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GEOPHYSICS and GROUND WATER: Part II

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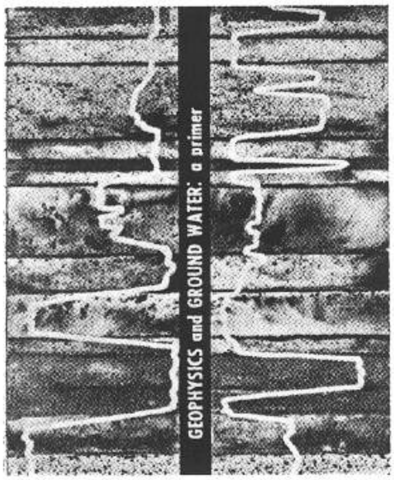

GEOPHYSICS and GROUND WATER: Part 2

APPLIED USE OF GEOPHYSICS

Last month as Part 1 of GROUND WATER AND GEOPHYSICS we explored, in a general way, the various techniques that are included under the term 'geophysics.' A variety of methods were summarized, including many newer techniques that are not yet completely applicable to routine ground water exploration.

In this issue, Part 2 of the series, the emphasis will be on those methods that are actually being used now, at least in a limited way, by researchers and contractors in the water well industry.

The major reason that geophysics has not been used extensively in the search for ground water is an economic one. But as good, clear supplies of water become more limited the search must expand, utilizing any methods necessary—even those that may be more costly.

The average water well contractor also has not had access to the extensive research organizations that have traditionally aided other mineral exploration groups.

But water is a mineral resource, and as such it has physical properties that can be measured and quantified. Just as oil, coal, or uranium resources can be identified through geophysical studies, so can water resources.

ELECTRICAL RESISTIVITY

The geophysical technique that was discussed the most extensively in the July Water Well Journal was electrical resistivity. Water, unless it is distilled, or demineralized, will conduct some electrical current. The more dissolved matter in the water, the greater the amount of current that will pass through it, or to put it another way, the lower the resistivity.

When water occurs in rocks, both the resistivity of the water and the resistivity of the rocks are 'averaged' into a single reading on a meter. This reading, or series of readings, must be interpreted on the basis of geology, known resistivities of rock and water, and the skill of the interpreter.

Thus, even though the information is numerical, it is still the geologist or geophysicist using these numbers that must decide if a favorable ground water body exists.

The equipment used for surface resistivity studies consists of a source of electricity, a series of electrodes to receive the current, and a recording meter or meters. The pattern and spacing of the electrodes vary, depending on the type of information required and the depth of the potential aquifer.

SEISMIC METHODS

Seismic methods are the classic type of surface geophysics. An artificial shock wave is generated and then detected at various distances and directions from the source. The shock waves are refracted (bent) or reflected at any change in rock type where a velocity change occurs.

The velocity of a seismic wave depends primarily on the density of the rock through which it passes. A dense rock gives a greater velocity reading than a porous one.

The oil industry has traditionally used seismic *reflection* studies which best give information about deep horizons. In contrast, seismic *refraction* methods normally cover only a few hundred feet of depth and are of much greater use in ground water studies.

The field procedures for seismic refraction investigations have been simplified with the help of compact and efficient instruments. Only a small charge of dynamite or even a heavy blow from a sledge hammer will produce a recordable shock wave.

Geophones (detectors) are spaced in a line. They receive the shock wave and convert the vibration into electrical impulses which are amplified and recorded.

Interpretation of refraction data assumes uniform layers bounded by planes. Because water tables often approximate planes, problems caused by complex geology are simplified for some applications. Again, general knowledge of rock types and structure are required for proper interpretation.

Seismic refraction is not infallible in the search for water. Because velocities must increase with depth to obtain usable results, it is possible to miss an unconsolidated aquifer that is overlain by denser, consolidated rock.

OTHER SURFACE METHODS

Soil temperature surveys, magnetomers, gravity surveys, and some remote sensing techniques have also been used in the search for ground water. The broad details were discussed in the July issue of the WATER WELL JOURNAL. Most of these types of surveys are used as part of an overall regional study, rather than for short-term studies to find water in one specific location.

BORE HOLE TECHNIQUES

Every water well contractor has used bore hole geophysics as part of his everyday work, although he may not identify them as such. Water level measurements are probably the most common type of down hole measurements.

A steel tape gives the most accurate results when a well is not pumping, although measurements with cable or even rope are not uncommon. Electrical water-level probes and air lines are used to measure water levels in pumping wells.

Even a rock dropped into a hole and timed can be used to estimate the depth to the water surface. Because two different factors are involved, however, the estimate may be incorrect by many feet. The two factors are: (1) time for the rock or other object to drop and (2) time for the sound to travel back up the well.

If a marble or a BB (air rifle shot) is dropped into a hole and timed, Table 1 can be used to give a reasonably accurate estimate of depth. This table was determined experimentally; it takes into account the density of the falling object, time for that object to drop, and time for the sound to return to the observer.

STRAIGHTNESS MEASUREMENTS

A cable tool driller has a general idea of straightness and alignment from the way his string of tools reacts. And anyone who has ever installed casing in a rotary-drilled hole also has a good idea of whether or not the hole is reasonably straight.

For numerical measurements of alignment, sophisticated instruments, such as the drift indicator or photoclinometer, can be used to tell the exact degree, and even the direction, of drift. Most equipment records only the total amount of drift at the bottom of the hole, although some instruments (Figure 1) give numerous readings that indicate the change in alignment over the entire length of the hole.

ELECTRICAL LOGGING

Electrical logging is one of the best-tested techniques used in bore hole logging today. Several types of probes are used to give information about the rock at various distances from the drill hole.

Although electric logging has been used commonly in the oil industry for more than 30 years, costs have been prohibitive for most water well operations. Recently, two factors have made the technique more accessible to the water well industry:

First, economics are changing. As well completion methods become more complex, electrical logs are used increasingly to determine the exact zones of interest.

Second, lightweight electrical logging equipment has been designed that allows for rapid, inexpensive measurement. Some equipment can be used by the water well contractor himself.

Electrical logging consists of two basic log types.

Spontaneous potential (SP) logs give an indication of the *naturally occurring* electrical differences between a surface electrode and an electrode that is moved progressively up (or down) the bore hole. More specifically, the method measures the electrical differences between the borehole fluid and the fluid contained in each formation.

Resistivity (or conductivity) logs use an *induced* electrical current to measure the potential between two adjacent formations. The spacing between the electrodes determines the depth of penetration of the rock formations by the current.

Conventional oil well resistivity logs show several readings from different probes. By necessity, the instrumentation is complex. In contrast, the most common type of resistivity logging used in the water well industry is known as 'single point resistivity' because it uses a single probe to measure the amount of current generated at the bore hole wall.

Most electrical log print-outs have an SP curve on the left-hand side of the log and one or more resistivity curves on the right side.

RADIOACTIVITY LOGS

Radiation logs are of two general types: Those that measure the natural radioactivity (gamma ray logs) and those that show radiation reflected from or induced in the formation from an artificial source (neutron logs). Radioactive logs can be used in cased holes where most other types of logging will not work.

All materials emit very low levels of gamma rays. However, minerals in shale and clay rock emit more gamma rays than do the minerals in sands, except under very special conditions. Thus gamma logs can be used to differentiate between sands and shales, even through casing.

Neutron logging has various uses, but is becoming an increasingly important tool to determine porosity of formations. A 'fast neutron' source is used to bombard the rock. When any individual neutron collides with a hydrogen ion (usually part of a water molecule), some of the neutron's energy is lost and it slows down.

A 'slow neutron' counter records the number of neutrons that have been converted to the new energy state. A large number of slow neutrons indicates a large amount of fluid, which in turn indicates a high porosity within the formation being logged.

CALIPER LOGGING

Caliper logging is used to measure the bore hole diameter. Such information is useful for determining areas of formation caving, casing lengths, packers, and perforations.

TEMPERATURE LOGGING

Temperature logging has a large number of applications which range from determining the

Table 1. Times and distances for a marble or BB falling freely in air. Units of time are seconds; units of distance are feet. From Stewart, 1970.

Time	*Dist.*	*Time*	*Dist.*	*Time*	*Dist.*	*Time*	*Dist.*	*Time*	*Dist.*	*Time*	*Dist.*
0.0	0.00	1.7	45.5	3.4	154	5.1	300	6.8	453	8.5	605
0.1	0.16	1.8	50.3	3.5	161	5.2	309	6.9	462	8.6	614
0.2	0.64	1.9	55.2	3.6	169	5.3	318	7.0	471	8.7	623
0.3	1.45	2.0	60.4	3.7	177	5.4	327	7.1	480	8.8	632
0.4	2.58	2.1	65.8	3.8	186	5.5	336	7.2	489	8.9	641
0.5	4.03	2.2	71.3	3.9	194	5.6	345	7.3	498	9.0	650
0.6	5.81	2.3	77.0	4.0	202	5.7	354	7.4	507	9.1	659
0.7	7.90	2.4	83.2	4.1	211	5.8	363	7.5	516	9.2	668
0.8	10.3	2.5	89.6	4.2	220	5.9	372	7.6	525	9.3	677
0.9	13.0	2.6	96.0	4.3	229	6.0	381	7.7	534	9.4	686
1.0	16.1	2.7	103	4.4	238	6.1	390	7.8	543	9.5	695
1.1	19.5	2.8	109	4.5	247	6.2	399	7.9	552	9.6	704
1.2	23.2	2.9	116	4.6	256	6.3	408	8.0	561	9.7	713
1.3	27.3	3.0	123	4.7	265	6.4	417	8.1	570	9.8	722
1.4	31.6	3.1	131	4.8	274	6.5	426	8.2	578	9.9	731
1.5	36.2	3.2	138	4.9	282	6.6	435	8.3	587	10.0	740
1.6	40.8	3.3	146	5.0	291	6.7	444	8.4	596	10.1	749

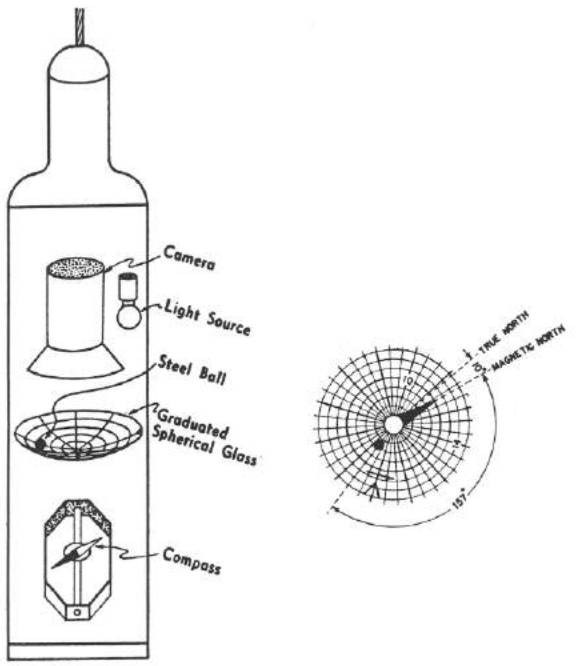

Figure 1. Diagrammatic view of a photoclinometer, used to determine direction and amount of drift in a drill hole.

natural geothermal gradient of an area to verifying that the cement on the outside of the casing has formed a proper bond. Temperature logging is also used to detect differences in water from different aquifers.

FLOWMETER AND TRACER LOGGING

The vertical movement of water in a well, although sometimes measured using a temperature log, is more commonly measured with either a flowmeter or a tracer device. Flowmeters are useful for relatively high velocities.

Tracer devices use either radioactive materials or a brine to measure water flow. The substance is injected into the well at some point and a detector records the time it takes for the tracer to reach a second point. Very low velocity movements (on the order of feet per day) can be recorded with such a tracer set up.

DOWN HOLE PHOTOGRAPHY

The down hole technique that has received the most publicity in the last few years has been the use of cameras or television transmitters to record the geology and well casing in place. Underwater, pressure resistant cameras are used, but television has the advantage that the viewer can actually see the picture as it is made. This image can be preserved on video tape for study at a later time.

Photographic methods, although still not completely a substitute for having an observer in the well, are still the closest thing to being there. Costs are dropping as the technique is perfected, and several companies now specialize in such work.

SUMMARY

This summary of topics discussed in the July Water Well Journal leads us into the other sections in this issue. The emphasis here is on practicality. The water well contractor and others in the water well industry should become aware that the once complicated tools of geophysics are no longer the expensive research toys they once were.

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SURFACE GEOPHYSICAL TECHNIQUES

SEISMIC AND GRAVITY SURVEYS

This article on surface ground water geophysics will discuss only seismic and gravity methods. Although electrical resistivity is also a recognized surface geophysical method, it will not be discussed in detail here because so many articles have already been published elsewhere. Some of these articles are listed in the *For More Information section.*

SEISMIC SURVEYS

Although seismic methods have long been used in the search for oil, it is only recently that they have been used in an attempt to solve problems related to ground water. For ground water prospecting, however, conventional petroleum industry instrumentation generally is considered to be too costly and too cumbersome to be practical.

Within the last 10 years, however, the geophysical industry has made revolutionary advances to meet the needs of ground water, engineering, and mining applications. Part of the advance has come through the use of printed circuits and battery-operated units that are compact and portable. Many of these units have been designed especially for shallow operations.

Experimentation has shown that *seismic refraction* is especially useful for determining depth to bedrock, the shape of the bedrock surface, elevation of the water table, and the extent of sand and gravel lenses. Thus, it is especially adapted to ground water studies.

PRINCIPALS OF SEISMIC REFRACTION

Seismic refraction is based on the principle that shock waves travel at particular, and often well defined, velocities through different materials. These velocities range from a low of about 400 ft/sec (feet per second) in dry top soil to more than 20,000 ft/sec in very dense rocks such as granite, limestone, and basalt (Table 1).

Because seismic waves are refracted, or bent, as they travel from one type of rock to another, the time that the waves are received at various distances from the source can be used to determine at what depth the waves change.

In short, the receiving instrument does nothing more than detect and record the time interval between the start of the shock wave and its arrival at the detector.

The seismic refraction method requires that two conditions be met before the depth to various horizons can be calculated accurately:

1. The velocity (which depends on rock density) must increase with depth. If velocity decreases, the wave will be bent downward until an increase in velocity occurs at some lower horizon. Only when the wave intercepts a more dense

Table 1. Velocities of seismic waves. Velocities are average and may be higher or lower under special conditions.

Rock Type	Average Velocity Range (ft/sec)
UNCONSOLIDATED ROCKS	
uncemented, unsaturated alluvium	350– 2,500
cemented, unsaturated alluvium	3,000– 7,000
uncemented, saturated alluvium	3,000– 7,000
cemented, saturated alluvium	6,000–11,000
glacial drift	4,500– 6,500
SEDIMENTARY ROCKS	7,000–20,000+
IGNEOUS AND METAMORPHIC ROCKS	12,000–24,000+

layer will it be refracted back to the surface.

2. Each layer through which the refracted wave travels horizontally must have a thickness that is great enough to permit transmission of the wave. The deeper a horizon is buried, the thicker it must be to properly refract the shock wave.

If these two limitations are understood and the geophysicist has a general knowledge of local geology, the method can be used with fairly accurate results.

FIELD PROCEDURE

Figure 1 shows a typical field situation where overburden is above a shale bedrock surface. For clarity, the seismic wave is being shown as received by the two end geophones only; actually, it is also being received at the other ten geophones.

If the instrument is equipped to record all 12 points at one time as shown, only one shock wave (either a hammer blow or a small explosion) is needed. If, on the other hand, only one geophone is available. it must be moved to each of the points in turn and a new shock wave initiated for each reading.

It makes no difference which procedure is used; the time of travel to each point from the source is a characteristic time, dependent on the depth to the refracting surface and the distance to the receiving point.

In this example, the bedrock is approximately horizontal. If the layer is tilted, the line must be run twice—once in each direction—to correct for the tilt.

INTERPRETATION

The data from each field station are plotted, either by hand for the smaller types of instruments or automatically on some of the larger ones. The plot, as shown on Figure 2, is essentially one of time against distance from the source of the shock wave. When the points are connected with straight lines (AB and BC), these lines will cross at some point B.

The break in slopes of the lines, which may or may not be as obvious as shown here, gives an indication of the depth to the first refracting surface. Point B determines the depth to bedrock. It must be emphasized that this distance is actually an indication of the depth to bedrock beneath the point at which the shock wave was generated.

Velocities of the wave in each type of rock are determined by calculating the slope of the line, in feet per second, for that type of rock.

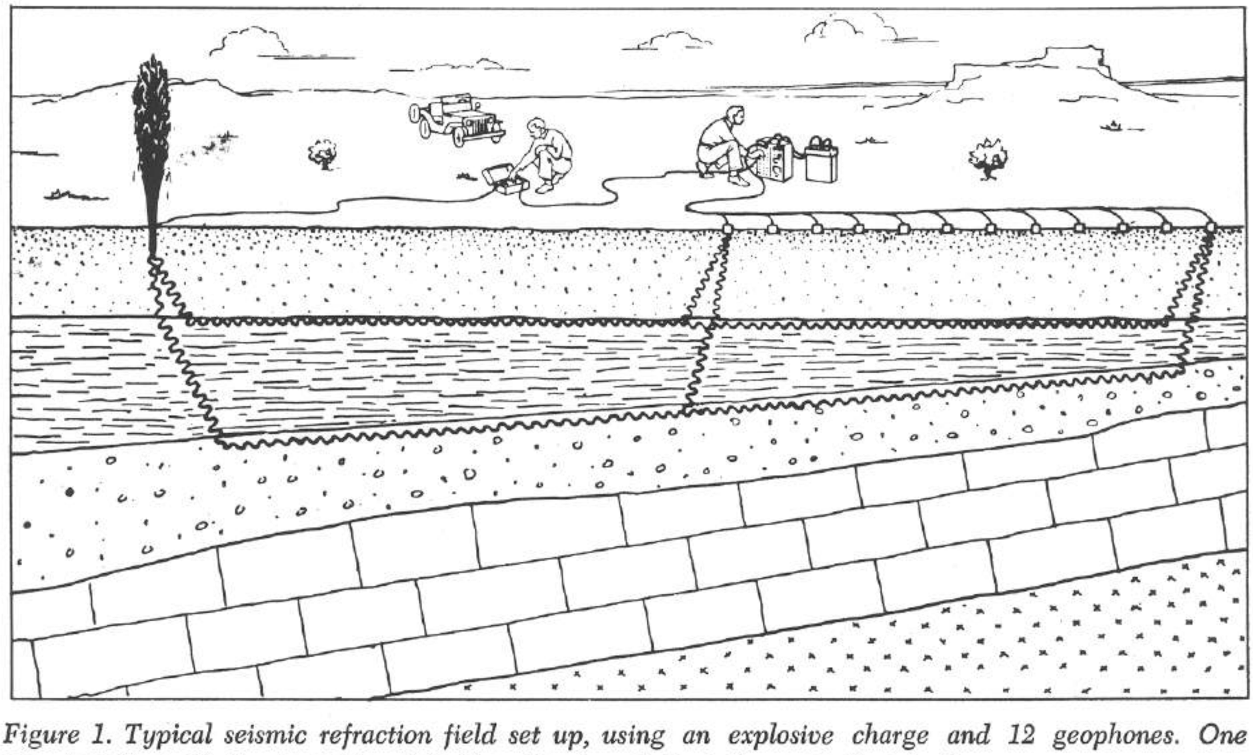

Figure 1. Typical seismic refraction field set up, using an explosive charge and 12 geophones. One man is setting off the dynamite while the other is watching the recording device.

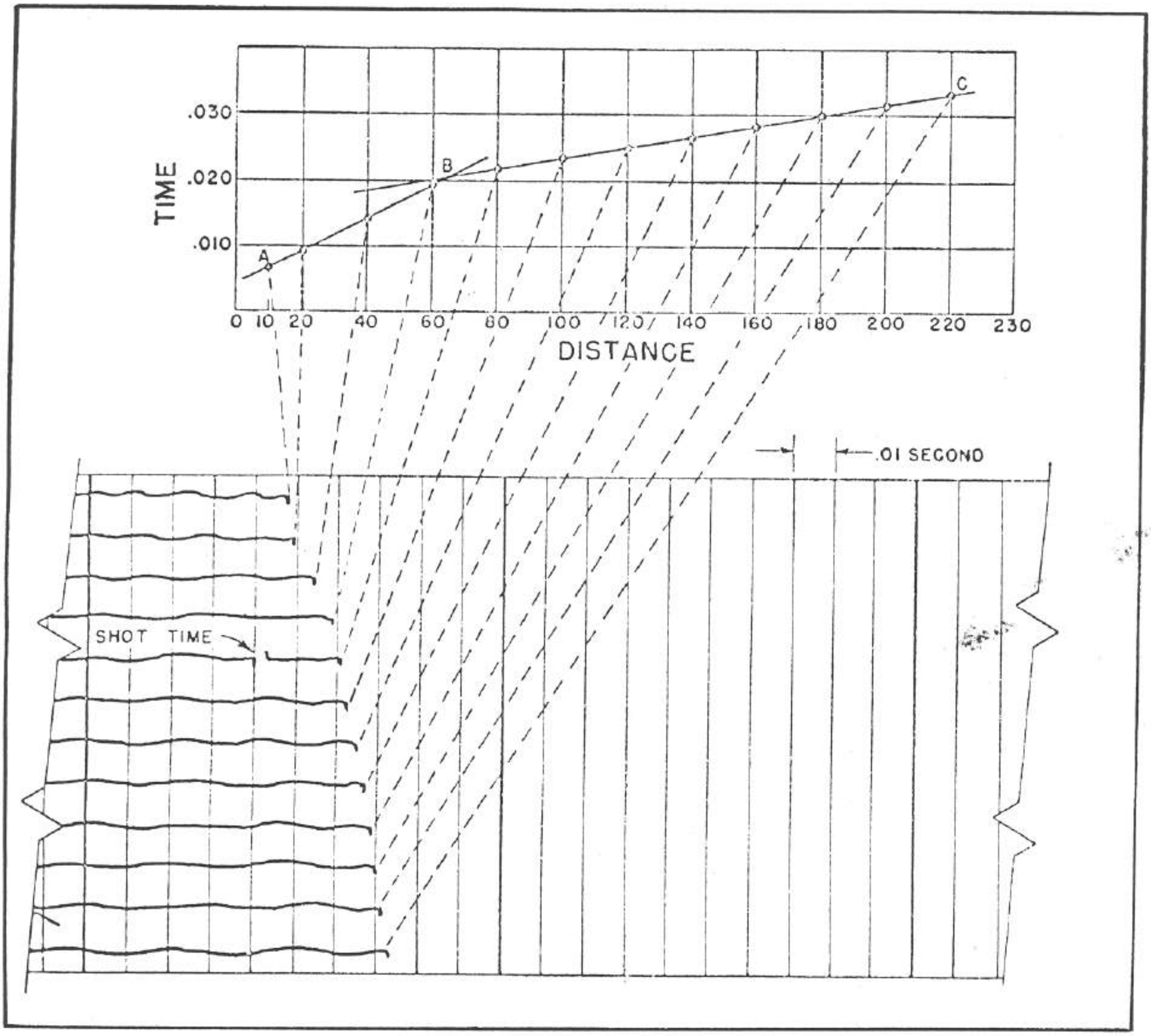

Figure 2. Time against distance plot obtained from a seismic shock wave. See text for explanation. From Century Geophysical Corporation, 1950.

APPLICATIONS

By moving the source of the shock wave along a line, a profile of the underlying bedrock surface (or other layer, such as the water table) can be obtained.

Figure 3 shows an example of how a buried stream channel cut into bedrock can be determined prior to drilling. Velocities in the bedrock are high—from 12,000 to 19,000 ft/sec. Velocities in the old stream channel are distinctly lower at about 7,500 ft/sec.

Zones of sands and gravels also below the water table are similar, but slightly lower. Lowest velocities of all are for unsaturated sediments above the water table.

It must be emphasized that the seismic instrument did not give this information as you see it printed here. The cross section was drawn on the basis of change in velocities, plus a basic knowledge of local geology. The interpreter knew that he was looking for a buried channel. The equipment was used to determine the exact location and depth of that channel.

COST AND TIME ESTIMATES

The least expensive portable refraction seismograph using a hammer for shock waves costs about $3,000. Equipment costs range upward to many thousands of dollars for the larger instruments using computerized print-outs.

A two man crew is required to operate the equipment, and readings at one field station can be completed in 20 minutes to an hour. The profile in Figure 3 shows 12 such stations, although ad-

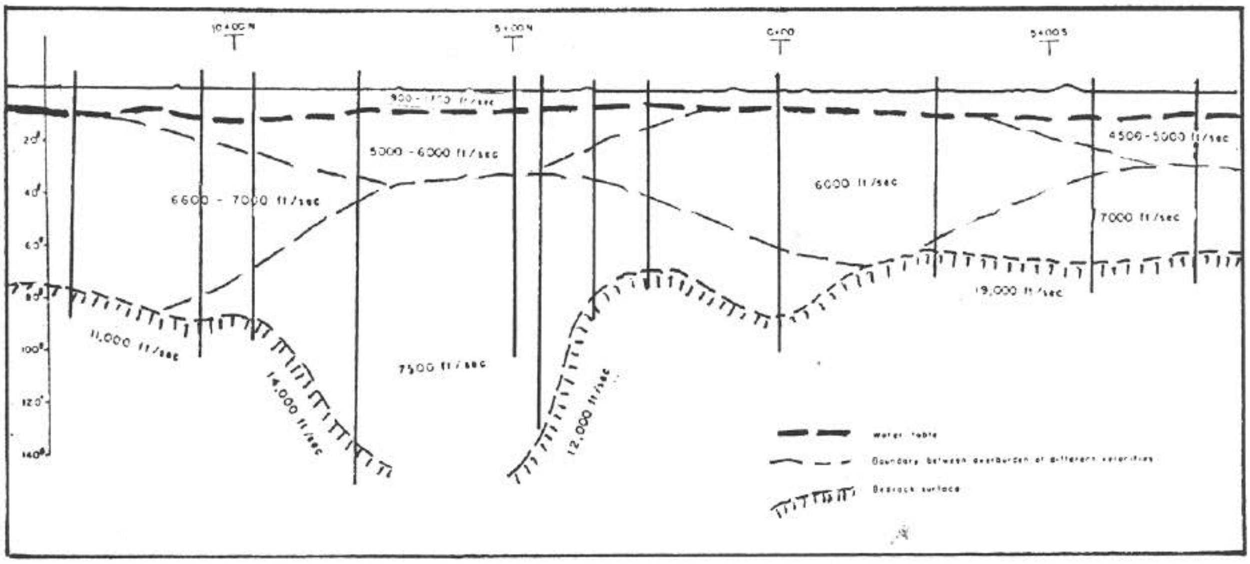

Figure 3. Profile across a buried stream channel, obtained using the seismic refraction technique. Modified from Stam, 1961.

ditional stations were probably used.

Interpretation time depends on the skill of the operator. If data are plotted in the field, the information may be available to the driller only hours after the field work is completed.

GRAVITY SURVEYS

Gravity surveys give only indirect information about ground water, in contrast to seismic surveys, which can be used to determine such things as the water table itself.

The most common type of gravity instrument used today is the gravimeter, which measures the direct effects of the pull of gravity on a mass suspended by a delicate spring.

Changes in the length of the spring are related directly to the vertical intensity of the gravity field. Optical or electrical methods are used to amplify movements of the spring so that very slight changes can be measured.

Gravity, which is recorded in gals or milligals, is a measure of acceleration. A gal is defined as the acceleration of one centimeter per second per second. A milligal is 0.001 gal. The term was invented to honor the memory of Galileo, who first demonstrated the effects of gravity.

PRINCIPLES OF GRAVITY SURVEYS

The numerical value of gravity at any point on the earth's surface is dependent on a large number of factors: First, gravity is directly related to the density and volume of earth materials beneath the point being measured.

It is also related, in a complex manner, to the distance from any attracting body. Thus, large variations in topography and changes in nearby rock types also affect the gravity value at any given station.

Because the earth is not all made of the same material and is not perfectly round, variations of gravity are also a function of latitude. In some areas, gravity values seem to change with time. This change is caused by earth tides, which are similar to ocean tides but on a much smaller scale.

Gravity studies, because they are relatively insensitive to small changes in geology, have been used in ground water studies to map large, buried valleys. They have also been used to locate sink holes and caverns in limestone areas.

FIELD APPLICATIONS

Field work is accomplished by one person using a gravimeter at a large number of stations. Most field gravimeters now in use weigh less than 25 pounds and are readily portable.

After the elevation of each station has been determined, it is only a matter of minutes to read the value of gravity at a station. Base stations, with known gravity values, are required for frequent checks of instrument drift and earth tide effects.

An example of a gravity study is shown in Figures 4 and 5. Because regional gravity gradients, caused by large, deep-seated structural features, tend to distort local changes, a regional correction is applied as shown in Figure 5.

A second correction, known as the Bouguer correction, takes into account the altitude of the station and the rock between that station and sea level. The residual gravity, then, reflects gravity changes caused by variations in local geology. Corrections can be calculated rapidly if a computer program is available. With a manual calculating machine, reduction of the data requires about 10 minutes for each station.

After all corrections have been applied, interpretation begins. The gravity low (−166 milligals) shown on these figures is produced by a thick accumulation of low density, valley-filling sediments. On the basis of rock density information, it was calculated that about 3,200 feet of sediments exist in the deepest part of the basin.

The steep slopes on the margins of the residual gravity profile are interpreted as buried faults along the mountain front. The exact location of such faults will have to be determined by other methods.

CONCLUSIONS ABOUT GRAVITY SURVEYS

In general, gravity studies are relatively rapid and inexpensive. Perhaps the greatest cost is that required to obtain an accurate elevation of each gravity station.

Gravity surveys cannot be used to pinpoint the best potential ground water sites directly. But they are useful for determining areas that require

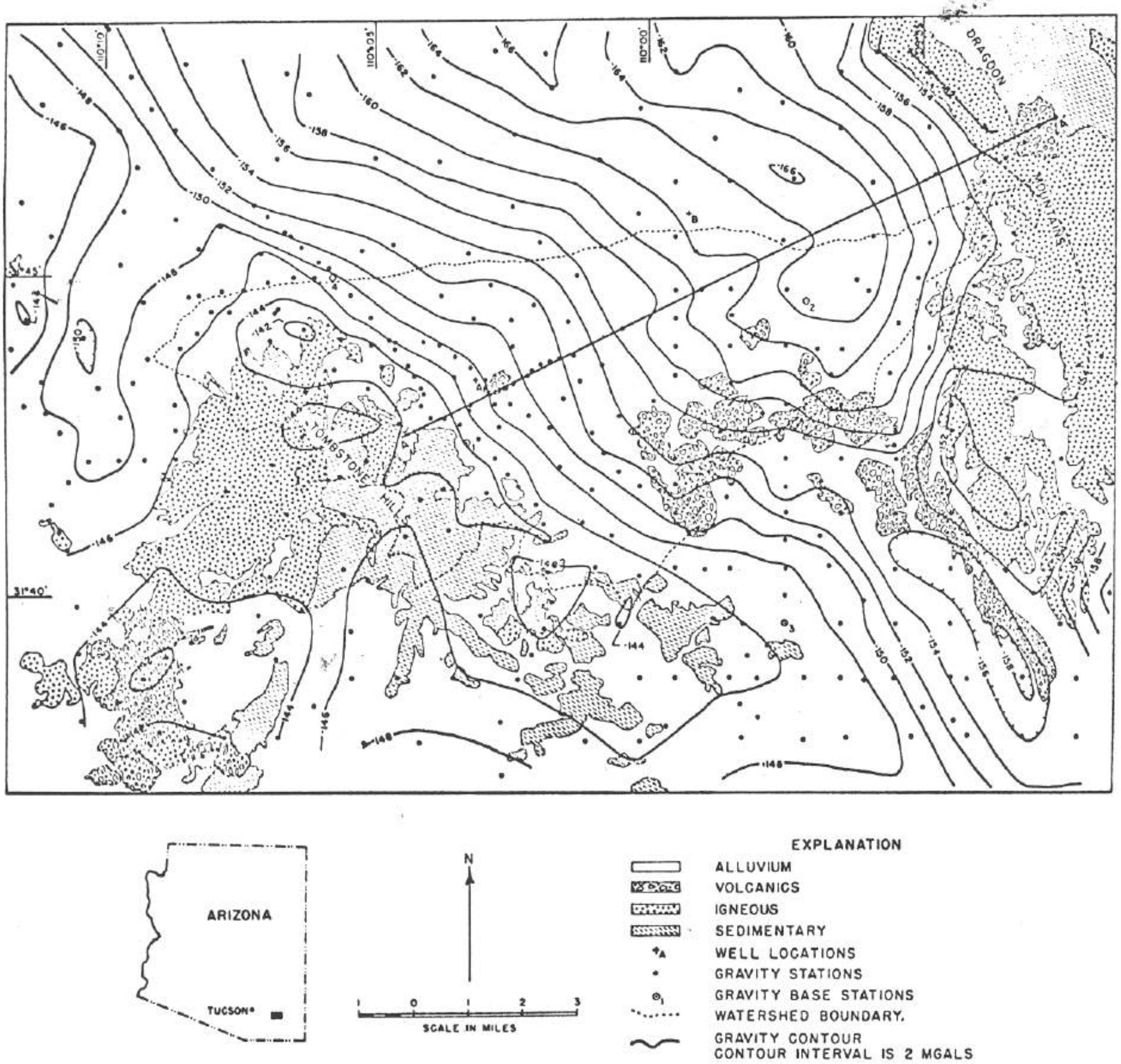

Figure 4. Simple Bouguer gravity map and generalized geologic map. From Spangler and Libby, 1968.

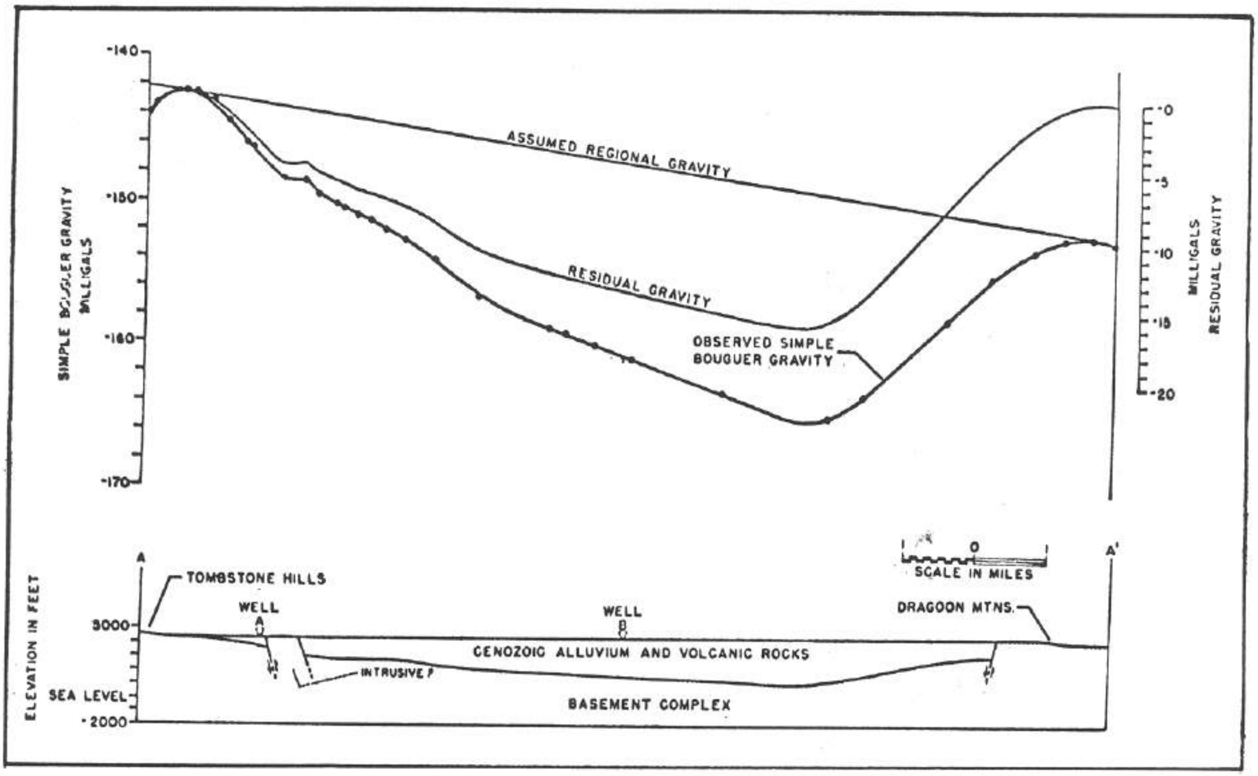

Figure 5. Profile across the area shown on Figure 4, illustrating observed simple Bouguer gravity, assumed regional gravity, residual gravity, and interpretive geologic cross section along gravity profile. From Spangler and Libby, 1968.

detailed work. Such surveys will not replace other surface or borehole studies, but they can reduce the time and expense of a general geologic study.

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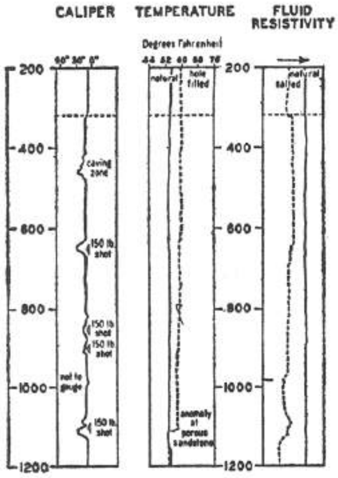

BORE HOLE GEOPHYSICAL TECHNIQUES

FIELD FORMATION TESTING

Bore hole geophysics includes the great variety of well logging techniques pioneered and developed by the petroleum industry plus a few special techniques developed for other purposes.

Because many exploration problems are common to both the petroleum and water well industries, it is only natural that there is a slow, but steady increase in the use of logging by water well contractors.

The summary of logging techniques in Table 1 is a very short review of those discussed in the July issue of WATER WELL JOURNAL. A large variety of logs are available today, although some are not completely suitable for the average water well project.

It must be emphasized that these logs have a variety of uses. The most common use in ground water work seems to be for interpreting an already-drilled bore hole. But logs can be just as useful for predicting what will be encountered in future wells within the same area.

USE OF LOGS TO IDENTIFY ROCK CHARACTERISTICS

No one type of log gives a complete picture of rock characteristics. But a combination of several logs can be used to make a fairly accurate determination of what is underground.

The spontaneous potential (SP) log on the left-hand side of Figure 1 is one of the most common logs used in all down-hole work today. The straight line portions of the log represent zones that are predominantely fine-grained rocks such as shales.

When the curve moves toward the left, away from this 'shale line,' sandy zones are indicated. Normally the curve will shift to the left (negative side), but if the water in the sand is very fresh, the curve may reverse and shift to the right, as in the shallowest sand layer shown on the figure.

Resistivity values (Figure 1, second column) increase to the right. Dense rocks, such as granite and some limestones, are indicated by high resistivities. Medium high values, in combination with negative or extremely positive SP logs, indicate water-saturated sands.

The dotted line log indicates resistivity values at some distance from the bore hole wall. This log, which is common in petroleum industry work, requires a more complex instrumentation than is normally used in water well logging.

The microlog is primarily used in oil field logging also. Its main use is for locating very thin beds, such as streaks of sand within shale horizons.

Gamma (natural) radiation, under normal conditions, is highest in clays and shales because such rocks naturally are composed of a very small percentage of radioactive minerals. Sands or sandstones, which are made up mostly of quartz grains, give off less natural radiation. Limestones also typically show low radiation values.

The neutron log which, as in Figure 1, often looks like a mirror image of the gamma ray log, is also useful for delineating general rock types. Neutron logs are obtained by bombarding the formation with artificial radioactivity and recording the results.

The caliper log, on the far right side of Figure 1, delineates different formations on the basis of the diameter of the bore hole. Soft, unconsolidated rocks have a tendency to cave and enlarge the hole. Consolidated, hard rocks tend to remain approximately the size of the drill bit.

Table 1. Suggested Logging Techniques for Groundwater Investigations (from Keys, 1969).

Information Needed on Properties of Rocks, Fluids, Wells or Groundwater System.	Conventional Logs which Might be Utilized.
Lithology of aquifers and associated rocks.	Electric, sonic, or caliper logs in open holes. Radiation logs in open or cased holes.
Stratigraphic correlation of aquifers and associated rocks.	Electric, sonic, or caliper logs in open holes. Radiation logs in open or cased holes.
Total porosity or bulk density.	Calibrated sonic or gamma-gamma logs in open holes. Calibrated neutron logs in open or cased holes.
Effective porosity or true resistivity.	Calibrated resistivity logs.
Clay or shale content.	Natural-gamma logs.
Permeability.	No direct measurement by logging. May be related to porosity, injectivity, sonic amplitude.
Secondary permeability—location of fractures and solution openings.	Single-point resistivity, or caliper logs, sonic amplitude, borehole television.
Specific yield of unconfirmed acquifers.	Neutron logs calibrated in percent moisture.
Grain size.	Possible relationship to formation factor derived from electric logs. Clay content from gamma logs.
Location of water level or perched water outside of casing.	Electric, fluid resistivity, gamma logs in open hole or inside casing. Neutron or gamma logs outside casing.
Moisture content above water-table.	Neutron logs calibrated in percent moisture.
Rate of moisture infiltration.	Time interval neutron logs or radioactive tracers. Temperature.
Direction, velocity and path of groundwater flow.	Single well tracer techniques—point dilution and single well pulse. Multiwell tracer techniques.
Dispersion, dilution and movement of waste.	Fluid resistivity and temperature logs, gamma logs for radioactive wastes, sampler.
Source and movement of water in a well.	Injectivity profile, flowmeter, or tracer during pumping or injection. Differential temperature logs. Time interval, neutron, or gamma-logs.
Chemical and physical characteristics of water—including salinity, temperature, density and viscosity.	Calibrated fluid resistivity and temperature logs in hole, neutron chloride logging outside casing.
Determining construction of existing wells, diameter and position of casing, perforations, screens.	Gamma and caliper logs, collar and perforation locator, borehole television.
Determining optimum length and setting for screen.	All logs providing data on lithology, water-bearing characteristics and correlation and thickness of aquifers.
Guide to cementing procedure and determining position of cement.	Caliper, temperature, or gamma-gamma logs.
Locating corroded casing.	Under some conditions caliper, or collar locator.
Locating casing leaks or plugged screen.	Tracers and flowmeter.

In much water well logging, SP, single point resistivity, and perhaps gamma ray logs are used together. They form a package that gives the most information for the least amount of money.

Most logging work is done on a contract basis. Cost is determined by mileage costs, the set-up fee, and logging costs, either by the foot or a lump sum for the well. In some parts of the country, wells 500 feet deep or less can be logged for above three variables for a maximum cost of several hundred dollars.

A few state geological surveys and some federal projects also log water wells for their own information. Copies of these logs generally are available to the driller or well owner.

USE OF LOGS PLUS DRILLING RATE

Geophysical logs are often used in conjunction with drilling rate information to aid in identifying formation characteristics. During drilling, the machine operator must keep a record of bit penetration rate. This data can be quantitative (in feet per minute) or even qualitative, using such terms as fast, slow, or very slow.

After the logs are run, the penetration rate is matched up with the logs, as shown in Figures 2, 3, and 4. The combination of data helps to interpret even more rock properties than can be obtained from the logs or the drilling rate alone.

For instance, in Figure 2 the geophysical logs distinctly separate the clays from the sand layers. But the fast drilling rate for the entire sec-

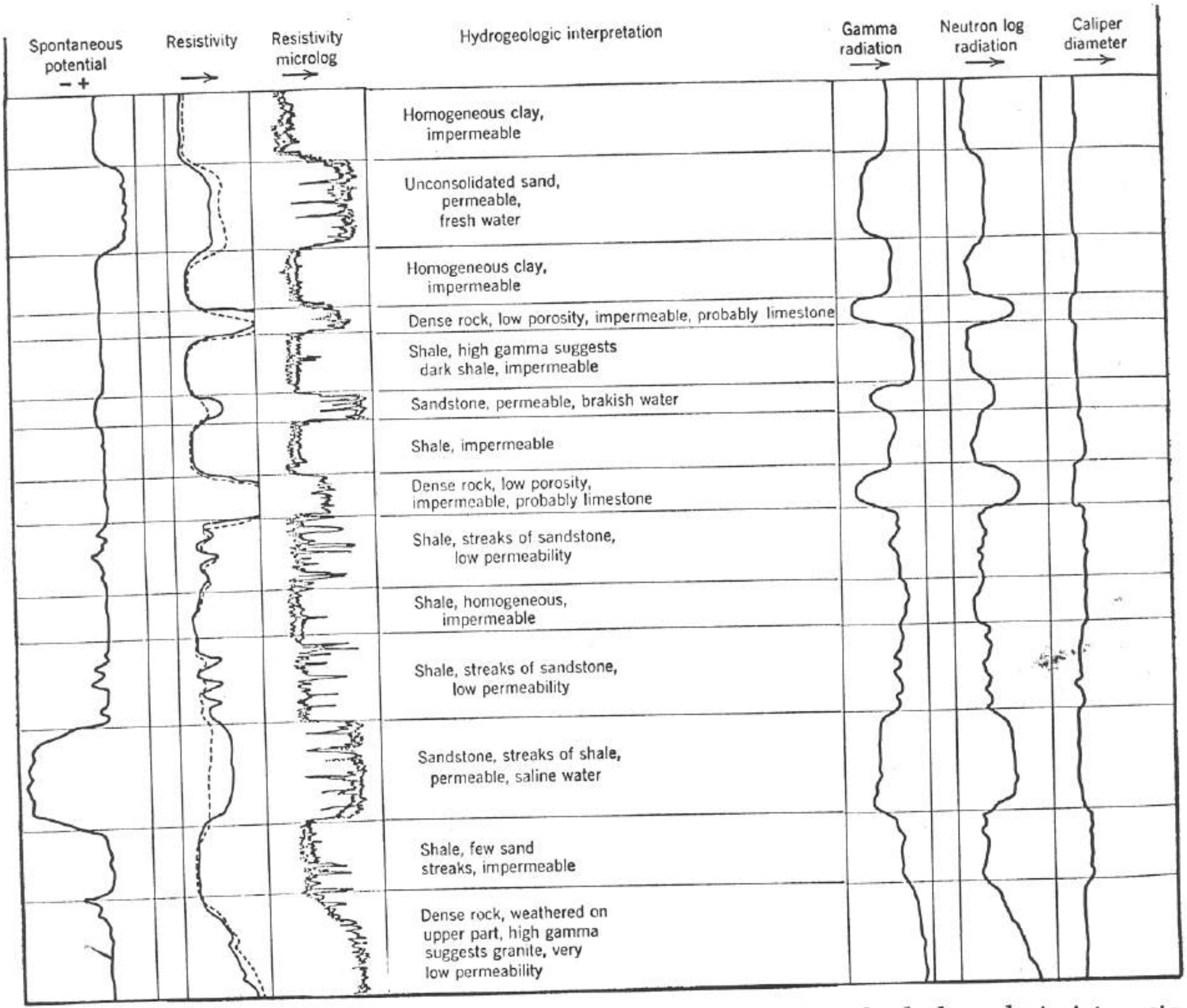

Figure 1. A combination of six logs of a hypothetical test hole showing the hydrogeologic interpretations. Reprinted from Hydrogeology by Davis and DeWiest, 1966, by permission of Wiley and Sons, Inc.

tion shows that the sands are loose (uncemented) and probably will need to be screened for proper well development.

In Figure 3, both the high and low porosity sandstones have similar characteristics on the logs. But the difference in drilling rates helps to show that a difference in porosities occurs. The low porosity is caused by some sort of natural cement, perhaps silica, that slows down the bit in these rocks.

Figure 4 also shows that drilling rate is one of the best methods for delineating differences in natural rock cement of a thick and otherwise relatively uniform rock formation.

SPECIAL SURVEYS–TEMPERATURE

One of the most useful, yet relatively inexpensive, surveys is the temperature log. If it is made within a short time after the well casing has been cemented, it can be used to determine the location of the cemented zone. Figure 5 shows that cement adequately seals the annular space between the outer and inner casing.

In many areas of the United States, natural gas in water wells is a hazard, or at best, a nuisance. Under most conditions, a temperature survey can pinpoint the zone or zones from which the gas is leaking. Figure 6 shows that only one gas leak occurs, which can be cemented off during well completion.

Recording thermometers for very deep holes cost several thousand dollars. But a non-recording temperature probe with up to 500 feet of cable costs only a few hundred dollars. This type of probe must be lowered to the desired depth, allowed to come to equilibrium, and the temperature read on the meter.

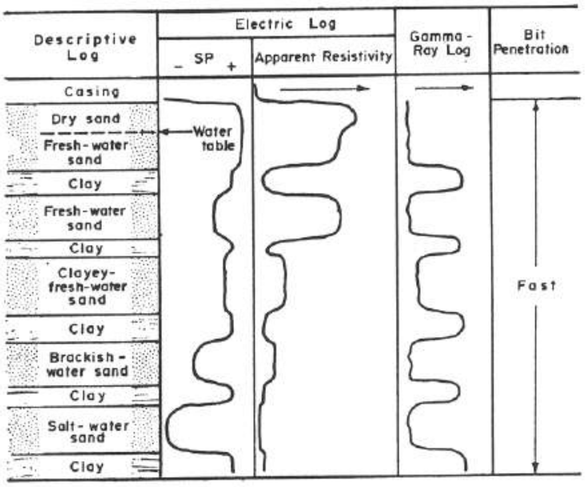

Figure 2. Artificial geophysical logs of a sand and clay sequence. Mineralized water in lower sands reduces their apparent resistivities to that of clay, but gamma ray log distinguishes clay from sand layers. Reprinted from Ground Water and Wells, 1966, with permission of UOP Johnson Division.

The probe is then lowered to another depth, and the temperature reread. The process is continued to the bottom of the hole. Temperature is plotted against depth and a line drawn to connect the points.

SPECIAL SURVEYS—VELOCITY AND CONDUCTIVITY

Figure 7 shows how a combination of fluid velocity and electrical conductivity can be used to separate aquifers in an artesian well. The velocity measurements show that four aquifers exist.

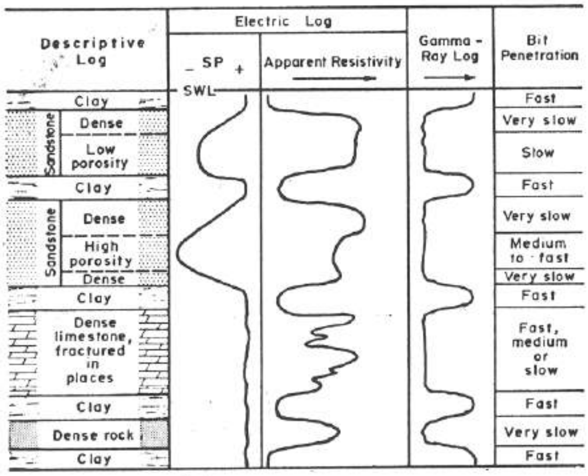

Figure 3. Artificial geophysical logs of consolidated rock layers separated by clay beds. Reprinted from Ground Water and Wells, 1966, with permission of UOP Johnson Division.

The small diameter of the bore hole through hard rock zones increases the flow rate in these zones, but each aquifer is still distinct. Only the middle two aquifers contain fresh water, as shown by the low electrical conductivity. High mineral content of water gives a high conductivity reading.

With information obtained from this combination of fluid velocity and conductivity, the well can be completed so that it yields only fresh water. The upper and lowermost artesian zones must be cemented off to prevent brackish water from mixing with the fresh water.

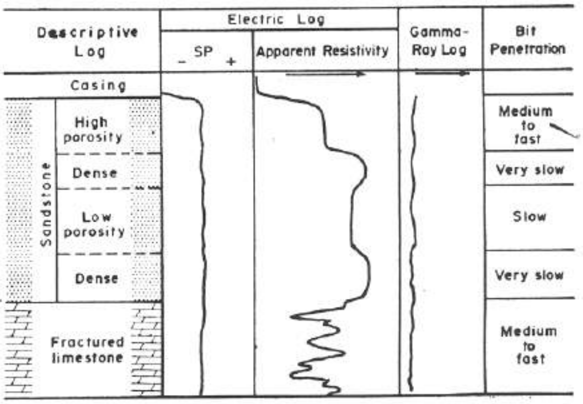

Figure 4. Artificial geophysical logs of consolidated rocks. Porous layers are fresh water aquifers. In the absence of clay beds, the gamma ray log shows nothing. Reprinted from Ground Water and Wells, 1966, with permission of UOP Johnson Division.

SPECIAL SURVEYS—PHOTOS AND TV

Photographic, and more recently, television surveys have been used to evaluate water well conditions. Photographic devices can be used in clear water and in some brine solutions. Wells containing cloudy water often can be viewed after chemical agents have been used to precipitate the mineral matter.

The camera or television transmitter is lowered down the hole, usually at a constant rate. Depth is calibrated using a cable marked at intervals.

Various types of pictures are available. Photographic techniques include movie film, color pictures, and even three-dimensional photos.

Television has the advantage that it can be seen live during the survey. It also can be recorded permanently on video tape.

Photographs or television can be used to identify geologic formations in open holes, as part of a well completion survey, to check damaged walls, to aid in removing foreign matter from a well, and to assist in development or well cleaning.

The types of photograph that can be obtained is shown in Figure 8. Photographic or television surveys usually are contracted to companies that specialize in such work. The survey may cost several hundred dollars, but it can more than pay for itself by saving days of work to locate a section of damaged casing or to help retrieve an object that does not belong in the well.

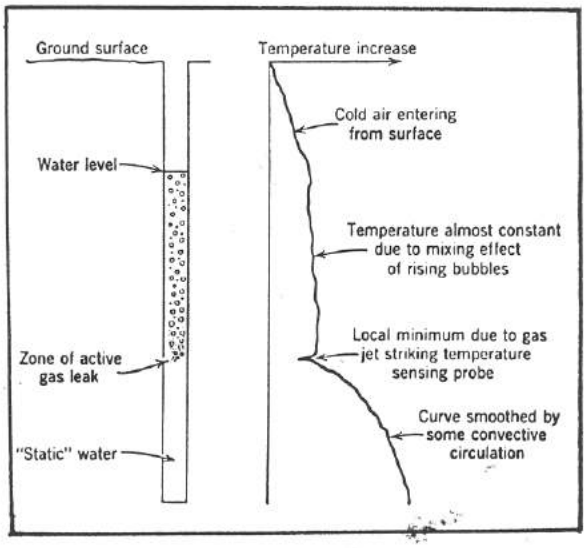

Figure 6. Schematic diagram showing temperature log used to pinpoint location of expanding gas entering a well. Reprinted from Hydrogeology by Davis and DeWiest, 1966, by permission of Wiley and Sons, Inc.

SUMMARY

This short review of how the water well contractor can use various bore hole methods to make his work easier, yet better, is only that—a short review.

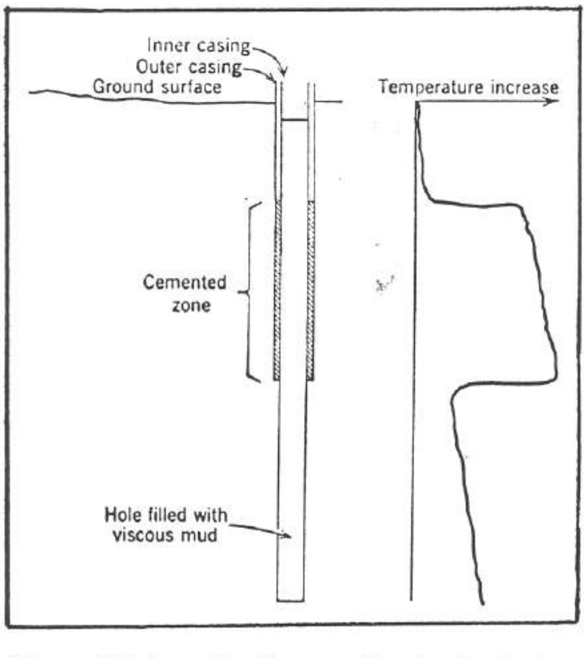

Figure 5. Schematic diagram showing heat given off by cement as it hardens. Reprinted from Hydrogeology by Davis and DeWiest, 1966, by permission of Wiley and Sons, Inc.

Increasing number of articles discuss the various methods and explain how they can be adapted to the water well industry. In order to stay in business, the contractor must make his product—a better water well—competitive and still show a profit. Some of these geophysical techniques can do just that, but only the contractor can decide which ones will best suit his needs and those of his customers.

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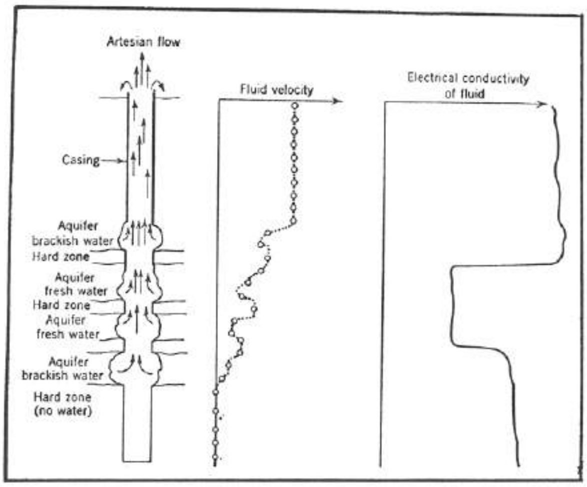

Figure 7. Fluid velocity and electrical conductivity logs of a hypothetical artesian well. See text for explanation. Reprinted from Hydrogeology by Davis and DeWiest, 1966, with permission of Wiley and Sons, Inc.

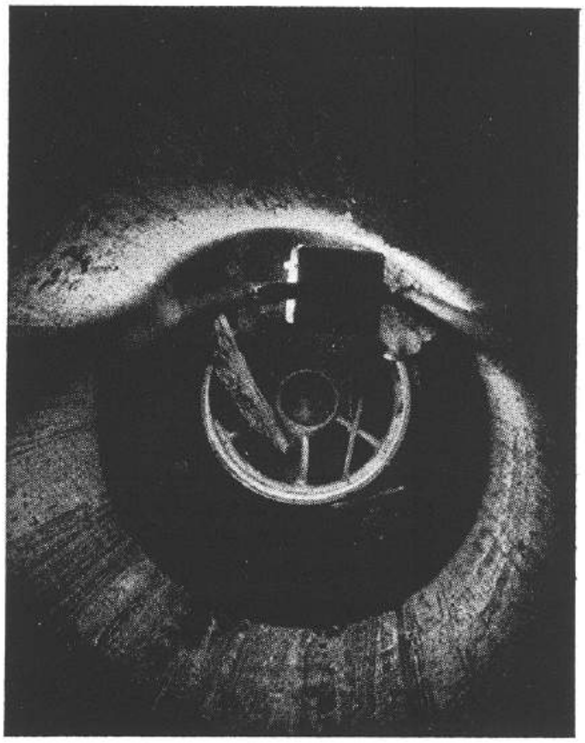

Figure 8. Photograph of 8 inch pump bowls in 16 inch well casing. Photograph from Owen F. Jensen, Jr., Layne Texas Company, Inc.

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