## Introduction

Structures within and underneath basalt sequences are often poorly resolved by reflection seismic data. Accordingly potentially hydrocarbon bearing sediments below basalt sequences are very difficult to image by seismic data only. We propose to derive additional information about sub-basalt sediments by combining first-arrival tomography, FTG gravity and magnetotelluric (MT) data through joint inversion. Each data set contains complementary information and accordingly the combination of these methods during the inversion allows resolution of structures that are not resolvable by individual methods. To link the different data types in the inversion process we invoke the existence of a relationship between different physical parameters. Although such an assumption may carry errors for certain structures, both synthetic studies (e.g. Heincke et al., 2010) and field studies have shown that this relatively strong assumption and coupling mechanism may actually be applied in this particular geological context and yields greatly improved inversion results.

Our investigation area is License L006 which is located about 150 km southeast of the Faroe Islands (Fig. 1) in the Faroe-Shetland Trough. This area is an attractive site for joint inversion because of the many comprehensive three-dimensional data sets collected by different geophysical methods, including a pattern of wide-angle seismic lines, a marine 3-D FTG survey and a large number of MT measurements on a 3-D grid. In addition, data from a 3-D reflection seismic survey and from a borehole located in the central part of this area allow us to 1) directly compare joint inversion results with other information and 2) derive petrophysical relationships required for the joint inversion from borehole logging data (Fig. 2). By means of the extensive and comprehensive data base we are able to consider a number of important aspects. First of all, we can test the applicability of current joint inversion strategies to large 3-D field data sets. In addition, it is possible to investigate which kind of information (e.g. basalt thickness and physical properties of underlying sediments) can be reliably resolved by such a combination of data types in a joint inversion. Finally, given that the data were acquired about 15 years ago without a view to joint inversion, this project provides an interesting test case as to whether data sets that are spatially somewhat incoherent in the experimental set up may still be used for joint inversion.

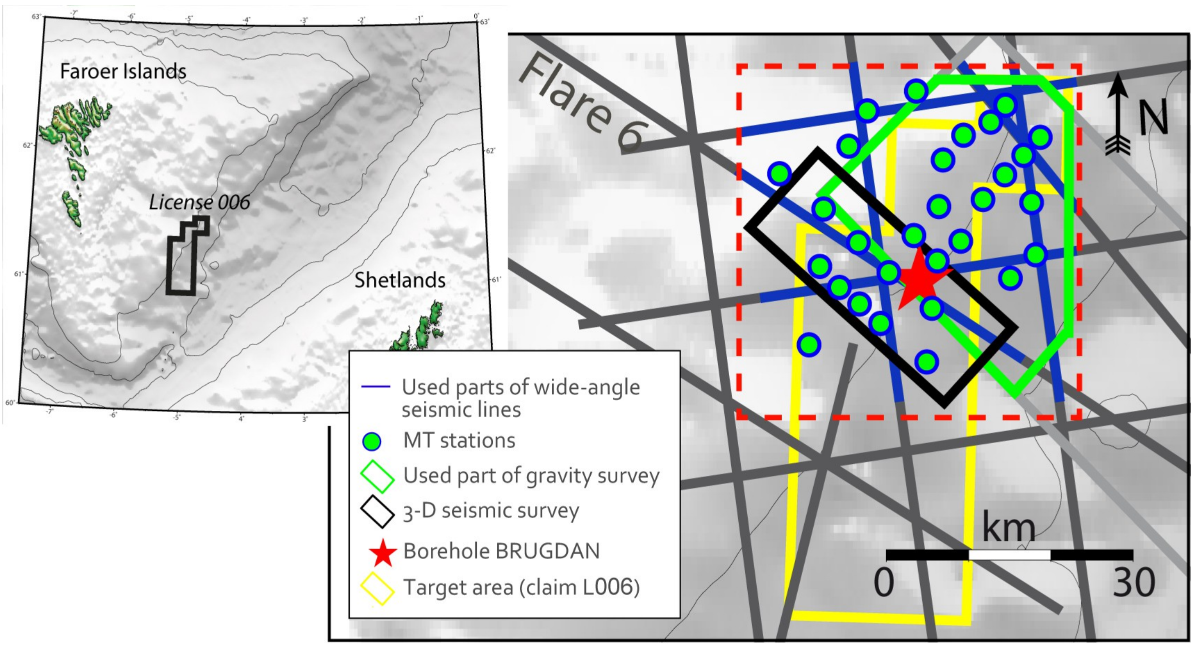


*Figure 1: Map of the investigation area. All data sets used for the 2-D and 3-D joint inversion are shown. The red-dashed rectangle outlines the area where the 3-D joint inversion is performed.*

Joint Inversion Methods

For our joint inversions, we used two different schemes. Both codes combine seismic tomography, magnetotelluric and gravity data and have been developed by the marine EM-group at *GEOMAR*. Although some algorithms in the two codes are very similar (e.g. meshes of both codes consist of rectangular cells having constant physical properties), the philosophy and basic concepts are to some extent different. The code JINV2D is a 2-D inversion scheme that does not require any balancing between the different data sets and ensures adequately-low data misfits for all data types by adaptively varying the coupling constraints (Heincke et al., 2010). The other code, JIF3D (Moorkamp, 2010), is a 3-D inversion scheme that is massively parallel programmed and uses iterative inversion solvers (BFGS) that are memory efficient. We perform all 2-D and 3-D inversions with the JINV2D program and the JIF3D program, respectively.

**Joint inversion applied on data sets from the Faroe -Shetland Trough**

2-D inversion:

A two-dimensional joint inversion is applied along the wide-angle seismic profile *FLARE6* (Fig.1). About 50.000 first arrival times, the impedance from 12 MT stations with a frequency range of 0.006 -0.015 Hz and the gravity field from 425 locations are used in these joint inversion tests. We chose this line because the *BRUGDAN* borehole is drilled in the direct vicinity and the line intersects the 3-D seismic survey area.. The field set-up is, however, not optimal for a 2-D joint inversion because no MT stations are located in the eastern part of the section, and the western part is not covered by the gravity survey. Furthermore, some of the used MT stations lie up to 7 km off side the profile and require projection on the 2-D seismic line. Due to these offsets MT data do only approximately represent the resistivity structure along the profile.

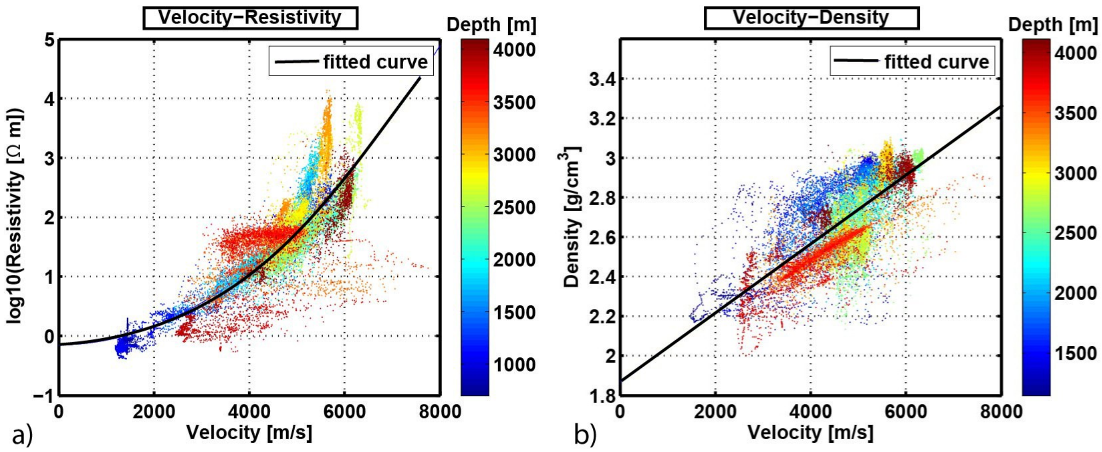


*Figure 2: Cross plots of the logging data from the borehole BRUGDAN. Color coding of the dots is associated with the actual depths. Black lines show the parameter relationships that are used for both 2-D and 3-D joint inversions.*

Prior to joint inversion, the different data sets were inverted separately. The resulting single inversion models however were rather inconsistent and difficult to interpret. However, through joint inversion a comprehensive model exhibiting a similar low misfit to the different data sets as individual separate inversion could be derived. The resulting joint inversion model is shown in Figure 3a. The model exhibits quasi-horizontal high-velocity, high-resistivity and high-density anomalies in a depth range of 2000 to 4000 m. The upper and lower boundaries in good agreement with the top and base basalt estimates from the 3-D reflection seismic data (Fig.3a). Physical parameters from the joint inversion model along the borehole show a good general agreement with the logging data (Fig 3b), however small scaled variations are, as expected, not resolved. Verification of the joint inversion model below the extent of the borehole can only be achieved through joint inversion results by other algorithms (see 3D joint inversion discussed in text) or comparison with independent data such as a wide angle seismic studies (e.g. Fliedner and White, 2003). In fact, while the 2D joint inversion shows no indication of the existence of a basement at the base of the model. However, the existence of a crystalline basement has been inferred from the wide angle seismic data. The difference between the two models suggests that the 2-D joint inversion not have sufficient resolution at this depth.

3-D inversions:
We apply the 3-D joint inversion to the complete northern part of License L006 (Fig.1). The data setup can be considered as truly three-dimensional, because it consists of a pattern of 6 crossing seismic profiles and comprises 26 relatively uniformly distributed MT stations. Only the FTG gravity survey does not cover the whole region but only the eastern part. Due to the fact that the complete the complete inversion matrix is solved in a single matrix with JIF3D, it turned out that adequate balancing between the different data misfit terms in the objective function is crucial. To avoid bias introduced by the balancing, we decided to simplify the situation by combining seismic and MT data only in a first step. Gravity data as a third method will be added in a second step (not shown here).

In areas away from the seismic lines where MT station coverage is also low the resolution is typically significantly lower than in other parts of the model which are better covered by data. To avoid a patchy model due to inhomogeneous data coverage in model, we use for all presented 3-D inversions typically a significantly higher regularization (smoothing) in horizontal directions than in the vertical direction.

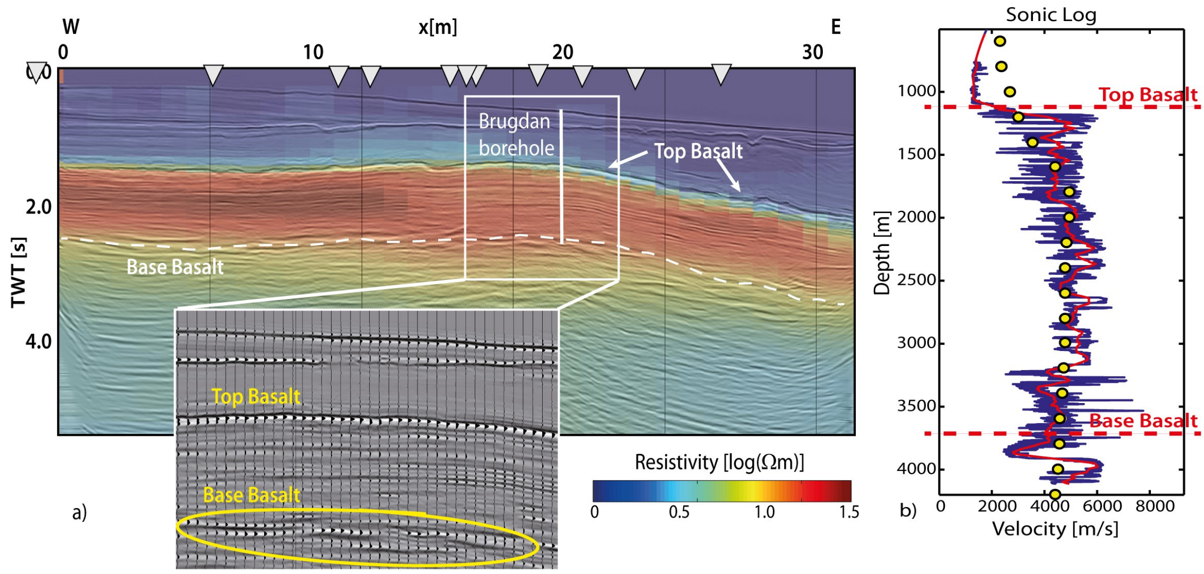


*Figure 3: Results from the 2-D joint inversion. a) The resistivity distribution (colors) from the joint inversion is superimposed over a cross-section from the 3-D reflection seismic data set (see Fig. 1). Grey triangles indicate the locations of used MT stations. The white dashed line indicates the base basalt interpreted from the combination of borehole, reflection seismic and joint inversion data. In b) the sonic log from the BRUGDAN borehole (blue line) is compared to the 2-D joint inversion results along the borehole (yellow dots). The red line corresponds to the sonic log after determining the mean for a moving window (window length = 100 m).*

As for the 2-D inversions, results from the 3-D joint inversion are more consistent than the ones from the individual inversions, but their data misfits are typically slightly higher. In contrast to the 2-D joint inversion, the 3-D model shows a highly-resistive (high-velocity) body below the basaltic sequence. This anomaly (B in Fig. 4) trends NE-SW and lies beneath the mostly horizontal high-resistivity anomaly A (Fig.4), which lies within the basaltic sequence. Considering the map of regional basement trends from Gallagher and Droomgole, 2007, it is apparent that the anomaly coincides both in location and orientation with the East Faroe High interpreted as an uplifted basement structure.

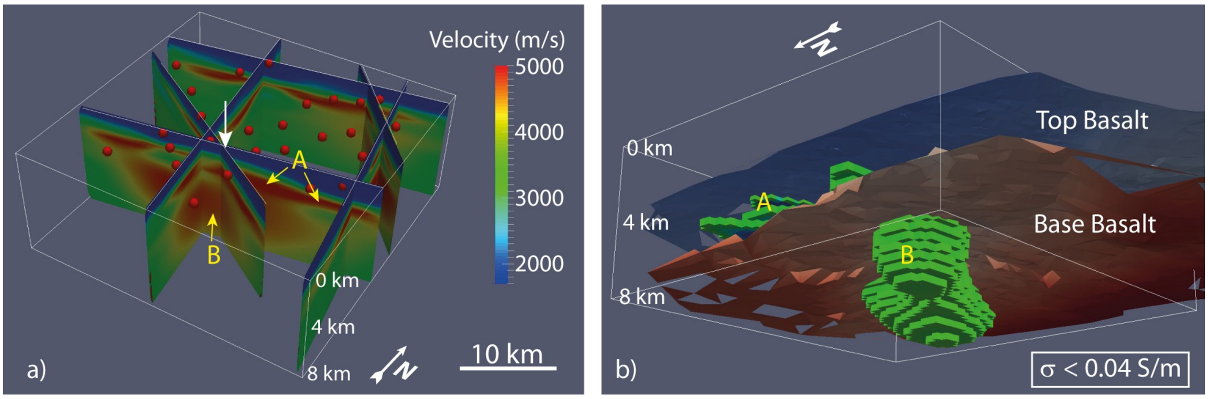


*Figure 4: Final results from the 3-D joint inversion of seismic first arrival time tomography and MT data. a) Seismic velocities are shown along the cross-sections of the used seismic profiles. Red dots and white arrow denote the locations of the MT stations and of the BRUGDAN borehole, respectively. b) From a different perspective, the joint-inversion high resistivities >25 Ωm are plotted in green. The blue and red surfaces show the top and base basalt determined from wide-angle seismic data. Two anomalies can be distinguished, hypothetically associated with (anomaly A) the sequence of basalt flows and (anomaly B) either intrusives or crystalline basement.*

## Conclusions

In our 2-D and 3-D sub-basalt studies from the Faroe-Shetland Basin we obtain more consistent results with joint inversion of seismic, MT and gravity data than with the corresponding individual inversions. The data misfits are for all tests in the same range or only slightly larger. Features relevant for sub-basalt investigations such as the shape of the basaltic sequence are more realistically represented by the joint inversion strategies than by individual inversions. Furthermore, the 3-D joint is able to resolve some high-resistivity structure below the basaltic sequence that has the same strike directions as regional trends.

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