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Exploration with controlled-source electromagnetics under basalt cover in India

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Recently, there has been increased interest, mostly offshore and to some extent onshore, in the controlled-source electromagnetic (CSEM) method because of its ability to map thin resistive layers sometimes associated with hydrocarbons.

CSEM can complement other geophysical techniques in difficult areas, in particular areas with basalt cover and high seismic velocities. One CSEM method, long-offset transient electromagnetics (LOTEM), has intriguing possibilities because its acquisition/processing can be carried out in a manner similar to seismic surveys. In addition, the number of measurements per day is relatively high and the subsurface resistivity structures are reliable. Unlike marine CSEM, where we often look for a resistive reservoir in a conductive background, land EM methods are also often looking for resistive sediments to infer structural or stratigraphic information.

This article describes how LOTEM was used for subbasalt imaging in India in the late 1980s. A well drilled in the late 1990s confirmed the LOTEM interpretation which was based on various 1D inversion methods and 3D modeling.

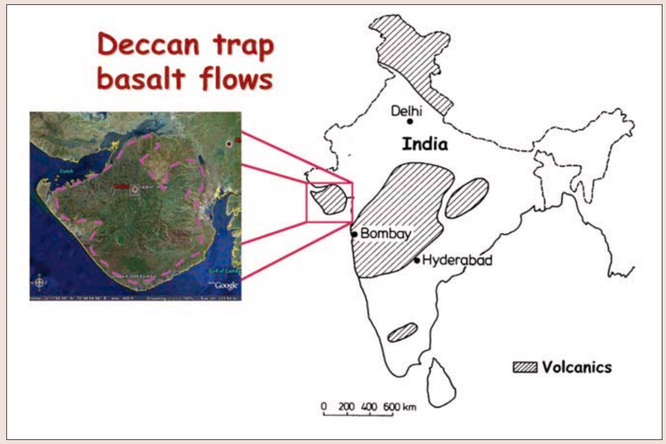


Figure 1. The LOTEM survey was on the Saurashtra peninsula in northwestern India. The dashed outline on the satellite image on the left shows the basalt cover.

Background. The objective of the LOTEM survey was to map Mesozoic sediments below the Deccan Trap basalts in northwestern India (Figure 1). The oil-producing Bombay High area is to the southeast in the Gulf of Cambay and an exploratory well with oil shows was drilled to the north in the Cutch, the gulf north of the Saurashtra peninsula. The key objective for the LOTEM survey was to determine if sufficient reservoir rock was below the Deccan traps in the basalt flows.

LOTEM uses a grounded wire transmitter and an induction loop and electric field receivers (Figure 2). The transmitter is kept stationary while the receivers are laid out in a spread that is moved in a manner similar to seismic surveys. Present configurations use second-generation 24-bit multichannel systems. At each site one can mix the field components so that two components of the same type are always present at adjacent sites. This prevents data gaps and allows calibration across/along the spread to overcome near-surface statics, being a broadband system.

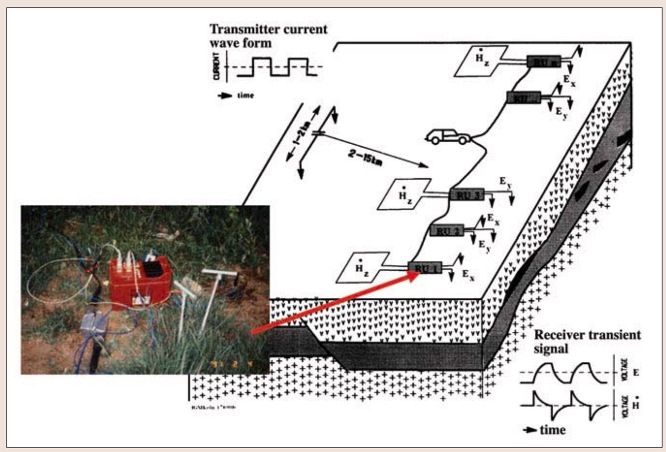


Figure 2. LOTEM survey configuration. On the left is the controlled-source transmitter and on the right is the receiver layout, including electric and magnetic field sensors.

The induction currents generate a secondary electromagnetic field, which is recorded as a time series and stacked. The LOTEM signals, as shown on the right of Figure 2, are recorded in raw form and then digitally processed prestack to get maximum signal-to-noise ratios including prestack deconvolution (Strack and Vozoff, 1996). After prestack processing, the data are stacked and, after further poststack processing, converted into apparent resistivities which are then either inverted or directly imaged.

Special care must be taken in all steps because preservation of the original data amplitude and timing is essential.

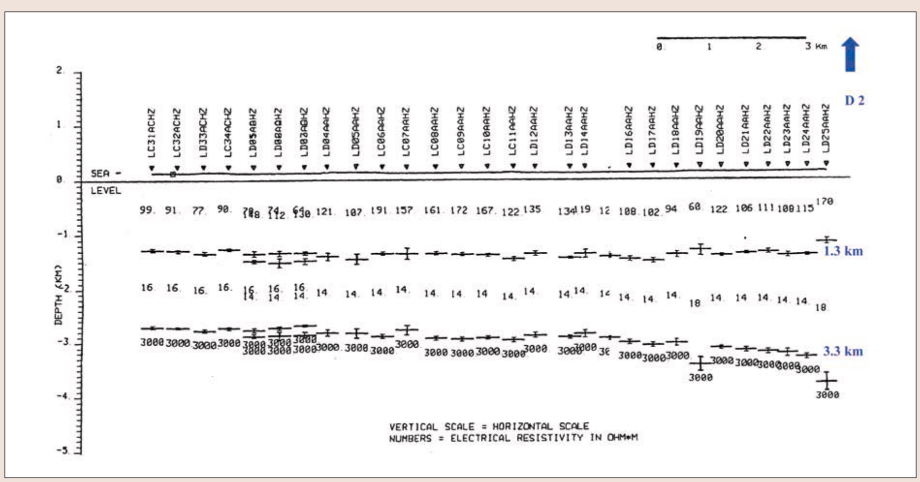
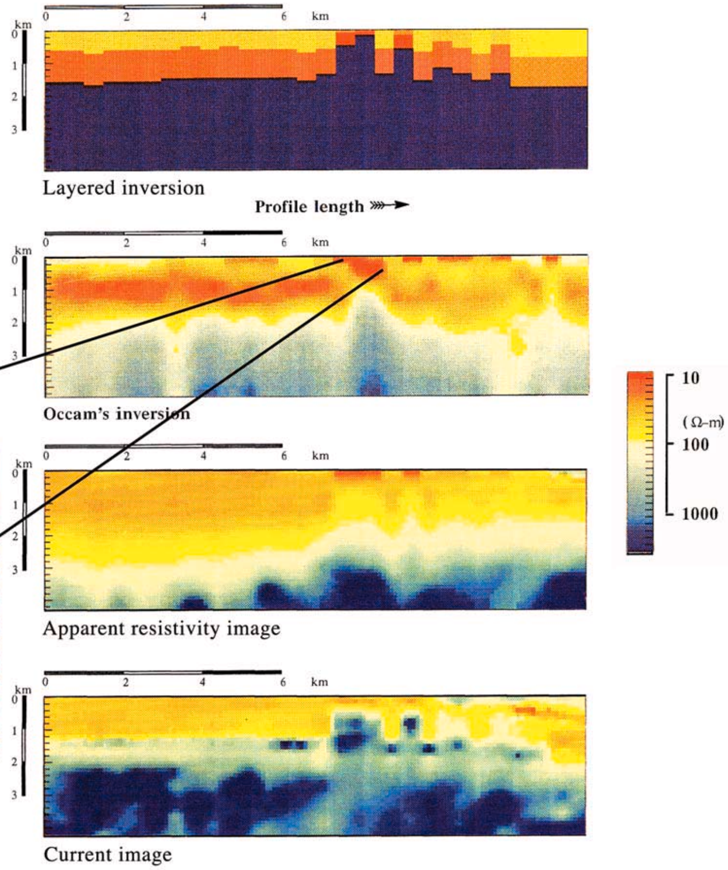


Figure 3. Resistivity interpretation results for one EW profile showing the conductive sediments below the trap basalts. Here, inversion was used. The small error bars indicate the 95% confidence interval and are influence in the inversion by the data errors. Well D 2 is a few km northeast from the end of the profile. The well-derived layer boundaries are indicated on the right.



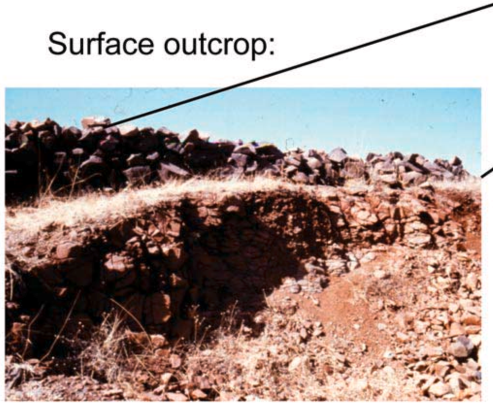


Figure 4. Examples of various inversions and images for a profile east of Rajkot that exhibits a dyke-like structure. The top two diagrams on the right show the layered and smooth inversion results. The bottom two diagrams show different inversion images, one based on apparent resistivity transformation and one based on a spatially varying image current. Below is a picture of the surface outcrop.

Field work and interpretation methods. The data analyzed in this case study were acquired in the late 1980s during field work sponsored by the German government and India's ONGC. The survey, covering around 400 sites in Gujarat, was carried out over three months. The acquisition parameters were based on forward numerical modeling of the survey response and the resistivities from a prior deep geoelectric sounding survey. The data were of excellent quality, and interpretation was straightforward.

Figure 3 shows an example of one-dimensional stitched inversion using both electric and magnetic fields. The low-resistive sediments can be clearly seen under the more resistive basalt cover and above another resistive unit (later to be found to be basalt). The small error bars of the layer interfaces reflect the high data quality. Most inversions were run automatically overnight.

However, in a few cases, a more sophisticated approach was needed. Figure 4 shows several one-dimensional inversion results that all indicate a structure in the section. Notice the break in the horizontal structure that looks like a dyke. The four displays show two inversion results at the top and two direct data images at the bottom. Because the one-dimensional inversion requires a starting model and one can be quite off in that, different inversion and imaging algorithms were used, layered inversion and smooth inversion (Constable et al., 1987), and the data images are apparent resistivities and current images (Strack, 1992). The latter are a more direct presentation of the data. Both inversions and images consistently show the dyke-like 3D structure. At the figure's left is a photo of the outcrop at surface where dyke-style structure was confirmed. Recent inspection of the area using satellite images (Google Earth) shows a dyke-like feature with a slight dip.

This can be further verified using 3D modeling. Figure 5 shows a plan view of the model. The transmitter and receiver

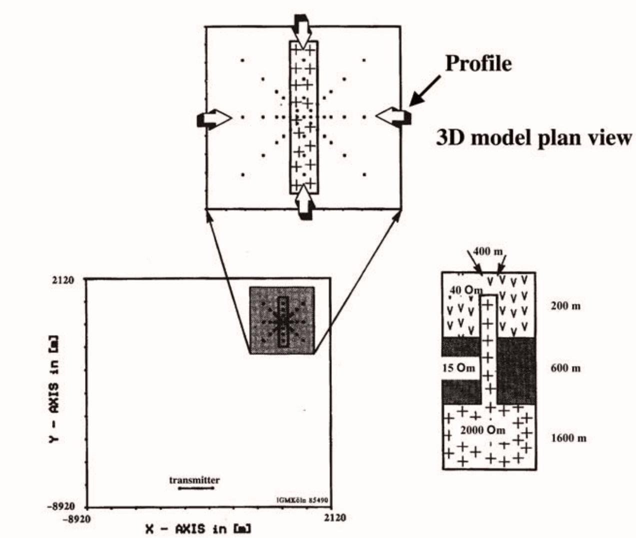


Figure 5. Plan view and section view of the 3D model.

locations are as in the field survey but with shorter profiles and diagonal across the dyke. Here, we will focus only on two objectives of the 3D modeling: first, confirmation that the anomaly is a resistive dyke and that in the presence of this anomaly we can use the total conductance to map the structure of the anomaly. Further aspects such as vertical location of the anomaly and influence of the 3D anomaly on 1D inversion were investigated and supported the validity interpretation methodology. The model is finite in extent, but for practical purposes, it can be considered infinite.

Figure 6 shows a 3D model section view along the profile at the top and current images below. The current images were derived from the synthetic data of the 3D model using an algorithm described in Strack (1992). This image shows similarities of the dyke and thus confirms that the 3D intrusion is resistive (conductive anomalies could not generate images with characteristics similar to the data). It also confirms that we do not necessarily see a dyke-like feature from the data, and the dyke could actually be dipping to one side.

Subsequently, we generated a large set of model data for several profiles and used different inversion and modeling methods (Kriegshaeuser, 1992). Here, we have selected the one used by ONGC for the interpretation. Figure 7 shows a plan view of the total conductance for the first and second layer across the dyke structure. The diagrams show the results after the 3D synthetic data were inverted with a 1D model (after adding noise). The top shows the inversion results for the vertical magnetic fields and electric fields. The bottom shows the joint inversion results of both field components—the electric field, E, and the magnetic field, H. The electric field is clearly more sensitive to the resistor while the magnetic field does not see the resistor in the total conductance of layer 1 and 2 which is derived from the anomalous behavior of the total conductance over the 3D resistive anomaly. In fact, only the electric field alone clearly outlines the dyke. The Rajkot field data have two third electric field measurements, which is why you see the resistive dyke in the field data. (Electric fields are more sensitive to resistors than magnetic fields.)

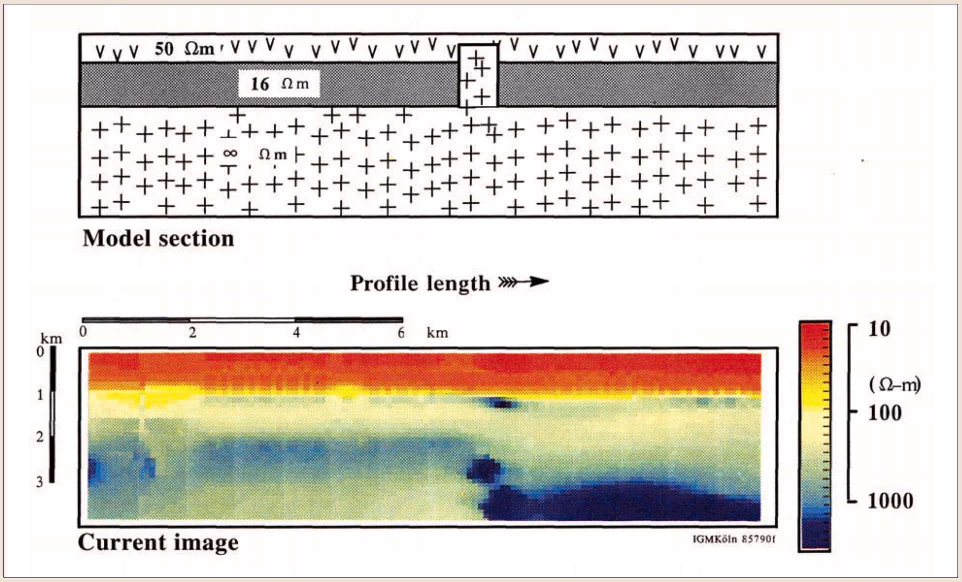


Figure 6. *3D model section view (top) in WE profile direction and current image of the 3D model data.*

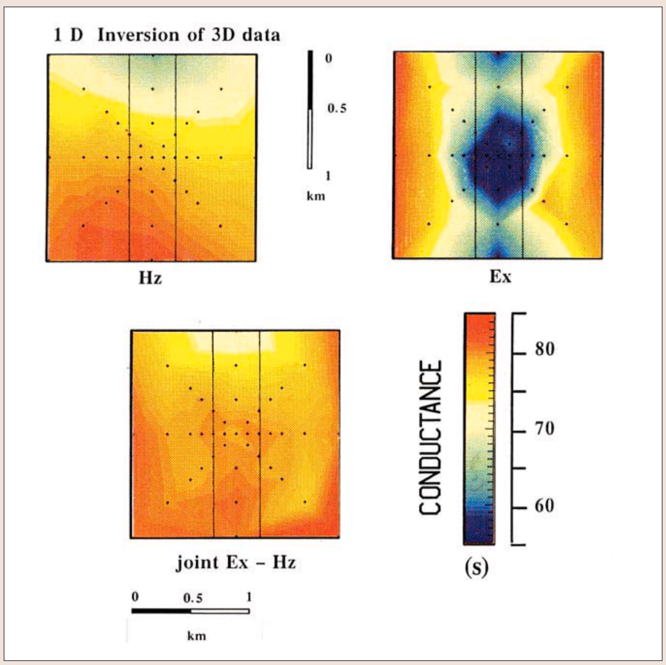


Figure 7. *Plan view of the total conductances for the first and second layer across the dyke structure. The diagrams show the results after the 3D synthetic data were inverted with a 1D model. On the top are vertical magnetic fields and electric fields shown respectively. The bottom shows the joint inversion results of both (After Kriegshaeuser, 1992).*

One part of the final interpretation included the derivation of a total conductance map. These maps are used to estimate the amount of conductive sediments below the trap basalt. Before deriving the total conductance map, the data were corrected for 3D effects using the dc components of the electric field measurements (dc limits). Figure 8 shows the total conductance map which indicates a thickening of the sediments below the basalt and what was then thought to be resistive basement in the darker reds to the northwest.

The data were integrated with gravity, deep seismic, and deep electrical sounding, and a well was drilled mostly on the LOTEM results. The interpretation from the well report is shown in Figure 9. Trap basalts are in the well in the top and bottom. The interface boundaries are within 90–95% of the depth indicated from well logs.

The case history shows that LOTEM is a viable method to obtain geophysical information from below basalt covers. Large data quantities were acquired using a normal seismic crew. The data were interpreted including 1D and 3D mod-

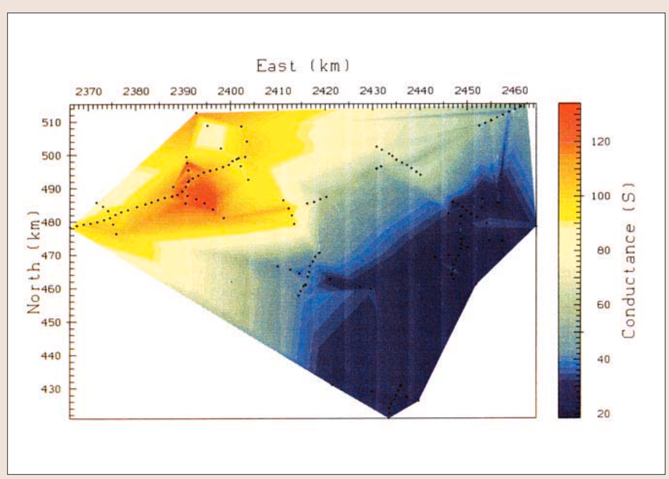


Figure 8. *Total conductance map survey area. The Lotem stations are shown as black dots.*

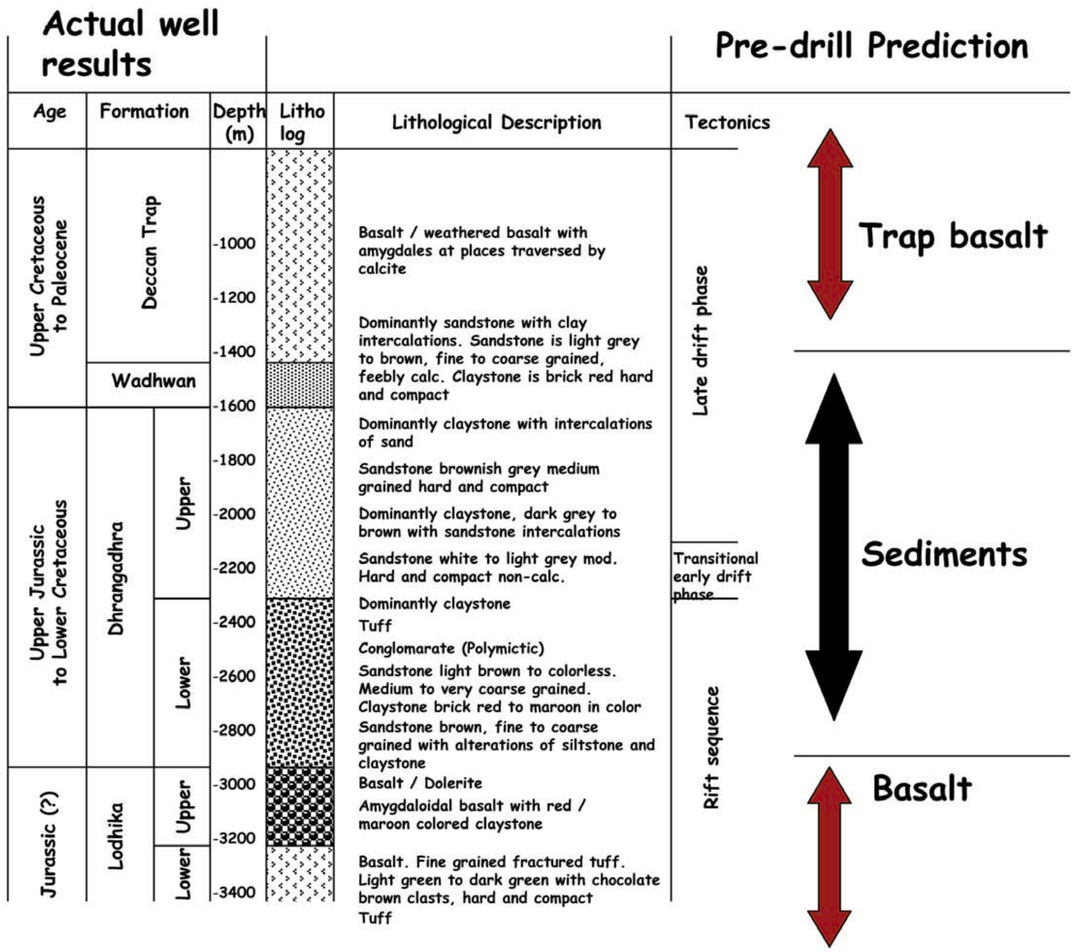


Figure 9. Interpretation derived from well-log report with major lithological units indicated on the right. These units are with 90–95% agreement with the LOTEM predictions.

eling and various inversion methods. Today's new generation multichannel systems can even record electromagnetic and seismic data in the same recording unit and yield higher data volumes with better data quality than shown here.

The future. The work in India was performed during the late 1980s with the interpretation being done during subsequent years while developing 3D interpretation capabilities. The exploration and subsequent drilling went on independently. The experience in India (and from a sister project in China) resulted in the design of the first seismic-style multichannel acquisition system for electromagnetics (Rueter and Strack, 1991). Today, the understanding of the method has evolved, and most seismic systems can be used with minor modifications to acquire electromagnetic data. While the physics is still the same, modern data handling and imaging techniques will improve the quality of the information derived from these methods.

The renewed interest in electromagnetics as a marine direct hydrocarbon indicator has spawned various companies to offer CSEM onshore. The difficulties CSEM faced in the early 1990s (limited 3D modeling capabilities) are now being addressed aggressively. Oil companies are acquiring array data sets and 3D modeling/interpretation capability.

Suggested reading. "Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data" by Constable et al. (GEOPHYSICS, 1987). "Marine electromagnetic methods—A new tool for offshore exploration" by Constable (*TLE*, 2006). "Sea-bed logging (SBL), a new method for remote and direct identification of hydrocarbon-filled layers in deepwater areas" by Eidesmo et al. (*First Break*, 2002). "Interpretation of 3D effects in long-offset transient electromagnetic (LOTEM) soundings in the Münsterland area/Germany" by Hordt et al. (GEOPHYSICS, 1992). Einige Aspekte der 3-D Interpretation von Lotem Daten by Kriegshaeuser (Diplom thesis, University of Cologne, 1992). "Bedrock exploration system using transient electromagnetic measurements" by Rueter and Strack (patent WO 91/14954, 1991). "Marine gas hydrate electromagnetic signatures in Cascadia and their correlation with seismic blank zones" by Schwalenburg et al. (*First Break*, 2005). "Case histories of long-offset transient electro-magnetics (LOTEM) in hydrocarbon exploration" by Strack et al. (*First Break*, 1989). *Exploration with Deep Transient Electromagnetics* by Strack (Elsevier, 1992). "Integrating long-offset transient electromagnetics (LOTEM) with seismics in an exploration environment" by Strack and Vozoff (*Geophysical Prospecting*, 1996). "Marine EM technique for gas-hydrate detection and hazard mitigation" by Weitemeyer et al. (*TLE*, 2006). TLE

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