



**SEISMIC REFRACTION STUDIES OF THE
SUBSURFACE GEOLOGY OF WALNUT GULCH
EXPERIMENTAL WATERSHED, ARIZONA**

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ABSTRACT

Seismic methods, combined with well and geologic data, were used to define the subsurface hydrologic and geologic conditions of the Walnut Gulch Experimental Watershed and its peripheral area, near Tombstone, Ariz. Surface geology of the watershed indicates an alluvium-filled area between igneous intrusive and sedimentary rocks that support the Tombstone Hills on the southwest and the Dragoon Mountains on the northeast.

In 11 areas, 52 seismic refraction profiles, aggregating a length of 115,550 feet of in-line seismic profiling, were conducted. Velocities derived from reversed seismic profiles and profiles conducted over outcrops averaged 2,200 f.p.s. for channel fill, 5,000 f.p.s. for unconsolidated alluvial deposits, 8,800 f.p.s. for conglomerates, and, depending on the particular unit, 12,300 to 15,600 f.p.s. for basement-type rocks. In many areas 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 groundwater or basement was ± 6 percent, while that for groundwater alone was ± 10 percent.

Analysis of the time-distance data and correlations with surface geology, gravity, and well data provided a framework from which geologic sections were constructed. These sections reveal the identification, depth, attitude, and extent of geologic units comprising the basement and alluvium complex. Extensions of many surface structural features to depth were noted.

SEISMIC REFRACTION STUDIES OF THE SUBSURFACE GEOLOGY OF WALNUT GULCH EXPERIMENTAL WATERSHED, ARIZONA¹

F. Libby, D. E. Wallace, and D. P. Spangler²

Seismic refraction studies were initiated on Walnut Gulch Experimental Watershed in the summer of 1967 and were completed in 1968. This watershed is an outdoor hydrologic laboratory near Tombstone, Ariz. (fig. 1), under the direction of the Agricultural Research Service, USDA. It is the subject of intensive hydrologic and sediment yield studies.

The purpose of the seismic study was to provide information concerning substrata conditions affecting the disposition of ephemeral stream channel water losses and groundwater movement and storage. The geophysical study area was increased to 290 square miles by including a peripheral area around the 58-square-mile watershed.

Ephemeral stream channel losses have been measured on Walnut Gulch by comparing inflow-outflow data on several channel segments. These measured losses have been explained in relation to the channel and subchannel geologic materials and related phenomena. The transmission losses need to be related to the channel geologic material to enable extrapolation of the data for design projects on unmeasured areas. A study of groundwater movement and storage in the watershed is continuing, with information needed on the piezometric surface and the extent of aquifer alluvium.

Specific objectives of the seismic 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 watershed aquifer alluviums; and
3. Determine the depth of regional water table.

Fifty-two seismic profiles, aggregating a length of

115,550 feet of in-line seismic profiling, were conducted in 11 areas (fig. 1).

Previous Work

Geological investigations have been conducted in conjunction with mining activities in the Tombstone Hills (part of which constitutes the southwest portion of the watershed) since the latter part of the 19th century. In the earliest reference, Blake (2)³ referred to the general geology and some local ore occurrences. Church (4) applied local stratigraphic names and enlarged on the general geology after further mine developments.

Jones and Ransome (10) published the first comprehensive work with a regional geologic map in a report dealing primarily with the occurrence of manganese ores. Rasor (13) submitted a mineralogic and petrographic study of the Tombstone Mining District to the University of Arizona as a dissertation.

Butler, Wilson, and Rasor (3) increased the scope of Ransome's original work, including a more detailed description of the geology. Gilluly (6) concluded this series of notable investigations with a regional study of the stratigraphy and bedrock geology of the Tombstone Hills, Dragoon Mountains, and the northern half of the Mule Mountains.

Hollyday (9) made a geohydrologic analysis of mine dewatering and water development in the Tombstone Hills.

A number of mining companies have been involved in exploration programs on and around the watershed. An aeromagnetic survey of Tombstone and vicinity by Andreasen, Mitchell, and Tyson (1) has been released to the U.S. Geological Survey open file. Spangler and Libby (16) conducted a reconnaissance gravity survey covering 290 square miles (including the watershed) as part of an integrated geophysical study of the area.

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³Underscored numbers in parentheses refer to literature cited, p. 14.

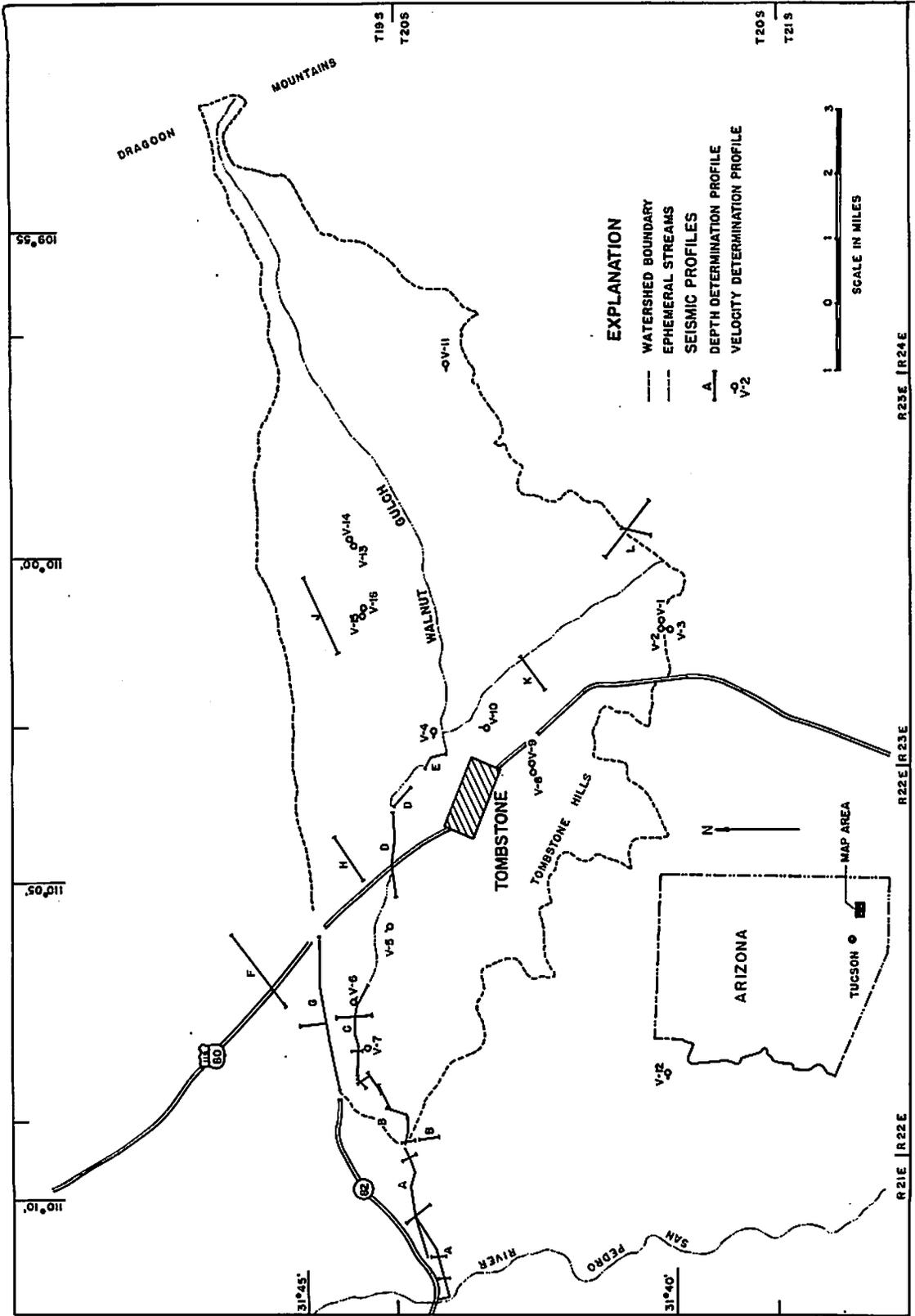


Figure 1.—Location of Walnut Gulch Experimental Watershed and periphery showing seismic study areas.

GENERAL GEOLOGY

The survey area, with isolated mountain blocks separated by a broad alluvium-filled basin, is typical of Basin and Range physiography.

Deep-seated igneous 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 (fig. 2). Great thicknesses of sedimentary rocks (mostly limestone) make up the topographic relief of the Tombstone Hills, which are underlain by, and adjacent to, large igneous bodies of Tertiary age. The igneous lower Dragoon Mountains of Triassic-Jurassic age have no sedimentary caprock; the only residual sedimentary rocks in this area are small limestone drag blocks along fault zones.

Late Tertiary volcanics in the southeast portion of the study area are relatively thin beds of andesite-

rhyolite flows and tuffs and are in an 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 area.

The alluvium that fills the intermontane basin consists of deep Tertiary and Quaternary sand, gravel, clay, and caliche conglomerate. Previous data indicate the alluvium is more than 1,200 feet deep in places and contains a large volume of groundwater. Much of the conglomerate is extremely well cemented, approaching the strength and appearance of structural concrete. These conglomerates act as rock units and exert much structural control on surface stream channels and groundwater flow.

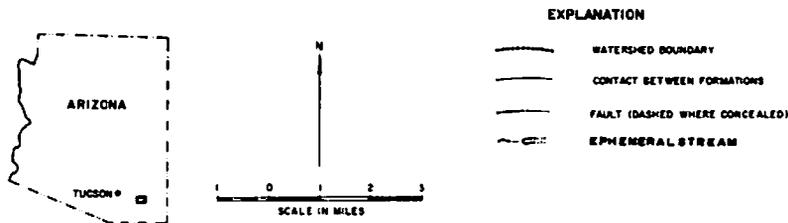
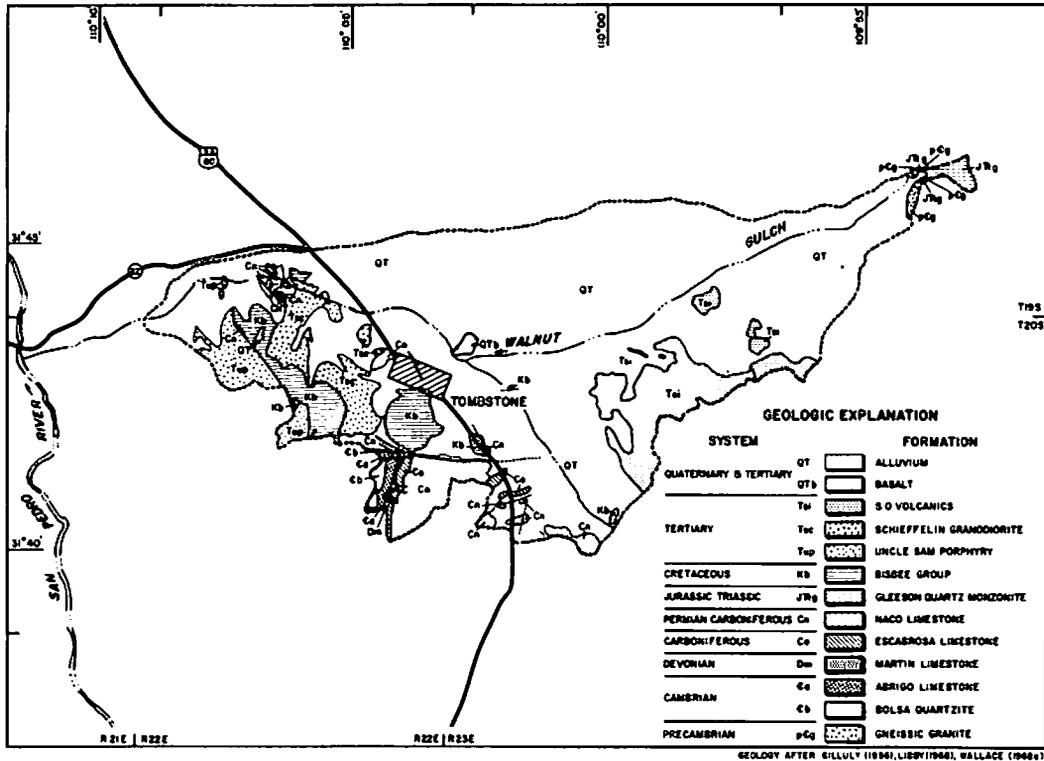


Figure 2.—Geologic map of Walnut Gulch Experimental Watershed.

SEISMIC SURVEY

A network of 360 gravity stations established over the watershed and its peripheral area helped define configuration of the basement complex, provided depth approximations of the deep alluvium, and determined the bearings for subsequent seismic traverses (16). Criteria for choosing the areas for seismic study were (1) areal priorities for the information, (2) control from surface geology and well data, or both, (3) a gravity survey, (4) terrain conditions, (5) distribution to provide coverage of the study area, (6) capabilities of the equipment, and (7) permission for ingress and egress on private land. Geologic and scheduling conditions required the use of a long geophone spread with sensitive equipment to speed survey progress in the field, and provide the depth penetration capability required to measure the thicknesses of alluvium in the watershed without using excessive explosives.

Fifty-two individual seismic profiles were made which, if put end to end, would make a line about 22 miles long (table 1). Most of the profiles were completed in the stream channel of the mainstem of Walnut Gulch, where large transmission losses occur during flow events (11). Several profiles were made in the deep alluvium portions of the watershed, where past drilling efforts had never reached bedrock but had shown alluvium depths in excess of 1,200 feet.

Instrumentation

The two sets of seismic instruments used were an Electro-Tech Port-Seis Interval Timer on loan from the Geophysics Laboratory of the University of Arizona and a refraction system designed by the Electrical Engineering Department of the University of Arizona in cooperation with the Agricultural Research Service.

TABLE 1.--Number and length of seismic profiles in the watershed area

Name of profile	Area (fig. 1)	Number of shot-profiles	Total length of profiles <i>feet</i>
San Pedro River to flume 1	A	13	24,950
Fume 1 to Montijo Flats	B	8	12,850
Lamb's Draw	C	7	12,500
Rifle Range	D	4	9,200
Gleeson Road	E	1	2,300
Willow Wash	F	3	10,600
Highway 82	G	7	15,750
City Dump	H	1	4,100
Bennett Ranch Road	J	3	10,050
Lime Tank	K	2	5,750
New Cowan Road	L	3	7,500
TOTAL		52	115,550

The first system was portable and provided 12 data traces, plus a shot-instant trace and 100-c.p.s. (cycles per second) timing marks on 4- by 5-inch Polaroid film. Reading accuracy was ± 1 msec. (millisecond). Recording time was adjustable between 200 and 400 msec. Twelve 30-cp.s. geophones could be attached to either a 600-foot cable with takeouts every 50 feet or an 1,800-foot cable with takeouts every 150 feet. Transistorized amplifiers, coupled to 125-c.p.s. galvanometers, transferred the seismic signal from the geophones to the film. A 90-volt blaster was used to detonate the explosives.

The second system, mounted in a 4-wheel-drive van, used a Century Model 408 oscillograph that provided 24 data traces with the shot-instant on trace 12 or 13. Data traces and 10- and 100-c.p.s. timing marks were made on Kodak Linagraph No. 809 paper. The paper was developed in the field by wet chemical processing in an aerial photographic film-developing unit. Reading accuracy was ± 1 msec. Recording time could be as long as desired and could be controlled manually or automatically. Twelve Geospace 7.5-c.p.s. geophones were permanently attached to a 1,355-foot cable with takeouts every 110 feet. Two cables were used with 100-foot lead-ins to the recording van, which was located in the middle of the spread. Vacuum tube amplifiers, coupled to 100-c.p.s. galvanometers, were used during the summer of 1967. A 120-VAC generator mounted on the front of the van provided power. Before the summer of 1968, the system was modified to use solid-state amplifiers, powered by wet cell batteries. This latter system produced greater amplification and eliminated vibrations from the generator. A 255-VDC blaster with insulated telephone wire from a mounted power reel was used to detonate the explosives.

Field Procedure

Field procedure varied with site conditions and information requirements, but the maximum spread length procedure was used most. The 12-channel unit had an 1,800-foot spread length, and the 24-channel unit had a 2,200-foot spread length. Where very deep subsurface penetration was required, the shotpoint was placed well away from its nearest geophone, whereas relatively shallow strata could be recorded using a close-in shotpoint. Most of the profiling was done with a spread length of 2,200 feet and an in-line shotpoint offset 50 feet from each end. Many of the offsets in the deep alluvial deposits were determined by a combined

study of the gravity and well data. The seismic profiles were shot from both ends, giving reversed time-distance data.

Three variations of the in-line profiling were used in the survey. A continuous series of reversed profiles was made in the channel and in area G. Short reversed profiles, crossing approximately at right angles, and spaced along the continuous profiles, permitted closer control of velocity, depth, and dip. Discontinuous profiling was selected for areas where terrain was rugged

or partially inaccessible and greater distribution was desired.

Shotholes up to 20 feet deep were loaded with Apache Powder Company 60-percent Amogel in 2-inch, 1-pound sticks, and the charges were detonated with Atlas no-delay electric blasting caps. This combination propagated a satisfactory seismic wave. Charges ranged from 1 pound to 28 pounds per shot, with 3 pounds being most common on a 2,200-foot spread with a 50-foot offset.

INTERPRETATION

If boreholes or sonic logs are not available, the velocities must be determined by measurements along the surface (7). Velocity determinations were conducted on surface exposures (fig. 1) of geologic units to interpret the seismic profiles and extrapolate useful relationships to density. Locations were selected to give 250 feet or more of fresh in-line exposure on a level surface.

Several refraction velocities were taken from the reversed seismic-profile records in which nearby exposures of well-control data justified a direct identification of rock type. Velocities for the channel and alluvial deposits also were determined from several seismic-profile records. These data were then used to compile a table of seismic velocities (range and average) representative of the study area (table 2).

The range of velocities agrees very well with the histograms of seismic-wave velocities for similar rock units presented by Grant and West (7). One exception—the lower end of the velocity range for the Uncle Sam

porphyry—may have been caused by fracturing. Because the high end of the range of velocities for channel deposits is represented by only one value, the true range is probably closer to 1,150 to 3,500 f.p.s. (feet per second). Only two values represent the low end of the range for unconsolidated alluvium, with the true range probably closer to 4,000 to 6,000 f.p.s.

A convenient plot of density versus velocity, using values from table 2, indicates that bulk densities tend to increase with seismic velocity (fig. 3). Relationships of velocity versus density have been described as a function of lithification accompanying age and compaction (7).

TABLE 2.—Seismic velocities and densities of geologic units in the watershed

Geologic unit	Geologic symbol	Velocity range	Velocity average	Density average
		ft./sec.	ft./sec.	
Recent channel deposits	Qal	1,150-4,900	2,200	..
Quaternary-Tertiary alluvial deposits	QT
Unconsolidated Conglomerates		3,350-6,000	5,000	2.02
Quaternary-Tertiary basalt	QTb	6,000-12,350	8,800	2.34
S. O. volcanics	Tsi	..	¹ 15,600	2.80
Pre-S. O. volcanic sedimentary rocks	Ts	..	¹ 12,300	2.33
Schieffelin granodiorite	Tsc	7,550-10,925	9,700	2.48
Uncle Sam porphyry	Tup	12,300-17,700	15,450	2.68
Bisbee group	Kb	10,100-16,400	13,350	2.61
Naco limestone	Cn	12,100-16,400	13,650	2.70
		11,850-16,000	13,350	2.69

¹ Values based on a single unreversed velocity profile.

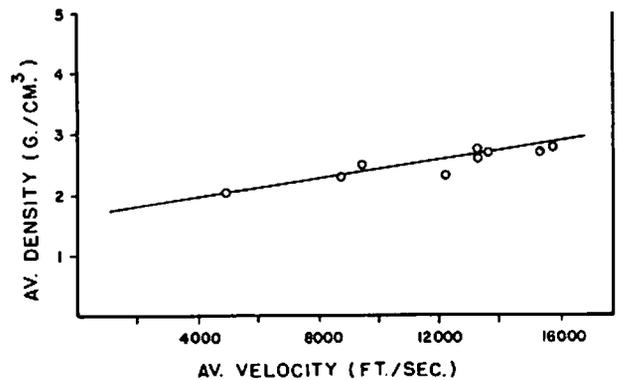


Figure 3.—A plot of bulk density versus seismic velocity for geologic units in the watershed

The magnitude and sign of the total error in seismic-calculated depths are functions of field techniques, instrumental compatibility, and interpretation. Assuming proper field techniques and instrumental compatibility, Northwood (12) classified interpretative

refraction errors by their causes under three general headings: (1) errors caused by incorrect reading of data; (2) errors caused by incorrect assumptions; and (3) errors caused by incorrect geologic interpretation of the velocity layers.

Using this type of analysis for the watershed, seismic-calculated depths to the groundwater table and basement were compared to actual depths derived from data on a nearby well. Figure 4 illustrates this comparison graphically. In general, the deviations do not suggest a systematic error one might expect if all the calculated depths were greater, or less, than the actual depths. The accuracy of predicting the depth to either groundwater or basement was ± 6 percent. The accuracy of predicting the depth to groundwater alone was ± 10 percent, and that for basement alone was ± 4 percent.

The prediction becomes less accurate with greater depths. Northwood (12) explained this as a function of reading errors caused by greater offset distances. Greater offset distances cause decreases in the signal amplitude

and an attenuation of the higher frequency components. Errors were kept to a minimum by increasing the charge and depth of shothole. For example, shotholes 4 feet deep and 50 feet in-line from a 550-foot spread contained 2-pound charges, whereas shotholes 20 feet deep and 1,300 feet in-line from a 2,200-foot spread contained 21-pound charges.

The prediction of depth to the groundwater table was less accurate than the prediction of depth to the basement. This difference may be explained by the greater horizontal distances over which the groundwater depths were projected from individual wells to the seismic profiles. Changes in groundwater level between the time of reading and the time of the seismic profile also may have caused minor errors. Finally, the capillary zone and its variable thickness and effect on seismic response are unknown and need further investigation.

The seismic data were interpreted by the critical distance and time intercept methods (8) (5). Interpretations were most commonly based on 2- and 3-layer

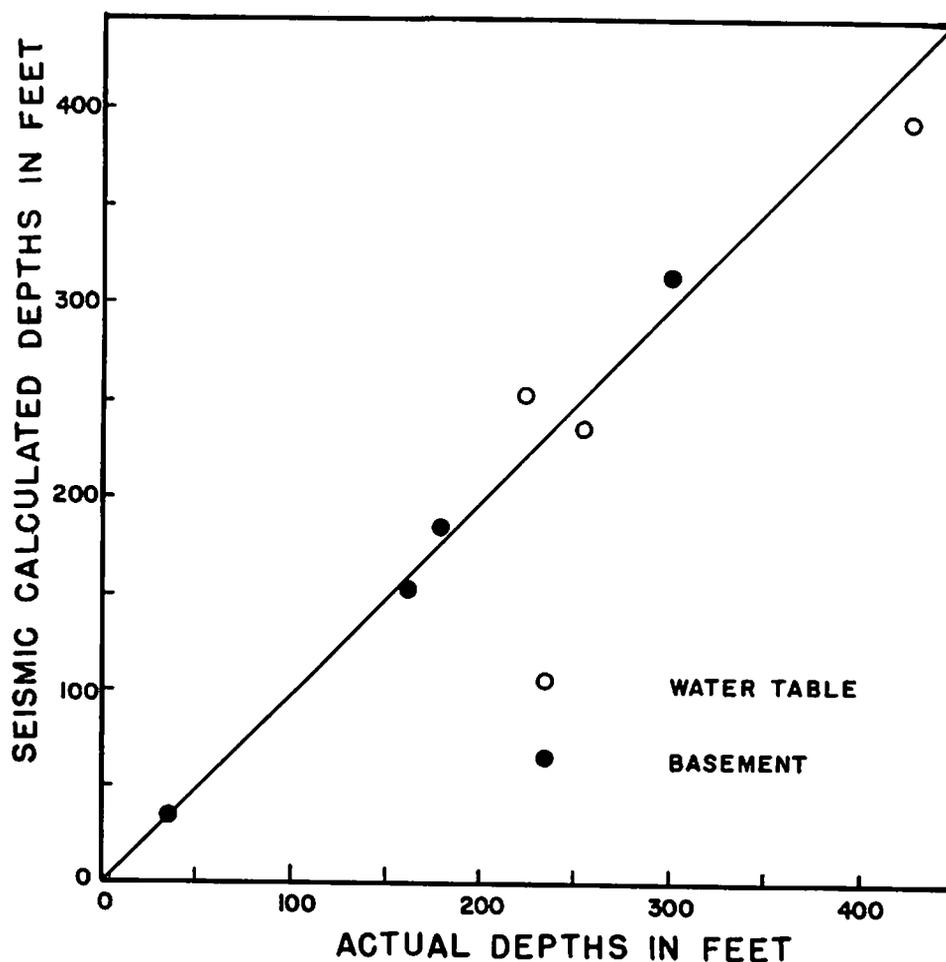


Figure 4.—A plot of seismically calculated depths versus depths derived from well logs.

horizontal and dipping interfaces. In a few instances, 4-layer and fault solutions were applicable.

San Pedro River to Flume 1 (Area A)

A continuous seismic profile, containing seven reversed profiles and one overlapping, unreversed profile, was conducted up the channel of Walnut Gulch for 2.5 miles, starting 1,200 feet downstream from the confluence of Walnut Gulch and the San Pedro River. Plate 1 presents these data and several profiles across the channel, and contains (1) an equal-scale planimetric map showing the location of all traverses in area A; (2) time-distance diagrams showing travel time to individual geophones; and (3) geologic interpretations based on the time-distance diagrams. For orientation, the geologic sections are noted by the four compass quadrants. Flume 1—a prerated, critical-depth, concrete structure for measuring the total streamflow from the upper 58 square miles of the Walnut Gulch drainage basin—is located 100 feet from the northeast end of the profile (plate 1).

The dominant geologic structure in area A, an alluvium-filled trough, was first noted by the gravity survey which predicted a north-trending structural depression 800 to 1,200 feet beneath the channel and centered 1.2 miles below flume 1. Surface geological investigation revealed the Uncle Sam porphyry exposed in several locations near area A. Using this information and velocity determinations (table 2), the basement rock forming the trough was interpreted as the Uncle Sam porphyry. The porphyry dips 12° toward the center on the right flank and 10° on the left flank. Profile A1 on the left flank indicates the porphyry rises to within 125 feet of the bed of the San Pedro River 1,200 feet downstream from the Walnut Gulch confluence. If the flanks maintained this attitude, the trough would be 1,300 feet deep at its center.

Because no recorded refractions from the basement could be identified on the time-distance diagrams in the center of profile A1A-A7', a 2,300-foot reversed spread with shotpoints offset 850 feet was attempted in profile A10. Although refracted arrivals cannot be positively identified from the basement on this profile, the two most distant points on the reversed curve may be recording basement refractions. Because this is the earliest time interval at which a basement refraction could occur, a minimum thickness of the alluvial deposits can be estimated. To make such an estimate, we calculated a basement velocity of 13,000 f.p.s. between the points. The results of true velocities on the flanks, and the reported value in table 2 of 13,350 f.p.s. for the Uncle Sam porphyry, show that 12,000 f.p.s. is reason-

able. The assumption that the basement is flat in this area for estimating purposes is reasonable from an inspection of gravity gradients and because projections from the flanks in profile A1A-A7A' indicate a greater depth than that calculated from gravity results. The intercept time of possible basement refraction is 0.194 second. A minimum total thickness of 650 feet for the sedimentary section was determined using the velocities from the seismic profile. The trough has: a minimum depth of 650 feet based on the earliest possible refractions from profile A10; a maximum depth of 1,300 feet if the flanks in profile A1A-A7A' maintain the same slopes; and an estimated depth range of 800 to 1,200 feet based on gravity data. Until more data (i.e., a longer seismic spread in the channel or a drill hole to basement near the axis) become available, a depth of 1,000 feet to the Uncle Sam porphyry seems reasonable near the center of the trough.

The sediments in the trough may be grouped into two broad units: Tertiary and Quaternary alluvial deposits; and Recent channel and flood plain deposits. The oldest and thickest unit contains the Tertiary and Quaternary alluvial deposits that are exposed in the east bank of the San Pedro River at profile A1 and outside the channel of Walnut Gulch below flume 1. Remnants of the older alluvium remain along Walnut Gulch approaching the San Pedro River flood plain. Surface exposures of the remnants are shown in profiles A10 and 11, in which offsets in the time-distance curves could have been misinterpreted as faults. A similar offset in the time-distance curve of profile A4 is interpreted as a buried erosional scarp that has 32 feet of relief. From a geomorphological viewpoint, the buried scarp expresses, in a subsurface manner, topographic evidence of the edge of the San Pedro River flood plain.

In general, the time-distance diagrams reveal a decrease in velocity within the older alluvial deposits as the axis of the trough is approached. A relatively shallow water table tends to give uniformity to the seismic results. Apparently the alluvial deposits become younger and less consolidated as the center of the trough is approached. Assuming the subsurface deposits in the center are not composed of claylike material (which can give similar velocities), we concluded that the area occupied by profiles A4, A5, A11, and A12 is best suited to future groundwater testing and development. This area also contains large thicknesses of low-velocity Recent channel fill that imply greater transmission losses during flood flows. Finally, the irregular interface between the two units, as suggested by the erratic travel times in profile A5, may provide temporary storage areas for the transmission losses until the losses are depleted by percolation to the groundwater table (17).

The Recent channel and flood plain deposits within the San Pedro flood plain were divided into two subunits, based on an intermediate slope in the time-distance diagrams. The two units, channel fill and subchannel fill, reach a maximum thickness of 200 feet on the northwest end of profile A9. The interface between these deposits and the older alluvial deposits in profiles A8 and A9 indicates a gradient of 2 to 4 percent, which is four times the present gradient of the San Pedro River. Although the profiles are oriented approximately parallel to the strike of the river, very recent changes in its course are evident in the field and on topographic maps. The steeper gradients may represent apparent slopes within much older meander loops. Tilting or change in erosional regime may be other explanations.

Mapping the water table by seismic methods in area A was hindered by (1) insufficient water-level data to correlate with slope intercepts on the time-distance plots, and (2) near coincidence with other interfaces. These interfaces were between the channel fill and subchannel fill in the San Pedro River flood plain, the channel fill and older alluvial deposits in the center of the area, and the older alluvial deposits and the Uncle Sam porphyry near flume 1.

A theoretical plane surface connecting the bed of the San Pedro River with the known occurrence of groundwater immediately above flume 1 could approximate the water table. This theory assumes that the water table has a constant slope, and the San Pedro River is effluent. The first assumption appears valid from solutions of the time-distance curves of profiles A6 and A7, in which an interface exists in the deep alluvium at a depth of 130 feet. The second assumption may have minor local departures. For example, 40 feet of dry, low-velocity channel fill was determined on profiles A2 and A2A near the Southern Pacific Railroad (plate 1). When projected, this establishes the water table 20 feet below the San Pedro River. Therefore, the recently formed reach of the river has not had sufficient time to entrench itself into the well-cemented alluvial deposits exposed on its eastern bank. If this is true, the local nature of the river is influent, creating a groundwater mound at the Walnut Gulch confluence. Finally, any flow beneath Walnut Gulch channel may be diverted to an old meander of the San Pedro River.

Flume 1 to Montijo Flats (Area B)

Between flume 1 and the lower end of Montijo Flats, the channel of Walnut Gulch consists of a series of meanders deeply entrenched in the Tombstone Piedmont. The planimetric map illustrates the limits such

meanders place on the longer seismic spreads (plate 2, area B). Because the spread had to cross one of the meander loops in profile B1, older alluvium is noted in the profile midsection.

The four spreads in the channel in area B are shown as a composite cross section in profile B1A-B4A'. Profiles outside the channel were discontinuous, with varying lengths to avoid serious topographic effects. Except for the short profiles of B7 and B8 in Montijo Flats (where 300 feet of alluvium had been penetrated by a well), all profiles were sufficiently long to record refractions from the basement. Evidence from the longer profiles of B3 and B4 in the channel indicates depths of 450 feet to the basement, which is the Uncle Sam porphyry in area B.

Probably the most striking feature of area B is the amount of relief on the porphyry. This relief varies from the 3,620-foot elevation in profile B4 to a surface exposure at 4,075 feet in profile B6. Surface relief on the porphyry is even more pronounced southeast of area B in the flanks of the Tombstone Hills. True velocities of the porphyry ranged from 10,100 f.p.s. to 14,100 f.p.s. and averaged 12,200 f.p.s. Although the lower velocity suggests some weathering, drilling several holes confirmed the presence of fresh rock.

An old meander loop has been interpreted from the delay times on the time-distance plot of profile B1. The asymmetrical cross section of the old buried channel appears entrenched 80 feet into the porphyry. A 3,760-foot elevation on the channel bottom and a similar one in the southeast section of profile B5 suggests lateral continuity. Wallace and Renard (17) mentioned the presence of an old meander loop from surface evidence in this area. This loop is considered more recent than the one entrenched within the porphyry. Seismic response did not indicate the presence of the stratigraphic boundaries within the alluvium that might be expected from a buried channel. The buried channel may show as a structure only on the interface between the porphyry and the alluvium. Later deposition within and above the depression must have been relatively uniform.

A buried porphyry ridge crosses the Walnut Gulch channel between profiles B1 and B2. If the ridge is consistent with other plunging ridges noted along the edge of the porphyry, it will plunge to the northwest. Indications from seismically determined depths to the regional water table and from the magnitude of relief on the ridge beneath the channel are that most subsurface movement of water in the saturated zone is deflected away from the channel to the northwest.

Mapping of the water table northeast of the buried ridge to Montijo Flats was successful because a sufficient

thickness of alluvium existed between the water table and the porphyry. The water table, 250 feet deep, approximately parallels the land surface slope. Drillers' logs from wells in the Montijo Flats helped correlate seismic velocities with the saturated zone (fig. 4). West of the ridge in profiles B5 and B1, the water table could not be detected because of the proximity of the interface to the porphyry. Soske (15) described a similar problem as the blind zone problem.

Seismic velocities above the porphyry and below the water table north of the buried ridge suggest well-cemented alluvial deposits of Quaternary and Tertiary age (table 2). Velocities ranged from 8,575 f.p.s. to 10,125 f.p.s., with an average of 9,375 f.p.s. Southwest of the buried ridge, the absence of well-cemented deposits suggested that the ridge may have been a boundary between sedimentational regimes during deposition. Loosley to partially cemented alluvium above the water table had seismic velocities ranging from 4,250 f.p.s. to 6,000 f.p.s., with an average of 5,230 f.p.s. Overlying the 250 feet of alluvium is a thin veneer of Recent channel fill averaging 18 feet in thickness, with a velocity of 2,200 f.p.s.

Lamb's Draw (Area C)

Three bedrock types—the Naco limestone, the Bisbee group, and the Uncle Sam porphyry—occur in the subsurface interpretation of profile C1A-C4A' (plate 2, area C). Internal contacts in area C were interpreted from the geologic map in figure 2 because the seismic velocities of the three formations show little contrast (table 2). The Naco limestone crops out in the hills on both sides of profile C4 and is folded and faulted in a complex manner. In several areas below the concrete apron (an old highway crossing), the channel fill deposits are swept clean, and the exposed rock resembles marble. Profiles C6 and C7 show a fairly uniform slope to the north and northwest, although the time-distance data of profiles C3 and C4 indicate that the interface between the Naco limestone and the overlying alluvium is uneven. The Bisbee group is exposed between the Uncle Sam porphyry and the Naco limestone in a wide outcrop one-half mile southeast of profile C2 and has a strike that lends itself to this projected interpretation. From the seismic data, we could not determine if the contact was intrusive or faulted. A sharp ridge of the Uncle Sam porphyry is exposed immediately south of profile C5 and deflects the channel from a southwest to northwest course. Profile C5 shows that the ridge plunges sharply beneath the channel to the north.

From west to east in profile C1A-C4A', 375 feet of Tertiary and Quaternary alluvial deposits thin to approx-

imately 80 feet over the buried, plunging porphyry ridge, thicken to 200 feet over the Bisbee Group, and lens out beneath the channel fill in the midportion of profile C4. Velocities within the alluvial deposits beneath cross profiles C5, C6, and C7 indicate a range of consolidation from loose to partially cemented. The profile velocities beneath the channel imply a slightly higher degree of consolidation because of the higher moisture content.

The water table was not detected in area C, although it was known to be 250 feet deep in the west and southwest portions of area B. The western time-distance curve of profile C1 would be expected to show a 9,000-f.p.s. segment between the 6,750-f.p.s. velocity and the 12,650-f.p.s. velocity if the saturated zone was to be detected. This omission is similar to the western profiles in area B. East of the plunging porphyry ridge in area C, the regional water table was not detected, although it was believed to be near the contact with the Bisbee group.

Recent channel deposits average 25 feet in thickness and increase from zero in certain portions of the channel on profile C4 to between 35 and 40 feet in profiles C2 and C3. Seismic velocities within these channel deposits are similar to those in areas A and B. The 3,200-f.p.s. velocity in the thicker deposits is 1,000 f.p.s. higher than the average and may be a function of saturation, because the traverse was conducted shortly after a runoff event.

Rifle Range (Area D)

A continuous, in-line seismic profile up the Walnut Gulch channel and intersecting U.S. Highway 80 northwest of Tombstone is shown as area D in plate 2. A 1.5-mile channel length between areas C and D was omitted in this study because exposures of the Naco limestone and the Schieffelin granodiorite eliminated the need for seismic coverage. The geology and hydrogeology of a shallow, perched water aquifer within pockets of the Schieffelin granodiorite, one-half mile west of area D, had already been studied intensively (14).

Time-distance graphs from profile D1A-D4A' reveal an interface of granodiorite sloping east toward the deeper alluvium. The 4° slope shown in the geologic cross section and derived from the time-distance curves is only an apparent slope. A northwest structural trend, and geologic, hydrogeologic, and other geophysical data suggest a maximum gradient oriented N.35° to 45° E. These integrated data conclusively show a subsurface drainage pattern almost the reverse of that suggested by the surface slope of the channel. Transmission losses to the channel fill in the area of U.S. Highway 80 do not

have subsurface hydraulic continuity with the shallow, perched water aquifer to the west and down channel. Although we do not know the exact location of the groundwater divide created by the Schieffelin granodiorite between these two areas, the seismic data indicate its presence immediately west of profile D1.

Inspection of the time-distance graphs in profiles D1 and D2 reveals similar downdip velocities of 13,500 f.p.s. and 12,300 f.p.s., respectively. On the other hand, an updip velocity of 19,200 f.p.s. in profile D1 is almost twice that of 10,180 f.p.s. in D2. These data indicate that the slope of the granodiorite determined in profile D1 does not extend at the same rate beneath all of profile D2. The slope was extended as far as the seismic data would justify and was terminated by a normal fault. A fault interpretation appears reasonable from an inspection of drilling logs that reveals the basement at a depth of 160 feet immediately southwest of the profile with at least 1,160 feet of alluvium to the northeast. Spread lengths in the seismic profiles were not sufficient to determine the depth to basement on the downthrown side of the fault.

Time-distance graphs east of the fault (plate 2, area D) indicate three apparent facies of the Tertiary and Quaternary alluvial deposits. These facies are believed to result primarily from consolidation or cementation. Scattered exposures along the channel bed did not show visible differences in the conglomerates.

A high-velocity conglomerate at a depth of 250 feet in profile D3 correlated with a hard, gray conglomerate logged in a well one-half mile south at a depth of 280 feet. This conglomerate is the controlling factor of the water table's position in this area.

The 6,000- to 9,000-f.p.s. velocity for the conglomerates exposed in the channel suggests minimum transmission losses in the areas traversed by profiles D3 and D4. Conglomerates are not exposed in the channel bed in profile D2, and the seismic velocity for the channel fill is higher than average. This area has been interpreted as a gradational zone between the high-velocity, well-cemented conglomerates in the basin proper and the channel fill overlying the Schieffelin granodiorite.

Gleeson Road (Area E)

Area E in plate 2, approximately one-half mile up the Walnut Gulch channel from area D, reveals channel fill 10 to 20 feet thick and two facies of the Tertiary and Quaternary alluvial deposits. The upper facies, with an average seismic velocity of 5,750 f.p.s., increases in thickness from 70 feet up channel to 160 feet down channel. This facies is thought to correlate with a partially cemented, cobble and boulder conglomerate in

a thick, cutbank exposure immediately up channel. A lower facies, with a velocity of 8,550 f.p.s., correlates with exposures 1,000 feet down channel. This indicates the unit is either downthrown by faulting, or that an 8° rise is necessary to return it to the channel surface between areas D and E. The lack of high-velocity slopes on the time-distance graphs shows that basalt, exposed 500 feet east of profile E, does not extend beneath the channel. This tends to confirm the presence of a fault, discussed under area D.

Willow Wash (Area F)

Area F consists of a seismic profile with a bearing of N. 55° E. located 1 mile northwest of the watershed boundary of Walnut Gulch in Willow Wash (fig. 1 and plate 2). Information from well and gravity data west of U.S. Highway 80 indicated that the basement rocks exposed in the Tombstone Hills extended northwest, north, and northeast beneath the alluvial deposits. Therefore, knowledge of the basement attitude in area F was necessary to strengthen this indication. Information on groundwater occurrence in area F and the nature of the overlying alluvium was also essential to substantiate a "noselike" extension in a preliminary water table map.

Geologic interpretations of profile F1A-F3A' in plate 2 revealed a very thick deposit of alluvium overlying a sloping basement identified as the Bisbee group. To determine the degree of slope and identify the rock type, we had to depend on information from the drilling logs and the first arrival times from profile F1. This analysis is limited by the assumption of uniform dip and the use of an apparent velocity in the depth calculation. Nevertheless, the 8° to 10° northeast slope compares favorably with the 12° to 14° approximation from gravity data. The velocities and slope intercepts derived from the time-distance graphs suggest that the Tertiary and Quaternary alluvial deposits extend to a depth of at least 1,200 feet on the northeast and consist of three horizons.

A depth determination of 900 feet to the lower horizon was based on the unreversed travel-time curve of profile F3. A constant interface was extended west as a dashed line in the cross section and was based on the lack of offsets in the travel-time curve. Profile F2 was too short to provide sufficient penetration to the lower horizon. Also, the final three traces in profile F3 imply a slower velocity above the basement and beneath profile F2. The 11,750-f.p.s. velocity would place this material in the well-cemented conglomerate range (table 2). With the water table as an upper interface and an average velocity of 10,000 f.p.s., an intermediate horizon has a 600-foot thickness that decreases southwest over the

basement. The velocities shown in table 2 suggest this horizon is also well-cemented conglomerate. The 4,875-f.p.s. velocity in the upper horizon of profile F3 is typical of the loosely to partially cemented alluvial deposits above the water table in the Walnut Gulch Experimental Watershed. A veneer of Recent channel deposits completes the section.

Highway 82 (Area G)

Area G (plate 3) extends 2.5 miles east-west along Arizona Highway 82 and lies between area C (one-half mile south) and Area F (1 mile north) (fig. 1). In general, the data from area G corroborated findings in areas C and F. The basement complex supporting the Tombstone Hills plunges beneath the alluvium to the northwest, north, and northeast. In the central portion of area G, depths to basement were 275 to 325 feet. The basement was not detected in the most westerly profile, indicating a thick alluvial cover there. The most easterly profile revealed a basement slope to the northeast of 10° with a final depth of 575 feet. This slope agrees with findings in most of the other profiles oriented northeast. Based on the seismic velocities and projections in figure 2, the 13,000- to 15,000-f.p.s. basement velocity east of center was interpreted as the Bisbee group. The highest velocities could indicate the Schieffelin granodiorite. Wallace and Cooper (18) inferred its presence beneath this area from a chloride ion concentration map derived through a water-quality study of the groundwater. A velocity of 12,000 f.p.s. for the basement west of center was interpreted as Naco limestone. A profile oriented to the northwest near the center, and showing a small dip, confirms the presence of a shelflike feature that was previously inferred from gravity data.

Overlying the basement are Tertiary and Quaternary deposits ranging in velocity from 5,000 to 7,000 f.p.s. First arrivals necessary for correlation to a water table were not positively identified in area G. We postulated that the high elevation of the basement did not permit development of the regional water table, although the overlying alluvium is 300 feet thick. The presence of a 300-foot dry hole that penetrated the basement immediately east of area G appears to confirm this postulate.

City Dump (area H)

In area H, large offsets of the shotpoints prohibited first arrivals of the upper layer from showing in the time-distance graphs (plate 3). For depth calculations, we assumed a 5,200-f.p.s. velocity for the loose Tertiary and Quaternary alluvial deposits from an average of several adjacent profile areas. Based on this assumption, a thickness of 125 feet on the southwest increased to

275 feet on the northeast. A second interface, 425 feet in depth and increasing to 500 feet on the northeast, separates two layers with velocities greater than 10,000 f.p.s. A lithologic interpretation of well-cemented conglomerates for both layers is based partly on drillers' logs from a well to the southeast, which showed that basement was not penetrated in a total depth of 1,160 feet. The interface also correlates with a deep interface in area D to the southeast and area F to the northwest (plate 2).

Bennett Ranch Road (Area J)

Beneath area J in the north-central portion of the watershed, Tertiary and Quaternary alluvial deposits extend the full 1,000-foot depth explored by the seismic profiles (plate 3). This finding is substantiated partly by drillers' logs from wells to the southwest and northeast, which show alluvial deposits the full extent of their respective depths of 500 and 662 feet. An inspection of gravity profiles reveals a thickness of 2,000 feet for the alluvial deposits beneath area J. Time-distance graphs showed three velocity layers of 4,875, 9,000, and 11,350 f.p.s. The upper interface between loose alluvium and conglomerate is irregular and has a maximum depth of 150 feet. The lower interface is interpreted as the water table and reveals a depth of 400 feet on the southwest, increasing to 475 feet on the northeast. This gives the impression of a water table inclined toward the Dragoon Mountains. However, a 2.5-percent slope in the topography gives a net 0.8 percent water-table gradient to the southwest beneath area J.

Lime Tank (Area K)

We chose a seismic traverse in area K (plate 3) for exploring the extent of a normal fault inferred from seismic data in areas D, E, and H (plates 2 and 3). A layer coincident with the land surface, and 530 feet in depth beneath the southwest portion of area K, had a velocity of 13,050 f.p.s. This velocity could represent either the Bisbee group or the Naco limestone (table 2). An exposure of the Naco limestone and the Bisbee group in a faulted complex one-fourth mile southwest and an exposure of the Bisbee group three-fourths mile north did not offer a positive means of choosing between them (fig. 2). A tentative assignment of the Bisbee group beneath area K was based on the nature and location of the northern outcrop. Because first arrivals from the Bisbee group were not detected on the time-distance graph of a long seismic profile extending to the northeast, an offset was inferred in the interface that was determined from a shorter spread to the southwest. We calculated the minimum depth to the interface to be

780 feet, making 250 feet a minimum estimate for the displacement on the fault. Based on seismic velocities and exposures northwest and southeast of area K, the section overlying the Bisbee group was interpreted as pre-S.O. volcanic sedimentary rocks. These exposures, limited to the beds and banks of washes, were too small in area to show in figure 2. A surface veneer of Tertiary and Quaternary alluvial gravels thickens to 75 feet on the northeast. A water table interface may be associated with a change in velocity from 8,300 to 10,825 f.p.s. This occurs at a depth of 200 feet on the southwest and 300 feet on the northeast. A mining shaft one-half mile northwest revealed a depth of 254 feet to water.

New Cowan Road (Area L)

In area L, 5 miles southeast to Tombstone, seismic profiling was conducted across the watershed boundary to determine if the groundwater and surface water divides were coincident (plate 3). Figure 2 indicates that Naco limestone crops out one-half mile to the southwest and the S.O. volcanics one-fourth mile to the northeast. Table 2 indicates an average velocity of 9,700 f.p.s. for the pre-S.O. volcanic sedimentary rocks and an average

velocity of 8,800 f.p.s. for the Tertiary and Quaternary conglomerates.

Geologic cross sections, interpreted from the time-distance data in profiles L1, L2, and L3 (plate 3), show an average depth of 65 feet for the loose alluvial deposits with a velocity of 4,500 f.p.s. This depth increases to 95 feet to the southeast in profile L2 and decreases to 41 feet to the north in profile L3. The attitude of the interface between the loose Tertiary and Quaternary alluvial deposits and the underlying pre-S.O. volcanic sedimentary rocks is approximately the same as the surface attitude.

An interface within the sedimentary rocks has been interpreted as separating a sandstone-mudstone facies from a conglomerate facies. This interpretation is based on the time-distance graphs, a limestone conglomerate outcrop 2,000 feet west of area L, and a driller's log from the nearest well, 1 mile southeast. Several minor steplike faults have been interpreted from the displacements in the time-distance graphs of profiles L1 and L3. The attitude of the interface derived from profile L3 suggests that the pre-S.O. volcanic sedimentary rocks dip beneath the S.O. volcanics, which crop out immediately to the northeast. This supports field observations by Gilluly (6) in adjacent areas.

DISCUSSION

Although the velocity with which a layer transmits seismic waves cannot be used to clearly identify its exact lithology and its hydrologic characteristics, the velocity can be used successfully in calculating or predicting depth to the layer. Errors caused by incorrect geologic and hydrogeologic interpretation of velocity layers can be reduced if a framework of control can be established from a few wells in an area, and if a number of velocities are first determined directly on known outcrops. Problems of interpretation may still arise if the ranges or averages of velocities of several different formations group around common values (as noted in table 2 with the Naco limestone, Bisbee group, and the Uncle Sam porphyry).

Rock fracturing and weathering may influence the arrival times in velocity determinations over outcrops. In this study, we chose the highest value derived from the time-distance graph as representative. Placing the geophones and charges properly in rock, to get a good signal on the record, also involved problems.

Water-saturated alluvial deposits had significantly higher seismic velocities than their unsaturated equivalents. The large velocity range in the conglomerates (table 2) was primarily a function of cementation or saturation or both. A partially cemented, nonsaturated conglomerate occupied the lower end of the range,

extending from 5,000 to 7,000 f.p.s. A well-cemented, fully saturated conglomerate occupied the upper end of the range, extending from 9,000 to 12,000 f.p.s. Without well logs for control, it is difficult to relate a change in slope on the time-distance curves from the 4,000- to 7,000-f.p.s. range to the 7,000- to 9,000-f.p.s. range to a change in stratigraphy or to the effects of the water table.

One of the usual assumptions made in seismic-refraction interpretation, which may not represent field conditions precisely, is that velocity layers are recognizable as first breaks. Soske (15) referred to significant deviations from this assumption as the blind zone problem and pointed out that such deviations frequently occur where the water table is near the interface with the underlying bedrock. In our study, efforts to detect groundwater levels were more successful in areas where a thick, saturated alluvium with an intermediate velocity overlies a high-velocity bedrock. Seismic profile B4 (plate 2) gives an example of a time-distance graph and interpreted profile showing an increase in seismic velocity caused by the groundwater interface. In portions of areas A, B, C, D, and G, 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.

As Dobrin (5) noted, refraction shooting across a fault may reveal parallel, displaced linear segments on the time-distance graphs. In this case, the segments correspond to the upthrown and downthrown sides of the fault, and the throw is determined by the difference between the intercept times of the two segments. However, the displaced segments do not appear on the time-distance graphs in area D. Seismic profile D2

(plate 2), reveals a dipping interface of Schieffelin granodiorite. If the granodiorite had maintained the same slope beneath the reverse shot on the southeast, an apparent updip velocity would have been much higher than the noted 10,180 f.p.s. Well data and seismic profiles east of profile D2 reveal deep alluvium, and therefore justify the fault interpretation.

SUMMARY AND CONCLUSIONS

The seismic refraction survey method used in Walnut Gulch Experimental Watershed has proved to be a useful and rapid method of collecting information on subsurface structural geology, groundwater depths, and densities of geologic materials.

Fifty-two seismic refraction profiles were conducted in 11 areas in and around the watershed, aggregating a length of 115,550 feet of in-line seismic profiling (fig. 1 and table 1). In general, the seismic refraction profiles provided sufficient data to construct geologic sections for each of the 11 areas. These sections revealed (1) the identification, depth, attitude, and extent of geologic units comprising the basement complex; (2) the identification, depth, attitude, and extent of geologic units comprising the alluvium complex; (3) structural features such as faults, buried ridges, and buried channels; and (4) the presence, depth, and attitude of the regional water table.

The usual seismic spread length was 2,200 feet. The complete field unit consisted of 24 geophones, solid state amplifiers, a dry paper recording oscillograph, a d.c. power source, and a 4-wheel-drive van for transport.

We presented seismic profiles at scales of 1:6,000 and 1:12,000 and discussed the surface and subsurface geology. Seismically measured water table depths and depths from well logs were compared graphically, and a graph was prepared to show the correlation between seismic velocities and densities of geologic material.

Like all survey methods, the seismic refraction survey method has certain limitations. The most serious limitation we found was that of depth penetration. Because of

excessive noise amplification with increasing spread lengths, we could not measure the complete section of alluvium in portions of the watershed.

Analysis of geophysical, borehole, and geologic data provided a basis for interpreting the hydrogeology of the Walnut Gulch Experimental Watershed. In general, surface and subsurface boundaries of the watershed are not coincident. Mapping of the water table in many areas revealed depths 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 depths to either groundwater or basement by the seismic method was ± 6 percent, whereas that for groundwater alone was ± 10 percent. Recent alluvial history of channel deposits was inferred from the geologic sections and interpretations in areas A, B, C, D, and E.

The alluvium can be classified on the basis of seismic velocities into a loose, gravel-type deposit with a velocity of 5,000 f.p.s. and a thickness of up to 300 feet. An intermediate velocity of 5,000 to 9,000 f.p.s. represents partially cemented conglomerates. The lower boundary of these conglomerates near the margins is the basement, and within the graben structure, the lower boundary is a high-velocity conglomerate. The upper boundary of the high-velocity conglomerate appears to be a controlling factor on the water table in areas D and J northeast of Tombstone. In area F, the upper boundary of the high-velocity conglomerate is 900 feet in depth, and the water table is developed at the upper boundary of the lower velocity conglomerate.

LITERATURE CITED

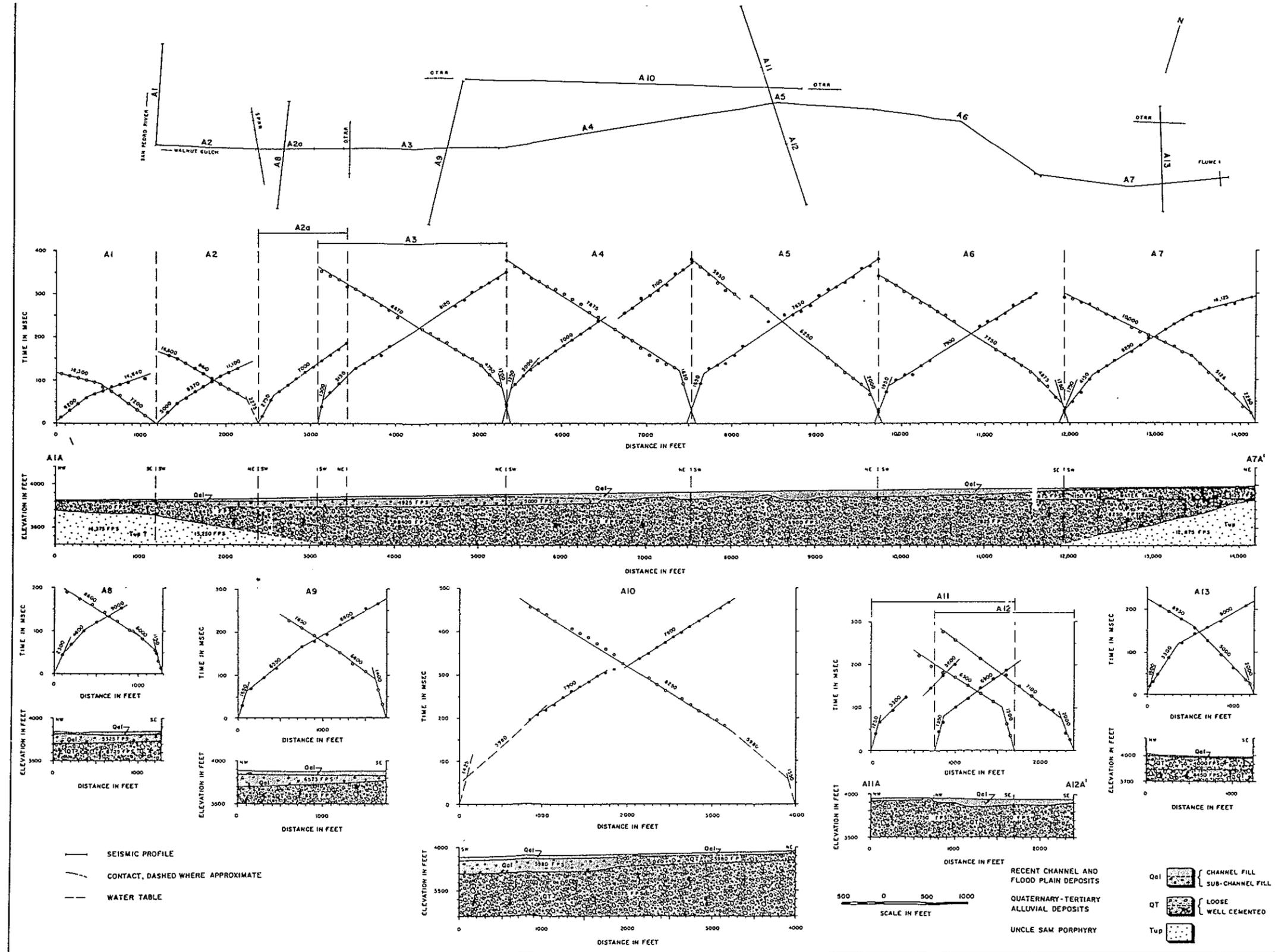
- (1) Andreasen, G. E., Mitchell, C. M., and Tyson, N. S.
1965. Preliminary aeromagnetic map of Tombstone and vicinity, Cochise and Santa Cruz Counties, Arizona. U.S. Geol. Survey open-file rpt.
- (2) Blake, Wm. P.
1882. Geology and veins of Tombstone, Arizona. Amer. Inst. Mining Engin. Trans. X: 334-345.
- (3) Butler, B. S., Wilson, E. D., and Rasor, C. A.
1938. Geology and ore deposits of the Tombstone District, Arizona. Ariz. Bur. Mines Bul. 143, 114 pp.
- (4) Church, J. A.
1903. The Tombstone, Arizona mining district. Amer. Inst. Mining Engin. Trans. 33: 3-37.
- (5) Dobrin, Milton B.
1960. Introduction to geophysical prospecting. 446 pp. New York.
- (6) Gilluly, James.
1956. General geology of central Cochise County, Arizona. U.S. Geol. Survey Prof. Paper 281, 169 pp.
- (7) Grant, F. S., and West, G. F.
1965. Interpretation theory in applied geophysics. 583 pp. New York.
- (8) Heiland, C. A.
1946. Geophysical exploration. 1013 pp. New York.
- (9) Hollyday, Este F.
1963. A geohydrologic analysis of mine dewatering and water development, Tombstone, Cochise County, Ariz. Univ. Ariz. M.S. Thesis, 90 pp.
- (10) Jones, E. L., Jr., and Ransome, F. L.
1920. Deposits of manganese ore in Arizona. U.S. Geol. Survey Bul. 710: 96-119.
- (11) Keppel, R. V., and Renard, K. G.
Transmission losses in ephemeral stream beds. Jour. Hydraul. Div., Proc. Amer. Soc. Civil Engin. 88(HY-3): 59-68.
- (12) Northwood, E. J.
1967. Notes on errors in refraction interpretation. Seismic Refraction Prospecting, Soc. of Exploration Geophysicists: 459-465.
- (13) Rasor, C. A.
Mineralogy and petrography of the Tombstone mining district, Arizona. Univ. Ariz., Ph. D. Dissertation.
- (14) Renard, K. G., Keppel, R. V., Hickey, J. J., and Wallace, D.E.
1964. Performance of local aquifers as influenced by stream transmission losses and riparian vegetation. Amer. Soc. Agr. Engin. Trans. 7(4): 471-474
- (15) Soske, J. L.
1959. The blind zone problem in engineering geophysics. Geophysics 27: 198-212.
- (16) Spangler, Daniel P., and Libby, F.
1968. Application of the gravity survey method to watershed hydrology. Groundwater 6(6): 21-26.
- (17) Wallace, D. E., and Renard, K. G.
1967. Contribution to regional water table from transmission losses of ephemeral streambeds. Amer. Soc. Agr. Engin. Trans. 10(6): 786-790.
- (18) Wallace, D. E., Cooper, L. R.
1969. Natural chemical dispersion in groundwater from various rock types in a portion of the San Pedro River Basin, Arizona. Jour. Hydrol. 2, ART. 477: 121-135.

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GEOLOGIC INTERPRETATION OF AREA A SEISMIC PROFILES
(SAN PEDRO RIVER TO FLUME 1)

Plate 1.—Geologic interpretations of seismic profiles in area A.

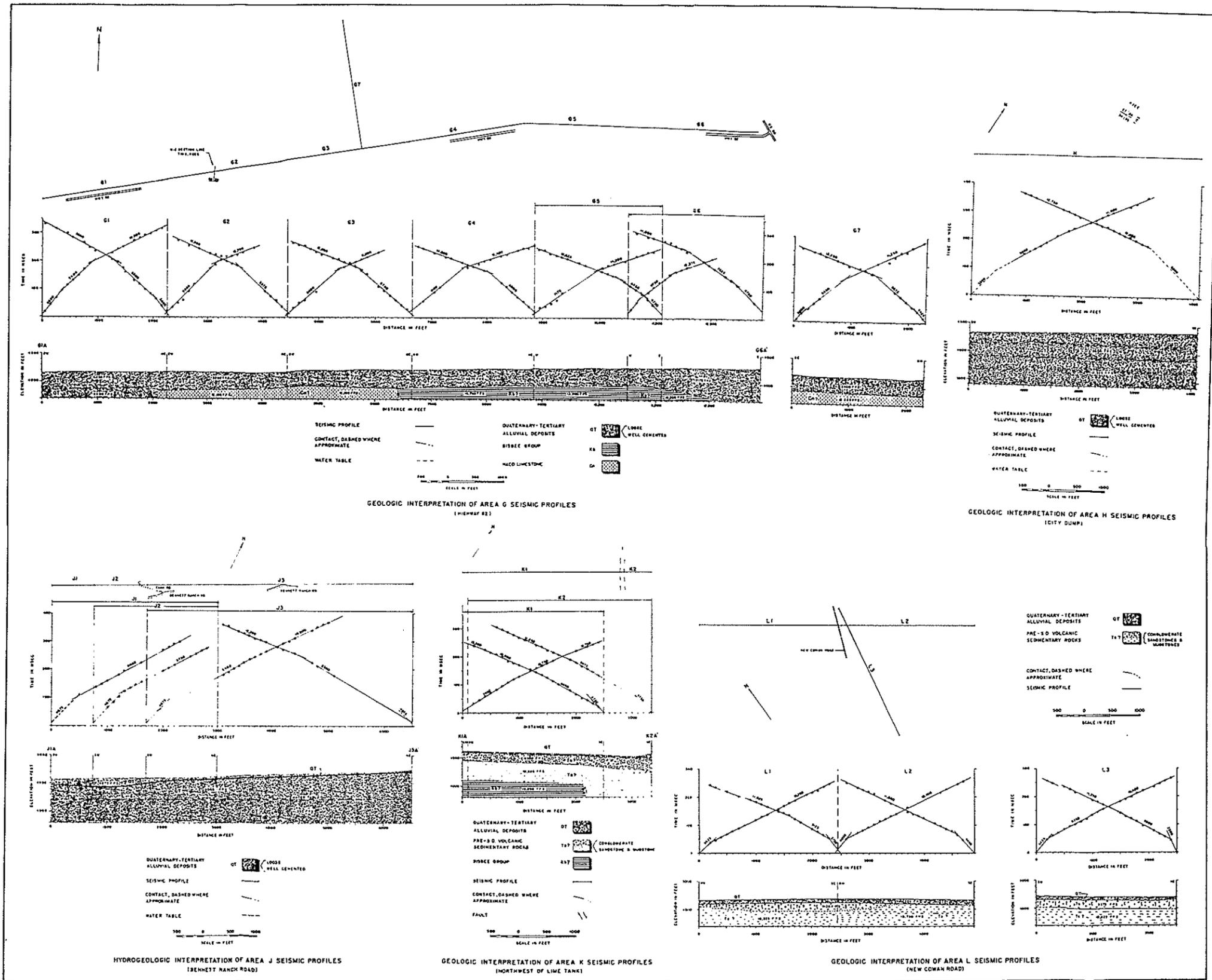


Plate 3.—Geologic interpretations of seismic profiles in areas G, H, J, K, and L.

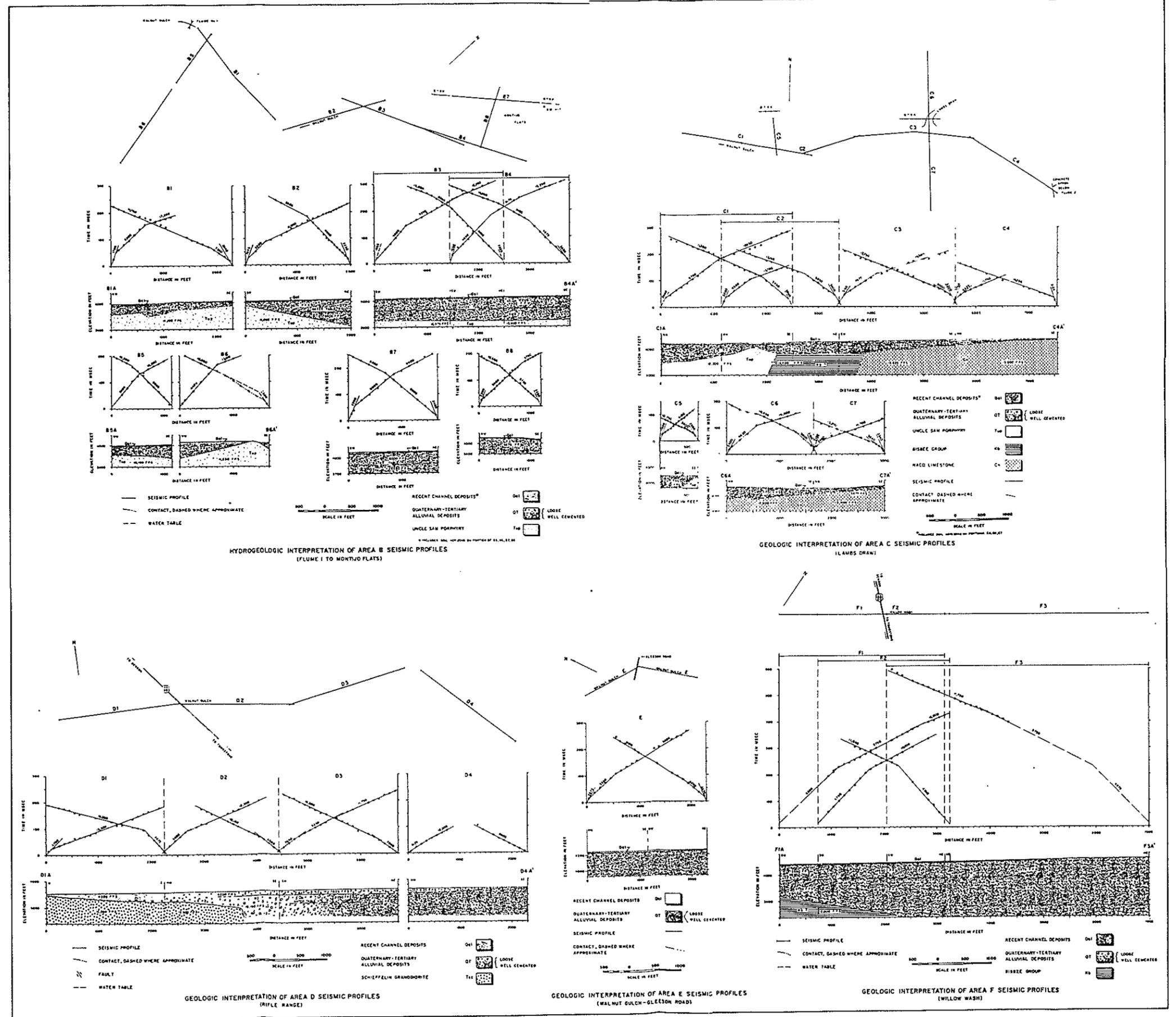


Plate 2.—Geologic interpretation of seismic profiles in areas B, C, D, E, and F.