GEOPHYSICS IN GROUND-WATER STUDIES IN THE SOUTHWEST[1/]

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INTRODUCTION

As Heiland said in 1937, "Prospecting for water is one of the most difficult problems of practical geophysics requiring exceptional geologic ability on the part of the geophysicist, " or, it might be added—vice versa. We have found some truth in another statement of Heiland's, which is, from a commercial point of view geophysical exploration for ground water is not particularly attractive in that costs normally far exceed those of surface geological surveys; they may even approach expenses for drilling, particularly in shallower, simpler, and smaller projects of the past in the Southwest. However, as our projects have become larger, deeper and more complex, especially in Arizona, and as our geoscience abilities have improved, instrumental techniques have taken on new importance.

In 1917 the U.S. Geological Survey published Water-Supply Paper 416 entitled "The Divining Rod—A History of Water Witching, " by Arthur J. Ellis, which included a bibliography of some 573 titles on "Water Witching" dating from the early 1500's. Since this time some new instruments and methods have been added.

Today, preservation of our society is very dependent on continued successful water-resources development. Consequently, the public is beginning to question geohydrologists who either lack understanding and avoid geophysics entirely, or misuse it because, as in their own field, it doesn't always involve absolute categorical answers.

Moreover, geophysics is still often called in for water exploration after problems or troubles are encountered. Hence much of our experience is in so-called difficult areas, but this is also changing with new problems, applications, and scientific concepts.

Since the fundamental related aspects of geophysics are essentially identical to those of geohydrology, the geophysical method or methods selected for any problem are dictated by the geophysical targets anticipated from geologic analysis.

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Though not fully understood, it is generally agreed that ground water situates in direct relation to, or is controlled by, a complex combination of various parameters, some of which are relatively constant while others are continuously variable. Some of the more specific and familiar terms are: porosity, permeability, volume, density, and quality. These same terms have a direct effect on any applied geophysical measurements. Other physical effects, such as magnetic susceptibility, probably have little direct relationship to ground water, but they often provide important indirect solutions to some problems. The integrated effect of all these parameters on ground water is perhaps somewhat analogous to an alternating-current electronic network, but for lack of a better hydrologic simile, we here use the term "channel"—especially for the more local or detail problems, but even in the largest sense it may more or less apply as well.

For purposes of geophysical exploration in the Southwest we think in terms of at least four different types of "channelization." The first and most obvious is alluvial-filled erosional channels on bedrock. The second may be a semblence of facies control or channeling within unconsolidated alluvium. The third, normal facies channeling in sedimentary rocks—and the fourth, fracture or fault channelization in sedimentary or crystalline bedrock. It is realized that this, geologically, may be considered as either an oversimplification or a complication of the problem; however, such a system of classification seems to lend itself to geophysical analysis.

At this time there are still no generally accepted consistent and dependable methods for the direct detection, identification, location, and evaluation of water in natural subsurface occurrences.

MORE DIRECT METHODS

Geophysical methods for water exploration may be classified as either "more direct" or "indirect." Most success has been achieved with surface applications—or by work done in drill holes. Aerial applications to date are not too good except for very regional indirect-type work. More direct methods include: resistivity, induced polarization and possibly electromagnetics, self-potential and other of the electrical methods, and perhaps infrared. Seismic may also be considered a more direct method, but is covered below under indirect.

Resistivity

The most commonly and successfully applicable of the direct methods to date is resistivity. Simply stated, resistivity is based on relative conductivity of water-saturated alluvial or formational zones as opposed to those which are dry. Obviously resistivity analysis is often complicated by the presence of facies that are either highly conductive or resistive for reasons other than the presence or absence of water. Such conditions as clay lenses or beds, lake-bed sediments, volcanic rocks, etc., can obscure the resistivity picture.

There are numerous techniques of measurement and types of resistivity equipment, but all are based on the same principle and give essentially the same results.

Normally at least 4 and usually 5 men are needed to conduct a conventional resistivity survey. Depending on the types of problems and areas, costs may range from less than $1.00 to more than tens of dollars per acre. In constant-depth profiling, production may be several profile miles per day depending on the electrode spacing used, the terrain and vegetation encountered, and the ability of a vehicle to traverse the length of the profile. In depth-probe measurements, as many as 4 or 6 probes per day at different locations may be possible.

Induced Polarization (I. P.)

More recently developed induced-polarization equipment has been used as a resistivity-measuring device with excellent results here in the Southwest (Vacquier and others, 1957). By use of this somewhat more resolving approach, we can reduce the number of men required to conduct a survey to 3 or 4 and obtain both profile and depth information from the same setup. Also, the necessity for a vehicle being able to traverse the entire profile line is materially reduced. All this is accomplished by use of a different electrode configuration from that necessary for use with conventional resistivity gear.

The method of induced-polarization measurement was developed primarily for the exploration for disseminated sulfide mineralization. In one technique the direct-current (D. C.) resistivity of the ground is measured and compared to the alternating-current (A. C.) impedence. Moist clay-coated sand grains may exhibit the phenomenon of induced polarization much in the manner of sulfide particles. Water, clay, sand, or even a mixture of these do not polarize, and it is only situations similar to the above-described condition of a clay coating on sand grains that can provide definitive information in the sense of induced polarization. However, with the conventional D. C. resistivity being one of the I. P. field measurements, the simultaneous obtaining of both may be very useful and definitive for water exploration.

Self-Potential

Some observers have noted marked spontaneous-polarization effects over certain ground-water channels. Self-potential observations are normally made as a part of both resistivity and I. P. surveys and, while so far we have been unable to recognize a consistent pattern to these effects that can be reliably related to ground water, they do give some aid to the interpretation of these other methods and may prove more directly beneficial in the future.

Electromagnetic

Electromagnetic methods are also based on conductivity but include that which affects alternating current as well as direct current. In practice, alternating current is passed into the ground between the electrodes or induced (inductively) from coils. Distribution of the resulting field of electromagnetic radiation is studied by means of measurement with directional-finding coils. Depending on the type of equipment, 1 to 4 men are required to conduct a survey and costs are about the same as those of the other electrical methods. There are a number of variations in the techniques and instrumentation of electromagnetic surveying, but all are based on the same principle.

Infrared

This approach is still very theoretical and experimental; it reportedly deals with surface or near-surface measurements of earth-core radiation and with differential wavelength filtering and absorption caused by ground-water accumulations.

INDIRECT METHODS

The indirect methods include gravity, magnetics, and seismic. These methods rely on the measurement of subsurface physiographic or structural variations that may control the location and/or flow of water. Most generally these methods are used to map basins, bedrock configuration, or delineation of broad rock types.

Of these methods, hammer seismic and magnetics are the cheapest. Gravity is usually about equivalent to the electrical methods and portable dynamite-seismic.

Seismic

Seismic equipment may vary from the rather simple sledge hammer and electronic scaler-timer refraction unit with capabilities of possibly as much as 150 feet of penetration to more complex and expensive refraction and reflection equipment with capabilities of many thousands of feet. In practice, elapsed time is measured from the imparting of an energy wave to the ground via a sledge hammer, in the shallowest cases, or a dynamite shot in the deeper studies, until it reaches an energy sensitive receiver. Often the character of the wave is also recorded. From these data the depth to velocity interfaces corresponding to lithologic changes can be determined. Under certain ideal conditions, the seismic velocity of unconsolidated, water-saturated formations will suggest the presence of water directly by exhibiting sudden velocity increases to approximately 5,000 feet per second, which is the average velocity of water. In some cases, wet rocks have higher velocities than their equivalents do when dry.

Magnetics

Magnetic exploration is sometimes useful in bedrock-configuration studies. It is based on the principle of variation in the magnetic properties of different rocks. For example, igneous or metamorphic bedrock or basic dikes and sills often have a higher magnetite content and therefore a higher magnetic susceptibility than sediments or alluvium.

Gravity

Gravity surveys are sometimes applicable to water exploration but generally only in the larger scale studies. It is similar to magnetic exploration in that bedrock configuration is mapped, and it relies on the principle of measuring density contrasts between basement rocks and sediments or crystallines.

Drill-Hole Methods

There are a number of geophysical measurements applicable to logging in drill holes. Most common drill logs are made of the resistivity, self-potential, and various radiometric properties of the formations encountered in the hole. The first two rely on the same principles as the surface measurements. The radiometric measurements rely on the natural (in the case of gamma-ray logging) or induced (neutron logging) radioactivity of formations. Very excellent correlations between resistivity measurements and neutron logging can be obtained and be interpretative of hydrocarbons or water. Electromagnetic and seismic velocity measurements can also be made in drill holes, as can magnetics and gravity, but the latter have not yet experienced wide application, although considerable use may be developed in the future (Brown and Gamson, 1960).

CONCLUSIONS

The success of geophysical exploration methods is limited by various physical-property contrasts and the geometry of the geological situation. Normally, in Arizona, we consider that resistivity data are interpretable at least to depths of 200 or 300 feet, but under ideal conditions with proper equipment this limit may be far exceeded; on the other hand, highly conductive non-water-bearing layers near the surface may limit resistivity penetration to that layer. Resistivity or possibly I. P., however, are the only geophysical methods generally applicable to all of the four geohydrological situations before described.

In the very common Southwest case of shallow alluvial-filled channels on bedrock, where maximum depths considered would be on the order of 150 feet or less, postulating the horizontal width of the channels at a minimum of one-fifth of the depth and the channel relief at a minimum of one-tenth of the depth, with other conditions being favorable, shallow sledge hammer seismic refraction might provide the answer. Broad, deep channels or basins of considerably greater depth might be mapped by gravity, magnetics, or "heavy duty" seismic exploration. Resistivity is, of course, possibly applicable in both situations with profiling probably more suitable for the shallower case and depth probing for the deep, broad channel.

The second geohydrological situation, facies channeling within alluvium, may be geologically controlled by several factors, including the coarseness of gravel and sand grains, variable clay concentration, lenses, impermeable precipitates, and often to some degree by the modern drainage pattern. In this case, resistivity or induced polarization is the most obvious, direct, and possibly the only approach.

Facies channeling within consolidated sediments may provide a somewhat more complicated problem than channeling in alluvium in that moisture at the alluvial sedimentary contact, if such exists, may obscure resistivity analysis, and depths to water would normally be greater. Again resistivity and possibly induced polarization would be the only methods capable of providing definitive interpretation.

The fourth condition, fracture or fault control and/or meteoric waters, may best lend itself to resistivity interpretation with the added possibility, particularly if water is deep, that gravity or magnetics may best delineate the structural control if there is sufficient magnitude of vertical displacement. In this case seismic surveys may also provide the desired analysis.

In summary, it must be emphasized again that the selection of the suitable geophysical method for water exploration is dependent on competent geological analysis of the situation. With this coupled to proper evaluation of the geometry and expected physical-property contrasts, we have the prerequisite ingredients for successful geophysical results—not only in Arizona, but anywhere in the world.

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