SEISMIC REFRACTION STUDY OF DIXIE VALLEY, NEVADA

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SEISMIC REFRACTION STUDY OF DIXIE VALLEY, NEVADA

A DISSERTATION

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FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

By

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February 1967

I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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ABSTRACT

Seismic refraction studies of Dixie Valley, Nevada, have revealed a buried complex of normal faults which form a long subsurface trough with a "graben in graben" structure. The inner graben, situated beneath the west side of the valley floor, narrows to five miles and contains an accumulation of sedimentary and volcanic deposits of Cenozoic age which reach a maximum thickness of 10,500 ft. The depth to bedrock in the outer graben along both sides of the narrow depression ranges from 1000 to 5000 ft. This basin structure indicates that Dixie Valley subsided along a complex system of step faults rather than along single boundary faults. Velocities ranging from 5000 to 8000 ft/sec are associated with unconsolidated to semi-consolidated clastic sediments of Pleistocene and Recent age. A seismic velocity boundary below which the velocity increases to an average of 10,000 ft/sec is characteristic of the entire Dixie Valley region; this higher velocity is correlated with volcanic rocks in the upper part of the Miocene to Pleistocene section that partly caps the Stillwater Range to the west. This boundary is found at depths ranging from 300 ft in the outer graben to 3500 ft in the inner graben. An average basement velocity of 16,000 ft/sec measured in the southern part of the valley is associated with limestones, slates and metavolcanic rocks exposed in the adjacent mountains, and with the granitic rocks that intruded this Mesozoic section. Farther north, velocities as high as 20,700 ft/sec are characteristic of grabbroic rocks included in a Jurassic complex that is exposed in the northern parts of the Stillwater and Clan Alpine ranges. A special study was made of side refractions in a reversed profile parallel to the outcropping fault zone bounding the Stillwater Range west of Humboldt Salt Marsh. The study shows that this fault zone dips 45° to the east, and its sharp changes in strike are conserved to a depth of at least 2500 ft. The geometric constraints of the fault pattern argue against large scale strike-slip faulting in Dixie Valley, and other geophysical evidence supports an interpretation of primarily dip-slip displacements. The average displacement rate during the life of the basin is on the order of one ft per thousand years.

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I. INTRODUCTION

A. Introduction and Purpose

The Basin and Range Province of the western United States may be viewed as part of the worldwide rift system which lies mainly along ocean ridges (Menard, 1964). Deep seismic exploration in the western United States has revealed that the earth's crust is unexpectedly thin and the upper mantle velocity is anomalously low (Pakiser and Steinhart, 1964). This unusual property, associated with others such as regional Cenozoic volcanism and high heat flow, match the characteristics of the ocean ridges. Gravity measurements in the same area show that the Basin and Range Province is in regional isostatic balance and that great thicknesses of Cenozoic sediments fill the basins (Thompson, 1959).

However, little is known of the internal structure and rates of deformation of these deeply alluviated basins. Seismic exploration, combined with aeromagnetic and gravity surveys, has been needed to establish the detailed internal structure of a typical rift valley. Measurements of the depth and attitude of the deeply buried surface of pre-Tertiary rocks and of the layers within the valley fill may in turn reveal the pattern of faulting and the history of subsidence which can be related to the surrounding geologic features. The conclusions of such a study may be helpful in understanding the rifting mechanisms in the African rifts, the Oslo and Rhine grabens, and the oceanic rift zones.

Dixie Valley, which is located in west central Nevada, was chosen for this study because it lies along the most active seismic belt in the Basin and Range Province. Large earthquakes accompanied by displacements of the ground surface occurred in 1903, 1915, and 1954. The epicenters of these shocks and the historical faults are shown in Figure 1 (Slemmons, 1957). The strike-slip component of the 1954 faults is often invoked in recent literature as evidence of strike-slip fault control of Basin-Range structure. (Shawe, 1965). The detailed study of the geometry of the western side of Dixie Valley presented in this report has a strong bearing on this theory.

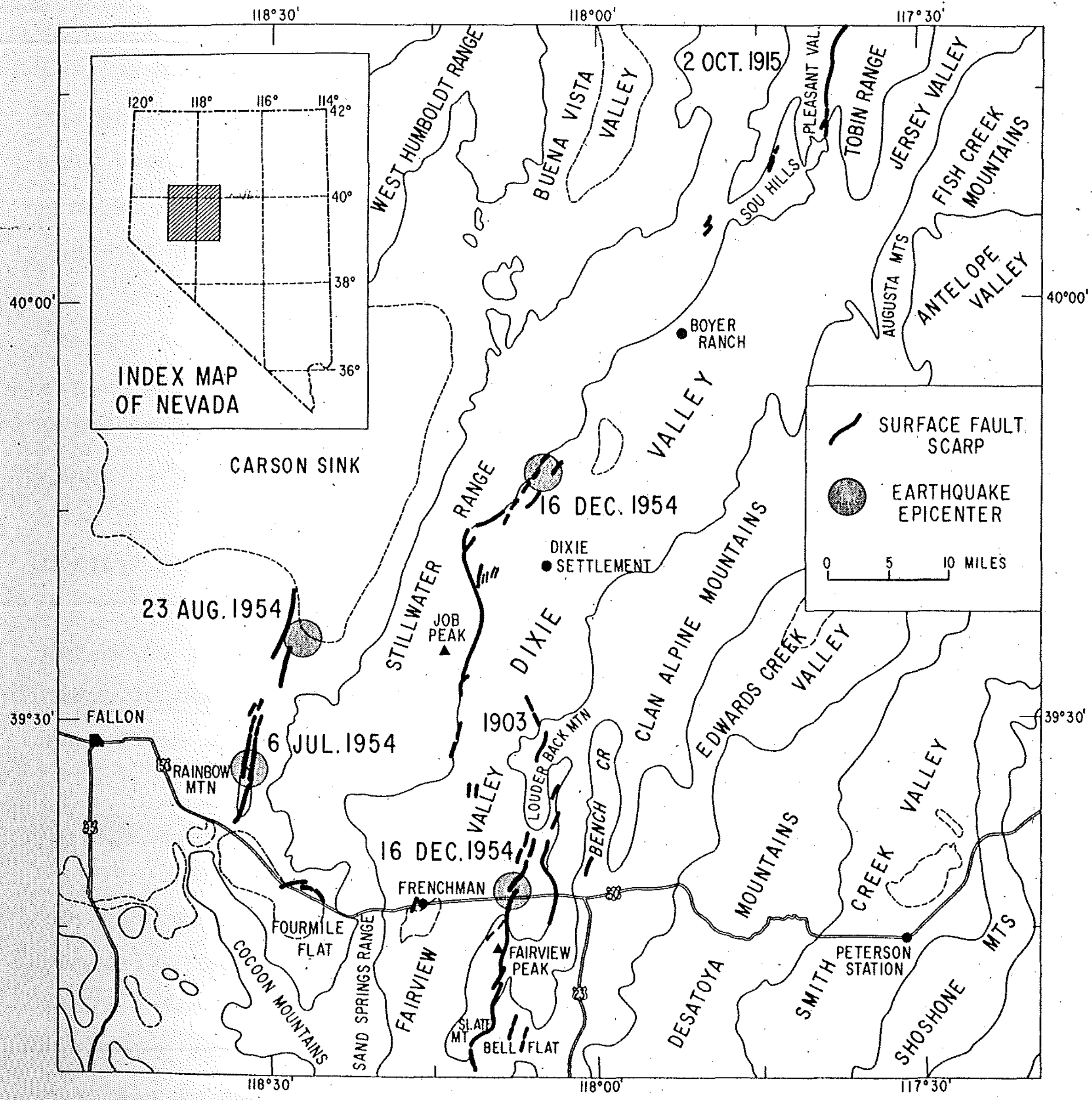

Figure 1. Location Map. Historical faults of 1903 and later are shown. After Slemmons (1957).

Moreover, the seismic velocities measured during this study will be useful for velocity calibration of microearthquake monitoring stations which are operating in the area (Ryall, oral communication, 1966).

B. Previous Work

Earlier published work in the Dixie Valley-Carson Sink region has been primarily of a geologic nature, the subsurface studies being limited to hydrologic investigation from shallow well data (Cohen *et al.*, 1963). The stratigraphy and structure of the extreme north end of the project area have been discussed by Muller and others (1951). Most useful to the present project has been the recent mapping of the Stillwater Range and parts of the West Humboldt and Clan Alpine Ranges by Page (1965) and Speed (1963).

Geophysical work in and near the area under study consists of a reconnaissance gravity survey along U. S. Highway 50 between Hazen and Austin and across the Stillwater Range west of Dixie Settlement (Thompson, 1959), a recent gravity survey of the Carson Sink-West Humboldt region (Wahl, 1965), and a complete geological-geophysical investigation of the Sand Springs Range-Fairview Valley-Fourmile Flat area to the south of the present project (University of Nevada, 1962).

To supplement the present seismic work, an aeromagnetic survey of the Dixie Valley-Carson Sink area (Smith, 1965) and a study of side refractions at Mud Springs (Herring, 1966) were made. An extensive gravity survey of the Dixie Valley-Fairview Valley area is in progress (Thompson, 1966).

C. Field Work

The seismic refraction survey of Dixie Valley was undertaken during the summers of 1964 and 1965. Because of the lack of access roads, it was generally impossible to select locations which would yield the most nearly ideal information for the seismic profiles. The geometric requirement of extending each profile to obtain reversed apparent velocities was not possible in the east-west direction because of the narrow width of the valley. North of Dixie Settlement, the central part of the basin was inaccessible because the sticky-wet surface near and on the Humboldt Salt Marsh would not support vehicles. Consequently most of the seismic lines were located along both sides of the valley far enough from the mountain fronts to avoid side refraction.

During the 1965 field season numerous cloudbursts inundated the central part of the valley, washing out most of the roads and creating serious delays in the field work.

It was possible to shoot large explosive charges in the air because the population is sparse throughout the project area.

II. GEOLOGIC SETTING

A. Physiography

The Dixie Valley area displays typical physiographic features of the Basin and Range Province i.e., elongated north to northeast-trending mountain ranges separated by narrow valleys. The ranges bordering Dixie Valley--the Stillwater to the west and Clan Alpine to the east--are deeply dissected, complex fault-block mountains rising as much as 5,000 ft above neighboring valleys (Fig. 2). The mountains are generally bounded by steeply-dipping north to northeast-trending normal faults.

The mountain ranges in the project area are flanked by broad alluvial fans which slope gently toward the valley floor, the lowest area of which is occupied by the Humboldt Salt Marsh. The generalized geological map shown in Figure 2 outlines the structural elements of the area. Most of the information used in the following description was taken from the geologic map of part of the Stillwater Range published by Page (1965).

B. Major Rock Units

1. Triassic Rocks: The most important rock unit in the central map area is a large expanse of gray-black slate and phyllite. Slaty cleavage throughout this unit generally parallels bedding except near axial parts of folds where it approaches the axial plane. For the most part, only incipient recrystallization is evident; however, near granitic contacts, andalusite has been observed (Page, 1965).

Complex deformation of the unit prohibits direct measurement of the slate-phyllite-limestone sequence, but Page estimates its thickness as 5000 to 10,000 ft, of which only about 10% is metaquartzite and limestone.

Fossil identification has placed the age of this unit as Late Triassic.

A large body of allochthonous black to gray Upper Triassic limestone is present in the southern part of the project area. Fossil evidence indicates this unit is of the same age as the Upper Triassic slate upon which it rests, implying significant lateral transport of rocks formed in a different sedimentary environment. Triassic limestone is also present in the

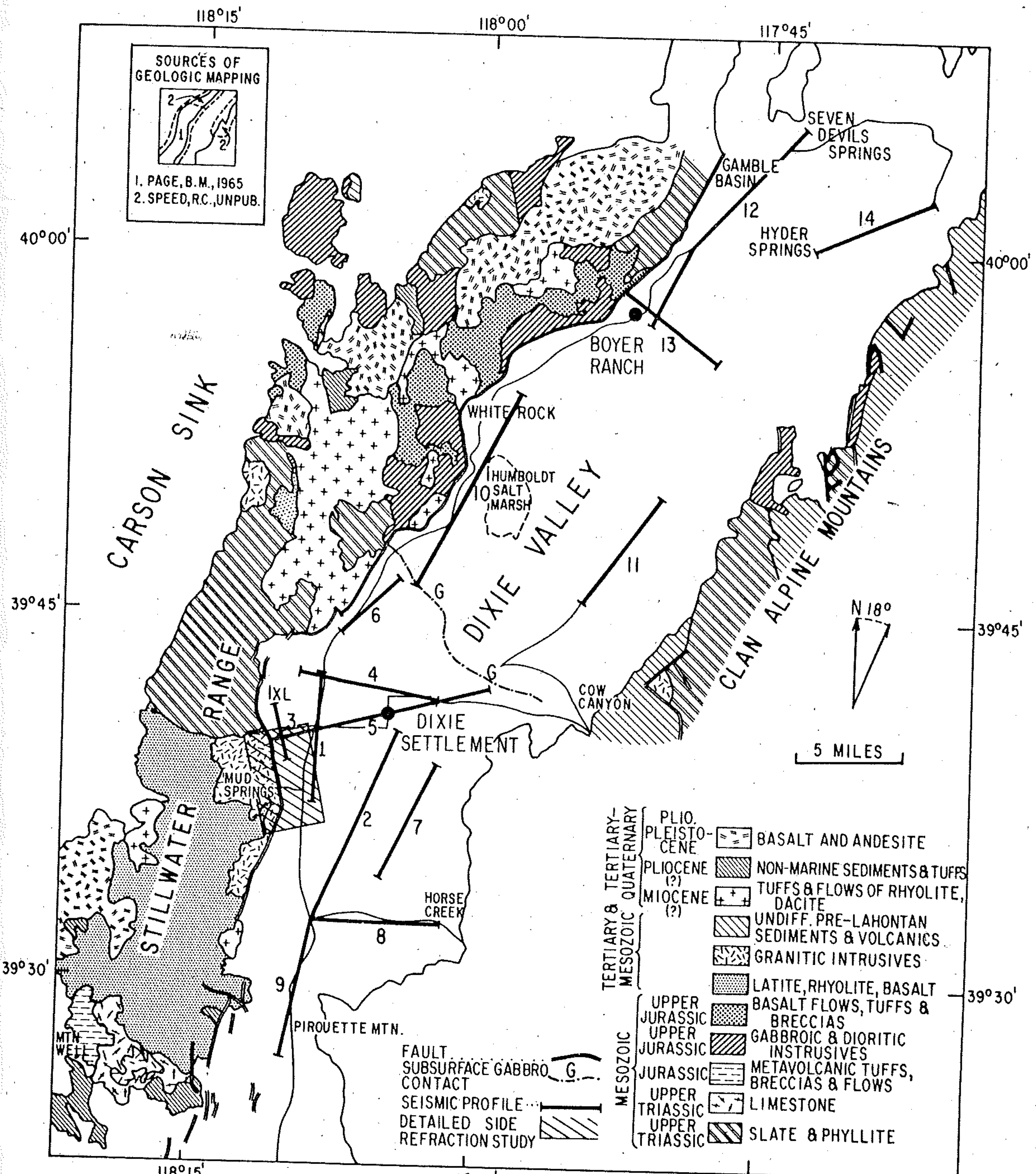

Figure 2. Geological Map showing locations of seismic profiles.

northern part of the Stillwater Range a few miles north of Boyer Ranch in thrust contact with the Triassic slates, the slates forming the upper plate and the limestones the lower one (Speed, written communication, 1966).

2. Jurassic Rocks: Bordering the Triassic limestone to the west in the southern end of the Stillwater Range is a sequence of altered and locally schistose metavolcanic rocks. They consist mainly of the fine-grained slaty andesitic tuffs, breccias, thin andesitic flows, quartzite, and calcareous sandstones. The volcanics are almost completely altered, but display certain relict textures. The sedimentary rocks are better preserved and unfossiliferous. This unit is in excess of 5000 ft thick, rests unconformably upon the allochthonous Triassic limestone and is thought to have been transported in as part of the La Plata thrust sheet (Page, 1965).

Of great importance to the present seismic study is the Humboldt Gabbroïc Complex which covers large areas in the northern part of the Stillwater, Clan Alpine, and West Humboldt Ranges. One part of this unit is composed of extensive basalt flows, lapilli tuffs, and breccias. Alteration is common, epidote and chlorite imparting a distinct green color. Normally associated with the Upper Jurassic gabbroïc intrusions, these rocks are quite possibly contemporaneous with and may represent an extrusive equivalent of the gabbro.

The intrusive rocks of the gabbroïc complex are represented by a large, seemingly tabular complex of gabbroïc and dioritic intrusions. These rocks form an igneous unit which includes hornblende gabbro, diorite, anorthosite, keratophyre, and gabbroïc pegmatite. Distinct layering is evident in the earlier parts of the suite along intrusive margins. This unit has been carefully studied by Speed who considers it to have been emplaced at very shallow depths, in places penetrating to the surface and forming the extrusive basalts discussed earlier. A potassium-argon date from the West Humboldt Range indicates an age of about 140 million years, placing it chronologically in Late Jurassic time. Profound alteration including albitization and dolomitization is common in this unit. The gabbroïc complex was mapped as two distinct units in Figure 2: the extrusive rocks as basalt flows, tuffs, and breccias, and the intrusive rocks as gabbroïc and dioritic intrusives.

3. Tertiary and Mesozoic Rocks: In the area of the Stillwater Range near Mud Springs and to the south, blue-gray weathered latite is abundant. Some of the latite shows fine flow layering. Rhyolitic tuffs and latite breccias are locally present with the flows. Exposed sections of the unit show a thickness of 2000 to 6000 ft. Near intrusive contacts with Oligocene or Lower Miocene granite, recrystallization and darkening are common.

Farther south, much of the exposed rock consists of devitrified welded tuff whose composition probably ranges from latite through silica-rich rhyolite. Curiously resembling porphyries, these gray to brown weathered rocks are extremely competent. Megascopically, only the presence of angular lithic fragments of Triassic slate, latite, and other volcanics attests to the pyroclastic origin of the unit. This entire sequence, varying in thickness from 2000 ft to possibly 10,000 ft, rests unconformably on Upper Triassic slate and limestone and on Jurassic metavolcanics. Along the east side of the Stillwater Range, the devitrified tuff has been intruded by Miocene or Oligocene granitic rocks and white felsite dikes.

A third unit of extrusive and intrusive rocks is grouped under the same heading. The intrusive rocks of this group are represented by basaltic andesites that invade the devitrified welded tuff and older formations near the center of the Stillwater Range. Extrusives of similar composition totaling about 8000 ft in thickness are exposed west of IXL Canyon. The latter three groups of rocks are mapped as a latite-rhyolite-basalt unit (Fig. 2).

Scattered plutons of Late Cretaceous or Tertiary granite, quartz monzonite, and granodiorite are exposed near the center of the map area. The latter two intrude latite and devitrified tuff near Job Peak, where they form a composite unit consisting of several successive intrusions. A potassium-argon date on biotite from the granodiorite in IXL Canyon indicates an age of about 28 million years. These rocks are mapped as granitic intrusives in Figure 2.

4. Rocks Younger than the Granitic Plutons: Capping much of the Stillwater Range is a sequence of post-granitic Miocene (?) volcanics including tuffs, breccias, and flows which vary in composition from latites through dacites and rhyolites. Intensive local alteration is common, although the silicic members retain fresh biotite and glass. Dissection has exposed only 1800 ft; however, total thicknesses may be on the order of 3000 to 4000 ft. These rocks are grouped under the heading: Tuffs and Flows of Rhyolite, Dacite. In other parts of the area, rocks belonging to this unit are included within the undifferentiated pre-Lahontan sediments and volcanics (Fig. 2).

Pliocene (?) sediments and tuffs cover a minor part of the map area; they are prevalent only in the southern Stillwater Range, where a sequence of 1500 ft is exposed in dissected pediment slopes and low hills. Of lacustrine and fluvial origin and locally including ash beds, this unit is probably equivalent to the Truckee Formation farther to the west.

In places overlying the Pliocene (?) sediments and other earlier units along the length of the Stillwater Range are flows of olivine, basalt, and basaltic andesite. Individual flows vary in thickness from 20 to 100 ft, although locally aggregate thicknesses of 1600 ft have been noted.

5. Late Cenozoic Lake Sediments: The late Cenozoic valleys of the Basin-Range Province contain great thicknesses of essentially unconsolidated lake and stream sediments. These range in age from Plio-Pleistocene to Recent and include alluvial fan detritus, stream channel deposits, and lacustrine sediments. The latter consist for the most part of silt and clay, although shoreline deposits of gravel and sand exist locally.

C. Major Faulting of the Stillwater Range

1. Thrust Faults: An apparent structural base of the Triassic slate is exposed in the central part of the Stillwater Range. There, a shale member of the slate rests discordantly on quartzite, and a distinct zone of brecciated shale defines the contact. South of Cox Canyon, the quartzite overrides Jurassic (?) metavolcanics which in turn are thrust upon an undated limestone. Apparently, these units form a section of an imbricate thrust zone. Page (1965) suggests that this zone may underlie all slates of the Stillwater Range.

North of Dixie Meadows, another thrust fault structurally higher than the previous zone is apparent. It is well exposed in Cottonwood Canyon near Boyer Ranch where quartzite of unknown age and Late Jurassic gabbroic rocks have overridden Upper Triassic slate. Speed and Page (1964) have suggested that the shallow intrusion of the molten gabbroic complex may have propelled the thrust sheet. The gabbroic rocks of the upper plate extend across the entire northern end of the region, covering an area of about 500 square miles. The Late Jurassic date of the gabbroic rocks implies a similar age for the thrusting.

2. Cenozoic Faulting: Typical of late Basin-Range structure, the Stillwater Range is essentially an uplifted horst of narrow, elongate, north-trending blocks separated by Cenozoic normal faults. Deformation of the Plio-Pleistocene basalts attests that some tilting accompanied block faulting, but these tilted flows rarely dip more than 12°. In some cases, normal faults interior to the range become the bordering fault where they extend to the range margins.

III. SEISMIC REFRACTION INVESTIGATION RELATING TO HYDROLOGY

The superficial sedimentary materials in Dixie Valley range from the poorly sorted debris of the high alluvial fans to the silts and clays of the Humboldt Salt Marsh; therefore, it is logical to expect large lateral variations in seismic velocity of the shallow, low-velocity zone. The thickness of this uppermost layer, which lies above the water table, was determined from the shallow well data in the central part of the valley (Cohen and Everett, 1963), but had to be investigated by seismic refraction on the alluvial fans. A detailed study of the velocity distribution in the near surface material was made on the alluvial fan west of Dixie Settlement and on most of the refraction profile sites.

A. Instrumentation and Field Procedure

A GT-2 Interval Timer built by the Geo Space Electrodynamic Corporation was used for this shallow refraction investigation. The instrument is carried in a suitcase and records on Polaroid film. The recording time is limited to 0.4 second. We used six channels; the geophones were fixed on a line at 50-ft intervals. This enables us to use a maximum spread length of 250 ft. The largest offset of the shot point with respect to the spread was 500 ft. Small charges ranging from 1/4 to 1 lb of 40% dynamite were used as sources of seismic energy. The charges were placed at a depth of one foot.

B. Interpretation of the Measurements and Conclusions

A total of 25 seismic profiles were recorded with the GT-2 Interval Timer. Six of these seismic lines were reversed. All data related to this investigation are summarized in Table 1. All apparent velocities that cannot be associated with reversed data are assumed to be true velocities and are used as such in the interpretation.

The first linear segments of the travel-time curves of eight of the long refraction lines recorded with the SIE seismic system (Chapter VII) represent velocities lower than 4500 ft/sec. These velocities are listed in the V_o column of Table 2.

The V_{oo} and V_o velocity layers form the "weathered" zone above the V_1 velocity layer which was associated with the water table. The reversed velocity which corresponds to V_1 is listed in the V_1' column (Table 1).

H_1 is the depth of the recorded refractor V_1 and was computed from the observed velocities by the conventional intercept-time method. In general a two-layer interpretation was made. Along two profiles, three different velocities were observed and an intermediate depth H_o to the top of the second layer was computed.

When the velocity V_{oo} of the upper layer was not observed, a velocity listed in the V_{oo} column was assumed. Each of these assumed velocities is shown in parentheses in Table 1. A three-layer interpretation was then made, which yielded a depth H_V to the top of the V_1 velocity layer (Table 1).

If the intermediate velocity V_o was not observed, its presence was assumed as a blind zone and another depth H_B was computed to the upper boundary of the V_1 velocity zone. The assumed velocity in parentheses in column V_o and the nomograms of Hawkins and Maggs (1961) were used for the interpretation. The nomograms yield, in terms of the calculated depth H_1, the thickness of the blind zone and the depth H_o to the top of the blind zone. Comparison of H_1, H_V, and H_B shows the range of uncertainty in the determination of the depth of the V_1 velocity layer.

The velocities in column V_{oo} range from 1000 to 1300 ft/sec; they are associated with the aerated sands and gravels which form the surface of the ground. The thickness of this surface layer varies from a few feet in the central part of the valley to about twenty feet on the high alluvial fans. For IXL-5 profile, an abnormally high thickness of 47 ft was found indicating that large lateral variations in thickness of the surface layer exist within the alluvial fans.

V_o includes velocities ranging from 1700 to 3300 ft/sec. This intermediate layer is probably composed of the same material as the superficial layer but may be more consolidated. It is well developed on the alluvial fans.

TABLE 1

SEISMIC DATA RELATED TO THE STUDY OF THE WATER TABLE

Profile	Location	Elevation (ft)	Velocities (ft/sec) V_{oo}	V_o	V_1	V_1'	Depths (ft) H_1	H_B	H_V	H_O
1	NW of Dixie Settlement	3400	1100	(2500)	5000	5250	6	8		5
2	NW of Dixie Settlement	3400	1250	(2500)	4750		4	5		3
3	NW of Dixie Settlement	3400	1100	(2100)	4000		6	7		4
4	NW of Dixie Settlement	3420	1100	2850	5880		15			5
5	SW of Salt Marsh	3380	1000	(2500)	4000	3320	3	4		3
6	SW of Salt Marsh	3380	1000	(2500)	4500		3	4		3
7	Alluvial Fan SW of Salt Marsh	3500	(1100)	2100	4550				64	2
8	Alluvial Fan SW of Salt Marsh	3500	(1100)	1850	5900				63	1
9	Low Alluvial Fan SW of Salt Marsh	3420	1150	(2100)	7150		34	45		22

TABLE 1 (continued)

Profile	Location	Elevation (ft)	Velocities (ft/sec) V_{oo}	V_o	V_1	V'_1	H_1	H_B	H_V	H_O
10	Low Alluvial Fan SW of Salt Marsh	3420	1050	(2100)	5900		29	39		20
11	East of Mud Springs	3520	1100	1700	5000		45	*41		14
12	W of Dixie Settlement	3450	1200	(2000)	5250		24	31		16
13	W of Dixie Settlement	3840	1250	(2500)	5000		30	49	*28	17
14	W of Dixie Settlement	3840	1000	(1850)	5400		21	33		11
15	E of Salt Marsh	3670	(1250)	3300	5000		*128		107	11
16	W of Cow Canyon	3450	(1250)	2200	4350				51	2
17	Cow Canyon	3680	(1250)	2800	5550	5550			135	23
18	SW of Cow Canyon	3600	(1250)	2400	7700				82	11
19	SW of Cow Canyon	3580	(1100)	2400	5000	5400			70	4
20	IXL-1	3490	1300	(2300)	5250	5250	34	44		23
21	IXL-2	3510	(1300)	2350	6250	6250			71	1
22	IXL-3	3550	(1300)	1750	5900				64	1
23	IXL-4	3600	(1300)	2300	5900				103	4
24	IXL-5	3660	(1300)	2950	4550				117	47
25	IXL-6	3850	(1300)	2800	5000				146	23

*Depth from Well Data

TABLE 2

SEISMIC DATA RELATED TO THE STUDY OF THE WATER TABLE

PROFILE	LOCATION	ELEVATION (ft)	V_o(ft/sec)	V_1(ft/sec)	H_1(ft)
8	HORSE CREEK	4400	2000	4600	40
9	PIROUETTE MOUNTAIN	3870	2000	4500	100
12	SEVEN DEVILS	3500	2500	5700	70
13	BOYER RANCH	3435	2000	5400	18
14	HYDER SPRINGS	3600	3000	6000	150
3	IXL CANYON	3850	2500	5000	130
A10	NW OF SALT MARSH	3750	2300	5000	100
E51	IXL CANYON STUDY	4010	2350	5000	150

The velocities in column V_1, ranging from 4000 to 7150 ft/sec, are related to unconsolidated, water-saturated sediments. The top of this velocity layer is correlated with the water table; therefore H_1, H_B, and H_V can be considered as depths to the water table at the profile location. As the composition of the clastic deposits below the water table may vary from clays and silts in the central part of the valley to gravel and sands on the alluvial fans, a wide range of velocities can be expected for the V_1 layer.

Along three profiles, velocities higher than 6000 ft/sec were measured. These velocities probably represent horizons below the water table which are partially cemented. The water table was a blind zone and could not be observed. Three refraction lines were shot close to water wells. The depths computed from seismic data agree within 10% with the depths to the water table measured in these wells (Table 1).

Figure 3 shows the locations of the profiles and the depths H_1, H_B or H_V to the water table determined by seismic refraction.

An E-W cross-section of the alluvial fan in front of IXL Canyon shows very clearly the near-parallelism of the surface of the ground and the water table (Fig. 4). The attitude of the water table was deduced from 9 N-S refraction profiles shot along this cross-section.

In conclusion, it should be noted that the GT-2 Interval Timer proved to be very efficient for such a seismic investigation because it permitted the rapid collection of a large amount of information on the general attitude of the water table in Dixie Valley.

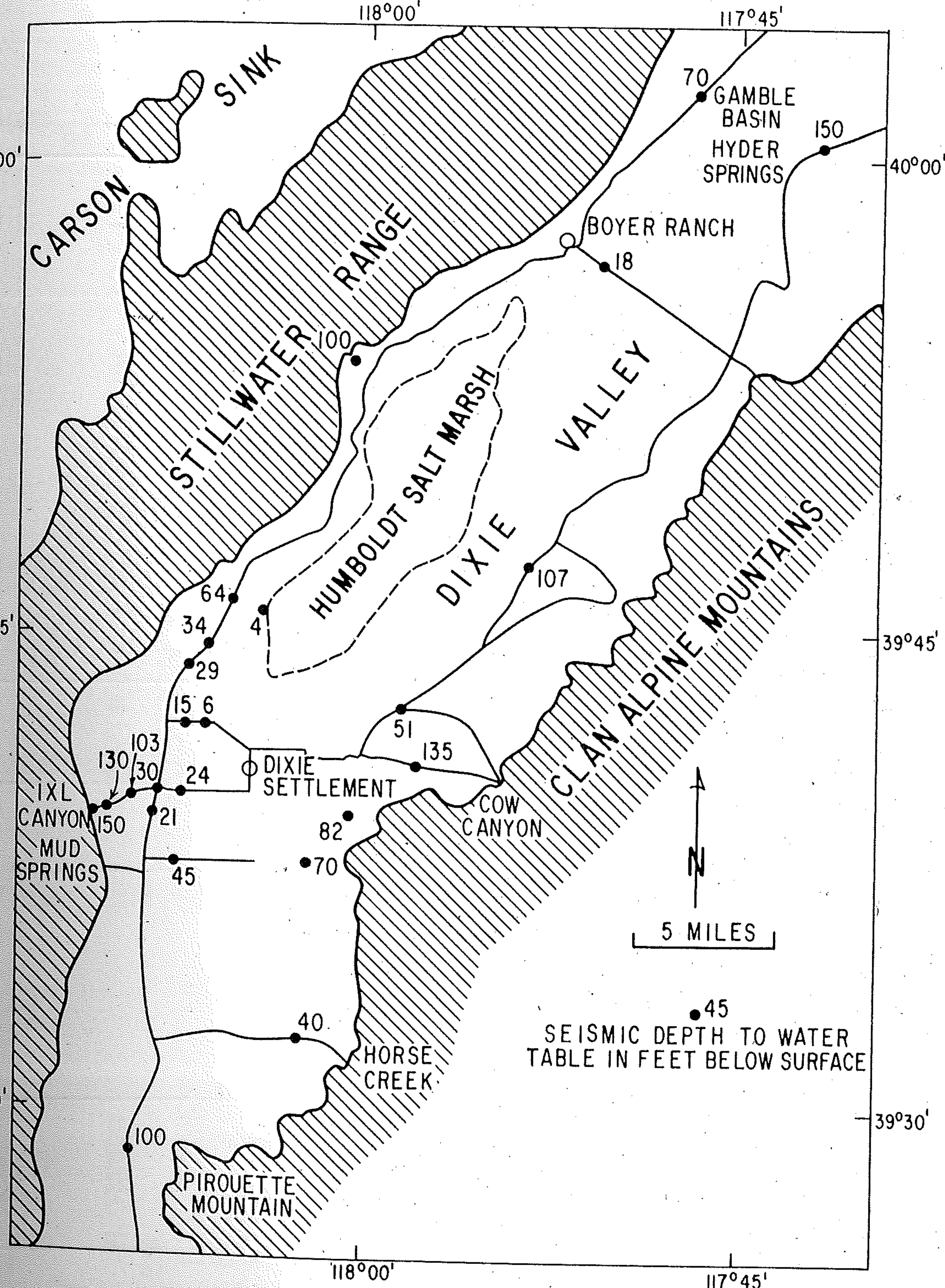

Figure 3. Locations of seismic profiles shot for the investigation of the water table.

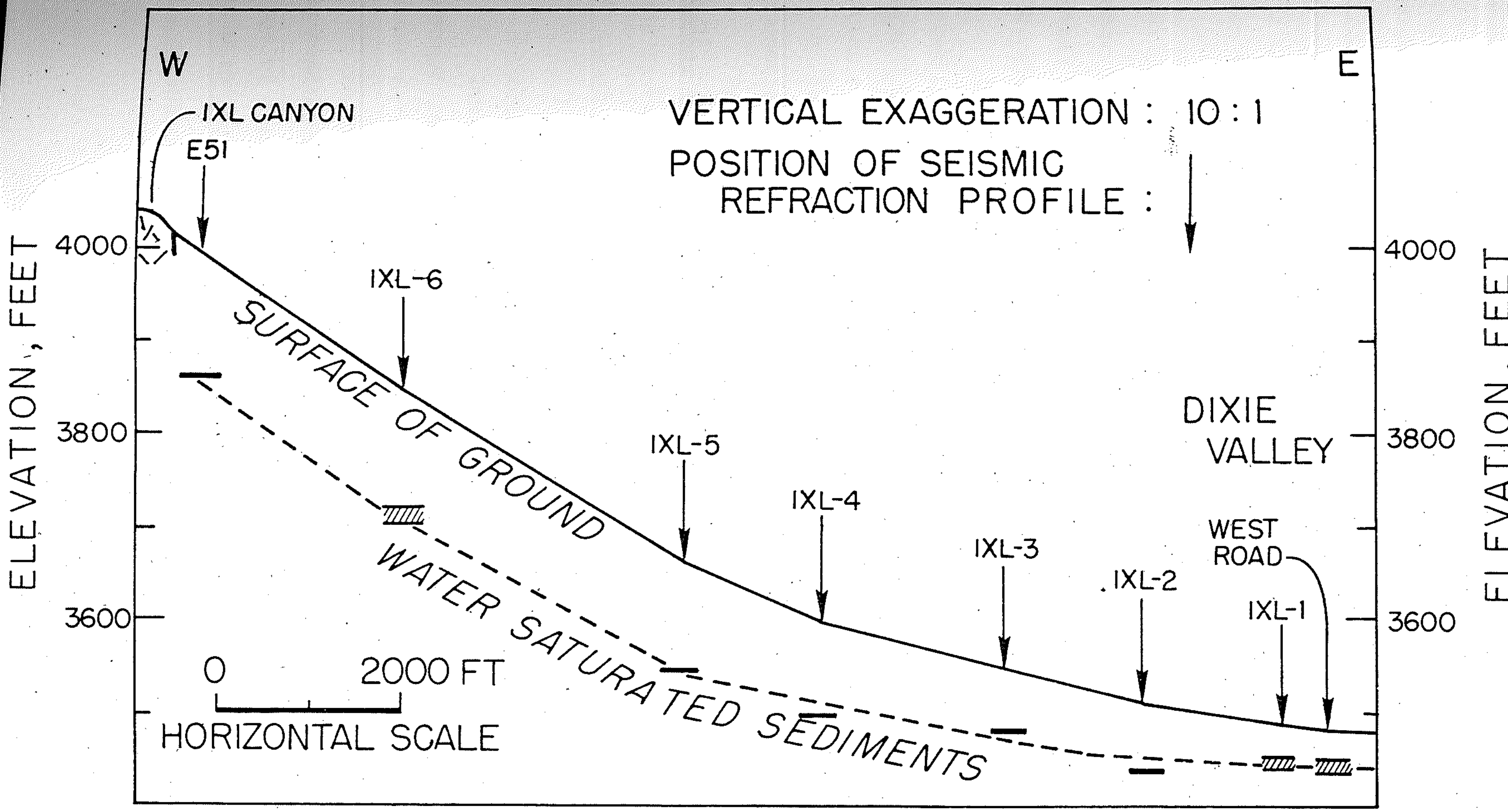

Figure 4. Position of the water table below the surface of the alluvial fan east of IXL Canyon.

IV. FIELD PROCEDURE FOR DEEP SEISMIC REFRACTION STUDY

A. Instrumentation

Four of the fourteen seismic refraction profiles recorded in Dixie Valley, were set up in an east-west direction, transverse to the topographic outline of the valley, and the others in a northeast direction (Fig. 2).

During the summer of 1964 two recording units were used. One was a six-channel 7000 B seismic system manufactured by Texas Instruments, Inc. with 4.5 cps geophones from Hall Sears, Inc. This unit was loaned by L. C. Pakiser of the U. S. Geological Survey. The spread used with this unit was 8200 ft long. The second unit consisted of twelve-channel amplifiers made by Southwestern Industrial Electronics (Model GA-33D) and geophones having a natural frequency of 4.5 cps from Hall Sears, Inc. This SIE recording unit was used with 2200 to 4600 ft spreads.

The recording instrumentation used during the 1965 field season consisted of a 24-channel amplified unit (Model GA-33D) made by the Southwestern Industrial Electronics Company and a 4600-ft spread composed of 24 geophones having a natural frequency of one or two cps from Hall Sears, Inc.

The latter recording setup proved to be the most efficient for our reconnaissance survey.

Radio transcievers manufactured by the General Radio-Telephone Company (Model VS-4) were used for communication and transmission of the shot instant. Shot times were estimated to have an accuracy of $\pm$ 0.002 sec for close shots and $\pm$ 0.005 sec for distant shots.

B. Seismic Energy Sources

Two types of explosive were used during the field work: Giant Petrogel (60% gelatin dynamite) in 1964 and Nitramon S-EL manufactured by Dupont de Nemours and Co. in 1965.

In order to get the maximum possible information in areas where drilling conditions were poor, shots in hot springs and in the air were used as means of converting energy to seismic waves. Shot holes drilled by hand or dug with shovels were not efficient.

Twenty-one shot holes were drilled with a rotary drill in the central part of the valley where the water table was near the surface. The drilling was easy but the use of drilling mud was necessary to prevent cave-ins. These shot holes, from 25 to 100 ft deep, provided excellent energy coupling and were used as many as three times. They were located at both ends of the longest profiles where suspended shots would have a poor shot efficiency. Charges up to 130 lbs were required for these distant shots. Those shots in hot springs were fired under 5 to 30 ft of water and had a good energy coupling.

An attempt was made during the first field season to obtain information on the attitude of the bedrock under the high alluvial fans near the mountain fronts. Shots were fired in 20-ft holes drilled in bedrock and recorded in the valley at distances of 2000 to 15,000 ft. The efficiency of these shots was very poor.

Since it is impossible to obtain a satisfactory shot hole in the poorly sorted debris and large boulders of the high and low alluvial fans, air shooting, a technique adopted by Buffet and Layat (1960) for refraction work in the Sahara, was used extensively. Buffet and Layat studied the influence of different parameters on the shot efficiency for small (less than 50 lbs) suspended charges. Their conclusions were extended to total charges as high as 180 lbs, and the following shot pattern was adopted: an individual charge of 20 lbs was fixed on a wood lath at the top of a 7-ft high steel post. For large shots, the 20-lb charges were positioned approximately 50 ft from each other in triangular or hexagonal patterns, similar to those used by T. C. Poulter (1950).

Air shooting was also successfully used in the central part of the valley at all shot points whose distances from the spread were less than 14,000 ft, and on the west side of the Humboldt Salt Marsh where the ground surface could not support drilling equipment. In the latter area, good first breaks from air shots with offset distances as great as 29,000 ft from both sides of the spread were recorded. Figure 5 shows how the total charge size of air shots was increased as the shot point was moved away from the end of the spread.

Energy coupling was better on the salt marsh, where the water table was near the surface, than on the high alluvial fans. This observation may be specific to the area under consideration, since Buffet and Layat (1960) observed the opposite in the Sahara.

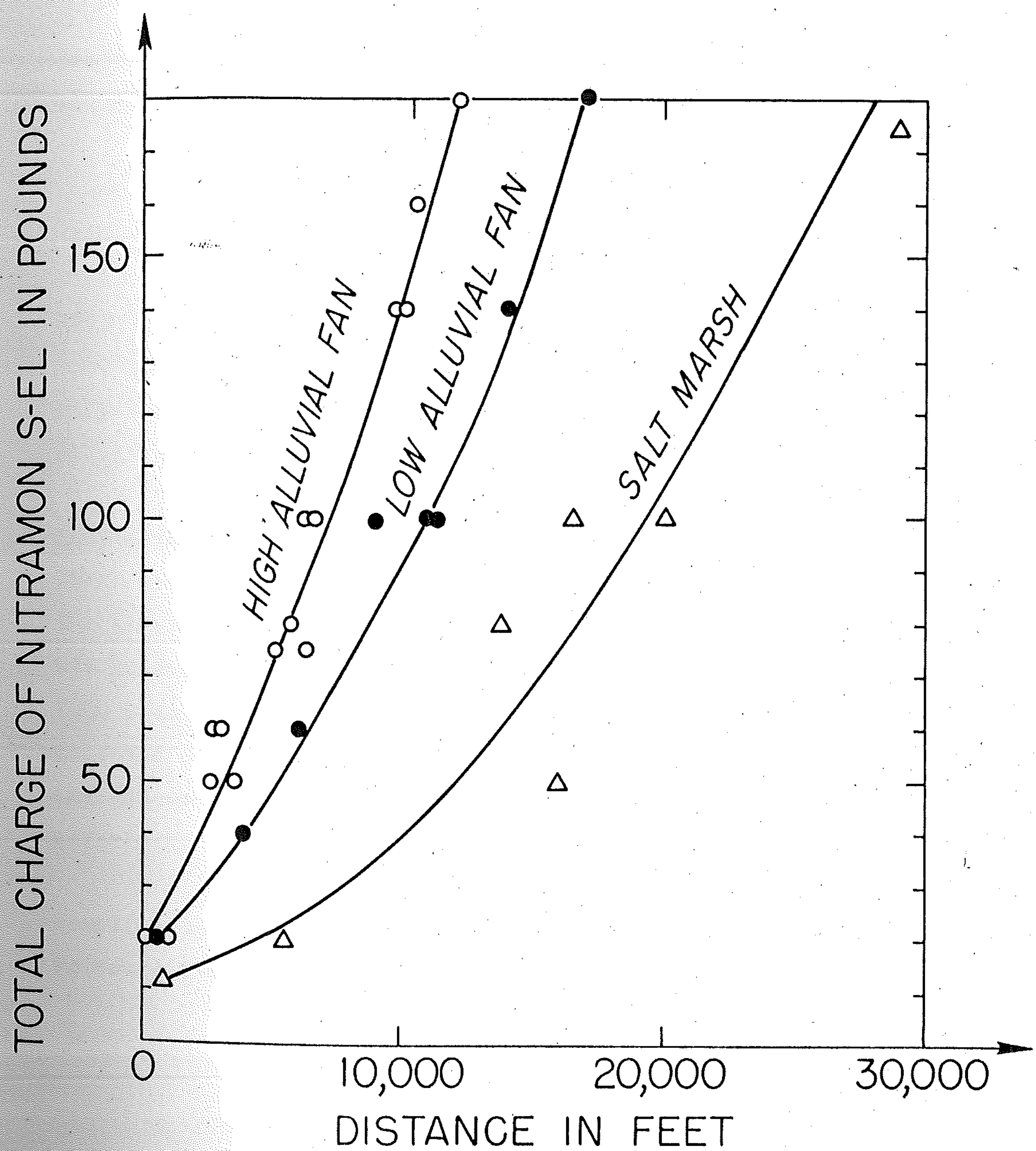

Figure 5. Total charge required for good record quality as a function of distance between shot and end of seismic spread.

V. SEISMIC RELECTION RESULTS

At the beginning of the 1964 field season an evaluation of the reflection technique was attempted in an area three miles east of the west end of profile 4 (Fig. 9), where the water table was shallow and the basement was expected to be deep. Ten-foot holes were drilled with a hand auger and small charges were used. The recording instrument was the 12-channel SIE seismic system with 35 cps geophones.

The only good and consistent events observed arrived at about 0.680 sec. This reflection corresponds to a horizon 2200 ft deep associated with the shallowest volcanic flow of the upper part of the Miocene to Pleistocene section. The fact that this horizon is situated at about the same depth as the 10,000 ft/sec velocity zone of profile 4, may confirm the assumption made later in this study that the apparent velocity of 13,000 ft/sec observed in this area by refraction is due to an east sloping 10,000 ft/sec velocity zone.

A combination of reflection and refraction techniques was also tried during the 1964 field season. Each time a shot was fired in one of the six 50-ft shot holes drilled in the center of the valley; two units were recording. The 12-channel SIE seismic system, set up near the shot point, recorded possible reflections from horizons deeper than the volcanic flows; the 6-channel 7000 B seismic system, located some distance away from the shot point, recorded energy refracted fron some horizon inside the sedimentary section. Charges as heavy as 50 lbs were fired, but no coherent event which could be correlated with a bedrock reflection was recognized.

It is concluded that larger charges of explosives in deeper holes or complicated patterns of suspended shots are needed in order to by-pass the volcanic flows and record reflections from the basement.

VI. REDUCTION OF DATA AND INTERPRETATION

The method of refraction profiling which proved to be efficient for previous reconnaissances of basin structures (Pakiser, Press, and Kane, 1960; Kane and Pakiser, 1961; Pakiser and Kane, 1963; Kovach, Allen, and Press, 1962; Zbur, 1963; Healy and Press, 1964) was used. The geophone spread was held fixed and the shot points were moved away from both ends of the spread to distances as great as 30,000 ft.

The seismic velocity layering beneath the geophone spread was determined with this technique by applying the usual assumptions pertinent to seismic refraction computations. In order to extend this information along the entire profile the following additional assumption was made: when the same apparent velocity of first arrivals across the spread came from two successive shots situated on the same side of the spread, it was assumed that the seismic energy was refracted from the same interface below the spread. As the Miocene to Pleistocene section is composed of numerous volcanic flows interbedded in non-marine sediments such a hypothesis may be unlikely and furthermore numerous small velocity reversals may be present. Nevertheless it is the only way one can obtain additional control on the depths and attitudes of the different velocity layers between the spread and the different shot points.

The apparent velocities observed from shots lying on one side of the spread were associated with reversed apparent velocities obtained from shots fired on the other side of the spread to give a true velocity section beneath the spread. When a new velocity zone was observed a corresponding average depth was computed by the conventional intercept time method (Nettleton, 1940). This depth was assigned to the part of the profile between the spread and the shot point and is called the normal depth.

If the same apparent velocity was observed from a more distance shot-point the geophone delay time corresponding to the normal depth previously determined was subtracted from the new intercept time to yield a shot point delay time. For conversion of this last delay time into depth, the velocity layering above the refractor at the shot point had to be known. The velocity layering under the spread was assumed to be continuous under the entire profile, unless additional information on the shot point area was available from another profile.

The position and depth of the refractor corresponding to a given delay time is represented on each seismic cross-section by a short line without continuity, since the information is valid only at this point. All dashed lines on the sections represent velocity layering assumptions. When velocity reversals are expected in the sedimentary section the range of uncertainty of the position of the basement is represented by shaded zones on the seismic cross-sections.

The preceding conclusions are well-grounded only if there are no horizontal velocity variations along the refractor.

Depths to seismic discontinuities along the profile can also be obtained by making use of the reciprocity principle (Ewing et al., 1937, Dix, 1952 p. 263). The apparent velocity measured for a given layer at the spread is compared with the apparent velocity obtained by plotting a travel time curve for which the shot points whose energy was refracted from this layer are considered as geophone locations and one of the geophones of the spread becomes the shot point. This last apparent velocity indicates the average dip of the interface between the two shot points. From the normal depth obtained at the shot point which is close to the spread, it is possible to compute a depth for the other shot point. Although the two methods are equivalent, the first has been used during the present study because no reciprocity principle must be assumed in its application.

The accuracy of the seismic refraction method has been studied in detail by Steinhart and Meyer (1961). They showed that it is difficult to obtain estimates of uncertainty for refraction depth calculations and even when obtained, these estimates may be suspect.

The interpretation of the data as presented in the following study is not unique and the model chosen to fit each set of travel time curves represents the simplest solution consistent with the seismic data and geology.

VII. ANALYSIS OF SEISMIC PROFILES

The location of the seismic profiles is shown on the geologic map (Fig. 2).

The major graben structures were initially assumed to be parallel to the physiographic trend of the valley with a corresponding thickening of the sedimentary section toward the center of the valley. Therefore it was considered illogical to make a classical interpretation of any transverse profile because of the lateral changes in velocity layering. Accordingly, three profiles were shot in a NNE-SSW direction (profiles 1-3) where only small lateral velocity changes were expected. This information was carried over to two sub-parallel transverse profiles (profiles 4 and 5). By delay time analysis, the transverse structure of the valley under Dixie Settlement was then determined.

Similarly, the information from profile 12, shot between Seven Devils and Boyer Ranch, was used for the analysis of the Boyer Ranch profile shot across the west side of the valley.

PROFILE 1: West Road Profile

The West Road profile was shot in a north-south direction on the west side of the valley along the main road of Dixie Valley. Recordings were made on three 4600-ft geophone spreads. The only air shots along this profile were S4 and S2; two shots were fired in most of the drilled holes. The travel-time curves and the seismic cross-section corresponding to the West Road profile are shown in Fig. 6.

All times were corrected to a 3500-ft datum. The superficial velocity of 5200 ft/sec was taken from Table 1 and corresponds to that measured in sediments lying below the water table.

Below the 6300 ft/sec layer an 8000 ft/sec layer was observed which was based on distinct breaks in the travel time curve. The horizontality and continuity to the south of the 10,000 ft/sec layer are controlled by the two geophone setups B9 and B11. It is assumed that this layer is also continuous to the north. The two apparent velocities 14,000 ft/sec and 17,000 ft/sec recorded on spread B9 from shot points N3 and N4 respectively

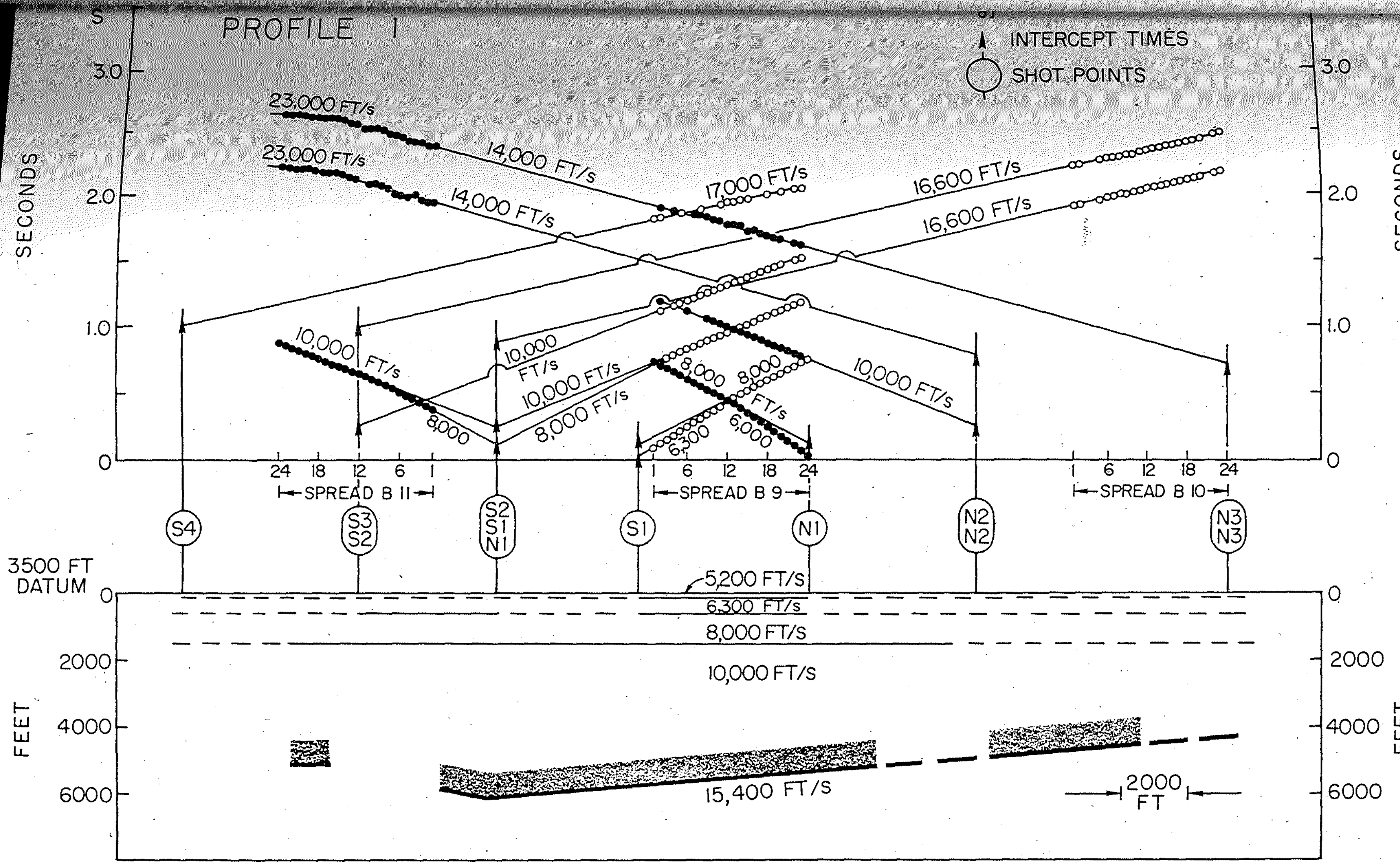

Figure 6. Time-distance curves and cross-section of the West Road Profile.

were correlated as down-dip and up-dip velocities of the bedrock with a calculated true velocity of 15,400 ft/sec.

The arrival times from the common shot point N3, which show an apparent speed of 14,000 ft/sec, on spread B11 line up with those of the wave refracted from the basement on spread B9. This alignment of arrival times proves that the basement can be represented between B9 and B11 by a plane dipping 4 degrees to the south. The normal depth to bedrock was computed using formulas for a dipping layer for the part of the profile between spread B11 and shot point N2.

The apparent speed of 16,600 ft/sec observed across spread B10 and the corresponding geophone delay time, show that the attitude of the basement between shot points N2 and N3 is in continuity with the one deduced from the observations made on spreads B6 and B11. The apparent velocity of 23,000 ft/sec which was observed across spread B11 was associated with a change in dip of the basement.

The seismic energy of shot S4 is believed to have been laterally refracted from bedrock at the Stillwater Range which is only 6000 ft west of the southern end of the profile. The information obtained from this shot completes the detailed study of Herring (1966) and determines the attitude of the basement at the eastern side of the cross-section shown in Fig. 21.

The line at the bottom of the shaded zone on Fig. 6 is the position of the pre-Tertiary bedrock as computed on the assumption that the 10,000 ft/sec layer continues downward to the 15,400 ft/sec basement. If the 10,000 ft/sec layer is only a thin high-velocity zone within the 8000 ft/sec layer, the basement could be as shallow as the top of the shaded zone. Since a 13,000 to 14,000 ft/sec layer was observed to exist between the 10,000 ft/sec layer and the basement in several places in the valley, a similar layer may exist along this profile as a blind zone. If that is the case, the calculated depth to the 15,400 ft/sec layer would be increased. The uniform velocity of 10,000 ft/sec assigned to the layer just above the basement can therefore be regarded as an average for a heterogeneous sedimentary section containing small velocity reversals and high velocity blind zones. Consequently the dark line on Figure 6 and on all following cross-sections represents the most reasonable attitude of the pre-Tertiary bedrock.

PROFILE 2: Central Road Profile

Seismic profile 2 (Fig. 7) was shot along a NNE-SSW trending road in the central part of the valley just south of Dixie Settlement. We recorded on a 4600-ft spread; shots N4 and S5 were fired in drilled holes; the other shots, in the air.

A water table velocity of 5000 ft/sec was assumed in order to compute a depth for the 6400 ft/sec velocity layer using intercept times at shot points S1 and N1. A velocity of 8600 ft/sec for the third layer was computed from the two apparent velocities, 8700 ft/sec and 8500 ft/sec.

The slight northward dip of the 8600 ft/sec interface under the spread is consistent with an abrupt increase in shot point delay time between N2 and N3, which was interpreted as a down-drop of the 8600 ft/sec velocity boundary and a consequent thickening of the 6400 ft/sec layer.

Constant thickness was assumed for the 8600 ft/sec layer under both shot point and spread, in order to calculate depths to the 10,000 ft/sec layer from the intercept time of the corresponding segment of the time-distance curve at shot point N3. This layer is a blind zone for the refracted arrivals from shot point S3.

The depth to the 16,000 ft/sec bedrock was computed from the intercept time at shot point S3.

The 25 msec offsets in the basement arrivals from shot points S4 and S5 were associated with a fault which uplifts the southern bedrock block about 350 ft. Depths to basement at shot points S4 and N4 were computed assuming continuity of the 10,000 ft/sec velocity layer from S1 to S4 and from N3 to N4 respectively. If the 10,000 ft/sec velocity layer proved to be thin, the basement would be about 500 ft shallower.

The apparent velocities observed along profiles 8 and 9 show a velocity layer between the 10,000 ft/sec layer and the basement. From the information of profile 8 and with the assumption of a true speed of 13,000 ft/sec, this layer should be about 4900 ft deep at the south end of profile 2. This information was carried over to the latter profile and yielded a maximum depth to bedrock of 6600 ft near shot point S5 (lower boundary of the shaded area in Fig. 7).

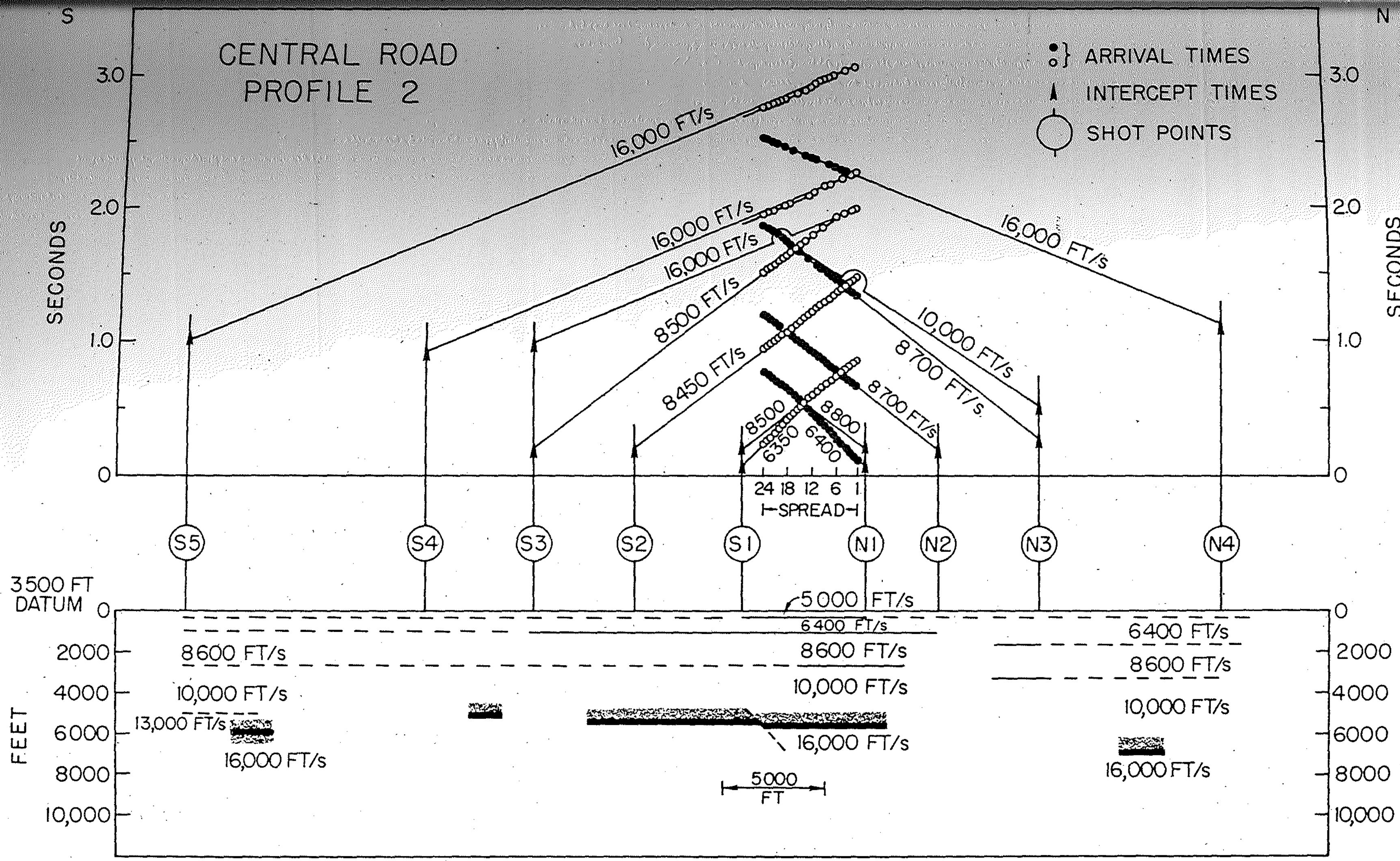

Figure 7. Time-distance curves and cross-section of the Central Road Profile.

PROFILE 3: IXL Canyon Profile

The main purpose of the IXL Canyon profile (Fig.8) was to test the efficiency of the air shooting technique on high alluvial fans. The profile was shot in a N-S direction one-half mile east from the mouth of IXL Canyon. The total length of this refraction line was 14,000 ft and the maximum average velocity observed was 11,300 ft/sec. No basement arrivals were recorded along the 2200 ft spread.

The gradual increase in velocity with depth from 5000 ft/sec to 11,300 ft/sec was conventionally interpreted as two velocity layers of 8000 ft/sec and 9300 ft/sec. The normal depth to the 11,300 ft/sec velocity boundary was computed from the intercept time at shot point N3. From the shot point delay times associated with the shots N4, N5, and S4 we deduced a down-drop of the 11,300 ft/sec horizon in the northern part of the profile and a rise of this same velocity boundary at the southern end of the profile.

The only control on superficial layering along the refraction lines of this entire study was obtained under the geophone spreads and this information was extrapolated to the entire profile. Any change in shot point delay time was then associated with a change in basement depth. But the profile 3 data show the existence of important structural features in velocity boundaries within the Cenozoic sedimentary section.

Therefore, with the assumption of continuity of these horizons, false structures may have been introduced in the basement. Consequently the structures of the 11,300 ft/sec horizon along this profile could also have been exaggerated by the assumption of continuity of the 5000 and 8000 ft/sec velocity layers.

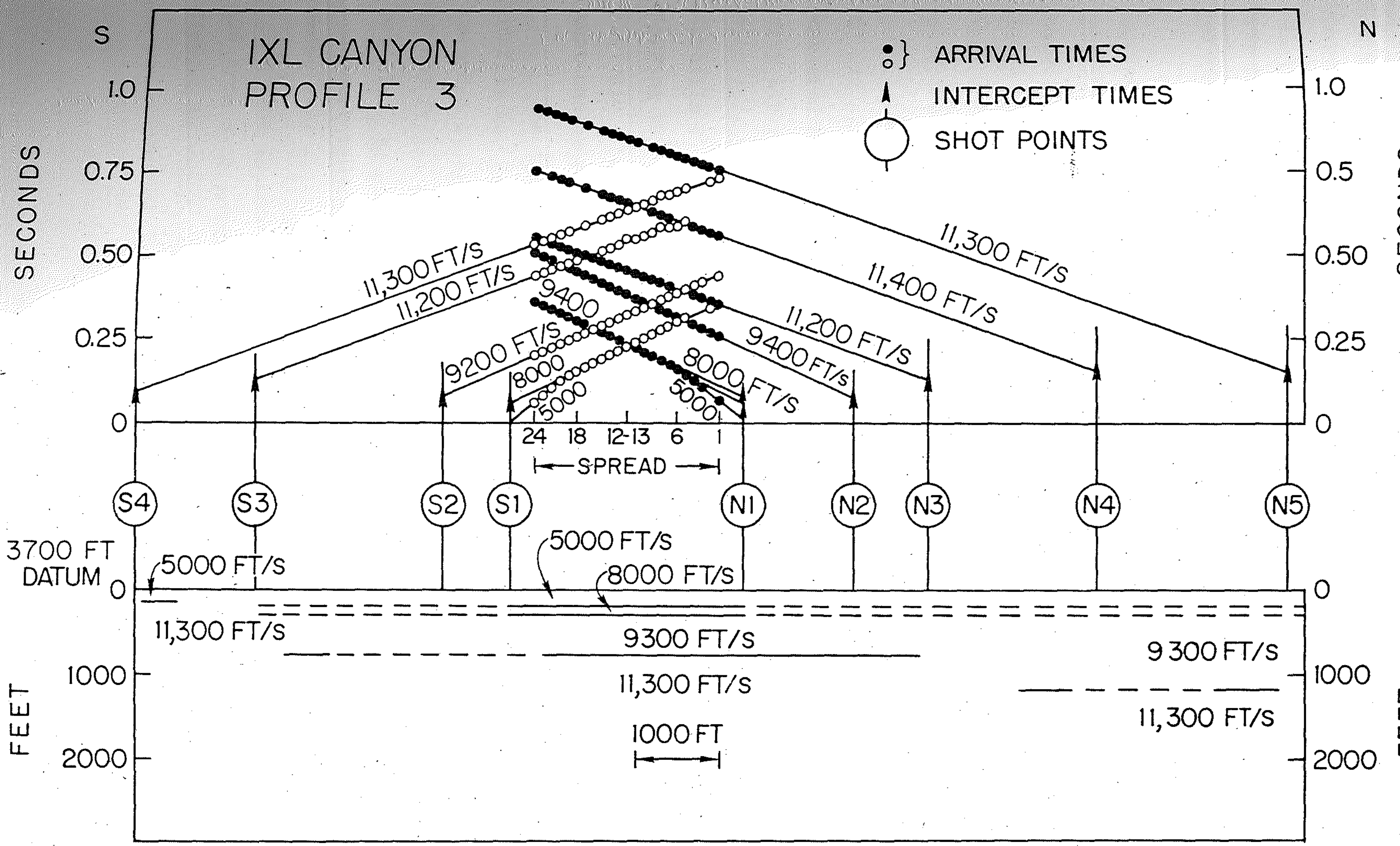

Figure 8. Time-distance curves and cross-section of the IXL Canyon Profile.

PROFILE 4: Crazy K Ranch Profile

Profiles 4 and 5 are the two E-W trending refraction lines across Dixie Settlement. They have shot point DP in common. The western end of profile 4 crosses the West Road profile at the northern end of spread B10, and the western end of profile 5 intersects the same line at shot point N1. The travel time curves for both profiles were corrected to allow for the slight offset of the shot points with respect to the general direction of the profiles.

The Crazy K Ranch profile (Fig. 9) consists of four individual spreads. On each setup energy arrivals were recorded from shots fired at point DP. All data were corrected to a 3500 ft datum. The superficial velocity of 5000 ft/sec represents an average of all speeds measured near Dixie Settlement in connection with the hydrogeologic study. In making the calculations it was assumed that this velocity is constant along the profile.

The depth to the 6000 ft/sec velocity layer determined under spread D3 was extended to the east. The apparent velocity of 8300 ft/sec measured along the D3 geophone setup was associated with a horizontal velocity layer whose lower boundary extended to the west to shot point CR. The 8500 ft/sec segment recorded on spread A105 from shot point 4 was correlated (profile 5) as an apparent up-dip velocity, with the 11,500 ft/sec layer dipping 10^{o} to the west. This interpretation was preferred, primarily on geologic grounds, to the alternate interpretation based on the assumption that the apparent velocities were true velocities of horizontal layers.

The information obtained in the northern part of the West Road profile was carried over under spread B14. The 10,000 ft/sec segment recorded along B14 from shot point CR was assumed to be refracted from the 10,000 ft/sec velocity layer determined under spread B9 of the West Road profile. By subtracting the corresponding geophone delay time from the intercept time at shot point CR, the depth to the 10,000 ft/sec boundary under shot point CR was obtained.

The 13,000 ft/sec apparent velocity recorded along spreads A26 and A34 from shot point DP can be interpreted as a down-dip velocity of a west-dipping basement, as a true velocity of a horizonal velocity layer, or as

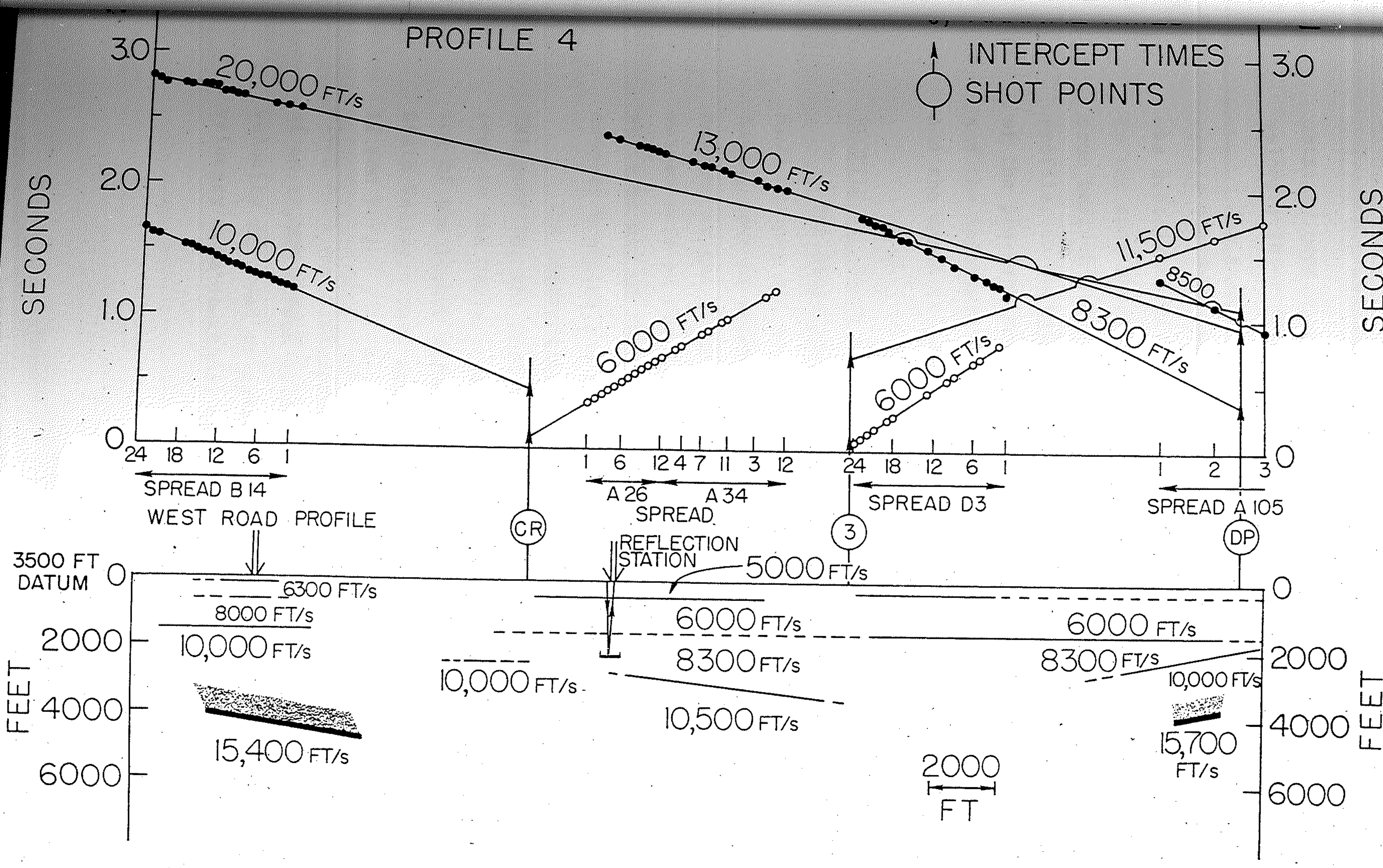

Figure 9. Time-distance curves and cross-section of the Crazy K Ranch Profile.

an up-dip velocity of a 10,500 ft/sec layer. The latter alternative seems to be the most probable since similar apparent velocities were recorded along the west side of profile 5 where a deepening of the 10,000 ft/sec horizon was observed from the data of profiles 1 and 3. All reflections obtained east of Crazy K Ranch came from the top of the 10,000 ft/sec velocity layer (Fig. 9).

The sole arrivals refracted from the basement were recorded along spread B14 from shot point DP. The apparent velocity of 20,000 ft/sec was associated with a 15,400 ft/sec basement with an apparent dip of 10° to the east whose depth was determined from the West Road profile. As a true bedrock velocity of 16,000 ft/sec was observed along the Central Road profile, an average velocity of 15,700 ft/sec was used as characteristic of the pre-Tertiary basement below Dixie Settlement. This average speed and the information under spread B14 yield a delay time at shot point DP and the depth to basement at this point.

PROFILE 5: Dixie Profile

The Dixie profile (Fig. 10) consisted of six spreads which were 8200 ft long and composed of six geophones each. All shots were fired in holes, four of which were drilled in valley sediments and one in granitic bedrock at the mouth of IXL Canyon. The energy from shots fired in welded tuff at Cow Canyon, which would have completed the information at the east end of this profile, was presumably absorbed in concealed low-density breccias and ash beds which underlie the welded tuff.

The information on superficial velocity layering obtained from the IXL profile, the West Road profile and the Central Road profile was carried over to the Dixie profile. These three north-south profiles show a deepening of the 10,000 ft/sec horizon from the west side towards the center of Dixie Valley. This suggests that the most plausible interpretation of the 12,800 ft/sec segments and the 8000 to 10,000 ft/sec segments recorded along A101 and A102 spreads is to associate them with apparent velocities of an 11,000 ft/sec velocity layer dipping to the east. The 12,700 ft/sec velocity recorded on spread A103 suggests that this 10,500 to 11,300 ft/sec velocity zone continues toward the center of the valley. Because of the

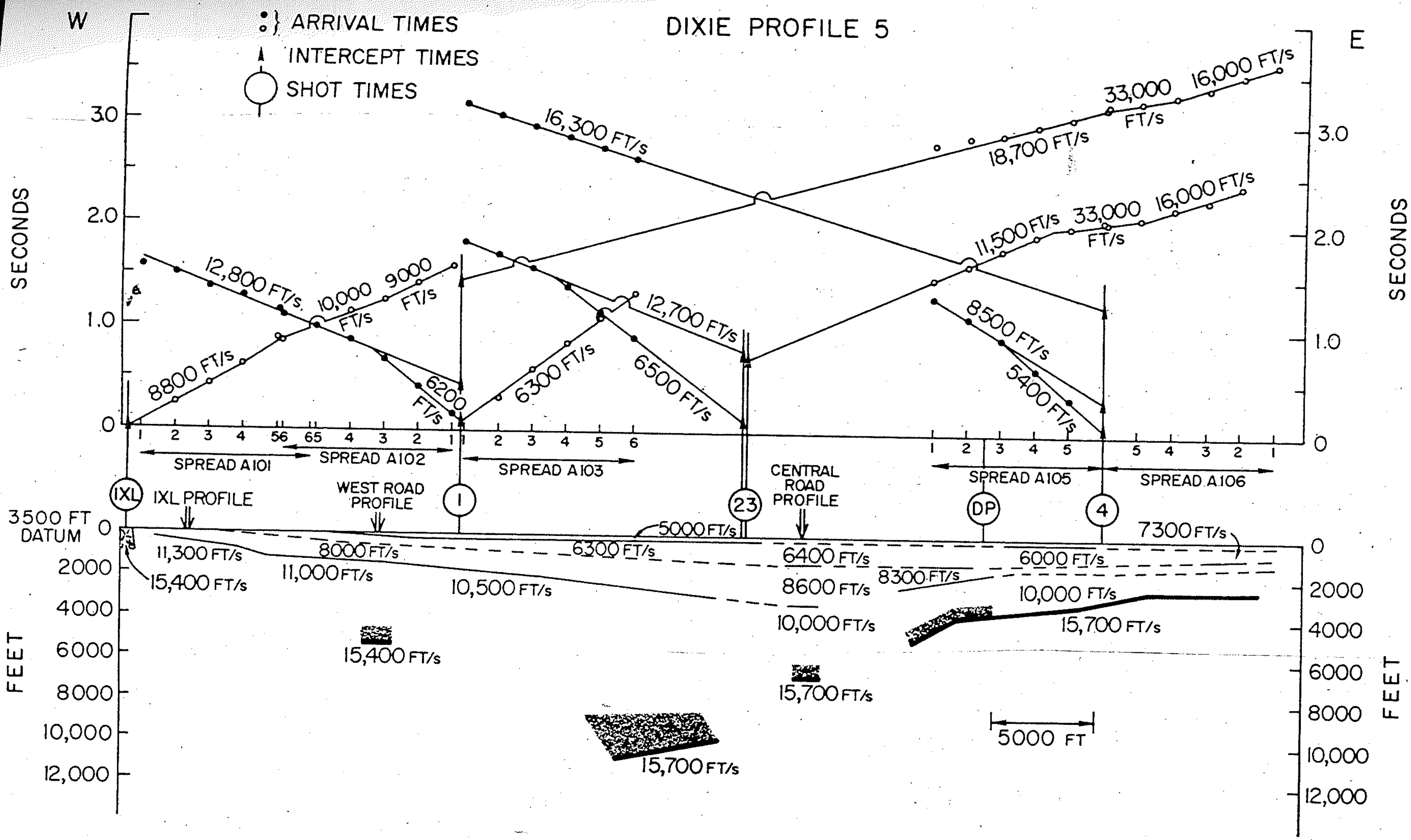

Figure 10. Time-distance curves and cross-section of the Dixie Profile.

similarity with the west side, the 11,500 ft/sec and the 8500 ft/sec velocities recorded on spread A105 were assumed to be apparent velocities of a 10,000 ft/sec velocity boundary dipping west.

All velocities higher than 15,000 ft/sec observed along Dixie profile were interpreted as basement refractions. An average basement velocity of 15,700 ft/sec was assumed for the depth computations using delay times. As the depth to bedrock under shot point DP was determined from the profile 4 data, a geophone delay time could be computed for spread A105. From the 18,700 ft/sec velocity segment recorded on the same spread from shot point 1, a delay time was determined at this point. The corresponding depth to basement is 10,500 ft if there are no velocity reversals in the 10,500 ft/sec velocity layer; it is the maximum depth measured during the survey.

The apparent basement velocity of 16,300 ft/sec recorded on A103 corresponds to a basement dipping to the west rather than to the east. This slope of the bedrock is due to the fact that the delay time is increased by the thickening of the 6,300 ft/sec and the 8000 ft/sec velocity layers toward the center of the valley. Depths to the 15,700 ft/sec layer under spread A106 and under shot point 3 were similarly computed.

The velocity layering beneath the geophone spread A106 was assumed to be similar to the one measured under the East Road profile (Fig. 12). A horizontal basement in the north-south direction under Dixie Settlement is indicated by the equality of the delay times at shot point N4 of the Central Road profile and shot point 3 of the Dixie profile.

PROFILE 6: Dixie Meadows Profile

The Dixie Meadows profile (Fig. 11) was shot about three miles north of West Road profile along the main north-south road on the west side of Dixie Valley. Conventional refraction techniques were used: three shots were fired in the same hot spring and the seismometer spread was moved away from the shot point.

The shallow velocity structure at the south end of the profile was determined from spread E50 data. This velocity layering is similar to that determined beneath the Salt Marsh profile (Fig. 15), which is situated

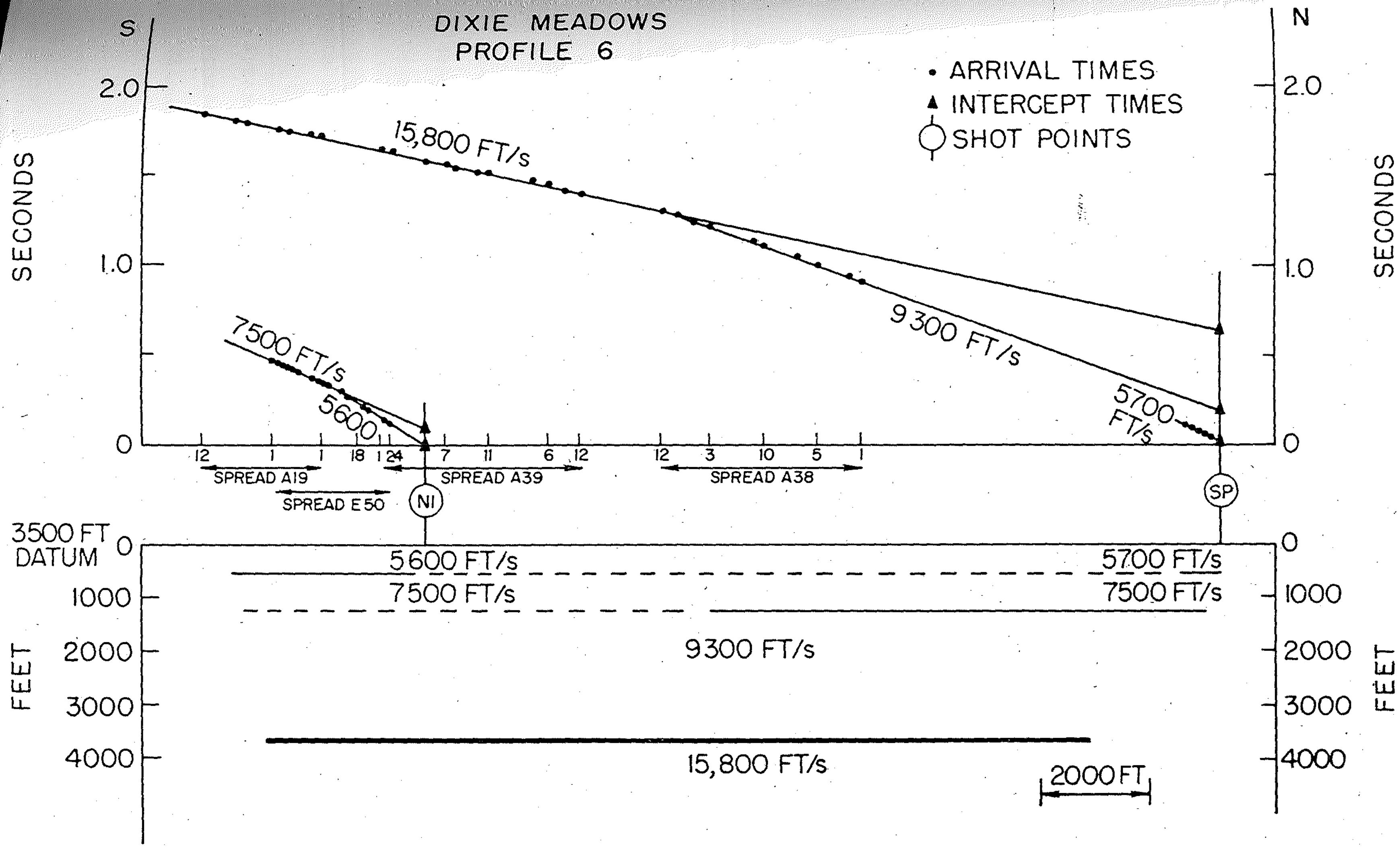

Figure 11. Time-distance curves and cross-section of the Dixie Meadows Profile.

along the west side of Humboldt Salt Marsh, as is shot point SP. Despite the difference in surface conditions between the northern and southern part of the Dixie Meadows profile, a similarity in seismic velocity layering justifies the assumption that the lateral velocity changes along this profile are small.

Since no reversal data were obtained all observed velocities were assumed to be true velocities. The depths of the three horizontal velocity boundaries were determined by conventional intercept-time methods.

PROFILE 7: East Road Profile

Suspended air shots were used exclusively as sources of seismic energy for the East Road profile (Fig. 12). All data were reduced to a 3650-ft datum and the velocity of 5000 ft/sec for the surface layer was taken from Table 1. The velocity boundary between the 7300 and 8300 ft/sec layers was computed to be horizontal between shot points S3 and N3; this boundary was assumed to remain horizontal along the rest of the profile.

The true velocity of the 14,700 ft/sec layer was obtained from the association of the apparent velocity of 24,800 ft/sec recorded from shot point S3 with the 11,000 ft/sec recorded from shot point N4. The attitude of the 14,700 ft/sec layer in the central part of the profile was determined from the intercept time of the 11,000 ft/sec velocity segment at shot point N3; the depth of this same layer below shot points S3, S4, N4, and N5 was determined from the delay times associated with these points.

PROFILE 8: Horse Creek Profile

Horse Creek profile was shot in an area where the gravity measurements (Thompson, 1966) suggested that the gravity low, associated with the deepest part of the graben around Dixie Settlement, is trending toward Horse Creek Canyon.

In order to minimize the weathering corrections all data were reduced to an inclined datum plane on the eastern side of the profile (Fig. 13).

The attitude of the 9300 ft/sec velocity layer below the geophone spread was determined from the intercept times of the 9700 and 8900 ft/sec apparent velocity segments and was assumed to be the same below shot points W2 and W3.

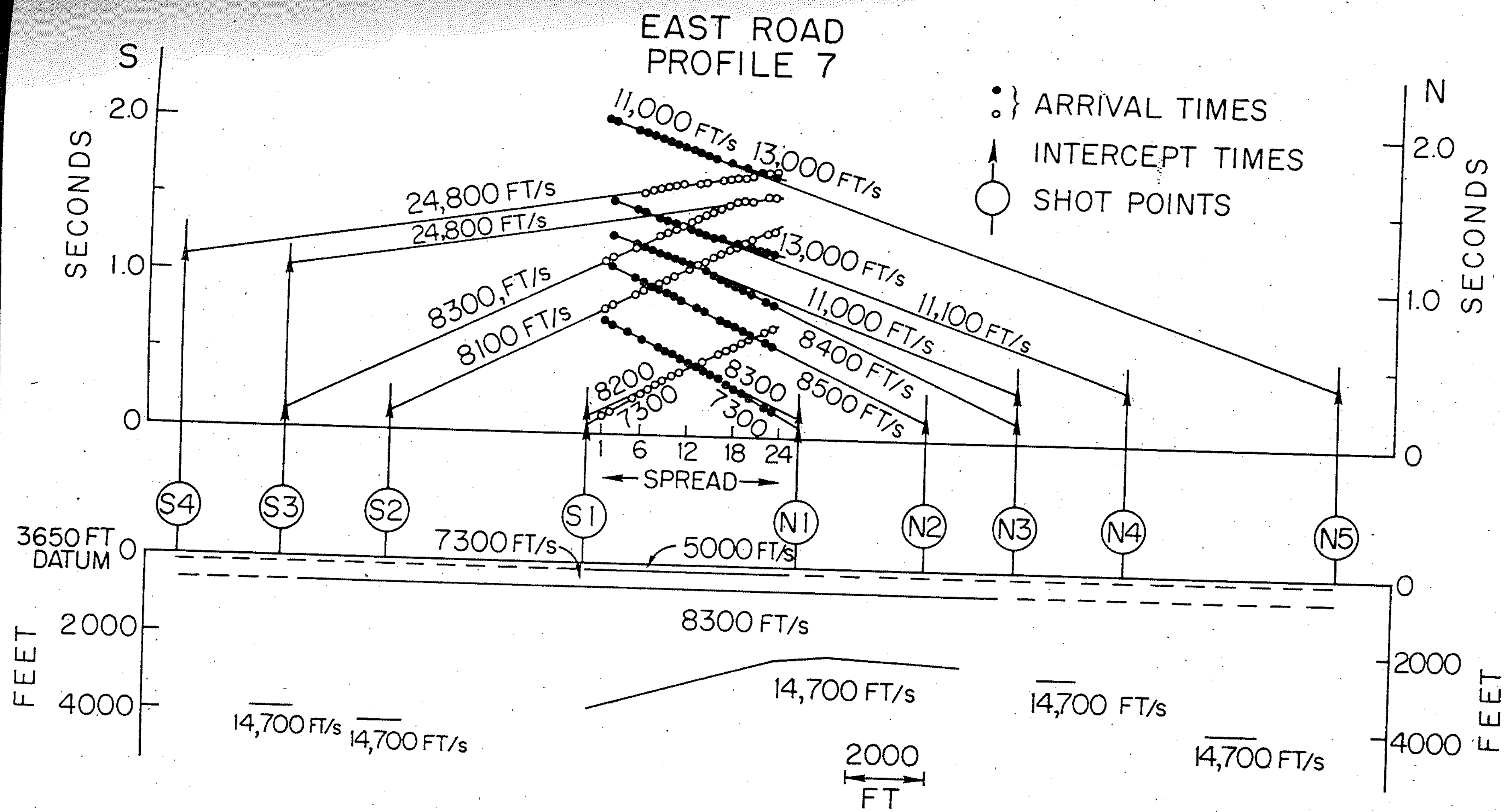

Figure 12. Time-distance curves and cross-section of the East Road Profile.

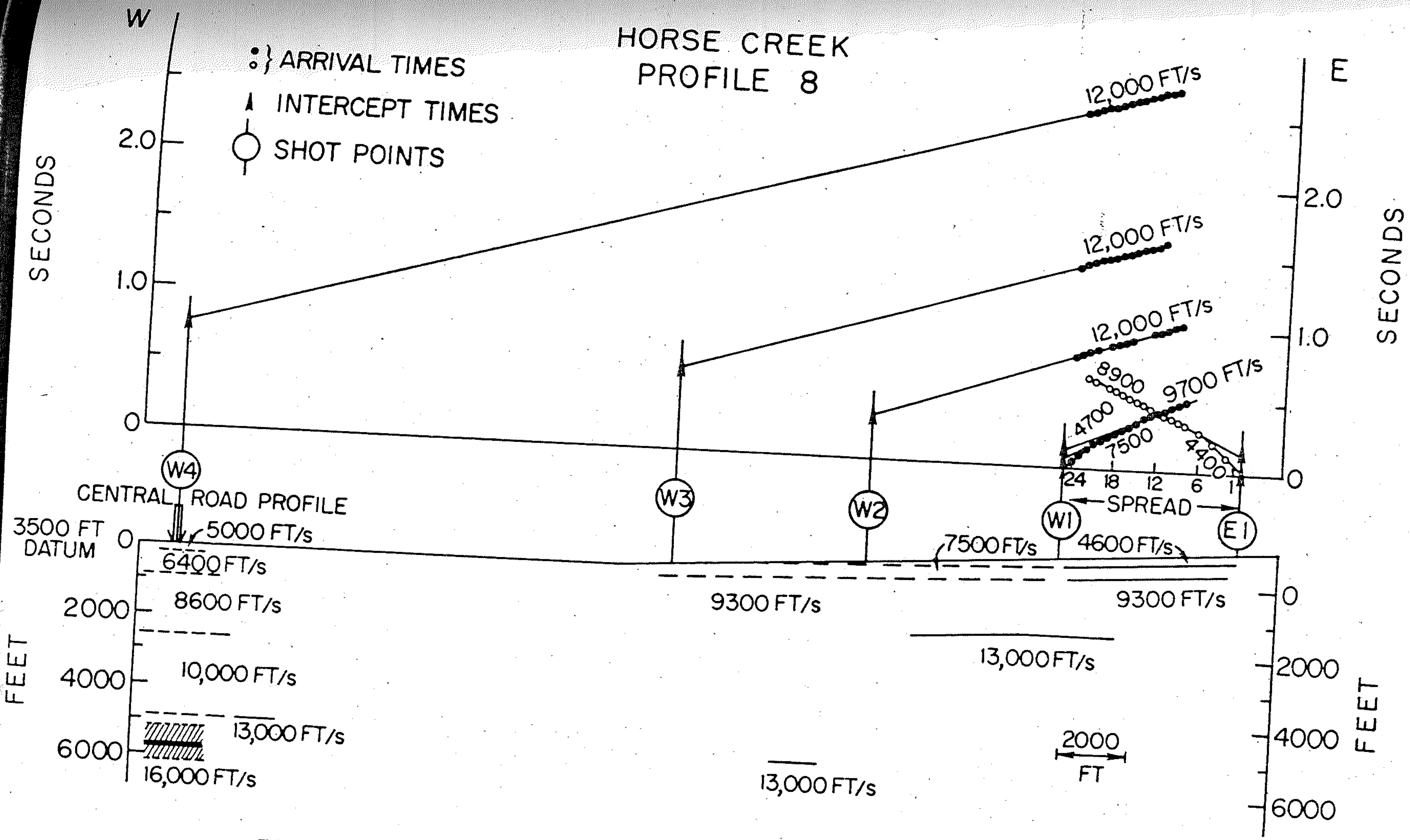

Figure 13. Time-distance curves and cross-section of the Horse Creek Profile.

The maximum apparent velocity recorded along Horse Creek profile was 12,000 ft/sec. In a first interpretation this velocity can be considered as the down-dip velocity of a portion of a 16,000 ft/sec basement dipping east. The delay time at shot point W4 would be about 0.2 sec larger than the one determined for this same shot point from the Central Road profile (Fig. 7), thus indicating a deepening of the valley floor to the east of W4 comparable to that observed along the Dixie profile (Fig. 9).

As the gravity gradient along the east side of the present profile (Thompson, 1966) indicates instead a west dipping basement, the following interpretation was preferred (Fig. 13): the 12,000 ft/sec apparent velocity is associated with an intermediate 13,000 ft/sec velocity zone situated between the 9300 ft/sec layer and the basement. Similar velocity zones were observed along Pirouette Mountain and East Road profiles (Fig. 14 and Fig. 12) and seem to be characteristic of the southern part of Dixie Valley. The normal depth to the 13,000 ft/sec layer is calculated from the intercept time of the 12,000 ft/sec segment at shot point W2. The depth below shot point W3 is computed from the increased delay time at this point and must be considered as a maximum since the continuity of the 9300 ft/sec layer is assumed across a discontinuity in the structure of the 13,000 ft/sec layer. An increase in depth of the 9300 ft/sec layer is more probable across this discontinuity; this increase would decrease the computed depth to the 13,000 ft/sec horizon. The superficial velocity layering determined along Central Road profile (Fig. 7) was used to compute the depth of this same horizon below shot point W4.

Since no basement refractions were observed, according to this last interpretation, the basement must be at least 6000 ft deep below the eastern end of Horse Creek profile.

PROFILE 9: Pirouette Mountain Profile

The shallow velocity layering below the 4600 ft spread of Pirouette Mountain profile (Fig. 14) was determined from the data recorded along this spread. The interpretation of the northern part of this profile was carried over from the Center Road profile (Fig. 7).

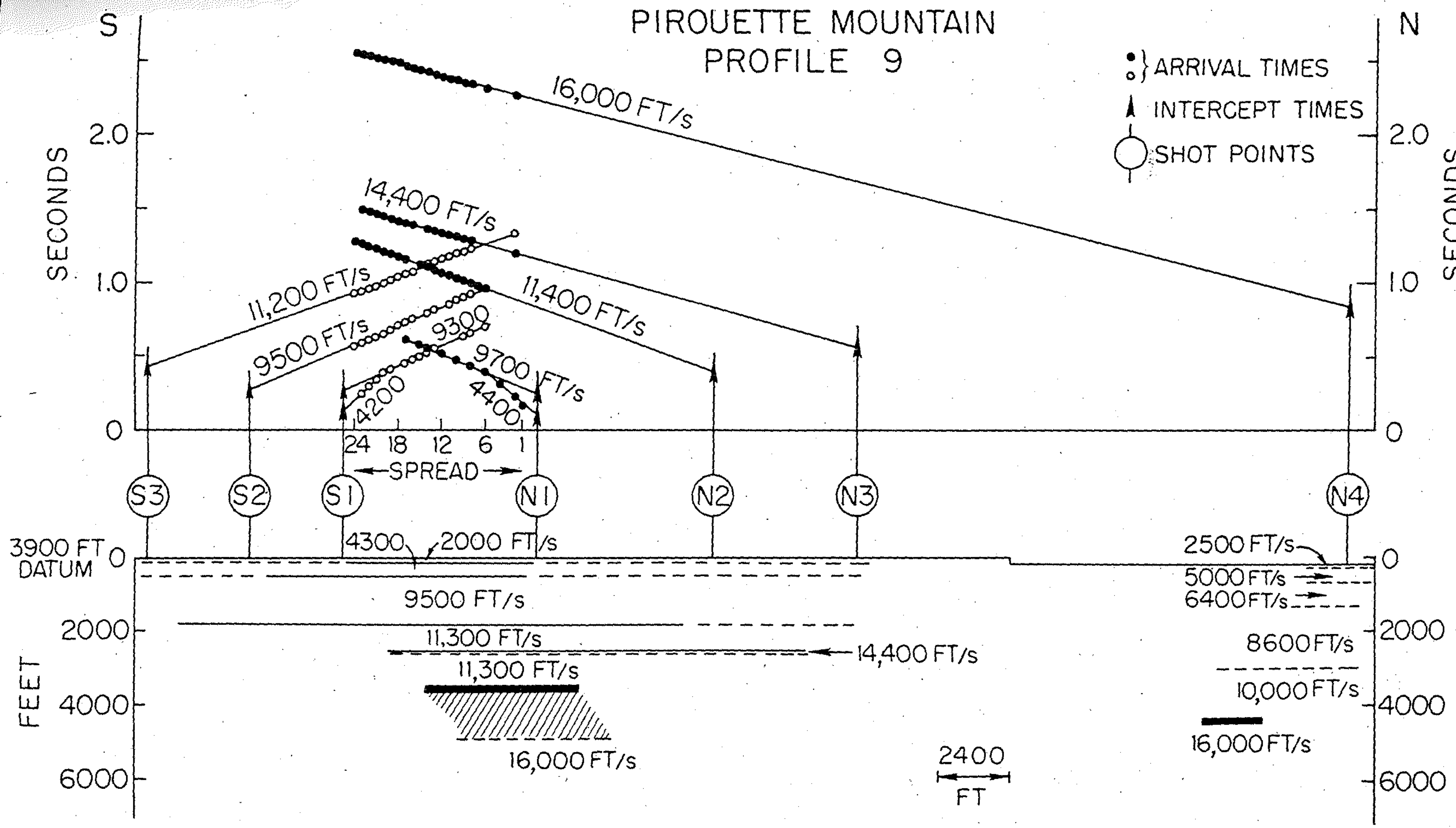

Figure 14. Time-distance curves and cross-section of the Pirouette Mountain Profile.

The attitude of the 11,300 ft/sec layer was determined from the intercept times of the 11,200 ft/sec and the 11,400 ft/sec segments at shot points S3 and N2. The small intercept time of the 14,400 ft/sec velocity segment at shot point N3 implies that part of the energy arrivals which form the 11,400 ft/sec velocity segment recorded from shot point N2 must be second events. No detectable arrivals refracted from the 14,400 ft/sec layer were received from shot point N2.

The apparent velocity of 16,000 ft/sec was assumed to be the true velocity of the basement below Pirouette Mountain profile. If the 14,400 ft/sec velocity segment represents only first arrivals, the 16,000 ft/sec layer must be at least 1000 ft below the 14,400 ft/sec layer in the southern part of the profile. From this minimum depth to basement (represented by a heavy line in Fig. 14) it is possible, through the intercept time at shot point N4, to determine a maximum depth to basement below this point. The 14,400 ft/sec layer was assumed to be thin in the previous calculation. In the absence of a velocity reversal below this layer, the basement may be as deep as the lower boundary of the shaded area in Fig. 14.

PROFILE 10: Salt Marsh Profile

Salt Marsh profile (Fig. 15) was shot along a 54,000-ft line oriented in a NNE-SSW direction on the west side of Humboldt Salt Marsh. Recordings were made on a single 4600-ft spread. Suspended air shots were used exclusively as sources of seismic energy. All data were reduced to a 3400-ft datum plane and the velocity of 4000 ft/sec for the surface layer was obtained from Table 1. Below this layer, velocities of 6100 ft/sec and 7600 ft/sec were measured and this layering was assumed to be continuous between shot points S4 and N2.

The velocity of 5700 ft/sec for the uppermost layer at shot point S5 was carried over from Dixie Meadows profile where this superficial layer was determined at shot point SP. The attitude of the 10,000 ft/sec layer is not well defined since only a small segment of the time distance curve obtained from shot N2 corresponds to this velocity. The attitude of the 9300 ft/sec layer from the Dixie Meadows profile was transferred to the area around shot point S5.

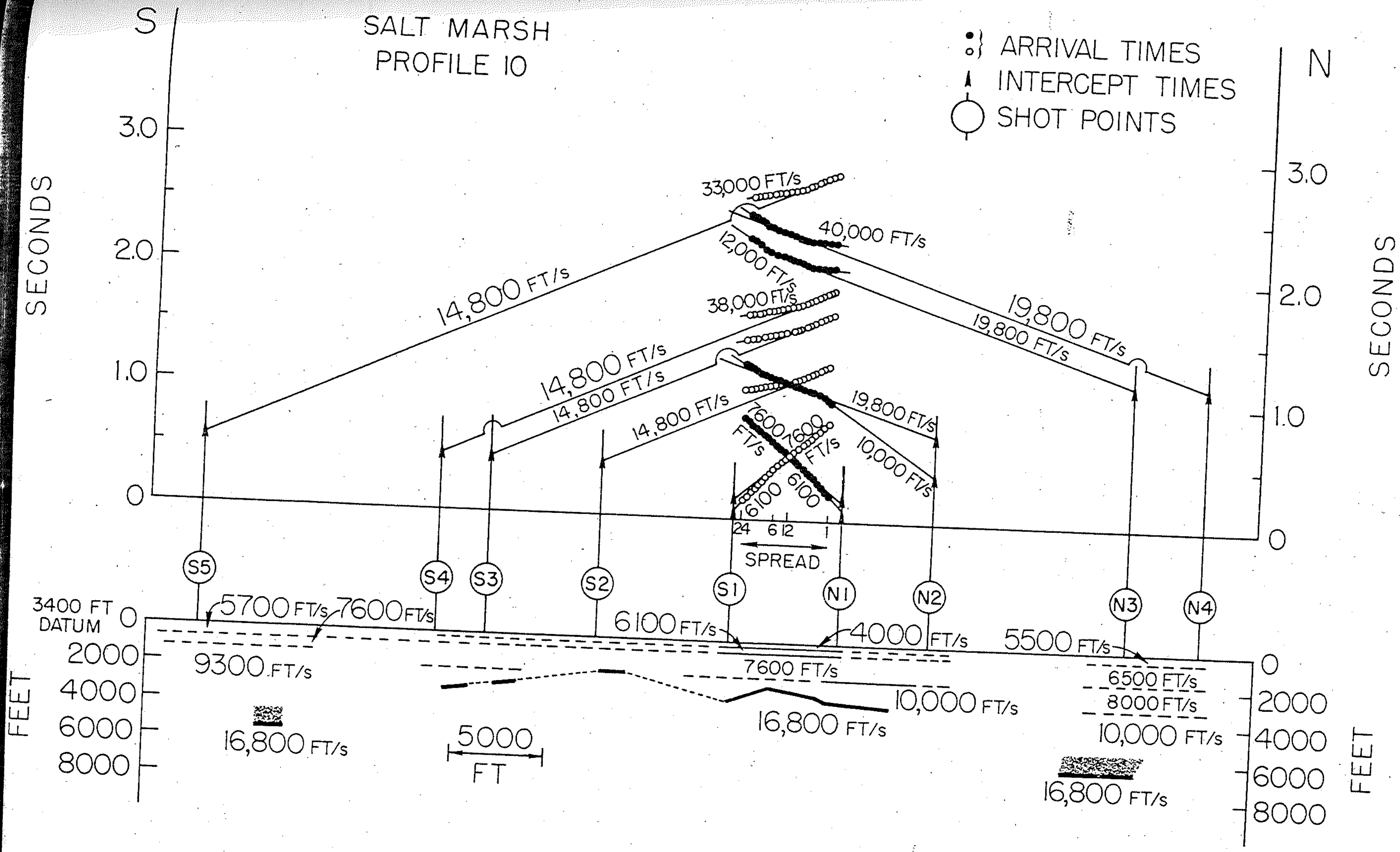

Figure 15. Time-distance curves and cross-section of the Salt Marsh Profile.

The apparent velocity of 19,800 ft/sec recorded from shot point N2 was associated with the 14,800 ft/sec velocity recorded from shot point S2 to yield a true basement velocity of 16,800 ft/sec. The normal depth to the 16,800 ft/sec layer was determined by correlating the 19,800 ft/sec velocity with a dipping plane solution between shot point N2 and the spread. Delay times related to all other shot points were computed on the assumption that the basement velocity is constant and equal to 16,800 ft/sec along the entire profile. Any lateral decrease in basement velocity will result in a decrease in computed depths to basement. Delay times at N3 and N4 are equal and are of the same order of magnitude as the one obtained for shot point 6 east of Boyer Ranch profile (Fig. 19). This indicates an abrupt deepening of the valley floor under N3 and N4 which must be accompanied with a change in superficial velocity layering. Consequently, the velocity distribution obtained for the eastern end of Boyer Ranch profile was used to compute the depths corresponding to the delay times of shot points N3 and N4.

A detailed layout of the Dixie Meadows and Salt Marsh profiles is shown in Fig. 16. Assuming basement continuity between shot points S4 and S1, a comparison of basement attitude determined between S4 and N2 with the corresponding distance of the Stillwater front to the profile, shows a striking similarity. This leads to the conclusion that the energy recorded along this profile is refracted from the east side of the Stillwater Range and that the front of the range must be continuous to the depth where side refraction takes place.

The interpretation of the Salt Marsh profile was made with the assumption that the ray paths are in the vertical plane of the profile. This vertical plane is represented by a dashed line in cross-section A-B of Fig. 16. The refractor is a plane perpendicular to this vertical plane through point N. The depth of this point was determined from the delay time associated with geophone 24 (Fig. 15). If the energy is side refracted, the refractor will lie tangent to the curve SN (cross-section AB of Fig. 16) which is the locus of points having the same geophone delay time.

Herring (1966) determined a parametric equation for this locus for a model formed by two horizontal layers bounded by a dipping high velocity

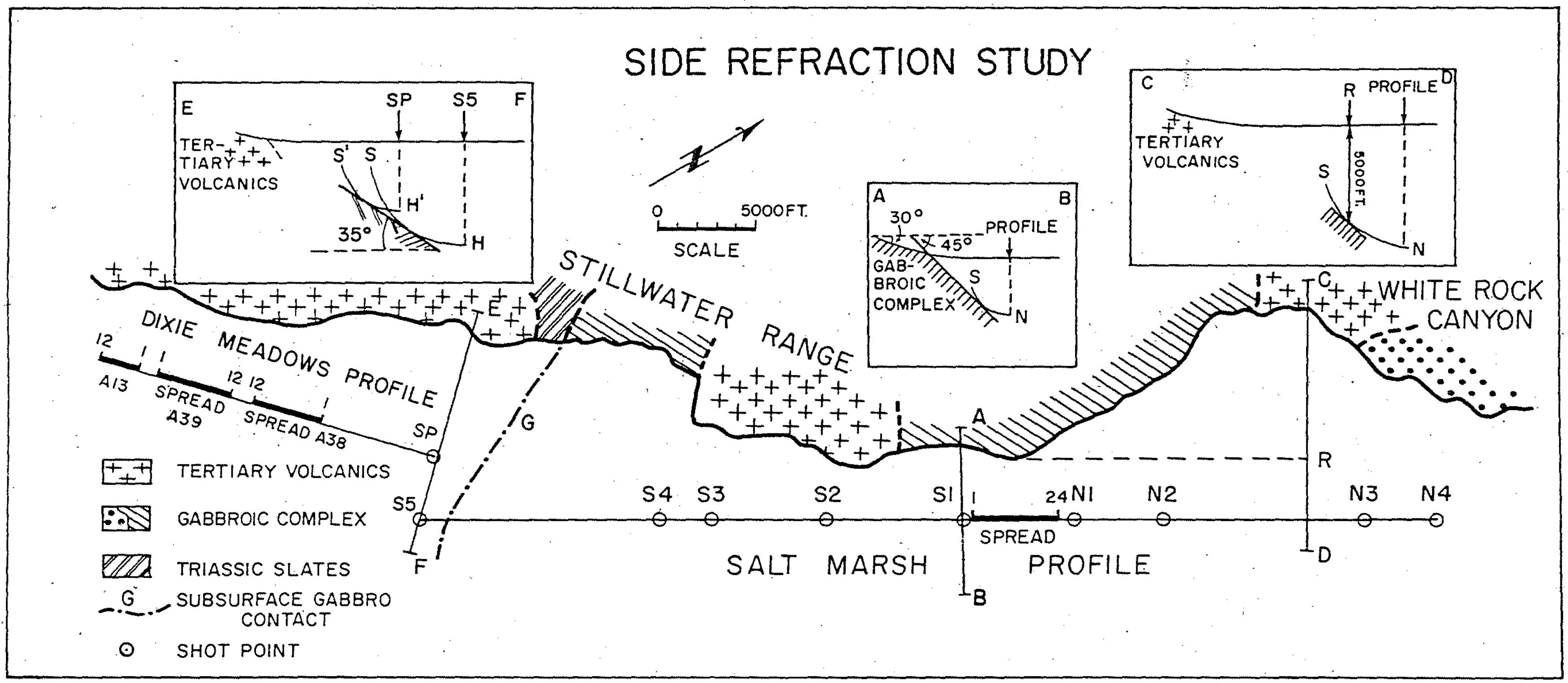

Figure 16. Detailed Map showing the layout of the Salt Marsh Profile and the Dixie Meadows Profile.

refractor whose strike is parallel to the line of the profile. All four side refraction curves SN shown in the three cross-sections of Fig. 16 were constructed by applying Herring's formula to the seismic data determined along the Salt Marsh and Dixie Meadows profiles.

Cross-section AB of Fig. 16 shows that the energy recorded at the geophone spread of the Salt Marsh profile is side refracted at a depth of 2500 ft from a plane dipping 45° to the east. The change from a topographic slope of 20° on the east side of the Stillwater Range to a bedrock dip of 45° beneath the alluvial fan supports the conclusion that this refracting surface is a fault zone rather than an erosional surface.

Cross-section CD shows that the basement is at least 5000 ft deep 1.5 miles southeast of White Rock Canyon. This reentrant of the Stillwater Range is therefore controlled by high angle faults which strike approximately at right angles to each other, or by one fault which bends through a right angle.

It is reasonable to assume that the energy of shot SP and shot S5, recorded respectively along Dixie Meadows and Salt Marsh profiles, is side refracted along the same basement plane; therefore this plane has an apparent dip of 35° to the southeast (cross-section EF of Fig. 16) and is 4300 ft below shot point SP.

PROFILE 11: Bernice Canyon Profile

Bernice Canyon profile (Fig. 17) was shot in order to clarify the structure associated with a large positive magnetic anomaly on the eastern side of Dixie Valley. The profile was 31,000 ft long and consisted of three 4600 ft spreads. All shots offset by more than 500 ft from the spreads were fired in drilled holes; they provided poor energy coupling, which is probably a result of high attenuation in the alluvial fan in this part of the valley.

The upper boundary of a 9000 ft/sec zone, at a depth of 160 ft, remains horizontal between spread B5 and spread D6. A 7200 ft/sec layer, recognized along spread D1 below the 4500 ft/sec layer, resulted in an increased depth to the 9000 ft/sec layer.

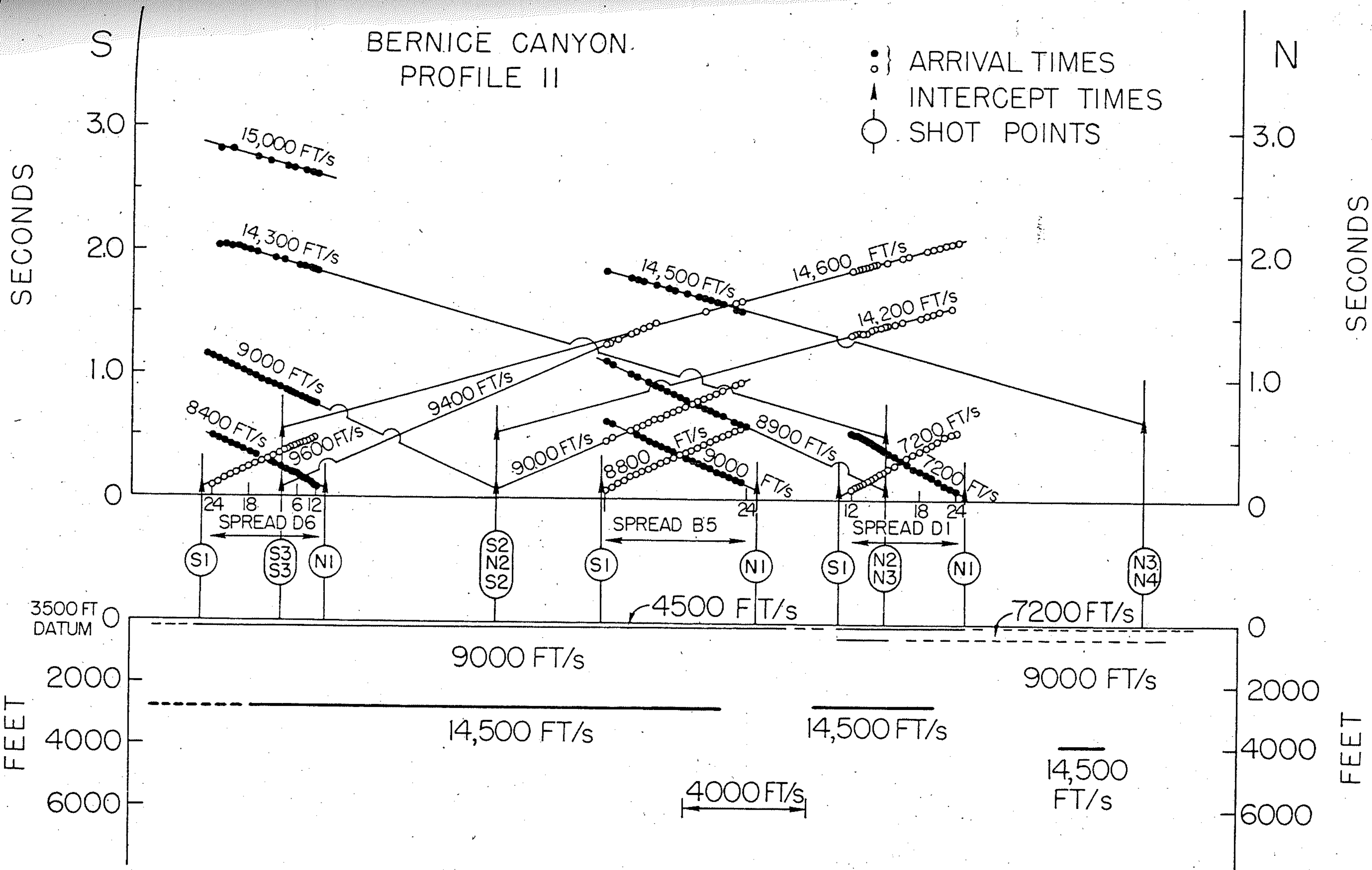

Figure 17. Time-distance curves and cross-section of the Bernice Canyon Profile.

The velocity of the 14,500 ft/sec layer was calculated from reversed data of the B5 setup. This layer is horizontal between spreads D6 and D1 on the basis of the intercept times of the 14,200 to 15,000 ft/sec velocity segments recorded on the same spreads.

The depth to the 14,500 ft/sec layer, computed beneath shot point N4 using the increased delay time at this point, must be considered a maximum since a horizontal 9000 ft/sec layer north of the profile was assumed. In reality this layer may be deeper under N4 to correlate with the increase in depth of the 14,500 ft/sec layer. The 15,000 ft/sec velocity segment shown on spread D6 was recorded from a shot which was fired at N4 without time break.

The maximum average velocity measured along this 31,000 ft profile was only 14,500 ft/sec and a depth penetration of about 8000 ft was reached. This leads to the conclusion that the 14,500 ft/sec arrivals are refracted from the basement.

PROFILE 12: Seven Devils Profile

The subsurface structure of Gamble Basin between Boyer Ranch and Seven Devils Springs was investigated from data obtained along Seven Devils profile (Fig. 18). Seismograms were recorded from shots fired in Seven Devils Springs on three 8200 ft spreads of six geophones each. These spreads were placed end to end. Reversed data in the same part of the profile were measured along the 4600 ft spread B8 of twenty-four geophones. Information on the southern part of the profile was deduced from the apparent velocities recorded along spread D4.

An apparent velocity of 7700 ft/sec was measured around Seven Devils Hot Springs and was associated with the weathered siliceous sinter dome deposited by the hot springs. These rocks were assigned a true velocity of 10,000 ft/sec. Beneath spread B8 a true velocity of 5700 ft/sec was observed for the uppermost layer. The apparent velocity of 6900 ft/sec was assumed to be the true velocity of the second layer.

The 10,000 ft/sec velocity segments recorded from shot point S2 along the north end of spread B8 and from shot point SD along spread A115 were interpreted separately as representing true velocities of horizontal layers whose depth was computed using intercept times at shot points S2 and SD.

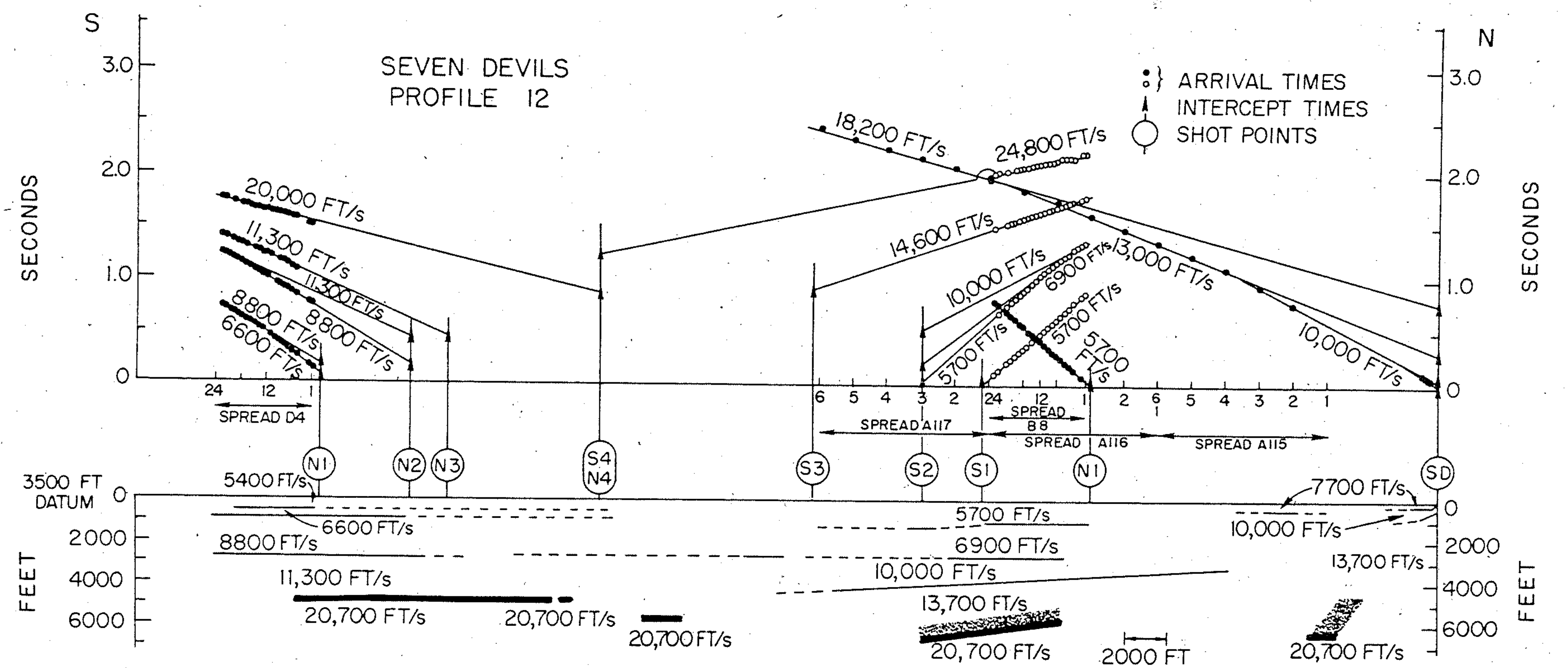

Figure 18. Time-distance curves and cross-section of the Seven Devils Profile.

The 13,700 ft/sec and 20,700 ft/sec layers were defined by association of the apparent up-dip velocities of 14,600 and 24,800 ft/sec recorded along spread B8 with the apparent down-dip velocities of 13,000 and 18,200 ft/sec recorded along spreads A116 and A117. Intercept formulas for a dipping layer were used to compute the normal depths to the 13,700 ft/sec layer between shot point S3 and spread B8.

There are two possible ways to compute the depth to 20,700 ft/sec basement from the intercept time of the 24,800 ft/sec velocity segment at shot point S4. Assuming that the basement is a plane dipping 7^{o} between S4 and spread B8, a depth to basement at S4 is obtained which is much larger than the horizontal distance from the profile to the front of the Stillwater Range. Any side refraction along this boundary will then result in earlier arrivals than those actually observed. Consequently, the 7^{o} dip was considered to be a local attitude of the basement below spreads A117 and B8 and depths below shot point S4 and these spreads were computed using delay time formulas and a constant basement velocity of 20,700 ft/sec.

If the 13,700 ft/sec layer were a thin high velocity zone inside the 10,000 ft/sec layer, then the basement, below spreads B8 and A117 and shot point SD, would be as deep as the top of the shaded area in Fig. 18. The 13,700 ft/sec layer in the southern part of the profile was not observed but may exist as a blind zone in that area and along Boyer Ranch profile (Fig. 19). In both regions the depth to basement was computed for a continuous 11,000 ft/sec layer because the effect of any velocity reversal in this layer would be compensated by the presence of the blind zone.

The energy recorded on spreads B8 and A117 was refracted from the bottom of Gamble Basin just below the spread but may have been side refracted just north of shot point S4 where the front of the Stillwater Range is 6000 ft west of the profile.

The 6600, 8800, and 11,300 ft/sec velocity segments recorded at geophone setup D4 were interpreted as the true velocities of three horizontal layers situated between the 5400 ft/sec layer and the basement. The 20,000 ft/sec segment represents an apparent down-dip velocity of the 20,700 ft/sec basement with a local apparent dip of 2^{o} to the south. The depth to the 20,700 ft/sec basement was calculated using the conventional intercept-time method for horizontal layers for the part of the profile between spread D4 and shot point S4.

PROFILE 13: Boyer Ranch Profile

Boyer Ranch profile (Fig. 19) was shot along a road trending east from Boyer Ranch across Dixie Valley. All data were reduced to a 3500 ft datum. All three geophone setups recorded an apparent velocity of 9700 ft/sec from shots fired in 20-ft holes drilled in the basement at shot point CW. At points 5 and 6 the shots were fired in 50-ft holes. The southern end of Seven Devils profile crosses Boyer Ranch profile 3400 ft west of shot point 5.

Intercept times at shot points 5 and 6 of the 6600 and 6500 ft/sec velocity segments control the thickness of the 5400 ft/sec velocity layer along the profile. The apparent velocity of 8000 ft/sec recorded along spread A110 was assumed to be the true velocity of a horizontal layer between shot point 6 and this spread. The interpretation of the southern part of Seven Devils profile showed an 8800 ft/sec layer whose attitude is carried over to Boyer Ranch profile. The upper boundary of this layer was correlated with that of the 8000 ft/sec layer determined along spread A110.

The 9700 ft/sec and the 13,100 ft/sec velocity segments given in the travel time curves of spread A109 and A110 were associated respectively with down-dip and up-dip apparent velocities of a 10,900 ft/sec velocity layer. The depth to this layer below spread A109 was calculated from the intercept time at shot point 5 using the intercept formula for a dipping layer; the continuation of the 9700 ft/sec velocity segment along the geophone setup A110 led to the determination of the attitude of the 10,900 ft/sec layer beneath this spread. The depth of the 10,900 ft/sec velocity zone below shot point 6 was calculated from the intercept time of the 13,100 ft/sec velocity segment at that point.

The true velocity of 20,700 ft/sec determined for the basement along Seven Devils profile was assumed to be characteristic of the bedrock beneath Boyer Ranch profile. The depth to basement determined from the data of Seven Devils profile was used to compute a one-way delay time for geophone 5 of spread A109 and a delay time for shot point 6. These delay times in turn lead to a basement depth below this latter point.

The high apparent velocity recorded between geophones 3 and 4 of spread A109 indicates the existence of a fault in the bedrock just west of

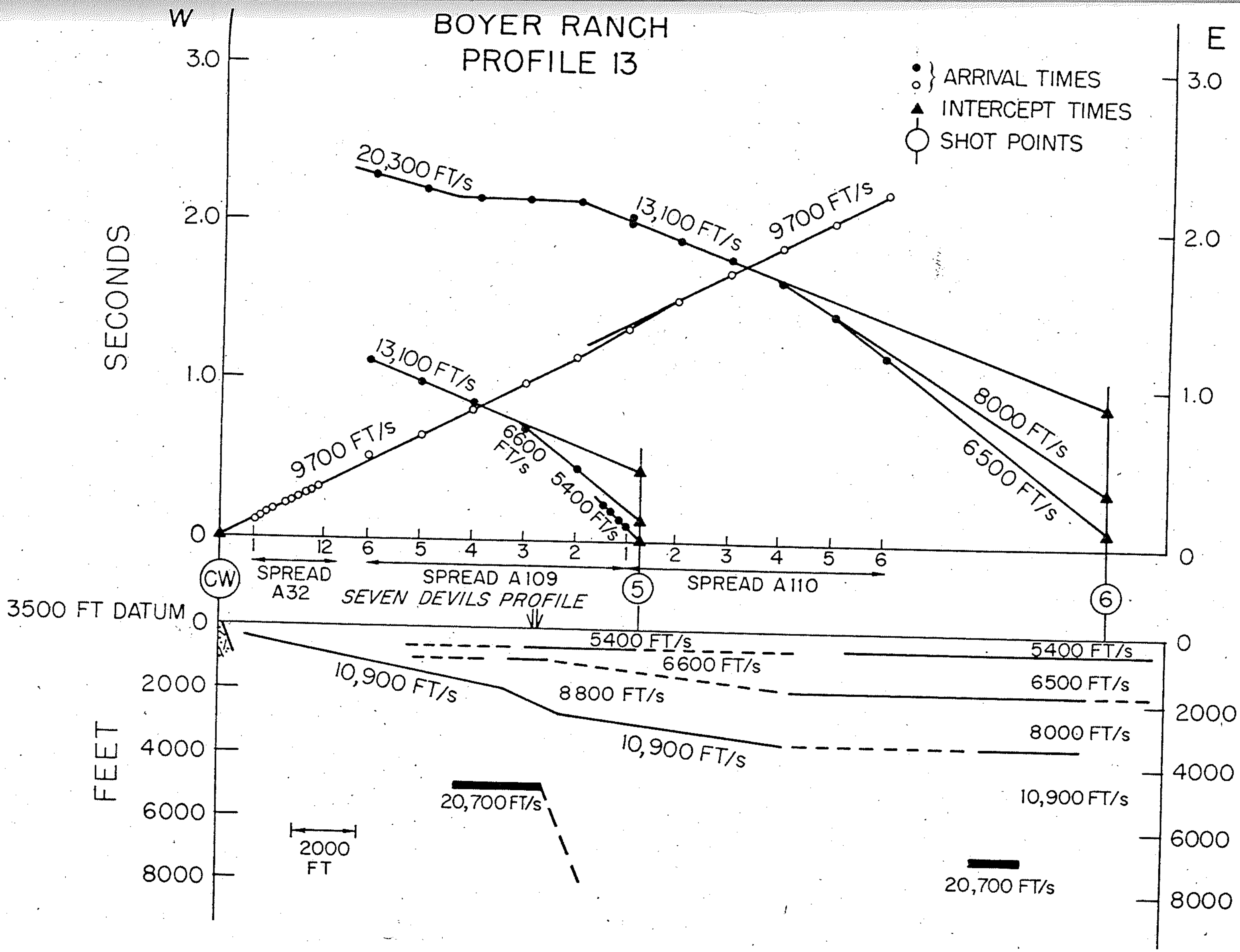

Figure 19. Time-distance curves and cross-section of the Boyer Ranch Profile.

shot point 5. The minimum step down observed in the time distance curve caused by the vertical displacement of the fault is 0.180 second which corresponds to a 2300-ft vertical down-throw of the basement on the east side of this fault. Such an attitude of the basement below spread A110 would cause the energy from shot point CW refracted from the bedrock to arrive as a first break around 2 sec at geophone 6 of spread A110. Unless these early arrivals were weak and the 9700 ft/sec velocity segment is a second event, the vertical offset along the fault is more than 2300 ft. The basement is therefore deeper below shot point 5 than beneath shot point 6.

PROFILE 14: Hyder Springs Profile

The three individual spreads of profile 14 (Fig. 20) were laid out NE of Hyder Springs (Fig. 2). Shots W1 and W5 were fired in Hyder Hot Springs and shots E4 and E3 were fired in drilled holes.

The depth to the top of the 10,500 ft/sec layer was determined below spread B7 and assumed to be constant along the northeastern end of the profile.

The depth to the 6000 ft/sec velocity layer below point E1 associated with spread D5 was calculated with a superficial velocity of 3000 ft/sec.

The 8200 ft/sec velocity segment recorded along the same spread was associated with a horizontal velocity layer.

Two apparent velocities of 11,200 ft/sec and 9000 ft/sec were recorded on spread D5 and associated as apparent up-dip and down-dip velocities of a NE dipping 10,000 ft/sec velocity layer. Depth below shot point W1 was computed from the intercept time of the 9000 ft/sec velocity segment.

The apparent velocity of 22,500 ft/sec recorded from shot point W2 was associated with the 12,500 ft/sec velocity recorded from shot point E2 to yield a true basement velocity of 16,000 ft/sec.

The 16,400 ft/sec velocity segment recorded along spread A119 from shot W5 shows the lack of significant structure in the basement between shot point W2 and spread B7. The normal depth to basement was therefore computed from the intercept time of the 16,400 ft/sec velocity segment at W2.

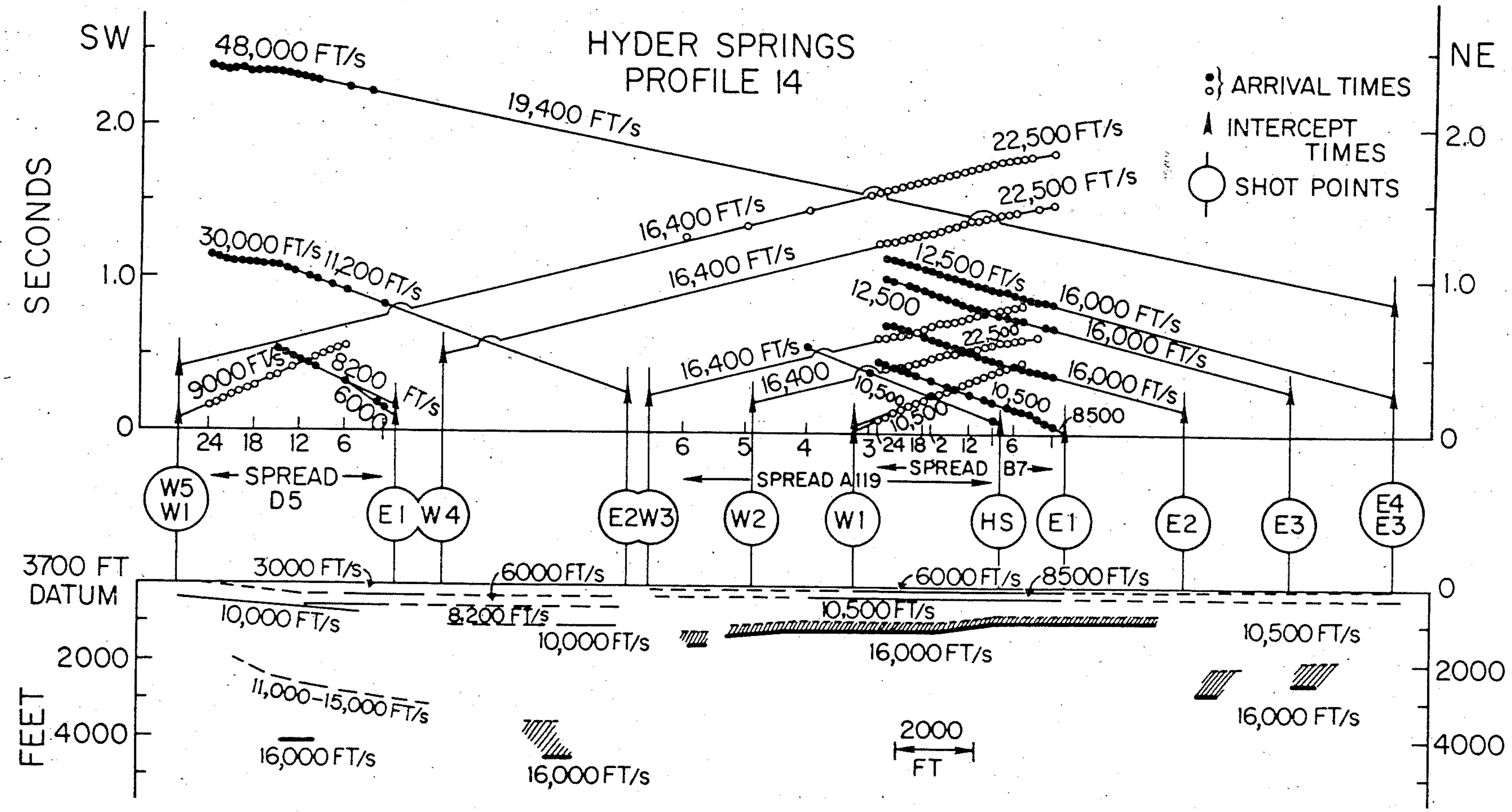

Figure 20. Time-distance curves and cross-section of the Hyder Springs Profile.

The increase in delay times associated with shot points E3, E4, W3, W4, and W5 was correlated with a deepening of the basement on both sides of the horst outlined below spreads A119 and B7.

The geophone delay time associated with the 48,000 and 19,400 ft/sec velocity segments recorded along spread D5 from shot point E3 corresponds to a refractor which is shallower than the basement determined from the shot point delay time at W5. This leads to the conclusion that the energy was refracted from the side of a siliceous sinter cone which exists below Hyder Hot Springs and whose attitude at depth is represented by the dashed line below spread D5.

Hot springs with associated siliceous sinter domes are convenient shot points and were used on Seven Devils and Hyder Springs profiles. Unfortunately they represent high velocity zones whose detailed structure is unknown. Therefore they may introduce significant errors in the interpretation of refraction data around them.

VIII. CORRELATION OF SEISMIC VELOCITIES WITH STRATIGRAPHY

A. In Situ Velocity Measurements

Table 3 summarizes the seismic compressional wave velocities and thicknesses of each velocity layer observed below the water table along the fourteen profiles studied in the previous chapter. It is difficult to relate these velocity layers to the stratigraphic units exposed in the ranges surrounding Dixie Valley because of the wide range of speeds with which seismic waves travel in the sedimentary or igneous rocks present in the area under study. To support the conclusions drawn below, additional information was obtained through side refraction measurements along outcrops of geologic units. These measurements are of greatest importance to the present study.

A true velocity of 15,400 ft/sec was calculated from two apparent velocities of 12,000 and 22,000 ft/sec measured along the granitic rocks exposed at the mouth of IXL Canyon. The data from the detailed side refraction study reported by Herring (1966) indicate an average velocity of 16,500 ft/sec for this same granitic pluton at Mud Springs. A 16,800 ft/sec velocity characterizes the gabbroic and dioritic rocks which form the front of the Stillwater Range just west of the Salt Marsh profile (Fig. 15).

The Cenozoic deposits which form most of the valley fill are composed of sedimentary and igneous material. Seismic velocities were measured for both kinds of rocks. A velocity of 10,000 ft/sec was obtained using side refraction for the Tertiary volcanics, mainly rhyolites and dacites, exposed in the White Rock Canyon. Herring (1966) associated the 10,000 ft/sec velocity zone found close to the surface below the southern part of profile E53 with a nearby outcrop of rhyolitic tuffs found about 1000 ft east of the fault scarp which runs along the base of the Stillwater Range.

Four refraction profiles were recorded with the GT-2 Interval Timer (described in Chapter III) in the Pliocene (?) non-marine sedimentary rocks at the southern end of the Stillwater Range near Mountain Well . Along exposures of semiconsolidated sands and clay beds which were above the water

TABLE 3

A. SUMMARY OF SEISMIC VELOCITIES

Profile	Location	Velocities (ft/sec) V_1	V_2	V_3	V_4	V_5	V_6	V_7
1	West Road	5200	6300	8000		10,000		15,400
2	Central Road	5000	6400	8600		10,000		16,000
3	IXL Canyon	5000		8000	9300	11,300		
4	Crazy K Ranch	5000	6000	8300		10,500		15,700
5	Dixie	5000	6300	8300		10,500		15,700
6	Dixie Meadows	5600		7500	9300			15,800
7	East Road	5000		7300, 8300			14,700	
8	Horse Creek	4600		7500	9300		13,000	
9	Pirouette Mt.	4300			9500	11,300	14,400	16,000
10	Salt Marsh	4000	6100	7600		10,000		16,800
11	Bernice Canyon	4500		7200	9000			14,500
12	Seven Devils	5700	6900			10,000	13,700	20,700
13	Boyer Ranch	5400	6500	8000		10,900		20,700
14	Hyder Springs		6000	8500		10,500		16,000

TABLE 3 (continued)

B. SUMMARY OF LAYER THICKNESSES

Profile	Location	Thicknesses (ft) h_1	h_2	h_3	h_4	h_5	h_6	hTotal
1	West Road	90	510	870		3000-4600		4470-6070
2	Central Road	260	650-1350	1700		2200-3500		4810-6800
3	IXL Canyon	140-190		0-120	0-870			
4	Crazy K Ranch	90-450	1000-1200	300-1900		1700		3800
5	Dixie	250	1000-1200	1700		2000-8000		2500-10,500
6	Dixie Meadows	550		660	2440			3650
7	East Road	170		460,1600-3500				
8	Horse Creek	200		380	1600-5000			
9	Pirouette Mt.	340			1300	700		3500-4300
10	Salt Marsh	200	330	1200				6000
11	Bernice Canyon	65-160		440	2640			2800
12	Seven Devils	1100	1600			1200	2300	6200
13	Boyer Ranch	500	1400	1700		3400		>7000
14	Hyder Springs		85-3000	210		7000		1000-4000

table, velocities ranging from 4000 to 5000 ft/sec were measured. Arrivals refracted from the upper boundary of an 8300 ft/sec layer which was 160 ft deep were observed by extending two of the refraction lines. This velocity was associated with non-marine sedimentary rocks lying below the water table and having a composition similar to the sand and clay beds exposed at the surface.

The 8300 ft/sec velocity which is a function of overburden pressure was measured under a pressure of 160 psi since 1 psi corresponds to about the pressure created by 1 ft of sediments of density 2.2 gr/cm^2. The influence of liquid saturation and overburden pressure on the compressional wave velocity in sedimentary rocks has been determined experimentally by a number of workers, such as Wyllie, et al. (1962), and King (1966). They have found that an increase in hydrostatic confining pressure increases the dilatational wave velocity. Most of the samples studied were sandstones saturated with salt water.

The increase in velocity to be expected in the sands and clay beds of the Pliocene (?) sedimentary section when these rocks are buried under Pleistocene and Recent alluvium was determined by assuming that the rate of increase found by King (1966) for the Bandera sandstone could be applied to these Pliocene (?) rocks. Since the sandstones are more consolidated than the sands and clay beds observed in the Mountain Well area, the velocities listed have to be considered as maxima. Table 4 contains these velocities and the depths at which they may be observed.

B. Correlation of Seismic Velocities with Stratigraphy

All observed velocities were classified into seven categories. The velocities in columns V_1, V_4, V_5, and V_7 are in general based on distinct changes in slope in the travel time curves while the velocities listed in columns V_2 and V_3, especially, may sometimes be the result of replacing a continuous increase of velocity with depth by a series of layers of constant velocity.

Velocities listed in columns V_1 through V_3 are associated with unconsolidated to semi-consolidated clastic sediments of Pleistocene and Recent ages. The two velocity discontinuities reported here are similar to those

TABLE 4

ESTIMATED MAXIMUM DILATATIONAL WAVE VELOCITIES
IN PLIOCENE (?) WATER-SATURATED NON-MARINE SEDIMENTS

Depth of Burial (ft)	Maximum Velocity (ft/sec)
160	8300
1000	9000
2000	9700
4000	10500
5000	10700
8000	11000

observed by previous workers in the sedimentary basins along the eastern front of the Sierra Nevada (Zbur, 1963; Healy and Press, 1964; Pakiser et al., 1964) and in the Colorado Delta Region (Kovach et al., 1962).

Velocities ranging from 4000 to 5700 ft/sec represent unconsolidated sediments just below the water table. It is important to note that the intermediate 6000-6900 ft/sec velocity zone can be identified only in the central part of Dixie Valley and is absent or exists as a blind zone along the margins. Therefore, this layer is believed to be composed of clays and silty material, common in the lower parts of closed basins.

The layers with velocities ranging from 7200 to 8500 ft/sec may represent more consolidated sands along the sides of the valley. Toward the center of the valley these layers are found at depths up to 1900 ft and may indicate an increase in velocity in the 6000-6900 ft/sec layer due to the increase in overburden pressure.

Mabey's (1956) seismic velocity tests on salt outcrops on the Searles Lake playa in southern California indicated a velocity of 10,000 ft/sec for surface salt. Where the salt body was covered by mud there was no crust and the test indicated a velocity of only 7700 ft/sec. From these observations it can be concluded that the V_3 velocity layers recorded in Dixie Valley near the center of the basin could also represent a zone of concentration of saline minerals. The combined thickness of the V_1 to V_3 velocity layers ranges from 300 ft north of Hyder Springs to 3500 ft beneath Dixie Settlement and east of Boyer Ranch. This indicates that a maximum thickness of 3500 ft of sediments were deposited in the Dixie Valley basin since Plio-Pleistocene time.

A seismic velocity boundary below which the velocity increases to an average of 10,000 ft/sec is characteristic of the entire Dixie Valley region and represents a distinct stratigraphic horizon within the valley fill. Since we measured similar velocities in rhyolitic tuffs and flows at White Rock Canyon and at Mud Springs, this higher velocity is correlated with the tuffs and flows of rhyolite of the Miocene to Pleistocene stratigraphic unit.

The non-marine sediments included in this section should create velocity reversals in the V_4 or V_5 velocity layers. Knowing the depth of these layers, it is possible to determine from the data of Table 4 the speed of the seismic waves in this low velocity zone. These data indicate that the velocity in the sediments can reach 10,000 ft/sec at a depth of 3500 ft and therefore no velocity reversals are likely below this depth. On another hand, the existence of an 8000 ft/sec layer at a depth of 3000 ft beneath Dixie Settlement where normally the Pliocene (?) sediments would have a velocity of 9 to 10,000 ft/sec, strongly suggests that clastic sediments of post-Pliocene age exist at that depth.

A maximum thickness of the Miocene to Pleistocene section of 8000 ft was measured below Dixie Settlement and is of the same order of magnitude as the thickness reported by Page (1965).

The presence of a 13,000 to 14,700 ft/sec velocity layer observed between the 10,000 ft/sec zone and the basement along the East Road profile, Pirouette Mountain profile, and inferred from the data of Horse Creek profile, is correlated with a competent volcanic flow interbedded in the Miocene to Pleistocene section. This flow seems to be present only in the southern part of Dixie Valley. Velocities ranging from 15,400 to 16,500 ft/sec measured south of Dixie Meadows are correlated with the Mesozoïc limestones, slates and metavolcanic rocks exposed north of IXL Canyon and with the granitic rocks which intruded this Mesozoïc section.

The southern subsurface margin of the Gabbroïc complex was determined from the data of the aeromagnetic survey completed by Smith (1965)(Fig. 2). Along the Salt Marsh profile, which was shot just north of the gabbro contact, a basement velocity of 16,800 ft/sec was measured by side refraction on gabbroïc and dioritic rocks. These rocks are considered to be the intrusive part of the Gabbroïc Complex.

The 20,700 ft/sec velocity measured between Boyer Ranch and Seven Devils was also correlated with the intrusive rocks of the Gabbroïc Complex while the 13,700 ft/sec layer found below the 10,000 ft/sec zone probably represents Mesozoïc basalt flows, tuffs, and breccias associated with the gabbroïc and dioritic rocks of the Gabbroïc Complex. From the data of Seven Devils profile it can be concluded that rocks from the Gabbroïc Complex form at least part of the bedrock below Gamble Basin and that the attitude of the pre-Tertiary basement is represented by the upper boundary of this 13,700 ft/sec velocity layer.

The 14,500 ft/sec velocity measured below Bernice Canyon profile was correlated with the extrusive rocks of the Gabbroïc Complex. The seismic waves reached a depth of penetration of about 8000 ft and no higher velocity was recorded. Therefore the minimum depth for the intrusive rocks of the Gabbroïc Complex below this profile is 8000 ft and any magnetic model which may be constructed to fit the positive anomalies in this area must accommodate the boundary conditions set forth by the seismic model.

Seismic velocities in the Gabbroïc Complex range from 13,700 ft/sec and 14,500 ft/sec in the extrusive rocks to as high as 20,700 ft/sec in the intrusive rocks. This wide spread reflects the heterogeneity of composition of the Gabbroïc Complex and makes it impossible to differentiate the nature of the basement for velocities less than 17,000 ft/sec without the support of the magnetic data. Another consequence of this inhomogeneity is that the delay time method used for the interpretation of the refraction data is less reliable in the northern part of the valley. The northwestern part of the subsurface contact of the Gabbroïc Complex lies approximately north of Gamble Basin, but it is not possible to define from seismic data the northeastern part of this contact since the 16,600 ft/sec velocity recorded along Hyder Springs profile can be correlated with both the Mesozoïc slates and the extrusive part of the Gabbroïc Complex.

IX. STRUCTURAL IMPLICATIONS

From the attitudes of the velocity boundaries determined by the seismic profiles, it is now possible to describe the subsurface structural configuration of Dixie Valley. It is a long trough showing a "graben in graben" structure controlled by normal faulting.

The inner graben whose detailed structure can be seen in Fig. 10, is about 5 miles wide beneath Dixie Settlement and lies slightly to the west of the topographic center of the valley. Its depth just west of Dixie Settlement was found to be 10,500 ft and two miles east of Boyer Ranch, at least 7000 ft.

The following depths to bedrock were determined for valley blocks bordering the trough to the west:

a. Five miles southwest of Dixie Meadows the basement is 3500 ft. deep;

b. About two miles east of IXL Canyon, the valley floor is 5400 ft deep;

c. At Boyer Ranch the basement is 4900 ft deep.

Fig. 21 is an east-west cross-section along Mud Springs Road; it combines the results obtained by Herring (1966) with the information of the southern end of West Road profile. It shows how the basement drops step-by-step valleyward from the topographic escarpment of the Stillwater Range. Three high-angle faults were detected between the west side of the valley and the west side of the inner graben. The dip of these faults was found to be 55^{o} to 70^{o} eastward.

Below shot point SP of Dixie Meadows profile (Fig. 16), the floor of the outer graben is 4300 ft deep and has a dip component of 35^{o} to the southeast.

About 1.5 miles southeast of the mouth of White Rock Canyon, in the basin formed by the reentrant of the Stillwater Range, the basement is at least 5000 ft deep (Fig. 16). Finally, the floor of Gamble Basin is 4000 ft deep and has a dip component of 3^{o} to the south.

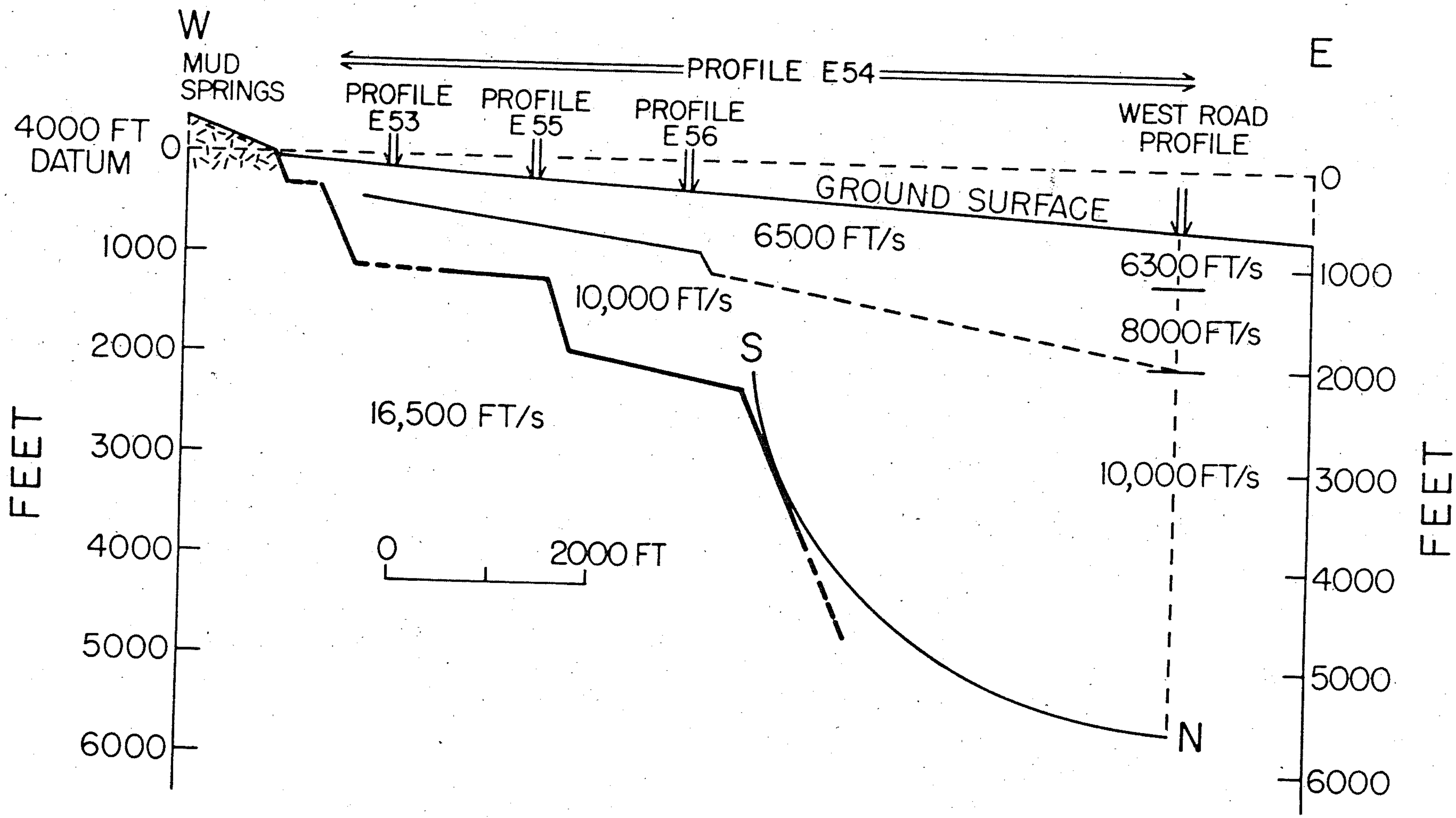

Figure 21. East-West cross-section along Mud Springs Road.

Below Dixie profile the floor of the outer graben rises eastward from a depth of 3800 ft to 2500 ft. Further north, the floor on the east side of this narrow depression is 2800 ft deep at Bernice Canyon profile and 1000 ft deep at Hyder Springs profile.

The continuity of the inner graben between Boyer Ranch and Dixie Settlement could not be verified in the present study but is inferred from the aeromagnetic survey (Smith, 1965) and from the gravity map of the Dixie Valley area (Thompson, 1966). West of Dixie Settlement, a maximum vertical offset of 5500 ft in the basement was determined along the western bounding fault of the inner graben. Similarly at the Boyer Ranch profile there is at least 2300 ft of offset.

From Dixie Settlement the southward continuation of the eastern fault zone of the inner graben can be deduced from the abrupt valleyward drop of the 13,000 and 14,700 ft/sec horizons observed along the western part of Horse Creek profile and the southern end of the East Road profile.

The northward continuation of this same zone cannot be determined from the present seismic data since the high-angle fault at the southwestern end of Hyder Springs profile is not necessarily related to the longitudinal trough but may represent the northeastern boundary of a transverse structure. The shallow depth of the bedrock determined below the Pirouette Mountain profile indicates either that the main longitudinal trough ends as a closed basin at the southern end of Dixie Valley or that its axis turns to the east below the Louderback Mountains.

The comparison of the depth of the pre-Tertiary basement obtained in the northern part of Pirouette Mountain profile with the depth at the southern end of the Central Road profile shows a structural relief of the bedrock of 1500 ft over a north-south horizontal distance of one mile. This structural relief forms the southwestern boundary of the Dixie Valley trough.

IXL Canyon profile and East Road profile show minor transverse structures in the velocity boundaries within the Cenozoic section, but it was not possible to establish their continuity across the valley. The layers which form the upper part of the Miocene-to-Pleistocene unit have been much less displaced by faults than the pre-Tertiary interface (Fig. 10). This leads to the conclusion that faulting was continuous or repeated at short intervals concurrently with deposition of the Cenozoic rocks.

X. CONCLUSIONS

The seismic refraction investigation of Dixie Valley revealed several structural features which are significant in the understanding of the structural history of the Basin and Range Province and supply new constraints on the theories of its formation.

The subsurface structural configuration of Dixie Valley is summarized in Fig. 10, which shows a concealed complex of normal faults forming a long subsurface trough with a "graben in graben" structure. The inner graben, situated beneath the west side of the valley floor, is as narrow as five miles and contains an accumulation of sedimentary and volcanic deposits of Cenozoic age which attain a maximum thickness of 10,500 ft. The last 3500 ft of this section were deposited since late Pliocene time.

The Dixie Valley and Rainbow Mountain fault scarps, which were formed during the 1954 earthquakes, each lie along the western side of a narrow trough. One of these troughs is the composite graben of Dixie Valley, which reaches a depth of 10,500 ft, and the other lies on the west side of the Stillwater Range and is 10,000 ft deep (Wahl, 1965). The Stillwater Range forms a horst rising 15,000 ft above the floors of these two grabens. Thus the most active seismic area in the Basin and Range Province is characterized by a total structural relief of three miles over a breadth of twelve miles.

The fault zone bounding the Stillwater Range west of the Humboldt Salt Marsh dips at least 45° to the east; its zig-zag pattern is conserved to a minimum depth of 2500 ft. The geometry of this fault zone is such that no large-scale strike-slip movement is possible along the zone.

At Mud Springs the western boundary fault of Dixie Valley has 4000 ft of throw (Fig. 21), whereas the western fault zone of the inner graben has a vertical offset of 5500 ft west of Dixie Settlement and at least 2300 ft at Boyer Ranch. This interior concealed fault may be more nearly straight than the Stillwater frontal fault and may therefore allow strike-slip displacement.

The following observations limit the amount of horizontal movement which could have taken place since the beginning of the Cenozoic:

a. The maximum possible strike-slip displacement of the southern subsurface contact of the gabbroic complex across Dixie Valley cannot be more than two miles (Smith, 1965).

b. Zbür (1963) observed en echelon normal faults in the sediments of Indian Wells Valley, California. He associated these features with right lateral strike-slip movement along a fault in the pre-Tertiary bedrock. However Burke (1966), who studied in detail the geomorphology of the Dixie Valley floor, did not see any such normal faults in the sediments above the west side of the inner graben.

Geophysical evidence thus strongly suggests that the maximum possible strike-slip displacement in Dixie Valley cannot be more than two miles. Therefore it is believed that all bounding and interior faults which form the structural framework of this basin are normal faults along which mainly dip-slip movement occurred.

From the present study it is possible to obtain average displacement rates for two successive intervals of geologic time. On one hand, the 15,000 ft of vertical deformation which took place in the last 15 million years would suggest an average displacement rate on the order of 1 ft per thousand years. On the other hand, it was found that depths of the volcanic rocks of Plio-Pleistocene age range from 300 ft in the outer graben to 3500 ft in the inner graben. Assuming original continuity the difference of 3200 ft implies also an average displacement rate of 1 ft per thousand years.

Therefore it can be concluded that the Dixie Valley region was deformed over the last 15 million years at a rate of about 1 ft per thousand years with dip-slip exceeding strike-slip movement.

BIBLIOGRAPHY

Buffet, A., and Layat, C.H., 1960, Nouvel Aspect de la Sismique Refraction au Sahara: Tirs non Enterrés; Geophysical Prospecting, Vol. 8, pp. 47-67.

Burke, D.B., 1967, Aerial Photograph Survey of Dixie Valley, Nevada; A. F. Cambridge Research Labs. Final Scient. Rpt. Part IV, AFCRL-66-848.

Cohen, P., and Everett, D.E., 1963, A Brief Appraisal of the Ground Water Hydrology of the Dixie-Fairview Valley Area; Dept. Consv. and Nat. Res., State of Nevada, Report No. 23.

Dix, C.H., 1952, Seismic Prospecting for Oil; New York, Harper and Brothers, 414 pp.

Ewing, M., Crary, A.P., and Rutherford, H.M., 1937, Geophysical Investigation in the Emerged and Submerged Atlantic Coastal Plain, Part 1: Methods and Results; Bull. Geol. Soc. Am., Vol.48, pp. 753-802.

Hawkins, L.V., and Maggs, D., 1961, Nomograms for Determining Maximum Errors and Limiting Conditions in Seismic Refraction Survey with a Blind Zone Problem; Geophysical Prospecting, Vol. 9, No. 4.

Healy, J.H., and Press, Frank, 1964, Geophysical Studies of Basin Structures Along the Eastern Front of the Sierra Nevada, California; Geophysics, Vol. 29, pp. 337-359.

Herring, A.T., 1967, Seismic Refraction Study of a Fault Zone in Dixie Valley, Nevada; A. F. Cambridge Research Labs. Final Scient. Rpt. Part II, AFCRL-66-848.

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

King. M.S., 1966, Wave Velocities in Rocks as a Function of Changes in Overburden Pressure and Pore Fluid Saturants; Geophysics, Vol. 31, pp. 50-73.

Kovach, R.L., Allen, C.R., and Press, Frank, 1962, Geophysical Investigations in the Colorado Delta Region; Jour. Geoph. Res., Vol. 67, pp. 2845-2871.

Mabey, D.R., 1956, Geophysical Studies in the Intermontane Basins in Southern California; Geophysics, Vol. 21, pp. 839-853.

Menard, H.W., 1964, Marine Geology of the Pacific; New York, McGraw-Hill, pp. 117-152.

Muller, S.W., Ferguson, H.G., and Roberts, R.J., 1951, Geology of the Mount Tobin Quadrangle, Nevada; U. S. Geol. Survey Geol. Quadrangle Map CQ-7.

Nettleton, L.L., 1940, Geophysical Prospecting for Oil; New York, McGraw-Hill, 444 pp.

Page, B.M., 1965, Preliminary Geologic Map of a Part of the Stillwater Range, Churchill County, Nevada; Nevada Bureau of Mines Map 28.

Pakiser, L.C., Press, Frank, and Kane, M.F., 1962, Geophysical Investigation of Mono Basin, California; Bull. Geol. Soc. Am., Vol. 71, pp. 415-448.

Pakiser, L.C., and Kane, M.F., 1962, Geophysical Study of Cenozoic Geologic Structures of Northern Owens Valley, California; Geophysics, Vol. 27, pp. 334-342.

Pakiser, L.C., Kane, M.F., and Jackson, W.H., 1964, Structural Geology and Volcanism of Owens Valley Region, California--A Geophysical Study; U. S. Geol. Survey Prof. Paper 438.

Pakiser, L.C., and Steinhard, J.S., 1964, Explosion Seismology in the Western Hemisphere; Research in Geophysics, Vol. 2, (Odishaw, Ed.) M.I.T. Press, pp. 123-147.

Poulter, T.C., 1950, The Poulter Seismic Method of Geophysical Exploration; Geophysics, Vol. 15, pp. 181-207.

Shawe, D.R., 1965, Strike-Slip Control of Basin-Range Structure Indicated by Historical Faults in Western Nevada; Bull. Geol. Soc. Am., Vol. 76, pp. 1361-1378.

Slemmons, D.B., 1957, The Dixie Valley-Fairview Peak, Nevada, Earthquakes of December 16, 1954: Geological Effects; Bull. Seism. Soc. Am., Vol. 47, pp. 353-375.

Smith, T.E., 1967, Aeromagnetic Measurements in Dixie Valley, Nevada: Implications Regarding Basin-Range Structure; A. F. Cambridge Research Labs. Final Scient. Rpt. Part III, AFCRL-66-848.

Speed, R.C., 1963, Unpublished progress map of parts of West Humboldt, Stillwater, and Clan Alpine Mountain Ranges, Nevada.

Steinhart, J.S., and Meyer, R.P., 1961, Minimum Statistical Uncertainty of the Seismic Refraction Profile; Geophysics, Vol. 26, pp. 574-587.

Thompson, G.A., 1959, Gravity Measurements Between Hazen and Austin, Nevada: A Study of Basin-Range Structure; Jour. Geophys. Res., Vol. 64, pp. 217-229.

Thompson, G.A., 1966, Unpublished Gravity Survey of Dixie Valley, Nevada.

University of Nevada, 1962, Geological, Geophysical, and Hydrological Investigations of the Sand Springs Range, Fairview Valley, and Four Mile Flat, Churchill County, Nevada; Report to Atomic Energy Commission for Shoal Project, Vela Uniform Program, 127 pp.

Wahl, R.R., 1965, An Interpretation of Gravity Data from the Carson Sink Area, Nevada; M. S. Research Project, Stanford University.

Wyllie, M.R.J., Gardner, G.H.F., and Gregory, A.R., 1962, Studies of Elastic Wave Attenuation in Porous Media; Geophysics, Vol. 27, pp. 569-589.

Zbur, R.T., 1963, A Geophysical Investigation of Indian Wells Valley, California; U. S. Naval Ord. Test Station Techn. Publ. 2795.