Special issue “Studies on electromagnetic induction in the earth: recent advances and future directions”

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PREFACE

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Special issue "Studies on electromagnetic induction in the earth: recent advances and future directions"

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The research community that studies electromagnetic (EM) induction in the Earth and planets continues to grow. The breadth of EM research has expanded well beyond the traditional focus on magnetotellurics (MT) to include airborne, land, and marine controlled-source EM. Advancements in the processing, modeling, inversion and interpretation of EM data have accompanied this growth and led to an increased visibility of EM research within the Earth science community. The biennial workshops on Electromagnetic Induction in the Earth, first held in 1972, continues to be the premier event for the vibrant international community of EM researchers. The 24th workshop on Electromagnetic Induction in the Earth was held in Helsingør, Denmark, from August 13–20, 2018. More than 330 presentations were given spanning a range of topics including (1) instrumentation, sources and data processing; (2) EM theory, modeling and inversion; (3) exploration, monitoring and hazards; (4) tectonics, magmatism and geodynamics; (5) marine EM; (6) rock/mineral resistivity and anisotropy; (7) global and planetary studies and (8) EM induction education and outreach. This special issue presents a compilation of 10 papers, described below, that highlight recent advances and future directions within the EM research community.

Investigations of crustal and lithospheric architecture continue to be a mainstay of MT studies. Comeau et al. (2020) present a study of the tectonic terranes of Mongolia based upon a 350-km-long MT profile. Their resistivity model images zones of elevated upper-crustal conductivity coincident with surface faulting and seismicity; they interpret these zones to mark suture zones within the Central Asian Orogenic Belt. The authors further image a distinct zone of lower-crustal conductivity in part of the model and suggest this conductor may be related to an exotic terrane speculated from geochemical data to exist in the same region. Finally, a step in lithospheric thickness is interpreted beneath Southern Mongolia from the model.

The emergence of national-scale MT initiatives over the last two decades has led to an explosion in the number of three-dimensional (3D), tectonic-scale resistivity models presented and published. Thiel et al. (2020) present one such model, describing MT modeling of the Australian Musgrave province based upon data collected as part of the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP). They present a 3D resistivity model of the lithosphere, arguing that conductive structures within the model reflect tectono-magmatic processes associated with the reworking of the Australian continent, including the amalgamation of cratonic components and deformation during younger orogenies.

3D resistivity models, such as the study by Thiel et al. (2020), rely upon complex inversion algorithms with considerable flexibility with regard to model discretization and regularization, the choice of start and prior models and the treatment of data and errors. Robertson et al. (2020) present a model-space exploration of the 3D inversion ModEM3DMT (Egbert and Kelbert 2012; Kelbert et al. 2014) using for their testbed a subset of data collected as part of AusLAMP. The authors investigate the influence of model covariance, the prior model,

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cell size and the choice of inverted data—evaluating the results both in terms of data misfit and model structure. Their results suggest a practical workflow for 3D inversion and for assessing the resultant models.

Rivera-Rios et al. (2019) demonstrate the functionality of a new 3D vector finite-element forward modeling algorithm, MoVFEM. The authors validate their algorithm against analytic or accepted numerical solutions for a number of complex models, including a 3D community model, a halfspace model with topography and a halfspace model with transverse anisotropy. The authors' results demonstrate the capabilities of the MoVFEM software and hint at future modifications to incorporate the MoVFEM algorithm within adaptive-mesh strategies.

Also on the modeling front, a study of interstation MT impedance responses, calculated from magnetic- and electric-field data recorded at different locations, is presented by Martí et al. (2020). The authors compare models resulting from inversion of local, interstation and 'quasi-MT' (modeling of interstation response as if they were local) responses for two synthetic fault models and find that inversions of the quasi-MT responses do not fully reproduce the synthetic structure but provide generally valid models. The authors subsequently apply this approach to measured data across a seismogenic fault in Spain, identifying a prominent fault-zone conductor. Given the reality of missing or bad data channels, interstation MT responses are sometimes all that are available. In this context, the authors' findings provide reassurance that interstation responses can be reliably used within a traditional inversion approach.

MT inversions also typically assume data errors are uncorrelated by specifying data variances, but not covariances, within the inversion. Guo et al. (2019) investigate the impact of this assumption using a one-dimensional trans-dimensional Bayesian inversion approach. The approach is applied to both synthetic and measured data and in each case the authors compare inversions with and without data-error correlations. In the synthetic example, they demonstrate that ignoring data-error correlation has a tendency to overfit the data and underestimate model parameters uncertainty; the ability to recover model structure is also shown to suffer as data-error covariance increases. Applied to measured data, however, the model results are nearly identical, suggesting a weak correlation between data errors.

Quantification of uncertainty within MT resistivity models, particularly applied to interpreted boundaries such as depth-to-basement or stratigraphic layering, is challenging given the non-uniqueness of the geophysical inverse problem, the differential resolution of conductive and resistive interfaces and the impacts of regularization on the resulting inverse model. Simpson and Heinson (2020) present a case study in Australia where a dense MT data set is combined with limited well-log data to resolve basin layering and the basement interface. The authors undertook a synthetic modeling exercise based upon well-log data, considering both deterministic and stochastic inversions. After examining uncertainty within the synthetic study, the authors apply their approach to map geologic interfaces and their associated errors throughout a broad region. The authors approach provides a practical workflow for handling model uncertainty in areas with limited independent geologic constraints.

MT data are increasingly collected in areas impacted by infrastructure, where non-MT signals dominate measured time-series and can lead to severe degradation of estimated MT responses. A variety of approaches to signal–noise separation operate in the time, frequency, or wavelet domains, but most have difficulty when noise is spatially coherent across broad regions or when data from a reference station is not available. Li et al. (2020) present a machine-learning algorithm for removing noise from MT data contaminated by persistent or coherent noise. The authors present their improved shift-invariant sparse coding (ISISC) method and apply it to synthetic data contaminated with either pseudo-random square wave or impulsive noise sources. They demonstrate the performance and effectiveness of the ISISC algorithm, applying their approach to real MT data sets contaminated with controlled-source EM noise and unknown non-MT noise. This data-driven approach offers an attractive possibility for removing complex periodic noise signals (e.g., pipeline signals) from MT data and pushes the applicability of MT closer to urban areas.

Other sources of MT noise are unique to the seafloor environment. Motion-induced EM signals due to seafloor currents are a common source of noise plaguing seafloor measurements. Chen et al. (2020) describe an adaptive-correlation filter which incorporates seafloor current-meter data as a reference signal in order to reduce motion-induced noise in marine MT data. The authors demonstrate the effectiveness of their approach on time-series collected over a region near the edge of the continental-shelf with strong seafloor currents as well as in a marine basin with weaker currents. Within the former environment, their results highlight the effectiveness of the approach in producing stable MT responses that are not seen using traditional MT processing. Given the increased use of ocean-bottom EM receivers, this advance may lead to considerable improvements in the quality of processed seafloor responses.

Moving from the seafloor to air, Baranwal et al. (2020) present an interpretation of airborne electromagnetic (AEM) data collected over the Mesozoic Ramså Basin in Norway. Their AEM models, derived from a spatially constrained inversion approach, compare favorably to borehole logging data as well as a number of electrical resistivity tomography profiles. The authors find that the conductivity of pore waters has a significant impact on the bulk resistivity within both the rocks of the sedimentary basin and the basement. The AEM models are used to refine the extent of the Ramså Basin. Additionally, a pair of conductive zones also identified within the models are tied to a graphite and sulfide-bearing outcrop.

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References:

Baranwal VC, Brönner M, Rønning J-S, Elvebakk H, Dalsegg E (2020) 3D interpretation of helicopter-borne frequency-domain electromagnetic (HEM) data from Ramså Basin and adjacent areas at Andøya, Norway. Earth Planets Space 72:52. https://doi.org/10.1186/s40623-020-01177-3

Chen K, Zhao Q, Deng M, Luo X, Jing J (2020) Seawater motion-induced electromagnetic noise reduction in marine magnetotelluric data using current meters. Earth Planets Space 72:4. https://doi.org/10.1186/s40623-019-1129-0

Comeau MJ, Becken M, Käufl JS, Grayver AV, Kuvshinov AV, Tserendug S, Batmagnai E, Demberel S (2020) Evidence for terrane boundaries and suture zones across Southern Mongolia detected with a 2-dimensional magnetotelluric transect. Earth Planets Space 72:5. https://doi.org/10.1186/s40623-020-1131-6

Egbert GD, Kelbert A (2012) Computational recipes for electromagnetic inverse problems. Geophys J Int. 189:251–267. https://doi.org/10.1111/j.1365-246X.2011.05347.x

Guo R, Liu L, Liu J, Sun Y, Liu R (2019) Effect of data error correlations on trans-dimensional MT Bayesian inversions. Earth Planets Space 71:134. https://doi.org/10.1186/s40623-019-1118-3

Kelbert A, Meqbel N, Egbert GD, Tandon K (2014) ModEM: A modular system for inversion of electromagnetic geophysical data. Comput Geosci. 66:40–53. https://doi.org/10.1016/j.cageo.2014.01.010

Li G, Liu X, Tang J, Deng J, Hu S, Zhou C, Chen C, Tang W (2020) Improved shift-invariant sparse coding for noise attenuation of magnetotelluric data. Earth Planets Space 72:45. https://doi.org/10.1186/s40623-020-01173-7

Martí A, Queralt P, Marcuello A, Ledo J, Rodríguez-Escudero E, Martínez-Díaz JJ, Campanyà J, Meqbel N (2020) Magnetotelluric characterization of the Alhama de Murcia Fault (Eastern Betics, Spain) and study of magnetotelluric interstation impedance inversion. Earth Planets Space 72:16. https://doi.org/10.1186/s40623-020-1143-2

Rivera-Rios AM, Zhou B, Heinson G, Krieger L (2019) Multi-order vector finite element modeling of 3D magnetotelluric data including complex geometry and anisotropy. Earth Planets Space 71:92. https://doi.org/10.1186/s40623-019-1071-1

Robertson K, Thiel S, Meqbel N (2020) Quality over quantity: on workflow and model space exploration of 3D inversion of MT data. Earth Planets Space 72:2. https://doi.org/10.1186/s40623-019-1125-4

Simpson JM, Heinson G (2020) Synthetic modelling of downhole resistivity data to improve interpretation of basin morphology from magnetotelluric inversion. Earth Planets Space 72:69. https://doi.org/10.1186/s40623-020-01178-2

Thiel S, Goleby BR, Pawley MJ, Heinson G (2020) AusLAMP 3D MT imaging of an intracontinental deformation zone Musgrave Province, Central Australia. Earth Planets Space 72:98. https://doi.org/10.1186/s40623-020-01223-0

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