GEOPHYSICAL STUDIES OF THE BASIN STRUCTURES ALONG THE EASTERN FRONT OF THE SIERRA NEVADA

Thesis by

John Helding Healy

In Partial Fulfillment of the Requirements

For the Degree of

Doctor of Philosophy

California Institute of Technology

Pasadena, California

1961

ABSTRACT

Eighteen seismic refraction profiles were shot and about 1200 gravity stations were occupied in the basins bordering the eastern Sierra Nevada between Owens Lake and the Garlock Fault. The results of these data show that basin structures with maximum depths averaging between 4000 to 6000 feet follow the front of the Sierra for this entire distance except for about ten miles near Little Lake.

These basins are usually narrow, fault-bounded structures with their deepest parts close to the front of the Sierras.

Analysis of the regional gradients indicates that the Mohorovicic discontinuity can play only a minor role in the isostatic support of the Sierra Nevada.

ACKNOWLEDGMENTS

The author acknowledges with gratitude the guidance and continued support of Professor Frank Press throughout this study, and also the support and suggestions of Professor Clarence R. Allen. The author thanks Professor Charles F. Richter for his helpful discussion of the seismology of this region.

Western Geophysical Corporation provided a seismic drill at cost for two weeks during the summer of 1959. This support is gratefully acknowledged.

Mr. Laszlo Lenches and Mrs. Elaine Biehler prepared most of the figures and Mrs. Biehler helped with the computations. This assistance greatly facilitated the preparation of this thesis.

Special thanks are due Ralph Gilman and Robert Nason for extensive participation in the field program, and Robert Kovach, Shelton Alexander and Frederick Tahse for their help on the seismic survey.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE		PAGE

INTRODUCTION

This is a report of a seismic and gravity survey along the eastern front of the Sierra Nevada. The work is part of a continuing study of the basin structures in the California-Nevada region.

The present study had a double objective: first, to use the seismic refraction and gravity techniques to define the depths and configuration of the basin structures along the eastern front of the Sierra Nevada from southern Owens Valley to the Garlock Fault and, if possible, to determine the pattern of faulting within the basins. The second objective was to evaluate the effectiveness and limitations of the seismic and gravity methods in this type of study.

About 1200 gravity stations were occupied, and eighteen seismic refraction profiles were shot in the area. The results of this data show the depths and shapes of the basin structures, and some information about the faulting within the basins can be inferred.

The effectiveness of the seismic and gravity methods has been closely examined in problems relating to petroleum exploration. However, some special difficulties peculiar to areas of rugged terrain have not been resolved. For example, the terrain correction for precise gravity surveys is particularly difficult in mountainous areas, and presently available techniques are not adequate for many problems.

A terrain correction program was developed for the Bendix G15 computer, and special programs to assist in the interpretation of seismic data were written and evaluated. These computer programs can greatly increase the effectiveness of the seismic and gravity methods.

Rapid lateral changes in lithology in the narrow basins present difficulties for both the seismic and gravity methods. Seismic refraction was successful in the central portion of the basins parallel to the structural trends, but was not successful at the margins of the basins near the bounding faults. The gravity method was exceptionally effective over the narrow basin structures, and the combination of seismic and gravity data was used successfully to determine the depths and shapes of basins.

In this report a general discussion of geology and seismicity precedes the description of the seismic and gravity survey.

DISCUSSION OF GEOLOGY

Physiography

The Sierra Nevada is one of the major mountain ranges in the western United States. On the east the range rises to a high ridge containing peaks with elevations exceeding 14,000 feet. From this ridge the range dips westward in a ramp-like structure and disappears sixty miles west of the ridge under the Tertiary sediments of the central valley of California. At the northern end the range decreases in elevation and disappears under the volcanics that make up the Cascade Range. At the southern end the range terminates abruptly at the Garlock fault, which separates the Sierra Nevada from the Mojave Desert.

The trend of the high ridge has an interesting pattern that may have some structural significance. From Lake Tahoe to Owens Lake the high ridge strikes north 35° west. This trend is parallel to the trend of the Central Valley, the Coast Ranges, and the continental slope. At Owens Lake the trend of the high ridge turns and strikes about north 9° west to a point near Walker Pass where the trend of the ridge turns again. From Walker Pass to the Garlock fault the high ridge becomes indistinct but the trend of the margin of the range strikes north 30° east.

These changes in trend of the high ridge appear to be related to significant changes in the basin structures bordering the Range to the east. The turning point of the ridge of Owens Lake is marked by the widening and deepening of the basin under Owens Lake and then the return to a shallower and narrower structure in Rose Valley. The change in the strike of the ridge at Walker Pass is accompanied by a narrowing of the broad Indian Wells Valley structure and a change in strike of the deep part of the basin which parallels the strike of the range.

The physiography of the Mojave Desert is distinctly different from that of the Sierra Nevada. The structural trends do not seem to be related to the trends in the Sierra Nevada or the Basin and Range province which border it on the northeast. The boundary between the Sierra and the Mojave Desert is a major fault zone including the Garlock fault. This fault is a gently arcuate feature which is concave toward the south and strikes approximately north 60° east. The Garlock is a predominantly strike-slip fault which can be traced from the San Andreas fault eastward to the vicinity of the Avawatz Mountains, where it appears to turn southwest with a zone of faulting from southern Death Valley.

The southeast boundary of the Mojave is the San Andreas fault zone. This fault is one of the largest known faults and is itself part of a worldwide tectonic system surrounding the Pacific Ocean. The Mojave Desert lies in the triangle between these two major faults, the Garlock and the San Andreas, both of which have been recently active, and yet the advanced geomorphic state of the area suggests that the Mojave itself has been curiously inactive. Recent detailed mapping by Dibblee shows that numerous relatively small faults striking northwest cut Recent sediments.

The Basin and Range province covers most of the state of Nevada and is characterized by elongated block-faulted mountains and basins. An east-west line across the center of the province crosses about fifteen range crests. The average distance from crest to crest of the ranges is about twenty miles, and the ranges are commonly two hundred miles in length trending nearly north-south. The trends of the ranges tend to shift parallel to the Sierra Nevada on the west, and some observers place the Sierra Nevada in the Basin and Range province.

The Sierra, the Mojave, and the Basin and Range province show remarkable contrasts between each other and yet each province shows a high measure of structural and physiographic consistency within its own boundaries. The boundaries between the provinces are major faults with lengths and displacements that suggest penetration into the Mantle, while within the individual provinces the scale of the features suggests that the structural breaks may be confined to the crust.

It is suggested that the properties of the crust may differ under each of these provinces and that the differences in physiography are largely the result of the response of different crustal sections to a more or less uniform regional stress pattern.

Rocks of the Area

Pre-Tertiary Rocks

Pre-Tertiary rocks in this area have all been metamorphosed and in many places intruded by rocks of the so-called Sierra Batholith. These granitic textured rocks have been dated by various radioactivity methods, and the general picture that emerges is one of regional metamorphism and intrusion taking place through the Jurassic and Cretaceous periods. This metamorphism has "homogenized" the Pre-Tertiary rocks so that granitic and metamorphic rocks have similar velocities and densities which contrast sharply with the velocities and densities of Tertiary sediments. Thus it is convenient and justifiable in this study to largely ignore the complexities of the Pre-Tertiary rocks and concentrate on the Tertiary geology.

Tertiary Sedimentary Rocks

On the eastern and southern border of the Sierra Nevada, which is the area of primary concern in this report, the Tertiary sediments have been deposited in narrow basins. Where the older Tertiary sediments are exposed, as in Red Rock Canyon, they are similar to sediments which are being deposited today in the central portion of the basins. The bulk of the sediments range from coarse sandstones to fine mudstones. However, rocks similar to the boulder conglomerates which make up the fans in front of the present Sierra scarp are not found in the Miocene and Pliocene exposures at Red Rock Canyon.

Dibblee (1952) has given an excellent description of the geology of the Saltdale quadrangle, where the best exposures of the Tertiary section are found. He describes two formations: The Ricardo Pliocene section which comprises about 7,000 feet of terrestrial sandstones, mudstones, and pebble conglomerates is separated by an angular unconformity from the Miocene Goler formation which comprises about 6,500 feet of sandstones, mudstones, and pebble conglomerates, resting on a basal fanglomerate.

The Ricardo formation contains several thin interbedded basalt and andesite flows and localized deposits of pumice and tuff.

Tertiary Volcanic Rocks, Miocene Pliocene

Volcanic rocks are widespread throughout the area of interest and may be important clues to the tectonic processes which are our primary concern. Most of the volcanic rocks occur in flows of basalt or andesite usually less than two of three hundred feet thick.* Where the source areas can

---

*In the region of Mono Basin rhyolites occur along with the more basic volcanics.

be observed the flows frequently lie on the uplifted granitic blocks rather than within the basin sediments. One exception is in Mono Basin, where a basalt flow has risen through a thick section of sedimentary rocks in the center of Mono Lake.

As mentioned earlier Dibblee has described basalt and andesite flows interbedded in the Pliocene Ricardo formation. These flows can be observed along Highway 6 through Red Rock Canyon. No volcanic rocks occur in the Miocene Goler formation at this location.

Webb (1937) describes basalt and andesite flows in the Kernville quadrangle north of the road from Walker Pass to Isabella. These flows were extruded on a relatively level surface at a time when the Sierra Nevada had reached an advanced stage of erosion. They are now erosional remnants sitting high in the eastern Sierra. Webb guessed the age of these flows as Pliocene and it seems reasonable to correlate them with the flows in the Ricardo formation; the erosional surface on which they rest may correlate with the erosional surface between the Ricardo and Goler formations in Saltdale quadrangle.

Basalt flows resting on an erosion surface were described by Lawson (1904) in the Olancha quadrangle. The Olancha quadrangle lies north of the Kernville quadrangle and west of southern Owens Valley. These flows lie on a surface which Webb correlated with the old erosion surface in the Kernville quadrangle, so it appears that the flows lying on this surface are of the same age.

Pliocene andesite flows uplifted west of Haiwee reservoir were described by Hopper (1939).

Tertiary Volcanic Rocks, Pleistocene and Recent

Lawson also described very recent small flows in Toowa Valley which had been extruded after the geomorphic evolution of the region had reached its present stage.

Pleistocene Basalt flows cover an extensive area east of Little Lake. The cinder cone in Rose Valley known as Red Hill is of this age, and much of the topography to the east is the result of Pleistocene or Recent volcanism. About twenty miles east of Red Hill in Rose Valley fumaroles are emitting steam and hot waters along recent fault scarps at Coso Hot Springs.

Hopper (1939) reports that west of Haiwee reservoir Pleistocene flows are erupted on a Pliocene erosion surface and have been faulted by later movement. Aerial photos show faults in the surface of similar flows south of Little Lake.

The Black Mountain Basalt in the Saltdale quadrangle rests on the Ricardo formation and is considered to be Pleistocene in age by Dibblee (1952). These flows are similar in many respects to the basalt flows near Little Lake.

The foregoing description lists most of the volcanic activity between Red Rock Canyon and southern Owens Lake. Similar occurrences could be described farther to the north along the front of the Sierra and strongly suggest that the extrusion of these volcanic rocks is an intimate part of the mountain building process.

Historical Geology

The Paleozoic history of this area is a complex story that is only partially revealed in the exposed metamorphic rocks. Great thicknesses of Paleozoic rocks were deposited in a geosynclinal environment and then metamorphosed during the latter part of Mesozoic time.

The period of metamorphism was followed by a period of regional uplift and erosion in late Mesozoic and early Tertiary time so that Tertiary sediments now lie on a basement of granitic or metamorphic rocks.

By early Pliocene time the general form of the present structures seems to have evolved, but the Sierra Nevada was apparently a broad surface of only moderate elevation. Axelrod (1957) estimates from paleobotanical evidence that the Sierra was a broad ridge with its summit near 3000 feet.

Putnam (1960) gives strong evidence for major Pleistocene uplift of the Sierra Nevada. He has mapped glacial deposits from four glacial stages in the vicinity of McGee Mountain on the eastern slope of the Sierra. The earliest glacial till, representing the McGee stage, lies at an altitude of from 10,000 to 10,800 feet. Judging from the position of the McGee till with respect to the present topography and the position of glacial tills representing three latter stages of glaciation, Putnam estimates an uplift of 3,000 to 4,000 feet since McGee time.

Evidence from volcanic activity and remnants of old erosion surfaces support Putnam's conclusion of major Pleistocene uplift.

Structure

Figure 2, is a fault map covering the area of the survey. This map was copied directly from a map prepared by C. R. Allen. Allen prepared this map using available published information, his own studies of aerial photos, and personal field observation of the faults shown on the map.

The author has examined the evidence for faulting in the areas covered by the geophysical surveys. The evidence comes primarily from the geomorphology. Small scarps in the fan surfaces, changes in the ground water level as indicated by vegetation, and abrupt changes in slope near the mountain front are the most frequent sources of fault evidence. Almost without exception the nature of the evidence implies movement in Recent or Pleistocene time.

The long north-south fault in the Sierras is the only major fault in the area which might have been inactive through the Pleistocene.

In addition to the faults shown on the map there are undoubtedly other major faults which have not yet been recognized. There are a number of topographic features in the Sierras that suggest major faulting in recent times. The Walker Valley between Walker Pass and Isabella is a very discordant feature. The size of Walker Valley suggests that it was eroded by a major river but only a small stream flows down the valley, and this stream is agrading its channel. Kelso Valley is another discordant feature lying south of Walker Valley. Kelso Valley is a low-lying oval-shaped valley surrounded on all sides by steep mountain fronts. This valley could not possibly have been formed solely by erosion as only one small stream drains the valley. Despite these strong suggestions for major faulting no faults have been mapped at these locations.

Von Huene (oral communication) has established new evidence for north-trending faults cutting the basin sediments in the eastern part of Indian Wells Valley. He has completed a detailed gravity survey in this area and his final interpretation will add important evidence about the nature of this faulting.

One conclusion that can be drawn from the surface evidence for faulting is that the faults along the Sierra front are in harmony with the present topography and basin structures. Repeated movements along these faults would largely account for the observed topography and the shapes of the basins as revealed by seismic and gravity data.

ALLUVIAL FANS AS INDICATORS OF BASIN DEPTHS

The character of the alluvial fans appears to be related to the rate of sinking of the basins. The most striking example of this is the contrast between the fans in Rose Valley and the fans in southern Owens Valley immediately to the north. In Rose Valley west of Haiwee reservoir, the fans extend several miles from the Sierra front with gently graded profiles. In southern Owens Valley west of Owens Lake, the fans are small and lie close to the source canyons. This change in fan character corresponds to the deepening of the basin structure between Rose Valley and Owens Valley. Since the character of the source area and climatic conditions appear to be nearly identical the only explanation for the difference in fan character is the rate of sinking of the basins.

SEISMICITY

Figure 3, shows all earthquakes in the area larger than magnitude 4.0 that have been recorded by the California Institute of Technology network between 1934 and 1956. These shocks are designated in the figure as magnitude 4 to 5, magnitude 5 to 6, magnitude 6.1, and earthquake swarms. Earthquake swarms appear to be a characteristic feature of this region. As many as one hundred small earthquakes may occur within a limited region in the course of a few days or weeks. Some of these swarms have a main shock with associated foreshocks and aftershocks, but other swarms have no shock large enough to qualify as a main shock. Swarms of this type are characteristic of volcanically active areas.

There are not enough seismic stations in the region to get a satisfactory fault-plane solution for the smaller shocks. Richter (1960) reported on two series of small earthquakes in this area, near Haiwee and near China Lake. He reports that initial compressions and dilatations in both groups of shocks were consistent but gave no simple fault-plane solutions.

Depth of focus of earthquakes in the area is not well known. The standard sixteen kilometer depth for southern California is used with reasonable success in routine calculations. This implies that the earthquakes are occurring in the crust. Chakrabarty and Richter (1949) gave the depth of the 1946 Walker Pass earthquake as 22 kilometers.

Perhaps the best depths available for a group of earthquakes were determined for the aftershocks of the Kern County earthquake of 1952, which occurred west of the present area. The focal depths of these shocks tended to lie in a layer somewhere between 10 and 20 kilometers. Uncertainties in the velocities are responsible for the large uncertainty in the depths of these shocks. (Richter, personal communication.)

Many possible hypotheses are suggested by the data on earthquakes in this area but the density of stations is not sufficient to resolve the crucial unknowns: exact location, depth, and radiation patterns.

The most significant known seismic event in the region was the 1872 earthquake at Lone Pine. Vertical displacements of ten to twenty feet and horizontal displacements up to 13 feet were reported. Unfortunately there is disagreement about the sense of the horizontal displacements. Richter (1958) gives a good summary of the known facts and the published reports. The story is obviously complex and has been seriously confused by inadequate early observations followed by detailed observations many years after the event. Despite these difficulties certain important facts can be established. This was a major earthquake undoubtedly exceeding magnitude 8 with vertical and horizontal displacements exceeding ten feet. Vertical movement on the fault was consistent with the present topography in that repeated movements of this nature would account for the mountain and basin structures in the area. It is also important to note that erosion eliminated much of the evidence of faulting in thirty five years between 1872 and 1907 when the earthquake area was studied in detail by Johnson (Hobbs, 1910).

CONCLUSIONS FROM GEOLOGY AND SEISMICITY

If an earthquake similar to the Owens Valley Earthquake of 1872 occurred every 1000 years with an average vertical displacement of ten feet, the Sierra Nevada would attain its present elevation in less than two million years. Considering the effects of erosion on the 1872 earthquake features this rate of uplift would not be inconsistent with the present geomorphic character of the Sierra front.

The old erosion surface high in the Sierras supports the idea of very recent uplift.

Extensive Pleistocene volcanism and the uplifting of Pliocene and Pleistocene sediments further support the conclusion that this area has undergone major tectonic activity in the last two million years. The seismicity of the area indicates that this tectonic activity is continuing at the present time.

SEISMIC REFRACTION SURVEY

Field Operations

Approximately eighteen seismic refraction profiles were shot along the eastern front of the Sierra Nevada to determine the thickness of sediments and the structural configuration in the basis bordering the range (fig. 4). This work was done in the summers of 1958 and 1959 by a crew from the Seismological Laboratory of the California Institute of Technology. Equipment consisted of an eight channel recording set-up using Houston Technical Laboratories' two-cycle geophones and United Geophysical low frequency refraction amplifiers. Shot holes were drilled by hand auger during the first field season and by a shot hole rig contracted at cost from Western Geophysical Company during the second field season.

The field operations were designed to yield maximum coverage in the limited time and with the limited funds available. To this end a field technique that gives the effect of a reversed profile without actually reversing the geophone spread was used (Dix, 1952, page 263). With this method the geophone spread is left stationary while the shot point is moved. The apparent velocity across the spread is compared with the apparent velocity measured from a plot of the travel times from the first geophone to the shot points.* This technique proved to be ideally suited to the type of reconnaissance operation needed for the preliminary study of basin structures.

Drilling conditions were extremely variable. There were three general types of terrain encountered, high fans, low fans, and dry lakes, and each type of terrain had characteristic drilling problems. The high fans were close to the mountain front and consisted of poorly sorted debris including large boulders. It was practically impossible to obtain a satisfactory shot hole in this material. The low fans were farther from the mountain front and consisted mainly of sands and gravels. Usually it was not possible to reach the water table with a shot hole, but fairly good energy coupling could be obtained with shallow holes just deep enough to prevent blow-out. The use of drilling mud was necessary to prevent cave-in. The desert lake terrain is frequently found in the central portion of the basis in this area. Lake sediments consist mainly of fine muds, and the water table is usually close to the surface. Shot holes drilled into the water table provided excellent energy coupling and could be drilled easily where the dry lake beds would support drilling equipment.

Drilling conditions are the most important consideration in planning a seismic program in this area because

---

*See profile 4 for effect of dipping beds.

they limit the area that can be studied and are the predominant factor in record quality.*

Interpretation

Each profile was interpreted separately without regard to velocities and depths measured at nearby profiles or to evidence from the gravity data. Thus correlations that exist between profiles are not the result of the carry-over of information from one profile to another. The error in the velocities indicated on the travel-time figures does not exceed ten per cent, and the error in the indicated depths is probably less than ten per cent subject to the correctness of the assumed velocity-depth structure.

Dips are accurately determined within 2° or 3°. It is assumed that the high velocity layer (15,000 to 16,000 ft/sec) is basement composed of granitic or metamorphic rocks as exposed in the mountains bordering the basins. Pleistocene and Recent sediments exposed at the surface have velocities ranging from 5,000 to 7,000 ft/sec when saturated with water and from 1,500 to 3,000 ft/sec when they lie above the water table. Intermediate layers have velocities ranging from about 8,000 ft/sec to 12,000 ft/sec and it is assumed that these layers are older and more compacted Tertiary sediments.

---

*The good energy coupling found in dry lake beds with the water table close to the surface is of special interest at this time for planning refraction seismic exploration of the crust.

Remarks on Individual Profiles

The salient features on each profile will be discussed first followed by a general discussion.

Profile 1. 36°17.5' lat. 117°19.5' long. sw* Bearing N54E.--This profile was shot in cooperation with the United States Geological Survey crew headed by L. C. Pakiser and Wayne Jaxson. The data from this profile was not sufficient for an independent interpretation but was used in the interpretation of profile two.

Profile 2 (fig. 5). 36°19.4' lat. 117°56.8' long. sw Bearing N46E.--This profile was shot in cooperation with the United States Geological Survey and the interpretation of the combined data was made by L. C. Pakiser. The velocities and depths are determined with high precision in this profile. Four distinct layers are indicated: a thin low velocity layer not shown in figure 5, a 6,200 ft/sec/layer, an 8,600 ft/sec/layer, and a 15,800 ft/sec/layer. The travel time curves indicate abrupt changes in velocity rather than a gradual increase in velocity with depth. The absence of a layer between the 8,600 ft/sec/layer and the basement which is found on profile 6 may indicate that this portion of the basin is younger than the deeper trough to the west.

---

*sw following the longitude will indicate the end of the spread to which the coordinates refer.

Profile 3 (fig. 6). $36^{\circ}17.5'$ lat. $117^{\circ}19.5'$ long. se Bearing N50W.--Drilling difficulties in the fan materials on the west side of Owens Lake prevented the completion of this profile. The velocities observed in the shallower layers differ from the velocities in profile 6 which was shot nearby.

Profile 4 (figs. 7 and 8). $36^{\circ}23.9'$ lat. $117^{\circ}51.6'$ long. se Bearing N60E.--This profile was shot from the southeast edge of Owens Lake heading out into the lake and shows that the basin floor dips steeply toward the northwest. The fade out and reappearance of the basement arrival is evidence for faulting of the dipping basin floor. The en echelon relation of the arrivals indicates a dipping surface as explained earlier.

Profile 5 (fig. 9). $36^{\circ}33.4'$ lat. $117^{\circ}51.8'$ long. nw Bearing N51W.--This profile shows shallow basement on the northeast side of the basin at Owens Lake. The absence of sediments with velocities higher than 6,000 ft/sec indicates that this is a recent extension of the basin.

Profile 6 (fig. 10). $36^{\circ}17.5'$ lat. $117^{\circ}19.5'$ long. s Bearing N1°E.--This profile was shot parallel to the main trend of the Sierra structures approximately over the deepest part of the basin as indicated by gravity. The absence of measurable dip indicates that the structural trend of the basin is parallel to the trend of the Sierra Block. A layer of 11,500 ft/sec velocity is interpreted as older Tertiary sediments and indicates that the Owens Valley feature has continued to deepen over an extended period of Tertiary time.

Profile 7 (fig. 11). 36°37.4' lat. 118°1.7' long. se N28½W.--This profile was shot east of Lone Pine parallel to the general trend of the valley. The correlation of the 11,750 ft/sec/layer with a similar layer on profile 6 strengthens the hypothesis that these are older Tertiary sediments. This profile was shot out of the deepest part of the basin as indicated by gravity.

Profile 8 (fig. 12). 36°48.0' lat. 118°8.5' long. se Bearing N12°W.--This profile was shot east of Independence roughly parallel to the trend of the valley and indicates that the valley sediments have thinned to 1,300 feet.

Profile 9 (fig. 13). 36°5.2' lat. 117°57.1' long. nw Bearing S12°E.--Record quality was poor on this profile and the basement arrival was not detected. The spread was moved a short distance to the southeast for profile 10.

Profile 10 (fig. 14). 36°5.0' lat. 117°56.7' long. nw S12°E.--The data from profile 9 was used for the shallow layers in the interpretation of this profile. A weak arrival with apparent velocity of 15,000 ft/sec was recorded indicating a high speed layer at a depth of about 2,000 feet. Second arrivals indicate a masked layer of intermediate velocity. The inclusion of this layer would increase the depth given for this profile.

Profile 11 (fig. 15). 35°42.8' lat. 117°49.2' long. nw S33E.--The record quality for the distant shots in this profile was poor, and the profile was repeated at approximately the same location the following summer. See profile 14.

Profile 12 (fig. 16). 35°29.7' lat. 117°55.9' long. sw N31E.--This profile was shot in the basin close to El Paso Mountains and is of particular interest because the sedimentary section is exposed in the El Paso Mountains (Dibblee 1952). The distant arrivals on this profile are weak and doubtful but the intermediate arrivals are definite and correlate with similar arrivals in other parts of the basin.

There is a high probability that the 7,750, 9,400 and 11,400 ft/sec layers are horizons in the Pliocene, Ricardo and Miocene, Goler formations exposed in the El Paso Mountains and in Red Rock Canyon. A similar range in velocities is found in Indian Wells Valley and in Owens Lake (profile 6). Thus the seismic data suggests that this trough existed in the Pliocene.

Profile 13 (fig. 17). $35^\circ 36.4'$ lat. $117^\circ 52.1'$ long. w East.--The basement arrivals on this profile are weak and questionable, and profile 16 was shot later to cover approximately the same ground. A fault at about 6,000' step out cuts the layer with 9,500 ft/sec velocity.

Profile 14 (fig. 18). $35^\circ 42.8'$ lat. $117^\circ 49.2'$ long. N S33E.--This profile is nearly a repeat of profile 11. Improved drilling equipment made it possible to use deeper holes and increase the charge size. The record quality for the distant shots was poor but better than on profile 11. A comparison of the travel time curves for profile 11 and 14 gives the reader an opportunity to judge the error involved in the final interpretation. The two profiles were parallel but separated by about 1,000 feet. The interpretations were completely independent and made about a year apart.

Profile 15 (fig. 19). $35^\circ 46.6'$ lat. $117^\circ 50.6'$ long. ne S17E.--This profile was shot to the north of profiles 11 and 14. The record quality was satisfactory. The irregular basement arrivals on this profile and on profiles 11 and 14 indicate an irregular basement surface probably due to graben faulting (see profile 17). The arrival with the apparent velocity of 6,480 ft/sec fades out at 5,000 feet from the spread indicating faulting or a near surface stratigraphic change.

<u>Profile 16 (fig. 20). 35°36.4' lat. 117°50.8' long. w N89E</u>.--This profile partially overlaps profile 13. Exceptional efforts were made to improve the record quality on this profile. Shot holes were drilled to 300 feet and charges as large as 100 lbs were fired up the hole. The best records were obtained with charges near the surface but deep enough to prevent cratering. Records were improved over profile 13 but arrivals from beyond 20,000 feet were poor.

<u>Profile 17 (fig. 21). 35°43.1' lat. 117°45.1' long. S N-S</u>.--This profile was shot to the east of profile 14. Record quality was very good. The break in the travel time curve in the 8,940 ft/sec layer is interpreted as portraying a graben structure.

<u>Profile 18 (fig. 22). 35°32.9' lat. 117°55.8' long. ne S21W</u>.--Profile 18 was shot to the west of profile 12 between the Sierras and the El Paso Mountains. The velocity structure agrees reasonably well with the velocity depth structure in profile 12 and indicates that the stratigraphic section exposed in Red Rock Canyon continues under this part of the valley.

TABLE 1

Summary of Seismic Velocities and Depths

Profile	Seismic Velocities (feet/second)							Depth (in feet)
	V_0	V_1	V_2	V_3	V_4	V_5	V_6	
2		6200			8600		15800	2200-3000
3		5040	6100	7600	9600			--
4		5800	6900		8800		15900	1300-6000
5	2000	5900					16500	2000
6	4900				8000	11500	15400	5900
7	3800	5700				11750	15500	2800
8		6000					15500	1300
9	2400			7180				--
10	2400			7180			15050	2120
11	2000	6000			9800		16600	6000
12	3700			7750	9400	11400	14400	5100
13	4650				9500		15100?	5000?
14	3200	5700		7780	9200		16000?	6000
15	2000	6480		7920	9180	12080	16000	7700?
16	4000	6240			9200	12160	17000	6800
17	2080	5760	6720		8940		16240	5900
18	3350	6580		7700		10320	16620	7400

Summary of Seismic Velocities

Table 1 is a summary of seismic velocities and depths to basement for 17 profiles. The velocities were divided into seven categories V_0 through V_6. V_0 includes all velocities less than 5,000 ft/sec. Velocities in this range are associated with a thin surface layer lying above the water table; this layer is often referred to as the "weathered layer" in commercial exploration.

The V_1 layer lies immediately below the surface layer. Velocities range from 5,040 to 6,580 ft/sec with an average velocity of 5,950 ft/sec. These velocities are associated with unconsolidated water saturated sediments.

Some of the entries in columns V_2 and V_3 result from artificially interpreting a gradual increase in velocities with depth as a series of step increases. However, certain entries in column V_3 are based on distinct breaks in the travel time curve, indicating an intermittent layer with velocities ranging about 7,500 ft/sec.

The average of the velocities in column V_4 is 9,110 ft/sec. The velocities range from 8,000 to 9,800 ft/sec. All of these velocities represent distinct breaks in the travel time curve indicating that this range of velocities results from a regional stratigraphic change.

The velocities in column V_5, ranging from 10,320 to 12,080, probably represent older tertiary sediments. This break between the velocities V_1 and V_5 may correspond to the unconformity between Miocene and Pliocene sediments mapped by Dibblee (1952) in Saltdale quadrangle.

The basement velocities are designated as V_6. The average of the basement velocities is 15,840 ft/sec. The basement velocities are distinctly greater than any velocities measured in the sedimentary section. The two largest deviations from the average were measured on profiles 12 and 14, and both of these profiles were shot in locations where irregularities in the basement depths are indicated.

The uniformity exhibited by the basement velocities indicates a homogeneous character of the granitic and metamorphic rocks in this region.

Conclusions from Seismic Data

The depths to basement as determined from seismic data are in good agreement with the gravity data in that they show the greatest thickness of basin sediments at points of largest gravity anomalies. Depths to basement below the present surface are greater than 6,000 feet at Owens Lake, in Indian Wells Valley, and in the southwest extension of Indian Wells Valley between the El Paso Mountains and the Sierras.

Velocities in the sedimentary section range as high as 12,000 ft/sec and appear to fall in four groups: unsaturated sediments (1,500 to 4,900 ft/sec), water saturated unconsolidated sediments (5,000 to 7,000 ft/sec), compacted sediments (8,500 to 9,500 ft/sec), and high velocity sediments (10,300 to 12,200 ft/sec). These velocities are high as compared to velocities in marine sediments at similar depths measured in California wells (see fig. 23).

The travel-time plots indicate that the increase of velocity with depth takes place abruptly in two to four sharp steps. This supports the conclusion that the velocity depth relationship has stratigraphic significance which results from events of geologic importance.

The high intermediate velocity layer present on some profiles may indicate the age of the sediments. The Pliocene section exposed in Red Rock Canyon almost certainly underlies profiles 12 and 18, and the comparison of the travel-time curves indicates the possibility that the Pliocene section is present in Indian Wells Valley and Southern Owens Valley. The presence of velocities between 11,000 and 12,000 ft/sec in Indian Wells Valley and southern Owens Valley may indicate the presence of Miocene sediments.

Faulting

Profiles 2, 4, 11 and 17 show faults that cut the sedimentary section to the near-surface layers. A graben structure in profile 17 indicates that the basin sediments are extending at this point.

GRAVITY SURVEY

Other Surveys

Kane and Pakiser (1961) have published the results of a gravity survey in southern Owens Valley between Independence and Haiwee. This work shows a regional gradient of about two milligals per mile, gravity decreasing to the west, and a local anomaly of 30 to 40 milligals associated with the valley structure. The local anomaly can be explained by an elongated trough filled with sediments ranging in depth from 3,000 to 8,000 feet. These basin depths are confirmed by seismic refraction data.

Mabey (1956) has published the results of a geophysical survey in Searles Lake basin. He found an anomaly of about twenty milligals associated with the sediments in the basin, which agreed with the results of seismic refraction and reflection studies (three lines) if a density contrast of 0.65 grams/cc was assumed. This density contrast seems high and may indicate an error in the seismic results. High velocity salt layers could be mistaken for the basement arrival or reduce the record quality so that the basement arrival could not be recognized.

Mabey (1960) has published a Geological Survey Professional Paper, "Gravity Survey of the Western Mojave Desert California." The gravity data show a number of closed gravity lows reflecting Cenozoic deposits in basins. The most striking anomaly is in Cantil valley joining the area of the present survey on the south. This anomaly is reproduced on the gravity map in figure 30 and additional work was done on the interpretation.

An important conclusion relating to crustal structure can be drawn from this survey. If a geologic correction is made for the Cenozoic deposits the residual gravity anomalies do not exceed 10 to 20 milligals over this whole region except on the boundaries where, in a number of places, there are gradients indicating change in crustal structure. This is positive evidence that the weight of the crustal column is uniform over the western Mojave Desert. Mabey's (1960) paper is a major contribution to the study of the regional gravity.

Howard Oliver is making an extensive regional survey of the Sierra Nevada. Unfortunately, the only published results of this work are the Bouguer anomaly for Mt. Whitney, -202 milligals, and an abstract from the GSA meeting, 1956. He reports: "Complete Bouguer anomaly values range from -20 mgals at the western edge of the Sierra to a minimum of -250 mgals just west of the Sierra crest, a distance of only 65 miles. Other studies show that farther eastward, a positive regional gradient of 1 mgal per mile continues at least as far as Death Valley. The form of this west-to-east Bouguer anomaly profile persists all along the strike of the Sierra: the maximum anomaly relief of 230 mgals is midway between Sequoia and Yosemite National Parks. The anomaly relief drops off much more rapidly to the south than to the north; Bouguer anomaly values in the Bakersfield-Inyokern profile range from -40 mgals to -140 mgals so the anomaly relief is only 100 mgals."

"Isostatic anomalies corrected for local geologic effects are very close to zero at the western edge of the Sierra Nevada. The central and eastern Sierra regions are overcompensated by 40-50 mgals, suggesting that current uplift along the Sierra Nevada fault zone may be caused by isostatic forces. However, there is no local isostatic anomaly to the 10,000 foot eastern scarp."

Roland von Huene (oral communication) has completed extensive gravity measurements in the Argus Range and in Indian Wells Valley. Some of this work overlaps the present study and the author has agreed with von Huene to concentrate his work along the Sierra front while von Huene's primary interest lies to the east. The author has purposely avoided detailed discussion of the problems of this area so as to keep the value of independent interpretation. von Huene is currently preparing his data for publication.

Gravity Field Methods and Error Estimation

About 1200 gravity stations were established along the eastern Sierra from Owens Lake to the Garlock Fault and along the southern Sierra between the longitudes of Johannesburg and Mojave. These observations were made during the summer of 1959 and during the months of January and February of 1961.

Worden gravimeters No. 533, No. 416, and No. 533 (after repair) were used in the survey. These instruments had scale constants of 0.5199, 0.5471, and 0.5244 milligal per scale division. Gravity stations were repeated every two or three hours to correct for drift and tide effects.

Errors in reading the meter were checked by repeated readings at the same point and were found to be less than 0.1 mgal. Drift and tide effects were not greater than 0.5 mgal during a traverse, and error from this source is estimated at less than 0.2 mgal. Thus maximum error in observed gravity is estimated at less than 0.3 mgal., and this estimation is supported by the readings of repeated stations.

Topographic maps of the fifteen minute quadrangle series were available for the area. Locations were determined from landmarks on these maps and a surveyor's speedometer on the vehicle used for the survey. Errors in location affect the gravity data through the latitude correction. If a location is wrong by 1,000 ft in latitude it will result in an error of 0.3 mgal in the Bouguer anomaly. Most stations are located within 500 ft. A few stations may be in error by 1,000 ft so the maximum error from this source is 0.2 mgal.

Elevations were multiplied by 0.05998 to reduce the gravity to the equivalent reading at sea level. Thus an error in elevation of 20 ft would result in an error in the Bouguer anomaly of 1.2 mgal. About one quarter of the stations were at points of known elevation accurate to better than two feet. The remainder of the stations were determined by altimeter. In the basins altimeter measurements yielded elevations accurate to within 10 feet as indicated by ties and repeated stations. On long lines into the mountains, accuracies decreased but the maximum error is estimated not to exceed 20 feet except on two exceptionally long lines in Jawbone Canyon and Nine Mile Canyon where the error may be 30 feet.

Almost all stations have an error in terrain correction less than 0.5 mgal. A few stations in very precipitous terrain as in Nine Mile Canyon may have a maximum terrain correction error of 2.0 mgal.

Table of Sources of Error

	Expected maximum	Absolute maximum
Observed gravity	0.2 mgal	0.4 mgal
Location	0.1	0.2
Elevation	0.6	1.2
Terrain correction	0.5	2.0
Total	1.4 mgal	3.8 mgal

It is estimated that 95 per cent of all stations are accurate to within one milligal.

Gravity Reductions

Gravity values were reduced to the complete Bouguer anomaly. Elevations were multiplied by 0.5998 to reduce the gravity readings approximately to the equivalent reading at sea level. This correction accounts for the variation in distance from the center of the earth, and the effect of an infinite layer of density 2.67 and thickness equal to the elevation of the station. Corrections for the curvature of this infinite sheet were made from the table in Swick (1942) giving Bullard's correction B.

Corrections for latitude were extrapolated from the table in Swick giving values of gravity as a function of latitude from the international gravity formula.

Terrain corrections were calculated on the Bendix G15 computer using a density of 2.67 out to a distance of 14 miles. The effects of topography very near the station were generally neglected.

In rough topography it is important to recognize that these corrections do not completely reduce the gravity readings to a flat plane at sea level because no allowance has been made for changing the relative position of the station with respect to anomalous bodies. This correction was not necessary for the accuracy of the present survey, but should be recognized as a source of uncertainty in profiles with rapidly changing elevations.

Gravity Interpretation

Gravity interpretation for two dimensional bodies were carried out by two methods: a method of direct integration proposed by Talwani (1959), and a method of automatic interpretation similar to one described by Bott (1958). The method of automatic interpretation proved to be the most efficient. In Talwani's method the line integral around a closed polygon is evaluated as the sum of the contributions z_i due to individual sides of the polygon.

$$z_i = a_i \sin\phi_i \cos\phi_i \left[\theta_i - \theta_{i+1} + \tan\phi_i \ln \frac{\cos\theta_i(\tan\theta_i - \tan\phi_i)}{\cos\theta_{i+1}(\tan\theta_{i+1} - \tan\phi_i)} \right]$$

When θ_i approaches ϕ_i, the precision required for the computation will exceed the precision of any computer, especially if θ_i and ϕ_i are near 90°. This difficulty might be avoided by testing θ_i and ϕ_i before each computation and taking additional steps to avoid the instability.

An automatic method for interpretation of two-dimensional anomalies similar to one described by Bott (1959) was developed for the Bendix G15 computer and the IBM 7090. The anomalous body is approximated by rectangles, and the type of instability encountered in Talwani's program is avoided by fixing the location of the stations at the center points of the rectangles.

The first step is to plot the measured anomaly and the extent of the basin. Anomaly values are then picked from the plot at equal intervals. The regional gradient is removed from these gravity values, and the residual values are the input to the program.

The program computes the first approximation by taking each interval gravity value and computing the thickness of an infinite sheet that would produce an anomaly equal to the gravity anomaly at that interval point. This thickness is taken as the depth of a rectangular prism underlying the gravity station. The calculation is repeated until a depth is assigned for prisms underlying all gravity stations (see fig. 27).

The next step is to calculate the anomaly for the trial body, subtract the calculated anomaly from the observed anomaly to obtain a g_i, and from this compute a z_i equal to the thickness of an infinite sheet that would give each g_i. Each z_i is then added to the initial trial body. Gravity is then recalculated for the new trial body. This process is repeated as many times as needed to fit the observed gravity.

Figure 27 shows the operation of this computation over a trial structure. The trial profile is Mabey's profile over Cantil Calley. A density contrast of 0.5 was used in this calculation and it was not possible to fit the observed gravity with this density. The two prisms at the center of the body would continue to increase their depths with each iteration, trying to match the curve at the center of the anomaly.

Density

Kane and Pakiser (1961) and Mabey (1960) have measured the densities of igneous and metamorphic rocks in this region and examined measurements by other investigators. They conclude that the standard crustal density of 2.67 is a good average for the region. There are rocks with densities that differ by 0.2 gm/cc from this standard value but most of the rocks composing the basement complex lie within 0.1 gm/cc of the standard crustal density.

The densities of the sedimentary rocks are more difficult to determine. Mabey (1960) uses an average density contrast between sediments and basement of 0.4 gm/cc but finds considerable variation in density between basins and, in some cases, large density variations within basins. Kane and Pakiser (1961) used a density contrast of 0.5 gm/cc in Owens Valley and obtained reasonable agreement with the seismic data.

It is probable that density variations in near surface sediments are reduced with increasing age and depth of burial. Since all the sediments come from the same parent rocks, the primary cause of density variations arises from differences in porosity.

Increasing depth of burial and age of the sediment will decrease the porosity and probably eliminate erratic density variations observed at the surface.

The best available method for appraising the density parameter in this area is the correlation of gravity anomalies with depths determined from refraction seismic work. Figure 24 is a plot of gravity anomaly versus seismic depth.

The gravity anomaly plotted is the difference in Bouguer anomaly (adjusted for regional gradients) between the location of the seismic profile and nearby basement outcrops. The straight solid lines in the figure are the gravity anomalies of infinite sheets having the indicated density contrasts. The gravity anomalies are plotted with circles centered on vertical lines that show the estimated error in the gravity value.

As the depth of the structure increases the width usually decreases proportionately, so that the densities indicated will be less than the densities plotted for an infinite sheet. As the seismic depth increases the indicated density will tend to decrease because of the expected increase of density with depth, but there will also be a decrease in the indicated density because the infinite sheet approximation becomes inadequate. In figure 24 showing the relation between seismic depth and gravity anomaly there is an apparent increase of density with depth. The greatest depth plotted is for profile 18. When this seismic profile is checked against the gravity profiles of figure 25 we find that the gravity anomaly is explained by a density contrast of 0.35. Thus, it appears that a large part of the apparent increase of density with depth would disappear if the gravity values were corrected for the limited extent of the structures as compared to infinite sheets.

When allowance is made for the effect discussed above, a density contrast between 0.3 and 0.4 gives good agreement between seismic depth and gravity anomaly.

Discussion of Gravity Map

The gravity contour map is presented in Figures 30 and 31. This survey joins the survey of Kane and Pakiser (1961) on the north, and Mabey's (1960) survey on the south. The contours on the top three or four miles on the map are supported by reference to Kane and Pakiser's published map (fig. 29). South of the Garlock Fault the contour map is extended by use of Mabey's data, especially in the region of Cantil Valley. Adjustments of about two milligals were necessary to join the data taken by the author to the data of the other surveys mentioned above. These adjustments come from the use of different base stations and the omission of the correction for the curvature of an infinite slab by the other investigators.

All the gravity stations shown on the map were occupied by the author. Stations occupied by Mabey or by Kane and Pakiser are not shown.

Four stations just off the western edge of the map lend additional support to the contours 860 through 875 near Walker Valley.

The most prominent features on the gravity map are the gravity lows associated with Cenozoic sediments. These anomalies coincide with topographic lows and are bounded by uplifted mountain blocks. Reference to the fault map (fig. 2) shows that these gravity anomalies tend to parallel major faults. The nature of these gravity lows will be examined in detail.

On closer examination the map reveals pronounced regional gradients with Bouguer anomaly values decreasing at two or three milligals per mile toward the north or northwest. A gradient is apparent across Cantil Valley between the Rand Mountains and the El Paso Mountains. Mabey's map of the Mojave Desert shows no significant regional gradients except on the boundaries of this province. Thus, in this region the Garlock Fault apparently divides a province with a uniform crustal structure from a province with marked changes in its crustal structure.

A profile running northwest from the El Paso Mountains across the oval-shaped gravity low and up to the closed 880 contour would show only a small regional gradient. However, if we continue this profile a few more miles to the northwest it crosses a regional gradient of about three milligals per mile. These sharp changes in the regional gradients suggest that the source of the gradients is shallow in the crust.

In the vicinity of Little Lake the granitic rocks are continuous across the valley floor and so there is no contribution to the anomaly from the Cenozoic sediments. South of Little Lake there is no apparent regional gradient but north of Little Lake the steep gradient into Rose Valley results from an increasing thickness of sediments combined with a steep north-trending regional gradient.

Gravity profiles interpreted by the automatic interpretive program are presented in Figures 25 and 26. These figures show the position of the profiles with respect to the coordinates of latitude and longitude and the trace of the basement outcrop. The broken horizontal lines indicate the shape of the rectangles used to approximate the anomalous body as explained above. The solid line is a geologic interpretation that would give approximately the same gravity anomaly as the series of rectangles used in the computation.

The gravity profiles plotted in the figures are "measured" gravity taken from the contour map. The computed gravity values fall within 0.2 milligals of the measured gravity, and the computed gravity curve could not be distinguished from the measured gravity curve as presented on the cross sections. The depths of the basin structures are plotted without vertical exaggeration.

Gravity Profiles in Rose Valley

These profiles are shown in Figure 26, and show that the Owens Valley structure continues into Rose Valley. Depths reach 5,500 ft and would be greater if a lower density contrast were used in the interpretation.

A density contrast of 0.5 gm/cc was used so that these results would be comparable to the interpretation of Kane and Pakiser (1961) on the northern extension of this structure.

Two attempts were made to get good basement arrivals on seismic refraction profiles in this valley. A weak arrival with apparent velocity of 15,000 ft/sec indicated a depth of about 2,000 ft, but this depth does not agree with the gravity interpretation. The most likely explanation for this disagreement is that the weak, high velocity arrival comes from an interbedded volcanic layer. The exact shape of the valley is difficult to determine because of the regional gradients. The depths of the basin are less in the vicinity of Haiwee Reservoir than the depths of the basin under Owens Lake. South of Haiwee Reservoir the basin deepens into an oval-shaped depression. This interpretation is in good agreement with the present surface elevations and with the nature of the alluvial fans.

Gravity Profiles in Indian Wells Valley

These profiles are presented in Figure 25. The profiles were taken near actual gravity lines to reduce the amount of extrapolation to a minimum. A density contrast of 0.35 was used on all profiles and gives a reasonably good agreement with the seismic data. Regional gradients were removed from individual profiles.

A number of faults are suggested by the profiles. The main Sierra fault appears to be displaced into the basin about a mile from the contact between basin sediments and basement rock.

A series of step faults gives a better fit to the gravity data than a single fault.

Irregularities in the basement surface in the vicinity of Walker Pass are shown by two profiles. These irregularities support the evidence of faulting provided by the seismic profiles and the unusual surface topography.

A Comparison of Two Methods on the Interpretation of Mabey's Profile in Cantil Valley

The gravity anomaly over Cantil Valley is the sharpest anomaly in this region and is particularly important because of its relation to the Garlock Fault. Mabey's (1960) profile across this valley was reinterpreted to provide a comparison between the automatic gravity interpretation program and the interpretative techniques used by Mabey.

Figure 27 shows basin configuration at three stages in the iterative computation used by the program. There is apparently no basin shape with a constant density contrast of 0.5 gm/cc that can produce the observed anomaly. Figure 28 shows similar results using density contrasts of 0.6 and 0.7 gm/cc. We are forced to the conclusion that the observed anomaly cannot be explained without resorting to density variations within the basin sediments.

Figure 28 shows Mabey's interpretation compared to the automatic interpretation. There is good general agreement between these two interpretations; both show the existence of density contrasts within the basin, both show the basin floor dipping into the Garlock Fault, and both indicate that the basin is bounded on either side by steep faults. Mabey's interpretation shows the Garlock as a vertical fault; a fault dipping about 60° would give a better fit to the automatic interpretation. The Cantil Valley Fault shown on

Mabey's profile would fit the automatic interpretation better if it was moved about two kilometers toward the center of the basin. A reasonable interpretation of the observed gravity can be found without requiring a large throw on the El Paso Fault as indicated by Mabey.

The power of machine methods in gravity interpretation can be seen from the above discussion. Automatic computation allows the investigator to test many more solutions than would be possible by manual computation techniques. The program described in this paper is only a crude first attempt. Programs can be written which will take into account many more variables. Seismic results, surface geology results and variable density-depth relationships could all be inserted in the program in a relatively simple fashion.

CONCLUSIONS

Elongated basin structures follow the eastern front of the Sierra Nevada from the vicinity of Bishop to the southern termination of the range at the Garlock Fault.

Kane and Pakiser's (1961) gravity data (fig. 29) on southern Owens Valley and their unpublished survey covering northern Owens Valley show that a narrow Cenozoic basin begins at Bishop and continues southward to Owens Lake. The present study shows that this basin structure extends at shallower depths as far south as Little Lake. In the vicinity of Little Lake granite crops out in the valley floor, but a few miles south of Little Lake the basin reforms and widens into a broad structure in Indian Wells Valley. The deep portion of Indian Wells Valley tends to parallel the front of the Sierra Nevada to the vicinity of Walker Pass where the basin structure narrows again, turns with the front of the Sierra and deepens in an oval shaped basin between the Sierra Nevada and the El Paso Mountains.

With the exception of the interruption at Little Lake this structure follows the Sierra front for a distance of over 150 miles.

Kane and Pakiser's (1961) survey shows that the basin structure in southern Owens Valley is from three to eight miles wide with depths between 3,000 and 8,000 feet. These results are confirmed by the seismic data reported in this paper.

The basin structure in southern Owens Valley narrows at the southern end of Owens Lake but continues through Rose Valley to Little Lake. Seismic profiles in Rose Valley did not reach the basement but gravity profiles indicate depths of 5,500 feet.

The basin structure terminates near Little Lake and for about six miles there are no significant Cenozoic sediments.

Two faults intersecting nearly at right angles define the northwest corner of the basin structure under Indian Wells Valley. One of these faults parallels the front of the Sierra; the other fault which is indicated by the gravity data, is an east-west trending fault striking the Sierra front in the vicinity of Nine Mile Canyon.

A few miles southeast of the intersection of these faults, basement depths of 6,000 ft are indicated by the seismic and gravity data. Basement depths of five to six thousand feet continue to the vicinity of Walker Pass, where the basin structure narrows and trends southwestward into an oval shaped structure between the El Paso Mountains and the Sierra Nevada. Depths here reach 7,500 feet.

The basin structure in Cantil Valley between the Rand Mountains and the El Paso Mountains, and the basin structure between the El Paso Mountains and the Sierra Nevada are closely related features. Pliocene sediments uplifted in the Rand Mountains were probably deposited in a larger basin including both of the basins mentioned above. Uplift of the El Paso Mountains during the Pleistocene divided the larger basin.

Several lines of evidence indicate that the basin in Cantil Valley has been sinking in an absolute sense, during the same time the El Paso Mountains were rising. Cantil Valley is a low point topographically. The depth of this basin may exceed 10,000 ft, which puts basement 8,000 ft below sea level. Analysis of the gravity data shows exceptionally low density sediments in the central part of the basin, which probably results indirectly from rapid sinking.

A major part of the vertical displacement between the floor of the basin in Cantil Valley and the El Paso Mountains has taken place on the Garlock Fault. Analysis of the gravity data indicates that this vertical displacement exceeds 10,000 ft.

In addition to the anomalies caused by low-density Cenozoic sediments, anomalies which originate in the crust are observed in the gravity map. There are regional anomalies related to crustal thickening. Other anomalies of a more local character are related to density changes within the crust at depths shallow compared to the depth of the Mohorovicic discontinuity.

The magnitude of the Bouguer anomaly in the area of the survey is -100 to -175 milligals. Near the coast the Bouguer anomaly is near zero. In the western Mojave the anomaly is close to -110 milligals, and if a correction is made for areas of sedimentary rocks the residual anomaly is flat over this area. Along the western edge of the Sierra the anomaly parallels the trend of the Sierra and is about -100 milligals. It is difficult to account for negative anomalies of this magnitude without requiring some crustal thickening. If 0.5 gm/cc is taken as crust-mantle density difference, a -175 milligals anomaly would require an increase of about nine kilometers in crustal thickness.

Examination of the regional anomalies in the area of the survey shows that they cannot be entirely explained by changes at the Mohorovicic discontinuity. The regional gradient alternates between areas of relatively small regional gradient to areas with regional gradients as high as three milligals per mile. These high values of both the first and second derivatives of gravity with respect to horizontal distance place severe limitations on the depths of anomalous masses.

Press (1960) gives a standard section for the California-Region. This section was determined from a combination of seismic refraction, gravity, and phase velocity data in the triangle with corners at Pasadena, China Lake, and Boulder. He gives a two-layer crust. The first layer is 23 kilometers thick with a velocity of 6.1 kilometers and a density of 2.78 gm/cc. The second layer is 26 kilometers thick with a velocity of 7.65 km/sec and a density of 3.23 gm/cc. The mantle velocity is taken as 8.1 km/sec and the density as 3.37 gm/cc.

A step of 10 kilometers in the Moho from 45 kilometers to 55 kilometers will produce a maximum gravity gradient of about 0.6 milligals per mile. If this step was at the intermediate layer where the density contrast is 0.45 gm/cc and the drop in the intermediate layer was from 25 to 35 kilometers, the maximum gravity gradient would be 3.21 milligals per mile.

Since gravity gradients in the Sierras are as large as two or three milligals per mile, we conclude that if the densities of the crustal layers in the crust under the Sierras are the same as those given by Press for the California-Nevada region, it would be impossible to produce the observed regional gravity anomalies by changes at the Mohorovicic discontinuity alone. Changes in the depth of the intermediate layer, however, could produce gradients of the same magnitude as those observed in the Sierras, but rapid changes in the magnitudes of the observed gradients require mass anomalies in the crust above the intermediate layer.

We are, therefore, forced to the conclusion that density changes at the Mohorovicic discontinuity can contribute to the isostatic compensation only on a regional basis. Much of the observed compensation of the Sierra takes place at the intermediate discontinuity or even higher in the crust.

One of the most interesting observations from this survey is the persistent nature of the narrow basin structures along the front of the Sierra Nevada. It is difficult to account for this relationship between the basin structure and the Sierra Nevada unless both of these features result from the same tectonic process.

Since the floors of the basins in places lie thousands of feet below sea level, it is almost certainly established that these basins are subsiding in an absolute sense. Other lines of evidence indicate the Sierra Nevada has attained the major part of its present elevation over the same period of time in which the basins have been sinking.

Thus, this area provides a very restrictive natural experiment in tectonics. None of the proposed hypotheses on the formation of the basin and range structure or more general hypotheses on mountain building are adequate to explain the observed facts. The contemporaneous rising of the mountains and sinking of the basins rules out hypotheses based on simple tension or simple compression. The individual mountain and basin structures are not isostatically compensated, but compensation appears to occur on a regional basis with no direct relationship to structural features observed at the surface. This indicates that isostasy has no direct roll in the formation of these structures.

This area appears to provide an excellent opportunity for the study of tectonic processes because the nature of movement severely restricts the number of hypotheses that might offer an explanation. The fact that the movement is continuing at present makes it possible to perform a number of important experiments. In particular, a detailed study of the nature and location of earthquakes with respect to these structures, and detailed knowledge of the variation of intermediate layers in the crust in this region would provide important information about the tectonic process.

REFERENCES

Axelrod, D. I. 1959. "Late Tertiary Floras and the Sierra Nevadan Uplift," Bull. Geol. Soc. Am., 68, 19-46, January.

Bott, M. H. P. 1960. "The Use of Rapid Digital Computing Methods for Direct Gravity Interpretation of Sedimentary Basins," Royal Astron. Soc. Geophys. Jour., V. 3, No. 1, pp. 63-67.

Chakrabarty, S. K., and C. F. Richter. 1949. "The Walker Pass Earthquake and the Structure of the Southern Sierra Nevada," Bull. Seisml. Soc. Am., 39, 93-107, April.

Dibblee, T. W., Jr. 1952. "Geology of the Saltdale Quadrangle, California," Calif. Div. Mines Bull. 160.

Dix, C. H. 1952. "Seismic Prospecting for Oil," Harper & Brothers, New York (book).

Hobbs, W. H. 1910. "The Earthquake of 1872 in Owens Valley, California," Gerl. Beitr. Geophys., 10, 352-385.

Hopper, R. H. 1939. "Geologic Section from the Sierra Nevada to Death Valley," Ph.D. thesis, California Institute of Technology.

Kane, M. F., and L. C. Pakiser. 1961. "Geophysical Study of the Subsurface Structure in Southern Owens Valley, California," Geophysics, 26, 12-26, February.

Lawson, A. C. 1904. "The Geomorphology of the Upper Kern Basin," Univ. Calif. Pub., Bull. Dept. Geol., 3, 291-376.

Mabey, D. R. 1956. "Geophysical Studies in Southern California Basins, Geophysics, 21, 839-853.

1960. "Gravity Survey of the Western Mojave Desert, California," U. S. Geol. Prof. Paper No. 316-D.

Nettleton, L. L. 1942. "Gravity and Magnetic Calculations," Geophysics, 7, 293-310, July.

Oliver, H. W. 1956. "Nature of Isostatic Compensation for the Sierra Nevada, California (Abs.)," Bull. Geol. Soc. Am., 67, 1724.

Press, F. 1960. "Crustal Structure in the California-Nevada Region," Journal of Geophysical Research, Vol. 65, No. 3, 1039-1051.

Putnam, W. C. 1960. "Faulting and Pleistocene Glaciation in the East-Central Sierra Nevada of California, U.S.A.," Int. Geol. Cong. Rep. of Twenty-first Session.

Richter, C. F. 1958. "Elementary Seismology," W. H. Freeman and Company, San Francisco, 768 pages.

1960. "Earthquakes in Owens Valley, California, January-February, 1959," Bull. Seism. Soc. Am., 50, 187-196, April.

Swick, C. H. 1942. "Pendulum Gravity Measurements and Isostatic Reductions," U. S. Coast and Geodetic Survey Spec. Pub. 232.

Talwani, M. J., L. Worzel, and M. Landisman. 1959. "Rapid Gravity Computations for Two Dimensional Bodies with Applications to the Mendocino Submarine Fracture Zone," Journal of Geophysical Research, Vol. 64, No. 1, 49-59.

Webb, R. W. 1936. "Geology of a Portion of the Southern Sierra Nevada of California, the Northern Kernville Quadrangle," Ph.D. thesis, California Institute of Technology.

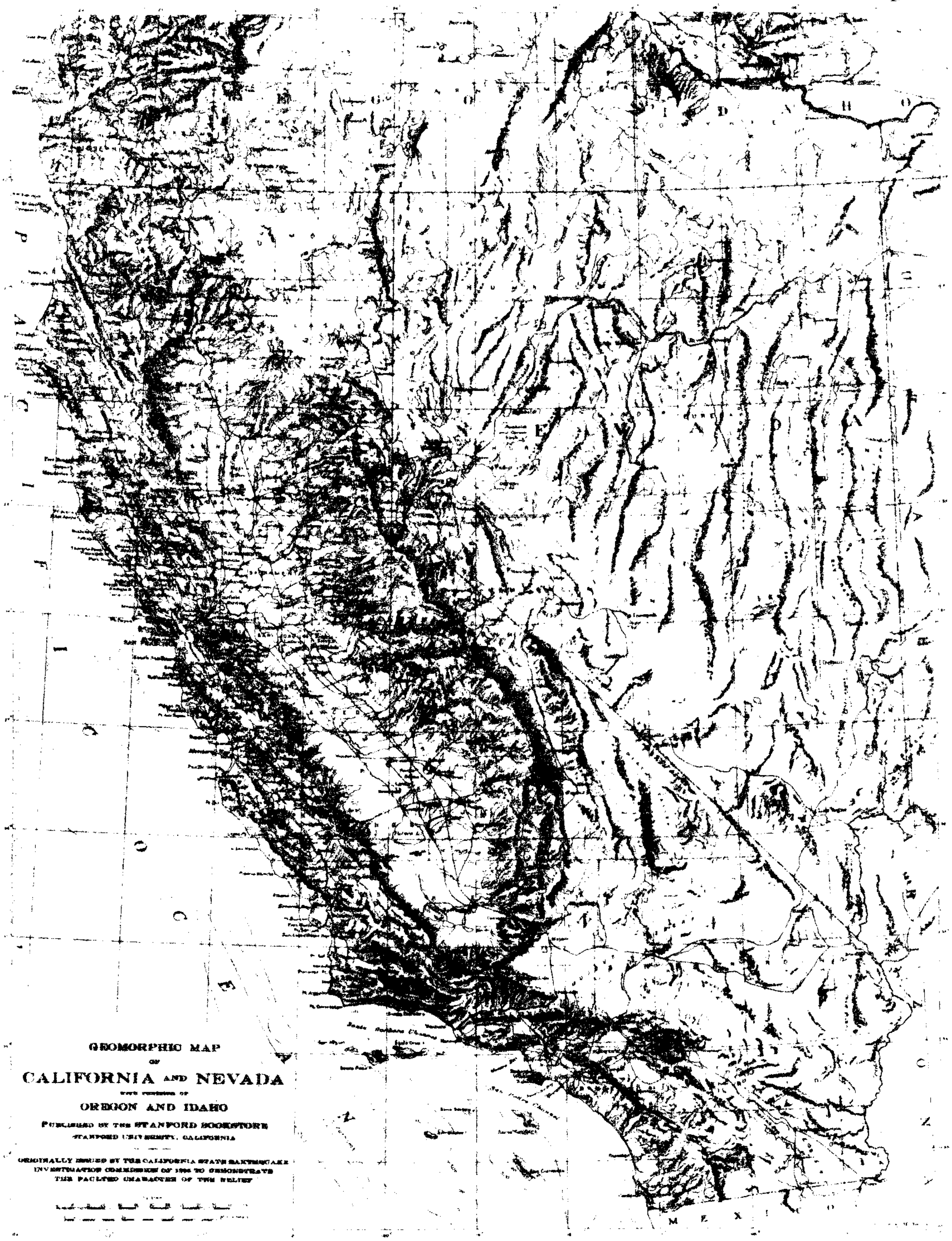


Fig. 1

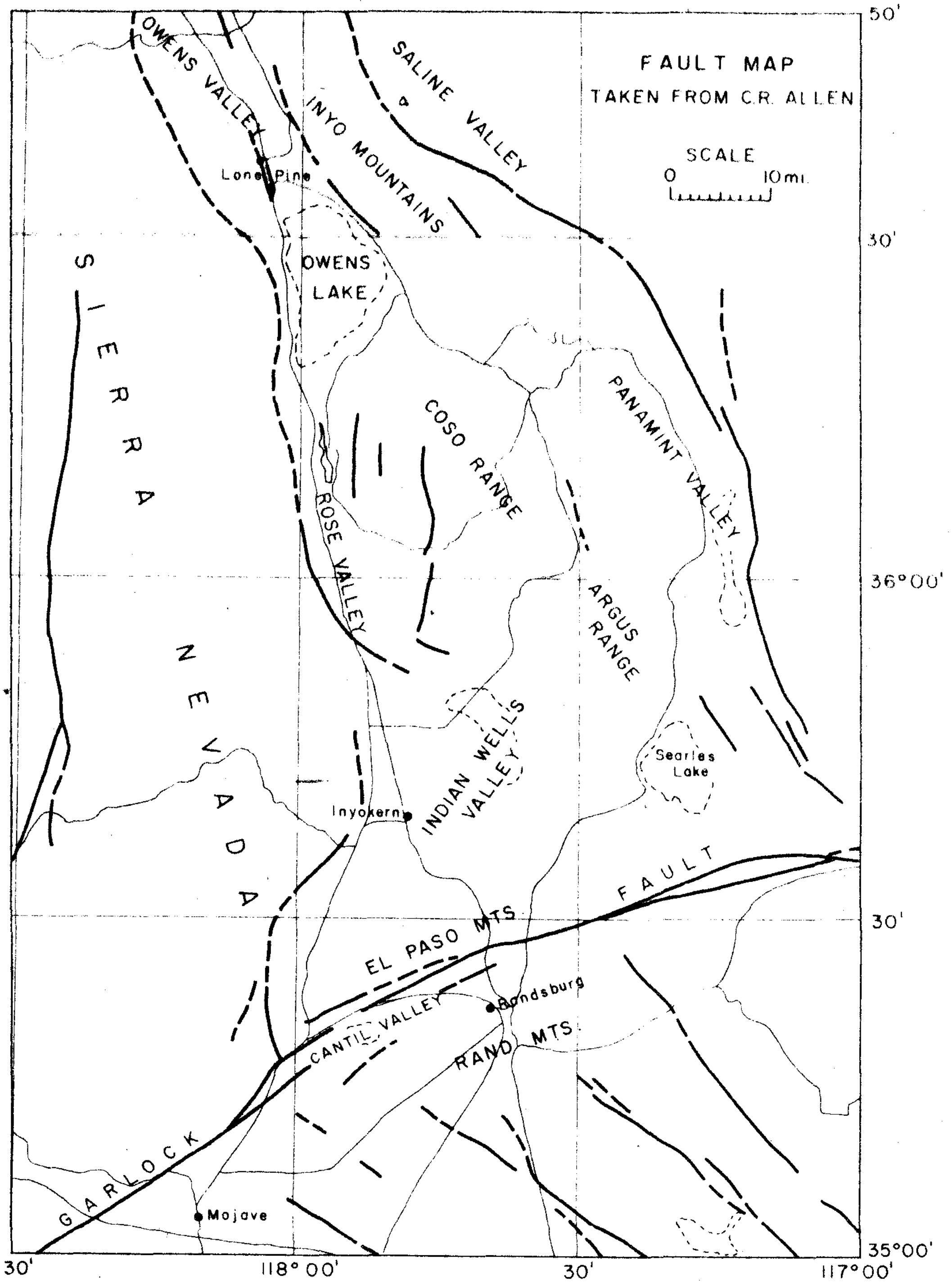

FAULT MAP
TAKEN FROM C.R. ALLEN
SCALE
0 10mi.
50'
30'
36°00'
30'
35°00'
30'
118°00'
30'
117°00'
OWENS VALLEY
SALINE VALLEY
INYO MOUNTAINS
Lone Pine
OWENS LAKE
SIERRA NEVADA
COSO RANGE
PANAMINT VALLEY
ROSE VALLEY
ARGUS RANGE
INDIAN WELLS VALLEY
Searles Lake
Inyokern
FAULT
EL PASO MTS
Randsburg
CANTIL VALLEY
RAND MTS
GARLOCK
Mojave

Fig. 2

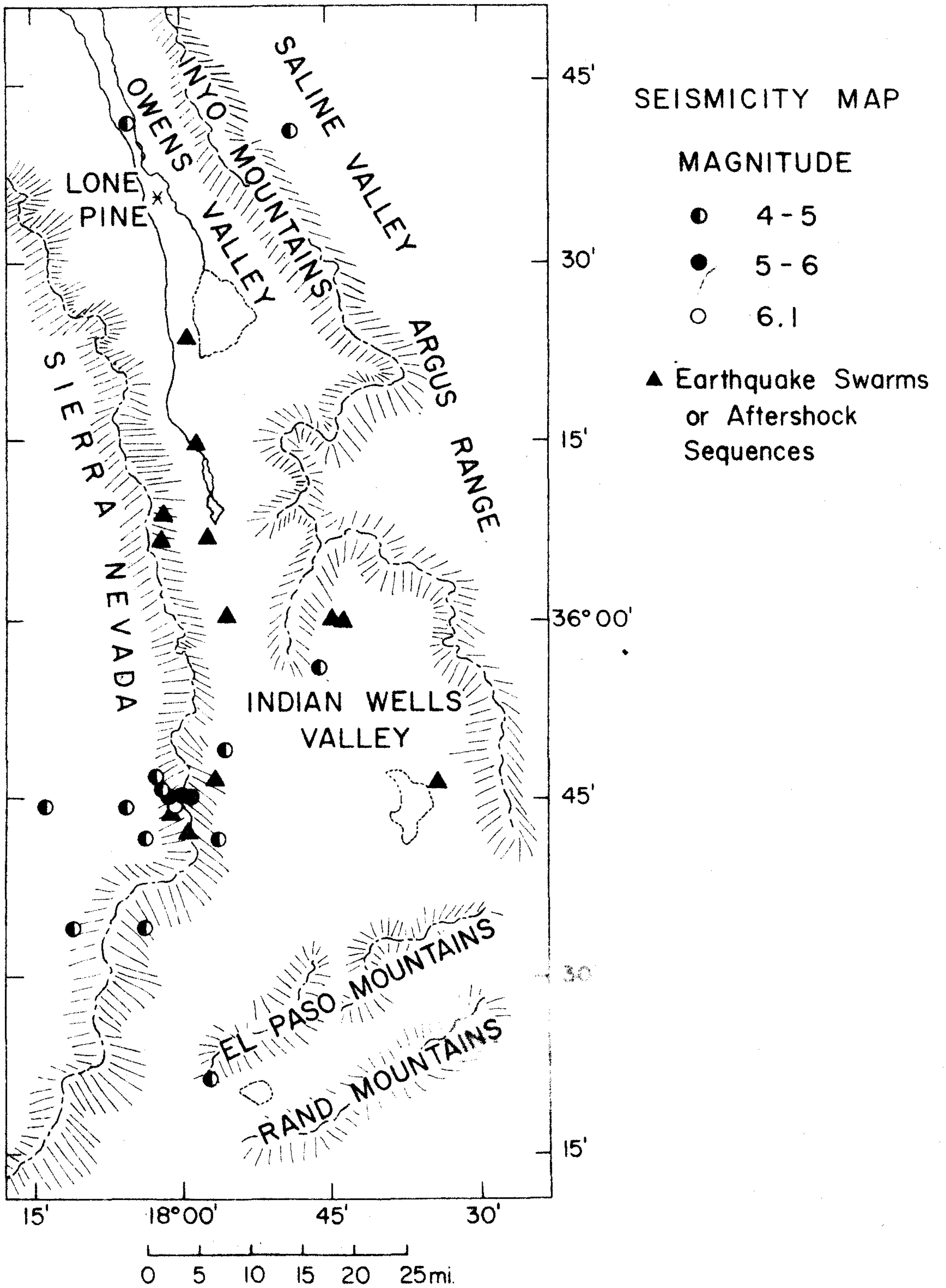
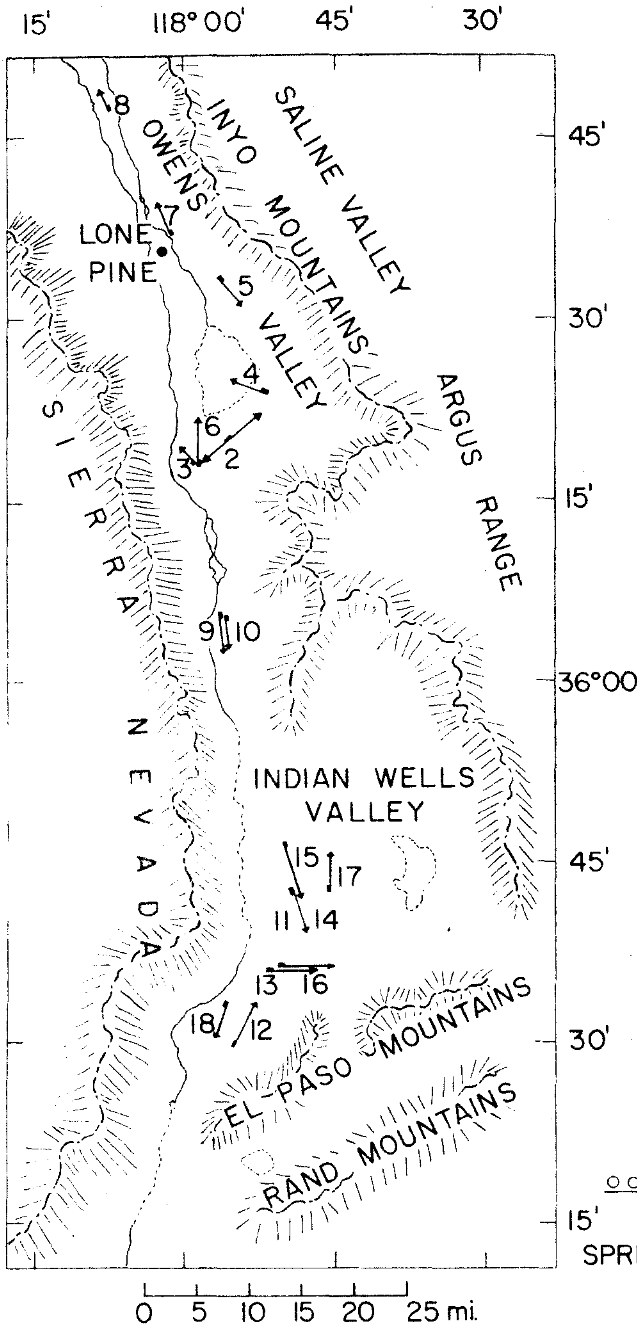

SEISMICITY MAP
MAGNITUDE
4 - 5
5 - 6
6.1
Earthquake Swarms or Aftershock Sequences
SALINE VALLEY
INYO MOUNTAINS
OWENS VALLEY
LONE PINE
ARGUS RANGE
SIERRA NEVADA
INDIAN WELLS VALLEY
EL PASO MOUNTAINS
RAND MOUNTAINS
45'
30'
15'
36° 00'
45'
15'
15'
18° 00'
45'
30'
0 5 10 15 20 25 mi.

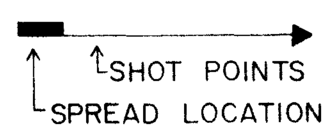
Fig. 3



LOCATION OF SEISMIC REFRACTION PROFILES

PROFILE	DEPTH	DIP
2	3500 ft.	2°
3		
4	1400	21°
5	2000	- 6°
6	6000	0°
7	2800	0°
8	1300	0°
9&10	2100	0°
11	6000	0°
12	5100	0°
13	5000?	
14	6000	0°
15	7700	0°
16	6800	0°
17	6000	0°
18	7400	0°

Estimated accuracy
Depth ±10%
Dip ± 2°



SHOOTING SCHEME

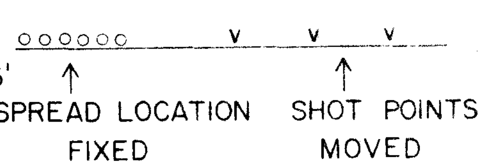


Fig. 4

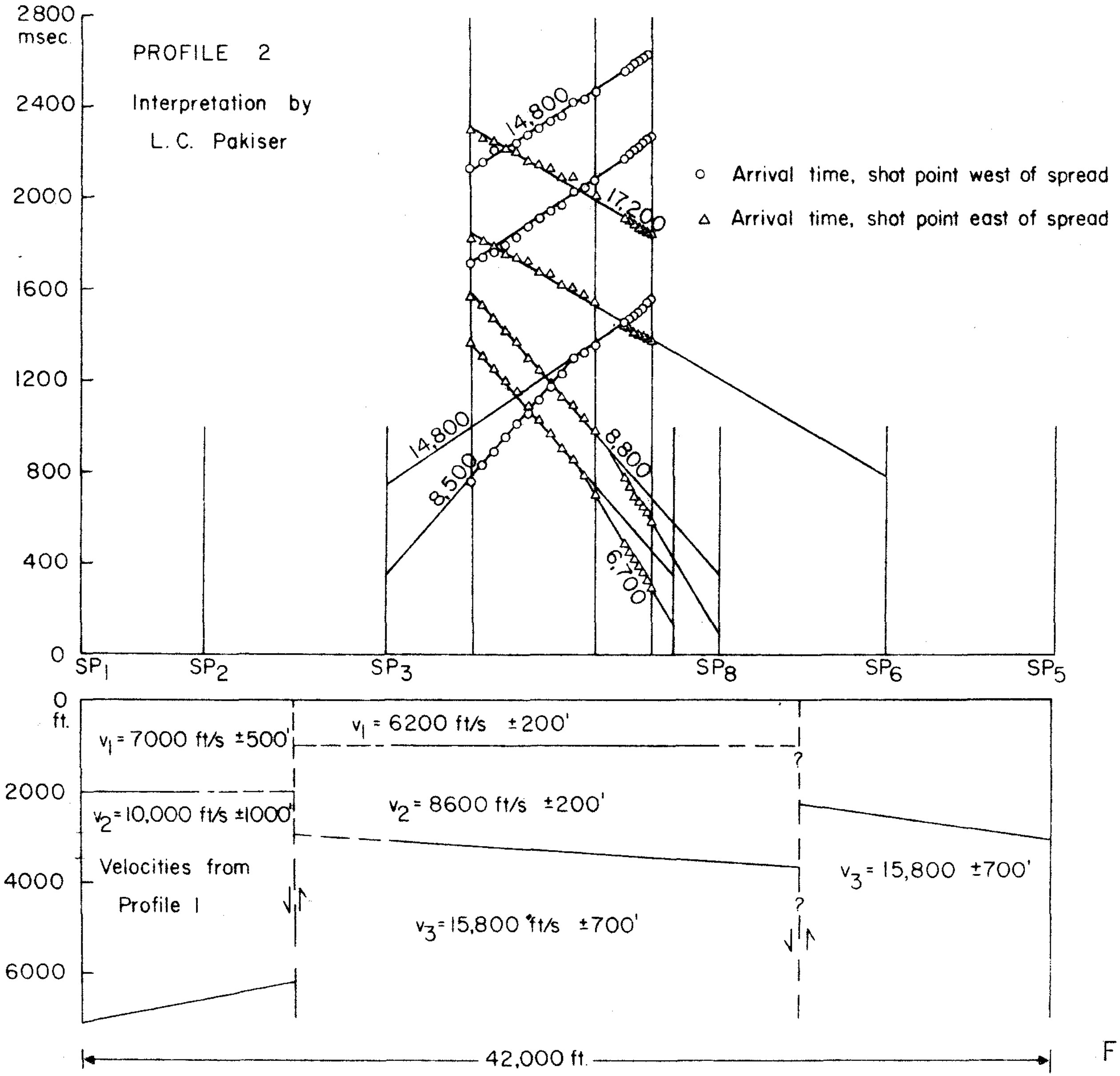

PROFILE 2
Interpretation by
L. C. Pakiser
○ Arrival time, shot point west of spread
△ Arrival time, shot point east of spread
2800 msec.
2400
2000
1600
1200
800
400
0
14,800
17,200
14,800
8,500
8,800
6,700
SP1
SP2
SP3
SP8
SP6
SP5
0 ft.
2000
4000
6000
v1 = 7000 ft/s ±500'
v1 = 6200 ft/s ±200'
v2 = 10,000 ft/s ±1000'
v2 = 8600 ft/s ±200'
Velocities from
Profile I
v3 = 15,800 ft/s ±700'
v3 = 15,800 ±700'
?
?
42,000 ft.

Fig. 5

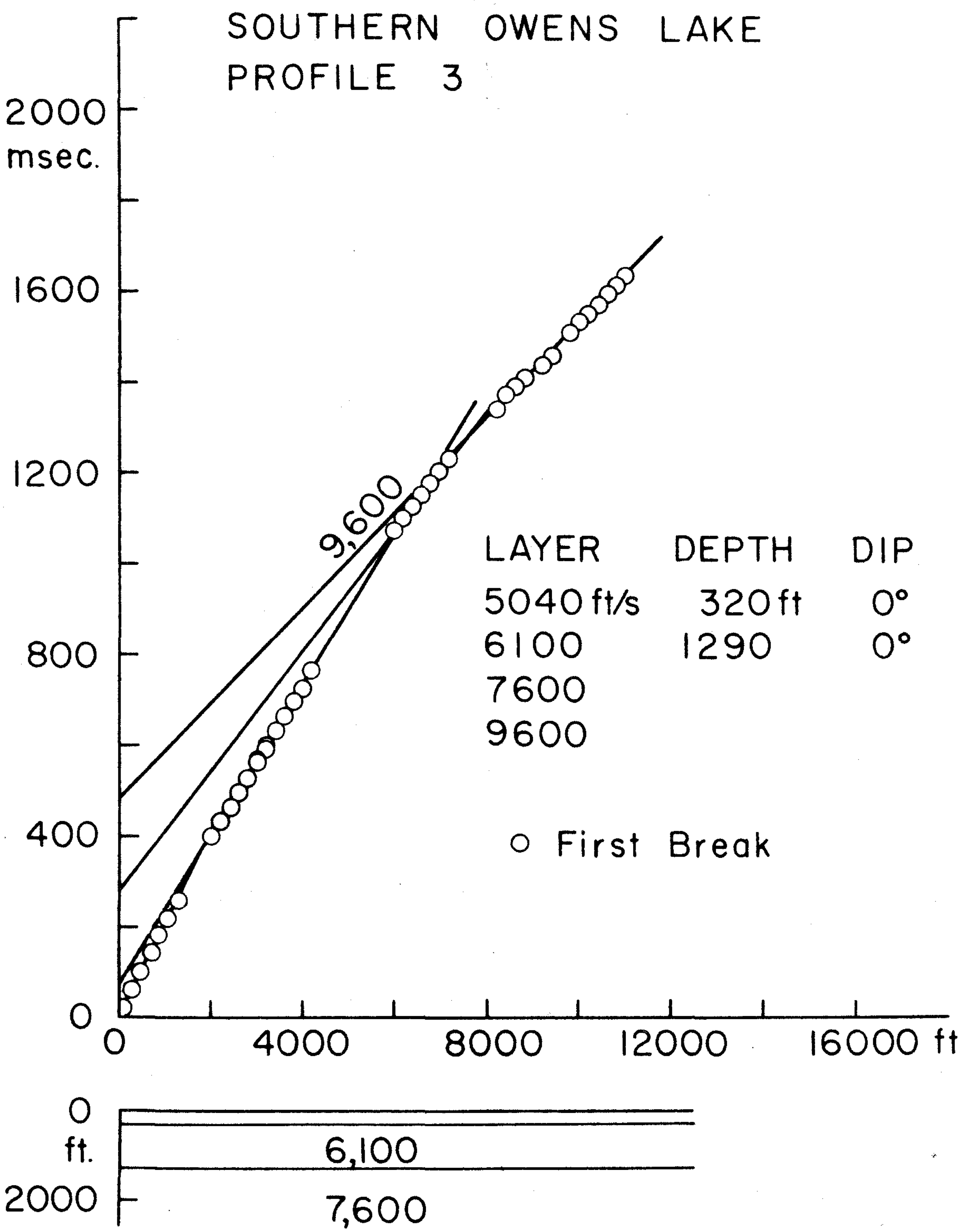

SOUTHERN OWENS LAKE
PROFILE 3
2000
msec.
1600
1200
800
400
0
9,600
LAYER DEPTH DIP
5040 ft/s 320 ft 0°
6100 1290 0°
7600
9600
First Break
0
4000
8000
12000
16000 ft.
0
ft.
2000
6,100
7,600

Fig. 6

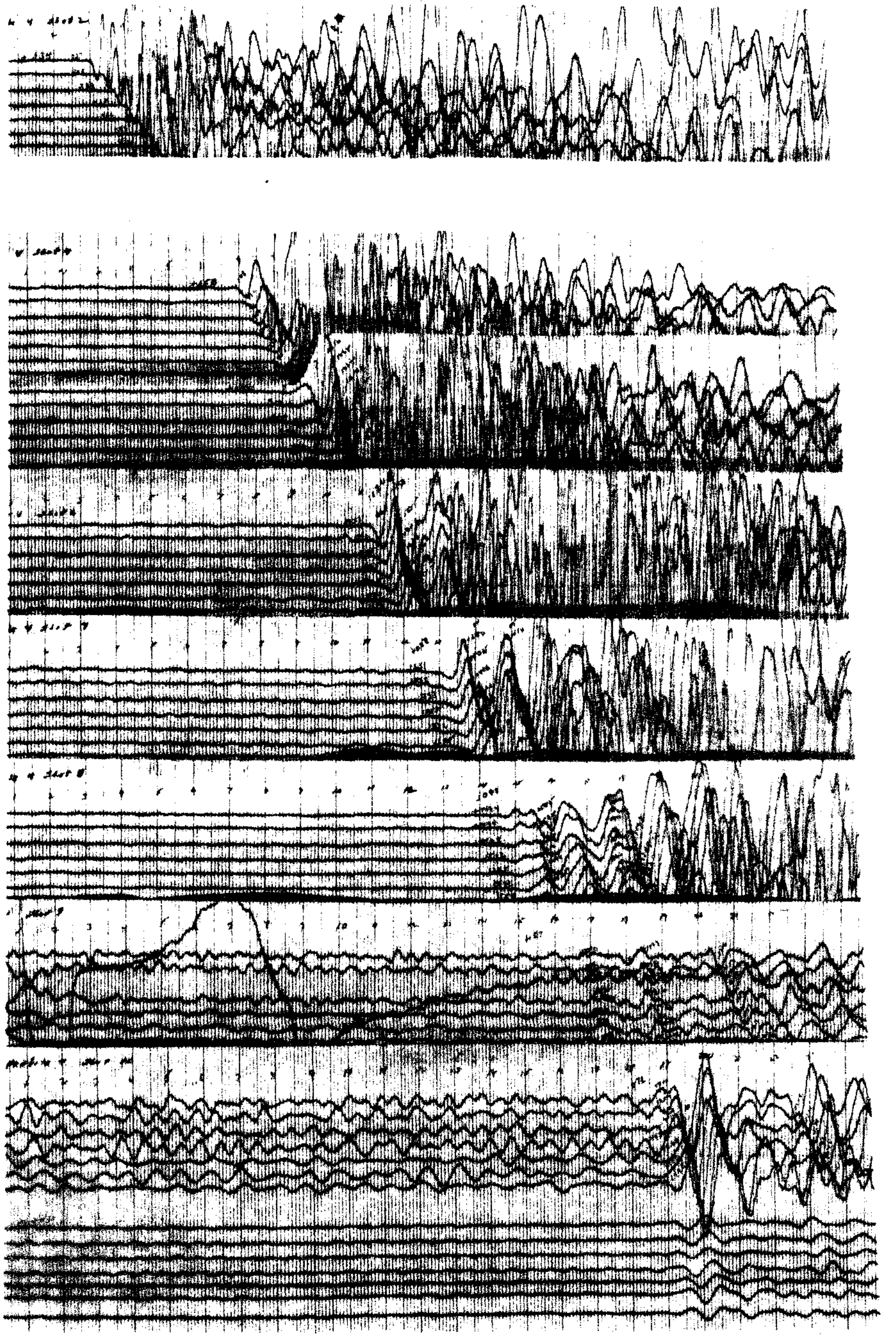


Fig. 7

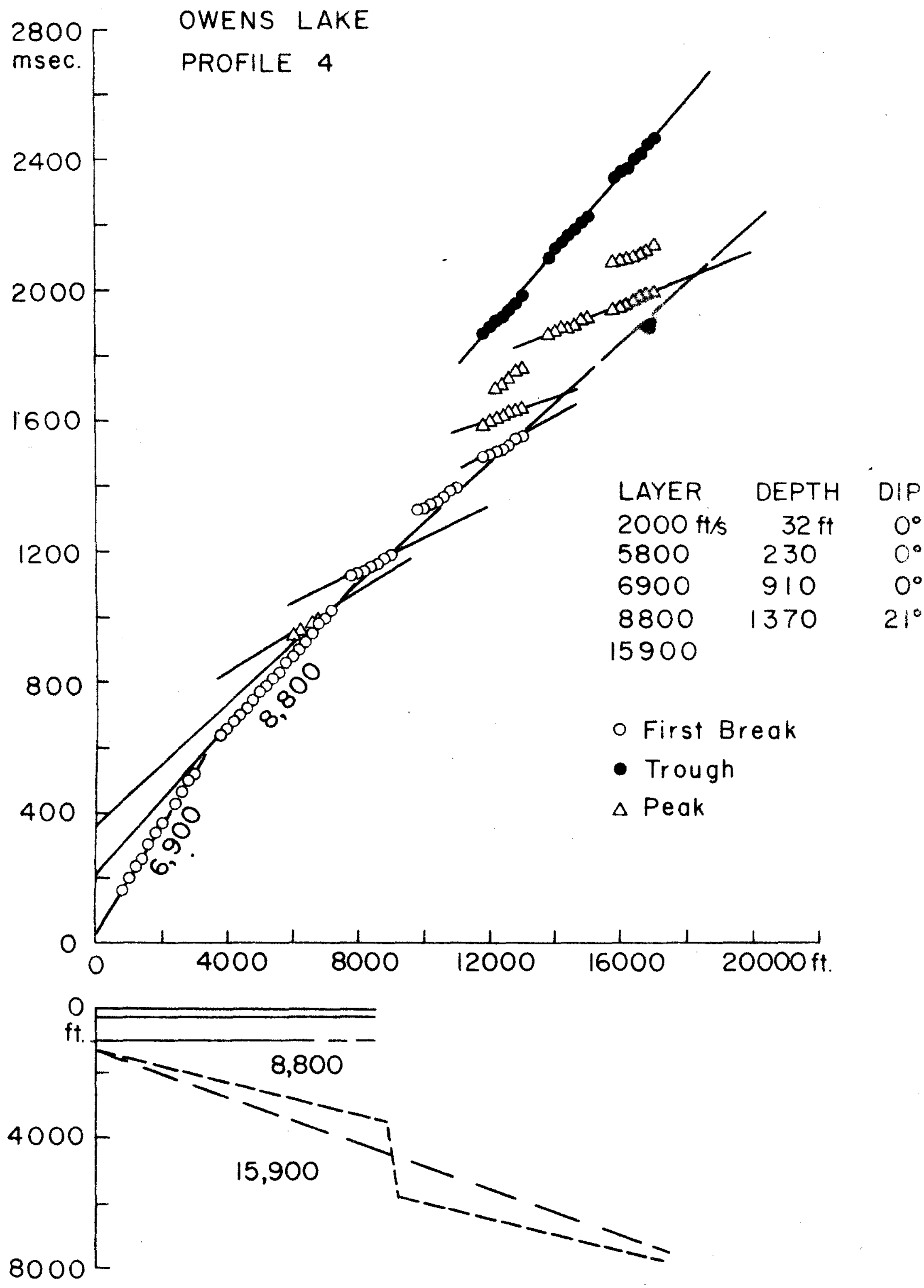

OWENS LAKE
PROFILE 4
2800 msec.
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000 ft.
6,900
8,800
LAYER DEPTH DIP
2000 ft/s 32 ft 0°
5800 230 0°
6900 910 0°
8800 1370 21°
15900
First Break
Trough
Peak
0 ft.
8,800
4000
15,900
8000

Fig. 8

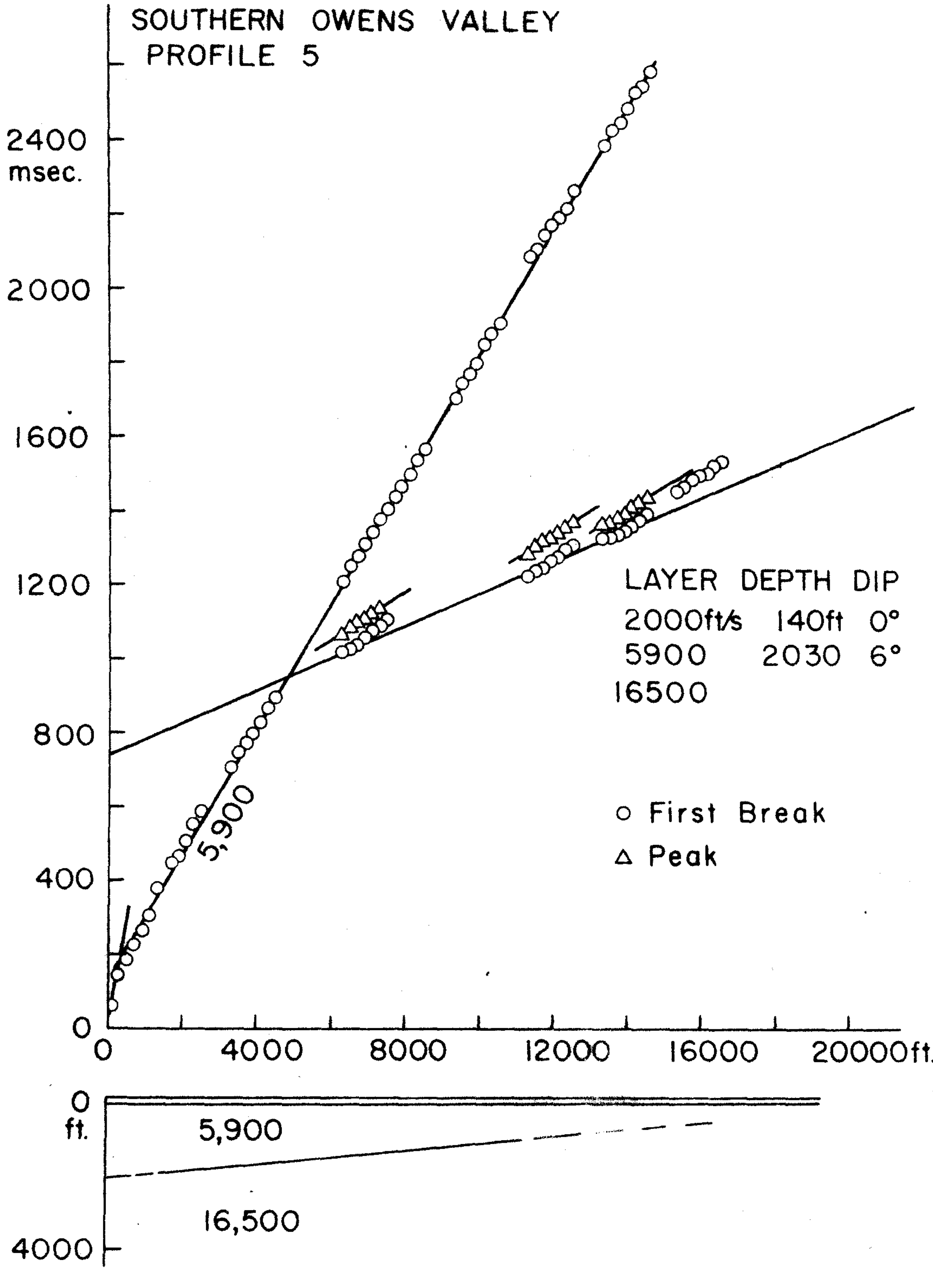
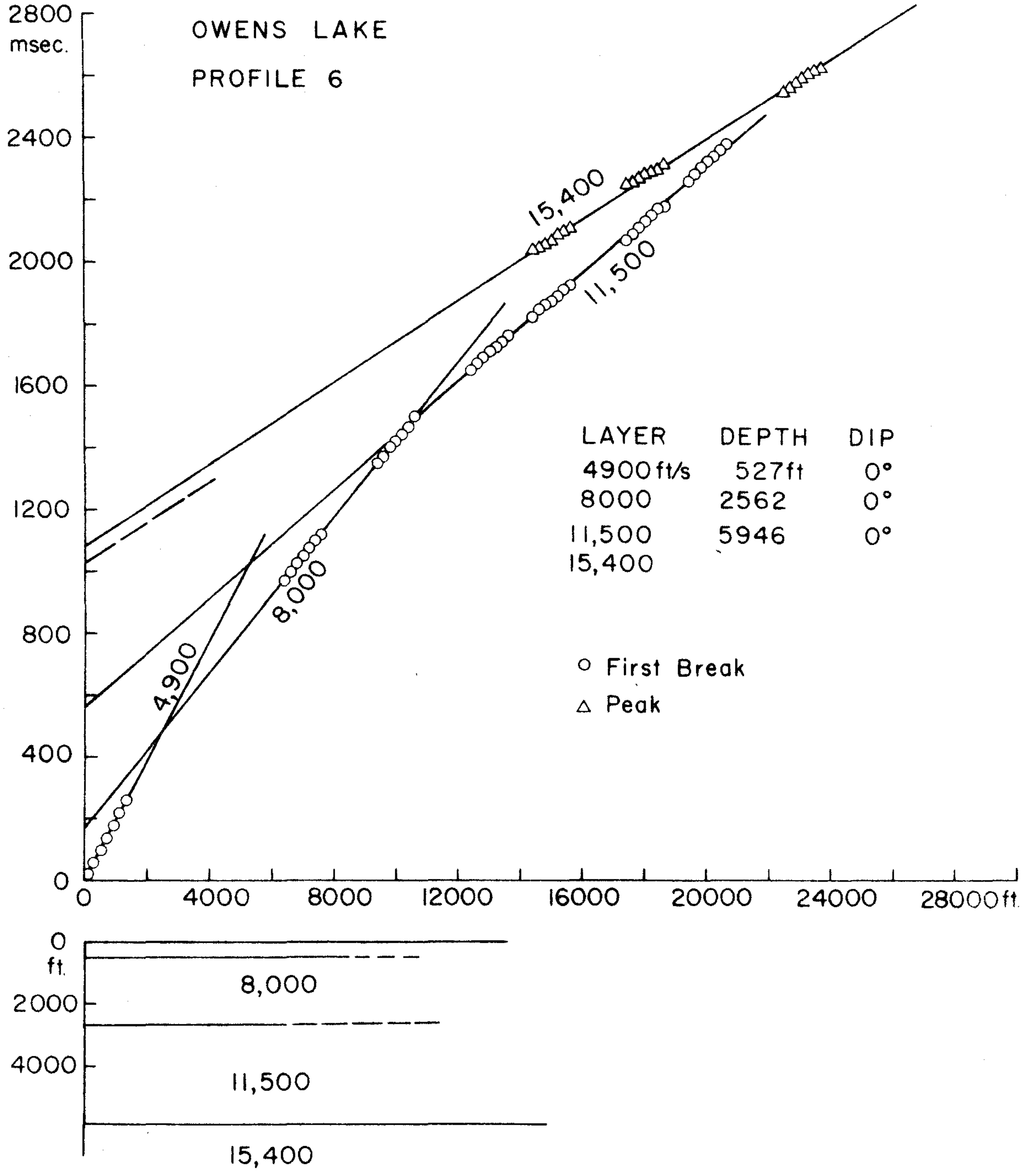

SOUTHERN OWENS VALLEY
PROFILE 5
2400
msec.
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000ft.
5,900
LAYER DEPTH DIP
2000ft/s 140ft 0°
5900 2030 6°
16500
○ First Break
△ Peak
0
ft.
5,900
16,500
4000

Fig. 9



OWENS LAKE
PROFILE 6
2800 msec.
2400
2000
1600
1200
800
400
0
4000
8000
12000
16000
20000
24000
28000 ft.
15,400
11,500
8,000
4,900
LAYER DEPTH DIP
4900 ft/s 527 ft 0°
8000 2562 0°
11,500 5946 0°
15,400
○ First Break
△ Peak
0 ft.
2000
4000
8,000
11,500
15,400

Fig. 10

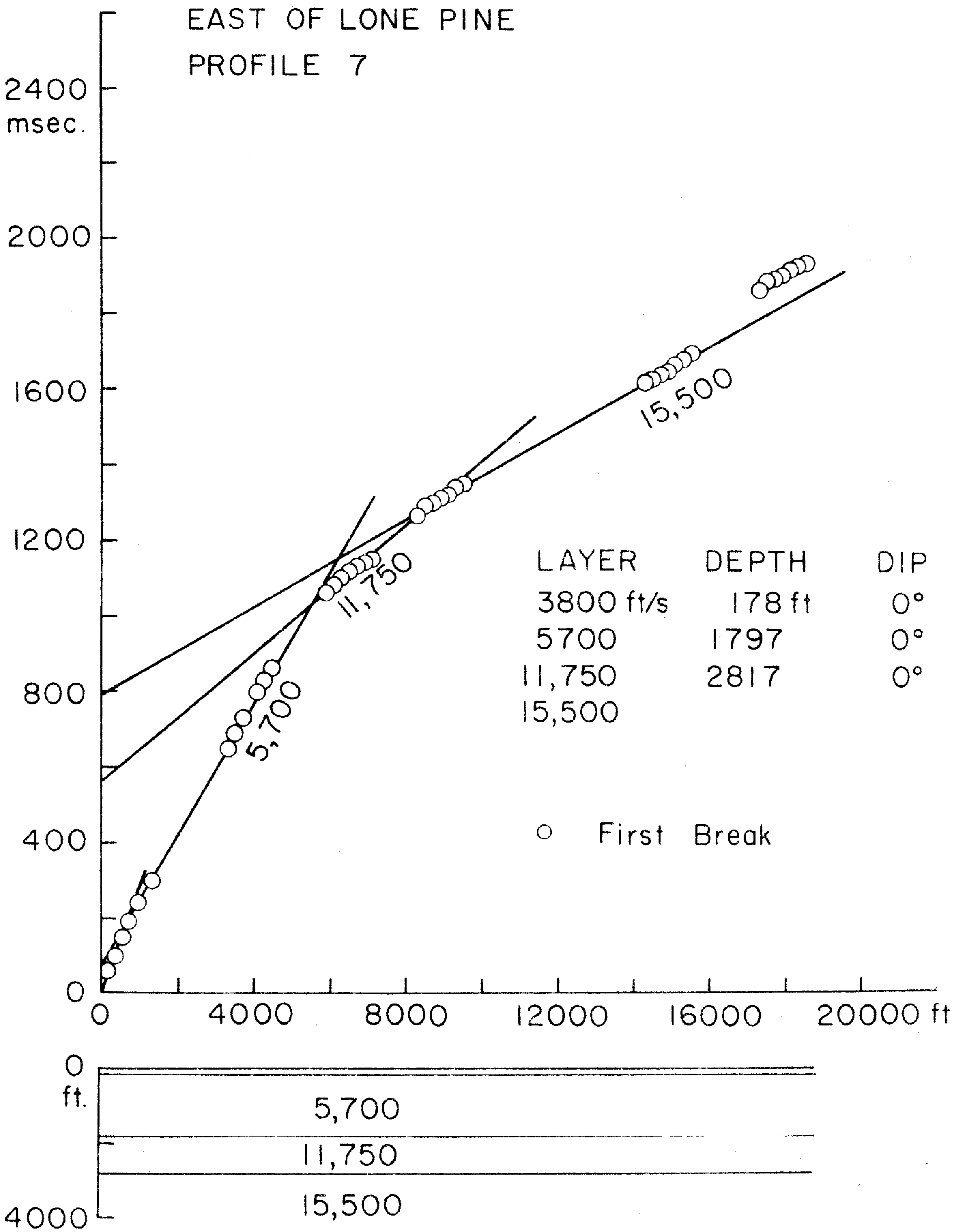

EAST OF LONE PINE
PROFILE 7
2400 msec.
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000 ft.
5,700
11,750
15,500
LAYER DEPTH DIP
3800 ft/s 178 ft 0°
5700 1797 0°
11,750 2817 0°
15,500
First Break
0 ft.
4000
5,700
11,750
15,500

Fig. 11

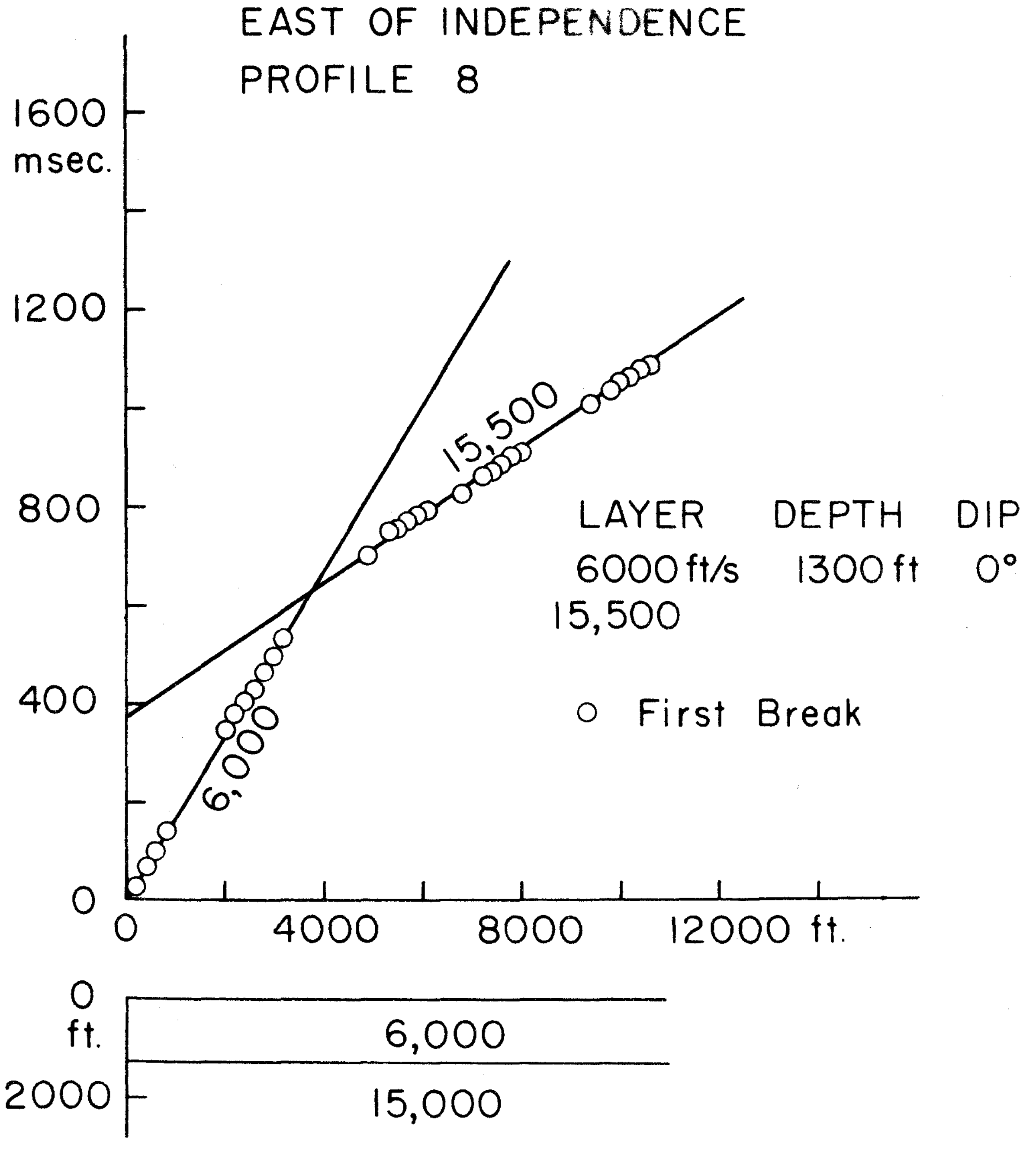
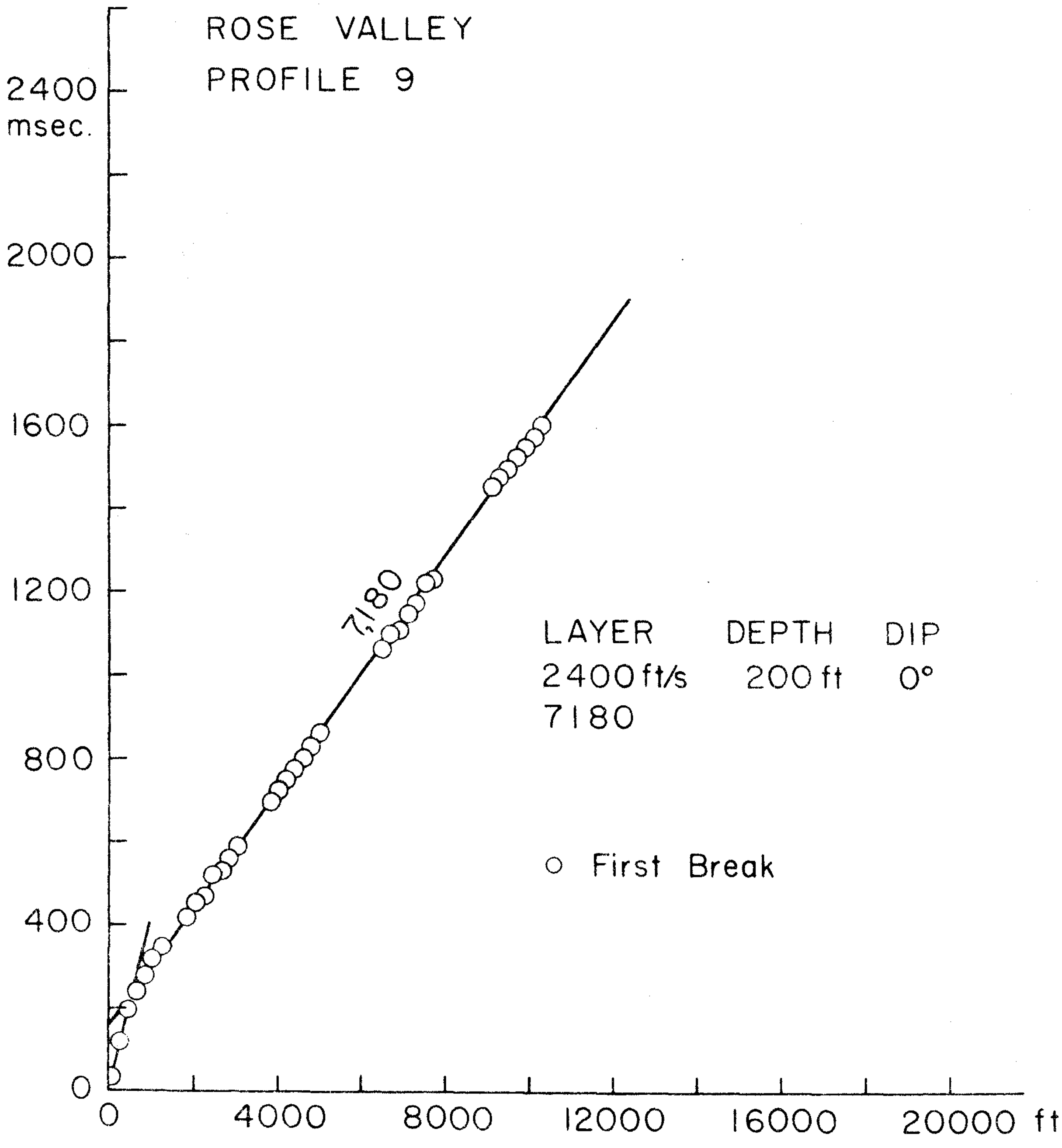

EAST OF INDEPENDENCE
PROFILE 8
1600
msec.
1200
800
400
0
15,500
6,000
LAYER DEPTH DIP
6000 ft/s 1300 ft 0°
15,500
First Break
0
4000
8000
12000 ft.
0
ft.
2000
6,000
15,000

Fig. 12



For interpretation see Profile 10

Fig. 13

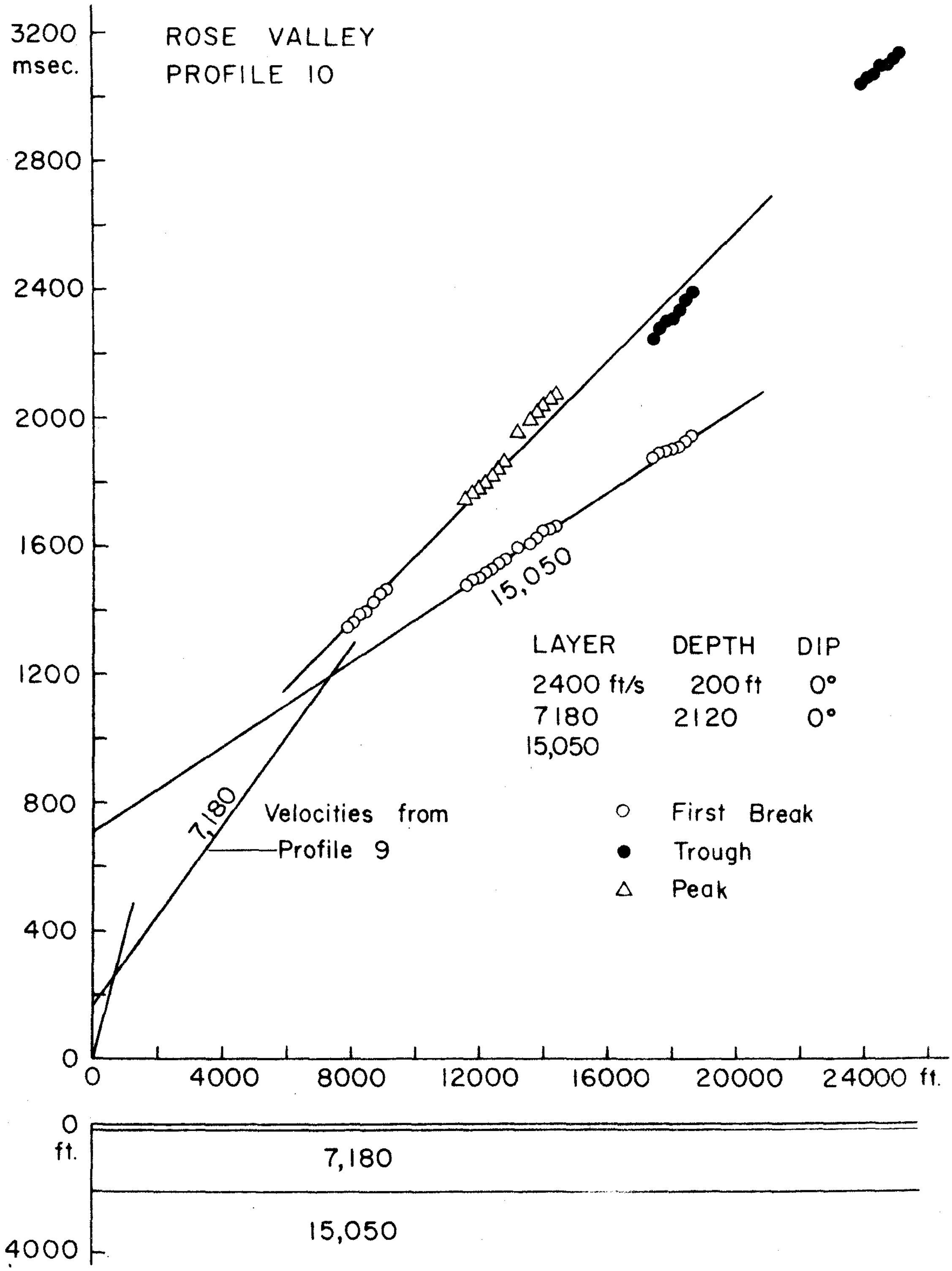

ROSE VALLEY
PROFILE 10
3200
msec.
2800
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000
24000 ft.
15,050
7,180
Velocities from
Profile 9
LAYER DEPTH DIP
2400 ft/s 200 ft 0°
7180 2120 0°
15,050
First Break
Trough
Peak
0
ft.
7,180
15,050
4000

Fig. 14

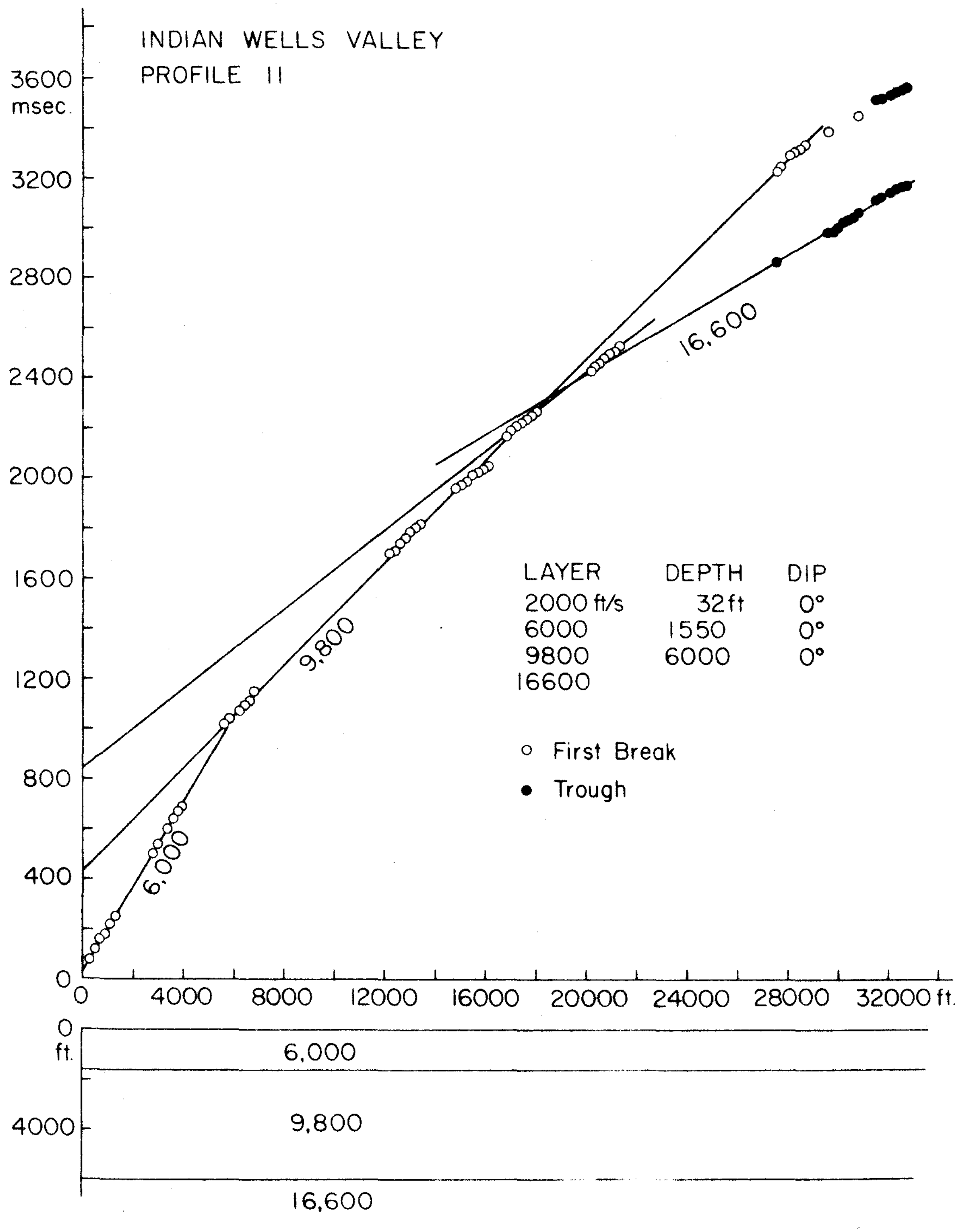

INDIAN WELLS VALLEY
PROFILE II
3600
msec.
3200
2800
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000
24000
28000
32000 ft.
6,000
9,800
16,600
LAYER DEPTH DIP
2000 ft/s 32 ft 0°
6000 1550 0°
9800 6000 0°
16600
First Break
Trough
0
ft.
6,000
4000
9,800
16,600

Fig. 15

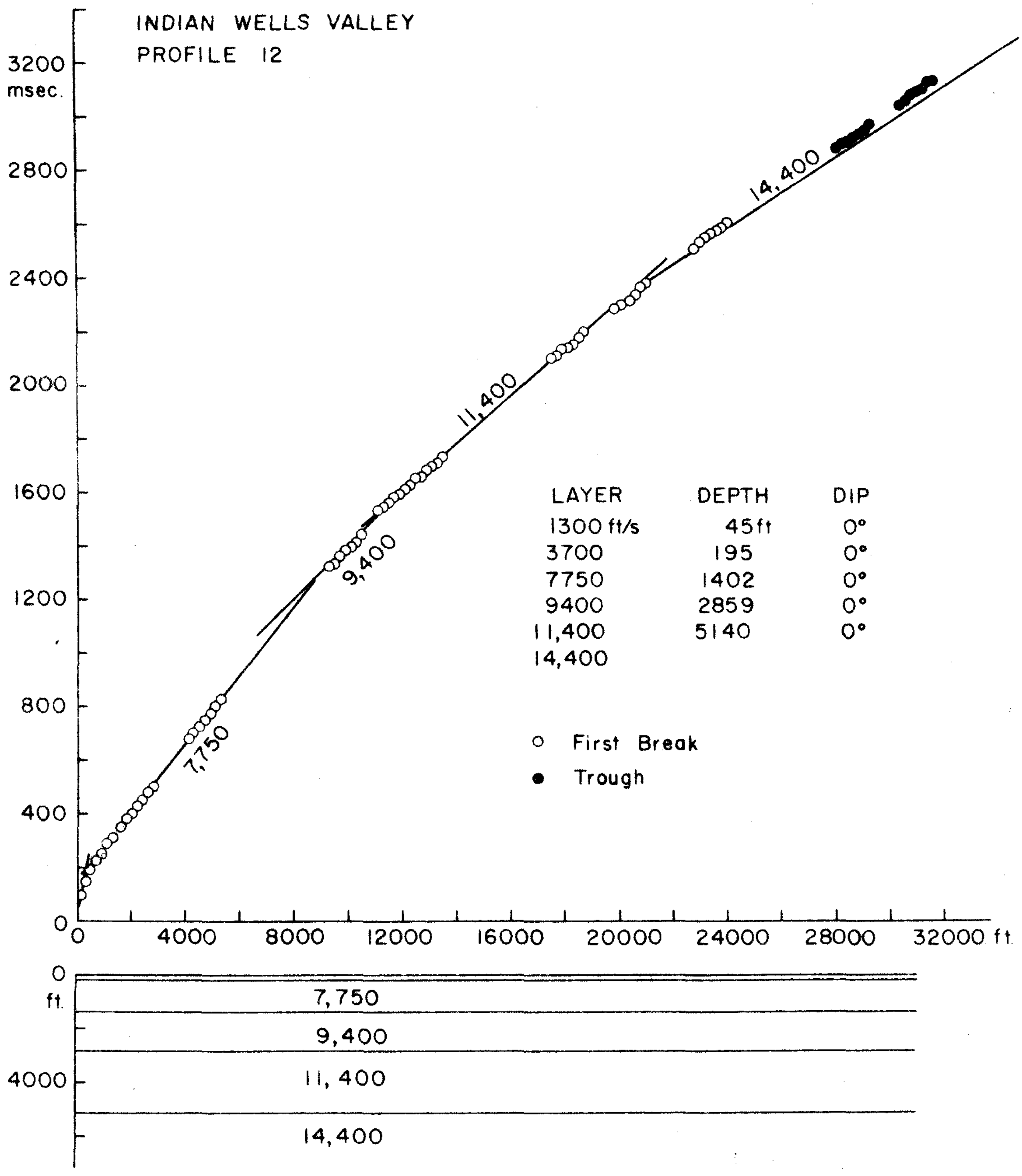

INDIAN WELLS VALLEY
PROFILE 12
3200 msec.
2800
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000
24000
28000
32000 ft.
7,750
9,400
11,400
14,400
LAYER DEPTH DIP
1300 ft/s 45 ft 0°
3700 195 0°
7750 1402 0°
9400 2859 0°
11,400 5140 0°
14,400
First Break
Trough
0
ft.
4000
7,750
9,400
11, 400
14,400

Fig. 16

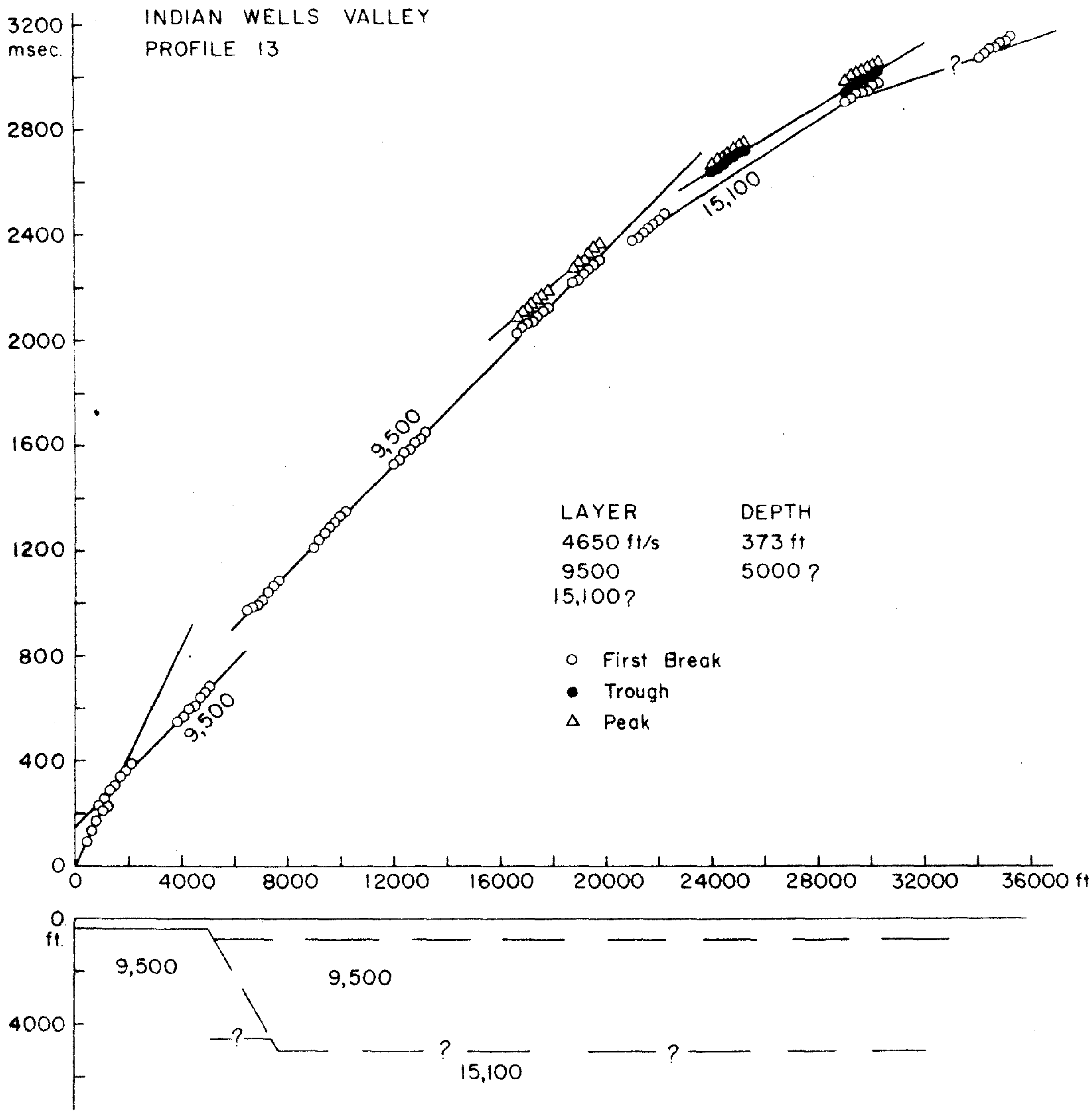

INDIAN WELLS VALLEY
PROFILE 13
3200
msec.
2800
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000
24000
28000
32000
36000 ft.
9,500
9,500
15,100
?
LAYER
DEPTH
4650 ft/s
373 ft
9500
5000 ?
15,100?
First Break
Trough
Peak
0
ft.
4000
9,500
9,500
?
?
?
15,100

Fig. 17

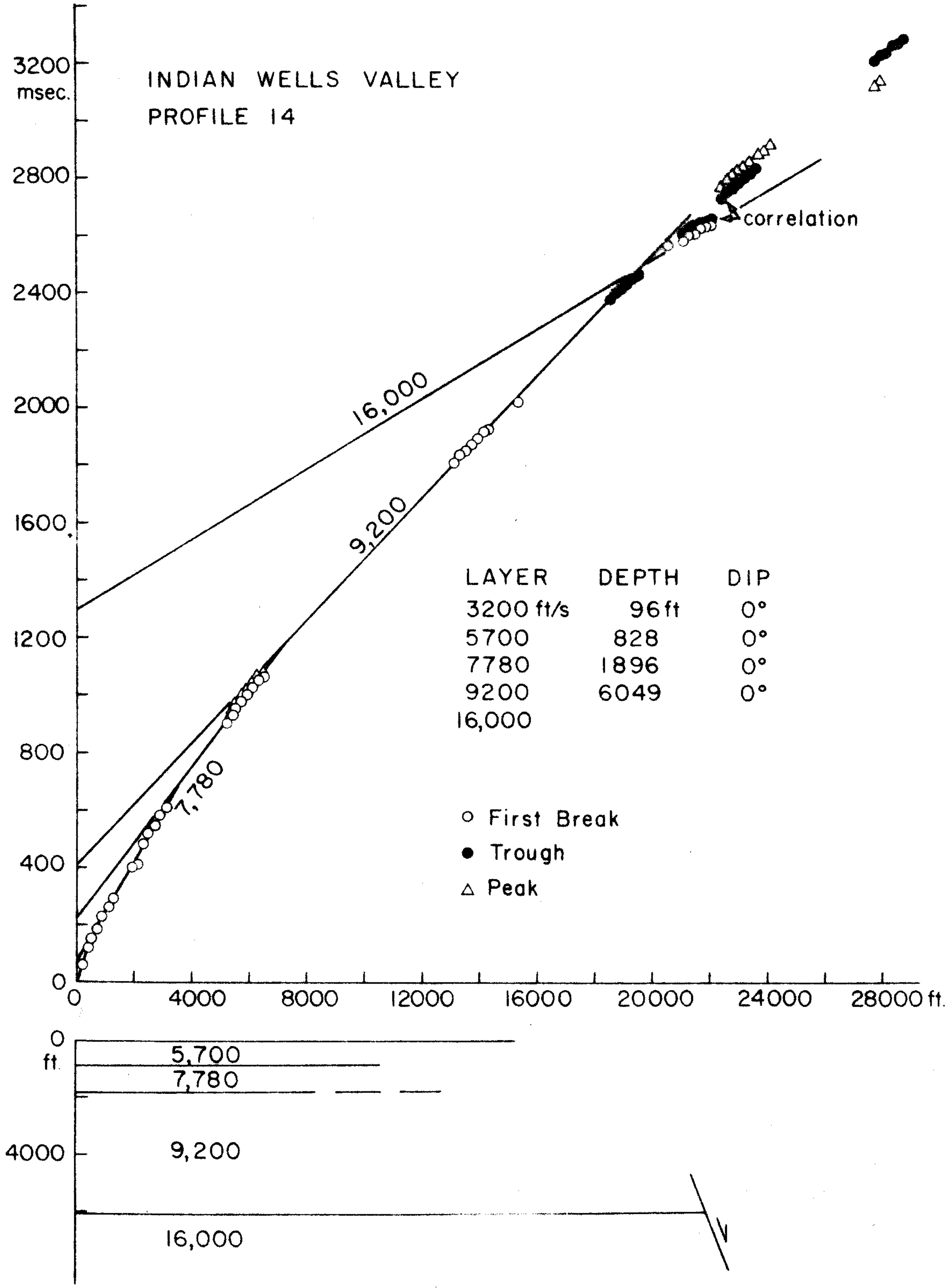
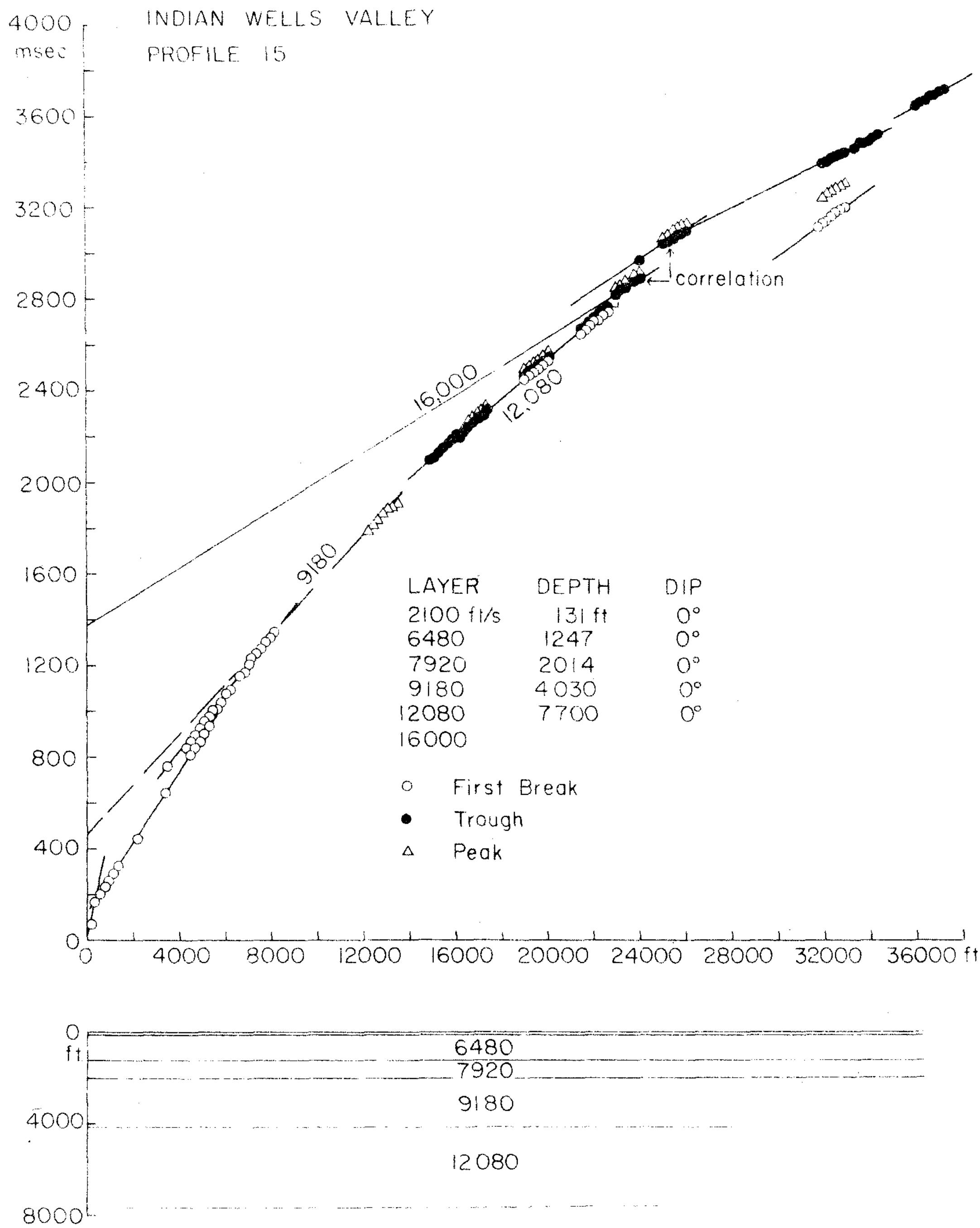

3200
msec.
2800
2400
2000
1600
1200
800
400
0
INDIAN WELLS VALLEY
PROFILE 14
correlation
16,000
9,200
7,780
LAYER DEPTH DIP
3200 ft/s 96 ft 0°
5700 828 0°
7780 1896 0°
9200 6049 0°
16,000
First Break
Trough
Peak
0
4000
8000
12000
16000
20000
24000
28000 ft.
0
ft.
4000
5,700
7,780
9,200
16,000

Fig. 18



INDIAN WELLS VALLEY
PROFILE 15
4000 msec
3600
3200
2800
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000
24000
28000
32000
36000 ft
16,000
12,080
9180
correlation
LAYER DEPTH DIP
2100 ft/s 131 ft 0°
6480 1247 0°
7920 2014 0°
9180 4030 0°
12080 7700 0°
16000
First Break
Trough
Peak
0 ft
6480
7920
9180
4000
12080
8000

Fig. 19

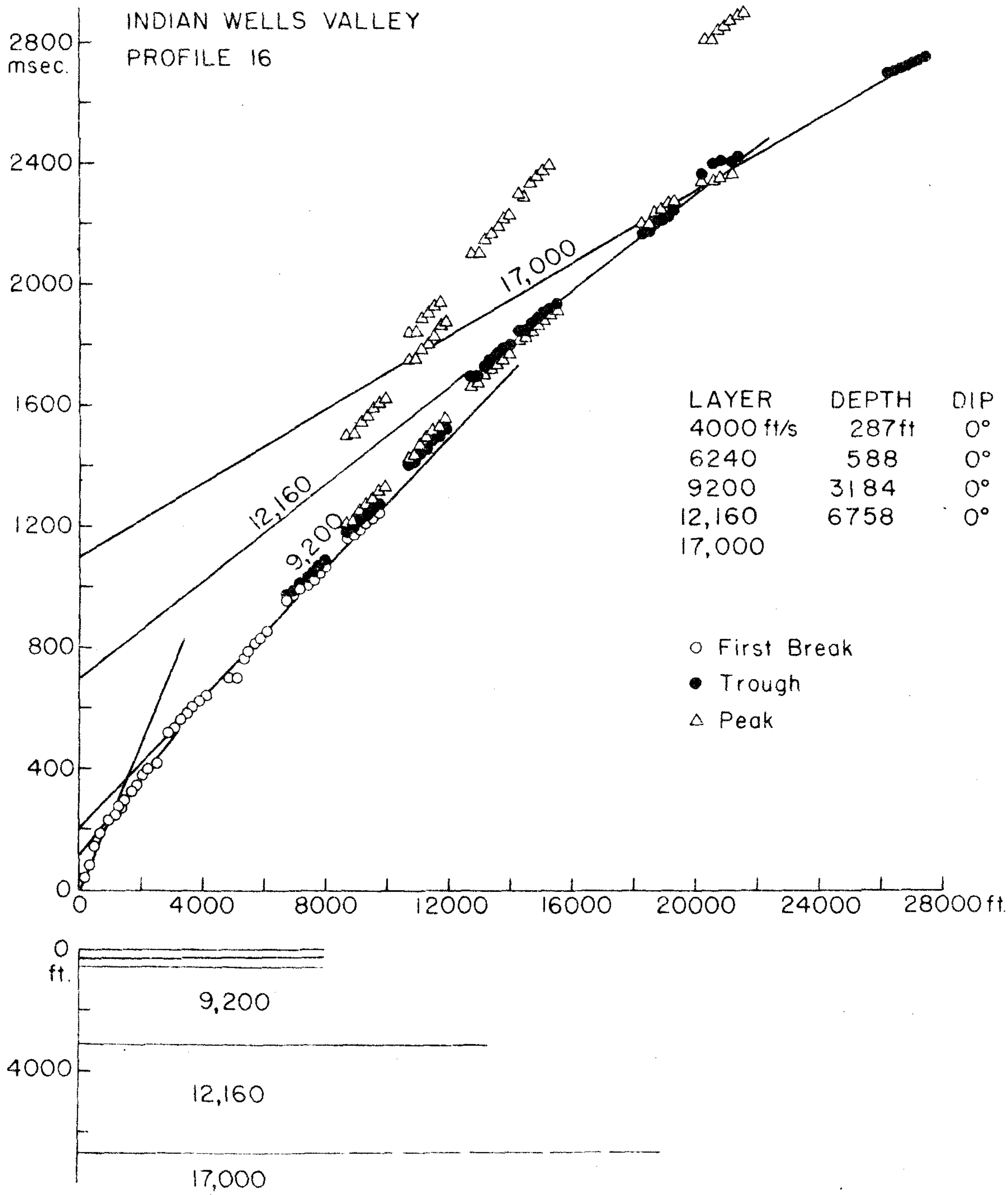
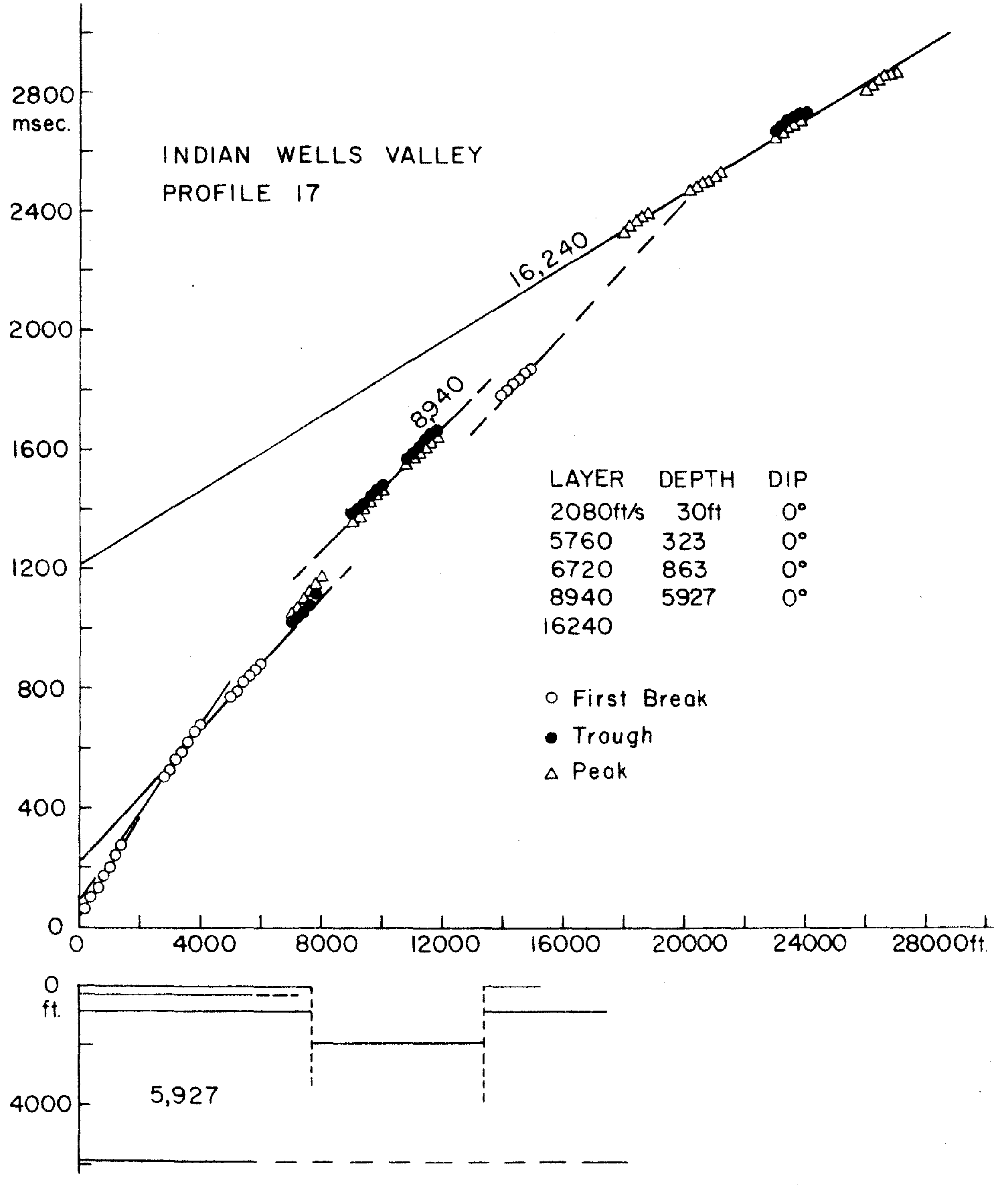

INDIAN WELLS VALLEY
PROFILE 16
2800 msec.
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000
24000
28000 ft.
17,000
12,160
9,200
LAYER DEPTH DIP
4000 ft/s 287 ft 0°
6240 588 0°
9200 3184 0°
12,160 6758 0°
17,000
○ First Break
● Trough
△ Peak
0 ft.
9,200
4000
12,160
17,000

Fig. 20



INDIAN WELLS VALLEY
PROFILE 17
2800
msec.
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000
24000
28000ft.
16,240
8940
LAYER DEPTH DIP
2080ft/s 30ft 0°
5760 323 0°
6720 863 0°
8940 5927 0°
16240
○ First Break
● Trough
△ Peak
0
ft.
4000
5,927

Fig. 21

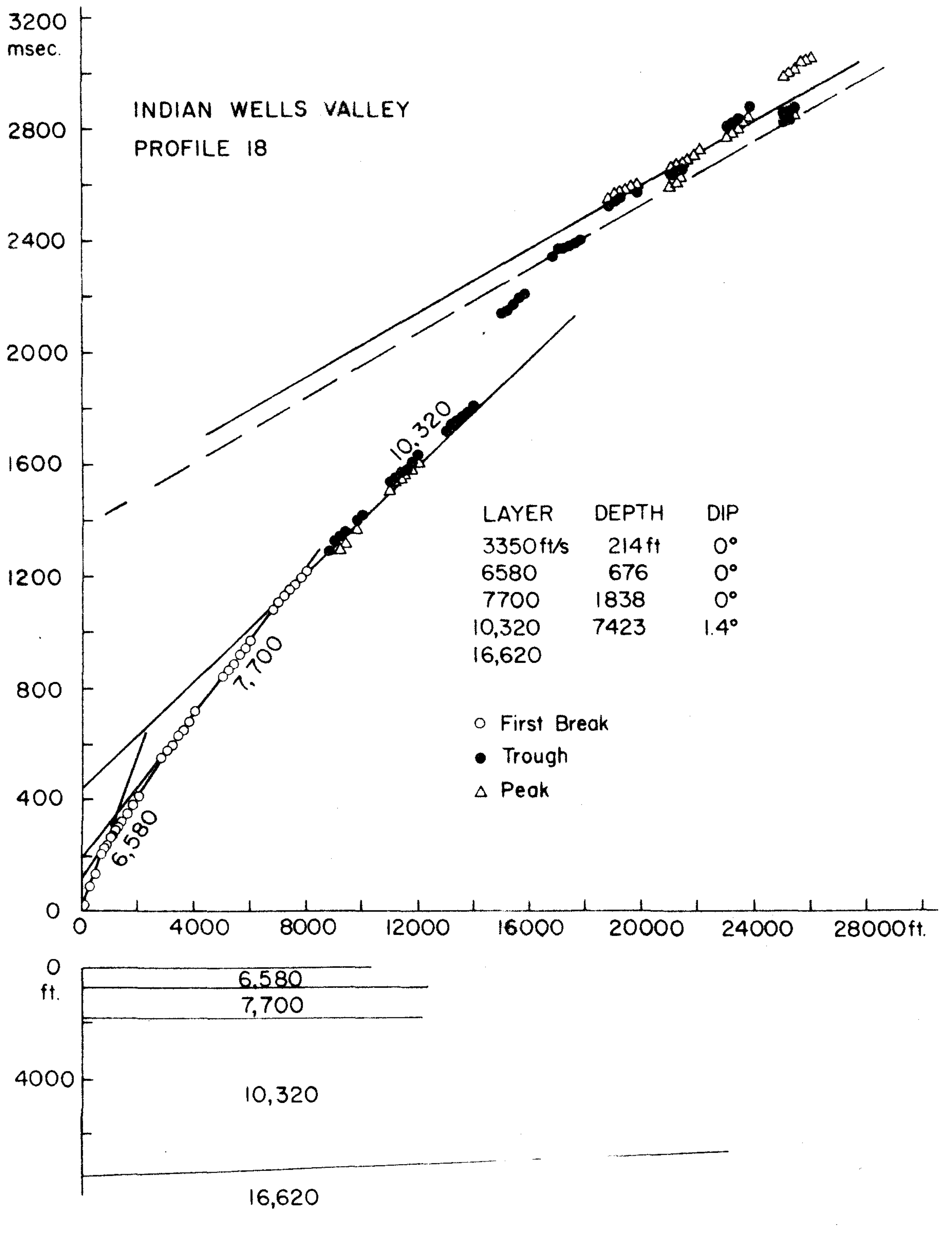
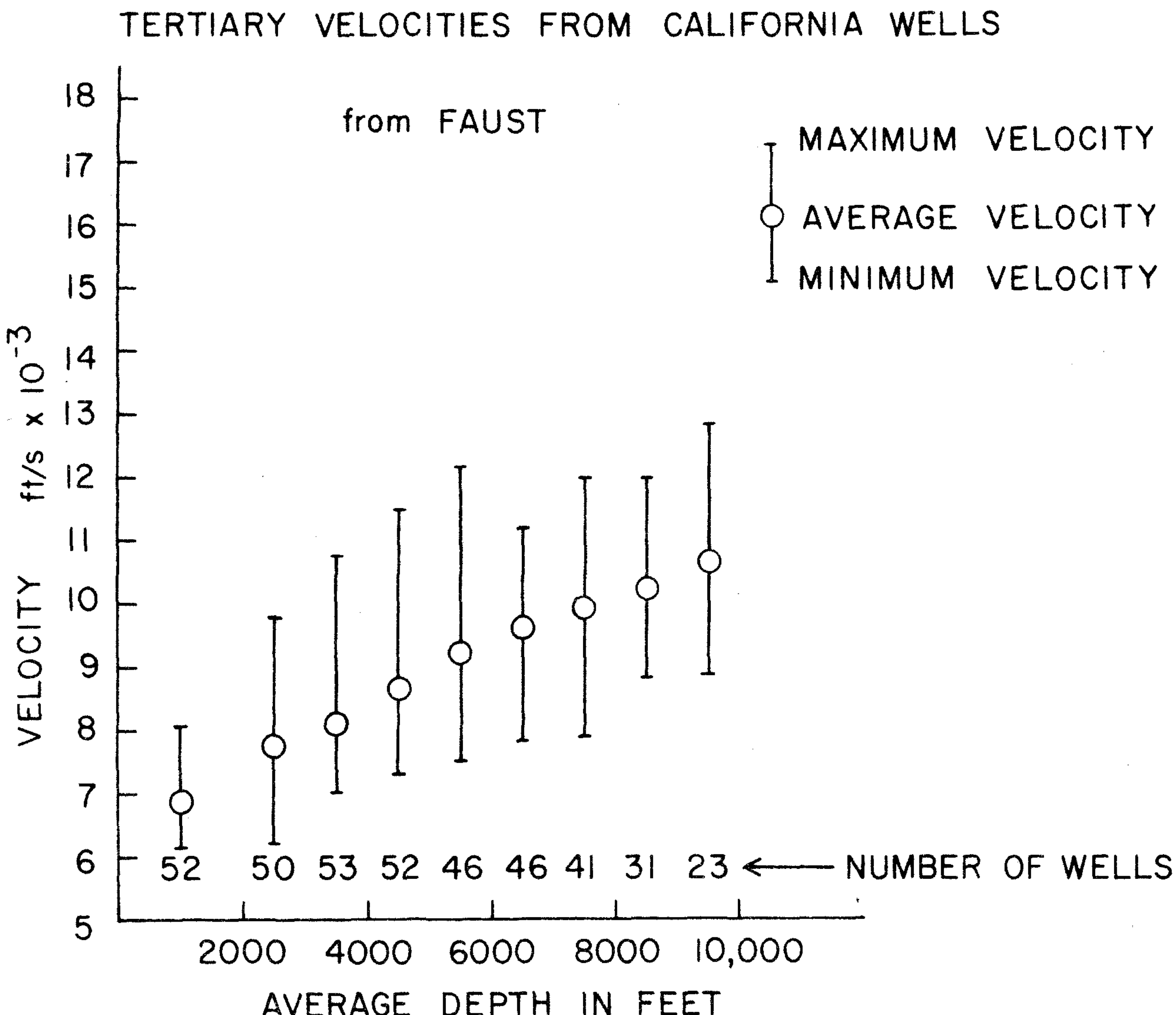

INDIAN WELLS VALLEY
PROFILE 18
3200 msec.
2800
2400
2000
1600
1200
800
400
0
0
4000
8000
12000
16000
20000
24000
28000 ft.
10,320
7,700
6,580
LAYER DEPTH DIP
3350 ft/s 214 ft 0°
6580 676 0°
7700 1838 0°
10,320 7423 1.4°
16,620
First Break
Trough
Peak
0 ft.
4000
6,580
7,700
10,320
16,620

Fig. 22



TERTIARY VELOCITIES FROM CALIFORNIA WELLS
from FAUST
MAXIMUM VELOCITY
AVERAGE VELOCITY
MINIMUM VELOCITY
VELOCITY ft/s x 10^-3
18
17
16
15
14
13
12
11
10
9
8
7
6
5
52 50 53 52 46 46 41 31 23
NUMBER OF WELLS
2000
4000
6000
8000
10,000
AVERAGE DEPTH IN FEET

Fig. 23

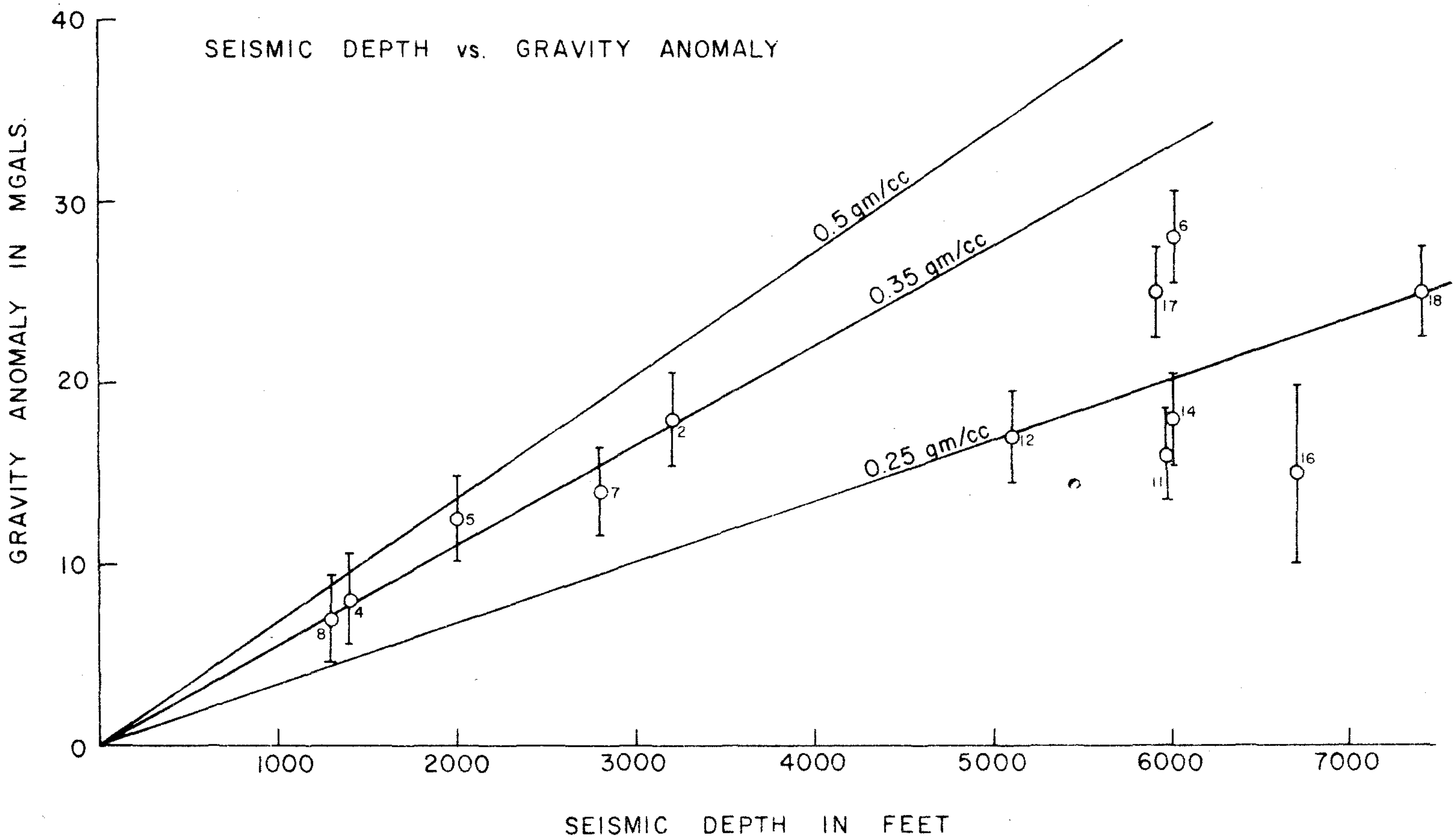

SEISMIC DEPTH vs. GRAVITY ANOMALY
GRAVITY ANOMALY IN MGALS.
SEISMIC DEPTH IN FEET
0.5 gm/cc
0.35 gm/cc
0.25 gm/cc
0
10
20
30
40
1000
2000
3000
4000
5000
6000
7000
2
4
5
6
7
8
11
12
14
16
17
18

Fig. 24

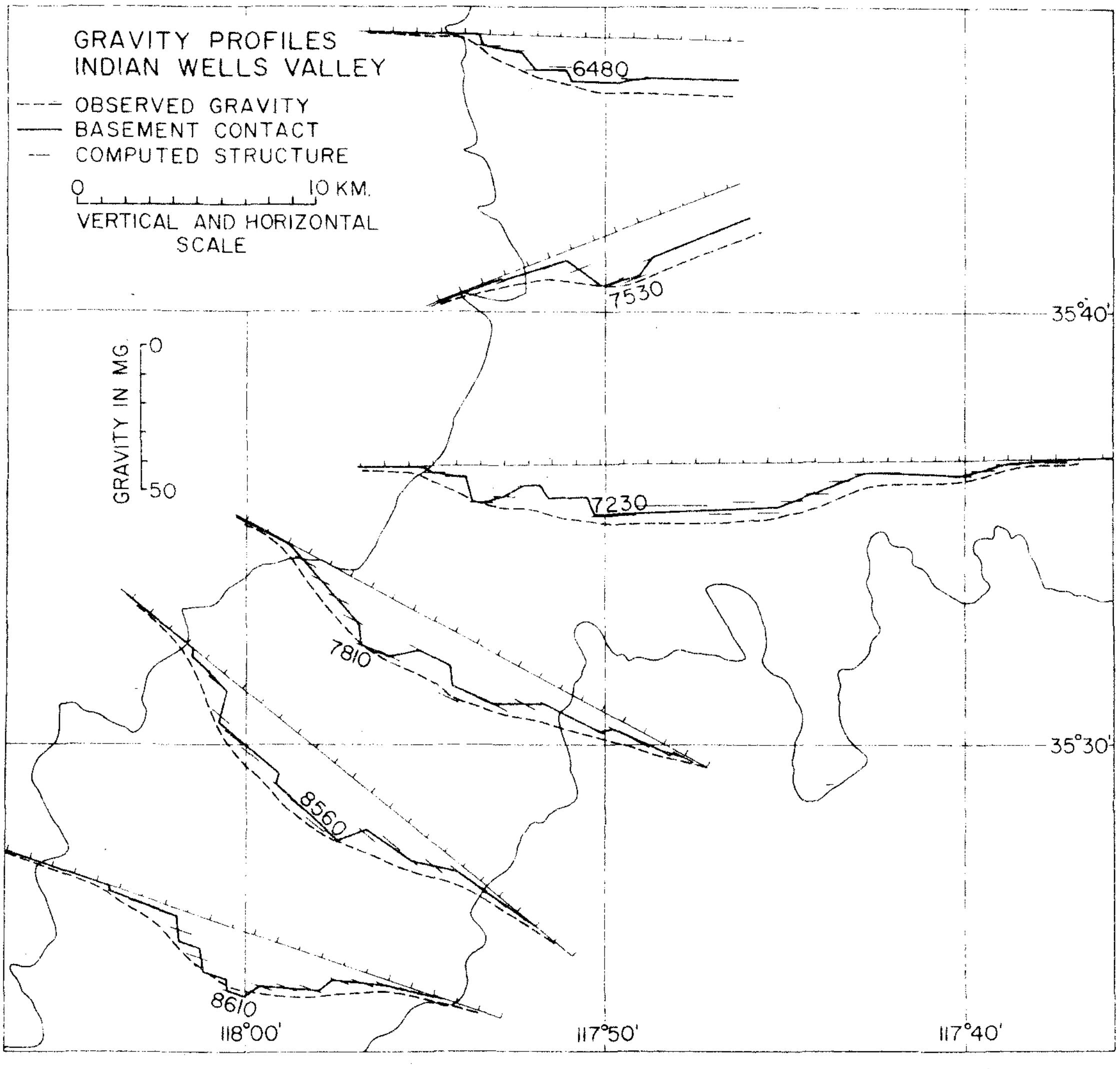

GRAVITY PROFILES
INDIAN WELLS VALLEY
OBSERVED GRAVITY
BASEMENT CONTACT
COMPUTED STRUCTURE
0
10 KM.
VERTICAL AND HORIZONTAL SCALE
GRAVITY IN MG.
0
50
6480
7530
7230
7810
8560
8610
35°40'
35°30'
118°00'
117°50'
117°40'

Fig. 25

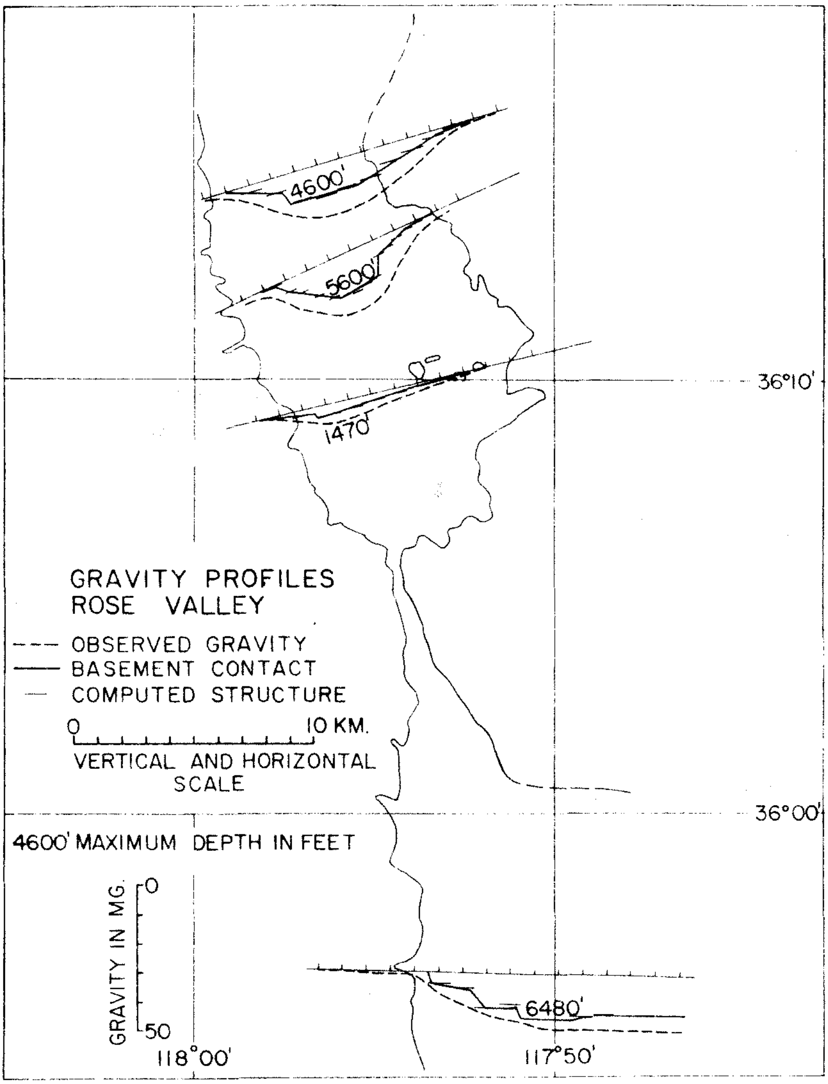

36°10'
36°00'
GRAVITY PROFILES
ROSE VALLEY
OBSERVED GRAVITY
BASEMENT CONTACT
COMPUTED STRUCTURE
0
10 KM.
VERTICAL AND HORIZONTAL
SCALE
4600' MAXIMUM DEPTH IN FEET
GRAVITY IN MG.
0
50
118°00'
117°50'
4600'
5600'
1470
6480'

Fig. 26

CONVERGENCE OF ITERATIVE GRAVITY INTERPRETATION

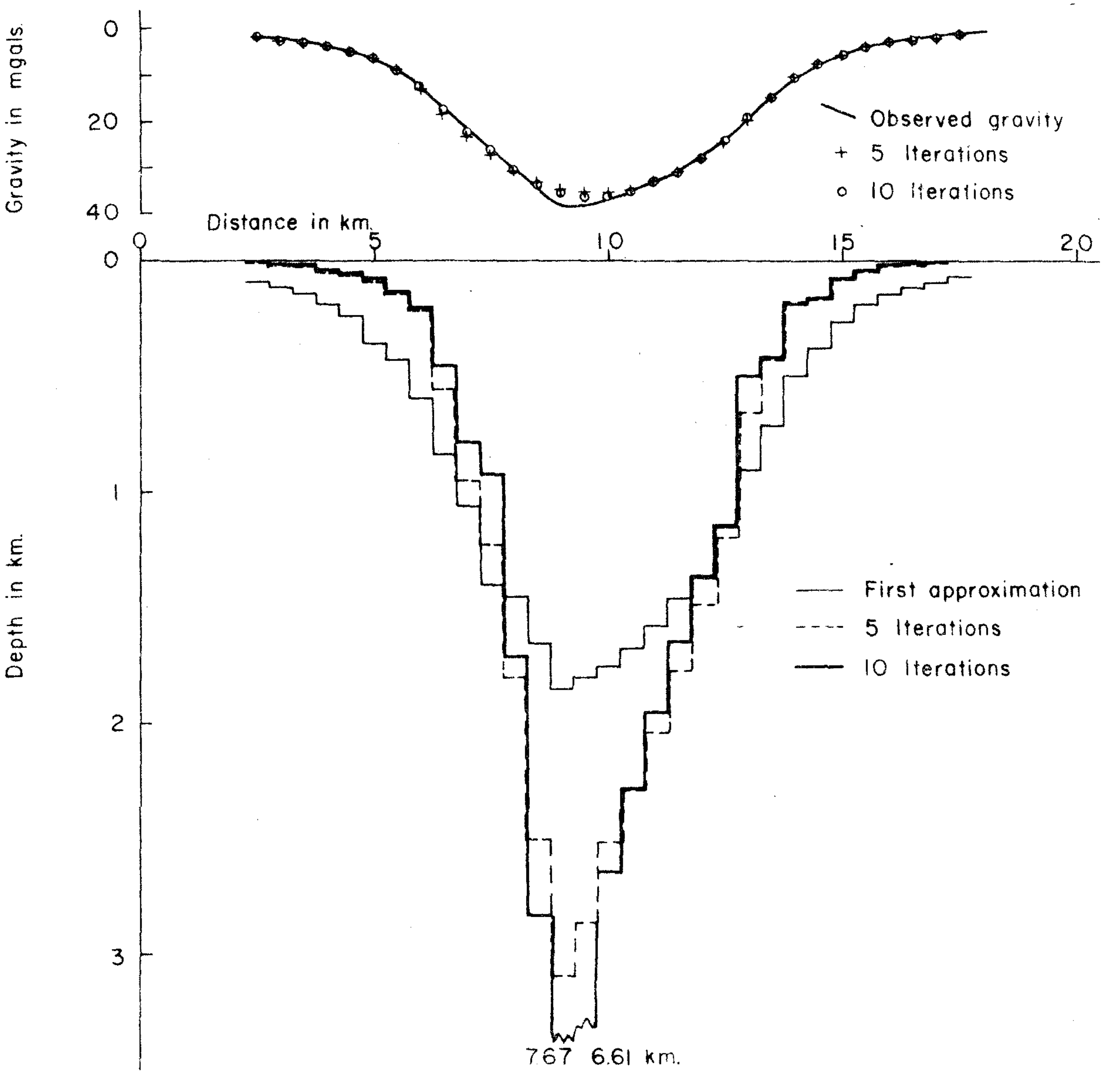


Fig. 27

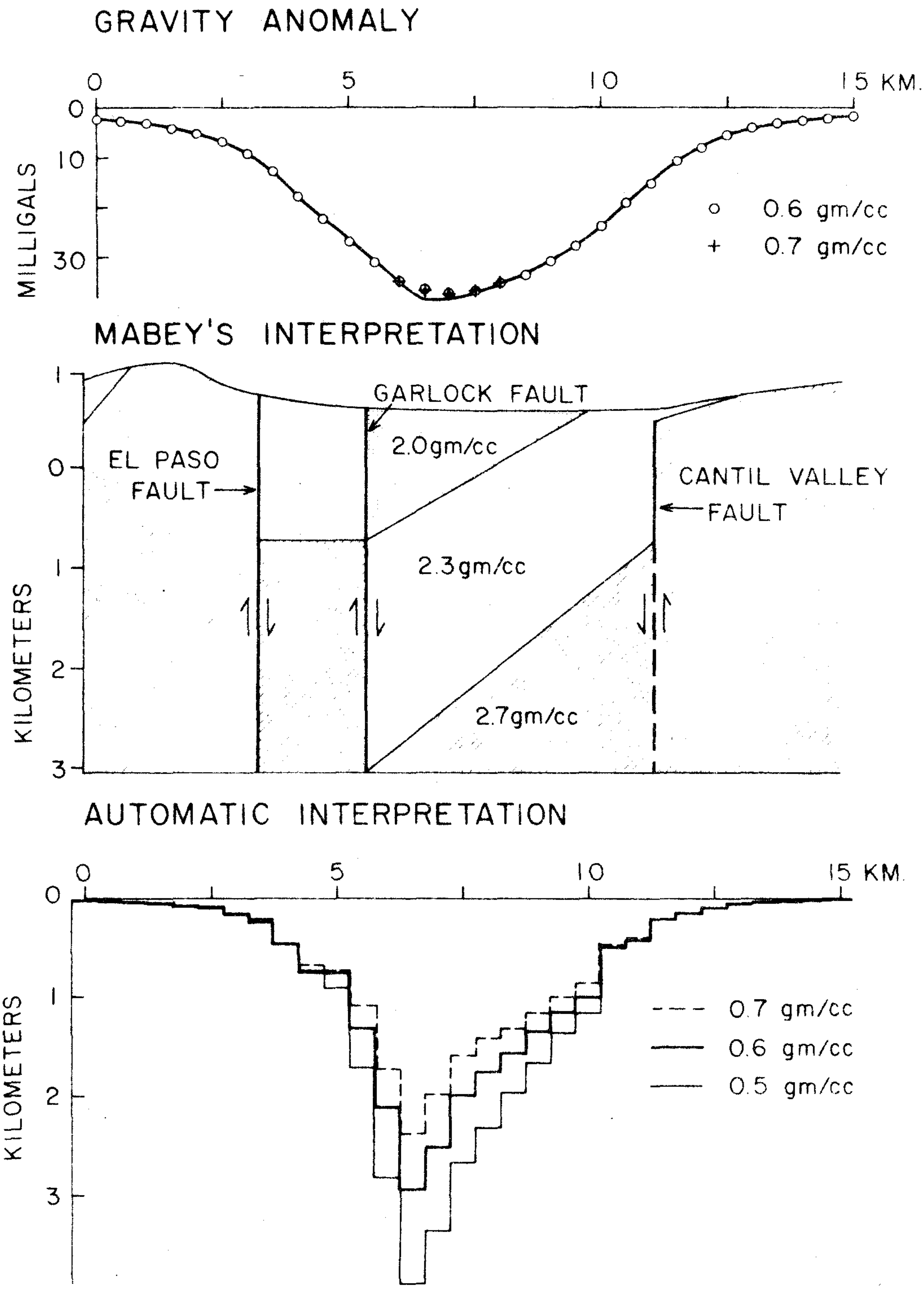
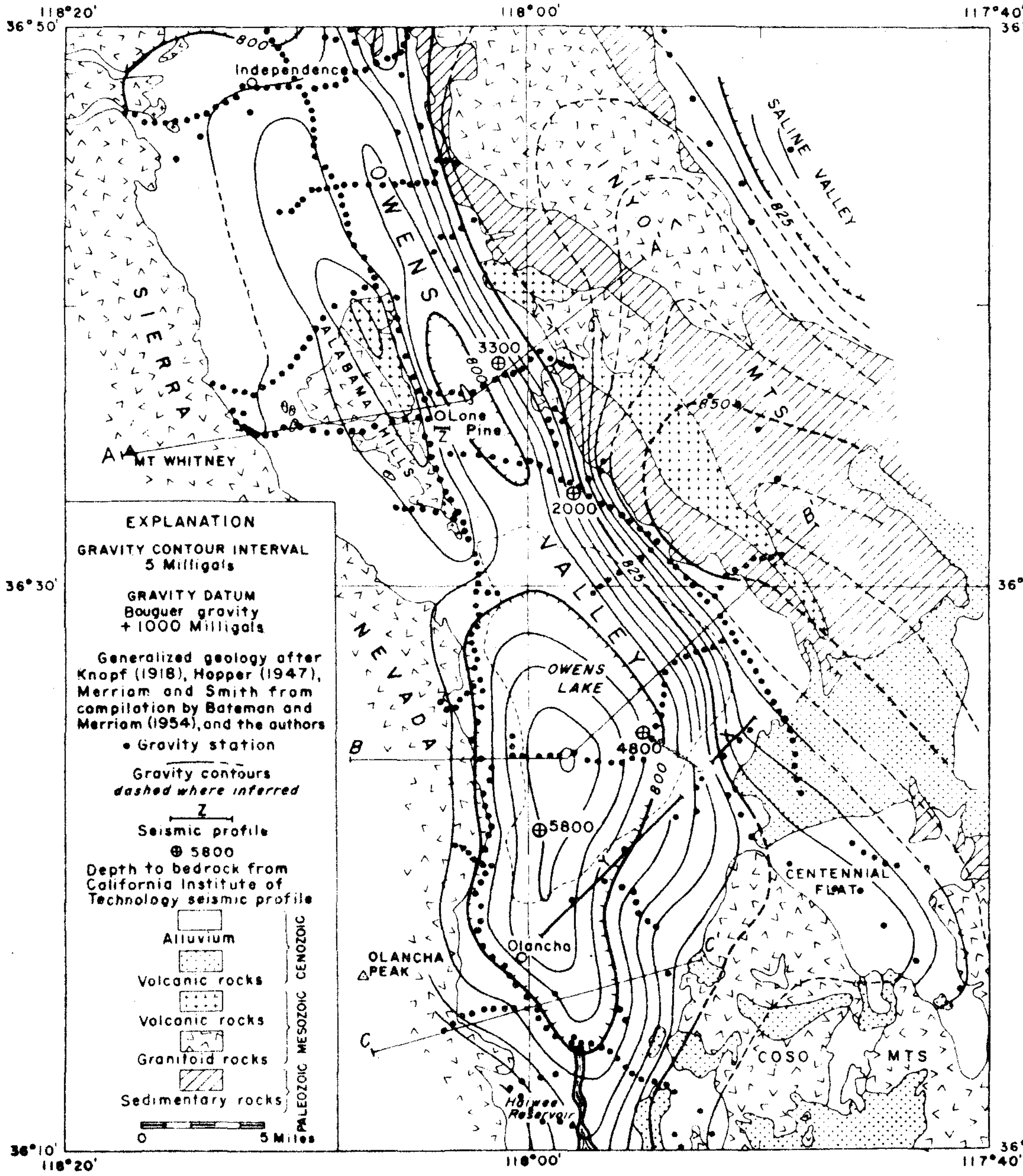

GRAVITY ANOMALY
0
5
10
15 KM.
MILLIGALS
0
10
30
o 0.6 gm/cc
+ 0.7 gm/cc
MABEY'S INTERPRETATION
GARLOCK FAULT
2.0gm/cc
EL PASO
FAULT
CANTIL VALLEY
FAULT
2.3gm/cc
2.7gm/cc
KILOMETERS
1
0
1
2
3
AUTOMATIC INTERPRETATION
0
5
10
15 KM.
KILOMETERS
0
1
2
3
0.7 gm/cc
0.6 gm/cc
0.5 gm/cc

Fig. 28



Geologic and gravity anomaly map of southern Owens Valley.

from

Kane and Pakiser (1960)

Fig. 29

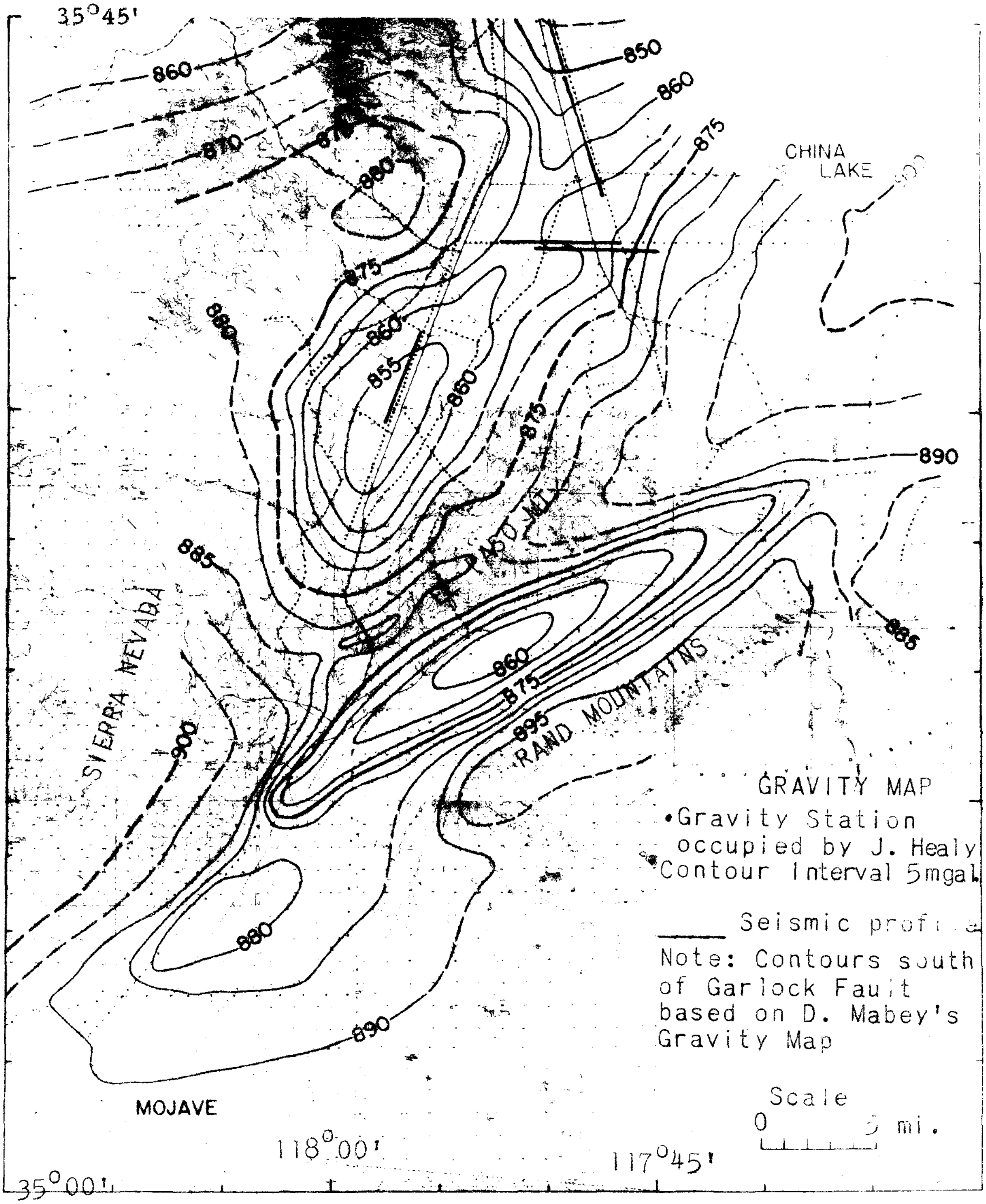

35°45'
860
870
875
880
850
860
875
CHINA
LAKE
875
880
860
855
860
875
890
885
SIERRA NEVADA
860
875
895
RAND MOUNTAINS
885
900
GRAVITY MAP
•Gravity Station
occupied by J. Healy
Contour Interval 5mgal
Seismic profile
Note: Contours south
of Garlock Fault
based on D. Mabey's
Gravity Map
880
890
MOJAVE
Scale
0
5 mi.
118°00'
117°45'
35°00'

Fig. 30

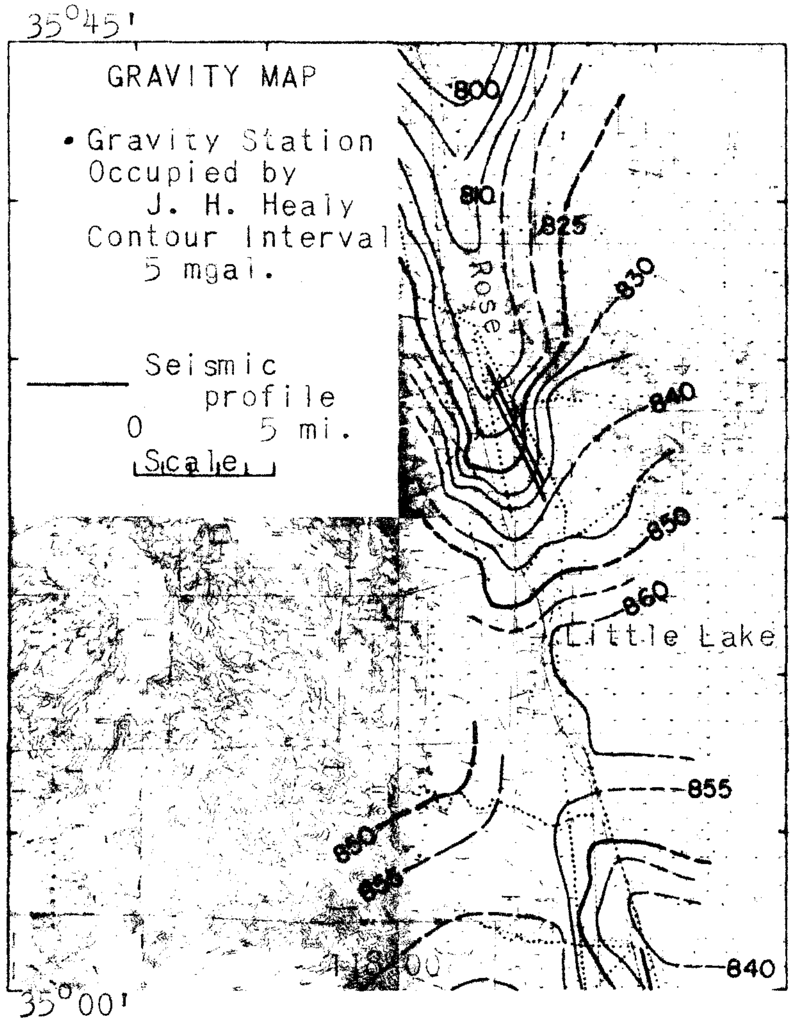

35°45'
GRAVITY MAP
• Gravity Station
Occupied by
J. H. Healy
Contour Interval
5 mgal.
Seismic
profile
0 5 mi.
Scale
800
810
825
830
840
850
860
Rose
Little Lake
855
850
855
840
35°00'

Fig. 30