Geophysical Methods of Exploring for Buried Channels in the Monument Valley Area, Arizona and Utah

GEOLOGICAL SURVEY BULLETIN 1083-F

Prepared on behalf of the U.S. Atomic Energy Commission

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By R. A. BLACK, F. C. FRISCHKNECHT, R. M. HAZLEWOOD, *and* W. H. JACKSON

EXPERIMENTAL AND THEORETICAL GEOPHYSICS

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GEOPHYSICAL METHODS OF EXPLORING FOR BURIED CHANNELS IN THE MONUMENT VALLEY AREA, ARIZONA AND UTAH

By R. A. Black, F. C. Frischknecht, R. M. Hazlewood, and W. H. Jackson

ABSTRACT

Uranium deposits in the Monument Valley area of Utah and Arizona are found in buried channels cut into the Moenkopi formation of Early and Middle(?) Triassic age and filled with sedimentary rocks of the Shinarump member of the Chinle formation of Late Triassic age. Exploration for uranium deposits in this area consists of locating these buried channels and drilling within their limits to detect possible ore bodies. The U.S. Geological Survey conducted extensive geophysical investigations in Monument Valley to determine the physical properties of pertinent rock units and to determine the uses and limitations of various geophysical methods in uranium exploration. Uranium deposits in this area are not directly detected by geophysical methods, other than radiometric measurements, but physical-property studies show that seismic-velocity and electrical-resistivity contrasts exist between the Shinarump member and the Moenkopi formation and between the Shinarump member and the Monitor Butte member of the Chinle formation, which overlies the Shinarump member in parts of the area.

Seismic-refraction measurements were made over known channels, and by using the delay times of waves arriving at each detector, this geophysical method was found to be successful in locating channels and in defining their size and shape in many parts of Monument Valley. The seismic-refraction method was subsequently used successfully in many exploratory surveys to locate buried channels. In places, however, the high seismic velocity in Monitor Butte strata overlying the Shinarump and in lenses within the Shinarump limits the use of the refraction method and may render it useless for purposes of locating buried channels. The experimental seismic-reflection measurements that were made in Monument Valley indicate that this geophysical method has little application to the problem of locating buried channels in this area.

Electrical-resistivity measurements utilizing both vertical- and horizontal-profiling techniques were successfully used in some parts of Monument Valley to locate buried channels. In general, however, the resistivity data were not amenable to theoretical analysis, and only qualitative information could be obtained about the channel location, size and depth. Electromagnetic measure-

ments were also tested over known channels with slingram- and turam-type equipment, and the resulting data compared reasonably well with the resistivity data over the same channels. These preliminary results are encouraging, particularly as the electromagnetic measurements can be made more quickly and cheaply than resistivity measurements, but not enough data have been obtained to determine fully the uses and limitations of these methods of locating buried channels. Experimental potential-drop-ratio measurements were also made over channels with encouraging results, but again not enough data have been obtained to evaluate this method fully.

Gravimetric measurements over buried channels detected small gravity lows of about 0.05 milligal, but the precision and time required for the measurements and surveying make this method impracticable for locating channels. Vertical-intensity magnetic measurements were also made over known channels, but no anomalies were observed that correlated with the position of the channels.

INTRODUCTION

Geophysical investigations were made on the Colorado Plateau by the U.S. Geological Survey, on behalf of the U.S. Atomic Energy Commission, as early as 1949 to assist in the exploration for uranium deposits in the Morrison formation of Late Jurassic age. From 1949 to 1952, geophysical measurements were made, primarily with electrical-resistivity methods, to delineate parts of the Salt Wash member of the Morrison formation favorable for uranium mineralization. When the geologic-mapping program of the Geological Survey was extended from the uranium deposits in the Morrison formation to those found in the Shinarump member of the Chinle formation of Late Triassic age, the uranium deposits in the Shinarump member were found to be localized in channels cut into the Moenkopi formation of Early and Middle(?) Triassic age and filled with Shinarump sediments.

The Shinarump member is composed predominantly of sandstone, and the Moenkopi formation is predominantly siltstone. This marked lithologic contrast suggested the possibility of locating the Shinarump and Moenkopi contact by geophysical means and detecting and delineating the buried channels that are the most favorable places to drill for uranium deposits.

Electrical-resistivity and gravity measurements were made in the Koley Black area of Monument Valley (fig. 57) in 1952 by the Geological Survey to test the usefulness of these methods in locating and defining the configuration and trends of buried channels. The electrical-resistivity measurements were shown to be successful in locating and tracing buried channels, but little could be determined about the channel configuration or the absolute depth by this method. The gravity measurements seemed successful in locating the approximate position of the channels, but they required such careful survey control

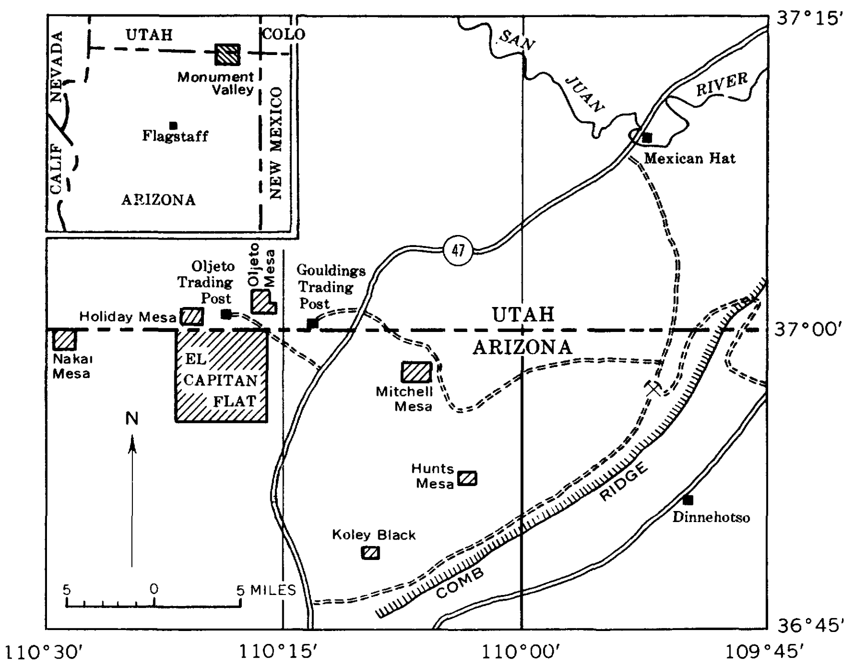

FIGURE 57.—Index map of Monument Valley showing areas in which geophysical measurements were made.

that the gravity method was considered too costly and time consuming to be practicable.

The first tests of the seismic-refraction method in the Monument Valley area, for locating buried channels, were made in 1952 by the U.S. Bureau of Reclamation for the U.S. Atomic Energy Commission (Wantland and Casey, 1952). The success of these preliminary tests led to further testing of the seismic-refraction method by the Geological Survey in 1953, and measurements were made over known channels on Nakai, Hunts, and Oljeto Mesas, and in the Koley Black area of Monument Valley (fig. 57). The seismic tests were successful in locating buried channels where the Shinarump member was either exposed at the surface or covered by windblown sand, and they also furnished information about the channel configurations.

In 1954 seismic-refraction surveys were made on Holiday Mesa and on Mitchell Mesa (fig. 57) to delineate the channel patterns in these areas prior to exploratory drilling. In both areas the seismic-refraction measurements clearly outlined the major channel trends. Subsequent drilling on Holiday Mesa confirmed the geophysical results; Mitchell Mesa has not been drilled at the present time [1959].

Seismic-refraction surveys were also made in El Capitan Flat area (fig. 57) during 1954 and 1955 to determine the trends of buried channels. These surveys were made first on a reconnaissance basis to locate major channel patterns in an area of approximately 30 square miles and then were continued on a detailed basis to map specific channel trends. Drilling was done in conjunction with the geophysical exploration to test the preliminary interpretations of the seismic data and to provide control for final interpretation. Several previously unknown channels were located by these seismic measurements, and their existence was verified by drilling in connection with the seismic measurements, or as a result of later drilling in this area by private concerns.

When more drill-hole data became available, as a result of both private and government drilling programs in Monument Valley, other geophysical methods such as the electromagnetic, magnetic, seismic reflection, and potential-drop-ratio methods were tested where subsurface conditions were well known. It is the purpose of this report to discuss the usefulness of these geophysical methods in finding buried channels, as demonstrated by the results of the various geophysical tests and exploratory surveys that have been made in the Monument Valley area.

The work reported herein was done by the U.S. Geological Survey on behalf of the Division of Raw Materials, the U.S. Atomic Energy Commission. The authors are indebted to S. M. Horowitz, formerly of the U.S. Geological Survey, for physical-property data on rocks of the Monument Valley area, and to J. C. Roller, U.S. Geological Survey, for part of the seismic data used in this report.

GEOLOGIC SETTING

Monument Valley lies in northeastern Arizona and southeastern Utah, within the area of the Monument Upwarp. The upwarp area has been eroded and dissected to produce the mesas, buttes, and deep canyons that characterize present-day Monument Valley. The area is arid and in many places the surface consists of windblown sand.

The sedimentary rocks exposed in Monument Valley range from Permian to Jurassic in age. Of these rocks, only the ones with which we were concerned in making the geophysical measurements are discussed. These are, in ascending order, the Moenkopi formation of Early and Middle(?) Triassic age and the Shinarump and Monitor Butte members of the Chinle formation of Late Triassic age.

The Moenkopi formation consists of compact dark-red-brown bedded and laminated siltstone. The upper third of the formation contains beds of dark- to light-gray limy sandstone ranging from 2 inches to about 1 foot in thickness. These beds contain ripple marks and appear to be continuous for distances of at least 1 mile along their strike. The top of the Moenkopi formation is an erosion surface over which the Shinarump sediments were spread. Channels cut into the Moenkopi and filled with Shinarump sedimentary rocks are considered the most favorable places to explore for uranium deposits in the Monument Valley area (Isachsen and Evensen, 1955).

The Shinarump member is a unit of complexly bedded coarse-grained sedimentary rocks and until recently was considered to be a formation overlying the Moenkopi and underlying the Chinle formation. Stewart (1957) redefined the Shinarump as the basal member of the Chinle formation. The Shinarump member, which is the chief uranium-bearing unit in Monument Valley, is composed of lenticular strata of light-yellow-brown sandstones that are separated by contrasting sediments such as mudstone or siltstone. The Shinarump member is composed principally of fine- to medium-grained sandstone, but locally there are beds of coarse-grained to conglomeratic sandstone. The sediments filling the channel bottoms are commonly conglomeratic and in places contain carbonaceous material such as plant fragments and fossil logs. Mudstone, in layers 1 foot or more thick, is found in the channel deposits; it is also found throughout the Shinarump section as thin seams and clay balls.

The Monitor Butte member of the Chinle formation, which overlies the Shinarump in this area, consists of dense red or dark-gray mudstone that becomes increasingly sandy and silty at the base. The siltstone and fine-grained sandstone at the base of this member are laminated, and the lowest laminated siltstone unit has been used to define the contact between the Monitor Butte member and the Shinarump member.

As previously mentioned, the uranium deposits in the Monument Valley area are found in channels cut into the Moenkopi formation and filled with Shinarump strata. These channels range from small ones 10 to 20 feet wide and 5 to 10 feet deep, to large channels 200 to 2,000 feet wide and 70 to 200 feet deep. Some channels are continuous for distances of many miles; others are discontinuous and disappear in a few hundred feet or less. Some channels are straight, others meander, and in many places a single large channel branches into several smaller channels. In the Monument Valley area, features commonly associated with uranium deposition (Mitcham and Evensen, 1955) include bends in meandering channels, intrachannel scours, and rapid changes in facies from sandstone to mudstone within the channel sediments. It seems evident that exploration for uranium deposits in Monument Valley, aside from wildcat drilling, is a problem of locating these buried channels and drilling within the channel limits, particularly in intrachannel scours and at bends.

PHYSICAL PROPERTIES

Studies of the electrical properties and seismic velocities of rocks comprising the Monitor Butte and Shinarump members of the Chinle formation and Moenkopi formation have been made in the El Capitan Flat area of Monument Valley. The data from these studies helped determine the uses and limitations of geophysical methods in locating and describing buried channels. The physical-property data were obtained from laboratory analyses of drill cores, electric logs, seismic-velocity logs, theoretical analysis of electrical-resistivity data obtained by surface measurements, and analysis of seismic-refraction data.

As part of the physical-property studies carried out by the Geological Survey in Monument Valley, electric logs were taken in drill holes with multiple-electrode logging equipment designed to obtain self-potential logs, single-point resistance logs, lateral logs, and normal logs at 4-inch, 8-inch, and 24-inch electrode spacings. One such electric log is shown in figure 58, along with the lithologic log of the drill hole and the average-velocity and interval-velocity logs. The resistivity portion of the electric log was obtained with an 8-inch electrode spacing. Laboratory measurements on cores from this drill hole indicate that the rocks are in general undersaturated, oxidized, and contain relatively high salinity pore-water solutions. (S. M. Horowitz, written communication, 1957.)

As shown by the lithologic log in figure 58, the drill hole penetrated siltstone of the Monitor Butte member down to 24 feet, sandstone and conglomerate of the Shinarump member from 24 to 96 feet, and mudstone and siltstone of the Moenkopi formation from 96 to 116 feet. Comparison of the resistivity log with the lithologic log shows that the siltstone of the Monitor Butte has a rather uniform low resistivity of 40 to 80 ohm-meters. From these values and from values for siltstones of the Monitor Butte member in other drill holes for which electric logs are available, the normal resistivity range for this rock unit is 20 to 100 ohm-meters. The self-potential part of the electric log shows a positive deflection that corresponds to the position of the siltstone in the Monitor Butte member.

The electrical-resistivity log shows a sharp change in character at the contact between the Monitor Butte and Shinarump members. The smooth, regular, low-resistivity response produced by the siltstone of the Monitor Butte member contrasts sharply with the highly variable, but generally much higher, resistivity response of the rocks constitut-

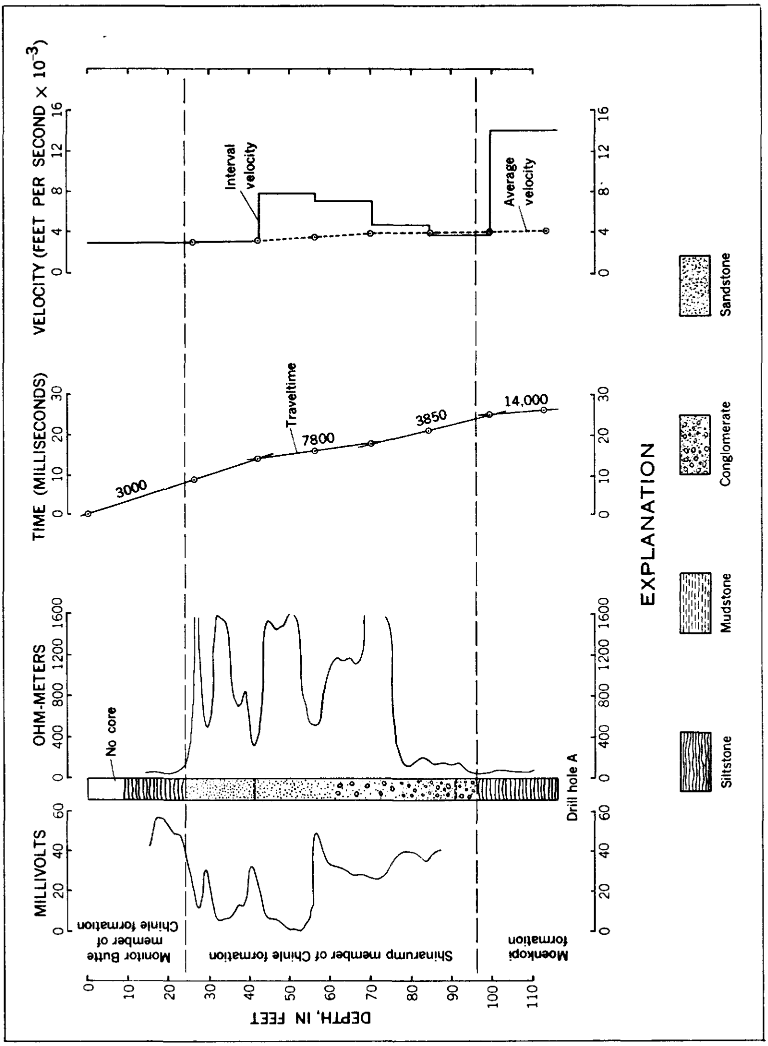

FIGURE 58.—Lithologic, electrical, vertical traveltime, average velocity, and interval velocity logs of a drill hole in Monument Valley.

ing the Shinarump member. In the interval between 24 feet and 80 feet, the resistivity is seldom less than 400 ohm-meters and often reaches apparent-resistivity values of 1,600 ohm-meters. Laboratory studies by S. M. Horowitz (written communication, 1957) on cores from this drill hole indicate that this variation in apparent resistivity is mainly caused by variations in pore-water saturation, and to a lesser extent by changes in lithology. The relatively low apparent-resistivity values at depths of 30, 41, and 55 to 58 feet are due to shale or siltstone beds, clayey sandstone, or pyritic sandstone lenses at these depths.

Electric logs and laboratory measurements of cores show that a normal range of resistivity for saturated rocks of the Shinarump member is 125 to 200 ohm-meters. The high resistivities noted on the electric log in figure 58 indicate a low degree of saturation for the greater part of the Shinarump section in that drill hole. The rocks in the interval between 80 and 96 feet show a fairly uniform low resistivity of 120 to 160 ohm-meters, indicating that the base of the Shinarump member is saturated with ground water. The electric log for the Shinarump section of this drill hole illustrates the wide range of resistivities that may be found within any given Shinarump section. Depending on the degree of saturation, and to a lesser extent on grain-size variation, the sandstones of the Shinarump have a resistivity range of 125 to 2,000 ohm-meters. Mudstone and siltstone strata within the Shinarump generally have a low resistivity, ranging from approximately 25 to 100 ohm-meters, although their apparent resistivity is somewhat higher on the electric logs where these rocks appear as thin beds between highly resistant sandstones.

The self-potential log in the Shinarump interval in general shows a negative deflection that corresponds to the sandstone beds and a positive deflection that corresponds to low-resistivity shales. The self-potential log seems to be most sensitive to changes in shale content, although on other electric logs obtained in the El Capitan Flat area, strong negative deflections seem to be associated with pyrite concentrated in carbonaceous shales in the Shinarump member.

In the drill hole shown in figure 58, the Moenkopi formation occupies the interval between 96 and 116 feet, and it has a low resistivity ranging from 40 to 100 ohm-meters. Again, in general, electric-log data in the Monument Valley area indicate an average resistivity of about 75 ohm-meters for the Moenkopi.

The self-potential log of drill hole A did not extend into the Moenkopi section, but on other self-potential logs obtained in El Capitan Flat, a positive deflection was associated with the upper part of the Moenkopi formation.

The electric-log data as discussed in the preceding paragraphs indicate that the Monitor Butte member and the Moenkopi formation have low, reasonably uniform resistivities both laterally and vertically, but that the Shinarump member varies considerably in resistivity both laterally and vertically. This variation in resistivity seems to be controlled primarily by percentage of saturation and to a lesser extent by lithologic changes within the member. Where the sandstones of the Shinarump member are relatively undersaturated, a large resistivity contrast exists between the Shinarump member and the overlying Monitor Butte member and the underlying Moenkopi formation. Under these conditions, changes in thickness of the Shinarump member due to channeling would be expected to produce large resistivity anomalies. Also lateral and vertical resistivity changes due to changes in lithology and percentage of saturation would produce anomalies that may bear no direct relationship to channeling. Where the rocks comprising the Shinarump member are completely saturated, the resistivity contrast between this member and overlying and underlying rocks is fairly small. Although changes in thickness of the Shinarump member produced by channeling might produce resistivity anomalies, they are probably rather small.

Vertical-traveltime, average-velocity, and interval-velocity logs are also shown in figure 58. Velocity logs were obtained by lowering a geophone into the drill hole to various depths and detonating small dynamite charges at the surface near the drill hole; by detonating small charges in the hole at various depths and placing a number of geophones on the surface near the drill hole; or by placing a cable containing a number of barium titanate detectors in the drill hole and detonating a small dynamite charge at the surface. In all these methods the principle is the same: the measured quantity is the time required for a seismic wave, generated in the ground by an explosion, to travel from the explosive source to one or more detectors spaced at known distances from the source. Knowing the distance and time, the average vertical velocity of the acoustic wave can be computed. When a single detector is used in the borehole, the detector is lowered to positions at intervals of 10 to 20 feet, and a dynamite charge is detonated at the surface each time the detector is placed in a new position. This arrangement can be reversed by placing the charges at various positions in the drill hole and a number of detectors at the surface. The latter method has the advantage of obtaining a number of traveltimes (depending on the number of surface detectors used) for each explosion, and if one detector is not working properly the seismic-wave arrival will still be recorded.

A major disadvantage of drill-hole shooting is that even small charges may sometimes cause caving of the drill hole, and therefore an insufficient number of points may be obtained for purposes of plotting the drill-hole velocity curve. The use of multiple detectors in an inhole-velocity cable has the obvious advantage of obtaining a number of measurement points within the drill hole from one explosion. In practice, except in deep holes, the barium titanate detectors used in the multiple-detector cables lack the sensitivity of the single electromagnetic inductive detectors; also the drill hole must be filled with fluid, whereas the electromagnetic inductive detector can be used in dry holes.

The end product of a successful drill-hole survey by any of the above methods consists of a series of measurements of the fastest traveltime of an acoustic wave from an explosive source to a detector. A plot of such a series of measurements taken in drill hole A is shown in figure 58 as a plot of vertical traveltime versus depth in the drill hole of the measurement points. Average vertical velocities from the surface and vertical velocities in the intervals between measurement points are also shown. In this case the weathered layer, in which the seismic velocity is low, seems to be approximately 41 feet thick and includes the Monitor Butte sediments and the upper part of the Shinarump member. Below the weathered layer the vertical velocity in the Shinarump is nearly 7,800 fps (feet per second) to a depth of approximately 70 feet and then is much slower, nearly 4,000 fps, to a depth of 100 feet, where the velocity changes to 14,000 fps in the Moenkopi.

In drill hole A the velocity in the Monitor Butte member is as low as that in the weathered Shinarump, probably because of weathering, and thus is lower than that in the unweathered part of the Shinarump section. Therefore the presence of Monitor Butte strata capping the Shinarump member would not adversely affect surface seismic-refraction measurements. In some other parts of Monument Valley, however, the velocity in the Monitor Butte member is greater than that in the Shinarump member and sometimes approaches that in the Moenkopi. Where this occurs, the resultant velocity inversion makes it impossible to determine correctly the depth to the Shinarump-Moenkopi contact.

The velocity variation shown in the Shinarump is not unusual; velocities ranging from 3,000 to 10,000 fps have been measured in Shinarump sections. These velocity variations are much more apparent on velocity logs than on the traveltime curves plotted from sur face seismic-refraction data. From surface seismic measurements it has been found that velocity in the Shinarump in Monument Valley averages about 6,600 fps. The most significant thing shown by the velocity logs is that the velocity in the Moenkopi formation is much higher than that in the Shinarump member. This is borne out by velocity data obtained for the Moenkopi formation from other drill-hole velocity logs and from surface seismic-refraction data. In general, the velocity in the Moenkopi formation ranges from about 10,000 to 15,000 fps.

The velocity data indicate that where beds in the Monitor Butte, in which the velocity is high, are absent, a favorable velocity contrast exists between the Shinarump and the Moenkopi formation. Therefore, it should be possible to map the Shinarump-Moenkopi contact by the seismic-refraction method. Where the Monitor Butte member overlies the Shinarump member, it may or may not be possible to determine accurately the Shinarump-Moenkopi contact, depending on the velocity in the Monitor Butte member. Velocity variation within the Shinarump member, both laterally and vertically, is a complicating factor that is discused further under "Seismic Methods."

The ore minerals comprising the uranium ore bodies found in channel deposits in Monument Valley are present in such small amounts that their physical properties do not exert any significant influence on the overall electrical conductivity or seismic velocity in the host rocks.

GEOPHYSICAL METHODS OF EXPLORATION

Although uranium deposits in Monument Valley are not directly located by geophysical methods other than radiometric surveys, geophysics has an important place in exploration for these deposits. Exploration procedure for uranium deposits by any method is first to locate potential uranium-bearing channels and then to determine if economic quantities of uranium minerals are present in the channels. The first phase, that of locating potential uranium-bearing channels, is a geologic problem well suited to geophysical solution. There are many places in Monument Valley where channels can be located by visual observation of Shinarump outcrops in mesa rims or in canyons. Where this is possible, and the trend of the channel can be determined reasonably well by direct observation, such as on a small mesa where a channel crops out in the rim and perhaps in reentrants, it may then be possible to determine the economic uranium content of the channel by a relatively few drill holes. In such places geophysical work to trace the channel trends is unnecessary. On larger mesas, however, and in large areas in Monument Valley where the Shinarump exposures do not reveal channel cross sections, geophysical surveys provide valuable guidance to drilling. Buried channels can be located and traced, and some information obtained about the size and shape of the channels with pertinent geophysical methods. With this information, drilling can then be concentrated in the most likely places for the occurrence of uranium deposits.

SEISMIC METHODS

Drill-hole velocity logs show that the seismic velocity is less in the Shinarump member than in the Moenkopi formation. The velocity logs also show that the seismic velocity in the Shinarump member varies considerably from drill hole to drill hole because of changes in the amount and type of cementation, water saturation, weathering, mud and shale lenses, and other factors. In practice, however, this variation in the seismic velocity in the Shinarump member is often not as serious as would be expected from casual inspection of the velocity logs. The lenses that cause the greatest variations in the seismic velocity in the Shinarump member (mudstone and shale lenses and thin layers of cemented sandstone) may act as shallow refractors within the Shinarump member and produce discontinuities in what normally would be the direct-arrival portion of the time-distance plot; and in extreme cases these variations may obscure the direct arrivals altogether. In many places, however, the lenses are too thin to carry refracted energy for any great horizontal distance and do not appreciably affect the traveltimes of the inclined portions of the refracted-ray paths from the Moenkopi formation.

Lateral changes in velocity in the Shinarump member from causes other than lensing may also cause difficulties in interpretation of the seismic-refraction data, but such conditions can frequently be recognized from the time-distance plots and an approximate correction can be made to the data.

The effect of the Monitor Butte member on seismic measurements is almost unpredictable. In places the Monitor Butte is soft, weathered sandy mudstone that grades rather imperceptibly into the Shinarump member. In these places the seismic velocity is low and the mudstone may be considered a part of the weathered layer and corrected for in the conventional manner. In other places the basal rocks of the Monitor Butte member contain laminated beds in which the seismic velocity is higher than in the Shinarump member, and the resulting velocity inversion makes it impossible to determine accurately the depth to the Shinarump-Moenkopi interface.

In spite of these difficulties, tests of the seismic-refraction method in Monument Valley were generally successful, and this method was widely used in locating and delineating buried channels in Monument Valley.

Reflected arrivals were recorded accidentally during routine seismic-refraction studies. Experimental measurements were made later using seismic-reflection equipment specially designed for shallow work to determine if the reflection method could be used to locate buried channels. Although some reflections were obtained from the Moenkopi formation, the results indicate that this geophysical method is not well suited for locating buried channels in Monument Valley.

REFRACTION MEASUREMENTS

EQUIPMENT AND FIELD PROCEDURES

The seismic-refraction measurements in Monument Valley were made with standard 12- and 24-trace portable seismic-refraction equipment mounted in a 4-wheel-drive vehicle on specially constructed mounts.

Both miniature and standard-size geophones ranging in frequency from 6 to 18 cycles per second were used in the refraction measurements, but the lower frequency geophones produced superior records.

The field method most often used was continuous profiling with reversed shots. Geophone spacings were roughly determined by the depth to the Moenkopi formation in the particular area surveyed. Spread lengths were adjusted so that at least one-half of the geophones received refracted energy as first arrivals. At the beginning of the tests, profiles were shot with spreads end to end, but as new interpretive procedures were developed it became clear that it was desirable to overlap the spreads by 25 to 50 percent. At first, shallow shot holes were used, but the rocky nature of the area made it a time-consuming job to drill even shallow holes, and "blowouts" frequently occurred. To save time and to eliminate danger from flying rock fragments, experiments were made with single shots detonated on a steel pole (fig. 59) a few feet above the ground. This method produced good records and had the advantage of speed and safety. In air shooting, a 2½- to-10-pound stick of 60-percent seismic dynamite is impaled on a wooden dowel that is inserted in a wooden block. A hole is drilled in the wooden block so that the block will slide over the steel pole. The dynamite is detonated by a No. 6SSS seismic electric-blasting cap. The block and dowel disintegrate, leaving no flying debris. The block is used to protect the shooting pole and to prevent its forming steel splinters.

In addition to the conventional safety measures used in drill-hole shooting, special precautions should be taken when the air-shooting technique is used. Vehicles and personnel should be at least 300 feet from the shot point. The charge should be placed 3 feet or more above ground level to prevent blasting away surface material, and all metal bands must be removed from the dynamite. The cap wire should never be tied around the charge, and the cap should be placed in the side of the dynamite away from the shooter. Small fragments of cap

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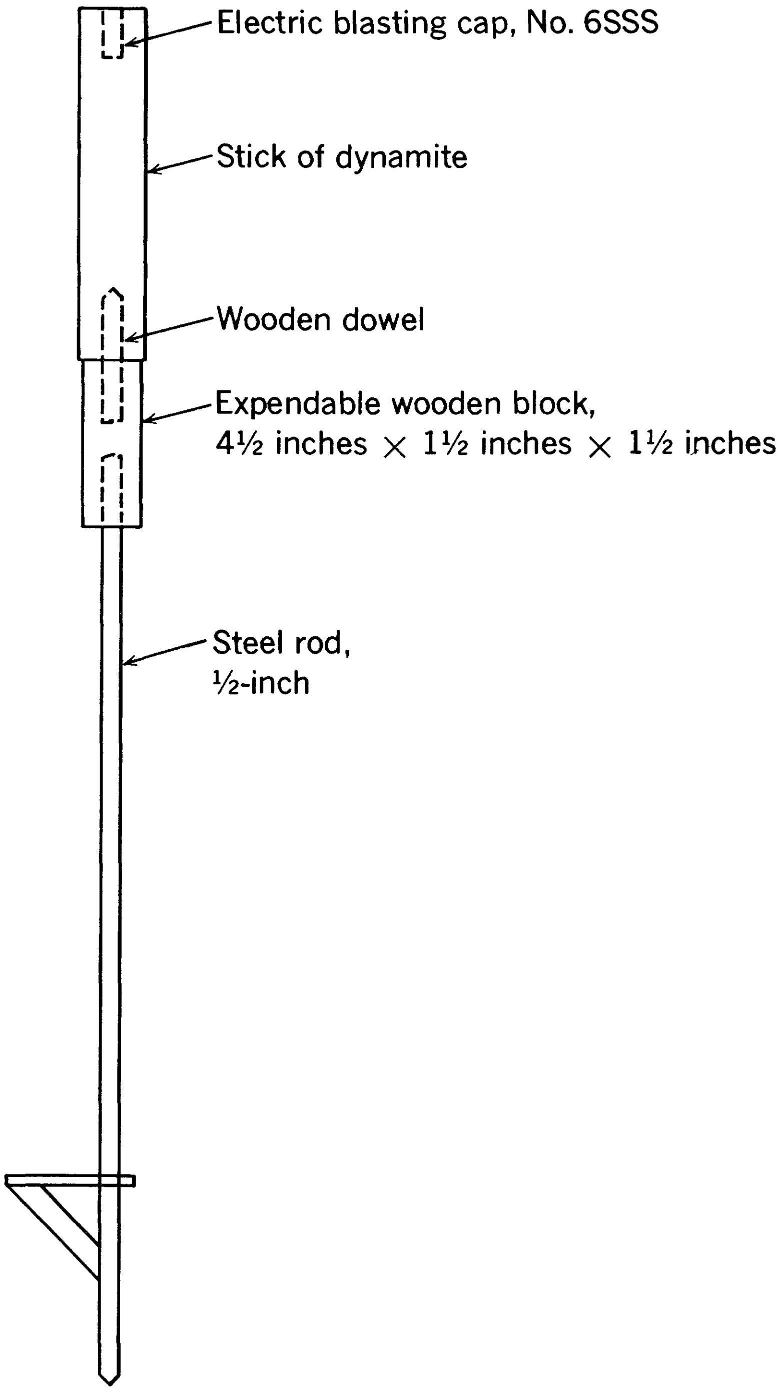


FIGURE 59.—Sketch of shooting pole used in air shooting

wire may be thrown for considerable distances and may cut cables placed too near a shot point. Cables close to the shot point should be covered, if possible, with a few inches of earth to prevent damage. Exposed field personnel should be equipped with safety hats and should keep the instrument truck between themselves and the shot point.

INTERPRETATION OF REFRACTION DATA

The data obtained from the seismic-refraction measurements in Monument Valley could not be interpreted by using critical-distance and time-intercept formulas because these methods are based on the assumption that the refracting interface is a plane surface.

In Monument Valley the important refracting interface in exploration for buried channels is the top of the Moenkopi formation, which is an irregular surface of erosion. Many of the channels in Monument Valley have widths that are less than the typical spread lengths used in the seismic-refraction measurements. The refracting surfaces in these instances must be considered as curved surfaces, and conventional methods of interpretation will yield erroneous values for the depth to the refracting interface.

An interpretation procedure for curved refracting surfaces (Pakiser and Black, 1957) was tested and found successful for interpreting seismic-refraction measurements made over buried channels. This procedure, which is a modification of an interpretation procedure suggested by Barthelmes (1946; Dobrin, 1952), consists essentially of graphically calculating the delay time for each geophone and treating delay-time variations as resulting from variations in the depth of the refractor. In practice the conventional refraction formulas were used for preliminary analysis of the seismic-refraction data obtained in Monument Valley, and the delay-time procedure was used in interpreting the curved refracting surfaces in the channel areas.

The delay time has been defined as the additional time required for a wave to travel any segment of a ray trajectory over the time that would be required for a wave to travel the horizontal component of that segment at the highest velocity reached by the trajectory (Nettleton, 1940, p. 250). If the depths at the shot point and detector are not equal, because of either dip or surface-elevation changes, the time (t) for a wave to travel from the shot point to any detector beyond the critical distance for a two-layer case is given by the equation

$$t=\left[\frac{X}{V_2}+(Z_s \cos i)/V_1+(Z_d \cos i)/V_1\right] \cos \theta,$$

where X = horizontal distance from shot point to detector,

V_1 = seismic velocity in upper layer,

V_2 = seismic velocity in lower layer,

Z_s = distance of V_1–V_2 interface below shot point,

Z_d = distance of V_1–V_2 interface below detector,
i = critical angle of incidence,
θ = angle of dip of V_1–V_2 interface.

For a horizontal V_1–V_2 interface the equation for (t) is reduced to

$$t=\frac{X}{V_2}+(Z_s \cos i)/V_1+(Z_d \cos i)/V_1$$

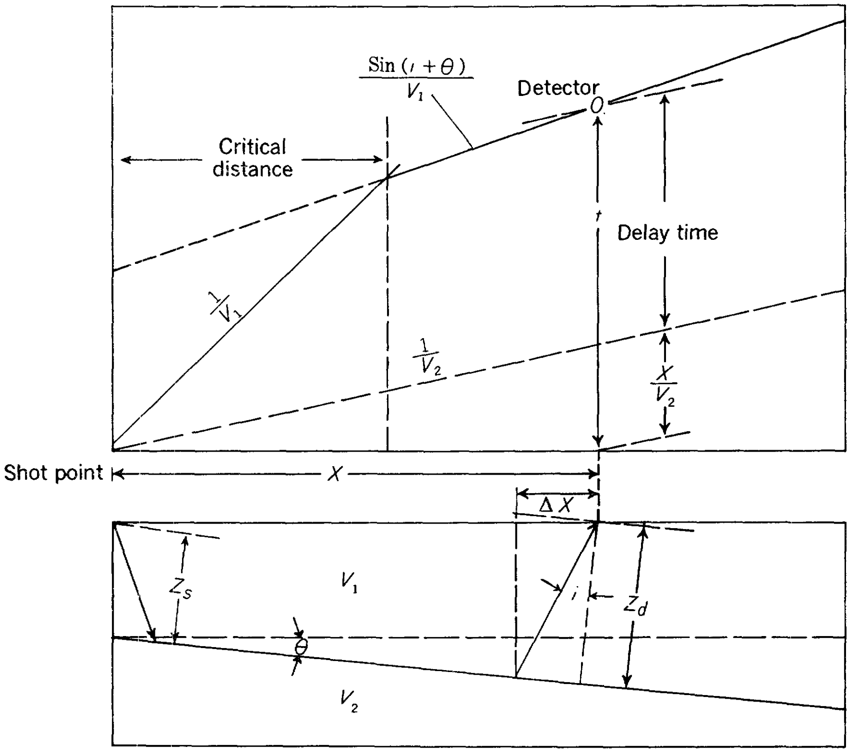
It is from this equation that the method of interpretation by use of delay times is developed. Errors resulting from neglecting dip are negligible for dips of up to 10°, and they are not serious for dips as great as 25°. The two quantities $Z_s \cos i$ and $Z_d \cos i$ in the above equation represent the delay times at the shot point and at the detector, respectively. The sum of the delay times for the shot point and any detector beyond the critical distance can be determined graphically by subtracting the quantity X/V_2 from the detector arrival time. As the delay time for the shot point remains constant for any given spread, variations in the delay times for the detectors are proportional to variations in depths beneath those detectors. The graphic procedure for obtaining the delay time for a detector beyond the critical distance and the ray path of the refracted wave is shown in figure 60.

Figure 61 illustrates the effect of a buried channel on the refracted arrivals of a reversed spread. The following procedure is used in making a graphic delay-time analysis:

1. First a time-distance graph is drawn (fig. 61*A*). The velocity in the lower medium, the Moenkopi formation, is shown on the time-distance curve as V_2. The velocity in the upper medium, the Shinarump member of the Chinle formation, is designated as V_1. The symbol V_{2a} is the apparent velocity in the lower member. The open circles represent arrival times at the detectors from shot point 1 and the dots represent arrival times at the detectors from shot point 2.
2. On the above graph a line with a slope of $1/V_2$, where V_2 is the known velocity of the refracting medium, is drawn through the origin.
3. The delay time for each detector beyond the critical distance is determined (figs. 60, 61*B*). The vertical offset in the two delay-time curves indicates that the depth to the refracting horizon is greater at shot point 1 than at shot point 2.
4. As shown in figure 60, the point to which the depth is determined on the refracting horizon is displaced a distance ΔX toward the shot point from each detector position. The migration distance ΔX is computed from the formula

$$X=Z \tan i$$

where Z is the depth to the refracting interface at the shot point from which the refracted arrivals were recorded. In figure 61, Z was computed to be 60 feet at shot point 1 and 50 feet at shot point 2. The migration distances for the refracted arrivals from these shot points were thus 21 feet and 18 feet respectively.



EXPLANATION

X= horizontal distance from shot point to detector
θ= angle of dip
V_1 = seismic velocity in upper layer
V_2 = seismic velocity in lower layer
Z_s = distance of V_1-V_2 interface below shot point
Z_d = distance of V_1-V_2 interface below detector
i = critical angle of incidence
t = traveltime from shot point to detector

FIGURE 60.—Graphic procedure for obtaining the delay time for a detector beyond the critical distance and the ray path of the refracted wave.

5. The delay times are migrated (fig. 61*C*).
6. The two migrated delay-time curves are next adjusted vertically for the best fit (fig. 61*D*). In this example the dots were shifted vertically by 3 milliseconds. An average curve is then drawn through the adjusted points.

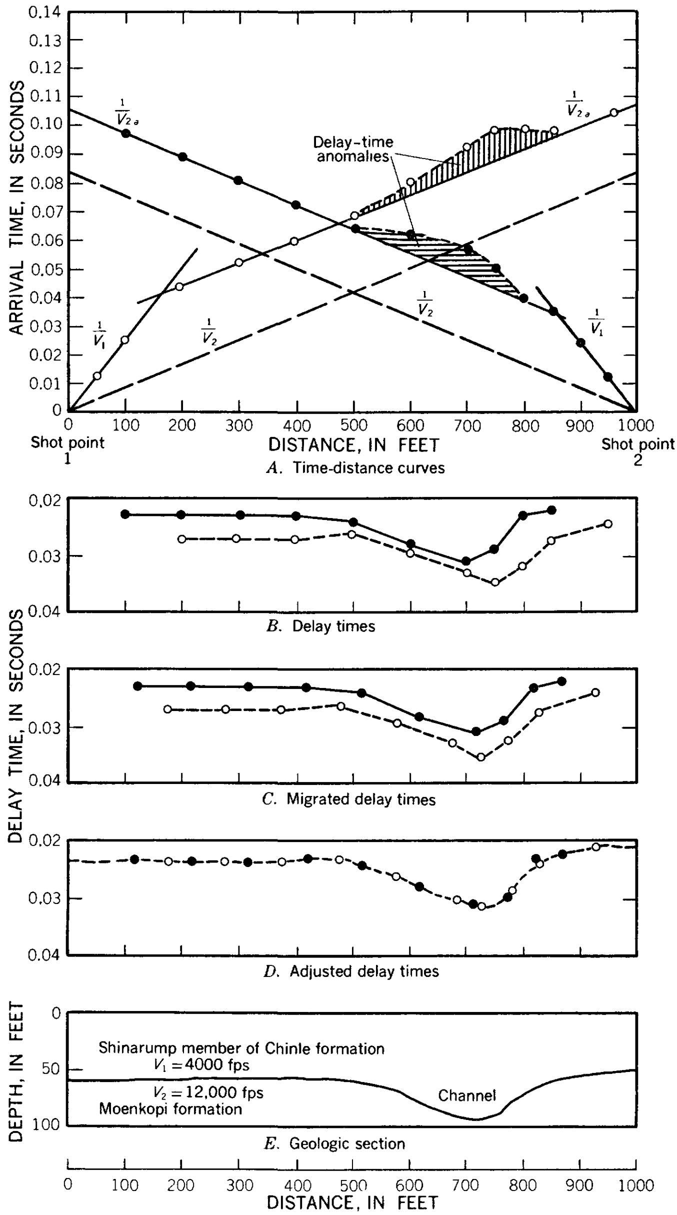


FIGURE 61.—Seismic data over a buried channel, and the resulting geologic section, as determined from delay times for a reversed spread. (fps, feet per second.)

7. From the adjusted delay-time curve the difference in depth, ΔZ, between a datum point and each migrated and adjusted detector position is determined from the formula

$$\Delta Z = \frac{\Delta t_D V_1}{\cos i}$$

where Δt_D represents the difference in delay times between the two points. The datum point may be a drill hole or the computed depth at the shot point if a large enough part of the plane of the refracting interface exists to permit the use of conventional formulas to compute this depth. In this example the computed depth of 60 feet at shot point 1 was used as a datum point, and ΔZ was computed to be a 4.3 feet per millisecond delay.

8. Finally, the subsurface profile of the refracting interface is constructed from the depth differences computed for the various detector positions with reference to the datum point. Depth to the interface is then plotted beneath each migrated detector position to form a profile such as in figure 61*E*. If no absolute datum point can be found for any given spread, the configuration of the refracting horizon relative to any point on the delay-time curve can be determined. It is thus possible to locate buried channels even if reliable depth control is not available.

Variation in thickness of the weathered layer, in which the velocity is very low, may cause large arrival-time delays. Routine corrections for the weathered layer are seldom possible except at shot points, but time delays caused by the weathered layer can often be recognized on the delay-time curves. The effect of a change in thickness of the weathered layer on the time-distance plots and on the delay times before and after migration is shown in figure 62. The depth to the Moenkopi formation as computed for shot points 1 and 2 is 60 and 50 feet respectively (fig. 61). The velocity in the Moenkopi, Shinarump, and the weathered layer is 12,000, 4,000, and 1,000 fps, respectively. The weathered layer is negligibly thin except for the interval between 500 and 800 feet on the spread, where the layer reaches a maximum thickness of about 8½ feet.

Comparison of the delay-time curves of figures 61 and 62 shows that both the channel and the weathered layer produce downward deflections of the delay-time curves and that the magnitudes of the time delays are approximately equal. There is, however, a significant difference in the delay-time curves produced by the channel and by the weathered layer. The time variations caused by changes in the thickness of the weathered layer coincide in horizontal position on the

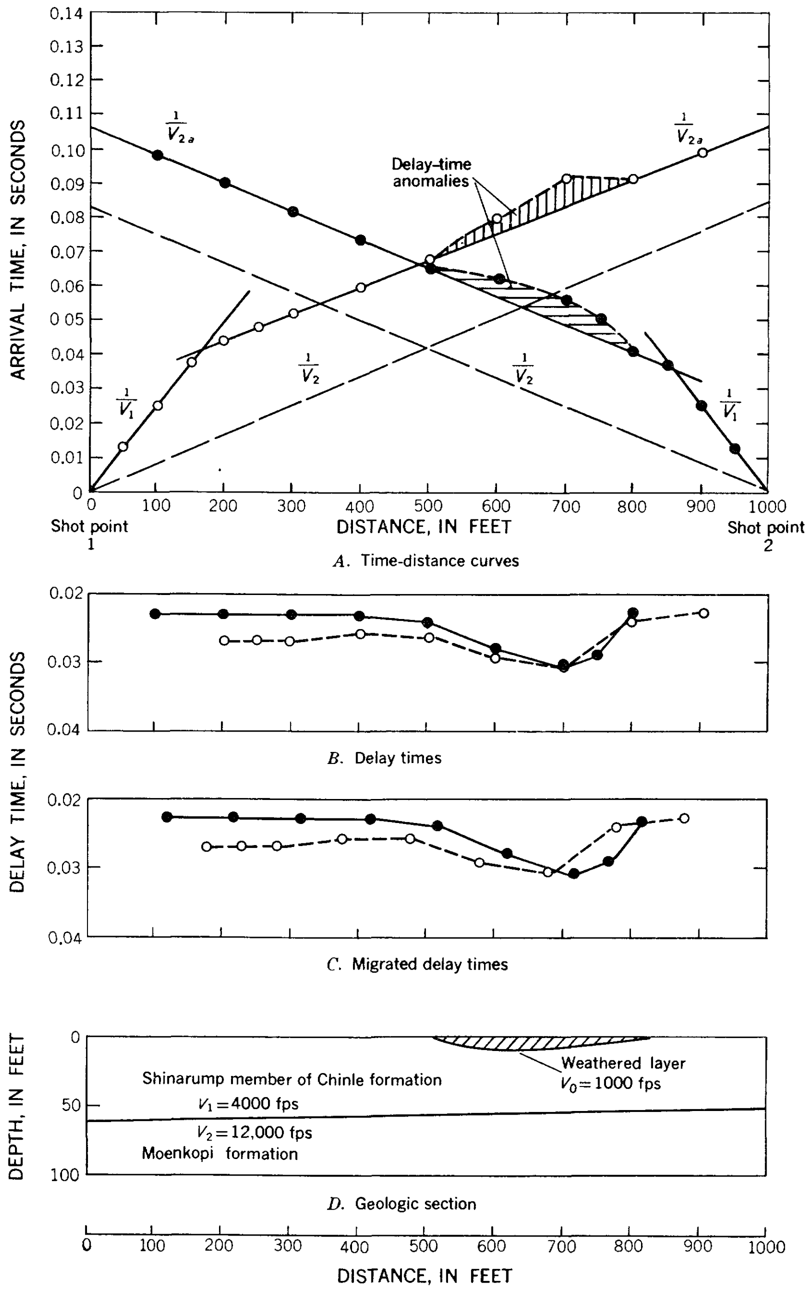


Figure 62.—Seismic data over a weathered layer of variable thickness, and the resulting geologic section, as determined from delay times for a reversed spread.

delay-time plots for the reversed spread and tend to diverge in horizontal position when the points are migrated toward their respective shot points. The reverse is true for the time variations caused by channeling, and this difference can often be used to distinguish anomalies caused by changes in thickness of the weathered layer from those caused by channeling.

In places in Monument Valley the Shinarump member contains thin mudstone lenses that act as refractors and cause the time-distance plots to resemble those that would be obtained from three layers. An example of a possible misinterpretation of time-distance plots caused by a mudstone lens is illustrated in figure 63.

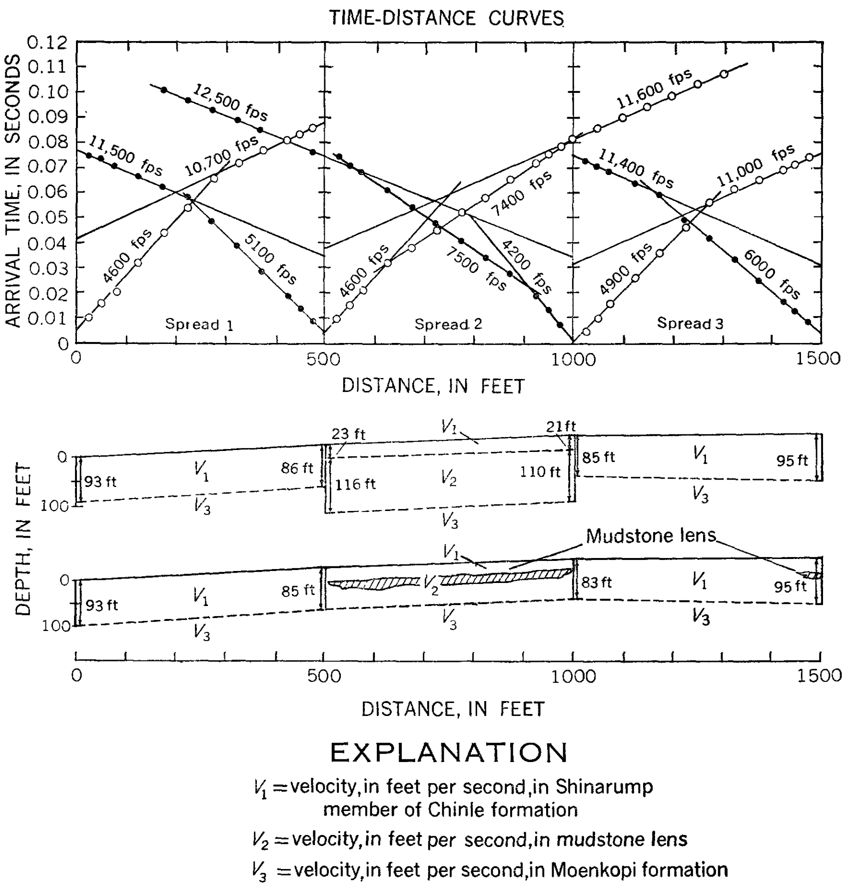


FIGURE 63.—An example of a possible misinterpretation of time-distance graphs caused by a mudstone lens (after Pakiser and Black, 1957, fig. 5).

The first interpretation of these time-distance plots assumes that spreads 1 and 3 represent 2-layer conditions, and spread 2 a 3-layer condition. Computations made with these assumptions produce the improbable geologic section shown immediately beneath the time-distance plots. The second interpretation assumes that the 7,500- and 7,400-fps segments of the time-distance plots for spread 2 are caused by a thin mudstone lens within the Shinarump member. Spreads 1 and 3 are interpreted as before, but computations are made for spread 2 by extending the V_1 segments of the time-distance plots until they intersect the extensions of the segments representing the highest velocities shown by these plots.

Using these intersections as the critical distances, the time-distance plots are solved as standard two-layer problems. The resulting geologic section is shown as the lower section. Consideration of local geologic conditions indicates that the second interpretation is much more reasonable than the first. The error introduced by the procedure used in the second interpretation is generally less than 10 percent of the true depth to the Moenkopi formation if the mudstone lens does not constitute more than 25 percent of the Shinarump member thickness and if the velocities in the various units do not vary widely from those used in this example.

Some of the channels contain mudstone or shale lenses that act as refracting horizons and completely mask a channel. Such a condition is shown in figure 64, where the refracting horizon within the channel limits is far above the actual interface between the Shinarump member and the Moenkopi formation. On a series of 4 parallel seismic profiles it is not uncommon to obtain channel anomalies on two profiles, no anomaly of any kind on the third profile, and a channel anomaly on the fourth profile. This suggests that either the channel is discontinuous or that the profile, along which no anomaly was obtained, crosses the channel where a refracting horizon within the Shinarump member obscures the channel. Either possibility may be correct, but other geophysical methods must be used to supplement the seismic-refraction measurements before the correct solution can be determined.

Another major problem in the interpretation of seismic-refraction measurements in Monument Valley is the variation of the velocity in the Monitor Butte member. Where this member overlies the Shinarump member and the velocity in it is greater than that in the Shinarump member, accurate computations of the depth to the Moenkopi formation cannot be made. In places, however, it has proved possible to map the relative configuration of the Shinarump-Moenkopi interface and to detect buried channels under these same

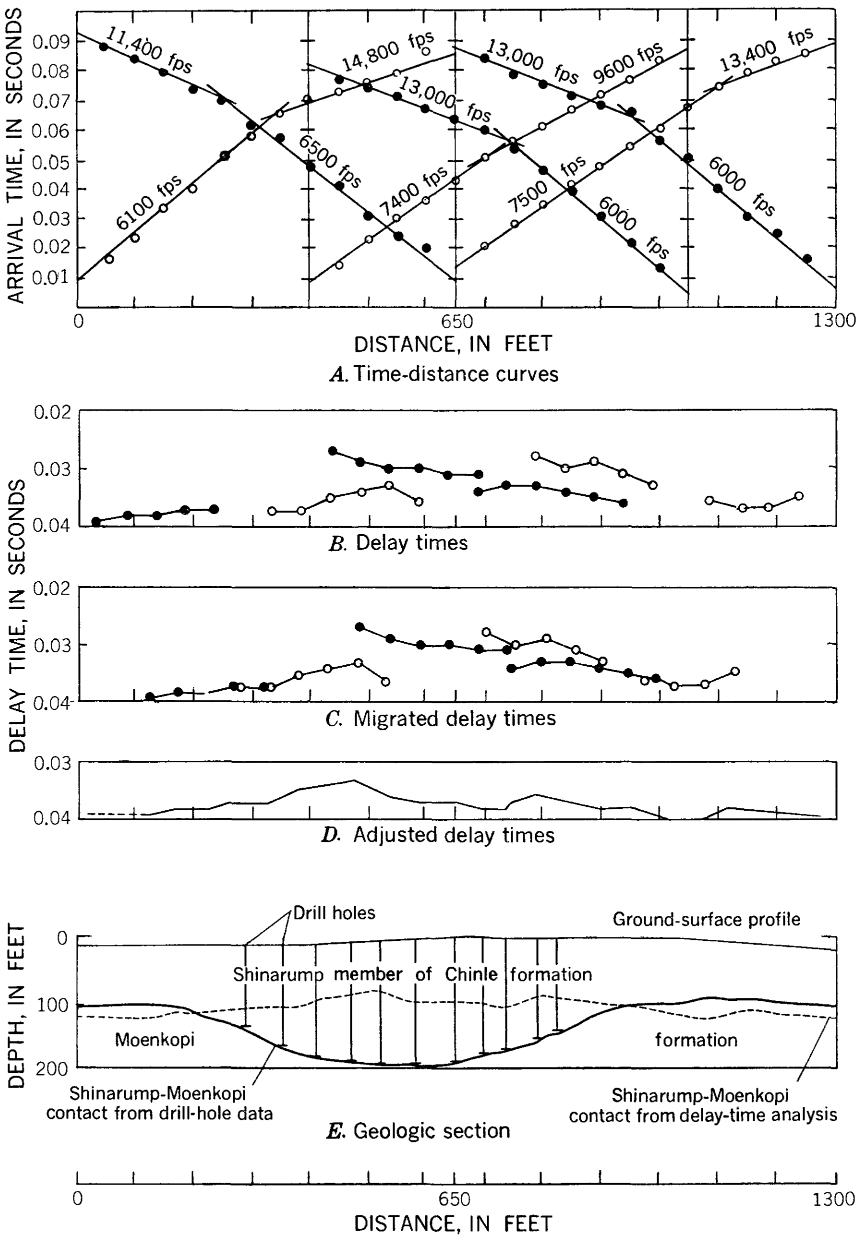


FIGURE 64.—Masking of a buried channel by refraction from a horizon within the channel limits, but above the actual interface.

conditions by delay times. If no geologic control is available along the profile, the delay times are simply plotted and examined for evidence of channeling. If the velocity in the part of the Shinarump member in and immediately above the channel is known, from velocity logs in nearby drill holes for example, an approximation of the depth of scour can be made from the delay times, although the depth to the interface cannot be determined.

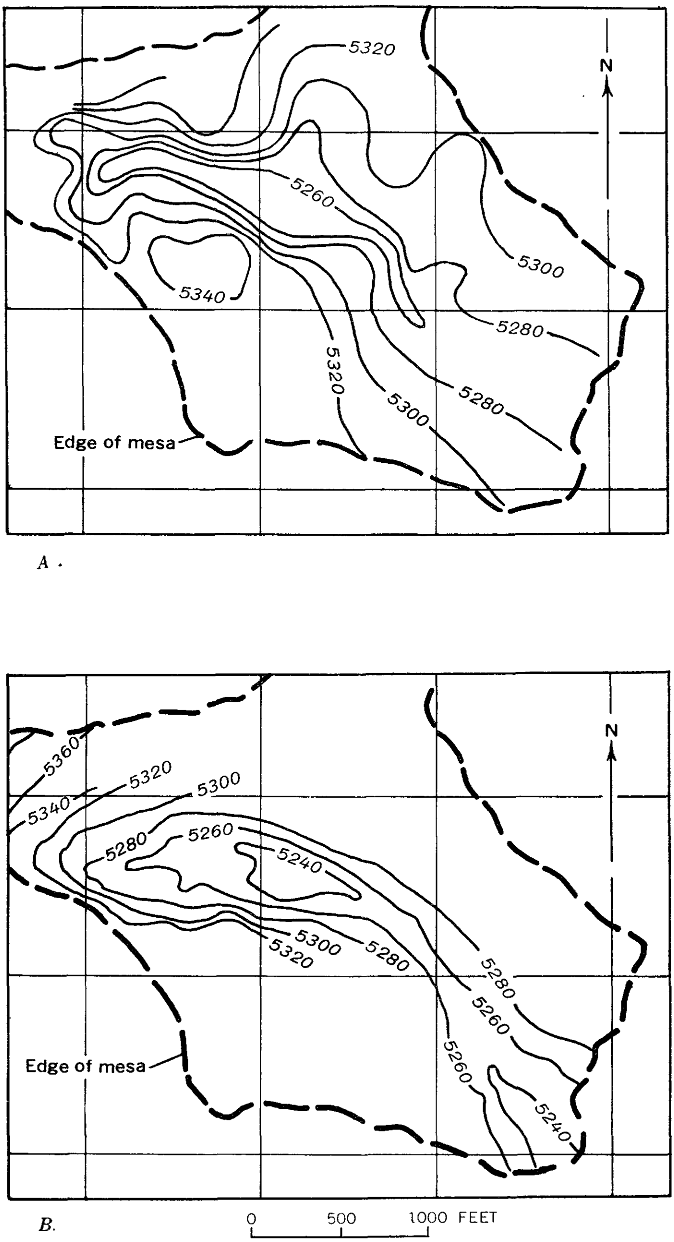
RESULTS OF REFRACTION TESTS

The seismic tests made in Monument Valley by Wantland and Casey (1952) were made over a channel on Nakai Mesa that was known from drilling to be 1,500 to 2,000 feet wide and 50 to 75 feet deep. Conventional methods of interpreting depths at the shot points were used, and Wantland and Casey were successful in mapping the channel trend. The Nakai channel offered nearly ideal conditions for the initial experimental studies, but the results of these tests could not be used to evaluate the seismic-refraction method for channel exploration in general. Many additional factors such as the effect of changes in channel width and depth, steepness of channel slopes, and more important, the effect of lithologic variations within the Shinarump member and the effect of various kinds of overburden, including rocks of the Monitor Butte member, had to be investigated before the seismic-refraction method could be fully evaluated for locating buried channels in Monument Valley.

Seismic-refraction measurements were made at Koley Black, Hunts, and Oljeto Mesas, where various types and sizes of channels were known to exist from drill-hole or outcrop data. Some of these channels were continuous, some intermittent, and some branched into two or more smaller channels, but in each area the tests were made where the Shinarump was either exposed at the surface or covered with sand. Refractions from the Moenkopi formation were obtained in all the test areas, and in each area an indication of the known channel or channels was obtained.

Exploratory seismic-refraction measurements were then made at Holiday and Mitchell Mesas (fig. 57) to locate buried channels before exploratory drilling for uranium deposits in these areas. Figure 65*A* is a subsurface-contour map of the Shinarump-Moenkopi interface that was prepared from the results of seismic-refraction measurements on Holiday Mesa. A channel is clearly indicated on this map. This area was later drilled, on the basis of the seismic-refraction measurements, to determine whether the Holiday Mesa channel contained a uranium ore deposit. A large ore body was found in the channel.

Figure 65*B* is a subsurface-contour map of the Shinarump-Moenkopi interface that was prepared from drill-hole data. These two



CONTOUR INTERVAL 20 FEET

DATUM IS MEAN SEA LEVEL

FIGURE 65.—Subsurface-contour maps of the Shinarump-Moenkopi interface on Holiday Mesa. *A*, Based on seismic-refraction data; *B*, based on drill-hole data.

maps show a close correlation between the seismic-refraction and drill-hole data.

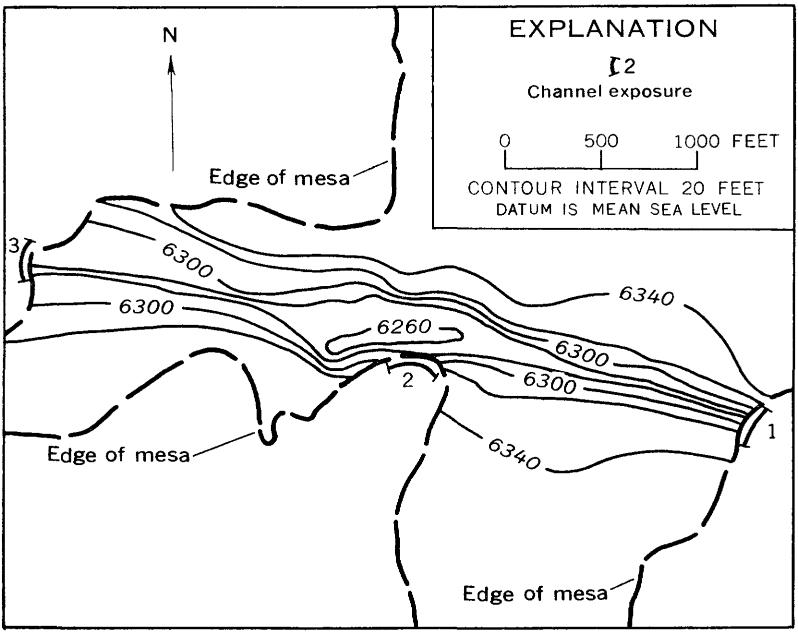


FIGURE 66.—Subsurface map of part of Mitchell Mesa, showing contours of the Shinarump-Moenkopi interface as determined from seismic measurements, and channel outcrops discovered by geologic reconnaissance.

Mitchell Mesa (fig. 57) was selected for seismic exploration because a preliminary geologic reconnaissance had located channel outcrops containing uranium minerals. Figure 66 is a map of part of Mitchell Mesa. The geologic reconnaissance had delineated a channel cross section (exposure 1 on fig. 66) and what seemed to be a longitudinal section of the same channel (2). Another channel section (3) was hidden by talus and was not discovered in the initial geologic reconnaissance. Uranium minerals were found in channel outcrop 1.

The actual trend of the channel was in some doubt because of the tentative identification of outcrop 2 as a longitudinal section of the channel. The mesa area was small, and under ordinary circumstances geophysical measurements tracing the channel trend would not have been economical. In this case, however, the seismic-refraction measurements were made to determine the channel trend and depth so that an accurate estimate could be made of the amount of drilling needed to test the channel for uranium deposits. Portable seismic-refraction instruments and necessary supplies were packed to the mesa top and the trend and depth of the channel were then rapidly determined by the seismic measurements. Figure 66 is subsurface-contour map of the Shinarump-Moenkopi interface as determined from the seismic measurements. The seismic measurements showed that the channel at outcrop 1 continues across the mesa to the west, and that outcrop 2 is actually a longitudinal section of a part of the channel. Detailed seismic investigation of the western mesa rim located the channel section at outcrop 3.

Figure 67 illustrates the use of the delay-time procedure to locate a channel on Oljeto Mesa (fig. 57). The location of the channel on spread 2 is clearly indicated by the delay times.

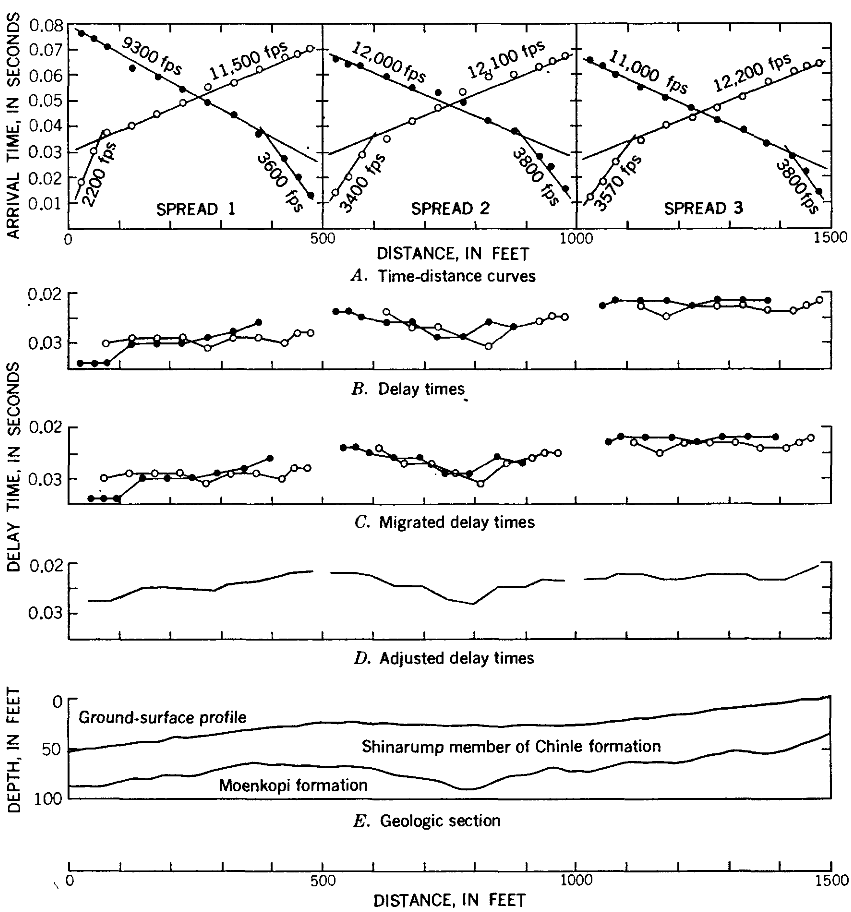


FIGURE 67.—Time-distance graphs and delay times for a series of end-to-end reversed spreads along a traverse over a buried channel on Oljeto Mesa (after Pakiser and Black, 1957, fig. 8).

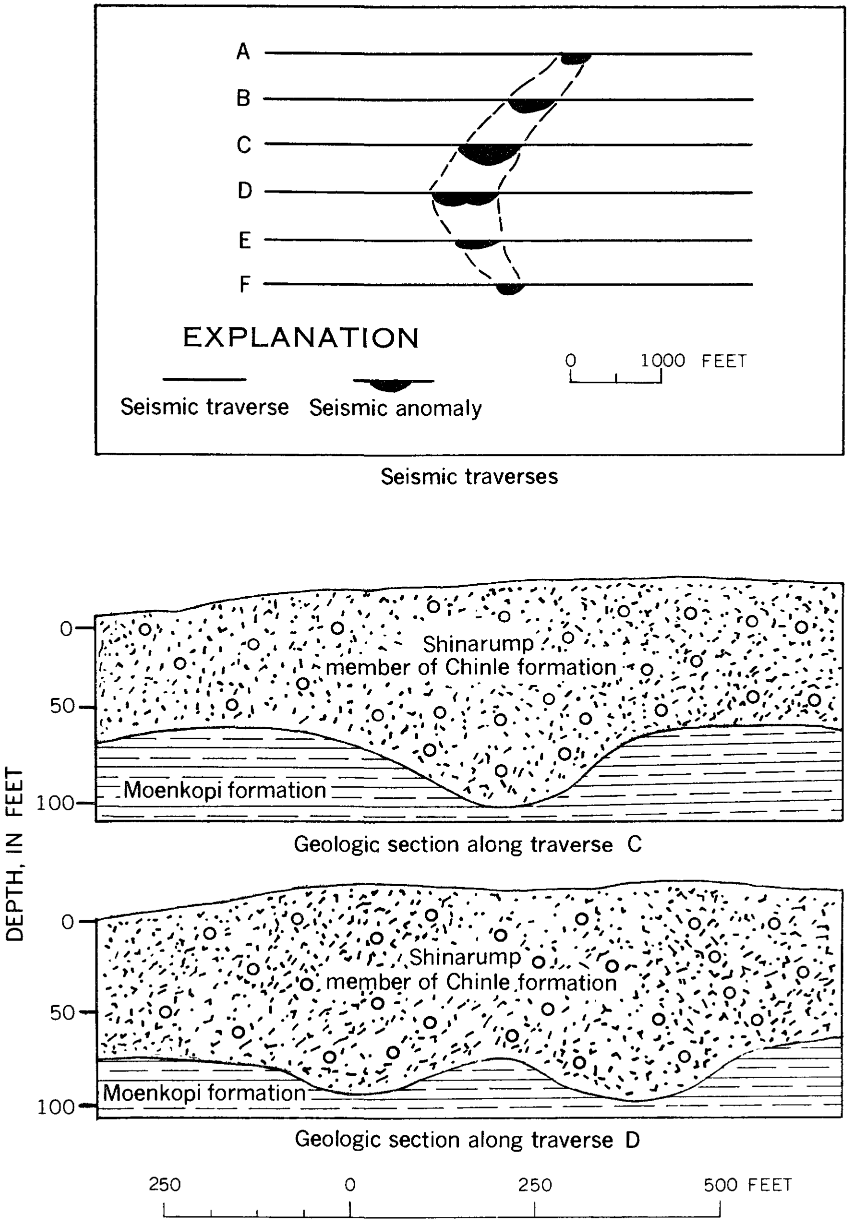


FIGURE 68.—Seismic anomalies along a series of seismic traverses, and geologic sections across two of the anomalous areas, as computed from seismic delay times.

A plan view of a series of seismic traverses, A through F, along which seismic-refraction measurements were made in Monument Valley is shown in figure 68. The location of the delay-time anomalies on these traverses due to a buried channel is shown in black. The geologic sections across the anomalous areas on traverses C and D (fig. 68) illustrate the detail that can often be obtained from delay times. It is interesting to note that the channel becomes broader and shallower where it changes direction, and it seems to have two somewhat deeper scours within its limits. This kind of detailed information could be useful in planning a drilling program, as the bends can be considered good starting points to investigate the possibility of uranium deposits in any given channel.

The seismic-refraction measurements that have been discussed in the preceding paragraph have all been made in areas where the Shinarump member was either exposed at the surface or covered by material in which the seismic velocity is low, such as windblown sand or alluvium. In many places in Monument Valley, however, the Shinarump member is covered by the Monitor Butte member, in which the seismic velocity in places may exceed the velocity in the Shinarump member. The results of seismic-refraction measurements in one such area in El Capitan Flat (fig. 57) are shown in figures 69 and 70. The channel cross sections were obtained from drill-hole data. Because the time-distance plots obtained from the seismic-refraction measurements reflect weathering and lithologic changes in the Monitor Butte member, depth computations at the shot points are not reliable. A delay-time analysis of the seismic-refraction data, made with simplifying assumptions, was used in locating the channels, although the depth to the Shinarump-Moenkopi interface could not be determined.

Delay times were graphically determined for assumed velocities of 11,000, 11,500, 12,000, and 13,000 fps in the Moenkopi, and an assumed velocity of 5,000 fps for V_1 was used in computing the migration distances and relative depths. The 11,500-fps V_2 velocity was the most reasonable value, as borne out by the velocities in the Moenkopi shown on time-distance plots for measurements outside the channel boundaries. The time-distance plots, geologic section determined from drill-hole data, and the Shinarump-Moenkopi interface determined from delay times for traverse 1 are shown in figure 69. Depths to the refracting interface could not be determined accurately from the time-distance plots, and depths indicated by data from drill hole 536 were used in computing delay times. As this figure indicates, the seismic and drill-hole data agree rather well on the channel location and configuration.

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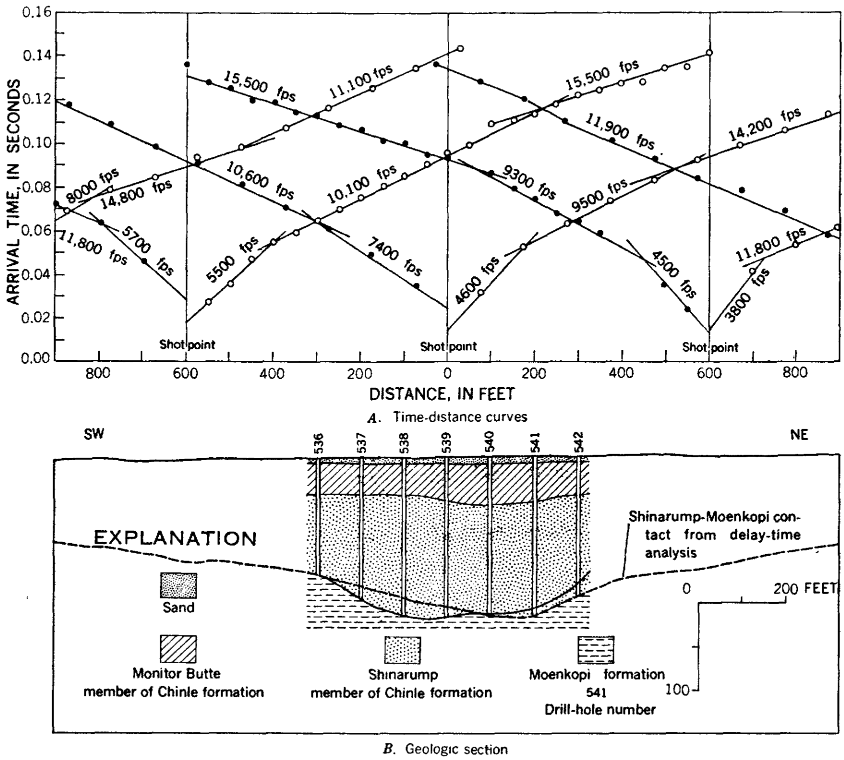

FIGURE 69.—Time-distance curves, the geologic section as determined from drill-hole data, and the Shinarump-Moenkopi interface as determined from delay times, for seismic-refraction measurements over a buried channel on traverse 1.

The time-distance plots, geologic section determined from drilling, and the Shinarump-Moenkopi interface determined from delay times are illustrated in figure 70 for traverse 2. The delay time computations were based on the depth to the Moenkopi formation given by data from drill-hole 554. As shown in figure 69, the contact determined by delay times closely approximates the actual contact determined by drilling. If drill-hole data had not been available along these traverses, the adjusted delay times would still indicate the positions and relative configurations of the buried channels.

LIMITATIONS

The most serious limitation of the seismic-refraction method of locating buried channels is that the resolving power of the method decreases with increased depth to the refracting interface. For a fixed number of detectors the spacing must be increased with increased depth to the refracting interface; thus, fewer detectors will receive refracted arrivals from the curved interface constituting the

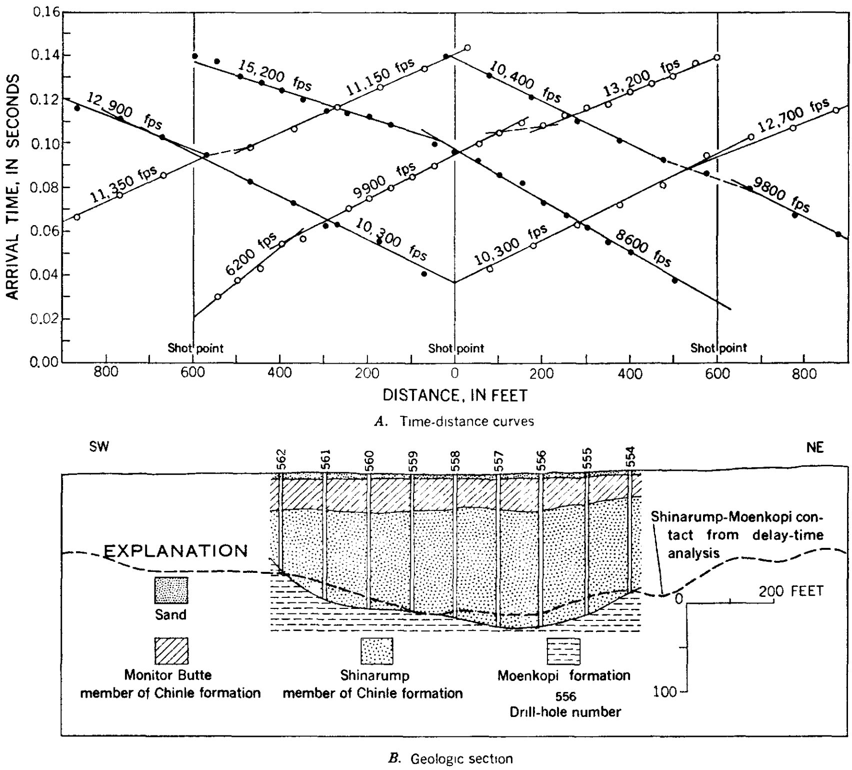

FIGURE 70.—Time-distance curves, the geologic section as determined from drill-hole data, and the Shinarump-Moenkopi interface as determined from delay times, for seismic-refraction measurements over a buried channel on traverse 2.

channel cross section. It is thus more difficult to detect the channel anomaly from the delay times. This difficulty could be resolved by repeating measurements at smaller spacings over suspected anomalies, but increased thicknesses of overburden may result in lateral and vertical velocity changes that could obscure the effect producted by a buried channel. If velocity inversion is also present in the overlying rocks, the depth to the desired refracting interface cannot be calculated.

These difficulties indicate that the seismic-refraction method is best for locating buried channels either in areas containing outcrops of the Shinarump member, or where the overburden is relatively thin and constant in thickness and the velocity in it is relatively constant and lower than in the Shinarump. Some of the problems associated with velocity and thickness changes in the overlying material can be overcome, but sometimes these changes may make interpretation of the seismic data difficult, if not impossible. It has proved possible to map buried channels in some parts of Monument Valley where the Shinarump member is overlain by as much as 100 feet of Monitor Butte rocks. In other places much smaller thicknesses of Monitor Butte rocks have made interpretation impossible because of the extremely high and variable seismic velocity and the irregular thickness of the Monitor Butte rocks along the seismic profile.

Changes in velocity within the Shinarump member also present difficulties that cannot always be resolved; for example, the mudstone lenses within the Shinarump may complicate the interpretation of the time-distance plots and may even obscure the channels completely.

In spite of these difficulties, the seismic-refraction method has been quite successful in locating buried channels in Monument Valley. Seismic-refraction measurements in many of its large areas not yet systematically explored for buried channels would prove useful. Other geophysical methods may be used where local conditions prevent the use of the seismic-refraction method.

EXPERIMENTAL SHALLOW-REFLECTION MEASUREMENTS

During a series of seismic-refraction measurements on Hunts Mesa in 1953, erratic arrivals were noted on the first few geophones of a conventional refraction spread. These arrivals were tentatively identified as reflections and were confirmed by shooting short spreads in the zone of the erratic arrivals (Pakiser and Warrick, 1956). Although these reflections were recorded by accident, interest was aroused in further testing seismic-reflection methods in delineating the Shinarump and Moenkopi contact. Experimental shallow-reflection measurements were therefore made in Monument Valley in 1954 to determine if reflections could be obtained from the Shinarump and Moenkopi contact and if channels could be mapped with this geophysical method.

The experimental shallow-reflection measurements were made with specially designed instruments. A 12 trace oscillograph with high-frequency galvanometers and high paper speed, amplifiers with high-frequency filters, fast automatic-gain control, and variable presuppression control were used to make the measurements (Pakiser, Mabey, and Warrick, 1954). Standard field methods, employing both in-hole and single air shots and inline and split spreads, were used in these tests. Various sizes and configurations of shot patterns were tested; multiple geophones were also used.

Some shallow reflections were obtained from these test measurements, but they could not be correlated from shot point to shot point. Some evidence indicates that reflections were from the Shinarump and Moenkopi contact, but they were of poor quality and many bordered on the indiscernible. Where reflections did appear on several traces, abrupt changes in stepout time were common.

If it had proved possible to obtain good quality reflections from the top of the Moenkopi formation, the seismic-reflection method would be a valuable tool in channel exploration in Monument Valley. This geophysical method, with its high resolving power, and its freedom from velocity inversion, would be a valuable addition to the seismic-refraction and electrical-resistivity methods for finding buried channels. Conditions in the Monument Valley area that prevent the recording of good quality reflections affect the seismic-refraction measurements as well, but refracted events can still be recorded. Among these adverse conditions are lateral changes in the seismic velocity in the Shinarump member; the presence of mudstone lenses within the Shinarump member which may act as reflecting horizons that contribute reflected energy in the form of noise; the absence of the weathered layer (in the classical sense), in which the velocity is low; and the usual impossibility of placing the shot below the water table. Therefore, shallow reflections frequently were not obtained, and where they were obtained the reflections were usually discontinuous and of poor quality. For these reasons, the seismic-refraction method is more applicable than the shallow-reflection method in locating buried channels in Monument Valley.

ELECTRICAL METHODS

Data obtained from the physical-property studies make it clear that resistivity contrasts do exist between the Monitor Butte and the Shinarump members and between the Shinarump member and the Moenkopi formation. A larger contrast in resistivity may also exist within the Shinarump member than between the basal Shinarump and the Moenkopi formation (fig. 58); however, in surface-resistivity measurements the composite resistivity of a relatively large unit of the earth is measured. Thus the relative volume of the various materials must be considered. In terms of total volume, a large enough contrast in resistivity generally exists between the Shinarump member and the Moenkopi formation to produce resistivity anomalies, detectable on the surface, over thicker parts of the Shinarump member caused by channeling. Changes in resistivity within the Shinarump member will also probably result in anomalies, detectable on the surface, which may or may not be due to channeling. It should be emphasized that the electrical-resistivity and potential-drop-ratio methods depend upon the resistivity contrast between adjacent strata, whereas the electromagnetic method depends upon the absolute values of resistivity.

ELECTRICAL-RESISTIVITY MEASUREMENTS

The average resistivity of the Shinarump member is higher than that of the Moenkopi by a ratio of about 5 to 1. Therefore, under conditions of uniform overburden and optimum size and depth of burial, a channel could be expected to produce a resistivity anomaly that could be detected with surface measurements. Channeling, however, often results in abrupt lithologic changes, both vertically and laterally, which may occur not only within the channel fill but also in the Shinarump above the scour. Under these conditions the anomalies resulting from the changes in lithologic properties will be superimposed upon those caused by the more deeply buried channel bottom. The anomaly from the channel, as determined from surface measurements, may be easily recognizable, slightly distorted, or completely obscured depending upon the number, size, distribution, and resistivity of the disturbing bodies. Anomalies resulting from channels therefore may be caused predominantly by the Shinarump channel fill, lateral lithologic variations in the Shinarump member, or both.

The heterogeneous nature of the Shinarump member (p. 165) results in a wide range of resistivity throughout the section. The magnitude of the anomalies is dependent not upon the absolute resistivity of the disturbing bodies compared to that of the surrounding medium but upon the ratios of the resistivity of the bodies to that of the surrounding medium. Therefore a change in resistivity from 400 to 1,600 ohm-meters (1:4) for bodies within the Shinarump member may be less significant than the changes between the Moenkopi formation and the channel fill, which is usually about 1:5.

In places the Shinarump member is covered by a siltstone of the Monitor Butte member, that has about one-fifth the average resistivity of the Shinarump. Assuming no lateral changes within the Monitor Butte, this siltstone would influence the resistivity measurements only by reducing the magnitude of the anomalies.

EQUIPMENT AND FIELD PROCEDURES

All routine resistivity measurements in Monument Valley were made with Geoscope d-c equipment (Lee, 1936); however, a few measurements were made with Gish-Rooney equipment to compare the results obtained with direct current and commutated direct current. Current electrodes made of stainless-steel rods, and nonpolarizing potential electrodes made by placing a copper electrode in a porous ceramic jar filled with a saturated solution of copper sulfate, were used for the d-c measurements. Heavy-duty 45-volt radio "B" batteries supplied the power.

The Lee partitioning configuration (Lee, 1936) was used exclusively in the Monument Valley resistivity measurements. Four equally spaced electrodes C_1, C_2, P_1, P_2 (fig. 71), are placed in a straight

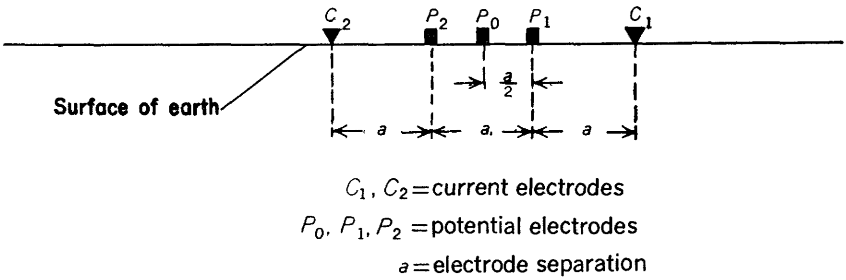

FIGURE 71.—The Lee partitioning configuration for electrical-resistivity measurements.

line along the surface of the ground; the distance between adjacent electrodes is designated as the electrode separation a. A fifth electrode, placed at the center of the configuration midway between the two inner electrodes, P_1 and P_2, is called P_0.

If current, I, is flowing between the outer electrodes, C_1 and C_2, and the resulting potential difference, V_1, is measured between P_1 and P_0, and V_2 is measured between P_0 and P_2, the following relationships are obtained:

$$\rho_1 = 4\pi a \frac{V_1}{I}$$

$$\rho_2 = 4\pi a \frac{V_2}{I}$$

where ρ_1 and ρ_2 are defined as apparent resistivities of the left and right portions of the earth respectively, of an imaginary plane intersecting P_0 at right angles to the configuration.

Two methods in making resistivity measurements were used: vertical- and horizontal-resistivity profiling. In vertical-resistivity profiling the central point of the configuration occupied is fixed and the electrode separation expanded at some convenient interval. In horizontal-resistivity profiling the electrode separation is fixed, and the configuration is moved as a unit along a traverse. The center of the configuration, the point occupied by the P_0 electrode, is designated as the station location for both vertical- and horizontal-resistivity profiling.

In areas investigated in detail by the vertical-profiling method, measurements were usually made on a grid pattern, and the traverses crossed a channel or assumed channel location at right angles. The electrode configurations were oriented either parallel to, or at right angles to, the traverse line except in locations where there was little or no soil covering the bedrock. At these places the configuration was either oriented in a direction to avoid the outcrop, or the station was offset to a more suitable location. Many of the areas were on tops of mesas. In these areas, stations were located at least 100 feet from the mesa edge to minimize the distortion of the current-distribution pattern.

Horizontal-profiling measurements were made along traverses at right angles to the estimated strike of the buried channel. Measurements were obtained at several different electrode separations on the same traverse. This practice provided some information as to the relative depths of anomalous bodies and made it possible to distinguish some anomalies caused by near-surface disturbances from those due to bodies at greater depths.

HORIZONTAL-PROFILING MEASUREMENTS

The information obtained from horizontal-profiling measurements is primarily qualitative, and while the geometrical properties of a channel such as depth and cross-sectional shape cannot be determined by this method, several valuable generalizations can be made in detecting a channel and tracing it across an area.

The interpretation of horizontal-resistivity data in the location of channels has been largely empirical or based on model studies. The lack of theoretical solutions of data over channels is due primarily to the time required for the computation of theoretical curves. Cook and Van Nostrand (1954) present the values of the apparent resistivity for profiles over ellipsoidal and hemispherical sinks. A theoretical curve based on the Lee configuration for a filled hemispherical sink having a diameter of 150 feet and a 1:5 resistivity ratio of the material inside the sink to that outside the sink is shown in figure 72. The outstanding feature of each curve is the resistivity low directly over the sink with a maximum and minimum on either side. Minimums C, C', D, and D' occur where the current electrodes cross the sink boundary, and maximums A, A', B, and B' occur where the potential electrodes cross the boundary.

The resistivity values are not plotted at the position of the P_0 electrode, but at a point midway between P_0 and P_1 for the ρ_1 values and between P_0 and P_1 for the ρ_2 values. This plotting method, known as "offset plotting," is used throughout this report.

The profile in figure 72 is typical of the anomaly observed over a sink filled with material of lower resistivity than that of the surrounding rock. If the conditions were reversed, that is, if the resistivity of the material in the sink were higher than that of the surrounding rock, the observed profile would be inverted, but it would still have the same general characteristics. A, A', B, and B' would be

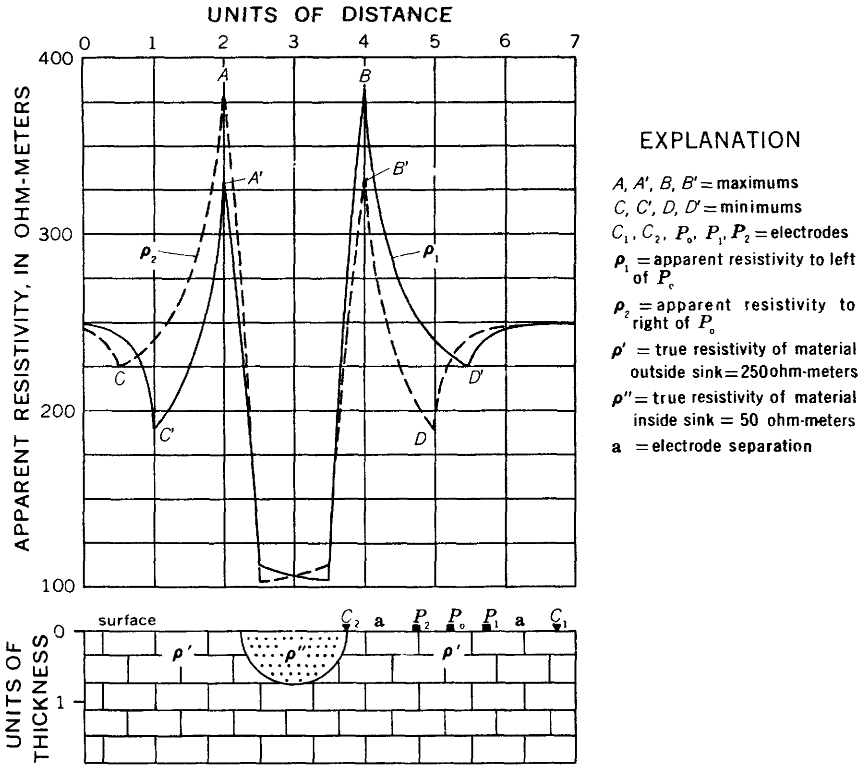

FIGURE 72.—Theoretical horizontal-resistivity profile over a filled hemispherical sink. (From Cook and Van Nostrand, 1954, fig. 6.)

minimums, whereas C, C', D, D', and the anomaly directly over the sink would be maximums. In cross section the shapes of the channel and the above-described sink are very similar; however, while the channel may be assumed to have an infinite length, the sink has a length equal to its width. Although the difference in length of the two bodies would result in curves having different maximums and minimums, the same features would persist and the location of the discontinuities with respect to boundaries would be the same. The width and position of the disturbing body can be estimated by determining the distance betwen discontinuities A and B, which occur at a distance $a/4$ outside the boundaries of the body. The center of the body falls midway between A and B or at the point where the ρ_1 and ρ_2 curves cross.

Horizontal profiling measurements taken at various locations across the Shasta Copper channel (figs. 73–76) indicate the heterogeneous nature of the channel fill. All the profiles have an anomalous resistivity high that can be correlated with the channel location.

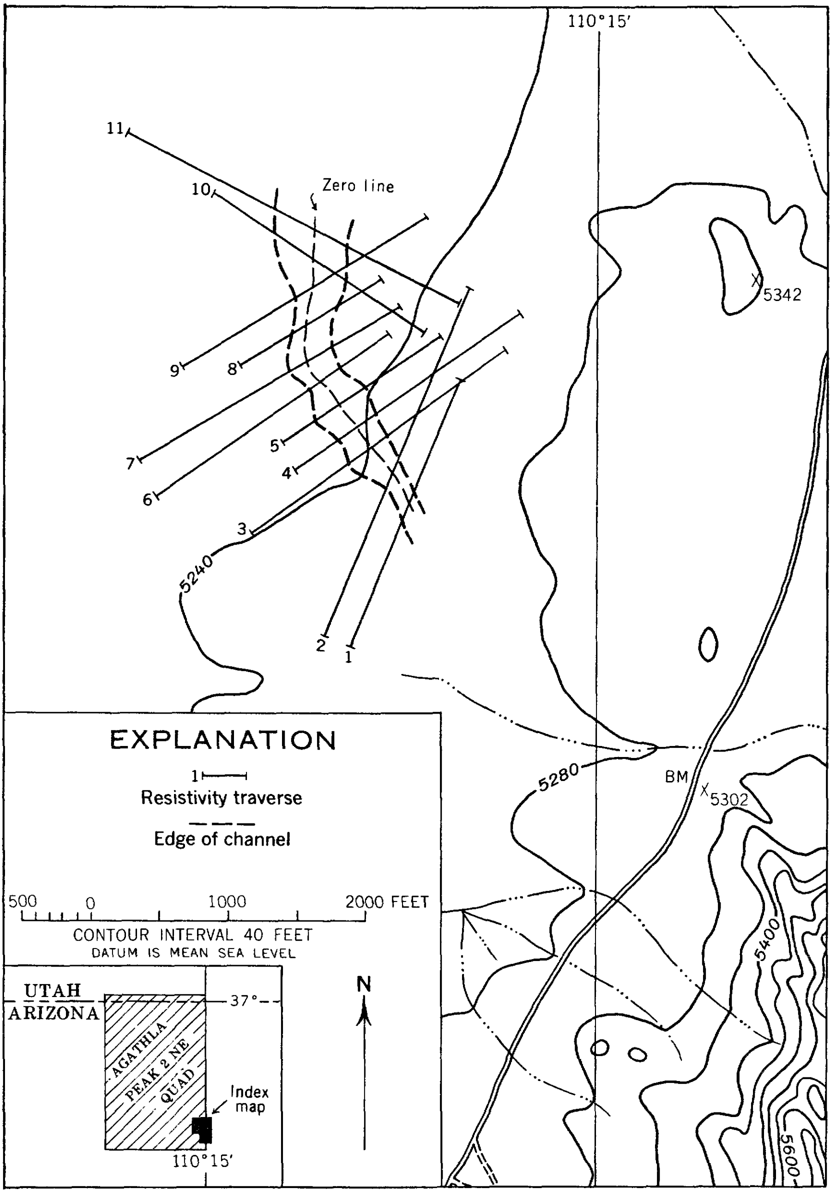

Figure 73.—Index map showing location of resistivity traverses across the Shasta Copper channel (see figs. 74–76).

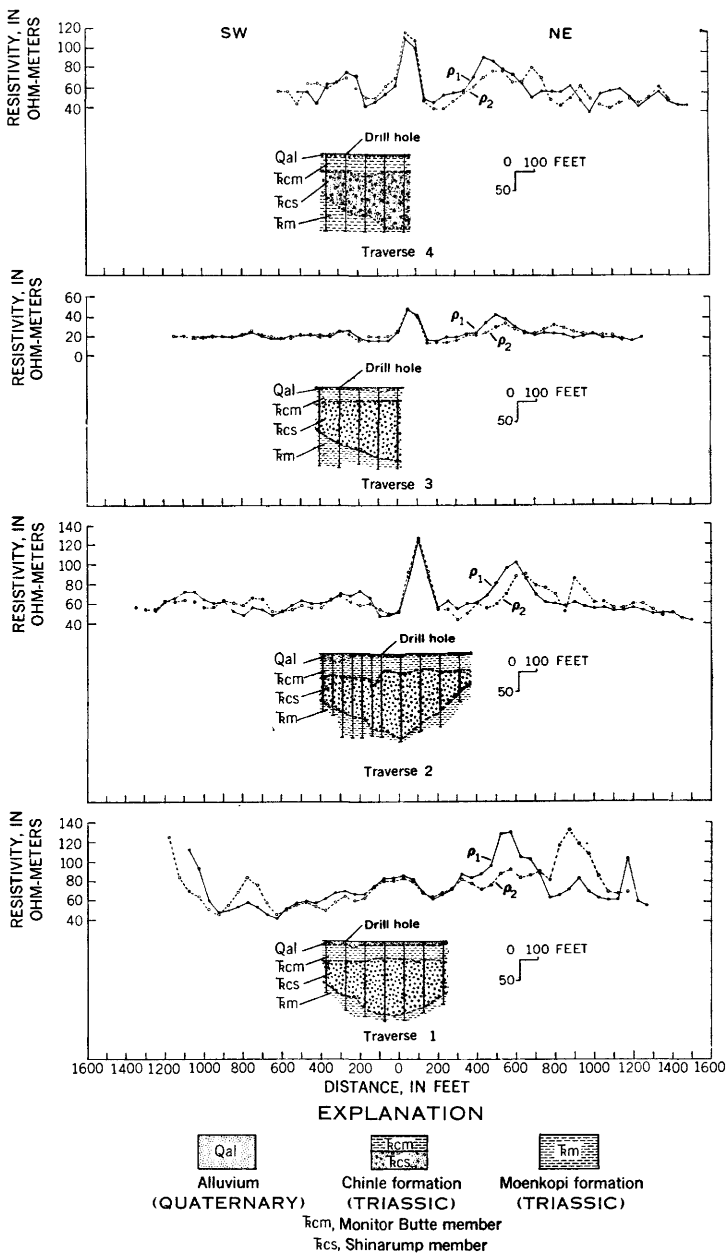

FIGURE 74.—Horizontal-resistivity profiles and geologic sections from drill-hole data along traverses 1–4, Shasta Copper channel.

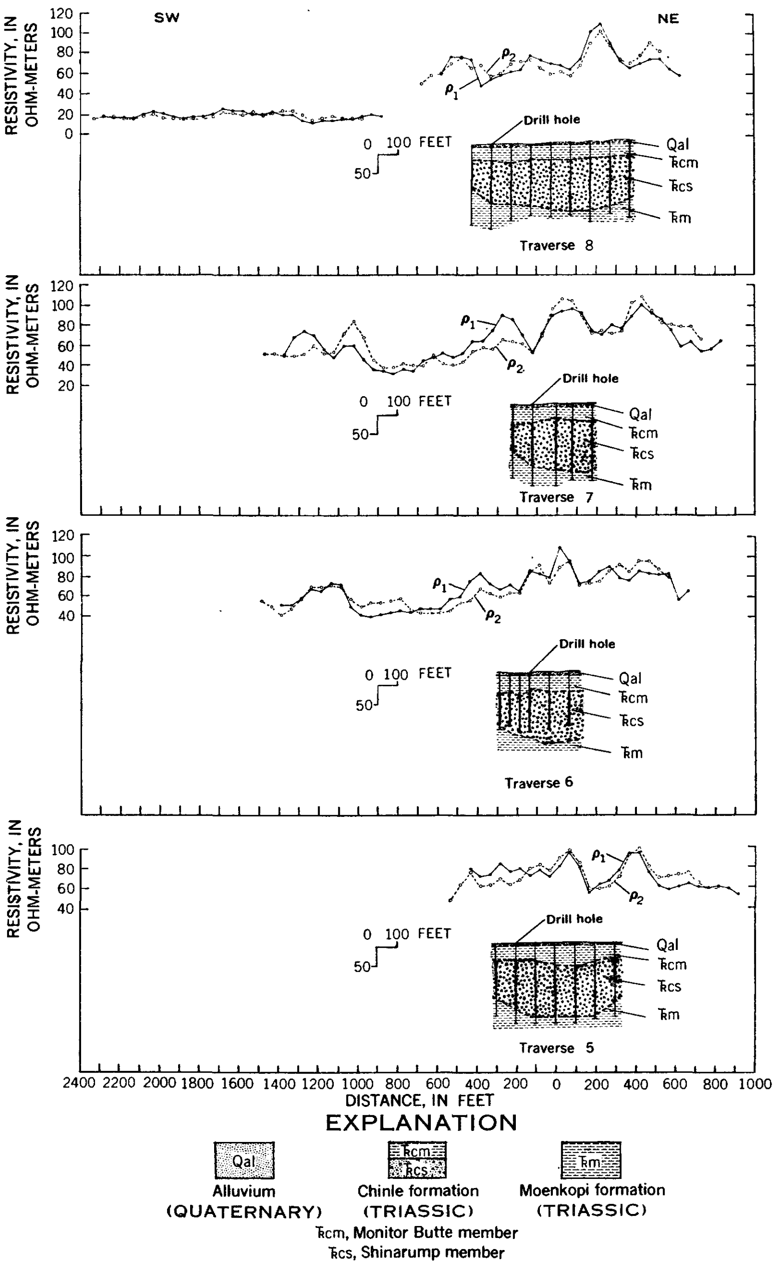

FIGURE 75.—Horizontal-resistivity profiles and geologic sections from drill-hole data along traverses 5–8, Shasta Copper channel.

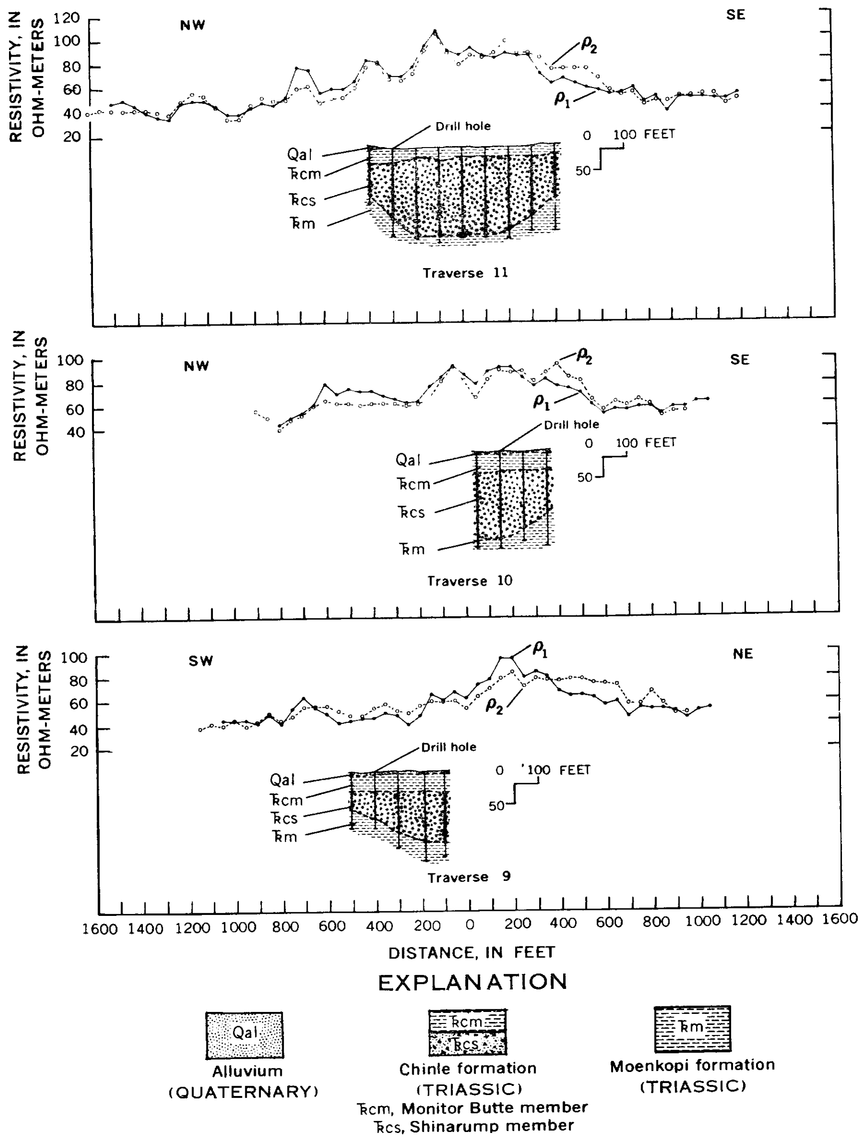

FIGURE 76.—Horizontal-resistivity profiles and geologic sections from drill-hole data along traverses 9–11, Shasta Copper channel.

The anomalies can be placed in two general groups: those having a sharp center peak with pronounced highs on either side (traverses 2–4), and those having only a broad central high that in many cases extends over the entire channel section (traverses 10, 11).

Preliminary measurements were made along traverse 1 at three different electrode separations (fig. 77) to aid in determining the opti-

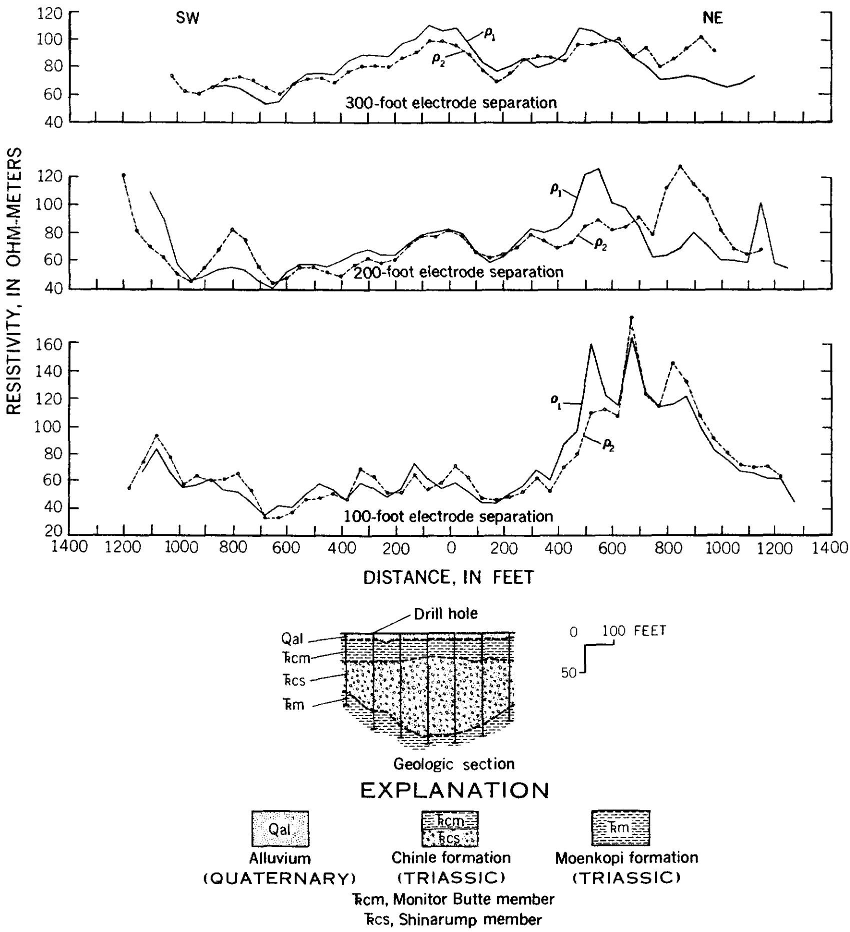

FIGURE 77.—Horizontal-resistivity profiles and geologic section from drill-hole data along traverse 1, Shasta Copper channel.

mum separations to be used in the immediate area. The outstanding feature on the 100-foot-separation profile is the broad resistivity high centered 800 feet northeast. Because the anomaly becomes smaller with increased electrode separation, it may be assumed to be caused by a near-surface feature, probably in the Monitor Butte member or in the upper part of the Shinarump member. There is no indication of the channel anomaly on the 100-foot-separation profile; however, the anomaly begins to appear on the 200-foot profile and is stronger on the 300-foot profile. The surface irregularities on the 100-foot curve are almost completely absent on the 300-foot separation curve.

The profiles in the first group (traverses 2–4, 7, 8) agree well with the inverted theoretical curve (fig. 72), although the maximums and minimums are not as pronounced, possibly because of the tempering effect of the highly conductive shale in the Monitor Butte. Sharper peaks and troughs could have been obtained by taking more closely spaced measurements in the anomalous zone. With an electrode spacing of 200 feet, the side peaks should occur at approximately 300 feet on either side of the central high, with ρ_1 occurring to the south and ρ_2 to the north. On traverses 2, 3, 4, 7, and 8 the ρ_1 side peaks are prominent; however, the ρ_2 maximums are somewhat obscured on traverses 2, 3, and 4 by the resistivity high between 500 and 600 feet northeast. The relative width of the central high is a measure of the depth of the disturbing body; therefore, the anomalies over the channel on traverses 2, 3, 4, 7, and 8 are probably caused by a highly resistive body, relatively small in cross-sectional area and located within the channel scour, or are associated with the channel and located in the upper Shinarump section.

Profiles 9, 10, 11, and to some extent 1 and 6, are influenced primarily by the total volume of the channel. These anomalies of the second group indicate a large body with a higher resistivity than that of the surrounding medium. The "noise" or irregularities superimposed on the broad anomalies are due to smaller bodies of high resistivity located at or near the surface.

VERTICAL-PROFILING MEASUREMENTS

Adverse surface conditions often limit the accuracy of the vertical-profiling method in determining the thickness of the Shinarump member. Little, if any, overburden covers the bedrock over much of the Monument Valley region studied. In many places the exposed rocks are actually exfoliation slabs, partly insulated from the underlying bedrock by air-filled planes of parting. These conditions result in abrupt changes of surface and near-surface resistivity, causing irregularities in the data. The irregularities are especially pronounced in measurements taken at shorter electrode spacings, an especially important part of the data when depth determinations are made by matching field curves with computed curves. However, satisfactory data can usually be obtained even in areas having unfavorable surface conditions if care is taken in orienting the configuration and in placing the electrodes.

In areas where the Shinarump member is covered by several feet of alluvium it is usually possible to obtain vertical profiles which can be interpreted by comparison with theoretical curves. Profiles plotted from the field data generally show a minimum of 3 electrical layers (corresponding to the alluvium, the Shinarump member, and the Moenkopi) and in many places the profiles show as many as 5 electrical layers as a result of vertical changes in resistivity within the Shinarump member. These vertical changes in resistivity are associated with changes in lithology and water content. For the simple 3-layer curves, interpretation is made by direct reference to theoretical 3-layer curves (Wetzel, and McMurry, 1937). For the more complicated conditions where the profiles show 4 or more layers, interpretation is made by partial-curve matching, using theoretical 2-layer curves (Roman, 1934) to supplement the 3-layer curves.

Where the first part of the field profile is too irregular to permit a theoretical analysis to be made, a qualitative interpretation can often be made by matching curves from adjacent stations with respect to curve shape and location of inflection points on the curves.

APPLICATIONS AND LIMITATIONS

The results of the horizontal- and vertical-resistivity profiling measurements show that, subject to certain limitations, these methods can be used to locate buried channels in Monument Valley. However, the information obtained by these methods is more qualitative than quantitative, and although the location of buried channels may be determined, these methods can seldom be relied upon to give the depths, widths, or shapes of buried channels.

The horizontal-profiling method is preferred because of its greater speed and lower cost. Preliminary vertical-resistivity measurements should, however, be made at various locations in the area to be explored in order to determine the optimum electrode spacings. In general, the electrode spacings should be 1 to 3 times the depth to the Shinarump-Moenkopi contact. Station spacing for the horizontal-profiling measurements should be one-half the electrode spacing, although shorter intervals are often required to map resistivity anomalies in greater detail. The horizontal-profiling measurements are made on traverses at right angles to the estimated trends of the buried channels, and the distance between traverses is governed by the channel curvature, local geologic and topographic factors, and the amount of detail required for a given channel trend.

The Lee partitioning configuration has proved more useful than the Wenner configuration for horizontal-profiling measurements. One additional man is needed when using the Lee partitioning configuration and a few seconds additional time is necessary for taking measurements, but the additional information obtained is of great value in interpreting the data and is well worth the additional time and personnel.

The limitations of electrical-resistivity methods for locating buried channels in Monument Valley are partly inherent in the methods themselves and are partly a result of local geological and topographic conditions. Interpretation of electrical-resistivity measurements cannot be considered to present unique geologic solutions even if field curves can be perfectly fitted to theoretical curves. All that can be said is that the electrical layering for the field station corresponds to the theoretical conditions assumed in preparing the reference curve. This electrical layering may or may not correspond to stratigraphic or lithologic layering in the earth. Where the field curves do not fit theoretical curves, interpretation of resistivity data is, of necessity, empirical. In Monument Valley it is frequently difficult to obtain measurements that plot as smooth curves that are amenable to theoretical interpretation. This is partly because of poor electrode contacts and partly a result of lateral and vertical resistivity changes in the near-surface materials. Therefore, most of the vertical-resistivity measurements must be interpreted by empirical rather than theoretical means.

To produce a resistivity anomaly, the geologic target of the resistivity survey must have a sufficient contrast in resistivity with respect to the surrounding material so that measurable distortions are produced in the normal potential gradient. Such a contrast exists for buried channels in Monument Valley, but lateral changes in resistivity of near-surface materials and distortions produced by poor electrode-contact conditions may in some places obscure anomalies caused by channeling.

In spite of the limitations, electrical-resistivity measurements, when properly made and interpreted, can contribute valuable information to programs of channel exploration in Monument Valley, particularly when used as a supplement to seismic-refraction measurements.

POTENTIAL-DROP-RATIO MEASUREMENTS

The potential-drop-ratio method was used in the El Capitan Flat area to test a potential method using fixed current electrodes. The only available equipment that had adequate sensitivity was the 400-cycle a-c ratiometer, which was used for the electromagnetic measurements.

In the usual potential-drop-ratio work described in the literature, the potential electrodes are placed along a line that intersects one of the current electrodes and is normal to the line joining the current electrodes. In the El Capitan Flat area the potential electrodes were placed along the line joining the current electrodes or else at an arbitrary angle with this line.

The potential-drop ratios were always normalized by dividing the observed ratio by theoretical ratios calculated for a homogeneous earth. To calculate these theoretical ratios, first the potential, V, due to the two current electrodes was calculated at traverse points which were separated by a distance equal to the electrode separation, using the expression

$$V=\frac{\rho i}{2\pi}\left(\frac{1}{r}-\frac{1}{r'}\right)$$

where ρ = resistivity of the earth,

I = current flowing between electrodes,

r = distance from point in question to current electrode C_1,

r' = distance from point in question to current electrode C_2.

Then the drop in potential between adjacent points was calculated and the quotient of the adjacent potential drops was taken to obtain the desired potential-drop ratios. These computations are fairly easy and rapid to make when the traverse is along the line joining the current stakes, but they are much more laborious when the traverse is at an arbitrary angle.

Most of the normalized potential-drop-ratio curves are extremely erratic and jagged, and very little can be learned from them. Normalized potential-drop, or what are approximately potential-gradient, curves were calculated from the normalized ratios, and curves that are much smoother and easier to interpret were obtained. For traverses along the line passing through the current electrodes, a 1:1 ratio was assumed to exist between the actual potential drop and the theoretical potential drop between two points at one end of the line. This ratio was multiplied by the normalized potential-drop ratio, thereby giving the ratio between actual and theoretical potential drops at the next station. This procedure was carried out for the entire traverse by successive multiplication of the ratios. The resulting curve was plotted on semilog paper in order to give equal emphasis to highs and lows. The zero-decibel level was arbitrarily made equal to a normalized potential drop of 1.00. This normalized potential-drop curve is roughly equivalent to a resistivity curve made with fixed current electrodes. If the actual current flowing and the potential drop between any two electrodes were known, all the data could be presented as apparent resistivities.

RESULTS OF POTENTIAL-DROP-RATIO MEASUREMENTS

The normalized potential-drop profiles shown in figure 78 were obtained with current electrodes spaced 2,600 feet apart. The ener-

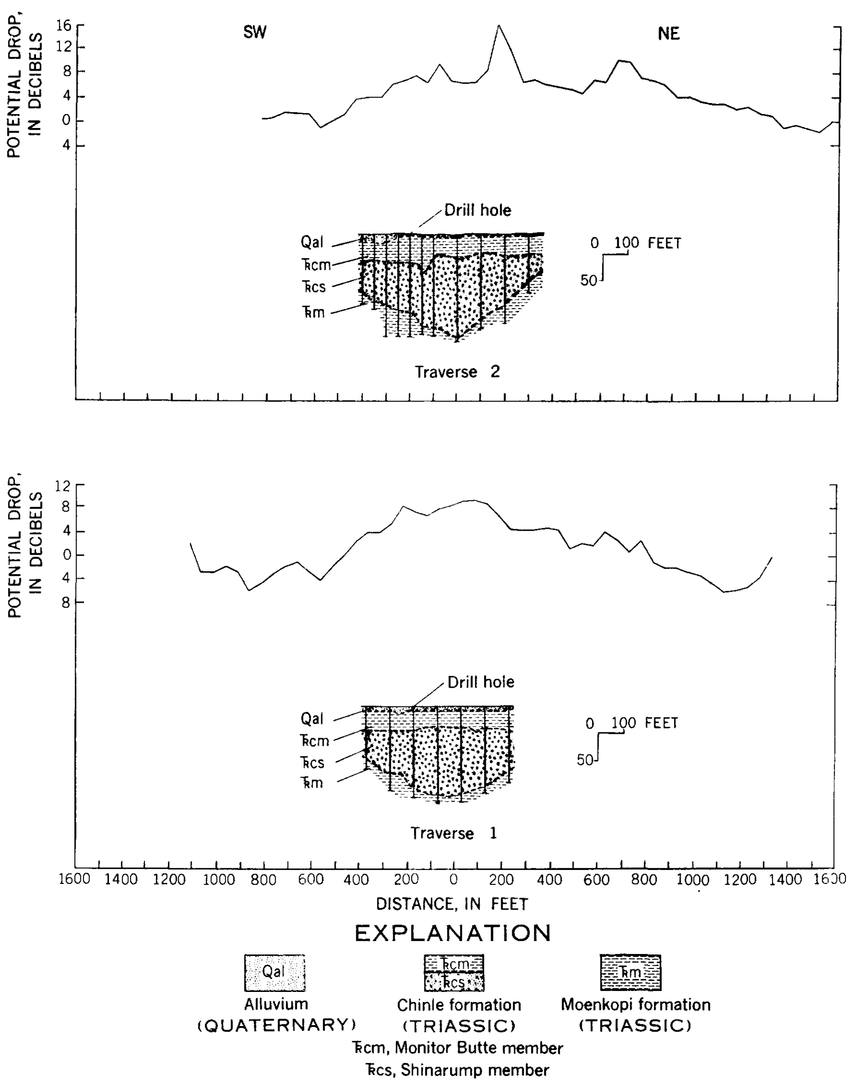

Figure 78.—Normalized potential-drop profiles at 50-foot intervals, and geologic sections from drill-hole data along traverses 1 and 2, Shasta Copper channel.

gizing cable was laid down as shown in figure 79 to minimize induction effects. A 400 cycles per second current of 1 to 2 amperes was passed between C_1 and C_2 and the ratio of potential differences between AB and BC was measured. Stakes A, B, and C were positioned 50 feet apart and moved toward C_2 at 50-foot intervals. Both in-phase and out-of-phase potential-drop ratios were measured, but the out-of-phase ratios were very small and erratic and were not used.

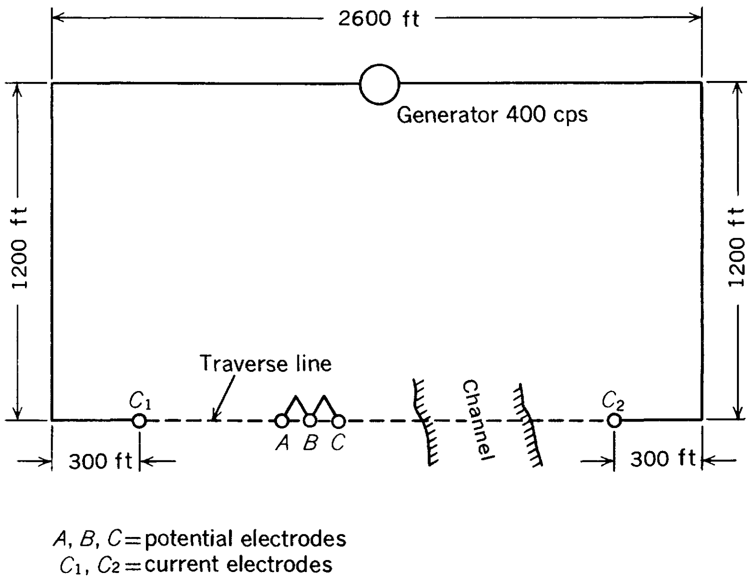

FIGURE 79.—Sketch of layout for potential-drop-ratio measurements.

The potential-drop profiles show broad gradual highs approximately centered in the middle of the traverse, with somewhat smaller features superimposed. The smaller features are not directly related to the geometry of the contact between the Shinarump and the Moenkopi, but they probably represent a series of units having different resistivities that are indirectly related to the channel.

The broad gradual high is roughly centered over the channel, although it does extend somewhat beyond what might be defined as the edges of the channel. This large high is probably caused by a volume of high-resistivity Shinarump within the channel. However, in a general way the potential-drop curves are symmetrical with respect to the center of the current-electrode arrangement. A possible explanation of this gross behavior of the curve is that skin effect caused a crowding of the current flow toward the surface near the center of the traverse. An apparent anomaly may have been caused when the results were normalized by assuming a d–c distribution. The low values of potential drops that occur at about 200 feet from either current electrode might be explained on the basis of a three-layer earth. The relative resistivities are high for the surface layer, low for the intermediate layer, and high for the lower layer. This would cause low potential-drop values at a distance from the current electrodes where most of the current flow would be in the intermediate layer.

ELECTROMAGNETIC MEASUREMENTS

The most common use of electromagnetic methods is in prospecting for massive sulfide ore bodies. However, electromagnetic methods have been used with varying degrees of success on such problems as mapping shallow horizons in sedimentary rocks, locating ground-water aquifers, and tracing buried structures that contain graphitic beds.

As a result of surface and inhole-resistivity measurements made in Monument Valley the authors believed that sufficiently large volumes of Moenkopi or Monitor Butte rocks would cause a significant electromagnetic response but that the Shinarump rocks would have relatively little effect on electromagnetic measurements. Hence, the problem of locating buried channels in the Monument Valley region was visualized as one of locating insulators surrounded by more conductive material.

SLINGRAM AND TURAM METHODS

Equipment for testing two electromagnetic methods and their variations was available to the Geological Survey when the Monument Valley studies were made. The method most extensively used was slingram; the other method was turam.

In the slingram method two small portable coils are used; one serves as a transmitter and the other as a receiver. A battery-powered vacuum-tube oscillator energizes the transmitting coil at 3,600 cycles per second. A ratiometer measures the ratio of the signal induced in the receiving coil to a signal sent directly from the transmitting coil by wire—if there is no conducting material in the vicinity, this ratio is a constant that depends only upon the coil separation. Eddy currents are induced in any conductors in the vicinity of the coils, and the magnetic fields associated with these eddy currents are superimposed upon the original field so that the ratio of the two signals is not constant but depends upon the conductivity and the geometry of the conductors.

In general, the time of arrival of the signals associated with eddy currents is behind or ahead of the time of arrival of the reference signal. Hence, the ratiometer actually measures two ratios; one depends upon the amplitude of the part of the receiver signal which is in phase with the reference signal, and the other depends upon the amplitude of the portion of the receiver signal out of phase with the reference signal. The ratio of the in-phase anomaly to the out-of-phase anomaly is small for poor conductors and large for good conductors. This ratio also varies with the frequency and the size and shape of the conductor.

It is generally found in electromagnetic work that the in-phase ratio is much more erratic or "noisy" in character than the out-of-phase ratio. One reason for this is that errors in coil spacing and orientation due to topography and other causes affect the in-phase ratio much more than they affect the out-of-phase ratio.

In the turam method (Hedström, 1940), a long cable grounded at both ends and excited by an engine-driven alternator operating at 400 cycles per second is used as the energizing source. Two small receiving coils, separated by a distance of 20 to 200 feet, are used to make measurements along traverses normal to the cable. A ratiometer is used to measure the in-phase and out-of-phase ratios of the voltages induced in the two coils. The data obtained are usually normalized; that is, the field ratios are divided by theoretical ratios that have been calculated by assuming an absence of conducting material.

The method described by Enslin (1955) was tried using the turam equipment. The results were not encouraging, probably because the method is not suitable for working over conductive horizontal strata.

The interpretation of electromagnetic data depends largely upon theoretical and scale-model results. No theoretical or exact scale-model results are available for a buried channel. However, theoretical results such as those by Wait (1955) can be used to help estimate the magnitude of the anomaly to be expected over a channel and scale-model results obtained using metal sheets surrounded by air can indicate the shape of the anomaly. For example, Wait's curves indicate that measured by the slingram method with a 200-foot coil separation and a frequency of 3,600 cycles per second, the in-phase ratio should change from about 129 to 104 percent and the out-of-phase ratio from −14 to +7 percent in passing over a thick block of Moenkopi having a resistivity of 20 ohm-meters to a thick block of Shinarump having a resistivity of 200 ohm-meters.

A basic difference between the slingram and the turam methods is that in with the slingram method the source of energy as well as the receiving device is moved for each new station, whereas with the turam method the source remains fixed. Because of this difference, slingram anomalies are, in general, more complicated by edge effects than turam anomalies over the same body. However, with the slingram method each portion of the earth is treated in the same way. Similar disturbing bodies give rise to similar slingram anomalies, but with the turam method the anomaly depends upon the body's relationship to the energizing cable and to other bodies in the vicinity. Thus identical bodies do not in general cause identical turam anomalies. This distinction between the slingram and the turam method is very similar to the distinction between the conventional resistivity method and the potential-drop-ratio method.

Considering the horizontal extent of the conducting units and the lithologic and geometric grading of one unit into another, it is expected that in Monument Valley slingram data will be more useful than turam data. Any difficulties in interpreting slingram anomalies because of edge effects should be more than offset by the fact that, unlike comparisons of turam anomalies, any large slingram anomalies can be directly compared without taking into account such factors as the distances from the energizing cable.

The depth range of turam is greater than that of slingram because of the greater distance between the source and the receiver and also the lower frequency used. At a coil spacing of 200 feet, which was the maximum spacing of the equipment used, geometrical considerations probably limit the depth of slingram investigations to 100 feet or less for the poorly conducting rock units found in Monument Valley. A thick layer of conducting material such as the Monitor Butte would act as a shield and further limit this depth range.

RESULTS OF ELECTROMAGNETIC MEASUREMENTS

In using the slingram method in Monument Valley, the in-phase ratio was usually so erratic that it was not used. For the slingram method only the out-of-phase ratios are shown in this report. Along any one traverse, adjacent observations have an accuracy of about 0.2 to 0.4 percent relative to each other. There may be as much as 1 percent instrument drift from one end of a line to the other, and the base or zero level between individual traverses is not usually the same. Also there may be errors of about 5 percent in the sensitivity of the instrument from one profile to another because of changes which were made in the level of the reference signal.

In the Monument Valley studies the slingram method was most commonly used with the coils placed in the line of the traverse, oriented in a horizontal position, and spaced 150 feet apart. Figures 80, 81 and 82 include typical results obtained with this coil arrangement (plan of traverses shown in fig. 73) for 3 traverses made over a buried channel where the Shinarump member is covered by 15 to 50 feet of the Monitor Butte member. Figures 80 and 82 also show measurements that were made with the coils horizontal and with a separation of 150 feet, but with the coils broadside to, rather than in the line of, the traverse. A few slingram measurements were also made with the coils in vertical coaxial and vertical coplanar positions as illustrated in figures 80 and 83. Turam measurements were made using several techniques, but only the most successful results are shown in figure 83. These measurements are the ratios of the vertical fields on traverses normal to the energizing cable.

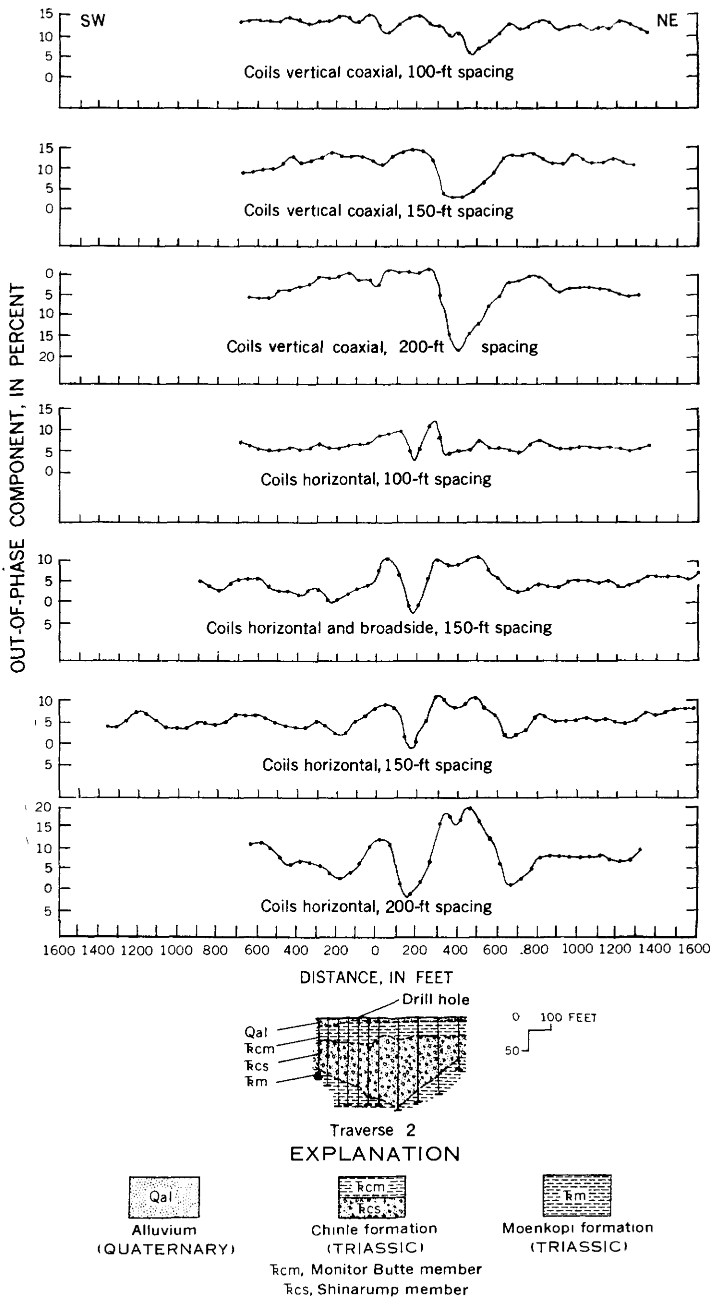

FIGURE 80.—Slingram profiles with coils horizontal and coils vertical coaxial, and geologic section from drill-hole data, traverse 2, Shasta Copper channel.

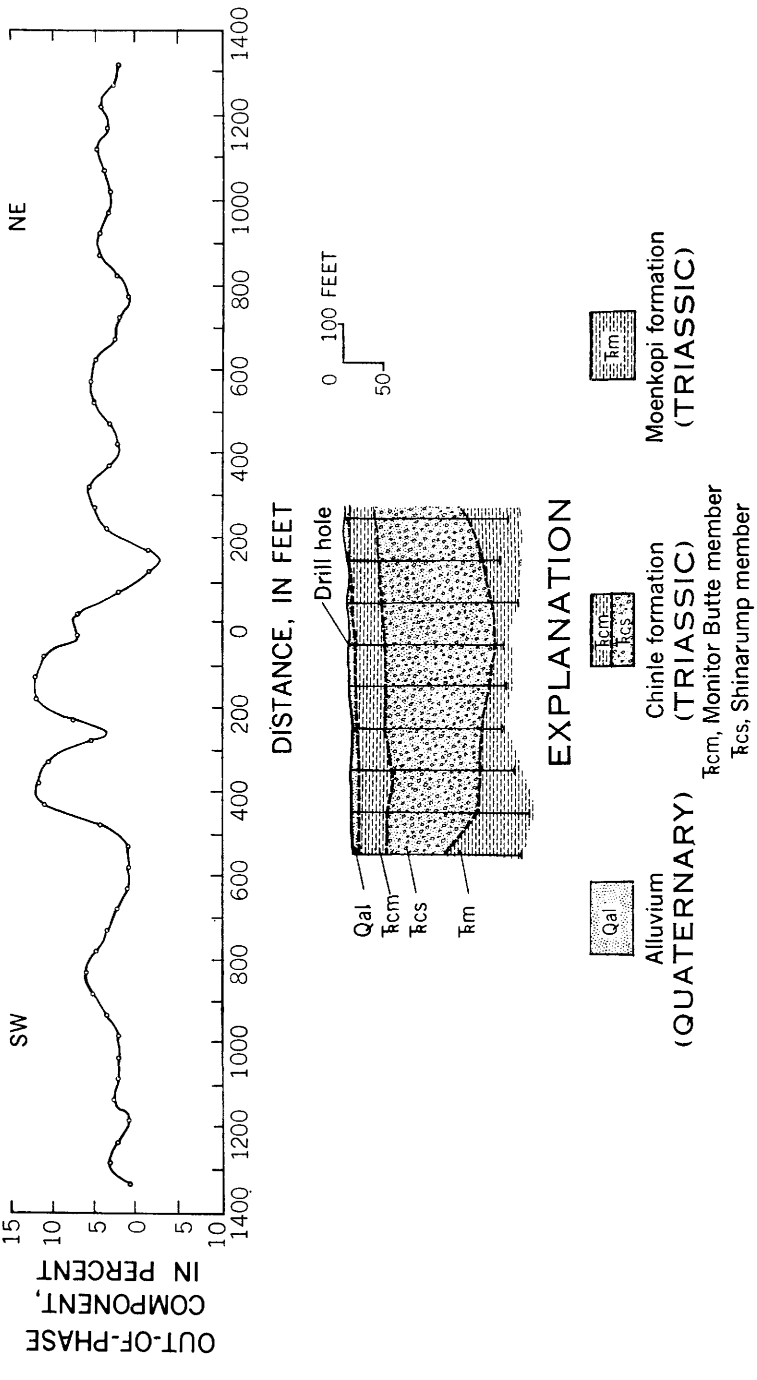

FIGURE 81.—Slingram profile with coils horizontal and at 150-foot intervals, and geologic section from drill-hole data, traverse 8, Shasta Copper channel.

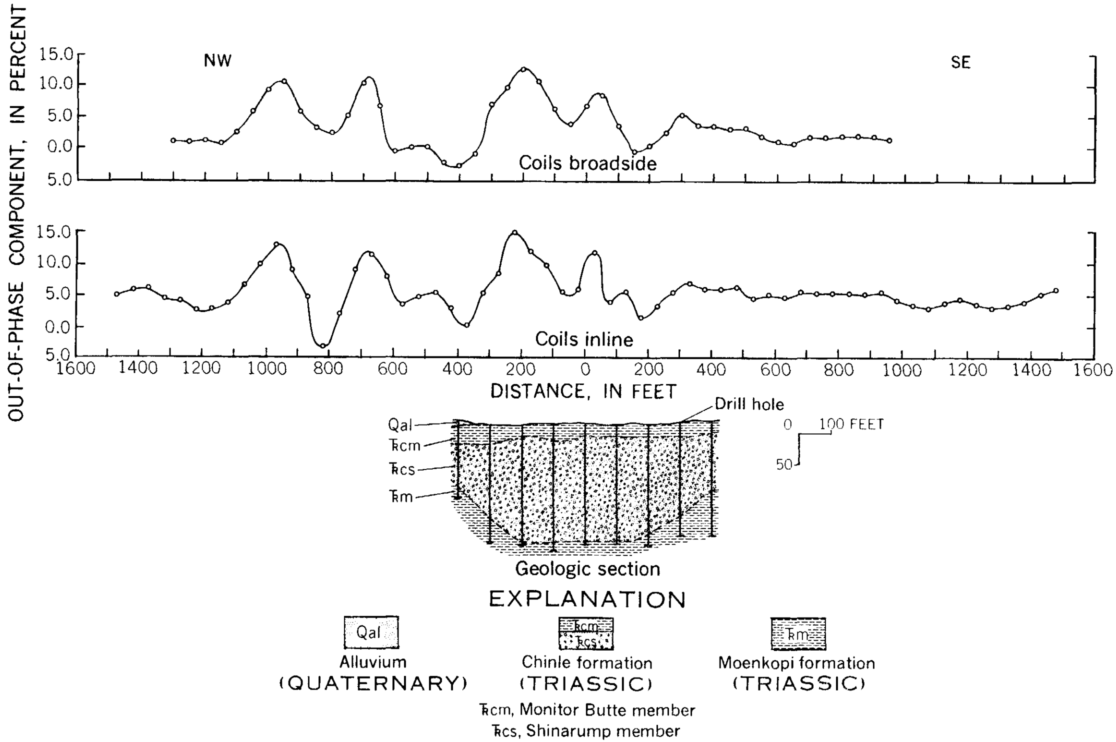

Figure 82.—Slingram profiles with coils horizontal and at 150-foot intervals, comparison of inline and broadside techniques, and geologic section from drill-hole data, traverse 11, Shasta Copper channel.

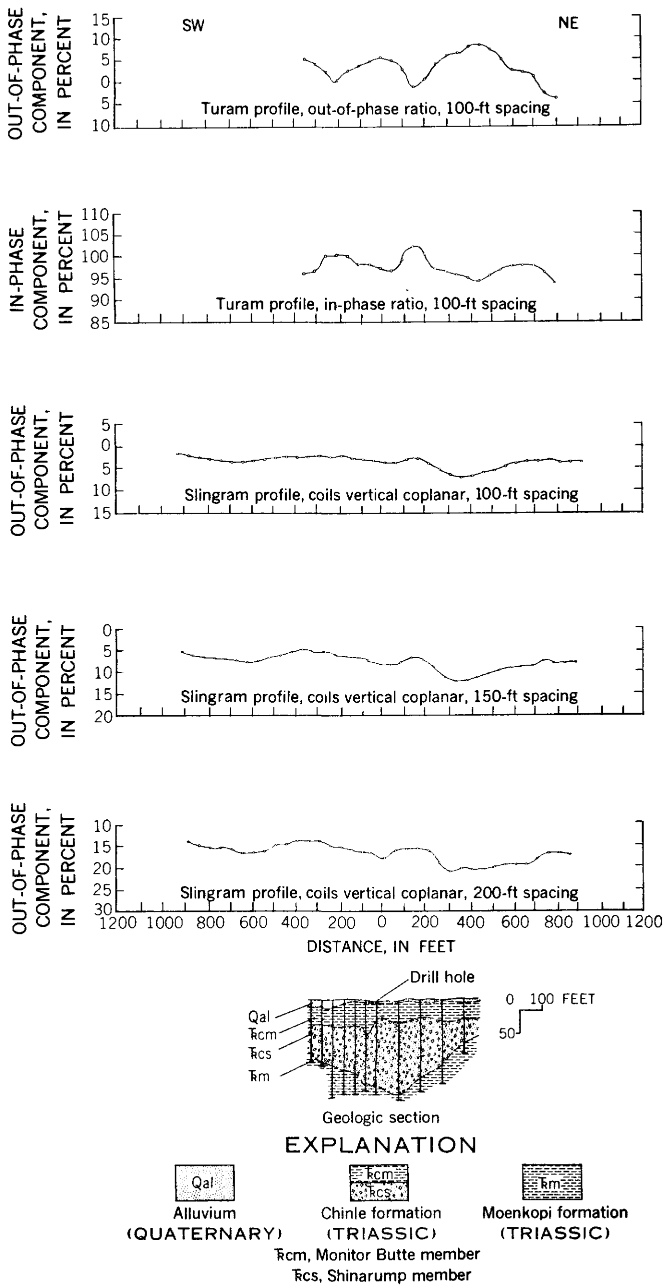

FIGURE 83.—Slingram profiles with coils vertical coplanar, and in-phase and out-of-phase turam profiles, traverse 2, Shasta Copper channel.

If no other information were available, the inline slingram anomalies would probably be interpreted as representing a series of conducting bodies with the lows in the curves being edge effects occurring on either side of the conductors. However, the broadside slingram and the turam measurements demonstrate that the lows represent more than edge effects about the conductors. With the broadside slingram techniques, edge effects are small when the traverse is normal to a linear feature. As stated previously, turam anomalies are much less complicated by edge effects than are slingram anomalies. The excellent agreement between the inline and the broadside slingram measurements, together with the correlation of the major slingram anomalies with the turam anomalies, indicates that edge effects are not very important in electromagnetic measurements in this area. Thus, each slingram reading may be regarded as a measure of the actual conductivity in the vicinity of the point of measurement.

Having established the significance of the slingram results it is apparent that they are not related to the geometry of the contact between the Shinarump and Monitor Butte, but rather to a series of conductive and nonconductive rock units which, because of their position, appear to be indirectly related to the channel. These units may be traced over considerable distances by correlating adjacent profiles. In general the individual units are continuous between traverses 1 and 8. At traverse 8 the pattern changes and a different system of units is recognized between traverse 8 (fig. 81) and traverse 11 (fig. 82). Between traverses 1 and 8 the slingram anomalies are more regular in form and occur more nearly over the center of the channel than they do between traverses 8 and 11. It is difficult to visualize the exact geologic nature of these "electrical units." The conducting units may be some sort of mud bars, and the nonconducting units may be sand bars and linear deposits of conglomeratic material.

Figure 80 shows an anomaly of about 8 percent for a traverse made with the coils vertical and coaxial at a spacing of 100 feet. From model data this limits the possible depth of the conductive unit to no more than 40 or 50 feet. If other evidence to the contrary were disregarded, the anomalies would seem to arise from within the Monitor Butte member. Because this seems unlikely, the source of at least some of the anomalies must be in the very top of the Shinarump member and not within the channel fill. The areal and vertical distribution of the sources of these anomalies seems to indicate that the original channels in the Moenkopi tended to perpetuate themselves as channels in the Shinarump member during the deposition of the Shinarump. Geologic and geophysical evidence over another channel where the Monitor Butte member is absent tends to substantiate this hypothesis. Figure 84 includes a slingram profile taken over this channel. As in the previous example, the anomalies are a series of highs and lows offset from the center of the channel. Geologic mapping shows that the sedimentary structures in the section above this channel trend parallel to the channel and almost normal to the general trend of similar structures in the area.

OTHER GEOPHYSICAL METHODS

MAGNETIC MEASUREMENTS

The possibility that heavy minerals, including magnetite, might be present in channels at the base of the Shinarump suggested the use of the magnetic method as a means of locating channel structures. To test this method an experimental magnetic survey was made in three areas over known channels of various sizes, widths, and depths.

A vertical magnetometer with a scale constant of 22 gammas per scale division was used to make the measurements. Stations were spaced at 25-foot intervals along a line at right angles to the direction of a known channel. Base stations were established and occupied at time intervals not exceeding 1½ hours to permit close control of diurnal variations. The vertical magnetic field intensities were computed

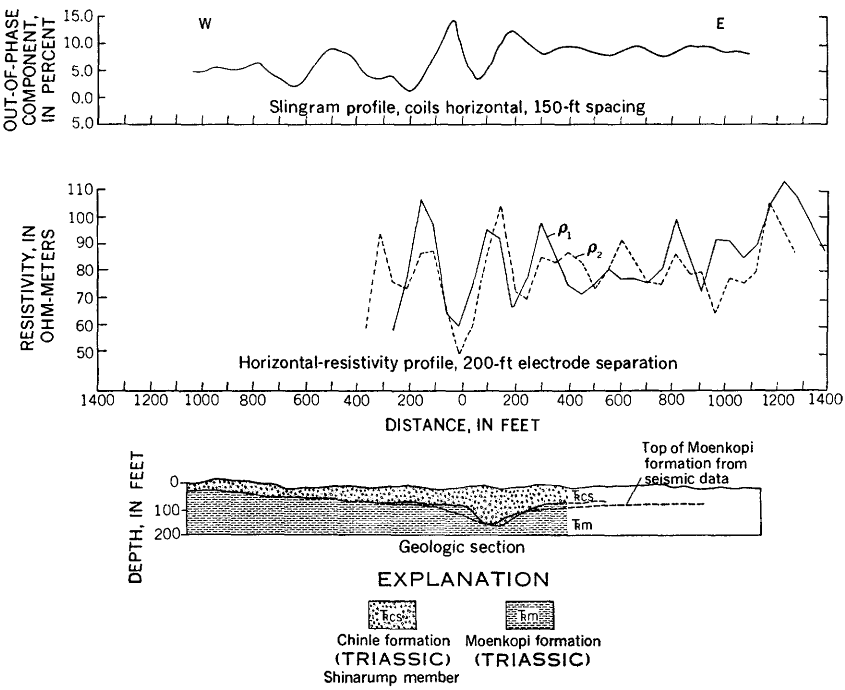

FIGURE 84.—Horizontal-resistivity profile and slingram profile (coils horizontal), seismic depths, and geologic section of the AEC channel.

by conventional methods and profiles were plotted from the values obtained. The variations from the average vertical magnetic field intensities of the profiles did not exceed ±5 gammas. The results of the magnetic survey indicate that this method is unsuitable for locating buried channels in the Monument Valley area.

GRAVITY MEASUREMENTS

The average density of a number of sandstone samples of the Shinarump and mudstone samples of the Moenkopi was measured and the Moenkopi was found to be approximately 0.1 gram per cubic centimeter more dense than the Shinarump. This contrast, although small, suggested the possibility of locating channels using gravity measurements. The Koley Black Mesa area was chosen for testing the gravity method because of its relatively level terrain and its large number of channels.

Preliminary calculations indicated that the expected anomalies would be less than 0.04 mgal (milligal); therefore, strict accuracy was required during instrumental operation and surveying. Measurements were made with a Worden gravimeter with a scale constant of 0.102 mgal per scale division using a 4-step oscillating method (Roman, 1946). The estimated accuracy of the individual station values was 0.01 mgal. Observations were taken at 20-foot intervals along 3 adjacent traverses, each 800 feet in length, that were normal to a series of channels.

A number of gravity lows of approximately 0.05 mgal were observed, and some correlated with channel locations. The curves were too irregular, however, for a reliable interpretation of subsurface structure. Most of the anomalies occurred in areas having sandy overburden, and subsequent drilling indicated that parts of the area are covered by as much as 3 feet of sand. Differences in the thickness of the sandy cover in parts of the area can explain the irregularity of the data and many of the anomalies.

While it is possible that gravity measurements could be used to detect and delineate large, deep channels, the accuracy required is so exacting and time consuming that this method cannot be considered economically feasible.

COMPARISON OF GEOPHYSICAL METHODS

From the foregoing discussion it is apparent that each of the methods that has proved applicable to the problem of locating buried channels also has its limitations. Fortunately, in many places, stratigraphic and lithologic factors that may limit the use of one of these geophysical methods do not necessarily affect the others. For example, seismic-refraction methods usually can be used with excellent results in parts of Monument Valley where the Shinarump is exposed at the surface. In the same areas, however, lack of overburden may limit the usefulness of electrical-resistivity measurements by introducing surface effects caused by changes in electrode contact or by shallow lateral resistivity changes.

A geologic section from drill-hole data of a channel in Monument Valley is shown in figure 84, along with the results of seismic-refraction, electrical-resistivity, and slingram measurements on a traverse across the channel. The contact between the Moenkopi formation and the Shinarump member is shown as a solid line where determined from the drill-hole data and as a dashed line where determined by delay-time analysis of the seismic-refraction data. The seismic results agree well with the location and configuration of the channel as determined by drilling, although the absolute depths do not agree exactly. There is no doubt that the channel would have been located by the seismic measurements. The horizontal-resistivity profile is highly irregular and the anomaly caused by the channel is superimposed on effects produced by near-surface variations. The slingram results are less erratic than the resistivity results, and there seems to be an indirect relationship between the anomalies and the location of the channel scour. The resistivity anomaly 125 feet east on the traverse line may have been caused by the buried channel, but the masking effect of other resistivity highs and lows prevents positive identification of the anomaly caused by the channel. Here, the seismic measurements undoubtedly are superior in establishing the channel location.

Seismic and electrical measurements made over another channel in Monument Valley are shown in figure 85. Here the Shinarump member is covered by 30 to 80 feet of Monitor Butte rocks and 3 to 10 feet of windblown sand. The seismic-refraction measurements cannot be used to determine the depth to the Shinarump-Moenkopi interface because the seismic velocity in the Monitor Butte member is higher than the Shinarump member. By using relative delay times based on a depth obtained from one of the drill holes in figure 85, the refracting interface shown by the dashed line in the geologic section was determined from the seismic data. Apparently there is a refracting surface within the channel and well above the bottom of the channel, as the dashed line does not follow the channel configuration indicated by the drill-hole data.

The horizontal electrical-resistivity profile clearly shows an anomaly over the buried channel. It is not uncommon for refracting beds within the channel to obscure completely the presence of the channel on the seismic data, but often these same beds have little effect on the electrical-resistivity anomaly. This is probably because of the rela-

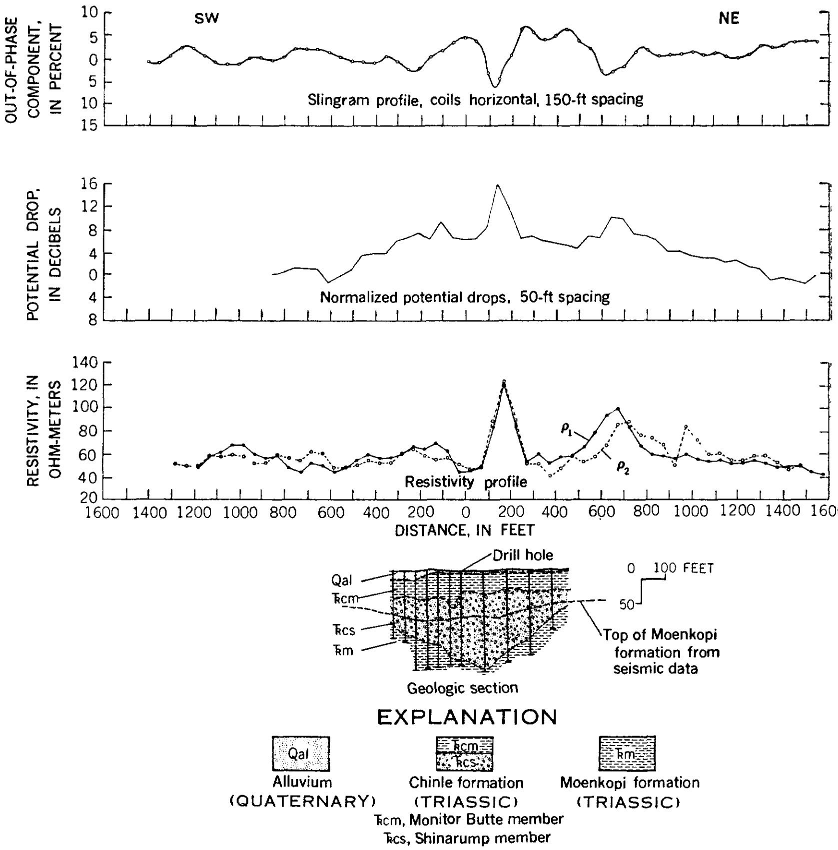

FIGURE 85.—Slingram, potential-drop, and resistivity profiles, seismic depths, and geologic section from drill-hole data, traverse 2, Shasta Copper channel.

tively minor effect of thin lenses on the overall resistivity of the material included in the resistivity measurements. Good correlation is observed between all the major resistivity, potential-drop, and slingram anomalies. In general, resistivity highs show up as less pronounced slingram lows, whereas slingram highs show up as rather small resistivity lows. Some of the smaller anomalies may be "noise," and therefore the apparent correlation is fortuitous; however, this apparent correlation between resistivity and slingram curves suggests that caution should be used in interpreting many of the resistivity anomalies as edge effects.

Between traverse 1 and traverse 8 as exemplified by figures 74, 75, 80, and 81, both the resistivity and the slingram curves seem to be influenced by the same series of resistive and conductive units. However, on traverses 9, 10, and 11 (figs. 76, 86), the correlation between the resistivity and slingram results is rather poor. All the

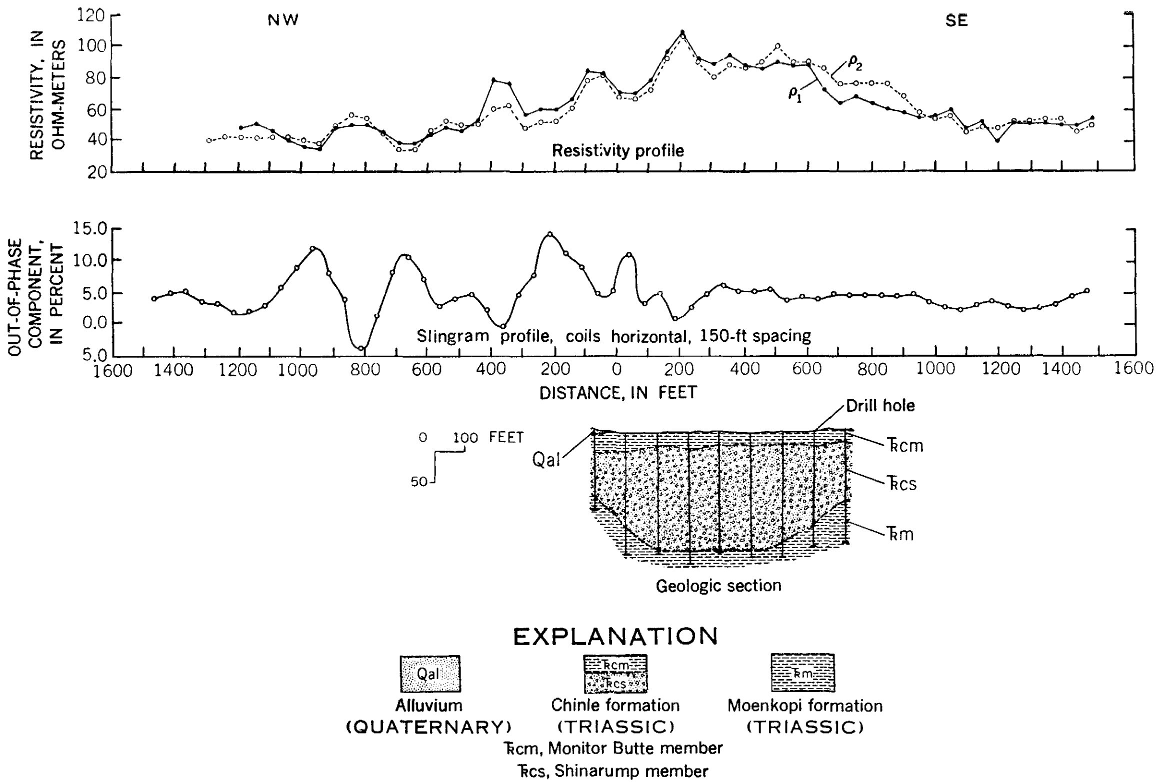

FIGURE 86.—Resistivity and slingram profiles, and geologic section from drill-hole data along traverse 11, Shasta Copper channel.

features on the slingram profile show up at least as minor features on the resistivity curve, but the slingram curve shows no reflection of the broad gradual high in the resistivity curve. These results indicate that between traverses 1 and 8 the sources of the anomalies contain a considerable volume of material and that the absolute conductivity of the conducting units is large. Between traverses 8 and 11 the broad resistivity high indicates a large volume of material that has a somewhat higher resistivity than the surrounding strata. The electromagnetic data indicate that this large volume of high-resistivity sediments is interbedded with thin lenses of highly conductive material. Electromagnetic anomalies are dependent upon the absolute conductivity of the disturbing bodies, whereas resistivity anomalies are dependent only upon the resistivity contrast between the body and the surrounding medium. A body at depth, such as a sheet that is large in two dimensions, can cause a large electromagnetic anomaly if the conductivity of the body is sufficiently high. However, a body at depth must contain a considerable volume of material to cause a large resistivity anomaly, even though the resistivity contrast may be great.

The resistivity and electromagnetic data combined present a more complete picture than either set of data alone. Between traverses 1 and 8 the resistivity and slingram data seem to be equally diagnostic of the channel, whereas between traverses 8 and 11 the resistivity data are much more diagnostic than the slingram. On the basis of the small amount of work done, the potential-drop-ratio method seems to have advantages over the other electrical methods used. The potential-drop-ratio data when presented in the form of potential drops are essentially the same as values of apparent resistivity. The advantages and disadvantages of the potential-drop-ratio method as compared with conventional resistivity are those of a fixed-source method as compared with a moving-source method. (See p. 210.) The potential-drop-ratio method is less complicated by edge effects than the resistivity method. The resistivity method treats each part of the ground in the same way, whereas with the potential-drop-ratio method the depth of penetration and other factors are different for each measurement. Thus resistivity anomalies can be more readily compared with each other than the potential-drop-ratio anomalies.

CONCLUSIONS AND RECOMMENDATIONS

Exploration for uranium deposits in the Monument Valley area of Utah and Arizona is inseparable from exploration for buried channels, for the ore deposits are found in these channels. The function of geophysics in a program of uranium exploration in Monument Valley is to locate and delineate these buried channels and thus confine exploratory drilling to the search for ore bodies within the channel limits, and to indicate the most favorable places within the channels to drill.

Seismic-refraction and electrical-resistivity methods have proved to be the most useful of the geophysical methods tested for locating and delineating buried channels. Seismic-reflection, gravimetric, and vertical-intensity magnetic measurements seem to be of little value in locating channels in the Monument Valley area, and electromagnetic and potential-drop-ratio methods have not been tested sufficiently to determine fully their usefulness and limitations. However, the close correlation of the data obtained by the two electromagnetic methods and the potential-drop-ratio method is significant because such measurements can be made much faster and more cheaply than with electrical-resistivity measurements. If usable data can be obtained with one of these cheaper and faster methods, these methods could supplement or replace the resistivity method as an auxiliary technique for use in conjunction with seismic exploration.

Some channels yield only very small electrical anomalies that are hard to separate from the background "noise." Thus electrical methods may be used successfully only on an empirical basis and where there is sufficient control. Areas in which anomalies in electrical measurements occur should certainly be looked upon as favorable places to drill. Once a channel has been discovered, electrical measurements provide an economical method of tracing it.

The amplitude and pattern of the small electrical anomalies that are usually regarded as "noise" vary from area to area. Often this noise is probably related to such irrelevant factors as surface conditions. However, it is suggested that some of this noise is related to sedimentary structures and lithology. If electrical surveys were made over large areas it might be possible to find ways in which the noise pattern could be used as a guide to localities favorable for the occurrence of channels.

Efficient use of geophysics in Monument Valley can reduce the overall cost in time and money of a uranium exploration program. The aim of any such exploration program is to find uranium ore deposits, which are known to occur in buried channels in the Shinarump rocks. An exploration program should be divided into three phases: preliminary geologic reconnaissance; location of buried channels, and determination of their size and shape; and detection of possible ore bodies within the channel limits.

Geologic reconnaissance could locate parts of the area where channels would be expected from outcrop data or from extrapolation of channel outcrops in surrounding areas. Places where the Shinarump member crops out or is covered by relatively thin overburden would then be selected for geophysical exploration. Holes should be drilled on widely spaced patterns, possibly on 1-mile centers, to establish basic geologic control. These holes would then be logged for lithology. Gamma-ray, resistivity, self-potential, and velocity logs should also be obtained. These data are useful in interpreting the geophysical data in addition to providing basic information on the physical properties of the rocks.

In the second phase of the program, geophysical measurements should be made to locate and outline the buried channels. Assuming that the preliminary geologic reconnaissance has provided some information about the channel trends, reconnaissance seismic-refraction measurements could then be made on traverses spaced a mile or more apart and at right angles to the postulated channel trends. A grid pattern would not be essential, however, and if the existing road and trail network provides more convenient locations for the reconnaissance traverses, these roads and trails should be used. Where evidence of channels is found on these reconnaissance traverses, short seismic-refraction traverses should be shot on both sides of the reconnaissance traverse to determine the channel trend. The channel could then be traced through the area by a series of short traverses at right angles to the channel trend.

In practice, channels have been traced for many miles in this manner, using offsets of 500 feet between traverses. Often, a channel may show on several parallel traverses, be missing on one or more subsequent parallel traverses, and then reappear on following parallel traverses. Horizontal electrical-resistivity profiles for the traverses on which there were no indications of a channel are then used to determine whether the channel is actually present or is discontinuous at these points. After the channels discovered by the reconnaissance traverses are traced, another series of reconnaissance traverses is run at intermediate spacings between the original reconnaissance traverses to detect other buried channels in the area. Channels indicated on these new lines are traced as before, and the reconnaissance grid is again closed, until the area is completely explored.

The third phase of the exploration program, drilling for possible uranium ore bodies begins when the first channel has been delineated. Channel bends and the deeper parts of channels are assumed to be the most favorable places for uranium deposits to occur, so such places indicated by the geophysical measurements are drilled first. As new channels are discovered, they are explored by drilling for possible ore bodies. Drilling is thus largely confined to the channels themselves.

The areas deemed favorable by geologic reconnaissance but unfavorable for geophysical exploration are now reconsidered in view of the new data from the surrounding geophysical and geological exploration, and a suitable exploration program is worked out for these bypassed areas.

In any such exploration program as just described, areas will probably be found where seismic-refraction measurements do not yield reliable results, perhaps because of thick and heterogeneous Monitor Butte cover, or lithologic changes within the Shinarump member itself. Where this occurs, the electrical methods can often be used to locate the buried channel. In other places none of the methods may provide reliable data, and drilling must be used both to locate and explore the channels. Geophysical methods are not, in any case, a substitute for drilling. Where properly made and interpreted, however, seismic-refraction and electrical measurements can contribute significantly to exploration programs for uranium deposits in Monument Valley.

REFERENCES CITED

Barthelmes, A. J., 1946, Application of continuous profiling to refraction shooting: Geophysics, v. 11, no. 1, p. 24–42.

Cook, K. L., and Van Nostrand, R. G., 1954, Interpretation of resistivity data over filled sinks: Geophysics, v. 19, no. 4, p. 761–790.

Dobrin, M. B., 1952, Introduction to geophysical prospecting: New York, McGraw-Hill Book Co., Inc., 435 p.

Enslin, J. F., 1955, A new electromagnetic field technique: Geophysics, v. 20, no. 2, p. 318-334.

Hedström, Helmer, 1940, Phase measurements in electrical prospecting: Am. Inst. Mining Metall. Petroleum Engineers Trans., v. 138, p. 456–471.

Isachsen, Y. W., and Evensen, C. G., 1956, Geology of uranium deposits of the Shinarump and Chinle formations on the Colorado Plateau, *in* Page, L. R., Stocking, H. E., and Smith, H. B., compilers, Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations International Conference on Peaceful Uses of Atomic Energy, Geneva, Switzerland, 1955: U.S. Geol. Survey Prof. Paper 300, p. 263–280.

Lee, F. W., 1936, Geophysical prospecting for underground waters in desert areas: U.S. Bur. Mines Inf. Circ. 6899, p. 10–14.

Mitcham, T. W., and Evensen, C. G., 1955, Uranium ore guides, Monument Valley district, Arizona: Econ. Geology, v. 50, no. 2, p. 170–176.

Nettleton, L. L., 1940, Geophysical prospecting for oil: New York, McGraw-Hill Book Co., Inc., 444 p.

Pakiser, L. C., and Black, R. A. 1957, Exploring for ancient channels with the refraction seismograph: Geophysics, v. 22, no. 1, p. 32–47.

Pakiser, L. C., Mabey, D. R., and Warrick, R. E., 1954, Mapping shallow horizons with the reflection seismograph: Am. Assoc. Petroleum Geologists Bull., v. 38, no. 11, p. 2382–2394.

Pakiser, L. C., and Warrick, R. E., 1956, A preliminary evaluation of the shallow reflection seismograph: Geophysics, v. 21, no. 2, p. 388–405.

Roman, Irwin, 1934, Some interpretations of earth-resistivity data (with discussion): Am. Inst. Mining Metall. Engineers Trans., v. 110, Geophysical Prospecting, p. 183–200.

——— 1946, An observational method to overcome zero drift error in field measurements: Geophysics, v. 11, no. 4, p. 466–490.

Stewart, J. H., 1957, Proposed nomenclature of part of Upper Triassic strata in southeastern Utah: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 3, p. 441–465.

Wait, J. R., 1955, Mutual electromagnetic coupling of loops over a homogeneous ground: Geophysics, v. 20, no. 3, p. 630–637.

Wantland, Dart, and Casey, R. D., 1952, Field tests for the United States Atomic Energy Commission on the use of the seismic geophysical method for tracing "buried channels" in the Monument Valley area, Arizona: U.S. Bur. Reclamation Geology Rept. G–123, 68 p., issued by U.S. Atomic Energy Comm. Tech. Inf. Service, Oak Ridge, Tenn.

Wetzel, W. W., and McMurry, H. V., 1937, A set of curves to assist in the interpretation of the three layer resistivity problem: Geophysics, v. 2, no. 4, p. 329–341.

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STEWART L. UDALL, *Secretary*

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Thomas B. Nolan, *Director*

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[The letters in parentheses preceding the titles are those used to designate the separate chapters]

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