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Some Limitations of Seismic Refraction Methods in Geohydrological Surveys of Deep Alluvial Basins[a]

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Some Limitations of Seismic Refraction Methods in Geohydrological Surveys of Deep Alluvial Basins[a]

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ABSTRACT

Seismic methods, combined with available well and geologic data, were used to define the subsurface hydrologic and geologic conditions of the Walnut Gulch Experimental Watershed, a deep, alluvial basin near Tombstone, Arizona. Surface geology of the valley indicates an alluvium-filled area between igneous intrusives and sedimentary rocks that support the Tombstone Hills on the southwest and the Dragoon Mountains on the northeast. Seismic determinations revealed depths to the water table ranging from near zero at the confluence of Walnut Gulch and the San Pedro River to 475 feet in the central portion of the watershed. The accuracy of predicting the depth to either ground water or basement was ± 6 percent, while that for ground water alone was ± 10 percent.

Seismic refraction methods failed to produce satisfactory results when certain conditions or combinations of conditions existed. The great depths of alluvium created the problem of estimating the seismic traverse length necessary to accurately determine the alluvium-basement interface. Increased compaction of alluvium with depth causes additional interpretation difficulties in some areas. Also, water-table elevation may not always be accurately determined if it is located above, and close to, a higher-velocity layer.

A minimum of gravity or well log information greatly increases the reliability of seismic information in these problem cases. Other methods may still be necessary to substantiate the seismic data obtained under these conditions.

INTRODUCTION

Field work for a seismic refraction survey of the subsurface geology of Walnut Gulch Experimental Watershed was completed in 1968. The watershed, located near Tombstone, Arizona, serves as an outdoor hydrologic laboratory under the direction of the Agricultural Research Service, USDA (Figure 1).

Transmission losses have been measured on Walnut Gulch by comparing inflow-outflow data on several channel segments (Keppel and Renard, 1963; Wallace and Renard, 1967). These transmission losses are very important in hydrologic work in the southwestern United States. Information derived from the seismic survey was needed to understand the disposition of these losses. Specific objectives of the survey were to:

1. Identify and map subsurface hardrock units, giving particular attention to those units underlying and bordering major stream channels.

2. Measure the thickness and extent of aquifer alluviums, with emphasis on differentiating unconsolidated units from conglomerates.

3. Determine the depth to regional water table.

The great heterogeneous mass of alluvium filling the central portion of the valley presented various interpretation difficulties. One major problem was the difficulty in distinguishing between saturated unconsolidated alluvium and the well-cemented conglomerates within the basin because the two formations often had seismic velocities within the same range. Great depths of alluvium also created the problem of estimating the distance required between the geophones and explosive charge, so that the velocity break would be recorded within the period of record of the instrument. Finally, the depth to water table could not always be satisfactorily determined in areas where a higher-velocity layer existed immediately below the water table.

SEISMIC PROCEDURE

Fifty-two seismic profiles were conducted in 12 areas (Figure 1) and totaled 22 miles of inline seismic profiling (Libby, Wallace, and Spangler, 1970). A network of gravity stations established over the watershed and its peripheral area helped define the configuration of the basement complex, provided depth approximations of the deep alluvium, and assisted in determining the bearings for the subsequent seismic traverses discussed herein (Spangler and Libby, 1968).

Most of the profiles were made in the stream channel of Walnut Gulch. Other profiles were made in the deep alluvial portions of the valley where past drilling efforts had never reached bedrock. These drilling efforts to depths of 1200 feet did not intersect the basement complex.

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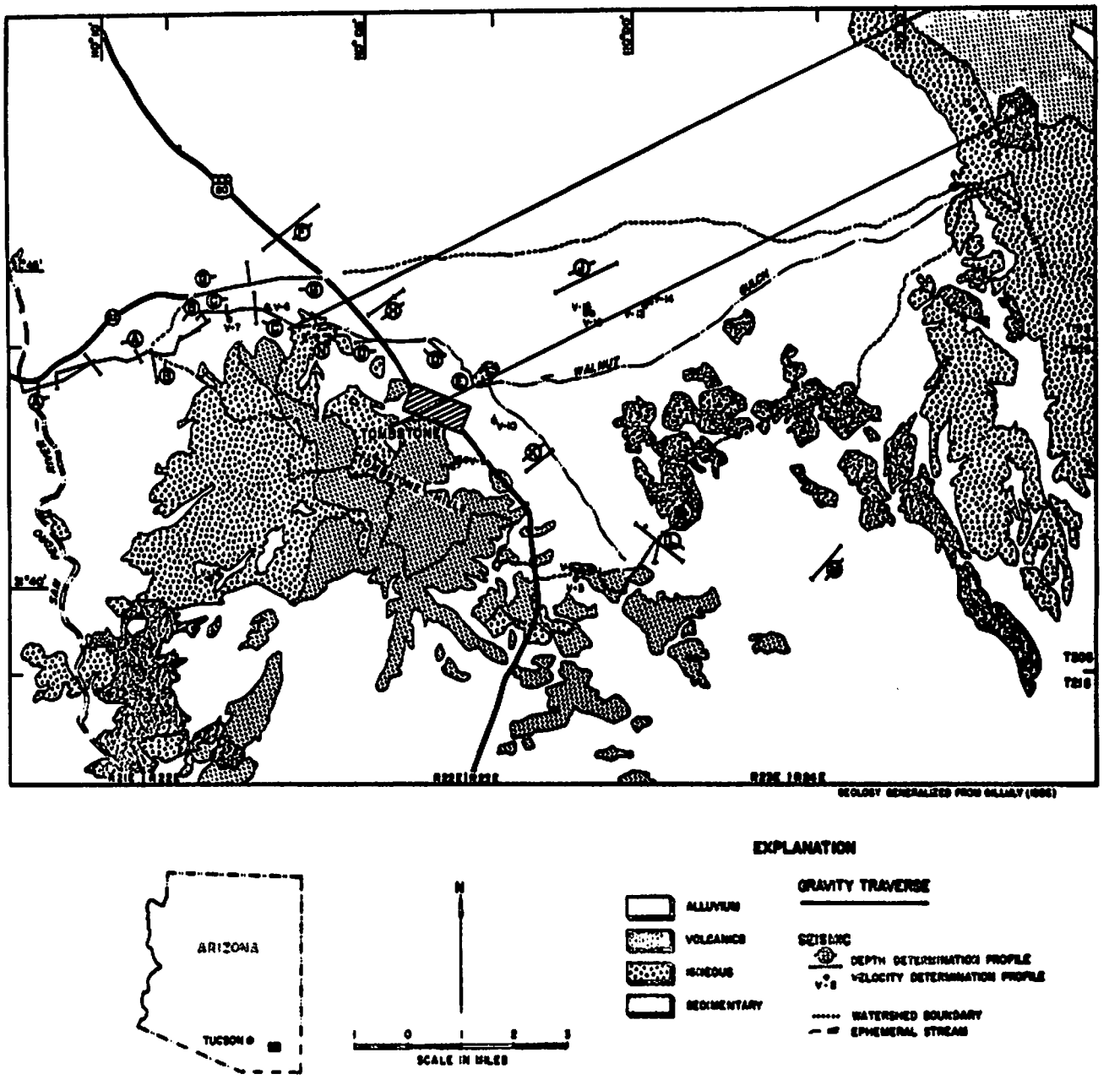

Fig. 1. Location map of study area, showing generalized geology and placement of seismic and gravity traverses.

In areas where boreholes and sonic logs are not available, seismic velocities of the various geologic units must be determined by measurements made along surface exposures (Grant and West, 1965). Several refraction velocities were taken from the reversed seismic-profile records in which nearby exposures or well control data justified a direct identification of rock type. These data were then used to compile a table of seismic velocities (range and average) representative of the study area (Table 1). The range of velocities agrees well with seismic-wave velocity histograms for similar rock units as presented by Grant and West (1965).

Two seismic units were used during the investigation. An Electro-Tech Porta-Seis Interval Timer[1] on loan from the Geophysics Laboratory of the University of Arizona was used with both 600- and 1800-foot geophone spread lengths. A second system, using a Century Model 408 oscillograph, was used with a 2400-foot geophone spread length. Reading accuracy was ± 1.0 millisecond for both systems.

INTERPRETATION

General Geology

The survey area is typical of Basin and Range physiography and contains isolated mountain blocks separated by a broad alluvium-filled basin. Deep-seated intrusions and accompanying high-angle reverse faults are responsible for the high relief areas that comprise the Tombstone Hills on the west and the lower Dragoon Mountains on the east. Great thicknesses of sedimentary rocks (mostly limestone) make up the topographic relief of the Tombstone Hills. They are underlain by, and adjacent to, large igneous bodies of Tertiary age. The igneous lower Dragoon Mountains

[1] Reference to manufactured products does not constitute endorsement by the U. S. Department of Agriculture.

Table 1. Seismic Velocities and Densities of Geologic Units in the Study Basin

Geologic unit	*Velocity range (ft/sec)*	*Velocity average (ft/sec)*	*Density average (gm/cm³)*
ALLUVIUM			
Recent channel deposits	1,150- 4,900	2,200	–
Quaternary-Tertiary alluvial deposits:			
Unconsolidated	3,350- 6,000	5,000	2.02
Conglomerates	6,000-12,350	8,800	2.34
IGNEOUS			
Quaternary Tertiary Basalt		15,600*	2.80
Schieffelin-Granodiorite	12,300-17,700	15,450	2.68
Uncle Sam Porphyry	10,100-16,400	13,350	2.61
VOLCANIC			
S. O. Volcanics		12,300*	2.33
Pre-S. O. Volcanics	7,550-10,925	9,700	2.48
SEDIMENTARY			
Bisbee Group	12,100-16,400	13,650	2.70
Naco limestone	11,850-16,000	13,350	2.69

* Values based on a single, unreversed velocity profile.

of Triassic-Jurassic age are without sedimentary caprock; the only residual sedimentary rocks in this area are small drag blocks along fault zones (Gilluly, 1956).

Late Tertiary volcanics in the southwest portion of the study area are relatively thin beds of andesite-rhyolite flows and tuffs, and are in overthrust position. Minor amounts of later Tertiary and early Quaternary rhyolite and basalt occur as intrusive dikes, sills, and plugs in the south and central portions of the study area. A Tertiary quartz-latite porphyry, the Uncle Sam Porphyry, forms an impermeable bedrock in much of the western portion of the study area (Figure 1).

The alluvium filling the intermontane basin consists of deep Tertiary and Quaternary sand, gravel, clay, and caliche conglomerate. Previous data indicate the alluvium is more than 1200 feet deep in places and contains a large volume of ground water. Much of the conglomerate is extremely well cemented, approaching the strength and appearance of structural concrete. These conglomerates act as rock units and exert structural control on both the surface stream channels and on ground-water flow.

Geophysical Interpretation

It was difficult to differentiate between unconsolidated saturated alluvium and conglomerates in some areas. When the unconsolidated alluvium was unsaturated, its seismic velocity was well below that of the conglomerates. However, when the water table was developed within the unconsolidated alluvium the seismic velocity of the formation increased to the velocity range of the well-cemented conglomerates (Johnson, 1954).

When a reliable well log is available from adjoining areas and surface investigations warrant projecting the water level information to the area in question, chances of determining the unconsolidated alluvium-conglomerate interface are greatly increased. If the interface recorded by refracted conglomerate velocities is much deeper than the normal depth of the water table, contacts between unconsolidated alluvium and conglomerates may be interpreted with reasonable reliability even though the saturated alluvium velocities and the conglomerate velocities may approach the same range.

In this study, seismic-calculated depths to the ground-water table and basement were compared to actual depths derived from nearby well data (Figure 2).

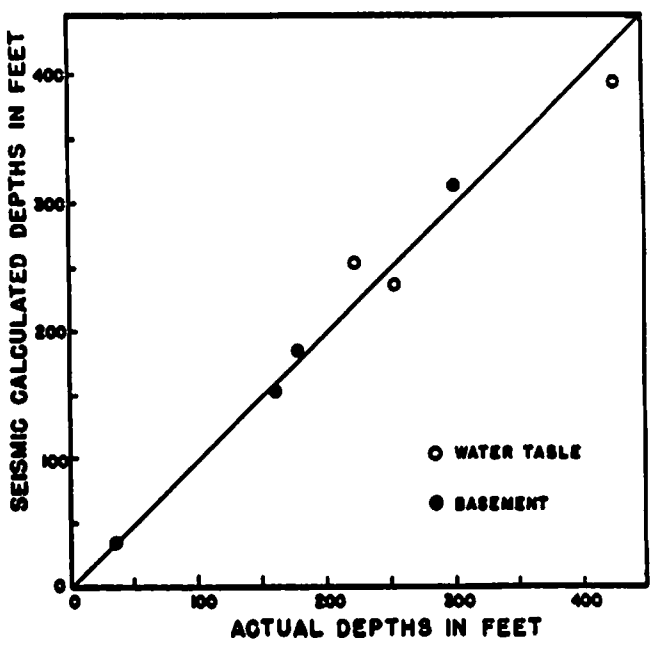

Fig. 2. Comparison of seismic-calculated depths to ground water with actual depths derived from observation well measurements.

In general, the deviations do not suggest a systematic error as one might expect if all the calculated depths were greater, or less, than the actual depths. The accuracy of predicting the depth to either ground water or basement was ± 6 percent. The accuracy of predicting the depth of ground water alone was ± 10 percent, while that for basement alone was ± 4 percent.

The depth to water table was successfully determined in areas having a thick layer of alluvium between the water table and a higher velocity bedrock. Figure 3 (east end of Traverse B) is an example of an area that produced an accurate determination of the water-table depth, as well as the depth to bedrock. The considerable depth separating the water table and the alluvium-bedrock interface in this area allowed an uninterrupted return of the water-table velocity.

An example of geohydrologic conditions existing in a sequence where seismic refraction methods will not produce satisfactory data is shown in Figure 4 (at the west end of Traverse B). Here the close proximity of the water table and the alluvium-bedrock interface causes interpretation difficulty. The velocity of the water-saturated alluvium is within the same general range as that of the particular bedrock encountered. Thus, the increase in velocity of the alluvium due to saturation could not be detected because the signal from the higher velocity bedrock overtook and masked out the slower signal from the alluvium. Soske (1959) referred to this situation as the blind-zone problem and has cited examples where a zone directly above a higher velocity interface may not be indicated by the seismic record.

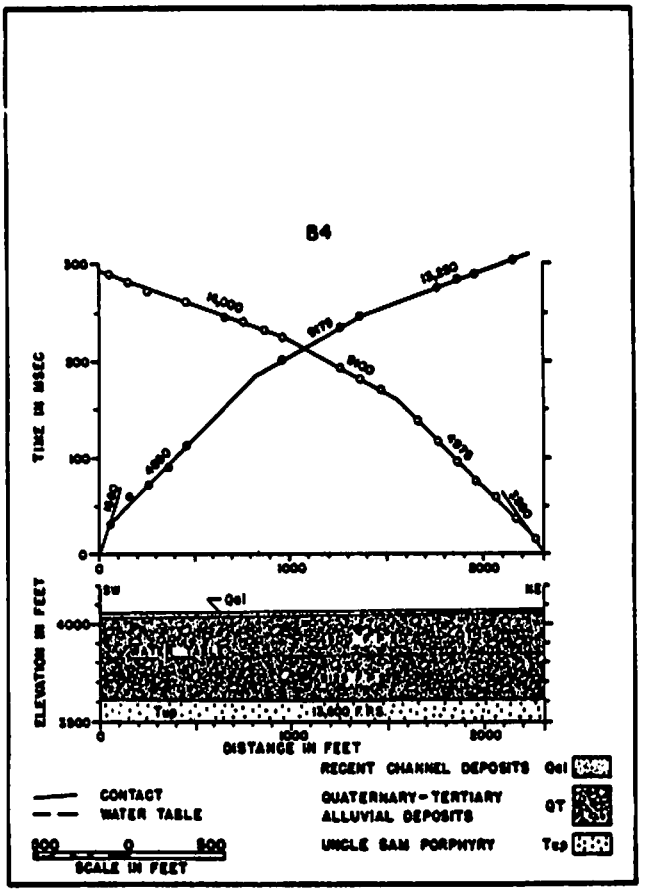

Fig. 3. Geologic setting in which water table was successfully determined by seismic refraction methods.

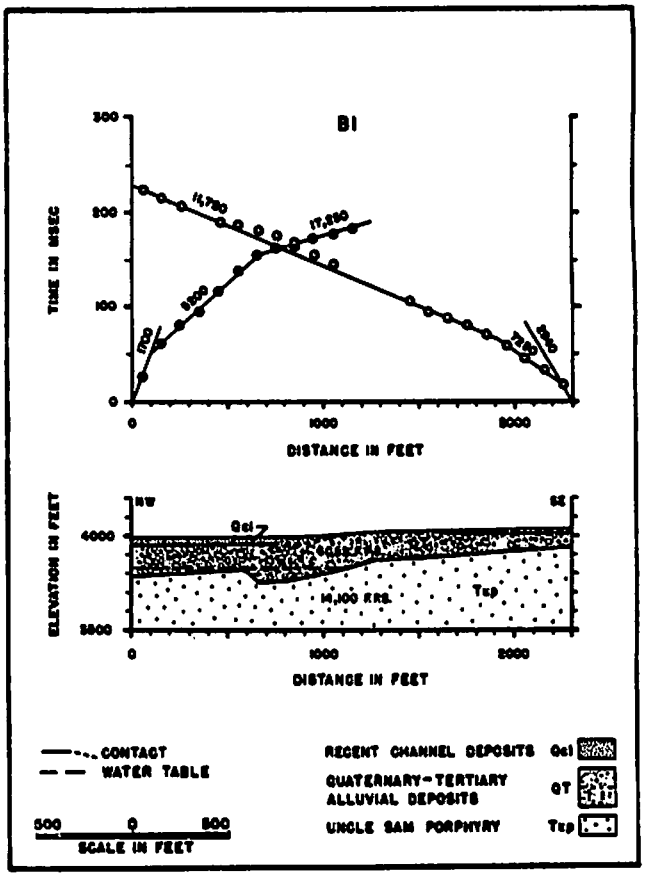

Fig. 4. Geologic setting in which the water-table depth could not be successfully determined by seismic refraction methods.

The contrast between the seismic velocity of the unconsolidated, dry alluvium and the water-saturated alluvium-conglomerate complex provided a sharp break in the time-distance graph at the water table with no interference from the deeper, higher-velocity bedrock formation. This contributed to the success of the survey in determining the water-table elevation.

The depth of alluvium between the water table and basement, which is necessary for successful water-table determination, may also act as a detriment in determining the alluvium-bedrock interface. Where great depths of alluvium or conglomerate exist, compaction with depth may bring the seismic velocity of the units up to the bedrock velocity range, in which

case no depth interpretation is possible for the alluvium-bedrock interface. This is often encountered in the central portions of alluvial basins and must be considered when planning seismic refraction surveys in deep alluvial areas. Traverses which passed over a deep trough in the study basin produced this problem; thus, only the water-table depth was obtained from seismic records in this case.

When seismic refraction traverses are attempted in deep alluvium, the intersection of the direct wave and the refracted wave (critical distance) may not fall within the instrument recording time (Lineham, 1951). This problem occurs because most smaller seismic units have cables with the geophones preset at specific intervals along the cable. Thus, the geophones cannot be spaced farther apart to lengthen the spread for deeper exploration. This necessitates varying the shot-point distance from the geophones in order to have the proper break appear on the record.

Costly exploration necessary to determine the approximate range of depths which may be encountered may be minimized if some measure of control is established in the area prior to the seismic work. The problem was overcome by determining the basin trends with reconnaissance gravity traverses run normal to the axis of the valley (Spangler and Libby, 1968).

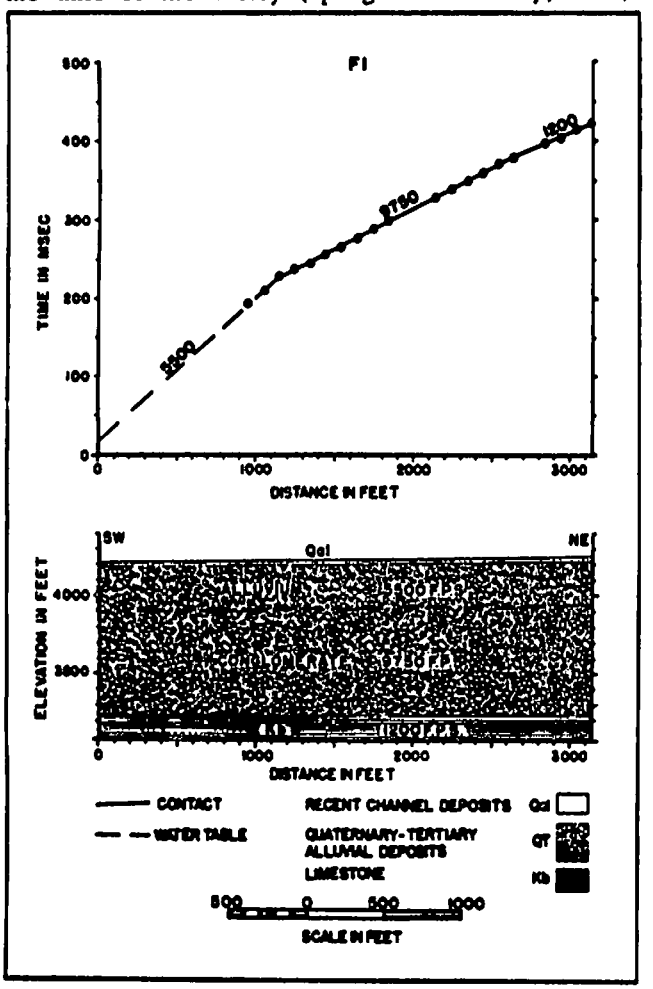

Fig. 5. Geologic setting in which the seismic traverse length was extended in order to analyze greater depths of alluvium.

Figure 5 (Traverse F1) shows an attempt to determine depth to bedrock in deep alluvium, with the first portion of the record missing due to the increased distance between geophone spread and shothole. By using an approximate basement depth from gravity measurements as a guide in determining the seismic traverse length, the alluvium-basement break was allowed to occur within the recording period of the seismic unit.

DATA EVALUATION

Although the velocity with which a layer transmits seismic waves cannot be used to clearly identify its exact lithologic and hydrologic characteristics, calculating or predicting depth to the layer can be very successful. Errors caused by incorrect geologic and hydrogeologic interpretation of velocity layers can be reduced if a control framework is established from wells in the area and if velocities are first determined on known outcrops.

Water-saturated alluvial deposits exhibited significantly higher seismic velocities than did their unsaturated equivalents. The large velocity range in the conglomerates (Table 1) was primarily a function of cementation or saturation, or both. A partially cemented, nonsaturated conglomerate would have a velocity at the lower end of the range, extending from 5,000 to 7,000 fps (feet per second). A well-cemented, fully saturated conglomerate would be expected to have a velocity near the upper end of the range and extend from 9,000 to 12,000 fps. This velocity increase due to saturation is similar to that found by Sjogren and Wager (1969) and Dugid (1968). A lesser increase was noted in an area where the water table was developed in a unit of much greater initial velocity. Here, the velocity increased by 1250 fps (from 9250 to 10,500 fps). It appears that the magnitude of velocity increase in a formation due to saturation is inversely related to the unsaturated velocity of the material. This phenomenon is being investigated. Without well logs for control, it is difficult to relate a change in slope on the time-distance graph to a change in stratigraphy or the effects of the water table when the velocity changes from the 4,000- to the 7,000-fps range to the 7,000- to 10,000-fps range.

One of the assumptions made in seismic-refraction interpretation, which may not represent field conditions precisely, is that velocity layers are recognizable as first breaks. Soske (1959) referred to significant deviations from this assumption in his blind-zone problem and pointed out that such deviations frequently occur where the water table occurs near the interface with the underlying bedrock. In the present study, efforts to detect ground-water levels were more successful in areas where a thick, saturated alluvium with an intermediate velocity overlay a high-velocity bedrock. Seismic profile B4 (Figure 3) gives an example of a time-distance graph and interpreted profile showing an increase in seismic velocity with a free water table. In other portions of the study area

(Figure 4), the water table was not detected because the returning signal from a high-velocity bedrock overtook and cut off the signal from the water table.

CONCLUSIONS

In general, the characteristic features of Basin and Range geology contribute to successful water-table depth determinations by the seismic refraction method. The great depths of alluvium, the large depth interval commonly encountered between water table and basement complex, and the sufficient velocity increase between the alluvial complex and bedrock are common features of the deep, alluvial-filled valleys of the Basin and Range Province. Subareas in which one or more of these conditions do not exist will naturally be encountered, and will thus require other techniques to obtain the desired information.

The "blind zone" situation is difficult to analyze by seismic refraction methods. Alluvial fill, when deposited on older erosional surfaces, often produces a highly irregular interface. If the water table is developed near this interface, refraction techniques may define the water table in one area but not in an immediately adjoining area. When seismic records show only bedrock at a lower elevation than where the water table had been determined in adjoining areas, the data must be questioned. Further work, preferably exploratory drilling, should be done to avoid erroneous interpretations in these areas.

The preset geophone spacing and cable length of most of the smaller seismic units necessitate varying the distance between the shothole and the geophone cables so that a deep alluvium-basement velocity break may appear on the seismic record. Sufficient reconnaissance gravity traverses to approximate the configuration of the basin proved a quick method of providing control so that seismic refraction may be successfully used for more detailed work in the deeper areas. By using two or three gravity profiles across a basin, the area in which seismics can be successfully used was greatly extended.

Seismic refraction surveys can be extremely valuable in reducing the cost of geohydrological exploration. If the limitations imposed on the method by various stratigraphic sequences and seismic characteristics of an area are carefully considered, exploratory drilling costs can be kept to a minimum.

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