

Optimizing EM data acquisition for continental shelf exploration

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The controlled-source electromagnetic (CSEM) method has been applied to oil and gas exploration and production for more than 10 years. During this time, most of the focus has been on derisking deep- and ultradeep-water drilling decisions. In this article, we will consider how EM methods can be optimized for continental shelf applications, which represent approximately 80% of offshore discoveries.

Historically, applications of EM on the continental shelf have been limited for two principal reasons:

- 1) *Noise*. The secondary field introduced by the air-water interface (“airwave”) was in the past viewed as a significant challenge, because it was believed to mask the subsurface response in shallow water environments, and limit the maximum depth of EM sensitivity.
- 2) *Resolution*. Many continental shelf areas are now fairly mature, and the majority of remaining near-field prospects are relatively small; traditional EM has lacked the resolution to be effective in many of these areas. In order for EM to become ubiquitous in shallow water, more resolution is required.

Recent developments in understanding the true role of the airwave, CSEM instrumentation, survey design, and operational methods (Figure 1), optimized for modern imaging methods, have largely overcome the challenges associated with shallow water.

Applications of EM methods

While marine EM methods have a broad range of applications throughout the E&P lifecycle, consistent, proven value of information has to date largely been found in two areas: detecting hydrocarbons and structural imaging.

Detecting hydrocarbons. The presence of hydrocarbons is almost always associated with a significant increase in reser-

voir resistivity (precisely the reason that the borehole resistivity log is so important). Quantitative interpretation of EM resistivity data to determine the presence, absence, location, distribution and volume of a hydrocarbon-related resistor can have a large economic impact because of both a reduction in the number of dry and uncommercial wells drilled (Hesthammer, 2010; Buland, 2011), and an increase in total portfolio value (Baltar and Roth, 2012), particularly when integrated interpretation of the data is performed in conjunction with other geophysical data (seismic, borehole logs, etc.). Future EM systems need greater sensitivity to both smaller and more deeply buried reservoir targets.

Structural imaging. In addition to mapping thin buried resistors associated with hydrocarbon accumulation, future EM systems will need to address the growing requirement to operate in areas with deep and complex resistivity structures. There are two motivations for this:

- When CSEM-derived resistivity is used as a direct hydrocarbon indicator (DHI), a proper interpretation of the data requires that we can adequately image the full anisotropic background 3D resistivity structure. Understanding the background becomes essential in areas where the geology is complicated and can involve resistive structures that are not associated with the presence of hydrocarbons. Seismic data and borehole resistivity logs can aid, particularly in more mature areas. However, triaxial borehole resistivity logs are not always available, geo-electric boundaries do not always coincide with acoustic impedance boundaries, and in frontier areas we may be limited to distant (if any) well control, and sparse 2D seismic.
- In many areas, highly resistive bodies (basalt, carbonates, and salt) may also be associated with significant seismic imaging challenges because of velocity and density contrasts. In these situations, resistivity models can be used to improve seismic imaging either indirectly, through guidance in seismic velocity model building, or directly through joint inversion of the seismic and EM data.

The recent significant increase in the availability of high-quality EM data has led to the development of increasingly sophisticated imaging techniques. We can now generate geologically accurate data-driven background resistivity models with little or no a priori information. There are several ways to independently obtain 3D, anisotropic structural resistivity models from 3D EM data (Morten et al., 2011; Herredsveld et al., 2012):

- 1) The anisotropic resistivity information from wide-azimuth CSEM data can define 3D structural resistivity variations, associated with the interface between sedimentary sequences and other resistive structures, such as basalt and salt.
- 2) Magnetotelluric (MT) data are derived from natural



Figure 1. Today's 3D EM vessels are comparable in size to the multistreamer 3D seismic vessels of only a few years ago, and are capable of deploying up to 200 receivers. The ability to deploy large, wide-azimuth grids has enabled cost-effective acquisition of well-sampled 3D subsurface volumes.

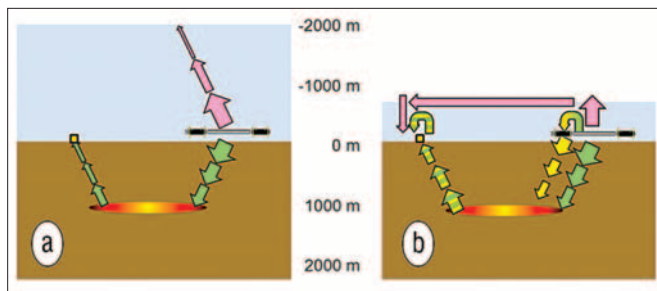


Figure 2. Cartoon illustration of important CSEM field propagation modes at deep- (a) and shallow- (b) water depths. Seawater is highly conductive and rapidly attenuates propagating EM fields. In deep water, it is therefore important to place the source close to the seabed to maximize the signal strength entering the subsurface. Any upgoing field is attenuated in the water column and can be ignored. In shallow water, the upgoing field couples to the air and gives large contributions to the measured fields. One mode will propagate with very high velocity and slow decay along the air-water interface, then back down to the seabed receivers. At the same time, the air-water interface will reflect useful source energy into the subsurface, causing additional reservoir response.

variations in the electromagnetic field and can be used to image deep, large-scale structure. Deep penetration can be accomplished through listening times of several days.

- 3) Both! A 3D EM acquisition typically provides both wide-azimuth CSEM, and MT data which can be jointly processed to determine both high-resolution images of shallow structure as well as deeper background and basin-scale variations.

Survey design and sensitivity optimization

When EM is used to remotely image the electrical properties of the subsurface, it is important to determine if the data have sufficient sensitivity to differentiate between potential target scenarios of interest. For example, the ability of the EM measurements to detect the higher resistivities associated with a hydrocarbon reservoir can be tested by considering simulated data. The important quantity is the magnitude of the target response compared to the data uncertainty. Project risk can be further minimized through careful application of pre- and

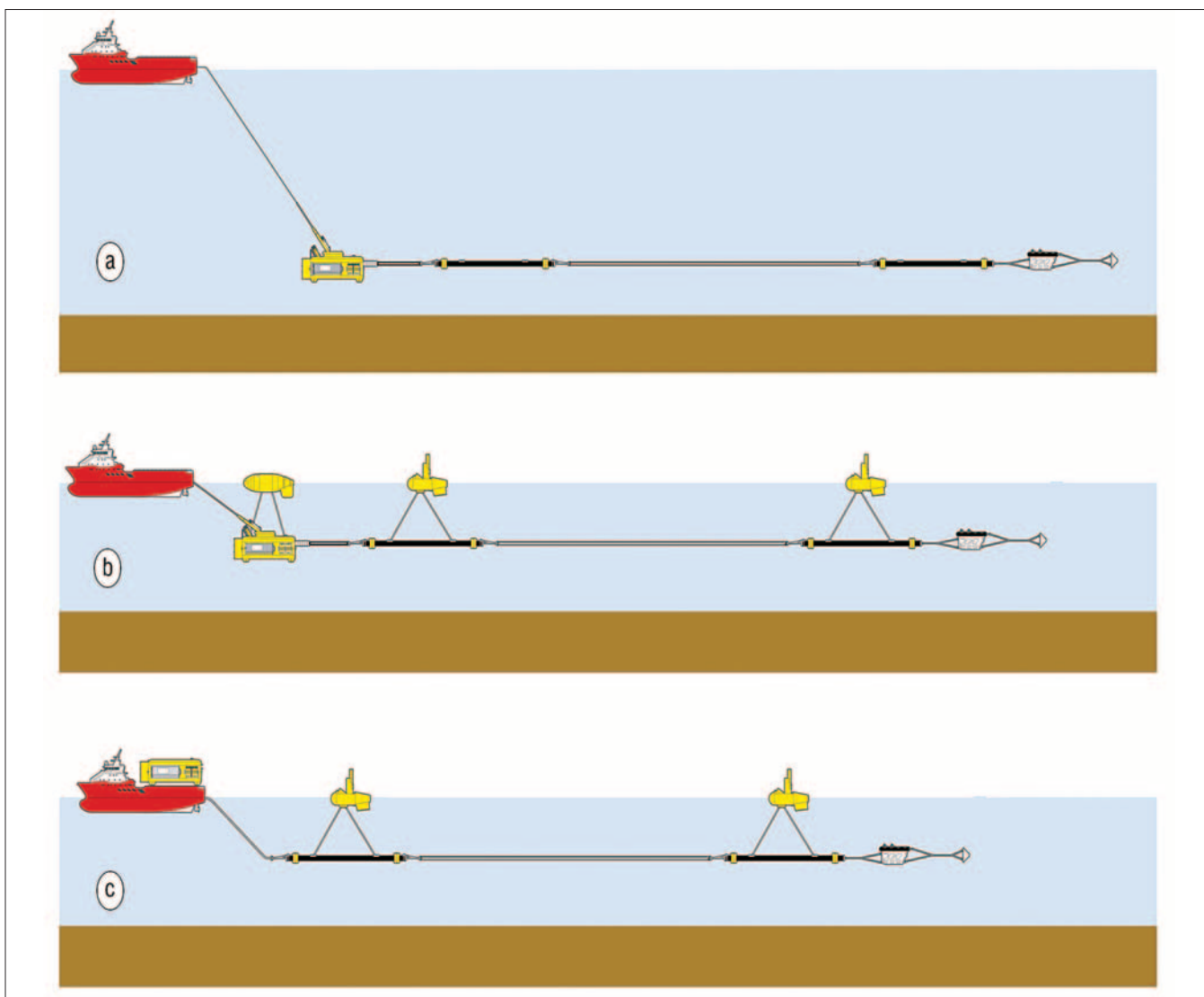


Figure 3. EM source systems. (a) Traditional deep-tow "seabed referenced" configuration with short-baseline acoustic positioning and control systems in a "towfish" close to the electrodes and the seabed. (b) Surface-towed configuration, with buoys used for GPS positioning, and to maintain the source at a constant depth. (c) Surface-towed configuration with deck-mounted high-power, high-fidelity control systems.

post-survey workflows using a rock physics framework (with appropriate uncertainty estimates) to relate the target electrical properties back to fundamental rock and fluid properties (electrical resistivity is, after all, merely a proxy for the real-world properties of interest). Survey data density, 3D azimuthal data coverage, and target imaging resolution requirements, must also be considered along with operational and environmental issues associated with the target survey area.

When optimizing the data acquisition for a project, it is important to account for the performance characteristics of the instrumentation being used. The total uncertainty of the recorded CSEM data can be estimated using the framework of error propagation. A detailed analysis, as presented by Mittet and Morten (2012), is beyond the scope of this article, but we can summarize the typical behavior of the measurement uncertainty ΔE with the commonly used sim-

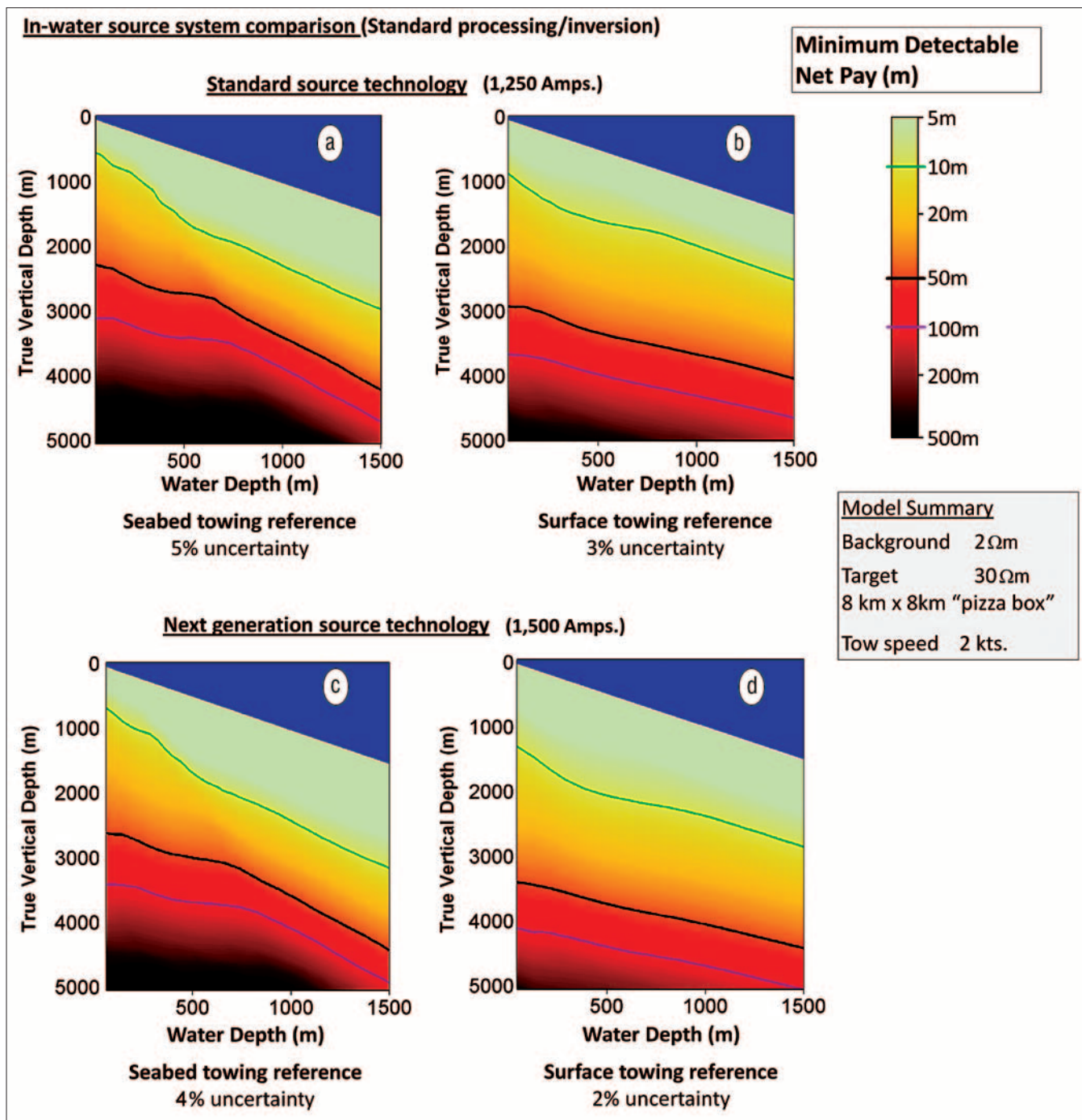


Figure 4. (a) and (b) illustrate the minimum pay thickness detectable using 3D EM for a typical reservoir using current state-of-the-art technology for source systems in Figures 3a and 3b. Note that in shallow water, a target having 50 m net pay (black contour) is detectable at depths of almost 3000 m using surface towing, but only 2200 m in the conventional deep-tow configuration. (c) and (d) illustrate that with only a modest source power increase and more accurate calibration and positioning, the envelope of detectability for small, shallow targets can be pushed more than 20% deeper. A realistic water-depth-dependent noise model has been used, with N varying from around $3.55e-9$ V/m in shallow water, to $1.95e-10$ V/m in 1500 m of water.

plified model, $\Delta E = \sqrt{(\alpha E)^2 + (N)^2}$. Here, E is the magnitude of a measured field component. The quantity α is the relative uncertainty which describes contributions because of inaccuracies in source and receiver positioning, source current, and sensor calibration. The quantity N represents the contribution from environmental noise caused by, e.g., ocean waves and swell, and magnetotelluric activity. Both α and N vary with water depth; N also has important frequency- and latitude-dependent components. Detailed knowledge about the performance of hardware components as well as extensive operational experience allows us to estimate α and N with sufficient accuracy for survey planning purposes.

The shallow-water environment

In order to understand how shallow-water EM applications differ from deep-water, let us briefly review the main differences in recorded data. EM field strength is rapidly attenuated in highly conductive media such as seawater. In deep water, with the source towed close to the seabed, the upward-propagating field can be largely ignored. In shallow water, this field reaches the air, where it propagates with minimal attenuation and with high velocity (the speed of light in air). This signal, often referred to as the “airwave”, constitutes a background signal contribution to the measurement that is up to two orders of magnitude larger than the background field measured in deep water. If the magnitude of the desired signals associated with the presence of hydrocarbons is of a similar magnitude in shallow water as in deep water, the sensitivity of the method would thus be reduced in shallow water.

More recently, it has been shown that EM energy reflected down from the air-water interface also results in larger magnitudes of EM fields that are generated by interaction with a hydrocarbon reservoir. This “secondary source” effect

partly counterbalances the increased background contribution from the airwave (Mittet, 2008). The seismic industry provides a clear analogy for this, where acoustic multiples can be modeled as useful signal, carrying subsurface information.

From an EM perspective, projects are normally described as shallow water when the airwave is a significant factor in analyzing the data. This is dependent upon the size and depth of burial of the target, and the source-receiver offsets required to detect the target. In general, water deeper than 500 m can be considered deep, while anything less than 200 m should be considered shallow, with a target-dependent region in between.

A range of approaches has been suggested to enhance the sensitivity in shallow water by mitigating the airwave signal. In acquisition, transient-source signatures aiming at temporal decoupling of the airwave signal have been applied (Ziolkowski and Wright, 2007). Unfortunately, in the marine environment, the early airwave arrivals will always overlap in time with the Earth response. In the processing stage, various decompositions aimed at reducing the airwave can also extract the desired signal component. For example, up-down separation (Amundsen et al., 2006) can determine the upgoing wavefield which does not contain the downgoing airwave signal, but still includes valuable information about the subsurface.

In recent years, the standard processing approaches for EM data have turned toward inversion methods. The airwave is a smaller problem for inversion if the forward modeling engine has a high accuracy in shallow-water environments. CSEM data acquired in water depths of 50–400 m are today successfully processed using the same inversion methods as data acquired in deep water. For some recent examples, see Fanavoll et al. (2012).

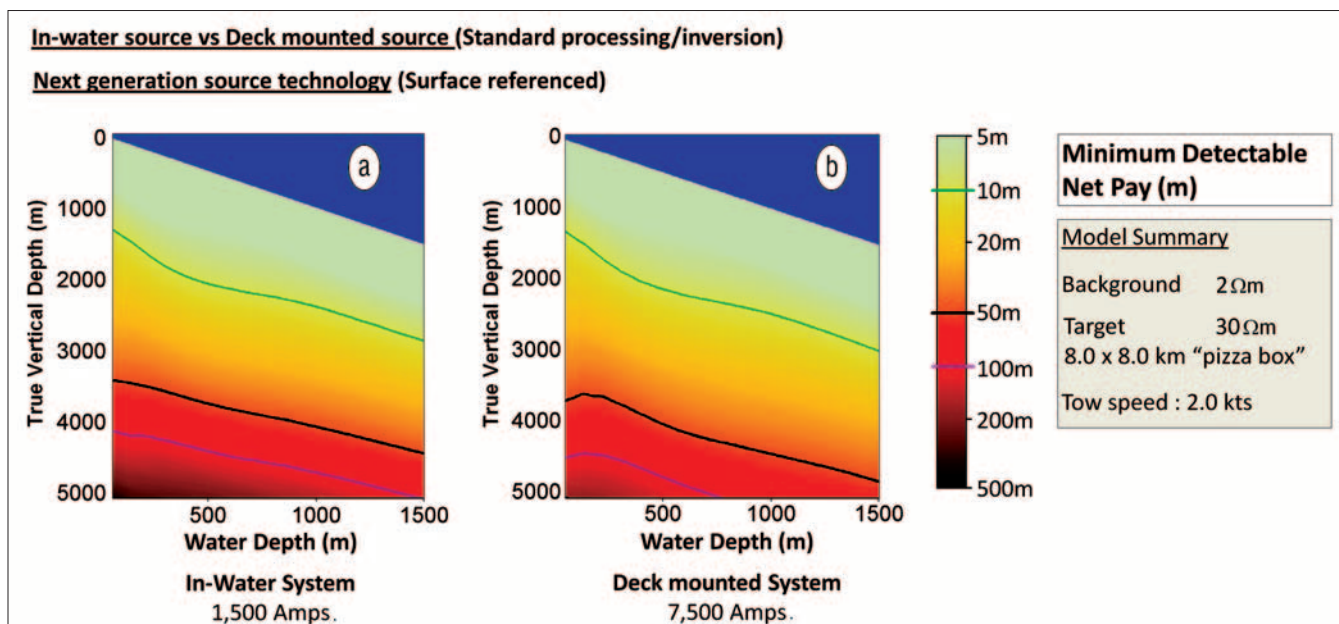


Figure 5. High-powered vessel-mounted source (b) can deliver an additional 10–15% penetration relative to a conventional in-water system (a).

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Shallow-water measurement uncertainty

Shallow water impacts both terms in the simplified uncertainty model equation which contribute to the measurement uncertainty, ΔE . The term αE scales with the field magnitude, and as explained above, the airwave generates a much

larger field in shallow water. The environmental noise N typically has larger magnitude in shallow water because of stronger swell noise and a less-attenuated MT signal. New shallow-water acquisition strategies need to minimize one, or preferably both, of these terms.

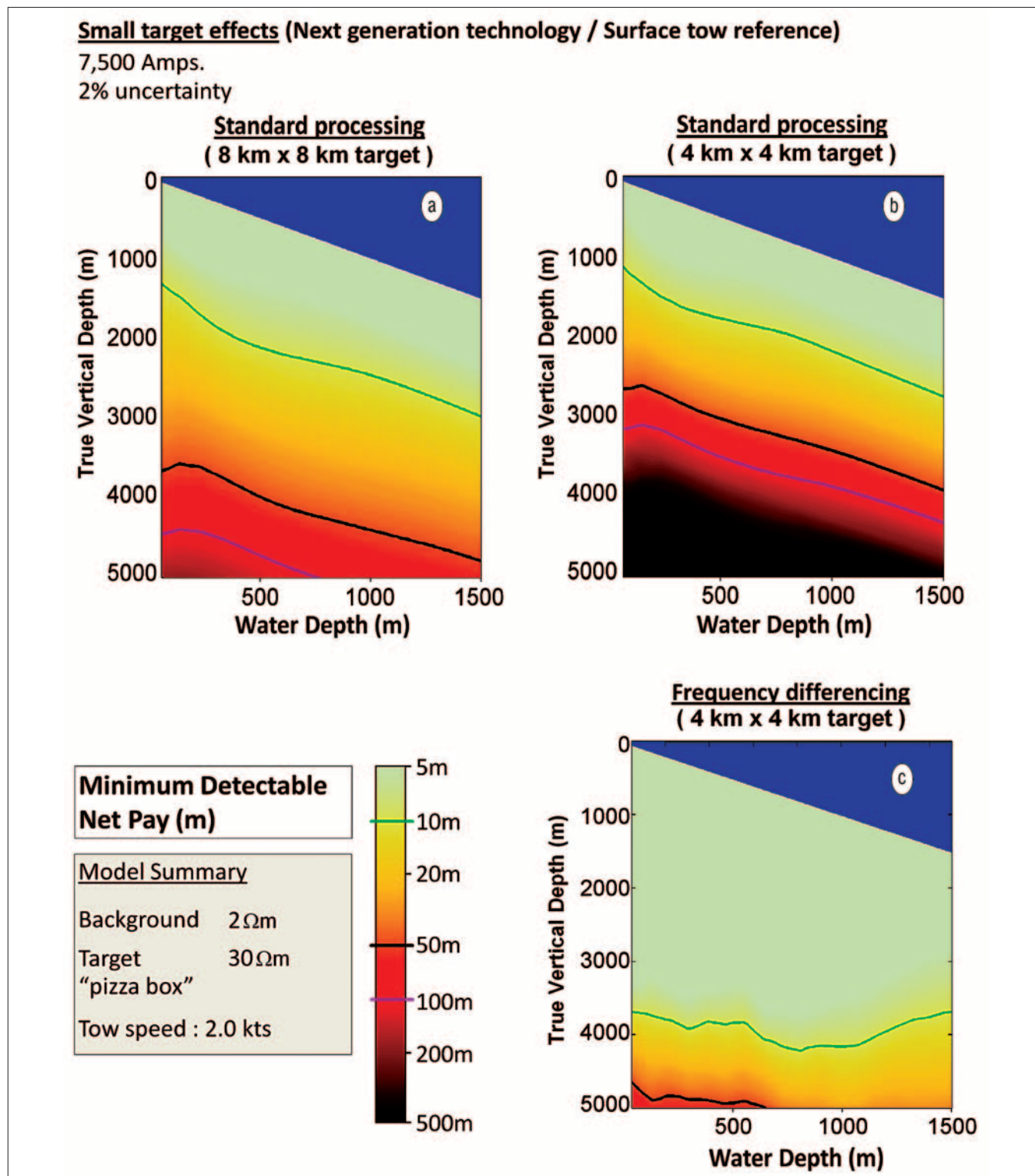


Figure 6. For the large target (a), conventional imaging technology combined with a high-power, high-fidelity surface-referenced source can detect a 50 m pay zone at a burial depth of more than 3500 m. For a similar but smaller target (b), the same pay zone would be detectable only at 2600 m. By applying frequency differencing (c), the same target could be detectable at depths of more than 4000 m if the uncertainty model described in the main text is accurate. The relationship between the differenced frequencies in this example is $f_2 = 2f_1$.

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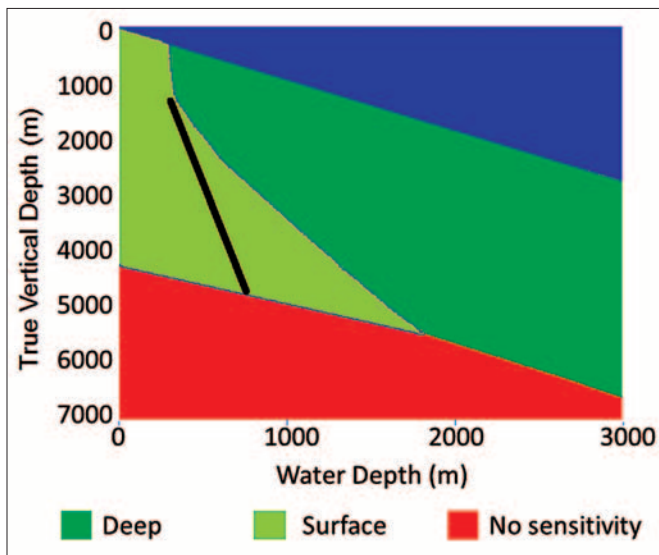


Figure 7. For seabed receivers, the source-towing method providing the largest peak reservoir sensitivity to a model similar to that in Figure 4 is shown here as a function of water depth and TVD. The regime of “no sensitivity” corresponds to a minimum detectable net pay thickness of more than 500 m. Once other imaging requirements are taken into account, the transition between preferred source towing method changes to a position approximated by the black line.

Shallow-water acquisition strategies: Receiver equipment

If resolution, depth of penetration, and structural imaging are important, noise levels at the sensors are a critical factor, irrespective of water depth. Seafloor node-based recording systems ensure that high-fidelity multicomponent electric and magnetic fields can be recorded. In shallow-water settings, radio telemetry systems can be used to provide real-time noise monitoring capability for seabed-deployed receivers. In addition, the availability of both electric and magnetic recording allows magnetotelluric processing, and the above-mentioned waveform decomposition.

Shallow-water acquisition strategies: Source equipment

When operating in deep water, attenuation of the source signal in the conductive seawater layer is minimized by towing the transmitter electrodes close to the seabed. The electrical and mechanical properties of long tow cables mandate that a transformer and other bulky control circuitry are close to these electrodes. Source position is typically obtained acoustically, with a short-baseline system on the vessel, and transponders on the source.

In shallow water, the range of possible source configurations is greater (see examples in Figure 3). Firstly, with less signal attenuation by the seawater, electrodes can be towed close to the sea surface, and directly positioned with GPS. The resulting reduction in positioning uncertainty leads to significant improvements in target sensitivity. There are also operational advantages in terms of reliability, productivity, and safety (Shantsev et al., 2010). Secondly, tow umbilicals are much shorter, making it feasible to locate the power transformer and control systems on the vessel, with only the electrodes deployed in the water. Deck-mounted equipment can

be much bigger, enabling a significant (6×) increase in source power. This enhances the signal-to-noise ratio of measured data, thereby enhancing sensitivity to small targets.

It is obvious that, in very shallow water, “surface referenced towing” is the preferred solution, but at some water depth, the improved power and accuracy of the surface-towed solution is offset by the attenuation caused by the thickness of the water layer. Using the sensitivity analysis approach outlined above, we now compare the performance of different acquisition systems in a range of water depths by considering their sensitivity to resistive target structures. In practice, this modeling is carried out presurvey to specific (often considerably more detailed) target scenarios of interest. It should also be noted that the comparisons here are focused specifically on peak target sensitivity. This is one of several imaging requirements that need to be considered when designing a survey (some of which are discussed later).

Surface versus seabed towing

Figure 4 shows the relative performance of two in-water source systems with seabed-towing and surface-towing configurations. The detection criterion used in this example is that the data difference from simulations with and without the target present is at least three times larger than the data uncertainty for the optimal frequency and source-receiver offset. The threshold of sensitivity to a target reservoir of interest is illustrated as a function of water depth and true vertical depth (TVD) to the target, in terms of the minimum-detectable net pay. This approach can then be extended fairly easily to determine the confidence with which the proposed survey can estimate resources in place.

The more accurate source navigation reduces the relative uncertainty term because the effective α becomes smaller. This enhances sensitivity to small, shallow targets that may constitute significant target response, but which can be difficult to detect in the increased background field in shallow water.

In-water versus deck-mounted systems

Figure 5 shows the performance of two surface-towed systems: one with in-water transformer and control circuitry and one with a higher-power ship-mounted system. The enhanced source current results in a larger signal-to-noise level, counteracting the large magnitude of N in shallow water, particularly important for deeply buried targets that constitute a target response of small amplitude.

New imaging techniques

New high-fidelity source systems also have the potential to offer additional benefits by enabling the application of noise-intolerant differential processing and imaging strategies. One such approach is to consider differences between closely spaced frequencies (Maaø and Nguyen, 2010; Chen and Alumbaugh, 2011). Frequency differencing is effective when the main contributions to measurement uncertainty are correlated between the data samples used for differences, and the target response varies between the frequencies more

rapidly than the background response. In this case, the ratio of target response to measurement uncertainty is larger for data differences than for original data. However, the effectiveness of this method has been difficult to demonstrate using the current generation of acquisition technology. Data acquired using a new deck-mounted source system could be particularly suited to this approach:

- 1) Enhanced current control permits closer and more sharply defined frequency content.
- 2) Higher signal-to-noise levels lead to the uncorrelated noise described by N being less significant compared to lower-power systems.

To study the potential detection advantage of a frequency differencing approach, we must determine a measurement uncertainty estimate for frequency-differenced data samples. Assuming strong correlation between measurement uncertainty contributions at closely spaced frequencies f_1 and f_2 , the relative uncertainty contribution will scale by total field difference, $\alpha[E(f_1) - E(f_2)]$. Figure 6 demonstrates the detection sensitivity improvement for a reservoir of smaller lateral extent. In this example, the frequency-difference sensitivity boost provided by the high-power, high-precision source system actually pushes small-reservoir detection levels above those for the larger reservoir with standard processing. Field testing of this concept is underway, and results should be published in the near future.

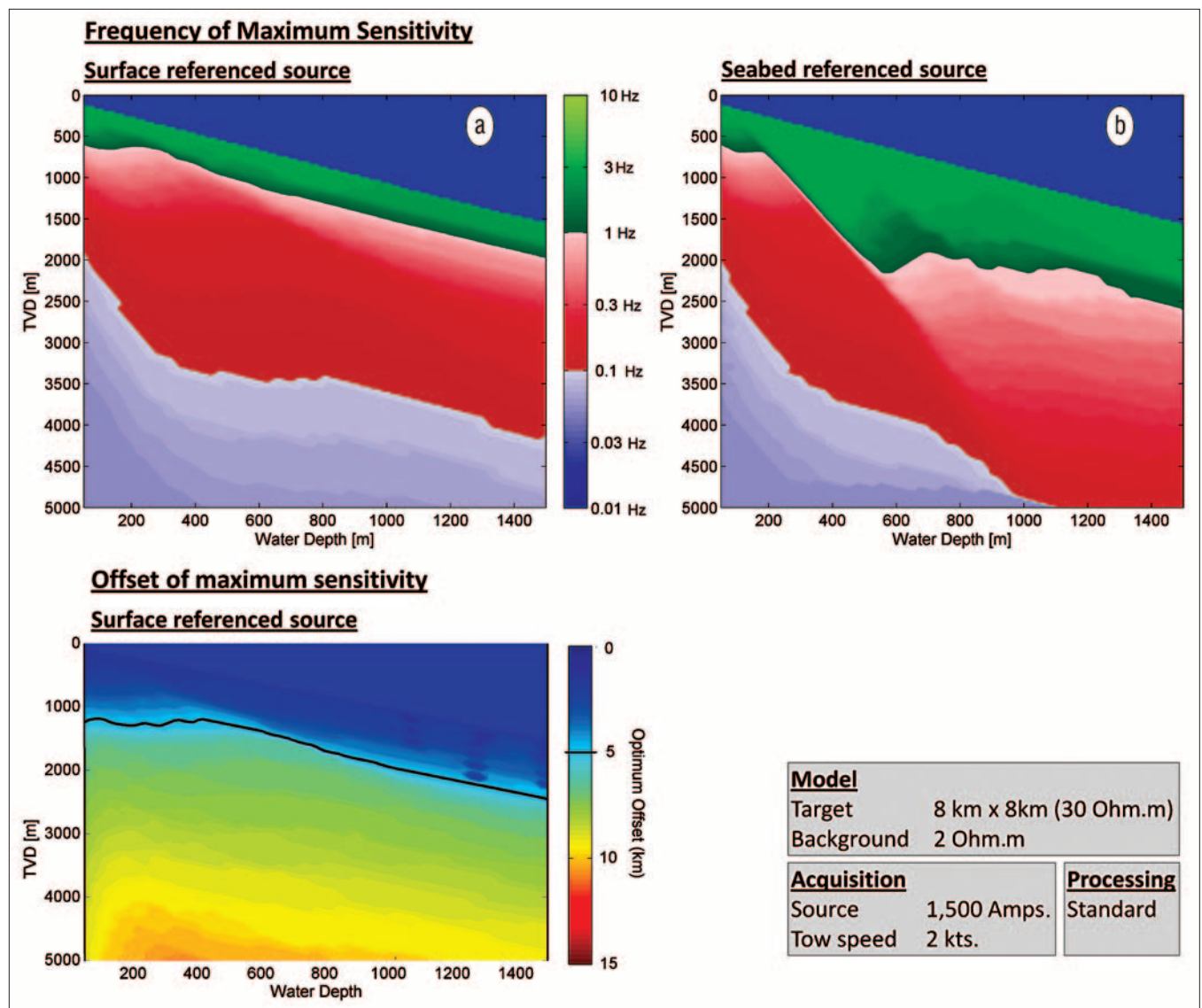


Figure 8. Other factors to be considered. (top) Source transmission frequency with the maximum target sensitivity, surface-tow and seabed-tow source configurations. Peak sensitivity always occurs at a higher transmission frequency with a seabed-towed configuration. Note that the region of sharpest transitions in frequency in the seabed-referenced source case (b) is caused by the switching between two domains of high sensitivity, as demonstrated in Shantsev et al., 2012. The sensitivity peak in shallow waters is due to signal paths involving air, and the sensitivity peak in deeper water to signals going purely through the subsurface. (bottom) Source-receiver offset at which the maximum response occurs. The acquisition geometry should contain offsets long enough to capture the maximum response. For many targets, this requires offsets in excess of 5–10 km. This requirement causes additional emphasis to be placed on the need for low noise.

The impact of surface towing on imaging quality

We have demonstrated that, in shallow water, a surface-towed source system provides higher detection sensitivity than an equivalent seabed-towed system. In many shallow-water cases, imaging quality is also improved (Shantsev et al., 2012). In deeper water, seabed towing is better because of less source signal attenuation in the water column. There is thus a crossover behavior for the most sensitive acquisition, as demonstrated in Figure 7. Once structural imaging requirements are taken into account, the greater attenuation in the water column of higher transmission frequencies (needed for accurate background imaging) moves this transition to shallower water depths for deeply buried targets (black line on Figure 7).

In many EM applications (such as appraisal well placement), the resolution of the recovered target image is also an important survey design consideration. This can be investigated with detailed, application-specific, synthetic inversion tests. Here, we illustrate the relative imaging quality by considering the transmission frequency that provided the peak target response in the next-generation source examples from Figure 4. As we can see in Figure 8, the seabed-towed system always provides peak target sensitivity at a higher frequency than the corresponding surface-towed system. Higher frequencies provide better spatial resolution; thus the seabed-towed system can provide a more detailed imaging result in cases where adequate sensitivity exists for both seabed-tow and surface-tow configurations.

Summary

Shallow water is no longer a “no-go” area for EM techniques. The next generation of EM systems have been developed to

- Record high-quality, high-resolution wide-azimuth CSEM and magnetotelluric data in order to ensure high-quality 3D, anisotropic background models and target images
- Deliver higher power and significantly greater bandwidth
- Ensure the best possible determination of source and receiver position and orientation
- Ensure well-known source and receiver transfer functions
- Ensure safe and environmentally benign operations.

These developments have taken place supported by, and even driven by, parallel developments in processing and imaging, such as the potential use of differential imaging techniques. These acquisition systems and their associated imaging methods will be tested over challenging, and well-understood targets in the near future. **TLE**

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