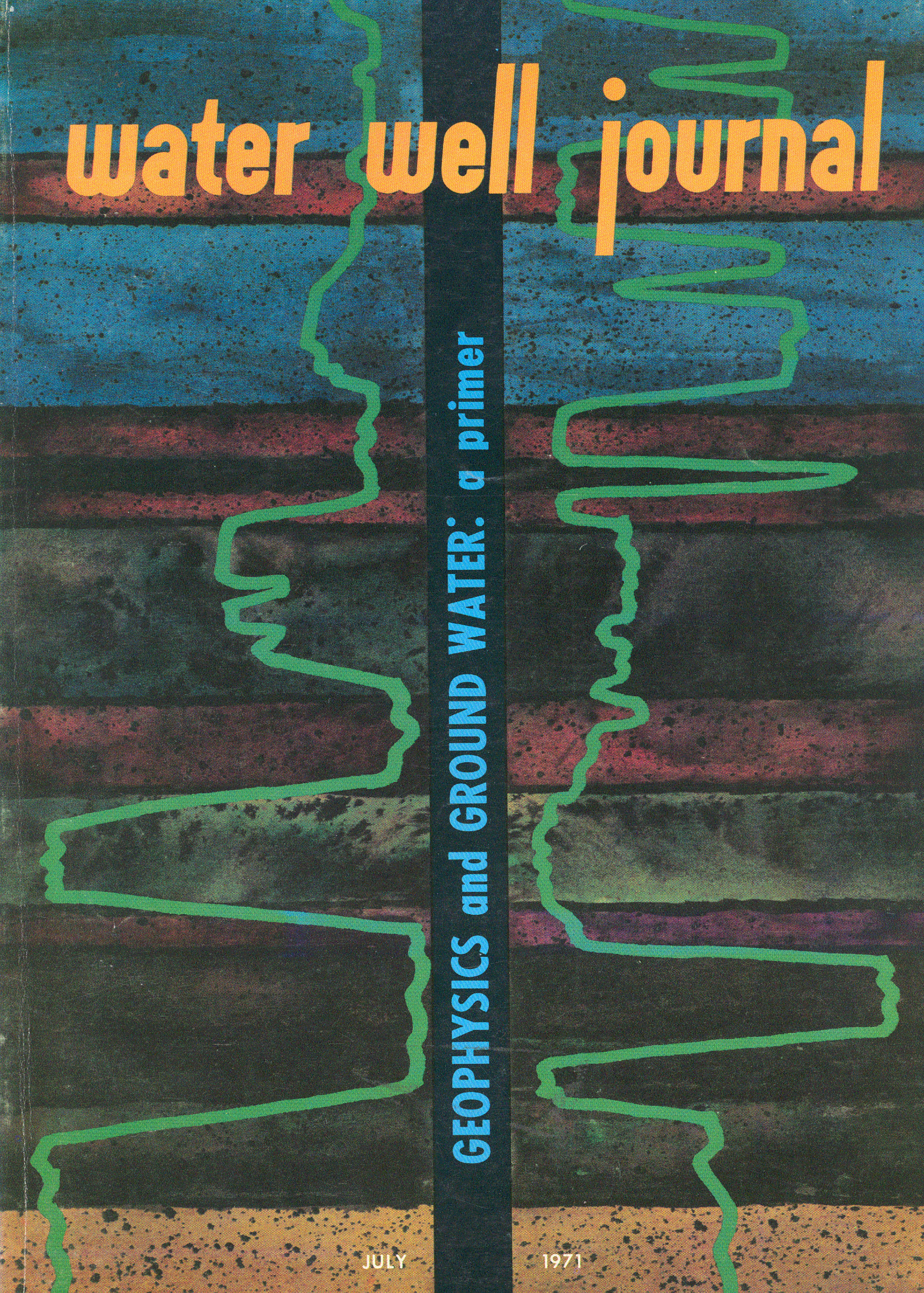
water well journal



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IN THIS ISSUE

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GEOPHYSICS and GROUND WATER: a primer

An Introduction to Ground Water Geophysics (Part 1)

INTRODUCTION

Along with the growing technological advances in the world today, the interpretation of very sophisticated geophysical data is becoming more simplified and, therefore, more usable in a practical sense by the ground water industry. Professional personnel, in co-operation with water well drilling contractors, are taking advantage of these new techniques which, not too many years ago, were only reserved for specialists in higher mathematics and physics.

A knowledge of the basic principles and practical aspects of ground water geophysics will assist the well contractor and others to more fully understand one of the many new tools of the ground water industry. Geophysics, in the past few years, has reached a place of vital importance to the scientific development and protection of the world's precious ground water supply.

This is the first of a two-part series on ground water geophysics. The first section of this series deals with an introduction to the basic principles and features of ground water geophysics. The second part, coming next month, will consider the applied aspects of ground water geophysics and will treat in detail the more important topics briefly outlined in this introduction.

This first section is divided into two parts—the first deals with *surface* geophysical techniques; the second, *borehole* geophysical techniques. Surface techniques include: (1) Resistivity, (2) Seismic Refraction and Reflection, (3) other survey methods—Soil Temperature, Magnetometer, Gravity, Remote Sensing, etc. Borehole techniques include: (1) Well Construction and Completion Measurements, e.g., defining hole alignment, Caliper Logging, Cement Bond Logging and Water Level Measurements, (2) Formation Testing, Electric Logging (Resistivity and Spontaneous potential), Radioactive Logging (Gamma and Neutron), Induction Logging and Sonic Logging, Downhole Photography, Side-wall Sampling and Fluid Logging (Temperature Logging, Fluid Resistivity Logging, Flowmeter and Tracer Logging).

The petroleum and mining industries are almost totally responsible for the development of the geophysical techniques and the interpretation methods in use today. It is unlikely that geophysical logging would have reached its present state of development without the economic impact provided by the search for oil and other minerals. The future world-wide search for ground water is heavily dependent upon geophysical logging techniques to play an ever-increasing role in the development of the ground water resources.

If ground water geophysics is to be widely used in ground water exploration and development, water well contractors and state and municipal agencies must be continually reminded of the advantage of obtaining more information from each and every hole drilled. It is necessary, as well, to firmly demonstrate how well logging can provide much of this information.

It is to assist in the achievement of these ends that this series on ground water geophysics is intended. This series, as well as those to come, is in association with the NWWA's Research Facility, where many highly scientific techniques are translated for practical understanding and use by the ground water industry.

SURFACE GEOPHYSICAL TECHNIQUES

ELECTRIC EARTH RESISTIVITY

ELECTRICAL EARTH RESISTIVITY

Aquifers can often be located easily and accurately from the earth's surface with electrical resistivity measurements. Such surveys are widely used mainly in search of water-yielding sand and gravel deposits; the method has been in use for at least 35 years.

Electrical earth resistivity has most often been used for municipal supply prospecting partly because the larger amount of water needed for municipalities requires a relatively thick water-bearing deposit which is more likely to be detected by resistivity surveying.

In practice, resistivity surveying utilizes a flow of electricity within naturally occurring subsurface materials. Electrodes are inserted into the ground's surface, equally spaced along a straight line. By systematically increasing the distance between electrodes, the electrical field is expanded to include a greater volume of earth materials. The resistivity of these materials to the electric current is measured, offering values which can strongly suggest the dimensions and composition of subsurface materials.

Generally, the farthest distance between electrodes approximates the depth to which the electric current penetrates, although experience frequently dictates modifications for this rule of thumb.

Unconsolidated glacial drift materials cover a wide range in their resistance to the flow of an electric current. The experienced surveyor can recognize these variations and on this basis can identify subsurface materials, to some degree.

Ideal conditions, including uniformly thick layers and homogeneity, rarely occur naturally. The most important variables that permit detection of aquifers within the glacial drift are depth thickness and contrast in actual resistivities of the aquifer and the material enclosing it.

Earth resistivity has been found to be most useful not as an isolated measuring system but when used in connection with knowledge of geology. The customary first step in preparing for a resistivity survey is assembling the available information on local geology. The geophysical interpretations are then made within this framework.

Many factors can conspire to distort the true value of an apparent resistivity reading. These include buried conductors like pipelines, phone cables, oil and water tanks; metal fences; overhead high voltage lines and high voltage transformers on poles; water moving downslope or percolating just after a rain; etc.

The experienced geophysical surveyor can recognize distortions from such causes and modify his reading accordingly. It becomes quickly evident that the earth resistivity method is not applicable to any site under all circumstances and that it requires an experienced operator. When the method is appropriate, however, it can provide data quickly and accurately without the time and expense of a test hole.

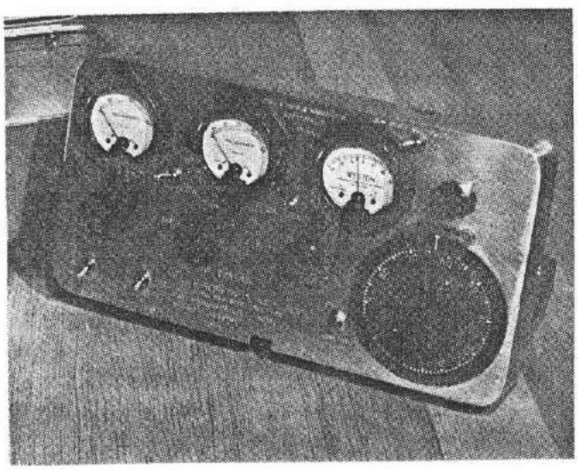
Electric currents flow readily through most ground formations largely because of the water contained in pore spaces. Rocks and soils are composed of silicate and carbonate minerals which are extremely resistant to electric current. The effectiveness of the electrode arrangement is based on the manner in which electricity flows through a 3-dimensional solid. It doesn't flow in a straight line from one contact to another, as it does in a wire; but spreads throughout the body it is traveling through. The current entering the ground at one electrode radiates out from that point to flow through the ground; then it converges on the other electrode through which it leaves the ground.

By progressively increasing the electrode separation, progressively deeper penetration is achieved. (The distance between electrodes is equal to the depth of penetration of the current.) The depth at which current enters a formation of higher or lower resistivity is signaled by a change in the resistivities recorded at the ground surface.

Earth resistivity also has potential as a technique for identifying zones of polluted water. In many cases, ground-water pollution is accompanied by changes in electrical conductivity as in oil field brine pollution, pollution by irrigation waters and pollution by sea-water intrusion.

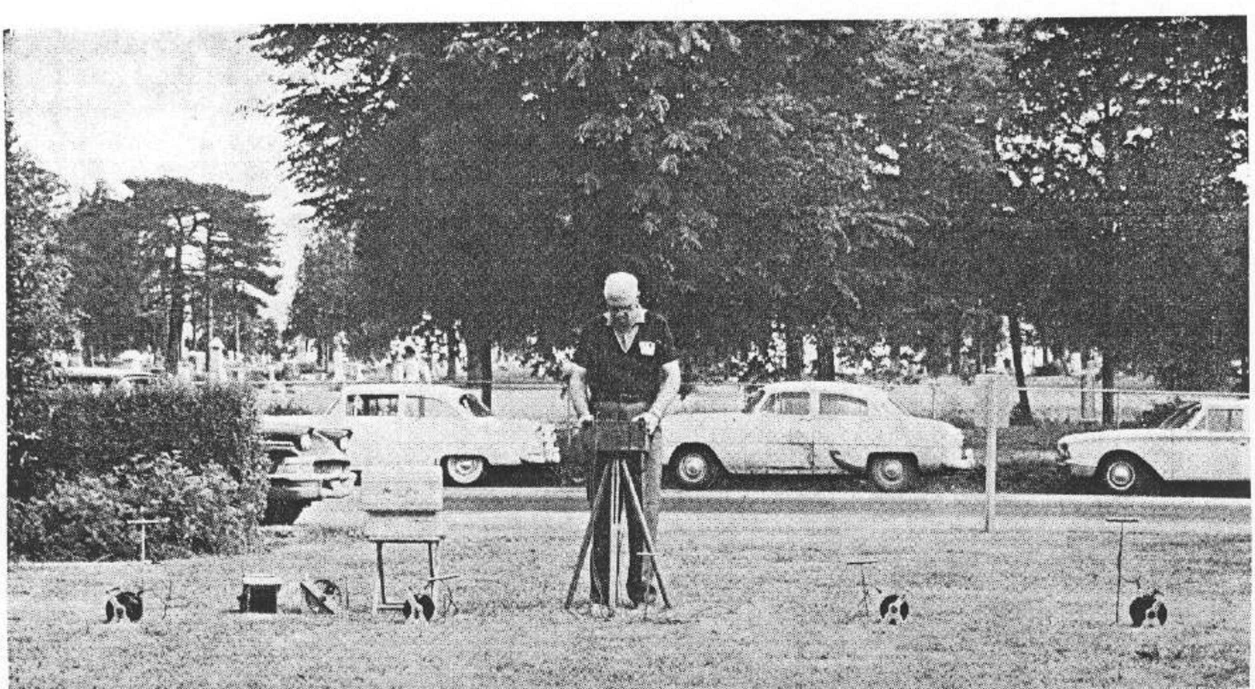
The electrical earth resistivity method, utilized by competent trained personnel and in conjunction with available geologic knowledge, is best suited to preliminary exploration of large areas—20 acres or more—where major quantities of ground water are sought. With the information obtained with this surface geophysical method, adequate test drilling of an area can be completed with only a fraction of the holes which would be required in a program of random drilling.

A great many factors effect the accuracy of the method. However, it can be said that there are many situations where resistivity should be used.



Control unit of Field Earth Resistivity Equipment

Field Earth Resistivity Equipment showing control unit and probes set up along a traverse.



SURFACE GEOPHYSICAL TECHNIQUES

SEISMIC RETRACTION and REFLECTION

SEISMIC REFRACTION AND REFLECTION

Classical seismology is the study of the vibrations caused at the surface of the earth by earthquakes, and the interpretation of these vibrations in terms of the internal constitution of the earth, the depth of the triggering disturbance and the amount of energy in that disturbance.

Seismic prospecting is more limited—and much more detailed in scope—and aims at determining the depth and attitude of the near surface layers of the earth.

Although the general theory of seismic prospecting is similar to that of earthquake seismology, the wave length of the disturbance received is very different.

The nature of the triggering disturbance and the enormous distances traveled by an earthquake wave result in considerable dropping out of the higher frequencies. The period of the wave received at the seismograph varies from a few seconds to as long as a minute.

In seismic prospecting, where the distances are much shorter and the waves are explosion or impact produced, the periods are in the range of 1/100 to 1/10 of a second. Thus very different sensing equipment is required than is used to record earthquakes.

There are 2 methods of seismic subsurface exploration—reflection and refraction. In the reflection method, a shock is generated at or near the ground surface, either by detonating an explosive or striking a steel plate with a sledge hammer. After an interval, the shock waves are reflected from one or more physical discontinuities and return to the surface where they are recorded, in one of several ways.

The refraction method measures waves from an explosive shock usually generated in the ground at the level of a discontinuity. When the wave hits a discontinuity where there is an abrupt change in elastic properties, the wave is refracted, or bent, at an angle which can be computed meaningfully.

Seismic analysis is based on the fact that sound waves travel faster in denser, more consolidated materials. To perform an analysis and obtain information about kinds of subsurface materials and depths of various layers, these are required: a way of producing a shock wave or sound in the earth, a receiver for that sound and a method for determining the time lapse in between.

In portable reflection seismographs, a sledge hammer is used to hit a steel plate placed on the ground. The hammer is wired to a portable console which registers the instant of impact. A receiver—geophone—which operates similarly to a microphone picks up the reflected sound waves and the console measures the interval.

Boulders in drift do not greatly affect depth information given by the seismic method, but they may lead to inaccuracies. On jobs where borings are used to verify seismic results and give exact soil information, only a few test holes are required. The combination of borings and seismic readings gives a quicker and more accurate picture of subsurface conditions than would test holes alone.

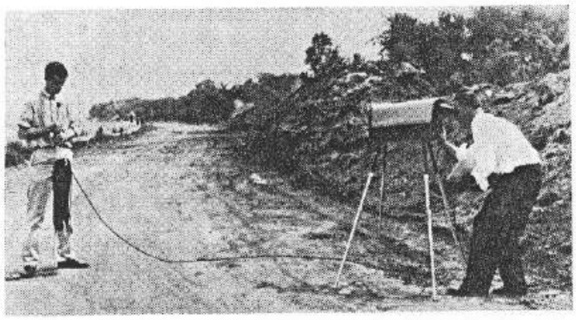
The limited strength of a hammer impact makes it normally difficult to obtain readings farther than 200′ from the geophone. This distance represents a depth of about 50′. Portable units can utilize powered seismic impactors or explosives to extend their sensitivity range to depths of 550′ or more.

The accuracy of depth determination depends on the complexity of the situation, but in most cases, where the conditions are uniform and only one or 2 layers overlie bedrock, accuracy is 5 to 10%.

Seismic methods, combined with available well and geologic data, were used to define the subsurface hydrologic and geologic conditions of the Walnut Gulch Experimental Watershed, a deep alluvial basin near Tombstone, Arizona. Surface geology of the valley indicates an alluvium-filled area between igneous intrusives and sedimentary rocks that support the Tombstone Hills on the southwest and the Dragoon Mountains on the northeast.

Seismic determinations in this area indicated depths to the water table ranging from near zero at the confluence of Walnut Gulch and the San Pedro River, to 475′ in the central part of the watershed.

The accuracy of predicting the depth to either ground water or basement was 6%, while that for ground water alone was 10%.



Field Seismic Recording equipment showing a traverse station and recorders.

Control monitor unit inside recording vehicle which will receive seismic information from geophone traverse stations.

Surveying team measuring traverse stations where geophones are placed.

SURFACE GEOPHYSICAL TECHNIQUES

OTHER SURVEYING METHODS

Temperature prospecting for ground water. A thermister in the tip of the probe measures the temperature of the soil. Above a shallow aquifer, soil temperatures are cooler in the summer and warmer in winter than in adjacent areas.

SOIL TEMPERATURE SURVEYING

In most respects, the geophysical techniques discussed up to this point have been concerned with measuring properties of rock formations, rather than water. However, the presence of water can affect such measurements.

Water in rock formations has specific properties, one of which lends itself to surface detection. This is the high specific heat of ground water.

In theory, this high specific heat of water can cause a shallow aquifer to act as a heat sink or a heat source that influences the near-surface temperatures to a measurable extent.

If the shallow aquifer is a linear deposit of permeable material, such as is commonly found in glacial drift and alluviated valleys, a temperature difference might be detected at the surface.

In typical operation, measurements of soil temperature are made 18″ below the land surface using an electronic thermometer—a thermistor at the end of a long probe.

MAGNETOMETER SURVEYING

Basically, a magnetometer measures the intensity and direction of magnetic forces. These instruments have been in use for many years especially for metallic ore prospecting. With some of the highly refined models, magnetometer readings can be obtained from aircraft.

The magnetometer is in use for water prospecting by one firm which claims 80% accuracy. The firm does not have a technical background and the relationship between areas having ground water and the instrument's readings is not known.

GRAVITY SURVEYING

The gravity survey method detects and measures variations in the earth's gravitational force. These variations are associated with changes in rock and alluvium density near the surface.

Because many geologic structures of interest in watershed ground water hydrology cause disturbances in the normal density distribution, the method is valuable in surveying ground water.

According to Newton, the value of gravity is directly proportional to the density and volume of a mass, and readings on a gravity meter reflect these variations in the earth materials beneath it.

The field techniques of a gravity survey are simple—one man can collect all field data. Usually a computer is used for processing that data, however.

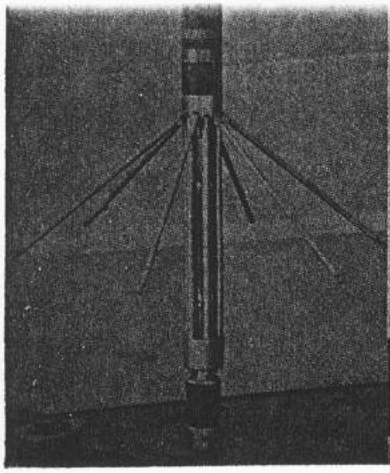
REMOTE SENSING TECHNIQUES

Remote sensing includes those surface-oriented surveying techniques which are conducted above the earth surface, either in aircraft or satellites. These include infrared photography, aeromagnetic surveys at low altitudes and other techniques which use photographic techniques.

The EROS satellite program promises continuing earth resource data including study of ground water.

Infrared photography can detect temperature differences in water; for example, it can cool ground water discharging into warmer river water as a visible phenomenon. Although the infrared technique points up thermal anomalies, ground-based surveys are needed to determine the presence and quality of water.

Aerial magnetic surveys can delineate subsurface rock structures which might control the flow of ground water.



BOREHOLE GEOPHYSICAL TECHNIQUES

WELL CONSTRUCTION and COMPLETION MEASUREMENTS

STRAIGHTNESS AND ALIGNMENT MEASUREMENT

Drift angle and direction of a borehole can be readily determined with a drift indicator or photoclinometer.

These devices range from simple to sophisticated, from devices which are run to the bottom of the hole and record, non-directionally, the degree of drift, to units which can take numerous readings along the borehole and record the degree of drift and the direction of drift.

Some punch holes on calibrated paper discs while others photographically record the readings of the unit.

Direction is ordinarily recorded by a magnetic compass, which performs only in uncased or plastic cased hole.

Continuous directional surveying of a well bore is possible, for example, with one unit which records on 10mm film a complete record of inclination from vertical and the magnetic direction of that deviation.

Directional surveys can detect crooked holes which are hard on drill stem, fatiguing it by bending, and unduly wearing it by abrasion.

In cases where wells are drilled near property lines, it is often important to know that the well is producing from the proper acreage.

CALIPER LOGGING

Calipers are highly sensitive borehole diameter measuring devices. The caliper tool has independently operating measuring arms which ride the wall of a borehole and detect variations as small as 1/4" in diameter.

Because of the independent action of each of the arms, the diameter recorded is that of the circle described by the tips of the arms.

Hole volumes can be simultaneously determined by a caliper log and casing variations can be measured. The caliper can also locate packer seats, shot holes, washed out areas and casing shoes.

Different caliper units have different numbers of caliper arms, usually 3 to 6. The reading is always an average of all arms and is recorded at the surface as a single curve.

CEMENT BOND LOGGING

It is possible to determine whether or not the cement is tight against the outside casing wall by running a cement bond log. This log is based on the principle that the signal strength of an acoustic signal traveling along the casing is greatly reduced where the cement is well bonded to the pipe, compared to no bonding or poor bonding.

The equipment used includes an acoustic energy transmitter which transmits 15 to 20 pulses per second. A receiving transducer, which reads the signal along the inside casing wall, is separated from the transmitter by an acoustic insulator.

A signal of constant strength is transmitted and a continuous recording at all depths is made of the signal strength at the receiver. The amplitude measurement then indicates the quality of the cement bond.

WATER LEVEL MEASUREMENT

Water level changes in a well have many causes. The more common ones are diversion and recharge of ground water.

There are, however, many other causes of minor fluctuations of water levels in wells. Barometric and tidal effects, earthquakes and loading effects such as floods and trains cause water level fluctuations. Diurnal effects by vegetative consumption are also significant.

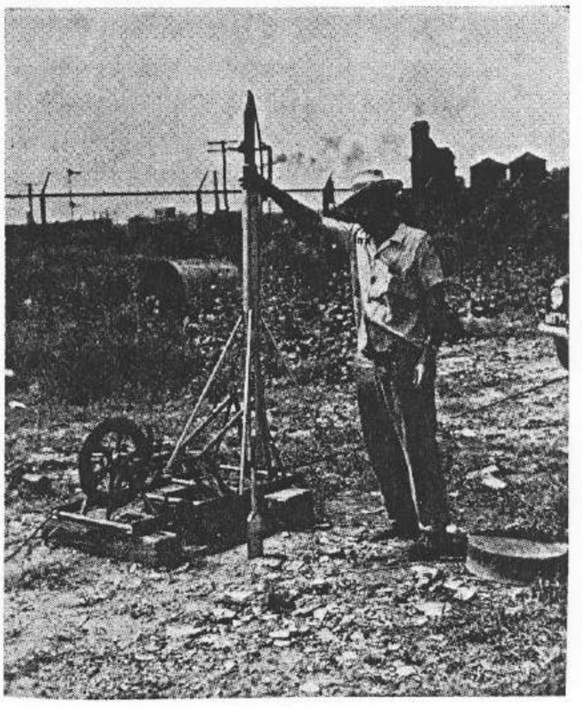
Changes in water levels due to barometric pressure changes are of the same order of magnitude as the fluctuations in barometric pressure, and are seldom greater than one foot. But this change can have a considerable effect on the interpretation of water level data when water levels are read to the nearest hundredth of a foot, as is done in many ground water investigations.

Sudden changes in water levels have been produced by a passing railroad train. These changes are, of course, of very short duration and are indicated on a water level recorder chart by a mere tick on the hydrograph. Interestingly, when sufficiently expanded, the changes in weight of the various sections of the train can be noted. The locomotive will raise the water level much higher than a loaded car and empty cars will raise the water level much less.

Diurnal (daily) water level fluctuations have been observed in relatively shallow wells located in vegetated areas. The level changes are caused by growing vegetation drawing its water supply from shallow ground water. The water levels lower in daytime and rise at night.

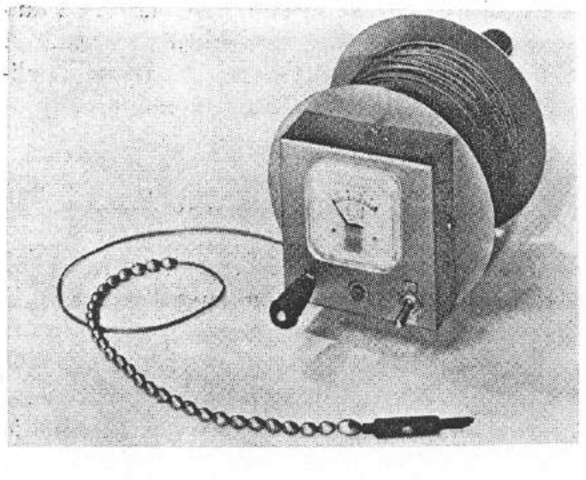
Determining depth to water at a given time can be accurately achieved with a minimum of equipment and a variety of simple techniques. Perhaps the most reliable method is the use of a steel measuring tape.

Other techniques include dropping marbles down the hole and timing the descent and the reverberations which begin when the marble strikes the water's surface; striking the casing and measuring the sound vibrations will also determine the depth to water.

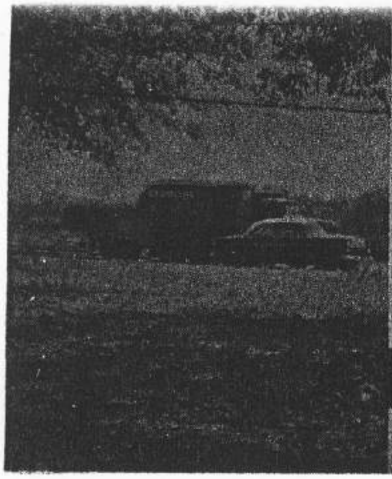


Caliper logging down-hole probe.

Continuous water level recording monitor with waterproof housing.



Water Level Indication Probe.



BOREHOLE GEOPHYSICAL TECHNIQUES

FORMATION TESTING

ELECTRICAL & RADIOACTIVE LOGGING

FORMATION TESTING

A great amount of research has gone into formation testing and identification. Prospectors for underground metals, petroleum, salt, water and other minerals have all created a cumulative demand for ways of gathering data on formations.

Many different types of formation logging techniques have been developed. These logs may simply be charts on which brief descriptions of cores are written opposing the depth from which the cores were taken. Or they can be sophisticated graphic plots which record various characteristics of these cores such as porosity, permeability, residual oil or water, etc.

Electrical logging is one of the important branches of formation logging. Essentially, it is the recording of the resistivities (or their reciprocals, the conductivities) of the formations, and the spontaneous potentials generated in the boreholes.

Other significant varieties of well logs measure the natural radioactivity of the formations (gamma ray logging), and the secondary effects from the bombardment of the formations by neutrons (neutron logging). Radioactivity logging is more recent and, although less universally employed than electrical logging, it has also proved extremely valuable.

Sonic logging can provide a record of the sound-velocity across the formations. With all of these logging techniques, "sondes" are utilized, which are down-hole measuring devices whose results are recorded at the surface.

In electrical and sonic logging, the measurements are performed in the uncased portions of the borehole only. Radioactive logging can record through casing.

In the oil industry, it has become general practice, either at intervals during drilling or after drilling, to run an electrical survey and/or a radioactivity survey to quickly obtain a complete record of the formations penetrated. This information may be supplemented by side-wall samples of the formations, taken from the wall of the hole, or by still other types of tests which can be performed—deviation surveys, dipmeter surveys, temperature surveys, drill-stem tests, formation tests, etc.

Such an approach is beginning to take hold in the water well industry. For example, about half the wells drilled in the San Joaquin Valley are electrically logged today.

Several different kinds of resistivity curves or logs can be recorded in boreholes in addition to the "SP" or spontaneous potential curve. These logs vary with the use of different conductivity or resistivity devices and include induction logging, normal and lateral conventional logs, micrologs, etc.

The general information provided by these logs includes differentiation between shales, hard rocks and permeable beds; definition of boundaries, and correlation, between beds; which makes possible the delineation of the thickness and lateral extension of potential aquifers.

In most cases, these logs can provide a qualitative discrimination between oil- or gas-bearing and water-bearing beds, as well as the location of oil-water contacts. Sometimes, the quantities of water saturation and porosity can also be determined.

The path of the current used for measuring is restricted only by the location of the electrodes between which the current flows. Therefore, the measurements are effected not only by the bed at the level of the device but also by the mud column and also possibly by the formations above and below.

The conventional devices are therefore not as suitable for investigating thin beds, particularly in hard rock areas.

The lateral log also uses electrodes, but the current is directed to flow into the formations within a horizontal plane of limited thickness. This makes it well adapted to investigation of thin beds.

In the second group of resistivity methods are those designed to investigate only a few cubic inches of material at the wall of the hole, practically eliminating the effect of the mud column on the measurements.

The delineation of various beds is much more accurate and detailed with these devices. The microlog is very sensitive to mud cakes which permits detection of permeable beds and the exact definition of their boundaries.

The lateral microlog uses a focusing system so involved that the effect of the mud cake is minimized, even eliminated when thin enough, so that measurements give values close or equal to the resistivity of the formations behind the wall of the hole. This is valuable for determining formation porosity.

When the porosity is high enough, the microlog can determine it, by use of appropriate correction charts.

ELECTRICAL RESISTIVITY LOGGING

Resistivity methods can be divided into 2 categories, depending on whether the amount of material being measured is large or small.

The devices in the first group are capable of measuring large volumes of material around the borehole, from 10′ to 100′ or more. These logs are used for defining formations, for obtaining correlations and for analyzing the quality and quantity of reservoirs in terms of saturation and porosity.

This group includes the induction log and those devices using electrodes. Induction logging uses currents induced in the formations surrounding the sonde. Response to the coils mounted on the sonde is confined to a horizontal slice of formation of limited thickness. The effects of the mud column and of adjacent beds are usually negligible.

The induction log performs best in soft or moderately consolidated formations drilled with fresh muds and it is generally more reliable than the conventional electrical log even in hard formations. The induction method can also be used in air-drilled holes.

Conventional electrical logging devices (normals and laterals) use electrodes from which electric currents flow into the formations and between which the resulting potentials are measured.

With these devices, the borehole must contain conducting liquids which allow currents to flow (water or water-base muds).

PRINCIPLES OF RESISTIVITY

Perfectly dry rocks are very rarely encountered in drilling. Therefore, electricity can pass through earth formations because of the water they contain.

Subsurface formations have measurable resistivities because of water contained in their pores or absorbed in their interstitial clay. The resistivity of a formation will depend on the resistivity of the waters present in that formation, the amount of such water present and the arrangement of the water channels.

The specific resistance is the resistance measured between opposite faces of a cubic meter of that material at a specified temperature.

The waters contained in the pores of strata can vary remarkably with geographic location, depth and geological age. Shallow ground waters are usually fresh with comparatively high resistivities. They may also contain calcium and magnesium salts, affecting their resistivity values.

Deeper waters are generally saltier, although this is a flexible rule influenced by the salinity of the seas present when the sediments were deposited, proximity to ancient river mouths with their fresher waters, increased salt concentration by leaching when the sediments were younger, etc.

There seem to be no simple formulas for relating formation resistivity to permeability. This does not mean that permeable beds cannot be distinguished from impermeable ones by electrical logging methods. Some logging devices can locate and define permeable beds with great accuracy—but they can't tell the degree of permeability.

SPONTANEOUS POTENTIAL LOGS

The spontaneous or self-potential (SP) curve or log is a record of naturally occuring potential differences between a surface electrode and an electrode in the column of conductive mud, as the downhole electrode is pulled up past different formations.

The electrodes are made of relatively stable material—lead—and any constant potential difference between the surface electrode and the one in the hole may be balanced out by an adjustable voltage from a potentiometer circuit.

Since the surface electrode is stationary, its potential is constant, so the SP log is a record of the variations in the potential of the down-hole electrode.

In general, it is possible to recognize on the SP log a well-defined base line, corresponding to shale sections. Deflections from this base line generally indicates permeable beds, such as sand.

Although the SP curve indicates the permeable zones, there is no direct relation between the magnitude of the SP deflection and the permeability or porosity of the bed.

Oil-base mud or salt-saturated mud interfere with reliable SP logging. But barring these conditions, the SP curve can usually be used to detect permeable beds, locate their boundaries, correlate such beds and obtain good values for the formation water resistivity.

INDUCTION LOGGING

Induction logging measures the conductivity (reciprocal of resistivity) of formations by means of induced alternating currents. Because this is an induction method, insulated coils rather than electrodes are used to energize the formations, and the borehole can contain any fluid—or be empty—but the hole must be uncased.

The advantage of induction logging, which has proved its superiority over the conventional electrical log in most cases, is its better ability to investigate thin beds, made possible by its focusing abilities and its greater radius of investigation.

In operation, an alternating current of constant magnitude and frequency is fed to the transmitter coil through an oscillator. The alternating magnetic field from this current induces "current loops" (sometimes called "eddy currents") in the formations surrounding the sonde.

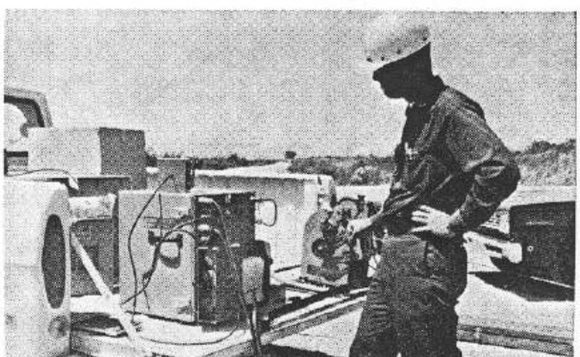
These currents, in turn, have a magnetic field of their own which induces a signal in the receiver coil. The signals are amplified, rectified to direct current and transmitted to surface recording equipment.

Induction logging provides an accurate and detailed record of the formations over a wide range of conductivity values. Its focusing ability has excellent resolving power, and shows almost no distortion opposite thin beds.

Depths of the interfaces between beds are determined accurately. Good boundary definition can be obtained for beds down to about 2′ thick.

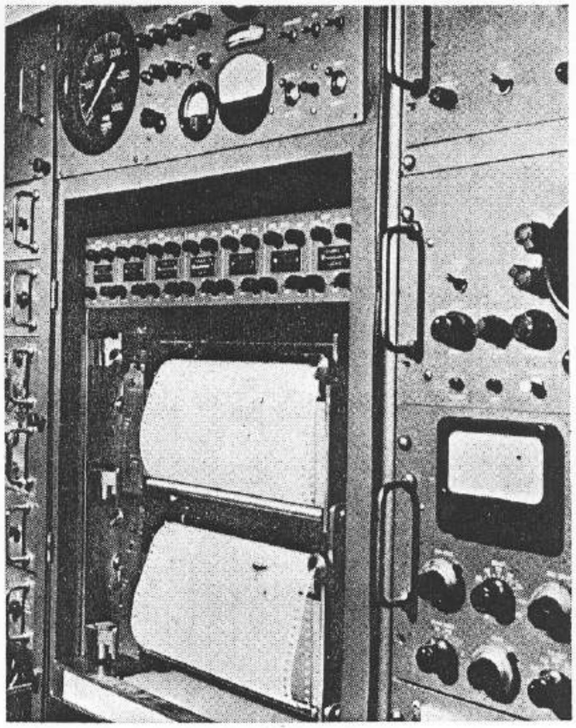
Induction logging is a superior method for investigating true formation resistivity, particularly for thin beds. It should continue to be a superior method for surveying empty holes and holes drilled with oil-based mud.

Typical logging arrangement, with drill-hole in foreground and logging monitors on truck.



Close-up view of logging monitors in field operation.

Logging truck in position to log hole. Cable-tool rig over drill-hole.



View of logging truck interior with recording monitors.

RADIOACTIVE LOGGING

Radiation logs are of 2 general types—those which measure the natural radioactivity of formations (gamma ray log) and those which show radiation reflected from or induced in the formations as a result of bombarding the formations with neutrons from a source in the sonde (neutron log).

GAMMA RAY LOGS

Gamma rays are high energy electromagnetic waves emitted by the nuclei of atoms. A nucleus will emit gamma rays either when disturbed by a collision with a particle or when naturally unstable.

For the sake of comparison, radio waves, which are produced by an oscillator and broadcast from an antenna of dimensions comparable with their wave length, vary in length from a few hundred meters for domestic broadcasting to a few centimeters for radar work.

Gamma rays are identical in every respect to these radio waves except that the wave length of the gamma rays is much smaller—the oscillator—antenna system is the small atomic nucleus itself.

When an atom of matter is disturbed in some manner, usually by some outside force, it oscillates, giving off the unwanted excess energy as a gamma ray, then returns to its former stable state.

In passing through matter, gamma rays do not penetrate a definite distance and then suddenly stop. Rather, they are gradually absorbed, each additional inch or foot of matter reducing their intensity by a given percentage.

Gamma ray absorption in heavy materials such as lead is very large, but in less dense materials such as limestone or water, the gamma rays can penetrate several inches at least.

A few elements in nature spontaneously emit gamma rays, namely those belonging to the radioactive families of uranium and thorium, plus the radioactive isotope of potassium. These are the gamma rays which are detected in the gamma ray log.

Of all the formations encountered in drilling wells, shales seem to contain the greatest concentration of radioactive salts. Therefore, the gamma ray log essentially distinguishes shales from other formations.

The recording equipment registers a deflection when the radioactivity increases. It is, in this regard, somewhat similar to the SP log with the added advantages of usability in both open and cased holes, empty or filled with anything.

The gamma ray log is used mainly for bed definition, determination of interfaces and correlation. In open holes filled with salty muds—where the SP curve lacks resolution—the gamma ray log will locate shales and shaly formations.

The gamma ray log is also used to control perforation depths.

Since human senses are not affected by gamma rays, they must be detected indirectly. As it passes through matter, the gamma ray strikes an electron and gives it considerable momentum. It is this fast moving electron which is detectable. At least 3 types of gamma ray detectors are currently in use in well logging.

In addition to differentiating shale formations, the gamma ray log is useful in wells filled with salty mud, which would not be readable with the SP log. One of the most important applications is in cased wells, either for workover jobs or for logging old wells which had been cased without electrical surveys. It is also useful in empty holes, where no SP curve can be recorded.

Since the gamma ray log can be recorded after the casing has been set, it is a very valuable tool for depth control in perforating jobs, where the problem is to place the perforator exactly at the depth of the formation to be produced.

NEUTRON LOGGING

Neutrons are electrically neutral particles. As they collide with other atomic nuclei they lose momentum. When they have been slowed down sufficiently, they can be readily absorbed by most materials.

In neutron logging, this absorption ("capture") by the atoms of hydrogen, silicon, sodium, chlorine, etc., results in the emission of very energetic gamma rays called "capture gamma rays."

The neutron logging method consists of placing a source of fast neutrons and a suitable radiation dectector close together in a sonde and lowering them into the borehole.

How far neutrons will travel before capture depends on the atoms they encounter. As the neutrons strike and bounce off atoms in the formation, they lose energy much as a billiard ball does when colliding with other balls. In this process, the moving ball loses much more of its energy when it hits a ball of equal weight than when it hits a much larger ball.

Since hydrogen atoms are the only ones which have weights almost equal to that of the neutron, they are the most effective in slowing down neutrons. Other atoms in rocks, like calcium or silicon, weigh some 25 times more than the neutron and absorb very little energy from a neutron, even in a head-on collision.

Besides the hydrogen content of the formation, the neutron log may also be affected by the chemical composition of the minerals of the rock and by the borehole conditions (diameter, type of mud, presence of casing). The effect of the chemical composition of the rock itself can usually be neglected, however. Some elements are strong neutron absorbers, but they are not abundantly present in sedimentary formations.

If the borehole conditions are about the same throughout the section surveyed, the intervals with a lower counting rate will correspond to higher porosity or greater shale content.

The neutron log is useful for delineating formations and for correlation in wells filled with water-based mud, oil-based mud or in empty holes, open or cased. Determination of porosity is probably one of its most important applications.

SONIC LOGGING

Sonic logging fundamentally involves the recording of the time required for a sound wave to travel through a specific length of formation. Such travel times are recorded continuously, versus depth, as the sonic sonde is pulled up the borehole.

The speed of sound in subsurface formations depends on the elastic properties of the rock, the porosity of the formations and their fluid content and pressure.

The sonic log is very detailed and reflects changes in lithology so accurately that it is perhaps the best log for correlation purposes.

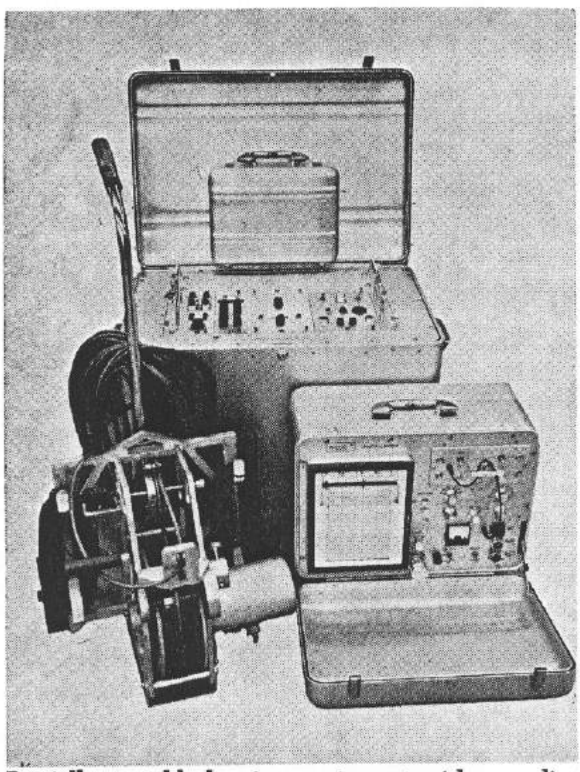
In moderate to hard formations, where low porosities are encountered, the sonic log is considerably affected by the amount of fluid in the formations, thereby giving reliable indications of porosity.

In soft formations of high porosity, sonic logs are more responsive to the nature of fluids and may sometimes indicate water or oil saturation.

The sonde used in sonic logging has a sound generator and one or more sound receivers. The body of the sonde is of low-velocity material to delay the reception of energy traveling through the sonde itself until after the sound pulse traveling through the formation has been received.

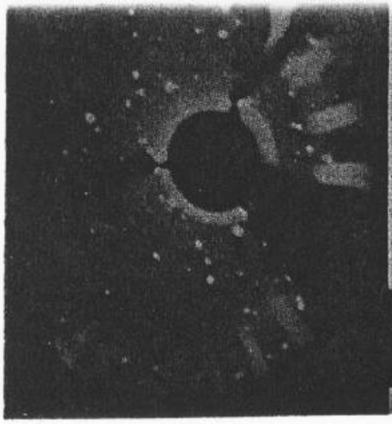
After the sound pulse is emitted by the generator, the energy passes through the mud and mud cake into the formation. The portion of this pulse energy which the receiver picks up has traveled the formations near the hole wall according to the path of least time. Its refracted "front", traveling through the mud cake and mud, causes the receiver to generate a signal.

For formations of uniform intergranular porosity under pressure, a relation between sonic velocity and porosity has been found. In medium to hard rock areas, porosity values can be obtained from the sonic log without regard to type of drilling liquid, hole size, invasion and adjacent beds.



Partially portable logging equipment with recording unit in front.

Totally portable logging equipment.



BOREHOLE GEOPHYSICAL TECHNIQUES

PHOTOGRAPHY SIDEWALL SAMPLING

PHOTOGRAPHY

Perhaps the next-best thing to drilling a 3′ hole and lowering a geologist into the ground for a first-hand visual inspection is to lower a camera into the hole and take some pictures—or even a TV camera and watch the show on a TV screen.

Early attempts to photograph boreholes met with the frustrations of pressure-crushed camera, oil-coated lenses and other problems. But experimentation led to development of a stereo camera that worked, capable of shooting 800 stereo sets on a single trip through the borehole.

Later, the Army Engineers developed the NX borehole camera—at a cost of $80,000—which fit down a 3″ hole and photographed a 360° slide of the hole wall as reflected on a conical mirror, along with a compass indicator and drift indicator. The camera was designed to use 8mm color movie film, but used the film a single frame at a time.

More recently, television cameras have been developed which can provide immediate and continuous visual inspection of a borehole wall —live and in color. Such cameras are typically under 3″ diameter, yet house the camera and about 1000 watts of lighting apparatus.

Suddenly, almost anything seems to be possible when the driller can actually see down the hole. In one application, a submersible pump fell to the bottom of an 89′ well and refused to be fished. A TV camera showed power lines and other cables had fallen with the pump and motor assembly and entwined themselves around the top of the assembly.

The camera was pulled and recovery tools were lowered, followed by the camera. With hands on the equipment and eyes on the TV screen, the operator was able to see what he was doing —and hoisted the pump without damage to the pump or the well.

TV cameras have been used to inspect screen deterioration and casing condition with great success. In one case, a pump has been pulled because the well was filling up with sand. A TV camera was lowered into the wire wound screen and grains of sand could be seen entering through 3 different holes at about 30 grains a minute.

Dynamite had been used to blow off the bottom of the casing in another well. Had it been blown clear off or only to one side? A TV camera showed clear jagged edges all around the casing. In another well, water was seen pouring through 100′ of perforations, cascading down and flowing out a thieveing formation.

ACOUSTIC PICTURES

A device which logs a continuous acoustic picture of a borehole wall uses sound waves instead of light. A motor rotates the downhole scanner-transducer which emits a pulsed narrow beam acoustic signal which travels through the borehole fluid, striking the wall of the hole. Some of the signal is reflected and picked up by the receiving transducer.

Any physical changes in the borehole wall show up as changes in picture intensity. In open holes, fractures, washouts and thin beds are clearly mapped. In casing inspection, this seismic viewer shows the exact size and shape of perforations, corrosion pits and casing splits.

SIDE WALL SAMPLING

Going beyond the stage where one can see visual images of a borehole, side wall sampling brings the borehole to the surface for naked eye inspection. Obviously, the greatest accuracy in identifying formations will result from having actual unpolluted samples on hand.

Percussion sample takers have been designed for taking cores from the wall of the borehole. For a long time, cores could be recovered from soft formations only. Today, hard formation bullets are able to take samples from almost any formation.

Also, special instruments for recovering fluid from the formations have now been engineered. These tools recover much smaller fluid samples than those obtained with conventional drill stem testers. But these samples are usually sufficient for formation evaluation. They also have the great advantage of being operated quickly at accurate depths without special conditioning of the well.

The side wall coring device shoots hollow cylindrical bullets which serve as core barrels. These bullets are driven by electrically ignited powder charges and remain attached to the gun by retrieving wires. Side-wall coring guns contain several bullets, each of which is fired separately at one of the levels to be cored.

Side wall samples are usually taken only in wells in which an electrical or radiation log has been run. These logs indicate the interesting uncored zones and those zones on which more information is desired.

In many formations, the large sample bullets recover cores which are big enough to permit quantitative determinations of porosity, permeability, fluid content and other data usually obtained by the analysis of conventional cores.

Formation testers and fluid samplers are designed for side wall sampling of formation fluid. No special well conditioning such as drilling small diameter holes(rat holes) is necessary.

The formation tester can take samples of from one to 5 gal and also record the formation shut-in pressure and the hydrostatic (mud) head.

The tester, in its collapsed position, is lowered to the formation to be tested, then expanded, forcing a pad tightly against the wall of the hole to form a seal between the mud column and the formation. 2 bullets are fired through the pad into the formation. Through these perforations and connecting tubes, the formation fluids flow into a chamber in the tool. When the chamber is filled, a valve is closed and the fluid sample sealed in at maximum pressure.

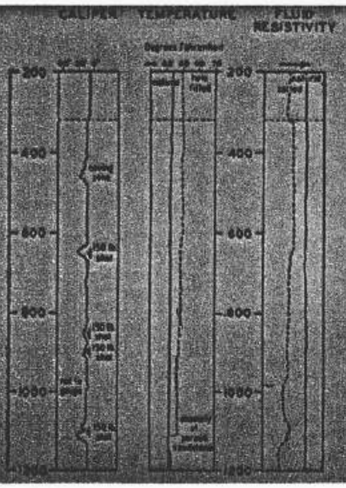
Throughout the entire test, electrical circuits permit a complete recording at the surface of the progress of the whole operation.

The fluid sampler operates in a manner similar to the side wall coring device, but it is designed to recover formation fluid rather than a core. The fluid sampler has selectively fired bullets, each connected by a metal tube to a small reservoir. When the bullet is fired, it penetrates the formation, then the nose opens and formation fluid flows through the tube into the sampler.

When the chamber is filled, the formation pressure is recorded at the surface. Then the tool is pulled upward, a movement which seals the sampler reservoir and pulls the bullet from the formation.

The fluid sampler can be used only in soft sands. The amount of fluid recovered is small and must come from the formation near the borehole. Nevertheless, unpolluted liquid is recovered, ordinarily.

Drill-hole camera apparatus.



BOREHOLE GEOPHYSICAL TECHNIQUES

FLUID LOGGING

TEMPERATURE LOGGING

It is a well known fact that the temperature of the earth increases with depth. The rate of increase (geothermal gradient) depends on the locality and the heat conductivity of the formations.

Temperatures encountered in drill holes are dependent not only on the natural geothermal gradient but also on the circulation of the mud. In a strongly circulated well, the mud is thoroughly mixed and its temperature tends to be uniform. When the drill pipe is removed and the well is allowed to stand, the mud temperature at each level changes at a rate which depends on the heat conductivity of the surrounding formations and on the volume of the mud. Almost all temperature surveys are made during the transition period, before thermal equilibrium has been reached.

Temperature surveys are useful for locating the height of cement behind the casing and the possible zones of channeling; locating the depth of lost circulation and for correlation with the electrical log for depth control in perforation operations.

Temperature measurements are made with a thermometer lowered slowly so it will have time to come to the temperature of the surrounding mud. Surveying speeds up to about 5000′ per hour may be used.

Because cement generates a great amount of heat as it sets, a temperature increase is generally observed at the level where cement is found behind the casing. Higher temperatures are usually recorded in caved sections where greater volumes of cement are deposited, permitting correlation with electrical logs.

For best results, temperature surveys are run a few hours after the cement is injected. With slow-setting cements, a wait of at least 12 hours is usual.

Used to locate an area of lost circulation, temperatures to the point of lost circulation would be cooler than that of the formations since mud taken by the formation is continually being replaced by the mud pumps.

Just below the point of lost circulation, the mud will have been idle in the hole for some time and will be at about the formation temperature. Temperature logs may be used to identify aquifers or perforated sections contributing water or gas to a well; to provide data on the source of water; as an aid in identifying rock types; and for calculating fluid viscosity and specific conductance from fluid-resistivity logs.

Temperature logs have been used to distinguish moving and stagnant water in a well and identify the source of recharge or injected waste water.

FLUID RESISTIVITY

Fluid resistivity logging is the measurement of resistivity of fluid between 2 electrodes in the hole. The fluid resistivity log may be used to locate points of influx or egress of waters of different quality, to locate the interface between sale and fresh water, to correct head measurements for fluid density differences, to locate waste waters and to follow the movement of saline tracers.

The resistivity of the fluid column is also important in interpreting SP, resistivity and neutron logs which may be affected by salinity changes.

FLOWMETER AND TRACER LOGGING

Some of the devices available for measuring vertical flow in water wells include the impeller flowmeter, the radioactive tracer ejector-detector and the brine ejector-detector.

Vertical flow measurements with these devices have measured relative aquifer permeabilities under pumping or injecting conditions. They are also useful for establishing the location of leaks in casing and as an aid in interpreting other logs.

The impeller flowmeter is simple and inexpensive but is limited to higher velocities and must be carefully calibrated. If tool movement can be held fairly constant, the flowmeter can provide a continuous qualitative log.

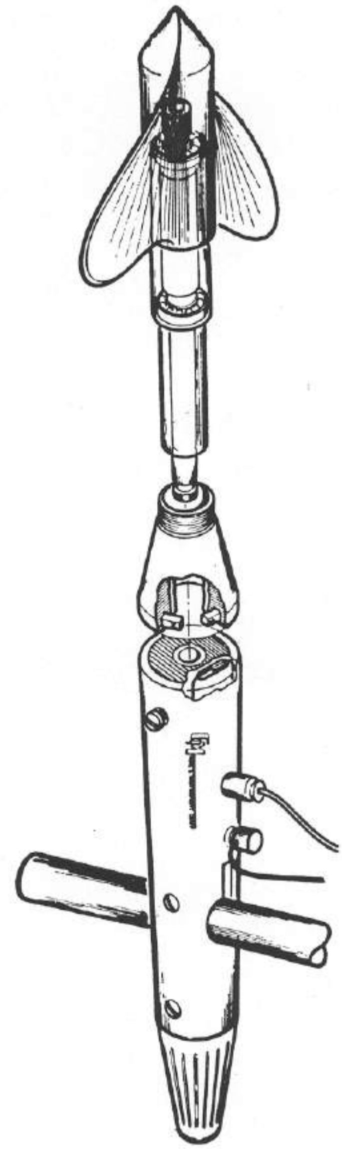
The radioactive tracer ejector-detector measures velocities of only a few feet per day. It is also the only method of measuring movement behind the casing.

A pump ejects a small amout of water-soluble tracer, usually an aqueous solution of iodine 131. The same radiation probes used for gamma logs can be placed near the ejector.

With this system, vertical flows up to 30′ per minute have been measured.

A brine ejector-detector system uses the same type of ejector pump and one of several types of fluid resistivity dectors. It uses less expensive, more readily available tracer that does not require licensing. But it is affected by the specific gravity of the tracer, has a lower detection sensitivity and can't reach flow behind casing.

Other in-hole tracers have been used to measure permeability, including insoluble radioactive tracers which are concentrated in the most permeable beds and a single-well pulse technique relating to the recovery time under pumping conditions of a slug of tracer placed in the well.



Magnetic-type flowmeter for down-hole current measurements.