Paleomagnetism of the Penatecaua magmatism: The CAMP intrusive rocks in the Amazonas Basin, northern Brazil

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A R T I C L E I N F O

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A B S T R A C T

The Penatecaua magmatism (~201 Ma) is part of the Central Atlantic Magmatic Province (CAMP) and is represented by voluminous sills in the Amazonas Basin, north Brazil. The sills appear south of the Amazonas River, particularly in the Medicilândia, Placas, and Rurópolis cities. To the north of the river, near Monte Alegre and Alenquer, smaller sills and NNE-SSW dikes prevail. Paleomagnetic data from 28 sampling sites of sills and dikes from all areas gave consistent results of normal polarity. Despite the large area of occurrence, the VGPs show small dispersion, consistent with a very brief emplacement time, as indicated by the radiometric ages. However, some sites, mainly from Alenquer and the southern sills, gave anomalous directions that may represent the record of a transitional geomagnetic field. The calculated paleomagnetic pole includes former data from Guerreiro and Schult (1986) plotting at 260.1°E 77.5°S ($N = 30$; $A_{95} = 3.8°$; $k = 48$) and agrees with other high-quality CAMP poles for South America.

1. Introduction

The Central Atlantic Magmatic Province (CAMP; Marzoli et al., 1999) corresponds to the extensive magmatism that affected all the Atlantic bordering continents and that once formed the Pangea supercontinent: North America, Europe, Africa, and South America (Fig. 1a). It may represent the culmination of a long rifting process (Lamotte et al., 2015). The CAMP rocks are recognized by their chemical composition and occurred briefly around the Triassic-Jurassic limit (~201 Ma; Blackburn et al., 2013; Davies et al., 2017, 2021). CAMP probably occupies an area exceeding 10^7 km^2, where at least 3 million km^3 of magma have accumulated as flows, sills, and dikes that may reach 800 km long. An example is the Messejana dike (Schermerhorn et al., 1978) that cuts Portugal and Spain for 500 km in a NE direction. May (1971) was the first to propose that the dike swarms around the North Atlantic resulted from the same tectonic event.

Ernst (2014) and Marzoli et al. (2018) describe CAMP as a peculiar igneous province as it shows no alkaline rocks and acidic types are rare, unlike other large igneous provinces (e.g., Paraná-Etendeka, Deccan, and others). The authors also pointed out that the CAMP basalts do not carry evidence for the involvement of a deep mantle plume. Its origin is related to the upper mantle enriched with incompatible elements and volatiles due to subduction events during the Proterozoic or Paleozoic (Merle et al., 2011; Callegaro et al., 2013). However, it is still unclear which mechanism generated the necessary heat source for magmatism of such proportions in a brief time interval.

In South America, the CAMP rocks are recognized in several countries, French Guyana (Nomade et al., 2000), Guyana (Deckart et al., 2005), Bolivia (Bertrand et al., 2014), and perhaps Venezuela (MacDonald and Opdyke, 1974). In Brazil, CAMP magmatism occurs mainly in the form of dikes and sills in the northern states (Lima and Bezerra, 1991; Marzoli et al., 1999; De Min et al., 2003; Ernesto et al., 2003; Merle et al., 2011; Silva et al., 2017; Pinto et al., 2017), and rare flows as the Lavras da Mangabeira (De Min et al., 2003; Ernesto et al., 2003), Anari and Tapirapuã (De Min et al., 2003; Montes-Lauar et al., 1994), and Taiano (Roraima; De Min et al., 2003; Pinto et al., 2017). In the Amazonas Basin (Fig. 1b), voluminous sills of the Penatecaua Formation (Costa et al., 2012; Davies et al., 2017) crop out south of the Amazonas

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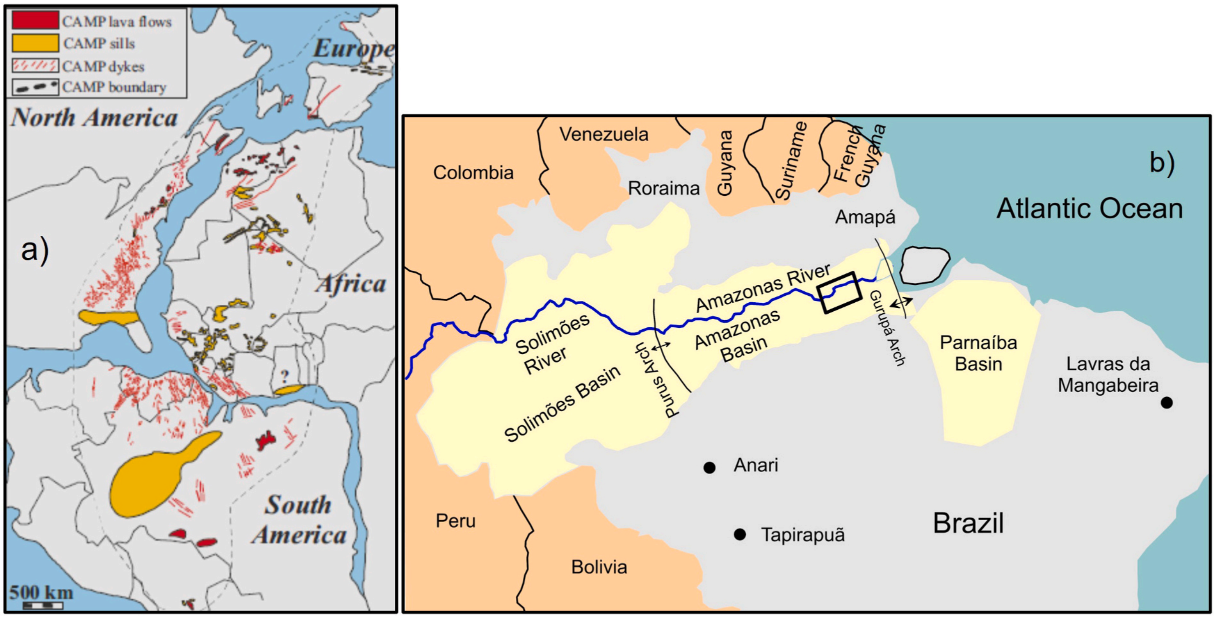


Fig. 1. a) Reconstruction of the Pangea supercontinent showing the emplacement of the CAMP magmatism (modified from Marzoli et al., 2018); b) location of Amazonas and Solimões basins in northern South America and other reference places where CAMP rocks were already studied. The rectangle indicates the study area.

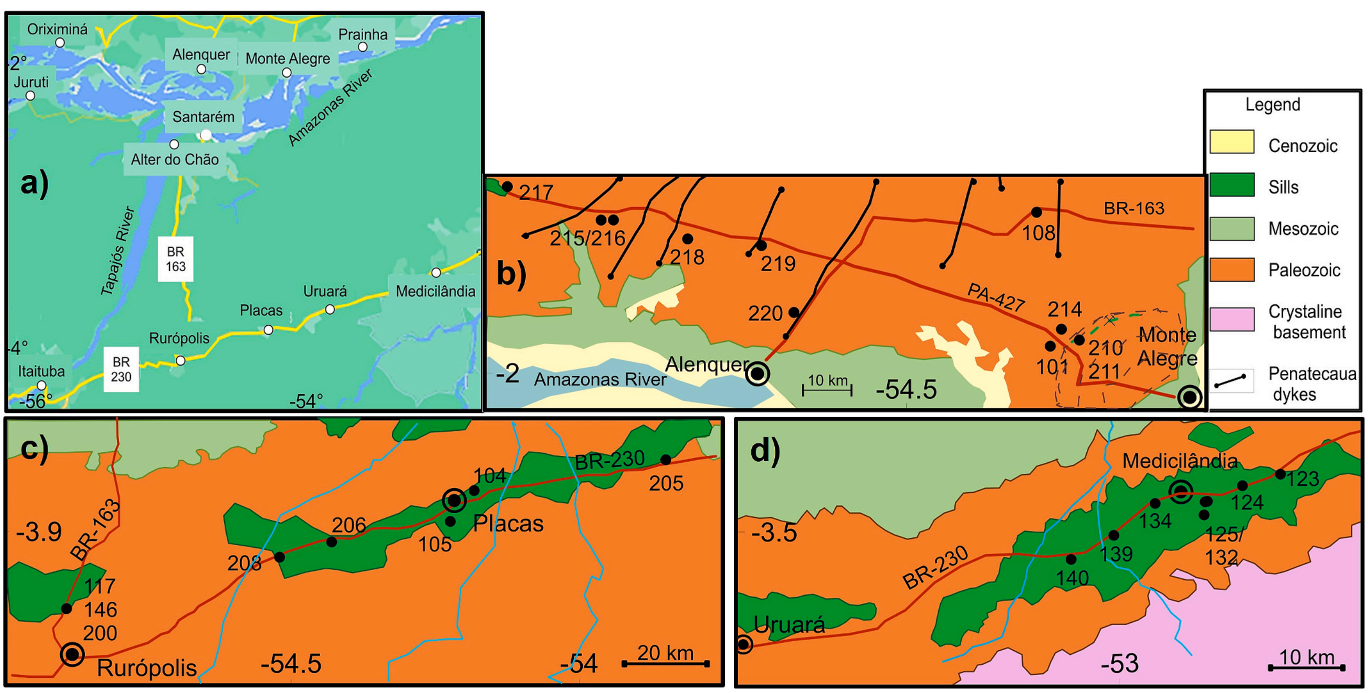


Fig. 2. a) General view of the investigated area. (b to d) Sketch geological maps based and sampling sites in the northern and southern areas. Geology is based on Faria et al. (2004) and Ferreira et al. (2004).

River and, to a lesser extent, in the north area, where dikes are the dominant mode of rock emplacement (Faria et al., 2004).

Previous paleomagnetic work on the South American CAMP rocks gave consistent paleomagnetic poles, which are related to the Mosquito flows and sills (Schult and Guerreiro, 1979; Ernesto et al., 2003) in the Parnaíba Basin and the Cassiporé and Roraima dykes (De Min et al., 2003; Ernesto et al., 2003), the French Guiana dikes (Nomade et al., 2000) and the Bolivar dykes and Guacamayas Group (MacDonald and Opdyke, 1974). However, two other results from the Anari-Tapirapuã flows (Montes-Lauar et al., 1994) and the Penatecaua dykes (Guerreiro and Schult, 1986) plot away from the other poles, although their radiometric ages (De Min et al., 2003; Davies et al., 2017) do not support these differences.

The former paleomagnetic study on the Penatecaua rocks (Guerreiro and Schult, 1986) was restricted to the Monte Alegre (AM) area (Fig. 2). This work presents new paleomagnetic data based on a much-enlarged sampling, including the occurrences of the north and south regions of the Amazon Basin where the major sills outcrop. In addition, the studied sites are well-dated (Davies et al., 2017), allowing the calculation of a reliable paleomagnetic pole.

Table 1
Paleomagnetic results for the Penatecaua sills.

Locality	Site	Lat. (°)	Long. (°)	Elev. (m)	Type	N/n	Dec. (°)	Inc. (°)	α_{95} (°)	k	Lat. (°)	Long. (°E)
Alenquer	215	−1.577	−54.985	35	HTi	7/7	7.7	−54.1	9.8	39	56.1	113.6
Alenquer	216	−1.577	−55.005	33	HTi	7/6	12.5	−39.8	9.2	54	65.7	96.0
Alenquer	217*	−1.485	−55.161	59	HTi	8/7	15.2	−63.0	8.1	56	44.9	109.5
Alenquer	218	−1.629	−54.862	41	LTi	9/7	7.7	−67.9	13.4	47	40.3	118.7
Alenquer	219	−1.648	−54.740	61	HTi	8/6	8.9	−54.1	11	38	55.9	112.1
Alenquer	220*	−1.832	−54.687	80	LTi	8/5	353.1	45.8	17.6	20	57.4	327.3
Monte Alegre	101	−1.832	−54.262	86	HTi	6/6	10.1	−12.4	8.5	63	79	59.4
Monte Alegre	108	−1.556	−54.285	57	HTi	7/5	8.3	−32.7	19.1	17	71.9	99.5
Monte Alegre	210#	−1.909	−54.214	35	HTi	6/6	15.0	−27.1	9.8	48	70.7	76.7
Monte Alegre	211#	−1.908	−54.214	35	HTi	7/7	11.7	−24.1	3.8	251	74.2	79.0
Monte Alegre	214*	−1.879	−54.243	56	LTi	8/6	335.5	−40.5	18.7	138	58.1	172
Medicilândia	123	−3.389	−52.708	157	LTi	7/7	354.5	−14.7	5.9	107	83.2	280.3
Medicilândia	124	−3.411	−52.777	165	LTi	7/6	16.7	−11.2	6.9	96	73.2	45.5
Medicilândia	125	−3.441	−52.841	196	HTi	7/6	3.8	−14.1	3.1	463	84.7	82.6
Medicilândia	127	−3.441	−52.841	196	LTi	7/6	13.1	−17.6	4.4	233	75.8	61.2
Medicilândia	130	−3.442	−52.845	177	HTi	7/7	10.1	−14.8	6.7	83	79.2	60.0
Medicilândia	132	−3.467	−52.847	227	HTi	7/7	11.3	−15.0	5.5	122	78.0	57.9
Medicilândia	134	−3.445	−52.936	102	LTi	7/7	6.6	−12.7	4.3	196	82.7	62.1
Medicilândia	139	−3.506	−53.011	217	LTi	7/7	10.0	−21.7	4.3	197	73.8	73.5
Medicilândia	140*	−3.552	−53.089	150	LTi	12/6	237.5	−20.2	6.1	123	−31.0	202.5
Placas	142	−3.866	−54.430	98	LTi	10/6	10.7	−9.3	12.1	31	79.3	40.2
Placas	145	−3.938	−54.183	114	LTi	9/6	356.2	−11.8	9.9	47	85.6	186.0
Placas	205*	−3.758	−53.847	227	LTi	8/4	17.4	−3.8	24.5	15	72.6	30.1
Placas	206*	−3.837	−54.224	117	LTi	8/4	286.3	−42.2	7.8	140	16.4	191.5
Placas	208	−3.900	−54.520	107	LTi	7/7	8.5	−8.3	9.2	44	81.5	37.5
Rurópolis	117	−3.939	−54.858	180	LTi	7/6	350.9	−24.3	3.6	344	77.4	169.9
Rurópolis	146	−3.939	−54.858	185	LTi	8/6	0.2	−16.7	4.1	263	85.4	122.5
Rurópolis	200	−3.939	−54.858	190	LTi	7/7	5.0	−13.3	6.2	96	84.2	64.8
Itaituba	201*	−4.366	−55.837	27	–	3/2	122.2	48.1	13.2	17	29.9	182.7

N = total number of samples; n = number of specimens in the mean; Dec. = declination; Inc. = inclination; α_{95} and k = Fisher's (1953) statistical parameters; Lat. = latitude; Long. = longitude; #cylinders and hand blocks; *sites excluded from the mean.

2. Geological aspects

The Amazonas Basin (Fig. 1) is 1300 km long and, on average, 380 km wide. It is contiguous to the Solimões Basin, and the Gurupá Arch limits the two basins (Wanderley Filho et al., 2010). Together, these basins occupy an area of around 1.1 million km^2 of the states of Amazonas, Pará, and Amapá in northern Brazil. The Solimões-Amazonas rivers cross the basins in nearly *E*-W direction. The sedimentary infilling of the Amazon basin started in the Lower Paleozoic and accumulated about 5000 m of sediments (Cunha et al., 2007). The tectonic evolution of the Amazon Basin was investigated by Nunn and Aires (1988), describing the episodes of subsidence that allowed the accumulation of sediments since the Ordovician. An analysis of the tectonic regime of the Amazonas Basin is given by Rossetti (2014). The Paleozoic sequence is marked by significant regional discontinuity due to tectonic events occurring at the edges of the Gondwana Plate. The Late Paleozoic Tapajós Group (Silva et al., 2003) comprises the marine and continental sedimentation of the Monte Alegre, Itaituba, Nova Olinda, and Andira Formations. Sedimentation ended with the deposition of the fluvial Alter do Chão Formation and the Solimões and Içá Formations (Cenozoic).

Data from drilling cores and geophysical studies (Cunha et al., 2007) indicate that almost 10^6 km^3 of basaltic magma was injected into the Paleozoic sedimentary sequences, mainly the Carboniferous and Permian levels. Issler et al. (1974) were the first to observe a mafic sill named the Penatecaua diabase according to the river near Rurópolis (PA). The sills are more voluminous south of the Amazonas River (Fig. 2), reaching lateral extensions of 50 km in Medicilândia (PA) and a thickness of about 900 m (Wanderley Filho et al., 2010). According to Wanderley Filho et al. (2010), the emplacement of the sills was controlled by the structural highs developed before the onset of the Penatecaua magmatism. In the Amazonas Basin, the sills show negligible tilting differently from what occurs in the Solimões Basin, probably affected by the Andean orogeny (Munis, 2009).

In the northern area, the Nova Olinda and Alter do Chão formations (Caputo, 2011) host the Jurassic sills, although they are less expressive. In contrast, several NNE-SSW trending dykes (Fig. 2) occur in the area. The mapped dykes usually have thicknesses of 5 to 25 m. However, they are not recognized in the field as the contacts are absent. On the eastern side, the Monte Alegre dome, a topographic high at ~10 km northwest of the homonymous city, is associated with a Penatecaua tholeiitic intrusion on its base (Montalvão and Oliveira, 1975) that Lopes et al. (2013) interpreted as a laccolith by a gravimetric survey.

The Penatecaua magmatism is associated with CAMP magmatism (Marzoli et al., 1999) and is classified as basalts and andesite basalts of the tholeiitic series in a De La Roche et al. (1980) diagram. Low TiO_2 content (< 2% wt%) is a characteristic of the CAMP lithologies (Marzoli et al., 2017). Recent studies on the Penatecaua rocks focused mainly on the petrographical and the petrological aspects of the intrusions showing that they belong to the same magmatic event (Silva et al., 2014; Costa et al., 2012; Santos and Oliveira, 1978; Macambira et al., 1977; Issler et al., 1974). The Medicilândia sill, located in the city of the same name in the state of Pará (Fig. 2d), is the largest in length, covering about 300 km^2, and is composed of diabase and gabbro (Costa et al., 2012). A magmatic zonation was identified by Costa et al. (2012), with primitive facies on the edges and evolved ones concentrated in the center of the intrusion. The most probable hypothesis of the threshold evolution indicates an origin related to different partial melting rates from the same source, followed by a fractional crystallization process. Further west, a diabase body emerges near Rurópolis (PA), where recent cuts of the BR-163 expose a long outcrop (Fig. 2c). Silva et al. (2014) state that this body is well preserved, with no significant weathering. It presents preferential fracture plans oriented to EN*E*-WSW, in agreement with the structures of the embedding rock. Petrographically, this sill is similar to the sill observed in Medicilândia.

The radiometric ages for the Penatecaua rocks based on the K/Ar and Ar—Ar methods (Cunha et al., 2007; Zalán, 2004; De Min et al., 2003; Aires, 1983; Thomaz Filho et al., 1974) vary from 210 to 190 Ma. Davies et al. (2017) recently obtained high-precision U—Pb age of ~201 Ma data for the Penatecaua rocks from the south and north of the Amazonas Basin. They found a mean age of 201.525 ± 0.065 Ma for the low-Ti

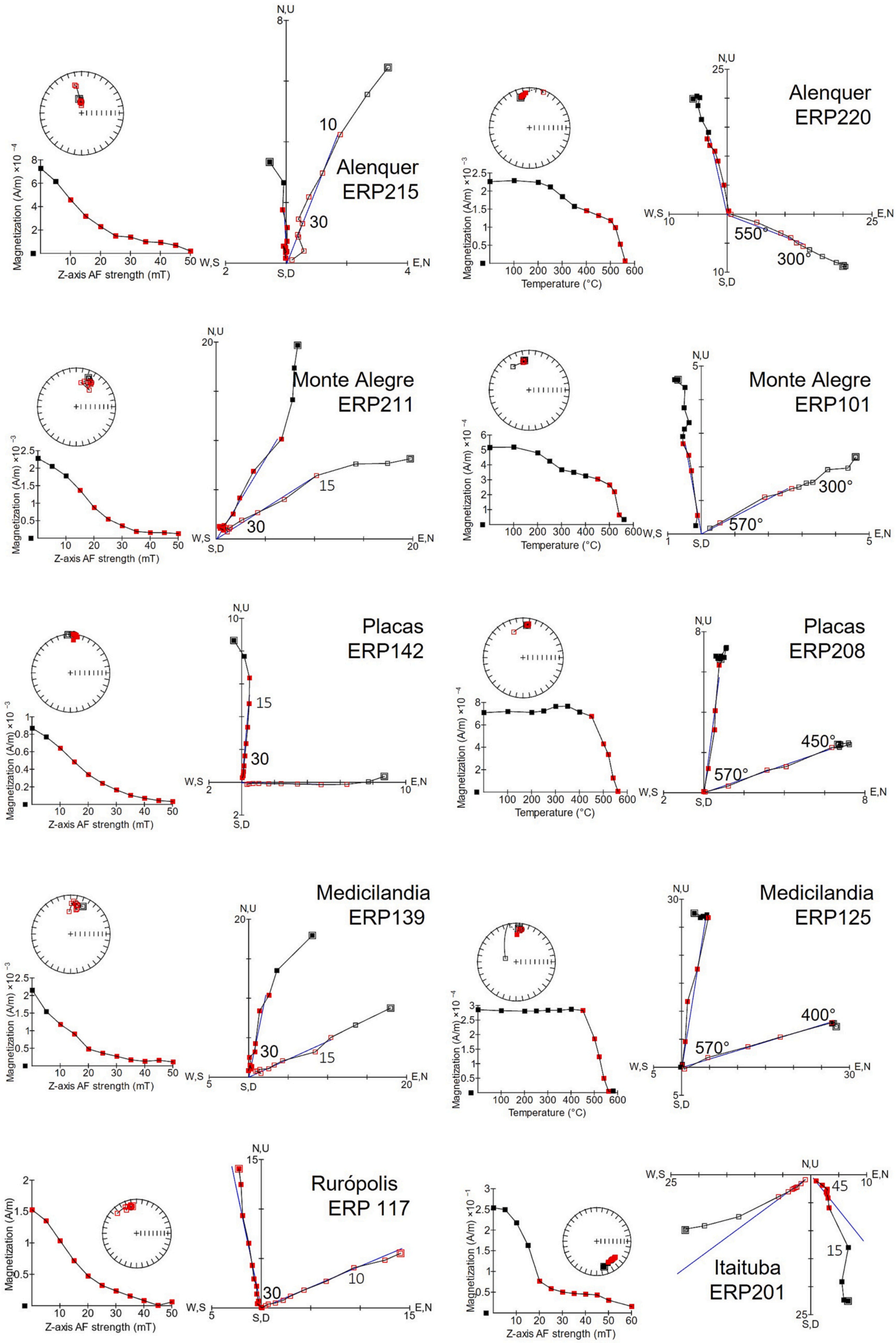


Fig. 3. Orthogonal diagrams, stereographic projections, and magnetization intensity variation during AF (diagrams on the left) and thermal (diagrams on the right) demagnetizations. Open (full) symbols correspond to negative (positive) inclinations. Blue lines are the adjusted magnetization components through the selected points (red dots). Diagrams according to the PuffinPlot software (Lurcock and Wilson, 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

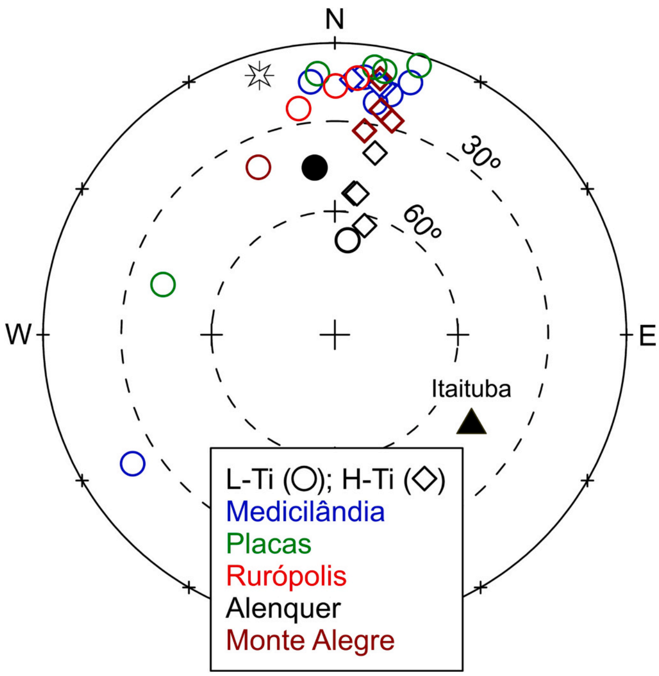


Fig. 4. Wulff stereogram with the mean characteristic magnetizations for the Penatecaua sites and the crystalline basement in Itaituba. Different symbols were used for the HTi and LTi rocks, and colors distinguish the studied areas. All sites have negative inclinations (open symbols), except for the LTi site 220 from Alenquer and Itaituba with Inc. > 0 (full symbols).

rocks and 201.364 ± 0.023 Ma for the high-Ti rocks. Therefore, both magma types were injected continuously and synchronously throughout 264 ± 57 ka.

Paleomagnetic samples (Fig. 2) were taken south of the Amazonas River along the Transamazonian road (BR-230) that cuts the basin in an E-W direction. Recent asphalting work exposed fresh outcrops of the sills near Medicilândia, Placas, and Rurópolis. In the north, sampling was concentrated near Alenquer and Monte Alegre cities (Fig. 2). In the latter area, sills and dykes are indicated on the geological map. Still, they were not identified as the contacts were absent. Oriented cylinders were cut with a gasoline-powered drill and oriented by magnetic and sun compasses. In some cases, hand blocks were extracted. A total of 28 sites were sampled (Fig. 2 and Table 1), including one of the Devonian silicified sediments from the Maecuru Formation (Vasquez et al., 2008) near Itaituba (west of Rurópolis).

3. Characteristic remanent magnetization

The natural remanent magnetization (NRM), measured in JR6 equipment, gave intensities varying in a narrow range of 0–5 A/m, except for some Alenquer samples with intensities up to 20 A/m. Standard specimens were initially submitted to alternating magnetic fields (AF) demagnetizations up to 50 mT. However, the magnetization vectors became unstable above 40 mT. In general, a unique characteristic remanent (ChRM) component remained after the cleaning of a secondary viscous component (Fig. 3) of low coercivity (≤15 mT). Another specimen from each site was submitted to thermal demagnetization up to 580 °C. At this temperature, the magnetization was erased. The ChRM was, in general, determined in the range of 200°-560 °C. No tilt corrections were necessary, as already mentioned, and as will be demonstrated by the anisotropy of magnetic susceptibility. Most high-coercivity or high-temperature components have NE directions with low upward inclination (Fig. 3 and Table 1), compatible with a normal polarity field and differing from the present local field. The Penatecaua magnetizations also differ from the Itaituba site of positive inclination and pointing SE. This is a positive field test, although only one Itaituba site was analyzed.

Although most data cluster around a mean direction dec = 6.4° and inc = −18.6°, some sites plot apart from the mean. The Monte Alegre and Alenquer sites show increasing inclinations reaching >60° with almost constant declinations describing a particular pattern associated with the HTi rocks that prevail in the northern area. On the other hand, Medicilândia site 140 has an SW direction indicating a reversed field. Unfortunately, it is the only data showing the possibility of a reversal record, although site 206 from Placas has a nearly *E*-W direction, compatible with a transitional field.

4. Magnetic mineralogy

The thermomagnetic K-T curves (Fig. 5) indicate that Ti-poor magnetite is the main magnetic carrier in the Penatecaua samples. An abrupt drop in susceptibility occurs at temperatures close to 580 °C (Fig. 5a to 5e), sometimes preceded by the Hopkinson peak. The Verwey transition close to −180 °C appears in some low-temperature K-T curves (Fig. 5f), confirming magnetite as the main remanence carrier. In the outcrops of Rurópolis, Silva et al. (2014) found primary opaque minerals included in the clinopyroxene and plagioclase grains. These authors also found sparse pyrite grains in the matrix. The pyrite transforms into pyrrhotite between 500 and 1200 °C (Wang et al., 2014). Pyrrhotite, in turn, may transform into magnetite at temperatures above 500 °C (Bina and Daly, 1994). This may be related to the irreversibility of the high-temperature K-T curves in the Rurópolis samples.

The progressive isothermal remanent magnetization (IRM; Fig. 6) acquisition curves indicate that the samples from all areas saturate at low fields (about 0.1 T). This behavior is compatible with magnetic carriers of low coercivities, such as magnetite. The HTi samples ERP219 and ERP132, one from Alenquer and the other from Medicilândia, were saturated with higher magnetizations. However, HTi and LTi samples gave similar values in the lower range of magnetization intensities. In a Day-Dunlop (Day et al., 1977; Dunlop, 2002) plot, the magnetic domain state of magnetite concentrates in the pseudo-single-domain (PSD) field with no distinction of the rock type (LTi or HTi). According to Dunlop (2002), the PSD field represents the binary mixtures of single-domain (SD) and multi-domain (MD) grains. Therefore, most Penatecaua samples would be 80% SD and 60% MD, except for two Medicilândia samples with about 60% SD and 40% MD. A further inspection of the magnetic mineral assemblages using the IRM-Unmix protocols (Maxbauer et al., 2016) revealed the mean coercivities (B_h) of the discrete mineral assemblages and their associated statistical parameters (DP) that make up the whole set of magnetic constituents of the samples. The results in Fig. 6 (d to g) suggest multicomponent coercivity phases as indicated by the Day-Dunlop plot. However, a 30–50 mT main component (Fig. 6g) dominates the spectra in all cases. The other components correspond to 10% or less of the total coercivity in each sample. Sometimes, a third or a second component may be an artifact of calculations, considering the data distribution and the corresponding errors.

5. Anisotropy of magnetic susceptibility (AMS)

Anisotropy of magnetic susceptibility (AMS) is related to the preferred orientation of magnetic minerals in rocks. The rock susceptibility is controlled by all minerals present in a rock, although the high-susceptibility minerals such as magnetite or Ti-magnetite, when present, are dominant. The AMS is represented by the three spatial axes of a tensor (k1, k2 and k3) for the maximum, intermediate and minimum anisotropy. In igneous rocks, the AMS main axis k1 has been primarily used as a proxy for magma flow direction (e.g., Hoyer and Watkeys, 2017), although this relationship may be complex. In sills, the AMS may indicate the magma flow and, eventually, the feeder location.

The AMS parameters of the Penatecaua rocks were measured in a Kappabridge instrument. For most sites, the maximum k1 axes are flat

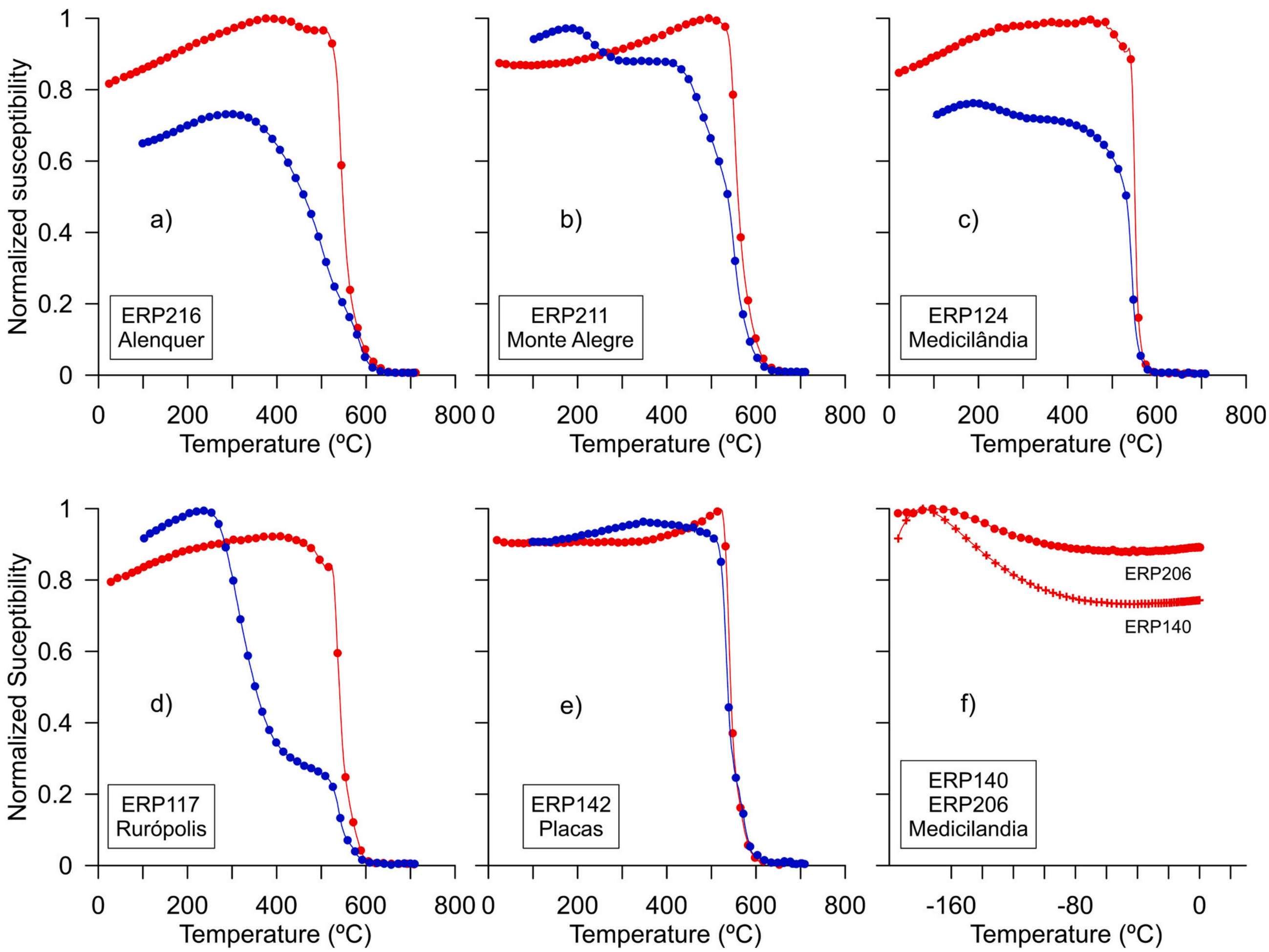


Fig. 5. Characteristic thermomagnetic curves (K-T curves) showing the susceptibility variation during heating and cooling cycles at high temperatures (a to e) and heating from low temperatures (f). Red lines = heating, blue lines = cooling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with inclinations not >30° (Fig. 7), and the smallest eigenvalue k3 clusters are close to the vertical (supplementary data is available). This magnetic fabric indicates that the sills are flat-lying and that there is no apparent tectonic correction to apply. In Monte Alegre, where some dykes occur, the k1 axes distribute in an N-NW direction, and the mean inclination is sub-vertical (sites 210 and 211 in Fig. 7c). The three studied sills in the south area behave similarly, with the k1 axes showing no clear trend in a particular direction. However, a slight tendency for an NW (N300°) direction appears in Rurópolis and Placas, the two neighboring bodies. In Medicilândia, the main tendency is N-NE. The k3 axes are vertical to sub-vertical, but they may be exchanged by the intermediate axes k2 due to the low anisotropy degree (Fig. 8).

Martin et al. (2019) investigated the magnetic fabric variation across a 6 m thick sill, concluding that a complex distribution of the magnetic fabric may be found depending on the sill growth history. The authors suggested that a detailed sampling should be performed to infer magma flow direction, as is common in literature (Liss et al., 2002; Polteau et al., 2008; Hrouda et al., 2015; Hoyer and Watkeys, 2017). The more prominent Penatecaua sills were sampled at different sites distributed laterally and vertically. Therefore, the data is representative of the fabric distribution inside the sills. In all investigated sites, the flow is horizontal to sub-horizontal and seems conditioned by the host sedimentary layers.

The anisotropy degree (P), given by the k1/k3 susceptibilities rate, is low and does not exceed 1.05 for most samples from all areas. However, the northern region has a subtle tendency for higher *P* values. For example, in Fig. 9c and d, the relationship between the eigenvalues (L = k1/k2; F = k2/k3) indicates the same tendency for magnetic foliation (F) or lineation (L) in the south and the Alenquer sites. Still, the lineation L predominates (Fig. 8d) in Monte Alegre, where dykes occur.

6. Discussion and conclusions

The mean characteristic magnetizations for most studied sites (Fig. 4) have N-NE directions with low negative inclinations differing from the present geomagnetic field and consistent with a normal polarity paleofield. Furthermore, the magnetizations of the Rurópolis, Placas, and Medicilândia sills follow the same pattern when the inclination and declination are plotted as a function of the elevation (Fig. 9). This similarity suggests that the three sills emplaced almost simultaneously, if not forming a unique and extensive body. They recorded a significant variation in magnetic declination and inclination, suggesting fast changes in the geomagnetic field. However, Fig. 9 represents the relative position of the investigated sites from the three localities but does not reflect a time-ordering of the magnetic events. Therefore, a model of multiple injections can explain the record of such magnetic features. Ernesto and Pacca (1988) described a similar effect in a 44 m long core of the Paraná tholeiitic basalts (southern Brazil). Apparently, the core crossed only one flow, with no apparent contacts, but the major and trace element contents allowed the distinction of three distinct zones. The paleomagnetic data indicated an approximately 50° declination variation at the core base and a magnetic perturbation in the

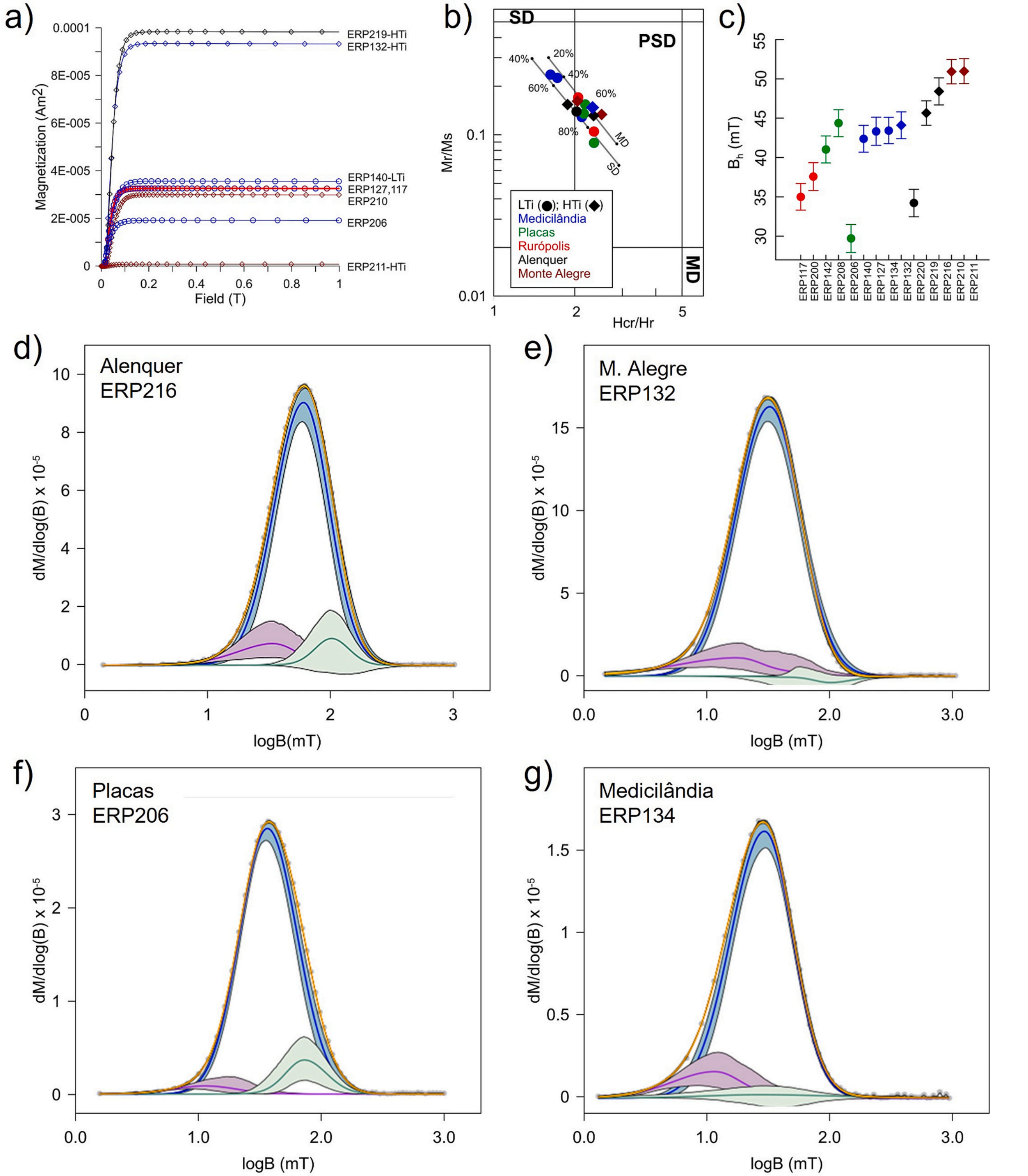


Fig. 6. a) Isothermal remanent magnetization of representative samples from all the studied areas; b) the Day-Dunlop (Day et al., 1977; Dunlop, 2002) diagram showing the domain states of some selected samples; d) variation of component 1 coercivity in the investigated samples; d-g) coercivity spectra from the IRM-Unmix protocols (Maxbauer et al., 2016). Colour and symbol patterns apply to a, b and c diagrams.

middle part, coinciding with the intermediate flow (or sill!) indicated by the chemical zonation.

Costa et al. (2012) recognized multiple injection pulses in Medicilândia, the younger pulses corresponding to the HTi rocks in the center of the sill. In contrast, the most primitive pulses are in the borders. The only three HTi sites in the southern area (Medicilândia sites 125, 130, and 132) were sampled approximately in the central part of the body (Fig. 2d) and at the higher levels (Fig. 9), intercalated with LTi samples, consistent with the multi-injection model. Davies et al. (2017) reported a mean age of 201.505 ± 0.065 for the LTi rocks and 201. 364 ± 0.023 Myr for the HTi rocks, which refers mainly to the northern area, where the HTi rocks prevail. Most of the VGPs are within a 45° polar cap

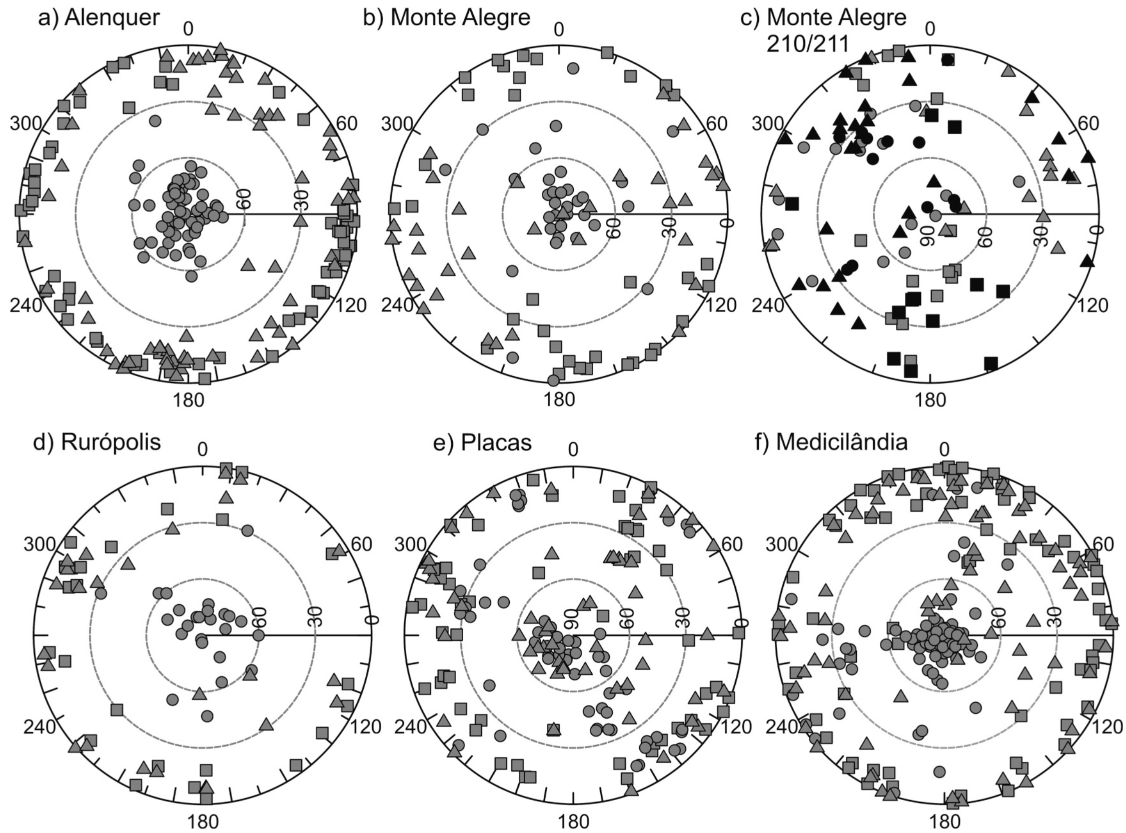


Fig. 7. Equal-area plot of the main AMS axes (k1,k2,k3) per specimen. (a, b, c) Sampling sites from the north and (d, e, f) and south areas. In (c), the Monte Alegre sites 210 (gray) and 211 (black) may correspond to dykes in the N-NW direction.

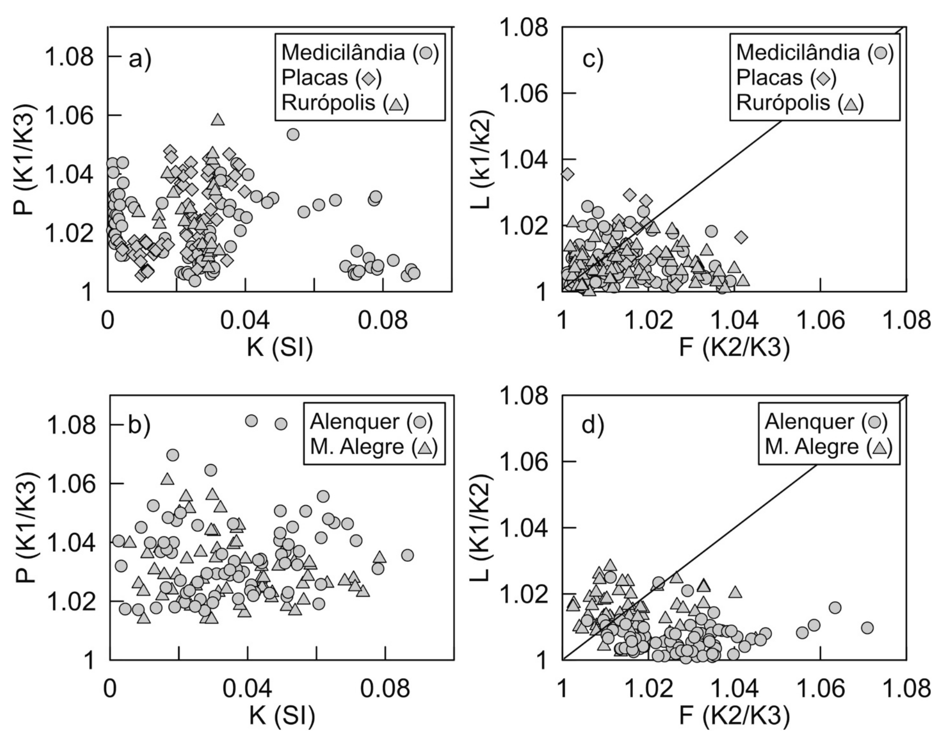


Fig. 8. Variation of the degree of anisotropy (P) versus bulk susceptibility (K) and lineation (L) versus foliation (F) in the Penatecaua southern (a, b) and northern (c, d) sites.

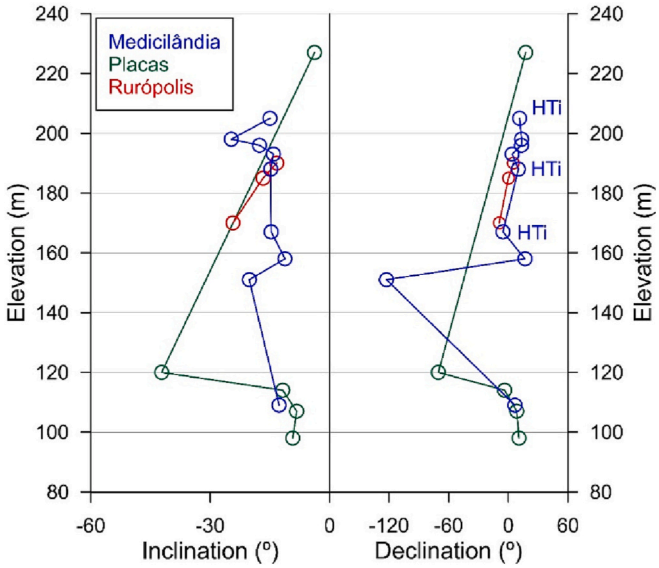


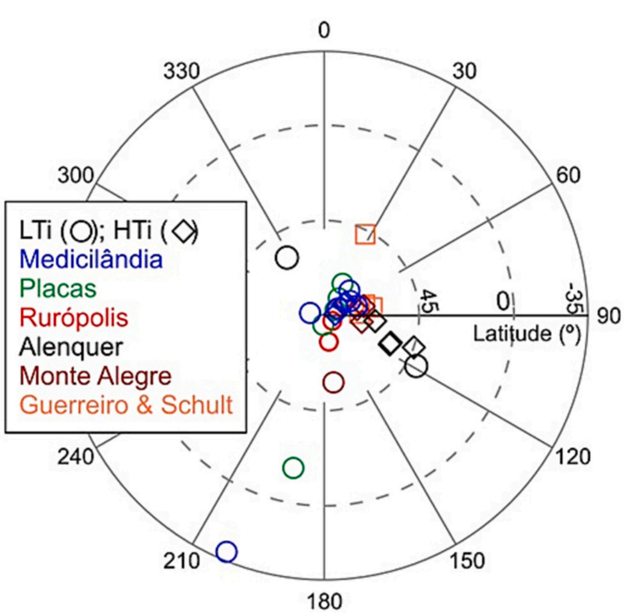
Fig. 9. The magnetization declination and inclination variation with the elevation within the Medicilândia, Placas, and Rurópolis sills. The three HTi Medicilândia sites are indicated.

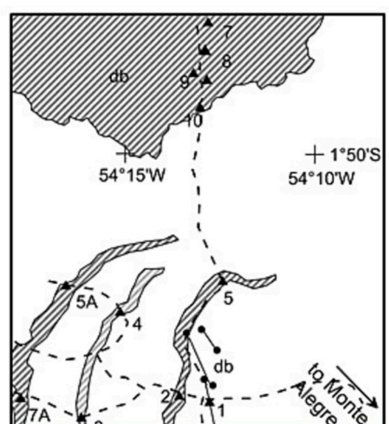
(Fig. 10), which is the dispersion area of the migrating pole due to the secular variation cycles. However, some VGPs plot at latitudes lower than 45° reaching even the southern hemisphere, and they can be associated with a transitional field during an excursion or even a reversal. A shortly reversed chron (E23r; Kent et al., 2017) may exist at 201.6 (Blackburn et al., 2013), immediately below the oldest CAMP basalts in the Newark basin. The E23r event was also reported by Deenen et al. (2011) in Partridge Island, Canada. However, outside North America, this chron still deserves confirmation. Font et al. (2011) questioned the record of the E23r in the Moroccan Tiourjdal limestones, arguing that chemical processes completely reset the magnetization. The anomalous sites of Medicilândia (ERP140) and Placas (ERP206) with VGP latitudes lower than 30° may corroborate this assumption. These sites are LTi type for which the mean age (201.505 ± 0.065 Myr) is very close to the E23r age.

Fig. 10a includes Guerreiro and Schult's (1986) VGPs from the Monte Alegre tholeiitic rocks. The sampling sites (Fig. 10b) are probably at the base of the Monte Alegre dome, according to their sketch map here reproduced, although the authors mentioned they are dykes. These paleomagnetic data well match the new data from this work. Therefore, a new paleomagnetic pole for the Penatecaua magmatism includes the data from Guerreiro and Schult (1986). After applying the Vandamme (1994) cut-off, the new pole plots at 260.1°E 77.5°S ($N = 30$; $A_{95} = 3.3°$; $k = 48$).

The Penatecaua pole matches the best northern South American poles (Table 2; Fig. 11) within the experimental errors. The listed poles were classified according to Meert et al. (2020), who reviewed the usually applied Van der Voo's (1990) criteria. The seven proposed criteria comprise (1) well-determined rock age (within ±15 Ma) and a presumption that magnetization is the same age; (2) application of demagnetization and statistical techniques to evaluate the magnetization components and elimination of paleosecular variation; (3) identification of remanence carriers; (4) fold test or similar to constrain the magnetization age; (5) the region was a rigid part of the craton since the time the magnetization was acquired; (6) positive reversal test; (7) no resemblance to younger poles based on a statistical level. Poles 3 to 5 and 7 (Penatecaua) are the best classified (4 to 5) and plot together. However, these poles do not reach the maximum classification as they are essentially based on normal polarity rocks. Therefore, no reversal test is possible. The fold test is not applicable either, but a field test, although insipient, was performed for the Penatecaua pole -its data were compared to the data from one site of the basement older rocks.

The less reliable poles are the Bolivar dykes and Guacamayas Group





Site	n/N	α_{95} (°)	Lat (°)	Long (°)
GS1	9/9	4.3	73.4	87
GS2	10/4	18.5	65.4	65
GS4	11/5	18.9	60.6	69
GS5	11/11	4.3	47.0	27
GS6	10/5	14.2	64.6	59
GS7	10/7	12.2	66.9	80
GS9	11/6	24.5	76.0	96
GS5A	10/7	12.3	72.4	74
GS7A	5/4	13.8	83.8	122

Fig. 10. a) Equal-area stereographic plot of the south VGPs for the Penatecaua magmatism. Colors identify studied localities, and the LTi and HTi rocks correspond to circles and diamonds, respectively. Squares are the results from Guerreiro and Schult (1986) represented in the sketch map (b) redrawn from the original. These data are displayed in the table.

Table 2
Lower Jurassic paleomagnetic poles from northern South America.

Formation	#	Clas.	Age (Ma)	N	Long. (°E)	Lat. (°S)	A_{95} (°)	k	Reference
Bolivar dykes, Venezuela	1	3	199[1]	5	245.6	66.9	4.2	338	MacDonald and Opdyke, 1974
Guacamayas Group, Venezuela	2	3	195[1]	5	300.7	70.5	12.4	24	MacDonald and Opdyke, 1974
French Guyana dykes#	3	5	199–195	24	243.2	81.7	4.1	53	Nomade et al., 2000
Combined Cassiporé-Taiano, Brazil	4	5	199–197	24	221.9	81.2	4.4	46	Ernesto et al., 2003
Northeastern Magmatism, Brazil	5	5	197*	33	223.9	78.1	5.2	25	Ernesto et al., 2003
Anari-Tapirapuã flows, Brazil	6	4	197*	15	250.3	65.5	3.6	1578	Montes-Lauar et al., 1994
Penatecaua magmatism, Brazil	7	5	201[2]	30	260.1	77.5	3.8	48	This work

#Combining the two groups; *Recalculated ages (Nomade et al., 2007); [1]K/Ar ages; Clas. = classification (Meert et al., 2020); N = number of sites; Long. = longitude; Lat. = latitude; A_{95} and k = Fisher's statistical parameters. [2] Davies et al., 2017, 2021.

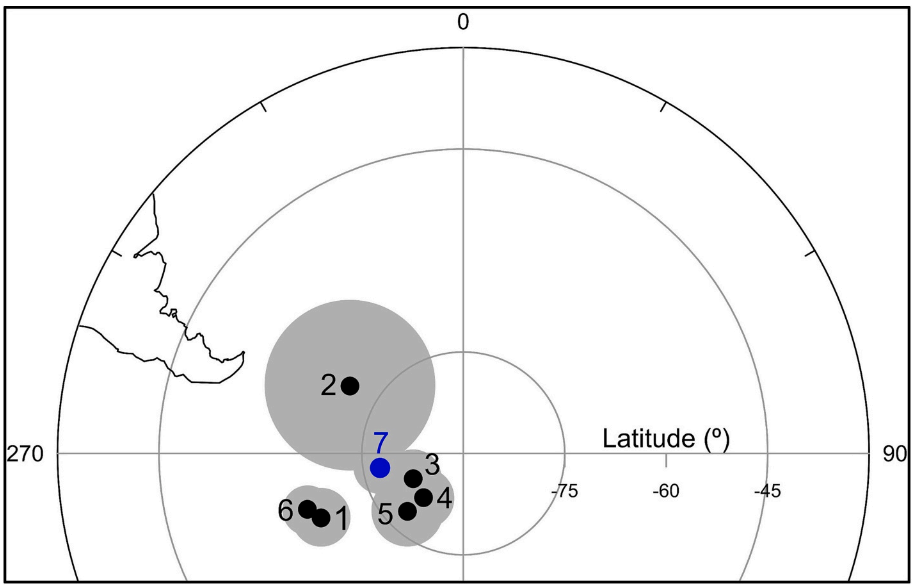


Fig. 11. South paleomagnetic poles of Lower Jurassic magmatic rocks from northern South America. The numbers are according to Table 2. The blue symbols indicate the Penatecaua pole of this work. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(MacDonald and Opdyke, 1974), with only five sites and remanences determined by older methods not attending the modern requirements. The Anari-Tapirapuã (Montes-Lauar et al., 1994) pole is based on 15 sites and probably did not eliminate the secular variation, as expressed by the high value of the k parameter. The old Penatecaua pole (Guerreiro and Schult, 1986) plots at 65.6°S and 249.5°E close to the Anari-Tapirapuã pole. In this work, incorporating more data made it closer to the other two high-quality poles. The other poles do not reach the maximum score because criteria 4 and 6 are not fully attended. Therefore, the best and concordant poles mark well the plate position during the Triassic-Jurassic boundary.

7. Concluding remarks

A reliable paleomagnetic pole of ~201 Ma for the CAMP event resulted from combining the new data and those previously published (Guerreiro and Schult, 1986) from the Penatecaua magmatism in the Amazonas basin. This pole agrees with other best-ranked CAMP poles from northern South America, reinforcing that the CAMP activity was short-duration. The majority of the Penatecaua VGPs group tightly in accordance with the short time interval of <300 kyr (Davies et al., 2017) for the emplacement of the whole magmatism. However, some sites are more dispersed, plotting >45° from the mean. This is the usually considered threshold for the drift of the earth's magnetic pole if only affected by secular variation. Beyond this limit, the pole is associated with an excursion or a reversal path. Although few, the Penatecaua rocks recorded some transitional directions. These directions belong to the LTi group of 201.5 Myr mean age. Although not widely accepted, a short reverse polarity event at 201.6 Ma (E23r; Kent et al., 2017) would precede the LTi group. Therefore, it is possible that the Penatecaua rocks registered the transition from reverse to normal field. Even if the E23r event does not exist (Font et al., 2011), the Penatecaua results point at least for an excursion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pepi.2023.107075.

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