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Analysis and 3D inversion of magnetotelluric crooked profile data from central Svalbard for geothermal application

Thomas I. Beka [a,*], Maxim Smirnov [b], Yngve Birkelund [a], Kim Senger [c], Steffen G. Bergh [d]

[a] Department of Physics and Technology, UiT-The Arctic University of Norway, N-9037 Tromsø, Norway
[b] Department of Civil, Environmental and Natural Resources Engineering, Luleå University of Technology, 971 87 Luleå, Sweden
[c] The University Centre in Svalbard, Pb. 156, 9171 Longyearbyen, Norway
[d] Department of Geology, UiT-The Arctic University of Norway, N-9037 Tromsø, Norway

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ABSTRACT

Broadband (0.001–1000 s) magnetotelluric (MT) data along a crooked profile collected to investigate the geothermal potential on Spitsbergen could not be fully explained by two-dimensional (2D) models; hence we interpret the data with three-dimensional (3D) inversion herein. To better accommodate 3D features and nearby off profile resistivity structures, the full MT impedance tensor data together with the tipper were inverted. As a model control, a detailed bathymetry is systematically incorporated in the inversion. Our results from testing different inversion settings emphasised that appropriately choosing and tuning the starting model, data error floor and the model regularization together are crucial to obtain optimum benefit from MT field data. Through the 3D inversion, we reproduced out of quadrant impedance components and obtained an overall satisfactory data fit (RMS = 1.05). The final 3D resistivity model displays a complex geology of the near surface region (<1.5 km), which suggests fractures, localized and regional fault systems and igneous intrusions in the Mesozoic platform cover deposits. The Billefjorden fault zone is revealed as a consistent and deep rooted (>2 km) conductive anomaly, confirming the regional nature of the fault. The fault zone is positioned between two uplifted basement blocks (>1000 Ωm) of presumably pre-Devonian (Caledonian) metamorphic rocks, and the fault may have been responsible for deformation in the overlying Paleozoic-Mesozoic unit. Upper crustal conductive anomalies (<10 Ωm) below the Paleozoic-Mesozoic succession in the western part of the 3D model are interpreted as part of a Devonian basin fill. These conductors are laterally and vertically bounded by resistive rocks, suggesting a conducive environment for deep geothermal heat storage. Having this scenario in an area of a known high heat-flow, deep faults and a thinned lithosphere makes the hypothesis on finding a technologically exploitable geothermal resource close to human settlement in the area stronger.

1. Introduction

Magnetotelluric surveys were conducted for the first time on Svalbard in 2013 and 2014, motivated by geothermal resource exploration to find alternatives for coal as the main energy source in the region. We collected the MT data in the 0.001–1000 s period range in a glacial plain close to permanent settlements in central Spitsbergen, between Longyearbyen and Sassendalen (SD, Fig. 1). This area became attractive for a geothermal survey due to its anomalous heat flow, and proximity to a Devonian graben and the regional Billefjorden fault system (Harland et al., 1974; McCann and Dallmann, 1996; Braathen et al., 2011). In addition, infrastructure necessary to execute a MT fieldwork (i.e. roads and easy access by snowmobiles) was better established in this area than other parts of the archipelago where for instance recent volcanism and thermal springs are documented (Harland, 1997; Banks et al., 1998; Pascal et al., 2011; Treiman, 2012).

The Svalbard region is attractive for various geophysical studies due to a well-established geological and stratigraphical framework. Apart from this, the remoteness of the area from signal corrupting industrial noise makes the archipelago well suited for carrying out a passive MT study. However, at high latitudes the ionospheric sources are close and this may bring distortion to MT data when acquired at such latitudes (Viljanen et al., 1999; Simpson and Bahr, 2005; Chave and Jones, 2012). Nevertheless, the depth of interest in our case is much smaller than the typical distance to the source, ~100–120 km (Sahr et al., 1991). Thus the plane wave condition for the depth of interest should be satisfactory.

The collected data could not be fitted satisfactorily with 2D isotropic inversion. Instead, we inverted the determinant of the impedance data for 2D interpretation in a previous work (Beka et al., 2015). The determinant was chosen for inversion due to its invariance under rotation

* Corresponding author.
E-mail addresses: thomas.beka@uit.no, thomab00@gmail.com (T.I. Beka).

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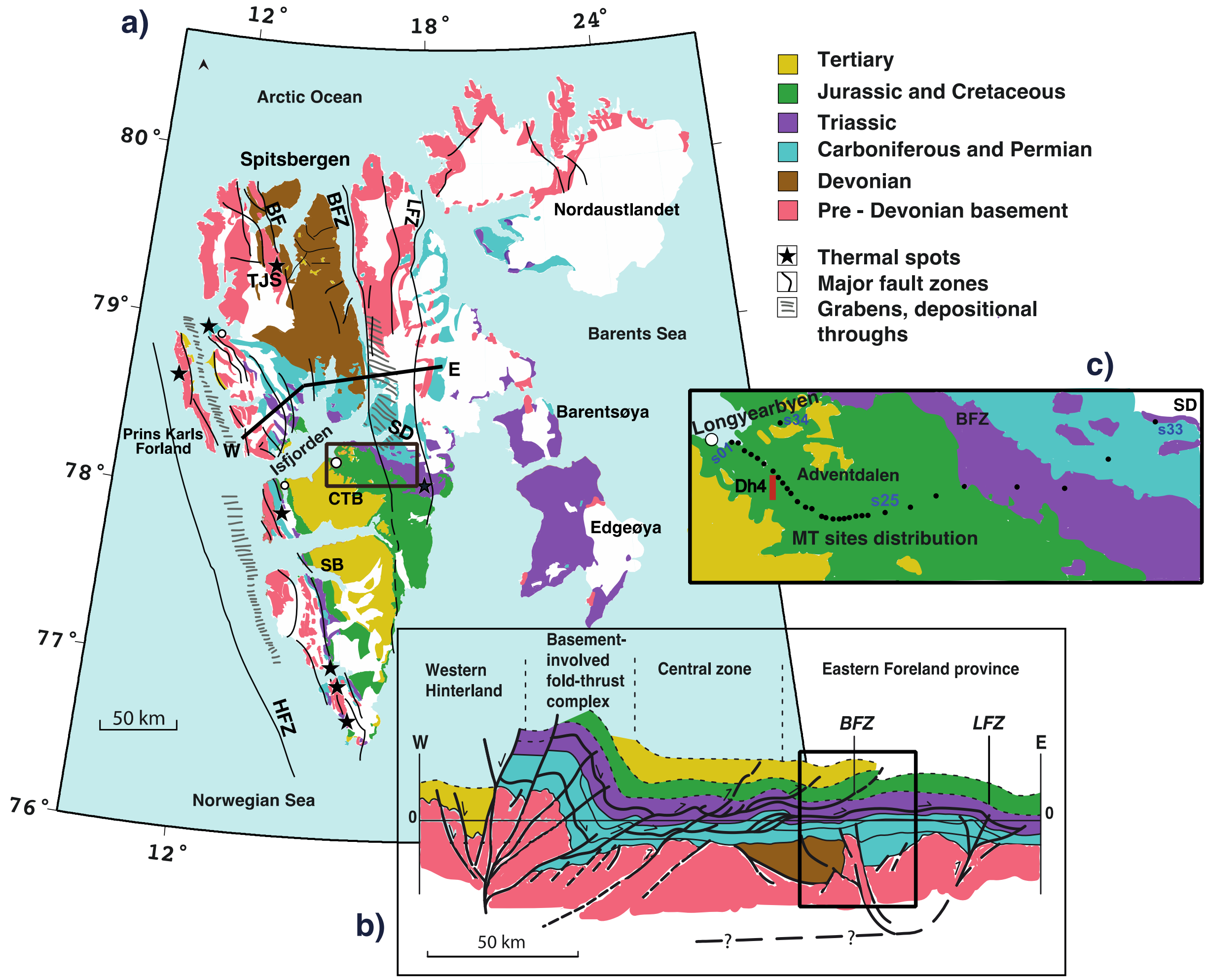

Fig. 1. Geological and tectonic map. a) Geo-tectonic map of Svalbard redrawn based on Dallmann et al. (2002). b) Schematic regional scale cross-section in a W-E transect across north central Spitsbergen redrawn based on Bergh and Grogan (2003). c) Location of the measured MT Stations corresponding the rectangle on panel a. LFZ = Lomfjorden Fault Zone; BFZ = Billefjorden Fault Zone; BF = Breibogen Fault; HFZ = Hornsund Fault Zone; TJS = Trollkildene and Jotunkildene; CTB = Central Tertiary Basin; SB = Sysselmannbreen; SD = Sassendalen; Dh4 = Deepest borehole of the UNIS CO2 Lab well park.

and robustness as a 2D inversion when data are affected by 3D distortion (Pedersen and Engels, 2005). The resistivity model obtained from the determinant inversion displayed good agreement with geological models of the area derived from seismic, gravity and surficial studies. From the 2D resistivity model we inferred a geological architecture for the area and used it to construct the main crustal scale stratigraphy of the area (Beka et al., 2015). However, adequate attention was not given to the data 3D behaviour during the previous work, interpretation was carried out in the conventional 2D manner because the data were collected from a single crooked profile. Nonetheless, there are evidences from synthetic data inversion where 3D interpretation of a profile data provided a more realistic image of the resistivity directly beneath and adjacent to the profile area (Siripunvaraporn et al., 2005), given that data are 3D distorted and the diagonal components of the impedance tensor are included in the inversion.

In this paper, we explore the MT data with 3D inversion by including an additional off-profile MT site and the tipper data from seven sites to better sense the nearby off-profile 3D conductivity structures. As data analyses, we compare various dimensionality tools and discuss in detail why we also need to model the data in 3D. We attempt to reinforce the inversion result by providing a detailed bathymetry to constrain the final model. We systematically derive depth of the sea from a recently compiled chart of the bathymetry in the Arctic (Jakobsson et al., 2012), in a manner compatible to the MT model through averaging the depth within submerged MT model cells. Through these, we attempt to resolve more realistic models of the subsurface resistivity structure and evaluate its geothermal significance. On the other hand, we also aim to perform systematic implementations of various inversion strategies to find the most suitable combination of the starting model, data error floor and regularization. To be able to freely experiment with various model parametrizations and regularizations, we carry out inversion with the ModEM 3D code (Egbert and Kelbert, 2012; Kelbert et al., 2014), by using its parallel version (Meqbel, 2009) for fast and concurrent computations. This code is currently in a wide use in the MT community (Samrock et al., 2015; Cherevatova et al., 2015b; Meqbel et al., 2014; Kühn et al., 2014; Tietze and Ritter, 2013) and it performs a gradient-based minimization of a regularized penalty functional to obtain adequate fit to observed data (Kelbert et al., 2014). We compare the resistivity structure of our final 3D model against conclusions derived from the previous 2D result; and use the 3D model to better understand the complex regional geological framework of the area at crustal depth scale.

1.1. Geological background

The stratigraphy of Svalbard is that of a crystalline and metamorphic basement of Precambrian and Caledonian rocks (Gee et al., 2008) overlain by a thick composite sedimentary sequence starting with Devonian and Carboniferous basin fills, and up to 3.5 km thick successive Permian through Eocene platform sedimentary deposits