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Investigation of a Mid-crustal Conductor in the North Gjallar Ridge, Offshore Norway, Inferred from Magnetotelluric Data

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SUMMARY

In this case study, we present the results of the processing, analysis and 2D inversion of Magnetotelluric (MT) data acquired in the North Gjallar Ridge (NGR), in the outer Vøring basin (Norway), in July 2014. Although the primary objective of the survey was to collect Controlled Source Electromagnetic (CSEM) data for hydrocarbon exploration purposes, a good quality MT signal was extracted alongside on 120 EM receivers. MT data in the NGR reveal an unusual drop in apparent resistivity values at long periods. Such behavior was already observed in the outer Vøring basin and the Exmouth plateau (offshore Australia), both are volcanic passive margins. Indeed, 2D inversion of MT data shows a consistent recovery of a conductor at mid-crustal depth (8-12 km) along the axis of the ridge. Imaging seismically crustal structures in the NGR has long been challenging due to the presence of a dense network of volcanic sills and dykes. On the contrary, MT signal can diffuse beneath them and sense deep geo-electrical structures. We tentatively interpret the conductor, which correlates with a positive Bouguer anomaly, as related to the presence of deep non-intruded sediments.

Introduction

In July 2014, a 3D electromagnetic (EM) multiclient survey was conducted by EMGS in the Vøring Basin, offshore Norway (*Figure 1*), a volcanic sedimentary basin with numerous igneous intrusions formed as part of the NE Atlantic break-up. The primary survey objective was to collect Controlled Source Electromagnetic (CSEM) data for hydrocarbon exploration purposes. However, magnetotelluric (MT) data were extracted alongside CSEM data processing, providing good quality MT data for periods ranging from 2 to 1500 seconds. Given the period range, the investigation of deep crustal resistivity structures was made possible. The purpose of this study is to show that, even when MT data are acquired as a by-product of a CSEM survey, efficient MT processing and 2D MT inversion yield valuable information on deep geo-electrical structures. To place the new MT results in the context of regional geology, we integrate our results with both geological models and regional geophysical data sets (e.g., Gravity and seismic data). The striking feature on the MT data is a consistent conductor located at mid-crustal depths of > 6 km, tentatively interpreted as a sedimentary unit not affected by magmatic intrusions.

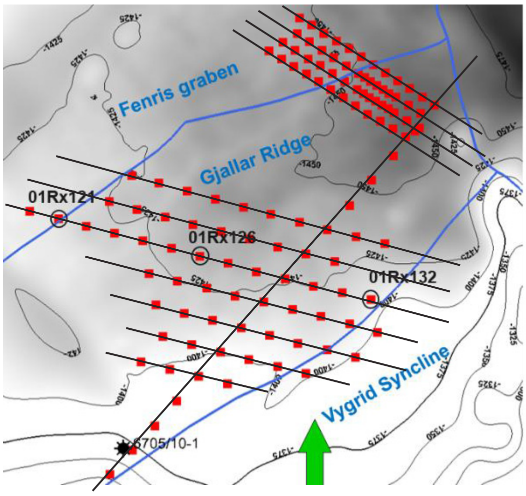

Figure 1: *Map of the survey area in the NGR. EM receivers are shown as red squares. The contoured surface represents the bathymetry, 1430 meters on average in the area. The blue solid line indicates boundaries of large geologic structures in the Vøring Basin (extracted from the Norwegian Petroleum Directorate fact maps). CSEM tow lines are highlighted by black lines.*

Magnetotelluric (MT) data analysis in the north Gjallar Ridge

After efficient processing, using the robust multi-station processing scheme (Egbert, 1997) combined with an EMGS auto-grouping algorithm (Markhus, 2013), the 120 receivers provided a good quality MT signal for periods ranging from 2 to 1500 s. Three typical MT responses along the line 01Tx103 are displayed in *Figure 2*, their location is indicated by black circles in *Figure 1*. Receiver 01Rx121 and 01Rx132 are located at the edges of the NGR whereas receiver 01Rx126 is located right in the center of it. For receivers 01Rx126 and 01Rx132, transverse electric (TE) mode responses show an unusual drop in apparent resistivity for periods starting from 100s. Myer et al. (2013) observes the same unusual behavior in both TE and transverse magnetic (TM) mode responses for receivers deployed in 2010, 35 kilometers south-east of the studied area. This is in contrast to most offshore sedimentary basins, where MT responses generally show an increasing trend in apparent resistivity with period (i.e. depth), associated, e.g., with a resistive basement or a usual porosity reduction with depth. For periods shorter than 100s, resistivity and phase curves for both modes are very close, showing that the MT signal senses a 1D layered earth. The TE and TM mode split do not occur consistently throughout the survey. Receivers located close to the NW bound of the ridge, like 01Rx121 in *Figure 2*, show close modes at all periods, indicating low dimensionality in the subsurface. On the other hand, towards the center and south-eastern boundary of the ridge, a split occurs consistently around 100s, with the TE mode dramatically decreasing whereas the TM mode remains on the same ascending trend. A large split in the modes at the center (01Rx126) and SE bound of the ridge (01Rx132) indicates high dimensionality in the data, and potentially 2D to 3D resistivity variations at depth.

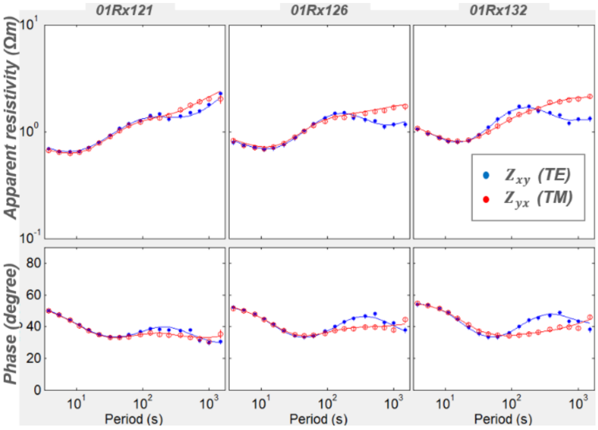

Figure 2: *Apparent resistivity and phase responses for three receivers located at the NW (01Rx121), center (01Rx126) and SE (01Rx132) bounds of the NGR. All MT impedance tensors have been rotated along the towline in this plot. The TE mode (in red) represents current flow induced along the geological strike (X axis, perpendicular to the line) whereas TM mode (in blue) represents the orthogonal components of the currents, along the inverted line (Y axis). The dots represent the observed data whereas the solid lines stand for the modelled one.*

By displaying the MT responses at a particular period in a plane view, the distribution of the anomalously low apparent resistivity values throughout the survey can be seen. *Figure 3* shows the MT responses (XY component) of every receiver positions at two periods, 1000 and 1200 seconds, in a plan view.

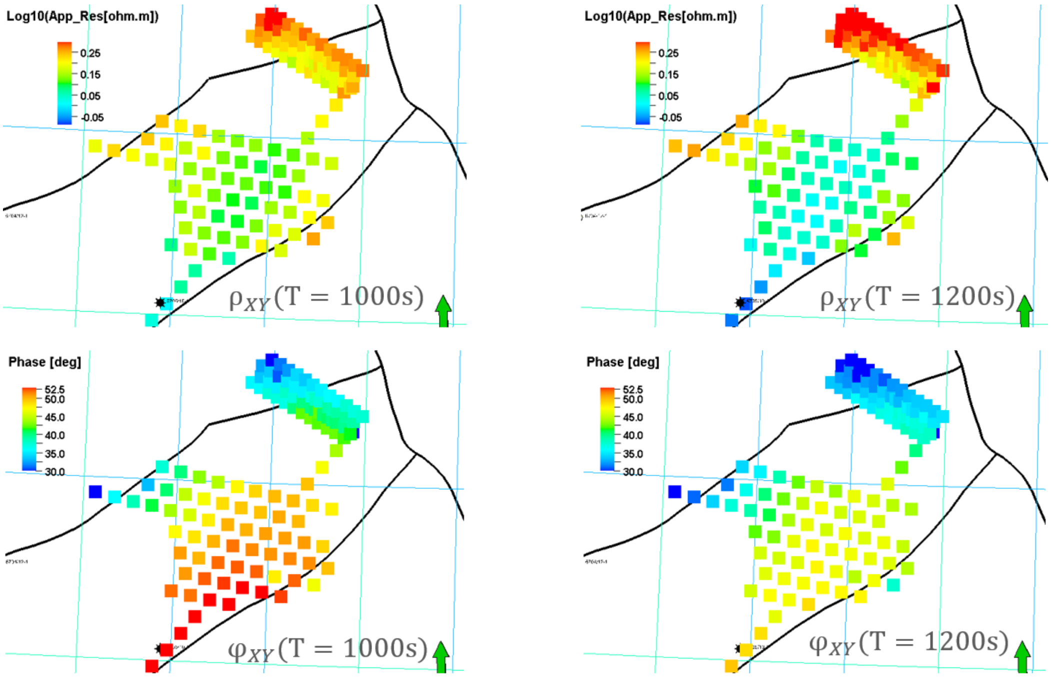

Figure 3: *Apparent resistivity and phase maps for two periods of the XY mode only. Each square represents an EM receiver. All MT impedance tensors are rotated to North. The black solid lines represents the structural edges of the ridge.*

At such long periods, the MT signal is affected by currents flowing at mid-crustal depth, around 8 to 12 km. All MT tensors were rotated to North, allowing all responses to be compared. Remarkably, low apparent resistivities are mostly concentrated in the center and near the SE bounds of the NGR. Similarly, a higher phase response correlates well with the extension of this potential conductor at crustal depth. Also, one can observe a decay in apparent resistivity, and corresponding increase in the phase, when going along the ridge axis from NE to SW.

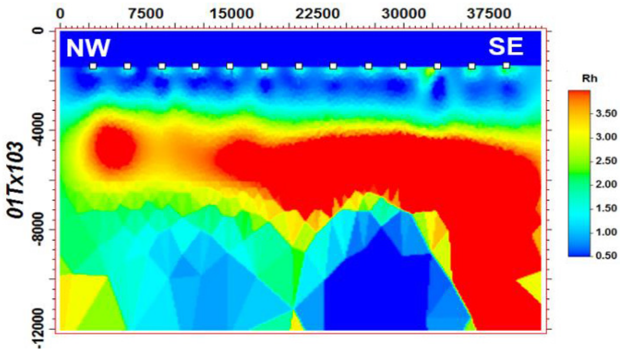

Figure 4: *2D MT inversion section along line 01Tx103. Receives are shown by white squares. TE and TM mode are inverted simultaneously. All inversions on the NGR converged to a RMS misfit of 1.0.*

2D MT inversion of the north Gjallar Ridge data

In the previous section, we show that a low apparent resistivity feature was present along the Gjallar Ridge axis, striking SW-NE. This observation validates the mode assignment as per *Figure 2*, as the preferential direction of current flow (X-axis) is most likely running along the ridge, and therefore striking almost perpendicularly the inverted lines (Y-axis). A representative inverted line, 01Tx103, is presented in *Figure 4*. The inversion scheme used is the MARE2DEM, a 2D parallel adaptive finite element code (deGroot-Hedlin and Constable, 1990). The final model explains the observed data, as shown in *Figure 2*, and reaches a RMS misfit of 1.0 and below. As expected, a conductive body is recovered, extending from the center to the south-eastern end of the line, at mid-crustal depth between 8 and 12 km below sea surface.

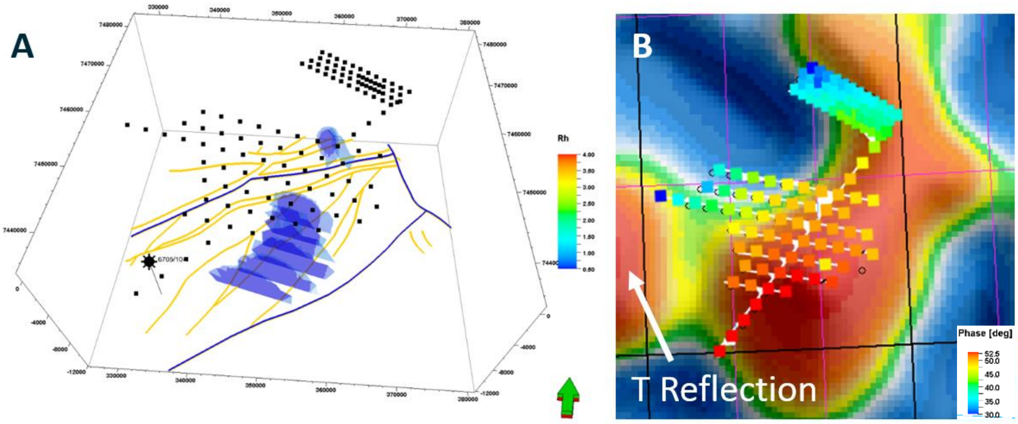

Figure 5: *A) 3D view of the conductor recovered by the 2D MT inversions on all NW-SE lines. A cut-off value of 1 Ωm was chosen to highlight the deep conductor presence on all lines. The EM receivers are shown by black squares. The dark blue lines represent the bounds of the structural elements in the NGR. The orange lines show the main faults B) Overlay of phase data (XY mode) for T= 720 seconds on a regional 100 km Bouguer gravity anomaly map (Berndt, 2002). The western Bouguer anomaly is related to the well-known "T reflection" mapped in the area (e.g., Gernigon et al., 2004)*

2D MT inversion was performed on all lines striking NW-SE, converging quickly to a RMS misfit of 1.0. All the inverted models provided consistent resistivity variations and a deep conductor is recovered. In *Figure* 5A, a 3D visualization of this conductor is shown. A cut-off value of 1 Ωm was chosen to highlight its presence on all lines. Firstly, the consistency of the conductor on all lines is striking. Both in terms of spatial extent and resistivity, one can follow the morphology of this conductor varying smoothly throughout the survey. The conductor seems to be horizontally confined to the centre and the south-eastern bound of the north Gjallar Ridge. Toward the northern EM grid, the conductor seems to get shallower and fade away in the NE, precisely where the ridge ends. In addition, the conductor shows very good lateral correlation with a positive Bouguer anomaly (*Figure 5B*). This correlation, based on two independent measurements with comparable resolution at crustal depths, builds confidence in the MT data. Previous interpretations of other mid-crustal conductors have been postulated previously for both the Vøring basin (Myer et al., 2013) and the Exmouth plateau offshore Australia (Heinson et al., 2005), and involve graphite coating of fault zones or layered mafic intrusions with magnetite-rich zones. However, we tentatively interpret the conductor to be related to a non-intruded section of the sedimentary basin, with the resistive section above (at ca. 4-8 km depth in *Figure 4*) related to an igneous complex of highly resistive sub-horizontal sills, transgressive sills and vertical dykes. These are clearly imaged in the area on seismic data.

Conclusions

In this study, we image a conductive body at mid-crustal depth below the north Gjallar Ridge by the analysis and 2D inversion of Magnetotelluric data. This conductor has a SW-NE strike, running along the axis of the ridge and fades away in the northern part of the NGR. It is therefore unlikely that it reaches the Vøring escarpment. Thanks to a 120 receiver dense grid of this 3D CSEM survey, we infer that this extensive crustal body in the Vøring margin may be related to a section of the sedimentary basin not intruded by igneous intrusions. Even if the MT data were acquired as a by-product of a commercial 3D CSEM survey, efficient MT data processing and inversion has allowed to resolve and map a crustal-depth conductor

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