CSEM performance in light of well results

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During the past several years, we have seen an increasing focus on the use of CSEM technology for hydrocarbon exploration in marine environments and, recently, a number of success stories have been published. The technology has been demonstrated to aid both detection and delineation of hydrocarbon-filled reservoirs.

The impact of any new technology on exploration success can be very difficult to assess since most data are proprietary. Marine CSEM data for use in hydrocarbon exploration have been acquired for nearly 10 years, and more data are now available to attempt understanding the impact of this technology on drilling success rates. This study is meant to be an objective observation of statistical results of 86 wells drilled on prospects and fields that contain marine CSEM data. As numerous parameters are not known to the authors, the study constrains the focus to provide information on observed results.

Basics

The concept of remote resistivity surveys is based on the knowledge that the propagation of an electromagnetic (EM) field in a conductive subsurface is mainly affected by spatial distribution of resistivity (assuming non-magnetic and non-polarizable materials). In marine environments, saltwater-filled sediments represent good conductors, whereas hydrocarbon-filled sediments represent examples of resistive inclusions that scatter the EM field. The EM field is scattered by subsurface inhomogeneities which are recorded by receivers on the seafloor (Figure 1a). The information obtained can be used to estimate the true subsurface resistivity distribution by applying inversion and migration techniques as well as numerous other analysis types (Figure 1b).

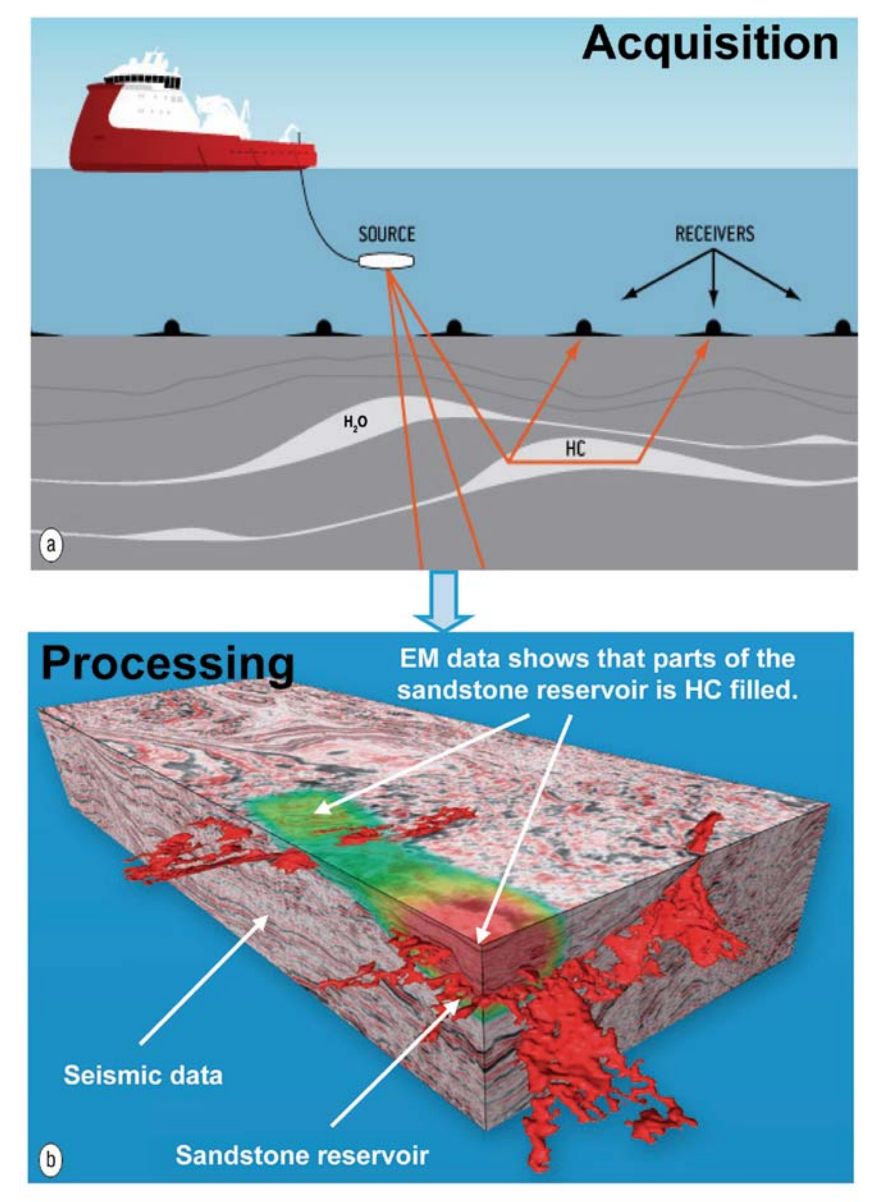

Figure 1. (a) During a typical CSEM survey, a dipole source is towed above EM receivers on the seafloor. The source emits an electromagnetic field that propagates in the subsurface (for simplicity, the energy propagation is shown as raypaths in the figure, although the energy at the low frequencies used mainly propagates through diffusion). The presence of hydrocarbon-filled sediments will scatter the EM field, and part of the scattered field propagates back to the seafloor where the signal is recorded by receivers equipped with electric and magnetic sensors. (b) To find out if oil or gas are present, acquired EM data must be processed and interpreted. This extensive and iterative process requires access to advanced processing and analysis tools.

During a typical marine CSEM survey, EM receivers are deployed on the seafloor. A mobile horizontal electric dipole source, towed 20–40 m above the seafloor (Figure 1a), continuously emits an EM field into the subsurface. The EM receivers continuously record the electric and magnetic fields. The attenuation of the EM field in the subsurface mainly depends on the frequency of the source signal and the subsurface resistivity. In order to map deep targets, the strength of the scattered field at the seafloor must be above the noise level. This requires suitable source frequency content, waveform, and current strength. Source current amplitudes are typically up to 1300 A, and source dipole lengths are 150–350 m. The source waveform determines the resulting frequency distribution and relative magnitude of harmonics that can be studied. Experience shows that a frequency range of 0.1-3 Hz is needed to map targets down to 3000 m below the mudline (seabed). It is important to cover a sufficiently broad frequency range to improve the depth resolution. The spatial resolution of the EM data is mainly limited by the signal strength, frequency, source-receiver spacing and, in practice, noise level.

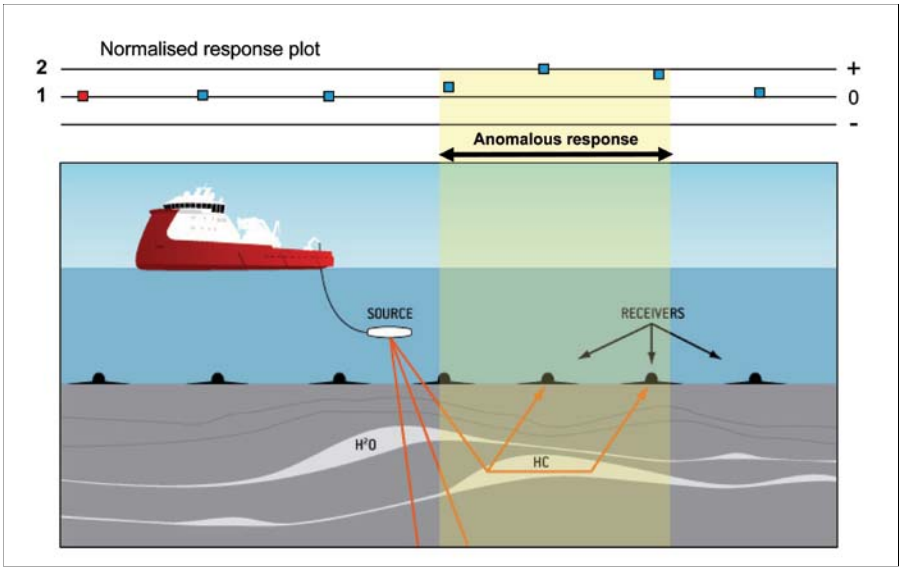

Figure 2. An objective and simple method for analyzing CSEM data is to generate normalized magnitude and phase plots. This is done by identifying a receiver outside the target region. This receiver is referred to as a reference receiver. For the reference receiver, an offset between source and receiver is chosen. Next, all other receivers are normalized against the reference receiver for the chosen offset and frequency. This allows identification of areas with anomalous responses compared to the general background trend, of which the maximum variation is referred to as the normalized anomalous amplitude response (NAR).

The database

By the middle of 2009, EMGS, a CSEM service provider, had collected more than 400 marine CSEM surveys. By the same time, Rocksource, a Norwegian oil company had analyzed marine CSEM data over more than 70 prospects related to their own business activities and tested the technology in 6 calibration areas. From the combined data set, 86 wells are currently available for statistical analyses. The database contains 36 calibration surveys across existing wells; 50 wells are exploration wells that were drilled after the acquisition of marine CSEM data.

In a previous publication by Johansen et al. (2008), a database of 52 wells with associated marine CSEM data were evaluated. Whereas that paper focuses on what is considered a technical success with respect to whether resistivity observations from wells are consistent with observations from CSEM data, the current paper focuses on what the drilling results demonstrate in terms of discovery rates from an objective as possible point of view.

The marine CSEM database contains wells from the Barents Sea (9, of which 2 are calibration surveys), Brazil (1 calibration survey), Ghana (1), Gulf of Mexico (7 calibration surveys), India (12, of which 2 are calibration surveys), Malaysia (3), Mediterranean (5, of which 2 are calibration surveys), North Sea (5, of which 4 are calibration surveys), Norwegian Sea (15, of which 7 are calibration surveys), offshore Sarawak (1 calibration survey), South China Sea (11, of which 4 are calibration surveys), Sulu Sea (1) and West Africa (15, of which 6 are calibration surveys). A calibration survey is defined as a CSEM survey acquired across an existing discovery or dry well. These data are valuable in terms of evaluating if a normalized anomalous response can be observed over a proven discovery or dry well, but must be disregarded for statistical evaluation of discovery rates. The global distribution of surveys within different basins and geological settings strengthens the validity of the statistical analysis.

In the database used for this study, the shallowest exploration prospect was 500 m below the mudline, while the deepest prospect was at 2500 m; water depths ranged from 150 to 2500 m for the exploration prospects. For the calibration surveys, the shallowest target was 200 m below the mudline while the deepest was 2100 m. The water depths for the calibration surveys range from 90 to 2500 m. The shallowest exploration discovery was 500 m below the mudline, while the deepest discovery was 2200 m.

The analyses

There has been no effort to interpret any data apart from identifying a simple, observable, and normalized anomalous amplitude response of the electric field at the fundamental frequency. This is to ensure consistency when comparing the different data sets, and to have minimum bias in the analyses. A normalized anomalous response considers the resistivity response of something anomalously resistive in the subsurface with respect to the background resistivity (Figure 2). This is done by identifying a receiver outside the target region which is assumed to represent the general background resistivity. This receiver is referred to as a reference receiver. During acquisition, the source will be towed above the receivers, emitting electromagnetic energy by alternating the current between two electrodes. The current alternating frequency and signature can be varied to provide a fundamental frequency as well as numerous harmonics to the fundamental frequency of varying strengths. In this study, only the amplitude variations of the electric field for the fundamental frequency are considered. Although this is a highly simplistic approach, the purpose is to be as objective as possible when comparing results. More detailed analyses are indeed both possible and preferred, but will be the topic of future publications.

For each CSEM line, a reference receiver and an offset

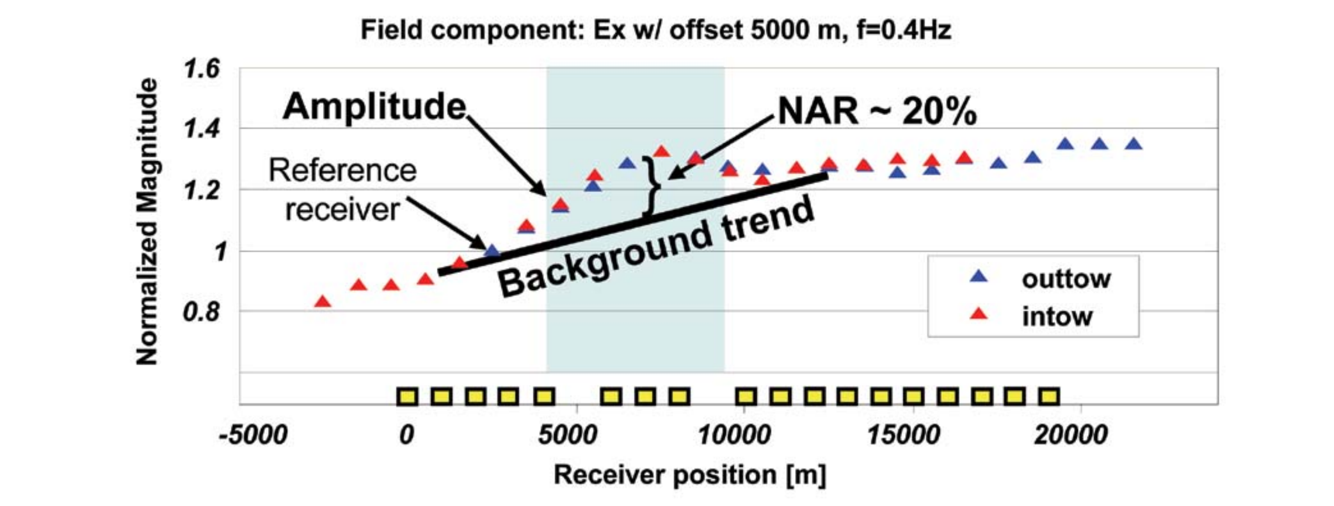

Figure 3. *An NAR plot from the Barents Sea. This example shows a maximum NAR of 20%.*

between the source and the reference receiver are chosen. Next, all other receivers are normalized against the reference receiver for the chosen offset and frequency and displayed in a normalized amplitude response plot (also called "normalized magnitude versus offset" or NMVO plot). This allows identification of areas with an anomalous response compared to the general background trend, of which the maximum variation is referred to as the normalized anomalous amplitude response (NAR). (The term NAR is used relatively loosely in this paper with the purpose of establishing a simple mean to analyze the data. The correct way to address the anomaly in the subsurface response, NAR, is to consider the amplitude of the complex-valued anomalous field divided by the amplitude of the complex-valued background field. Keeping in mind possible discrepancies, we still proceed with the definition adopted above as the simplification will not cause major changes in the discussed results apart from limited rescaling of the NAR threshold values.)

A normalized response value of 1 indicates that the chosen receiver has exactly the same electric field magnitude for the chosen offset as the reference receiver. A value of 1.5 indicates that the observed receiver has a normalized response 50% higher than the reference receiver. This indicates something in the subsurface has higher resistivity than observed at the reference receiver. This could potentially be a hydrocarbon-filled reservoir or something else resistive (cemented sandstone, volcanics, organic-rich shale, carbonates, salt, etc.). It may also be related to aspects such as survey geometry effects, airwave effects, bathymetry effects, etc.

Figure 3 shows an NAR plot from a prospect in the Barents Sea. The NAR for the amplitude with respect to the estimated background trend reaches a value of around 20% at the location of a mapped prospect. Such a response is considered significant.

Experience shows that when the NAR becomes less than 15%, it is commonly difficult to differentiate a clear subsurface anomaly due to lateral and vertical variations in the resistivity of nonhydrocarbon-bearing subsurface formations. In this study, an NAR cutoff value of 15% has been used to separate prospects with a significant CSEM anomaly from those without a significant anomaly. Although this is again a simplified approach, it serves the purpose for this particular study by keeping the analyses at an objective level.

The available database contains results of wells drilled by a number of oil companies. A well is considered a discovery if movable hydrocarbons were encountered (with the exception of three wells which encountered only very minor amounts of hydrocarbons and which are referred to as dry in this study). No information is available on the initial chance of success (initial Pg) based on standard geological and geophysical analyses. Nor is any information available on the reasoning for the drilling decision or location relative to observations from the CSEM data. As such, it is quite possible, and likely, that observations from CSEM data did not change the drilling decision or location for some wells due to existing drilling commitments and other factors. Any drilling decision that incorporated CSEM data would likely have been based on interpretation reports provided by service providers as well as the knowledge of the CSEM technology within the different oil companies. The extent of this knowledge is not known. As a result, only the most basic and conservative observations are presented.

The results

Of the 86 wells with associated CSEM data, 36 are calibration surveys collected to test the technology. Of the 22 calibration surveys acquired over existing discoveries, 19 (86%) show an NAR value above 15%. Of the 14 calibration surveys acquired over prospects proven dry, 13 (93%) show an NAR value less than 15%.

Perhaps of greater interest is the evaluation of success rates for wells drilled after acquisition of CSEM data. Figures 4–5 and Table 1 show the main results found through the evaluation of the current database.

Of the 86 wells drilled, 50 are listed as discoveries. When disregarding all calibration surveys, 28 out of 50 wells are discoveries. When considering wells drilled on prospects with an NAR above 15% (referred to as prospects with a significant

	Total # wells	# discoveries all NARs	%	# dry wells all NARs	# discoveries with NARs	%	# dry wells with NAR > 15%	# discoveries with NAR <15%	%	dry wells with NAR <15%
All wells	86	50	58	36	40	80	10	10	28	26
Calibration surveys	36	22	61	14	19	95	1	3	19	13
Excluding calibration surveys	50	28	56	22	21	70	9	7	35	13
India	10	5	50	5	5	63	3	0	0	2
West Africa	9	4	44	5	3	100	0	1	17	5
Norwegian sea	8	2	25	6	2	40	3	0	0	3
Barents Sea	7	6		1	3		0	3		1
South China Sea	7	5		2	4		2	1		0
Mediterranean	3	2		1	0		0	2		1
Malaysia	3	3		0	3		0	0		0

Table 1. *Main statistics for the current study. An NAR cutoff value of 15% for the fundamental frequency has been used to distinguish prospects with a significant CSEM anomaly from prospects with only a weak or no CSEM anomaly.*

CSEM anomaly in this study), 21 out of 30 wells are discoveries. For wells drilled on prospects with an NAR below 15% (prospects without a significant CSEM anomaly), 7 out of 20 wells are discoveries.

When disregarding all calibration wells, this provides an overall discovery rate of 56%. For wells on prospects with a significant CSEM anomaly, the discovery rate increases to 70%, whereas it drops to 35% for wells on prospects without a significant CSEM anomaly. Some prospects with an observed NAR below 15% may still have clear and localized CSEM anomalies above mapped prospects, while others clearly do not as numerous wells are actually drilled on prospects with no observable NAR.

Table 1 summarizes the findings for all areas and for the areas where more than one well is available. Figure 5 shows the discovery rate for all available data as well as for areas with at least 8 exploration wells (excluding calibration surveys) drilled on prospects with CSEM data. The number of wells available from the different areas is limited and more data are clearly needed to reach any firm regional conclusions. When excluding all calibration wells from the study and only considering areas with at least 8 wells available for analyses, India (10 wells) shows a discovery rate of 50% when all prospects are included in the analyses. If only prospects with NAR above 15% are included, the discovery rate is 63% (5 discoveries). Data from West Africa (9 wells) show an average discovery rate of 44% when including all prospects, but the discovery rate increases to 100% when only prospects with NAR above 15% are included (3 discoveries). In the Norwegian Sea (8 wells), the overall discovery rate for all wells is 25% with a discovery rate of 40% for wells drilled on prospects with NAR above 15% (2 discoveries).

As many as 20 of the 50 exploration wells were drilled on prospects showing an NAR in the CSEM data equal to or less than 10%. Half (10) of these 20 wells were drilled where none or even negative normalized anomalous responses were observed for the fundamental frequency. Four of these 10 wells were discoveries, and all four were classified by Johansen et al. as "hydrocarbon discoveries modeled subdetection" which means that well data revealed hydrocarbon-filled reservoirs with properties shown by modeling to be unfavorable (too small, too deep, or with too little resistivity contrast) for detection by CSEM.

Discussion

Throughout the history of oil exploration, the industry-wide average for wildcat commercial success has remained remarkably constant over time: approximately 25%. This results from a balance between several competing factors. Firstly, the simplest and most accessible geologic settings are drilled early and the more difficult basins are drilled later, after the simpler ones have been exhausted. Secondly, the large, easy-to-see prospects get drilled first in a play; the smaller, more complex ones are found later. One would expect these factors to result in a general decrease in success rate over time. The counterbalancing force has been continual improvements in technology. The widespread use of 3D seismic surveys in exploration, the understanding in rock physics, and the recognition of seismic DHIs (bright spots, AVO, etc.) have helped to keep the overall industry success average in the neighborhood of 25%. Areas in which the new technologies work well see improved success rates, which offset the declining successes in those geologic settings in which the new technologies are not effective.

Seismic data provide information on subsurface changes in density and velocity (commonly described by the product of the two, acoustic impedance or AI). EM data provide information on resistivity contrasts in the subsurface. The relationship between acoustic impedance, resistivity, and hydrocarbon saturation is complex (Figure 6). Simply put, the integration of prospect-scale understanding of density, velocity and resistivity can improve the understanding of whether

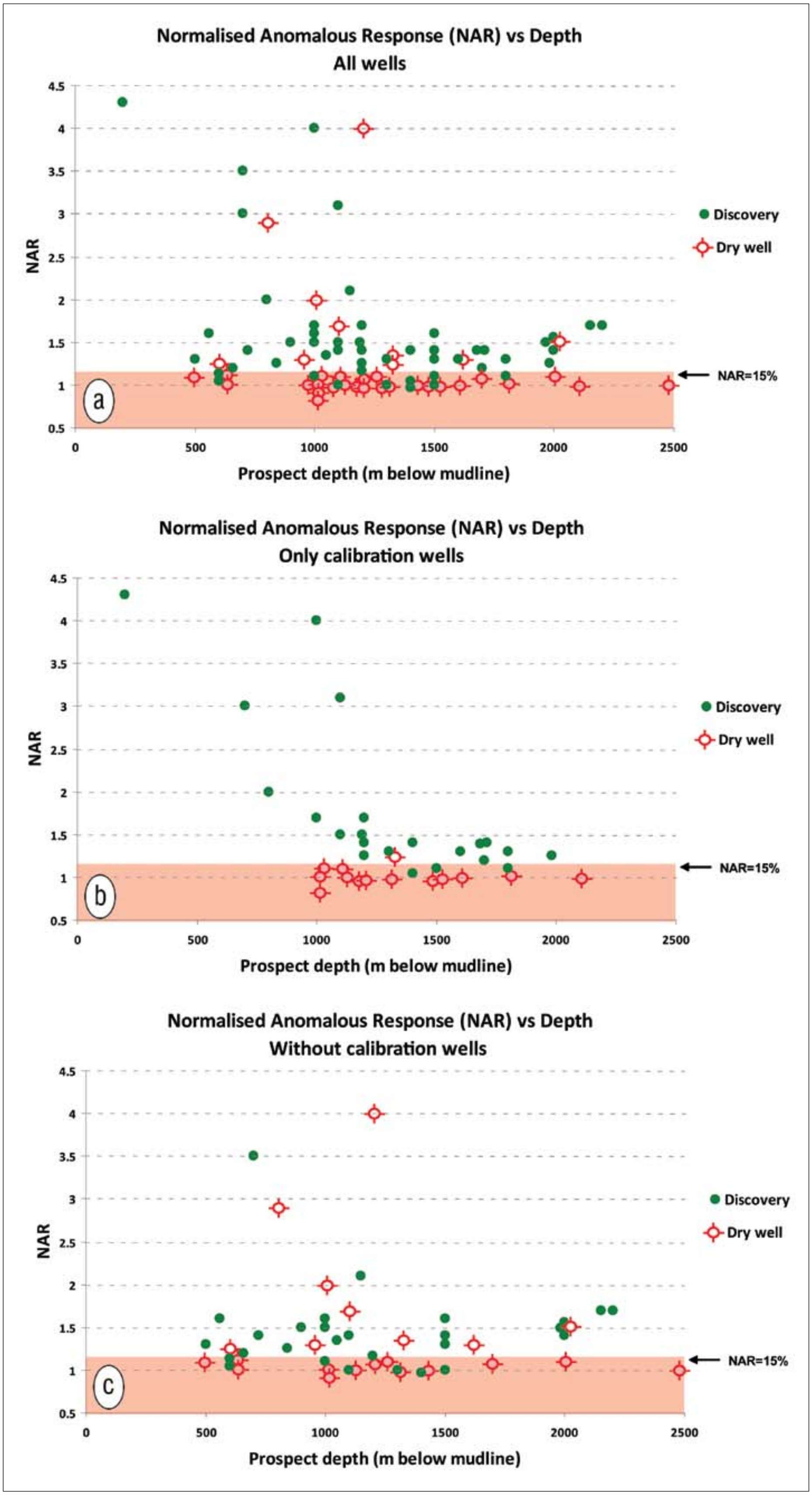

Figure 4. *The empirical data used in the current study. The observed NAR is plotted against the depth to prospect (below mudline). (a) Plot of all 86 wells including the 36 calibration wells. (b) Plot of all 36 calibration wells. (c) Plot of all 50 wells excluding the calibration wells.*

porous, hydrocarbon-bearing strata are likely to be present at a given location. The application of this integration across a broad portfolio can deliver increased degrees of exploration success.

Although we argue toward the need for an integrated approach when handling CSEM data, it is not known to what extent this has been implemented prior to drilling the wells in this study. As many as 10 wells were drilled on prospects showing no observable NAR for the fundamental frequency. It seems unlikely that observations from the CSEM analyses were key drivers for the drilling of these wells (or they would probably not all have been drilled). Another important aspect is the fact that 4 of the 10 wells actually were discoveries, even if the CSEM survey did not show a CSEM anomaly using the simplistic approach applied for this study. It is possible that more advanced analyses reveal information not present in the NAR plots (e.g., Boulaenko et al., 2007). However, an alternative explanation is that these wells were drilled in a setting not suitable for the CSEM technology, in which case CSEM data will not be able to effectively derisk a prospect (prospects too deep, prospects too small, not enough resistivity contrast to the surroundings, etc.). This is the explanation provided by Johansen et al. after post-well modeling studies of the discoveries. Similarly, an understanding of the dry wells drilled on prospects with NAR values above 15% requires in-depth post-well analyses of CSEM data in conjunction with other data types available.

Other important unknowns include the pre-CSEM initial chance of success for the different prospects as defined by the oil companies responsible for drilling the wells, as well as the actual success rate for wells drilled in the different areas in this study. While the global success rate for wildcat wells is on the order of 25%, the actual success rate for exploration wells drilled in the areas

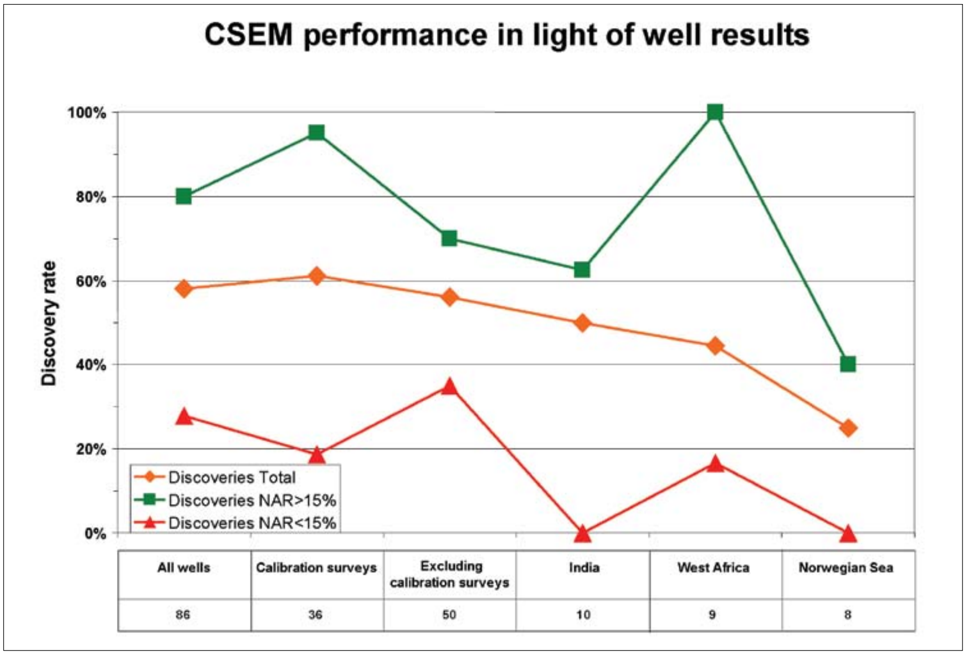

Figure 5. *Discovery rate for exploration wells drilled on prospects with CSEM data acquired prior to drilling the wells.*

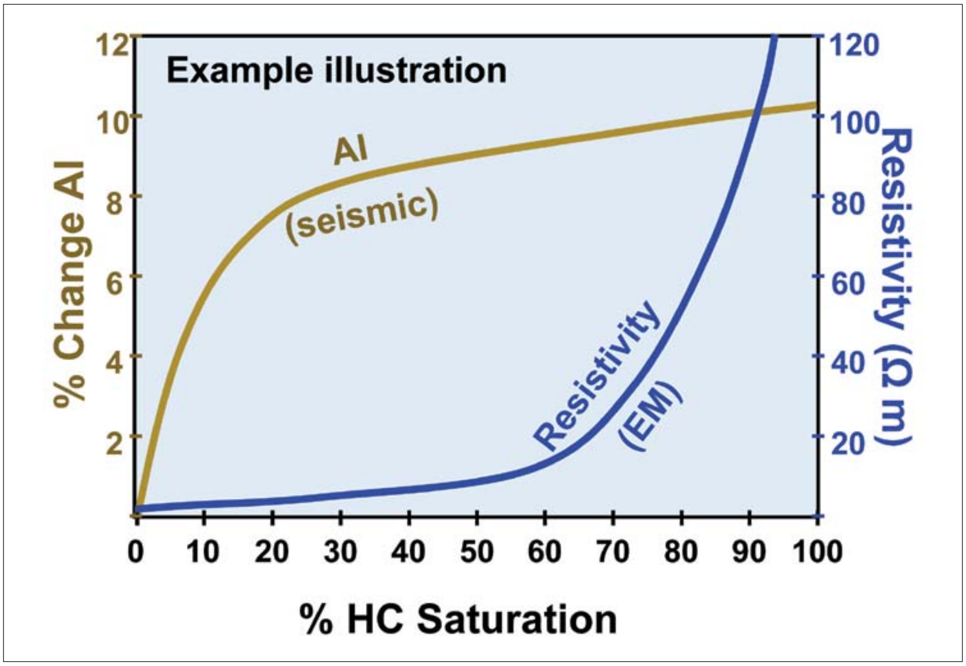

Figure 6. *Example of percentage change in acoustic impedance versus percentage change in hydrocarbon saturation. Whereas acoustic energy tends to react rapidly to small levels of hydrocarbon saturation, the amount of change decreases with higher HC saturation levels. In contrast, electromagnetic energy shows small changes in resistivity for low HC saturation levels, but the amount of change increases rapidly at higher HC saturation levels.*

discussed in this study may well be different. It may be argued that the general average exploration success rate for wells on prospects without CSEM data in the areas in this study is as high as 56% (same as the average discovery rate for all exploration wells in the specific database used), or it may be argued for an actual success rate closer to the global success rate of 25%. The truth is most likely somewhere in between these two values and it would be beneficial for future studies to identify the true success rates for the different areas. However, even if the general average success rate for the areas in this study is as high as 56%, there is still an average uplift of 14% (to 70%) for wells on prospects with a significant NAR (> 15%) compared to the average discovery rate for all exploration wells in this study.

An interesting observation from the calibration surveys is that 19 (86%) of the 22 discoveries show an NAR above 15%, whereas 13 (93%) of the 14 calibration surveys acquired over prospects proven dry show an NAR value less than 15%. If the data are representative, this is a strong indication that the CSEM technology will display a significant anomaly if hydrocarbons are present at depths and under conditions suitable for the technology. There also appears to be a clear correlation between the lack of hydrocarbons and lack of a significant CSEM anomaly.

Perhaps the most important finding in this study is that the difference in average discovery rate for wells drilled on prospects with a significant CSEM anomaly is twice the average discovery rate for wells drilled on prospects without a significant CSEM anomaly. It seems a fair conclusion that that the incorporation of CSEM data into the oil company's work flow can significantly help derisk prospects in CSEM suitable settings even if the true success rate for the different areas is not known for this study.

Summary and conclusions

The current study has evaluated an empirical database containing 50 exploration wells drilled on prospects with marine CSEM data acquired and analysed prior to drilling. Another 36 wells were available for calibration studies. The average discovery rate for the 50 exploration wells is 56%. When considering exploration prospects with a significant CSEM anomaly as observed on normalized response plots (NAR > 15%) at the fundamental frequency, the average discovery rate increases to 70% (based on 30 well results).

As many as 20 wells were drilled on prospects without a significant CSEM anomaly (NAR < 15% for the fundamental frequency). The average discovery rate for these wells is 35%. As such, the observed success rate for exploration wells drilled on prospects with a significant CSEM anomaly is twice that of exploration wells drilled on prospects without a significant CSEM anomaly. The same trend is observed for the areas with 8 or more wells available for analysis, the difference ranging from 40 to 83%.

As many as 10 wells were drilled on prospects showing none or even a negative NAR, and it would be of interest to better understand the rationale for drilling these wells (commitment wells, etc.). Three exploration discoveries in the database were on prospects showing an NAR value of only 5-10% for the fundamental frequency. Although this is a very low response, an example of how advanced integrated analyses can help understand even an NAR of 10% was presented by Boulaenko et al. (2007) related to the Luva discovery in the Norwegian Sea.

This study relates discovery rates to the most basic observations from CSEM data (normalized anomalous amplitude responses for the fundamental frequency), and should therefore be relatively objective. It is also the most extensive documentation of factual well results (86 wells) related to the CSEM technology documented to date. The results suggest that there is a correlation between the observed NAR and rate of exploration success for the wells in the database. This is strong positive evidence of the potential of the technology. The authors fully recognize that the application of the technology and the tracking of its impact is not a simple evaluation and further evaluation and other data are needed to fully understand the case made here, particularly on an individual well basis. It is also important to view the results in light of what is considered a technical success as described by Johansen et al. Finally, this study clearly illustrates that the CSEM technology does not eliminate risk, but has the potential to significantly reduce risk if applied correctly. As such, CSEM data should not be used on a single well basis. The technology serves as an important risk reduction tool in a portfolio setting where each prospect is analyzed as extensively as possible using an integrated approach where all available data are utilized.

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