

## Technique Improves Subsalt Imaging

By Stewart K. Sandberg

HOUSTON—Combining marine magnetotelluric (MMT) data with seismic and other surface geophysical techniques can reduce risk in mapping complex geological settings such as the Lower Tertiary trend and Gulf of Mexico subsalt-related plays.

Downhole geophysical techniques, such as wireline logging and logging-while-drilling, routinely combine information from several types of measurements in order to minimize ambiguity and increase confidence in the resulting reservoir characterization. By contrast, surface geophysical imaging is dominated by seismic methods, often performed as stand-alone projects.

With the development of new surface imaging techniques, it is now becoming increasingly common to reduce risk by adding information from other geophysical measurements, such as traditional vertical gravity and full-tensor gravity (FTG), magnetics, and/or electromagnetic methods. Combining several measurements is particularly valuable when imaging around salt bodies or other areas of complex seismic velocity variation.

At present, the marine geophysical market consists of controlled-source electromagnetic (CSEM) solutions to map thin resistive bodies, and marine MMT to outline large basin features. Magnetotellurics will provide an additional measurement of important features that create huge uncertainties in seismic data, such as the base of salt and basalt bodies—both key attributes in accurately interpreting geologic structures underlying subsalt.

The impact of this already is being seen in the Gulf of Mexico, where mag-

netotelluric data is integrated with wide-azimuth (WAZ) data in order to greatly improve complex subsalt images. Electromagnetic measurements are nondistinctive, while seismic measurements are unique. Therefore, CSEM and MMT are extremely complementary to seismic data. The key to extracting the value is through integrating these complementary measurements.

A new imaging technology called multimeasurement constrained imaging (MMCI) has been developed that improves salt body mapping and reduces risk in subsalt exploration programs by combining seismic technology, full-tensor gravimetry and MMT. Considerable success has been experienced to date using 3-D seismic with prestack depth migration techniques to improve the understanding of potential reservoir structures lying beneath salt formations. These techniques can be made more efficient and economical if MMCI techniques are applied first.

### Marine Magnetotellurics

Magnetotellurics is a natural-source, electromagnetic method of imaging subsurface structures. Natural variations in the earth's magnetic field induce electric (telluric) currents under the earth's surface. Measurements of orthogonal components of the electric and magnetic fields created by these induced currents can be processed and modeled to image the resistivity structure of the subsurface.

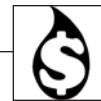
The MMT method generally refers to a magnetotelluric survey in which the data are recorded by receivers placed on the seafloor. Seawater attenuates higher-frequency data, and current flow is not only beneath the receiver, but also in the sea-

water above it. Electromagnetic investigations of the earth beneath the seafloor have a long history. Seafloor magnetotelluric instruments have evolved to be capable of reliably measuring the higher frequencies associated with structures shallower than the oceanic mantle and crust.

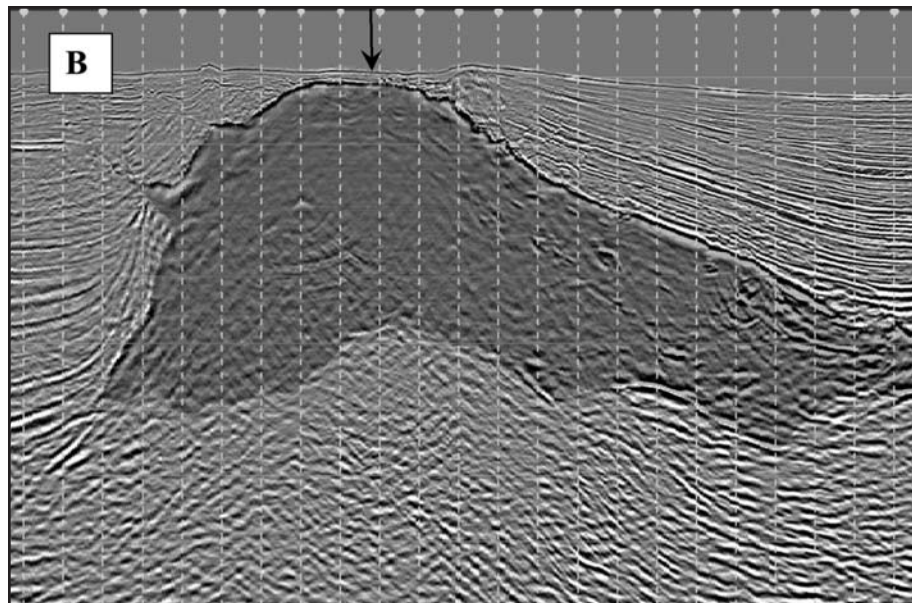
A self-contained magnetotellurics station consists of electric and magnetic field sensors and a data logging system that is deployed on the seafloor from a suitable survey vessel. The marine magnetotellurics station includes an anchor to hold it securely to the seafloor, an acoustic release mechanism to release the anchor, and flotation to bring the station to the surface. The receivers are tracked and located acoustically. The receivers are recovered and the data are downloaded, processed and interpreted in terms of electrical units first, and then geologic formations and structure.

The field components measured on the seafloor are influenced by the resistivity of the geologic formations beneath the site, and the resistivity of the subsurface (as a function of frequency) can be computed from the electromagnetic field measurements. Resistivity (as a function of depth and lateral position) is obtained through inversion and modeling of the resistivity/frequency relationship. Geologic structure is then interpreted from an analysis of the resistivity data and its relationship to corresponding seismic data and well logs.

As with any geophysical method, there are limitations on the depth of burial, formation thickness and resistivity contrasts that will affect the viability of an interpretation. The primary difference (other than the location of the receiver site) between MMT and the more famil-



**FIGURE 1**  
**Conventional Seismic Data with Interpretation of Salt**



iar land magnetotellurics is that the higher frequencies are attenuated by the conductive seawater above electromagnetic receivers in the marine environment, limiting the high-frequency range, and thus, the minimum depth of investigation.

**Mapping Complex Salt Bodies**

Mapping salt bodies in the Gulf of Mexico can be a challenge. Salt bodies often have complex structures and geometries resulting from their history of mobilization through the sedimentary section. Salt generally has a higher seismic velocity than the surrounding sediments that can diffract seismic ray paths and reduce the propagated energy that is transmitted to the sediments below. Rich-azimuth and wide-azimuth 3-D seismic acquisition geometries and coil-shooting circular geometry acquisition can increase the illumination of subsalt sediments. MMT brings valuable additional information.

In addition to higher seismic velocity, salt bodies in the Gulf of Mexico have a higher resistivity than the surrounding sediments. Resistivity is important because rock types important to hydrocarbon exploration can be differentiated on the basis of resistivity value. While magnetotellurics cannot be used to detect oil directly, the identification of favorable rock types and the presence of geologic structures capable of trapping hydrocarbons are critical to successful exploration.

Successful applications of marine mag-

netotellurics have emphasized difficult seismic areas, where because of the presence of volcanics, carbonates or salt, the seismic data are difficult to interpret or ambiguous. MMT leads to the deflection of telluric currents, which allows mapping of the salt using the MMT methodology.

There are several examples of using magnetotellurics to map salt bodies for hydrocarbon exploration. Magnetotellurics has been used onshore, for example, where seismic has had difficulty because of velocity inversion associated

with both salt and carbonate structures. In marine magnetotelluric applications, the base of salt has been delineated to an accuracy of better than 10 percent using both 2- and 3-D modeling. Salt structures, although fully 3-D, are shown to be adequately interpreted by means of 2-D inversion when the horizontal aspect ratio is greater than 2.0. Modeling results of MMT data collected over the Gemini prospect in the Gulf of Mexico illustrate the successful results of using 2-D modeling of a 3-D structure.

**Gulf Of Mexico Case Study**

An MMT survey performed in the Gulf of Mexico in 2006 was designed to map a salt body in the region. The base of the salt was difficult to interpret from conventional seismic data. The MMCI approach was used to develop interpretations that combined MMT, FTG, and conventional and WAZ seismic data. The study compared the results of 2-D interpretation of the MMT data versus a 3-D modeling approach.

A total of 171 receiver sites were occupied, making it the world’s largest MMT survey at the time. Receivers were positioned at 1.25-kilometer intervals along six 2-D lines with additional fill-in sites to make a 3-D grid in the middle part of the survey area around the well.

During the course of this project, information became available from a recently drilled well that provided the true base of salt at that position. Figure 1 shows the conventional seismic data with

**FIGURE 2**  
**2-D Smooth Inversion Modeling Result (Orange = High Resistivity)**

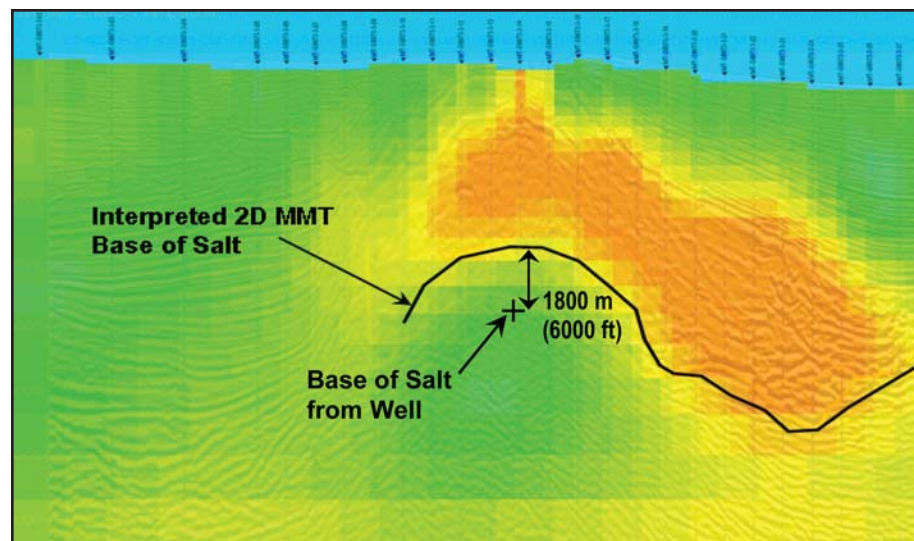
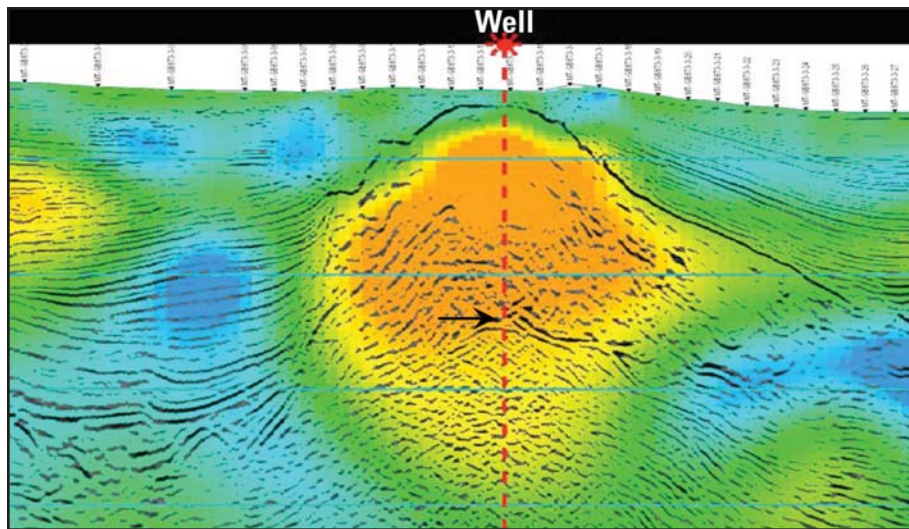




FIGURE 3

3-D Smooth Inversion Modeling Result  
(Orange = >23 ohm-m Resistivity)



the interpretation of salt. The vertical lines are MMT receiver sites, and the well position is indicated by the arrow.

Figure 2 shows a 2-D smooth inversion model and interpreted base of salt along a line oriented perpendicular to the strike of the crest of the salt body. Areas of high resistivity are colored orange. The interpretation of base-salt on this 2-D model is 1,800 meters too shallow where the line intersects the well.

The general discrepancy of a shallower base of salt in many 2-D models, and a deeper base encountered by the well, resulted in changing the modeling from 2-D to 3-D. In this case, the salt distribution in

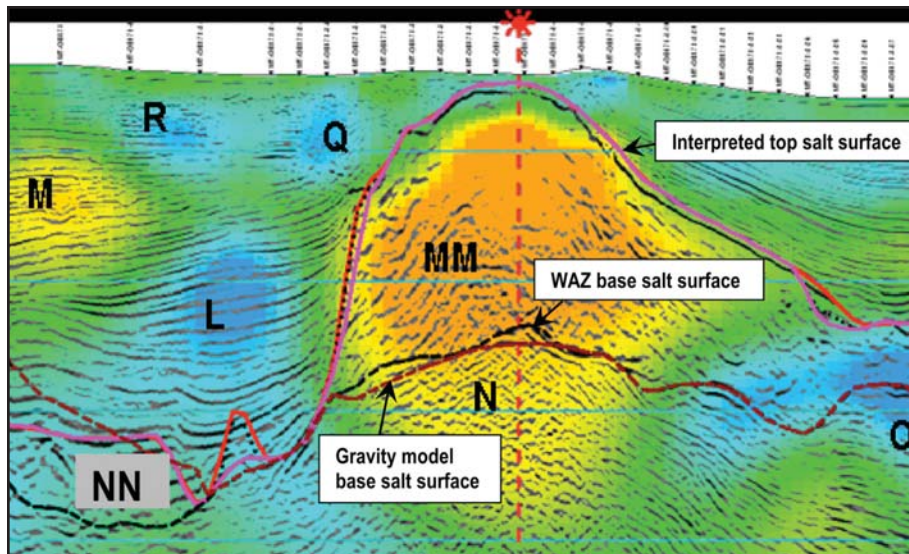
the study area was too complex for a simple 2-D interpretation of the MMT data.

Figure 3 shows a 3-D smooth inversion modeling result in the same location. The 23 ohm-m resistivity contour coincides with the depth of base-salt at the well location. In addition to the high-resistivity region coinciding with the main salt body, other complex resistivity variations are indicated by these 3-D modeling results. Orange denotes areas with greater than 23 ohm-m resistivity. The wide-azimuth seismic image is in the background, and the arrow marks base-salt at the well.

Figure 4 shows the 3-D resistivity

FIGURE 4

Interpretation Incorporating MMT and FTG Data



modeling result with an interpretation based on a combination of WAZ seismic, MMT, and FTG data. The wide-azimuth seismic image is again in the background.

Improved Modeling Results

While 2-D interpretation of the MMT data provided an incorrect base of salt at the well location for the complex salt body investigated, 3-D inverse modeling was able to determine not only the correct base-salt, but also produced additional detail of the subsurface. An interpretation that combined multiple geophysical methods (seismic, MMT and FTG) provided a model that was considered to be an improvement on any model based on using these methods individually.

Electromagnetics are perhaps the most significant technology to be added to the geophysical portfolio in recent years. The uptake by the industry is encouraging and continued growth is envisioned as the technology is further proven. Different geophysical methods sample either different physical properties (such as resistivity, acoustic velocity, density), or sample the same physical property in different ways (conventional seismic versus wide-azimuth seismic acquisition). The aim is increased resolution, enabling the best possible understanding of the relevant attributes of the exploration problem. However, there are intrinsic strengths and weaknesses of each geophysical method. A combined interpretation that explains all data sets can combine the strengths of all methods and provide a more complete image of the subsurface.

New volumes of marine magnetotelluric data continue to be acquired in the Gulf of Mexico. The MMT data are being incorporated with FTG data into a joint inversion, which is then combined with the latest WAZ 3-D seismic data to form an MMCI data set. The continued development of a portfolio of products and services that integrate different and complementary measurements will produce the best results possible. □

**STEWART K. SANDBERG** is the senior geophysicist for WesternGeco Electromagnetics. Based in Houston, he joined WesternGeco in April 2006. Sandberg holds a master's from the University of Utah and a doctorate in geophysics from Rutgers University.