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Reconnaissance Geothermal Resource Assessment Using Magnetotellurics Imaging on Svalbard, Norway

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ABSTRACT

Despite its location high up in the Arctic, the Svalbard archipelago has geological advantages that can be linked to accessible geothermal resource. In this paper we present broadband magnetotellurics (MT) pilot study from Spitsbergen, which was conducted in 2013 to assess the resource potential on the island. During fieldwork, good quality data were acquired in spite of challenges related to infrastructure. The collected data were interpreted in 2D according to the Occam´s principle. The resistivity models we obtained indicate an elongated composite conductive sedimentary layer stretching up to 2 - 3 km beneath the resistive permafrost, which we found covering up to a few hundred meters depth below the surface for the inner part of the measured profile. We constrained the MT model with existing geological knowledge on the island and used it to make reconnaissance geothermal resource assessment.

1. INTRODUCTION

Geothermal is often mentioned as a possible renewable option for future of Svalbard, even though not much research has been dedicated to specifically assess its potential until recently.

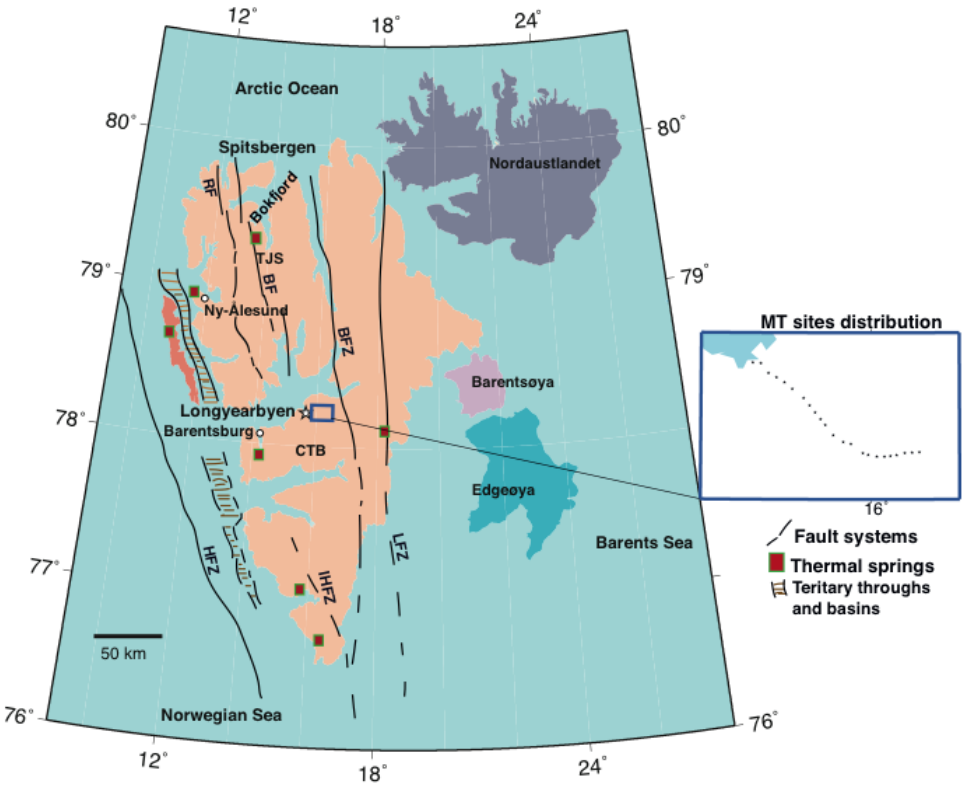

Figure 1: Svalbard with some of its major tectonic structures, redrawn based on Dallmann et al. 1999. The MT studied area and MT sites distribution are displayed by the rectangles. The map shows the location of the largest settlements on Svalbard (Longyearbyen, Barentsburg and Ny-Ålesund). TJS = Trollkildene and Jotunkildenen thermal-springs, CTB = central Tertiary basin, BFZ = Billefjorden fault zone, BF = Breibogen fault, LFZ = Lomfjorden fault zone, RF = Raudfjorden fault, HFZ = Hornsund fault zone.

The largest all-year-round human settlement close to the North Pole (Longyearbyen) is located on Svalbard (Figure 1). Besides mining, the town serves as a regional tourist and research destination. At present, the primary energy of the region is obtained from abundant coal reserves that are available in the region. In order to mitigate CO2 emissions from local power plants to the vulnerable arctic, geothermal as well as CO2 sequestration are considered as possible alternatives.

In general, proximity to the tectonic systems has given Svalbard some advantages when it comes to ground thermal structure. Beneath the thick permafrost sealing the ground up to 400 – 500 m in the deglaciated high altitudes and <100-200 m in costal lowland areas (Braathen et al., 2012), heat flow levels larger than what is commonly found in mainland Norway and in most part of northern Europe are registered (Khutorskoi et al., 2009; Slagstad et al., 2009; Vågnes and Amundsen, 1993). During a recent borehole study, temperature gradient surpassing 40 degree Celsius per km was measured under the permafrost (Elvebakk, 2010). Spitsbergen, the largest island on the archipelago, features a complex tectonic system. Among others, the northernmost discovered thermal springs in the world; Trollkildene and Jotunkildenen (TJS on Figure 1) are located on the island in the vicinity of a Quaternary-age volcanic system along Breibogen fault (BF) zone (Banks et al. 1998; Treiman, 2012). The island is also characterized by elongated north to south trending fault systems (Bælum and Braathen, 2012; Dallmann et al., 1999) and there are records for recent seismic activities (Mitchell et al., 1990; Pirli et al., 2010).

In this paper we present MT profile data we collected near Longyearbyen during the summer season in 2013. The study is undertaken as a pilot study for a larger scale field campaign, which we have planned to conduct in the near future on Spitsbergen. We present a preliminary two-dimensional model and discuss the geothermal outlook in light of the model.

2. PASSIVE MAGNETOTELLURICS

MT imaging is a geophysical method with a growing application in geothermal resource assessment (Harinarayana et al., 2006; Oskooi et al., 2006; Muñoz et al., 2010).

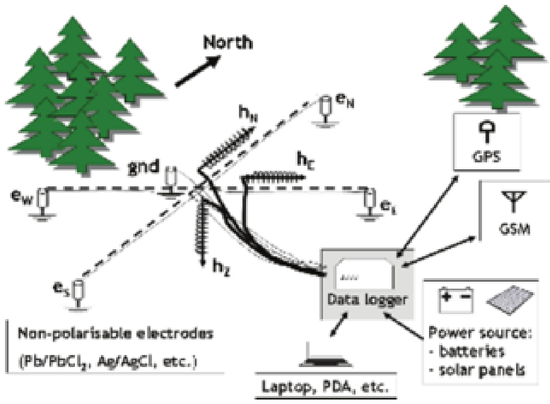

Figure 2: Broadband MT instrumentation consisting 3 magnetic coils corresponding to x, y and z direction as well as four electrodes planted perpendicularly in E-W and N-S directions. In addition, data logger, battery source and GPS are included in the instrument package. (Adopted from Smirnov et al., 2008).

Passive MT sounding employs naturally occurring earth's electromagnetic (EM) field caused by geomagnetic as well as thunderstorm activities. The method enables to derive the resistivity structure from tens of meters to hundreds of kilometers beneath the surface, given measurements of all EM components on the surface (Cagniard, 1953; Tikhonov, 1950). A typical broadband MT instrument set up is illustrated in Figure 2.

In general, MT gives large penetration depth, and with a lesser cost, it can provide supplementary information to seismic and borehole studies. Even though it is not sufficient to draw conclusion, a potential geothermal reservoir often coincides with a low resistivity zone (Spichak and Manzella, 2009). The method is considered suitable for geothermal assessment due the interrelationship between subsurface electrical properties and geothermal attributes, such as fluid content, porosity and temperature.

MT data analyses involve solving the inverse problem to infer the resistivity at a given depth from the measured data at the surface. These include searching for a certain resistivity model that can reasonably fit the measured data.

3. GEOLOGICAL SETTING

We carried out the study in Adventdalen, a glacial valley with large fluvial plain east of Longyearbyen. During the summer season the surface is covered by tundra type vegetation, and by snow or ice during winter. Underneath the tundra the subsurface is sealed by permafrost. Geologically, Sedimentary rocks of Early Permian to Eocene origin make up the area with a composite thickness reaching up to 3.5 km (Dallmann et al., 2001). The measured site belongs the western tectonic block of Spitsbergen that is transected by north to south trending Billefjorden Fault Zone (BFZ).

The main reason for selecting this specific location for the study is its vicinity to Longyearbyen, where energy is needed and a good road infrastructure in Svalbard context is available.

4. DATA ACQUISITION AND PROCESSING

During fieldwork, data are acquired from a profile including 24 sites spaced on average by 500 m. The first site is measured in the eastern outskirt of Longyearbyen and measurement continued deep in Adventdalen valley in the direction to BFZ in a west to east orientation.

Data are recorded with MTU2000 MT system developed at Uppsala university, Sweeden (Smirnov et al., 2008) in the period range covering 0.003 -1000 s. Magnetic fields in two horizontal directions are measured with Metronix MFS05 (Braunschweig, Germany) induction coils and Pb-PbCl type Uppsala built electrodes are used to measure the electric fields. For each measurement site, data are recorded for a period of 24 hours in dual sampling burst modes.

Data are sampled in 20 Hz during the entire recording and simultaneously at 1000 Hz during burst recordings at midnight for 2 hours, and data were measured simultaneously. Culture noise is at its minimum in the data due to the absence of industry, railway and large transmission lines on the island. During our summer measurement, logistics was the major constraint we encountered due to limited road access and restrictive rules toward the use of all-terrain vehicles in the tundra. Therefore, equipment had to be carried by field crew and moved from one site to the other for a part of the profile, which was not accessible by road. Only two out of the 24 measured sites are excluded from analysis due to instrumental problems caused by reindeer activity near installations.

The measured time varying electric and magnetic fields were processed with Robust Remote Reference algorithm (Smirnov, 2003). Dimensionality analysis gave a dominant regional strike azimuth of N30E.

5. INVERSION AND RESISTIVITY MODEL

Despite some evidence for 3D effect, it is reasonable to interpret data in 2D since a dominant principal direction for the impedance tensor could be identified. For inversion we chose the determinant of the impedance tensor due to its robustness against 3D distortion and invariance to rotation (Pedersen and Engles, 2005). Inversion is implemented with the Electro-Magnetic Inversion Least Intricate Algorithm (EMILIA) code (Kalscheuer et al., 2010; Cherevatova et al., 2014).

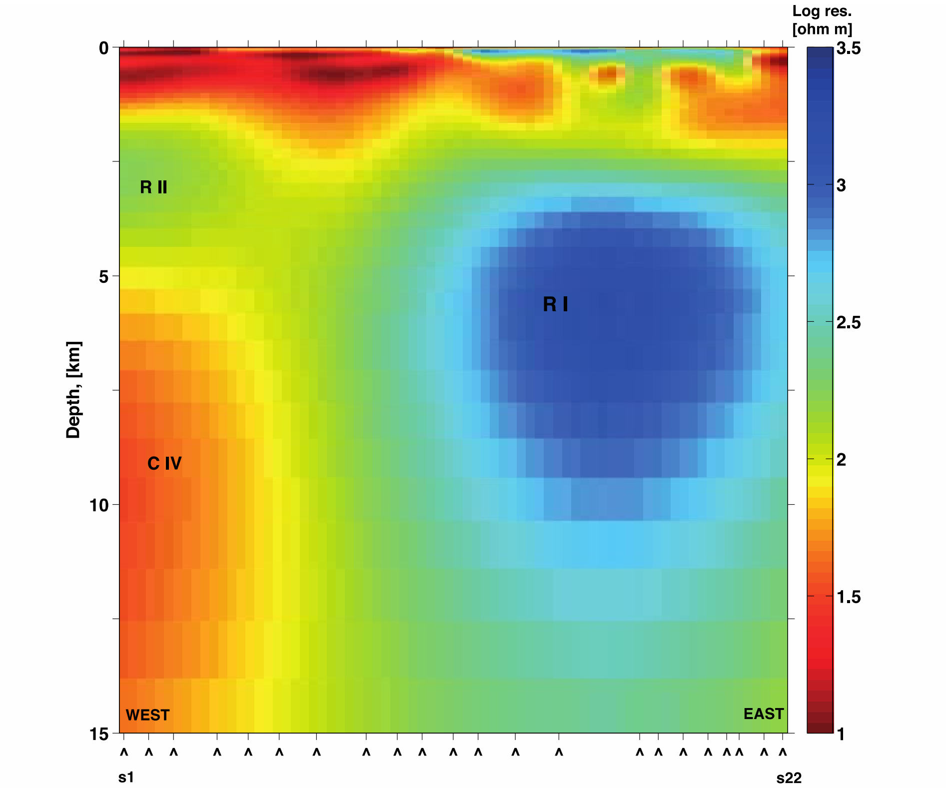

Figure 3: Two-dimensional resistivity model of the entire measured profile (x-axis) up to the depth of 15 km. The location of sites is indicated by ^, s1 stands for first and s22 for the last measurement site. The letter R and C on the model stand for resistors and conductors respectively.

The preliminary two-dimensional modeling result is presented in Figure 3 for a 15 km depth. The misfit RMS of the model is 0.89, while data-error floor is at 5%. There is a thick conductive layer of Paleozoic-Mesozoic origin stretching from west to east along the entire profile at shallow depth. Inversion places a large resistive body (R I) at about 4-6 km depth under the eastern section of the profile, which we have interpreted as a deposits of late Paleozoic and pre-Devonian origin. Beneath R I the resistivity decreases into a metamorphic basement rock by gradually leading to transiting to electrical asthenosphere, which is sensed to start at about 55 km depth. Presumably an intrusive weak resistor (R II) is located between the upper and lower (C IV) crustal conductive layers under the western section of the profile.

The upper 3 km layer of the model is investigated closely in Figure 4. Permafrost is identified as a horizontally elongated near surface resistor, PF. In agreement with the literature, PF's thickness decreases toward the costal west as indicated by the drawn solid line between C III and C I. There are isolated near surface strong lagoonal aquifer type conductors (C I, C II and C III) at 200-700 m depth.

The thickness of the permafrost gets lower toward the costal area in the west. This can be either due to the presence of a large amount of conductive oceanic sediment in the permafrost or simply because the permafrost gets thinner near the cost as some earlier studies indicated. For the inner part of the profile, the observed almost 200 – 300 m thick permafrost is reasonable for low land areas on Svalbard. There is a good agreement between the thickness of the conductive sedimentary layer (ca. 1.5 – 2 km with some increase in thickness beneath C II) and what is written about Adventdalen's sedimentary basin in the literature. As indicated in some previous geological studies, we also recognize signs of intruding resistive bodies (dykes) into the conductive host sedimentary sequence, for instance, as exemplified by R II.

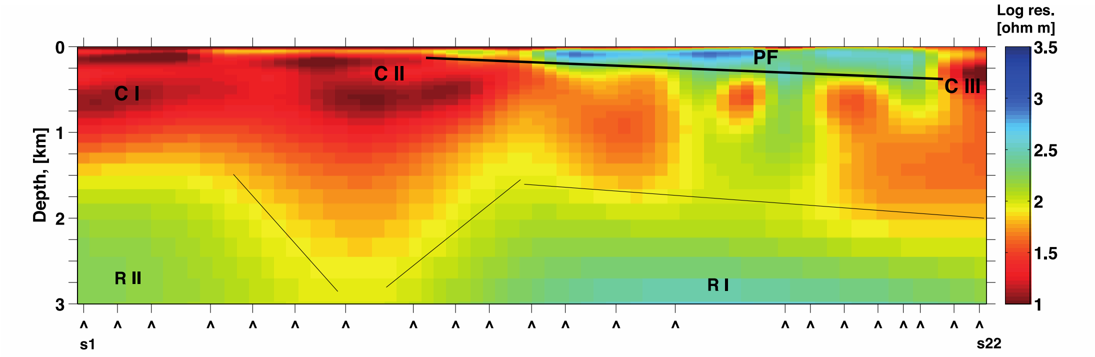

Figure 4: Resistivity model of the shallow crust to 3 km depth.

6. CONCLUSION AND OUTLOOK

Delineating the ground renewable energy resource on Svalbard has a long way ahead. In this respect, this first MT study brings a new perspective for what can be found under the permafrost in particular, and at crustal level in general. The presence of thick near surface conductive sedimentary layer followed by a conductive mid-crust basin, record of a high heat flow rate and vicinal tectonic structures support the positive geothermal outlook on the island and encourages the work in progress to identify a potential resource.

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