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Seismic Reflection Surveys Near LASL Geothermal Site

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SEISMIC REFLECTION SURVEYS NEAR LASL GEOTHERMAL SITE

by

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ABSTRACT

Data and interpretations are presented for a seismic reflection survey in the Barley Canyon area of the Jemez Mountains, Sandoval County, New Mexico, on the north side of the Los Alamos Scientific Laboratory Hot Dry Rock Project, Fenton Hill Site.

Some results of an earlier (1974) seismic reflection of the south portion of the Hot Dry Rock Project area are included. Possible correlations of geologic structure between the two surveys are indicated.

I. INTRODUCTION

During September 1976, a shallow seismic reflection survey was carried out in the Barley Canyon area of the Jemez Mountains, Sandoval County, New Mexico, on the north side of the Los Alamos Scientific Laboratory (LASL) Hot Dry Rock Project Fenton Hill Site. The purpose of the study was to obtain information on the geologic structure of the area, especially with regard to major fault or fracture systems at the depth of the top of Precambrian rocks (600 to 700 m).

Some results of an earlier seismic reflection survey of the south portion of the Hot Dry Rock Project area are included.[1] Possible correlations of geologic structure between the two surveys are shown.

The Fenton Hill Site is 3 km (2 miles) west of the ring fault zone associated with the Valles Caldera in the Jemez Mountains of northern New Mexico. Site location is in the NE 1/4, Sec 13, T19N, R2E NMPM. Land-surface elevation is 2648.7 m (8690 ft). Geothermal well GT-2 was drilled to a depth of 2932 m (9619 ft) and EE-1 was drilled to a depth of 3064 m (10 053 ft) using drilling procedures and equipment typical of hard-rock drilling. Details of the drilling project are summarized by Pettitt.[2,3]

II. GEOLOGY

Faults associated with the Rio Grande rift valley are thought to be the locus of former volcanic activity in the area.[4] One group of faults, the Jemez Springs fault zone, is about 5 km (3.1 miles) southeast of the site. The Jemez-Nacimiento Mountains area has been structurally active to varying degrees since Precambrian time. Structural activity after the last eruption from the Valles Caldera is evident along the Jemez Springs fault zone, the closest known fault being the Virgin Canyon fault.[5] Drilling information and geophysical logs suggest that fracture zones with unknown displacement were encountered in GT-2.[6]

GT-2 penetrated 137 m (449 ft) of volcanics, 238 m (780 ft) of Permian red beds and 355 m (1165 ft) of Pennsylvanian-Mississippian shales and limestones, before encountering granitic gneisses at 732 m (2402 ft).[7] The crystalline Precambrian rocks include granitic gneisses, granodiorite, monzogranite, biotite schist, and amphibolite. The textures range from fine- to coarse-grained and the colors from pink to black.[6]

III. REFLECTION SEISMIC SURVEY

A reconnaissance reflection seismic survey was done during September 1976 to delineate subsurface geologic features in the vicinity of GT-2 and EE-1. Three geophone lines were designed to give reflection data over regions of geologic interest, with a total of 19 000 m of data developed as shown on the location map, Fig. 1.

Field work and interpretation on this Barley Canyon survey were done by Charles B. Reynolds and Associates of Albuquerque, New Mexico.

After the three lines were proposed, they were scouted for feasibility. At that time it was intended that the easternmost line (JS-3) be recorded along the San Antonio Creek road, on the east side of San Antonio Canyon. Unfortunately, when the crew was ready to record this line, heavy rains had made the road, which is graded but not gravelled, extremely muddy and impassable. The line was moved to the next road west (high on the west side of the canyon) and recorded there. One day was also spent in trying unsuccessfully to tie the east-west line (JS-2) to Line JS-3, but steep bluffs, heavy timber and very wet conditions prevented this.

After the lines were scouted, recording began. Station locations along the lines were determined by chaining 50-m intervals with a surveyor's 50-m fiber-glass tape.

The seismic energy source used was a 150-kg shot-bag dropped a distance of 1 m. At some stations more than one drop was required; successive drops at the same station were summed in the field. The receiver system used was an array of six geophone cases spaced 4 m apart along a drag cable towed behind the weight-drop instrument truck. Each geophone case contained two 10-Hz digital-grade self-orienting geophones, and the output of all twelve geophones was summed (series) to produce a single signal. The receiver array thus had a theoretical length of 24 m. Distance from the weight impact point to the nearest (first) geophone was 4 m; the source to receiver array offset was thus 14 m.

The recording system was a Seaman Nuclear Corporation single-channel engineering-type seismograph with digital memory, modified to include frequency filters, programmed gain expansion, and a paper strip chart recorder. The filter passband used was 20 to 40 Hz. Recording was for 1 s after impact, with 4-ms sample interval.

For each recording an impact geophone to measure the time of impact of the weight was placed a few cm from the impact point by the weight-drop operator. The instrument operator then armed the seismograph, the weight was dropped, and the returns of seismic energy recorded for 1 s. The resulting seismic trace, displayed on a cathode ray tube, was examined by the instrument operator to decide whether one or more additional drops were needed. If so, the seismograph was re-armed, the weight dropped again, and the seismic returns from the successive drops added (vertically stacked) digitally. When the seismograph operator felt that enough drops had been recorded at that station, he made paper strip chart recordings of the summed seismic trace, cleared the seismograph, and prepared to move forward to the next station.

At the end of the field recording day, the day's results (i.e., the strip chart recordings) were assembled into variable area record sections. A copy of the record section for Line JS-2 is shown in Fig. 2. The traces are hung from a true-scale surface profile (impact or zero time at surface). The horizontal distance between adjacent traces is 25 m, and the vertical scale for the zero times is at the same scale. The vertical time scale is 0.050 s = 1 main unit on the chart.

IV. RESULTS

The resulting seismic data are judged to vary in quality both locally and vertically from good to poor and sometimes no-good. Overall quality is considered to be poor. (It is believed that the data quality in this area may be improved by the use of common depth point stacking. A comparative experiment using CDP in Barley Canyon is planned.)

Three principal reflecting horizons were recognized and an attempt made to trace them on the record section of each of the three lines (see Fig.

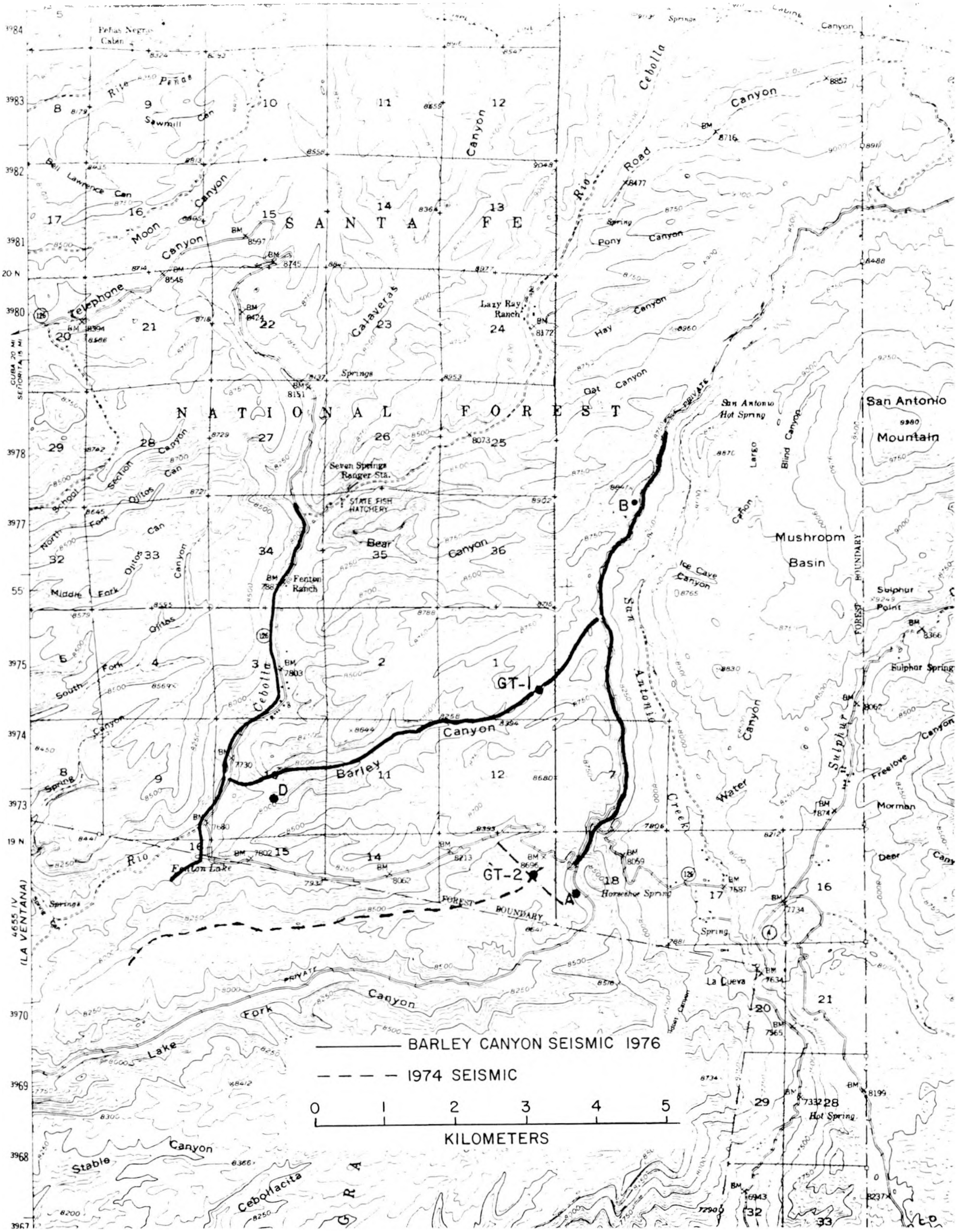


Fig. 1.
Location map-reflection seismic surveys.

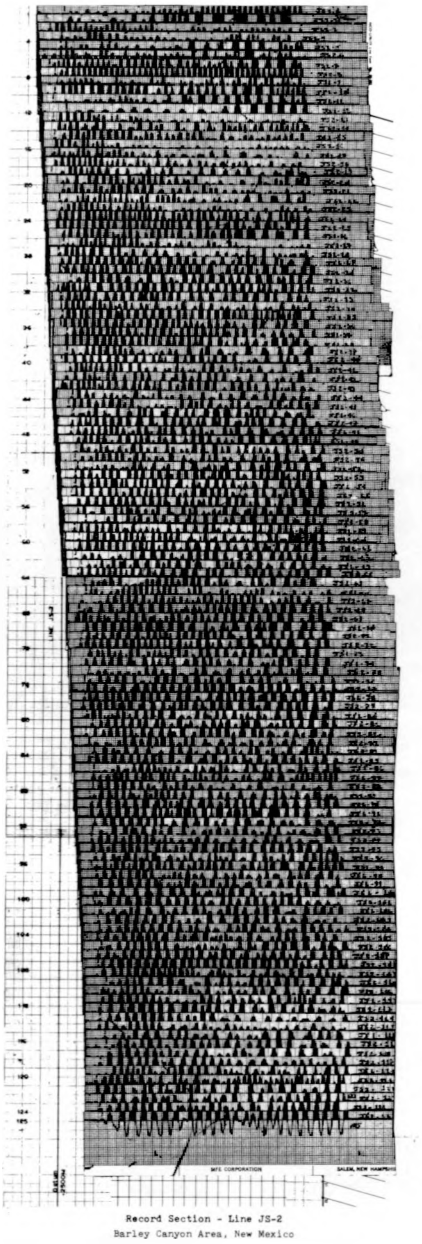


Fig. 2.
Station interval 50 m. Source 150 kg dropped weight. Receiver array 6 geophones spaced 4 m apart inline. Time scale 1 cm equals 0.050 second. Filter 20-40 Hz. Programmed gain. Data hung from time zero (surface).

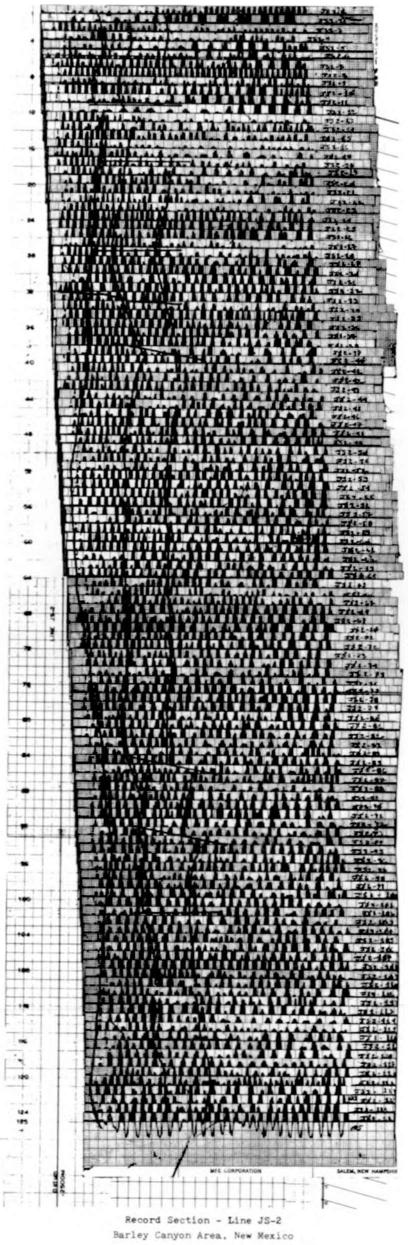


Fig. 3.
Station interval 50 m. Source 150 kg dropped weight. Receiver array 6 geophones spaced 4 m apart inline. Time scale 1 cm equals 0.050 second. Filter 20-40 Hz. Programmed gain. Data hung from time zero (surface).

3 which is an example for Line JS-2). The shallowest horizon is apparently a reflection from the base of the Cenozoic volcanics (or top of Paleozoic rocks). The next deeper seismic horizon or event is apparently a reflection from within the lower part of the Permian system, perhaps from the shallowest thick limestone unit, if such is present here. The deepest event which we tried to identify or follow on the record sections appears to be a reflector at or near the top of Precambrian basement rocks. All three reflectors appear to be at their best on Line JS-2, the Barley Canyon or roughly east-west line. This is fortunate in that it provides reasonably reliable reflection

identification at drill hole GT-1, which is near Station No. 25 on Line JS-2.

The direct seismic velocity information available in the area is a downhole velocity survey in the GT-2 drill hole. Because the shallowest geophone position in this survey was a short distance below the top of the Precambrian rocks, this survey gave only a total travel time from surface to below the top of the Precambrian. This time was corrected back to the top of Precambrian, using the velocity recorded in the shallowest interval measured in the Precambrian. The velocities through typical and similar Permian and Pennsylvanian rocks elsewhere in central and northern New Mexico were then examined on sonic logs from a number of wells drilled in petroleum exploration. The Pennsylvanian Magdalena group was found to be fairly constant in velocity from one well to another, at about 5000 m/s or somewhat faster. The overlying Permian Abo and Yeso formations were seen to have a velocity of about 4000 to 4500 m/s at the base, the velocity decreasing upward from there. The slowest Permian velocities are apparently found at the tops of the thickest Permian sections (assuming, of course, no evaporite content).

A sonic log from a well most nearly matching the experience of GT-1 and GT-2 in thickness, lithology, depth, and burial history of the Pennsylvanian and Permian strata was selected as a model for design of a velocity function. This model assumes that the bottom 350 m of the Permo-Pennsylvanian section is made up of the Magdalena group, with a vertical seismic velocity of 5200 m/s; and that above this 350 m the velocity decreases at the rate measured by the selected sonic log. The assumption is implicit that variations in thickness of the Permo-Pennsylvanian section are entirely the result of post-Permian, prevolcanics deformation and erosion at the top of the Permian. Because of the desire to keep the Magdalena group 350 m thick in the model, it was convenient to "invert" the velocity function, that is, treat it as if the Magdalena group was at the top of the interval, with the underlying Permian decreasing in velocity downward. This allowed a more convenient velocity treatment than the conventional approach. The resulting velocity function is:

$$V = 5200 \text{ m/s} \quad Z \leq 350 \text{ m}$$

and (1)

$$V = 6110 - 2.6Z \text{ m/s} \quad Z > 350 \text{ m},$$

where V is the average velocity through a thickness of Z m.

The velocity function designed for the Cenozoic volcanics was also based on sonic logs from similar lithologies elsewhere. In thick accumulations of Cenozoic volcanics of this general type in the western United States, it appears reasonably common that the highest velocities--in flows and welded tuffs--tend to be concentrated near the base and decrease upward. The occurrence of less dense tuffs and intercalated sediments increases upward. On the basis of sonic logs in such sections, plus shallow refraction surveys near Los Alamos, the following velocity function was designed for the volcanics.

$$V = 1300 - 5Z \text{ m/s} \quad Z < 160 \text{ m}$$

(2)

$$V = 500 \text{ m/s} \quad Z \geq 160 \text{ m},$$

where V is the average velocity through the volcanics and Z is the thickness of the volcanics. Again, to allow for the fact that variations in volcanic thickness occur mainly as a result of erosion at the top, this velocity function, like that for the Permo-Pennsylvanian section, is in an "inverted" form. This means that the fastest velocities near the base are always present and are the velocities used when the volcanics are very thin. Where the volcanics are thicker, the material added decreases in velocity with increasing thickness.

These two functions combined are called the GT-2 function and give a close fit to the total travel time observed in the velocity survey at GT-2, and a close fit to the base of volcanics and top of Precambrian at GT-1 (for the seismic events believed to represent those horizons).

In practice, the three selected events were converted from time to depth. First 0.015 s was subtracted from the reflection time after impact for each event to correct for instrumental delay. Next, the corrected reflection time for the base of volcanics event was converted to depth below surface using a time-thickness table computed from the velocity function designed for the volcanics, Eq. (2). The corrected reflection time for the base of volcanics event for each station was then subtracted from the corrected reflection time of the top of Precambrian event at the same station, to yield reflection time through the Permo-Pennsylvanian section. This travel time was then converted to thickness using a time-thickness table computed from a velocity function designed for the Permo-Pennsylvanian rocks, Eq. (1). The computed thickness of the volcanics for a given station plus the computed thickness for the Permo-Pennsylvanian strata at the same station thus gave the depth below surface for the top of Precambrian. The depth of the purple horizon (Lower Permian event) was determined by subtracting its corrected time from the corrected time for the top of Precambrian event, to give the travel time between the two events at that station. This difference time was then converted to thickness (between top of Precambrian and the Lower Permian reflector) using Eq. (1). Subtracting the resulting thickness from the depth of the top of Precambrian gave the depth to the Lower Permian reflector, preserving the Magdalena-at-bottom velocity distribution.

After depth to the three reflecting horizons had been computed as described above, migrated depth sections for the three seismic lines were constructed using the point arc method which is well suited to shallow seismic reflection. This method is shown in Fig. 4.

In the point-arc method of migration or depth conversion, a given seismic event is first selected (picked) and its time of arrival on each trace determined. In this example the event marked from Station 404 to Station 421, Fig. 4A, has been picked and timed. Next all these times are converted to depth using a known or assumed velocity (in this example V = 2000 m/s). A circular arc with radius equal to each computed depth is then drawn with its center at the corresponding station on the datum (Fig. 4B). Note that the horizontal and vertical scales on the depth section must be equal. Lastly, a curve is drawn tangent to the successive circles (Fig. 4C). This gives a good approximation of the form of the reflector. Where three or more arcs intersect in a point, as at the point marked on the curve of Fig. 4C, a diffraction or point reflection is suggested - possible fault evidence.

V. INTERPRETATION

For the Barley Canyon survey, two structure contour maps were made. These are illustrated in Figs. 5 and 6 and show contours on the base of volcanics reflector and the top of Precambrian reflector.

The map with contours on the reflector near the base of volcanics is Fig. 5. The contour interval is 25 m and elevations are in meters above sea level. Broadly, the map shows a surface dipping westward at an average of about 2.5 degrees. This surface is modified by three principal structural features. On the east there appears to be an arcuate horst, which probably represents part of the rim of the Valles Caldera. It is therefore presumably of late Tertiary or Pleistocene age. The GT-1, GT-2, and "A" drill holes are evidently located on this apparent ring horst. West of the horst the base of the volcanics is interpreted as being modified by a gentle, southwest-plunging anticline and syncline. Whether these two structures are of tectonic origin or simply represent topographic irregularities on the buried erosion surface on the top of the Permian beds is not clear. It is clear, however, that the base of volcanics is broadly synclinal between the Valles Caldera rim and the edge of the volcanics to the west. The seismic data show this well, but it was of course already demonstrated by GT-1 on the east (base of volcanics at +2535 m), drill hole "D" in the middle (base of volcanics at +2347 m), and an outcrop on the west (base of volcanics at about +2470 m in the canyon of Rio de Las Vacas).

Four faults are shown cutting the base of volcanics. Of these, three are associated with the rim horst on the east. The more easterly two of these three faults appear to show somewhat more

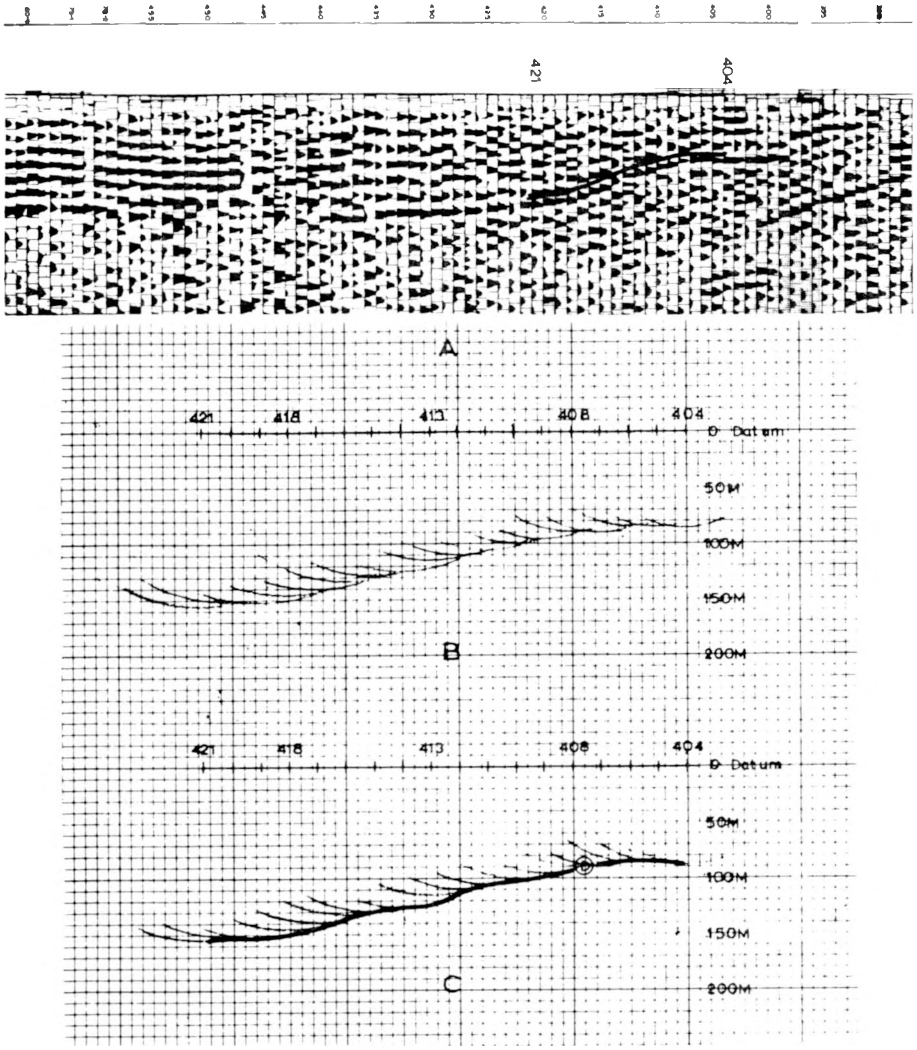


Fig. 4.
Point-Arc method of migration of shallow seismic reflection data.

throw at depth than at the base of volcanics, indicating that they may have begun movement before deposition of the first volcanics in this area. The most westerly of the three faults, however, (the one downthrown to the west) shows much more movement at deeper horizons than at the base of volcanics. It may thus have already been a major fault before the first deposition of volcanics here. The fourth seismic fault shown, in the northwestern part of the area, is clearly indicated by Line JS-1. It does not, however, appear to have a great amount of throw at base of volcanics. For that matter, neither do the other three faults just discussed. The strike directions shown for all four of these faults are based primarily on topographic evidence. The most easterly of the three faults affecting the horst, however, is exposed at the surface south of the map area.

A fourth fault, shown east of the area of seismic control, is a projection of a fault mapped at the surface by Smith, Bailey, and Ross.[8] It is shown here only to illustrate the probable <u>en echelon</u>, overlapping character of such faults forming the east or inner edge of the horst.

The map with structure contour on the reflector near the top of Precambrian (Fig. 6), like the base of volcanics map, shows an overall west dip (averaging about 5 degrees) much modified

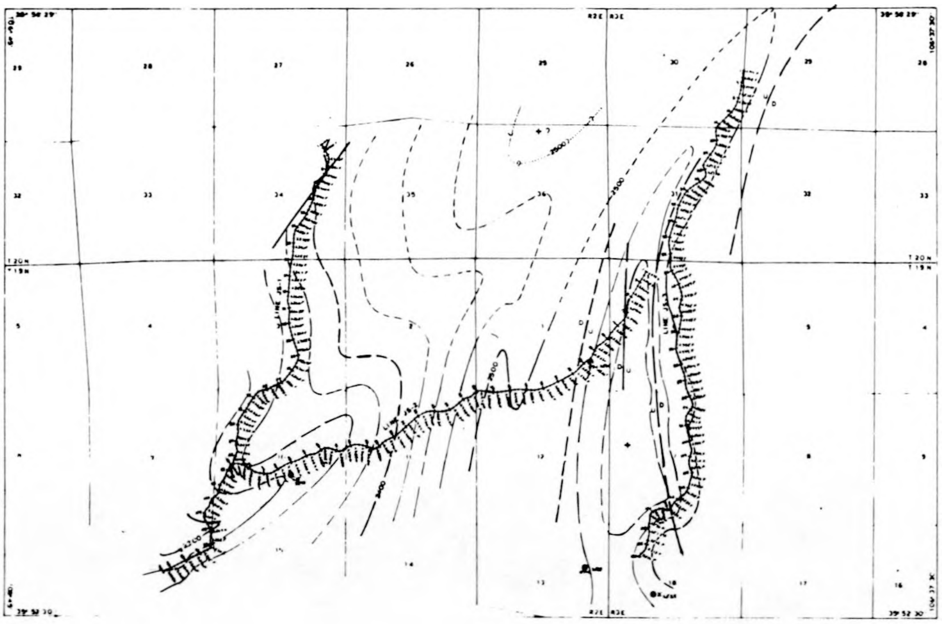


Fig. 5.
Contours on a seismic reflection near base of volcanics, Barley Canyon area.

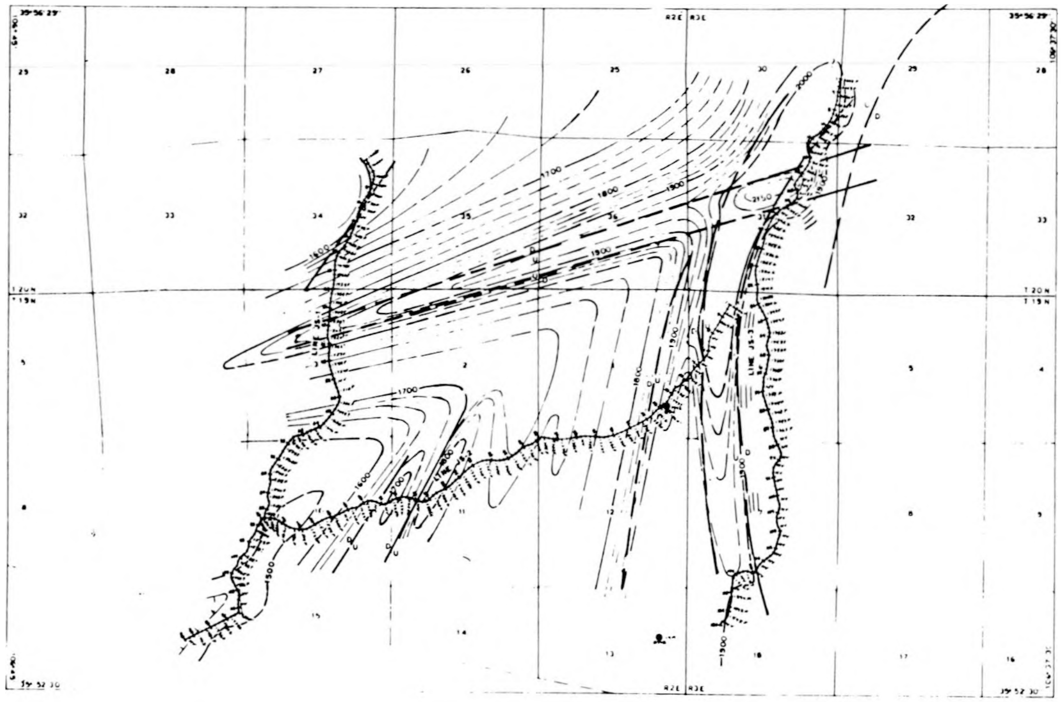


Fig. 6.
Contours on a seismic reflection near top of Precambrian Barley Canyon area.

by other structural features. The rim horst in the eastern part of the mapped area, discussed above, is apparently present at this depth also. It shows more structural relief at the top of Precambrian than at the top of volcanics, however, indicating that its development, though probably related to formation of the Valles Caldera, may have begun before deposition of the basal volcanics in this area. If this is so, rather than being simply part of the rim of the Valles Caldera, it may also have been related to the west side of the Rio Grande graben.

A second striking feature of this map (top Precambrian) is what appears to be a sharp, narrow structural high striking east-northeast across the northern part of the area. This feature could be a sharp anticline, but seems more likely to be a narrow horst block in a fault zone. It is here called the Bear Canyon high for convenience of reference. It is at least approximately coincident with a residual gravity maximum anomaly on Cordell's gravity map[9] (Fig. 7). The 15-minute quadrangle containing the geothermal site and seismic surveys is outlined on this map. There are also two other, more intense residual gravity maximum anomalies with a northeast trend, about 10 and 20 km south. Both these other gravity anomalies are coincident with known and mapped northeast-striking fault zones, probably at least in part, of prevolcanics age. It is suggested that the Bear Canyon high is a third member of that set. It is also interesting to note that if the trend of this feature as indicated by seismic and gravity evidence is extended to the west-southwest, it proves to be in line with a broad, faulted, northeast-plunging anticlinal nose with Precambrian exposed in its core.[8]

Indeed, in the canyon of the Rio de Las Vacas, the seismic and gravity trend encounters a small area of exposed Precambrian entirely surrounded by Pennsylvanian strata. Immediately east of this small Precambrian exposure (that is, on the east wall of the canyon) Permian beds are mapped as overlying the Pennsylvanian strata only a short distance above the Precambrian; if this is true and the relationships here are not complicated by faulting, the Pennsylvanian Magdalena group at this locality must be considerably thinned compared to its normal thickness. A similar apparent thinning is suggested by seismic lines JS-1 and JS-3. Consequently it appears possible that the Bear Canyon high is an extension buried by volcanics of an east-northeast striking faulted anticline or horst which may be of late Pennsylvanian or early Permian age. If this is true it is not surprising that there seems to be no expression of this feature at the base of volcanics. Field checking of this possibility in the Rio de Las Vacas and Ojitos Canyons might be helpful in evaluating the possibility of the Bear Canyon high.

The southwest-plunging syncline noted at the base of volcanics appears to be present at the top of Precambrian also, though not precisely coincident in position or perhaps in strike. Two faults, down to the northwest, are shown as affecting this syncline at the top of Precambrian. There also appear to be other faults cutting the top of Precambrian which are not shown, but only the faults regarded as best defined and of comparative importance are shown on the map.

VI. CONCLUSIONS FOR BARLEY CANYON SURVEY

A. The Barley Canyon area appears to lie on the east flank of a synclinal area between the Sierra Nacimiento to the west and the Valles Caldera to the east.

B. Other than gentle west dip, the principal structural feature at the base of the volcanics appears to be a north-south horst in the eastern part of the mapped area. This apparent horst may form part of the rim of the Valles Caldera, and may earlier have been related to the west side of the Rio Grande graben.

C. In addition to the north-south horst just mentioned, there is evidently a sharp, narrow faulted anticline or horst (Bear Canyon high) striking east-northeast across the northern part of the mapped area. This structure apparently involves only pre-Tertiary rocks and is suggested by seismic, gravity, and surface geologic evidence to be possibly of late Pennsylvanian or early Permian age.

D. The principal faulting zones in the mapped area indicated by this seismic survey are evidently

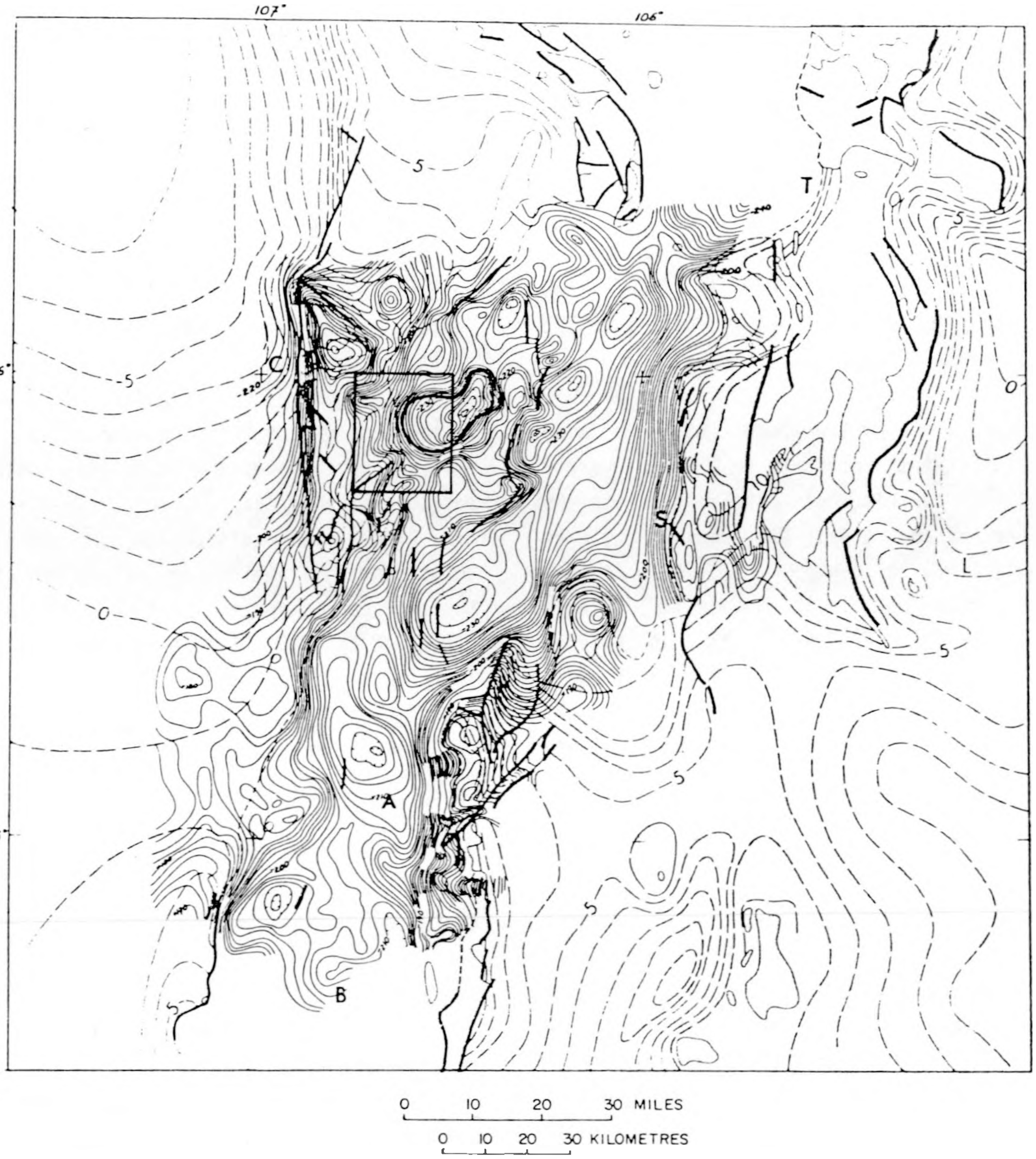


Fig. 7.
Preliminary complete Bouguer Anomaly gravity map of part of the Rio Grande graben in New Mexico contour. Interval is 2 mgals. Reduction density is 2.45 gm/cm^3.
From: Cordell, 1976.

related to the two uplifts (Bear Canyon high and rim horst) just mentioned.

VII. CORRELATION OF BARLEY CANYON SURVEY RESULTS WITH RESULTS OF 1974 SEISMIC SURVEY

Some results of the 1974 reflection survey on the south side of the geothermal site and possible correlations of the results of the 1974 survey follow. The dashed lines shown in Fig. 1 indicate sensor lines for the 1974 survey. Figure 8 shows locations of shot points and sensors for the 1974 survey and Fig. 9 gives depth sections with fault indications for sensor lines 2 and 3. Some of these faults were plotted in Fig. 10, a generalized geologic map of the geothermal site.

Faults indicated on depth sections shown for the 1974 survey in Fig. 9 and faults indicated by the Barley Canyon seismic survey in Fig. 6 are drawn on the map shown in Fig. 11 to give a

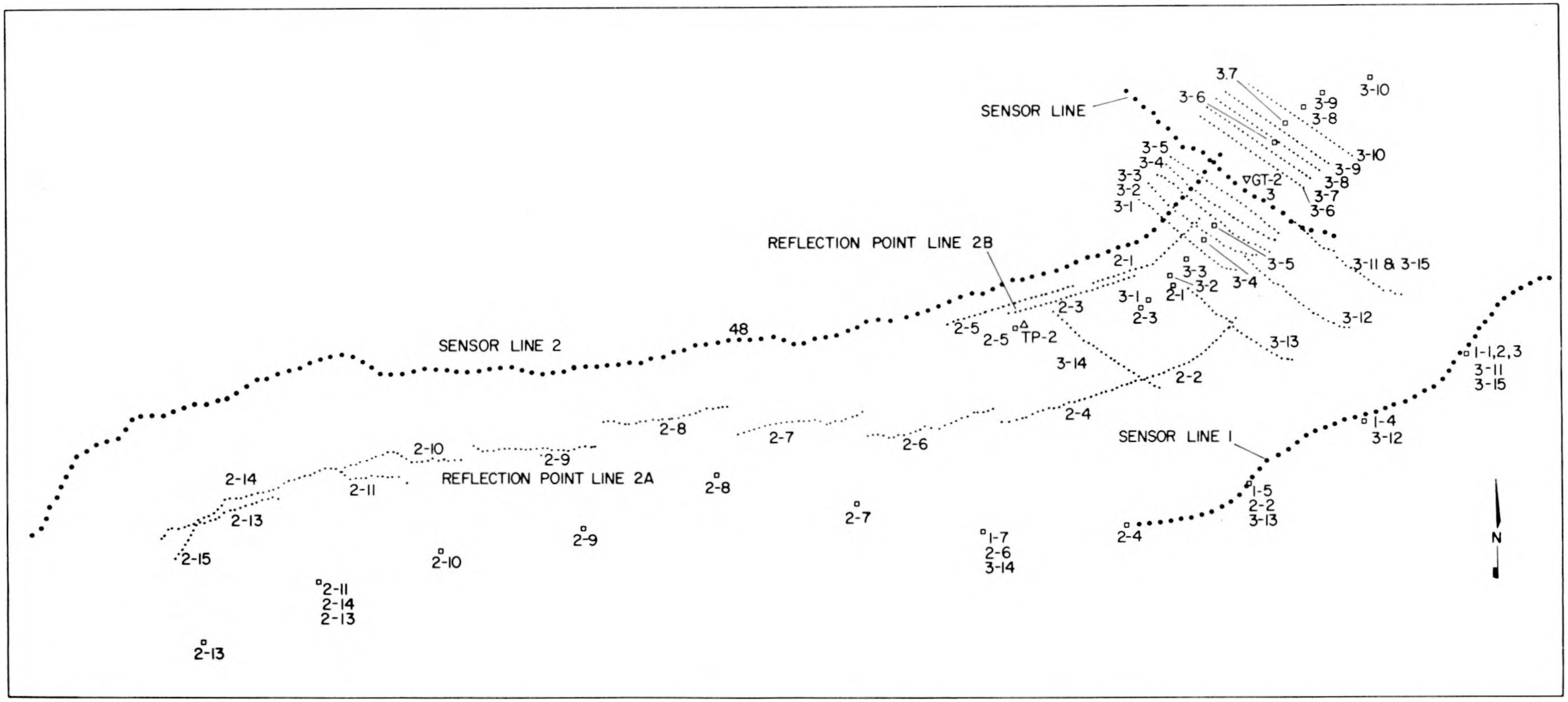
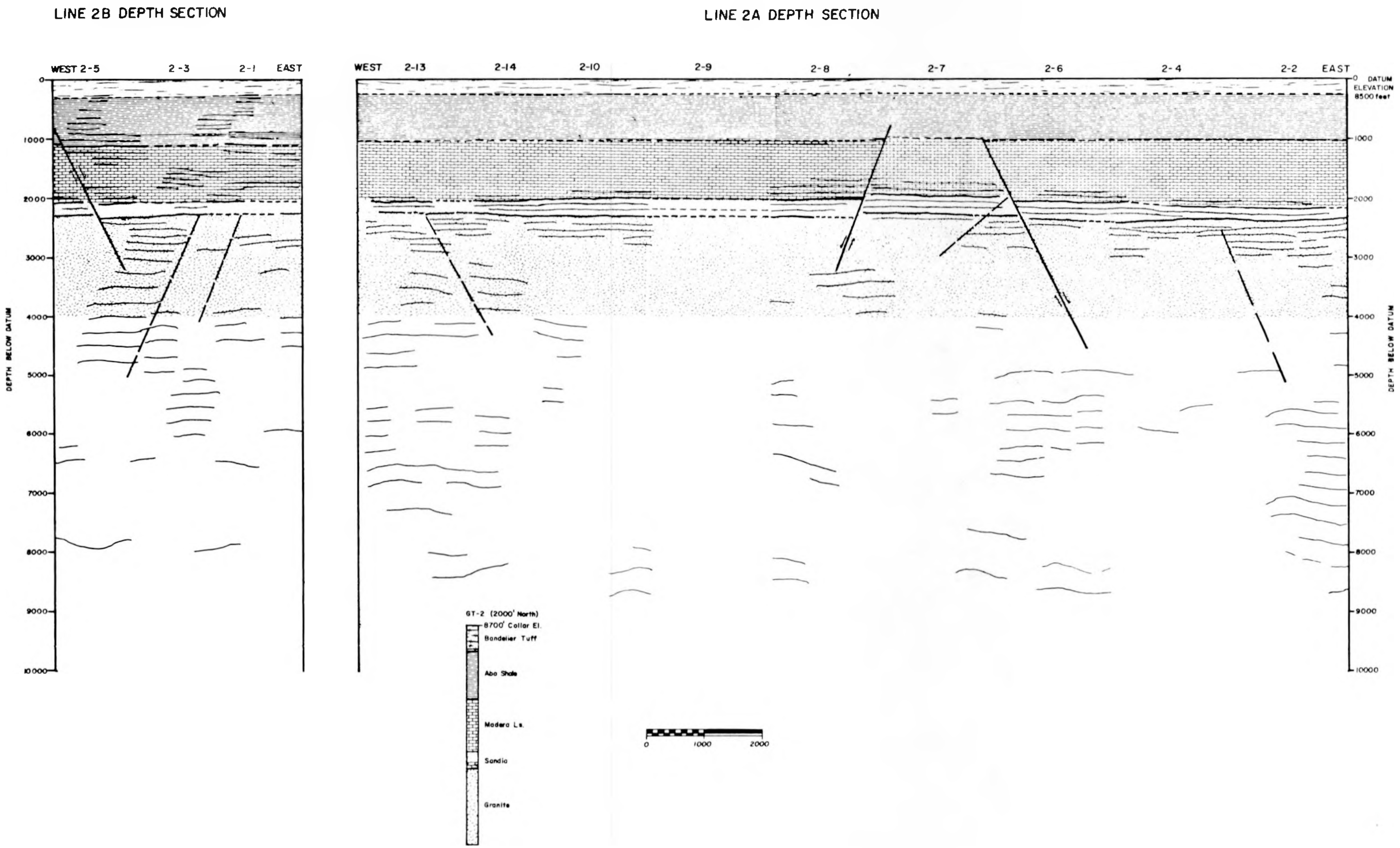


Fig. 8.
Seismic reflection lines, LASL geothermal site (scale: 1:32,000).
From: Kintzinger and West, 1976.



LINE 2B DEPTH SECTION

LINE 2A DEPTH SECTION

Fig. 9a.
Depth sections, Line 2 (ft). From: Kintzinger and West, 1976.

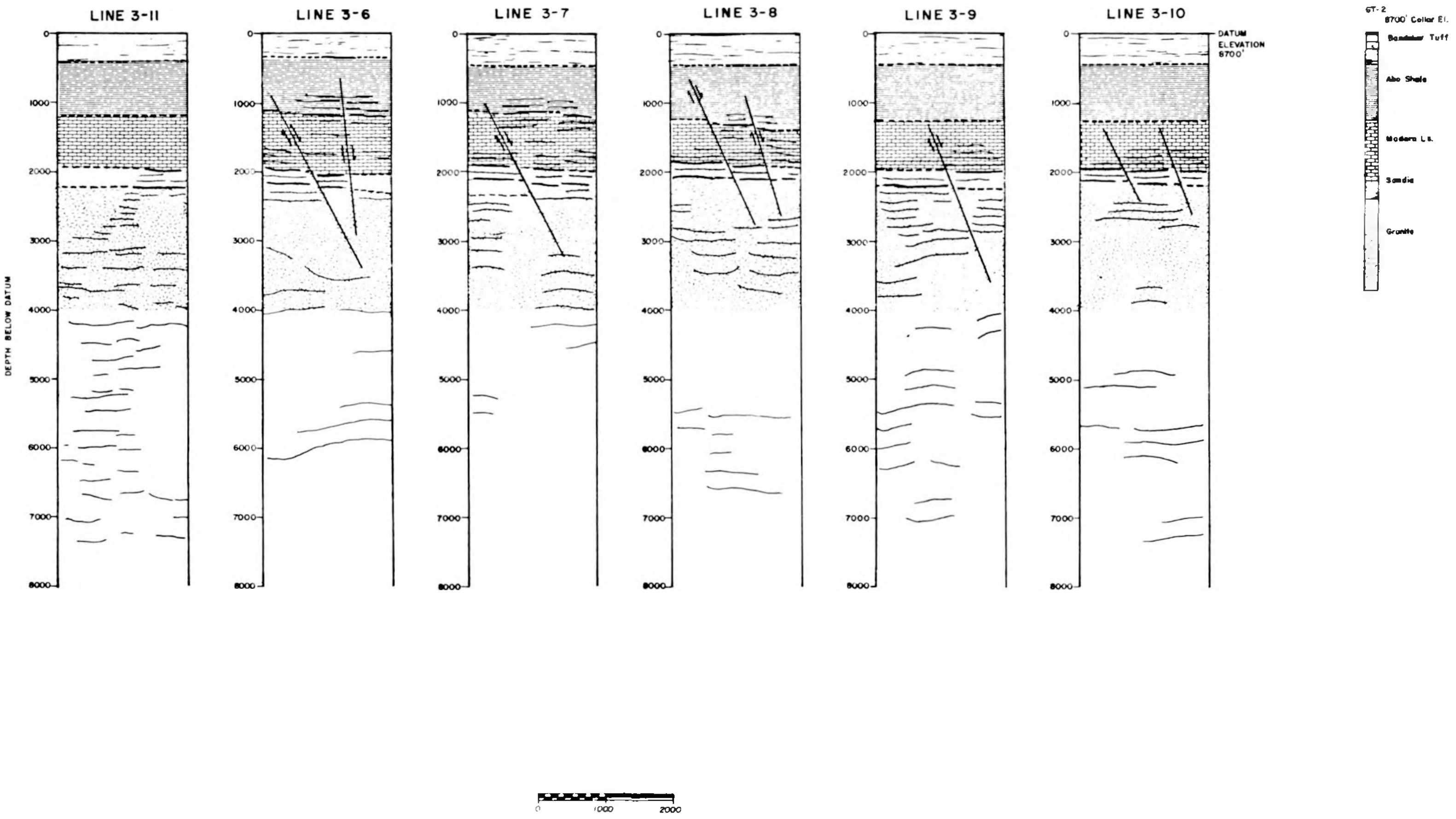


Fig. 9b.
Depth sections, Line 3 (ft), 1974 Survey. From: Kintzinger and West, 1976.

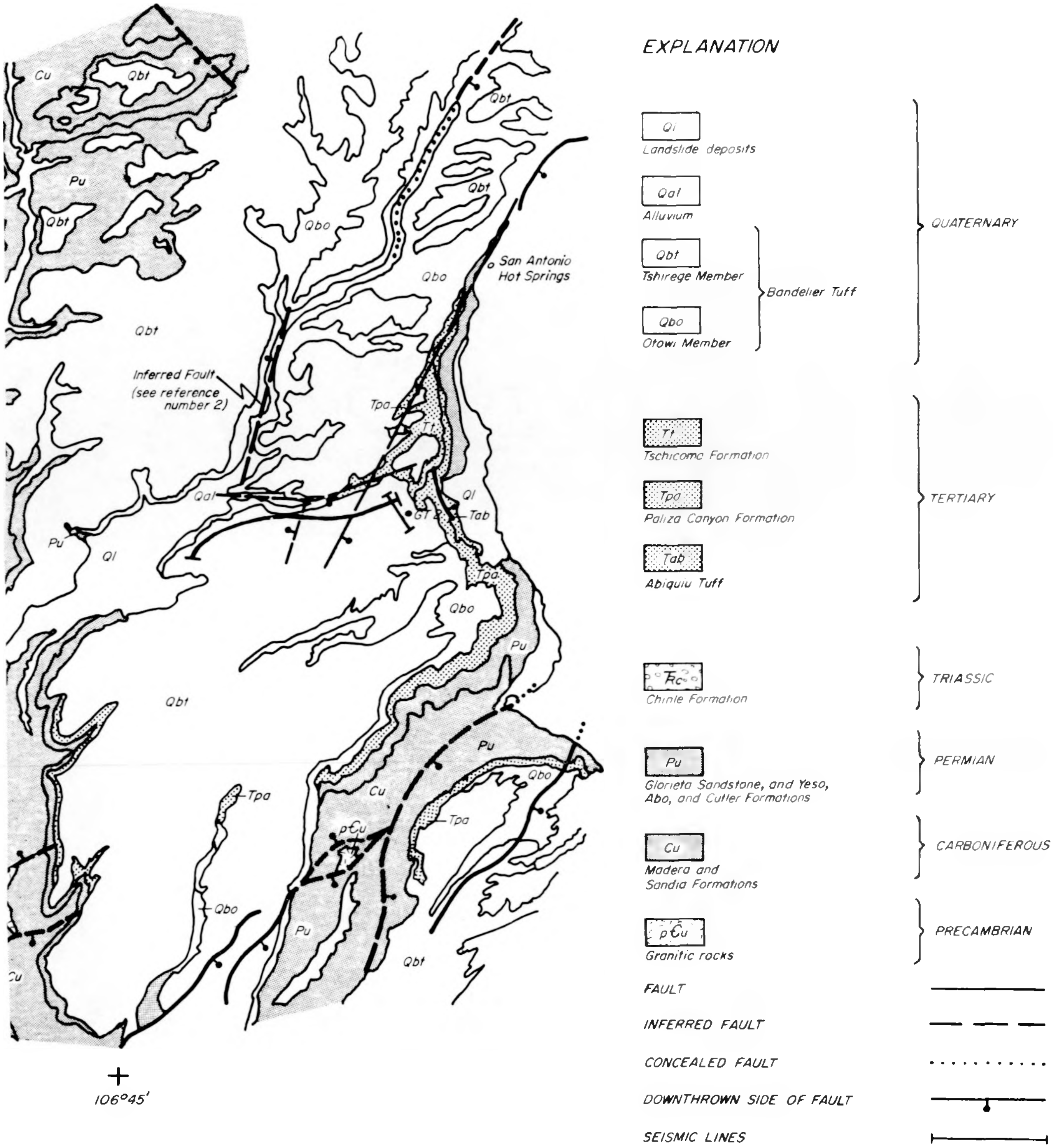


Fig. 10.
Generalized geologic map of LASL geothermal site (Scale: 1:166,667). From: Kintzinger and West, 1976.

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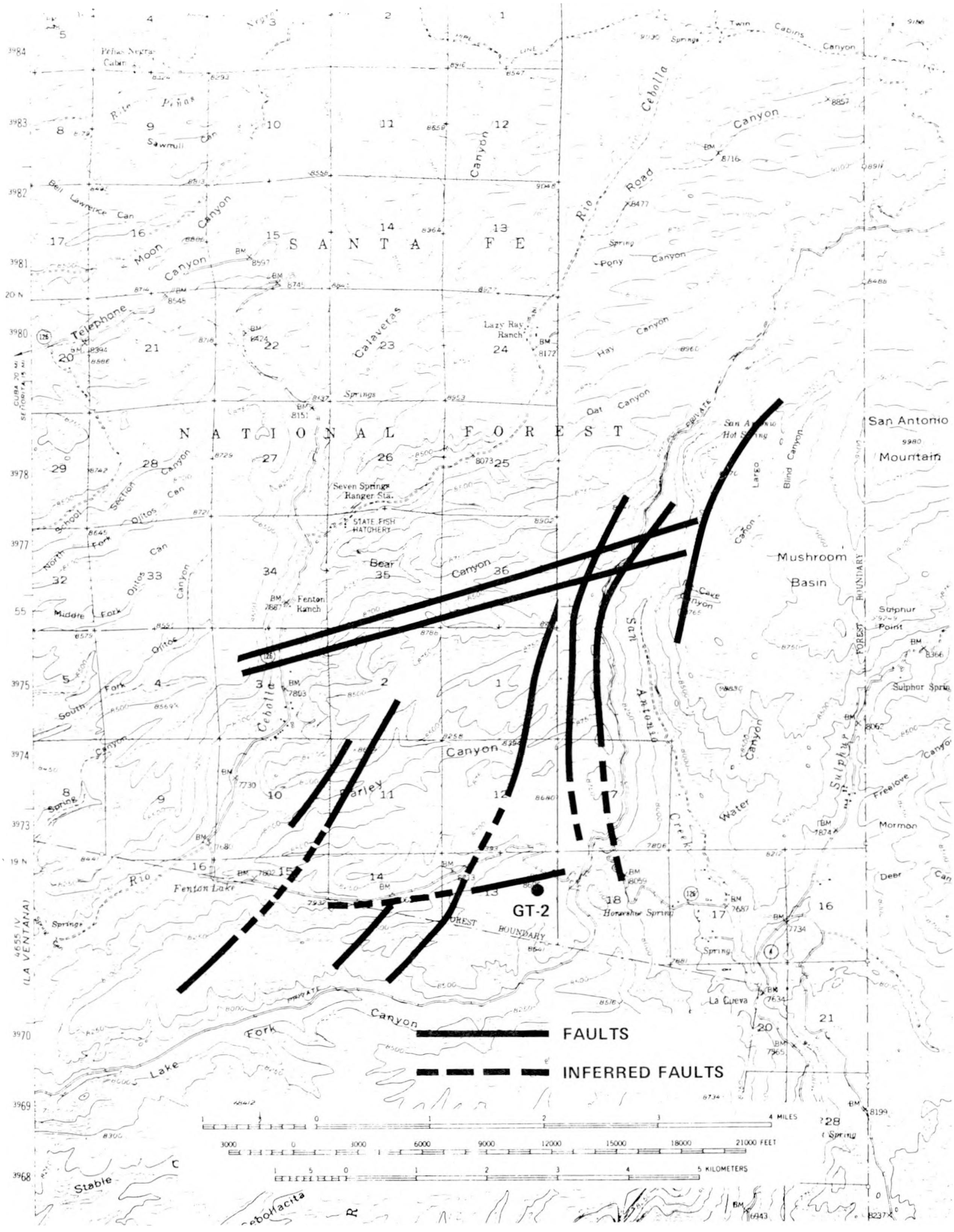

Fig. 11.
Structure map of the top of Precambrian near LASL geothermal project site.

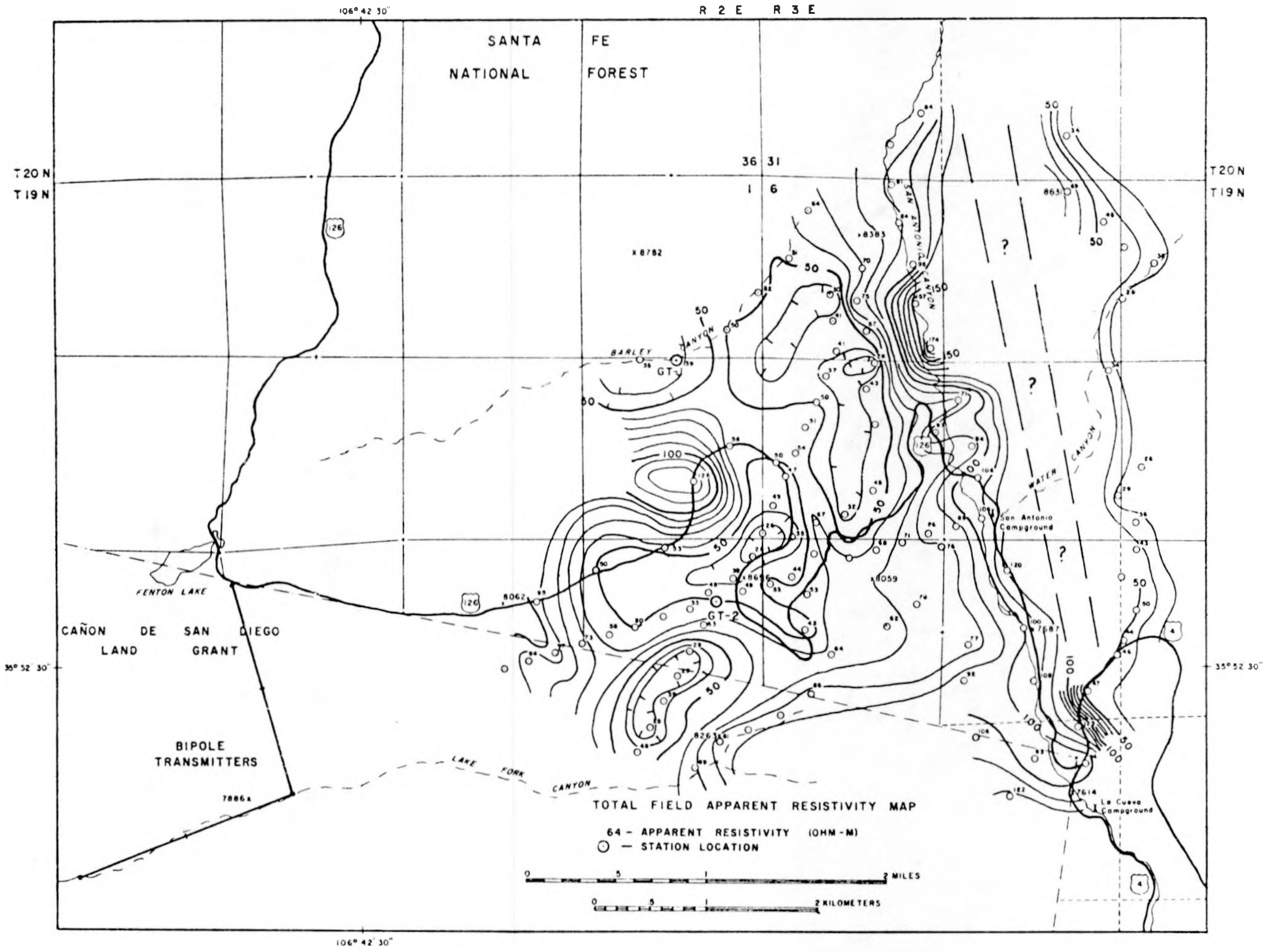

Fig. 12.
Total-field apparent resistivity map surrounding LASL GT-2 drill site.
(Mapped values pertain to more nearly east-west bipole transmitter.)
From: Jiracek, Smith, and Dorn, 1976.

Dry Rock Geothermal Project. It is interesting to note the northeast trend of the major fracture patterns in the geothermal project area.

Of interest is Jiracek, Smith, and Dorn's map of deep resistivities in the project area[10] (Fig. 12). This map indicates a north-easterly trend of resistivity lows through the geothermal project area. It is possible that the northeasterly trend of faults and deep resistivity values give an indication of a preferred northeast direction of fracturing in the crystalline basement. Also, of interest is the marked resistivity low at the east portion of the map. This is due to low resistivity values on the caldera side of the ring faults.

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