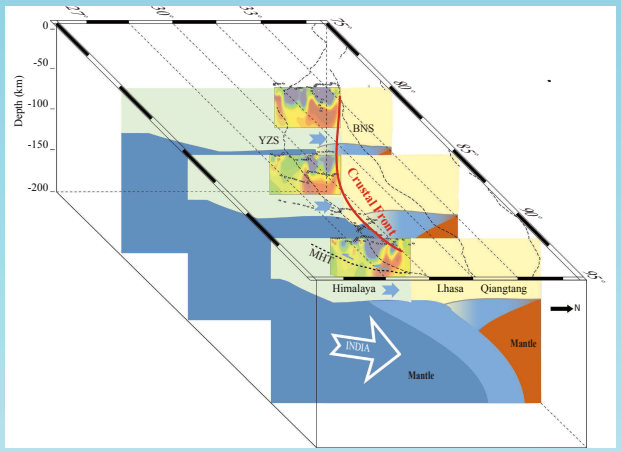
Earth, Planets and Space

Studies on Electromagnetic Induction in the Earth: Recent advances

EMIW2016
Chiang Mai, Thailand



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Journal Scope

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Siripunvaraporn *et al. Earth, Planets and Space* (2018) 70:47
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PREFACE

Open Access

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

Weerachai Siripunvaraporn[1*], Paul A. Bedrosian[2], Yuguo Li[3], Prasanta K. Patro[4], Klaus Spitzer[5] and Hiroaki Toh[6]

Research into electromagnetic induction of the Earth's and planetary interiors has increased considerably within the last decade. The 23rd Electromagnetic Induction Workshop (EMIW) held in Chiang Mai, Thailand, in August 2016 was a premier event for the international research community to exchange the latest developments in the field of electromagnetic induction. This special issue is intended to promote the activity of this vibrant and growing research community and to foster future interdisciplinary studies within the broader earth and planetary sciences. It is a compilation of 10 papers consisting of full research papers, letters, express letters, and a technical report on various topics ranging from terrestrial to marine, from instrumentation to inversion, and to interpretation.

1. Electromagnetic modeling

Most of the inversion techniques for magnetotelluric measurement often yield smooth structures. This makes it difficult to locate the interface boundary between resistivity contrasts. In "Regularized magnetotelluric inversion based on a minimum support gradient stabilizing function," Xiang et al. (2017) proposed a new MSG stabilizing function for imaging sharp interfaces for 1-D and 2-D MT inversion. By performing tests on synthetic data, they found that the new technique yields overall good performance in both data fitting and model recovery, and particularly in resolving geoelectrical interfaces. This suggests that the new technique will be useful for practical applications.

2. Engineering applications

Limitations such as highly resistive terrains, coils that are too long to fit in a narrow tunnel space, and the absence of a GPS signal make it difficult to use conventional surface EM receivers to measure the signal inside tunnels. In their work "Electromagnetic receiver with capacitive electrodes and triaxial induction coil for tunnel exploration," Kai et al. (2017) introduced capacitive electrodes and triaxial induction coils that help avoid these limitations. They successfully developed their new design, and their tests in a mine showed that the new equipment can be used to measure EM signals inside tunnels with typical noise characteristics.

Monitoring of hydraulic fracturing fluids is important for geothermal exploration. This can be conducted using many different methods. In their paper "Monitoring hydraulic stimulation using telluric sounding," Rees et al. (2018) found that a telluric sounding (TS) method is relatively cheap and easy to operate for monitoring hydraulic fracturing at depth compared to full magnetotelluric measurement. In the synthetic studies, consistent changes of the transfer function could be observed to be associated with the fluid movement. However, for the real data test from the Paralana geothermal system, South Australia, due to the high noise level, high-quality electric field data from a controlled source may be necessary.

3. Tectonic studies

As the electrical resistivity values of rocks of the crust and upper mantle are quite sensitive to the presence aqueous fluids and partial melts, MT plays a major role in these scenarios. In their research paper "Regional electrical structure of the Andean subduction zone in

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central Chile (35°–36°S) using magnetotellurics," Reyes-Wagner et al. (2017) used broadband MT data acquired in the Southern Volcanic Zone of the Andes to map the subduction zone and establish its relation with the volcanic arc at 35°–36°S latitude. Their final resistivity model brought out the resistive nature of the forearc structure and also a wide region of high conductivity extending from the volcanic front to the east indicating the highly active magmatism of the region.

The geodynamics of the Cambay Rift Zone, India, is quite complex. Danda et al. (2017) conducted a broadband and long-period MT profile with a length of 200 km in the area and processed the result to yield a 2-D resistivity model in their work "Geoelectric structure of northern Cambay rift basin from magnetotelluric data." They interpreted the high-conductivity zones as fluid emplacement in the west and the presence of fluids and/or interconnected sulfides in the east. In addition, a highly resistive body outside of the rift zone was interpreted as an igneous granitic intrusive complex.

Tracing the Indian crustal front beneath Tibet remains a controversial issue. In their paper "Varying Indian crustal front in the southern Tibetan Plateau as revealed by magnetotelluric data," Xie et al. (2017) used previous MT data to generate a 3-D geoelectrical model in southern Tibet to cope with the Indian crustal front. They found conductive layers beneath the mid- to lower crust, suggesting that the Indian crustal front varies irregularly from west to east. This observation was also supported by seismic results.

Understanding the locked fault is very important because locked zones can potentially generate a large earthquake in the future. Karaş et al. (2017) used MT data to produce a general 3-D resistivity model in their research paper "Electrical conductivity of a locked fault: investigation of the Ganos segment of the North Anatolian Fault (NAF) using three-dimensional magnetotellurics." The geoelectric model brought out the fault zone conductor (FZC) corresponding to the Ganos Fault, ophiolitic basement, and Kesan Formation. A distributed conduit behavior of fluid flow in the vicinity of the Ganos Fault was interpreted. The absence of any fluid pathway at greater depths and the mechanically strong and resistive media on both sides of the fault suggest a locked nature of the Ganos Fault.

4. Geomagnetic studies

Prior to the establishment of a new geomagnetic observatory, Padilha et al. (2017) presented a research letter titled "Effect of a huge crustal conductive anomaly on the H component of geomagnetic variations recorded in central South America." The authors reported anomalous amplification of the H component of the geomagnetic field that was recorded in the central-west region of Brazil. The anomalous behavior of the geomagnetic variations is due to the presence of a 1200-km-long conductor and was explained on the basis of classical electrodynamics as the reflection of EM waves at this interface with a very good conductor and the damping of the EM wave amplitude by the skin effect during its propagation through the conductive medium. The authors proposed that a detailed MT survey be carried out prior to the establishment of the new geomagnetic observatory to evaluate the influence of induced currents on the geomagnetic field.

5. Marine EM studies

In contrast to the MT data, which show no evidence of electrical anisotropy, recent seismic data from the NoMelt experiment presented a strong anisotropy in the upper mantle. Matsuno and Evans (2017) revisited the MT data to answer the question of whether electrical anisotropy really existed in the data in their express letter "Constraints on lithospheric mantle and crustal anisotropy in the NoMelt area from an analysis of long-period seafloor magnetotelluric data." Interestingly, they found that electrical anisotropy is possible at lower lithosphere depths. However, this is not related to the anisotropy found in the seismic data at upper and mid-lithosphere depths. Seismic anisotropy at this depth is not expected to generate measurable MT data.

To study the nature of old oceanic upper mantle, Baba et al. (2017) analyzed many seafloor MT data in the northwestern Pacific in their full research paper "Electrical conductivity of old oceanic mantle in the northwestern Pacific I: 1-D profiles suggesting differences in thermal structure not predictable from a plate cooling model." Significant differences in resistive layer thickness were observed between the four zones of investigation, and these could not be explained by only a plate cooling model. The authors suggested that these differences may have been caused by the influence of the plume associated with the formation of the Shatsky Rise or by spatially non-uniform and small-scale convection in the asthenosphere.

Authors' contributions
All authors of this article served as guest editors for this special issue. All authors read and approved the final manuscript.

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FULL PAPER Open Access

Electrical conductivity of a locked fault: investigation of the Ganos segment of the North Anatolian Fault using three-dimensional magnetotellurics

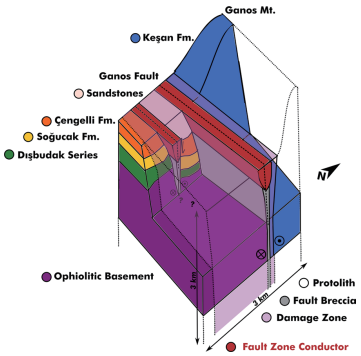
Mustafa Karaş, Sabri Bülent Tank* and Sinan Özaydın

Earth, Planets and Space 2017, **69**:107 DOI:10.1186/s40623-017-0695-2
Received: 3 January 2017, Accepted: 31 July 2017, Published: 15 August 2017

Abstract

This study attempts to reveal the fault zone characteristics of the locked Ganos Fault based on electrical resistivity studies including audio-frequency (AMT: 10,400–1 Hz) and wide-band (MT: 360–0.000538 Hz) magnetotellurics near the epicenter of the last major event, that is, the 1912 Mürefte Earthquake (M_w 7.4). The AMT data were collected at twelve stations, closely spaced from north to south, to resolve the shallow resistivity structure to 1 km depth. Subsequently, 13 wide-band MT stations were arranged to form a grid enclosing the AMT profile to decipher the deeper structure. Three-dimensional inverse modeling indicates highly conductive anomalies representing fault zone conductors along the Ganos Fault. Subsidiary faults around the Ganos Fault, which are conductive structures with individual mechanically weak features, merge into a greater damage zone, creating a wide fluid-bearing environment. This damage zone is located on the southern side of the fault and defines an asymmetry around the main fault strand, which demonstrates distributed conduit behavior of fluid flow. Ophiolitic basement occurs as low-conductivity block beneath younger formations at a depth of 2 km, where the mechanically weak to strong transition occurs. Resistive structures on both sides of the fault beneath this transition suggest that the lack of seismicity might be related to the absence of fluid pathways in the seismogenic zone.

Keywords: Fluid, North Anatolian Fault, Ganos Fault, Fault zone conductor, Locked fault, Electrical resistivity, Asymmetric damage zone, Magnetotellurics



Graphical abstract

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Electrical conductivity of old oceanic mantle in the northwestern Pacific I: 1-D profiles suggesting differences in thermal structure not predictable from a plate cooling model

Kiyoshi Baba*, Noriko Tada, Tetsuo Matsuno, Pengfei Liang, Ruibai Li, Luolei Zhang, Hisayoshi Shimizu, Natsue Abe, Naoto Hirano, Masahiro Ichiki and Hisashi Utada

Earth, Planets and Space 2017, **69**:111 DOI:10.1186/s40623-017-0697-0
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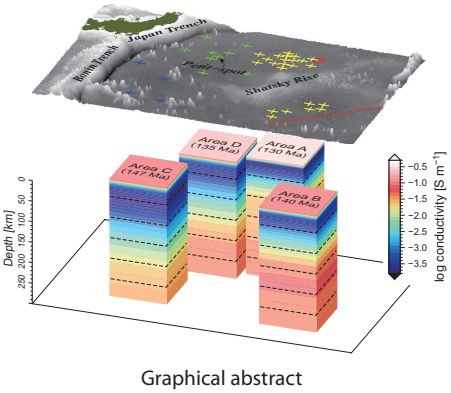
Abstract

Seafloor magnetotelluric (MT) experiments were recently conducted in two areas of the northwestern Pacific to investigate the nature of the old oceanic upper mantle. The areas are far from any tectonic activity, and "normal" mantle structure is therefore expected. The data were carefully analyzed to reduce the effects of coastlines and seafloor topographic changes, which are significant boundaries in electrical conductivity and thus distort seafloor MT data. An isotropic, one-dimensional electrical conductivity profile was estimated for each area. The profiles were compared with those obtained from two previous study areas in the northwestern Pacific. Between the four profiles, significant differences were observed in the thickness of the resistive layer beyond expectations based on cooling of homogeneous oceanic lithosphere over time. This surprising feature is now further clarified from what was suggested in a previous study. To explain the observed spatial variation, dynamic processes must be introduced, such as influence of the plume associated with the formation of the Shatsky Rise, or spatially non-uniform, small-scale convection in the asthenosphere. There is significant room of further investigation to determine a reasonable and comprehensive interpretation of the lithosphere–asthenosphere system beneath the northwestern Pacific. The present results demonstrate that electrical conductivity provides key information for such investigation.

Keywords: Geomagnetic induction, Marine magnetotellurics, Electrical conductivity, Oceanic lithosphere and asthenosphere, Northwestern Pacific



Graphical abstract

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FULL PAPER Open Access

Geoelectric structure of northern Cambay rift basin from magnetotelluric data

Nagarjuna Danda, C. K. Rao* and Amit Kumar

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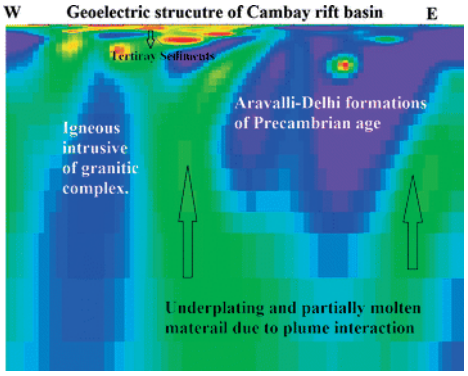
Abstract

Broadband and long-period magnetotelluric data were acquired over the northern part of the Cambay rift zone along an east–west profile ~ 200 km in length. The decomposed TE- and TM-mode data were inverted using a 2-D nonlinear conjugate gradient algorithm to obtain the lithospheric structure of the region. A highly conductive (~ 1000 S) layer was identified within the Cambay rift zone and interpreted as thick Quaternary and Tertiary sediments. The crustal conductors found in the profile were due to fluid emplacement in the western part, and the presence of fluids and/or interconnected sulfides caused by metamorphic phases in the eastern part. The demarcation of the Cambay rift zone is clearly delineated with a steeply dipping fault on the western margin, whereas the eastern margin of the rift zone gently dips along the NE–SW axis, representing a half-graben structure. A highly resistive body identified outside the rift zone is interpreted as an igneous granitic intrusive complex. Moderately conductive (30–100 Ω-m) zones indicate underplating and the presence of partial melt due to plume–lithosphere interactions.

Keywords: Cambay rift zone, Deccan basalt, Lithosphere, Magnetotellurics, Reunion plume



Graphical abstract

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Regional electrical structure of the Andean subduction zone in central Chile (35°–36°S) using magnetotellurics

Valentina Reyes-Wagner*, Daniel Díaz, Darcy Cordell and Martyn Unsworth

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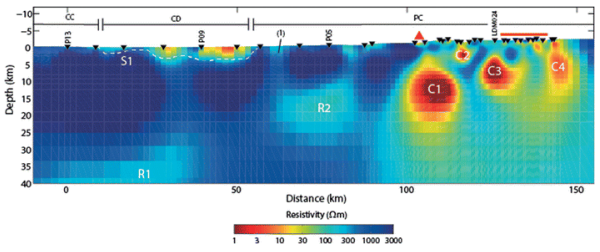
Abstract

A profile of broadband magnetotelluric stations was acquired between 2009 and 2016 at 35°–36°S in the Southern Volcanic Zone of the Chilean Andes to image the subduction zone and its relation with the volcanic arc at this latitude. This transect extends from the Coastal Cordillera across the Central Valley and the volcanic arc of the Principal Cordillera to the Argentine border. Two active volcanic complexes are found along this profile: Tatara-San Pedro is located on the modern volcanic front, and the Laguna del Maule volcanic field is found approximately 30 km to the east. The latter exhibits considerable signs of unrest, such as uplift rates of up to 25 cm/year, and has produced a high concentration of silicic eruptions in the last 25 ky. The data covered the period range from 0.001 to 1000 s. Robust processing techniques were used, including remote reference, and dimensionality was investigated by estimation of geoelectric strike, skew and analysis of the induction arrows. The data were modeled using a 2D inversion algorithm to produce a resistivity model which was consistent with surface geology and seismicity. The final resistivity model shows a generally resistive fore-arc structure, coincident with the tectonic environment, and a wide conductive region from the volcanic front to the east. This suggests a broad region of magmatism throughout the arc, related to three distinct magma bodies, associated with the Tatara-San Pedro and Laguna del Maule volcanic complexes and the Mariposa Geothermal System.

Keywords: Magnetotellurics, Volcanism, Southern Volcanic Zone, Deformation, Subduction zone



Graphical abstract

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FULL PAPER Open Access

Varying Indian crustal front in the southern Tibetan Plateau as revealed by magnetotelluric data

Chengliang Xie*, Sheng Jin, Wenbo Wei, Gaofeng Ye, Letian Zhang, Hao Dong and Yaotian Yin

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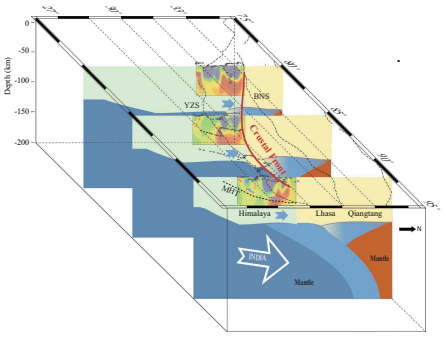
Abstract

In the southern Tibetan plateau, which is considered to be the ongoing India–Eurasia continental collision zone, tracing of the Indian crustal front beneath Tibet is still controversial. We conducted deep subsurface electrical modeling in southern Tibet and discuss the geometry of the front of the Indian crust. Three areas along the Yarlung-Zangbo river zone for which previous magnetotelluric (MT) data are available were inverted independently using a three-dimensional MT inversion algorithm ModEM. Electrical horizontal slices at different depths and north–south oriented cross sections at different longitudes were obtained to provide a geoelectrical perspective for deep processes beneath the Tethyan Himalaya and Lhasa terrane. Horizontal slices at depths greater than − 15 km show that the upper crust is covered with resistive layers. Below a depth of − 20 km, discontinuous conductive distributions are primarily concentrated north of the Yarlung-Zangbo sutures (YZS) and could be imaged from mid- to lower crust. The results show that the maximum depth to which the resistive layers extend is over − 20 km, while the mid- to lower crustal conductive zones extend to depths greater than − 50 km. The results indicate that the conductive region in the mid- to lower crust can be imaged primarily from the YZS to south of the Bangong-Nujiang sutures in western Tibet and to ~ 31°N in eastern Tibet. The northern front of the conductive zones appears as an irregular barrier to the Indian crust from west to east. We suggest that a relatively less conductive subsurface in the northern portion of the barrier indicates a relatively cold and strong crust and that the front of the Indian crust might be halted in the south of the barrier. We suggest that the Indian crustal front varies from west to east and has at least reached: ~ 33.5°N at ~ 80°E, ~ 31°N at ~ 85°E, and ~ 30.5°N at ~ 87°E and ~ 92°E.



Graphical abstract

Keywords: Indian crust, Southern Tibet, Electrical model, Partial melt

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FULL PAPER Open Access

Regularized magnetotelluric inversion based on a minimum support gradient stabilizing functional

Yang Xiang, Peng Yu*, Luolei Zhang, Shaokong Feng and Hisashi Utada

Earth, Planets and Space 2017, **69**:158 DOI:10.1186/s40623-017-0743-y
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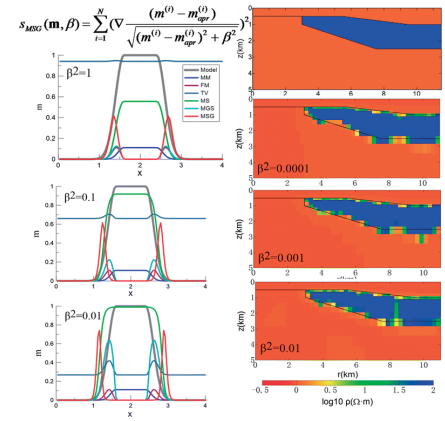
Abstract

Regularization is used to solve the ill-posed problem of magnetotelluric inversion usually by adding a stabilizing functional to the objective functional that allows us to obtain a stable solution. Among a number of possible stabilizing functionals, smoothing constraints are most commonly used, which produce spatially smooth inversion results. However, in some cases, the focused imaging of a sharp electrical boundary is necessary. Although past works have proposed functionals that may be suitable for the imaging of a sharp boundary, such as minimum support and minimum gradient support (MGS) functionals, they involve some difficulties and limitations in practice. In this paper, we propose a minimum support gradient (MSG) stabilizing functional as another possible choice of focusing stabilizer. In this approach, we calculate the gradient of the model stabilizing functional of the minimum support, which affects both the stability and the sharp boundary focus of the inversion. We then apply the discrete weighted matrix form of each stabilizing functional to build a unified form of the objective functional, allowing us to perform a regularized inversion with variety of stabilizing functionals in the same framework. By comparing the one-dimensional and two-dimensional synthetic inversion results obtained using the MSG stabilizing functional and those obtained using other stabilizing functionals, we demonstrate that the MSG results are not only capable of clearly imaging a sharp geoelectrical interface but also quite stable and robust. Overall good performance in terms of both data fitting and model recovery suggests that this stabilizing functional is effective and useful in practical applications.



Graphical abstract

Keywords: Regularized inversion, Stabilizing functional, Minimum support gradient

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FULL PAPER Open Access

Monitoring hydraulic stimulation using telluric sounding

Nigel Rees*, Graham Heinson and Dennis Conway

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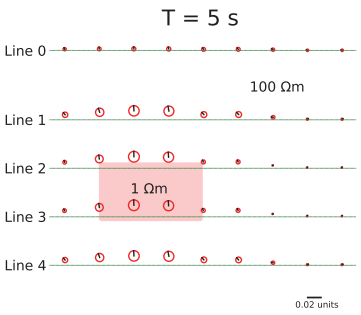
Abstract

The telluric sounding (TS) method is introduced as a potential tool for monitoring hydraulic fracturing at depth. The advantage of this technique is that it requires only the measurement of electric fields, which are cheap and easy when compared with magnetotelluric measurements. Additionally, the transfer function between electric fields from two locations is essentially the identity matrix for a 1D Earth no matter what the vertical structure. Therefore, changes in the earth resulting from the introduction of conductive bodies underneath one of these sites can be associated with deviations away from the identity matrix, with static shift appearing as a galvanic multiplier at all periods. Singular value decomposition and eigenvalue analysis can reduce the complexity of the resulting telluric distortion matrix to simpler parameters that can be visualised in the form of Mohr circles. This technique would be useful in constraining the lateral extent of resistivity changes. We test the viability of utilising the TS method for monitoring on both a synthetic dataset and for a hydraulic stimulation of an enhanced geothermal system case study conducted in Paralana, South Australia. The synthetic data example shows small but consistent changes in the transfer functions associated with hydraulic stimulation, with grids of Mohr circles introduced as a useful diagnostic tool for visualising the extent of fluid movement. The Paralana electric field data were relatively noisy and affected by the dead band making the analysis of transfer functions difficult. However, changes in the order of 5% were observed from 5 s to longer periods. We conclude that deep monitoring using the TS method is marginal at depths in the order of 4 km and that in order to have meaningful interpretations, electric field data need to be of a high quality with low levels of site noise.

Keywords: Telluric sounding, Hydraulic stimulation, Monitoring, Transfer functions



Graphical abstract

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LETTER Open Access

Effect of a huge crustal conductivity anomaly on the H-component of geomagnetic variations recorded in central South America

Antonio L. Padilha*, Livia R. Alves, Graziela B. D. Silva and Karen V. Espinosa

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Abstract

We describe here an analysis of the H-component of the geomagnetic field recorded in several temporary stations operating simultaneously in the central–eastern region of Brazil during nighttime pulsation events in 1994 and the sudden commencement of the St. Patrick's Day magnetic storm in 2015. A significant amplification in the amplitude of the geomagnetic variations is consistently observed in one of these stations. Magnetovariational analysis indicates that the amplification factor is period dependent with maximum amplitude around 100 s. Integrated magnetotelluric (MT) and geomagnetic depth soundings (GDS) have shown that this station is positioned just over a huge 1200-km-long crustal conductor (estimated bulk conductivity greater than 1 S/m). We propose that the anomalous signature of the geomagnetic field at this station is due to the high reflection coefficient of the incident electromagnetic wave at the interface with the very good conductor and by skin effects damping the electromagnetic wave in the conducting layers overlying the conductor. There are some indication from the GDS data that the conductor extends southward beneath the sediments of the Pantanal Basin. In this region is being planned the installation of a new geomagnetic observatory, but its preliminary data suggest anomalous geomagnetic variations. We understand that a detailed MT survey must be carried out around the chosen observatory site to evaluate the possible influence of induced currents on the local geomagnetic field.

Keywords: South America, Geomagnetic variations, Crustal conductor, Geomagnetic observatory, Reflection of electromagnetic waves, Skin effect

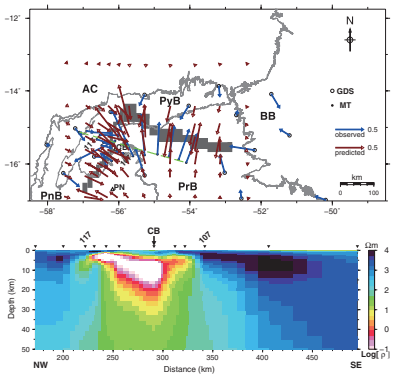

Fig. 5

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EXPRESS LETTER Open Access

Constraints on lithospheric mantle and crustal anisotropy in the NoMelt area from an analysis of long-period seafloor magnetotelluric data

Tetsuo Matsuno* and Rob. L. Evans

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Abstract

Despite strong anisotropy seen in analysis of seismic data from the NoMelt experiment in 70 Ma Pacific seafloor, a previous analysis of coincident magnetotelluric (MT) data showed no evidence for anisotropy in the electrical conductivity structure of either lithosphere or asthenosphere. We revisit the MT data and use 1D anisotropic models of the lithosphere to demonstrate the limits of acceptable anisotropy within the data. We construct 1D models by varying the thickness and the degree of anisotropy within the lithosphere and conduct a series of tests to investigate what types of electrical anisotropy are compatible with the data. We find that electrical anisotropy is possible in a sheared and/or hydrous mantle within the lower lithosphere (60–90 km depth). The data are not compatible with pervasive electrical anisotropy in the crust. Causes of anisotropy within the highly resistive upper and mid-lithosphere, as seen seismically, are not expected to cause measurable impacts on MT response.

Keywords: Electrical anisotropy, Oceanic lithosphere, Shearing, Water, Central Pacific

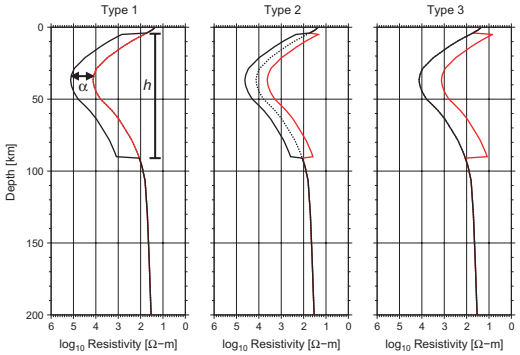

Fig. 1

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TECHNICAL REPORT Open Access

Electromagnetic receiver with capacitive electrodes and triaxial induction coil for tunnel exploration

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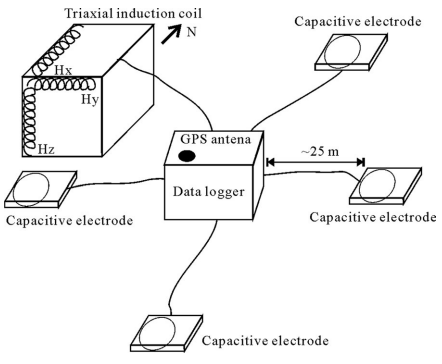
Abstract

A new type of electromagnetic (EM) receiver has been developed by integrating four capacitive electrodes and a triaxial induction coil with an advanced data logger for tunnel exploration. The new EM receiver can conduct EM observations in tunnels, which is one of the principal goals of surface-tunnel-borehole EM detection for deep ore deposit mapping. The use of capacitive electrodes enables us to record the electrical field (E-field) signals from hard rock surfaces, which are high-resistance terrains. A compact triaxial induction coil integrates three independent induction coils for narrow-tunnel exploration applications. A low-time-drift-error clock source is developed for tunnel applications where GPS signals are unavailable. The three main components of our tunnel EM receiver are: (1) four capacitive electrodes for measuring the E-field signal without digging in hard rock regions; (2) a triaxial induction coil sensor for audio-frequency magnetotelluric and controlled-source audio-frequency magnetotelluric signal measurements; and (3) a data logger that allows us to record five-component MT signals with low noise levels, low time-drift-error for the clock source, and high dynamic range. The proposed tunnel EM receiver was successfully deployed in a mine that exhibited with typical noise characteristics.

Keywords: Tunnel EM prospecting, Capacitive electrode, Triaxial induction coil, Low time-drift-error clock source, EM data logger



Graphical abstract

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Contents

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