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GEOLOGICAL SURVEY

Geophysical studies of the Syncline Ridge area Nevada Test Site, Nye County, Nevada

by

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Abstract

A wide variety of geophysical methods were employed to study a proposed nuclear waste site at Syncline Ridge on the Nevada Test Site, Nev. The proposed site was believed to be a relatively undisturbed synclinal structure containing a thick argillite unit of Mississippian age, the Eleana Formation unit J, which would be the emplacement medium. Data acquisition for the geophysical studies was constrained because of rugged topography in a block of Tippipah Limestone overlying the central part of the proposed site.

This study employed gravity, magnetic, seismic refraction and reflection, and four distinct electrical methods to try and define the structural integrity and shape of the proposed repository medium. Detailed and regional gravity work revealed complex structure at the site. Magnetics helped only in identifying small areas of Tertiary volcanic rocks because of low magnetization of the rocks. Seismic refraction assisted in identifying near surface faulting and bedrock structure. Difficulty was experienced in obtaining good quality reflection data. This implied significant structural complexity but also revealed the principal features that were supported by other data. Electrical methods were used for fault identification and for mapping of a thick argillaceous unit of the Eleana Formation in which nuclear waste was to be emplaced.

The geophysical studies indicate that major faults along the axis of Syncline Ridge and on both margins have large vertical offsets displacing units so as not only to make mining difficult, but also providing potential paths for waste migration to underlying carbonate aquifers. The Eleana Formation appeared heterogeneous, which was inferred to be due to structual complexity. Only a small region in the northwest part of the study area was found to contain a thick and relatively undisturbed volume of host rock.

Deep electrical soundings identified a very conductive region in the crust below Syncline Ridge at depths shallower than 10 km. Similar conductive regions have been observed associated with geothermal systems in the western United States and imply the potential for a blind geothermal system below Syncline Ridge.

The geophysical studies provided negative evidence for the suitability of the site for a nuclear waste repository. This evidence was a significant factor in the decision on April 20, 1978 to discontinue most work in the Syncline Ridge area and actively pursue exploration of alternate sites on NTS.

Introduction

In late November of 1977 surface geophysical work was started within the Syncline Ridge area of the Nevada Test Site (NTS, fig. 1) as one phase of investigations of a potential repository for nuclear waste. The targeted host medium for the repository was a thick unit of Mississippian argillite belonging to the Eleana Formation of Devonian and Mississippian age. Previous geological work and 14 drill holes in the site area had defined a relatively simple synclinal structure in the Eleana Formation. Objectives of the geophysical activity were to help determine the structural integrity and the available mass of the argillite.

The geophysical work described in this paper revealed significant structural complexity in the site area. This structural complexity was an important factor in a decision on April 20, 1978, to discontinue most efforts at Syncline Ridge and to pursue more favorable appearing sites. This report summarizes the surface geophysical work which was done at the site.

Geography and Geology

Syncline Ridge is located on the western edge of Yucca Flat, one of the Basin and Range valleys situated in the northeastern part of NTS about 97 km (60 miles) northwest of Las Vegas, Nev. (fig. 1). Syncline Ridge is a north-northeast trending topographic high extending from the northeast flank of Shoshone Mountain. The ridge is quite rugged with about 365 m (1200 ft) of topographic relief in the area of investigation. To the east of the ridge is Yucca Flat and to the west, separated by a narrow valley, is the Eleana Range. The rugged topography of the ridge proper limited the acquisition of extensive geophysical data to the surrounding pediment slopes and valleys.

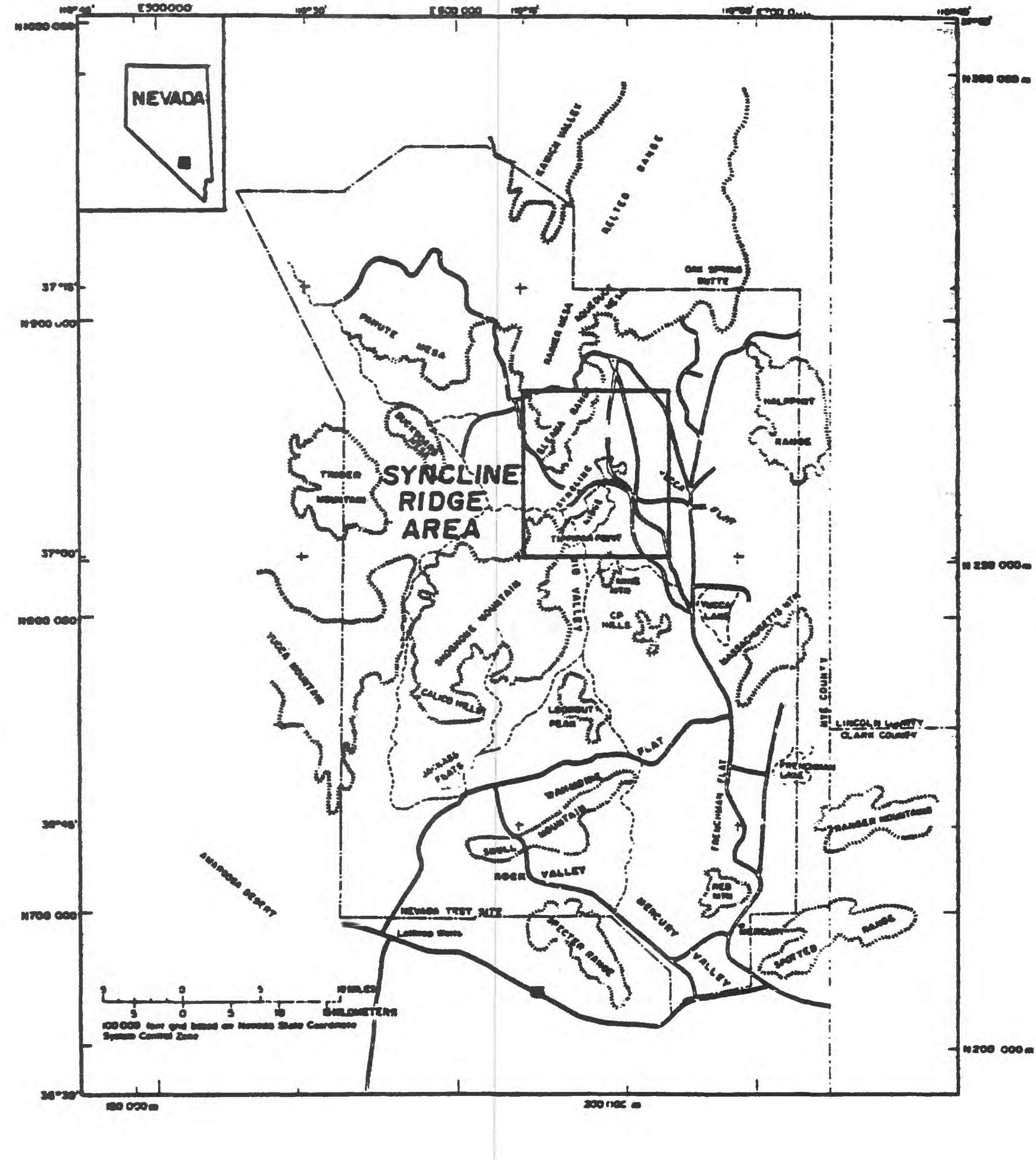

Fig. 1.--Index map showing the location of the Nevada Test Site and the Syncline Ridge area.

The geology of Syncline Ridge has been well described by Hoover and Morrison (1980) and will only be briefly summarized here. A summary geologic map from Hoover and Morrison (1980) is shown in figure 2. Structurally the Ridge is a northeast-plunging syncline with an axial fault mapped just southeast of the ridge crest. This axial fault where exposed is tight, narrow, and shows only minor displacement. The ridge is divided into a southern, central and northern block by two southeast-trending Mesozoic lateral faults (fig. 2). One originates in Gap Wash in the Eleana Range dividing the main part of Syncline Ridge in half. The other originates in the Eleana Range south of Pediment Wash cutting the ridge near the junction of Canyon and Gap Washes. The central block was of principal concern in this investigation because it was believed to contain the largest volume of relatively undisturbed argillite.

The principal lithologies in the study area are the Tippipah Limestone and the Eleana Formation. The Tippipah makes up the bulk of the ridge proper. Its outcrop pattern will be used as a reference in some of the following discussion.

In figure 2 the Tippipah is mapped as lying conformably on the Eleana Formation although drill hole and stratigraphic evidence suggests that the Tippipah may be in thrust contact in this area (Hoover and Morrison, 1980). The majority of the Tippipah exposed in the area consists of relatively pure light-grey to medium-grey limestone. Unit J of the Eleana Formation crops out or is present beneath shallow alluvium surrounding the ridge and is the potential repository medium. Unit J has a stratigraphic thickness of about 110m. It is divided into three subunits, a lower of 300 m thickness consisting of black siliceous argillite and siltstone; an argillite subunit 700 m thick 98% made up of argillite and an upper quartzite subunit 100 m

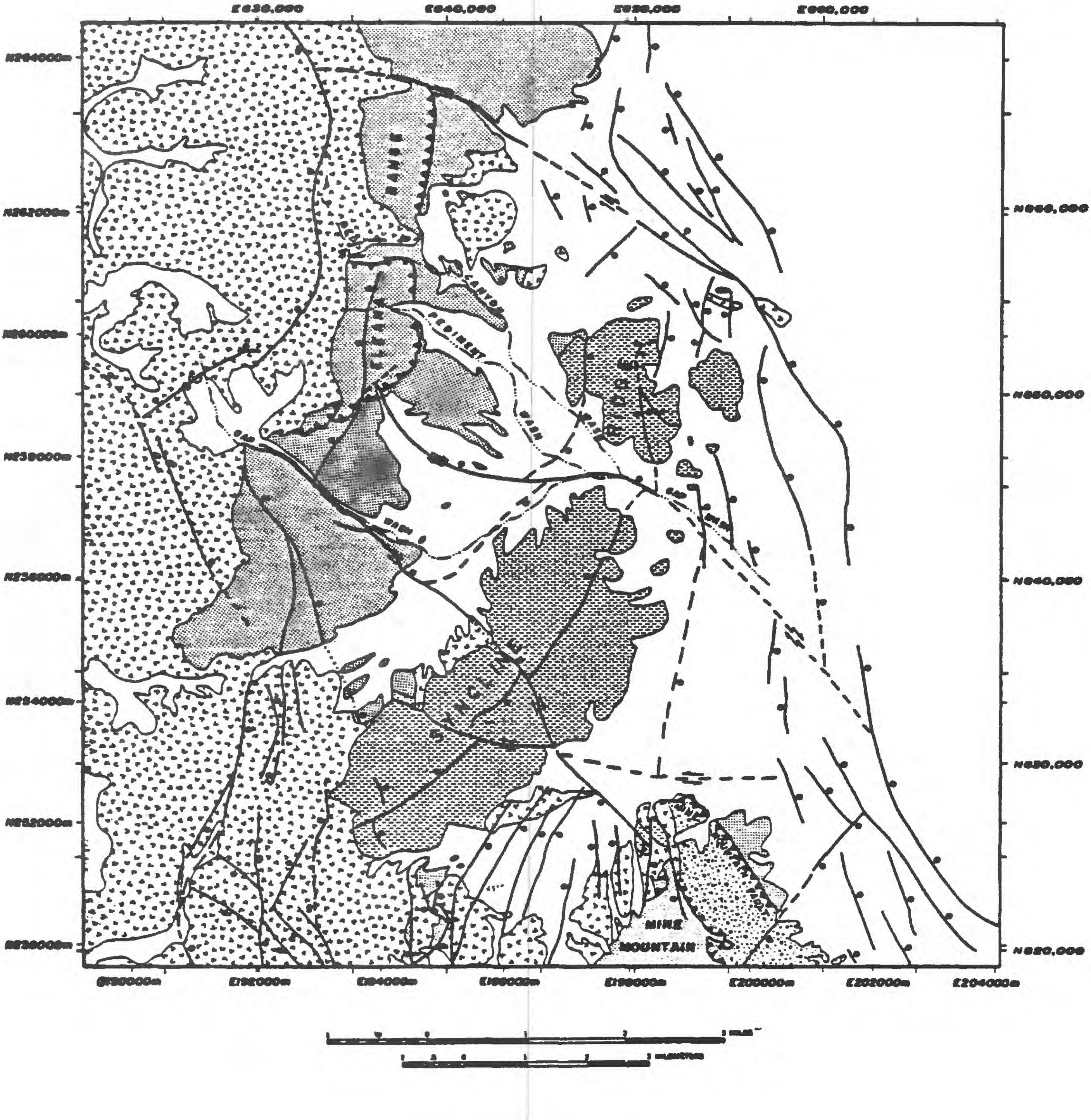

Figure 2.--Geologic map of the Syncline Ridge Area showing principal stratigraphic units and major structures, from Hoover and Morrison (1980).

thick consisting of about 30% argillite. The underlying unit I of the Eleana Formation is at least 2000 m below the surface in the central part of the area (Hoover and Morrison 1980). Limited exposures of Tertiary volcanics crop out adjacent to the Tippipah in the southern block. Tertiary and Quaternary alluvial deposits overlie the Eleana surrounding the ridge and are generally less than 50 m thick. One drill hole near the confluence of Pediment and Gap Washes encountered 122 m of alluvium. Prior gravity work has identified a small graben between the southern block and Mine Mountain where the alluvium may reach 300 m in thickness (Orkild, 1963).

Geophysical Investigations

A wide variety of geophysical investigations were made in an attempt to define the size and shape of the argillite subunit of unit J and to address the question of structural integrity of the Eleana. The presence of faulting was a major concern because it could provide paths for the escape of radio nuclides and disrupt the continuity of the repository. Some of the studies were designed to address principally the question of faulting. Shallow electrical investigations also were conducted on the east side of the ridge looking for evidence of Quaternary faulting which might have disturbed the alluvium.

This report will summarize the results of the various investigations discussing each method separately before integrating the results. Primary responsibility for the gravity and magnetic studies belongs to W. F. Hanna, for the seismic work, L. W. Pankratz, the slingram work V. J. Flanigan, the Schlumberger soundings (VES) L. A. Anderson, while the remaining work and general coordination fell to D. B. Hoover.

Previous Work

D. L. Healey (1978) had made a thorough regional gravity survey which was available and identified the principal faults bounding the site and information on alluvium thickness particularly on the eastern side of the site. Fourteen drill holes up to 1414 m deep in the central and northern block also provided important lithologic and physical property information for control of the surface geophysical studies (Hoover and Morrison, 1980; Hodson and Hoover, 1979). An unpublished report (Word and others, 1977) on a magnetotelluric survey in northern Yucca Flat for Lawrence Livermore Laboratories was generously made available by Dr. P. Kassameyer. Based on one-dimensional modeling the survey showed a conductive geoelectric section with resistivities decreasing with increasing depth to values of 2 to 10 ohm-meters at 10 km. Three cross-sections each showed that the conductive material became much shallower than 10 km on the west end of Yucca Flat. The most anomalous station was closest to Syncline Ridge 3 km due east of the northern block which showed resistivities less than 1 ohm-meter below a depth of 3 km.

In addition to the above, an 8.5 mile vibroseis reflection survey run in 1972 as part of the Yacht Prospect was available (Mossman and Garrette 1972). Two lines were run, one normal to the structure and through Gap Wash between the northern and central block and a second parallel to the structure on the east flank of the central block. The purpose of the survey was to define the geologic structure of the Eleana Formation to 1800 m depth (6000 ft). The results of the survey were ambiguous due to discontinuous reflection events. However the unpublished report concludes that the structure east of the ridge is more complex than to the west, that major faulting may exist just east of the synclinal axis with additional faulting or severe folding east of this.

Acknowledgments

Much of the work was done with the assistance of the geologists of Fenix and Scisson, Inc. whose assistance is gratefully acknowledged. The large amount of work that was done in a short time would not have been possible without the active support of many people of the USGS whose extensive knowledge of NTS made our job considerably easier. In particular thanks go to D. C. Mueller, G. D. Bath, R. D. Carroll and D. L. Healey for making their knowledge of previous geophysical studies available, and to Dave Hoover, the principal investigator for geologic studies, who contributed much to developing our models.

Geophysical Studies

Gravity and Magnetics

The important question of the subsurface distribution of unit J argillite of the Eleana Formation can best be analyzed by first establishing the regional geologic and geophysical framework upon which more detailed surveys can later be built. Two basic regional geophysical surveys have been made, one delineating Bouguer gravity anomalies and the other aeromagnetic anomalies. These surveys have as their chief function the identification of the principal subsurface contrasts of rock density or magnetization which may mark important structural features or changes in lithology.

Gravity Data

Gravity data in the study area, shown in figure 3, are derived from two independent surveys: a regional survey of D. L. Healey (1978) and a local survey by W. F. Hanna and H. E. Kaufmann in the central block. Most of the stations in both surveys were measured using LaCoste-Romberg meter G-177. All of the data have been corrected for combined tidal attraction and referenced to station Wa-128 at the Las Vegas, Nev., airport (Wollard and Rose, 1963). Bouguer gravity values were computed using a reduction density of 2.67 g/cm^3 and include terrain correction to a radius of 166.7 km.

The principal source of error in the gravity contour map is in the determination of station elevations. Although elevations on the margin of the area were obtained by precise leveling surveys (Healey, 1978) those in the central part of the trapezoidal shaped area (figure 3) were determined by interpolation between contour lines on the USGS Tippipah Spring, Nev., 7 1/2 minute topographic map. Because of this, interpolated elevation accuracy is estimated to be 3 m (10 ft), giving an uncertainty in Bouguer gravity of about 0.6 mgal.

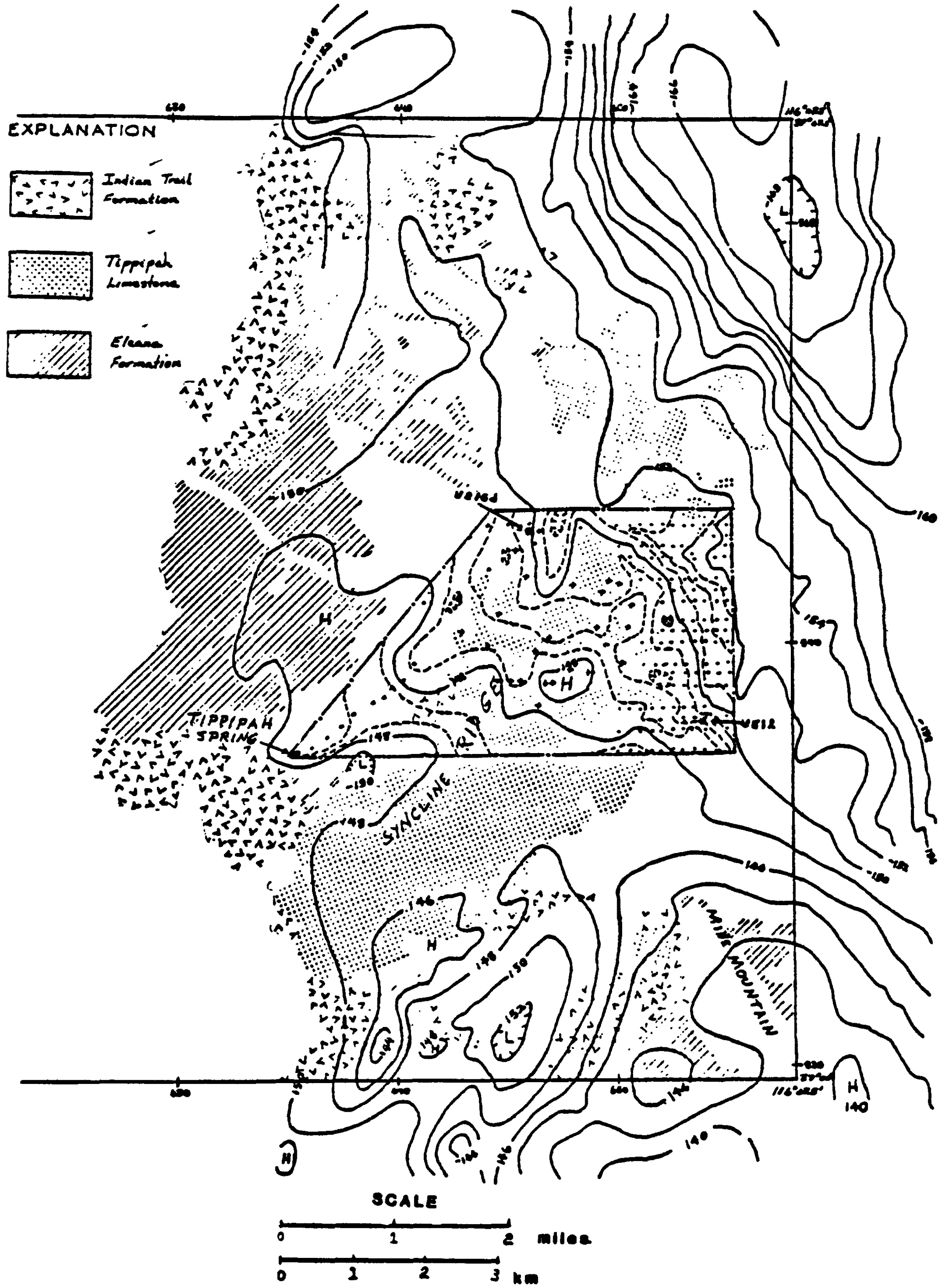

Figure 3.--Bouguer gravity anomaly maps, showing geologically mapped Eleana Formation, Tippipah Limestone, and Indian Trail Formation (Orkild, 1963) and boreholes UE16d and UE11 from which rock density data were obtained. Contour interval: 1/2 and 2 mgal. Cross: Station of W. F. Hanna and H. E. Kaufmann; Dot: Station of D. L. Healey (1978). Reduction denisty: 2.67 gm/cm^3. Terrain corrections made to a station radius of 166.7 km "H" indicates a relative high; hachures denote relative lows. Trapezoidal boundary delineates study area.

The principal source of rock density information are gamma-gamma logs from boreholes UE16d and UE11 (fig. 3) in the central block. These logs provide density information to depths of 808 m and 1606 m respectively in each hole. These logs show that there is no significant density contrast between subunits of the Eleana or between the Eleana and the Tippipah Limestone. The only appreciable density contrast occurs between Quaternary alluvium and the underlying Paleozoic rocks. Table 1 lists results from the gamma-gamma logs run in the boreholes.

Table 1.--Rock density data from gamma-gamma well logs. Depth intervals and rock units Hoover and Morrison (1980).

Borehole UE16d

Depth Interval m below ground	Rock Unit	Rock Density, g/cm³ N	Mean	Standard Deviation
0 - 27	Qal		Not determined	
27 - 539	PPt	148	2.50	±0.09
539 - 782	Mejuq	65	2.45	±0.23
782 - 911	Mejua	47	2.53	±0.06
Borehole UE1ℓ				
0 - 61	Qal	3	1.98	±0.04
61 - 302	Mejuq		Not determined	
302 - 396	Mejua		Not determined	
396 - 606	Mejuq	48	2.48	±0.05
606 - 1,414	Mejua	119	2.42	±0.30
1,414 - 1,615	Mejl	11	2.42	±0.07

Qal: Quaternary alluvium

PPt: Tippipah Limestone

Mejuq: Eleana Formation, unit J: upper quartzitic subunit

Mejua: Eleana Formation, unit J: argillite subunit

Mejl: Eleana Formation, unit J: lower quartzitic subunit

The Bouguer gravity anomalies within the trapezoidal study area have three principal characteristics: (1) the regional gravity contours have a distinctly northwest trend, nearly perpendicular to the mapped structure at Syncline Ridge, (2) the regional gradient is gentle compared to gradients outside of the area, and (3) superposed on the regional gradient are low amplitude anomalies having north to northeast trends, oblique to the regional trend and subparallel to the mapped structure. Anomaly values range from about -152 mgal near the northeast corner of the area to about -148 mgal near the southwest corner, the low amplitude anomalies having magnitudes of about 1 mgal. Because this amplitude is close to the estimated data error, individual anomalies probably do not accurately reflect the subsurface structure. The general trends however are believed to be significant. The predominant regional gradient represents the common flank of a high amplitude negative anomaly centered about 5 km northeast of the central block and a lower amplitude positive anomaly in the southwest part of the area. The superposed low amplitude anomalies have been isolated by constructing a residual anomaly map based upon an assumed regional background field. The residual anomaly map of figure 4, based upon a visually estimated regional field, highlights the northerly trends of the anomalies and more accurately indicates the location of the main positive anomaly contour closure, about 1.5 km northeast of the corresponding closure on figure 3.

The northeast trend of the regional gradient reflects a broad northeast to southwest lateral increase to subsurface rock density not related to the mapped structure of Syncline Ridge but related to a deeper regional density contrast. In the northeast part of the trapezoidal area (figure 3), this gradient appears as the continuation of the flank of a major gravity low (Healey, 1978) centered over Quaternary alluvium of Yucca Flat about 5 km to

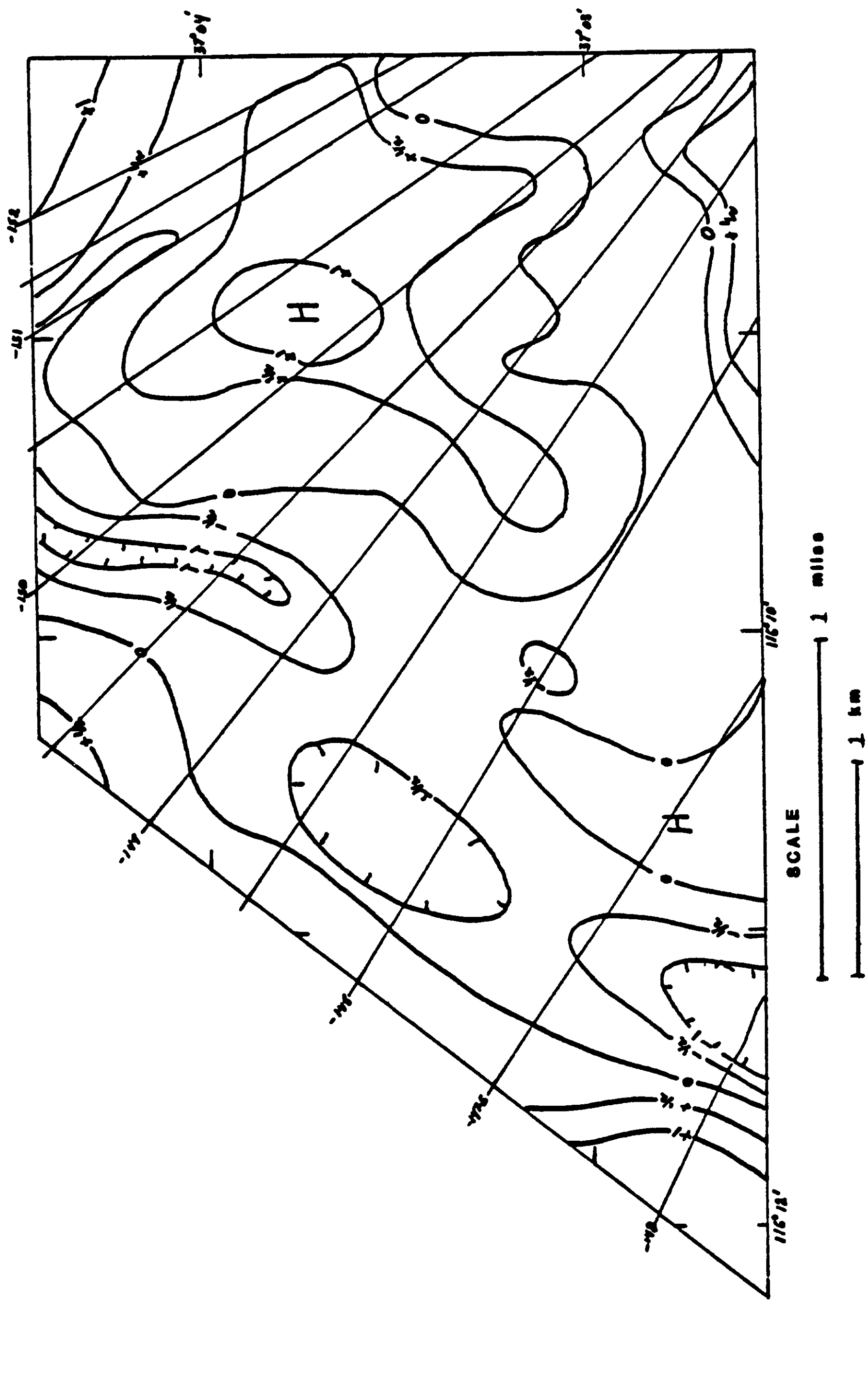

Figure 4.--Residual Bouguer gravity anomaly map of the study area showing the visually estimated regional field. H indicates relative high; hachures denote relative lows.

the north-northwest. In the southwest part of the area, the gradient forms part of a positive anomaly which extends from Mine Mountain northwestward to a broad tract of mapped Eleana Formation 2 km north of Tippipah Spring (Healey, 1968, 1978). It may be noted that a major lobe of the positive anomaly is developed over much of the southeastern part of Syncline Ridge just south of the trapezoidal study area. This positive anomaly lobe points to a sharp contrast of the rock density between the terranes underlying the northeast and southwest parts of Syncline Ridge.

The gentleness of the regional gradient is not surprising in light of the gamma-gamma log information, which indicates that there is no significant density contrast at depth between members of the Eleana Formation or between the Eleana Formation and the Tippipah Limestone. The low inclination of the gradient indicates that low density Quaternary alluvium is relatively thin, probably less than 100 m thick, and is in accord with existing borehole data.

Assuming that the residual anomalies shown in figure 4 are not entirely due to data error, they outline local regions of near-surface rocks having density contrasts which are small, on the order of 0.10 g/cm^3. Three north- to northeast-trending negative anomalies lie along the western contact between Tippipah Limestone and Quaternary alluvium. Because negative anomalies are not centered over Quaternary alluvium between Syncline Ridge and the Eleana Range the alluvium is inferred to be thin. The negative residual anomalies therefore may mark a local thickening of several 10's of meters in the alluvium adjacent to its contact with the limestone. The positive residual anomaly within the ridge may indicate a local region of relatively high density rock. This high is terminated by a northwest-striking discontinuity, which probably reflects effects of the lateral fault separating the northern and central blocks. In summary, the gravity data suggest that the stratigraphic section underlying Syncline Ridge is lithologically variegated and structurally complex.

Magnetic data

Aeromagnetic anomaly data in the study area (fig. 5) were obtained by private contract as part of a regional survey of the Timber Mountain area to the west. Total intensity data were obtained 400 ft (122 m) above ground with a one-quarter mile (0.4 km) spacing in an east-west direction. The anomaly producing rocks within or immediately adjacent to the study area are tuffs of Miocene age which are in contact with Tippipah Limestone. These rocks, according to the description of Orkild (1963), include nonwelded ash-flow and ash-fall tuffs, similar to those for which total magnetizations have been determined by Bath (1968). On the basis of the work of Bath (1968), the lower member tuffs are estimated to have magnetic susceptibilities within the range 1 to 5 x 10^{-4} emu/cm^3, normally polarized remanent magnetization intensities within the range 1 to 5 x 10^{-4} emu/cm^3, and normally polarized total magnetization intensities within the range 2 x 10^{-4} to 1 x 10^{-3} emu/cm^3.

The survey area is magnetically quiet, containing one distinct, positive 20-gamma anomaly, and a number of vague 5-gamma flexures in the threshold of the background noise level. The lone anomaly is associated with outcrops of tuff of the lower member of the Indian Trail Formation; an anomaly comparable in amplitude is associated with similar rocks 2 km to the southwest. The aeromagnetic map does not contribute to an understanding of the geologic terrane underlying Syncline Ridge but does shed information on the patches of Tertiary tuff which abut or overlap the Tippipah Limestone. Using approximate calculations for subhorizontal sheet-like models successfully applied by Bath (1968, p. 140) to lava and ash flows elsewhere in the Nevada Test Site, we may

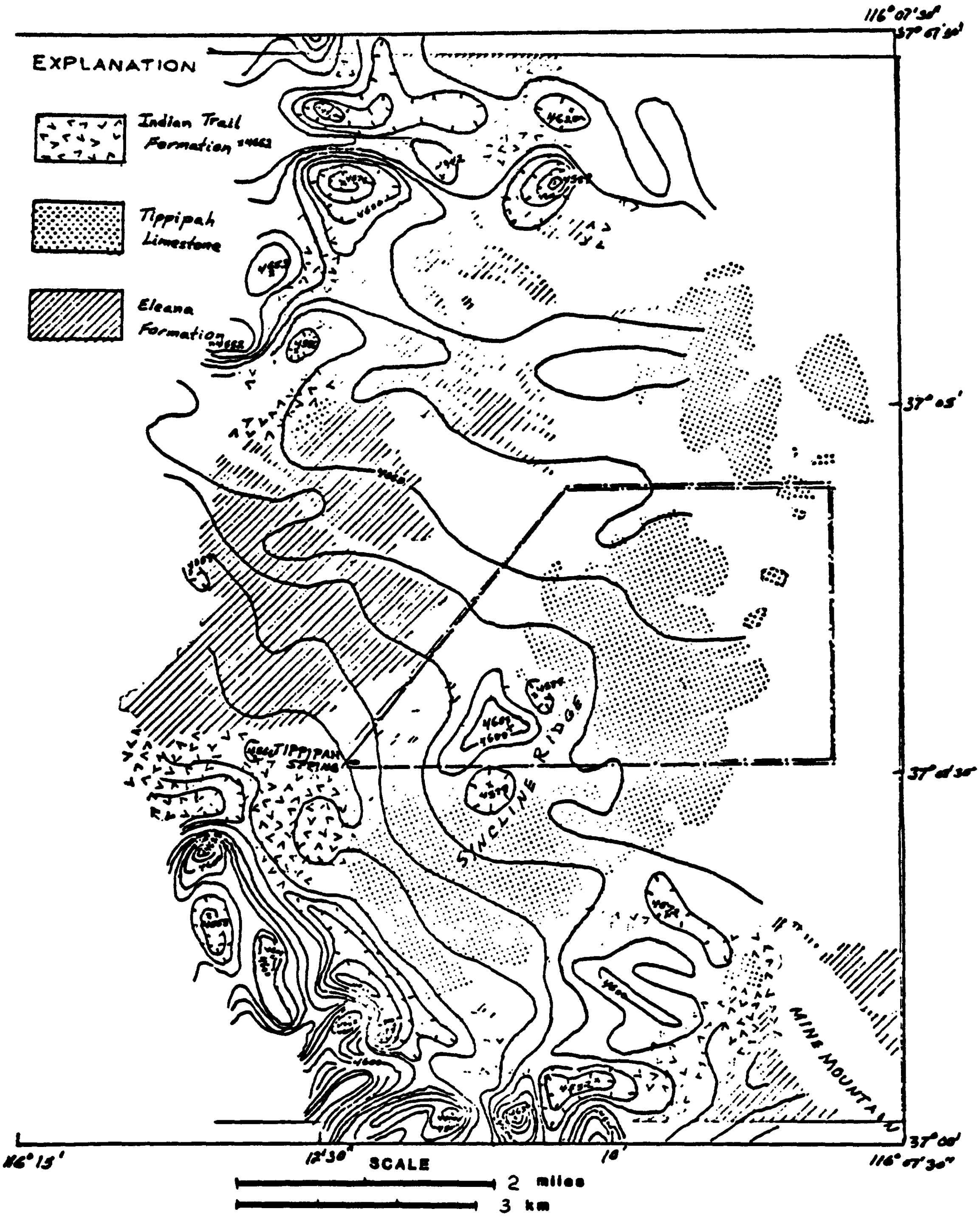

Figure 5.--Aeromagnetic anomaly map showing geologically mapped Eleana Formation, Tippipah Limestone, and Indian Trail Formation (Orkild, 1963). Survey flown 400 ft (122 m) above ground along east-west lines spaced one-quarter mile (402 m) apart. Contour interval; 10 gammas.

infer a tuff thickness of 10 to 50 m corresponding to an assumed range of total magnetizations of 2×10^{-4} to $\times 1 \times 10^{-3}$ emu/cm^3. It may be noted that the gently inclined, northwest-trending gradient throughout the area is related not to the earth's core regional field but rather to a distant flank of a high-amplitude anomaly complex associated with strongly magnetic welded tuffs and vitrophyres 2 km southwest of the study area.

Seismic Methods

The prior seismic reflection study by Seismograph Service Corp showed that significant problems existed with the acquisition of both refraction and reflection data in the Syncline Ridge area (Mossman and Garrette, 1972). In this early work a test refraction spread was measured in an attempt to obtain velocity and depth control on the near surface weathered zone. The results were negative. Because a key to obtaining useful reflection data in the future could be adequate definition of the weathered zone or zones, an extensive refraction program was undertaken in January 1978 to address this problem and to attempt to identify near surface faults and structure. U.S. Geological Survey equipment and personnel were used for this work. Additional reflection work had not been planned; however it was learned in late January 1978 that a Western Geophysical Company vibroseis crew was then operating in Yucca Flat on an unrelated program. Because of significant economies which were realized by not having to pay mobilization charges it was decided to conduct additional reflection surveys. From February 4 to 8, 9.0 km of additional reflection data were obtained.

Refraction surveys

Eleven refraction lines consisting of 17 spreads were shot in January 1978 using spread lengths of either 345 m (1130 ft) or 1380 m (4525 ft). Each spread consisted of 24 geophones equispaced at 15 m or 60 m depending on spread length. Geospace HS-1, 4.5 Hz geophones were used with an SIE Inc. PT-700 seismic data acquisition system. Normally five shots were used with each spread; at the center, each end, and offset one spread length from each end. High velocity gelatin was used as a source with charge size varying from 1 to 40 pounds.

Analysis of the refraction data was performed with an interactive computer program of H. D. Ackermann (unpub. program, 1981). When reversed coverage is available as was generally the case in this study, the computer program gives depth and velocity values on fixed distance increments for each layer observed. The derived models are normally presented as velocity cross-sections (appendix 1).

Figure 6 shows the location of the 11 refraction lines measured in the study area. The position along each line where either a 3.0 to 3.5 km/sec or a 4.0 to 6.0 km/sec layer was identified also is shown in the figure. The velocities represent different interfaces in the Paleozoic section, but we have not been able to correlate them with specific lithologic units. Arrows in figure 6 identify faults which were inferred from the seismic velocity-depth models. The velocity models for each line are shown in appendix 1.

From 2 to 6 individual layers were computed for the 11 lines with velocities increasing with depth. Table 2 summarizes the velocity layering observed on each line and the exploration depth. Some tentative correlations have been made between the observed layering and the near surface lithologies based in part on well logs. Borehole Uel-L is adjacent to the

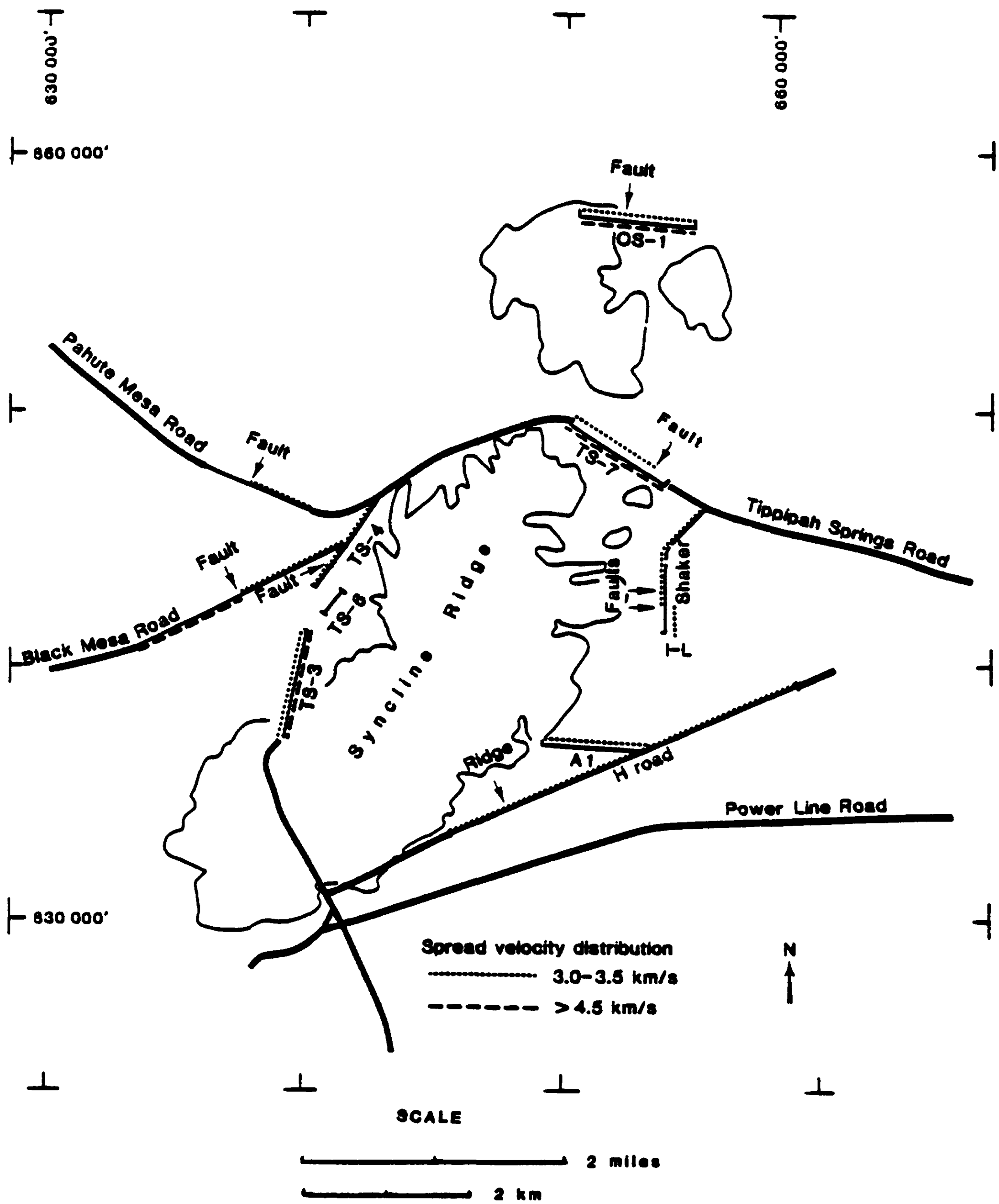

Figure 6.--Location map of 11 seismic refraction lines measured in the study area. Dotted lines above each spread show the interval over which a velocity layer of 3.0 to 3.5 km/s was observed and the dashed line the interval over which 4.5 km/s velocities and greater were found. Arrows indicate the location of faults identified on the lines.

Table 2.

Summary of observed layer velocities and depth of exploration for 11 refraction lines measured in the study area

SPREAD	TOTAL SPREAD LENGTH	MAX AVERAGE DEPTH	VELOCITIES LAYER 1	2	3	4	5	6
A-1	1380 m	175 m	x	1.4	x	2.5	3.5	x
HROAD	4300 m	300 m	x	1.2	1.6	2.1	3.2	x
PMROAD	1380 m	160 m	0.5	1.4	x	2.45	3.2-3.5	4.5
BMROAD	2760 m	150 m	0.8	1.1	x	2.50	3.3	4.0
TS-3	1380 m	300 m	0.8	x	1.6	2.6	3.5	4.3
PM-3	345 m	150 m	0.8	1.3	x	2.2	x	x
OS-1	1380 m	400 m	0.6	x	1.6	2.2-2.5	3.4	5.0-6.7
TS-4	1380 m	150 m	0.8	1.0	1.6	2.0-2.5	3.1	4.3
TS-7	1380 m	250 m	0.85	1.1	1.5-1.7	2.4	3.0	4.1-4.6
SHAKER	2000 m	200 m	0.4	1.2	1.7	2.4-2.7	3.5	4.0-5.0
TS-6	345 m	30 m	0.4-0.8	x	1.7-1.9	x	x	x

x = indicates layer not observed

southern end of the Shaker spread and UE16-f is adjacent to the western end of spread A-1. Alluvium can be reliably correlated with velocities of 2.0 km and less. From table 2 it can be seen that some spreads identified three distinct layers in the alluvial cover. These distinct layers are probably related to different ages of the alluvial units described by Hoover and Morrison (1980). However we have been unable to correlate any of the layers with specific alluvial units and no consistent spacial pattern of these low velocity layers is evident in the seismic models. The south end of line TS-3 was on outcrop of thin Tertiary non-welded tuffs seen in the magnetic data and not over 50 m thick. This line shows about 50 m of 1.6 km/s and less velocity material at the surface. We conclude that these Tertiary units would be indistinguishable from the alluvium, as would other Tertiary alluvium known from the area (Hoover and Morrison, 1980).

Velocities above 2.0 km/sec are correlated with the Paleozoic rocks in the study area. We, however, have been unable to correlate individual layers of the seismic models with specific lithologic intervals observed in the boreholes, except possibly for a deeply weathered zone at the top of the Eleana Formation. Borehole Uel-L showed a 58 m thick zone of weathering (Hoover and Morrison, 1980) which it is believed developed during a long, wet, stable period prior to the local Tertiary volcanism. This weathered zone correlates in part with a 2.4 km/s layer observed on the Shaker line. The weathered zone in the Eleana Formation has only been observed on the east side of Syncline Ridge so that layer velocities near 2.4 km/sec do not necessarily correlate with this weathered horizon.

Several lines, in particular OS-1, extended onto outcrop of the Tippipah Limestone. Observed velocities for this unit were quite low for limestone and indistinguishable from Eleana Formation velocities. Thus neither density nor seismic p velocities provide a means of geophysically distinguishing these distinctive lithologies.

Based on the above correlations and lateral changes in seismic velocities the seismic sections show a number of significant structural features. Faulting or erosion is interpreted as cutting the alluvium on lines H Road and Shaker, both on the east side of Syncline Ridge. This may suggest but is not conclusive evidence for Quaternary faulting within the central block. A number of other faults were interpreted on the cross-section but appear to be restricted to Paleozoic rocks. In general those faults identified on the eastern side of the ridge correlate with mapped faults or reasonable extensions of mapped faults. On the west side the correlation is not as clear and there is insufficient data on which to infer trends from the seismic sections.

A number of lines show structural relief on top of or within the Paleozoic section. This could result from faulting, folding, or erosion, of what ever horizon is being mapped. The most significant structural feature in all of the sections is a graben-like feature and fault interpreted on line TS-7. Vertical offset of this feature is 130 m. Line TS-7 is parallel to a lateral fault projected through Gap Wash which separates the northern and central blocks. The features on this line lie east of the extension of the axial fault in the central block.

Variations in alluvial thickness identified in the seismic sections correlate in general with trends shown in the gravity map (fig. 4). Line TS-4 crosses one of the small closed gravity lows discussed earlier, which is on the western edge of the ridge. The seismic section shows the alluvium thickening from 30 meters south of the low to 65 m in the low. This confirms the earlier inference that this gravity anomaly could be the result of local alluvial thickening, which is probably true of the others.

The faulting indicated in the Paleozoic rocks shown in the velocity sections BM Road and TS-4 and the thickening of the alluvial section on the southwest end of H Road seems quite consistent with the major Northwest trending lateral fault which separates the central and southern blocks. In addition a mapped fault on the northeast side of the northern block correlates well with one in the fifth layer of OS-1.

Reflection surveys

Experience gained from the 1972 reflection survey and from the work by Western Geophysical Company in Yucca Flat was used to establish the recording parameters used in this survey. Three lines were recorded in the study area (fig. 7) which combined with the earlier SSC data provided coverage encircling the Ridge. Line W-1 starts on the western edge of an east-west line run for Southern Methodist Univ. (SMU). Line W-1 runs south-west across the central and southern blocks. Line W-2 crosses Syncline Ridge along a road in the southern block and line 3 runs north-south on the western flank of the Ridge and along the valley separating Syncline Ridge from the Eleana Range. The location of the two SSC lines are also shown in figure 7.

The recording and operating parameters used in this survey are given in table 3. A 48-channel LRS Coba recording system was used throughout the survey with Mark Products L-10A, 10 Hz geophones. The energy source was 4, Y-900 LF vibrators (Gardner, 1978). Processing of the data was done at Western Geophysical's Denver Digital Center using standard methods. As in the earlier SSC work the data quality of the record sections was marginal at best. A number of different processing parameters and techniques for improving the data quality were tried. Velocity analyses were run and various

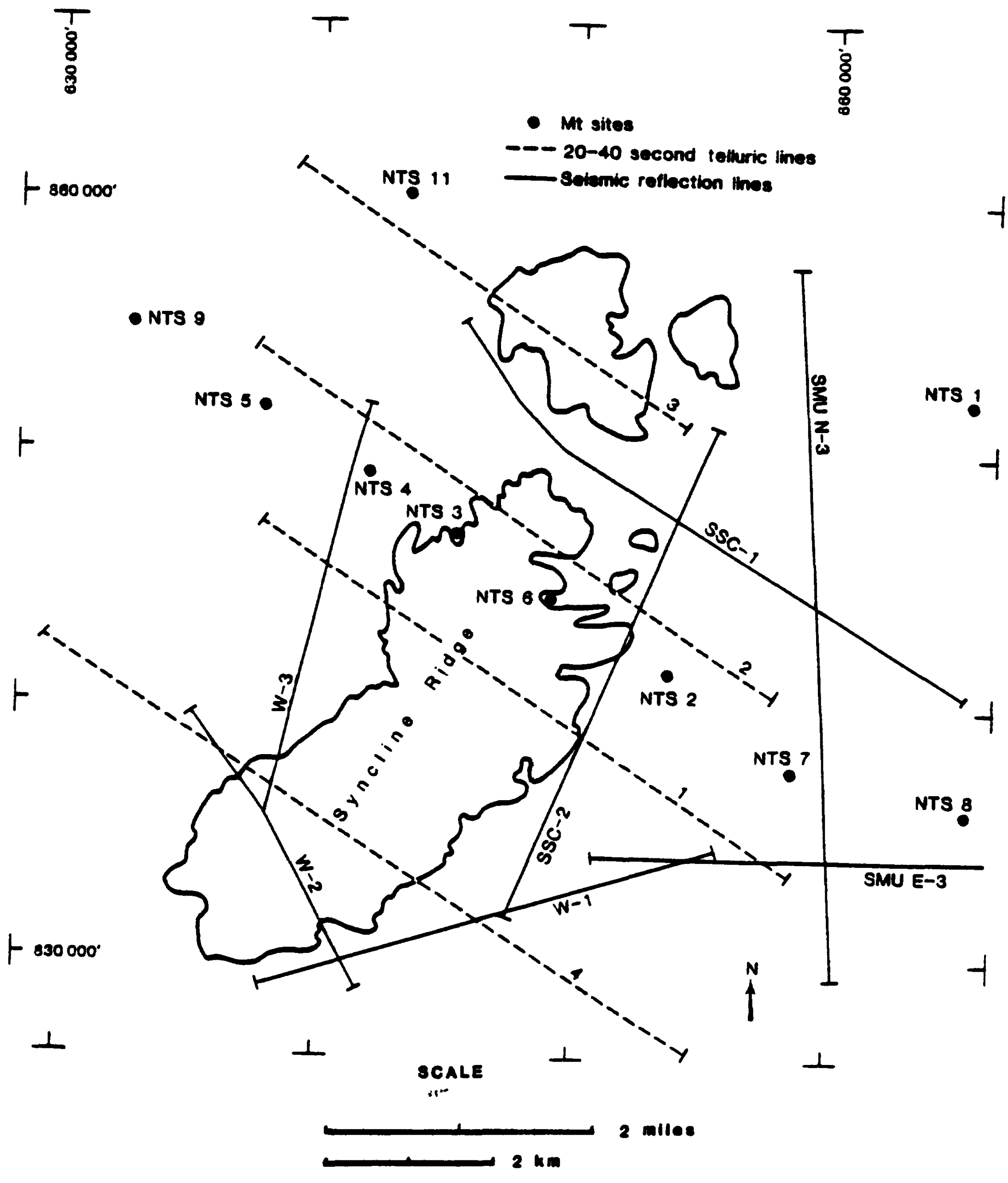

Figure 7.--Location map of five seismic reflection lines measured by Seismograph Service Corp. (SSC) and by Western Geophysical Co. (W), along with magnetotelluric sounding location and E-field ratio telluric traverse locations in the study area.

Table 3.

Operating Parameters of Reflection Survey

Recording	24 fold CDP
Sample rate	4 milliseconds
Channels	48
Group interval	220 feet
Vibrator point interval	220 feet
Spread	5720-660-0-660-5720 feet
Geophones per group	36
Number of sweeps/VP	16
Length of sweep	16 seconds
Listening time	5 seconds
Sweep frequency range	14-56 Hz
Recording filter	out-62 Hz

velocity-depth functions were tried. Deconvolution tests before and after stacking and multichannel filtering tests didn't improve the data quality (Gardner, 1978).

It should be noted that the SMU line in Yucca Flat which was tied to line W-1 revealed good reflections from the paleozoic section. The seismic data quality decreases rapidly west of the north-trending normal faults which define the eastern border of the study area. Drill hole data shows that west of this line the Eleana Formation lies below relatively shallow alluvium while to the east the alluvium thickens and a thick section of Tertiary volcanic rock overlies the Paleozoic.

A number of geologic factors could be responsible for the poor data quality. Random scattering may be occurring from faults and fractures and in steep dipping layers. Drill hole data show bedding plane dips in the Eleana Formation ranges from 0° to 60° at the site. The relatively low velocity argillite may be absorbing much of the energy. In addition static corrections may be in error due to a rapidly changing and variable "weathering" layer. This latter may be especially severe because as mentioned earlier there appear to have been three distinct weathering episodes which are still preserved at the site: Quaternary, Tertiary, and pre-Tertiary.

The completed seismic sections provided by both Western and SSC are shown in figures 8 through 12. The SSC sections had been marked lightly to emphasize the few reflections which could be carried for any distance and inferred faults were marked. Although the data quality is poor, SSC line 1 (fig. 11) which runs across the northern end of the central block we believe gives an accurate picture and the most detailed view possible of the structural configuration at Syncline Ridge. The other geophysical data sets are in agreement with this general picture. The only prominent reflection

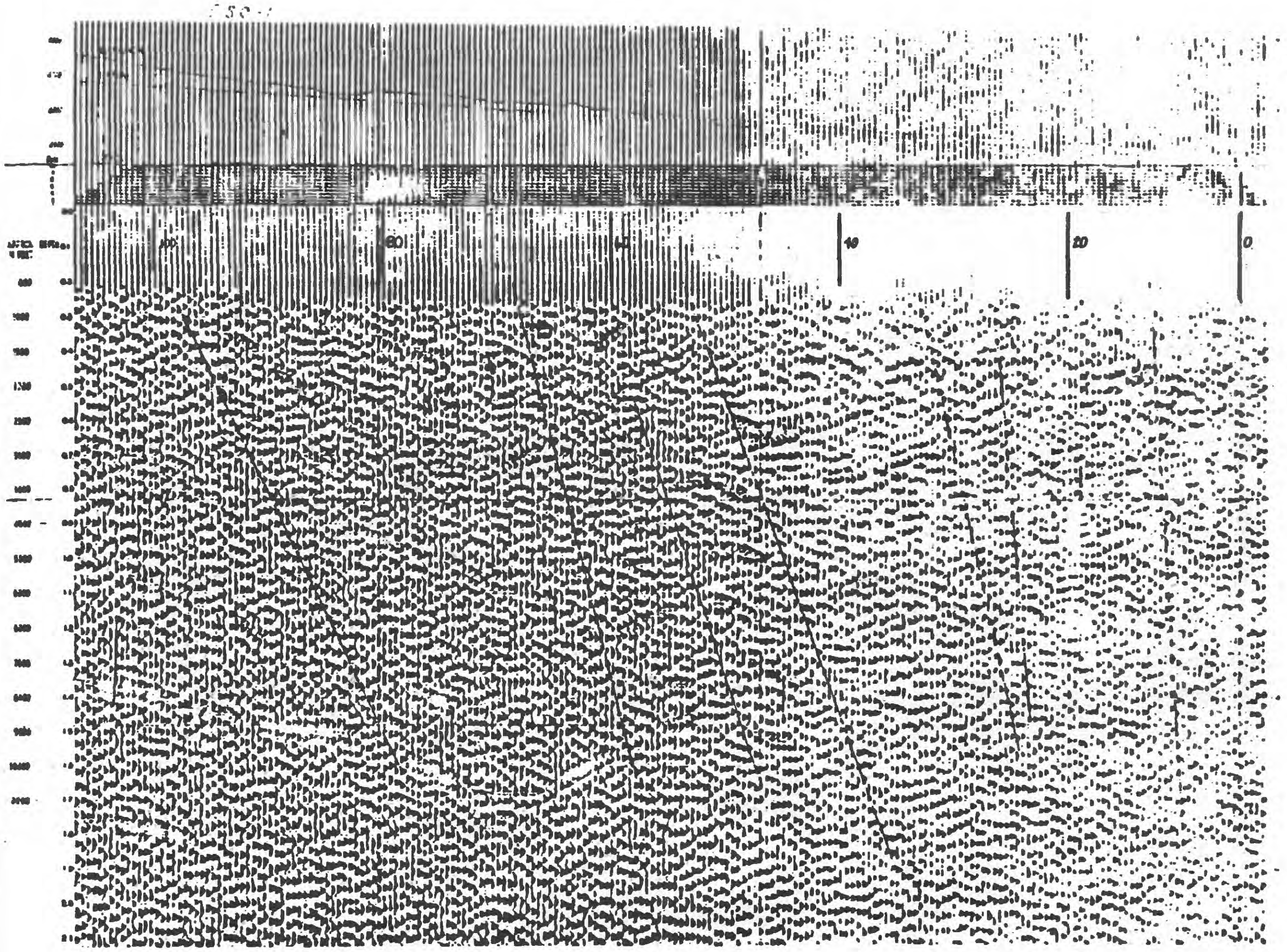

Figure 8.--Seismic reflection time section for Seismograph Service Corp. Line 1 Syncline Ridge.

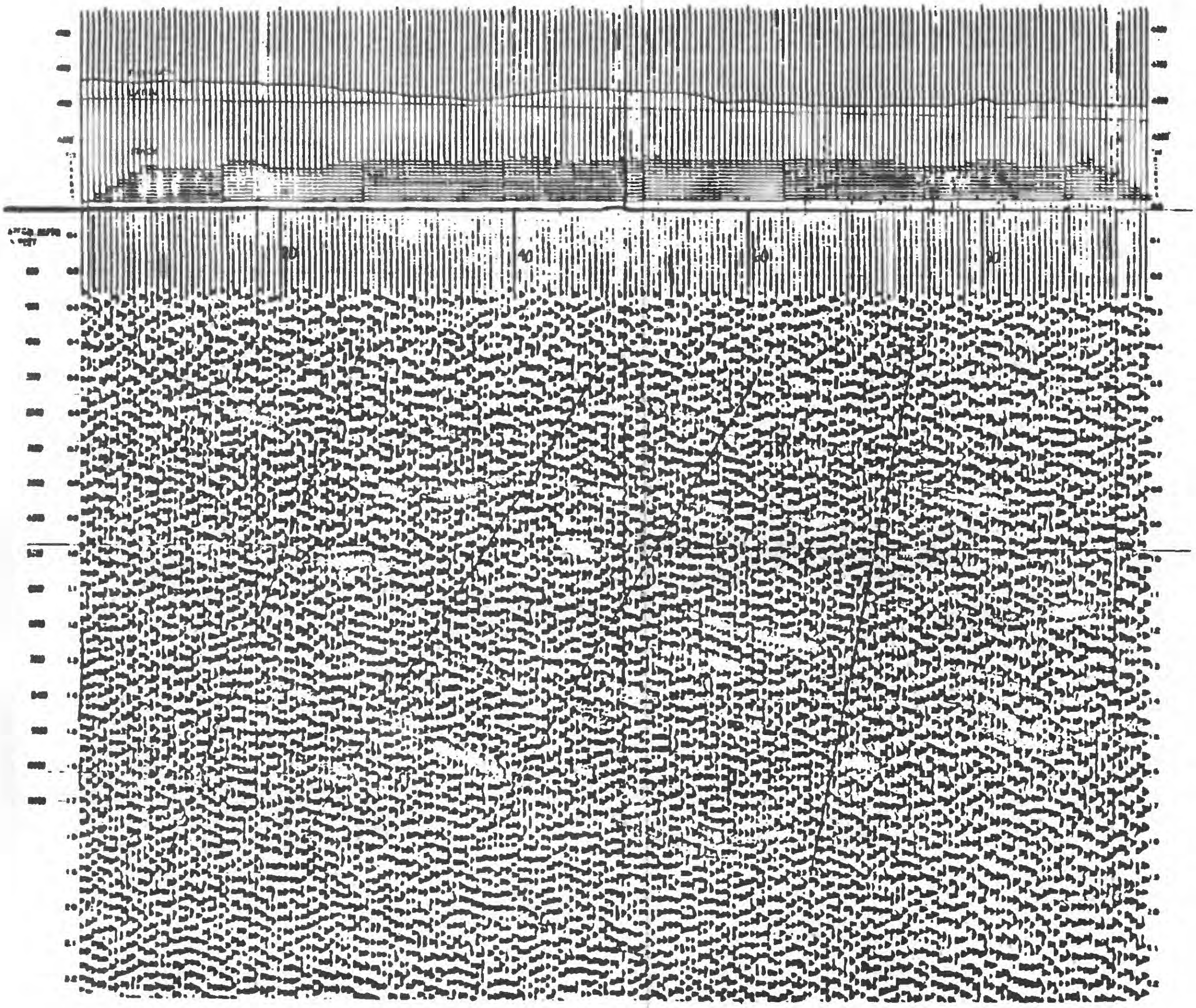

Figure 9.--Seismic reflection time section for Seismograph Service Corp. Line 2, Syncline Ridge.

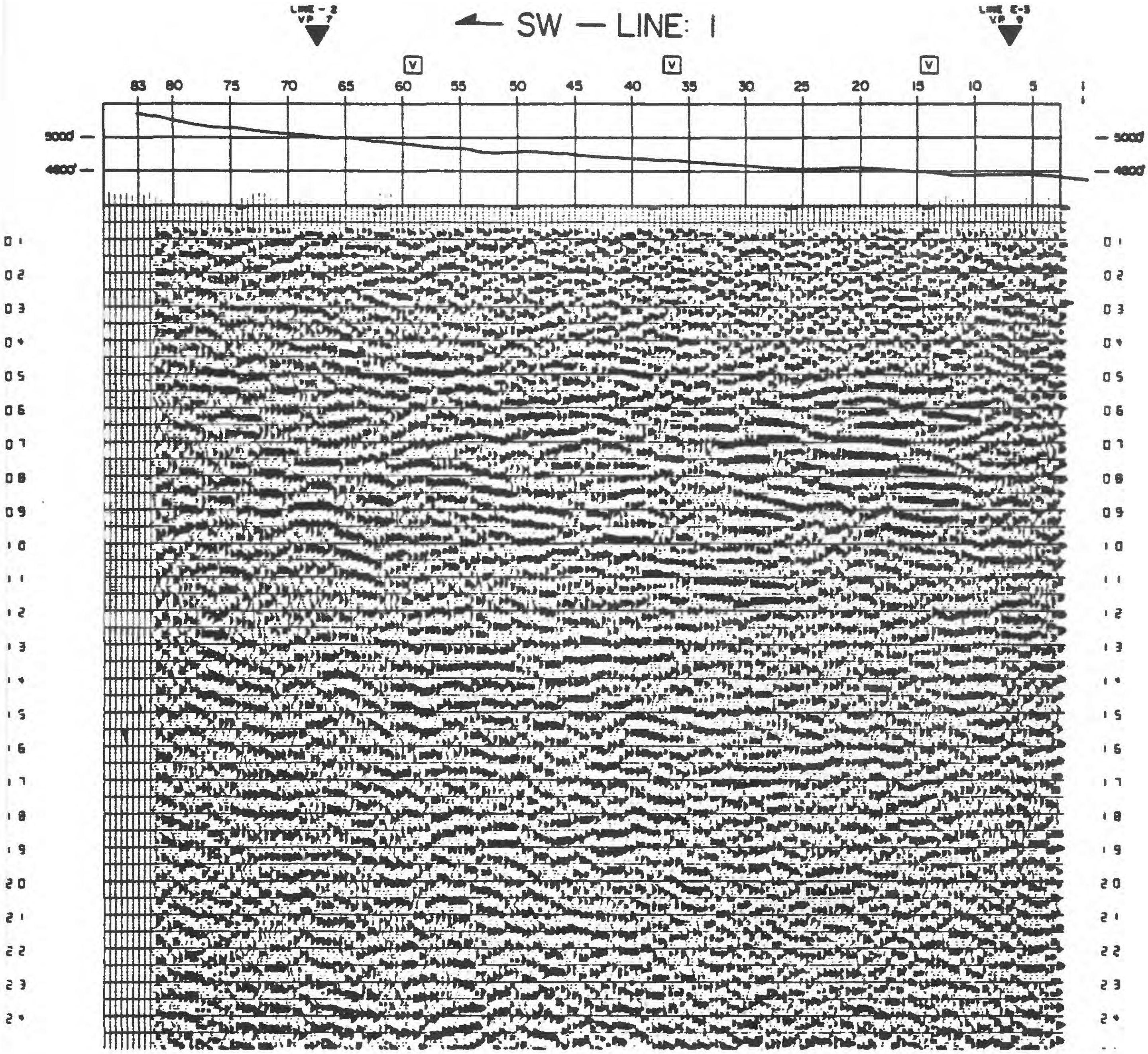

Figure 10.--Seismic reflection time section for Western Geophysical Co. line 1, Syncline Ridge.

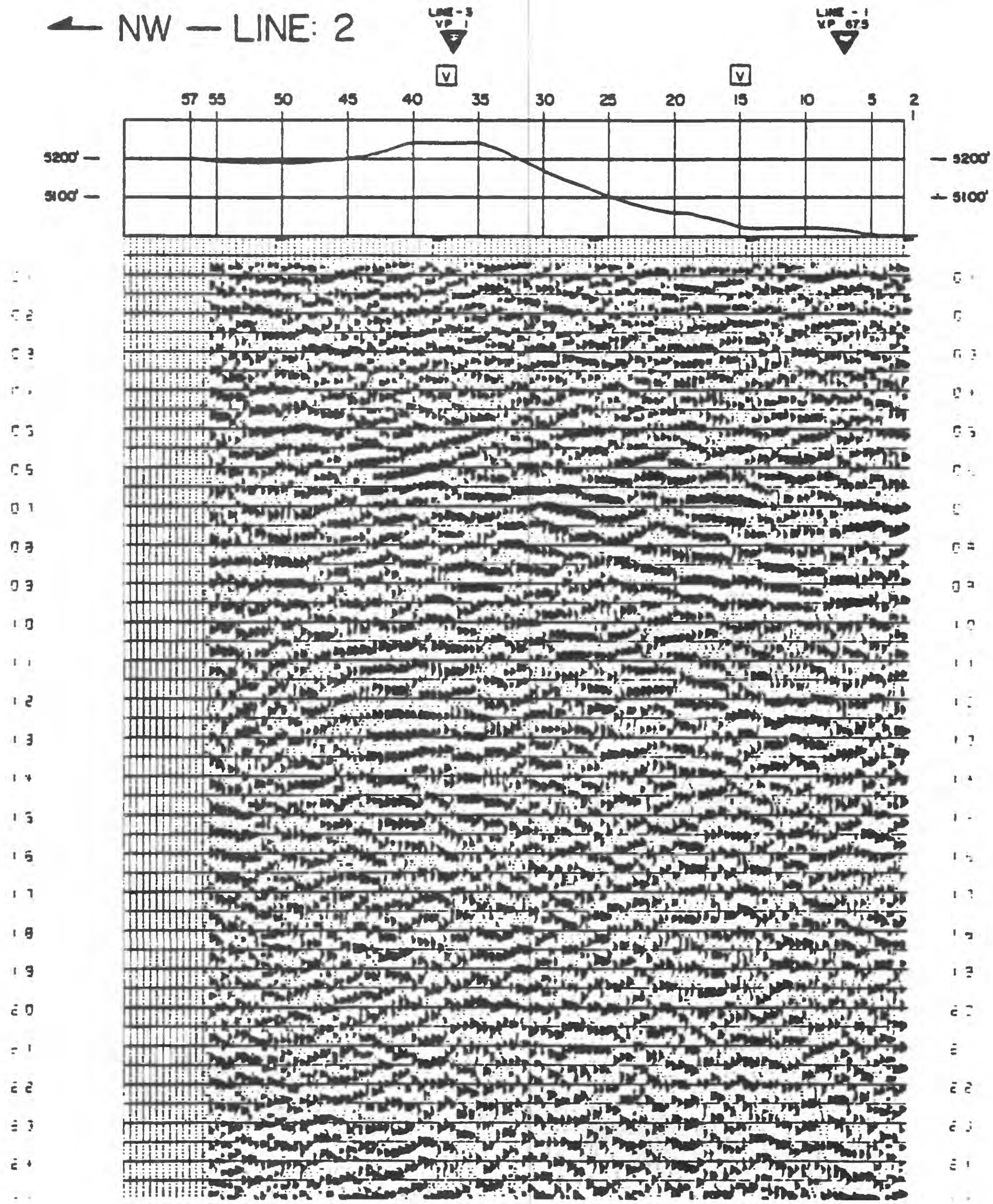

Figure 11.--Seismic reflection time section for Western Geophysical Co. line 2 Syncline Ridge.

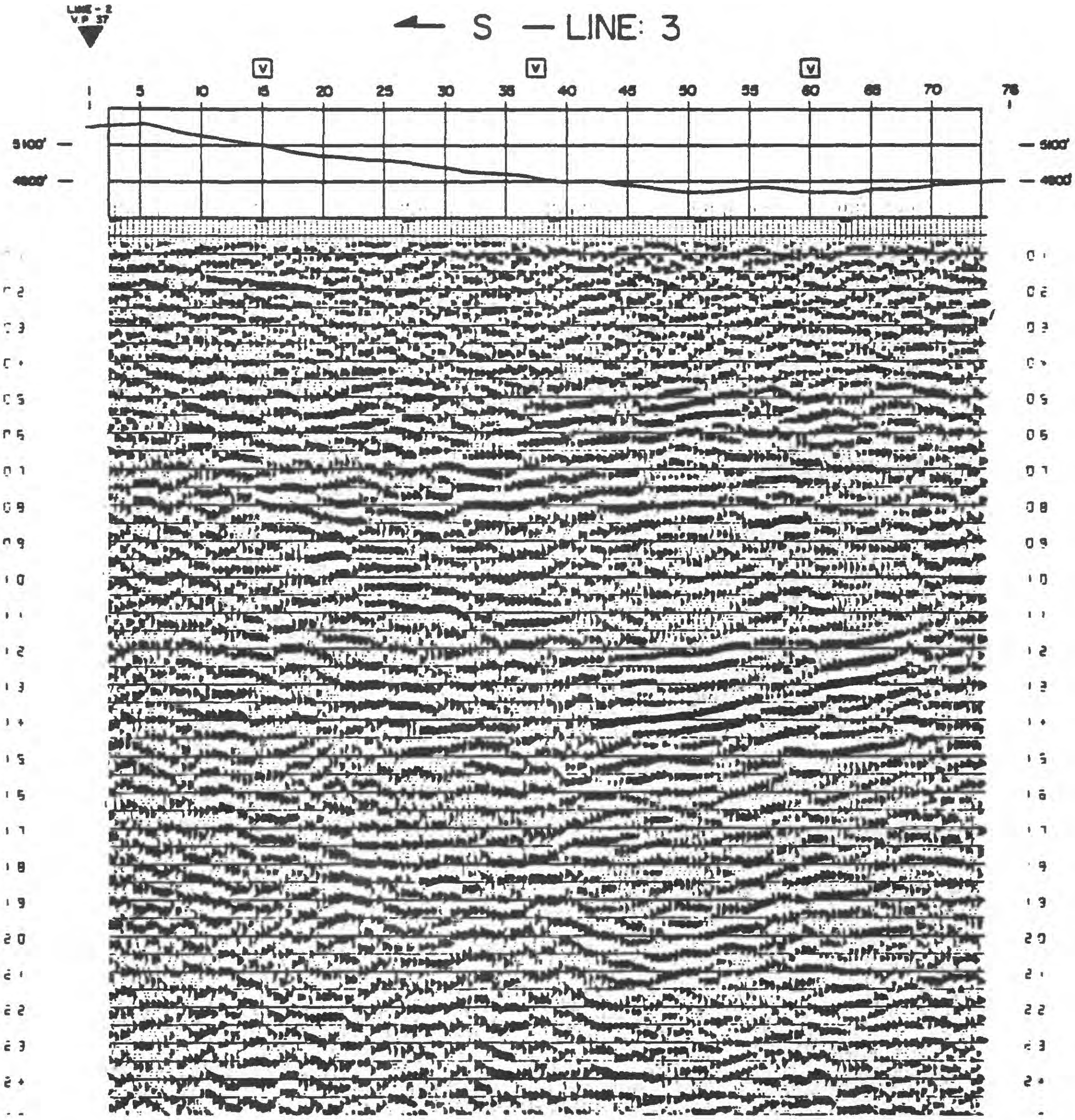

Figure 12.--Seismic reflection time section for Western Geophysical Co. line 3, Syncline Ridge.

event on these sections is seen on the northwest end of line SSC-1 (fig. 8) and the north end of line W-3 (fig. 12). These appear to be the same reflecting horizon beginning at about 1.3 seconds at the end of the respective sections. If the average velocity through the section is 4.0 km/sec this horizon is at a depth of 2.6 km (8500 ft). This may mark the base of the Eleana where older Paleozoic carbonate rocks are expected. Hoover and Morrison (1980) estimate the Eleana Formation at the site to be at least 2.0 km thick. The synclinal structure is evident on line SSC-1 but not on W-2 (fig. 11) both of which cross normal to the structural axis. Faulting which was interpreted on SSC-1 offsets what we infer to be the base of the Eleana Formation downdropping the central part of the structure. This faulting provides a potential short pathway from the repository to the underlying carbonate aquifer.

Because of the poor data quality and other data also implying structural complexity no further attempt was made to interpret the reflection data. We believe the principal cause of the poor data quality is the highly variable upper few hundred meters which prevents good stacking of the data. The structural complexity is in an area with widely varying dips. The greatest complexity is on the east side of the ridge and the least disturbed on the northwest part of the study area.

Electrical Methods

A number of electrical methods were tried because of the Eleana argillite unit and particularly the argillaceous subunit of unit J is quite conductive and should be electrically distinctive. Schlumberger vertical electrical soundings (VES) were used extensively around Syncline Ridge where access and gentle topography permitted. The principal function of the VES was to map the argillite. Slingram electromagnetic traverses, a shallow exploration method was used on the east side to assess its applicability to defining Quaternary faulting. Magnetotelluric (MT) soundings were used to get deep structural information particularly in view of anomalous results observed in an earlier MT survey. E-Field ratio telluric traverses were employed so as to get some electrical data in and across the ridge itself. Details of the VES work have been published by Anderson and others (1980) and for the Slingram results by Flanigan (1979).

Schlumberger VES

Figure 13 shows the location of the VES and lines of section presented by Anderson and others (1980) and figures 14-16 shows their interpreted sections AA', BB' and CC'. A total of 44 soundings were made using a direct current source. The transmitter and receiver system are of U.S. Geological Survey manufacture. Conventional field operating methods were used in the survey (Keller and Frischknecht, 1966). The sounding curves were inverted using computer programs developed by Zohdy (1974, 1975). These programs produce a geoelèctrical cross-section based on an equivalent one-dimensional earth. The principal source of error in the derived geoelectric sections is the assumption of one-dimensionality in the inversions. The prior geophysical data and the VES data reveal extensive lateral heterogeneity which has not been accounted for in the models presented.

Electric logs from the deeper drill holes in the study area provided a means of correlating lithologies with resistivities (Anderson and others, 1980). Resistivities of 20 to 40 ohm-m generally characterize the high argillite parts of unit J, quartzite intervals go as high as 300 ohm-m, and the Tippipah Limestone is generally over 1000 ohm-m. It is interesting to observe that density and seismic velocity obtained from the well layer are

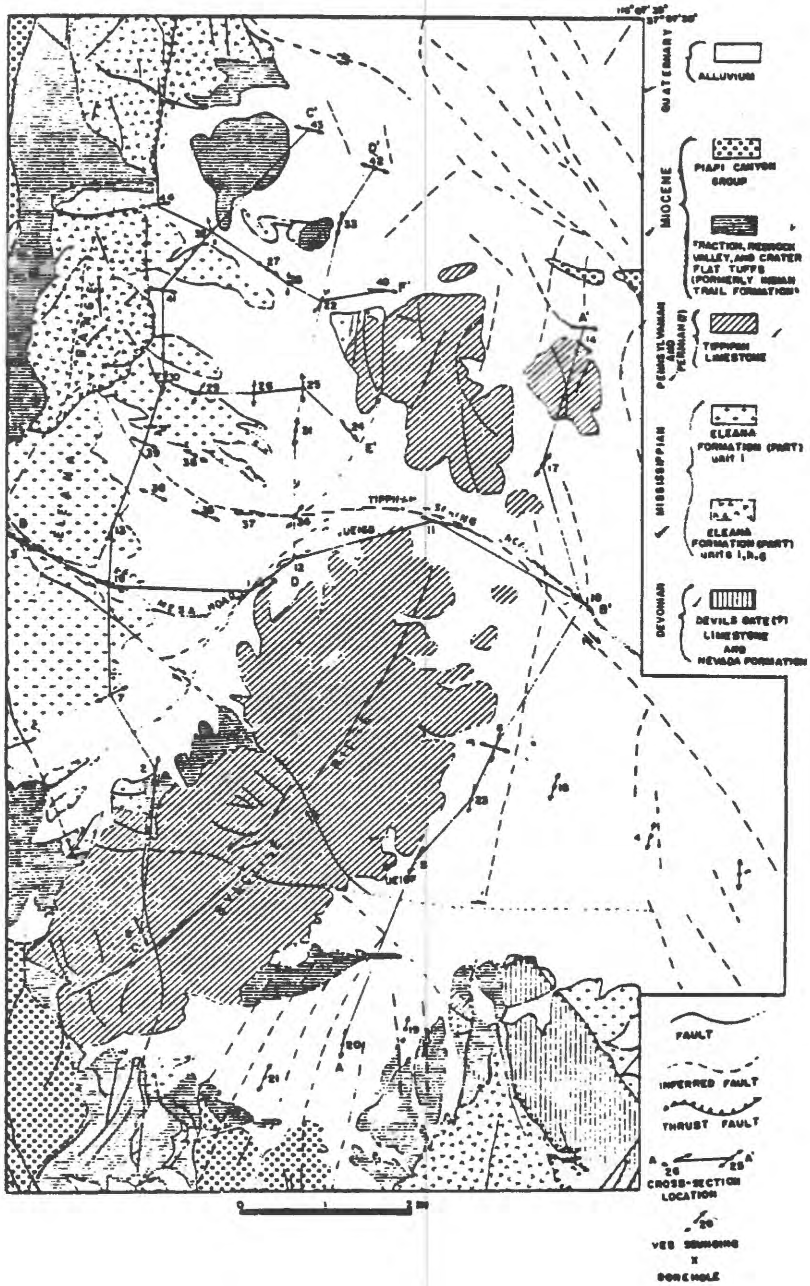

Figure 13.--Map of the study area showing the location of Schlumberger soundings, the generalized geology and line of geoelectric sections, from Anderson and others (1980).

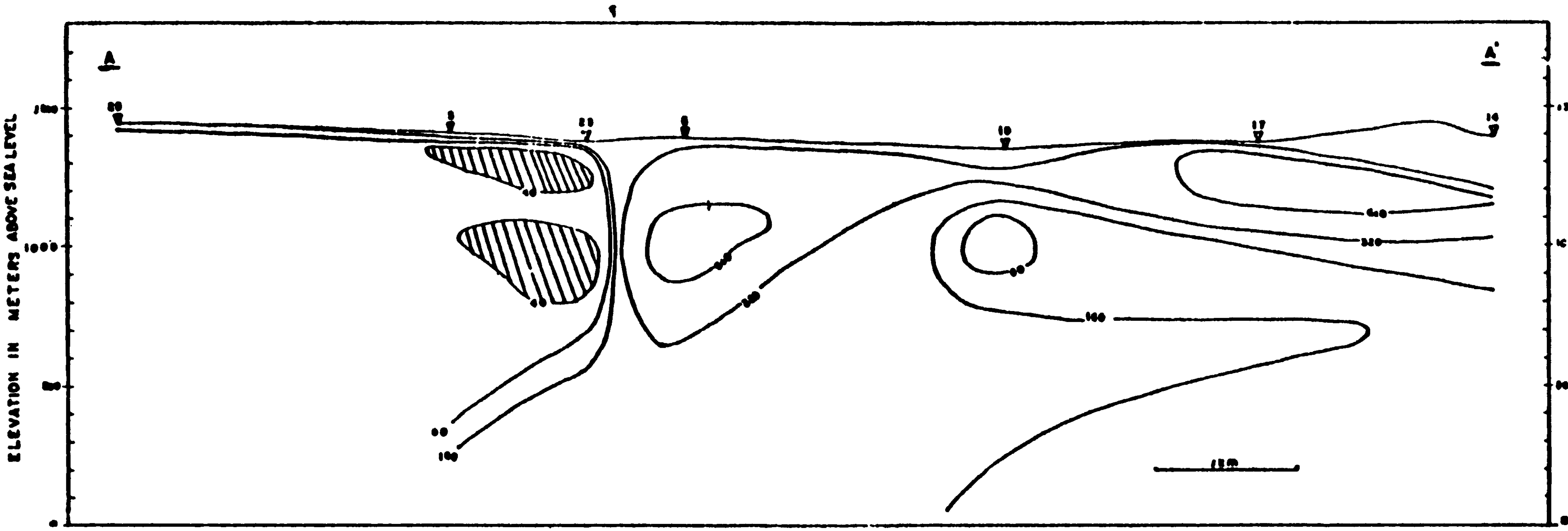

Figure 14.--Geoelectric cross-section A-A′ (fig. 13) compiled from interpreted resistivity sounding data. Contours increase in geometric progression from a value of 20 ohm-meters. Patterned areas are those intervals considered to be composed primarily of argillaceous argillite (Hoover and Morrison 1980) of the Eleana Formation. Vertical exaggeration is 2X. From Anderson and others (1980).

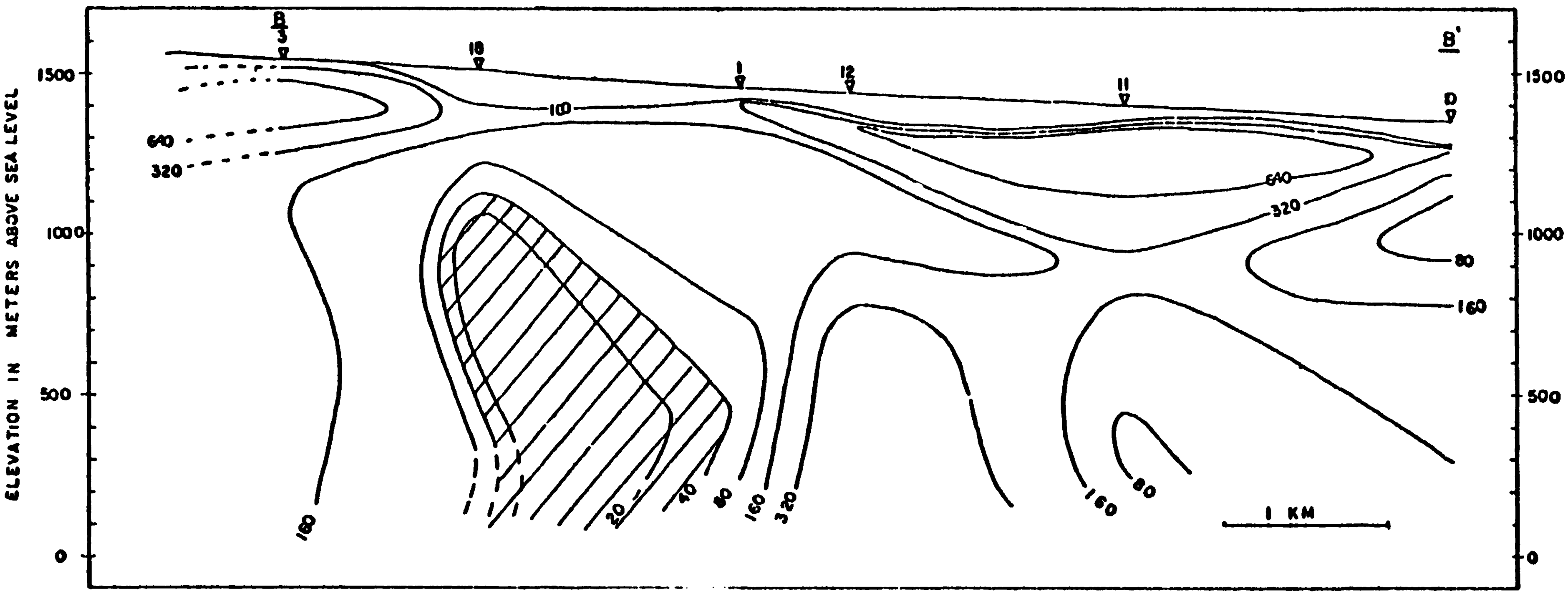

Figure 15.--Geoelectric cross-section B-B' (fig. 13) compiled from interpreted resistivity sounding data. Contours increase from a value of 20 ohm-meters. Dashed contours indicate inferred values of resistivity. Patterned areas are those intervals considered to be composed primarily of argillaceous argillite of the Eleana Formation. Vertical exaggeration is 2X. From Anderson and others (1980).

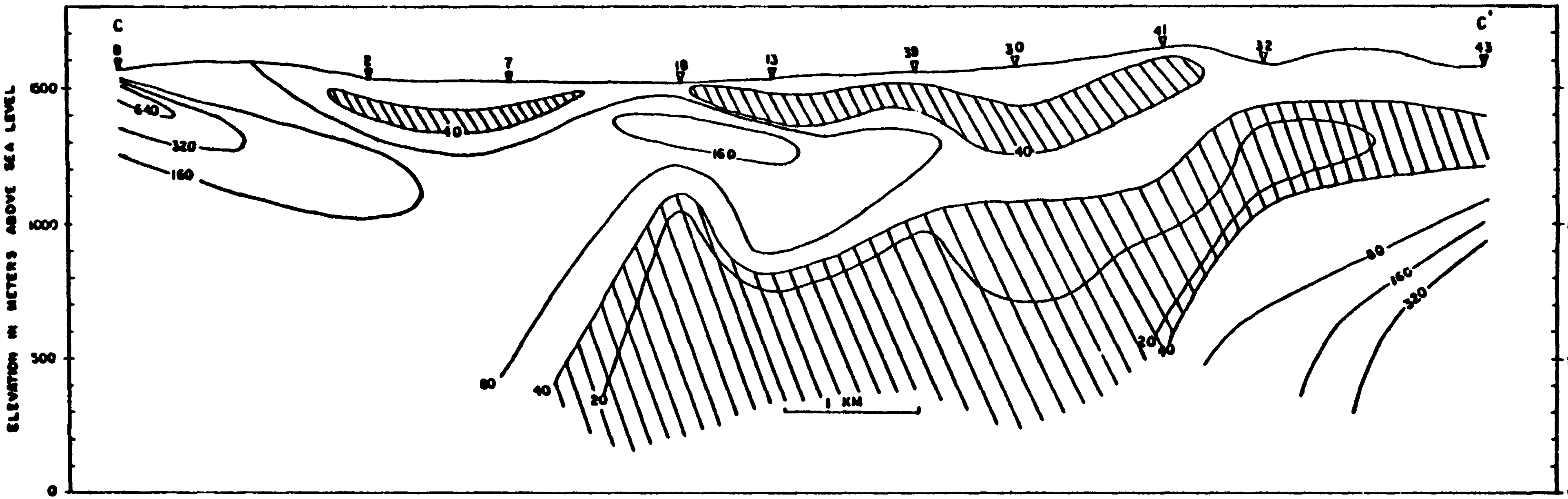

Figure 16.--Geoelectric cross-section C-C′ (fig. 13) compiled from interpreted resistivity sounding data. Contours increase in geometric progression from a value of 20 ohm-meters. Patterned areas are those intervals considered to be composed primarily of argillaceous argillite of the Eleana Formation. Vertical exaggeration is 2X. From Anderson and others (1980).

very nearly the same for the Tippipah and Eleana Formations yet the resistivities vary over such a wide range. The seismic refraction data however does indicate a wide range in velocity for the Eleana Formation.

Figure 14 shows geoelectric section A-A′ along the eastern edge of Syncline Ridge. A thick section of argillite is seen on VES 5 and 23 both within the central block. But a distinct discontinuity exists between VES 23 and VES 6 also within the central block. This electrical discontinuity and by inference lithologic discontinuity occurs rapidly as VES 23 and VES 6 are separated by only 750 m. On VES 6 and further north no resistivities were observed which are consistent with a thick section of the argillite subunit of unit J within the depth of exploration. Yet drill hole UE1-L 500 m east of VES 6 as well as VES 16 and 4 show a thick interval of argillite. VES 15 was made normal to VES 6 to help assess the effect of lateral inhomogeneities. Sounding 15 shows less evidence of lateral effects but yields the same results. These data constrain the location of what is inferred to be a major fault and indicate a northeast strike, at least in the central block. A fault interpreted near station 55 on the SSC seismic line 1 would be consistent with this trend and shows downdropping of the northwestern block. This would be consistent with the electrical data which suggests a thick section of limestone is beneath VES 6. Note the similarity with VES 3 made at the center of the Ridge in the southern block (fig. 16).

Figure 15 shows section B-B′ which runs across the structure following Gap Wash. This electrical section shows that the only thick unit of argillite lies in the valley to the west of Syncline Ridge. As would be expected it also shows the limestone is thickest at VES 11 on the syncline axis.

Section CC′ (fig. 16) is a north-south section along the front of the Eleana Range. This shows a major electrical discontinuity between VES 18 and

7. The lateral fault separating the central and southern blocks passes between these two stations. The electrical discontinuity is an expression of this fault and shows that distinct lithologic units occur on either side. From VES 18 to 41 a fairly uniform electrical section is observed also showing a thick interval of argillite in both the central and northern blocks. The lateral fault separating these two blocks is not clearly seen in this electrical data. VES 32 on Red Canyon marks the northern end of the zone containing a thick sequence of argillite. Faulting near this location is suggested by the electrical data.

Additional details may be found in Anderson and others (1980). The Schlumberger data, however, clearly shows that a great deal of heterogeneity exists in the central block and that the argillaceous unit considered for the repository has undergone significant vertical movement. This electrical data shows that the largest block of thick argillite is in the northwest part of the study area suggesting that it may be the least disturbed. A similar conclusion was drawn from the seismic reflection data.

Slingram surveys

Figure 17 shows the location of slingram traverses run on the eastern flank of Syncline Ridge to assess the usefulness of the technique for identifying faulting in the alluvium. Commercially available equipment was used operating at frequencies of 222, 444, 888, 1777, and 3555 Hz. Details of the survey are given by Flanigan (1979). Coil separation was 244 m selected as optimum based on modeling of a resistive alluvium overlying conductive argillite. Seven lines were run across the graben in the southern block and 24 east-west lines in the central block starting at the outcrop of the Tippipah Limestone going east. Two parallel northeast lines were also run along and adjacent to seismic line H Road.

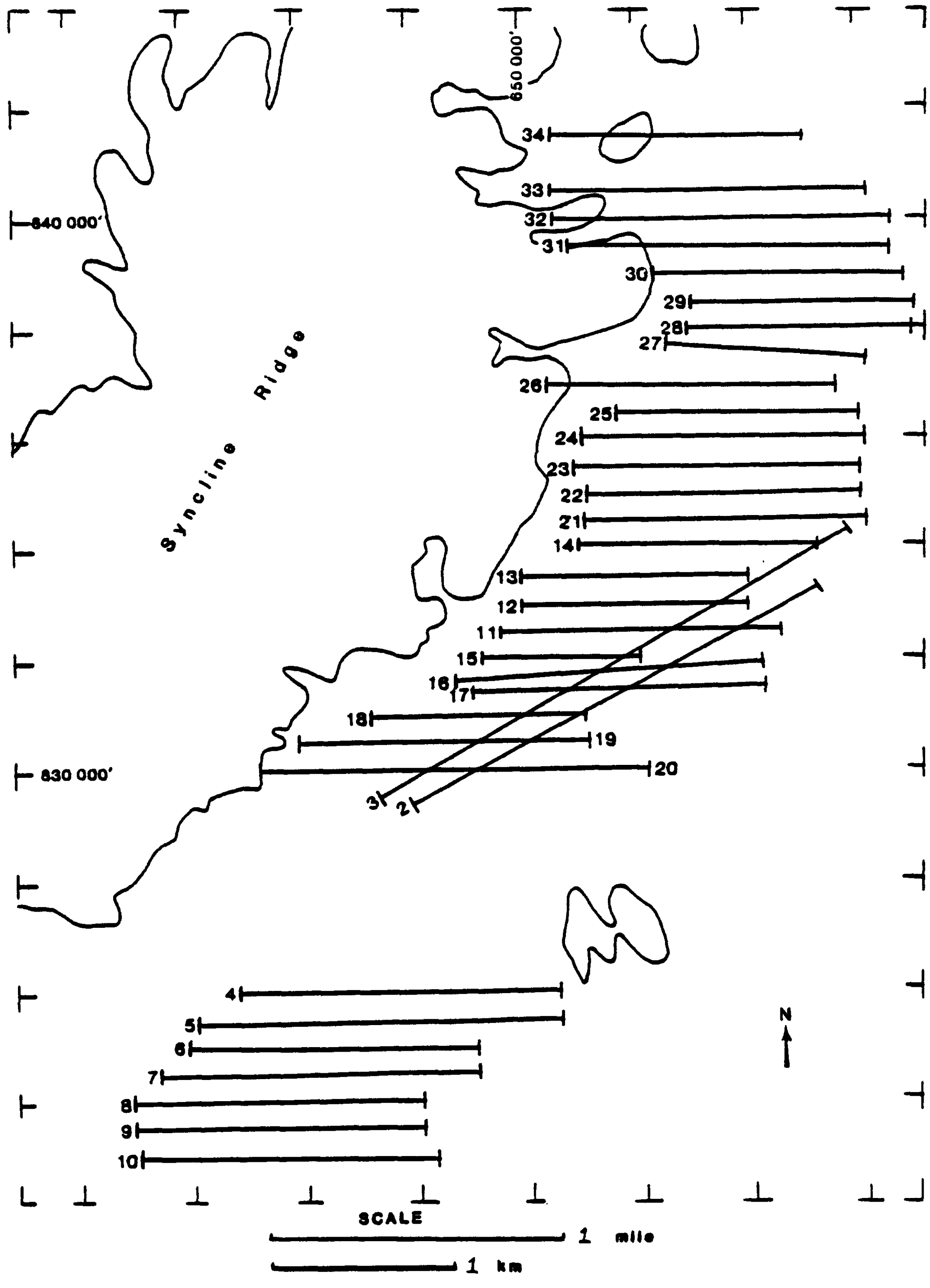

Figure 17.--Location map showing slingram traverses run over alluvium on the eastern side of Syncline Ridge. The outcrop line of Tippipah limestone is shown for reference. Adopted from Flanigan (1979).

A contour map of the slingram response from the southern block is shown in figure 18. Gradients on the eastern and western edges of the map separate regions on the edges where conductive rocks are at shallow depth as opposed to the center of the graben where thicker resistant alluvium is present. Although numerous faults have been mapped trending north to northeast across the graben (Hoover and Morrison, 1980), the thickness of the alluvial cover in the center probably masked the response of the deeper structure.

A contour map of data obtained in the central block taken from Flanigan (1979) is shown in figure 19. The most prominent feature is a northeast trending low in the real component which identifies an area of more conductive rock. This feature is just east of the outcrop of the Tippipah Limestone but is abruptly terminated at each end. On the southwest it terminates on the lateral fault separating the southern and central blocks. The northeastern end terminates south of VES 6 (fig. 13) apparently by an east-west trending feature.

Flanigan (1979) inverted selected portions of the data to derive a layered earth model for a few lines, and observed that models could not be made to satifactorally fit both the real and imaginary data sets. He attributes this principally to too complex a near surface geoelectric section which cannot be represented by his one-dimensional models.

The slingram results show various trends on the east side of Syncline Ridge which correlate in part with similar trends in other data sets. The data however is ambiguous because it is not clear how much of the response is due to bedrock topography. The method appears to have little utility in this area for identifying Quaternary faulting.

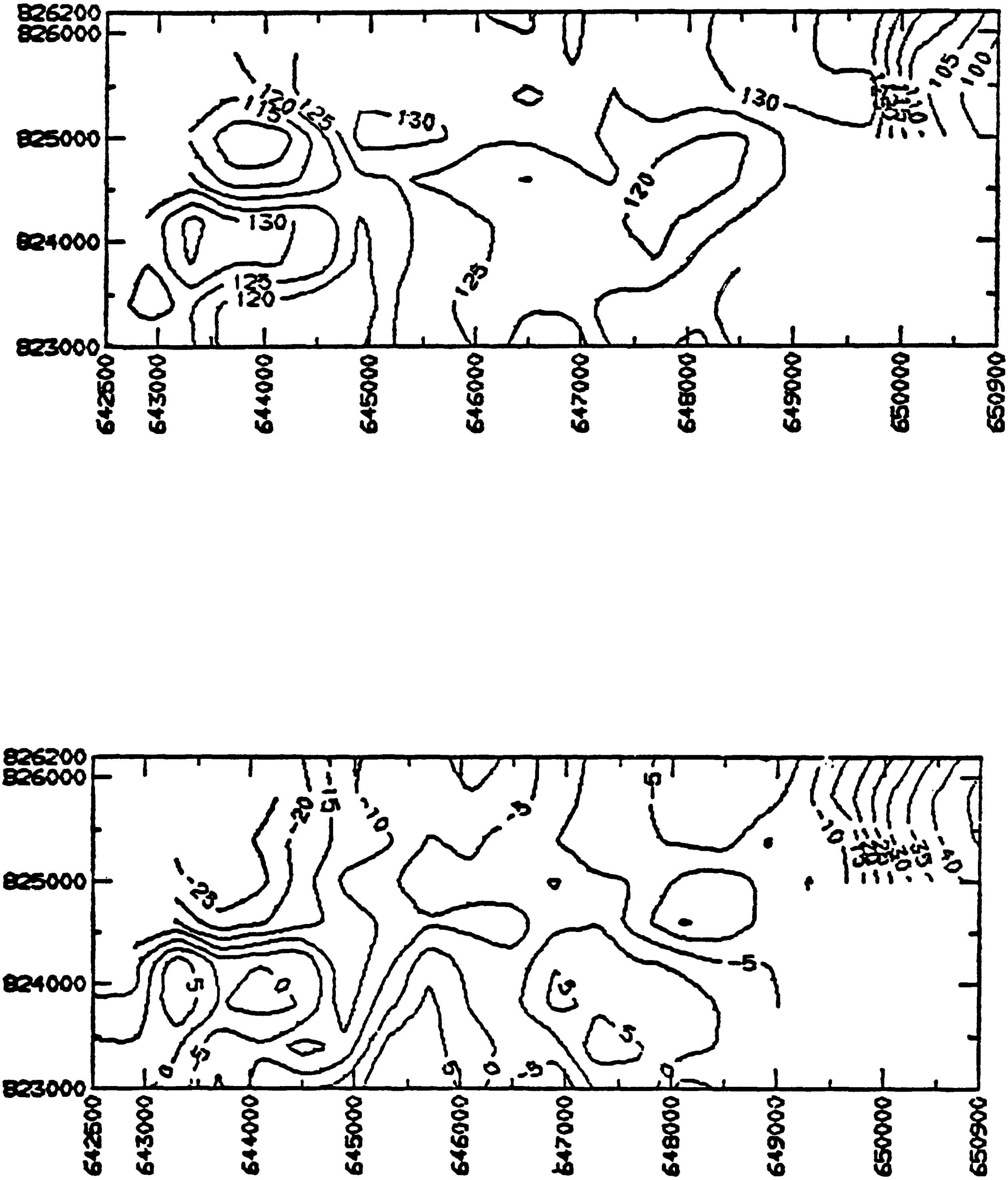

Figure 18.--Contour map in the southern block of Syncline Ridge showing slingram real and imaginary response at 444 Hz, from Flanigan (1979). Contour values are in percent of the primary field.

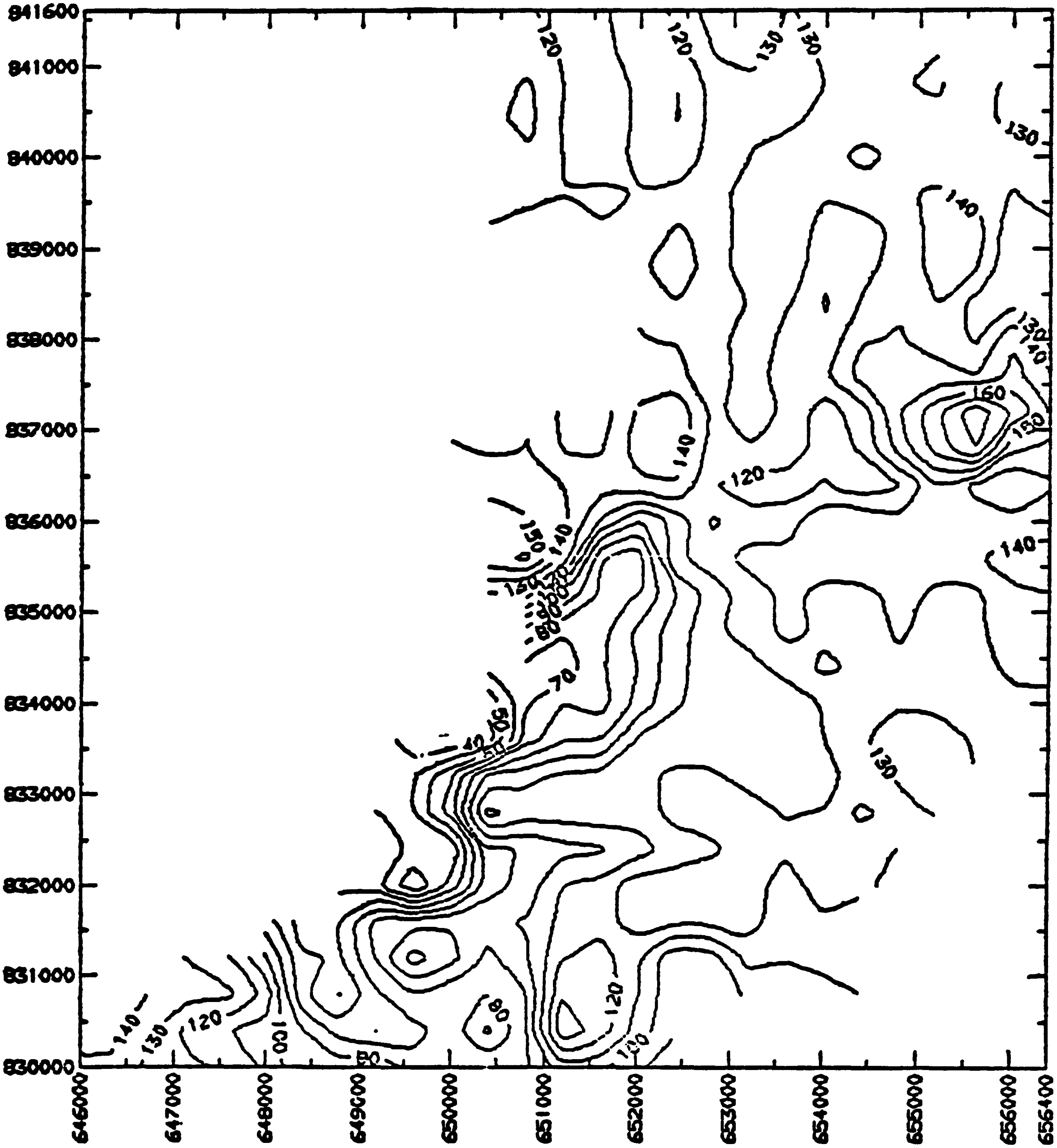

Figure 19.--Contour map in the central block of Syncline Ridge showing the slingram real response at 1777 Hz, from Flanigan (1979). Contour values are in percent of the primary field.

Magnetotelluric surveys

In February 1978 a contract was issued to Williston, McNeil and Associates, Golden, Colo., for a series of tensor magneto-telluric (MT) soundings covering the frequency range of 0.001 to 25 Hz. A digital data acquisition system was used based on a PDP-1103 computer system. A three component cryogenic magnetometer was used for sensing the magnetic field. Further details of the instrumentation are given in the final report by the contractor (Williston, McNeil and Associates, 1979). Data processing was by proprietary codes of the contractor but following the approach described by Vozoff (1972).

Locations of the MT sounding sites obtained in the study area are shown on figure 7. The sites were selected so as to give a detailed cross section normal to the structure in the central block and to tie to a previous survey. NTS 1 (fig. 7) was made at the same site as a station of the previous survey which revealed a highly conductive crust at 3 km depth. In general the data obtained were noisy with significant scatter observed on the sounding curves. This was attributed both to non-natural noise sources and to low natural signals. Data quality was so poor on station 1 that no attempt was made to invert the sounding. An estimate of the depth to the crustal conductor however was made by identifying the descending branch of the sounding curve and assuming infinite conductance for the basement layer giving a depth of 13.5 km.

Figure 20 gives the results of one-dimensional inversions and asymptotic interpretations for the line of MT stations 8, 2, 6, 4, 5 and 9. The section shows a conductor of 1 ohm-m present beneath the site at depths of 6 to 10 km. However station 8 in Yucca Flat shows a thick resistive section (1000 ohm-m) extending to 38 km. This same general picture was observed on two previous detailed MT lines in Yucca Flat about 7 km north of Syncline Ridge and for which data quality was significantly better. These data show that a significant crustal discontinuity exists on the western side of Yucca Flat separating the flat from the proposed site. The discontinuity in electrical properties also appears to correlate with the boundary separating areas of poor seismic records from good record areas.

MT surveys are often limited by data scatter which puts rather wide limits on model resolution. The method, however, is the only practical means at present for obtaining deep crustal electrical information. For this reason the method has recently been extensively used in geothermal exploration in the western United States. One of the most interesting results to come from this work is the widespread observation of conductive zones in the crust at depths of 2 to 20 km such as observed at NTS. The resistivity of these conductive regions are typically less than 1 ohm-meter, and in geothermal areas often at depths less than 10 km. The mapping of such zones is an important aspect of geothermal exploration. The physical nature of these conductive zones is not fully understood at this time.

The MT results in the study area by themselves do not constitute strong evidence for a geothermal resource beneath the site. However, an anomalous crustal condition is present suggesting the potential for a geothermal system. This potential would have to be thoroughly evaluated at the site for it ever to be reconsidered for nuclear waste disposal.

Telluric traverses

Beginning in January 1978 four E-field ratio telluric traverses were run across the study area (fig. 21). The method and instrumentation have been described by Beyer (1977). Work was done by a U.S. Geological Survey

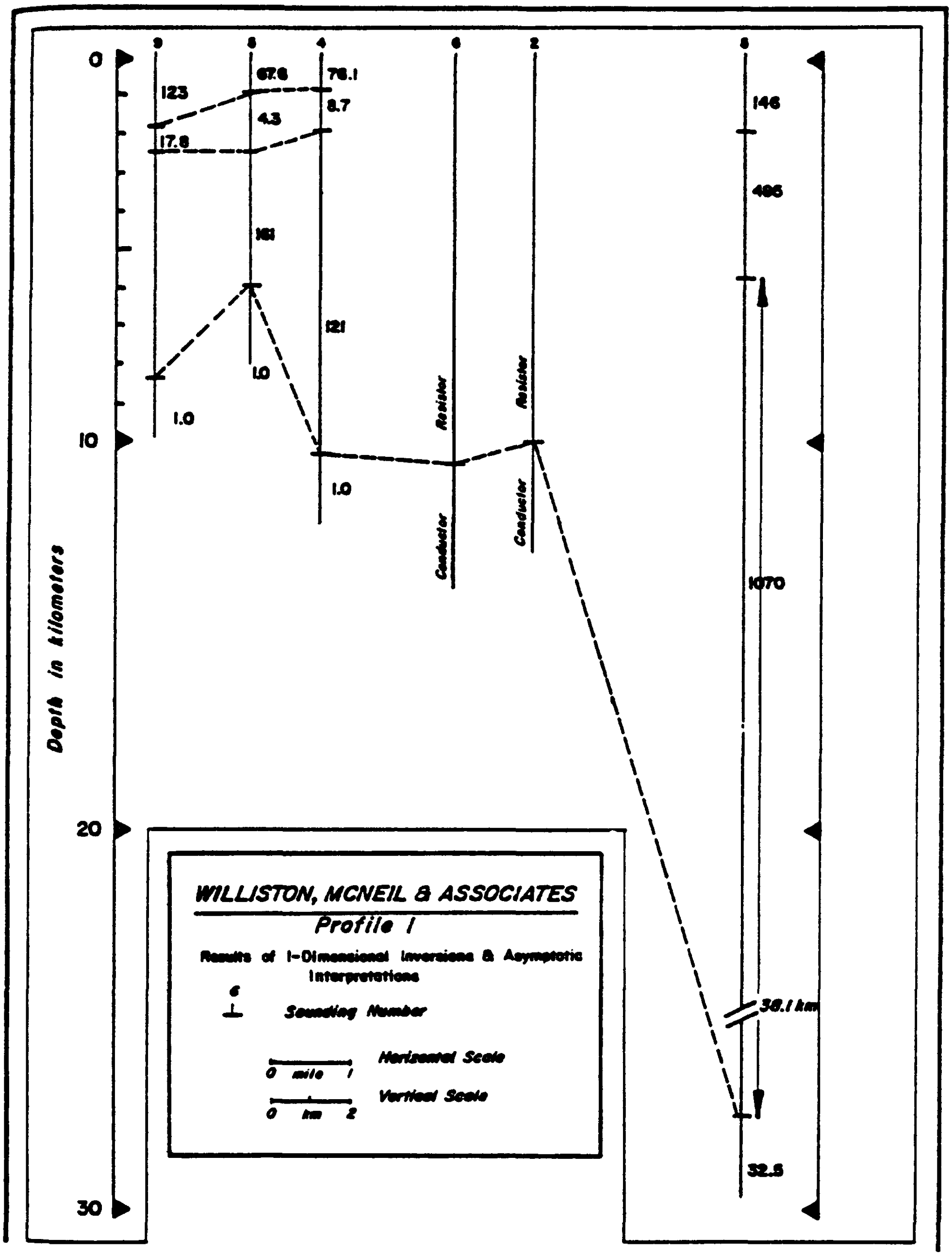

Figure 20.--Magnetotelluric geoelectric section at Syncline Ridge derived from one-dimensional inversion and asymptotic interpretation of sounding data, from Williston, McNeil and Associates (1979).

crew using equipment manufactured by the USGS. For the survey 500 m in-line dipoles were used and measurements of the Earth's natural field were made in the 20-40 sec period range. While the electrical fields at this period range sample a large part of the crust short spacial wavelength anomalies represent features of comparable extent.

Data reduction was accomplished as described by Beyer (1977). At least three sets of electric field ratio's were obtained at each recording site to insure data quality and input connections were reversed at each station to prevent cumulative error due to small differences in each recording channel. Typical station error is estimated at 3%.

Lines were referenced to each other by simultaneously recording signals at one dipole position on two lines and computing the ratio of the observed signals from the two parallel dipoles. This permitted contouring between the lines. We had hoped to be able to tie the telluric map to the MT data so as to obtain a resistivity map of the region at 20-40 sec periods. However because of the larger MT data, heterogeneity of the site, and non-correspondence of stations, only a telluric field ratio map was made (fig. 21). The resistivity map values would be proportional to the square of the electric field which was mapped. The MT data suggests that the unity contour in figure 21 would correspond to a resistivity in the range of 2 to 20 ohm-m.

The telluric map shows north to northeast trends generally following the surface structural trends. In the central and southern blocks, northeast trending lows are found on the eastern and western margins of Syncline Ridge and along or just east of the ridge crest. These lower values may be due to lower resistivity caused by fracturing along fault zones or to structural thickening of the Eleana Formation or both. On line 4 across the southern block the graben on the east side is defined by two lows correlated

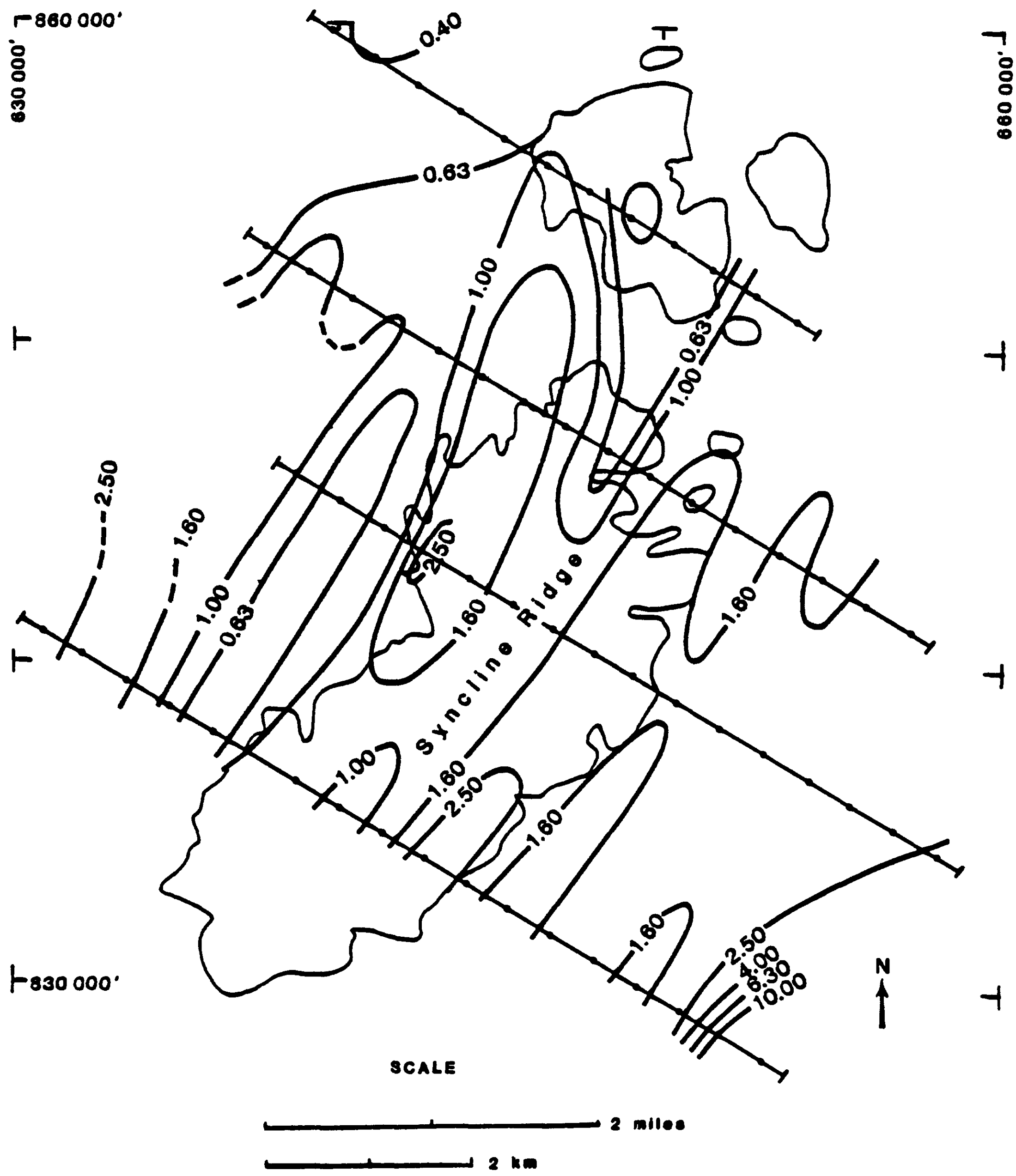

Figure 21.--Contour map of the relative electric field at 20-40 sec periods in the Syncline Ridge study area, derived from the four E-field ratio telluric traverses shown.

with the boundary faults. Very high resistivities are evident on the extreme southeastern end of this line on the flank of Mine Mountain.

Line 3 crosses the northern block where the resistivity is generally lower. Two regions on this line have values more typical of the other lines. One is over the western part of the outcrop of Tippipah Limestone and the other is on the eastern end of the line, presumably underlain by Eleana Formation. While contouring was carried between line 2 and 3 structural conditions on Gap Wash between the lines may cause the contouring to be misleading. The low values in the northwestern part of the survey show a broad region of low-resistivity rock supporting the VES data which showed a thick section of low-resistivity argillite in the same area.

Summary

The geophysical studies show that the Syncline Ridge study area is structurally complex. The general geological framework presented by earlier studies is supported. The geophysical work, however, reveals more extensive faulting and larger vertical offset than had been recognized earlier, and extensive variation in the proposed host rock within the site. Although the geophysical work was quite extensive many structural questions remain due to the complexity of the site.

The lateral fault separating the southern and central blocks is supported in the geophysical data. The lateral fault separating the central and northern blocks is not as clearly defined in part due to insufficient data. Lateral physical properties contrast across the inferred trace however are not distinct as further south. The graben on the east side of the southern block was identified by several methods. The general synclinal structure is verified by the seismic reflection data. The central axis appears displaced west of the axial fault. The central portion of the syncline has been down dropped between the axial fault along the ridge crest and a northeast-trending fault on the western edge of the ridge. The eastern half of the ridge proper appears to have suffered more extensive faulting with significant vertical movement along a fault on the eastern margin of the ridge. The axial fault which had not been considered to have undergone much displacement from earlier geological studies, appears as a major geophysical discontinuity, the geophysical data implying significant movement and fracturing. Faulting cutting alluvium was identified on the eastern side of the ridge, thus probably of Quaternary age, which implies recent movement.

The Eleana Formation, which is the proposed host medium here, appeared from electrical studies to lack continuity. This is inferred to be due to structural complexity. A small area in the northwest part of the study area was identified where the Eleana argillite subunit appears relatively undisturbed and of sufficient thickness for repository use.

Several deep crustal structural features were noted which could have significance for the repository siting. A north-trending crustal feature identified by seismic and electrical studies bounds the eastern margin of the site approximately along Nevada coordinate E 662,000. West of this line, very conductive rocks were identified at less than 10 km depth, possibly implying a potential geothermal system and resource. Gravity and MT data also show that the deeper crustal structural trends are realigned from the north to northeast direction seen at the surface to northwest at depth.

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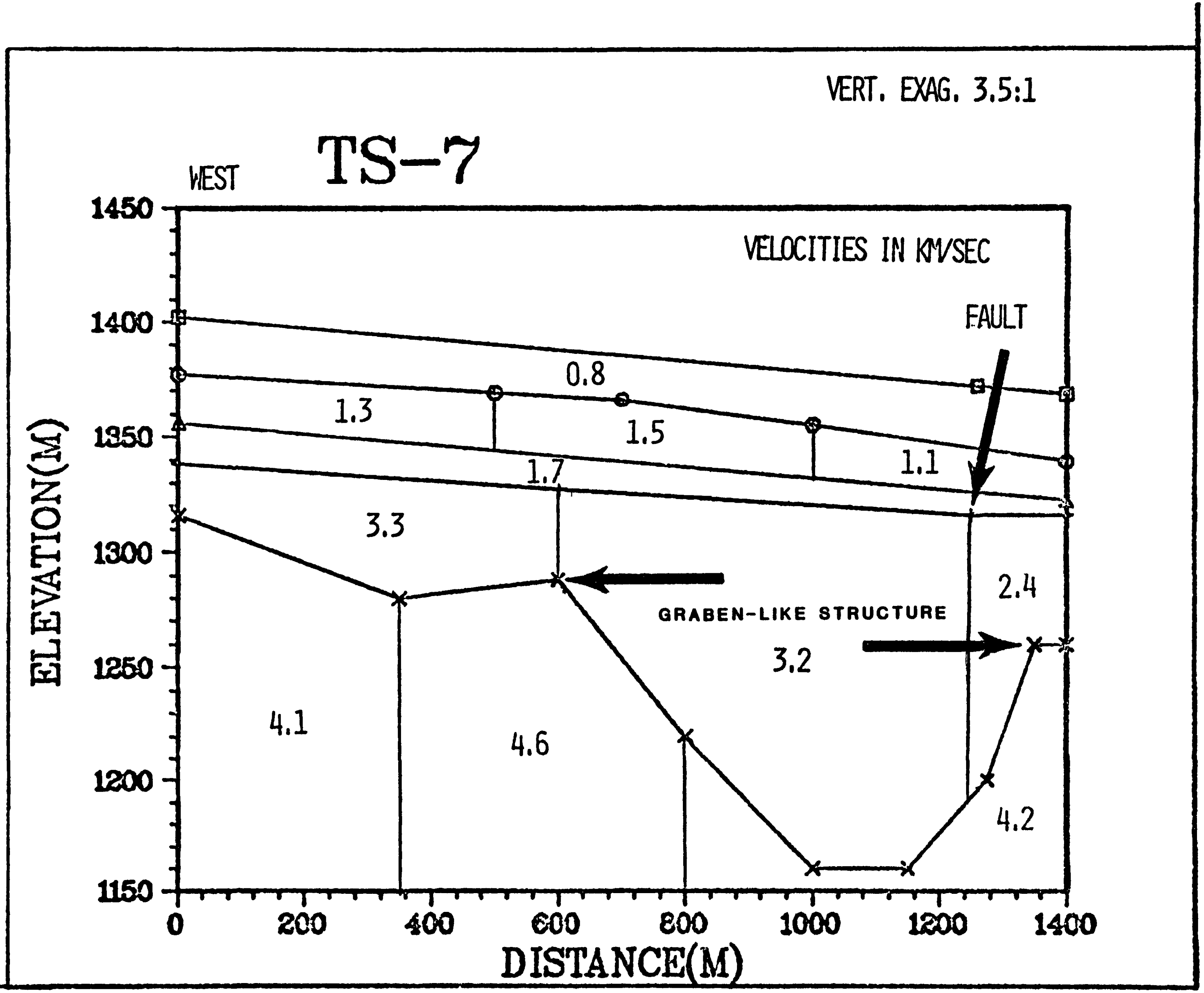
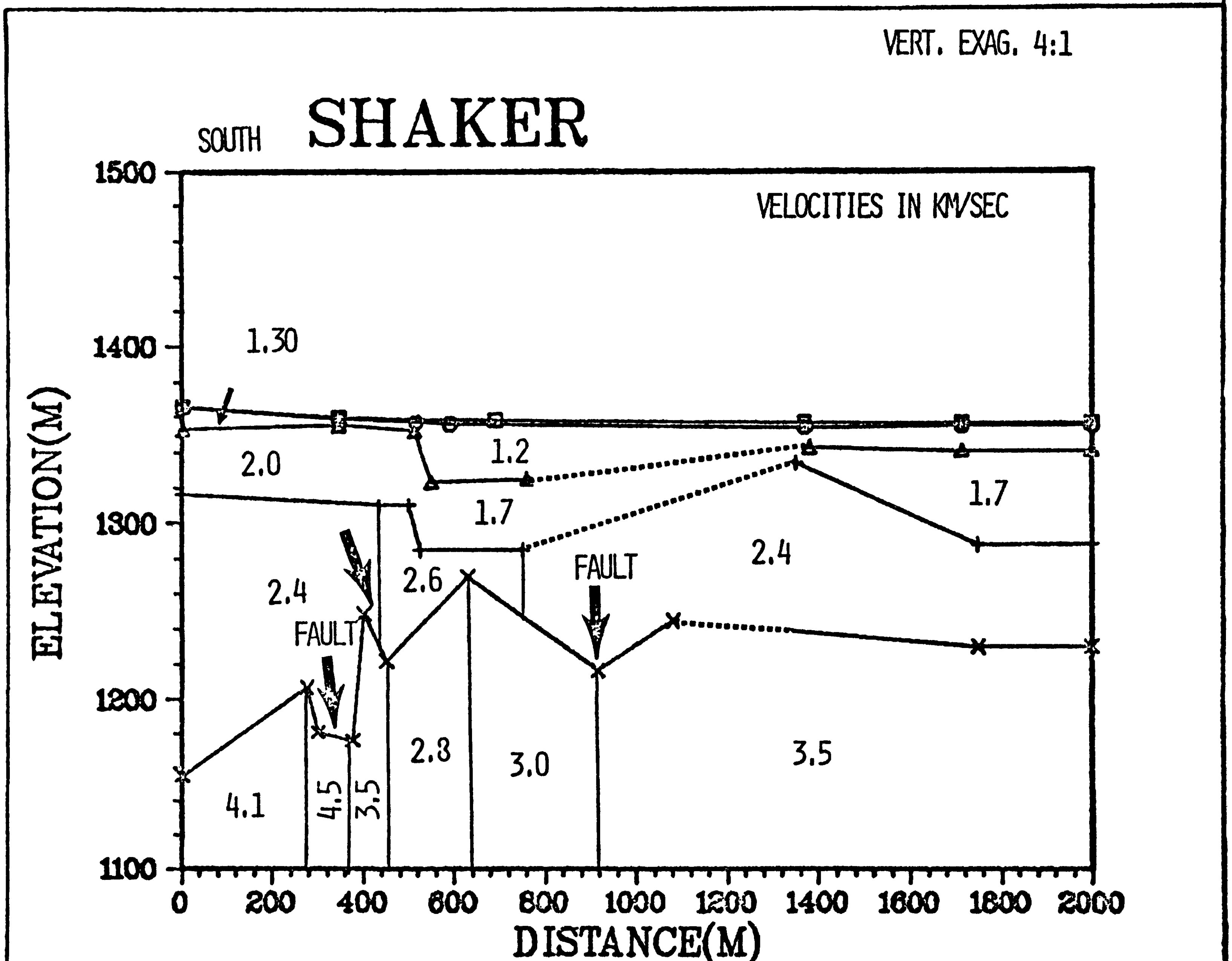
Appendix 1.

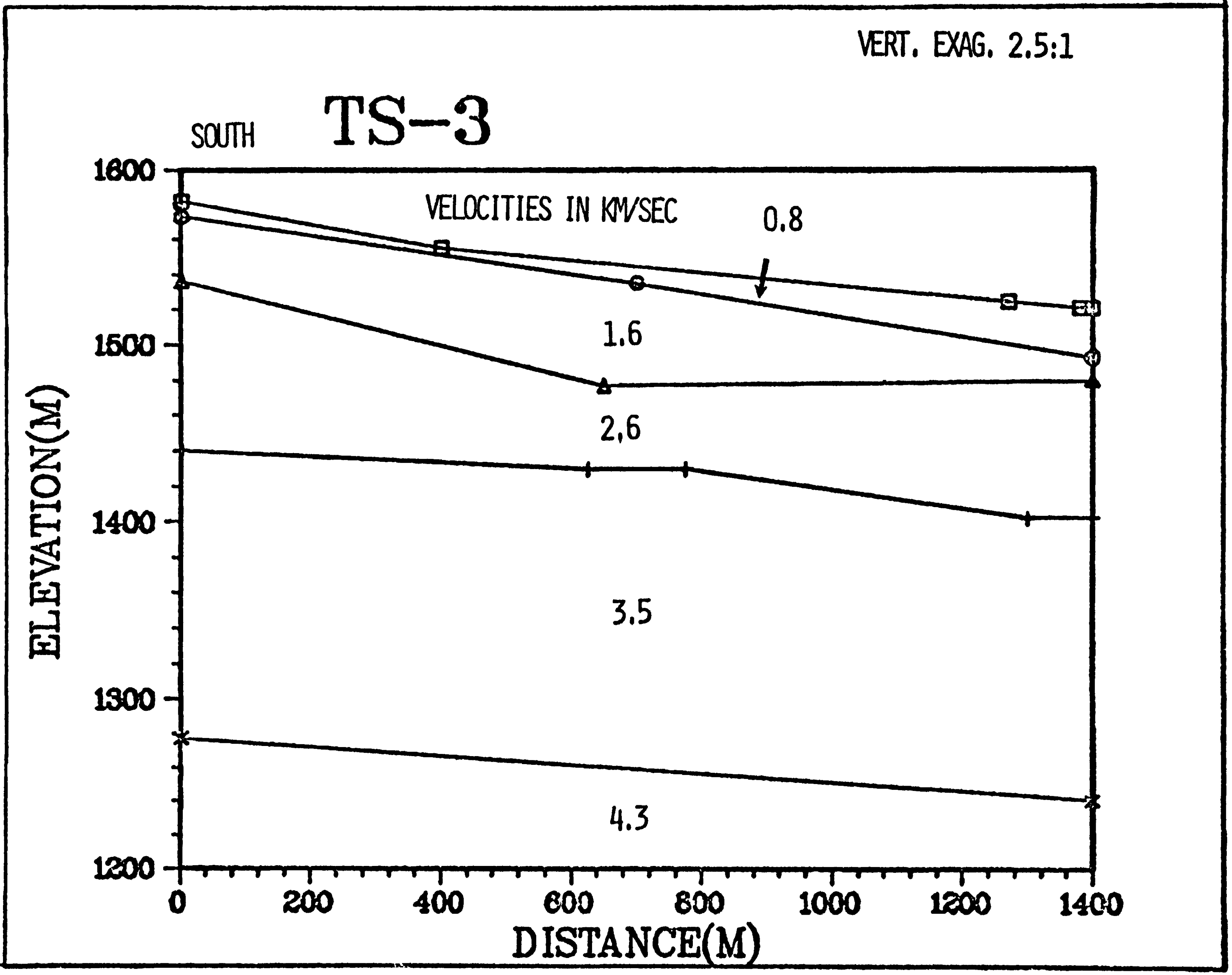
The following seismic refraction velocity sections were derived from an interactive computer program of H. D. Ackermann (unpub. program, 1981).

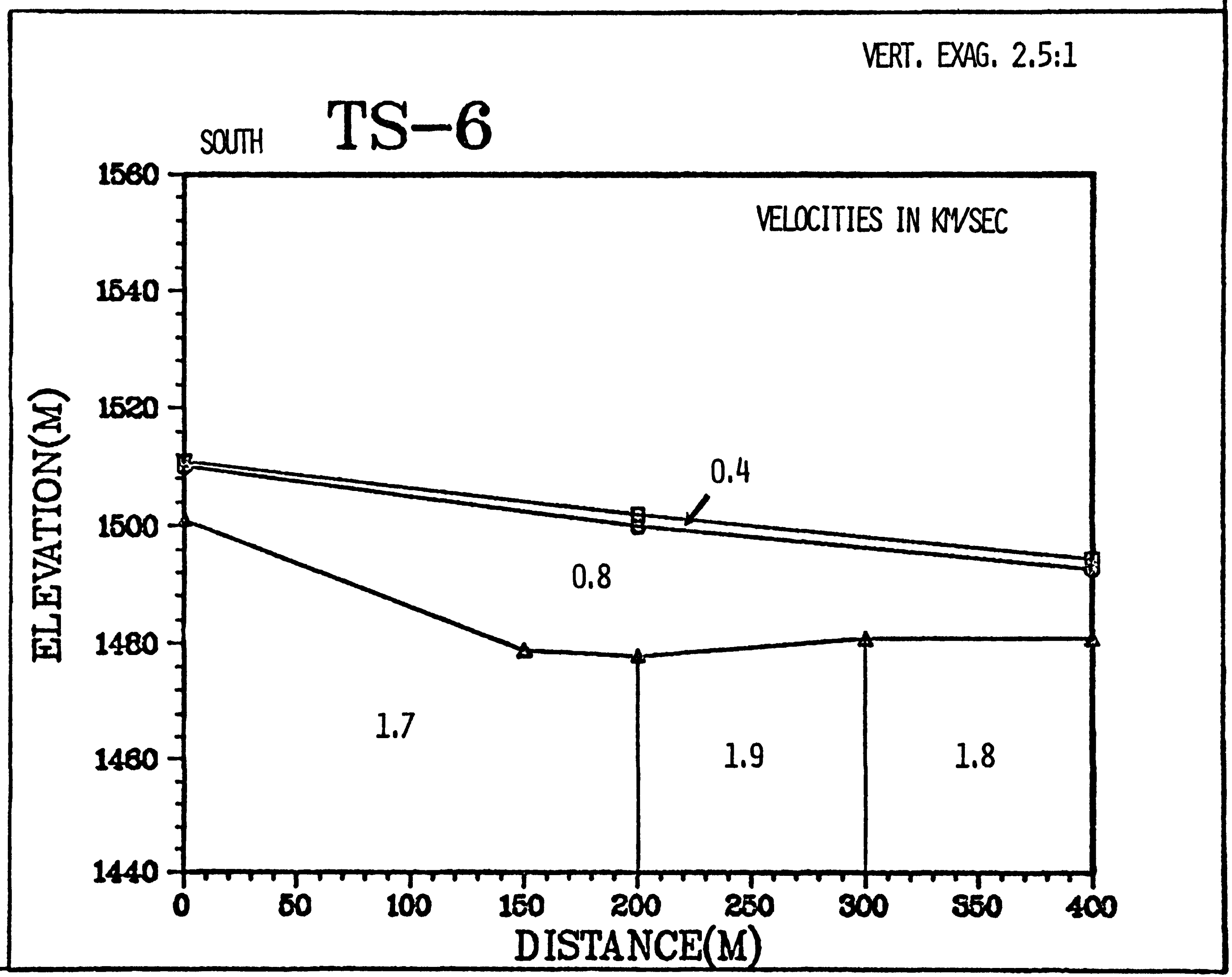


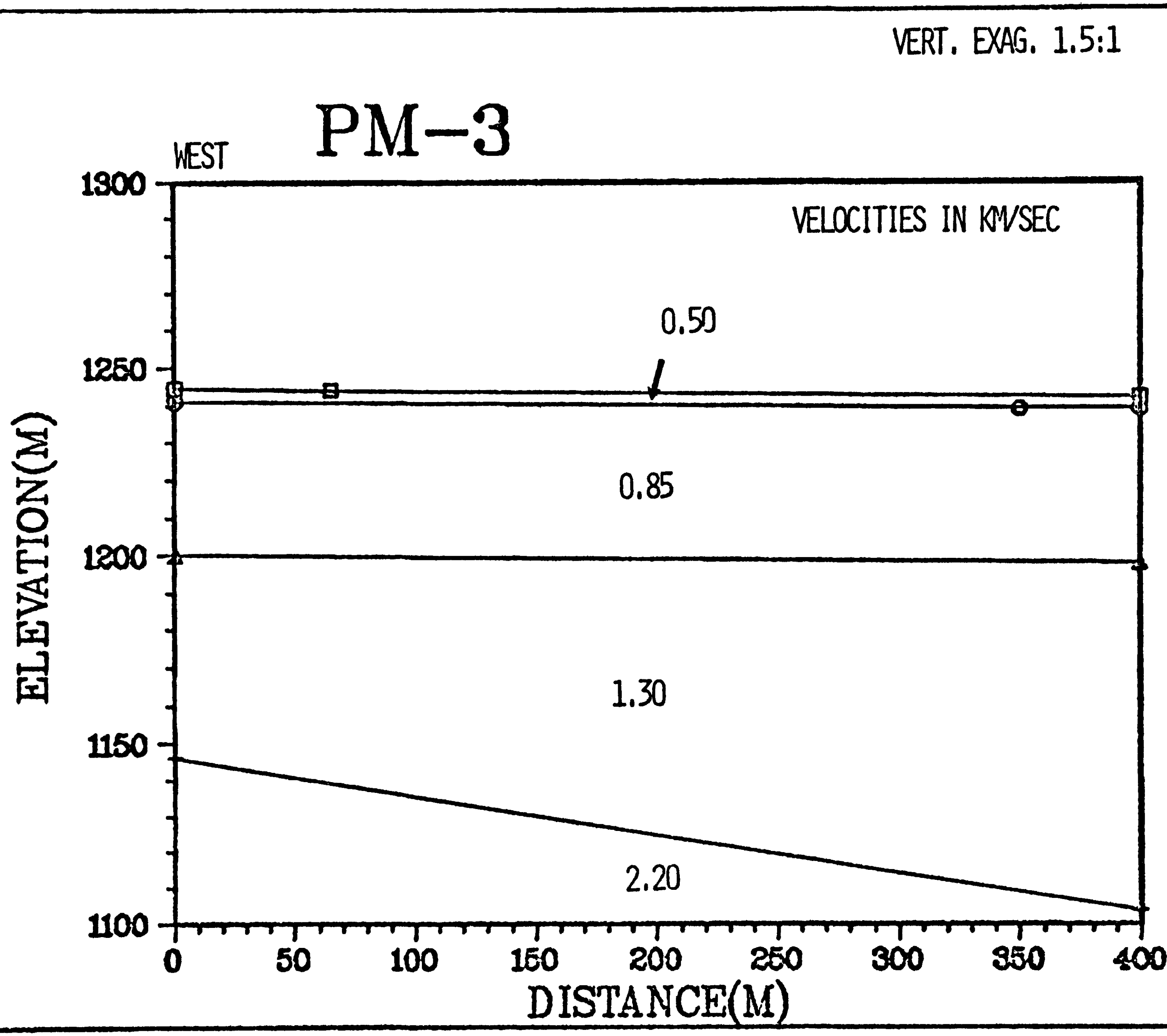
TS-7
WEST
VERT. EXAG. 3.5:1
VELOCITIES IN KM/SEC
FAULT
0.8
1.3
1.5
1.1
1.7
3.3
2.4
GRABEN-LIKE STRUCTURE
3.2
4.1
4.6
4.2
ELEVATION(M)
1450
1400
1350
1300
1250
1200
1150
0
200
400
600
800
1000
1200
1400
DISTANCE(M)



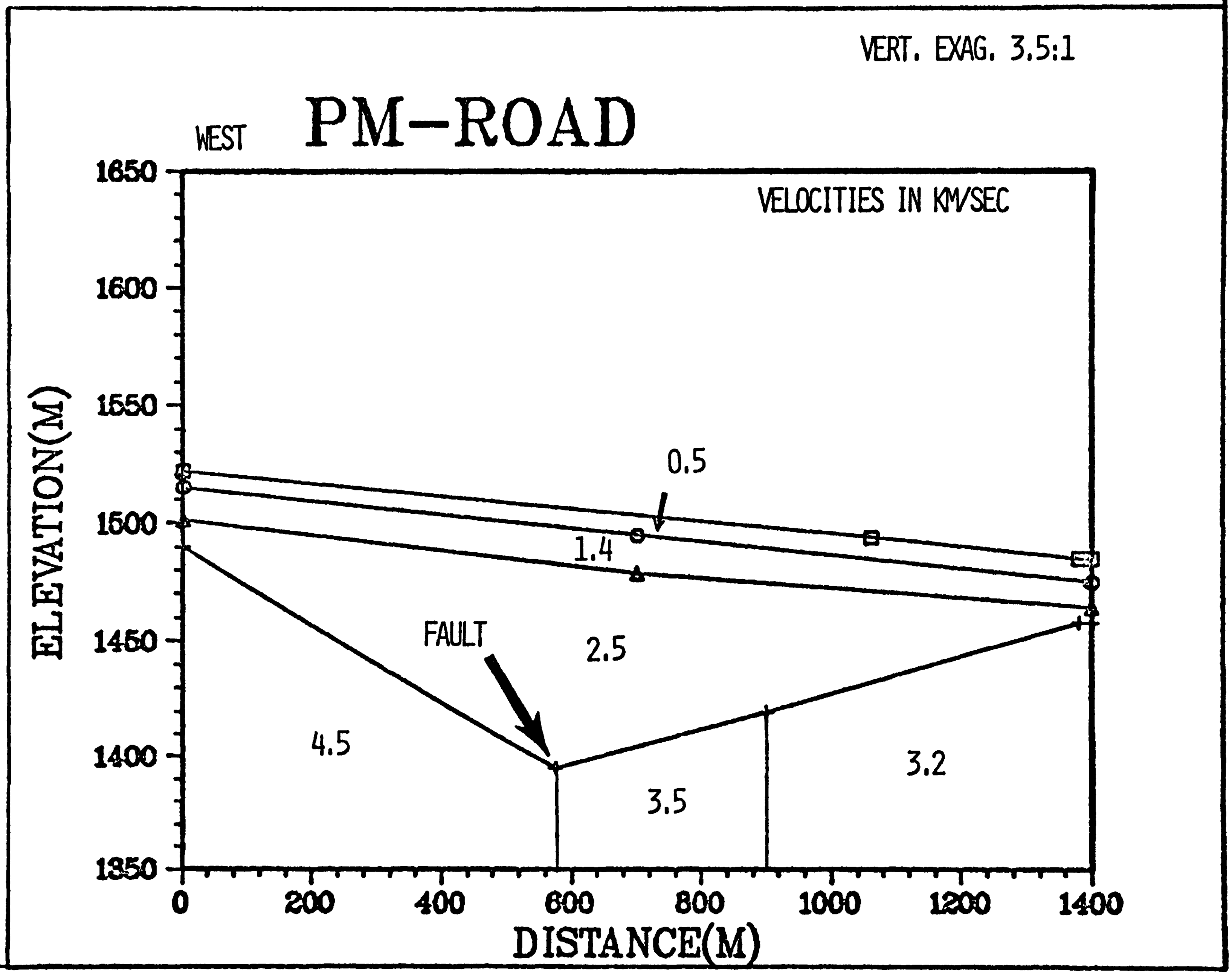
VERT. EXAG. 4:1
SOUTH
SHAKER
VELOCITIES IN KM/SEC
1.30
2.0
1.2
1.7
1.7
2.4
2.6
2.4
FAULT
FAULT
4.1
4.5
3.5
2.8
3.0
3.5
ELEVATION(M)
1500
1400
1300
1200
1100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
DISTANCE(M)

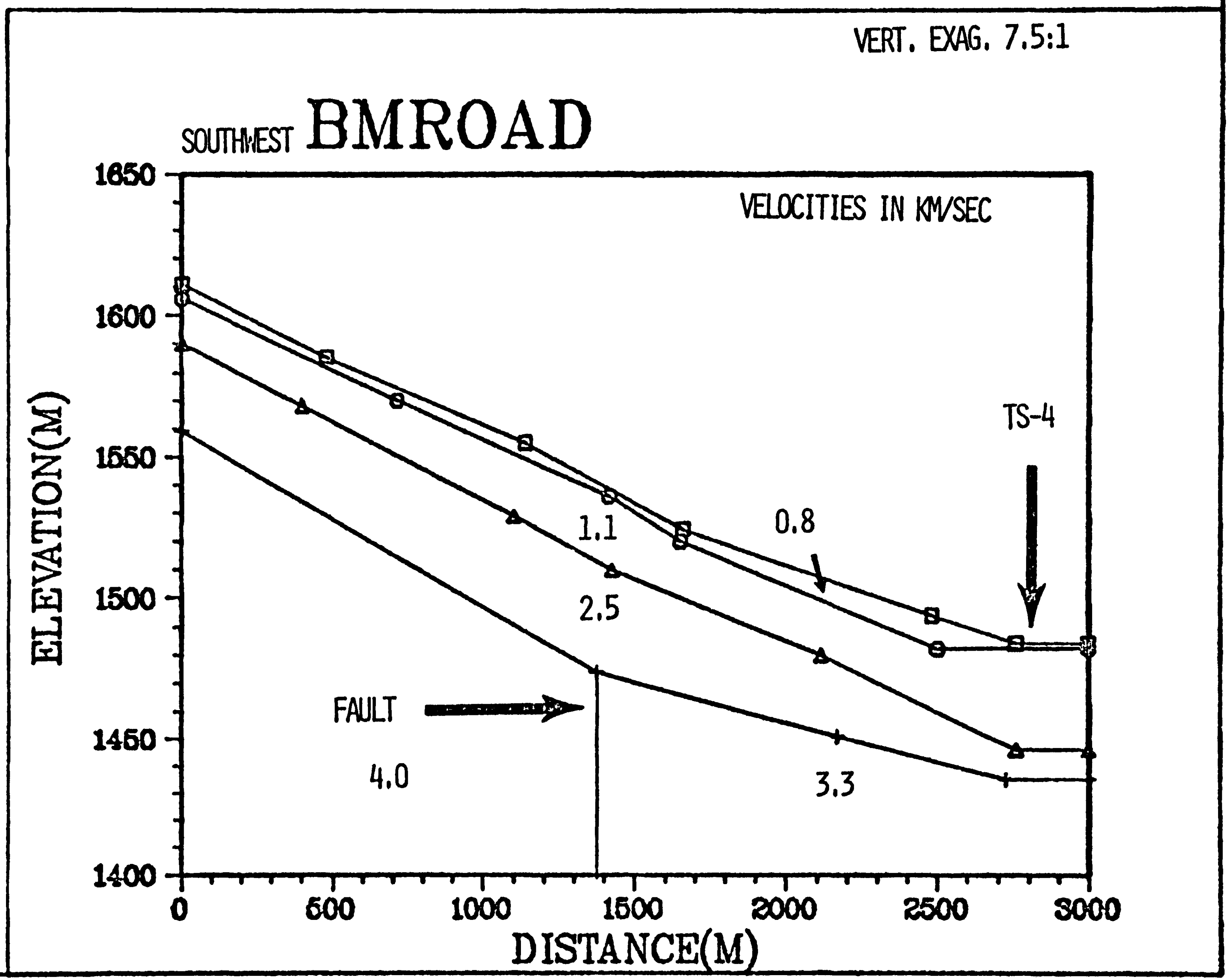

VERT. EXAG. 2.5:1
SOUTH
TS-3
VELOCITIES IN KM/SEC
0.8
1.6
2.6
3.5
4.3
ELEVATION(M)
1600
1500
1400
1300
1200
0
200
400
600
800
1000
1200
1400
DISTANCE(M)

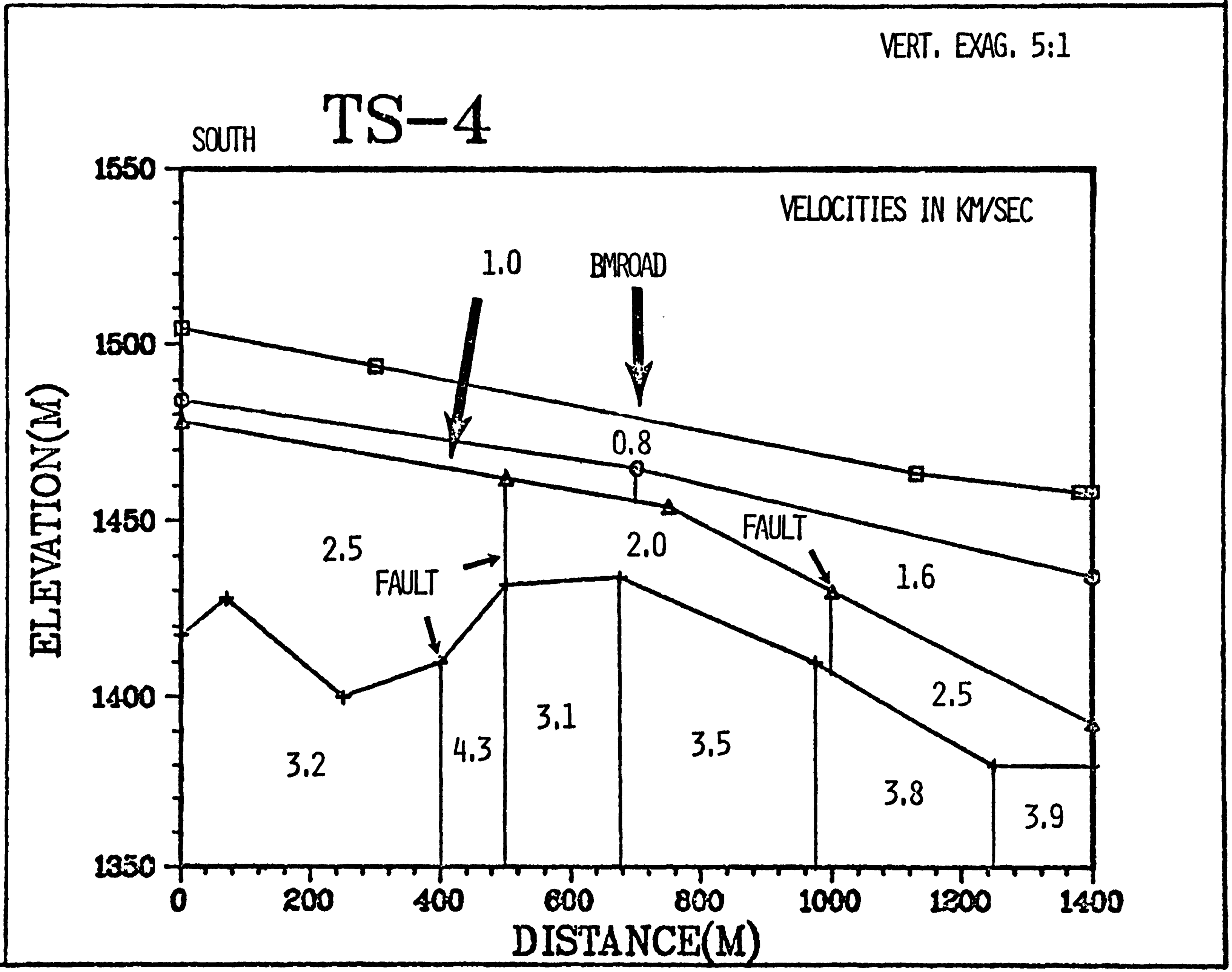

VERT. EXAG. 2.5:1
SOUTH
TS-6
VELOCITIES IN KM/SEC
0.4
0.8
1.7
1.9
1.8
ELEVATION(M)
1560
1540
1520
1500
1480
1460
1440
0
50
100
150
200
250
300
350
400
DISTANCE(M)

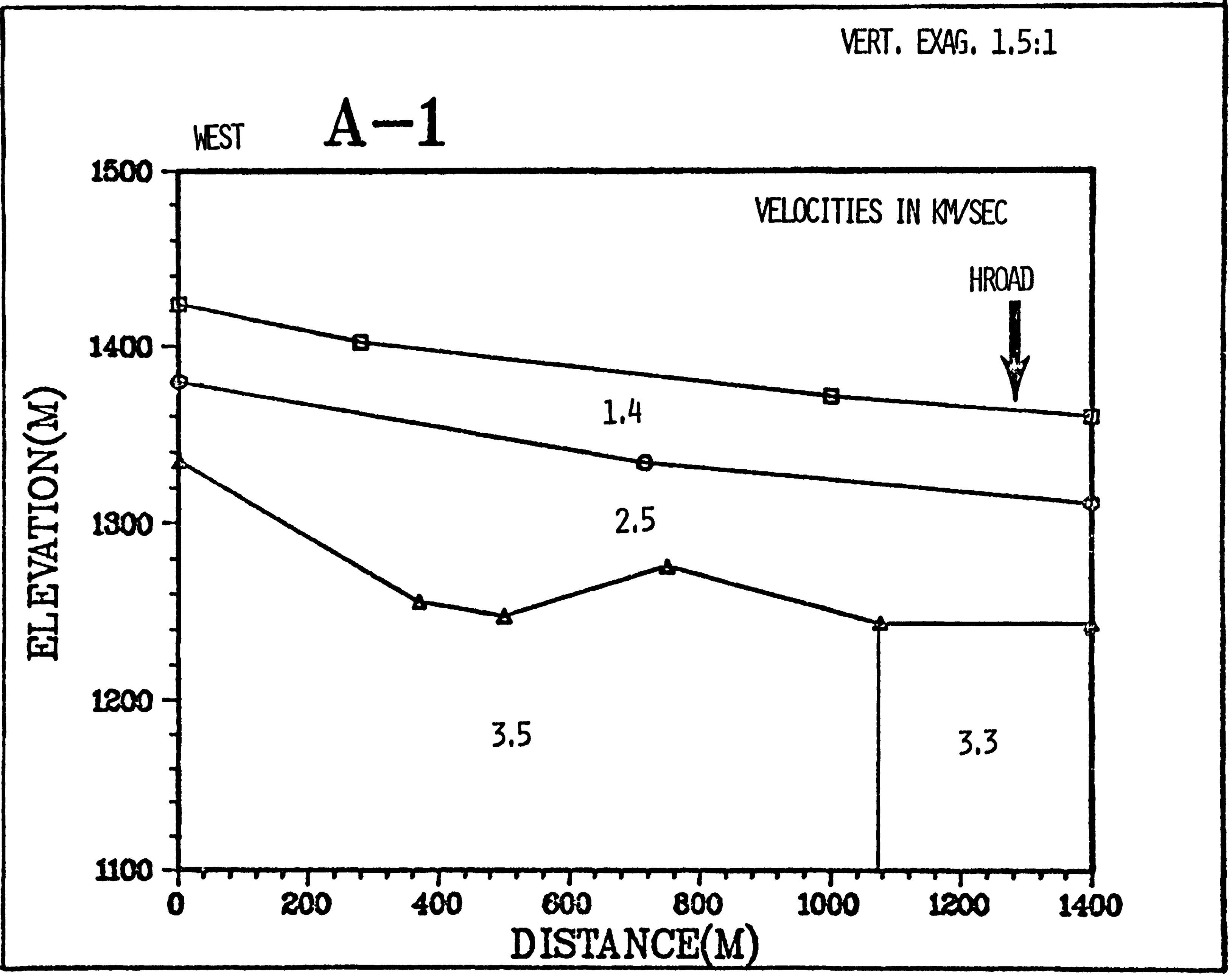


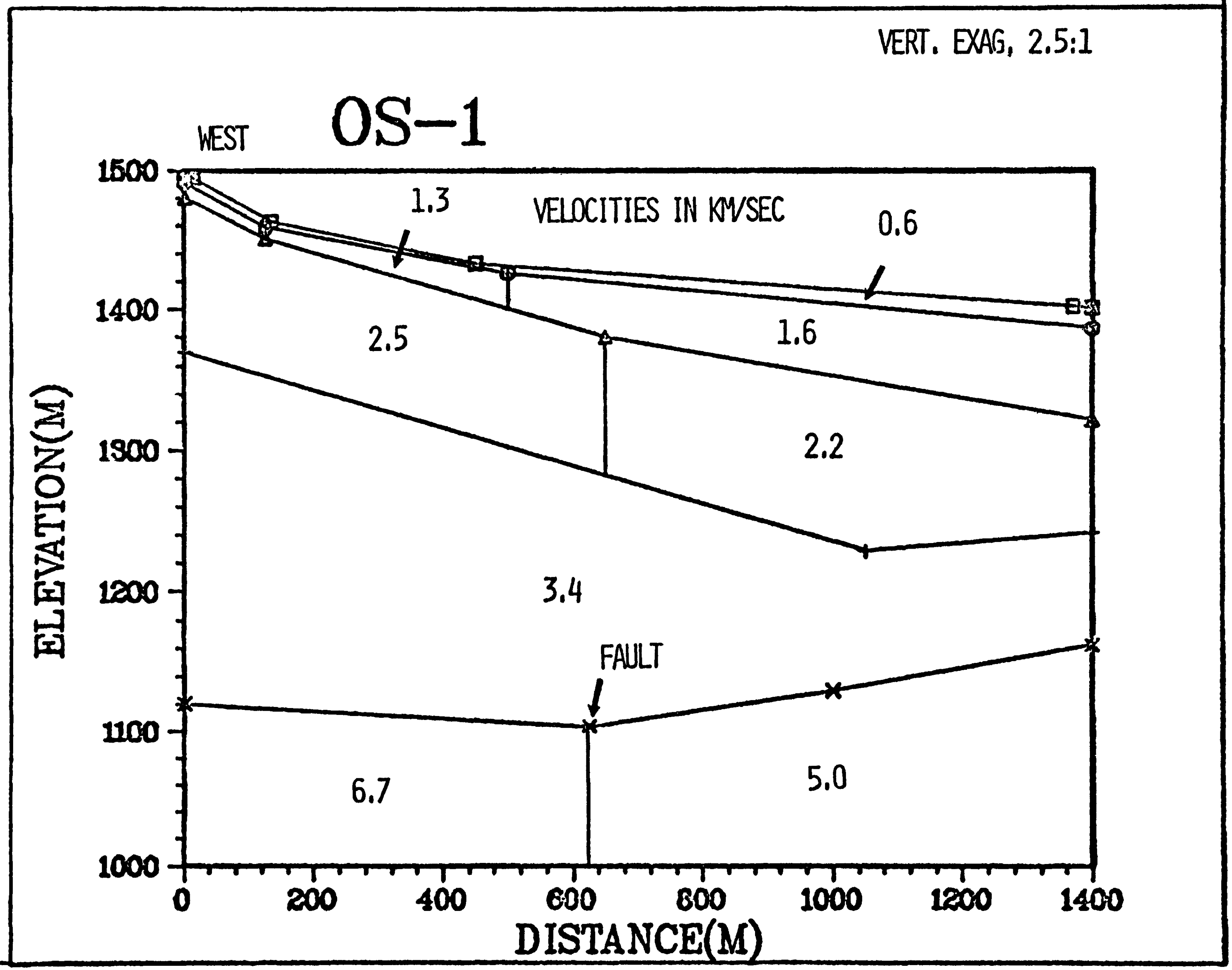
VERT. EXAG. 1.5:1
PM-3
WEST
VELOCITIES IN KM/SEC
0.50
0.85
1.30
2.20
ELEVATION(M)
1300
1250
1200
1150
1100
0
50
100
150
200
250
300
350
400
DISTANCE(M)

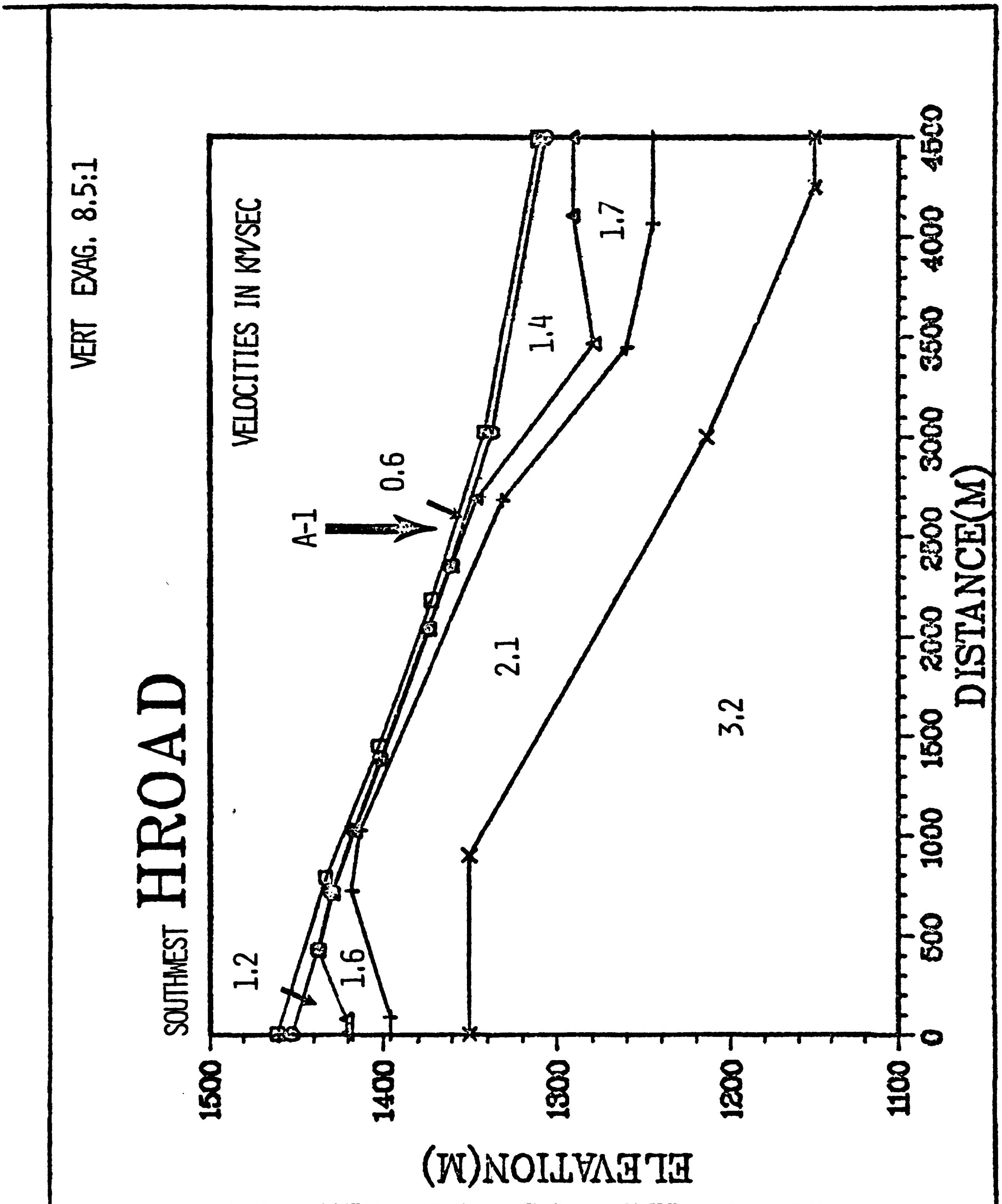

VERT. EXAG. 3.5:1
WEST
PM-ROAD
VELOCITIES IN KM/SEC
0.5
1.4
2.5
FAULT
4.5
3.5
3.2
ELEVATION(M)
1650
1600
1550
1500
1450
1400
1350
0
200
400
600
800
1000
1200
1400
DISTANCE(M)


VERT. EXAG. 7.5:1
SOUTHWEST BMROAD
VELOCITIES IN KM/SEC
0.8
1.1
2.5
TS-4
FAULT
4.0
3.3
ELEVATION(M)
1650
1600
1550
1500
1450
1400
DISTANCE(M)
0
500
1000
1500
2000
2500
3000


VERT. EXAG. 5:1
TS-4
SOUTH
VELOCITIES IN KM/SEC
1.0
BMROAD
0.8
2.5
FAULT
2.0
FAULT
1.6
2.5
3.2
4.3
3.1
3.5
3.8
3.9
ELEVATION(M)
1550
1500
1450
1400
1350
DISTANCE(M)
0
200
400
600
800
1000
1200
1400


VERT. EXAG. 1.5:1
WEST
A-1
VELOCITIES IN KM/SEC
HROAD
1.4
2.5
3.5
3.3
1500
1400
1300
1200
1100
ELEVATION(M)
0
200
400
600
800
1000
1200
1400
DISTANCE(M)


VERT. EXAG, 2.5:1
OS-1
WEST
VELOCITIES IN KM/SEC
1.3
0.6
1.6
2.5
2.2
3.4
FAULT
6.7
5.0
ELEVATION(M)
1500
1400
1300
1200
1100
1000
0
200
400
600
800
1000
1200
1400
DISTANCE(M)



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