Near-Surface Electromagnetic Surveying

The E&P industry typically focuses on deep formations, but frequently the near-surface layers also need to be evaluated. Land-based electromagnetic surveys provide insights into this often complex zone. The interpreted resistivities of these layers help map and define features for applications as diverse as seismic studies and aquifer delineation.

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The near surface of the Earth is a complex place, the result of dynamic action by wind, water and other forces of nature. In those first tens of meters below the surface, the jumbled detritus of weathering is gradually buried. The near-surface layers, like those below, vary in resistivity according to their mineral and fluid compositions. This property allows their investigation using electromagnetic (EM) surveys.

Often, surveys are performed using an artificial source of EM radiation, rather than the magnetotelluric (MT) radiation resulting from the interaction of the solar wind with the Earth’s magnetosphere. On land, there are two general methods of controlled-source electromagnetic (CSEM) measurement for generating the signal and detecting the response. The grounded-source method requires burial of source and receiver electrodes in electrical contact with the earth. The grounded receivers measure the response electric field; response magnetic fields are also measured to provide control during modeling. The grounded-source method uses a current loop on the surface to induce a variable magnetic field, and the same or another loop to detect the response signal.

The grounded-source method is efficient and sensitive to horizontal resistive targets because the electric field has a vertical component. The grounded receivers measure the response electric field; response magnetic fields are also measured to provide control during modeling. On land, however, the surface conditions must be suitable for creating and maintaining electrical contact. This prerequisite excludes the practical application of this method in large, arid dunes—sand grains are nonconducting. But in some areas, contact can be improved by drilling patterns of shallow holes for source and receiver electrodes and wetting the soil as the hole is refilled. Deeper investigation into the Earth requires stronger current sources, among other factors, and the high contact resistances on land mean this requires high-voltage systems to drive that current.

The inductive-source method does not require electrical contact, since the current loop generates a magnetic field through a time-varying signal. This field generates a response electric field, but because the electric field is largely horizontal, the process is not as efficient for imaging horizontal layers of resistive hydrocarbons as the direct injection of current using the grounded-source method. Again, both the electric and magnetic response fields can be measured using the inductive-source technique. Coils for the current loops are square and for near-surface investigation range from about 10 to 300 m [30 to 1,000 ft] on a side. Far larger loops have been used for deeper, but low-resolution, investigation.

A companion article (see “Electromagnetic Sounding for Hydrocarbons,” page 4) describes the basic physics of the EM interaction with the Earth and discusses marine EM studies. It also covers MT in detail, because the objectives of those studies are similar for land and marine environments. This article focuses on investigations...
using the inductive-loop method for near-surface imaging, illustrated by two WesternGeco cases from the United Arab Emirates. One study mapped an aquifer in Abu Dhabi for a water-storage project. The second determined near-surface resistivity variations in Dubai sand dunes, providing valuable input for making static corrections in a seismic survey of the area.

**Stacking Time Sequences**

Maxwell’s equations describe the basic physics behind the interplay of electric and magnetic fields in a time-varying current loop. A current loop generates a magnetic field. If the current changes, the induced field also changes. The opposite is also true: Changing the flux of a magnetic field within a conducting loop induces a changing current. A simple way to generate such a current is to move a magnet toward or away from a wire loop. The movement changes the flux through the loop, inducing a current. This current induces a response magnetic field oriented to oppose the change in flux through the loop caused by the moving magnet.

No actual magnet is required for this effect to take place. One coil with an imposed time-varying current sets up a time-varying magnetic
field in response. Current is induced in a second coil positioned close enough to experience the changing flux. This is the configuration of a transformer (left). Energy passes from one circuit to the other through the changing magnetic field.

One method that uses inductive measurement for evaluating the near surface is a time-domain electromagnetic (TDEM) survey. A conducting loop of wire set out in a square on the surface of the Earth acts as the first coil, and the second loop forms in conducting formations of the Earth itself. The primary magnetic field from the transmitter loop generates horizontal currents, called eddy currents, immediately beneath the loop. These currents induce a response field that can be detected at a surface receiver loop, but this field also travels farther into the subsurface, generating progressively weaker eddy current loops with larger radii and smaller response fields (below).²

The transmitter and receiver loops can be the same wire coil when an appropriate time sequence of current steps is applied, or coxial but separate coils in a typical setup. In all inductive-loop TDEM surveys, the time sequence begins by turning the current on to a constant DC value. Sufficient time elapses for transient responses in the subsurface to decay. Then, electronics shut the current off in a rapid, controlled ramp, inducing a known electromagnetic force in the immediate subsurface. The transient electromagnetic force generates eddy currents, producing a secondary magnetic field that decays with time. The secondary field is detected by the receiver coil. After enough time has elapsed, the sequence repeats with opposite polarity. Stacking many repeated responses improves the signal/noise ratio.

As the eddy currents move progressively deeper into the subsurface, the response field contains resistivity information about deeper layers. Fundamentally, the resistivity variation with depth determines the rate of decay of the transient; higher conductivity results in slower decay. Inversion of the stacked data from a TDEM sounding reveals the distribution of near-surface resistivity.

The measured signals are very small, so land surveys must consider and avoid, if possible, any sources of noise. Electric trains, power lines, electric fences, buried utility cables, pipelines and water pumps distort the local measurement; large temperature variations and wind impact stability; and variations in soil moisture and permeability affect uniformity.³

TDEM is not commonly used directly in oil and gas exploration, although it has utility in evaluating surface statics for seismic studies. The method is applied widely for exploration within the mining industry, employing both terrestrial and airborne sources. It is also a tool for environmental and water-resource management, as shown in the first of the following case studies from the Middle East.

**Sounding for Water Storage**

A recent land-based EM application helped to locate potential water-storage sites in the UAE.⁴ The Environment Agency–Abu Dhabi (EAD) is managing a study for the government to evaluate storage plans for 30 billion British imperial gallons [136 million m³, 36 billion galUS] of fresh water in the northeast area of the Emirate.⁵ The country wants a freshwater reserve for emergency periods and to meet peak

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² Land EM Figure 21

³ Land EM Figure 22

⁴ Land EM Figure 23

⁵ Land EM Figure 24
The water for this aquifer storage and recovery (ASR) project will be transported via pipeline from a water-desalination plant in the Emirate of Fujairah.

EAD retained Schlumberger to identify and test a potential ASR site. This involved defining the subsurface storage zone and surrounding formations, aquifer thickness and related hydraulic parameters. Schlumberger selected a preferred site and constructed three pilot wells, which were tested to determine the aquifer's potential.

Geologic studies of the area found that deep-seated faults had been reactivated in the Late Tertiary Period by the northeastward displacement of the Arabian Peninsula, resulting in a series of tightly folded faults. The overlying layer of Quaternary Period sediments, consisting of eolian sands and alluvium, were primarily deposited along the reactivated faults and in the synclines between them, giving the sediment thickness a directional bias. The directionality can influence groundwater flow, creating a preference for flow parallel to the structure.

Schlumberger evaluated this geologic structure in 2006 during the drilling, logging and testing periods. Logs from the pilot wells indicated a resistivity contrast between the targeted sand-and-gravel aquifer and the underlying clay-rich layer. Because TDEM data are useful for aquifer characterization, the evaluation over the ASR site included a survey to define the lateral extent of the aquifer—necessary to compute the potential water-storage volume. In a time-domain survey, the apparent resistivity of the underlying formations is determined from the time variation of the electric and magnetic response fields. For the ASR study, the same set of coils placed on the surface was used for both current and receiver loops. The survey covered a 6- by 7-km [3.7- by 4.4-mi] area.

A 1D Occam inversion at each receiver yielded resistivity input for constructing a 3D model. The maximum depth obtained by the inversion was about 250 m [820 ft]. Resistivity logs from the three wells were compared with the inversion results at adjacent sounding locations (right). The top of the underlying clay unit is clear in the eastern part of the survey area but less obvious in the western part.

Comparison of TDEM soundings with resistivity profiles from logged wells. The TDEM resistivity measurements from soundings correlate closely with the resistivity logs from adjacent wells. The soundings at S049 and S013 show reasonable correlation for the contact between the aquifer and the clay-rich unit below (violet), which is true for most other soundings in the eastern part of the investigated area. The contrast is not as clear at S071, where the more resistive lower unit does not provide a sufficient contrast for the TDEM measurement. This trend follows for most of the soundings in the western part of the survey. The top of the water table (blue dashed line) was determined from a map of the water depth by interpolating between wells in the area.


5. A British imperial gallon is equivalent to 1 galUK.

6. An Occam inversion is a smooth inversion that does not predefine the number of layers.
The TDEM data clearly show a discontinuity in the resistivity distribution in the clay unit (left). There is also a difference in resistivity between the eastern and western compartments; the western part exhibits significantly greater resistivity at a given depth. The anomaly aligns with a seismically mapped thrust fault. The seismic interpretation was based on a survey acquired in the early 1980s and reprocessed in 1992 to highlight the shallow structures.

The shallow units above the anomaly are expected to show some structural complexity; they exhibit rapid variations in saturated thickness and possibly no saturated thickness in some areas. On the eastern side of the discontinuity, the horizontal extent of saturated thickness is suitable for an ASR unit. The western side of the discontinuity shows some potential, but has a larger risk: The interpretation in that area has a greater uncertainty because of the poor resistivity contrast between the saturated sands and the underlying clay. The discontinuity in the clay formation should not be seen as a complete hydraulic barrier in the shallower aquifer layer. Paleochannels or tear faults—those striking perpendicular to the overthrust fault—are expected to provide preferential flow paths from east to west across the line of the discontinuity.

This TDEM study suggests that around 4 billion imperial gallons [18 million m³, 4.8 billion galUS] of water can be stored at this site, giving it the capacity for daily production of more than 20 million imperial gallons [91,000 m³, 24 million galUS] for 200 continuous days.

Mapping the Dunes

Within the same regional setting as the water-storage site, a 2D seismic survey was conducted for Dubai Petroleum Establishment (DPE). The same clay layer forming the base of the storage-site aquifer is present in this area; it provides a marker for the base of the weathered surface layer. The depth of the clay varies across the survey area, and lines of dunes add local variation.
to the depth of the weathered layer. Sand dunes generally exhibit low seismic velocity, and defining the velocity variation and thickness of the surface layer is crucial for deriving a long-wavelength static correction for the seismic data.

The seismic crew drilled several upholes to log the velocity of the surface and underlying clay layer. The upholes typically were at seismic-line intersections and, for practical reasons, away from the higher dune crests. However, this pattern often does not sample the near-surface variations found in sand dune areas, so finer sampling was desired. DPE elected to use a TDEM resistivity survey to map the area because it would be more cost-effective than drilling more upholes and would avoid additional drilling on the environmentally sensitive dunes.

The survey comprised 505 sounding sites using square loops of 50 m [164 ft] on a side, except for a few sites that used 75-m [246-ft] square loops for deeper penetration. Spacing between sounding points was generally about 1,000 m [3,280 ft]; GPS was used to position the sites. The effective time for decay ranged from 0.01 to 10 ms; the pulse repetition rate was 6.3 Hz.

Given the subhorizontal nature of the zone of investigation and its shallow depth compared with the TDEM station spacing, 1D resistivity inversion modeling was selected for the analysis. Two 1D resistivity inversion methods were applied. The first one incorporated about 15 layers extending to a depth of about 200 m [650 ft]. Layer thickness increased logarithmically with depth. Resistivity was a free parameter, and this inversion yielded a detailed, smooth variation of resistivity.

The detailed fit provided a starting point for the second inversion. Termed a layered fit, it used the minimum number of layers required to fit the data to less than 5% root-mean-square misfit. This was typically two to five layers. Analysts selected the starting definition of these layers from the detailed fit. The layered model generated stronger resistivity contrasts than the detailed one.

Interpreters created a 2D model with grid blocks 200 m wide and 5 m [16 ft] deep along a seismic line. They used the sounding sites along the seismic line to evaluate the surface layering. Model resistivity values were obtained by interpolating between the 1D smooth inversions at those sounding sites. The result is a detailed description of the location of the bounding clay layer at the bottom of the low-velocity zone. The resistivity data were not calibrated to seismic velocities.

The seismic processing team used these maps during the estimation of the surface static corrections. The velocities for the surface zone were interpolated from velocity measurements taken at the upholes. The TDEM approach gave the seismic interpreters a geologically consistent way to remove the effects of the laterally varying sand velocities. The resistivity analysis also highlighted variations within and below the low-velocity weathered layer.

**Sounding Deeper**

Both case studies used TDEM methods to examine near-surface features. However, because using inductive-source techniques is inefficient for defining deep targets, the method is not the exploration tool of choice for examining deeper structures. The industry is improving techniques for using the alternative, grounded-source method to inject current into the earth.

The source for the grounded method must be able to inject a large current at a voltage that is sufficient to overcome contact resistance in areas where the soil is dry. This combination has been difficult to achieve. The method using direct injection of current is more sensitive to resistive targets, making it a more likely method than the inductive-loop option to provide a direct hydrocarbon indication.

—MAA