obtained in the sedimentary column which has P wave velocities of 4000-8000 ft/sec (1219-2438 m/sec) (P. R. Kintzinger, personal communication, July, 1974). Most reflection shooting was done

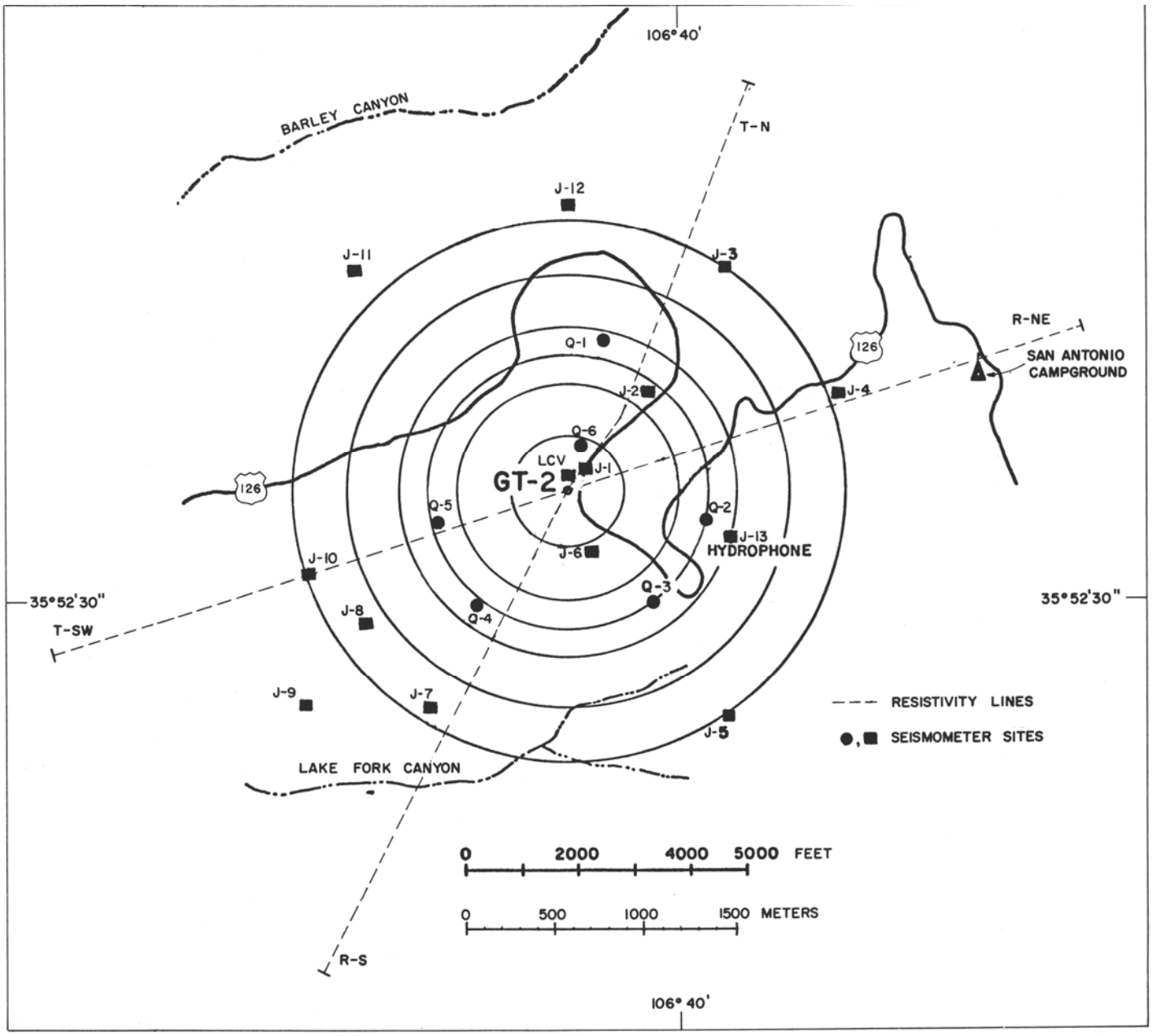

Figure 3. Location map of LASL local seismometer array and UNM resistivity lines near GT-2 drill site. Q-22 and J-9 Division sites represented by circles and squares, respectively. (Map, modified from original, courtesy of K. H. Olsen.)

broadside rather than in-line with the geophonc spread to reduce the time overlap of the desired deeper reflections with signals traveling slowly through surface volcanics. A vibroseis survey was also recently run near GT-2 but results are not yet available. Additional borehole seismic studies have been made; these will be discussed in the later section on Heat Flow and other Borehole Geophysics.

GRAVITY AND MAGNETIC STUDIES

Gravity and aeromagnetic surveys were initiated by the USGS in the Jemez Mountains area in 1962; on December 8, 1972 the maps became available as open files (Cordell, 1972; USGS, 1972). Less detailed reconnaissance maps of the gravity (U.S. Air Force, 1968) and magnetics (Zietz and Kirby, 1968) of the area were included in reports of the transcontinental geophysical surveys run between latitudes 35°-39° N. These maps were briefly discussed by West (1973). The 1972 open-file gravity and magnetic maps cover an area from latitudes 35°30 to 36°15 N and between longitudes 106°00' and 107°00' W. The contour interval of the gravity map is 5 milligals and the Bouguer reduction density is 2.45 g/cm3. The gravity map plots values of the absolute complete Bouguer anomaly. The total intensity magnetic map is contoured relative to an arbitrary datum with a contour interval of 20 gammas. The aeromagnetic survey was flown in 1962 with a flight elevation of 11000 ft (3353 m) north of latitude 35°45' N and 9000 ft (2743 m) elevation to the south. It has been reported (Cordell, 1970) that the Valles Caldera is marked by gravity and magnetic minima and is located at an intersection of gravity, magnetic, and structural trends.

Cursory inspection of the open-file gravity map clearly shows the parallelism of contours of a pronounced gravity minimum with the elliptical shape of the Valles Caldera; an exception is the nosing of the gravity minimum to the north-northeast over the Toledo Caldera. The steepest portions of the gravity gradients associated with these contours are probably associated with the ring faults (Fig. 2) bounding the Valles Caldera, as postulated by Smith and others (1961). The ring faults may mark boundaries along which the central portion of the volcano collapsed to form the caldera and along which resurgent domes were later intruded. The absolute value of the NNE-trending gravity minimum is -240 milligals and occurs over the eastern portion of the caldera in the area of Cerros del Abrigo and Cerro del Medio Domes. The residual gravity minimum appears to be about -40 milligals compared to the region to the west of the caldera and about -20 milligals relative to the east. A portion of this negative gravity anomaly is surely due to volcanic and sedimentary fill which thickens in the vicinity of Cerro del Medio and Valle Grande (Smith and others, 1970). Excluding this effect, the remaining negative anomaly probably indicates the presence of a large intrusive body underlying the caldera (Cordell, 1970). At a recent congressional hearing on geothermal resources, Eaton (1973) stated that current interpretation of the pronounced gravity low over the Jemez Mountains is that it is due to a partially molten body in the subsurface.

Outside the region of the caldera, to the east, the gravity map shows a number of broad positive and negative closures trending nearly parallel and west of the Rio Grande. The positives and negatives probably indicate structural highs and lows, respectively. West of the caldera, a broad positive anomaly occurs in the San Pedro Mountains. The axis of the Nacimiento Mountains and associated faulting is clearly marked by a steep gravity gradient with contours trending almost perfectly N-S the entire length of the map. Smaller features are evident in the gravity map, for example, the Jemez Fault (Fig. 2) coincides with a distinct ridge in the gravity contours.

The aeromagnetic map of the Jemez Mountains is inherently more complicated than the gravity map. This is, in part, associated with higher spatial frequencies intrinsic to magnetic anomalies, particularly in volcanic terrain, but also to reversed magnetization of some of the rock units in the area. (Doell and others, 1968). Units correlated with the Matuyama reversal epoch include the upper and lower Bandelier Tuff (K-Ar ages 1.09 and 1.37 million years). The study by Doell and others (1968) included samples of these units from Redondo Dome and Cerro del Medio Dome, respectively.

The two largest negative magnetic anomalies appearing on the 1972 map may be associated with reversed magnetization of Redondo and Cerro del Medio Domes. A magnetic closure several hundred gammas more negative than the regional values occurs about 2 km south of Red)ndo Peak and a lessor minimum is centered directly over Cerro del Medio. Magnetic patterns throughout the area, particularly over the Valles Caldera and to the immediate north, are marked by complex magnetic maxima and minima. The magnetic "grain" is, in many instances, contrary to that expected from magnetic induction by the earth's present field (approximate declination and inclination of 130 E and 63° N, respectively), therefore, remanent magnetism is considered an important contributor to the observed fields.

A total field magnetic anomaly aligned nearly as expected from induction alone has been studied with surface traverses by Woltz (1972). The anomaly is located near the Seven Springs Fish Hatchery (Fig. 4). Judging from the open-file magnetic map (available after the completion of Woltz's work) the anomaly is "riding" on a much broader anomaly of approximately the same orientation. That the smaller feature mapped by Woltz does not clearly appear on the aeromagnetic

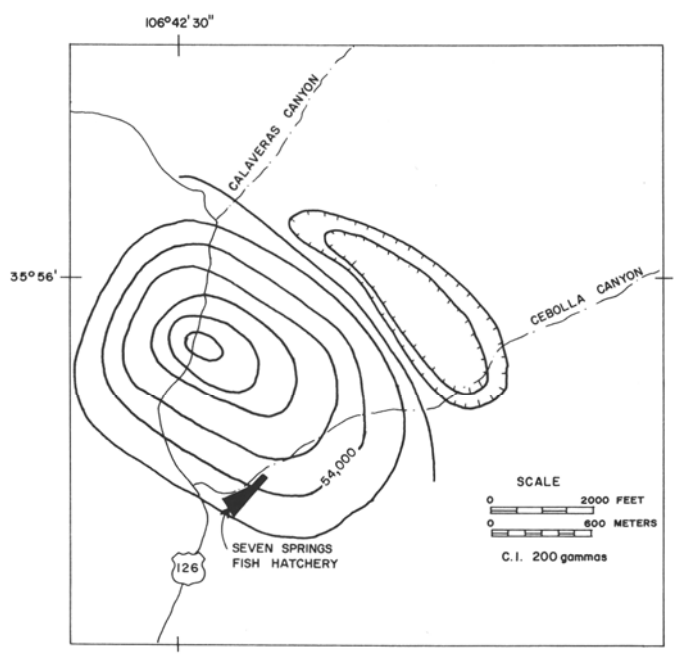

Figure 4. Smoothed, observed ground magnetic anomaly nea Seven Springs Fish Hatchery. (Modified from Woltz, 1972.)

map is explained by the attenuation of short wavelength anomalies due to upward continuation. Using a computer program written by this author, based on the prismatic model of Bhattacharyya (1964), Woltz obtained reasonable fits to the smoothed, observed anomaly by neglecting remanent magnetism. Smoothing was necessary to remove the high spatial noise present in surface traverses over the volcanic terrain composed mainly of Bandelier Tuff. The "best" computer fit suggested an intrusive source with a volume susceptibility contrast of at least 0.004 cgs which intruded to within 700 feet (213 m) of the surface. Deeper sources also fit the observed anomaly quite well; given the simplicity of the prism model and lack of further constraints, no attempt was made to "accurately" model the anomaly.

RESISTIVITY STUDIES

Electrical resistivity studies have been initiated in the Jemez Mountains by UNM in conjunction with the LASL geothermal tests. The project is supported by the National Science Foundation and is under the direction of the author. The resistivity method has been described as the most powerful geophysical exploration technique for geothermal resources (Meidav, 1974). This is particularly true in exploration for hot, wet systems such as in New Zealand and in the Imperial Valley of California but its application in hot, dry-rock environments has not been established. Evaluation of the technique in such an environment in the Jemez Mountains is one of the major objectives of the research project. Other objectives include an attempt to aid in defining hydraulically induced fractures and the application of new generalized inversion techniques to interpret the resistivity measurements. With these goals, a trailer-mounted 50 kilowatt resistivity transmitter has been constructed at UNM and is now field operational. The constant current unit is capable of transmitting pulses in the range from DC to 10 Hz with peak values of over 40 amperes at 1,200 volts. Sensitive portable recorders are used to measure voltage levels in the microvolt range at distances of several kilometers from the transmitter.

In order to measure the geoelectric section surrounding GT-2 and attempt to detect hydraulically induced fractures, two resistivity sounding/profiling lines have been measured and are currently being occupied (Fig. 3). Nearly 20 shallow resistivity soundings using Schlumberger arrays to a maximum outer electrode separation (AB) of 1 km have been centered at points 500 m apart along the lines. The soundings were made using a commercially available resistivity unit which transmits only 25 milliamps at 11 Hz. An average of preliminary results of two orthorgonal soundings at GT-2 is shown in Figure 5 by the observed apparent resistivity curve. The orthogonal sets of resistivity data were nearly identical, indicating local horizontality of the near-surface layers at GT-2. True resistivities and appropriate depths to model layers are shown in Figure 5 along with the corresponding theoretical values automatically fit by generalized inversion (Inman and others, 1973). The dry Bandelier Tuff on the surface is characterized by high resistivity (800 ohm-m) but it is not nearly as resistive (3000 ohm-m) as the bottom layer which is responsible for the apparent resistivity increased beyond AB/2 spacing of 150 m. This deeper layer is the extremely dry Paliza Canyon Tuff, above the water table, as confirmed by drilling analysis and borehole resistivity measurements (see section on Heat Flow and other Borehole Geophysics). Borehole resistivity logs show this layer

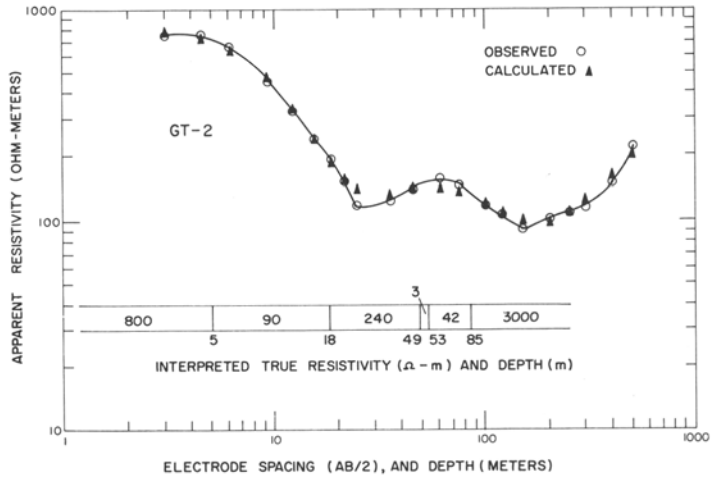

Figure 5. Observed Schlumberger resistivity sounding at GT-2 drill site and six-layer model interpreted by generalized inversion.

at about 80 m depth, whereas the six layer model fit places it slightly deeper, at 85 m depth. The conductive layer (3 ohm-m) interpreted between 49 and 53 m depth is probably a clay layer in the tuff.

Deeper resistivity probings using the dipole-dipole technique have only recently begun along the two test lines shown in Figure 3. An example of the preliminary results using 1 km dipoles along the T-SW, R-NE test line is given in Figure 6 in pseudo-section form. Transmitted signals were square waves at 10 seconds period with peak amplitudes of 5 and 10 amperes. The apparent resistivities plotted in Figure 5 tentatively agree with theoretical dipole-dipole soundings based on layered models constructed from the shallow Schlumberger soundings and the borehole resistivity logs. Shallower apparent resistivity values (26.4 ohm-m) are representative of the sedimentary section extending to 733 m depth at GT-2. Deeper values, up to 50 ohm-m, are beginning to express the effect of the more resistive Precambrian basement. Extensive dipole-dipole resistivity soundings are to be made in the vicinity of GT-2 and

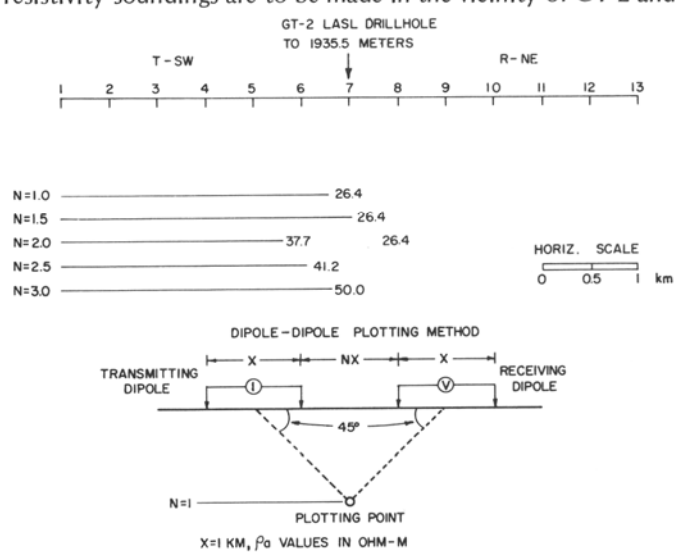

Figure 6. Preliminary apparent resistivity pseudo-section plot of dipole-dipole soundings at GT-2 drill site. One kilometer transmitting dipoles located across sites 2-4 and 4-6; one kilometer receiver locations connect sites 8-10, 9-11, and 10-12.

results will be automatically interpreted by generalized inversion routines. Results of the initial studies will be presented at the forthcoming annual international meeting of the Society of Exploration Geophysicists (Jiracek and Kintzinger, 1974).

HEAT FLOW AND OTHER BOREHOLE GEOPHYSICS

Heat flow in the Jemez Mountains has been studied in conjunction with the LASL geothermal project. Measurements were made at test holes A, B, C, and at Granite Test 1 in Figure 2 as a joint effort by LASL and NMIMT. Test holes A, B, and C are along a 13 km arc, concentric with and 3 km west of the ring fault. Heat flow values along this arc are in the range 5.0-5.5 HFU (Potter, 1973); the small range of values suggests a field symmetric about a central source (R. M. Potter and R. L. Aamodt, personal communication, July, 1974). Heat flow calculated from 785 m deep GT-1, 4 km west of the ring fault, is approximately 3 H FU (M. Reiter, personal communication, May, 1973; Potter, 1973). Preliminary heat flow measurements at GT-2 (Fig. 2) are about 5 HFU but the effects of hydraulic convection have not been ruled out as yet (Potter, personal communication, July, 1974). The geothermal gradient in the Precambrian section of GT-2 is about 55°C/km compared to 45°C/km in GT-1. Bottom hole temperature in GT-1 was about 100°C, whereas at the bottom of GT-2 (1935.5 m depth) the temperature is approximately 140°C. The recent geothermal well drilled by Union Oil Company to a depth of 2112 m on the Baca Location in the Valles Caldera is reported (Union Oil Co., 1974) to contain water under hydrostatic pressure at temperatures above 250°C. Besides the temperature logging in GT-1 and GT-2, other logs that have been run include caliper, gamma-ray, neutron, formation dens ity, continuous velocity, 3-dimensional sonic, self-potential, resistivity, and borehole seisviewer.

Apparent bulk densities in the volcanic and sedimentary sections at GT-2 are highly variable, generally between 2.0 and 2.6 g/cm3. The Precambrian section is characterized by densities in the range 2.5 to 2.8 g/cm3. Continuous velocity logging yielded P wave velocities ranging from 1950 to 2700 m/sec in the tuffs and generally higher values were calculated for the sedimentary section. P wave velocities for the shales and clays averaged between 2380 and 3000 m/sec, for siltstones and sandstones between 2920 and 3100 m/sec, and were typically about 3900 m/sec in the limestone layers. Corresponding S wave velocities were approximately one-half the P wave values (W. D. Purtymun, personal communication, July, 1974). P wave velocities of 5486 to 5791 m/sec were logged in the lower crystalline Precambrian basement.

SP and conventional resistivity logs were run for most of the , GT-2 hole with a notable omission occurring between 1812 ft (552 m) and 2535 ft (773 m) where the unconformity between Pennsylvanian limestone and Precambrian granite was encountered at a depth of 2404 ft (733 m). Conventional resistivity logs consist of short and medium normal logs and a lateral log. Distance between the potential measuring electrodes for the normal logs is 16 in (0.41 m) and 64 in (1.62 m), respectively; the distance from the .downhole current electrode to the center of the potential electrodes is 18 ft 8 in (5.7 m) for the lateral device. Generally speaking, the greater the spacing, the deeper the probe investigates into the formations beyond the zone invaded by drilling mud. For the normal devices the depth of investigation is estimated to be twice the spacing and for the lateral probe it is approximately the length of the spacing (Birdwell, 1964). Consequently, the apparent resistivity recorded by the lateral measurement more nearly represents the true *in situ* resistivity of the formation. Resistivity values at GT-2 recorded by the lateral probe vary from about 10 ohm-m to well over 1000 ohm-m in the volcanic-sedimentary section and average nearly 1 1000 ohm-m in the Precambrian. The high resistivity in the volcanic section corresponds to dry Paliza Canyon Tuff above the water table. It is unfortunate that no provisions were made to measure resistivity values above 1000 ohm-m where the recordings went off scale. Apparent resistivities above 1000 ohm-m were "seen" by the lateral device in both the volcanic section (described above) and in the Precambrian. Zones where appreciable water was encountered, e.g. at about 3230 ft (948 m) depth in the Precambrian, are clearly seen on the resistivity records as abrupt decreases to below 100 ohm-m in the apparent resistivity values.

A new device, the borehole televiewer (BHTV) or seisviewer, has been used in both GT-1 and GT-2 to inspect boreholes and evaluate formations. The system was originally developed by Mobil Oil Company (Zemanek and others, 1969) and logs a continuous acoustic picture of the borehole wall as if the hole were split vertically at local magnetic north and laid flat (Fig. 7). Pulses of about 2 MHz frequency are directed toward the borehole wall at a rate of 2,000 pulses/second as the tool rotates and moves vertically. This motion results in a spiral strip of borehole wall being probed; the movement is such that nearly the entire wall is scanned. Bac4<scattered energy is measured and recorded on the surface as a photograph of an intensity modulated oscilloscope trace as in Figure 7. A fluxgate magnetometer in the device starts each sweep in the local magnetic north direction. In general, a smooth borehole reflects better than a rough one, a surface perpendicular to the transducer reflects better than tilted facets, and other phys'cal-acoustic properties may be important. When discontinuities such as fractures, drilling irregularities, or chips are scanned, the amplitude (recorded by light intensity) decreases and the record images the discontinuity as a dark section. A vertical fracture appears as two vertical lines and a dipping fracture shows up as a single cycle sinusoid as illustrated in Figure 7. The orientation of the sinusoid minimum is the direction of the dip of the fracture and dip angle is given by tan-1 h/d where h is the peak-to-peak value of the sinusoid and d is the hole diameter. The seisviewer has been particularly useful in GT-2 in defining the natural fracture patterns, and thus, the infered stress relations with depth. It is anticipated that it will aid in determining orientations of the hydraulically produced fractures.

SUMMARY

Geophysical studies in the Jemez Mountains of New Mexico are in a state of increased activity associated with the world's first hot, dry-rock geothermal feasibility tests by LASL. LASL personnel have emplaced a regional seismic network in the vicinity and a local network is centered about the geothermal granite test hole, GT-2. The regional network has been in operation for less than one year and has measured several events associated with the Pajarito fault complex. A preliminary search for seismic signatures characteristic of a magma

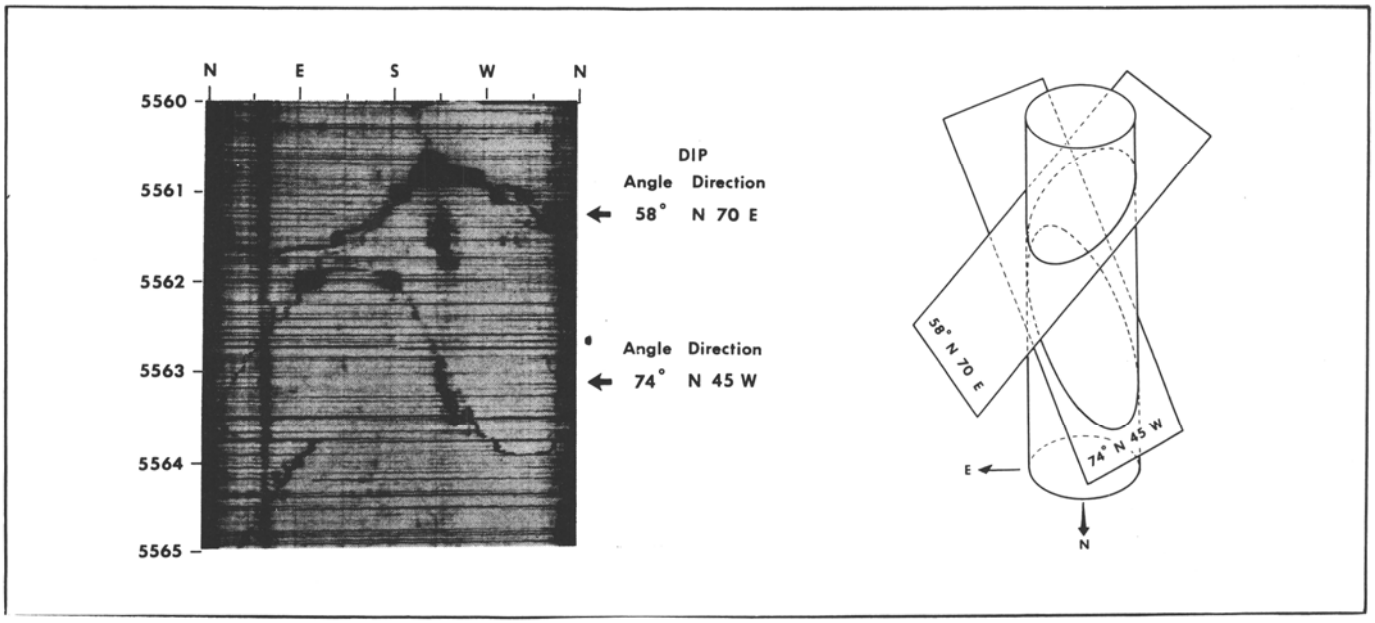

Figure 7. Isometric view of borehole intersected by two fractures of different dips and strikes with corresponding section of seisviewer log. (From Birdwell, 1969.)

chamber beneath the Valles Caldera have been negative. Heat flow measurements by NMIMT at LASL test holes have yielded values of roughly two to four times the world average of about 1.4 HFU. Radial distribution of the values suggests a source centered under the Valles Caldera. Several suites of geophysical borehole logs have been run at the GT-1 and GT-2 test holes and researchers from UNM are investigating the GT-2 site by deep resistivity soundings and profiles.

Prior to the renewed geophysical activity, seismicity reports dealing with the Jemez Mountains region have accumulated for more than a century and confirm the surprisingly low seismic activity in the area. The USGS has studied the Jemez Mountains area with gravity and aeromagnetic surveys. A pronounced gravity low over the Valles Caldera may indicate a solid or semimolten intrusive at depth. Magnetic patterns and anomalies may be significantly affected by reversed remanent magnetism of some of the volcanic units. Reversed units include the Bandelier Tuff which covers Redondo Dome and forms many plateaus of the Jemez Mountains.

The Jemez Mountains will continue to be the object of extensive geophysical studies which will relate, particularly, to the geothermal potential of the region and the relationship of the volcanism to the Rio Grande rift. Although considerable geophysical data is accumulating, it is too early to interpret the combined results. Many basic questions, such as whether or not a molten magma chamber exists beneath the Valles Caldera, are still unanswered. It is hoped that there will be a free exchange of data between all researchers in the Jemez Mountains; ultimate understanding of the area can only be accomplished by integrating *all* geological, geochemical, and geophysical studies.

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