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Application of Electromagnetic Scanning to an Australian Frontier Basin with Complex Bathymetry

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Abstract

Apache is exploring a large block offshore Australia. Part of the area is covered with good quality 3D seismic and a number of prospects have been identified from this data. Additional potential prospects were inferred from 2D seismic in the relatively under-explored deep water area of the block. With the current high cost of 3D seismic and drilling programs, it was considered very important to high-grade the prospects and to correctly assess the prospectivity of the deep water area.

Initially it was thought that traditional target-oriented CSEM surveys over each prospect would provide the required information. However, after further study, it was decided to cover the entire area with electromagnetic scanning. This approach provides a coarse 3D view of the entire area providing information not just about prospects identified from seismic, but potentially also revealing new hydrocarbon leads.

A highly rugose seafloor in combination with a high resistive overburden of varying thickness appeared as a major concern for the scanning survey. A wide, deep submarine canyon provided both operational challenges and data processing issues. The rugosity of the seafloor and varying overburden thickness constitute significant local as well as regional variations to the background resistivity distribution, making it difficult to extract potentially hydrocarbon related anomalies from the scanning data.

A novel approach to dealing with this problem was adopted, which takes advantage of complementary information from existing well logs and the available seismic data. A number of 1D inversions constrained by resistivity logs were performed at various locations across the survey. The results of the 1D inversions were then used to build a reference resistivity model that conforms to the bathymetry and the seismically derived overburden thickness. Detailed 3D simulation of the scanning survey for this resistivity model generated synthetic reference responses, which adequately account for most of the bathymetry and overburden related variations in the scanning data. Using these synthetic reference responses to normalize the scanning data, a number of interesting anomalies became apparent, one of which coincides with a known oil reservoir. The same anomalies had been masked by regional trends in previous results obtained by conventional single-receiver referencing.

The results obtained significantly increased our confidence in the interpretation of the scanning data and highlight the increased value obtained from an integrated analysis with complementary geophysical data.

Introduction

Electromagnetic scanning is a reconnaissance application of seabed logging [1] which employs coarse grid acquisition to assess the prospectivity of large areas [2], [3]. The idea is to detect potentially hydrocarbon-bearing resistive formations independent of their seismic expression and high-grade those prospects already identified from seismic data.

We present results from a recent scanning survey conducted in an Australian offshore basin as part of a major exploration campaign involving modern 3D seismic acquisition and the drilling of exploration wells. The survey covered an extensive area of 1650 square km where water depths range from approximately 100 m to more than 2500 m. The area hosts a producing oil reservoir and a number of exploration prospects previously identified from 2D and 3D seismic, which had been available over part of the survey area.

The scanned basin is characterized by a highly rugose seafloor topography and a complex geology with rock properties that have challenged seismic interpretation in the past. From a seabed logging perspective, the complexity of the geology manifests itself mainly through a carbonate-dominated overburden of largely varying thickness, where resistivity data from wells indicate a sharp increase in resistivity with depth. The prospects are located in the stratigraphic sequence below the overburden at 400-3500 m depth below seafloor and range from about 10 to 20 square km in size.

Accounting for the strong bathymetry effect and regional geological trends represented a technical challenge for the extraction of meaningful resistive anomalies from the scanning data. To address these issues, we applied a novel processing technique called “reference modeling”. This technique approximates the bathymetric and regional trends in the data by simulating the acquired survey for a resistivity reference model of the area. The simulation uses the exact navigation input from the survey, thus generating synthetic receiver responses which can be used to extract anomalies from the measured data.

We adopted an integrated approach which combines information from the scanning data, resistivity well logs, and seismic horizons to generate a representative reference model. The model building is driven by partial inversions of the scanning data, and multiple model iterations with various degrees of constraints from well log and seismic data are used to obtain a full understanding of the regional variation of the scanning data. The results presented in this article have been achieved by a model which is primarily based on well log constraints and assumes little seismic knowledge. Future model iterations that put more weight on seismic horizons are planned once new results from the application of advanced depth imaging technology are available.

Basin Geology

The geological evolution of the basin in which the scanning survey was acquired led to a stratigraphic sequence that is broadly classified into three main units: a carbonate-dominated overburden, a formation of marine siliciclastics, and a base sequence of mainly non-marine volcanoclastic sediments.

Primary target for exploration is the intermediate formation of marine siliciclastics which hosts all confirmed oil and gas accumulations in the area. The base formation overlying the Palaeozoic igneous basement is known to have some source rock potential for gas generation. The carbonate overburden provides the primary regional seal as well as necessary load to mature the source rocks of underlying formations.

Resistivity logs from wells that have penetrated the upper two stratigraphic units, exhibit three distinct resistivity zones (see Fig. 1). From a seabed logging perspective, the approximately exponential resistivity increase observed in the overburden deserves most attention. With resistivity values sometimes exceeding 15 Ωm and seismic indicating a thickness variation from 2200 m in shallow water to less than 500 m in deep water,

the overburden has a significant effect on the seabed logging response and contributes strongly to the regional trend in the scanning data. Beneath the overburden, low resistivities in the range of 0.5–2 Ωm define a good contrast for hydrocarbon reservoirs with resistivities in the order of 50–100 Ωm . The beginning of the third resistivity zone is marked by a slight increase in resistivity and clear bedding-related fluctuations.

The bathymetry in the survey area (Fig. 2) is characterized by rapidly increasing water depth towards the east and a wide, up to 2000 m deep submarine canyon. The sharp transition from shallow to deep water exhibits a complex system of narrow erosion channels that can be several hundreds meter deep.

Due to the complex geological setting and bathymetry, it proved essential to use all available information from well logs and seismic to remove regional trends in the scanning data and to correctly identify those anomalies on which further exploration efforts should be targeted.

Data Acquisition

The scanning data consist of electric and magnetic fields excited by a deep-towed, horizontal electric dipole source and recorded by a grid of EM receivers deployed on the seafloor.

As shown in Fig. 2, the survey layout consists of ten source towlines and 84 seafloor receivers positioned on a 4 by 4 km grid. By using a 2 km receiver spacing over some of the prospects, the scanning approach is combined with the traditional target-oriented application of seabed logging aimed at prospect ranking. The towlines were directed along NNE, roughly parallel to the main bathymetric contours.

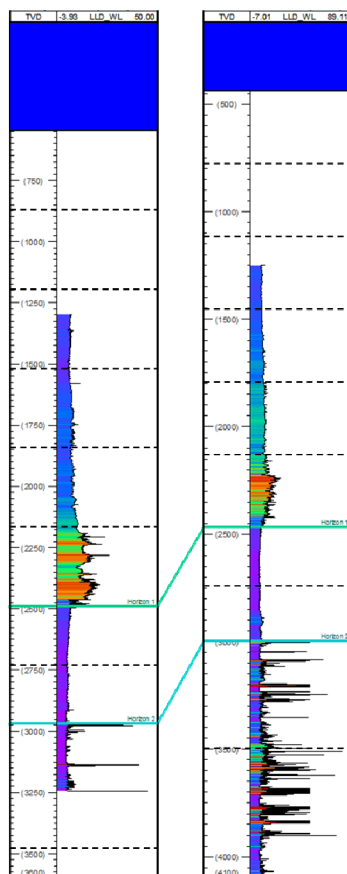


Fig. 1—Examples of resistivity logs from the survey area exhibiting three distinct resistivity zones (solid boundaries). A subdivision into ten layers (dashed boundaries) was used for statistical analysis and to define the inversion model.

The data were acquired using a layout which is sometimes referred to as a “rolling” grid. For each source towline, receivers beneath that towline as well as the two neighboring lines are active, yielding both inline and azimuth data. Upon completion of the towline, one line of azimuth receivers is picked up and redeployed to form the next set of acquisition lines. This process repeats until all source towlines have been acquired. The rolling grid allows covering large areas with a limited number of receivers. In addition, it gives the possibility to QC the data at regular intervals during the acquisition, which is highly advantageous when scanning in such operationally challenging environments.

The source emitted a composite waveform [4] optimized for the frequencies of 0.25, 0.5 and 0.75 Hz. Using such composite waveform, the transmitter operates at its peak current of 1250 A at all times and focuses the available source power on those frequencies that the prospects proved most sensitive to during the survey feasibility modeling. For this survey, the feasibility study indicated good sensitivity for 0.5 and 0.75 Hz. The lower base frequency of 0.25 Hz penetrates deeper into the subsurface and was thus included in the waveform design.

To avoid the risk of source contact with the highly rugose seafloor, the altitude of the 270 m long source had to be adjusted continuously, which resulted in deviations of up to 100 m from the planned source altitude of 30 m. In addition to the altitude fluctuations, strong underwater currents led to non-negligible source feathering, both of which the processing of the scanning data needed to correct for.

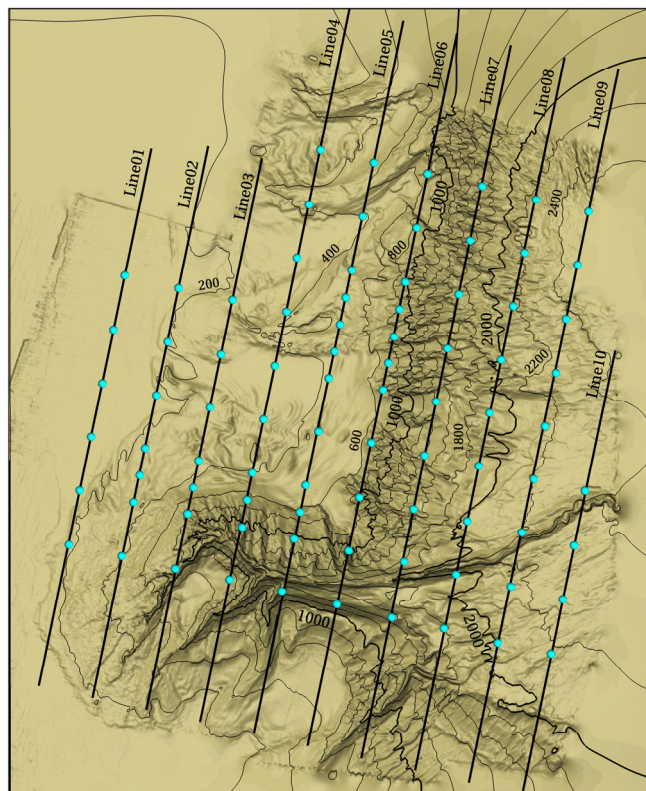


Fig. 2—Bathymetry map and survey layout.

Reference Modeling

For traditional, target-oriented seabed logging surveys, it has been customary to identify a single receiver off the prospect and to use its measured response to normalize the responses of other receivers [5], [6]. Implicit in this approach is the assumption that variations in background geology and bathymetry are minimal over the survey area. This is a reasonable assumption for most small, target-oriented surveys, but it is inappropriate for this scanning survey. This led us to apply a new referencing approach called reference modeling.

The basic idea of reference modeling is to generate a separate reference response for each receiver which captures the bathymetry, the background resistivity distribution and the source navigation specific to the receiver. Such responses are generated by 3D simulation based on a reference resistivity model built from the results of a partial inversion of the scanning data. The following sections describe the three main steps of the reference modeling workflow—1D inversion, reference model building and survey simulation—as applied to this scanning data set.

1D Inversion

The first step in building a reference resistivity model is to recover the resistivity-depth profile at various locations of the survey area by 1D inversion of the data from several carefully selected receivers. To avoid getting inversion artifacts due to neglecting the strong airwave fluctuations associated with bathymetry variations, we employed the simulating annealing algorithm described in [7]. This algorithm significantly reduces such artifacts by including an approximate up-down wavefield decomposition in the forward operator.

The 1D inversions were constrained by resistivity logs from 9 wells located in the northwestern and central parts of the survey area. To this end, each log was divided up into the three main resistivity zones described above. Each resistivity zone was subdivided further to define ten depth zones to which the inversion must assign different resistivity values (Fig. 1). Statistical analysis of the resistivities over these depth zones for all available logs provided resistivity limits and qualitative resistivity-depth trends that the inversion had to adhere to. For receivers with no nearby wells, the depth trend observed in the seismic data was used as a guideline to specify the base of the overburden in the inversion model.

Reference Model Building

The resistivity-depth profiles obtained from the 1D inversions are then interpolated and extrapolated to populate a model of the resistivity distribution beneath the seafloor. To obtain a geological meaningful subsurface model, the interpolation

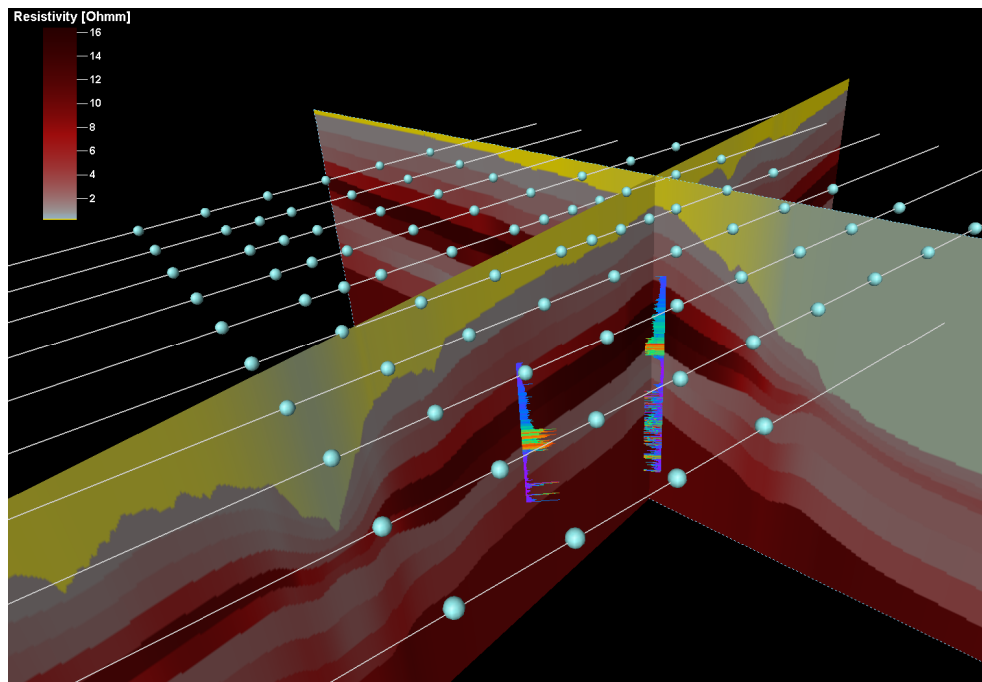


Fig. 3—Reference resistivity model obtained from a guided interpolation of the inversion results together with two of the resistivity well logs used as inversion constraints.

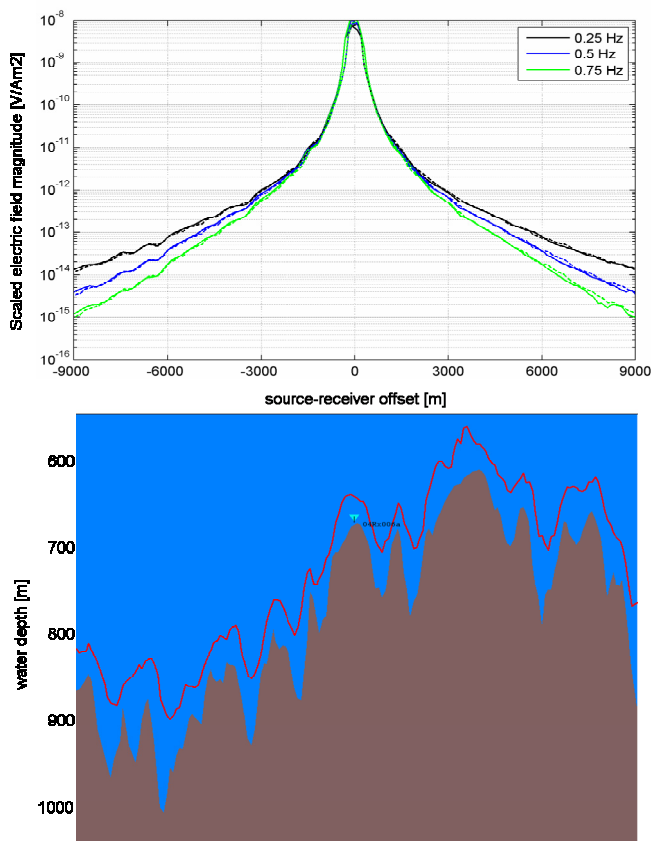


Fig. 4—Comparison of a synthetic reference response (dashed) with its measured counterpart (solid) [top]. Corresponding bathymetry along the towline and source trajectory [bottom].

procedure can be guided by auxiliary data. Since our geological understanding of the scanned basin indicates that the resistivity-depth trend is primarily correlated with the water depth and the overburden thickness, we used these two parameters to guide the interpolation. In addition, we used a recursive layer based framework that allows the model building process to “cut” erosion channels into the overburden. By merging the resulting subsurface model with a seawater conductivity distribution estimated from CTD probe readings taken along the source towlines, the wanted reference resistivity model was obtained (Fig. 3). From the figure, we note that the resistivity model describes the thinning out of the resistive overburden towards deeper waters and conforms to the trends observed in the resistivity logs, as exemplified by the two logs included in the display.

Survey Simulation

The reference resistivity model was used as input to an electromagnetic simulation code based on a fast finite-difference time-domain (FDTD) method [8]. The code simulates the scanning survey as acquired, i.e. using the exact source and receiver navigation, thus naturally accounting for the undulating source trajectory and source feathering in this survey. The code outputs one synthetic reference response for each receiver-towline combination. In accordance with the rolling grid acquisition, we therefore have three synthetic responses per receiver, one associated with the inline source towing and two separate ones associated with the azimuth source towing.

Fig. 4 shows an example of a synthetic inline receiver response generated by reference modeling and compares it against its measured counterpart. Included in the figure is

the bathymetry along the towline and the source trajectory. We observe that the measured response exhibits strong fluctuations reflecting the varying coupling of the source field into the subsurface as the source is towed over the rugose seafloor. From this example, it is very clear that no single measured reference response could be used to normalize the responses of all receivers in this scanning survey. The synthetic reference response, however, follows these fluctuations to a high degree, illustrating the strength of this approach.

Data Processing

The synthetic responses obtained from the reference modeling were processed identically to their measured counterparts. The processing included an approximate up-down wavefield decomposition [9] and azimuth processing [10].

Up-down wavefield decomposition combines the electric and magnetic fields to separate the upward traveling constituent of the wavefield, which has probed the subsurface, from the downward traveling constituent, which has not and is a result of source energy that has traveled along the sea surface (commonly referred to as the airwave).

Azimuth processing estimates the part of the response contributed by the source component in the direction of the receiver. This response is called the TM response or inline response, as opposed to the TE or broadside response contributed by the source component perpendicular to the direction of the receiver. It is well known that only the TM response exhibits an anomalous behavior over thin resistive structures such as hydrocarbon reservoirs. In addition, azimuth processing makes it possible to merge the data acquired by inline and azimuth receivers into a single, more densely sampled anomaly display.

After processing, the synthetic reference responses are used to normalize the measured responses, resulting in normalized magnitude and phase-difference responses. Sorting of the normalization results into the midpoint-offset domain followed by gridding gives anomaly cubes (x-y-offset) such as the one shown in **Fig. 5**. These cubes can be visualized in 3D together with other geological information. Alternatively, the normalized responses can be stacked over short, intermediate and large offset ranges to produce a set of three anomaly maps providing a rough depth division of the response into shallow, intermediate and deep.

Results

Fig. 6 shows three electric field anomaly maps for small, intermediate and large offsets computed from the 0.5 Hz data.

The maps reveal five interesting anomalies marked by ovals. One of these anomalies coincides with the location of the known oil reservoir. With conventional single-receiver referencing, these anomalies had been masked to a great extent by regional trends and bathymetry effects.

The southwestern, central and northern anomalies become most apparent at large offsets, indicating that they are likely associated with resistive structures beneath the carbonate overburden, i.e. in the stratigraphic sequence that host all known hydrocarbon accumulations in the basin. Interpretation-aiding simulations were run to validate this depth-offset relationship. It can be argued that the southwestern anomaly is already visible at intermediate offsets—hence marked as dashed—although this is difficult to ascertain due to the strong residuals just south of the anomaly (explained in more detail below).

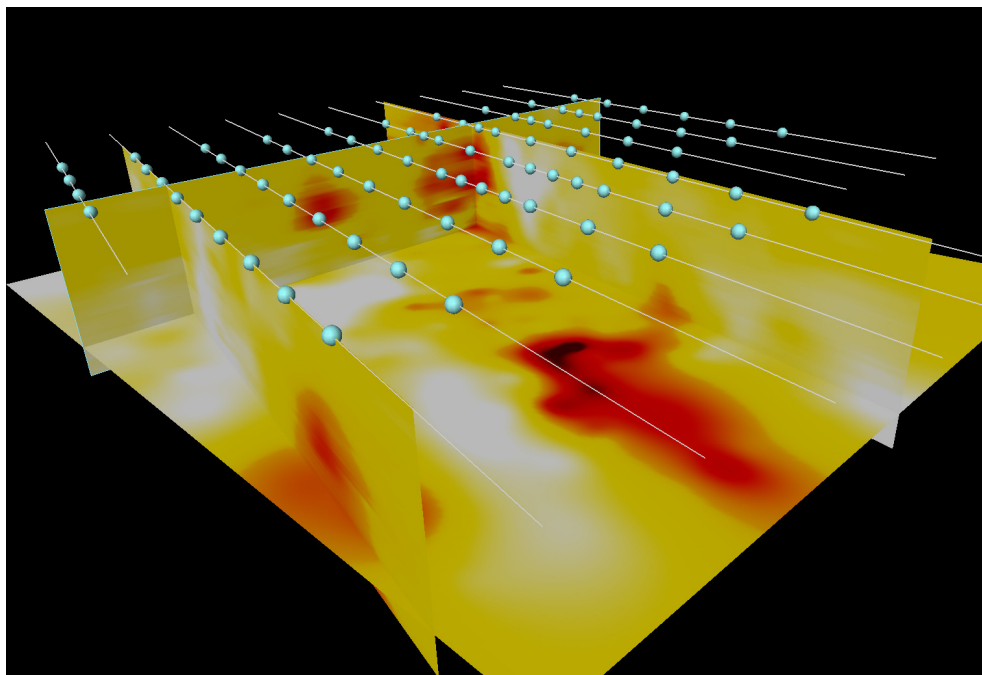


Fig. 5—Electric field anomaly cube showing normalized magnitude (0.5 Hz). The vertical axis represents source-receiver offset.

Towards deeper waters where the overburden is thinner, the observed anomalies are clearly visible already at intermediate offsets. The southern anomaly disappears again towards large offsets, whereas the large anomaly in the northeast remains. This may be an expression of the size of the geologic structures that these anomalies relate to, a hypothesis still subject of our analysis.

The rectangle in the small offset anomaly map marks the submarine canyon, which is clearly recognized by its long, thin signature running from west to east.

The maps indicate that our reference model does not yet capture all the geological complexity inherent in the data. Just east of the northern anomaly—at the abrupt transition from shallow to deep water—and south of the southwestern anomaly near the “tail” of the submarine canyon, we observe very strong residuals. These residuals build up starting from very small offsets, pointing to an inadequate representation of the overburden. This result highlights the important role seismic plays in constraining the reference model, as no seismically derived overburden thickness was available for the southern part of the survey area at the time of this publication.

We anticipate that future reference model iterations that fully incorporate seismic horizons will further confirm the observed anomalies and remove some of the remaining residuals.

Conclusions

We acquired an electromagnetic scanning survey to assess the prospectivity of a large area offshore Australia. The area’s rough seafloor topography and complex geology make geophysical exploration a challenging undertaking, requiring a combination of modern acquisition, processing and data integration technologies to draw the right conclusions.

Careful analysis of the scanning data using a novel processing technique called reference modeling revealed a number of interesting resistive anomalies and confirmed a known oil reservoir, which had not been evident in previous results obtained from conventional, single-receiver referencing. In such a complex setting, we see a clear benefit from integrating scanning, well log and seismic data to obtain a representative reference model with which many of the regional residuals and bathymetry effects in the scanning data can be suppressed. Future reference modeling updates are planned that fully incorporate seismic data once we have complete depth imaging coverage of the survey area. We anticipate that these updates will further suppress some of the remaining residuals, increase our confidence in the observed anomalies and help us to fully understand their origin.

The results achieved so far are encouraging and the analysis of the scanning data will be an on-going activity as we continue to build our understanding of the basin.

Acknowledgements

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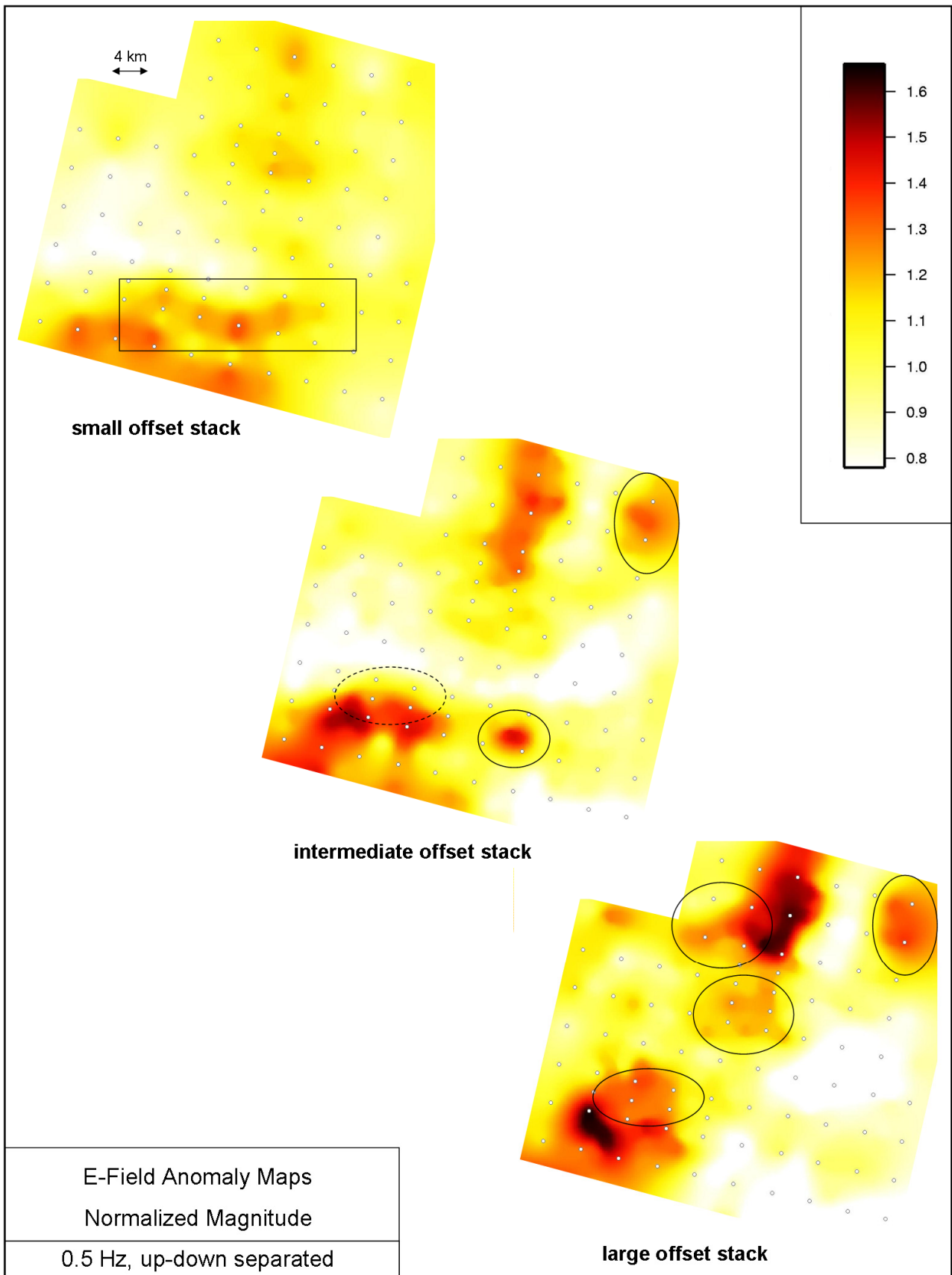


Fig. 6—Electric field anomaly maps revealing a number of interesting anomalies (ovals). The submarine canyon has left a clearly visible trace in the short offset map (rectangle).