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INTERPRETATION OF GRAVITY SURVEYS IN GRASS AND BUENA VISTA VALLEYS, NEVADA

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IN GRASS AND BUENA VISTA VALLEYS, NEVADA

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ABSTRACT

Continuing the LBL study of geothermal exploration techniques and the assessment of potential reservoirs begun in 1974, detailed gravity surveys were made in the vicinity of Leach Hot Springs, Grass Valley, and Kyle Hot Springs, Buena Vista Valley, in northern Nevada. The terrain-corrected Bouguer gravity values were gridded, corrected for regional gradients (Grass Valley only) by a least squares polynomial fit to the data, and then processed by means of an inversion scheme to yield a contour map of the basement configuration. The three-dimensional inversion algorithm assumes a two-layer earth of variable first layer thickness but constant density contrast between layers. Although a fit to observed data can be obtained for a range of density contrasts, a contrast of 0.06 g/cm^3 gave interpreted results most consistent with results from other geophysical data: (a) agreement between the minimum thickness contours and the margins of exposed Paleozoic rocks and Cretaceous intrusives; (b) agreement between the calculated basement depth and report information from a deep drill hole in Grass Valley; and (c) agreement between estimated basement depths and interpretation of seismic reflection-refraction data. To illustrate the information value of the depth-to-basement calculations, we show comparisons of gravity, electrical resistivity, and seismic interpretations along selected profile lines. Gravity and seismology gave nearly identical results for the location and dip of the Hot Springs fault in Grass Valley. The gravity interpretation agreed reasonably well with that of the electrical basement, although the electrical basement is consistently 200-400 meters deeper than the density or velocity interface.

The Hot Springs fault was projected to surface and its surface trace is found to correspond closely with a mapped set of closely-spaced, northeast trending faults passing through Leach Hot Springs. The gravity data and other geological-geophysical evidence suggest the possibility of a fault-related association between the current hot springs activity at Leach, the heat-flow anomaly in Section 14, and the mercury deposits in the Goldbanks Hills. The three heat flow anomalies in Grass Valley and Leach Hot Springs in Buena Vista Valley all seem to lie at the intersection of north-south trending basin and range faulting and northeast-southwest trending faults. Excess-mass calculations were made for the gravity anomalies at Leach and Kyle Hot Springs, each anomaly believed due to precipitated secondary minerals. The Kyle system is three times more massive and considerably younger than the Leach system, suggesting that the Kyle Hot Springs system has been the more active system and thus is more promising as a geothermal resource than Leach.

INTRODUCTION

A program of gravity measurements was initiated in Grass and Buena Vista valleys in 1975 and 1976, respectively, as part of the Lawrence Berkeley Laboratory's study of exploration techniques in geothermal exploration and assessment of potential reservoirs. The basic program had three main goals:

1. to evaluate selected geothermal reservoirs in northern Nevada on the basis of detailed geological, geochemical, and geophysical data;
2. to compare and evaluate geophysical techniques used in exploration and reservoir delineation;
3. to develop new techniques, including necessary instrumentation, for deep exploration.

Detailed gravity surveys were undertaken around Leach Hot Springs (Grass Valley) and Kyle Hot Springs (Buena Vista Valley) to help meet goals (1) and (2) above. These locations lie within an area of higher-than-normal heat flow, the Battle Mountain high heat flow area shown in Figure 1 (Sass et al, 1971). Temperatures at depth in some hot springs in the area, determined from chemical geothermometers exceed 150°C - 170°C and total dissolved solids in the surface waters are less than 5000 ppm (Mariner et al, 1974). These systems are thus in the medium temperature, high quality category.

Gravity results were previously presented and discussed by Beyer et al (1976) and Goldstein et al (1976) in Preliminary Open File Reports. Here we present more detailed interpretations of the data.

GRASS VALLEY (Leach Hot Springs)

Geologic Setting

Beyer et al (1976) presented the following geological summary of the area: "The Leach Hot Springs area is located in Grass Valley, Nevada, approximately 50 km south of Winnemucca. The Sonoma and Tobin Ranges bound the valley on the east while the valley is constricted south of the hot springs by the Goldbanks Hills, locus of earlier mercury mining. Grass Valley is bounded on the west by the basalt-capped East Range. The distribution of major lithologic units in the region is illustrated on the geologic map (Figure 2) and their stratigraphic relationships on the cross-section (Figure 3). The intricate fault and lineament pattern, based strongly on photo interpretation (Noble, 1975), is shown on a separate map (Figure 4). Paleozoic siliceous clastic rocks and greenstones are the oldest bedrock types in the region. In places in the Sonoma and Tobin Ranges, the Paleozoics are in thrust-fault contact with Triassic siliceous clastic and carbonate rocks. The Paleozoic and Triassic rocks have been intruded by granitic rocks of probable Triassic age in the Goldbanks Hills; elsewhere the granitics are probably of Cretaceous age. Though not exposed in the Leach Hot Springs area, Oligocene-Miocene rhyolitic tuffaceous rocks are probably present in the subsurface. They are overlain by a sequence of interbedded sandstone, fresh water limestone and altered tuffs, which are in turn overlain by coarser conglomeratic sediments (fanglomerates) derived from mountain range fronts steepened by the onset of basin and range faulting. The fanglomerates are opalized in places by siliceous hydrothermal activity associated with fault zones; occasionally the locus of mercury mineralization. Opalization of mercury deposits in the Goldbanks Hills and

East Range closely resembles the opalized sinter at Leach Hot Springs. The Tertiary sedimentary sequence is overcapped by predominantly basaltic volcanic rocks whose ages, dated by the potassium-argon method, range from 14.5 to 11.5 million years.

Characteristic of the hot spring systems observed in northern Nevada, Leach Hot Springs is located on a fault, strongly expressed by a 10 to 15 m high scarp trending northeast. Normal faulting since mid-Tertiary has offset rock units vertically several tens to several hundred meters (idealized cross-section, Figure 3). As shown on the fault and lineament map (Figure 4), the present-day hot springs occur at the zone of intersection of the northeast trending fault and the north-northwest-south-southeast trending lineaments.

Total surface flow from the Leach Hot Springs system has been measured at 130 $\ell\,min^{-1}$ (Olmsted et al, 1975). Surface temperatures of the springs reach 94°C, boiling at their altitude, and water temperatures at depth are estimated to be 155°C to 170°C, based on silica and alkali-element geothermometers (Mariner et al, 1974). Application of mixing-model equations (Fournier et al, 1974), based on silica contents and temperatures of warm and cold spring waters, indicates that the temperature of hot water at depth within the Leach Hot Springs system may exceed 200°C. Material deposited by Leach Hot Springs, presently and in the past, is predominantly SiO_2."

A heat flow map of Grass Valley, holes shown as dots, is given in Figure 5. A total of 82 holes ranging in depths of from 20 m to 500 m were drilled by the U. S. Geological Survey in the period 1974-1977 (Olmsted et al, 1975; Sass et al, 1976; Sass et al, 1977). This work begun by the Water Resources Division later evolved into a joint LBL-USGS effort to detail the heat flow pattern. The principal anomaly occurs around Leach Hot Springs and smaller highs occur 5.5 km southwest and 11 km southeast of the springs, the Section 14 and Panther Canyon anomalies, respectively. There is evidence that all three anomalies are due, at least in part, to hydrothermal convection.

Gravity Results

Gravity data were obtained with a Lacoste-Romberg gravimeter at over 350 stations covering about 200 square kilometers (Figure 6). Most of the stations were at 0.5 km intervals along portions of line E-E' which passes over Leach Hot Springs. Additional stations were obtained in the vicinity of Leach Hot Springs, in the Sonoma and Tobin Ranges to the east of Grass Valley, in the East Range to the west of Grass Valley, and at various off-line sites in Grass Valley. Gravity station elevations along geophysical lines were surveyed to within ±0.03 m. Remote stations in the mountain ranges were located where elevations are known to ±.3 m in the valley and ±1.0 m in the rugged terrain.

A gravity station established by the U. S. Air Force at the Winnemucca Airport was used as the base station. Readings were tied into this station twice daily during the early and final days of the survey, and at least once daily at other times.

The complete (terrain-corrected) Bouguer anomaly was calculated using a Bouguer density of 2.67 g/cm^3. These data are contained in Figure 6, the station locations shown as dots. We estimate that nearly all values are accurate to within ±1.0 mGal.

To make a quantitative interpretation of these data we first entered station coordinates and Bouguer values onto punched cards. These were computer-processed by Computer Graphics, Inc., of Berkeley to yield a set of gridded values, interpolated, and extrapolated to a rectangular grid of 51 x 51 grid points. The gridded data were later reduced to a 26 x 26 array for the sake of computational economy. A least-squares polynomial fit to the data was made for regional removal. First, second, and third-order surfaces were calculated, but it was later determined that the first-order residual (Figure 7) gave interpreted results most consistent with results from other geophysical data. The gravity data in Figure 7 covers a slightly larger area than in Figure 6 because new stations were later added in Grass Valley.

Using the regional-corrected Bouguer data, we estimated the apparent depth-to-basement over the survey area by means of a two-layer inversion program. In the computer code the basement is assumed to consist of rectangular prisms centered below each grid point. Depth to each prism is variable but the density contrast between prisms and surface layer is constant. For a given density contrast, the depths to prisms are sought which minimize, according to various criteria, the difference between observed and calculated fields. For most density contrasts chosen the first layer thickness was well determined after six iterations. At this stage the observed and calculated gravity values differed by less than 0.1 mGal at all points. Beginning with a $\Delta\sigma$ of 0.35 g/cm^3, and eventually reducing $\Delta\sigma$ to 0.05 g/cm^3, we tested various density contrasts. A best fit at $\Delta\sigma$ = .06 g/cm^3 was determined on the basis of the following factors: agreement between the minimum thickness contours and the margins of exposed Paleozoic rocks and Cretaceous intrusives; agreement between calculated basement depth and report information for a U. S. Geological Survey drill hole (QH-3 in Sec. 14, T.31.N, R.38E)

(Sass et al, 1977); and agreement between depth of basement along lines E-E' and D-D' and dipole-dipole resistivity and seismic reflection results.

Figure 8 shows the apparent depth-to-basement map ($\Delta\sigma$ = .06 g/cm^3) in closest agreement with other data. Contours outside the irregular boundary were eliminated because of the limitations of survey data. Agreement seems poorest along the southwest margins of the areas, but this situation might have been better if stations had extended farther west into the Goldbanks Hills and East Range. The small density contrast found to fit the data may be due to the fact that the valley fill material is composed largely of compacted Tertiary sediments and volcanic interbeds.

To examine the physical significance of the depth-to-basement calculations, the profile data for line E-E' were plotted and shown in Figure 9 together with the finite difference interpretations of dipole-dipole data (Beyer, 1977) and the finite element interpretation of seismic refraction and reflection data (Majer, 1977). East of the Hot Springs fault the gravity interpretation agrees with a reflecting horizon believed to mark the contact between surficial Tertiary sediments and volcanics and the underlying Paleozoic rocks. A similar correspondence extends west of the Hot Springs fault, where the common reflecting and density-contrast interface is downdropped to a depth of slightly more than one kilometer below the surface. It is also interesting that gravity and seismology give nearly identical results for the location and dip of the Hot Springs fault.

West of the fault, in the downdropped block, Beyer (1977) obtained a fit between observed and calculated apparent resistivities for which the 150 $\Omega \cdot$m "basement" depth falls midway between the density interface (also corresponding to the Tertiary-Paleozoic contact from refraction data) and the deeper high-velocity basement. The lack of correlation between the deep resistivity interpretation and the gravity-seismic results may be due to various factors: (1) lack of concordance between resistivity and density variations within the earth; or, more likely, (2) the nonuniqueness problem that often makes it difficult to determine accurately the thickness of a middle layer when it is sandwiched between two layers of higher or lower resistivity. However, the resistivity results correlate well with both gravity and seismic interpretations at several points in the cross section: the general location of the Hot Springs fault; the depth to the Qal-Tertiary interface at 2W - 4W; and the basement rise at 8W - 9W. The basement rise at 9W could be modeled well from the resistivity data and also shows up as a decrease in P-wave delay. This feature may correspond to a concealed horst or an intrusive flanked by sediments.

The apparent depth to basement derived from gravity data is plotted for line D-D' in Figure 10 in which we also show the interpretation of dipole-dipole resistivity. As on line E-E', the density interface parallels the electrical basement but falls 200 to 300 meters above the interpreted resistive basement. Again we suspect that the gravity data provide the more accurate estimate of valley geometry; the electrical interpretation being affected by the inherent problem of poor resolution of second-layer parameters when that layer is sandwiched top and bottom by more resistive layers. Supporting evidence for the accuracy of the gravity interpretation is that Paleozoic rocks are reported at 1240 ft in U. S. Geological Survey drill hole QH-3 located near 6W line D-D' (Sass et al, 1977).

Using the depth-to-basement contour map, although the Bouguer gravity map could be used for this purpose, an interpretation of the valley structure was made (Figure 11). In this figure we show faults and their relative displacement inferred from the basement configuration. Although different in some details from the faults mapped at surface (Figure 4), the inferred faults show many of the same trends and, in a few cases, both mapped and inferred faults compare remarkably well in location.

Mapped and inferred faults fall into three major directional sets: (1) a northwest set related to the basin-and-range structure and well exposed along the margins of the Sonoma and Tobin ranges, (2) a northeast set which in places offsets northwest-trending faults, and (3) a northerly-trending set. Locations of these inferred faults are approximate in the sense that no attempt was made to estimate fault dips and thereby find their surface projections. Only the Hot Springs fault (Figure 11) was projected to surface and its surface trace is found to correspond closely with a mapped set of closely-spaced, northeast-trending faults passing through Leach Hot Springs. The gravity data suggest that the Hot Springs fault may swing southerly and link up with the north-south faults mapped in the area between the East Range on the west and the northern end of the Goldbanks Hills on the east. If this is the case, it is interesting to speculate on whether there is a fault-related association between the current hot springs activity at Leach, the heat-flow anomaly in Section 14, and the mercury deposits in the Goldbank Hills.

Another northeast-trending fault, inferred from gravity data, is the Panther Canyon fault, so-named because of its approximate alignment with the northeast-trending Panther Canyon which forms the boundary between the Sonoma and Tobin Ranges. Three zones of microearthquake swarm activity were detected, one within the canyon and two extending southwestward into Grass

Valley (Beyer et al, 1976). Based on preliminary fault plane solutions, it was initially proposed that the faulting had a right-lateral strike-slip component, but more recent work shows predominantly normal faulting, extension in the northwest-southeast direction (E. Majer, 1977, personal communication). Nearly coincident with this tectonic feature is a gravity bulge, resistivity high detected for several bipole locations during bipole-dipole surveying (Beyer et al, 1976; Beyer, 1977) and a ground noise low (Liaw and McEvilly, 1977). These data suggest a shallow basement, perhaps a concealed ridge of Paleozoic rocks trending southwest-northeast between the southern end of the Sonoma Range and the Goldbank Hills. Limited surface evidence for this fault has been found north of Panther Canyon (Figure 2), and the area is made more interesting because of the 6 HFU heat flow anomaly detected near the mouth of the canyon (Figure 5). The association of heat flow anomalies at places where northeast-trending faults intersect northwest-trending faults, as noted in three areas in Grass Valley, may constitute an important exploration guide.

The gravity anomaly at Leach Hot Springs is believed to be caused by densification of the Tertiary and Quarternary valley fill sediments due to precipitating minerals, mainly silica. To study this anomaly, an excess mass calculation was made by applying Gauss' equation to the residual anomaly (Figure 12) after removal of the regional and local geologic effects:

$$M = \frac{1}{2\pi G} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Delta g(x, y)\, dx\, dy,$$

where $G = 6.67 \times 10^{-8}$ dyne $cm^2/gram^2$. Graphical integration of the data gives an excess mass estimate of 2.5×10^8 metric tons which compares reasonably well with earlier independent estimates of 2.7×10^8 metric tons made before regional removal.

Taking the excess height, h, of the residual depth-to-basement anomaly, we calculated the anomalous volume, V,

$$V = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(x, y)\, dx\, dy,$$

which we can associate with the excess mass. The volume is $13.3 \times 10^8 m^3$, which gives an anomalous density, m/V, of $0.18\ g/cm^3$. This suggests that the depth-to-basement calculations, for which we selected $0.06\ g/cm^3$ as a good average figure, does have local errors, such as at Leach.

From the excess mass one can obtain an approximate age of the geothermal system—knowing the flow rate and assuming the ppm of dissolved solids that precipitate along the paths of ascending waters. This is not a particularly accurate dating method because the two transport quantities are seldom known with sufficient reliability. A more accurate approach to dating is based on radiometric species studies (Wollenberg et al, 1977), and this gives a minimum age of approximately 3.1×10^5 years. Using this age with the information that the present flow of $0.5 \times 10^6\ m^3/yr$ has remained constant for a long time (Olmsted et al, 1975), one can then show that a maximum of 1600 ppm solids need to precipitate from the water to account for the gravity anomaly.

The local residual gravity high in Section 14 was also derived graphically (Figure 12). Attention was drawn to this anomaly because of a nearly coincident 4 HFU heat flow high. This gravity anomaly has a lower amplitude (2 mGal) and broader appearance than the Leach anomaly, suggesting a deeper source. Excess mass calculations were not carried out for this anomaly which, based on gravity and resistivity interpretations (Figure 10), is probably due to a north-south-trending horst of pre-Tertiary rocks extending northward from the Goldbanks Hills. The heat flow anomaly was modeled, and it can be explained by a high thermal conductivity of the concealed pre-Tertiary basement (Majer, 1977). However, a thermal gradient reversal was measured within the basement rock intersected by hole QH-3, and therefore a convective component for the heat flow anomaly is indicated (Sass et al, 1977).

BUENA VISTA VALLEY (Kyle Hot Springs)

Geologic Setting

Goldstein et al (1976) presented the following geological summary of the area. "A geologic map of the Kyle Hot Springs Quadrangle (Figure 13) was compiled from observations by LBL personnel, reconnaissance mapping by Muller et al (1951), and air-photo interpretation by Noble (1974). Figure 14 is the accompanying idealized geologic cross section (Z-Z'). Roberts et al (1958) provided lithologic descriptions of the rock units.

Pre-Tertiary basement rocks, exposed in the East Range to the east of the study area, consist of Paleozoic eugeosynclinal and Mesozoic miogeosynclinal rocks. The Harmony Formation, of Cambrian age, is the oldest exposed unit in the area and crops out in a small area on the north side of Hot Springs Canyon. It consists of feldspathic sandstone, arkose, and grit with some chert. Most of the East Range in the Kyle Hot Springs Quadrangle is underlain by the Ordovician Valmy Formation. The Valmy consists of phyllitic argillite, greenstone, and a pure vitreous quartzite which caps some of the minor ridges in the northern part of the quadrangle. The Inskip Formation, primarily graywacke and conglomerate of Mississippian age, occurs in the upper part of Hot Springs Canyon. These Paleozoic eugeosynclinal rocks have been thrust over a crystalline limestone unit of probably Triassic age, exposed for about 5 km along the range front south of Hot Springs Canyon.

The East Range is capped by vesicular basalt of Tertiary age which dips gently eastward and covers the east flank of the range in the adjacent Mt. Tobin Quadrangle. Granite Mountain, which projects westward into Buena Vista Valley in the southern part of the quadrangle, is composed of two masses of granitic rocks, the northern unit is a quartz monzonite of

Tertiary age (Silberman and McKee, 1971) and the southern unit is a granodiorite of Permo-Triassic age.

Tertiary sedimentary rocks crop out in only one small area of about one square kilometer along the range front north of Granite Mountain. We assume that these sedimentary rocks and possible associated volcanic rocks underlie the Quaternary alluvium of the valley floor. The thickness of alluvium increases valleyward from the East Range reaching two to two and a half kilometers into the central part of Buena Vista Valley (Erwin, 1974). Pleistocene shorelines of Lake Lahontan contour the valley a few kilometers west of Kyle Hot Springs. The active hot springs are presently depositing predominantly $CaCO_3$, although opalized sinter is abundant in older deposits and predominates at the inactive "fossil" hot springs area a few kilometers south of the active springs.

Both the active and inactive hot springs occur in an area of numerous intersecting faults. Air-photo and on-site observations by Noble (1974) indicate that Kyle Hot Springs are localized by intense faulting and fault intersections. These are indicated on the geologic map, Figure 13. A prominent system of normal-fault scarps follows the western front of the East Range, northward from Granite Mountain, passing east of Kyle Hot Springs. Another prominent fault system trends southward from near the mouth of Klondike Canyon, thence southwestward to pass through the active hot springs. This system continues southwestward through the old, now inactive, spring area. The active and inactive spring areas at Kyle therefore are situated within a belt about two kilometers long by one kilometer wide which contains an unusually large number of faults and fault intersections. Another intense zone of intersecting faults is apparent in alluvium at the western end and northwestern edge of Granite Mountain; however, fracturing here does not appear as intense as at Kyle Hot Springs."

Gravity Results

Gravity data were obtained with a Lacoste-Romberg gravimeter at 204 stations covering approximately 100 square kilometers (Figure 15). Traverse lines were extended into the East Range within Klondike-Sulfur canyons and French Boy Canyon. In general, a station spacing of 500 meters was maintained along geophysical traverse lines. Line separations varied but averaged approximately three kilometers.

Station elevations were estimated from topographic maps to an accuracy of ±0.3 meters on the alluvial fans. Elevation accuracy of ±1.5 meters was estimated for bedrock stations with reported bench mark elevations.

A concrete base for an historical monument at the intersection of the Unionville and Buena Vista Valley roads was used as the gravity base station. Survey readings were tied to the base station daily and the base station was tied to the gravity base at the Winnemucca airport three times during the survey.

The complete Bouguer anomaly, corrected for topography, was calculated using a Bouguer density of 2.67 g/cm^3 (Figure 15). These data were later gridded and machine-countoured, extrapolations made automatically so that the data set fills a rectangular area (Figure 16).

Computer interpretation of the Buena Vista Valley data was carried out in a manner similar to that previously described for the Grass Valley data. The major difference was that the limited aerial coverage made it impossible to define and correct for the regional gradient in Buena Vista Valley.

The apparent depth-to-basement computations were therefore carried out on the Bouguer data. On the basis of interpretation results for the Grass Valley gravity data, we assumed a 0.06 g/cm^3 density contrast and did not run through a range of contrasts. The choice of an initial average depth estimate of 800 feet provided a depth-to-basement map which, after four iterations, gives minimum depth contours conforming reasonably well with the margins of the East Range where Mesozoic and Paleozoic rocks are exposed (Figure 17).

The depth-to-basement contours suggest fault directions and locations similar to the known faults and lineaments seen on aerial photographs. These faults and lineaments are mainly range-bounding faults which trend northeasterly near Granite mountain and then swing almost 90° to a northwesterly strike in the McClure-French Boy Canyon area. The gravity data indicate a shallow dipping pediment extending a mile or two from the range front and then a steeper drop in the center of the valley. Valley fill thicknesses are greater than observed in Grass Valley, amounting to over 5000 feet in the deepest portion within the survey area. The basement structure does not show the same high degree of complexity as that around Leach.

There are no deep drill holes to check the accuracy of the gravity interpretation, but in Figure 18 we show the apparent depth-to-basement profile along line D-D' plotted against a two-dimensional resistivity model fit to the dipole-dipole data. The correlation between gravity and electrical results is not as good as in Grass Valley, due in part, we believe, to the geologic complexity which has made the electrical data very difficult to interpret. There is a good correlation for the basement depth at

6W-7W, and there is good coincidence for a fault structure in the vicinity of 2W.

The gravity contours near the present Kyle Hot Springs show a slight "nosing" effect of 2 mGal which may be due to a small zone of densified rock and spring deposits coming to surface. A broader and more subtle bulge in the gravity contours occurs one to two kilometers south-southwest of Kyle Hot Springs, in the vicinity where hot springs deposits, principally $CaCO_3$, and numerous fault intersections were mapped. To examine this effect in detail, a careful subtraction of the background gravity was made to produce a residual gravity contour map of the local anomaly (Figure 19). The shape of the residual anomaly suggests that initial and secondary fracture permeability along a northeast-trending fault zone may have been largely responsible for the upward percolation of thermal waters leading to mineral precipitation and the gravity anomaly. In this respect, the Kyle system is similar to the Leach system, both showing evidence for a controlling northeast fault. In addition to the inference possible from the gravity data, there is a mapped fault extending northeastward away from the vicinity of Kyle Hot Springs. There are also several northeast-trending lineaments in the area as mapped from aerial photographs.

The abrupt termination of the residual anomaly on the east suggests a northwest-trending fault running parallel to the range margin and coincident with a zone of lineaments on aerial photographs. In this feature we see structural similarities between the Kyle system, the Leach system and two other high heat flow areas in Grass Valley; all four areas occur at the intersection of a northeast-trending and northwest-trending fault. On the other hand, there are some important differences between the two known systems. For example, from the residual gravity anomaly we find that the excess mass associated with the Kyle system is approximately 7.0×10^8 metric tons, nearly three times the mass of the presently more active Leach system. In addition to its greater size, the Kyle system is younger than Leach, only approximately 78,000 years based on relative radon and uranium concentrations in hot and cold spring waters (Wollenberg et al, 1977). Therefore, although the two systems share some geologic similarities, Kyle appears to be the more active. Part of the difference in the precipitation rate can be attributed to higher TDS in the Kyle waters, five times greater, but it also implies a higher average flow rate over the life of the system.

SUMMARY

The complete Bouguer gravity data from surveys in Grass and Buena Vista Valleys were interpreted by means of an iterative two-layer inversion process to obtain the depth to "basement" beneath the valley-fill material. Basement in this sense is an interface which, for a density contrast that must be determined by trial and error, has zero depth at the range fronts and the correct value at points where there is subsurface information; e.g., drill results. Supported by evidence from a deep U. S. Geological Survey drill hole in Grass Valley, a density contrast of $0.06\,g/cm^3$ was found to give a reasonable fit to the Paleozoic rock subcrop and the Paleozoic rock outcrop at the Sonoma Range. The depths to Paleozoic rocks were also found to agree very well with the seismic interpretation obtained by means of a finite element model of seismic reflection and refraction data along part of line E-E', Grass Valley. Gravity and seismic interpretations also give very close agreement on the location and dip of the Hot Springs fault. The gravity interpretation was compared to resistivity models obtained from

dipole-dipole measurements on two lines. In general, the gravity interpretation agrees reasonably well with the configuration of the 150 $\Omega \cdot m$ basement, although the electrical basement is usually 200m to 400m deeper than the density and velocity interface. This difference has not been explained, but could be due in part to resolution and nonuniqueness problems in the resistivity interpretation. One might modify the resistivity model to determine whether a better fit to the density-velocity model is possible. However, this has not been done.

The Grass Valley gravity inversion reveals a complex basement picture which was interpreted in terms of numerous inferred normal faults, some of which have surface expressions. Inferred faults trend mainly north-south and northwest-southeast, but there is also a set of northeast-southwest trending faults. The latter are interesting because they not only conform to the regional trend of hot springs in northwestern Nevada, but two of them are associated with local thermal anomalies. The Hot Springs fault passes through Leach Hot Springs and there is an unexplained 6 HFU thermal anomaly near the Panther Canyon fault, at the mouth of the Canyon. We can speculate that the intersection of older northeast-trending faults and the younger basin and range faults may provide the fracture permeability for ascending thermal waters.

Two local gravity highs, both associated with heat flow anomalies, were analyzed. Excess mass calculations for a 5 mGal residual anomaly centered at Leach Hot Springs gave an excess mass of 2.5×10^8 metric tons, believed due mainly to precipitated silica, and an excess density of about $0.18\ g/cm^3$. This is equivalent to a silicified pipe one kilometer in diameter and 1.9 kilometers in depth extent. This vertical dimension seems sufficient to explain the 100 ms P-wave advance at Leach Hot Springs, but joint modeling of gravity and seismic delay data has not been done.

The smaller Section 14 gravity anomaly was not studied in detail as it was believed to be caused by a shallow basement high, possibly fault controlled, extending northward from the Goldbanks Hills. The coincident 4 HFU anomaly has a convective component, as determined from drilling.

Gravity data from Buena Vista Valley were processed in a similar manner, a density contrast of 0.06 g/cm^3 gave a zero depth-to-basement that conforms closely with outcropping Mesozoic-Paleozoic rocks of the East Range. Over the valley, the depth-to-basement agrees well with the 50 $\Omega \cdot$m electrical basement determined from a model study of dipole-dipole resistivity data. A bulge in the gravity contours two kilometers south of Kyle Hot Springs suggested a densification from precipitating $CaCO_3$, the principal deposit found at Kyle Hot Springs. A careful subtraction of the background gravity produced a broad 2 mGal local residual anomaly. The anomaly shape suggests it may be localized by northeast and northwest-trending faults, similar to the fault directions at Leach Hot Springs. The excess mass calculated for the anomaly is approximately 7.0×10^8 metric tons, nearly three times larger than the excess mass for the Leach anomaly. On the other hand, the age of the Kyle system, determined from radioelement abundances (Wollenberg et al, 1977), is approximately 78,000 years, considerably less than the age determined for the Leach system. This implies that the average flow rate within the Kyle system must be considerably greater. Part of the difference in mass can be attributed to the fact that the total dissolved solids in the Kyle discharge waters is five times greater than at Leach

(Wollenberg et al, 1977). Nevertheless, the evidence suggests that the Kyle system may be more active and more promising as a geothermal resource than Leach.

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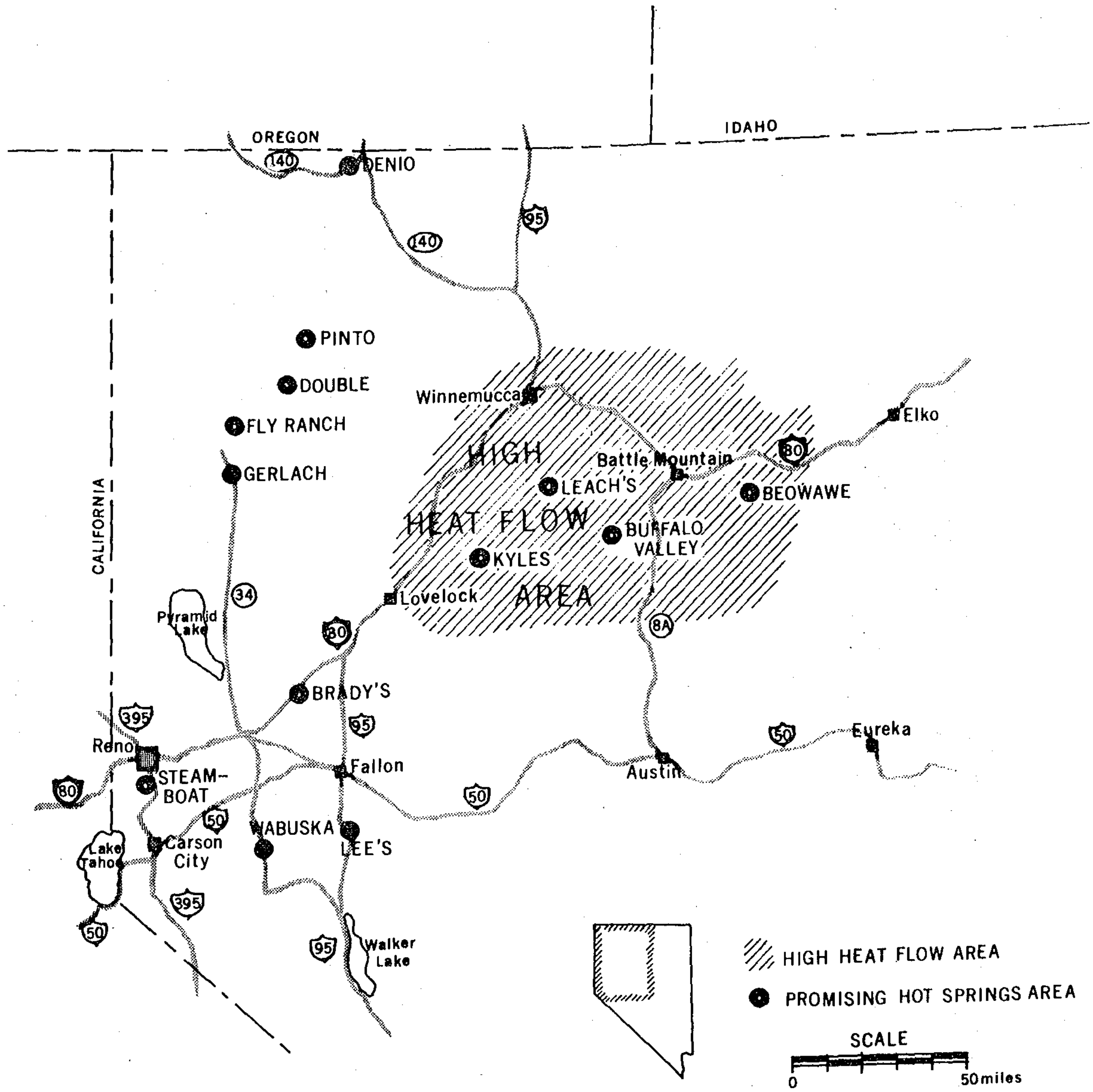
Fig. 19 Local Residual Gravity Anomaly, Kyle Hot Springs Area, Buena Vista Valley, Nevada

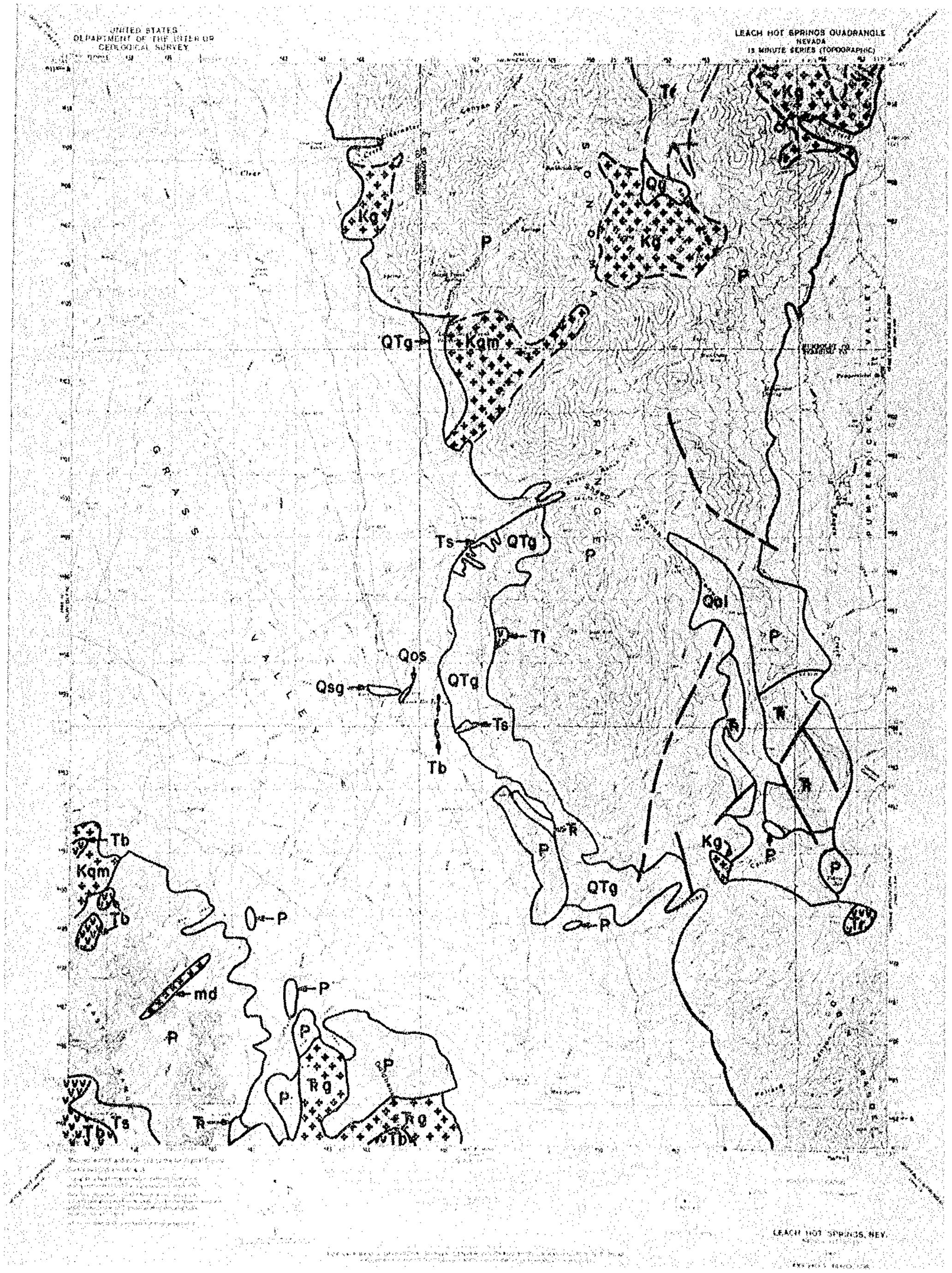
0 0 0 0 4 9 0 4 0 8 5



Hot Springs in Northwestern Nevada

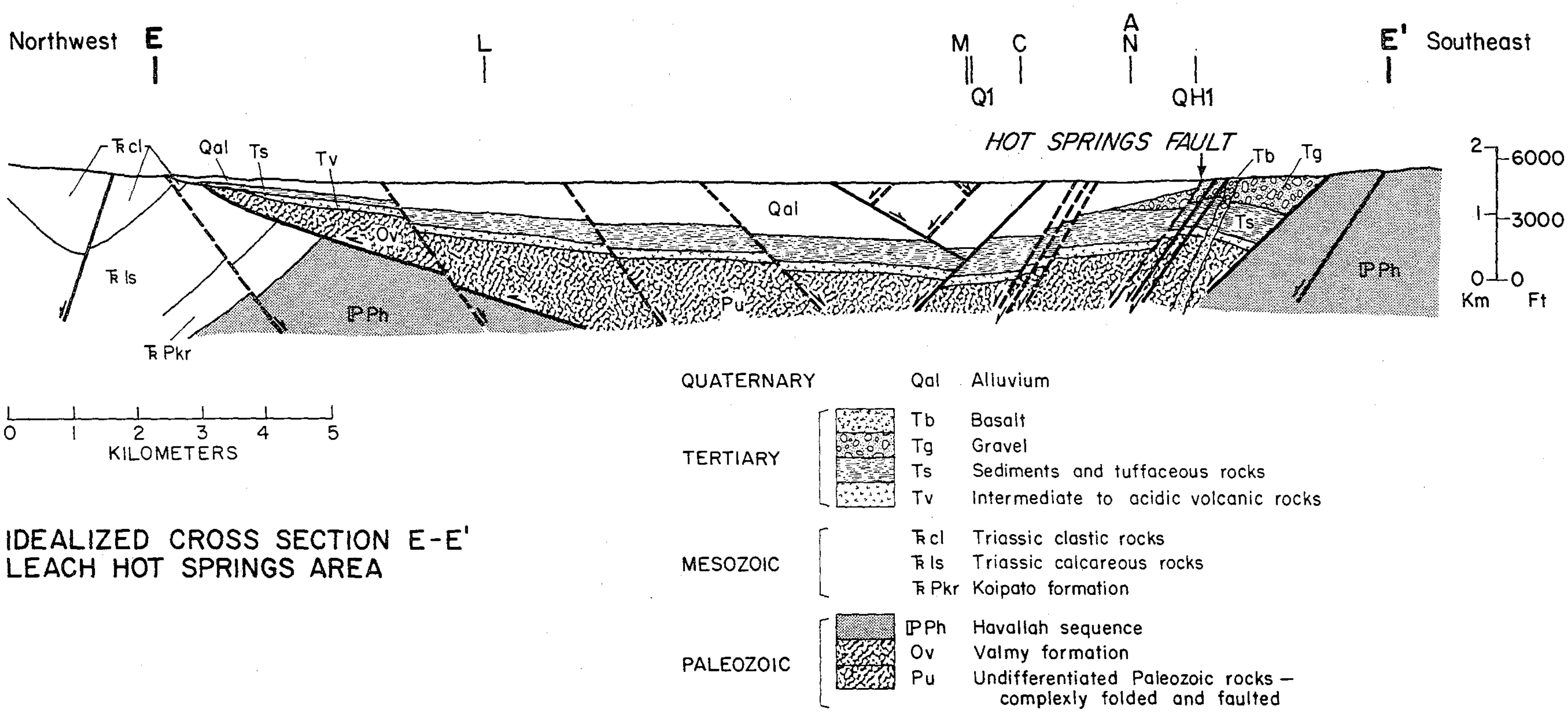
XBL 735 676

Fig. 1



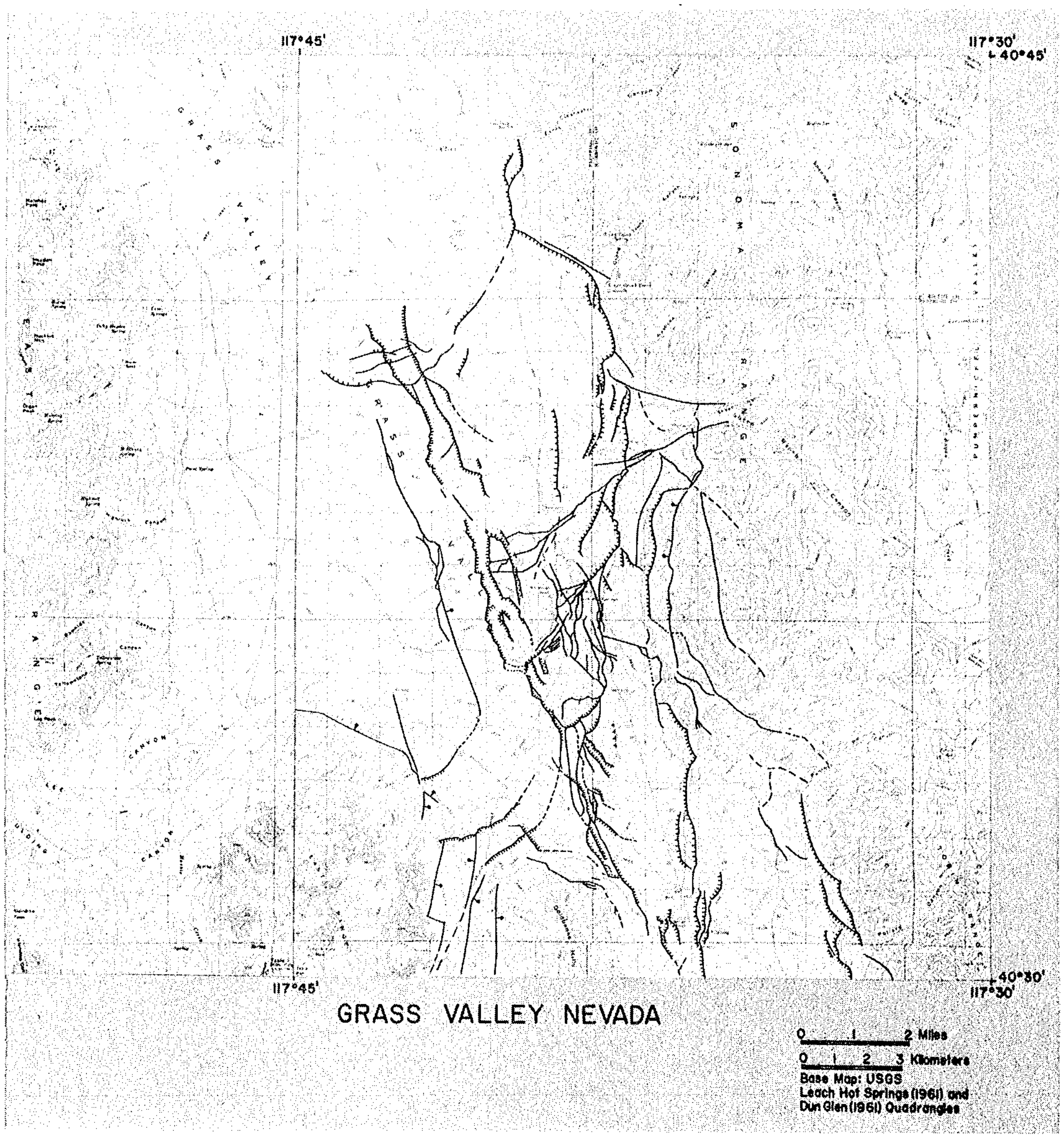
CBB 751-49

Fig. 2



IDEALIZED CROSS SECTION E-E'
LEACH HOT SPRINGS AREA

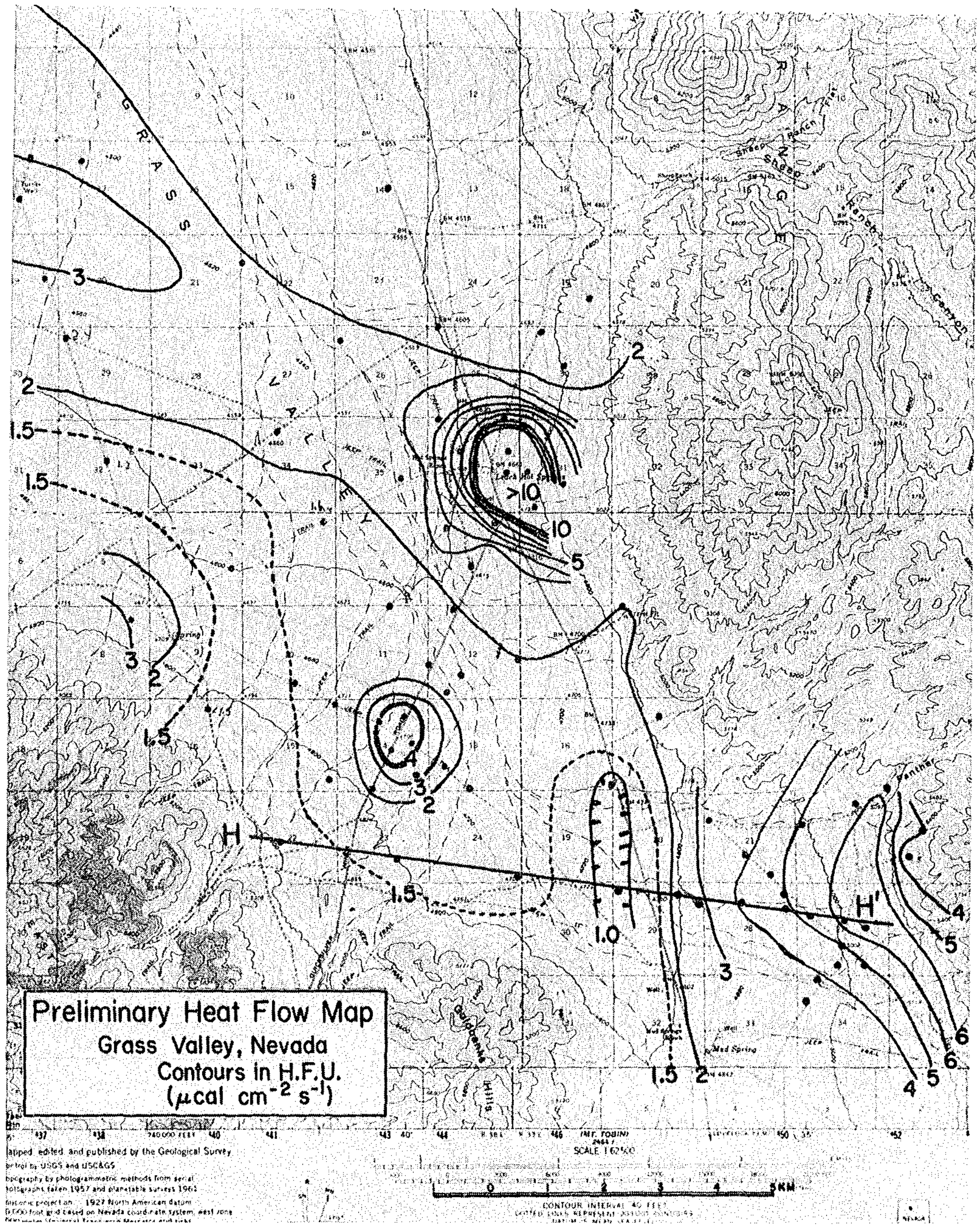
Fig. 3



CBB 7410-7615

Fig. 4

0 0 0 0 4 9 0 4 0 8 7



XBB 774-3595

Fig. 5

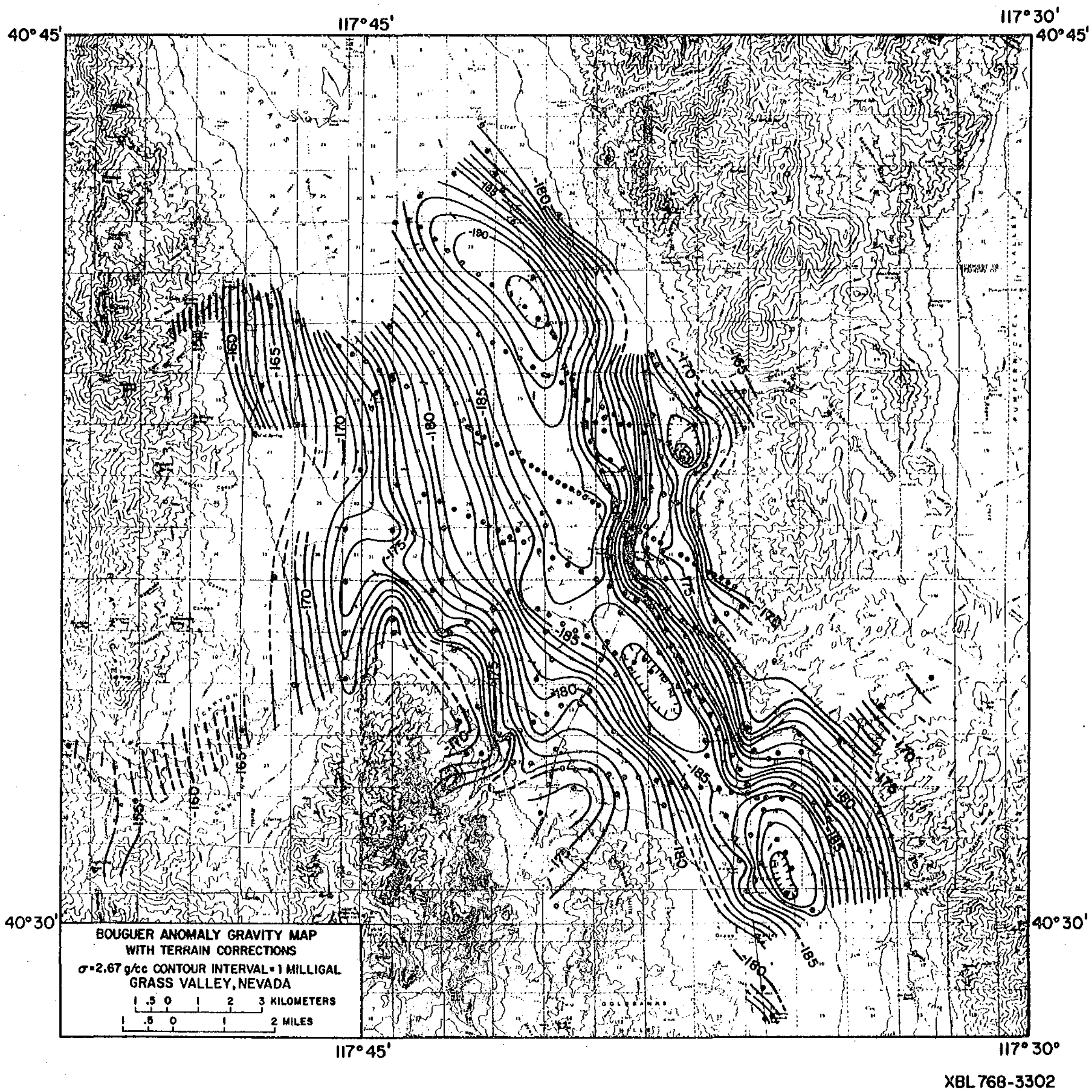
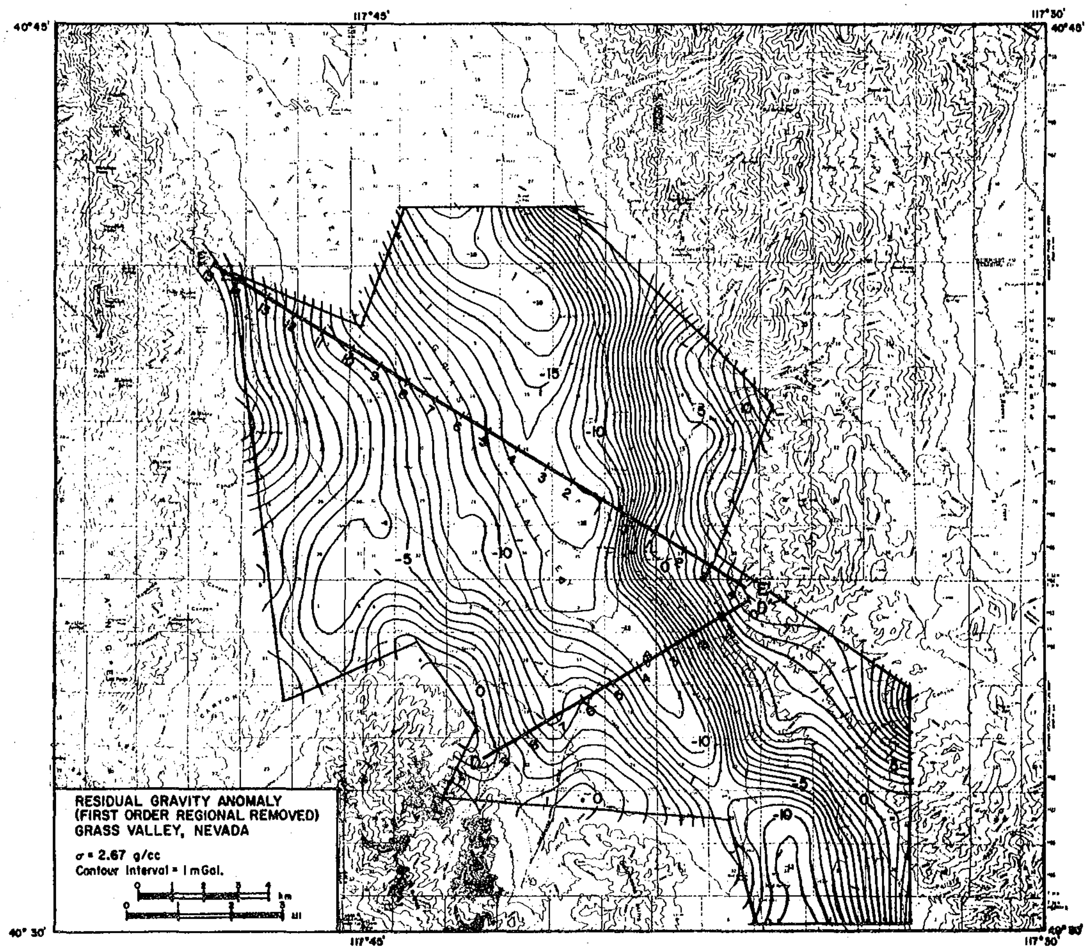

117°45'
117°30'
40°45'
40°45'
40°30'
40°30'
117°45'
117°30°
BOUGUER ANOMALY GRAVITY MAP
WITH TERRAIN CORRECTIONS
σ=2.67 g/cc CONTOUR INTERVAL=1 MILLIGAL
GRASS VALLEY, NEVADA
KILOMETERS
MILES
XBL 768-3302

Fig. 6



XBL 779-1873

Fig. 7

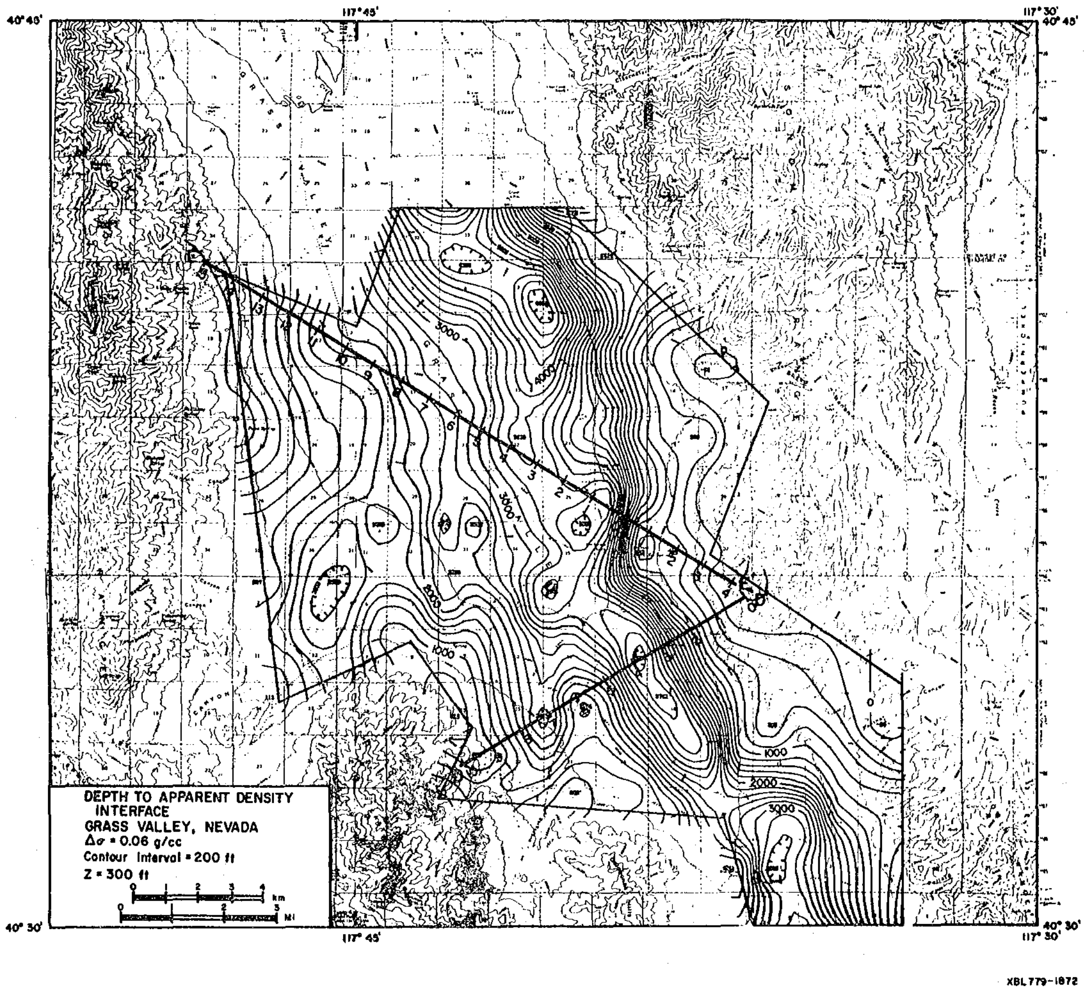
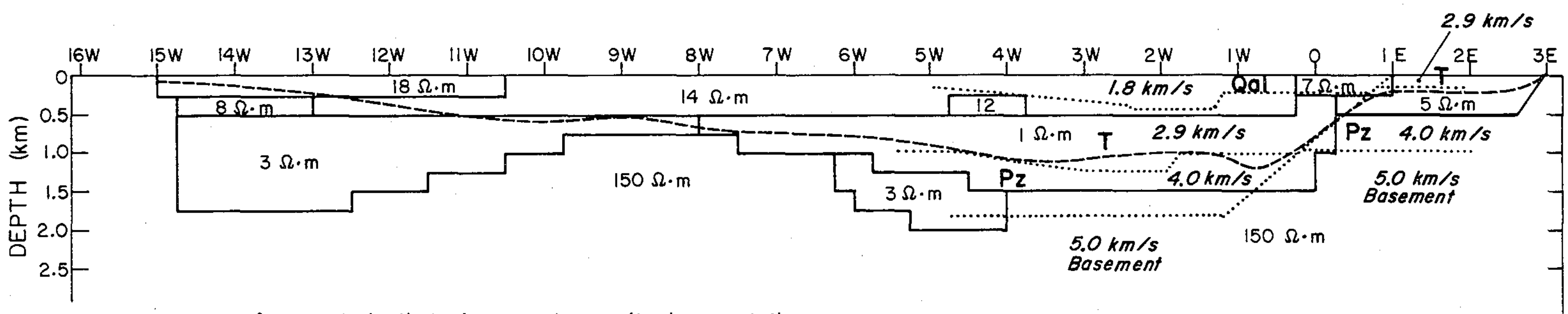

DEPTH TO APPARENT DENSITY INTERFACE
GRASS VALLEY, NEVADA
Δσ = 0.06 g/cc
Contour Interval = 200 ft
Z = 300 ft
40° 40'
117° 45'
117° 30'
40° 45'
40° 30'
3000
1000
2000
XBL 779-1872

Fig. 8



- - - - - - - - Apparent depth to basement, gravity interpretation
$\Delta\sigma = 0.06$ g/cm^3

[1 Ω·m] Finite difference interpretation, dipole-dipole resistivity
a = 1 km

··············· Finite element seismic reflection-refraction interpretation

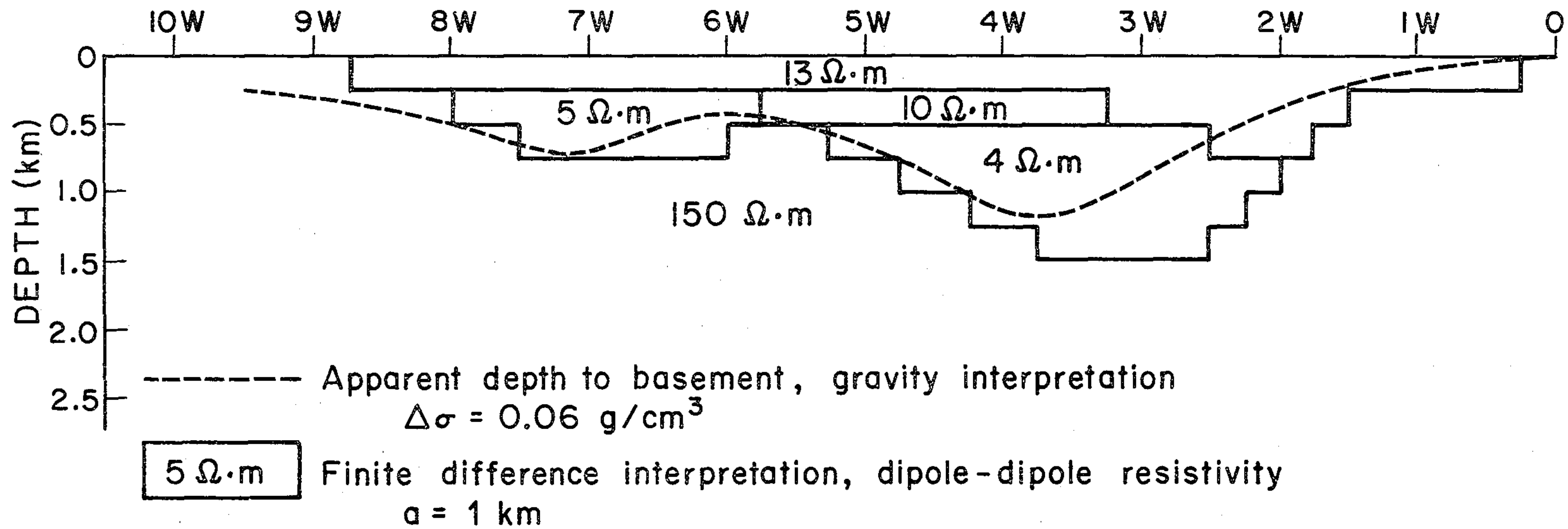
Qal = Quaternary alluvium
T = Tertiary sediments and volcanics
Pz = Paleozoic sediments

GEOPHYSICAL INTERPRETATION PROFILE
LINE E-E'
Grass Valley, Nevada

Scale: Horizontal = Vertical
1:50,000

XBL 779-1871

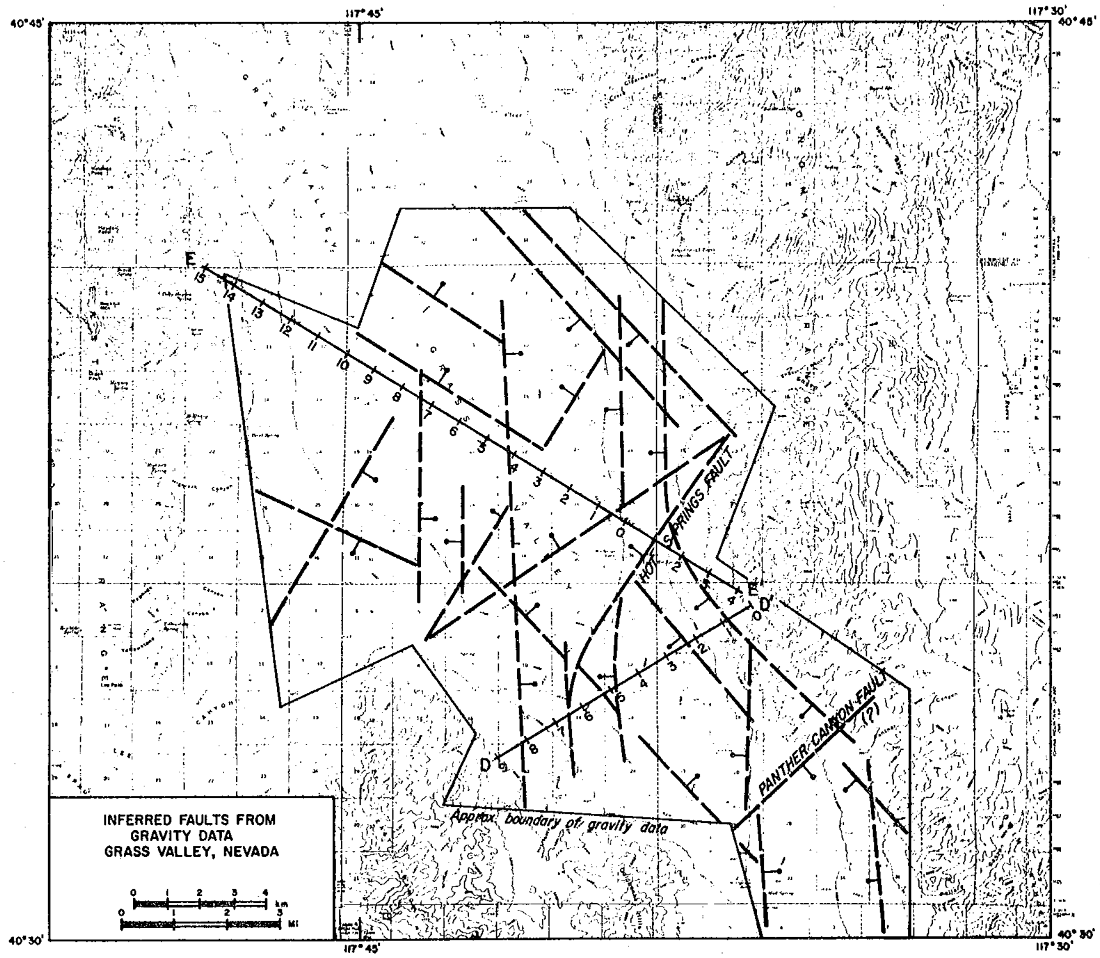
Fig. 9



GEOPHYSICAL INTERPRETATION PROFILE
LINE D-D'
Grass Valley, Nevada
Scale: Horizontal = Vertical
1:50,000

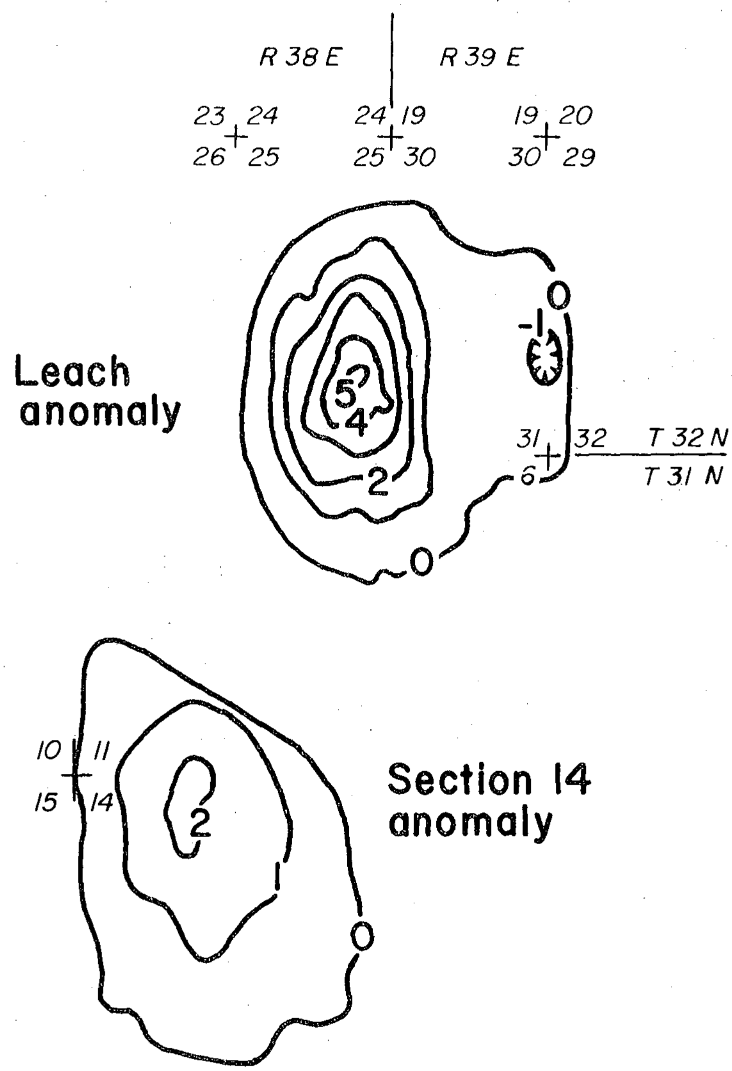
XBL 779-1868

Fig. 10



XBL779-1874

Fig. 11



RESIDUAL GRAVITY ANOMALIES
DUE TO POSSIBLE SILICIFIED BODIES
(from First-Order-Regional Corrected
Bouguer Map)

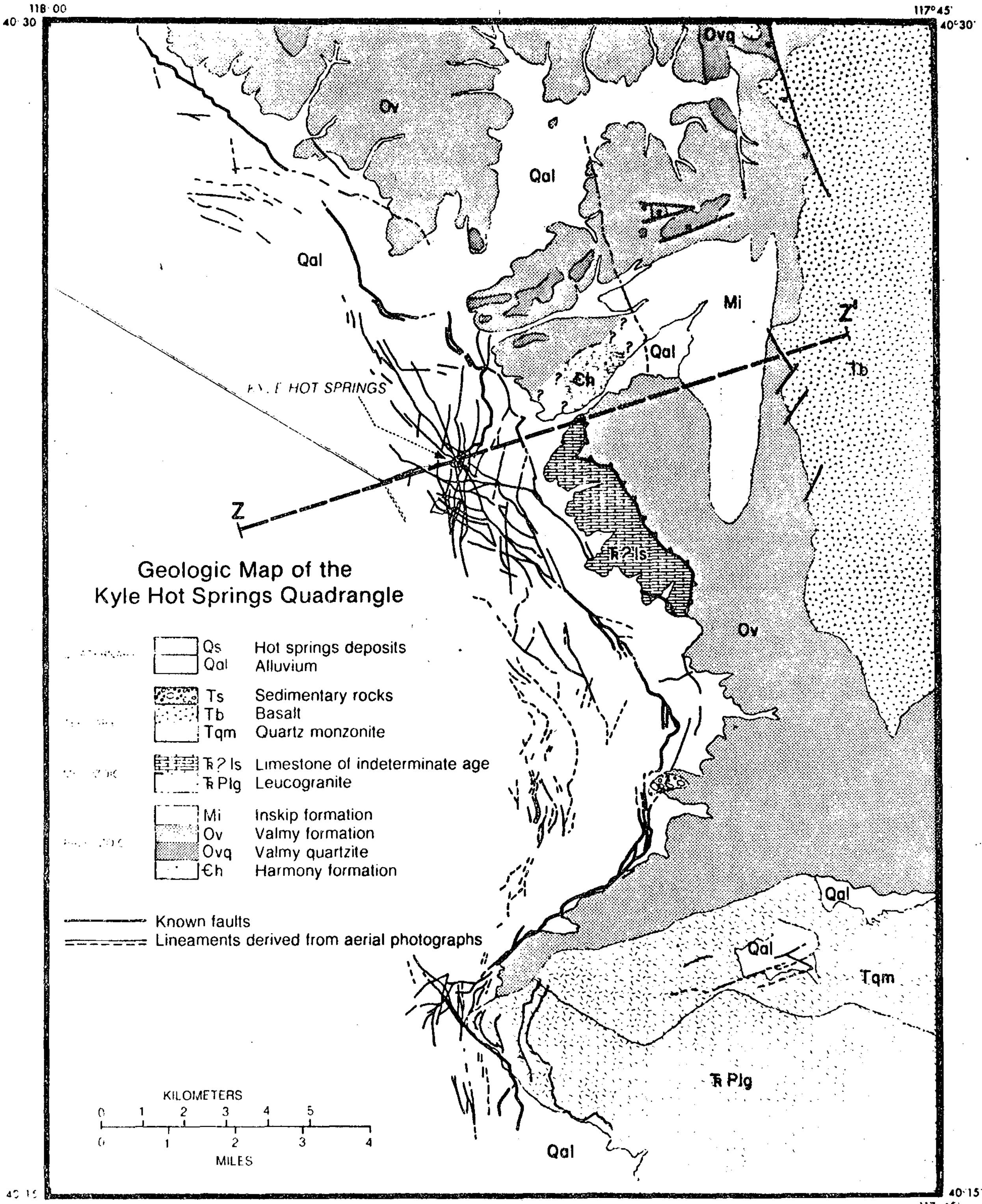
Grass Valley, Nevada

Scale: 1:62,500
Contour interval = 1 mGal

XBL 779-1870

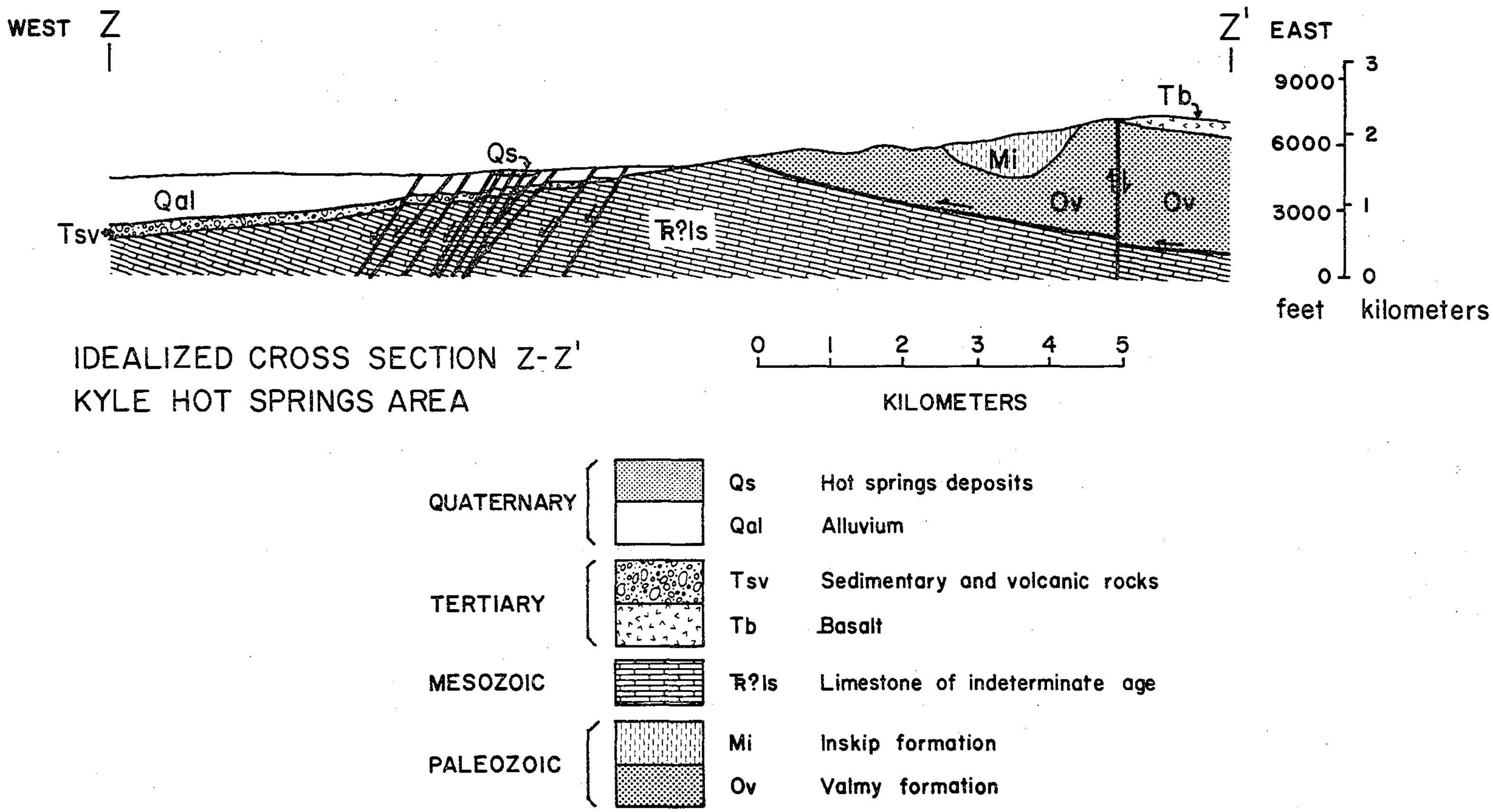
Fig. 12

0 0 0 0 4 9 0 4 0 9 1



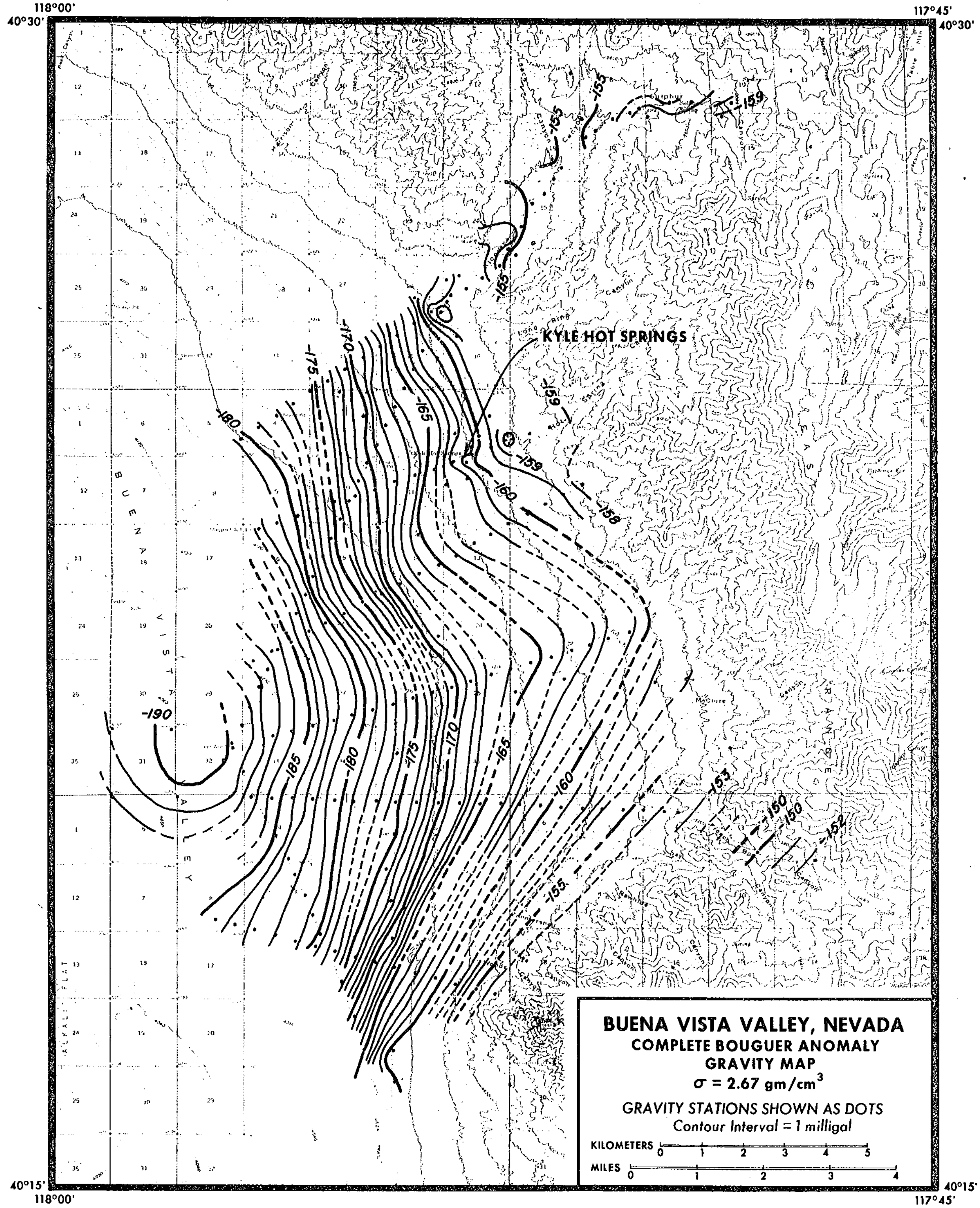
XBL 7611-4415

Fig. 13



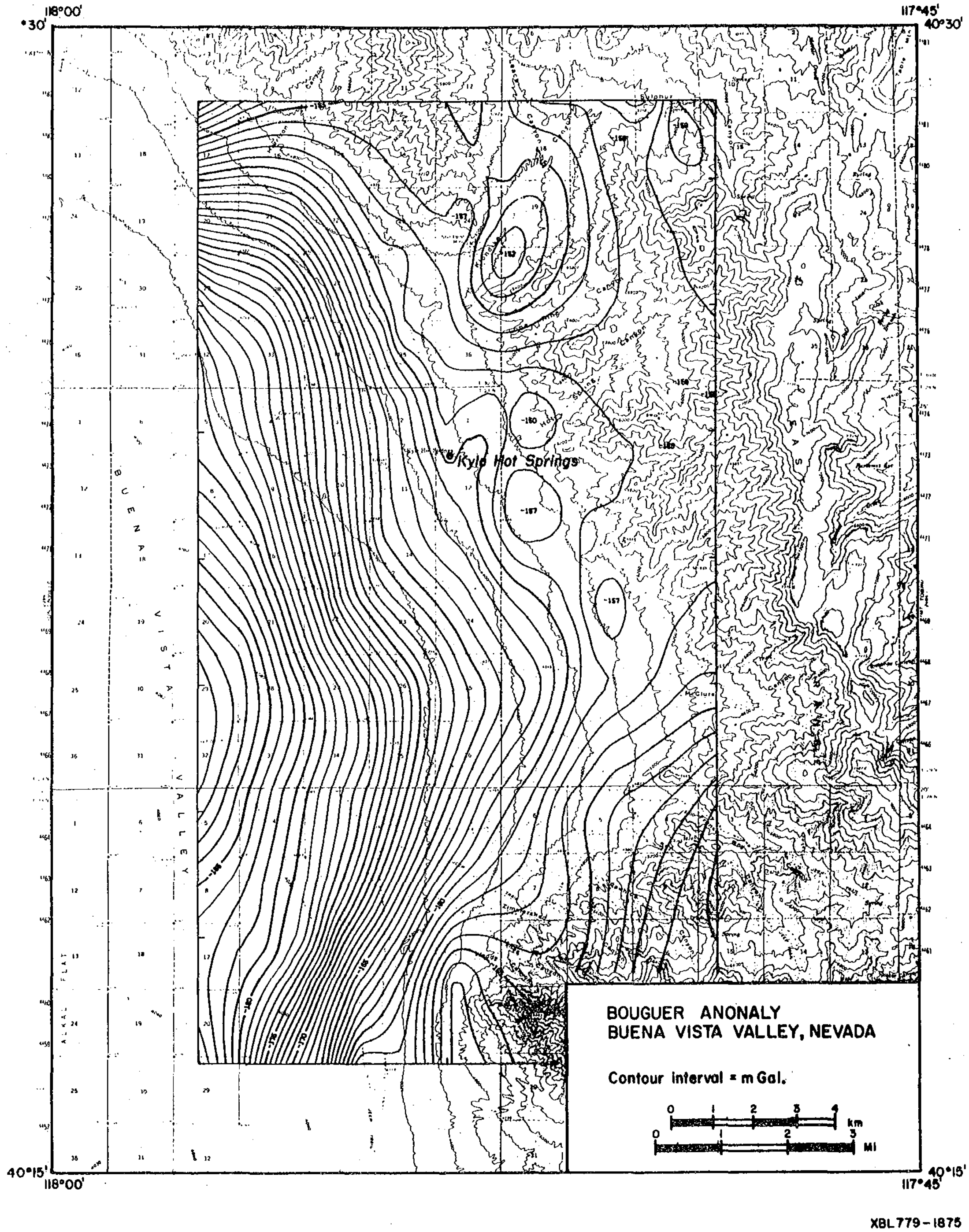
XBL 7612-10937

Fig. 14



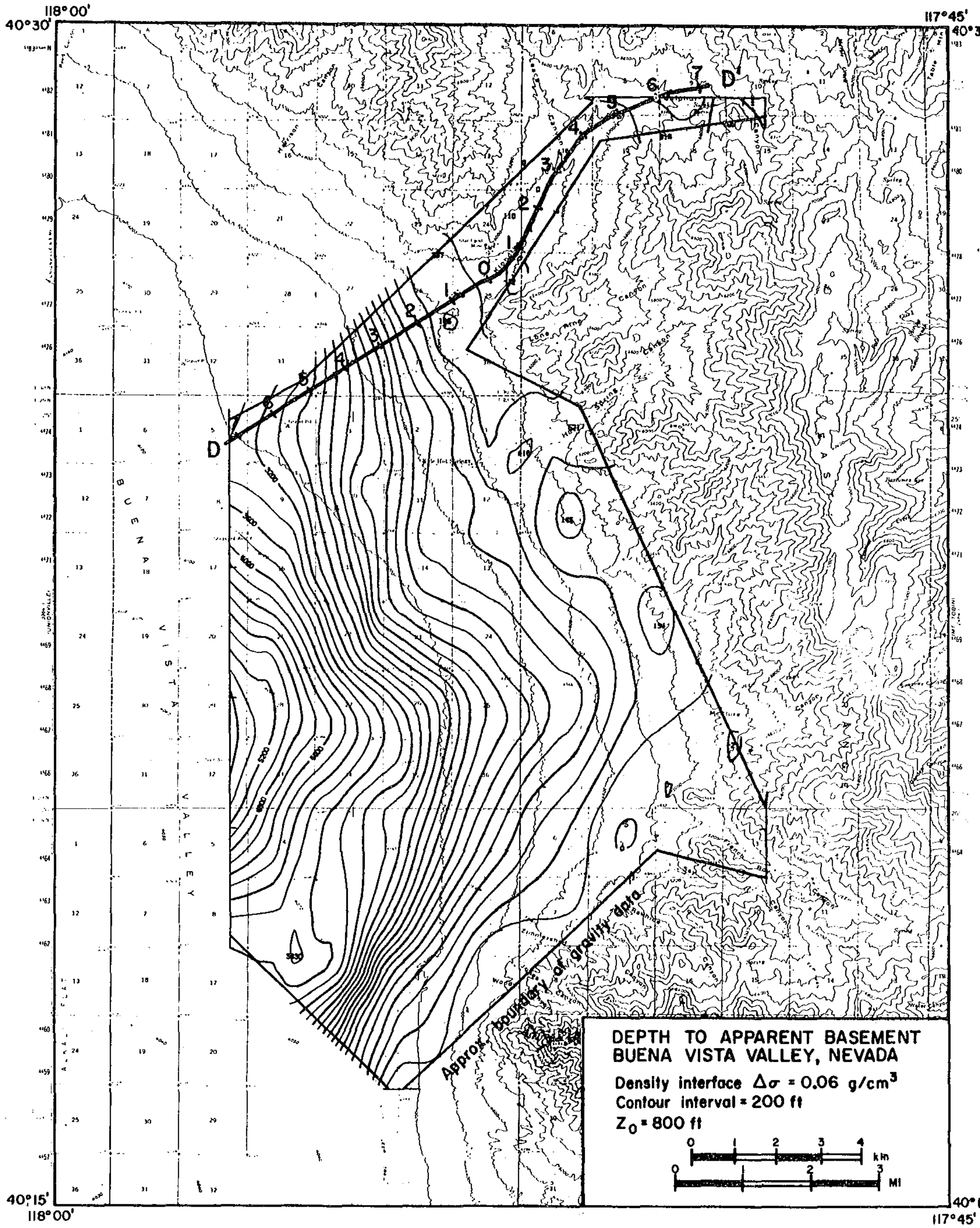
XBL 7612-10926

Fig. 15



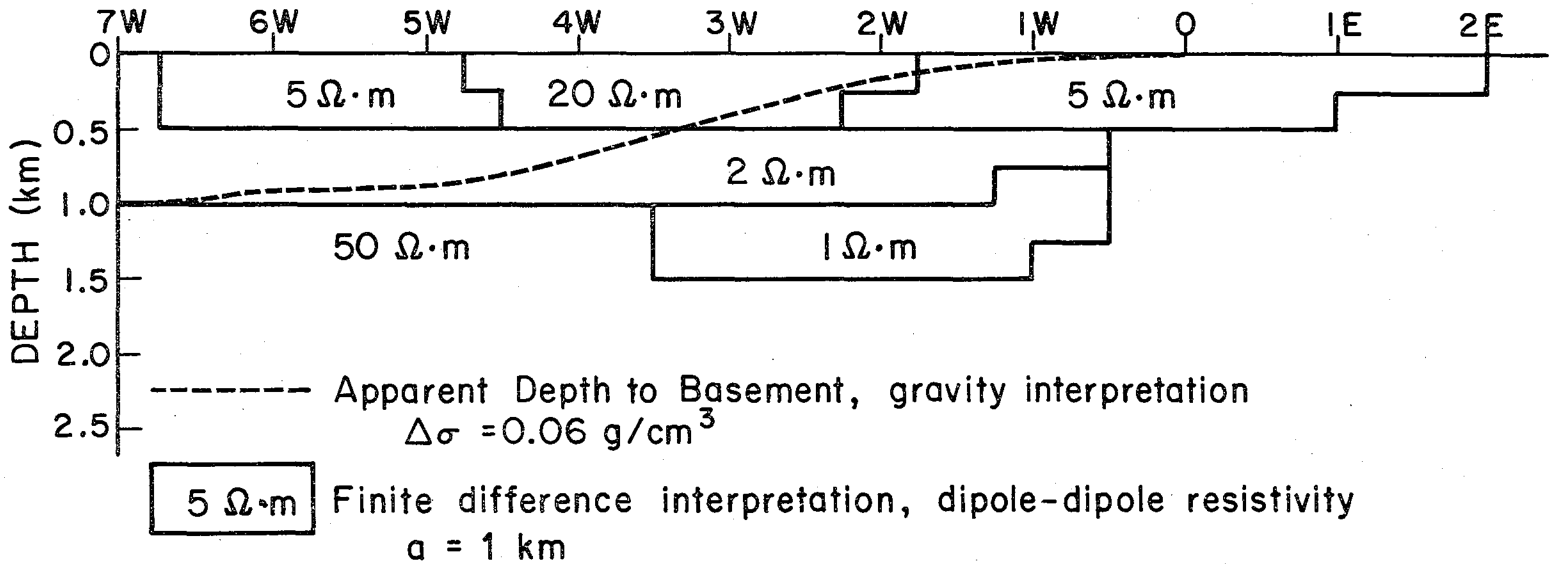
118°00'
117°45'
40°30'
40°15'
BOUGUER ANONALY
BUENA VISTA VALLEY, NEVADA
Contour interval = m Gal.
km
MI
Kyle Hot Springs
BUENA VISTA VALLEY
XBL779-1875

Fig. 16



XBL 779-1947

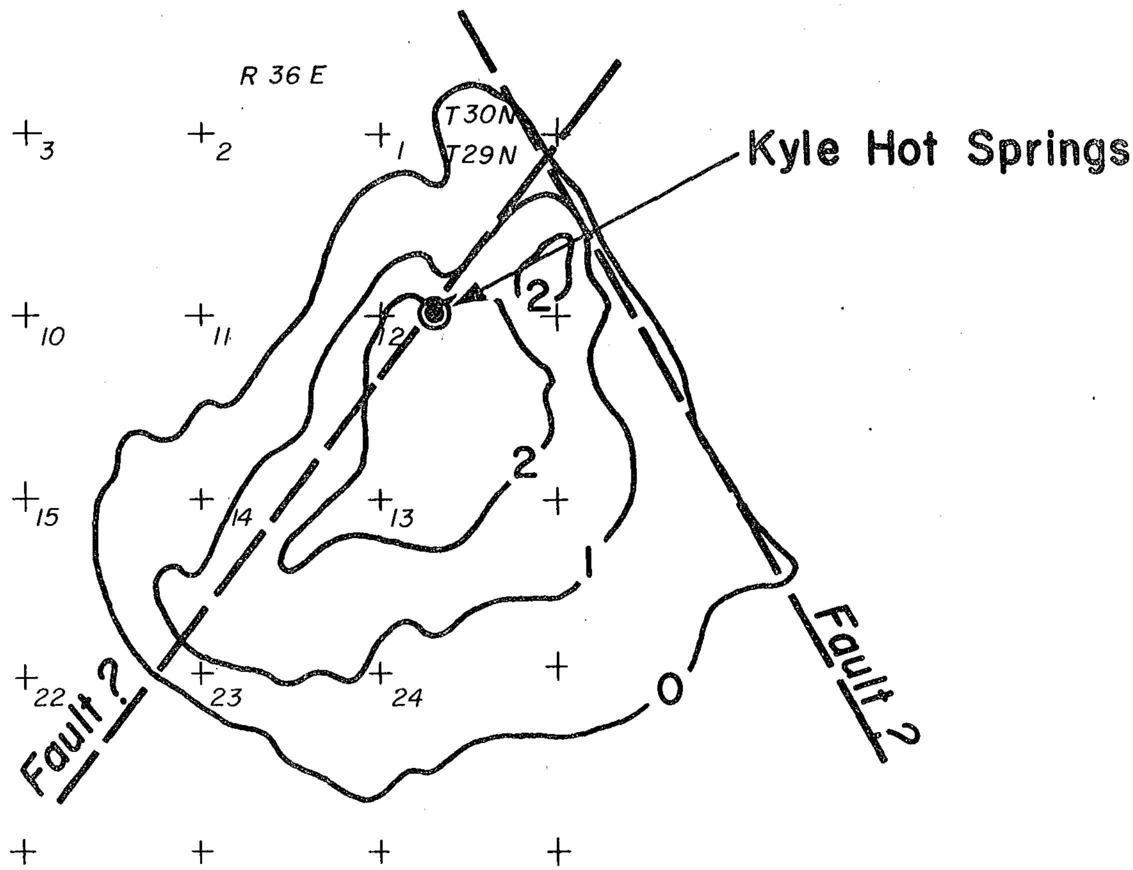
Fig. 17



GEOPHYSICAL INTERPRETATION PROFILE
LINE D-D'
Buena Vista Valley, Nevada
Scale: Horizontal = Vertical
1:50,000

XBL 779-1867

Fig. 18



RESIDUAL GRAVITY ANOMALY
KYLE SYSTEM
Buena Vista Valley, Nevada
Scale: 1:62,500
Contour interval = 1 mGal

XBL 779-1869

Fig. 19