MODELLING AND INVERSION OF MAGNETOTELLURIC DATA FOR 2-D AND 3-D LITHOSPHERIC STRUCTURE, WITH APPLICATION TO OBDUCTED AND SUBDUCTED TERRANES

Stephan Thiel

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School of Earth and Environmental Sciences
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For Magda

Contents

List of Figures

List of Tables

Abstract

The thesis presents the application of the magnetotelluric (MT) sounding method to image Earth's crust in Oman and South Australia. The aim of these MT surveys is to provide constraints on the geological interpretation of emplacement scenarios and the tectonic evolution of the geological domain. The thesis concentrates on the methodological aspects of the MT technique, e.g. the data analysis and modelling of electromagnetic fields. The phase tensor approach by Caldwell et al. (2004) is applied to the data and provides insights into the dimensionality of the MT data in even complex and electrically distorted terranes. Modelling and inversion of the MT data is performed with various 2-D and 3-D codes to show how the interpretation of the data can benefit from multiple modelling approaches.

Data collected in a 2-D survey across the Oman ophiolite mountains show complex behaviour and 2-D inversion and 3-D forward modelling resolve ambiguities in the emplacement scenario of the Oman ophiolite. It is believed that initial underthrusting of the Jurassic-Cretaceous oceanic lithosphere was followed by exhumation. Further oceanic thrusting subsequently led to rising of lower-plate eclogites and eventually gravitational collapse of the ophiolite onto the margin (Gray et al., 2000).

The 3-D inversion code by (Siripunvaraporn et al., 2005a) was expanded to incorporate static shift corrections and inversion model misfits have therefore improved significantly compared to inversion models without static shift correction. 2-D and 3-D surveys across the South Australian Gawler Craton reveal deep crustal conductors which are connected to near surface mineralisation systems of the IOCG Olympic Dam deposit in the north-eastern part of the craton and the Au-dominated central Gawler Craton provinces.

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

Stephan Thiel

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Introduction

This aim of this work is to present some of the recent advancements and newly developed tools for the analysis and modelling of magnetotelluric (MT) data and to provide an understanding of these new tools in two-dimensional (2-D) and three-dimensional (3-D) lithospheric structures, with application to obducted and subducted terranes.

Magnetotellurics (MT) is an electromagnetic sounding method, which belongs to the geophysical techniques that are governed by the diffusion equation (Telford et al., 1976). It is the only geophyiscal technique capable of imaging the electrical resistivity structure between the near-surface and the upper mantle. Geoelectric structures in the crust and mantle of the Earth generate large scale eddy currents induced by fluctuations in the Earth's magnetic field. Measurements of period-dependent fluctuations in the electric and magnetic field on the surface can be used to obtain depth-related information of the resistivity distribution. Based on Maxwell's theory with quasi-stationary approximation the measured fields can be converted to apparent resistivity and phase (Cagniard, 1953; Tikhonov, 1950). The penetration depth is dependent on the frequency of the signal and the conductivity of the subsurface. The conductivity of rocks in the Earth range over ten orders of magnitude (Guéguen and Palciauskas, 1994) and the MT method is therefore a useful tool to image the resistivity distribution of the lithosphere. Ore bodies, interconnected fluids, partial melt and graphite films along grain boundaries can cause a substantial increase in conductivity (Nover, 2005).

Galvanic distortion is a common problem in MT due to small-scale inhomogeneities which have an effect primarily on the electric field measurements and lead to distortion of the regional (inductive) field response. Its removal has been subject to ongoing research (Bahr, 1991; Ledo et al., 1998; Utada and Munekane, 2000). New MT analysis tools have been developed in recent years, which improve the discrimination between galvanic distortion effects and regional MT responses (Weaver et al., 2000; Utada and Munekane, 2000; Becken and Burkhardt, 2004; Bibby et al., 2005) and the determination of the dimensionality of the regional resistivity distribution (Weaver et al., 2000; Caldwell et al., 2004). The strong point of the approach of the seven invariants (Weaver et al., 2000) and the phase tensor approach developed by Caldwell et al. (2004) is the independence of galvanic distortion and thus determination of the regional dimensionality without assumptions. Previous decomposition methods required dimensionality assumptions about the subsurface (Groom and Bailey, 1989; Bahr, 1991). The phase tensor approach was utilised in only a few field examples, e.g. across the Taupo Volcanic Zone, New Zealand (Ingham, 2005; Heise et al., 2007a). The advantages of the phase tensor provided the motivation to apply it in other areas, such as the Oman ophiolite mountains (see Chapter 4), where near-surface inhomogeneities potentially have a strong effect on the regional field response. The Oman Mountains have been the focus of a number of recent studies on obduction mechanisms (Chemenda et al., 1996; Gray and Gregory, 2003; Breton et al., 2004) and are cited as the classic example of Tethyan ophiolite obduction (Moores et al., 2000; Wakabayashi and Dilek, 2003; Robertson, 2004). The 2-D survey conducted in 2005 is a pilot study, aimed at defining the crustal structure of ophiolite environments to help distinguish between different emplacement scenarios for these large slabs of oceanic lithosphere.

Imaging large scale lithospheric structures in an areal array is an all-encompassing and demanding task in terms of data collection, analysis and in particular modelling of the MT data. In most cases, MT modelling consists of 2-D inversions or 3-D forward modelling of the lithosphere (Jones et al., 2005; Korja, 2007). However, the recent availability of 3-D inversion codes which are computationally feasible to perform (Siripunvaraporn et al., 2005a), have led to new attempts in analysing MT data sets collected from 3-D surveys. The 3-D code developed by Siripunvaraporn et al. (2005a) is based on the 2-D data space Occam code of Siripunvaraporn and Egbert (2000) and depends on the size of the data rather than the model parameters, reducing computational costs. To date there are only a few examples where the 3-D inversion code has been applied to field data sets (Bedrosian et al., 2007; Heise et al., 2007b). In this thesis, the 3-D code is expanded to incorporate static shift and used on a large 800×500 km areal array of MT stations separated about 100 km to study the lithospheric structure of the Gawler Craton. Knowledge about sedimentary basins and the seafloor topography were included in the modelling and taken into account in the interpretation of the lithospheric resistivity models.

The late Archaean to Palaeoproterozoic Gawler Craton in southern Australia covers an area of $\sim 530000\,\mathrm{km}^2$, yet its geological evolution is only poorly understood due to its substantial lack of outcrop and extensive regolith cover. The Gawler Craton consists of a central late Archaean to early Palaeoproterozoic core, surrounded by regions of Palaeoproterozoic rock that have been interpreted to belong to various tectonic domains on the basis of the limited available geological and geophysical constraints (Teasdale, 1997). The craton underwent major deformation during the 2.44 Ga Sleafordian Orogeny, the 1.73-1.7 Ga Kimban Orogeny and the 1.56-1.54 Kararan Orogeny (Teasdale, 1997). No evidence has been found for major deformation occurring after 1450 Ma (Parker, 1993). There is substantial economic interest in the Gawler Craton due to prosperous mineral deposits such as the iron oxide copper-gold Olympic Dam deposit along the eastern margin of the craton (Heinson et al., 2006).

Thesis outline

The thesis consists of six chapters. Chapter 1 introduces the basics of electromagnetic induction and their sources. It highlights the behaviour of the MT reponses in the presence of 1-D, 2-D and 3-D lithospheric structure. The second chapter lays the foundation for differentiating between small-scale and regional structures. In most of the cases the regional structures are important for further analysis, while small-scale features at the near-surface distort the electric fields. Distortion analysis is an essential part of current MT data handling and help to extract regional information of the measured fields. This chapter also deals with the dimensionality analysis of the data and is a necessary step before inversion of MT data in two dimensions can be undertaken. The phase tensor approach by Caldwell et al. (2004) allows a distortion-free dimensionality analysis and is introduced in detail. Chapter 3 gives an overview of the 2-D and 3-D inversion routines used throughout the thesis. A more detailed review on 3-D inversion follows in Appendix E.

Chapters 4 to 6 focus on the application of the magnetotelluric method to obducted and subducted terranes. Chapter 4 shows the results of the MT survey across the Oman ophiolite mountains. The MT method has been applied to study the lithospheric structure underneath the Samail ophiolite to provide constraint on possible emplacement scenarios. This chapter has been submitted to Geophysical Journal International and is accepted with revision. Chapter 5 focuses on a 2-D survey across the Nuyts and Fowler subdomains of the Gawler Craton, South Australia. 2-D and 3-D modelling of the data help to better understand the tectonic evolution in this part of the Gawler Craton. The last chapter deals with a 800 × 500 km array of MT sites separated about 100 km from each other. The dataset was 3-D inverted and compared with existing potential field datasets. The models represent an unprecedented image of the crust and upper mantle underneath the Gawler Craton.