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# Joint inversion of marine magnetotelluric and gravity data incorporating seismic constraints
## Preliminary results of sub-basalt imaging off the Faroe Shelf

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ABSTRACT

Breakup of the North Atlantic during the early tertiary was accompanied by widespread and massive magmatism, resulting in the coverage of large areas of the North Atlantic with flood basalts. These flood basalts hamper seismic investigations of underlying sequences and thus the understanding of the rifting, subsidence and evolution of the margin which, in turn, increases the risk for hydrocarbon exploration. In this paper we present a methodology for the simultaneous joint inversion of diverse geophysical datasets, i.e. free air gravity and magnetotelluric soundings (MT) using seismic a priori constraints. The attraction of the joint inversion approach is that different geophysical measurements are sensitive to different properties of the sub-surface, so through joint inversion we significantly reduce the null space and produce a single model that fits all datasets within a predefined tolerance. Using sensitivity analysis of synthetic data, we show how each data set contains complementary important information of the supra and sub-basalt structure. While separate inversions of individual datasets fail to image through the basalt layer, our joint inversion approach leads to a much improved sub-basalt structure. Application of the joint inversion algorithm to satellite gravity data and MT data acquired on the FLARE10 seismic line south west of Faroe islands supports the existence of a 1 km to 2 km thick low velocity region that might be indicative of the existence of a sedimentary basin underneath the basalt layer. Though in this paper we demonstrate the use of joint inversion on a sub-basalt target, we believe it has wider applicability to other areas where conventional seismic imaging fails.



## 1. Introduction

The geology of the sub-surface affects physical properties, such as density, seismic velocity or electrical resistivity. Conversely, estimates of the physical properties of the Earth can be obtained through the process called inversion from geophysical data such as gravity, seismic or electromagnetic profiles respectively. Inversion of geophysical data of any kind is inherently non-unique, so a variety of Earth models may fit the data equally well. This is due to the fact that: a) the data are typically measured on the surface only, while physical properties vary in three dimensions; b) the geophysical response is insensitive to certain features due to the fact that the resolution capability of the data at a given depth is low or the changes of the physical parameter due to particular features are small; c) data measurements contain noise and are band-limited so there is an inherent uncertainty for any given datum; and d) our models are simplifications of the true Earth.

There is inherent non-uniqueness in the different methods, based on the physics of the responses. While there are usually many models or a large part of the model space which may fit a given gravity data set, the number of model fitting magnetotelluric (MT) data is small and yet smaller again for seismic data. While this is the general case, it is still model dependent. Sub-basalt imaging is one of the applications or type models in which traditional seismic data have proven to be less effective (e.g. Wombell et al., 1999; White et al., 1999). More sophisticated seismic data acquisition and analyses, such as two-ship data acquisition, refraction analysis of long offset data or low frequency information in reflection data (Ziolkowski et al., 2003; White et al., 2008) are needed to obtain any constraint on the seismic velocity variations underneath the basalt.

Geophysical data are sensitive to property variations on different scales and often contain complementary information. The key problem is how optimally synthesizing the information obtained by various methods. Comparison of models derived from inversion of a single data type may be misleading since these models may only partially represent the true model due to the non-uniqueness of the response. So, how can one most efficiently combine the complementary information content in different data? One approach is simultaneously inverting all of the

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geophysical data in a process called joint inversion. In a joint inversion approach, a misfit is calculated for each type of input data for a common model, and these misfits are combined within the inversion program to drive improvements in the model fit. Hence the advantage of joint inversion is more flexibility over the relative influences of each data type and their interrelationships.

This technique has been used in the past with success. Vozoff and Jupp (1975) developed a scheme to invert DC resistivity and EM data, both of which measure the same physical property, the electrical resistivity, for a layered model. This concept has been successfully used in a variety of studies (e.g. Schmutz et al., 2000) and also in the inversion of seismic data using both reflected and refracted energy to constrain velocity structure (e.g. Trinks, 2005). These approaches employ the same methodologies and are still typically limited to deriving a single property of the subsurface, though in some cases this may constrain several properties, e.g. pre-stack inversion of seismic data that can simultaneously produce models for compressional- and shear-wave velocities and density.

Several attempts have been made to invert data sets measuring different physical properties. These have mainly been focused on finding a common structural feature in the model (Haber and Oldenburg, 1997; Gallardo and Meju, 2003; Musil et al., 2003). In these cases the scientists have combined seismic or georadar data which both contain significant structural information with other geophysical data yielding a considerable improvement in data interpretation.

Here we report on a joint inversion approach, which capitalises on the different strengths of the three types of geophysical data: gravity; MT and reflection seismics. The algorithm we develop is a joint inversion of electromagnetic and gravity data using a priori constraints derived from seismic data. The research was motivated by the sub-basalt imaging issues for the north-west European margin, where potentially oil-bearing sub-basalt sediments are of vital interest for continued exploration and production of hydrocarbons. Traditional seismic imaging of the area delivers a sharp picture of the supra-basalt sediment sequence and top of the basalt, however, sub-basalt imaging is severely limited (Maresh and White, 2005). Other types of geophysical data contain complementary information. For MT methods the highly resistive basalt layer is transparent, and the response is mainly governed by the low resistivity sediments above and beneath the basalt. Gravity measurements on the other hand are particularly sensitive to the high density basalt layer and top basement structure and less sensitive to lower density sedimentary layers.

The two integrative methods, i.e. magnetotellurics and gravimetry, do not contain strong structural information, yet hold the most information about the sub-basalt sediments and basement in the models considered here, so we chose to develop a joint inversion code not based on common structure but through a linkage of the physical parameters density, velocity and electrical resistivity. Therefore a prerequisite of our approach to the joint inversion problem is the capability to express the common Earth model simultaneously as electrical resistivity, seismic velocity and density distribution. While analytical conversion between some physical properties (e.g. Wyllie et al., 1958) may exist for special settings, in general it is impossible to find relationships that are generally valid. We therefore resort to using commercial and ODP borehole data in the region and develop empirical relationships between the physical properties.

In this paper, we use a representative Earth model to investigate quantitatively the complementary information content of the various geophysical responses. Next we investigate to what degree the Earth model may be retrieved from the calculated synthetic geophysical responses and we compare inversion results from single methods and joint inversion results. Finally, we illustrate the capabilities of the joint inversion approach on sample MT, gravity and seismic data collected on the Faroes shelf.

## 2. Physical property relationship

Fig. 1a shows compressional seismic velocity v plotted against the electrical resistivity r derived from induction logs for ODP borehole 642e gathered in the Voring basin off the Norwegian coast and a commercial borehole dataset gathered off the Faroes shelf. Fig. 1b depicts seismic velocity versus density data d for the ODP borehole (density values for the commercial borehole have been omitted due to strong scattering and noise). The raw data plotted in Fig. 1a and b exhibits some scatter that is partly due to noise in the measurements and/or local effects within the immediate vicinity of the borehole, and which actually bear little influence on the response of integrative methods such as gravimetry and MT. A correlation between the rock parameters is yet easily visible. The observed range of density is very small. The range of seismic velocity of one order of magnitude is also relatively small and varies between 1.5 km/s, the velocity in water and 6.5 km/s, the velocity of basalt. The electrical resistivity on the other hand changes over two orders of magnitude.

In this region, electrical conduction is caused by electrolytes, i.e. fluids, in the rocks; electrical resistivity is therefore dependent on porosity but also on connectivity of the pore space. The latter dependency explains the change in slope observed in the seismic velocity/resistivity relationship. The electrical bulk resistivity is small and varies slowly in the low velocity region since connected fluid pathways exist. At a critical point, corresponding to a seismic velocity of about 3 km/s to 3.5 km/s, the compaction is sufficiently high such that the pore space starts to become disconnected. The changes in the bulk electrical resistivity are then more pronounced, and increases in the seismic velocity, or compaction are reflected by rapidly increasing resistivity values. For a first approximation we fit two lines:

$$\text{for } v < 3600\ \text{m/s}:\ \log_{10}(\rho) = 1.20{*}\log_{10}(v) - 3.86 \tag{1a}$$

$$\text{for } v > 3600\ \text{m/s}:\ \log_{10}(\rho) = 6.46{*}\log_{10}(v) - 22.57, \tag{1b}$$

corresponding to the lower and higher velocity regions, where velocity and density units are given in m/s and resistivity in Ω m.

For the velocity $v$ and density $d$ relationship of the sub-surface rocks a simple linear fit was sufficient, given by:

$$d = 1.700 + 2.0 \times 10^{-4}{*}v \tag{2}$$

with density in g/cm$^3$ and velocity and density of saltwater layer set to 1500 m/s and 1 g/cm$^3$ respectively.

The fitting of the borehole data is crude, but it captures the essence of rock property relationships in such a setting, which are characterized by increasing velocities giving rise to increasing electrical resistivities and densities. Investigations of the sensitivity of this relationship on a 1D joint inversion showed that the true model structure is recovered if synthetic MT and gravity data generated using Eqs. (1a), (1b) and (2) are inverted using rock property relationships shifted to the upper or lower limit of the scatter in Fig. 1. The presence of sedimentary structure beneath the basalt layer could still be resolved. Thus, the crude rock property approximation used here is sufficient to develop a first step towards the development and understanding of joint inversion of different geophysical data; however, it needs to be refined in future.

## 3. Geophysical response to sample sub-basalt Earth model

A 2-D Earth model developed as part of the EU-SIMBA project (Martini et al., 2005) was used to calculate synthetic geophysical responses for the testing and evaluation of the joint inversion strategy. This model represents a sedimentary structure that includes an extrusive basalt layer underlain by a basement. Fig. 2a shows the 2-D model using its original physical parameterisation in seismic velocity. This model was converted into resistivity and density models using Eqs. (1a), (1b) and (2). Since MT and gravity yield integrated responses over the whole model, the detailed model as shown in Fig. 2a is unnecessary, so we use a simplified model (Fig. 2b) where the heterogeneous basalt layers are replaced