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LETTER

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

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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

Background

Observation and modeling are fundamental to monitor the temporal evolution of the geomagnetic field and to getting insight into the processes involved in its generation and modification. In particular, geomagnetic observatories are permanent measuring stations where precise, continuous long-term measurements of the geomagnetic field are made, thus making it possible to study field variations of both external and internal origins. Several of the observatories of the INTERMAGNET network have been reconfigured since 2010 to a 1-Hz recording, which has made their data suitable for studies on a global scale of most of the rapid geomagnetic variations caused by external sources (e.g., Kleimenova et al. 2013, 2014) and even development of new substorm indices (Nosé et al. 2012). Even with the advent of geomagnetic measurements from space, the role of the ground geomagnetic observations remains crucial because satellites provide a limited resolution of the field distribution at the Earth's surface due to their orbit altitude.

A problem with this complementary information given by observatory recordings is that they are spatially sparse in large parts of the world. For example, there are only four observatories operating in continental South America with data available through INTERMAGNET. This is clearly insufficient to resolve geomagnetic activity on a region crossed by the equatorial electrojet current system (EEJ) and characterized by the global minimum intensity of the geomagnetic field (South Atlantic Magnetic Anomaly—SAMA). To fill partially this gap a new geomagnetic

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observatory is being established in central South America (Pantanal region, Center-West Brazil). Preliminary analysis of geomagnetic variations has shown large variations in the Pantanal data when compared with data from six geomagnetic observatories in the same range of latitude or longitude, what was attributed to effects generated by the SAMA (Siqueira and Pinheiro 2015). However, other studies have shown that amplitude enhancement of geomagnetic variations in the SAMA is restricted to the center region of the anomaly (Trivedi et al. 2005; Shinbori et al. 2010), far away from the observatory site.

According to Chi et al. (1996), the amplitude of geomagnetic variations observed on the ground is affected by many physical processes. They include the intrinsic magnitude of the incoming electromagnetic wave generated by solar wind and/or magnetosphere events, a local time dependence in the ionosphere and an amplification factor related to the underground conductivity structure. In the latter case, the secondary currents induced in the solid Earth by the time-varying magnetic field of external origin are responsible for anomalous behavior in geomagnetic components recorded at observatories in different regions worldwide, such as central and northern Japan (Rikitake et al. 1956), western South America (Schmucker 1969) and southern India (Singh et al. 1977). Further, use of temporary arrays of ground-based magnetometers has allowed the identification of extensive anomalies in underground conductivity at several locations around the world (see, for instance, reviews by Gough 1973; Gough and Ingham 1983; Arora 1997; Egbert 2002a; Neska 2016).

In this study, we report anomalous amplifications in the north–south (H) component of the geomagnetic field recorded at a station in the vicinity of the proposed site for the Pantanal geomagnetic observatory. We show that the amplitude enhancement of the ground geomagnetic variations is associated with a huge crustal conductor recently detected in central South America by electromagnetic induction surveys. Following the standard procedures established by IAGA for knowledge of the homogeneity of the magnetic field surrounding the site of any observatory (Jankowski and Sucksdorff 1996), we recommend evaluating first the areal extent of the internal conductivity anomaly and its influence on the geomagnetic field before using the data from the observatory, or even for choosing a new site for its installation.

Data sources

Geomagnetic field variations within the South American continent are available from digital fluxgate magnetometers operating during different times at several temporary and permanent stations. Figure 1 shows a map with the geographic location of geomagnetic stations used in this study together with contours of relevant geomagnetic coordinates during the two periods of data analysis. The position of the dip equator (solid lines), the schematic extent of the EEJ effects (dashed lines) and an outline of the SAMA region (isoline of 23,000 nT of the total magnetic field in 2015) are indicated. The complexity of the geomagnetic main field in this region can be seen and is characterized by a large deviation between the geographic and magnetic meridians and by a significant drift of the dip component. The locations of the four permanent geomagnetic observatories from the INTERMAGNET network are also included. The data used in this study are freely available to any scientist wishing to use them for non-commercial purposes and can be obtained from the Kyushu University (1994 experiment), INTERMAGNET and from the Brazilian EMBRACE program (2015 experiment).

Data analysis

1994 experiment: nighttime continuous pulsations

Geomagnetic field data from central South America are part of equatorial stations operated by Kyushu University around the world. Specifically for the stations used in this study, data are available during the interval from September 1993 to January 1995. High-sensitivity fluxgate magnetometers (amplitude resolution of 0.05 nT) with a self-time calibration system were installed and provided digital data with 3-s sampling (Tachihara et al. 1996). These data were previously used in a number of studies to investigate different characteristics of geomagnetic variations at very low and equatorial latitudes (e.g., Shinohara et al. 1998; Padilha et al. 2003; Rastogi et al. 2008).

The six stations lie roughly along the 10° magnetic meridian across the center of the continent. PRM was positioned at the dip equator, four stations were at two pairs of nearly conjugate points under the EEJ influence (ARI-VIL and POV-COL), and the remaining one was just outside the EEJ belt (CB). Figure 2 shows typical variations of H field at these stations for a magnetically quiet day (mean Kp index of 3^{-}). The effect of the narrow EEJ currents can be clearly seen with the stations presenting the same daily variation pattern but with significant differences in amplitude. As expected, the daily range (maximum value of H in relation to the base level at night) is observed around noon (1540 UT, equivalent to 1140 LT) and increases toward the dip equator (133 nT at PRM, 116–120 nT at the pair ARI and VIL, 92–93 nT at the pair COL and POV and 50 nT at CB).

The time series recorded at each station were processed to detect simultaneous ultralow-frequency (ULF) events. Time–frequency spectrograms form the basis for event detection and were derived by applying a Butterworth band-pass filter in specified Pc3–Pc5 pulsation frequency

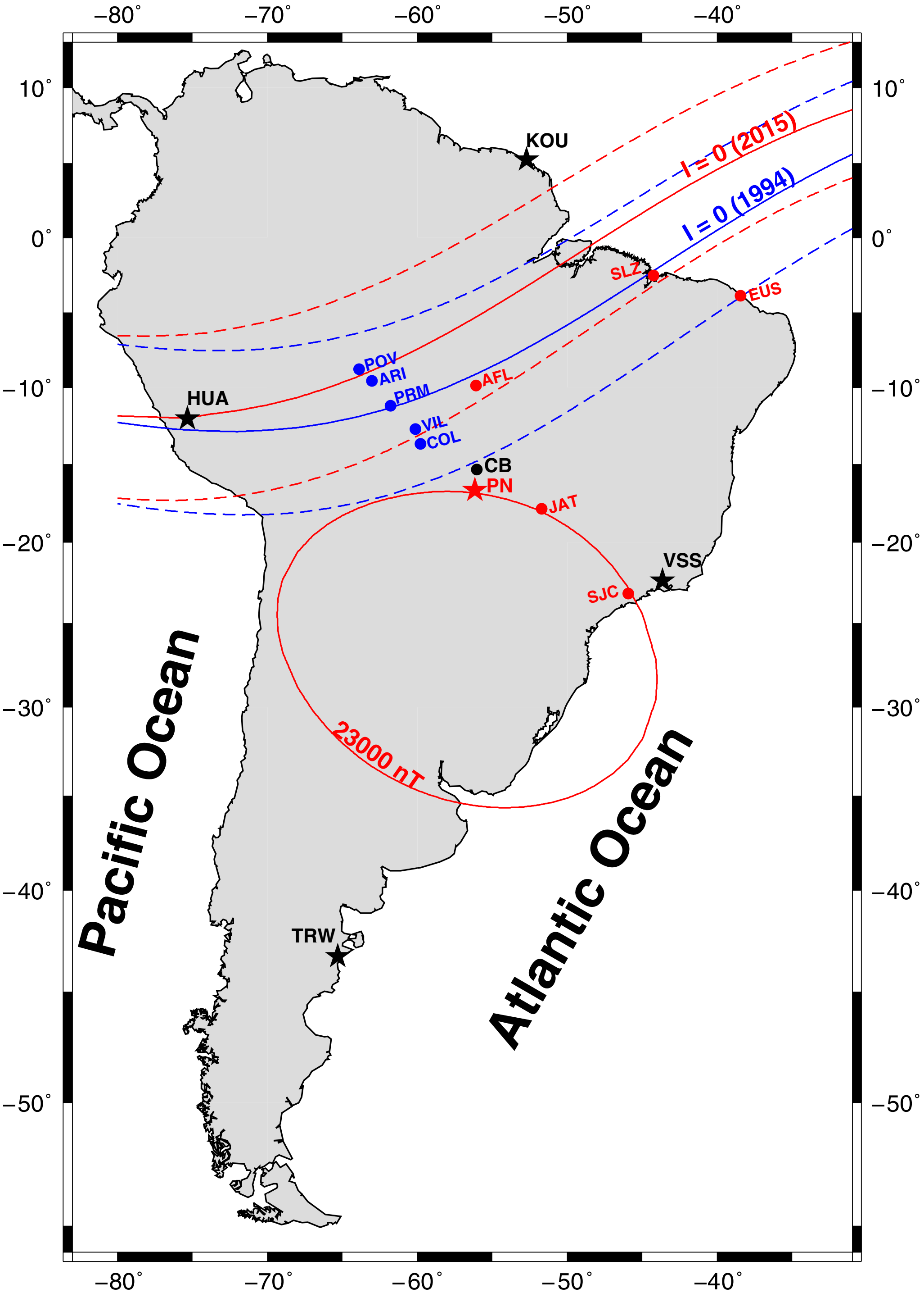

Fig. 1 Map of South American geomagnetic stations and the influence of the EEJ at different times and the SAMA at 2015. Sites and geomagnetic coordinates in *blue* are from the 1994 experiment, whereas sites and geomagnetic coordinates in red are from the 2015 experiment. The *solid lines* show the dip equator in both experiments, and *dashed lines* represent ±10° dip angles. The 23,000 nT isoline outlines the SAMA in 2015. Site CB (Cuiabá) is nearly the same in both experiments. Location of the permanent geomagnetic observatories (KOU, HUA, VSS and TRW) and of the proposed new geomagnetic observatory (PN) is also indicated

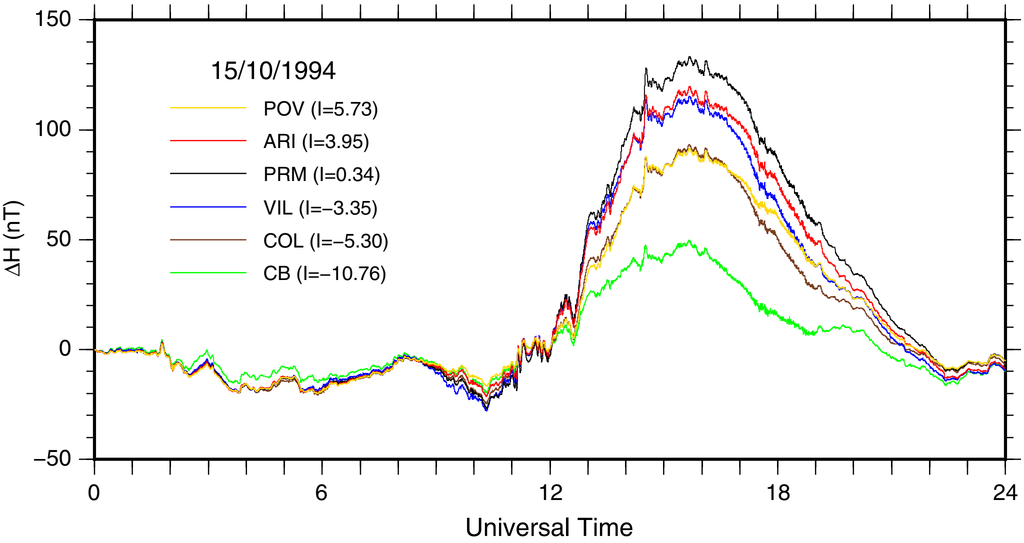

Fig. 2 Variations of the magnetic field H-component at stations near the magnetic equator on October 15, 1994. Magnetic inclination angles are presented for each station which has the following abbreviations and geographic coordinates: Porto Velho (POV; 8.8S, 63.9W), Ariquemes (ARI; 9.56S, 63.04W), Presidente Medici (PRM; 11.2S, 61.8W), Vilhena (VIL; 12.72S, 60.13W), Colibri (COL; 13.7S, 59.8W) and Cuiabá (CB; 15.35S, 56.05W)

ranges to the original data and computing the amplitude spectra by direct Fourier transform. Wave packets with power exceeding predefined threshold power levels were chosen for further visual inspection.

Ground pulsations near the geomagnetic equator are known to be strongly polarized to the H-component (except around dawn; Saka and Alperovich 1993). Therefore, analysis is concentrated on this component. In addition, to discard local ionospheric effects (EEJ), nighttime events are selected for analysis. Figure 3 shows examples of nighttime H-component data recorded at the 1994 equatorial stations, narrow band filtered within the Pc3 and Pc5 ranges. In both cases, the signals exhibit the wave packet structure typical of Pc pulsations.

The amplitudes of the two events in all stations, as well as the ratio of the amplitude in CB to the amplitude in the other stations, are shown in Table 1. The greatest Pc3 amplitude is observed in CB (0.73 nT), which is amplified in relation to the other stations by a factor ranging from 22% (station VIL) to 38% (stations PRM and COL).

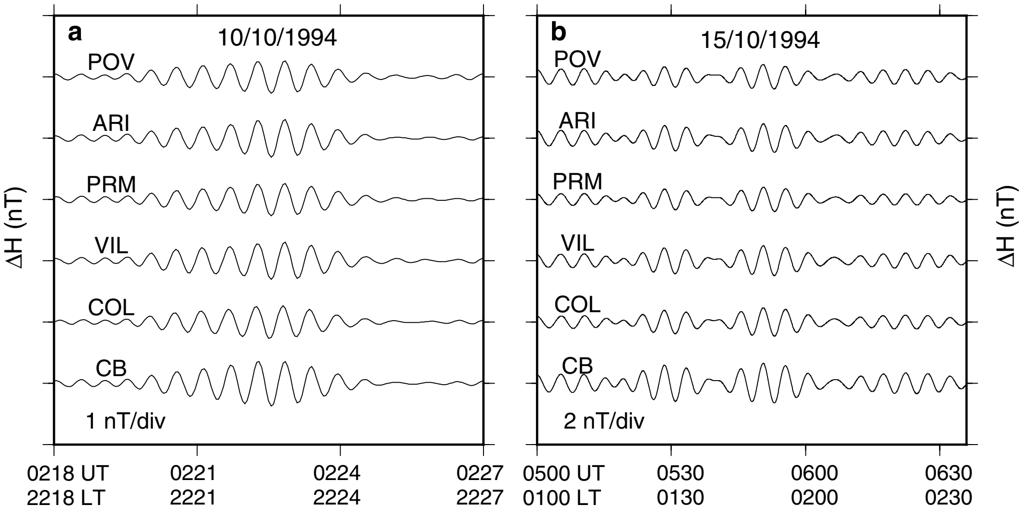

Fig. 3 Nighttime ULF waves in Pc3 and Pc5 bands after narrow band filtering. **a** Pc3 pulsation with center frequency in 30.3 mHz and frequency bandwidth of ±4 mHz. **b** Pc5 pulsation with center frequency in 3.33 mHz and frequency bandwidth of ±0.4 mHz

Table 1 Amplitudes and amplification factors at CB for the Pc3 and Pc5 pulsations

Station	Pc3 amplitude (nT)	Amplification at CB	Pc5 amplitude (nT)	Amplification at CB
POV	0.54	1.35	0.80	1.63
ARI	0.59	1.24	0.93	1.40
PRM	0.53	1.38	0.82	1.59
VIL	0.60	1.22	0.94	1.38
COL	0.53	1.38	0.95	1.37
CB	0.73	–	1.30	–

Amplification at CB is the ratio of the amplitude at the CB station to that at the other stations

Similarly, the largest Pc5 amplitude is also observed at CB (1.3 nT), amplified by factors between 37% (COL) and 63% (POV) to the other stations. Considering that amplitude of the nighttime ULF waves would not be expected to vary significantly at these relatively close equatorial sites, the amplification factor is most likely related to abnormal conductivity structure under the CB site.

2015 experiment: the St. Patrick's Day geomagnetic storm

As part of the Brazilian space weather program, the EMBRACE magnetometer network is being planned to cover most of the eastern South American sector. Geomagnetic data are acquired by commercial fluxgate magnetometers with 1-s sampling rate (for details of magnetometer sensitivity and calibration procedures see Denardini et al. 2015). The six stations chosen for this study are shown in Fig. 1. Four of them (AFL, CB, JAT and SJC) are roughly aligned perpendicular to the dip equator (corrected geomagnetic coordinates, and consequently the magnetic meridian, are undefined in this region of N-NE Brazil; Laundal and Richmond 2016), with AFL under the EEJ influence. The two other stations in NE Brazil form pairs with sites along this line at the same geomagnetic longitude (SLZ and AFL, EUS and CB).

This magnetometer chain is used here to study the nighttime effects of the geomagnetic storm of March 17, 2015, also termed as the St. Patrick's Day storm, currently the strongest geomagnetic storm occurred since the beginning of the solar cycle 24. The storm was associated with a coronal mass ejection (CME) launched from the Sun on March 15, 2015. The CME hit the Earth's magnetosphere and generated a storm sudden commencement (SSC) recorded by ground observatories at around 0445 UT on March 17, 2015. It was characterized as a two-step storm, driven by two successive southward interplanetary magnetic field (IMF) structures, which led to intense particle precipitation and an enhancement in substorm activity with minimum value of Dst (disturbance storm time) index of −223 nT. More details on the event can be found in several recent papers (e.g., Wu et al. 2016, and references therein).

Figure 4 shows the SSC as recorded at the six Brazilian stations. Data from the permanent observatory KOU with 1-s sampling rate are also included for comparison. The abrupt increase in the northward component of the geomagnetic field can be seen, and the geomagnetic variations in all stations are similar during this initial phase of the storm that takes place during nighttime in the South American sector. These time series with sampling rate of 1 s make clear that the SJC station is noisier than the others due to 60-Hz local contamination.

The amplitude of the SSC and the amplification factor at CB in relation to the other stations are shown in Table 2. Similarly to what is observed in the pulsation activity, the CB station presents the largest temporal variation in the magnetic field during the geomagnetic storm.

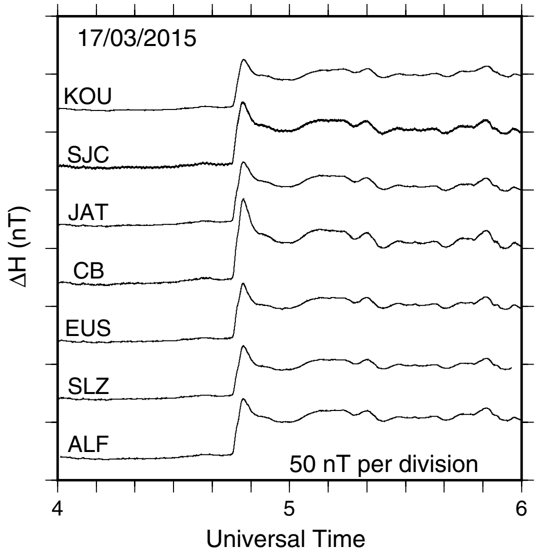

Fig. 4 Time series of the magnetic field H-component at the six EMBRACE stations and KOU geomagnetic observatory in eastern South America during 2 h on March 17, 2015. EMBRACE stations have the following abbreviations, geographic coordinates and magnetic dip angle: Alta Floresta (AFL; 9.87S, 56.10W; −7.9°), São Luiz (SLZ; 2.59S, 44.21W; −8.8°), Eusébio (EUS; 3.88S, 38.42W; −18.0°), Cuiabá (CB; 15.55S, 56.07W; −17.4°), Jataí (JAT; 17.93S, 51.72W; −25.2°) and São José dos Campos (SJC; 23.21S, 45.96W; −37.1°)

Table 2 Amplitudes and amplification factors at CB during the SSC

Station	SSC amplitude (nT)	Amplification at CB
KOU	43.4	1.67
SJC	56.4	1.28
JAT	54.6	1.33
CB	72.4	–
EUS	49.8	1.45
SLZ	45.9	1.58
ALF	50.4	1.44

CB amplification is the ratio of the amplitude at the CB station to that at the other stations

The PACA conductivity anomaly

A large geomagnetic depth sounding (GDS) array operated in south–central Brazil discovered a strong conductivity anomaly under the central–west South American Platform (Bologna et al. 2014). A 3-D forward modeling of GDS transfer functions (real induction arrows) suggested the presence of a 1200-km-long curved conductor running approximately parallel to the south–southeastern border of the Amazonian Craton in NW Brazil (Fig. 5). The anomaly lies, virtually in its entirety, within a narrow corridor parallel to geologic trend of the Paraguay and Araguaia belts and was thus called the Paraguay–Araguaia belt conductivity anomaly (acronym PACA). In order to map better the PACA and to elucidate its formation mechanism, further magnetotelluric (MT) data were acquired along a profile across the anomaly. A 2-D resistivity-depth model showed that the top surface of the anomaly is at a depth of about 2–5 km and that it has a width of some 100 km (Fig. 5). The anomalous body is highly conductive (bulk conductivity greater than 1 S/m) so that its base could not be defined due to the strong damping of the MT signals.

At the region where PACA is located, the surficial rocks within the belt show an increase in deformation and metamorphism. Considering the high conductivity of the structure, its observed geometry and surface rock exposures, Bologna et al. (2014) proposed that the most likely source of the anomaly is graphitized biogenic material in underthrust metasediments derived from a Neoproterozoic or Early Cambrian subduction zone in the Paraguay belt region.

The CB station is located exactly above the PACA (Fig. 5), and thus, the measured geomagnetic field at this station is expected to be significantly affected by the underground conductivity. Moreover, the declination of the geomagnetic field in this longitude sector is about N20W and is therefore oblique to the main direction of the conductor shown in Fig. 5. Induction effects are then expected to be felt in both horizontal components of the magnetic field. The southern extension and continuity of the conductor beneath the sediments of the Pantanal Basin can be hypothesized from the anomalous response at one site in the southwestern corner of the magnetometer array. However, lack of geophysical information from this area prevents further quantification and consequently evaluation of PACA effects on the PN geomagnetic observatory (see Fig. 5 for location).

Spectral analysis and discussion

It has been found that a great conductivity anomaly (PACA) lies under station CB where amplification of electromagnetic (EM) wave amplitude is observed for different frequencies. This huge conductive structure underneath the station causes localized abnormal induction currents that certainly play the major role in the anomalous ground geomagnetic variations measured in this region.

In order to quantify differences in amplification generated by the EEJ and by the internal induction effects, a spectral analysis was carried out on daytime-only and nighttime-only data from the 1994 campaign. To maximize both effects, the stations under the dip equator (PRM) and over the crustal conductor (CB) were chosen for comparison. Pre-conditioning was done to remove artificial power spikes from the time series, which was divided into segments of equal length for each day (10 h centered on midday and midnight for daytime and nighttime analysis, respectively), and a window function was applied to the ends of each data segment to reduce spectral leakage. Fourier transform was computed for each data window to obtain the raw power spectra, with the response of the different windows being smoothed at selected frequencies equally spaced on a logarithmic scale.

Figure 6 shows the power spectra of the horizontal components of both stations during nighttime and daytime. The lower amplitude of the magnetic signal in the EW direction (D-component) during both daytime and nighttime can be clearly seen in this figure. This results from the magnetic signal being linearly polarized along the magnetic meridian at equatorial latitudes. During nighttime, it is observed that the H-component power spectra are larger at CB than at PRM, with the power difference decreasing toward longer periods. This is related to the induction effects generated by the crustal conductor below CB. During daytime, it is observed that the H spectra at CB are larger than at PRM for periods shorter than 80 s. This can be explained by the amplitude enhancement at CB due to the crustal conductor and by the amplitude damping at PRM in the Pc3 pulsation range due to the Cowling conductivity of the EEJ (Sarma

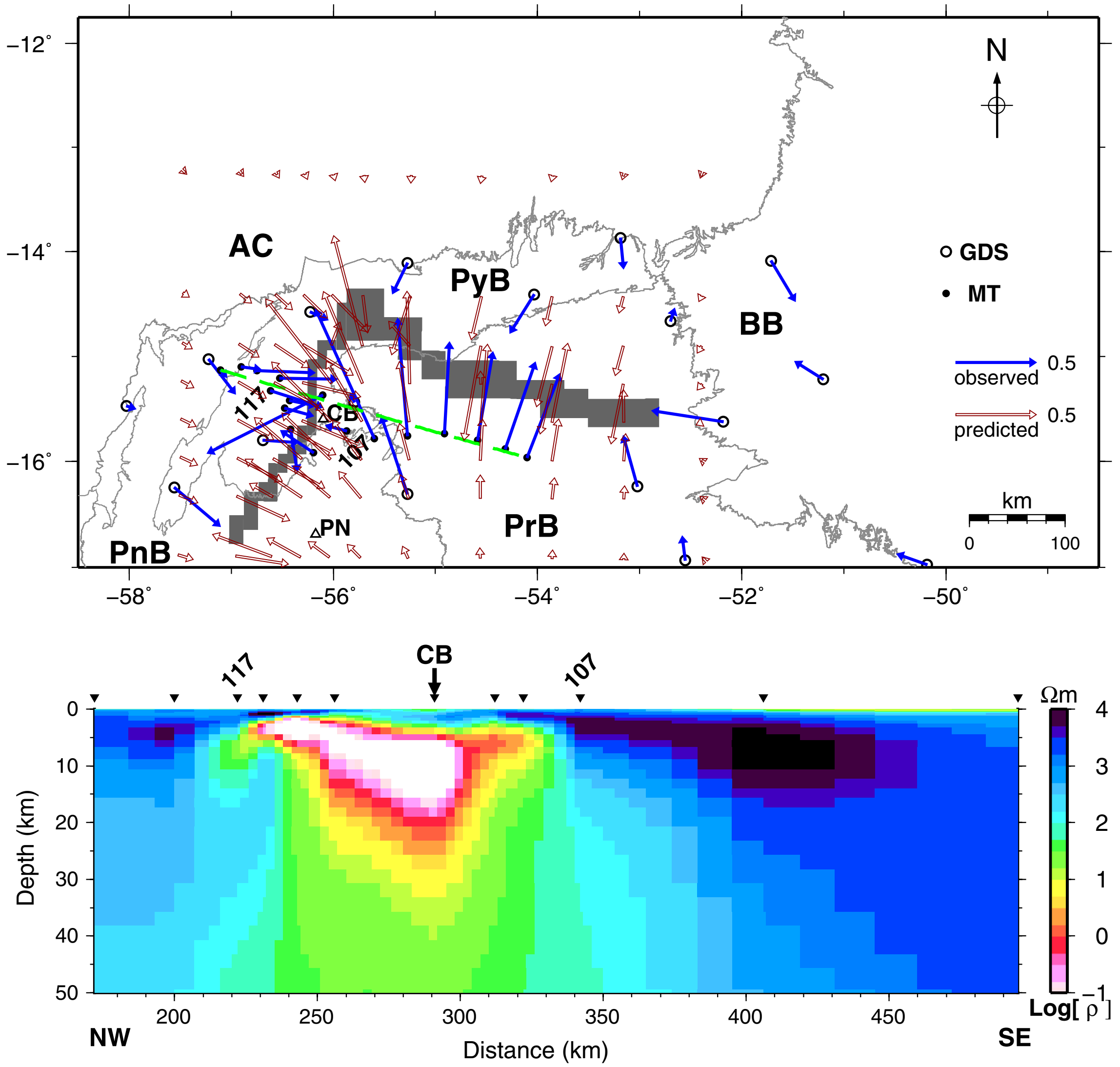

Fig. 5 Electromagnetic induction results from NW Brazil (Bologna et al. 2014). (*Top*) Observed and calculated real induction *arrows* for a period of 320 s, together with the PACA conductor at a depth of 20 km (*dark area*) as mapped by GDS modeling. *Green dashed line* is the location of the inverted MT profile. The main geologic structures are: Amazonian Craton (AC), Paraguay belt (PyB), Brasília belt (BB), Pantanal Basin (PnB) and Paraná basin (PrB). Location of geomagnetic stations (CB and PN) is also included. (*Bottom*) 2-D resistivity model across PACA obtained by inversion of MT data. Projection of the CB magnetic station on the MT profile is shown

and Sastry 1995). In periods longer than 80 s, amplification of the H-component by the EEJ prevails and the spectra are higher at PRM than at CB.

The Fourier coefficients obtained in the spectral analysis can be also used to derive magnetovariational transfer functions between the horizontal magnetic components of a local and a distant (reference) station. This method assumes that the magnetic field measured at a site is the sum of a normal and an anomalous field (Schmucker 1970). The normal field represents the sum of the external field and an induced field due to regional conductivity structure, whereas the anomalous field is due to local conductivity anomalies in which the normal field induces anomalous currents. Tensor transfer functions are established from an intercomponent period-dependent relationship. The diagonal elements of this tensor (commonly represented by Txx and Tyy) indicate the complex-valued spectral ratio in each component between the two stations. For uniform field sources and in the absence of local conductivity anomalies, the real components of the diagonal elements will be 1.0 for all periods. In case of difference in the electrical structure under the two stations, the diagonal elements will differ from 1.0.

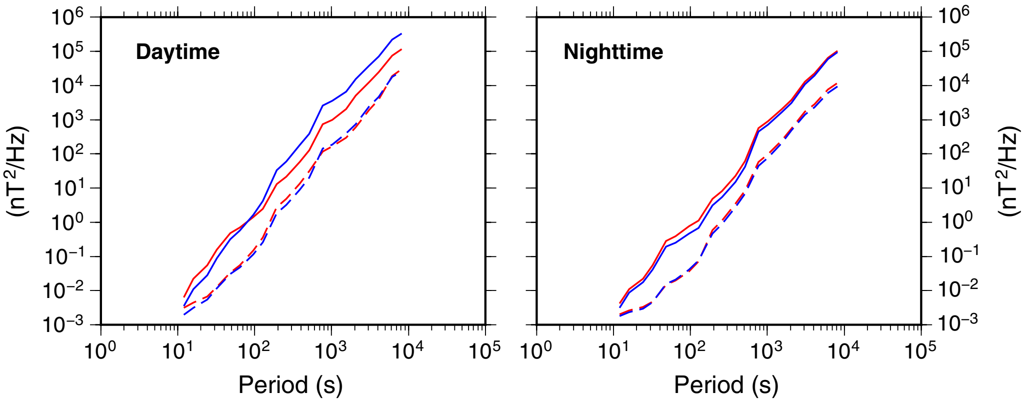

Fig. 6 Comparison of the power spectra of the *horizontal* components of the magnetic field at two stations during the 1994 experiment. *Red lines* for CB station, *blue lines* for PRM station. *Continuous lines* are H-component; *dashed lines* are D-component

In order to calculate the horizontal magnetic transfer function at CB, three criteria were observed: homogeneity of the source field, reference station sufficiently distant not to be contaminated by the crustal conductor and magnetic component with higher signal-to-noise ratio. Based on these criteria, nighttime data, PRM station as base and H-component (real part of Txx) were chosen to calculate the transfer function.

Figure 7 shows the variation of the Txx transfer function as a function of the signal period. Larger deviations in the shortest periods are probably caused by noise in the magnetic fields. Overall, the results are quite consistent when compared with the values previously derived from the individual events shown in Fig. 3 and Table 1. The individual Pc3 and Pc5 events have CB/PRM amplification of 1.38 and 1.59, respectively, while in Fig. 7 amplification factors of 1.36 and 1.50 are observed in the corresponding periods. In addition, the maximum amplitude of the transfer function is observed around 100 s, with a factor of 1.70. This can be compared to the results of magnetovariational studies in other important suture areas. For example, in the Trans-European Suture Zone (TESZ), a major tectonic boundary in central–eastern Europe, the main conducting body lies at depths of the order of 10 km and with highly conductive sediments at the surface (Ernst et al. 2008). In this case, the maximum response of the horizontal magnetic field is observed in periods of the order of 1000 s with amplitudes up to 1.8 (Habibian et al. 2010). The significantly lower period of the peak response at PACA may be associated with the shallow depth and lateral dimension of the conductor (top at 2–5 km depth and horizontal extension of about 100 km, according to the MT model of Fig. 5).

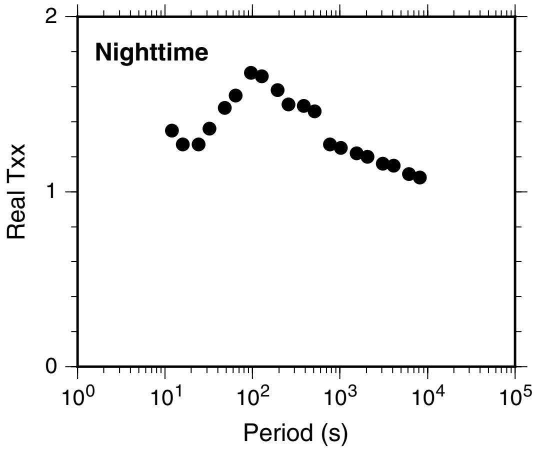

Fig. 7 Period dependence of the interstation transfer function between CB and the base station PRM. Results are shown for the real part of the nighttime H-component (Txx) transfer function

The magnification of the horizontal geomagnetic field amplitude observed at CB is broadly similar to that observed in other regional highly conductive structures throughout the world. Studies using magnetometer arrays to map lateral variations of conductivity in the crust and upper mantle have shown that large conducting anomalies induce anomalous magnetic fields that typically amplify the amplitude of the geomagnetic variations by some tens of percent (see, for example, discussion in Egbert 2002b, and references therein).

The PACA effects on the geomagnetic data can be explained within the framework of the classical electrodynamics theory (e.g., Jackson 1975). The magnetic fields recorded on the surface will be amplified because most of the energy transported by the downgoing incident EM wave will be reflected back at the interface with the very good conductor. The reflection coefficient (ratio of reflected to incident intensity) is very high in this case because just a small fraction of the energy is absorbed by the conductor. The situation approaches that of a perfect conductor, which develops a charge and current distribution on the surface so that external EM fields do not penetrate it.

Figure 7 shows that the amplification factor is frequency dependent. This result can be explained by the concept of skin effect. In the layers above the PACA, the EM field amplitude is attenuated as a function of the conductivity of the medium and the frequency of the signal so that low-frequency EM fields penetrate more deeply than high-frequency EM fields. Accordingly, a larger fraction of energy hits the interface with the conductor and is reflected at lower frequencies. On the other hand, as the frequency decreases the skin depth can become much larger than the lateral dimensions of the conductive anomaly. As a consequence, the presence of that anomaly does not affect magnetic fields. At these frequencies, the local induction disappears and galvanic anomalous field caused by charges only affecting electric fields becomes quasi-static (Berdichevsky and Dmitriev 2008). The balance between these two effects determines the amplification factor, which at PACA is maximum around 100 s.

Following Jankowski and Sucksdorff (1996), it is important that an observatory site be carefully chosen because its main function is to record short- and long-term variations of the geomagnetic field representative for a large area around this site. Before installing the PN observatory, standard procedures were followed to detect changes in the magnetic properties of the surrounding areas (Siqueira and Pinheiro 2015). These include a localized magnetic survey to detect strong magnetic gradients in the place where the absolute and variometer houses would be installed. However, no study on possible effects of induced currents was carried out.

With our available EM induction data, it is not possible to evaluate the continuity of the huge crustal conductor toward the Pantanal Basin. This information is crucial to verify the possibility that the chosen observatory site is affected by the PACA in the same way as the CB temporary station. Depending on the location of the conductor relative to the observatory, the H-, D- and/or Z-components can be severely affected by the anomaly and thus non-representative data of the regional geomagnetic field will be recorded. Moreover, our results show that the entire spectrum of magnetic pulsations is affected by the PACA induction effects, which can introduce several biases in the source characterization of these events (e.g., Arora et al. 2001). A localized MT survey is needed for a detailed mapping of the conductor around the current observatory site.

Summary and conclusions

In the present study, we report that a temporary station in the central–west region of Brazil presents anomalous amplifications in the H-component of the geomagnetic field recorded during two different periods of data analysis. At the same region, an integrated GDS and MT survey indicates that this station is located just over a strong 1200-km-long curved crustal conductor. The amplification characteristics of the geomagnetic variations by this conductivity anomaly are here explained on basis of two phenomena of classical electrodynamics: reflection of EM waves at the interface with a very good conductor and the damping of the EM wave amplitude by the skin effect during its propagation through a conductive medium. Possible extension of the conductivity anomaly to the south of our study area can cause significant effects in the geomagnetic variations to be recorded at the site chosen for installation of a new geomagnetic observatory in this region. We suggest that a detailed survey be carried out using deep-sounding EM methods to quantify the extent of the anomaly, allowing both to evaluate its possible effects in the geomagnetic field at the site chosen for the observatory and, in extreme case, to choose a new place for its installation.

Abbreviations

CME: coronal mass ejection; Dst: disturbance storm time index; EEJ: equatorial electrojet; EM: electromagnetic; GDS: geomagnetic depth soundings; IAGA: International Association of Geomagnetism and Aeronomy; IMF: interplanetary magnetic field; INTERMAGNET: INTErnational Real-time MAGnetic observatory NETwork (www.intermagnet.org); MT: magnetotellurics; SAMA: South Atlantic Magnetic Anomaly; SSC: storm sudden commencement; ULF: ultralow frequency.

Authors' contributions

ALP and LRA designed the study, interpreted the data and wrote the manuscript. GBDS and KVE analyzed the data and helped to improve the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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