

Preface to the Special Issue on “The 21st Electromagnetic Induction Workshop”

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Electromagnetic (EM) induction methods are used and continue to be developed for a wide range of applications, ranging from exploration near the Earth’s surface to the investigations of the deep mantle. In this research, important scientific and societal challenges, such as to search for hydrocarbons and other Earth resources, to probe the structure and dynamics of the lithosphere, to study environmental issues and to monitor and mitigate natural hazards, are addressed.

The Working Group I-2 of the International Association of Geomagnetism and Aeronomy on “Electromagnetic Induction in the Earth” has held biennial workshops since the Edinburgh, United Kingdom, Workshop of 1972. Here, selected topics are extensively explored by the participants, in the form of oral and poster presentations and discussion sessions. An essential and important part of the EM Induction Workshops (EMIWs) has been invited review presentations on themes selected by the program committee. These themes vary from workshop to workshop; usually, they highlight recent advances in the rapidly evolving fields of electromagnetic induction and introduce the important new directions of research as well as highlight and review results focusing on certain geological targets. The review papers presented at the workshops have traditionally been published as Special Issues of Surveys in Geophysics/Geophysical Surveys since the 1978 workshop in Murnau, Germany.

This Special Issue of Surveys in Geophysics contains nine expanded articles from review papers presented at the 21st Workshop on Electromagnetic Induction in the Earth. The workshop was held between 25 and 31 July, 2012, in Darwin, Australia. It was organised by the Working Group I-2 of the International Association of Geomagnetism and

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Aeronomy and Local Organising Committee led by Graham Heinson. The scientific programme of the Workshop was divided into nine themes, for which ten review presentations were given in the workshop:

1. EM Data Processing and Analysis.
Review: John Booker, The Magnetotelluric Phase Tensor: A Critical Review
2. Rock Resistivity.
Review: Anne Pommier, Interpretation of Magnetotelluric Results Using Laboratory Measurements
3. Theory, Modelling and Inversion.
Review: Eldad Haber and Michal Holzman Gazit, Model Fusion and Joint Inversion
Review: Gregory Newman, A Review on High Performance Computational Strategies for Modeling and Imaging of Electromagnetic Induction Data
4. Exploration.
Review: Richard Smith, Electromagnetic Induction Methods in Mining Geophysics from 2008 to 2012
Review: Gerard Muñoz, Exploring for Geothermal Resources with Electromagnetic Methods
Review: Kurt Strack, Future Directions of Electromagnetic Methods for Hydrocarbon Applications
Review: Esben Auken and Ahmad Ali Behroozman, An Introduction to the Use of New and Emerging Electromagnetic Techniques for Aquifer Characterization
5. Tectonics.
Review: Kate Selway, On the Causes of Electrical Conductivity Anomalies in Tectonically Stable Lithosphere
6. Anisotropy.
Review: Anna Marti, The Role of Electrical Anisotropy in Magnetotelluric Responses: From Modelling and Dimensionality Analysis to Inversion and Interpretation
7. Global Induction and Mantle Conductivity.
8. Marine EM.
9. Innovation.

John Booker (University of Washington, USA) reviews the use and misuse of the magnetotelluric phase tensor (PT), which has been widely used within the MT community since its first postulation in 2004. His review focuses on recent examples where the PT was used to estimate the dimensionality and strike direction. Booker revisits the theory behind the PT and argues that correct use of the tensor including meaningful thresholds for the third skew invariant, a 3D dimensionality indicator, as well as the importance of the error propagation for the uncertainty estimation of the PT estimates, leads to improved estimates to justify 2D modelling of the data. As the PT is a representation of the magnetotelluric impedance tensor, the PT is compared with other representations including induction arrows, the enhanced admittance phase tensor and the Mohr circle representation. Booker describes the progress made in using the distortion-free nature to modify modelling algorithms to purely solve for the inductive response of the impedance tensor. The paper also investigates a PT-consistent decomposition formulation which overcomes some of the strict 2D assumption of the traditional 2D impedance tensor decomposition methods formulated by Bahr and Groom and Bailey. The review concludes that PTs should form a more substantial part in 3D modelling and also in analysing the model fits of conventional 3D MT inversions. It provides a very useful resource for MT practitioners.

Anne Pommier (Arizona State University, USA) reviews the laboratory measurements of crustal and mantle rocks which provide an important link for interpreting geophysical measurements, in particular the electrical resistivity properties of these rocks. It is a timely review following a review on the laboratory conductivity measurements of mantle minerals by Yoshino (2010). Pommier begins by demonstrating how electrical measurements in the laboratory and the field differ, followed by approaches to combine the laboratory and MT results through joint interpretation as well as forward modelling and hypothesis testing. The review shows the controlling factors of the laboratory measurements, highlighting the influence of the pressure, temperature and length of experiments, scaling and oxygen fugacity. Pommier discusses the importance of hydration of crustal and mantle materials as a major driver to explain enhanced conductivities observed from MT. However, laboratory measurements have to be considered carefully when interpreting magnetotelluric models. The review concludes with recommendations to pursue multi-disciplinary approaches incorporating information about rheology, geodynamics and seismic measurements into MT modelling and interpretation.

Eldad Haber and Michal Holzman Gazit (University of British Columbia, Canada) review the current state of joint geophysical inversion and model fusion techniques, which are rapidly growing areas of research. This is one of the first papers to systematically evaluate a number of different joint inversion and model fusion techniques, providing a review of each approach with key references. The paper describes four different methods for joint inversion and model fusion. Haber and Holzman (2013) discuss the use of correspondence maps and suggest an improvement on the well-known gradient cross-product approach. Finally, the review covers a new approach known as Joint Total Variation. The review paper shows examples using synthetic DC resistivity data and borehole tomography and shows how model fusion and joint inversion can significantly improve over existing techniques.

Note that this paper was incorrectly published in the September issue of the *Surveys in Geophysics*.

Gregory Newman (Lawrence Berkeley National Laboratory, USA) reviews how computational methods are changing the way EM geophysical data can be modelled and interpreted. Until recently, modelling EM fields for complex 3D geological structures has been very limited. Whereas 2D modelling and inversion can be undertaken on desktop computers in the short timescales of a day or less, large-scale 3D modelling and imaging require significantly faster and more powerful computers. This review is timely as EM geophysicists are starting to have access to many more large-scale parallel computational resources, including cloud computing, but the transition from desktop computers is not straightforward. Newman reviews how codes should be run in parallel across many computational nodes to significantly speed up the computation time, but there are hardware and software choices to be made. The review also discusses future trends in high-performance computing and the anticipated impact on EM geophysics.

Gerard Muñoz (German Research Centre for Geosciences GFZ, Germany) presents a review on geothermal exploration, a topic that is very timely due to an increased need for renewable energy. The years since the review by Martínez-García (1992) have witnessed an important increase in the use and development in exploration methods investigating both the deep targets as well conventional geothermal systems. Muñoz reviews these developments focusing on electromagnetic methods as electrical conductivity data are important when characterising the geothermal systems of fractures filled with conducting geothermal fluids. He first describes the use of conceptual (conductivity) models of hydrothermal systems and highlights the importance of their development to avoid

misinterpretations. He goes through several examples from high-enthalpy geothermal systems (systems where the temperature is $>150\text{--}200\text{ }^{\circ}\text{C}$) as well as from non-volcanic systems (circulating hot fluids). The examples cover successful surveys in different parts of the globe but also report on unsuccessful investigation. After briefly covering the role of EM studies on monitoring-enhanced (engineered) geothermal systems, Muñoz completes his review by examining possible reasons for misinterpretations and suggests avoiding “anomaly hunting”, but to make interpretation by carefully integrating other geophysical and geological information into a conceptual model of the target area.

Richard Smith (Laurentian University, Canada) presents an important and comprehensive review of developments in electromagnetic methods in mining geophysics between 2008 and 2012 and since the review by Sheard et al. (2005). The review collects a representative sampling of literature allowing the outlining of long-term trends in mining geophysics. He has decided to divide his review into two general parts: one reviewing work published in refereed literature (universities, research institutes, service and mining companies) and another reviewing unrefereed literature, which is primarily extended abstracts from conferences and workshops. This stems from the nature of the mineral exploration where a great deal of important work on systems, interpretation, case histories, etc. is done by exploration companies who do not wish or have a need to publish their results in a rigorous academic fashion. Omitting this work form, the review would, however, result in a biased view. Smith’s extensive review covers several important fields of EM methods including data acquisition system development, system calibration, geometry monitoring and modelling and inversion. He reviews several application case histories to illustrate the developments such as a shift from 1D inversions to 3D inversions or the interest of applying and developing natural-field methods. The review will be very useful to practitioners in EM, both academic and explorers.

Kurt Strack (KMS Technologies—KJT Enterprises Inc., USA) presents an important review of electromagnetic (EM) methods used in hydrocarbon exploration in a time of renewed interest of EM followed by a recent success of the marine EM work. The onshore EM work is further fuelled by the exploration of shale carbons and monitoring of reservoirs as well as by improvements in borehole loggings methods. The latter may likely provide a link between the surface measurements and the in situ properties of a sub-surface. The paper describes the innovations in EM by three distinct groups—borehole, onshore and offshore applications—including an account of “What drives the development of technology”? The paper also discusses inhibitors of the new technologies. The paper is completed by thoughts on the future. Airborne EM applications with an emphasis on mining geophysics are described by Smith in this volume, and marine EM, in general, has been reviewed recently by Key (2012) and Edwards (2005).

Anna Marti’s (Universitat de Barcelona, Spain) review covers the increasingly important concept of anisotropic conduction within Earth materials. To date, most models of Earth’s resistivity have an assumption of isotropic conduction; that is, the resistivity is independent of the orientation of measurement. However, both field and laboratory measurements indicate that the Earth may be significantly anisotropic in conduction, from the near-surface to the deep lithosphere. This review provides a theoretical background on how electrical anisotropy in the Earth is manifested and provides key case study references. The review is divided into three sub-sections. Firstly, Marti reviews how the modelling of EM fields can be undertaken with anisotropic structures. Secondly, she considers how observed EM responses can be used to identify anisotropic structures. Finally, the review covers how such observations can be properly inverted and interpreted.

Kate Selway (University of Adelaide, Australia and Yale University, USA) investigates the causes of electrical conductivity anomalies in tectonically stable lithosphere. The review summarises the conduction mechanisms in stable lithosphere dominated by the temperature and hydrogen content following the laboratory measurements of mantle constituting minerals. The influence of graphite is also considered in stable tectonic environments as it has been very topical for over a decade in the MT community. In particular, the influence of composition, the tectonic history and fertilisation events is discussed in order to explain the large range of measured resistivity values observed in Proterozoic and Archaean lithosphere. The review concludes with the examples of magnetotelluric studies across the Slave Craton in Canada and the Gawler Craton in South Australia, where the discussion is placed in the context of the observed results for these areas. An emphasis is placed on the importance of incompatible elements lowering the resistivity in Archaean lithosphere as a result of fertilisation events and introduction of hydrogen and graphite in nominally anhydrous minerals.

The venue for the 21st EM Induction Workshop was the small, northernmost city of Darwin, with a population of about 125,000. It is a very multi-cultural and young city, with a rapidly growing economy. The Workshop was held in the dry season, with daytime temperatures hovering about 30 °C dropping to 20 °C overnight.

Despite the high Australian dollar, and the long travel distances that many of the delegates made, attendance at the Workshop continued the steady growth in numbers over the last two decades. A total of 273 delegates attended from 28 countries around the world, with approximately half of these delegates being students and early career researchers.

The delegates submitted 265 abstracts between them, which is very positive for the long-term future of the scientific discipline. Single-session presentations were made in the mornings, followed by posters in the afternoons. A total of 41 oral presentations were made over the five working days of the Workshop. A feature of these Workshops is that all of the 223 posters were on display for the entire week, allowing delegates to get to see the whole range of activity.

The EM community at these Workshops is drawn from many sectors, including Universities, Industry, Government research laboratories, National Research Agencies and Geological Surveys. The community significantly supported the Workshop through generous sponsorship. Thirty different companies and institutions supported the Workshop, with funds primarily to students to attend the Workshop. In particular, over 50,000 AUD (about 52,500 USD) was refunded directly in the form of cash payments, registration waivers and accommodation support to 49 students and early career researchers. Another 30,000 AUD of sponsorship significantly subsidised all the student and retiree registrations.

A great tradition of the Workshops is to mingle the science and social programs. With a benign climate and a small city footprint, Darwin was an excellent location. Social events included a 1-day excursion to Litchfield National Park (including swimming in various waterholes); a night at the world-famous deck-chair cinema which is an outdoor venue when the sun goes down; a visit to the Mindil Beach Markets and the sunset over the ocean; and the final night dinner outside at the Darwin Sailing Club on a beautiful warm evening.

The Working Group warmly thanks to the Local Organizing Committee for a very well organised workshop. Future workshops are planned for Weimar, Germany, 24–30 August, 2014, and Thailand, 2016.

Finally, we, as Guest Editors, thank nineteen referees for their careful and constructive reviews as well as the Springer Editorial Office, and in particular Michael Rycroft, Editor

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