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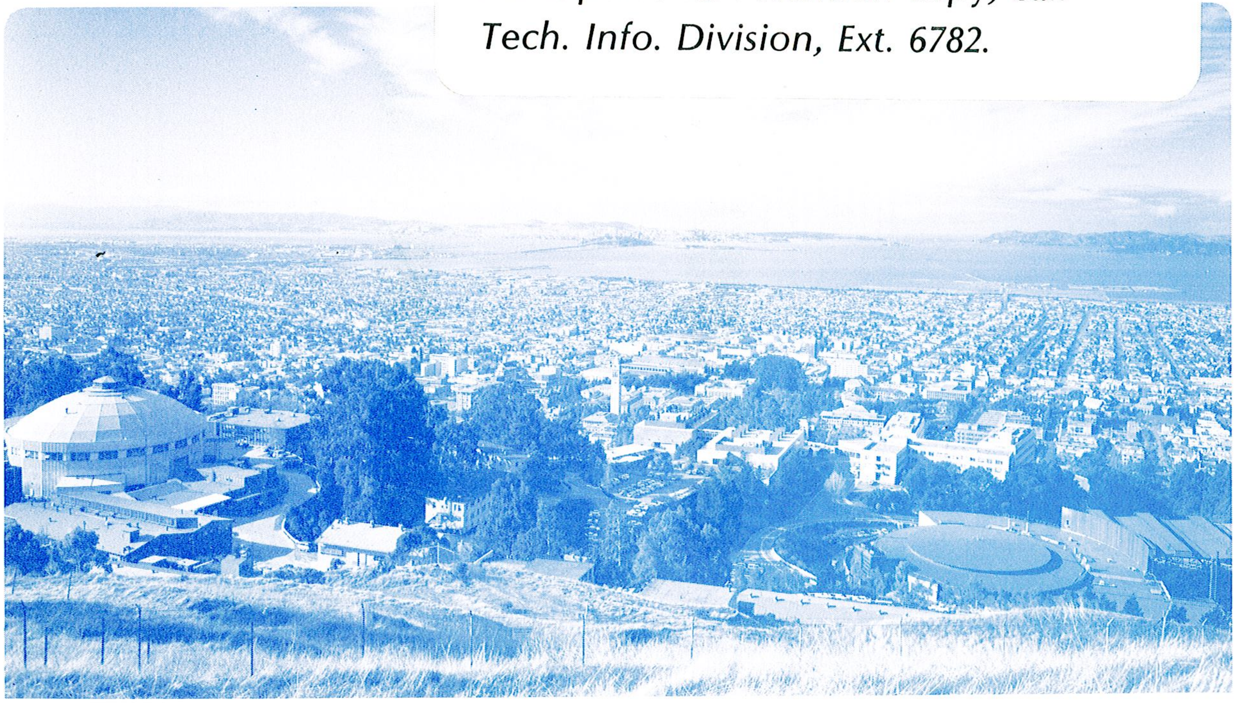

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ABSTRACT

The Baca location #1 geothermal field is located in north-central New Mexico within the western half of the Plio-Pleistocene Valles Caldera. Steam and hot water are produced primarily from the northeast-trending Redondo Creek graben, where downhole temperatures exceed 500°F. Stratigraphically the reservoir region can be described as a five-layer sequence that includes (1) caldera fill and the upper units of the Bandelier ash flow tuff, (2) the lower members of this tuff, which comprise the main reservoir rock at Baca, (3) the Pliocene Paliza Canyon volcanics, (4) Tertiary sands and Paleozoic sedimentary rocks, and (5) Precambrian granitic basement. Production is controlled by fractures and faults that are ultimately related to activity in the Rio Grande Rift system. Geophysically, the caldera is characterized by a gravity minimum and a resistivity low. A 40-mgal gravity minimum over the caldera is due mostly to the relatively low-density volcanics and sediments that fill the caldera and probably bears no relation to deep-seated magmatic sources. Two-dimensional gravity modeling indicates that the depth to Precambrian basement in Redondo Canyon is probably at least 3 km and may exceed 5 km in eastern parts of the caldera. Telluric and magnetotelluric surveys have shown that the reservoir region is associated with low resistivity and that a deep low-resistivity zone correlates well with the depth of the primary reservoir inferred from well data.

Telluric and magnetotelluric data have also identified possible fault zones in the eastern and western sections of the production region that may form boundaries to the Redondo Creek reservoir. These data also suggest that the reservoir region is located at the intersection of lineaments that trend north-south and northeast-southwest. Magnetotelluric results indicate deep low resistivity at the western edge of the caldera which may be associated with deep hot fluids. On the basis of geophysical and well data, we make three estimates of reservoir dimensions. The estimates of the aerial extent of the reservoir range from 10 to 30 km^2, depending on whether the Sulphur Creek or the Valle Seco area is considered as containing deep geothermal resources.

INTRODUCTION

In 1979, the U.S. Department of Energy (DOE) and Union Oil Company of California signed a cooperative agreement for the development of the Baca geothermal field in Valles Caldera, New Mexico (Figs. 1 and 2). The ultimate goal of the agreement is to demonstrate the feasibility of producing electrical power from geothermal reservoirs. In its capacity as technical advisor for DOE, Lawrence Berkeley Laboratory (LBL) is responsible for analyzing existing geotechnical and well test data for the purpose of resource evaluation and reservoir modeling at Baca (Bodvarsson et al., 1980). The purpose of this particular study is to analyze geological and geophysical data to estimate the size of the resource and describe the geological and geophysical characteristics of the reservoir and the surrounding region.

Adequate data are available for a reasonable evaluation of the Baca site. Geological data obtained within the Baca site include several reconnaissance and small-scale geological maps and a number of lithologic and temperature logs from boreholes (Union Oil, 1978). Regional geological mapping in the Jemez Mountains has been done by Smith et al. (1970). For comparison, borehole logs and core data are available from Los Alamos' Hot Dry Rock project at nearby Fenton Hill. Surface geophysical data include a reconnaissance gravity map, a series of regional and detailed geophysical surveys done for the Fenton Hill project, and a series of detailed electrical surveys within the Baca field. Other data include electrical and density logs from the Fenton Hill wells and geophysical logs from the Baca wells.

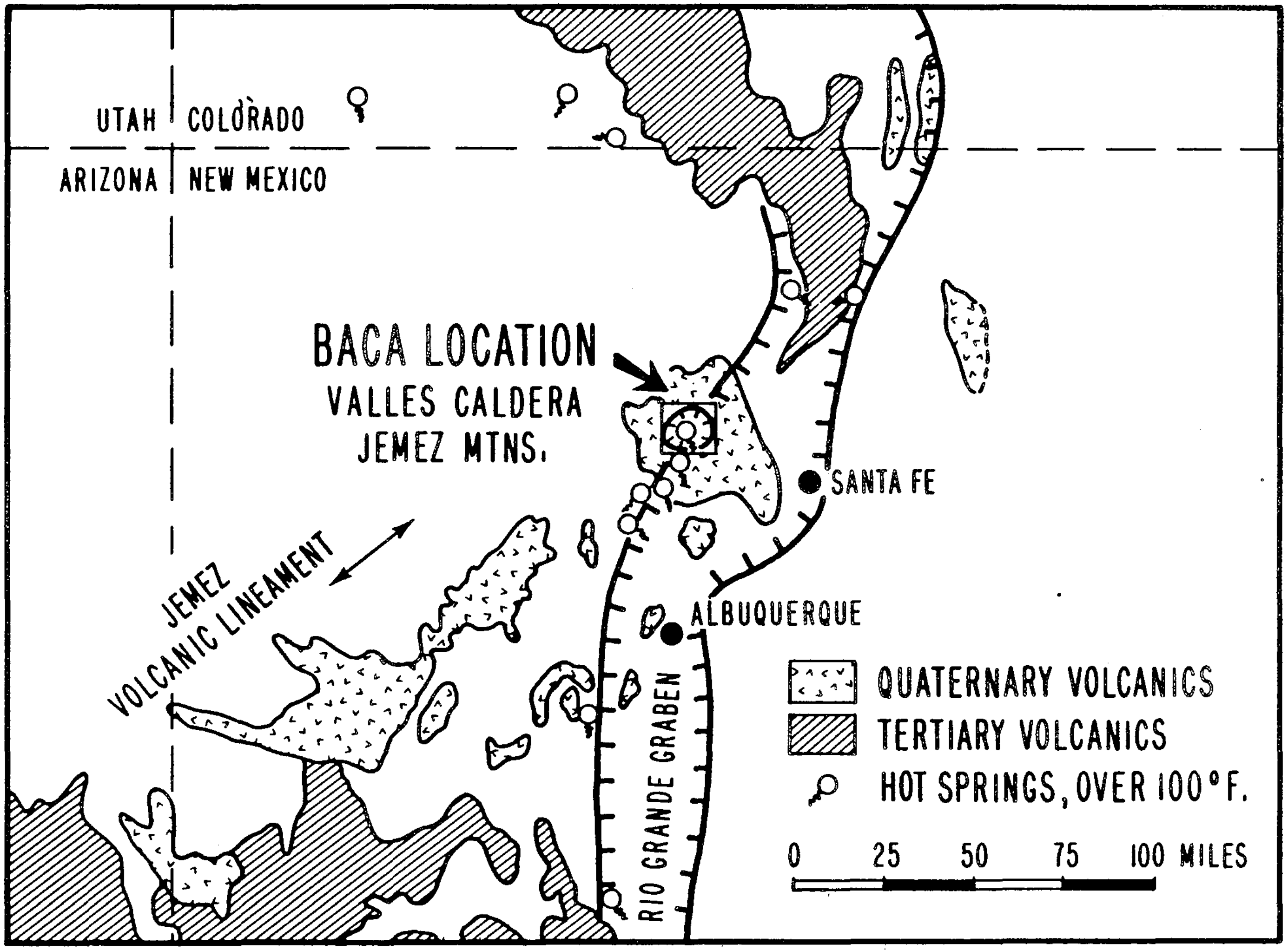

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Fig. 1. Regional location map for the Baca geothermal field, Jemez Mountains, New Mexico.

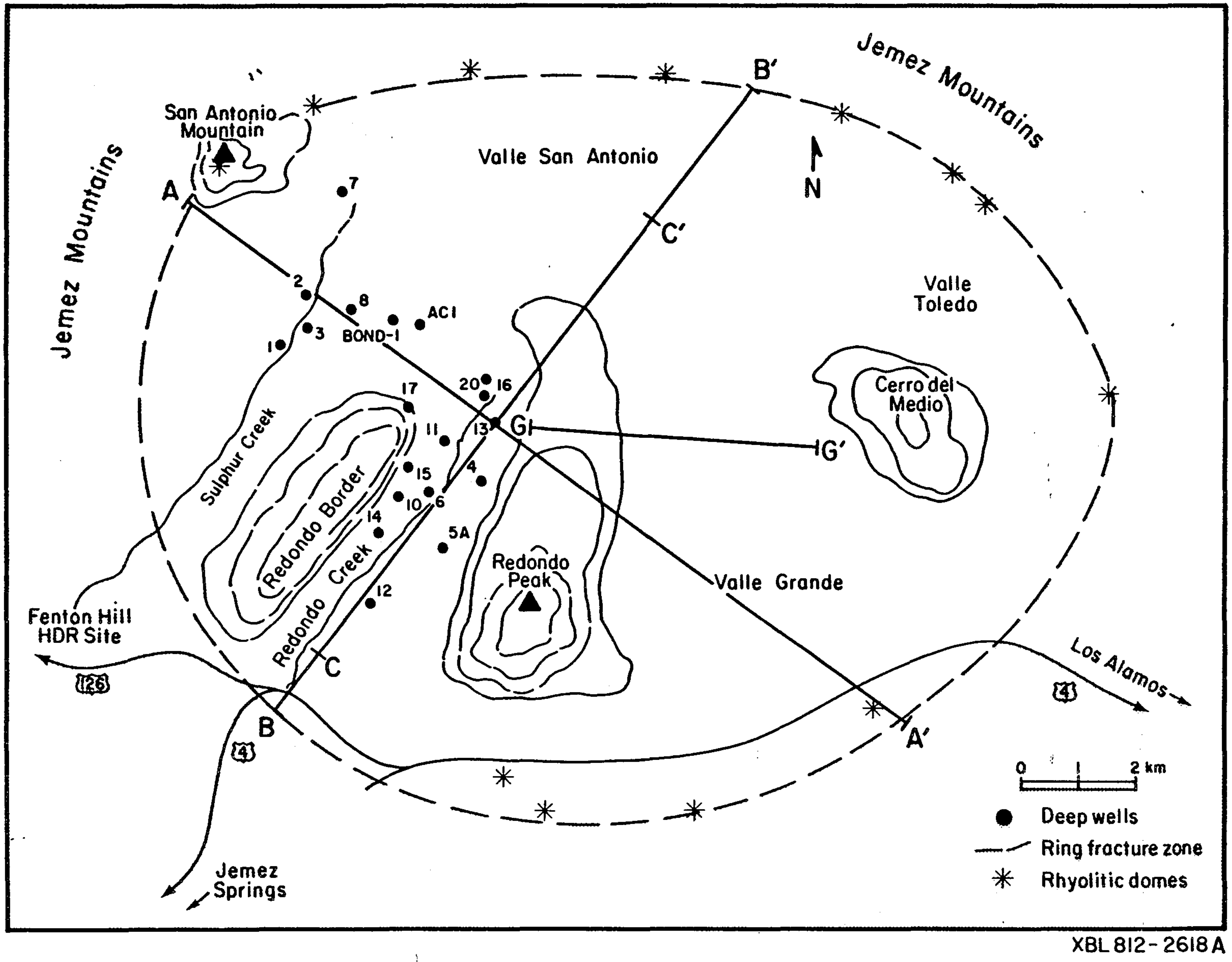


Fig. 2. Site location map for the Baca geological and geophysical study.

GEOLOGY

The Valles Caldera is situated at the intersection of two major geologic features: the north-trending Rio Grande Rift and the northeast-trending Jemez zone, an alignment of late Tertiary and Quaternary volcanic centers that extend from northern Arizona into Colorado (Fig. 1). Regional mapping was done by Bachman and Mehnert (1978), Kelley (1978), Goff and Kron (1980), and Golombek (1981). There has also been extensive mapping in the Jemez Mountains by Smith and Bailey (1966, 1968), Smith et al. (1970), Bailey and Smith (1978), and Smith (1979). The general relationship of the approximately 10-million-year-old Valles Caldera to other facets of the Rio Grande rifting, which began about 29 million years ago, can be found in the summaries by Chapin (1979) and by Eichelberger and Westrich (1980). The degree to which rifting influenced the formation of the Valles Caldera volcanics is an actively debated topic, as yet unresolved.

Two major rhyolite eruptions emanating from the center of the Jemez volcanic field are dated at 1.4 and 1.1 million years ago (Doell et al., 1968). Each event deposited more than 100 km^3 of material, which now comprises the lower and upper members of the Bandelier Tuff. Caldera collapse accompanied these eruptions, and resurgence followed. A prominent ring-fracture zone and rhyolitic lava domes also formed during these events (see Fig. 2).

Deep drilling in the western part of the caldera has encountered a geothermal system with downhole temperatures in excess of 550°F. The most productive geothermal wells are located in Redondo Canyon (Fig. 2); some of these wells exceed 9000 ft in depth (Dondanville, 1978; Union Oil, 1978; Atkinson, 1980). Production comes primarily from the lower member of the Bandelier Tuff and consists mainly of hot water, although zones of a water-steam mixture are reported (Dondanville, 1978; Bodvarsson et al., 1980; Grant, 1980).

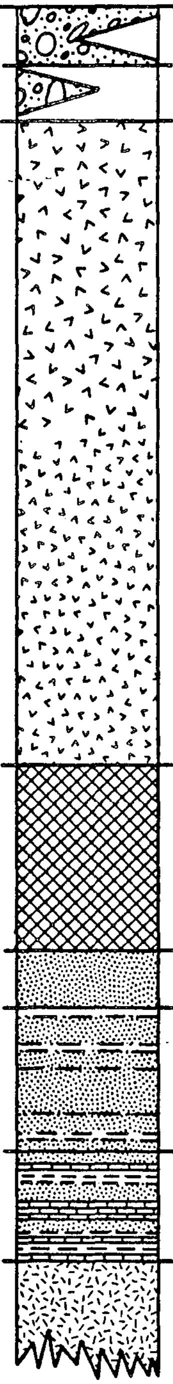
A detailed surface fault map of part of the western edge of the caldera has revealed the structural complexity of the area (Goff and Gardner, 1980). Mapping was done at a scale of 1:5000 in the Sulphur Creek area in the vicinity of unproductive yet very hot wells 1, 2, and 3 (Fig. 2). The detailed map reveals a 1.5-km-wide zone of intense, predominantly northeast-trending faulting extending from Sulphur Creek eastward.

Several hydrologic studies were done in the Jemez Mountains in an attempt to identify the source of the deep geothermal waters at Baca and to understand the deep and shallow groundwater flow patterns (Balleau, 1980; Mangold, personal communication, 1980). Because of the complexity of the system and the incomplete set of data, results are as yet inconclusive.

RESERVOIR GEOLOGY

Stratigraphy of the Baca area is well defined from borehole cuttings, as summarized in Fig. 3 and Table 1. We propose a five-layer model for the Baca reservoir: Layer 1 consists of caldera fill, the Redondo Creek Rhyolite, and the upper portion of the Bandelier Tuff down to a horizon where the temperature-depth curve becomes approximately isothermal. Layer 2, the lower segment of the Bandelier Tuff, is the major fracture-controlled reservoir as determined by Union Oil geologists. Layer 3, the Paliza Canyon volcanics, is a potential reservoir unit. Layer 4 includes the mixed Tertiary sands and older shales, sandstones, and limestones (this layer is probably a significant storage reservoir and may be a major production reservoir). Layer 5 is presumed to be the granite basement, but may also include highly metamorphosed sedimentary units.

LITHOLOGY



SECTION & MAP SYMBOL	DESCRIPTION	THICKNESS	AGE
Qcf	CALDERA FILL. Mainly landslide deposits. Coarse breccia, gravel and silt.	0 - 500′	QUATERNARY
Qvr	REDONDO CREEK RHYOLITE. Rhyolite flows, biotitic, amygdular.	0 - 500′	
Qb$_1$	BANDELIER TUFF. Welded to non-welded rhyolite ashflows and pumice.	4500′ - 6300′	QUATERNARY
Qb$_2$			
Tpa	PALIZA CANYON ANDESITE. Andesite, dacite flows and tuffs.	300′ - 2400′	PLIOCENE
Tu	TERTIARY SANDS, UNDIFFERENTIATED. Poorly consolidated, very fine sands, occasionally tuffaceous.	0′ - 500′	MIO-PLIOCINE
Pu	ABO FORMATION. Well consolidated, calcareous, fine red and purple arkosic sandstone and siltstone.	1600′+	PERMIAN
Cu	MAGDALENA GROUP. Gray to black limestone and shale and arkosic sandstone.	800′+	CARBONIFEROUS
p€	GRANITE. Dense microcline granite.		PRECAMBRIAN

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Fig. 3. Generalized lithologic log as defined from deep geothermal wells at Baca.

TABLE 1. Data for contour maps of Valles Caldera.

ELEVATION FT ASL*	WELL	°F AT 6200 FT ASL	FIRST 450° F FT ASL	°F AT 3000 FT ASL	DIFFERENCE IN °F 3000' TO 6200' ASL	BASE OF CAPROCK FT ASL	TD FT	TOP OF ANDESITE (Tp) FT ASL	TOP OF SEDIMENTARY UNITS (TU,PU,PC)FT ASL
9318	4	490	7350	590	100	7300	(6376)	3338	less than 2942
9290	5A	290	---	320 @ 3400'	30	7300	(6973)	2690	less than 2317
8726	6	440	5910	540 or more @ 4000'	100+	6500	(4810)	less than 3916	less than 3916
8724	7	390	5480	465 @ 3300'	75	6200	(5532)	NO Tp	5424
8631	8	480	6750	570 or more @ 4400'	90+	6300	(4384)	NO Tp	5531
8640	9	---	---	---	---	---	(5303)	---	---
8734	10	445	6080	520	75	5800	(6001)	3515	2805
9065	11	485	6200	570	85	6100	(6931)	3625	2500
8429	12	355	3820	470	115	6075	(9212)	1969	854
9292	13	460	6410	515	55	6300	(8228)	3580	1202
8605	14	320	3310	470	150	4900	(6824)	2805	2465
9117	15	490	6600	540 @ 3800'	50+	6520	(5505)	3900	less than 3612
9622	16	435	6090	570	135	6250	(7002)	4062	2742
8700	Bond 1	350 at 5820					(3675)		
8420	1	---		---			(2560)		
8480	2	415 at 6920					(4726)		
8420	3	390 at 6620					(2200)		

*ASL means "above sea level."

Detailed analyses suggest that this five-layer model could be further subdivided. For example, after analyzing well cuttings and cores, Union Oil geologists have subdivided the Bandelier Tuff into five separate units. Geophysical well logs also suggest that this five-layer section could be further subdivided. Density and conductivity variations are observed in all wells drilled within the Redondo Creek well field. These variations can be due to intersected fractures, temperature or mineral zonation, or lithologic changes. Although epidote, pyrite, and other hydrothermal minerals have been found in Baca wells, they have yet to be studied in sufficient detail to provide information on thermal history or rock-fluid interactions (Lambert and Epstein, 1980).

Detailed surface mapping in the Redondo Creek well field has revealed that faulting plays a major role in controlling fluid flow in Baca wells (Behrman and Knapp, 1980). High-angle north-northwest-trending normal faults were found to intersect all good producing wells at depths corresponding to the lower sections of the Bandelier Tuff. For wells that do not intersect such faults or that intersect them at a shallow depth, fluid production is much lower. Behrman and Knapp (1980) traced several of these high-angle faults throughout the Redondo Creek well field and have identified what they believe are the major graben faults in Redondo Canyon. The dominant trend of the faults was observed to change from north to northeast in the northern section of the well field. This shift may be significant for fluid production, since several productive wells are located in the region where the shift occurs.

To improve our understanding of the structural relationships of the layers within the Baca reservoir, we made several contour maps from downhole temperature and lithologic data (Figs. 4 and 5). Figures 4a and 4b show temperature contours at depths of 6200 and 3000 ft above sea level. Figure 4b indicates an area of 2 km^2 where temperatures exceed 550°F at the 3000-ft datum. The best production wells (11, 13, 15) are located in the eastern portion of this high-temperature zone. The steep decrease in temperature near well 5A suggests that this well is isolated from the others in the field either by faulting or by cold-water drainage off nearby Redondo Peak. Contours in Fig. 4c show the depths corresponding to the base of the low-permeability "cap rock" overlying the reservoir. These depths were chosen from the point on the temperature-depth curve at which the well becomes approximately isothermal. This cap rock may represent a region of self-sealing hydrothermal mineral precipitation within the Bandelier Tuff. Further analysis of cores and cuttings is necessary to establish the nature of this capping unit. Figure 4d is a contour map of the reservoir thickness; the upper boundary of the reservoir is defined as the base of the cap rock, and the lower boundary corresponds to the bottom of the Paliza Canyon volcanic series. This map suggests a progressive thickening of the reservoir to the southeast. This thickening may be the result of contemporaneous Redondo Creek graben faulting during the period of tuff emplacement. Alternatively, this thickening may be associated with tuff emplacement concurrent with the formation of the resurgent dome of Smith and Bailey (1968).

Figure 5 is a three-dimensional isometric projection of three prominent horizons at Baca. The figure shows that the reservoir has a slightly domal upper surface and a steeply dipping lower boundary. Note the absence of the Paliza volcanic unit in well 8. It is unclear whether there is some fault discontinuity between well 8 and the other wells or whether the volcanics merely pinch out. Two parallel cross sections through the geothermal

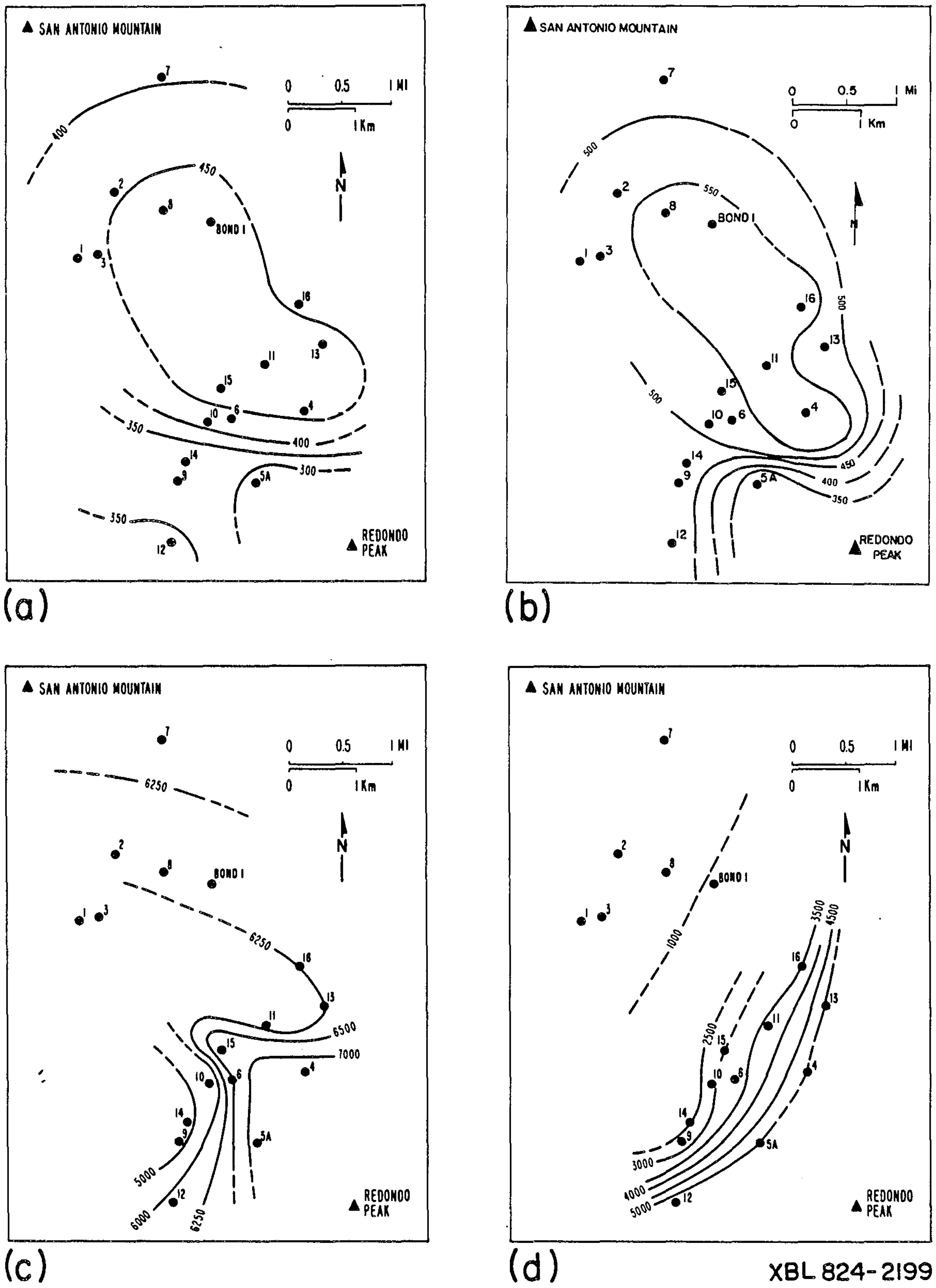

Fig. 4. Contours of temperature and stratigraphic horizons from deep wells. (a) Temperature °F at 6200 ft ASL. (b) Temperature °F at 3000 ft ASL. (c) Base of the cap rock (elevation ASL). (d) Thickness of the reservoir unit at Baca. The top is defined as the base of cap rock and the bottom as the base of the Paliza Canyon volcanics.

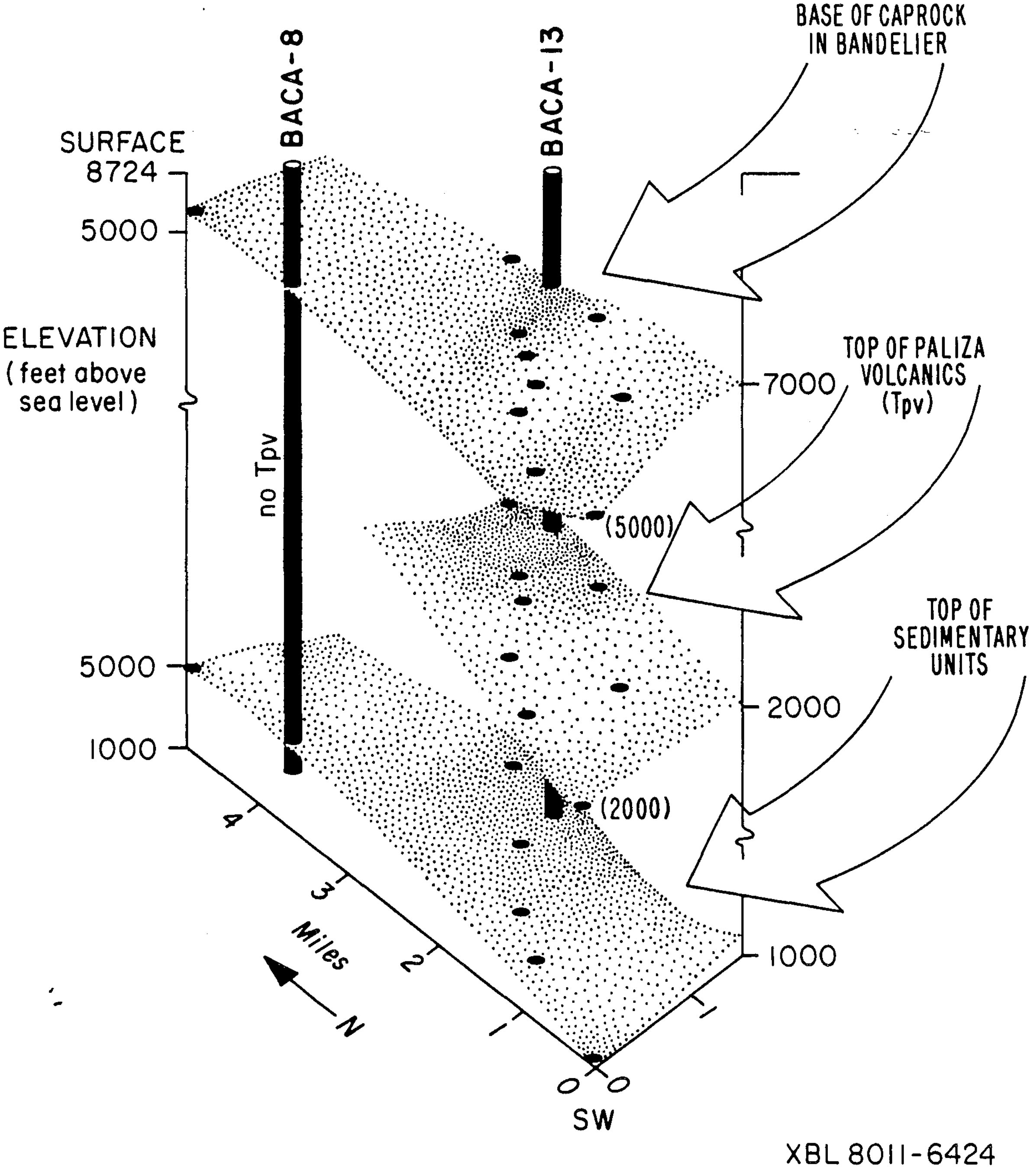

Fig. 5. Three-dimensional isometric projection of stratigraphic horizons within the reservoir.

reservoir (Fig. 6) suggest the presence of a steam zone and a steam cap. Note also the absence of this steam portion in productive well 13 and its poor development in well 11. Atkinson (1980) and Grant (1980) have suggested that the zones shown in Fig. 6 are perhaps best considered as two-phase zones.

GEOPHYSICS

Geophysical setting

The geophysical characteristics of Valles Caldera are distinctly anomalous by comparison with those of the surrounding Jemez Mountains. The caldera is a gravity minimum and a resistivity low. Natural seismic activity for the region is reportedly low (Jiracek et al., 1975; Dondanville, 1978). This is surprising, since the caldera lies within the seismically active Rio Grande Rift system, and high seismicity is associated with many geothermal systems.

A regional gravity map (Fig. 7) shows an elliptically shaped gravity minimum of 35-40 mgal centered over the caldera. The main reason for this minimum is that the great volume of Cenozoic volcanic and sedimentary rocks now filling the caldera is of lower density than the surrounding Paleozoic and Precambrian rocks in the Jemez Mountains. Earlier speculation that a deep-seated magma body was partly responsible for the low has largely been disproved by seismic evidence from distant earthquakes (Jiracek et al., 1975). Within the caldera, local gravity minima are observed in Valle Grande, near Valle Toledo, and in Redondo Canyon. Each of these regions is associated with intracaldera depressions, and a significant thickness of near-surface low-density alluvium is partly responsible for the low in Valle Grande.

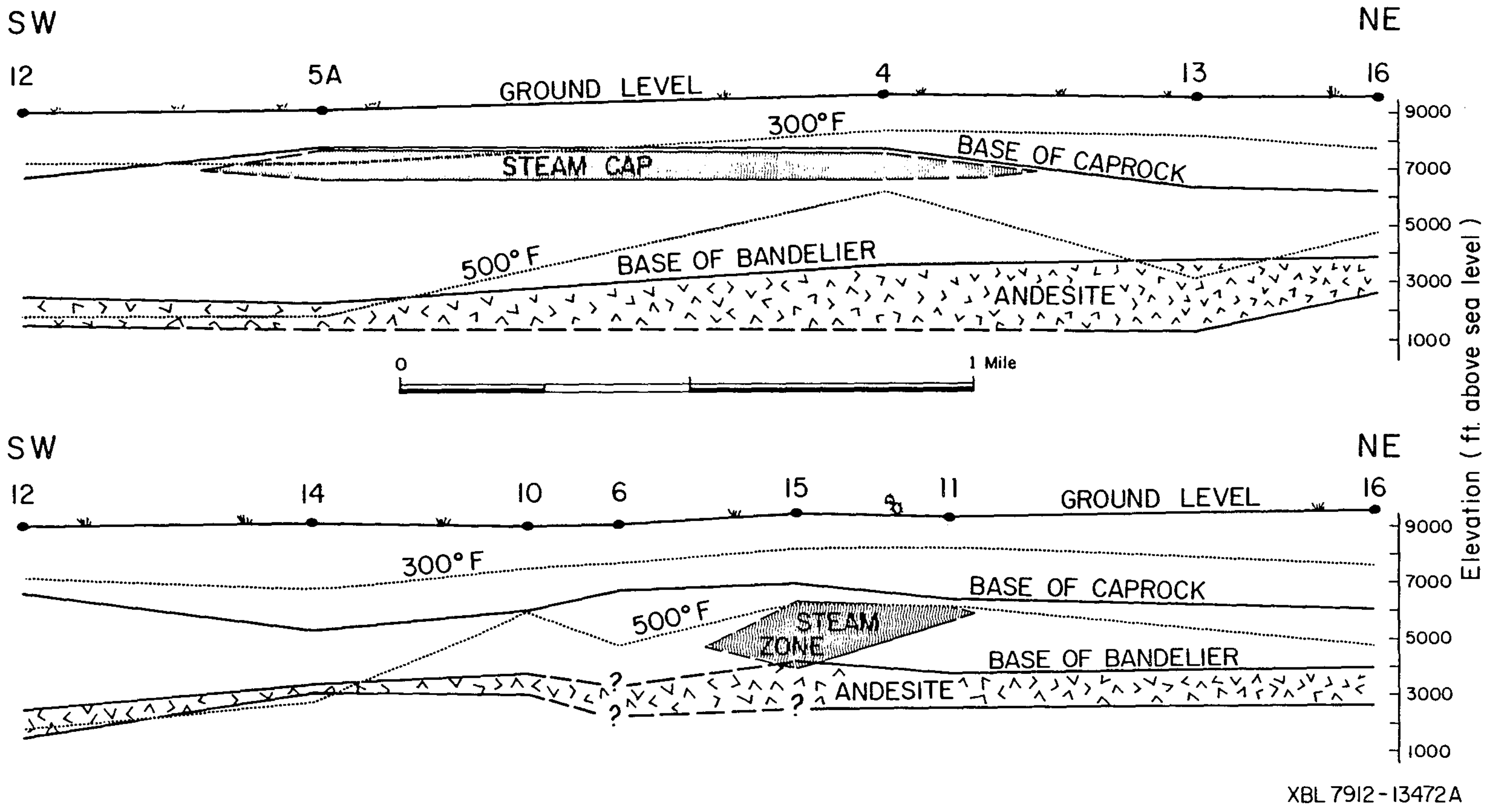

Fig. 6. Two-dimensional cross sections showing locations of steam zones found in deep wells at Baca.

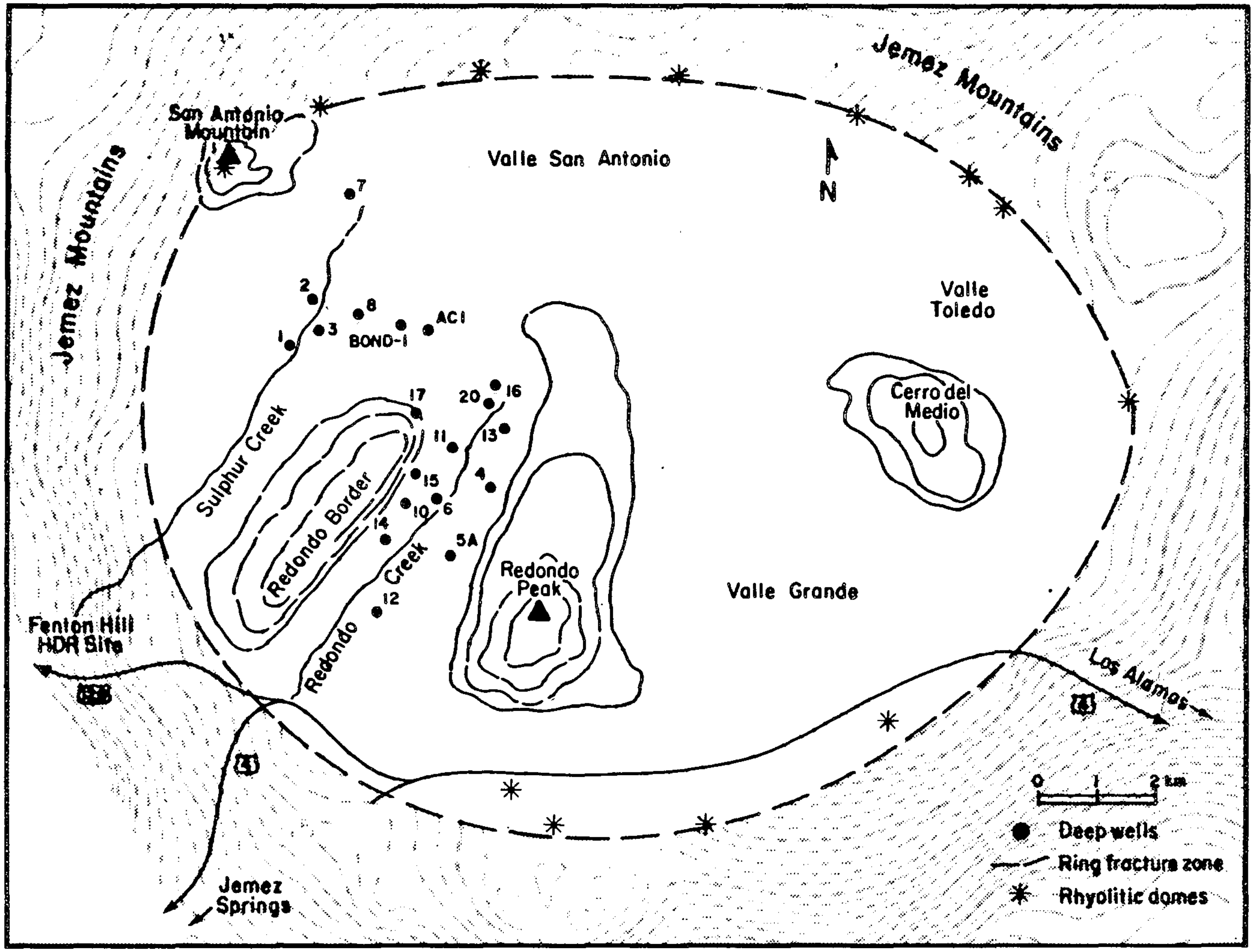

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Fig. 7. Regional gravity map for the Valles Caldera region; contour interval is 1 mgal.

Computer modeling of the observed gravity was done by Segar (1971). Segar modeled the surface of the basement (Precambrian?) within the caldera by assuming a single density contrast in a layer of variable thickness overlying the basement. This type of model gives a rough estimate for the depth to the basement surface and a good idea of overall structure, but it can give erroneous depth estimates where a low-density surface layer is present. Results from Segar's model indicate a total thickness of caldera volcanics and sediments of more than 5000 m in Valle Grande and almost 4000 m in Redondo Canyon. This implies a total vertical offset of 3000-4000 m from the position of the Precambrian basement outside the caldera (Jiracek et al., 1975). Several north-northeast-trending lineaments are evident within the caldera from gravity data. Near the northeastern edge of the map, a lineament seems to extend from the ring-fracture zone to the northern part of Redondo Creek, and there are also indications of north-south faulting near the western caldera margin. The northeast-trending structure may be a local expression of the Jemez lineament, an extensive northeast-trending structure that connects a number of volcanic centers in New Mexico (Baldridge, 1979). The north-south faults may represent Rio Grande Rift faulting that was contemporaneous with caldera collapse and which continues today. An important result from Segar's model is that the ring-fracture zone lies well within the topographic rim of the caldera, and for most of the caldera it is coincident with an inner ring of rhyolitic domes. At the western and northern margins, however, the ring-fracture faulting occurs considerably outside the ring of domes, suggesting that some of the domes may have erupted from fractures caused by Rio Grande rifting or an inward phase of ring-fracture faulting.

Generalized geophysical logs

Figure 8 shows two geophysical logs representative of well 13, a good producer. The composite logs were made by averaging logs from several adjacent wells with near-surface data supplied by surface dc resistivity measurements (McPhar Inc., 1973). The figure gives generalized density and resistivity logs for this area and is useful for determing whether the geophysical properties of the formations show enough contrast to allow mapping of the depth to and location of various buried horizons.

The density log indicates three major density units within the well section: a surface layer of caldera fill, lake deposits, and other recent alluvium (2.12 g/cm^3); the Bandelier Tuff and underlying volcanic and sedimentary units (2.3-2.4 g/cm^3); and the basement unit, consisting of the lower Paleozoic and the upper Precambrian (2.65 g/cm^3). There are, of course, significant density variations within each unit, but for modeling purposes the use of simple three-layer sections is sufficient for determining structure and identifying major subsurface lithologic changes. Density logs from the nearby Fenton Hill Hot Dry Rock wells, where the basement is shallow (Jiracek et al., 1975), indicate lower density for the Paleozoic sections and highly variable density for the Precambrian. This suggests that gravity interpretation in areas of shallow basement may overestimate the depth to basement.

The generalized resistivity log (Fig. 9) indicates a multilayer section with considerable resistivity contrast between the layers. The near-surface layer varies from 2 to 20 ohm-m; the lower values are indicative of regions of hydrothermal alteration, and the higher values are representative of alluvium and caldera fill in higher elevations where sediments are under-

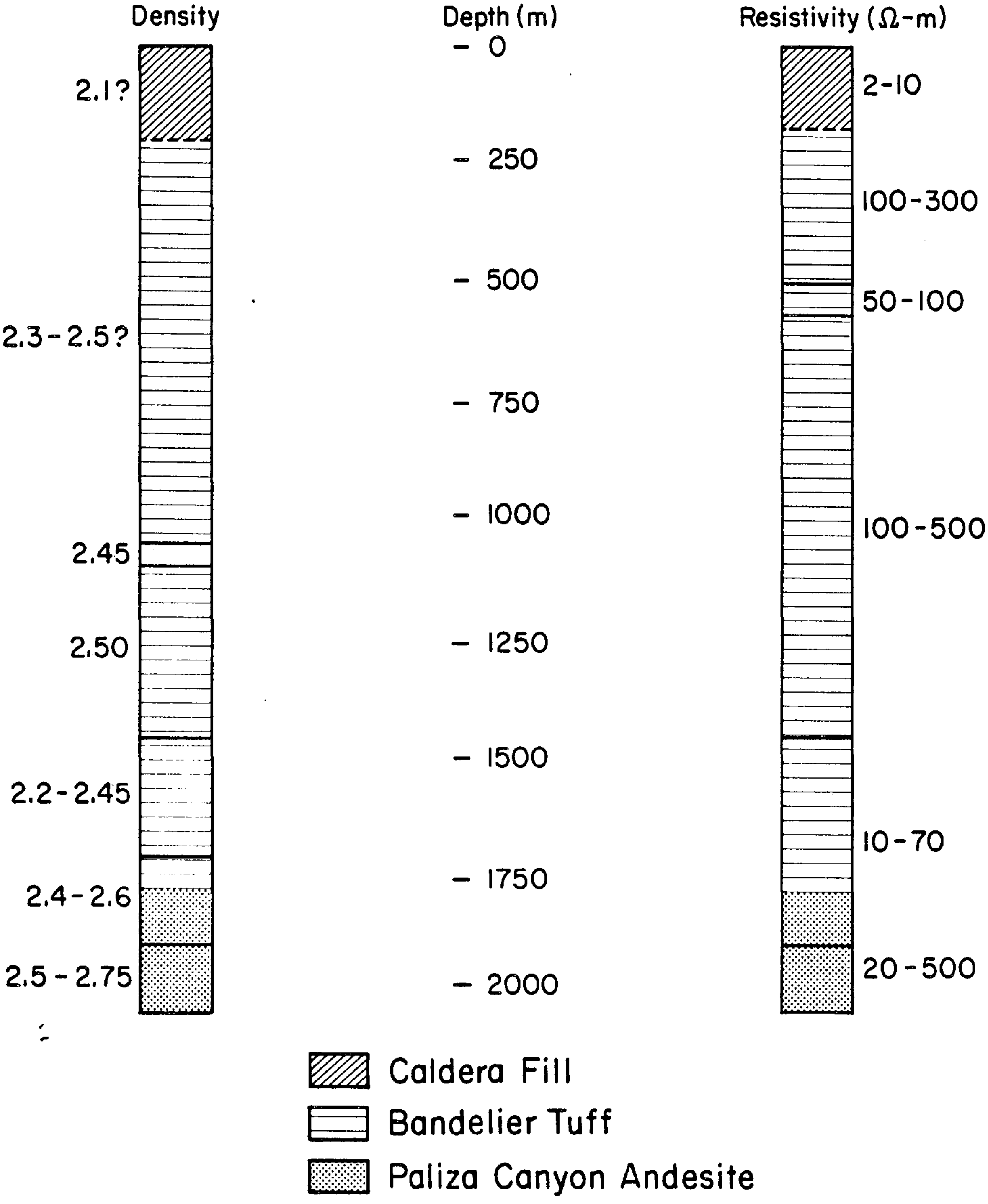

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Fig. 8. Generalized geophysical well log for the region near well 13.

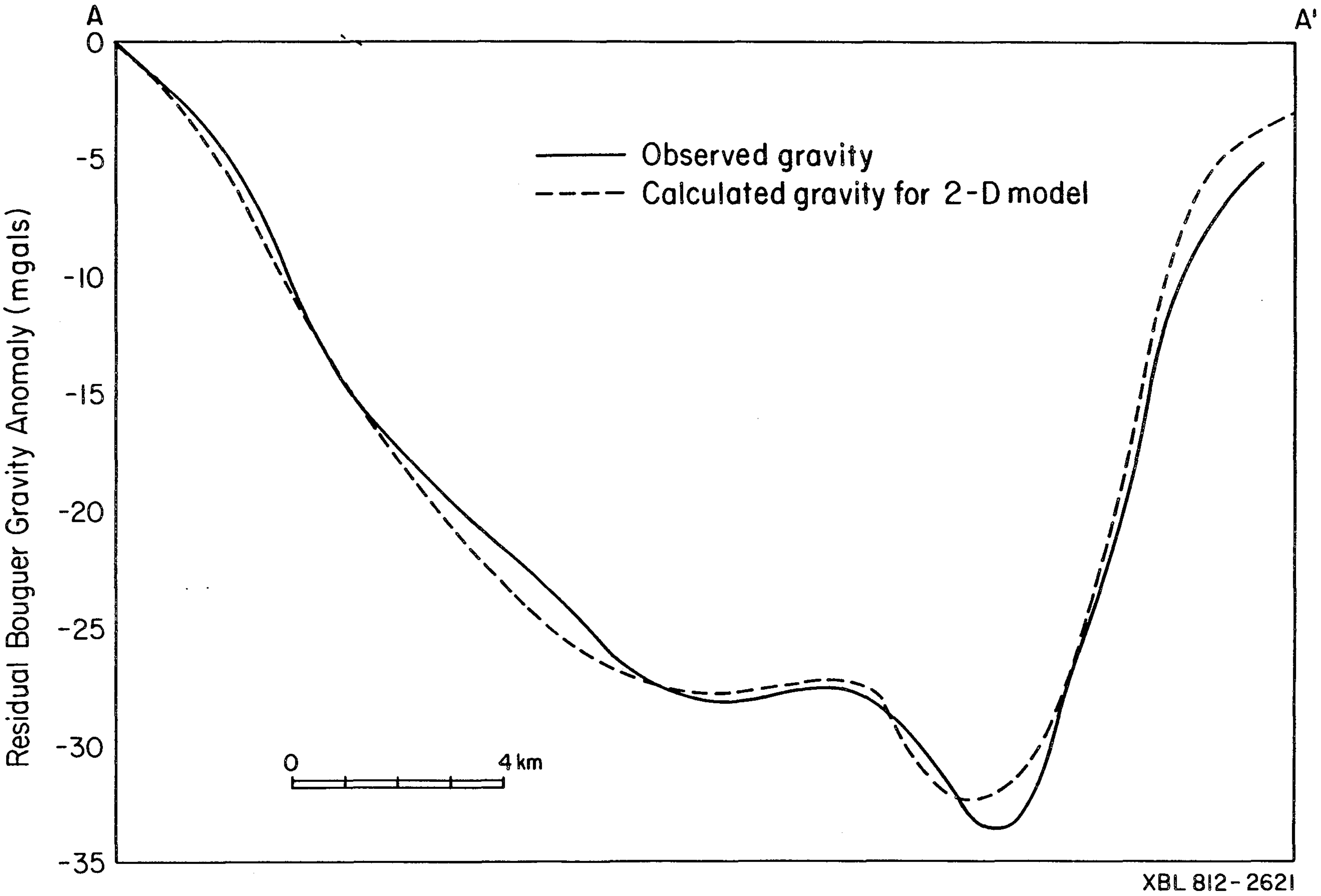

Fig. 9. Fit of calculated to observed gravity for profile A-A'. Model for calculated gravity is shown in Fig. 10.

saturated. The resistivity of the Bandelier Tuff, which underlies the surface layer, is variable. Upper sections show a resistivity of 100-500 ohm-m, which is consistent with the tight, well-cemented rocks; but at depths greater than 1 km in the production region, the resistivity in the tuff is quite low (10-70 ohm-m). This lower resistivity is probably caused by hot saline reservoir fluid, by increased porosity due to fracturing and dissolution of minerals, and by high subsurface temperatures. The resistivity contrast between this unit and surrounding units presents a good target for surface geophysical prospecting. The resistivity of volcanic and sedimentary units underlying the tuff is generally high except in the reservoir region, where they may contain substantial amounts of hot saline fluid. Well logs from well GT-2 at the Fenton Hill site show that the Precambrian basement has a variable resistivity, and metamorphic zones within the basement contain substantial water (West et al., 1975; Laughlin and Eddy, 1977). It is therefore possible that within the Baca geothermal area, Precambrian sections could also hold substantial quantities of geothermal fluid.

Geophysical profiles

Subsurface interpretations of geophysical data at Baca are presented for two orthogonal profiles; a northeast-trending line (B-B') along Redondo Canyon and passing through the present production zone; and a southeast-trending line (A-A') that begins at the caldera rim near Sulphur Creek, crosses B-B' at well 13, and ends at the eastern edge of the caldera (Fig. 12). Because of good vehicular access, most of the geophysical surveys performed at Baca included measurements along these profile lines.

Gravity Profiles

A computer program capable of two-dimensional modeling of gravity data was used in interpreting gravity observations along profiles A-A' and B-B' (Talwani et al., 1959). Densities of 2.12, 2.40, and 2.65 g/cm^3 were used for modeling the near-surface caldera fill, the underlying volcanics, and the basement sections, respectively (Fig. 8). Although correlation with well data was done whenever possible, there is some uncertainty to the model because of the nonuniqueness inherent in gravity interpretation. The model is meant as a general guide to subsurface structure, and is useful for identifying large-scale changes. The estimated depths away from drill holes may not be accurate.

Gravity data taken along A-A' were fitted to the model shown in Fig. 10, and the fit between calculated and observed data is given in Fig. 9. The dominant structural features shown by gravity along A-A' are the caldera rim faults, which represent 2000-3000 m of downdrop into the caldera; the eastern margin is probably the steeper of the two. The two-dimensional model suggests a maximum depth to basement at Baca of more than 4000 m in Valle Grande; this compares with a depth of 5000 m calculated by Segar (1971), and is likely to be more accurate than his estimate, since he did not account for the presence of a low-density surface layer. The model also indicates a basement depression in the Redondo Creek area, where bedrock is probably at least 3000 m deep. This graben is bounded steeply to the east by Redondo Peak, but slopes inward more gradually from the west. The model suggests a series of downdropped blocks extending from the western caldera rim into the Redondo Creek graben, a distance of about 8 km.

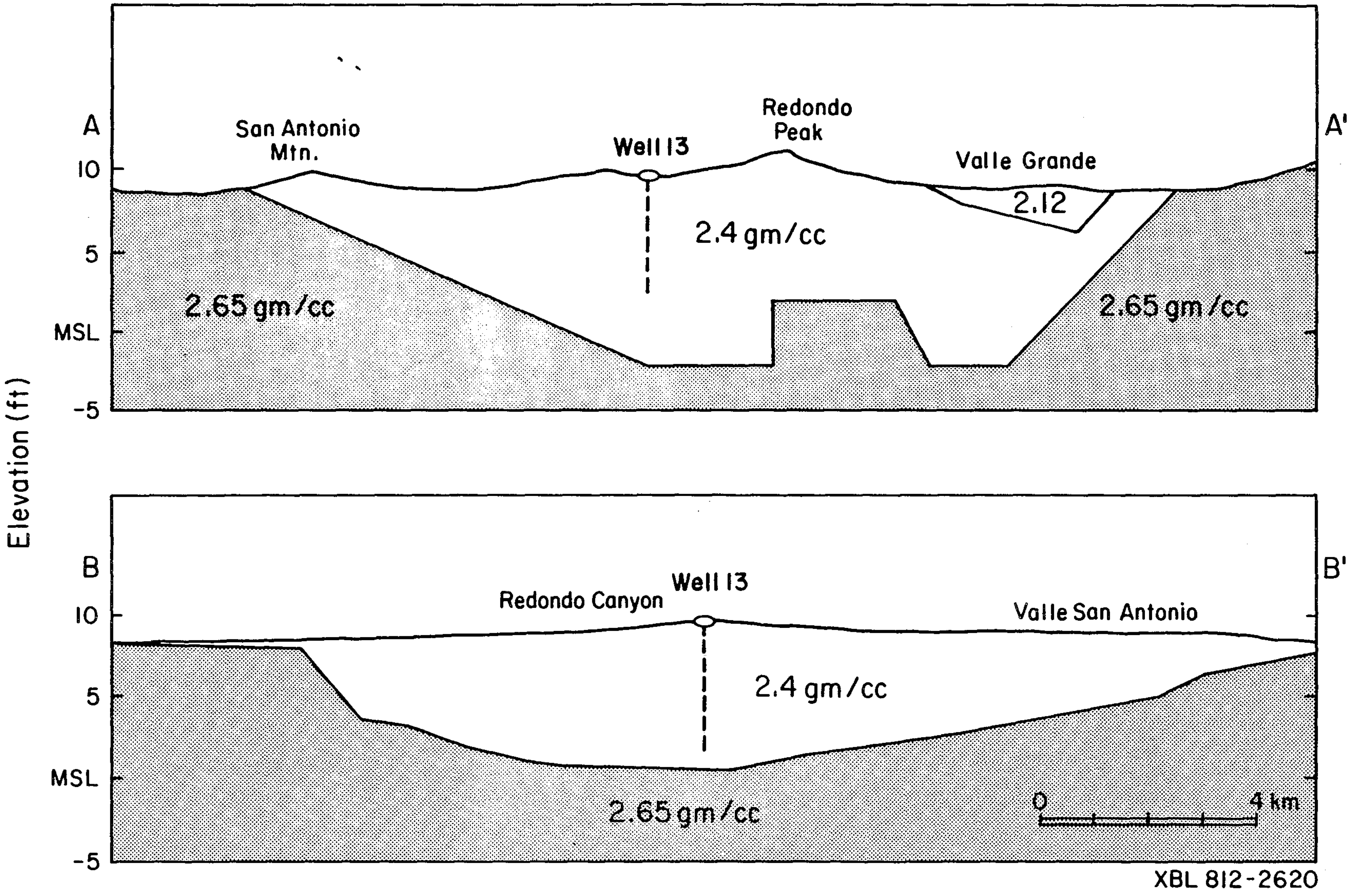

Fig. 10. Two-dimensional gravity model over Valles Caldera. The top shows east-west model A-A'; the bottom shows north-south profile B-B'.

Profile B-B' (Fig. 2) trends parallel to Redondo Canyon and parallel to the regional structural grain, which makes two-dimensional modeling somewhat inaccurate. For gravity interpretation along B-B', we used only one density contrast, since there was little well control outside of Redondo Creek. The depth to bedrock determined from profile B-B' is about 10% less than that determined from A-A' in regions where they overlap. Of the two, A-A' is probably the more accurate, since it crosses rather than parallels the regional structural grain. The B-B' model indicates that the southern caldera rim fault is significantly steeper than its northern counterpart. The northern rim shows a much more gradual deepening of the basement into Redondo Creek. In summary, the model indicates that the steeper bounding faults are to the south and east, and the shallow faults to the north and west. Thus the caldera appears to be tipped toward the southeast, or toward the center of the Rio Grande graben. This supplies further evidence that caldera formation was coincident with rift faulting.

Electrical profiles

Telluric profiles, magnetotelluric sounding, dc resistivity, and electromagnetic sounding surveys were all performed over the caldera in hopes of outlining deep drilling targets (Group 7, Inc., 1972; McPhar, 1973; Geonomics Inc., 1976). These data are used to help define the electrical structure in the reservoir region. The data were reinterpreted using computer models, and interpretations from the various surveys were compared for consistency of the subsurface models.

Telluric profile C-C' (Figs. 2 and 11) is a north-south line 12 km in length with stations every 300 m. The profile begins near the southern ring-fracture zone, crosses the central portion of the steam production zone,

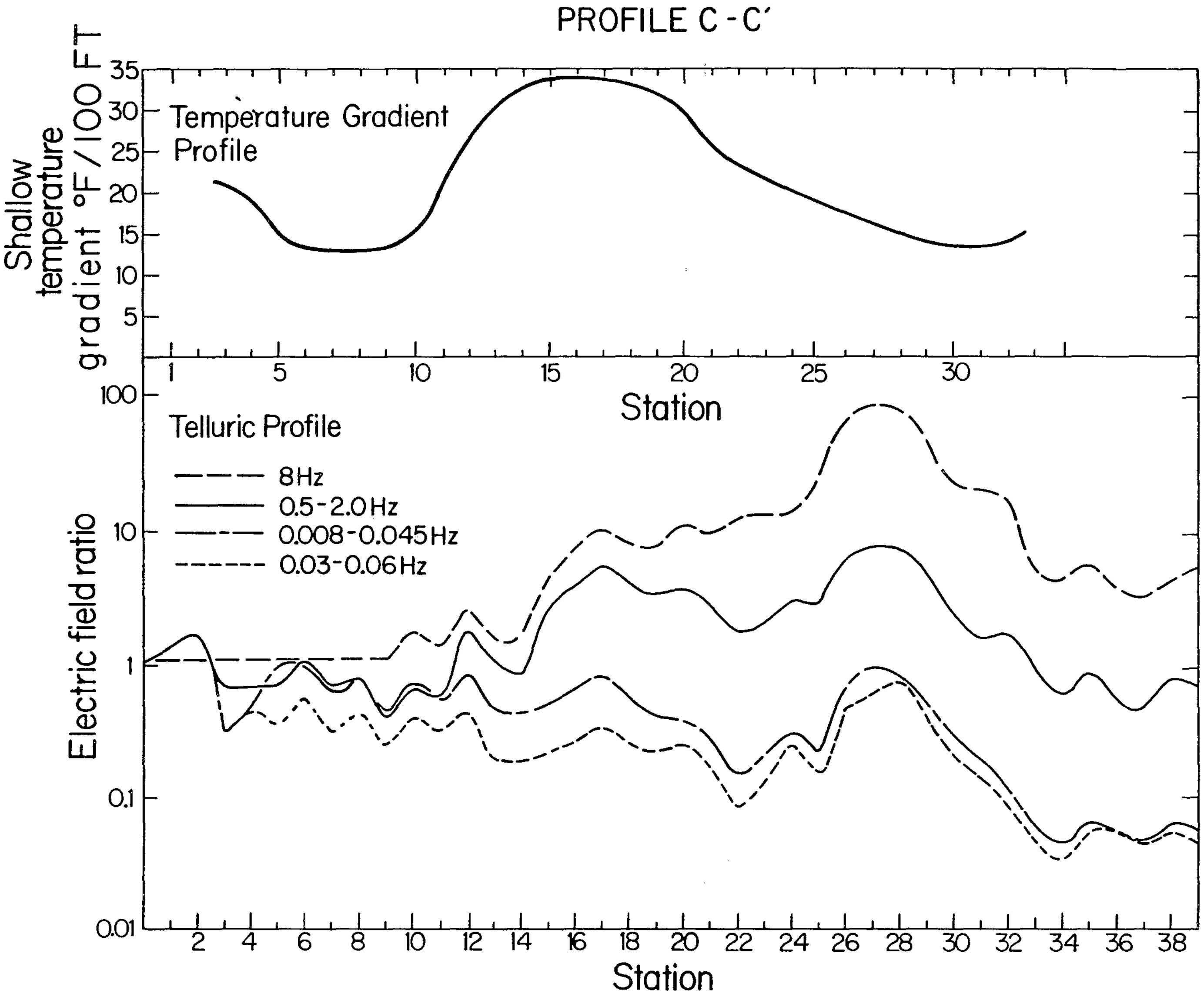

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Fig. 11. Profile C-C', showing temperature gradients and telluric voltage ratios (J-values). Station spacing is 300 m.

and ends in Valle Seco in the northern section of the caldera. Figure 11 is a plot of J-value versus station number, where J-value is defined as the telluric voltage ratio at a particular frequency or averaged over a frequency range between adjacent dipole segments; the values are normalized to a segment, usually at the beginning of the line. J-values are proportional to earth resistivity beneath the dipole segments. Abrupt changes in the J-value profile indicate lateral resistivity variations, such as faults or geologic contacts. Telluric voltages were measured in four frequency bands between 8 and 0.008 Hz. Higher-frequency plots give an indication of near-surface resistivity variation, and the lower-frequency plots give some idea of deeper resistivity changes.

The dominant feature of the telluric profile in Fig. 11 is the J-value low between stations 20 and 28. Since the anomaly is most pronounced at lower frequencies, the source is probably deep-seated. The J-value minimum is centered directly over the region of steam production, and it is probably related to the presence of hot, saline reservoir fluid. A plot of shallow temperature gradients shows a general correlation of a temperature-gradient high with the telluric low, but the region of highest thermal gradients is south of the telluric low, and deep wells in this area are hot but nonproductive. This indicates that the telluric (resistivity) response is more sensitive to the presence of saline water than to high temperatures. The dimension of the low-resistivity anomaly in the north-south direction, as indicated by telluric measurements, is about 2.5 km. The higher-frequency plots do not show a minimum over the production zone, which is to be expected, since they are much more sensitive to near-surface resistivity and may be sensitive to topography.

Telluric profile C-C' (Fig. 11) also shows a significant J-value minimum beyond station 29. This low is evident at all four frequencies, and may be caused by a significant accumulation of low-resistivity sediments in the Valle Seco area. This region does, however, have high geothermal gradients (Union Oil, 1978), and the presence of a thick insulating sediment wedge could allow for high-temperature geothermal fluids at depth. Stations 6-12 on profile C-C' show a series of rapid J-value changes at all four frequencies, indicating near-surface resistivity variations. Possible causes of these changes are faulting and the presence of hydrothermally altered zones in the near surface.

Figure 12 is a composite plot of eight magnetotelluric (MT) soundings along profile B-B', each fitted to a layered-earth model; a sample of a fitted apparent resistivity spectrum is given in Fig. 13. For all soundings, the apparent resistivity curves are for electric field sensors aligned with the regional geologic strike (north-northeast). Soundings taken in this alignment are most sensitive to the vertical earth structure, whereas other alignments can be more sensitive to lateral resistivity variations. The dominant feature of the resistivity cross section (Fig. 12) is the anomalous low-resistivity zone beneath 800 m in the steam production zone. The model shows that this region is approximately 3 km wide and 10-20 ohm-m in resistivity. The depth to and resistivity of the anomalous region are both consistent with well logs indicating that the reservoir region is detected from surface MT measurements. Magnetotelluric data do not indicate a higher resistivity formation beneath this anomalous low-resistivity zone, suggesting that it is probably fairly thick.

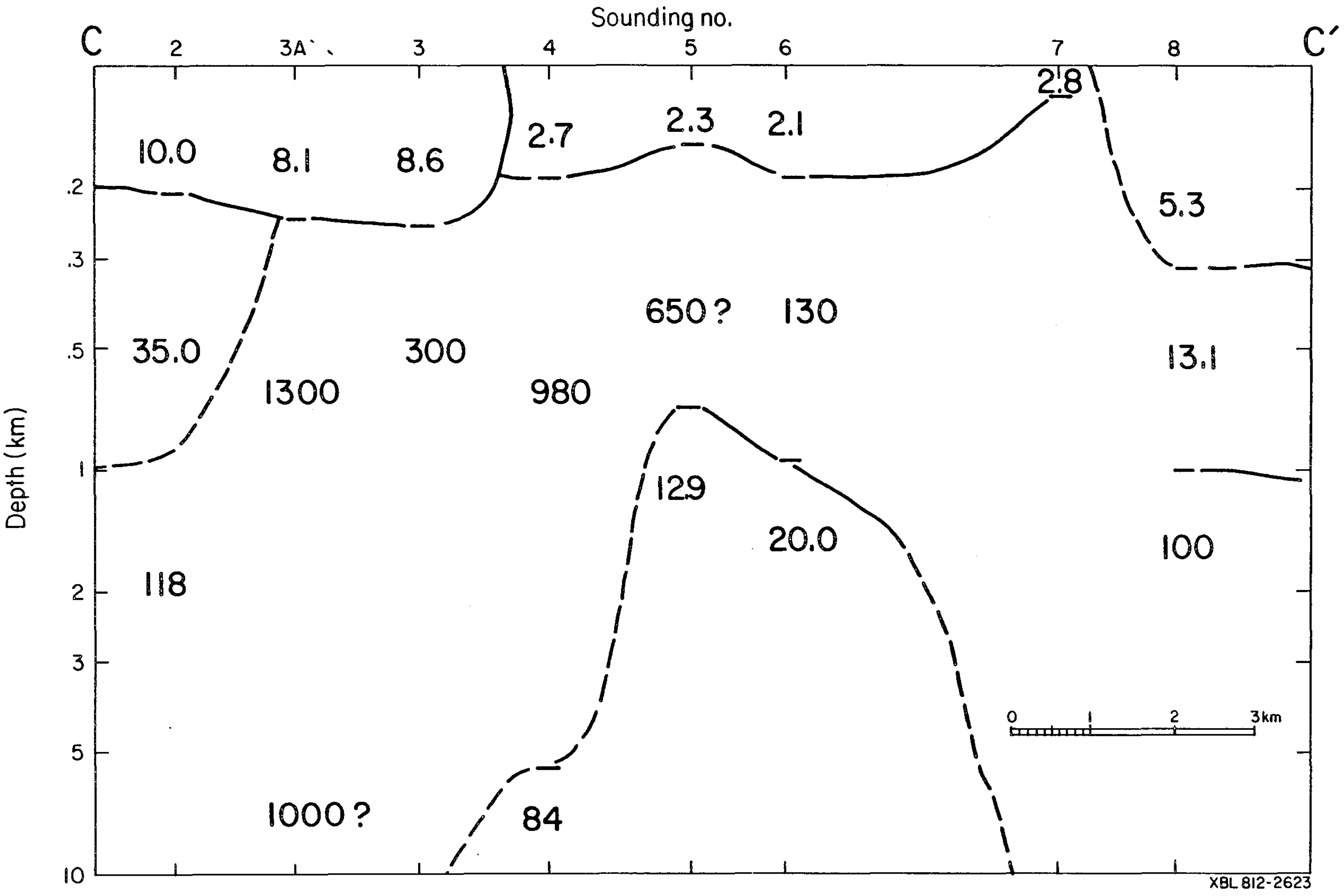

Fig. 12. Composite plot of layered-model inversions for MT soundings taken along profile C-C'.

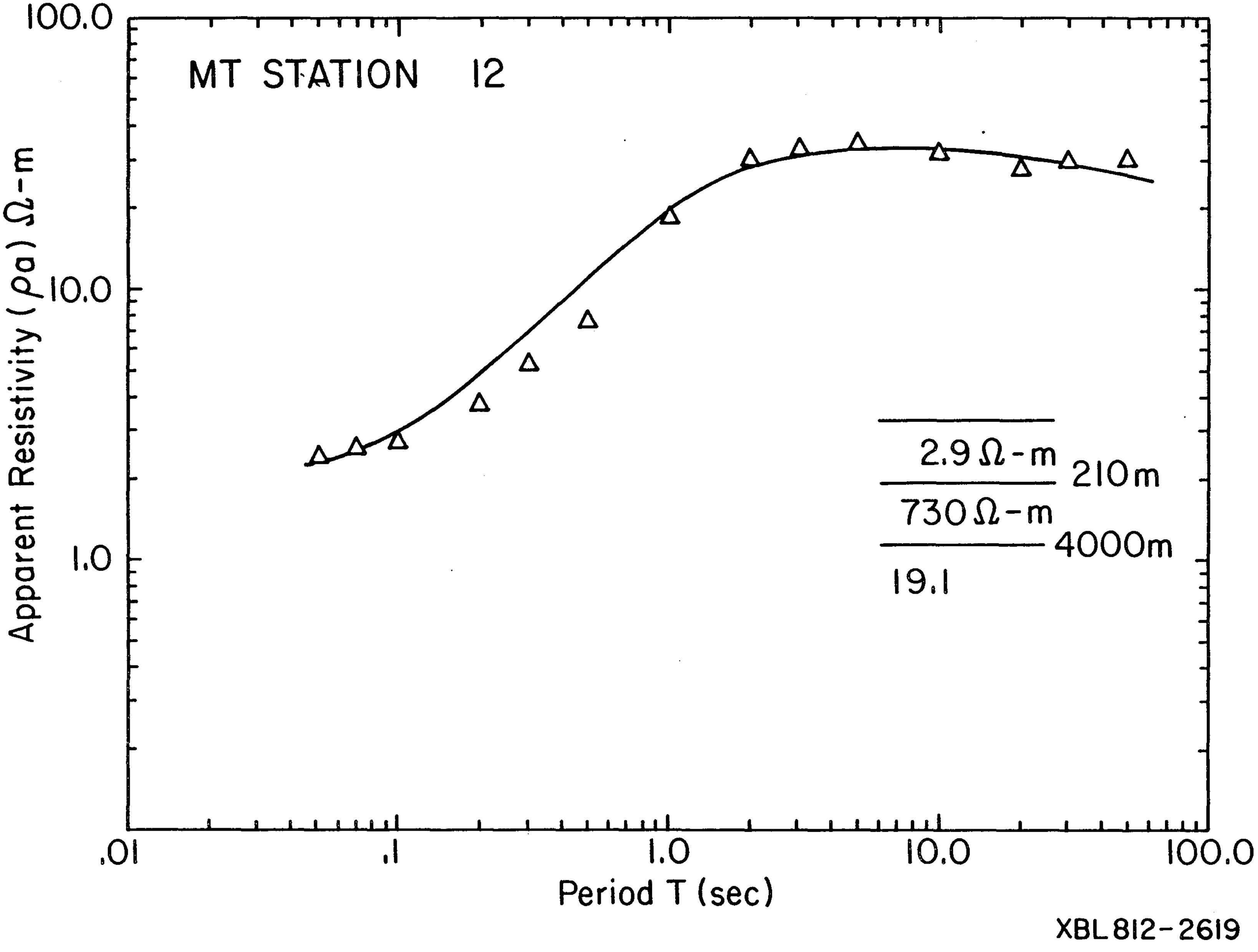

Fig. 13. Sample fit for layered-model inversion of an MT sounding.

Anomalously low surface resistivities are also evident in Redondo Canyon. These are probably largely due to hydrothermal alteration of the near-surface caldera fill and sediments; the altered zone is about 200 m thick. Outside of the canyon, the near-surface resistivity is 10 ohm-m to the south and 5 ohm-m to the north. In both cases, the thickness of the surface layer is greater than in Redondo Creek. Except for the present steam production zone, the resistivity at depth in Redondo Canyon is very high. The MT data indicate that the resistivity of the Bandelier Tuff is probably greater than 150 ohm-m; the underlying volcanic and sedimentary sections also have high resistivity. Soundings 2 and 8, which lie outside of Redondo Canyon, both show a more layered sequence than interior soundings. Depth to high-resistivity rock is one km or more for these soundings, and each shows a layer of intermediate resistivity between the surface and the higher resistivity substratum.

Because the terrain along the east-west profile (A-A' in Fig. 2) is rough, telluric profile measurements were made only in Jaramillo Canyon, which transects the area to the east of Redondo Canyon. Magnetotelluric soundings were made, however, all along the profile. Telluric profile G-G' (Fig. 14) is a 16-km east-west line beginning just west of Valle Grande, traversing through Jaramillo Canyon, and terminating in Redondo Canyon near well 13. The J-value plots for the higher frequencies show a general decrease in J-value westward, or toward Redondo Canyon. This indicates a thickening of sediments, or a decrease in the resistivity of the upper section, or both. The decrease is gradual up to station 17, where the profile crosses into Redondo Canyon. At this point the rapid decrease in J-value is most likely due to near-surface hydrothermal alteration. The lower-frequency plots

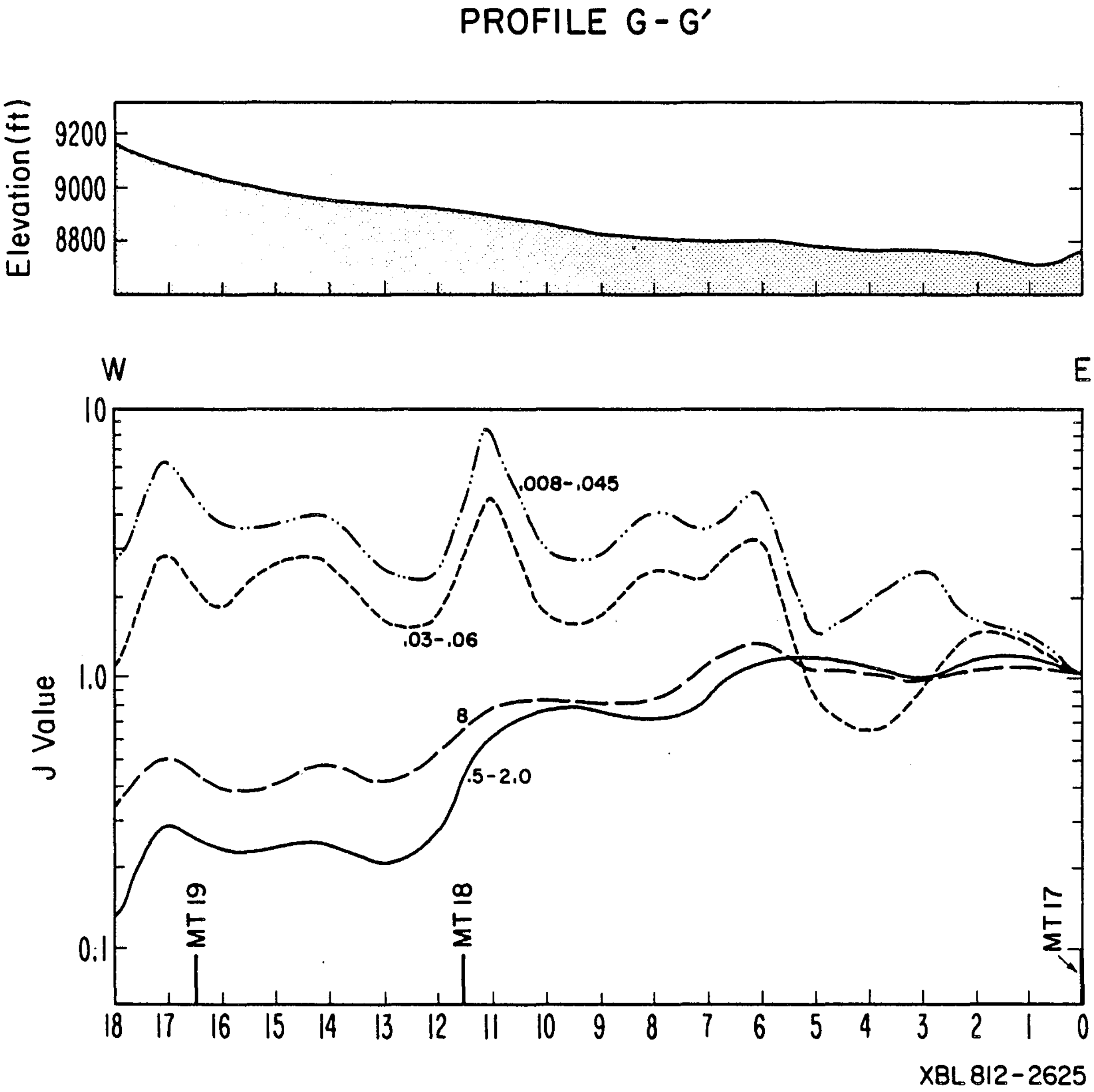

Fig. 14. Telluric J-value plot for east-west profile G-G'. Station spacing is 300 m.

indicate a more complex section that increases in resistivity westward toward Redondo Canyon. The increase is most likely due to a very resistive volcanic section that thickens westward toward Redondo Canyon. West of station 17, the low-frequency J-value plots decline very sharply again. Station 17 also correlates very well with mapped faults (Smith et al., 1970), indicating that the eastern field boundary probably lies within this region.

Magnetotelluric measurements along profile A-A' show variations similar to those of the above telluric profiles, but give more quantitative information on thickness and resistivity of units. Figure 15 is a two-dimensional composite of interpreted layered-model sections made from the magnetotelluric soundings. The shaded part of the figure designates a low-resistivity zone at a depth of 1 to 3 km. This zone is shallowest near good producing wells (e.g., well 13), and seems to dip westward toward the Sulphur Creek area. If this zone represents good reservoir rocks, production might be obtained from deep wells in Alamo Canyon and Sulphur Creek. The top of the low-resistivity zone for sounding 12 is particularly interesting because it lies within the Precambrian basement complex encountered in several Sulphur Creek geothermal wells. Because of the nearness of the ring-fracture zone, this deep, low-resistivity zone may indicate a hot-water reservoir within fractured segments of the Precambrian basement. The resistivity of the section east of MT sounding 19 is markedly higher than the section in the western part of the caldera; the sharp boundary may indicate the eastern boundary of the geothermal field. Sounding 23, located in Valle Grande, shows a substantial thickness of caldera fill above the higher-resistivity substratum. The depth to this high-resistivity contact is about 1.3 km, consistent with sediment depths modeled with gravity data. The very deep, low-resistivity layer for sounding 23 may be related to the presence of the nearby ring-fracture zone.

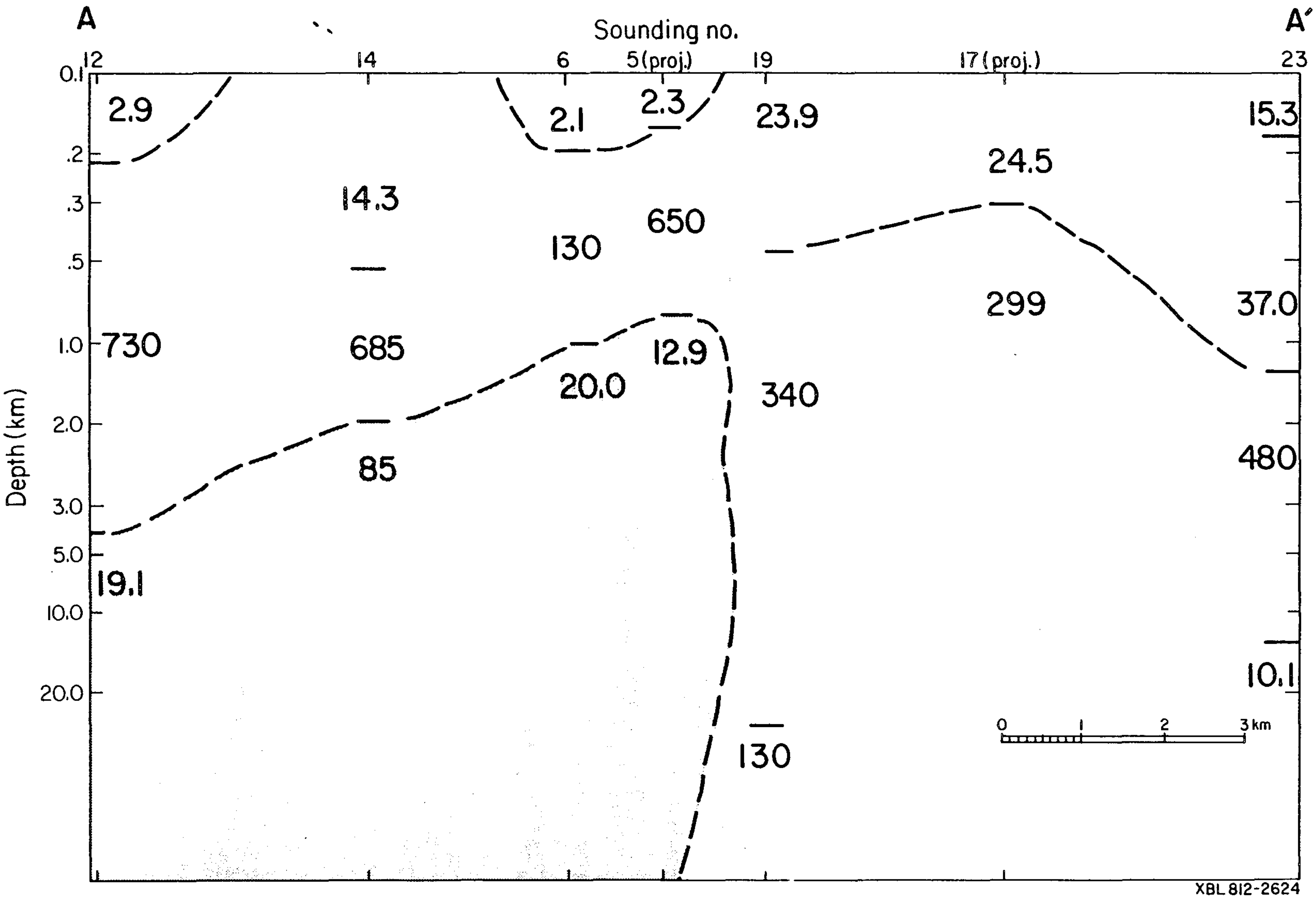

Fig. 15. Composite plot of layered-model inversions for MT soundings along profile A-A'.

ESTIMATE OF RESERVOIR DIMENSIONS

For the purpose of reservoir simulation studies (Bodvarsson et al., 1980), we estimated the aerial dimensions of the reservoir region from geological and geophysical data. We propose three possible estimates for the reservoir dimensions, each based on different assumptions (Fig. 16).

Case 1: Redondo Creek Reservoir. If we assume that the region of steam production is limited by the occurrence of a thick, fractured Bandelier Tuff reservoir section within the Redondo Creek graben, then the aerial dimensions may be estimated from geophysical and well data. Telluric and magnetotelluric data indicate structural discontinuities near well 10, north of well 16, just east of well 20, and immediately east of the Bond 1 well; none of those wells is productive. Magnetotelluric data show that the area interior to these discontinuities is characterized by a low-resistivity zone at depth. Assuming that this low-resistivity zone correlates with the Baca reservoir, we can estimate the dimensions of the reservoir by enclosing these crossing points within a rectangle; the total aerial extent in this case is about 10 km^2 (Fig. 16).

Case 2: Sulphur Creek extension. Magnetotelluric data suggest the presence of a deep, low-resistivity zone in the Sulphur Creek region. The data show that the conductor lies at a depth of nearly 3 km, which indicates that it lies within the Precambrian basement. Assuming that this region contains hot geothermal fluids in a fractured basement complex, and that the extensive faulting in Sulphur Creek would create fractures at depth, then the reservoir dimensions may be expanded westward to the ring-fracture zone. Existing wells in Sulphur Creek are hot but nonproductive, but all of them were

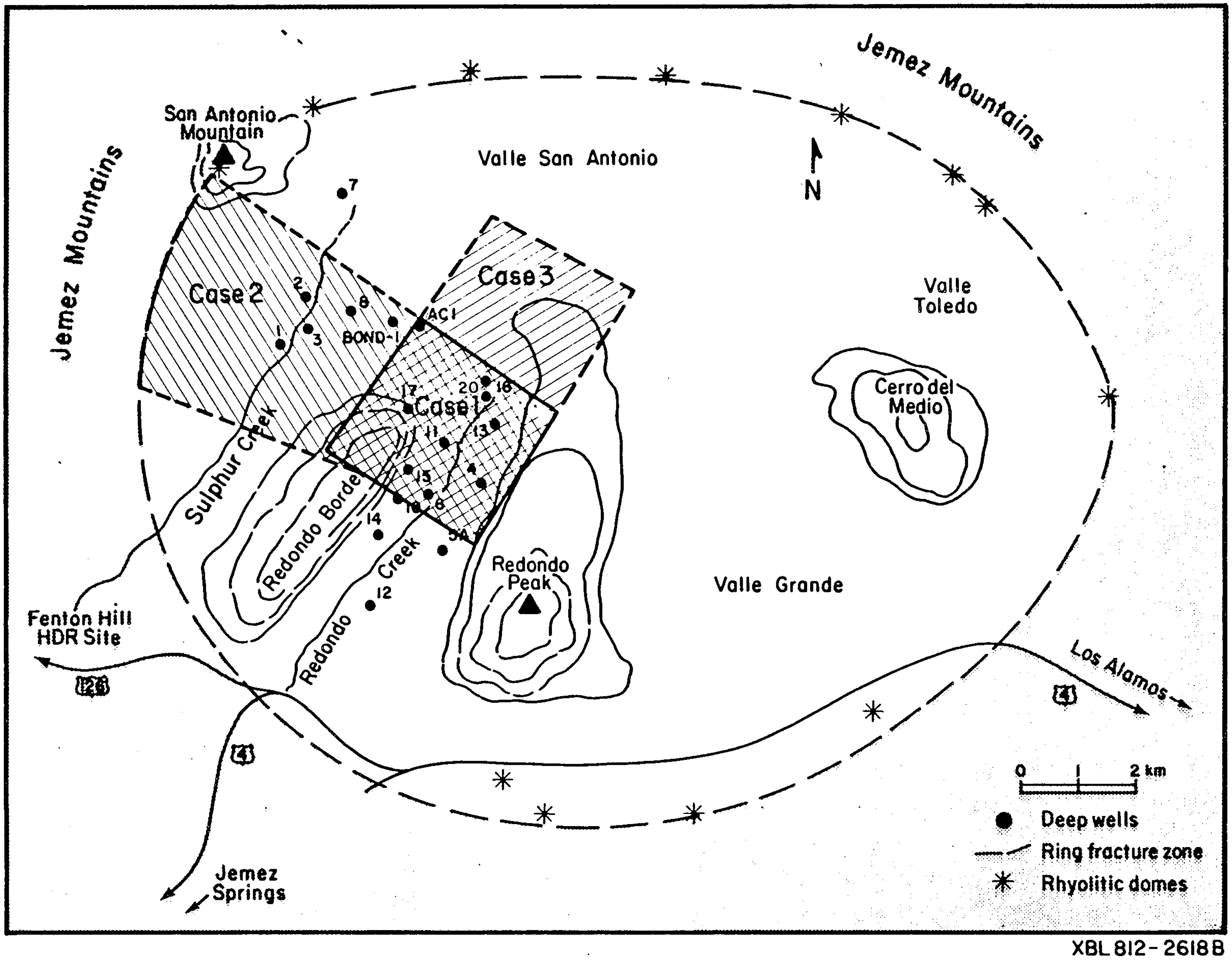

Fig. 16. Map of the Baca field, showing three possible cases for aerial boundaries of the deep geothermal field.

drilled only until basement was reached at a depth of about 1 km. The areal extent of this reservoir is about 30 km^2.

Case 3: Valle Seco extension. Gravity, thermal gradient, and electromagnetic data all suggest a possible northward extension of the Baca reservoir into the Valle Seco region. Surface thermal gradients are high, the depth to basement is at least 3 km, and the section is characterized by low resistivity down to great depth. By extending the Baca reservoir to the northern limit of Valle Seco, a reservoir areal extent of about 20 km^2 is inferred.

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