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Tectonic insight into a pericratonic subcrustal lithosphere affected by anorogenic Cretaceous magmatism in central Brazil inferred from long-period Magnetotellurics

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Abstract

Long period magnetotelluric soundings are available in a 180-km long WSW–ENE profile across the Alto Paranaíba igneous province, a complex Cretaceous alkaline province situated mostly in the southern Neoproterozoic Brasília fold and thrust belt in central Brazil. The data indicate 3D complexity at upper and mid-crust and a simpler 2D regional structure at lower crustal and upper mantle depths. A 2D inversion emphasizing long period data identifies a highly resistive block at the uppermost mantle below the central part of the profile, surrounded by a rapid decrease in resistivity with depth. Resistivities at the block are typical of dry olivine under upper mantle conditions and a deep cratonic lithosphere is defined for this region. It is proposed that the resistive block is a rheologically enduring structure preserved within a southwestward extension of the pericratonic lithosphere of the Archean–Early Proterozoic São Francisco craton that lies beneath the nappes of the Brasília belt. Lower resistivities at shallower upper mantle depths beneath the Sanfranciscana basin at the northeastern end of the profile can be interpreted either as an increased conductivity within the lithosphere or as a localized thinned out lithosphere. The conductivity enhancement possibly arises from the addition of small amounts of water to mantle anhydrous minerals during previous metasomatic percolations.

Keywords: Magnetotellurics; Central Brazil; Archean craton; Cretaceous magmatism; metasomatism

1. Introduction

In central and southern Brazil, voluminous magmatism occurred from Early Cretaceous until Eocene times. It includes the extensive Early Cretaceous Paraná flood basalt province and a number of Early Cretaceous to Eocene mafic–ultramafic alkaline provinces that surround the large Paleozoic–Mesozoic Paraná basin [1]. All of this magmatism has been associated either with the thermal and/or chemical influence of proposed mantle plumes impacting into the base of the continental lithosphere [2–4] or restricted to lithospheric mantle sources without appreciable plume-derived materials [5,6].

The products of the intense alkaline magmatism are circumscribed into several distinct geographic provinces from which the most important is the Cretaceous Alto Paranaíba igneous province (APIP) in central Brazil. The province is situated in the southern portion of the Neoproterozoic Brasília fold and thrust belt and is

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bounded by the Paraná basin to the southwest and the Sanfranciscana basin lying over the Archean–Early Proterozoic São Francisco craton to the northeast (Fig. 1). The APIP magmas correspond to one of the volumetrically largest mafic–potassic provinces in the world and are composed of intrusions of kimberlites, lamproites, a large volume of kamafugites, and a number of carbonatite-bearing plutonic alkaline complexes [8].

Specific problems related to the tectonic evolution of this region have been addressed by several studies on geochronological, isotopic and petrological data from outcropping volcanics, metasediments and granites [3,9]. However, many geodynamic issues remain unsolved. These include the still controversial delimitation of the hidden western border of the São Francisco plate, the extent of lithosphere remobilization by the Brasiliano orogenies, the nature and physical state of the rocks underlying the thrust-sheets and cratonic cover units, and the search for either a deep lithospheric root that could explain the occurrence of Cretaceous kimberlites and lamproites, or traces of a root-erasing process linked to the upwelling mantle material accountable for the multi-compositional Cretaceous volcanic complexes. Suitable deep geophysical information, which could contribute to the solution of such problems, is scarce and only regional potential-field and localized seismographic analyses are presently available [10–13].

Complementing seismic-wave data, long period magnetotellurics (MT) has been shown to contribute relevant information on tectonic structures, processes and evolution of the upper mantle [14,15]. In the APIP region, the abundance and compositional variety of the volcanics, amply studied by petrology, geochemistry, geothermobarometry, trace-elements and isotopes, afford a rare opportunity to examine the full potential of the MT method to constrain geophysical properties of

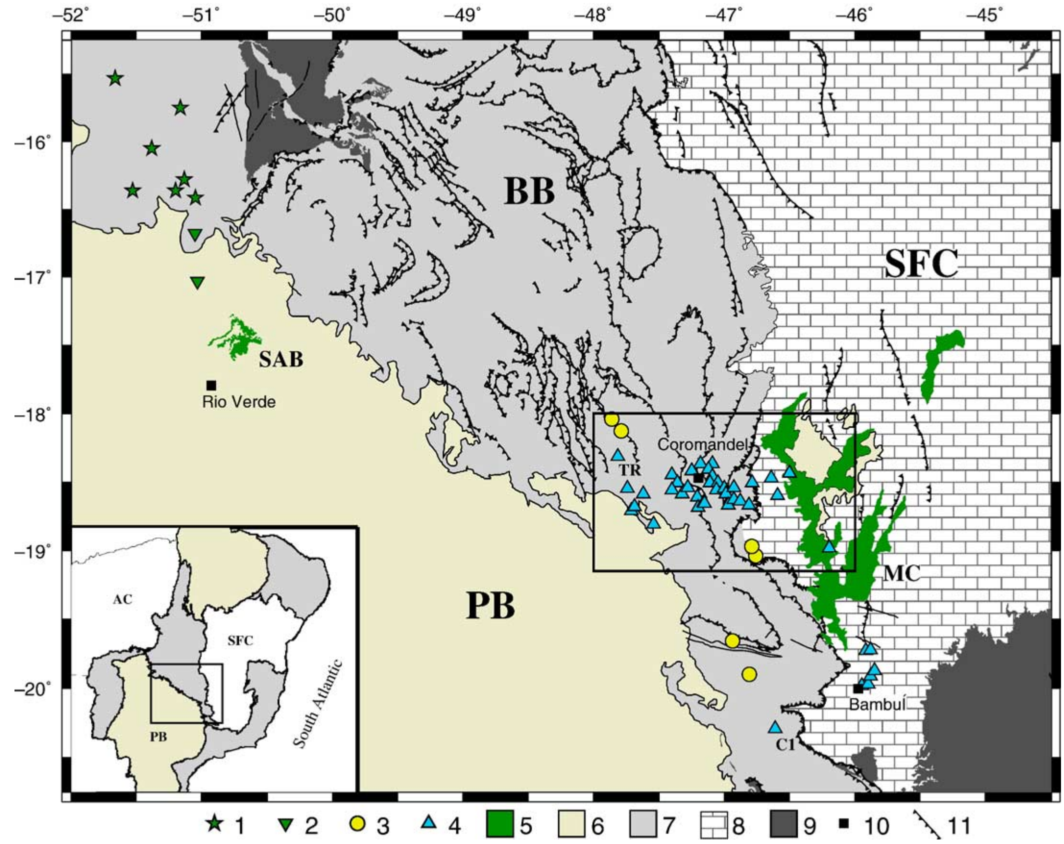

Fig. 1. Schematic outline of the main geological subdivisions in central-southeastern Brazil with the location of the Cretaceous alkaline volcanics (modified from [3,7]). 1—kamafugitic plutonic complexes (Iporá province); 2—kamafugitic diatremes (Iporá province); 3—carbonatitic complexes (APIP); 4—kimberlitic–lamproitic diatremes (APIP; TR—Três Ranchos, C1—Canastra); 5—kamafugitic lava flows (SAB—Santo Antonio da Barra (Iporá province), MC—Mata da Corda (APIP)); 6—Phanerozoic sedimentary basins (PB—Paraná basin); 7—Neoproterozoic belts (BB—Brasília belt); 8—Neoproterozoic sedimentary cover; 9—Archean–Paleoproterozoic basement; 10—major towns; 11—faults. SFC is the São Francisco craton and AC is the Amazonian craton. The square box delimits the study area shown in Fig. 2.

the mantle that are complementary to the geological information obtained by other means.

In this paper we describe the results of a deep MT study across the APIP, where data were acquired, analyzed and modeled using the most current equipment and techniques. As the method is particularly sensitive to the detection of any laterally connected conductive medium, and gives well constrained quantitative information about the depths to lithospheric transition zones, it completes locally restricted observations from the geochemical data. The final two-dimensional (2D) conductivity model provides a vertical image that yields relevant new information on the current geophysical state of the upper mantle under the study area, from which inferences can be drawn on different mantle processes and on an evolutionary tectonic scenario.

2. Geological context

The APIP is composed of ultra-potassic/potassic and ultramafic/mafic diatremes, lavas and hypabyssal intrusions, mainly kimberlites and madupitic olivine lamproites, and kamafugite–carbonatite rocks. Diatremes of kimberlitic and lamproitic affiliations are concentrated in the central region of the province (mainly around the town of Coromandel) whereas kamafugitic associations predominantly occur eastward, in the volcano–sedimentary rocks of the Mata da Corda group filling a rift-related half-graben (Fig. 2). The kimberlites are presumed to be derived from great depths in thick and cold ancient lithospheres, probably by partial melting of metasomatized upper mantle rocks. The kamafugites, however, are derived from much shallower depths in the mantle [4]. Large alkaline–carbonatite complexes occur to the northwest and southeast of the study area and are probably genetically linked to the kamafugitic magmatism [16].

The majority of radiometric ages for the magmatism cluster between 90 and 80 Ma [3], but the activity could have lingered longer, from 120 to 75 Ma [4]. U–Pb ages of perovskite of Mata da Corda (68–81 Ma) and Santo Antonio da Barra (88–90 Ma) kamafugites show that the westernmost pulse may be as much as 10 Ma older than the easternmost, indicating an eastward decrease in age of the kamafugite magmatism [17]. Also, Read et al. [18] point out that diamondiferous kimberlites with-

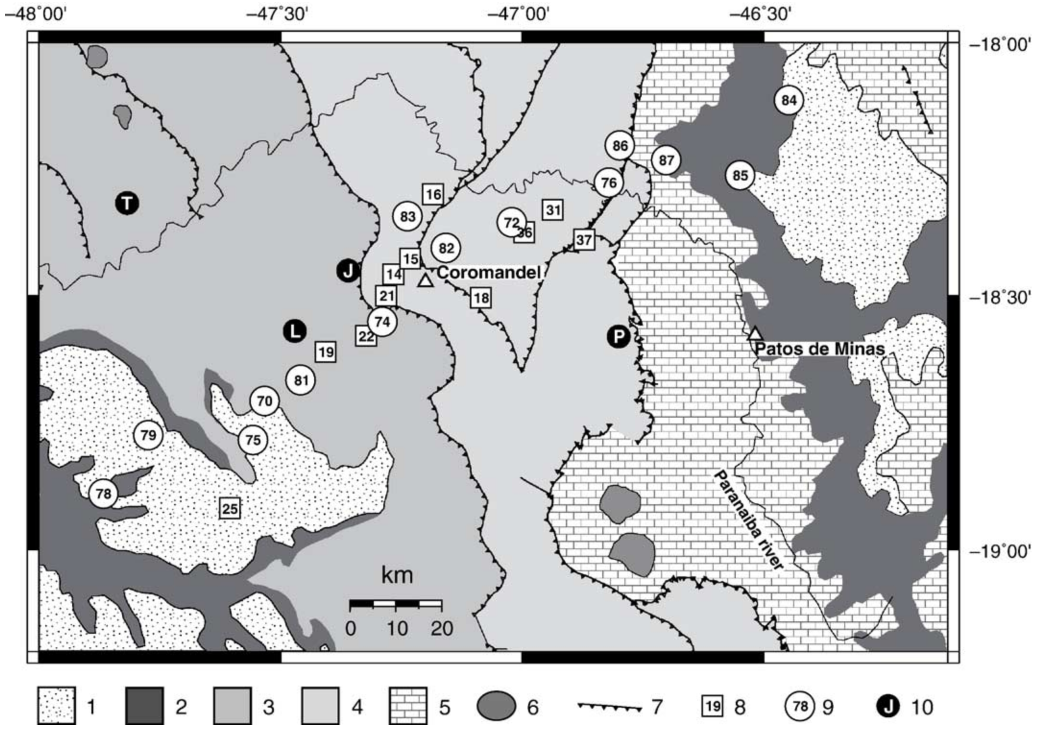

Fig. 2. Generalized geological map of the study area. 1—Cretaceous sedimentary cover; 2—Jurassic–Cretaceous volcanics; 3—Neoproterozoic Brasília belt (internal domain); 4—Neoproterozoic Brasília belt (external domain); 5—Neoproterozoic sedimentary cover of the São Francisco craton; 6—Cretaceous alkaline/carbonatite complexes; 7—thrust faults; 8—wide-band MT sites; 9—full MT sites (joint wide-band and long-period); 10—some Cretaceous diatremes of kimberlitic affinity (T—Três Ranchos; L—Limeira; J—Japecanga; P—Pântano). Open triangles denote major towns.

in the Brasília belt were dated at 95 Ma (Três Ranchos) and at 120 Ma (Canastra), an indication that the alkalic magmatism commenced with kimberlites (~120–89 Ma) and culminated with kamafugites (~90–68 Ma).

The São Francisco craton granite–greenstone terrain was stabilized in the mid–late Archean but was later affected in its western and eastern margins by the Brasiliano (0.8–0.5 Ga) tectonism. At the southwestern margin, where the APIP is situated, the craton is overlain by a thin-skinned fold and thrust belt of allochthonous to para-allochthonous units (Brasília belt). The belt is subdivided into three tectonic domains. From east to west they are: a cratonic domain comprised by Archean–Paleoproterozoic rocks of the São Francisco craton, locally covered by Neoproterozoic autochthonous to para-autochthonous pelitic–carbonatic rocks, an external domain composed mainly by thrust systems of predominantly thick passive margin metasedimentary successions of low-metamorphic grade, and an internal domain, formed by metamorphic nappes of intermediate to high-pressure metamorphic facies. The transition between the different domains is gradational, which makes the exact boundary of the craton at depth a matter of dispute [19].

3. Magnetotelluric data acquisition and processing

The MT method uses surface measurements of temporal fluctuations in the natural electromagnetic (EM) field to infer lateral and vertical variations of electrical resistivity of the Earth's interior. For this study, the EM components were recorded at 25 stations along a 180 km profile, in a WSW–ENE direction, crossing the cluster of diatremes in the central part of the APIP (Fig. 2). The eastern limit of the profile lies on the Cretaceous cover of the São Francisco craton (locally named Sanfranciscana basin), whereas the western limit falls on the Paraná basin. At each location, short period measurements, range of 0.0008–1024 s, were made using a single-station wide-band MT system (Metronix GMS05). At 14 of these sites, long period measurements, 20–13653 s, were made using remote-referenced long-period MT systems (Phoenix LRMT). A full description of the MT data acquisition and processing is given by Bologna et al. [20].

3.1. Geoelectric strike azimuths

The MT responses from each site were analyzed to correct for galvanic distortion effects caused by local near-surface inhomogeneities, define the dimensionality of the data, and determine the appropriate geoelectric strike direction, using the Groom–Bailey matrix decomposition technique [21]. The dataset for periods between 0.01 and 10,000 s was subdivided into six one-decade-wide bands. Data at periods shorter than 0.01 s were discarded because the decomposition model was inadequate for such periods (model of distortion fits the data with large mean chi-squared misfit). The best-fitting period independent twist and shear parameters and regional 2D strike were determined within each band.

The strike azimuths from single site decompositions are shown in Fig. 3. For the first bands the azimuths were derived from the 25 wide-band soundings, whereas for the last band they were derived mostly from the 14 long-period soundings. Strikes are not plotted for some of the sites affected by noise at periods longer than 10 s. The first two bands, grouping periods shorter than 1 s that correspond to signal penetration down into the upper crust, present geoelectric strike trending roughly E–W (or N–S because of the 90° ambiguity in the determination of the strike). Stronger site-to-site variation, especially in the shortest period band, is associated with complex upper crustal structure and noise in the measurements [20]. At longer periods, from 1 to 100 s (bands 3 and 4), the fields are sensing mainly the middle and lower crust. At the southwestern sites, the strikes are somewhat more diffuse, slightly rotated clockwise in relation to above. They are highly perturbed to the northeast of the Paranaíba river, around the surface limits of the Mata da Corda volcanics. These strong lateral variations are associated with differences in the extensive magma emplacement during the Cretaceous, that affects mid-crustal structures in different ways along the MT profile. These include the occurrence of an anisotropic layer in the central-western side and localized 3D effects close to the eastern end of the profile, related to the trend of extension for magma extrusion [20]. At periods longer than 100 s (bands 5 and 6), where the fields are probably sampling the upper mantle, the strike is more coherent than at short periods, giving a predominantly NW (or NE) direction.

This analysis indicates a very complex geoelectric section, consistent with a pericratonic lithosphere with sections affected differently during continental convergence and later modified by widespread anorogenic magmatism. To resolve the 90° ambiguity in strike determination, external information is required to distinguish between the two possible orthogonal directions at various depths. The E–W direction at upper crustal depths agrees with the main direction of the Brasiliano deformation in the area, involving the eastward trans-

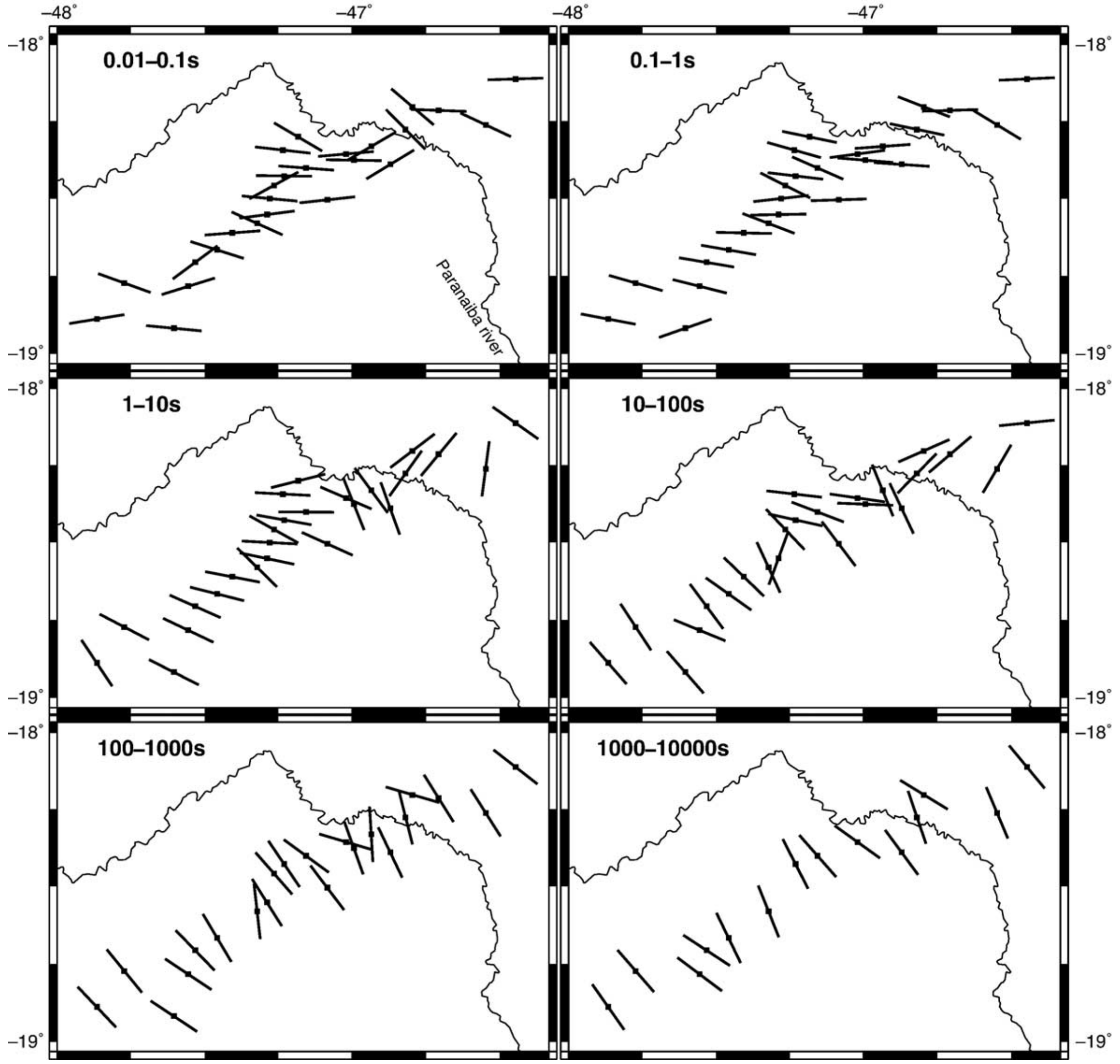

Fig. 3. Strike azimuths at each MT site derived from unconstrained Groom–Bailey decomposition for one-decade wide bandwidths from 0.01 to 10,000 s.

port of allochthonous overthrust sheets. In this way, the shallower E–W geoelectric strike can be ascribed to internal fabric that parallels the transport direction [20].

At greater depths, a NW strike is more consistent with the surface strike of the major terrane boundaries of the Brasília belt and between the belt and Paraná basin and São Francisco craton (Figs. 1 and 2). The strike azimuth for the deeper structures matches the NW trend for the fast polarization directions of S-wave splitting measurements in the realms of the southern bounds of the São Francisco craton [12]. Coincidental parallel geoelectric strikes at upper mantle depths and seismic anisotropy suggest related sources for both parameters, similar to what is observed elsewhere [22,23]. The preferred orientation of seismic waves has been interpreted to be parallel to the zone of collision between a cratonic block beneath the Paraná basin and the São Francisco craton, in the final stages of Gondwana amalgamation [12]. Thus, the coherent geoelectric strikes observed at upper mantle depths could be associated with a general alignment of olivine induced by a relic strain, possibly resulting from ancient continental collision processes.

3.2. Induction arrows

Another datum obtained in MT surveys is the magnetic transfer function response, which relates the vertical component of the magnetic field to the two horizontal components of each single-station. These quantities are often plotted in map view in the form of induction arrows, facilitating a qualitative areal assessment of the degree of conductivity variations in the subsurface. The directions of the reversed real component of the induction arrow are orthogonal to the local geoelectric strike and, for simple 2D structures, the arrows point towards more conductive regions.

Reversed real induction arrows are displayed in Fig. 4 for three period intervals that are affected mainly by lower crust and upper mantle structures (arrows for shorter periods are presented in [20]). They are derived from magnetic variations measured with fluxgate magnetometers (long period MT systems). Three sites for which the induction arrows are not well resolved have been omitted. Excepting for an anomaly at shorter periods located close to the Paranaíba river, possibly indicative of currents flowing in conducting 3D structures at mid-crustal depths, their magnitudes are very small (less than 0.1) suggesting that no meaningful regional vertical field is present for most of the area. At the two shortest period bands, the arrows generally point SW, i.e., parallel to the profile, giving additional confirmation of the NW geoelectric strike direction derived from tensor decomposition. At the longest periods, the small arrows point consistently to the SE, indicating a prominent regional structure in that direction. A recent magnetometer array study in central-southeast Brazil [24] showed that this effect is related to current concentration in conducting sea water (coast effect), located 600 km southeast of the MT profile, and to other regional features at large distances from the studied region. Such effects appear to be more significant for vertical transfer functions than for horizontal impedances [25]. Residual induction arrows, obtained after vector removal of the coast effect for these long periods, have very low amplitudes and do not show a preferential orientation, which are typical of 1D structures.

3.3. Apparent resistivity and phase responses

In a 2D Earth (where the structure is uniform in one direction), geoelectric strike direction is well defined, period independent, and parallel to the geologic strike. However, analysis of geoelectric strike variation along the MT profile shows a clear deviation from this picture. Apart from 3D distortions by near-surface heterogeneities, the dimensionality is variable in the allochthonous surficial terranes of the Brasília belt with a mid-crustal 2D anisotropic structure in the central-southwestern part of the profile and a large 3D induction anomaly to the northeast [20]. The compounded effect of these structures is that induction arrows may be widely deflected by the presence of anisotropy, which conceals the location and geometry of the high conductivity zone. Beneath this complex domain, the bulk of the autochthonous lithospheric rocks has a much simpler 2D signature with a NW strike.

In spite of the 3D complexity of the study area, only 2D interpretation is possible when data are acquired along a single profile. To minimize errors in the 2D models caused by 3D effects, only subsets of the MT data that are relatively robust under a 2D assumption are emphasized. As 3D distortions seem to be concentrated at upper and mid-crust depths, a possible approach is to consider two different period ranges to decompose the data, assuming different strike angles within each interval. Shallower and deeper sections can be then obtained from separated 2D inversions. A

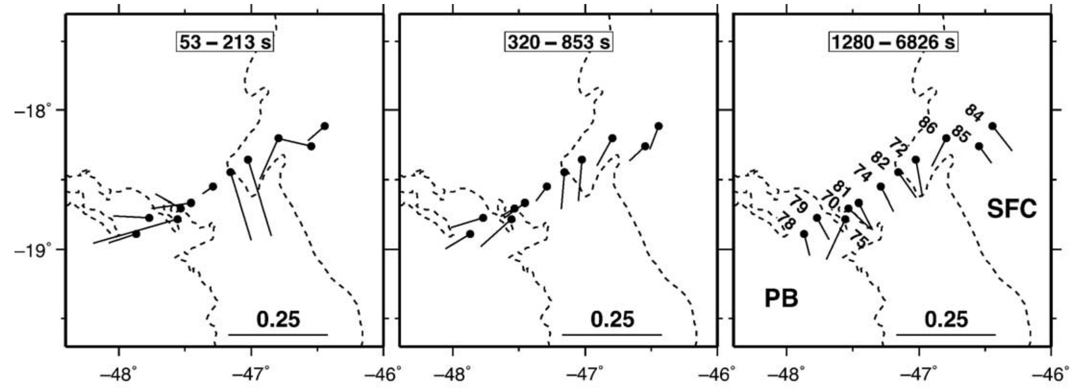

Fig. 4. Real induction arrows from single-station transfer functions for three period intervals. Arrows have been reversed to point towards induced internal currents. PB stands for Paraná basin and SFC for the São Francisco craton.

similar approach was previously used on MT data from the Southern Canadian Cordillera [26] and evaluated by theoretical studies on the limitations of 2D interpretations of 3D data [27]. In the APIP, the mid-crustal anisotropy acts on long period electric fields like a local scaterer, imposing static shifts on the long period electric fields [28]. A more detailed analysis was made for the large heterogeneity in the northeast end of the profile because, at the scale of the 3D body, induction distortion could be generated affecting seriously the long period responses. The decomposition model was fitted to the measured data period-by-period and site-by-site allowing a detailed scrutiny of the 3D character for that region [29]. It was observed that the 3D effect is restricted to some sites and at periods lower than 50 s, implying that the anomalous feature is relatively shallow. At longer periods and at sites to the northeast and southwest of the affected zone, the distortion effects become negligible so that the decomposition analysis can recover the 2D impedances.

The best-fitting average strike was derived by using the data from the entire profile at periods longer than 1 s, excluding those sites close to the Paranaíba river, clearly affected by the anomalous mid-crustal structure. The strike angle that best fits these sites over the selected period range is N45°W. To test the 2D characteristics of the impedance tensor, the seven-parameter Groom–Bailey distortion model, with the strike parameter fixed at N45°W and the twist and shear parameters frequency invariant, were fitted to the data of all stations. Excepting for periods shorter than 1 s and for some sites largely affected by the 3D crustal structure, the distortion models fit the data well, which implies that a 2D description of regional structures is a reasonable assumption. Data decomposition was extended up to 0.01 s to provide a reference for static shift estimates, but the results obtained from 2D inversion for the upper and middle crust are clearly not well-constrained.

For the 2D inversion, a careful site selection was required to minimize 3D effects. Selection criteria included good data quality, based on low error bars and minimal scatter of the MT responses, and reliable model of distortion. The ultimate nine selected sites present low model misfit and small shear and twist distortion parameters for long periods, an indication that the geoelectric structure fits well the 3D/2D approximation of the Groom–Bailey decomposition.

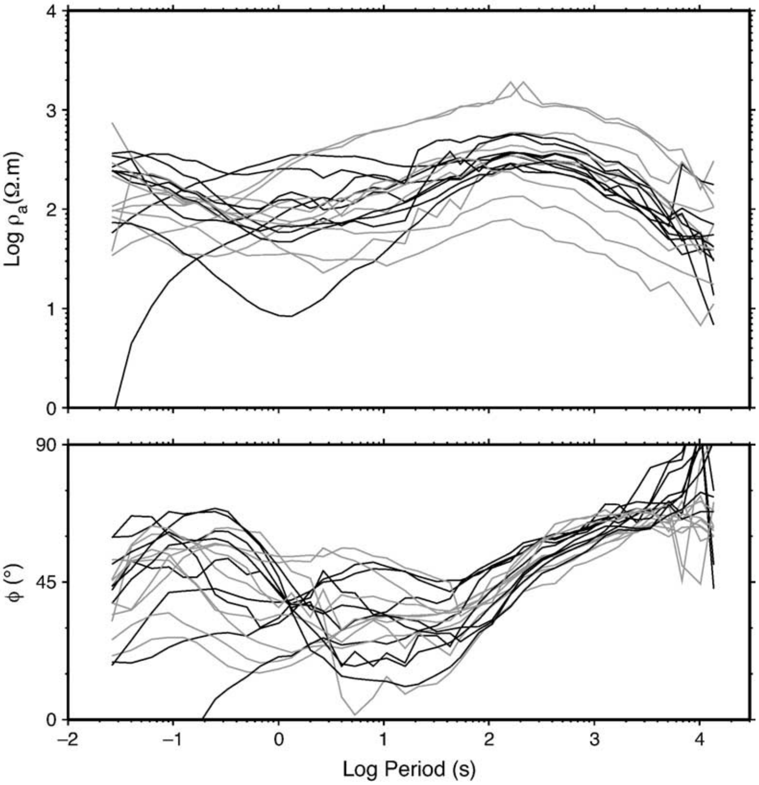

Fig. 5. Stacked apparent resistivity and phase curves (modes TE and TM in gray and black solid lines, respectively), from the nine sites chosen for the 2D modeling.

Stacked curves of apparent resistivity and phase data, corresponding to electromagnetic induction in orientation parallel and perpendicular to the strike direction, are shown in Fig. 5 for the sites chosen for modeling. For periods shorter than 100 s, there are significant differences between the soundings because of crustal heterogeneities. For periods longer than 100 s, the phase data of both TE and TM modes are very similar for all soundings, suggesting that the occurrence of electrical anisotropy is not a very pronounced effect in the upper mantle beneath this region of the Brazilian shield. The well defined 2D geoelectric strike in the NW direction at these periods can be then associated to a slightly enhanced conductive texture in that direction.

The absolute levels of the apparent resistivity curves at each site (static shifts) were estimated as part of the 2D inversion procedure. The used approach was to fit the phase data with a smaller error floor and to allow a larger misfit of the apparent resistivity data. A small phase misfit ensures that the modeled apparent resistivity curves present the same shape as the observed curves, yet allows a frequency-independent shift. The model then reflects the regional trends of the apparent resistivity data without distortions from local features caused by static shifts.

4. Two dimensional inversion

2D inversions were performed on the decomposed data by using an algorithm that seeks to estimate static shifts and to generate a smooth model simultaneously [30]. At the nine selected sites, data were taken at twelve periods between 0.01 and 10,000 s, equally spaced in logarithm scale, in both polarization modes (TE and TM, with currents parallel and perpendicular to the electrical strike, respectively). The choice for joint inversion of both modes was based on theoretical studies showing that this approach gives better estimates of deeper 2D structures under localized 3D anomalies [27]. The induction arrows have not been interpreted jointly with the MT responses because some sites have large errors, long periods seem affected by coast effect and distant structures, and theoretical studies have shown that arrows are severely affected when anisotropic structures are present [31]. To account for static shift effects, the inversions used error floors of 2° in the phases and 24% in the apparent resistivities. The starting models were either uniform half-spaces or a layered half-space determined from 1D inversion of the geometric mean of each site.

The final 2D resistivity model is shown in Fig. 6 and has an overall RMS misfit of 1.65 related to the as-

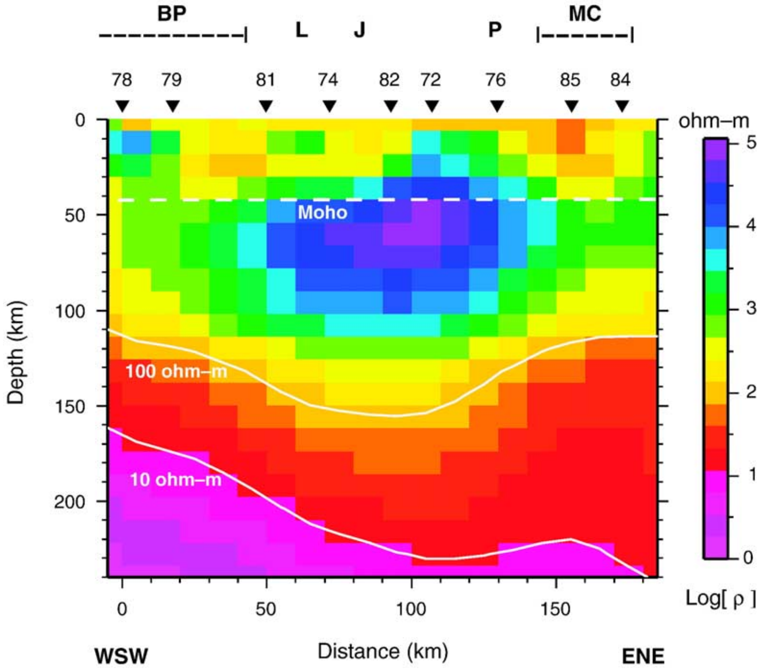

Fig. 6. 2D resistivity cross-section obtained by inversion of TE and TM modes distortion-decomposed apparent resistivity and phase data of selected stations along the APIP profile. BP and MC are the locations of the Paraná basin and the Mata da Corda volcanics, respectively; L, J and P are projections on the profile of some kimberlitic pipes (see Fig. 2 for details). Dashed white line represents crustal thickness (Moho) based on seismic data [32]. Deep contours of 10 and 100 Ω m are also shown as continuous white lines.

sumed error floor. Comparisons between the data and model responses are shown in Fig. 7 for the apparent resistivities and phases of the nine selected sites. There are good agreements between the calculated and observed data, with the largest misfits in phases being observed in the TM-mode at sites 76 and 85, the ones

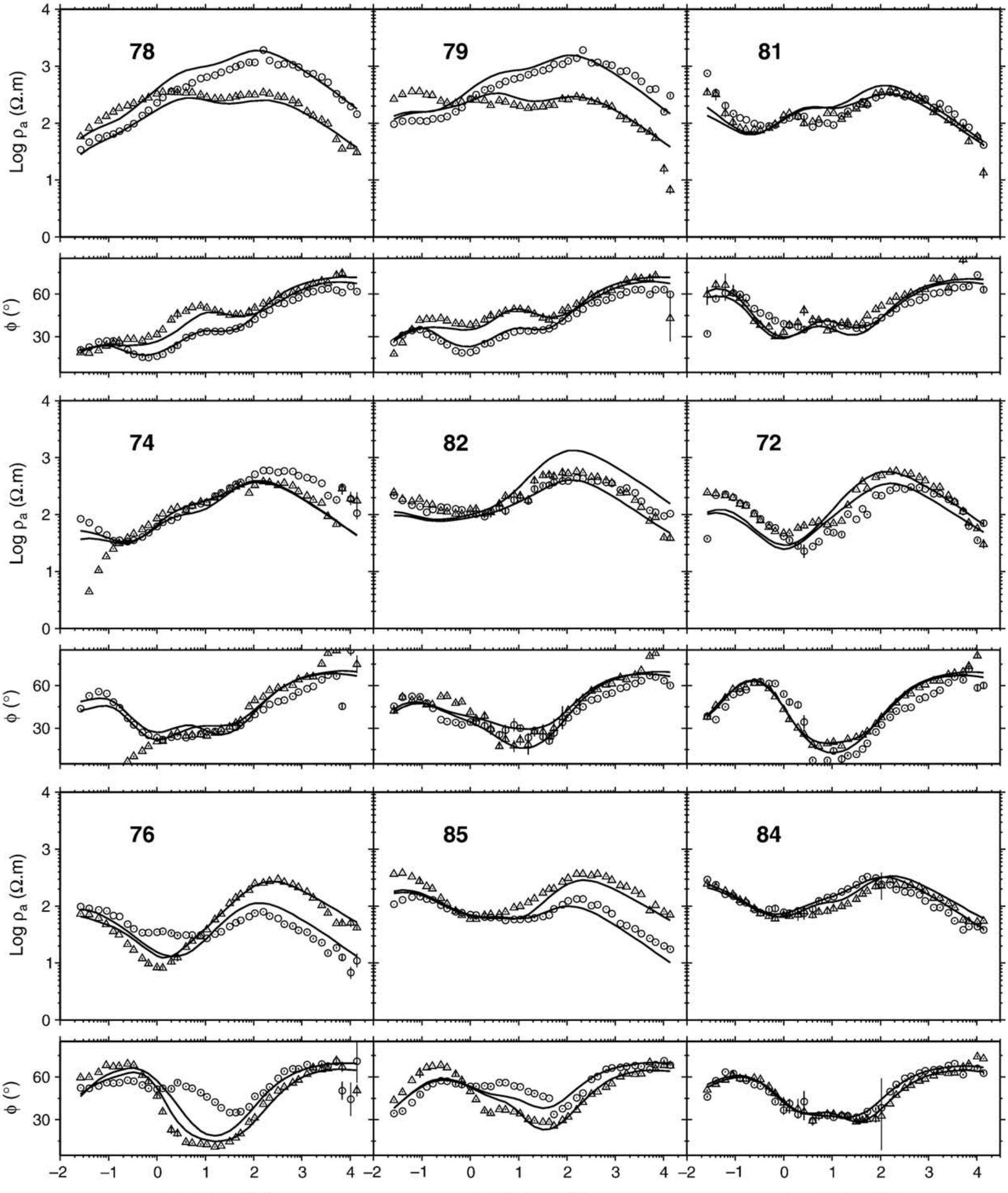

Fig. 7. Calculated apparent resistivity and phase (lines) from the best-fit model of Fig. 6. The observed responses used for the inversion are shown together, where circles are TM mode and triangles are TE mode. Error bars represent one standard deviation.

most affected by the mid-crustal anomaly. This can be explained by considering that the TM-mode has a higher sensitivity to electrical charges concentrated at the boundaries of a conductive structure.

The robustness of the model was tested for different inversions, by adding and removing sites, changing the inversion parameters and using different inversion codes. Also, the upper crustal structure derived from inversion of short period data with the E–W strike [20] was fixed and long period data (1–10,000s) were used to resolve lower crust and upper mantle structure. Very similar results were obtained, with the main features presented in Fig. 6 being required to fit the data.

The most salient feature of the 2D model is the presence of a very high resistivity region at depths up to 120 km below the central part of the profile, surrounded by a rapid decrease of resistivity with depth. In order to determine the degree under which this result is required by the data, forward responses were calculated with and without the resistive feature and also considering its extension along the whole profile. Sensitivity tests showed that the high resistivity structure is required by the low phase values at periods around 10 s in the center sites (especially the TM mode at site 72). A possible extension of this highly resistive feature at upper mantle depths beneath the Mata da Corda volcanics is not supported by phase and apparent resistivity data at site 84. Other tests indicated that resistivities of at least 10,000 Ω m are necessary to occur within the modeled block because of the low phase values at periods around 10 s in the central stations. However, the depth to the top of the block is not well constrained due to the uncertain resistivity of upper crustal layers.

5. Craton extent and conductivity mechanisms

The model identifies a highly resistive block (values around 10,000 Ω m) at lower crust/upper mantle depths below the central part of the profile. It is located beneath the outcrops of the Brasília belt, limited by the border of the Paraná basin to the SW (between sites 79 and 81) and the border of the Sanfranciscana basin to the NE (between sites 76 and 85). Surrounding this resistive deep keel, the upper mantle resistivity rapidly decreases with depth in an almost step-like fashion.

Firstly, it was considered whether the resistive block could be related to the presence of ancient continental and possibly oceanic fragments caught up in the Brasília belt during the convergence of colliding continents, as suggested by other studies [4,33]. However, it is unlikely that a large, geoelectrically homogeneous and highly resistive structure could be generated and buried deep into the lithospheric mantle of an area predominantly dominated by thin-skinned tectonics. In a more likely explanation, the study area is proposed to be located over deep autochthonous rocks of the São Francisco craton, extending much more to the west than inferred by surface geology and underlying the Neoproterozoic imbricated nappes of the Brasília belt. In this case, the Brasiliano tectonic effects were confined within the brittle upper and intermediate crust. The higher conductivity beneath the Sanfranciscana basin reflects a transient, localized major change in geothermal conditions of the deep lithospheric mantle during the Cretaceous, at the onset of the kamafugite magmatism [18].

The resistivity values for the lower crust are consistent with laboratory studies on silicic dry rocks at temperature appropriate for the depths involved [34], with lateral variations probably due to petrologic composition variations associated with tectonic processes. For the uppermost mantle, the resistivity of the resistive keel, up to 120 km, agrees with laboratory measurements of dry olivine under upper mantle conditions, which predict not only a resistive mantle but also a mantle with no significant anisotropy [35,36].

A resistivity decrease towards greater depths is in agreement with thermally activated solid-state conduction in upper mantle minerals. In this way, MT can be applied as a proxy to estimate the depth to the seismic lithosphere–asthenosphere boundary (LAB). In this case, the LAB is mapped at a strong decrease in electrical resistivity of around two orders of magnitude, possibly related to the onset of partial melt, also accountable for the asthenospheric low seismic velocity. A possible manner of interpreting a geoelectric LAB in a resistivity-depth section is to define a resistivity value as the transition between a mantle–layer supposedly with partial melt (lower resistivities) subjacent to one without partial melt (higher resistivities). Typical values used in the literature to identify the transition are 100 Ω m [37] or 10 Ω m [38]. Both contours are shown in the 2D resistivity model presented in Fig. 6.

The 100 Ω m contour clearly shows the deeper keel beneath the central part of the profile. Resistivities of 100 Ω m are observed at depths of about 110 km under Paraná and Sanfranciscana basins and of about 150 km under the resistive central region. Due to static shift effects, these depths are better constrained under both basins than under the Brasília belt, but larger depths beneath the central region are assured. Small amounts of disconnected melts can decrease the resistivity to values around 100 Ω m at depths of 100 to 150 km [39]. Also, the temperature of crystallization of the

Mata da Corda kamafugites [8] and the thermobarometry of the Três Ranchos intrusion [40] imply the occurrence of contrasting paleogeotherms between the colder keels from where kimberlites and lamproites originated and the warmer adjacent regions where kamafugites and carbonatites occur. However, most of the enhanced temperature would probably have subsided through heat dissipation since the Cretaceous events, resulting in a significant decrease of the present thermal contrast. In fact, a large temperature difference (more than 200 °C) is not expected to have persisted up to the present day at shallow upper mantle depths, for horizontal distances of 50–60 km. Seismic tomography indicated low velocities at lithospheric depths in the southern part of the APIP, centered in the carbonatite complexes of Araxá and Tapira [41]. This MT profile is located in the central part of the APIP, outside the limits of the seismic anomaly, where high velocity of seismic waves is observed. Relatively low heat flow [42] at the region of the MT profile also gives low priority to this possibility and indicates that the transition from more resistive to more conductive values at depths between 100 and 150 km is too shallow to be attributed to a LAB.

Depths to the 10 Ω m contour in the 2D resistivity model are around 160–180 km under the Paraná basin and at more than 200 km under the central and northeastern part of the profile, suggesting a lithospheric deepening towards the interior of the craton. Apart from larger static shift effects beneath the central part of the profile, the geometry of this boundary is also poorly constrained at depths larger than 200 km because it is sensed by the longest periods available in the MT responses. Other geophysical information for this region register fast seismic velocities down to 200–250 km under the southern part of the São Francisco craton [41] and to 150–180 km under the eastern Paraná basin [43]. Also, typical paleogeotherms at the time of kimberlitic eruption in the APIP [18,40] closely approximate a 37–40 mW/m^2 heat flow model for steady-state conductive lithosphere, similar to the geotherms observed in other Archean cratons [44]. Using geotherms determined both from thermobarometric data on xenoliths and from surface heat flow in typical Archean settings, temperatures in the range of 1250–1300 °C (typical for a LAB) would be expected at depths between 200–250 km [45]. All these results support the notion that the thicknesses derived from the 10 Ω m contour are probably more adequate to represent the LAB in the APIP region.

The inference of lithospheric thicknesses is extremely sensitive to the choice of the contour value at the northeastern border of the profile, where slight changes in resistivity produce significantly large changes in LAB depths. This variation can be interpreted either as an increased conductivity within the lithosphere or as a localized decrease in lithosphere thickness. Different mechanisms can be proposed to explain conductivity enhancement at upper mantle depths, including the presence of fluids, conductive minerals (graphite, sulfides) or diffusion of hydrogen [46]. Some of them can be ruled out in the study area. The age of the last tectonothermal event (Late Cretaceous) excludes the possibility of fluids as the main cause of the low resistivities and there is no evidence for sulfides in mantle xenoliths from the APIP [40]. Hydrous mantle minerals, such as phlogopite, are very common in xenoliths from the APIP [47] and have been suggested to enhance mantle conductivity [14]. However, this possibility must be regarded with caution because the conductivity of such rocks has not been measured at appropriate conditions in laboratory and MT soundings at another region with extensive mantle metasomatism showed high resistivities [48]. Widespread carbonatite-bearing intrusions in the APIP indicate that carbon, in the form of graphite, could be important to enhance conductivity in the upper mantle. This mechanism could be dominant only at upper mantle shallower depths on both sides of the profile because at the base of the lithosphere, below the graphite–diamond stability field, it would generate a resistivity increase [46]. However, oxygen fugacity determined from deep xenoliths shows an increase of log fO_2 after the Cretaceous thermal event from FMQ to FMQ+2 and FMQ+3, without a clearly defined depth pattern [47]. Nevertheless, the ubiquitous metasomatism represents oxidation conditions too high for the graphite stability. At greater depths, our preferred explanation is the diffusion of hydrogen resulting from the addition of small amounts of water in the olivine crystal lattice [49]. This process provides an effective method of increasing mantle conductivity to the values observed in the APIP and due to its temperature dependence can also explain the gradual conductivity enhancement with depth. It must be considered however that the influence of hydrogen diffusion in olivine is significantly mitigated if the mantle is found to be isotropic [50].

6. Cretaceous magmatism and evolutionary model

There is a striking spatial correlation of the upper mantle conductivity with the mafic–potassic magmatism. Rocks of kamafugitic affinities tend to occur in regions coincidental with the enhanced conductivity at shallower upper mantle depths, whereas the ones of kimberlitic and lamproitic associations occur in regions with a deep resistive keel. Adjacent regions beneath carbonatites could also be underlain by anomalous conductivity because of the close mantle source association between carbonatites and kamafugites [16]. As already discussed, this picture also correlates with contrasting Cretaceous geotherms between the cool (resistive) central region and the warm (conductive) lateral regions, but temperature differences are not expected to exert significant control on present day conductivity distribution at upper mantle depths beneath the APIP.

Detailed variations in the chemical properties of kamafugites, lamproites and kimberlites from the APIP led different studies to suggest heterogeneities in the melt source regions of these rocks (e.g., [3,51]). The considerable lithospheric thickness derived from this study and isotopic characteristics of the volcanics [5] pose serious constraints for a lithospheric mantle source for all these magmas, with the diversity of composition reflecting the heterogeneity of the lithosphere. High CaO and Sc of the kamafugites have been interpreted as indicative of a clinopyroxene-rich mantle source at relatively low pressures (less than 25 kbars, [3]), whereas high-pressure assemblages in xenoliths from the Três Ranchos pipe suggests a much deeper (more than 150 km, [40,47]) clinopyroxene-depleted source for this kimberlite. These results support a model in which the systematic lateral variations in geochemistry and rock types are taken as indicative of vertical geochemical heterogeneities associated with different depths of melting in the sub-continental lithospheric mantle [4]. On the contrary, the observed enduring thick lithosphere does not favor the model of a Mesozoic mantle plume acting as the main source of the magmatism. If the alleged Trindade or Tristan da Cunha plumes had any role in the APIP volcanism it would not supply magma, but only heat to trigger the magmatic activity [2,17].

Dry olivine-dominated rheologies are known to remain strong enough and sufficiently buoyant, because of their depleted nature, to survive through immense time intervals [52]. Beneath the APIP, the cold, refractory (volatile-poor) and electrically resistive cratonic lithosphere, was apparently the least affected by the Cretaceous events. However, in the region beneath the Mata da Corda kamafugites, geochemical and petrological data suggest a major change in the composition and thermal structure of the lithosphere.

A temporal evolutionary model for the southwestern São Francisco pericraton, proposed by Read et al. [18], reconciles the observation of the present-day occurrence of an external on-craton setting (deep resistive root) and an internal off-craton setting (conductive inverted wedge). Following their model, the Três Ranchos and Canastra kimberlites provide evidence of the earliest conditions of the São Francisco pericratonic mantle. The lithosphere below the entire western craton was colder, drier and thicker up to the Early Cretaceous, and later evolution probably led to localized lithospheric thinning and to warmer geothermal regimes below the Sanfranciscana basin in the Late Cretaceous. In this case, the western São Francisco craton would be much like other cratonic areas with documented thermal erosion of the lithosphere, e.g. the Wyoming province, the Colorado plateau, the East Sino-Korean craton and the Kaapvaal craton [53].

As previously discussed, the MT data do not discern between an increased conductivity within the lithosphere or a localized decrease in the lithosphere thickness beneath the Sanfranciscana basin. Even though the suggested delamination of up to 75 km of the lithospheric section, at the onset of the voluminous Mata da Corda kamafugite magmatism [18], does not conflict with the MT data, constraints from heat flow and seismic velocities point towards a non-thermal origin for the present day conductivity distribution in this region. It can be speculated that a delaminated ancient lithosphere was replaced by a more fertile, volatile-rich sublithospheric mantle material. Since water oozes from the olivine into the melt, the ensuing dehydration would likely produce a resistive deep mantle and a conductive lithosphere above it.

7. Summary and conclusions

The 2D model for the lithospheric mantle indicates a resistive deep keel (depths larger than 150 km) underneath the center of the APIP, encompassed by more conductive mantle material below depths of about 100 km. Such results are consistent with geochemical data, which indicate that the mafic–potassic intrusions were generated from heterogeneous sources at distinct depths in the lithospheric upper mantle, and suggest that relict heterogeneities was already present by the time of the Cretaceous magmatic events. The highly resistive block is tentatively interpreted as a lateral extension of the São Francisco craton under the younger thin-skinned tectonics of the Brasília belt, locally affected by a major thermal event beneath the Sanfranciscana basin.

The São Francisco pericratonic domain extends, therefore, further southwest from the limits indicated by the surface geology. This interpretation agrees with the spatial distribution of alluvial diamonds and the occurrence of diamondiferous kimberlites in Três Ranchos and Canastra pipes, located over 100 km to the west of the outcropping Archean–Early Proterozoic rocks of the São Francisco craton, as also suggested by other studies [3,4,18,40]. The presence of diamonds in the Early Cretaceous kimberlites indicates that the mantle beneath part of the APIP was sufficiently thick and cold to maintain the diamonds in stable equilibrium at that time and the detection of a present-day deep resistive keel beneath the Brasília belt indicates that this region was not extensively overprinted by the Late Cretaceous tectonothermal events. The occurrence of a thick lithosphere, inferred from MT modeling, and of diamondiferous kimberlites also support the concept of a non-plume source for the generation of the Cretaceous magmatism.

Enhanced conductivity and interpretation of geochemical and petrological data [18] concur with a cratonic mantle root beneath the Sanfranciscana basin locally removed by Late Cretaceous tectonothermal events. However, geophysical constraints impose a non-thermal origin for the significant conductivity increase at upper mantle depths in this region, which favor a model of mechanical decompression for the melt-generating processes. Hydrogen dissolved in olivine, probably during the extensive mantle metasomatism in the APIP region, is more likely than other mechanisms to explain these results, although this interpretation is not unique.

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