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TOMBSTONE MINING DISTRICT

Cochise County, Arizona

Block 1
Miscellaneous
(In area of Mutual Interest)
Misc. Information &
Reports

DOHERTY REPORT

TOMBSTONE PACKET

COMPILED JERRY E. DOHERTY

Tombstone Summary
Tombstone Geologic Structure Map
Workings Above the Water Table
Workings Below the Water TAble
General Geologic Map of Tombstone District (Ransome)
Geologic Map of Tombstone District
Claim Status Map
Sections A - F

TOMBSTONE SUMMARY

By Jerry E. Doherty

December 30, 1976

The information available for the Tombstone Mining District on the subject of ore reserves and ore potential is quite vast. This report is a summary of numerous reports and evaluations by geologists, engineers, mine operators, consultants and promoters written on the Tombstone Mining District at a previous time.

DISCOVERY

The Tombstone Mining District was discovered by Ed Schieffelin in 1877. He was camping in the vicinity when he noticed rock similar to the gold-silver bearing rock he had seen at other mines. Subsequent sampling and assaying disclosed that Schieffelin had made a most important discovery which would result in one of the most famous mining camps in the United States. Within three years Tombstone was a prosperous city with thousands of residents.

EARLY MINING

Early mining was on the outcropping ledges and fissures of high grade ore in the area. This "glory hole" mining yielded considerable quantities of ore. Large tonnages of high grade ore were also mined near the surface from the apexes of anticlinal structures that predominate in the vicinity of the Toughnut Mine.

Subsequent mining was concentrated on the anticline structures (general plunge easterly), fissures, replacement beds and veins, and along the contacts of the near vertical dikes that strike north-south through the district. These structures were pursued down to the water table and laterally for considerable distances. Many unknown structures were disclosed as a result.

GEOLOGIC HISTORY

Pre-mineral ground preparation in any mining district is critical. The channelways for mineralizing fluids must exist and be of such a nature as to carry the mineralizing solutions away from their source and keep them contained until the chemical, temperature and pressure controlled exsolution point of the various minerals is reached and they precipitate out forming ore bodies. The nature and chemical composition of the rock types comprising the channelway is also a factor: the more reactive the rock type is to the hydrothermal fluids, the more likely it is to be mineralized. Tombstone was well prepared.

An intrusion of quartz latite porphyry (Uncle Sam Porphyry) came into sedimentary units comprised of limestone, shales, cherts, sandstones, quartzites, etc. already folded and faulted by tectonic activity, causing some doming activity which undoubtedly opened up weaknesses, existing joints and faults producing wide spread fissuring. Into many of these fissures came intrusions of andesite porphyry and slightly later intrusions of rhyolite porphyry dikes along many of the same and some additional fissures.

Next a series of steeply dipping north-northeast trending fissures developed probably as a result of stresses built up in the rock from the final intrusion of Schieffelin granodiorite. Subsequent to this episode and most likely related to it came a magmatic segregation of gold, silver, copper, manganese, lead, zinc and various other minerals of lesser economic importance in an aqueous solution. This solution migrated away from its source along the various faults, fissures, joints, breccia zones, and open bedding planes until exsolution occurred producing the mineralized structures observed throughout the district. It would be safe to say that nearly every structure occurring within the structurally induced syncline that comprises the Tombstone Mining District is mineralized at some point. Some structures are mineralized throughout their extent.

TYPES OF STRUCTURES AND ORE CHARACTERISTICS

According to the University of Arizona Bulletin No. 143, the most productive deposits, in order of their decreasing importance, were those associated with north-south dike fissures, faults, anticlines and northeast fissures only. Much depended on the rock type encountered by the ascending ore solutions. In general, it seems that porous or broken limestone capped by shale or other impermeable units were the most favorable host rocks.

The hosts themselves can also be listed in order of decreasing importance as producers. In order they are mineralized fault breccias and gouges, blue limestone, novaculite, "10-foot" and "6-foot" limestones, shales and sandstones of the Bisbee formation, Naco limestone and dike material.

The accompanying table graphically shows these structure-rock character relationships. As an example, the best ore has been produced from the areas where the northeast fissures have intersected fault breccias and gouge, or the fissures are made up of these two materials. Less importance is an intersection of a northeast fissure with the "10-foot" and "6-foot" limestone units of the Bisbee formation. Of lesser importance is the intersection of the north-south dike fissures with these same units. The least productive combination would be dike material in an anticline or roll.

The effect of accessory minerals in the rock on mineral deposition is not known but appears to be minimal.

Generally all ore mined to date has certain characteristics: it occurs in broken or porous rock, some type of alteration invariably occurs around the mineralized zone, ore shoots are almost always continuous and connect to a main fissure at some point, and ore is usually associated with various oxide and some carbonate minerals, but changes to the character of auriferous to argentiferous sulfides below the water table.

WATER TABLE

The water table is approximately 4115 feet above sea level or about 500 feet below the surface. It was known that the gold-silver values continued undiminished for short distances below the water and believed that they should continue for hundreds of feet.

In an effort to exploit this possible ore, attempts were made to dewater the Tombstone mines. These proved only temporarily successful as political hassles, carelessness, mechanical failures and caving ground forced the suspension of pumping. However, the 1000 foot level in the vicinity of the Grand Central and the Contention Mines was reached and the water was being successfully controlled before trouble closed the deep levels.

Even though dewatering operations eventually failed, much data was gained. It was proved that the ore continues down wherever it has been pursued. Some subwater table mining was done in the Contention, Grand Central, Luck Sure, Emerald, West Side and Silver Thread mines. It was discovered that not only does the ore continue, but the gold and silver content tends to increase with gold showing the greater gain. In addition, quite good values in lead, zinc and some manganese sulfides have been encountered.

It was further proven that by continuous pumping at a rate of 4500 gallons per minute the dewatering could be effected to the 1000 foot level and a steady gain on dewatering the Tombstone basin was made. A substantially lower pumping rate of about 2100 gallons per minute is all that would be required to reach the 800 foot level.

PRODUCTION

In trying to arrive at an overall production figure, a great many unknowns were encountered. Ore from company operations outside of Tombstone was grouped with ore from Tombstone branch operations on occassion. Some mines kept no records of ore shipped to the many custom mills that operated in the Tombstone Mining District. Some high grade ore was not milled but sent directly to the smelter, and other mines had their own mills at the mine site and usually kept no records or poor records at best. Portions of mines were leased out to private individuals. The price of gold and silver fluctuated considerably and many production reports were given in dollars and cents rather than ounces of gold and silver or pounds of other recovered elements (lead, zinc, copper and manganese). Three major factors unmentioned in any publication but nevertheless important in an estimate of total production must be the possible falsifying of mill and smelter records, the high penalties placed on the ore by these concerns to increase their profits, and the practice of "high-grading" or stealing of high grade ore, free gold and native silver by the miners themselves. Taking these factors into consideration, it is easily seen that any given figure will have to be up-graded by an unknown percentage.

Based on production figures and records from several different sources and by applying known and assumed facts to calculate unknown values and quantities, this writer arrived at a set of figures giving production from 1879 through 1936. These calculations showed 1,587,195 tons of ore shipped valued at $38,000,000. This ore contained 217,118.52 ounces of gold and 33,803,559 ounces of silver. In addition, there was in excess of 2,500,000 pounds of copper, 25,000,000 pounds of lead, 1,000,000 pounds of zinc and an unknown amount of manganese derived from the Tombstone mines.

Dr. C. J. Sarle's report on the Melgren Mines of the Tombstone Mining District of September 5, 1928 gives a production figure of "approximately $79,000,000" contributed by the twenty odd mines in the main Tombstone area. No details are given as to how Dr. Sarle arrived at this figure. Elsewhere he states, "The ores of the whole Tombstone Mining District may be classified as high grade. The earlier operators shipped and milled ore having an average value of $100 per ton or better and hundreds of tons were shipped from Tombstone running a thousand dollars or more". (Per ton)

A report by William P. Blake to the Development Company of America entitled "Tombstone and its Mines, a Report Upon the Past and Present Condition of the Mines of Tombstone, Cochise County, Arizona", gives the value of aggregate production of gold and silver from the mines of Tombstone placed by "competent judges" from records and estimates at not less than $34,000,000. This report is dated 1902. Tombstone would continue limited production for another 34 years! Blake's "competent judges" also give an average value of $45 per ton of ore based on samples and smelter returns.

Butler, Wilson and Rasor in their 1938 "Arizona Bureau of Mines Geological Series No. 10, Bulletin #143," give a grand total for all ore from 1879 through 1936, including copper, lead and zinc, of $37,103,008. Their figures are based on old records, "other sources" and published figures in the Mineral Resources of the United States.

In summary, it can be said that whatever set of figures the reader decides to believe, they will still show the ore mined in Tombstone is some of the richest yet produced in the United States.

CLOSING OF THE MINES

It is generally assumed that the water encountered in the mines was the reason for the closing of the Tombstone operations. Previous work had shown that the water could be controlled with proper management and maintainance of equipment. The cost of pumping had only a slight cost effect on the overall operations. Other factors must be blamed for bringing an end to mining.

Most of the known easy to reach high grade ore had already been mined. The cost of developing additional ore was not only expensive but economically infeasible as it was generally remote from the few remaining hoisting facilities. Milling and treating the ore was again a problem since most mills had been closed. The price of silver remained below $1.25 per ounce.

If a single blame had to be given to any one thing, it would probably be poor coordination of efforts on the part of the various management personnel for not instigating a program of steady development in advance of actual mining which would include systematic dewatering to make more ground available for developing, and increasing the efficiency of the mining and hauling techniques.

Noteable is the fact that many hundreds of thousands of tons of good milling ore were bypassed or broken and left in the stopes and the stopes allowed to cave because of the quest for only high grade ore. With proper procedures this ore also could have been mined at a profit.

RECENT ACTIVITY

Periodically some work is done in Tombstone. Some of the surface dump material and underground gob is screened to recover the gold and silver in the fine material. An occassional bit of ore is mined from a pit or high grade pocket near the surface but most efforts are met with little profit.

Thousands of feet have been drilled in an effort to prove ore reserves and the continuation of ore at depth, however much of this data is unavailable for evaluation. Those few assays that can be matched with structure samples show mineralization in varying degrees indicating that the ore shoots persist below the 1,000 foot level. The spotty nature of the ore and the surprising fact that some soft oxide ore occurs well below the water table should cause concern as to the validity of drilling results to give a true picture of the mineral value of a structure over any lateral or vertical extent. Associated with many of Tombstone's structures are wide voids and solution cavities which cause loss of both diamond drill core and cutting recovery.

Some geophysical and geochemical work has been undertaken by various companies but the results were not conclusive and added little to what was already known about the district.

The most recent work has been done by 1971 Minerals Ltd. This work has primarily been a cyanide heap leaching of the waste dumps and setting up of an in situ underground leaching system to recover gold and silver from the gob remaining in the Goodenough Stope which is one of the large manto deposits on the crest of an anticline. 1971 Minerals Ltd. has also done some shallow drilling in the vicinity of the Tranquility and Silver Thread mines in an unsuccessful effort to prove some shallow open pit mineable ore reserves.

FUTURE POTENTIAL

Within the Tombstone Mining District are many large areas with little or no development work other than a few small pits, shafts, or adits. At least 100,000 feet of structures have been mapped on the surface and all belong to one of the systems of known ore producers. Many of these structures have been mined to some extent, but many have not been touched either on the surface or underground. In addition, many known producing structures and horizons have no known surface exposures. Undoubtedly, some ore remains at the surface that can be mined by open pit methods. A systematic detailed areal geologic mapping project in conjunction with a surface sampling program placing special emphasis on the projections of known ore bearing structures from the underground workings will delineate these areas.

The large manto stopes on the apexes of the anticlines contain roughly 100,000 tons of gob which carries good values in gold and silver. No average grade has been computed due to lack of data but a figure in excess of 10 ounces of silver and .15 ounces of gold per ton would not be unreasonable as these were some of the first structures mined and "take only high grade" was the rule.

Huge tonnages of low grade ore are piled at various places throughout the mines or used as back fill in much of the workings. Because almost all development work has been driven on mineral bearing structures, we could anticipate that most of the gob is mill grade ore and need only be hoisted to the surface for processing.

In order to arrive at a feasible mining plan it will be necessary to initiate a program of sampling and measuring all gobbed areas to get an accurate tonnage and grade figure.

Few sections along the mined structures are available due to poor records and unsystematic mining procedures. Those that are available show a very interesting trend in that the amount of mining adjacent to the shafts is considerable but diminishes drastically with distance from the hoisting facility. This trend applies to all Tombstone structures but to a lesser extent with the manto stopes in the rolls or anticlines. Occasionally this is due to the shafts being sunk on higher grade ore, but more commonly it is due to the inconvenience and extra work of a longer tramming distance. The result has been a considerable tonnage of developed but unmined ore.

Due to the stable nature of the ground in the district, dike fissures excepted, most of the workings are open and readily accessible. As a result, an excellent estimate of the value of this ore can be obtained by channel sampling the developmental drifts and raises and sampling within the blocks of ore between levels and raises where stoping provides access into the blocks.

Further exploration of the Tombstone ore body can be done in two ways. They are, drilling either from surface or from stations cut at various locations underground, and subsurface exploration with drifts, cross-cuts and raises. Both ways have their advantages.

The most accurate assay value of a structure at any one point is given by a sample cut perpendicularly across the structure to avoid the affects of mineral zonation within the structure. The problem of accurate sampling is made more complicated by secondary enrichment and oxidation which has tended to form local pockets of high grade ore. The mineralized zones have been further complicated by more recent faulting and decalcification which has produced additional open fissures and solution cavities.

It is the writer's opinion that accurate assay data probably cannot be obtained from the upper 600 feet of the district by drilling. However, due to the decrease in the effects of oxidation and enrichment, the credibility of the assays will undoubtedly increase with depth.

Many drill holes, both diamond and rock bit, have lost all returns due to intensely broken ground and voids in and adjacent to the structures. Several hundred thousand dollars have been spent drilling to intersect ore zones at depths of up to 1,200 feet only to lose some or all of the core or the cuttings throughout the intersection itself. The newer reverse circulation drills offer the best solution to this perplexing drilling problem.

Using the reverse circulation drilling method, it is possible to drill for considerable distances down the heart of these mineralized faults and fissures or drill at small acute angles to the structures in order to get longer and therefore more representative sections and still get cutting returns after penetrating voids in broken or loose ground. This plan of drilling should not be misinterpreted as giving a completely true representation of the mineralized material between and adjacent to the structural boundary. But, the information and reliability is a great improvement over that provided by other drilling techniques.

Drilling's major advantage over drifting for structure testing is the ability to quickly test and pursue structures in remote and untested areas. Another advantage is that of being faster than conventional underground mining techniques to develop ore reserves. However, in the Tombstone type of deposit, the reliability of the data is questionable at best.

By driving a drift on a structure, it is possible to see the dimensions and rock characteristics of the ore shoot and to thoroughly sample it. Small high grade pockets may be sampled and easily averaged into the remainder of the vein to give the overall grade.

Conventional drifting costs about $50 per foot of advance. Drilling costs are about $25 per foot of diamond drilling, $12 per foot of reverse circulation drilling and $7 per foot for down hole percussion hammer drilling. Drilling is of course cheaper than drifting per foot of advance, but when comparing drifting and drilling from the standpoint of dollars spent per foot of vein proven or disproven, it is easily seen that drilling is many times more expensive and the information gained is inconclusive.

The manto deposits are not confined to any one particular stratigraphic unit. In several instances, the mining began in one horizon and shifted upward or downward to another higher grade rock unit. Study of these ore occurrences has shown that there are a number of rock units in each anticline that are potential ore producers. In some instances, these units are completely untested. Also there are possible extensions to the manto deposits that have not been tested as yet, as well as two rolls that are virtually untouched. Checking these targets is a simple matter of getting in the proper rock unit on the apex of the roll and drifting.

TOMBSTONE EXTENSION AND THE WESTERN TOMBSTONE AREA

There are two additional areas sometimes included in the Tombstone Mining District that have not been previously mentioned. They are the Tombstone Extension and the Western Area.

Mining in both areas has been conducted on vein or fissure type deposits and along dike filled fissures. Generally it can be said that except for the absence of known manto deposits, both areas are nearly identical in ore occurrences to the main Tombstone District. All three areas most likely owe their origin to the same sources of structuring and mineralization.

The Tombstone Extension which lies about 7,000 feet southeast of the town of Tombstone is wholly in the upper Bisbee Formation. It has had only a small total production of lead ore from three mines, the Tombstone Extension, Carper and the San Diego Mines. Most of the lead type ore contained about .071 ounces gold per ton. The Tombstone Extension Mine was the largest producer of lead in Arizona in 1932-1933.

Total production from the Tombstone Extension District is reported to be 15,195.65 tons of ore carrying 1,082.64 ounces gold, 180,490.66 ounces silver and 6,335,743.64 pounds of lead. The Total gross value of all ore shipped was, at the original prices, $408,941.08.

The Western District, located about 12,000' southwest of Tombstone, is in the Bisbee sediments and in the Uncle Sam quartz latite porphyry. The best known mines are the State of Maine, Bonanza, Chance, Joseph and San Pedro.

Limited development work was done to the water table which stands at about 4,400 feet elevation, or about 200 feet below the sufface at the Bonanza Shaft. As with the Tombstone Mining District, many tons of ore were developed and left unmined for various reasons. Nearly all mining has been carried out on only five of the 23 known veins. The other 18 are practically virgin of any exploration.

Much high grade ore was mined in the Western District. Some 1,000 ounces of silver and several ounces of gold per ton ore was often found. One small shipment of 4½ tons from the Joseph #1 assayed at 5,005 ounces silver and 5.01 ounces gold per ton. The biggest producer was the State of Maine at $3,500,000. Its ore was reported to average about $60 per ton which represents approximately 55 ounces silver and .10 ounces gold per ton. A "very low estimate" of the average value of ore from the entire Western Mining District is $25.00 per ton according to C.J. Sarle in his 1928 report on the Mellgren Mines.

The total production for the entire district is reported to be around six to eight million dollars at the old prices. Unfortunately, only very poor and sketchy production records are available.

COPPER POTENTIAL

There is a very real possibility that the structures in the Tombstone Mining District will eventually become major copper veins at depth. Abundant copper oxide minerals are seen in nearly all structures. Some copper credit was given to the mines by the mills and smelters in the early days. As should be expected, the copper content of the ore increases with depth and locally heavy copper sulfides were reported from some of the deeper workings below the water table.

The standard porphyry copper zoning of (from perimeter to source), gold silver, lead, manganese, zinc, arsenic-antimony, copper and molybdenum seems to be holding generally true for the Tombstone deposit. All evidence points to the possibility of a large vein type copper deposit lying at depth beneath Tombstone. This vein deposit is quite possibly resting on a disseminated porphyry copper deposit typical of other deposits in south and central Arizona.

This opinion has been expressed by many qualified mining personnel who are familiar with porphyry copper deposits and this writer enthusiastically concurs.

STRATIGRAPHIC UNITS ASSOCIATED
WITH TOMBSTONE'S ORE DEPOSITS

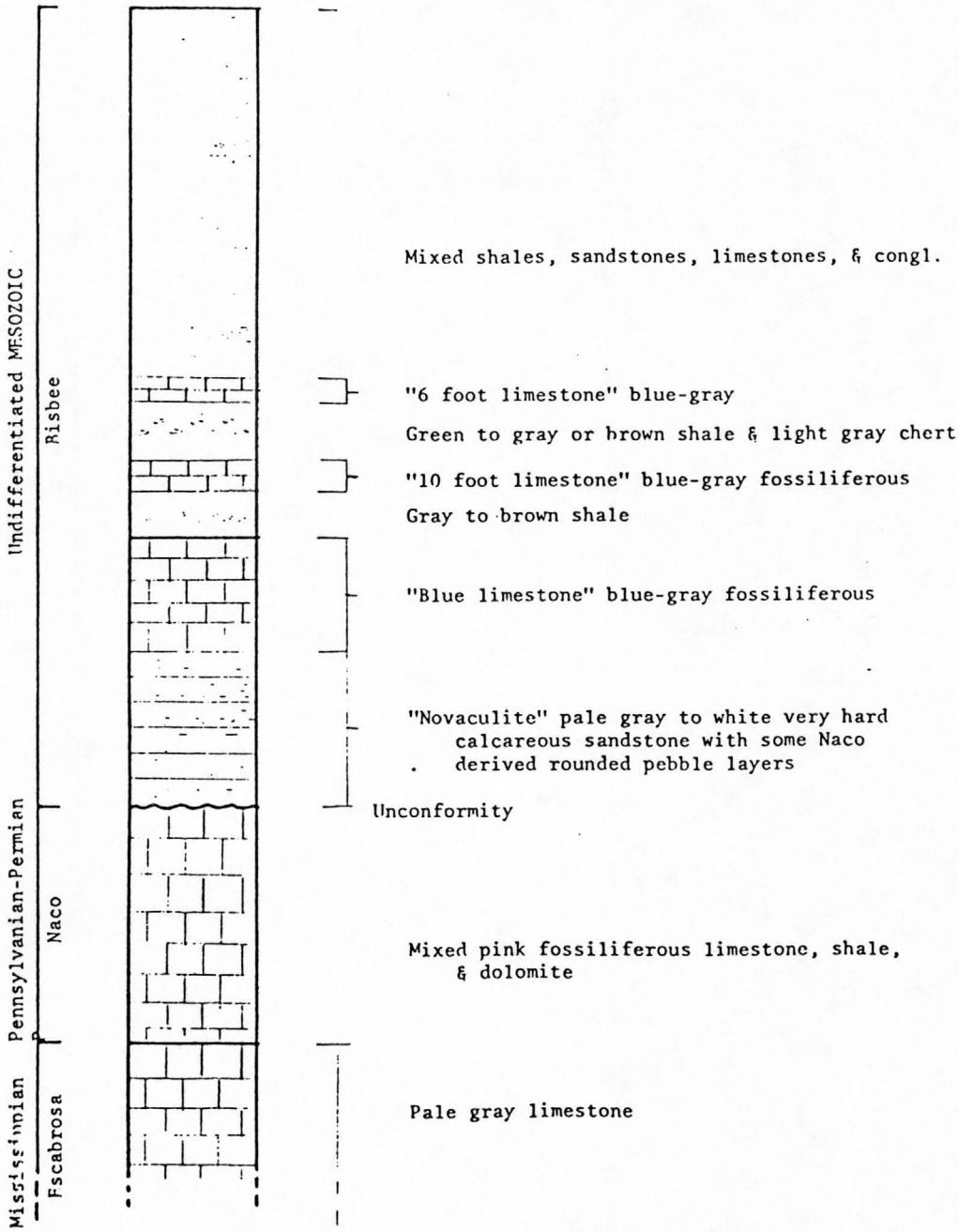
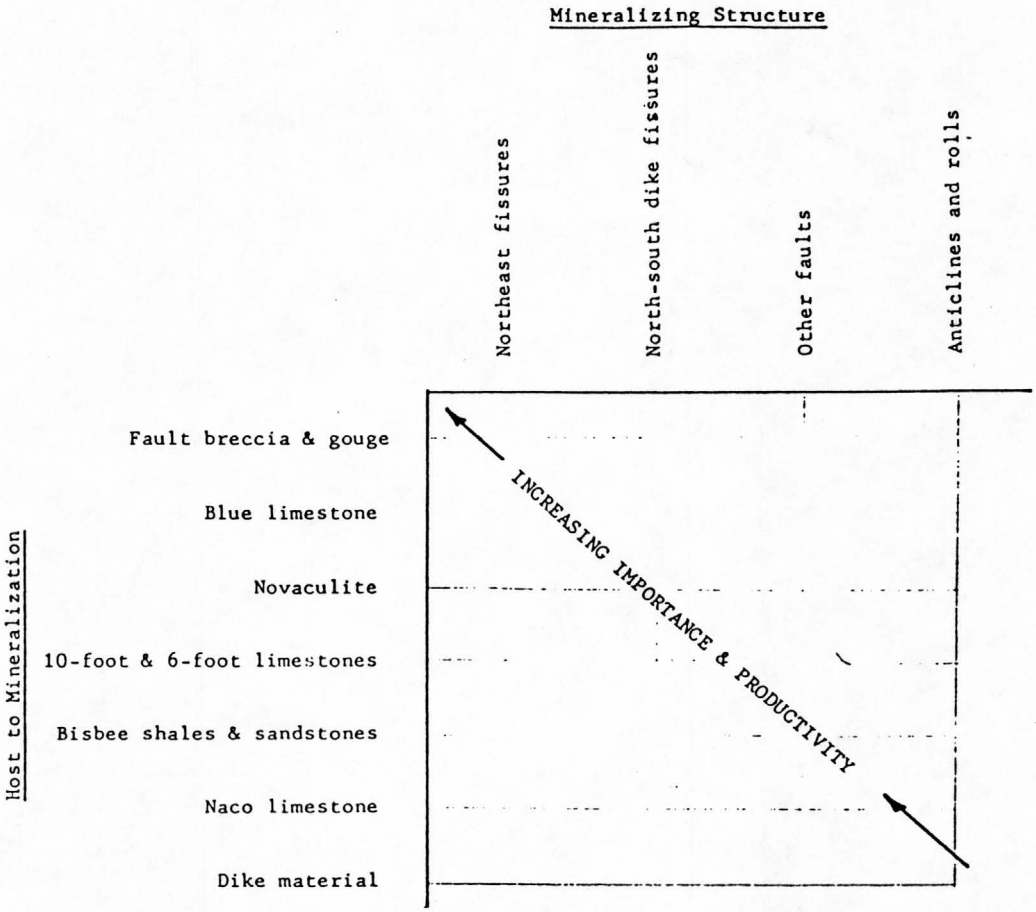


TABLE SHOWS THE RELATIONSHIP OF STRUCTURES
TO ROCK UNITS IN REGARDS TO MINERALIZATION



COMPILED PRODUCTION RECORDS

OF THE

MAIN TOMBSTONE MINING DISTRICT

EAR	TONS	OZ. GOLD	$/OZ.	VALUE	OZ. SILVER	$/OZ.	VALUE
.879-1880	55,567.63	5,219.06	20.71	108,086.71	1,889,299.40	1.17	2,210,480.30
81	128,452.02	9,312.09	"	192,853.33	4,367,369.00	1.11	4,847,779.
82	131,296.23	9,798.81	"	202,541.46	4,464,072.00	1.05	4,955,120.00
83	75,248.76	9,440.80	"	195,519.06	2,558,458.00	"	2,686,381.00
84	33,582.35	8,783.08	"	181,897.58	1,141,800.40	"	1,198,890.50
85	31,735.78	9,078.25	"	188,010.52	1,079,016.60	"	1,132,967.50
86	25,885.45	8,628.48	"	178,695.86	880,105.25	.99	871,304.20
87	14,500.00	5,559.16	"	115,130.17	494,765.13	.98	484,869.83
88	14,510.79	6,578.23	"	136,235.06	493,366.95	.94	463,764.94
89	5,511.82	3,022.61	"	62,598.23	187,401.77	1.00	187,401.77
1890	13,537.11	5,636.18	"	116,725.21	460,261.70	1.05	483,274.79
91	15,361.77	7,356.34	"	152,349.80	522,300.20	1.00	522,300.20
92	13,573.48	4,273.13	"	88,496.56	461,498.20	.87	401,503.44
93	14,126.68	3,638.72	"	75,357.81	480,310.50	.78	374,642.19
94	11,213.11	2,888.23	"	59,815.15	381,245.79	.63	240,184.85
95	11,213.11	2,888.23	"	59,815.15	381,245.79	"	240,184.85
96	11,213.11	2,888.23	"	59,815.15	381,245.79	"	240,184.85
897-1901	135,607.73	15,409.97	"	319,140.45	2,034,116.00	.60	1,220,469.60
902-1906	224,602.14	25,522.97	"	528,580.72	3,369,032.10	"	2,021,419.30
07	48,443.60	5,504.95	"	114,007.60	726,654.00	"	435,992.40
08	51,266.00	4,097.83	"	84,866.00	357,414.00	"	595,690.00
09	27,123.00	2,275.18	"	47,119.00	201,700.00	"	336,166.66
1910	4,619.00	1,059.73	"	21,947.00	116,520.00	"	69,912.00
11	8,797.00	2,155.49	20.67	44,554.00	224,098.00	"	134,458.80
12	7,405.00	1,363.18	"	28,177.00	158,377.00	.584	92,492.17
13	5,760.00	1,229.56	"	25,415.00	126,392.00	"	73,812.93
14	6,063.00	1,380.36	"	28,532.00	108,868.00	"	65,320.80
15	9,003.00	1,216.01	"	25,135.00	100,115.00	.67	67,077.05
16	57,200.00	3,950.36	"	81,654.00	343,453.00	"	230,113.51
1917	57,474.00	3,373.05	"	69,721.00	444,139.00	"	297,573.13
18	19,507.00	1,389.40	"	28,719.00	283,412.00	.28	79,355.36
19	27,445.00	1,945.82	"	40,220.00	450,366.00	"	126,102.48
1920	28,946.00	1,787.76	"	36,953.00	456,855.00	"	127,919.40

COMPILED PRODUCTION RECORDS

OF THE

MAIN TOMBSTONE MINING DISTRICT

YEAR	TONS	OZ. GOLD	$/OZ.	VALUE	OZ. SILVER	$/OZ.	VALUE
1921	18,594.00	1,506.58	.67	31,141.00	423,688.00	.28	118,632.64
22	44,347.00	2,322.45		48,005.00	613,700.00	1.12	687,344.00
23	32,770.00	3,092.60	"	63,924.00	495,943.00	"	555,456.16
24	15,448.00	2,458.64	"	50,820.00	247,642.00	"	277,359.04
25	27,760.00	2,676.73	"	55,328.00	241,381.00	"	270,346.72
26	47,708.00	2,989.65		61,796.00	226,579.00	.90	198,521.10
27	31,196.00	3,132.90	"	64,757.00	159,944.00	"	143,949.60
28	24,172.00	2,296.61	"	47,471.00	164,161.00	"	147,744.90
29	15,601.00	1,670.54	"	34,530.00	99,423.00	"	89,480.70
1930	8,734.00	1,874.50	"	38,746.00	74,937.00	.3876	29,045.58
31	15,623.00	2,203.92	"	45,555.00	101,504.00	.3075	31,212.48
32	5,067.00	501.50	20.00	10,030.00	48,021.00	.2739	13,152.95
33	7,016.00	1,846.42	19.95	36,836.00	100,323.00	.2591	25,993.69
34	3,701.00	3,685.04	35.15	129,529.00	296,737.00	.6383	189,407.22
35	12,907.00	3,287.38	36.68	120,581.00	243,087.00	.7458	181,294.28
36	9,305.00	2,921.81	34.99	102,234.00	147,218.00	.7687	113,166.47
TOTAL	1,635,638.70	217,118.52	$21.371	$4,639,966.00	33,803,559.00	$.904	$30,559,196.00

DRILLING SUMMARY
1930'S TO DATE

Consultants in:
• base & precious metals • uranium
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• interpretation-image processing
• worldwide Mobilization

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Registered Professional
Geologist

Southwestern Exploration Associates, Inc.

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PHOENIX, ARIZONA

February 28, 1979

TOMBSTONE DRILLING SUMMARY

Drilling Group	Date	Drill Hole No.	Depth	Location
Bunker Hill	1936	DD-1	23'	T.D.C. Claims
Bunker Hill	1936	DD-2	75'	T.D.C. Claims
Bunker Hill	1936	DD-3	123'	T.D.C. Claims
Bunker Hill	1936	DD-4	151'	T.D.C. Claims
Bunker Hill	1936	DD-5	78'	T.D.C. Claims
Bunker Hill	1936	DD-6	20'	T.D.C. Claims
Bunker Hill	1936	DD-7	6'	T.D.C. Claims
Bunker Hill	1936	DD-8	40'	T.D.C. Claims
Bunker Hill	1936	DD-9	56'	T.D.C. Claims
Bunker Hill	1936	DD-10	180'	T.D.C. Claims
Bunker Hill	1936	DD-11	211'	T.D.C. Claims
Bunker Hill	1936	DD-11	75'	T.D.C. Claims
Bunker Hill	1937	CDH-1	380'	T.D.C. Claims
Bunker Hill	1937	CDH-2	75'	T.D.C. Claims
Bunker Hill	1937	CDH-3	460'	T.D.C. Claims
Bunker Hill	1937	CDH-4	430'	T.D.C. Claims
Bunker Hill	1937	CDH-5	385'	T.D.C. Claims
Bunker Hill	1937	CDH-6	295'	T.D.C. Claims
Bunker Hill	1937	CDH-7	506'	T.D.C. Claims
Bunker Hill	1937	CDH-8	298'	T.D.C. Claims
Bunker Hill	1937	CDH-9	295'	T.D.C. Claims
Bunker Hill	1937	CDH-10	385'	T.D.C. Claims
Bunker Hill	1937	CDH-11	400'	T.D.C. Claims
Bunker Hill	1937	CDH-12	215'	T.D.C. Claims
Bunker Hill	1937	CDH-13		T.D.C. Claims
Newmont	1954	DD-7	1650'	Silver Thread
Newmont	1955	DD-9	667'	West Side

Drilling Group	Date	Drill Hole No.	Depth	Location
Duval	1967	RDH-1	247'	T.D.C. Claims
Duval	1967	RDH-2	250'	T.D.C. Claims
Duval	1967	RDH-3A	250'	T.D.C. Claims
Duval	1967	RDH-3	108'	T.D.C. Claims
Duval	1967	RDH-4	80'	T.D.C. Claims
Duval	1967	RDH-5	50'	T.D.C. Claims
Duval	1967	RDH-6	250'	T.D.C. Claims
Duval	1967	RDH-7	219'	T.D.C. Claims
Duval	1967	RDH-8	148'	T.D.C. Claims
Duval	1967	RDH-8A	148'	T.D.C. Claims
Frankovitch	1959	DDH-1	230'	T.D.C. Claims
Frankovitch	1959	DDH-2	95'	T.D.C. Claims
Frankovitch	1959	DDH-3	51'	T.D.C. Claims
Frankovitch	1959	DDH-4	40'	T.D.C. Claims
Frankovitch	1959	DDH-5	270'	T.D.C. Claims
Frankovitch	1959	DDH-6	188'	T.D.C. Claims
Frankovitch	1959	DDH-7	90'	T.D.C. Claims
Frankovitch	1959	DDH-8	192'	T.D.C. Claims
Frankovitch	1959	DDH-9	125'	T.D.C. Claims
Frankovitch	1959	DDH-10	511'	T.D.C. Claims
Frankovitch	1959	DDH-11	287'	T.D.C. Claims
Frankovitch	1959	DDH-12	180'	T.D.C. Claims
Frankovitch	1959	DDH-13	146'	T.D.C. Claims
Frankovitch	1959	DDH-14	329'	T.D.C. Claims
Frankovitch	1959	DDH-15	350'	T.D.C. Claims
Frankovitch	1959	DDH-16	160'	T.D.C. Claims
Frankovitch	1959	DDH-17	205'	T.D.C. Claims
Frankovitch	1959	DDH-18	77'	T.D.C. Claims
71 Minerals	1976	RDH-1A	75'	Skip Shaft Area
71 Minerals	1976	RDH-101	55'	Skip Shaft Area
71 Minerals	1976	RDH-106	60'	Skip Shaft Area
71 Minerals	1976	RDH-107	60'	Skip Shaft Area
71 Minerals	1976	RDH-108	60'	Skip Shaft Area
71 Minerals	1976	RDH-109	60'	Skip Shaft Area
71 Minerals	1976	RDH-110	60'	Skip Shaft Area
71 Minerals	1976	RDH-111	60'	Skip Shaft Area
71 Minerals	1976	RDH-112	60'	Skip Shaft Area
71 Minerals	1976	RDH-113	60'	Skip Shaft Area
71 Minerals	1976	RDH-114	80'	Skip Shaft Area
71 Minerals	1976	RDH-115	60'	Skip Shaft Area
71 Minerals	1976	RDH-116	60'	Skip Shaft Area
71 Minerals	1976	RDH-117	80'	Skip Shaft Area
71 Minerals	1976	RDH-118	80'	Skip Shaft Area
71 Minerals	1976	RDH-119	80'	Skip Shaft Area
71 Minerals	1976	RDH-120	60'	Skip Shaft Area

Drilling Group	Date	Drill Hole No.	Depth	Location
Austral Oil	1968	DD-1	252'	West-Fox
Austral Oil	1968	DD-2	876'	West-Fox
Austral Oil	1968	DD-3	550'	West-Fox
Austral Oil	1968	DD-4	98'	West-Fox
Austral Oil	1968	DD-5	216'	West-Fox
Austral Oil	1968	DD-6	257'	West-Fox
Austral Oil	1968	H-1	300'	West-Fox
Austral Oil	1968	H-2	215'	West-Fox
Austral Oil	1968	H-3	500'	West-Fox
Austral Oil	1968	H-4	300'	West-Fox
Austral Oil	1968	H-5	250'	West-Fox
Austral Oil	1968	H-6	250'	West-Fox
Austral Oil	1968	H-7	250'	West-Fox
Austral Oil	1968	H-8	100'	West-Fox
Austral Oil	1968	H-9	140'	West-Fox
Austral Oil	1968	H-10	426'	West-Fox
Austral Oil	1968	H-11	250'	West-Fox
Austral Oil	1968	H-12	270'	West-Fox
Austral Oil	1968	H-13	250'	West-Fox
Austral Oil	1968	H-14	250'	West-Fox
Austral Oil	1968	H-15	250'	West-Fox
Austral Oil	1968	H-16	170'	West-Fox
Austral Oil	1968	H-17	285'	West-Fox
Austral Oil	1968	H-18	313'	West-Fox
Austral Oil	1968	H-19	490'	West-Fox
Austral Oil	1968	H-20	300'	West-Fox
Austral Oil	1968	H-21	270'	West-Fox
Austral Oil	1968	H-22	290'	West-Fox
Austral Oil	1968	H-23	207'	West-Fox
Austral Oil	1968	H-24	270'	West-Fox
Austral Oil	1968	H-25	290'	West-Fox
Austral Oil	1968	H-26	500'	West-Fox
Austral Oil	1968	H-27	200'	West-Fox
Austral Oil	1968	H-28	230'	West-Fox
Austral Oil	1968	H-29	235'	West-Fox
Austral Oil	1968	H-30	280'	West-Fox
71 Minerals	1973	HRD-1	265'	Seth Horn Claims
71 Minerals	1973	HRD-2	120'	Robbers Roost
71 Minerals	1973	HRD-3	120'	Robbers Roost
71 Minerals	1973	HRD-4	10'	Robbers Roost
71 Minerals	1973	HRD-5	10'	Robbers Roost
71 Minerals	1973	HRD-6	10'	Robbers Roost
71 Minerals	1973	HRD-7	35'	Robbers Roost

Drilling Group	Date	Drill Hole No.	Depth	Location
71 Minerals	1976	RDH-120A	80'	Skip Shaft Area
71 Minerals	1976	RDH-121	60'	Skip Shaft Area
71 Minerals	1976	RDH-122	60'	Skip Shaft Area
71 Minerals	1976	RDH-123	73'	Skip Shaft Area
71 Minerals	1976	RDH-124	80'	Skip Shaft Area
71 Minerals	1976	RDH-125	130'	Skip Shaft Area
71 Minerals	1976	RDH-126	60'	Skip Shaft Area
71 Minerals	1976	RDH-127	80'	Skip Shaft Area
71 Minerals	1976	RDH-128	80'	Tranquility Shaft Area
71 Minerals	1976	RDH-129	70'	Tranquility Shaft Area
71 Minerals	1976	RDH-130	70'	Tranquility Shaft Area
71 Minerals	1976	RDH-131	65'	Tranquility Shaft Area
71 Minerals	1976	RDH-132	70'	Tranquility Shaft Area
71 Minerals	1976	RDH-133	73'	Tranquility Shaft Area
71 Minerals	1976	RDH-134	80'	Tranquility Shaft Area
71 Minerals	1976	RDH-135	80'	Tranquility Shaft Area
71 Minerals	1976	RDH-136	65'	Tranquility Shaft Area
71 Minerals	1976	RDH-137	55'	Tranquility Shaft Area
71 Minerals	1976	RDH-138	50'	Tranquility Shaft Area
71 Minerals	1976	RDH-139	50'	Tranquility Shaft Area
71 Minerals	1976	RDH-140	50'	Tranquility Shaft Area
71 Minerals	1976	RDH-141	50'	Tranquility Shaft Area
71 Minerals	1973	AT-1	55'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-2	50'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-3	75'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-4	65'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-5	50'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-6	80'	Unpatented T.D.C. Claims

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Drilling Group	Date	Drill Hole No.	Depth	Location
71 Minerals	1973	AT-7	100'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-8	104'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-9	100'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-10	100'	Unpatented T.D.C. Claims
71 Minerals	1973	AT-11	100'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-1	50'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-2	45'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-3	48'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-4	10'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-5	10'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-6	10'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-7	48'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-8	48'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-9	48'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-10	48'	Unpatented T.D.C. Claims
71 Minerals	1973	TDC-11	48'	Unpatented T.D.C. Claims
71 Minerals	1973	RD-1	210'	Unpatented T.D.C. Claims
71 Minerals	1974	RD-1	608'	TMR Claims
71 Minerals	1974	RD-2	10'	TMR Claims
71 Minerals	1974	RD-3	185'	TMR Claims
71 Minerals	1974	RD-4	32'	TMR Claims
71 Minerals	1974	RD-5	500'	TMR Claims
71 Minerals	1974	RD-6	415'	TMR Claims
71 Minerals	1975	WWP-1	270'	State Of Maine
71 Minerals	1975	1-75	175'	Fox

Drilling Group	Date	Drill Hole No.	Depth	Location
71 Minerals	1973	E-1	50'	So. Charleston Lead Mine
71 Minerals	1973	E-2	50'	So. Charleston Lead Mine
71 Minerals	1973	E-3	50'	So. Charleston Lead Mine
71 Minerals	1973	F-1	35'	So. Charleston Lead Mine
71 Minerals	1973	F-2	50'	So. Charleston Lead Mine
71 Minerals	1973	F-3	50'	So. Charleston Lead Mine
71 Minerals	1973	F-4	50'	So. Charleston Lead Mine
71 Minerals	1973	F-5	50'	So. Charleston Lead Mine
71 Minerals	1973	F-6	50'	So. Charleston Lead Mine
71 Minerals	1973	F-7	50'	So. Charleston Lead Mine
71 Minerals	1973	F-8	50'	So. Charleston Lead Mine
71 Minerals	1973	F-10	55'	So. Charleston Lead Mine
71 Minerals	1973	E-4	85'	So. Charleston Lead Mine

1930 DRILLING SUMMARY

Diamond Drill Hole No.	Location	Remarks
1	West Side - 300 Level	Gold ore in very brecciated dark shale - last hole.
2	West Side - 300 Level	Slight mineralization
3	West Side - 300 Level	Slight mineralization
4	Sulphuret - 500 Level	Good - Au, Ag, & Pb in blue ls.
5	Sulphuret - 500 Level	Very Good - Au, Ag, Pb, & Zn in blue ls.
6	West Side - 300 Level	Slight mineralization in shale
7	Empire - 300 Level	Good - Au, Ag in Kaolin fault breccia
8	Empire - 300 Level	Slight - Ag in blue ls.
9	Sulphuret - 500 Level	Fair - Ag in blue ls.
10	Sulphuret - 500 Level	Some Au, Ag, Pb, & Zn in blue ls.
11	Sulphuret - 500 Level	Very Good - Au & Ag in ls.
12	Sulphuret - 500 Level	Some Ag in blue ls.

1930 DRILLING SUMMARY

Churn Drill Hole Number	Location	Remarks
CDH - 1	Blue Monday Claim	Very weak mineralization
CDH - 2	So. Ext. Toughnut	"
CDH - 3	Toughnut Claim	Weak mineralization
CDH - 4	"	Some weak silver
CDH - 5	"	Weak Au & Ag
CDH - 6	"	Weak Ag
CDH - 7	Mesquite Claim	Qual.
CDH - 8	Manzanita Claim	Qual. & Bisbee
CDH - 9	Taco Tecalote Claim	Qual. & Bisbee
CDH - 10	Cholla Claim	Qual. & Bisbee
CDH - 11	Cholla Claim	Qual. & Bisbee
CDH - 12	Nogales Claim	Qual. & Bisbee

NEWMONT DRILLING SUMMARY

Diamond Drill Hole Number	Location	Remarks
DDH- 7	Silver Thread	Intervals of very high-grade Ag, Pb, Cu, & Zn.
DDH- 9	West Side	Same as above.

DUVAL DRILLING SUMMARY

Rotary Drill Hole No.	Location	Remarks
1	Contention Area	weak mineralization, ore below Novaculite
2	So. Tranquility	weak mineralization, ore in Novaculite
3A	Contention Area	weak mineralization, low-grade ore in silty quartz sandstone
3	Contention Area	Los Hole in Novaculite
4	Contention Area	weak mineralization
5	Silver Thread Area	weak mineralization, last hole in stope
6	So. Tranquility	weak mineralization, ore in siltstone, shale, meta siltstone member
7	No. Empire	weak mineralization
8	E. Empire	weak mineralization
9	E. Empire	very weak mineralization

FRANKOVITCH DRILLING SUMMARY
(No Assays Shown)

Diamond Drill Hole No.	Location
1	Silver Reef Property
2	Silver Reef Property - Governor Henderson Claim
3	Silver Reef Property
4	Silver Reef Property
5	Silver Reef Property
6	Silver Reef Property
7	Silver Reef Property
8	Silver Reef Property
9	Silver Reef Property
10	Silver Reef Property
11	Silver Reef Property - #2 Claim
12	Poor X Claim
13	?
14	?
15	Roll 614
16	?
17	Ingersol Anticline
18	Vigina - Tribute Drift

TOMBSTONE DEVELOPMENT CO. - UNPATENTED CLAIMS
(18 Unpatented Claims)

Drill Hole No.	Remarks
AT-1	55' deep, no mineralization
AT-2	50' deep, good silver mineralization
AT-3	75' deep, very weak silver
AT-4	65' deep, no mineralization
AT-5	50' deep, no mineralization
AT-6	80' deep, some Ag
AT-7	100' deep, some Ag
AT-8	104' deep, good Ag
AT-9	100' deep, some good Ag
AT-10	100' deep, some very good Ag
AT-11	100' deep, weak Ag

Rotary Drill Hole No.	Remarks
TDC-1	very weak mineralization
TDC-2	weak mineralization
TDC-3	weak Ag, Cu, Pb, Zn
TDC-4	weak Ag & Cu
TDC-5	very weak mineralization
TDC-6	very weak mineralization
TDC-7	some weak Cu, Pb, & Zn
TDC-8	some weak Cu, Pb, & Zn
TDC-9	fair Pb & Zn
TDC-10	weak Au, Ag, Cu, Pb, & Zn
TDC-11	weak Au, Ag, Cu, Pb, & Zn
RD-1	210' feet

71 MINERALS DRILLING

Rotary Drill Hole No.	Location	Remarks
1A	Skip Shaft Area	Qual. - no samples
101	Skip Shaft Area	Qual. - no samples
106	Skip Shaft Area	Fair - mineralization
107	Skip Shaft Area	Fair - mineralization
108	Skip Shaft Area	Weak - mineralization
109	Skip Shaft Area	Weak - mineralization
110	Skip Shaft Area	Weak - mineralization
111	Skip Shaft Area	Weak - mineralization
112	Skip Shaft Area	Weak - mineralization
113	Skip Shaft Area	Weak - mineralization
114	Skip Shaft Area	Fair - hit stope
115	Skip Shaft Area	Fair
116	Near Skip Shaft Fissure	High-Grade Intervals
117	Skip Shaft Area	Qual. - no samples
118	Skip Shaft Area	Qual. - no samples
119	Skip Shaft Area	Qual. no samples
120	Skip Shaft Area	Qual. - no samples

Rotary Drill Hole No.	Location	Remarks
120A	Skip Shaft Area	Qual. - no samples
121	Skip Shaft Area	Qual. - no samples
122	Skip Shaft Area	Qual. - no samples
123	Skip Shaft Area	Qual. - no samples
124	Skip Shaft Area	Weak - mineralization
124	Skip Shaft Area	Weak - mineralization
125	Skip Shaft Fissure	Some High-Grade Intervals
126	Skip Shaft Area	Weak - mineralization
127	Skip Shaft Area	Fair - mineralization
128	Skip Shaft - Tranquility Area	Good - mineralization
129	Tranquility Shaft Area	Weak - mineralization
130	Tranquility Shaft Area	Weak - mineralization
131	Tranquility Shaft Area	Weak - mineralization
132	Tranquility Shaft Area	Good - mineralization
133	Tranquility Shaft Area	Good - mineralization
134	Tranquility Shaft Area	Weak - mineralization
135	Tranquility Shaft Area	Fair - mineralization
136	Skip Shaft Area	Weak - mineralization

Rotary Drill Hole No.	Location	Remarks
137	Skip Shaft Area	Weak - mineralization
138	N. Skip Shaft	Good - mineralization
139	Empire Shaft Area	Weak - mineralization
140	Empire Shaft Area	Weak - mineralization
141	Empire Shaft Area	Weak - mineralization

U.S. DEPT. AG.
SEISMIC REPORT

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

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UNITED STATES DEPARTMENT OF AGRICULTURE

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Trade names are used in this publication solely for the purpose of providing specific information. Mention of a trade name does not constitute a guarantee or warranty of the product by the U.S. Department of Agriculture or an endorsement by the Department over other products not mentioned.

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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, ARIZONA[1]

F. Libby, D. E. Wallace, and D. P. Spangler[2]

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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[1] Soil and Water Conservation Research Division, Agricultural Research Service, U.S. Department of Agriculture, in cooperation with the Arizona Agricultural Experiment Station.

[2] Research geologist, geologist, and geologist and University of Arizona graduate student, respectively, Southwest Watershed Research Center, USDA, Tucson, Ariz.

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

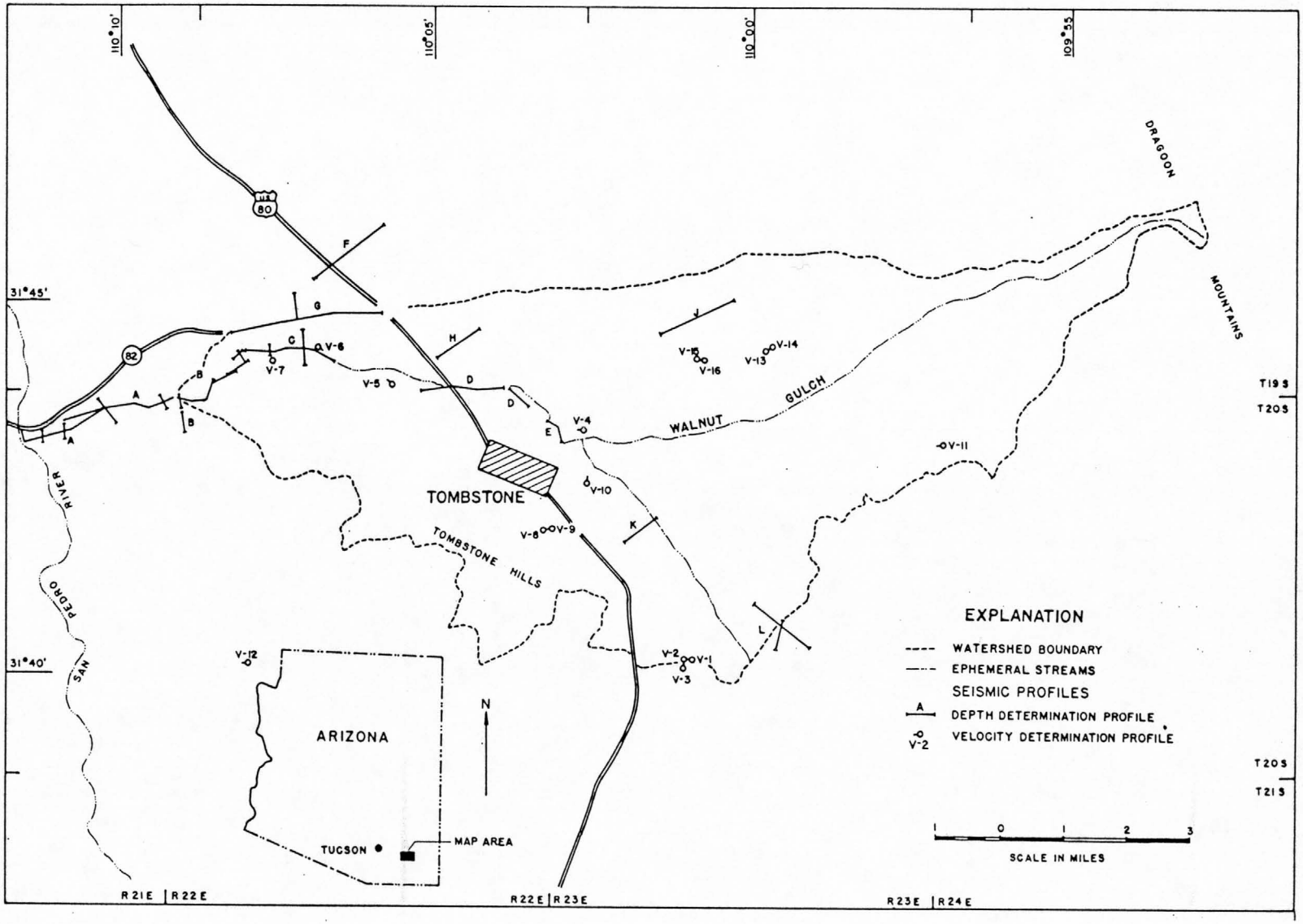

Figure 1.–Location of Walnut Gulch Experimental Watershed and periphery showing seismic study areas.

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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.

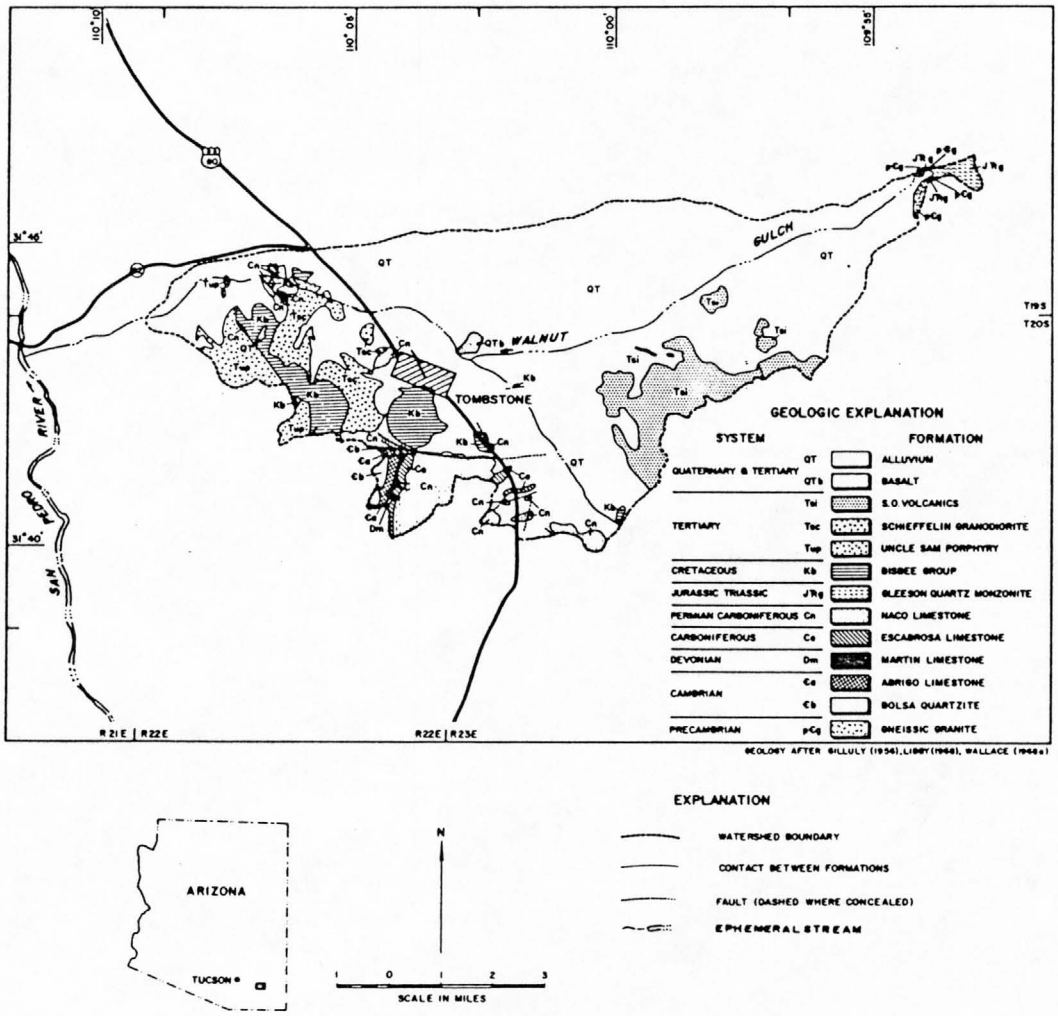

Figure 2.–Geologic map of Walnut Gulch Experimental Watershed.

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
			feet
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 premanently 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 alluvival 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.*	*g./cm.*^{3}
Recent channel deposits	Qal	1,150-4,900	2,200	--
Quaternay-Tertiary alluvial deposits	QT	--	--	--
Unconsolidated		3,350-6,000	5,000	2.02
Conglomerates		6,000-12,350	8,800	2.34
Quaternary-Tertiary basalt	QTb	--	[1]15,600	2.80
S. O. volcanics	Tsi	--	[1]12,300	2.33
Pre-S. O. volcanic sedimentary rocks	Ts	7,550-10,925	9,700	2.48
Schieffelin granodiorite	Tsc	12,300-17,700	15,450	2.68
Uncle Sam porphyry	Tup	10,100-16,400	13,350	2.61
Bisbee group	Kb	12,100-16,400	13,650	2.70
Naco limestone	Cn	11,850-16,000	13,350	2.69

[1] Values based on a single unreversed velocity profile.

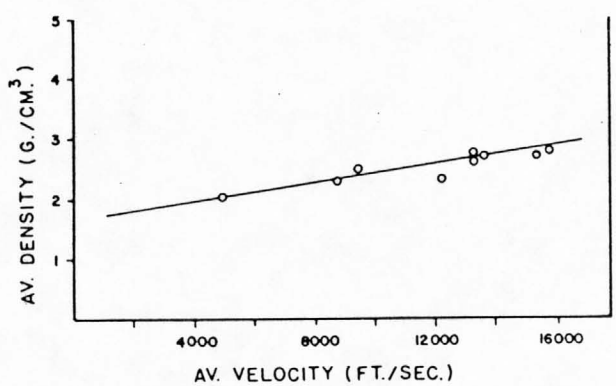

Figure 3.—A plot of bulk density versus seismic velocity for geologic units in the watershed

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

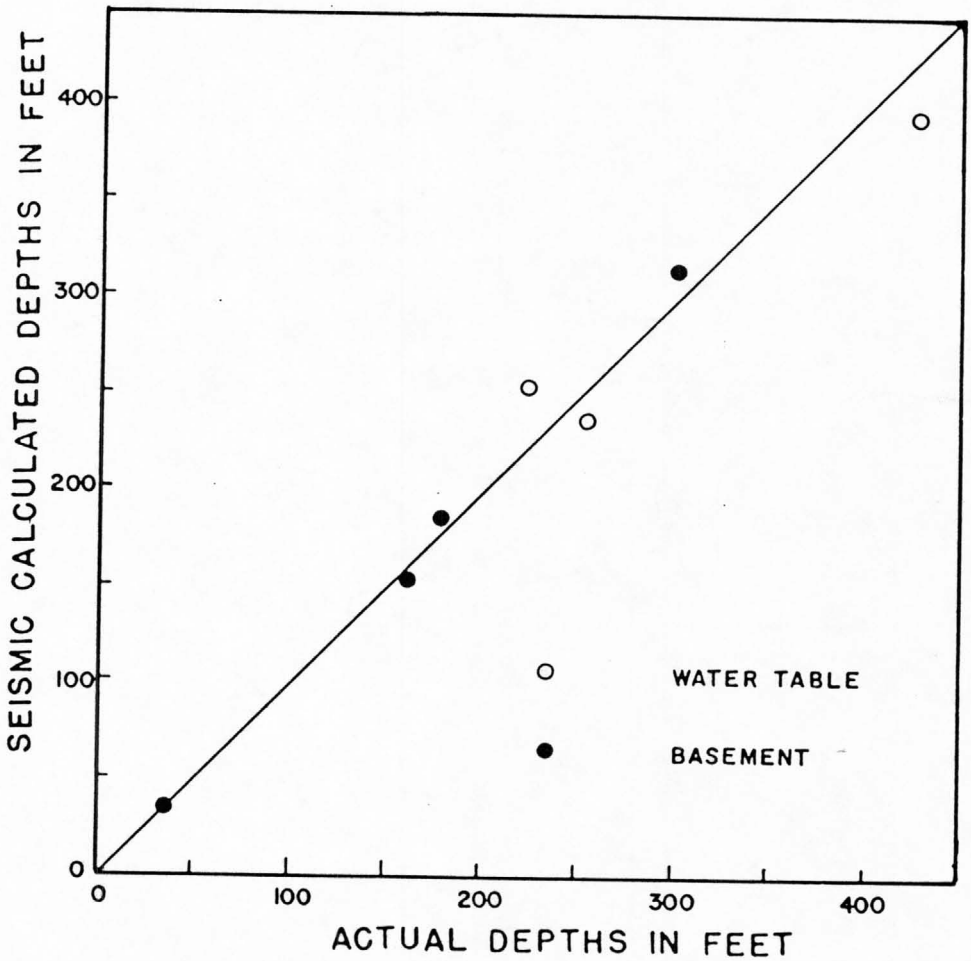

Figure 4.—A plot of seismically calculated depths versus depths derived from well logs.

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 reasonable. 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 Pediment. 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 approximately 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 is 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.ps. 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.

Nogales AMS Sheet.

June 11, 1965

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GRAVITY SURVEY

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Application of the Gravity Survey Method to Watershed Hydrology

by Daniel P. Spangler and Fred J. Libby

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Application of the Gravity Survey Method to Watershed Hydrology[a]

by Daniel P. Spangler[b] and Fred J. Libby[c]

ABSTRACT

A gravity survey covering 250 square miles and including the Walnut Gulch watershed at Tombstone, Arizona has been conducted. The watershed is one of the experimental areas of the Southwest Watershed Research Center, Agricultural Research Service in Tucson, Arizona.

The gravity survey method was selected as the geophysical method that would give a regional picture of the subsurface geology before making extensive surveys by the seismic refraction method. Basically, the gravity survey method detects and measures variations in the earth's gravitational force. These variations are associated with changes in rock and alluvium density near the surface. Many geologic structures of interest in watershed ground-water hydrology cause disturbances in the normal density distribution which give rise to anomalies.

The geology of the watershed is typical of Basin and Range province and contains deep basin fill deposits surrounded on the east, south, and southwest by igneous intrusives, volcanics, and sedimentary rocks. Concealed border faults may have a decided effect on the hydrology of the watershed.

Four base stations were established and 360 gravity stations occupied by a Worden Educator* gravimeter loaned from the Geophysics Laboratory of the University of Arizona. Bench marks and large scale topographic maps served as control. Raw field data were reduced to the simple Bouguer anomaly values through the use of a computer program.

The gravity survey reveals a 16-mgal. gravity low over the east-central portion of the watershed. This low is interpreted as indicating that about 3200 feet of low density alluvium underlies the area at this point. Gravity highs are associated with mountain ranges and igneous plugs where the more dense rocks occur.

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* Reference to this manufactured product does not constitute endorsement by the government.

Discussion open until April 1, 1969.

INTRODUCTION

Purpose and Scope of Investigation

The Southwest Watershed Research Center of the Agricultural Research Service (ARS) is conducting a series of studies in semiarid rangeland watersheds of the Southwest to evaluate future water yield potential and sediment yield of semiarid rangeland watersheds as related to measures for their conservation and sustained production of forage. One of the research objectives is isolation and analysis of geologic factors operating in the ground-water system.

During these studies on the Walnut Gulch watershed near Tombstone, Arizona, it became evident that determination of hydrogeologic relationships could not be determined without detailed knowledge of the subsurface geology. Therefore, a complete geophysical survey was initiated in 1967.

The gravity survey method was subsequently selected to provide basic data on configuration of the basement complex and aid in directional control of planned seismic refraction profiles. In addition, alluvial depth approximations from the gravity data, along with water well and seismic data, will aid in construction of the geologic framework.

This report describes the principles of the gravity survey method, the field procedures and data reduction technique used, and some interpretations derived from a study on the Walnut Gulch watershed during 1967 and 1968.

GRAVITY SURVEY

Principles and Variations of Gravity

The theory of gravity surveying is directly dependent on Newton's law of gravity:

$$F = \frac{G\,M_1 M_2}{r^2} \quad . \qquad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

In the cgs system, F is force expressed in dynes or $\frac{\text{gm-cm}}{\text{sec}^2}$, G is the gravitational constant whose value is $6.670 \times 10^{-8}\ \frac{\text{cm}^3}{\text{gm-sec}^2}$, M_1 and M_2 are the mass of two respective spheres or particles expressed in grams, and r is the distance in centimeters between their centers of mass.

From Newton's second law of motion, the relation between force, mass, and acceleration is:

$$a = \frac{F}{M_2} \qquad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

The acceleration a of a mass M_2 due to the attraction of a mass M_1 is expressed as cm/sec^2. The symbol a is often referred to as g, the gravitational acceleration, with the gal as the unit of dimension.

The basic density-mass-volume relationship is:

$$D = \frac{M}{V} \qquad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where D is density expressed in gm/cm^3. Equating (1) and (2) and substituting M = DV from (3):

$$g = G\,\frac{DV}{r^2} \qquad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

This basic relationship shows that the value of gravity is directly proportional to the density and volume of a mass (earth materials beneath the gravimeter) and inversely proportional to the square of the distance from the attractive body. As the earth is not perfectly homogeneous, spatial variations of gravity are also a function of latitude and the adjacent terrain.

Observed time variations of gravity are primarily a function of earth tide fluctuations and instrument drift.

Establishing Base Stations

A base station is a point at which the observed value of gravity is accurately known, and it represents an extension of control from a point where the absolute value of gravity was determined. As modern gravimeters (Figure 1) do not measure absolute values of gravity, a gravity base station network is necessary throughout the area of interest. In establishing gravity base stations, one should consider the permanence of the site, its ease of identification, accessibility, and any extraneous terrain effects.

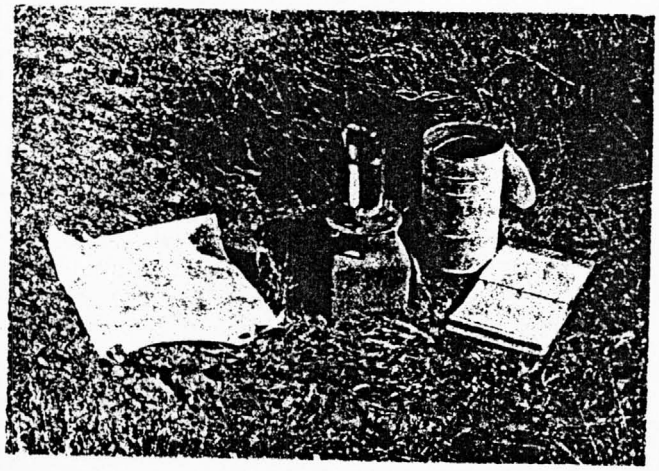

Fig. 1. A hand portable Worden Educator gravity meter placed on an elevation bench mark.

A new gravity base station is determined by making at least two traverses between it and a previously known base station. After corrections are made for earth tide and instrument drift, the instrument value is converted by a scale factor to milligals, and the difference is applied to the known gravity base station to obtain the observed gravity value of the new gravity base station.

The first gravity base station in the Walnut Gulch watershed was established at the ARS field office. The station was tied to the airport gravity base station at Benson, Arizona, 23 miles to the north. From the first station, a network of three other gravity base stations was established in the watershed (Figure 2).

Observation Stations

A total of 360 stations was observed on the watershed and surrounding area using a Worden Educator gravity meter. Station density averaged 1.4 per square mile. Some areas contained fewer than one station per three square miles, whereas other areas contained 8 stations per square mile. The frequency of sampling depended on detail desired, identification of station with respect to location and elevation, accessibility, and time available.

Short loops of two to three hours duration were made from a base station in order to minimize drift errors. When this was not possible and the loop was over four hours, earth tide corrections were applied.

Location and Elevation Determinations

The value of gravity decreases approximately 0.06 milligal per foot increase in elevation and increases approximately 0.1 milligal (middle latitudes) per 0.1 minute increase in latitude. Therefore, the most time-consuming element in field work of a gravity survey is determination of location and elevation of the station. Those areas having large numbers of well-distributed, accessible, and known bench marks are most desirable.

If a very precise survey (less than 1 milligal contour interval) is desired, transit, leveling, and chaining survey methods are necessary. For less detailed work, topographic maps referenced to mean sea level may be substituted. Davis (1967) concluded from a regional gravity survey in the Tucson Basin that topographic maps having less than a 40-foot contour interval were satisfactory for point elevation interpretation. Altimeter methods have been used as another alternative for elevation control, although their value is quite questionable, particularly during periods of rapidly changing barometric pressure or in rough topographic areas.

Density Determinations

As the value of gravity is directly proportional to the density of the adjacent materials (Equation 4), several surface samples of each rock type were analyzed by the volume-displacement method in compiling average densities for the rock units listed in Table 1.

The average for the igneous and sedimentary units combined was 2.66 gm/cm³, a value in close agreement with the 2.67 gm/cm³ commonly used in reducing gravity data. Sumner and Schnepfe (1966) found the density for a similar suite of rocks 24 miles south of Tombstone at Bisbee, Arizona to be fairly uniform, and in the range of 2.65 to 2.70 gm/cm³.

TABLE 1. ROCK DENSITY DATA

Rock units	*No. samples*	*Range (gm/cm³)*	*Average (gm/cm³)*
Alluvium	4	2.05–2.40	2.22
Volcanics	6	2.23–2.57	2.40
Igneous	15	2.52–2.93	2.63
Sedimentary	18	2.61–2.83	2.69

Density determinations of the alluvium noted in Table 1 compare with the average densities of 2.2 to 2.3 gm/cm³ reported by Mabey (1966) for major basins in the Basin and Range province. Actual density distribution within the alluvium may deviate substantially due to lateral variations and compaction at depth.

Reduction of Data

For gravity data to be most useful, Dobrin (1960) notes that observed gravity values should be corrected for latitude, station elevation, and the influence of the nearby topography. In general, the values are all reduced to a common datum in order to show anomalous areas.

As previously noted, the observed value of gravity is a function of latitude because the earth is neither spherical nor at rest. The rate of change of gravity with latitude in milligals per mile is 1.307 sin 2 ϕ where ϕ is latitude. A step in data reduction was eliminated by determining latitude and longitude for each of the gravity stations to the nearest 0.1 minute from field maps, using an analog to digital converter at the Southwest Watershed Research Center in Tucson, Arizona.

The elevation correction contains two parts: (1) the free air correction, and (2) the Bouguer correction. From Equation 4, it was noted that the gravity value was inversely proportional to the square of the distance. Therefore, the free air correction accounts for the difference in the distance between the datum chosen (sea level in this report) and the station elevation. The free air correction for a datum of sea level is approximately −0.094 mgal/ft. The Bouguer correction accounts for the attraction of a presumed flat infinite slab of rock material between the sea level datum and a horizontal plane passing through the station. If the density is taken as 2.67 gm/cm³, this correction is approximately +0.034 mgal/ft. The combined elevation correction for a gravity station is therefore −0.060 mgal/ft. If only the latitude and the elevation corrections are applied to the observed gravity values, the result then is simple Bouguer values.

Rough topography violates the assumption of a flat slab made in the Bouguer correction to some degree and, therefore, may dictate that terrain corrections be applied to the simple Bouguer values to give complete Bouguer gravity values. Terrain corrections were not applied in the compilation of Figure 2. A few selected stations were analyzed, and their values varied according to the type of terrain from 0.2 to 2.0 milligals. The percent error in depth calculations by not applying terrain corrections depends on the amplitude of the anomaly in question. In Figure 3 this error may amount to 10 percent of the depth shown in the large negative anomaly.

The Walnut Gulch watershed gravity data were reduced through the use of a computer program written by Davis (1967). Input for the computer program consisted of station number, latitude and longitude, elevation, time of reading, instrument value, the base station reading before and after a loop, and the base station's observed value of gravity. The program output was simple Bouguer gravity values.

Regional Gradient

Regional gradients in gravity caused by large deep-seated structural features often distort or obscure local anomalies. For this reason, regional gravity is often subtracted out so as to leave the residual gravity. The process of determining the plane of regional gradient is often a tedious one. In many cases, as noted by Dobrin (1960), the gravity cross section is drawn through the center of the anomaly, and the best straight line connecting the maxima is assumed to approximate the regional gradient. This procedure was used recently by Cook, Berg, and Lum (1967) in discussing a gravity profile across the Northern Wasatch Trench in Utah. In Figure 3, the relationship between the observed simple Bouguer anomaly, the assumed regional gradient, and the residual gravity was derived similarly.

GEOLOGY AND INTERPRETATION

Geologic Setting

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

Deep-seated igneous intrusions and accompanying high-angle reverse faulting are responsible for the high relief areas that comprise the Tombstone Hills on the west and lower Dragoon Mountains on the east (Figure 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 are without caprock; the only residual limestones in this area are small drag blocks along fault zones.

Late Tertiary volcanics in the southeast portion of the study area are relatively thin beds of flows and tuffs and are in overthrust position. Minor amounts of late 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 basalt plug, lying on a concealed fault alignment in the central portion of the study area, occupies a relatively small percentage of the surface but may be quite extensive along this fault.

The alluvium filling the intermontane basin consists of very deep Quaternary and Tertiary sand, gravel, clay, and well-cemented caliche conglomerate. From well data, it is known to be over 1,200 feet deep in places and contains a large volume of ground water in storage. A great deal of the conglomerate in the alluvium is extremely well cemented approaching the strength and appearance of a high grade structural concrete. These conglomerates act as rock units and exert much structural control on surface stream channels and the flow of ground water.

Interpretation

The gravity low noted in Figures 2 and 3 is produced by a thick accumulation of low-density alluvium and volcanic rocks of Cenozoic age. Because the gravity anomaly is several times longer than the thickness of the low-density units producing the anomaly, a profile across the watershed, approximately normal to the axis of the gravity low and well removed from the ends, has been analyzed as a two-dimensional feature.

The only geologic controls available in the vicinity of the profile are: (1) The surface position of the rock units and their contact with the alluvium; (2) Well A in Figure 4 showing a depth of 575 feet to sedimentary rock; (3) Well B in Figure 4 showing that at least 600 feet of alluvium have been penetrated;

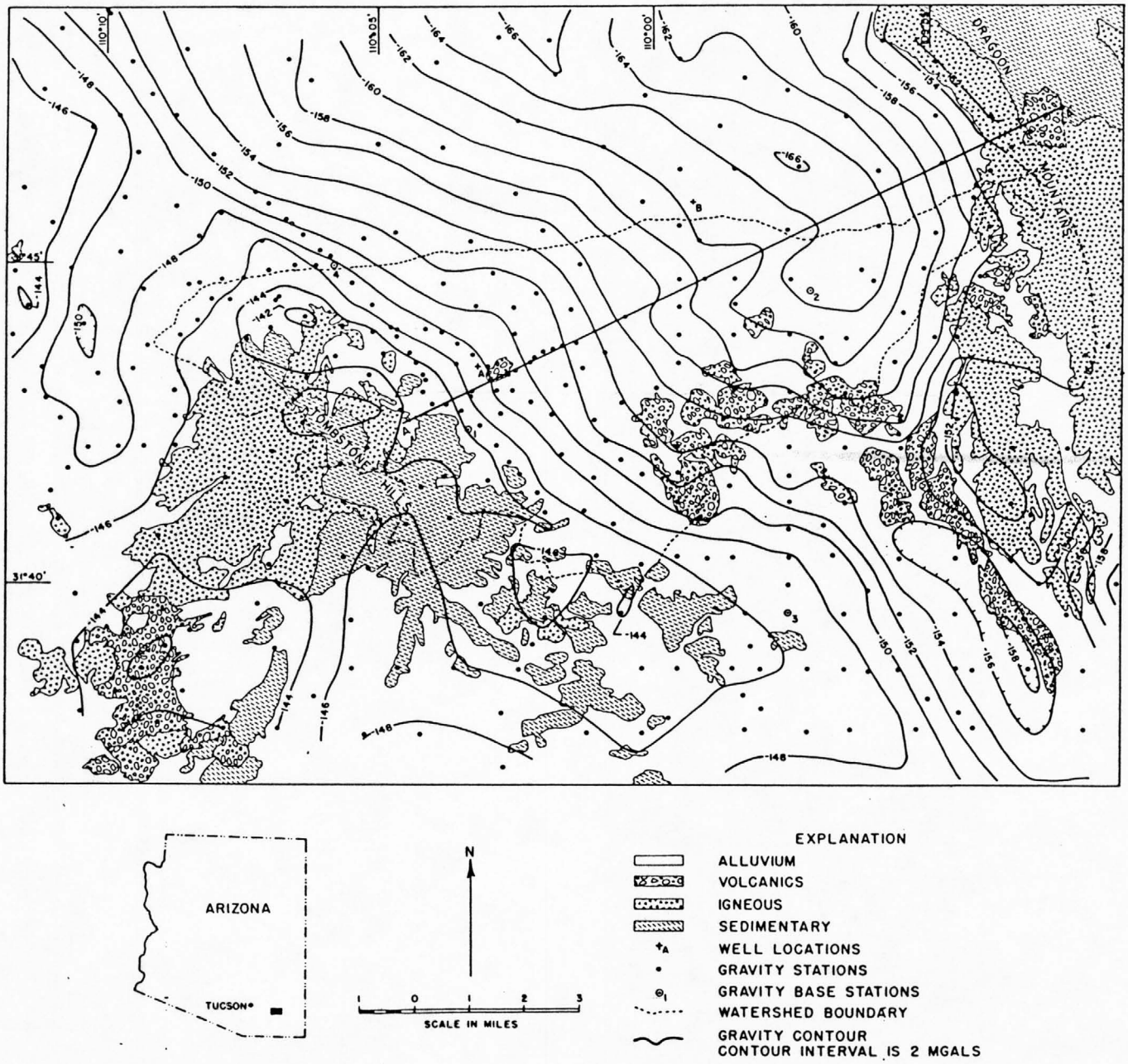

Fig. 2. Simple Bouguer gravity map and generalized geologic map. Geology modified from Gilluly (1956).

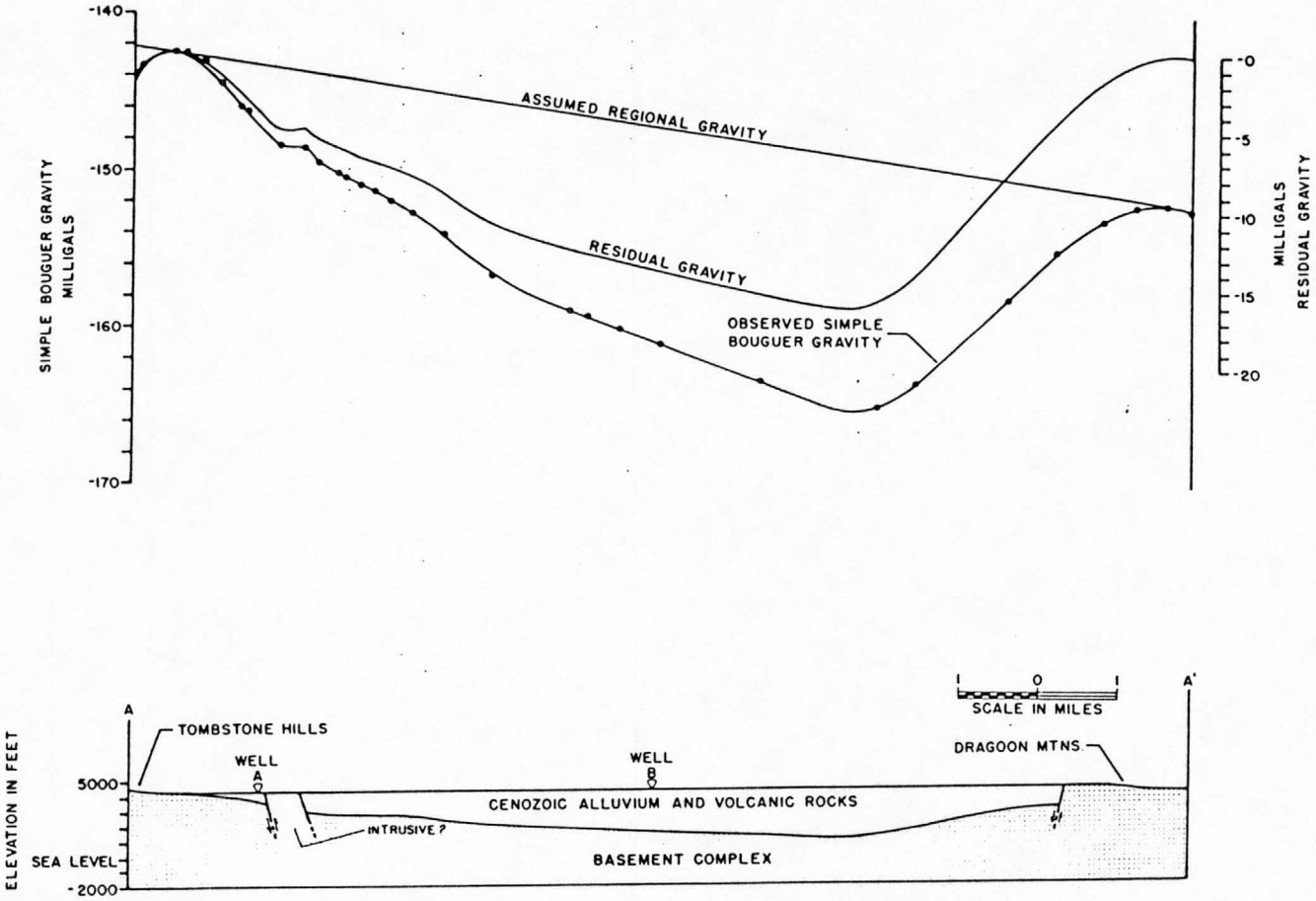

Fig. 3. Profile A-A' across Walnut Gulch watershed, illustrating observed simple Bouguer gravity, assumed regional gravity, and residual gravity (in milligals), and interpretive geologic cross section along gravity profile.

and (4) the approximate density of the major units throughout the watershed.

From density data in Table 1, the density contrast between the alluvium and its enclosing units (igneous and sedimentary) is approximately 0.4 gm/cm^3. With this density contrast, the measured gravity anomaly in the watershed could be produced by the 3,200-foot thick prism of alluvium shown in Figure 3.

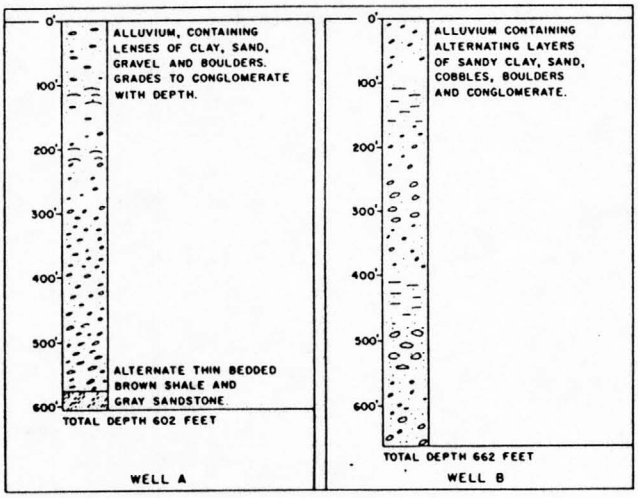

Fig. 4. Sample well logs from study area.

The steep slopes on the east and west segments of the residual gravity profile in Figure 3 have been interpreted as indicative of Basin and Range faults. Their actual form and location will demand more extensive study. A change in slope in the west segment of the residual gravity profile corresponds to a surface outcrop of intrusive basalt. The lineation and trend of the contours in Figure 2 in a predominantly NW-SE direction suggests structural control of ground-water movement.

SUMMARY AND CONCLUSIONS

It has been shown that the gravity survey method can be applied to watershed ground-water hydrology. The field techniques are simple, and one man can collect all field data. The time involved for a gravity survey will depend directly on the vertical and horizontal control available and the ease of access to the desired stations. Actual reading time once the station is occupied is less than 3 minutes.

Reduction of data is relatively straightforward if a computer program is available. Reduction time per station will average about 10 minutes when manual calculating machines are used.

Gravity surveys are sometimes performed on a contract basis for about $6 per station. This survey has cost ARS approximately $1,500, which is considerably less than a contract because of student

support and free use of a gravity meter loaned by the Geophysics Laboratory of the University of Arizona. This amount is equivalent to the cost of one water well drilled to a depth of 400 feet.

The gravity survey method will not replace other geophysical or bore-hole studies, but it can reduce the amount of time and expense in watershed ground-water hydrology studies by pointing out those areas needing additional detailed work.

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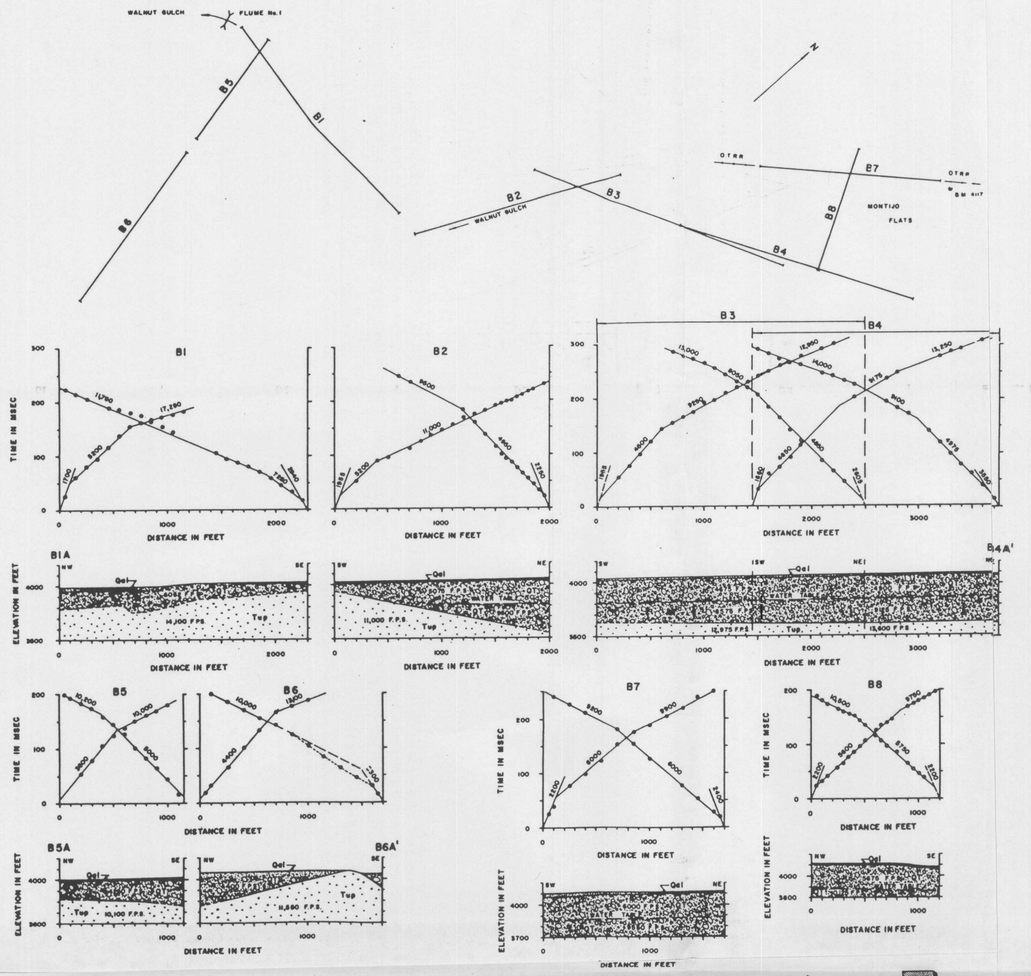
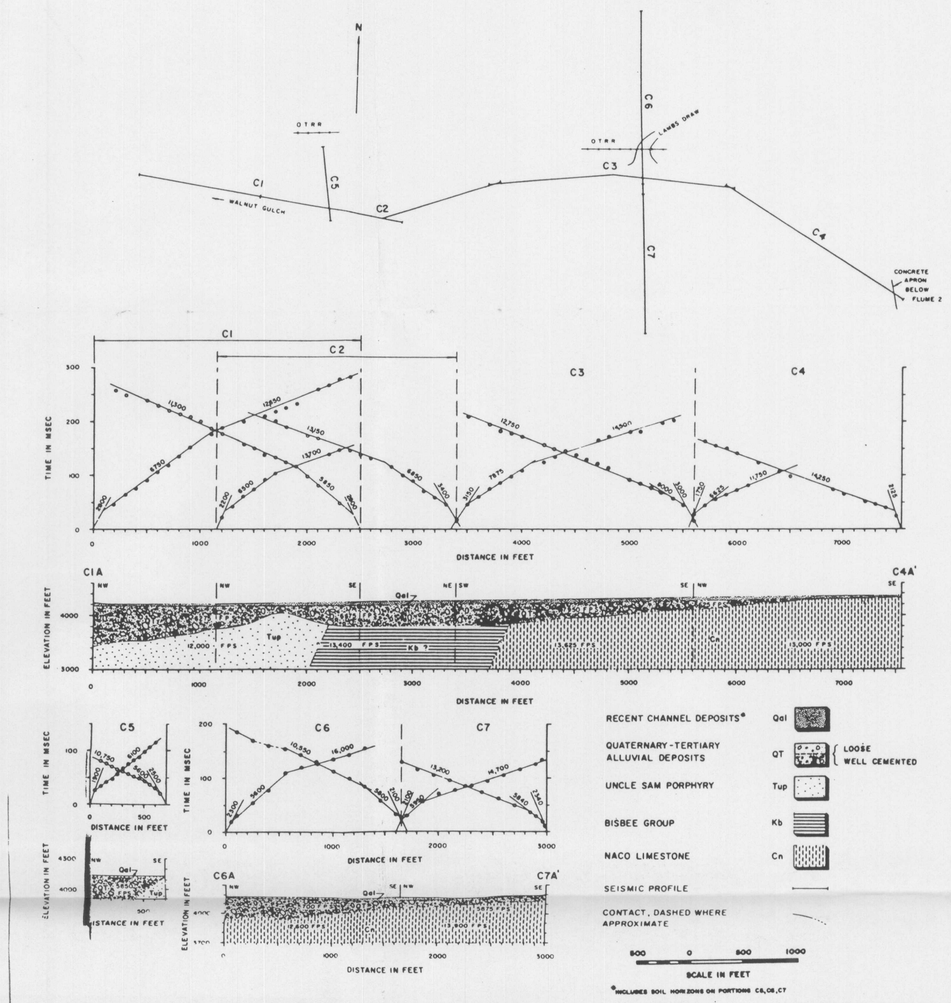
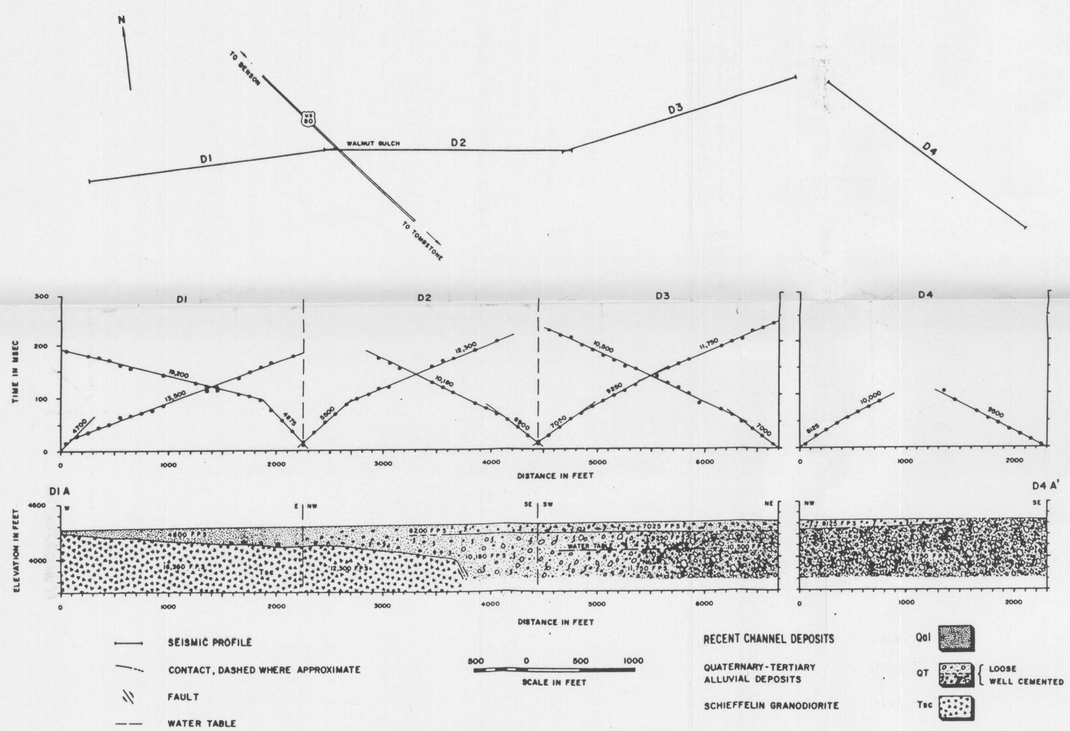


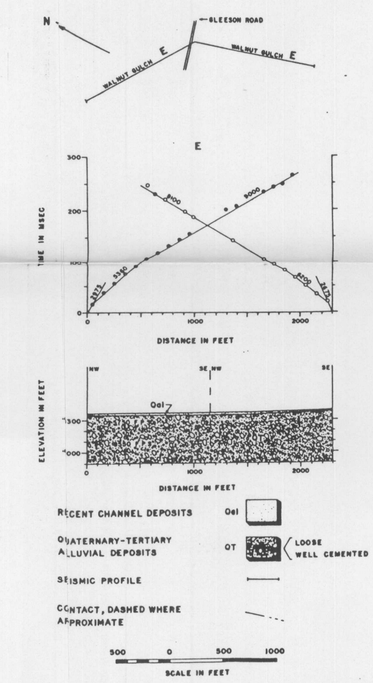
HYDROGEOLOGIC INTERPRETATION OF AREA B SEISMIC PROFILES
(FLUME 1 TO MONTIJO FLATS)



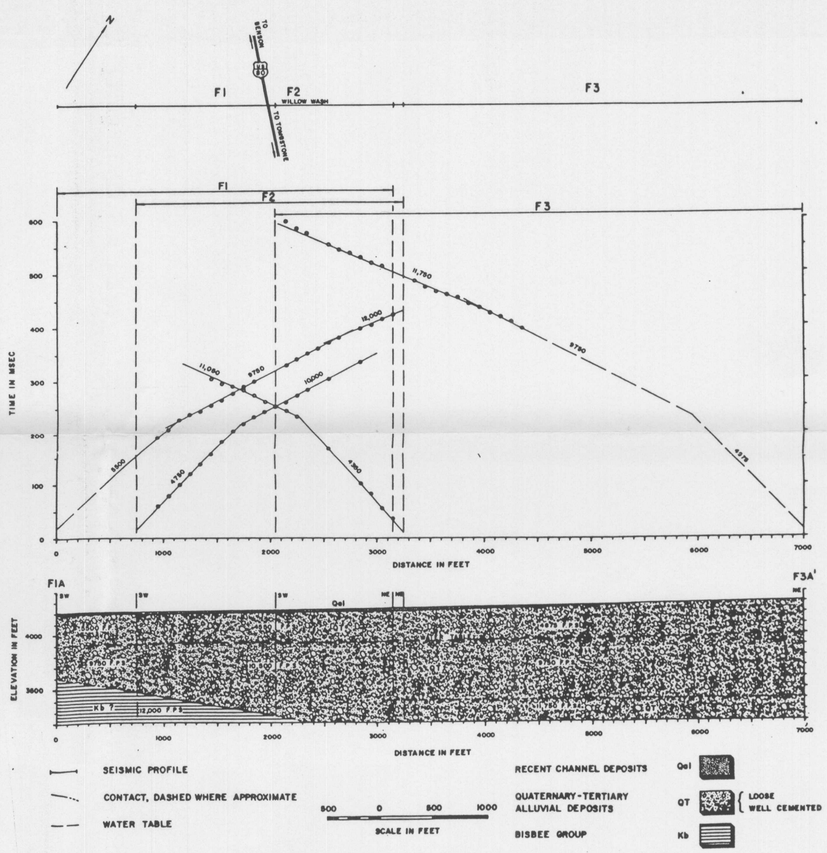
GEOLOGIC INTERPRETATION OF AREA C SEISMIC PROFILES
(LAMBS DRAW)



GEOLOGIC INTERPRETATION OF AREA D SEISMIC PROFILES
(RIFLE RANGE)

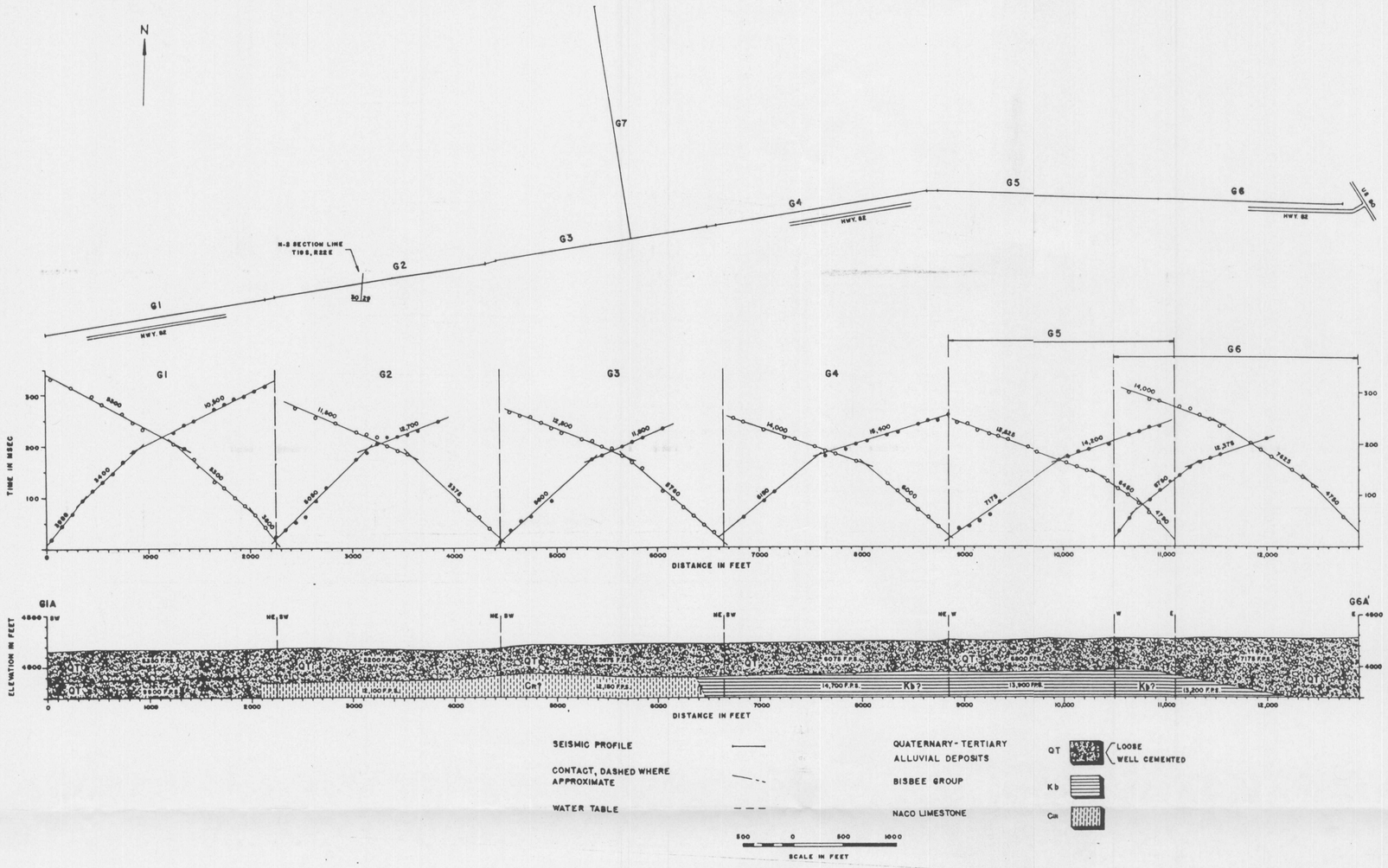


GEOLOGIC INTERPRETATION OF AREA E SEISMIC PROFILES
(WALNUT GULCH-GLEESON ROAD)

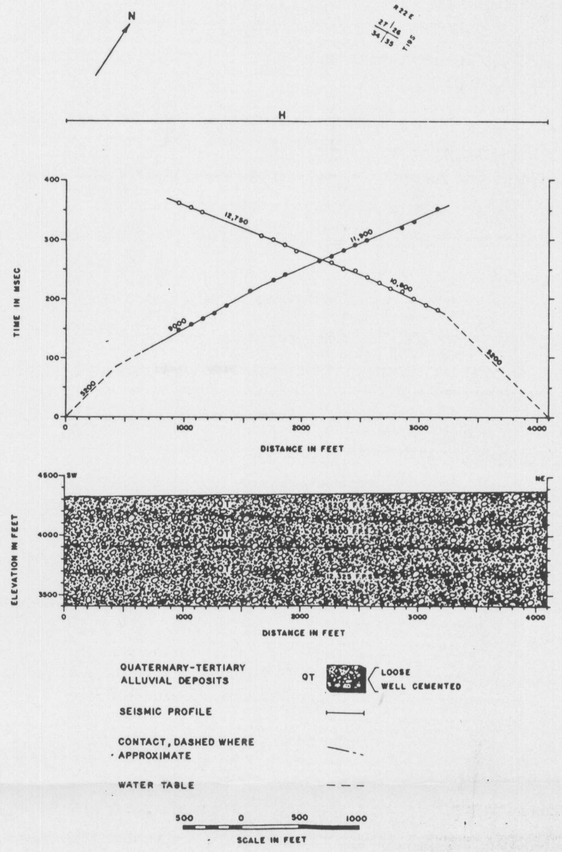


GEOLOGIC INTERPRETATION OF AREA F SEISMIC PROFILES
(WILLOW WASH)

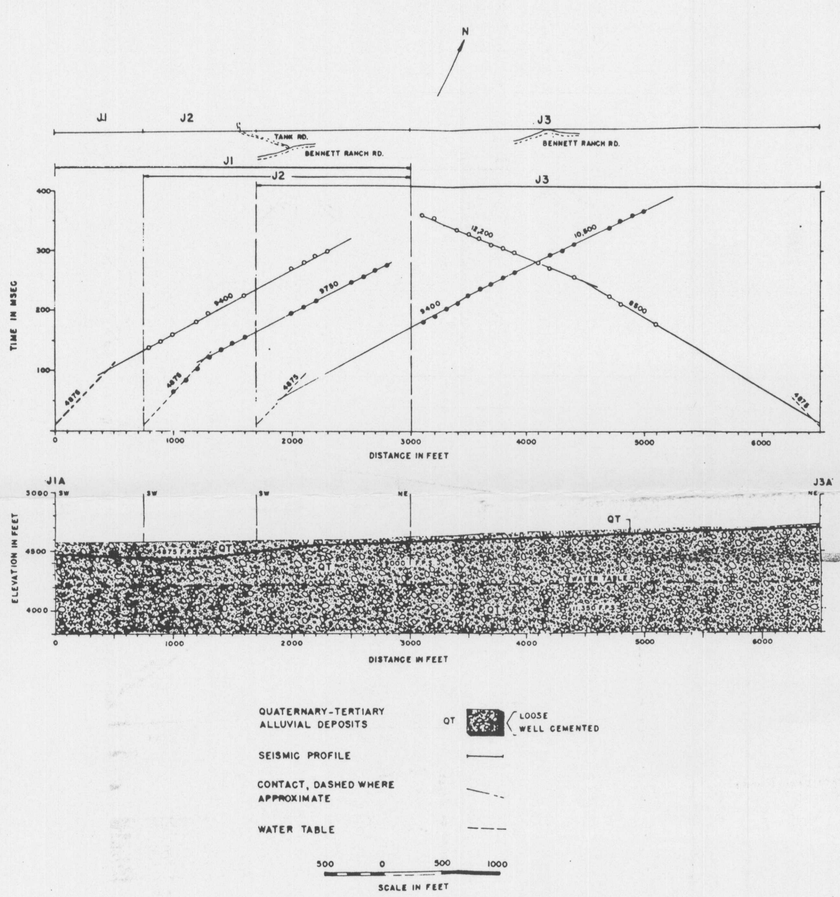
Plate 2.—Geologic interpretation of seismic profiles in areas B, C, D, E, and F.



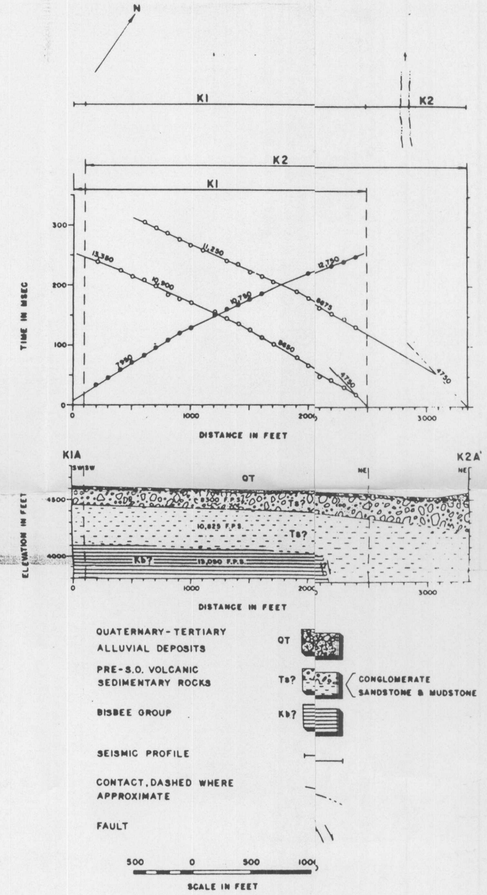
GEOLOGIC INTERPRETATION OF AREA G SEISMIC PROFILES
(HIGHWAY 82)



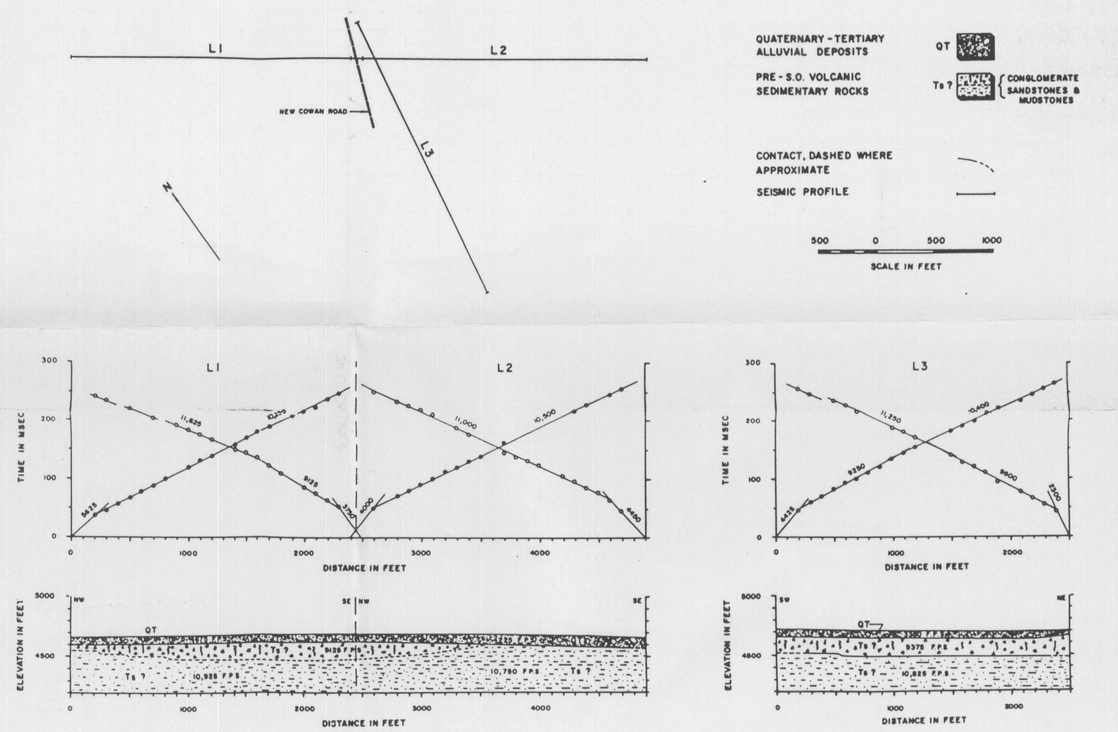
GEOLOGIC INTERPRETATION OF AREA H SEISMIC PROFILES
(CITY DUMP)



HYDROGEOLOGIC INTERPRETATION OF AREA J SEISMIC PROFILES
(BENNETT RANCH ROAD)

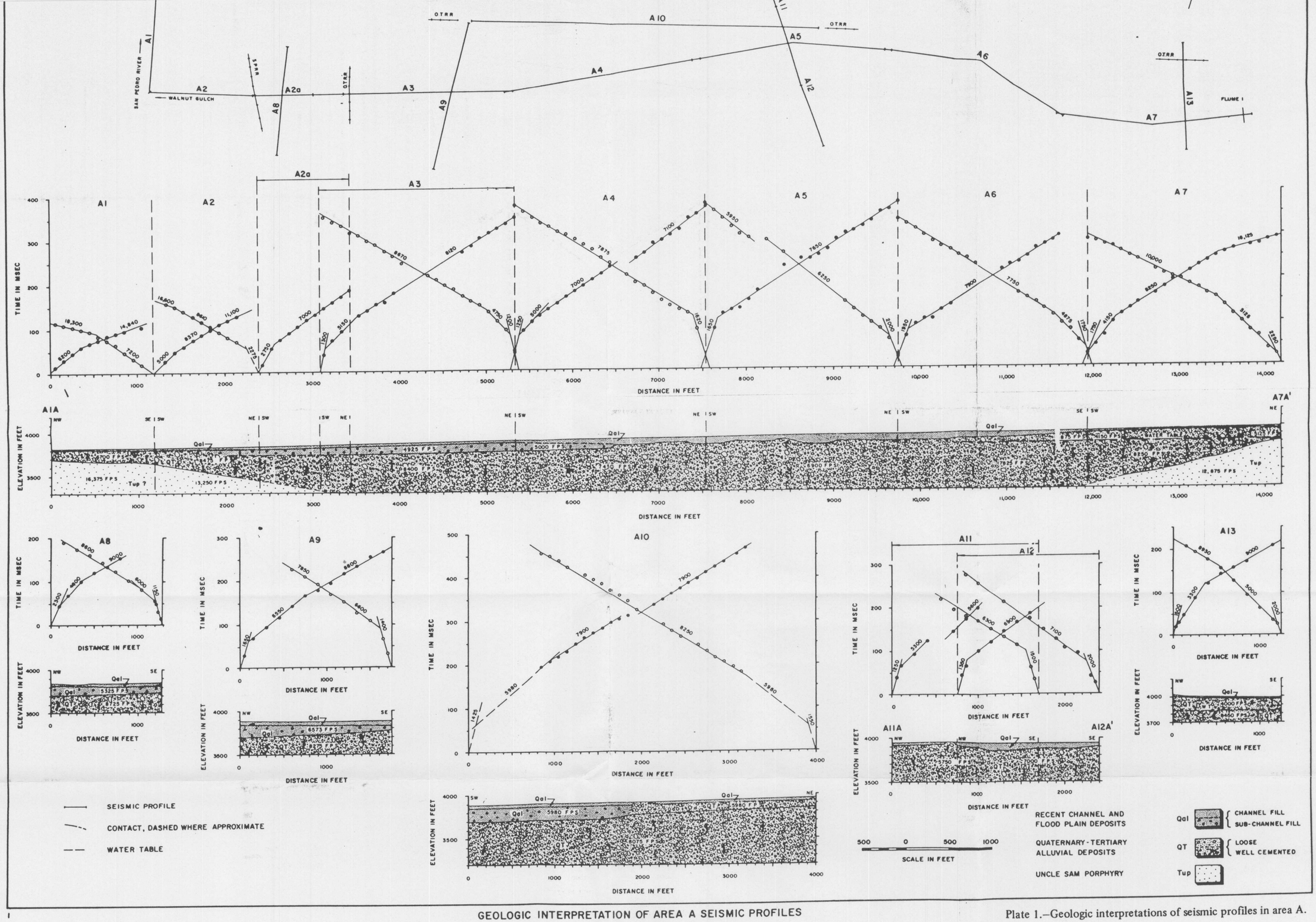


GEOLOGIC INTERPRETATION OF AREA K SEISMIC PROFILES
(NORTHWEST OF LIME TANK)



GEOLOGIC INTERPRETATION OF AREA L SEISMIC PROFILES
(NEW COWAN ROAD)

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



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

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