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Stress states during the emplacement of the eastern Rio Ceará-Mirim dike swarm, Borborema Province, northeastern Brazil

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Abstract

The Rio Ceará-Mirim dike swarm (RCMDS) of the Borborema Province is a suite of subvertical intrusions classically described in the state of Rio Grande do Norte as E-W-trending dikes, up to southern Ceará, progressively deflecting to NE-SW. The rifting processes involving the Atlantic Ocean opening in the Early Cretaceous is responsible for the Northeast Brazilian Rift System (NBRS) and RCMDS development. This paper investigates the morphological styles and stress states in eastern RCMDS, focusing on well-preserved dikes at the localities of Rio Salgado and Lajes (state of Rio Grande do Norte). Remote sensing techniques, fieldwork, and numerical models aimed to obtain data to propose correlations between the eastern RCMDS emplacement and the NBRS tectonic settling in the Early Cretaceous. The studied dikes are predominantly tholeiitic basalt-diabase ranging from a few centimeters to 150 meters in thickness, locally achieving tens of kilometers in length. Their morphological styles vary from symmetrical to asymmetrical, from sharp and straight to anastomosing/braided dikes, showing diverse *en echelon* patterns, steps, horns, bridges, and bridge xenoliths. Fractal analysis of the dikes framework indicate syn-magmatic strike-slip components. The majority of morphological markers and the average orientation of the Rio Salgado dikes indicate a NNS-SSW (010 Az) orientation for the least compressive axis and dextral displacements. Based on some occurrences of *en echelon* dikes showing syn-emplacement stages in the extension direction, we propose three main stages for the least compressive axis – initially oriented to NW-SE, changing to N-S, and finally to NNE-SSW. Mechanical models indicate that the eastern RCMDS were emplaced in deviatoric stress with low/intermediate fluid pressure ($P_f < \sigma 2$), which is in agreement with the observed morphological patterns.

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1. Introduction

Northeast Brazil comprises a series of rift-related basins linked to the Atlantic Ocean opening in the Early Cretaceous (Matos 1992) (Figure 1a). Tectonosedimentary events accompanied the plate drift, including continental rift deformations and associated magmatism (Matos 2000, 2021; Sial 1976). Preexisting lithological contacts and shear zones were key in the rifting processes across the Northeast Brazilian Rift System (NBRS), including the Potiguar Basin (Figure 1b) (Matos 1992, 2000; Szatmari et al. 1987; Françolin and Szatmari 1987).

The Rio Ceará-Mirim dike swarm (RCMDS) is classically described in the State of Rio Grande do Norte (RN) showing E-W striking dikes, up to southern Ceará, where it progressively shifts to NE-SW (Figure 1c). This deflection in the western RCMDS has been traditionally interpreted as influenced from the NE-SW Cariri-Potiguar trend, a basement reactivation zone that aligns some rift basins (Oliveira 1993; Bellieni et al. 1992; Ngonge et al. 2016; Hollanda et al. 2006). At the eastern RCMDS, the focus of this study, dikes truncate the NE-SW Precambrian foliation and volcanoclastic rocks occur in the non-outcropping basal syn-rift sedimentary layers of the Potiguar Basin (Pendências Formation) (Bellieni et al. 1992; Araripe and Feijó 1994; Pessoa Neto et al. 2007). Using anisotropy of magnetic susceptibility (AMS), Archanjo et al. (2002) highlighted that the RCMDS would be regionally fed by lateral flows of 350 kilometers with feeding zones at Lajes-RN and Currais Novos-RN (Figure 1c).

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Mizusaki et al. (2002) assembled geochronological data from the RCMDS, reporting ages between 145 to 110 Ma with a magmatic peak around 130 Ma, although this compilation also considers less accurate 40K-40Ar data. Ngonge et al. (2016), Souza et al. (2003), and Araújo et al. (2001) obtained, respectively, 126.9 ± 4 Ma, 132.2 ± 1 Ma and 143 ± 4 Ma to 110.7 ± 1 Ma ^{40}Ar-^{39}Ar mineral and whole-rock step-heating plateau ages. Paleomagnetic data register dikes emplacement from Late Jurassic to Early Cretaceous, but Jurassic dikes are not supported by recent radiometric approaches in this region (Bellieni et al. 1992; Ernesto et al. 1991).

Hollanda et al. (2019) proposed a new Early Cretaceous Large Igneous Province (LIP), the Equatorial Atlantic Magmatic Province (EQUAMP), between 135 and 120 Ma, almost synchronic with the Paraná-Etendeka LIP, Southeastern Brazil (Figure 1a). The EQUAMP was subdivided further into the Triassic-Jurassic Central Atlantic Magmatic Province (CAMP) (Bertrand et al. 2014; Marzoli et al. 1999). This categorization is based on geochemical and geochronologic similarities between 1000 kilometers of intrusions related to the RCMDS, the Canindé dike swarm and the Riacho do Cordeiro dike swarm (Figure 1b) (Hollanda et al. 2019; Melo et al. 2021; Fernandes et al. 2020; Matos 2021).

The dikes throughout Lajes-RN have been recognized since the 1960-1970 years, and these occurrences are responsible for the RCMDS' early descriptions (Sial 1976; Rodrigues 1976). The dikes at Rio Salgado (Lajes-RN) are an excellent opportunity for elucidating syn-magmatic stress fields due to their fresh exposures and morphological relationships in a ramified WNW-ESE dike tip (Figure 5).

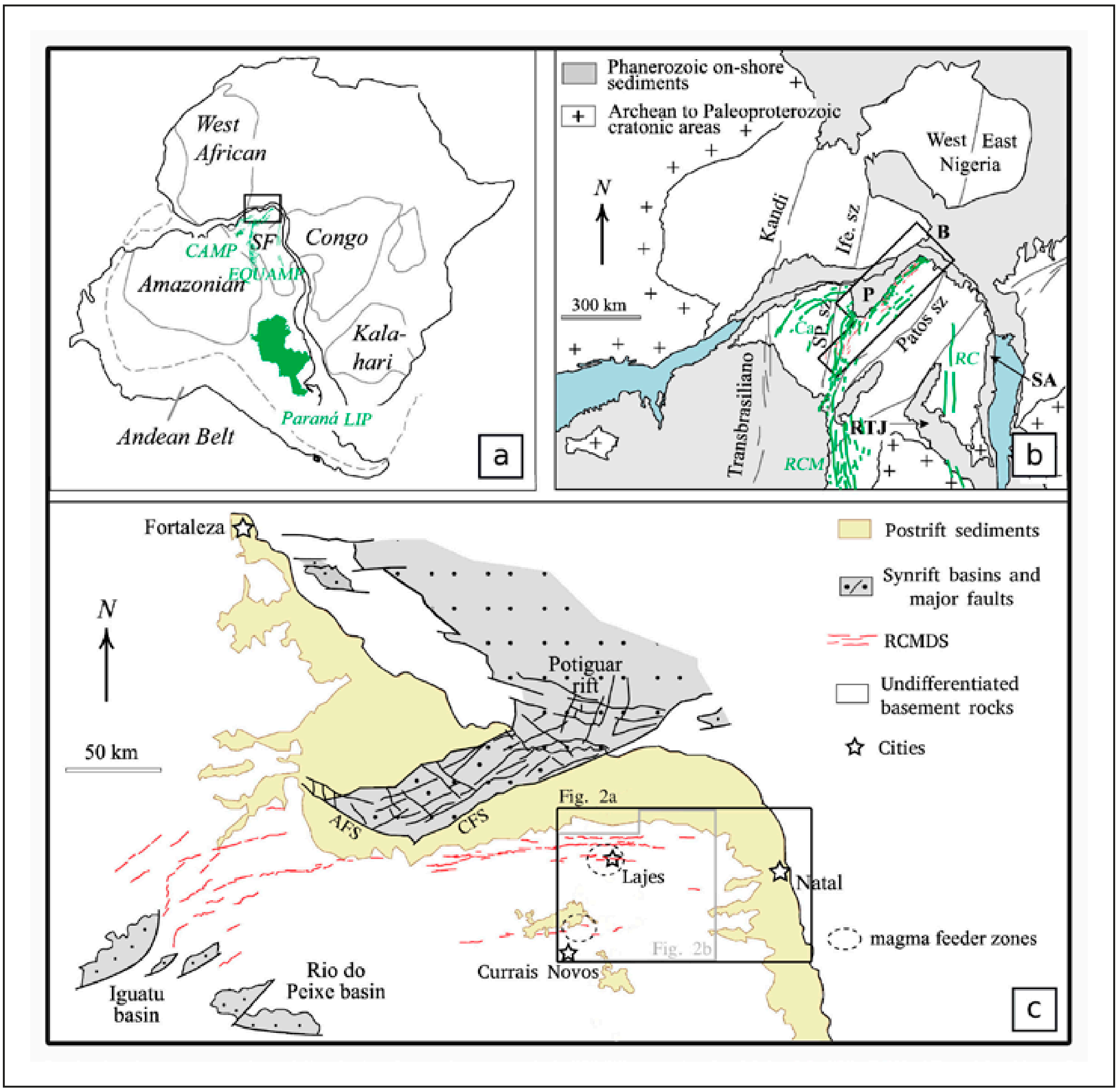

FIGURE 1: Geological context of the Rio Ceará Mirim Dike Swarm (RCMDS). Compiled from Angelim et al. (2006), Castro et al. (2012), and Ngonge et al. (2016). (a) Disposition of the continents in the Early Cretaceous, emphasizing cratonic areas (SF: São Francisco), principal Large Igneous Provinces (EQUAMP: Equatorial Atlantic Magmatic Province; CAMP: Central Atlantic Magmatic Province); (b) Predrift reconstruction of the main geologic features of northeastern Borborema Province and West Africa, presenting prominent Neoproterozoic ductile shear zones (Sz - SP: Senador Pompeu; Ife: Ifewara), major Mesozoic rift systems (P: Potiguar; RTJ: Recôncavo-Tucano-Jatobá; B: Benue; SA: Sergipe-Alagoas) and EQUAMP dikes swarms (Ca: Canindé; RCM: Rio Ceará-Mirim; RC: Riacho do Cordeiro) (c) Most recurrently described occurrences of the RCMDS (AFS: Apodi Fault System; CFS: Carnaubais Fault System).

This paper examines the structural control for the emplacement of E-W dikes in the eastern RCMDS, observed from well-preserved outcrops across Lajes-RN, and propose correlations to the NBRS' tectonic settling in the Early Cretaceous. A detailed morphological description of the Rio Salgado occurrences aimed to understand the stress fields' evolution during their emplacement. Further, the dikes' orientation was used to model the stress states influencing fractures development to understand the mechanisms for dike emplacement. Our data were compiled and adapted from field observations, sample collection, and photographic descriptions presented by Vasconcelos (2018).

2. Methodology

The methodology includes remote sensing derived from orbital and aero digital data, such as Landsat 8 bands fusion, SRTM (Shuttle Radar Topography Mission) digital elevation models, and CPRM (Serviço Geológico do Brasil) aerogeophysical surveys. All geoprocessing phases seek to understand the morphological styles and host rocks relationships in the eastern RCMDS, which were refined with fieldwork, petrographic description, and previous research. Moreover, a schematic representation of the fresh outcrops from Rio Salgado was performed to express the dikes' centimeter-scale patterns. The mapped area encompasses the RCMDS' occurrences from the central-eastern sector of the Rio Grande do Norte State, NE Brazil (Figure 2a).

The kinetic interpretation from dikes and fracture sets atitudes are, respectively, based on Anderson (1951) and Mohr-Coulomb criteria. We considered morphological patterns presented and/or discussed by Nicholson and Pollard (1985), Pollard (1987), Rickwood (1990), Hoek (1991), Rubin (1995), Correa-Gomes et al. (2001), Ernst and Buchan (2001), Clemente et al. (2007), Ghodke et al. (2018) and Magee et al. (2019). Mechanical models were performed according to Jolly and Sanderson's (1997) method and integrated with dilation tendency, slip tendency, and fracture susceptibility (Morris et al. 1996; Ferrill et al. 1999; Mildren et al. 2002; Stephens et al. 2018; Bhowmick and Mondal 2021).

3. Field Relations and Petrography

The RCMDS is geologically inserted into the Borborema Province, northeast most of South America. The Borborema Province displays a complex system of NE-SW crustal-scale ductile shear zones, involving Proterozoic terranes and Archean fragments, amalgamated into the actual configuration by the intrusion of extensive Neoproterozoic to Early Paleozoic Brasiliano plutonism (Sá 1994; Neves et al. 2014; Dantas et al. 2013; Nascimento et al. 2015; Souza et al. 2016; Ganade et al. 2021). According to Van Schmus et al. (2008), at 1.0 Ga the northern Borborema Province experienced extensional stress, allowing the deposition of intracratonic basins, currently represented by metasedimentary rocks. The mapped area shows four distinct dikes' host rocks, including Paleo-Neoarchean orthogneissic São José do Campestre Domain, Rhyacian orthogneissic Rio Piranhas-Seridó Domain, Mesoproterozoic-Neoproterozoic metasedimentary Seridó Group, and Neoproterozoic-Ordovician Brasiliano granitoids (Angelim et al. 2006 and references therein) (Figure 2a).

The regional semi-arid weather promotes fresh expositions due to weak chemical weathering, favoring remote sensing techniques. A preponderant number of outcropping dikes are found across Lajes-RN and Currais Novos-RN in the study area (Figures 2a, b). CPRM aerogeophysical surveys contributed to detecting subsurface tabular mafic bodies, and also provided fractal analyzes (Figure 2c).

The eastern RCMDS comprises a suite of subvertical tabular bodies composed of tholeiitic basalt-diabase rocks, with rare alkaline affinities (Bellieni et al. 1992; Oliveira 1993; Hollanda et al. 2006; Ngonge et al. 2016). The dikes' thickness ranges from a few centimeters to 150 meters, locally achieving tens of kilometers in length. Fresh hand samples vary from light gray colors, when crystals are predominant (Figure 3a), to darker shades in groundmass-rich thin rocks (Figure 3b). Crystallization is favored in central portions of thicker dikes, building up aphanitic borders grading towards medium-grained amygdaloidal phaneritic centers (Figure 3b). Rare subhorizontal N-S trending columnar joints may be observed.

Micropetrographic analyses indicate that the main lithotype includes inequigranular to porphyritic rocks, ranging from hypocrystalline to hypovitreous (Figure 3a, b), composed of augite, pigeonite, plagioclase, opaque minerals, apatite, vesicular zeolites, and late amphiboles. A subordinate facies is shown in thick dikes as centimetric unchilled leucocratic veins, composed of cryptocrystalline groundmass and quenched crystals (Figure 3a). Rare medium-grained holocrystalline equigranular rocks with olivine, titanaugite, pigeonite, plagioclase, biotite, opaque minerals, apatite, and late amphiboles can be found in a few dikes with alkaline characteristics (Bellieni et al. 1992). Micro- to cryptocrystalline aphyric rocks are commonly associated with chilled portions near the dikes' walls.

4. Stress Fields and Morphological Analyses

Dike swarms constitute important clues for geodynamic processes, paleogeographic reconstruction, and determining directions of magmatic flow and regional syn-magmatic stress fields (Rubin 1995). Also, they contribute to chronological and geochemical evidence for crustal evolution and their relationships to exogenous processes (Breitkreuz and Rocchi 2018).

At divergent plate boundaries, the stress conditions favor dikes intrusions because the regional stress axes in rift zones induce vertical extension planes (Gudmundsson 2012). Preexisting structures in the crystalline basement may control the structural framework of crustal extension, as they also possibly work as magma conduits (Giro et al. 2021). Therefore, dikes tend to be emplaced within or near the major mechanical anisotropy planes, such as faults, shear zones, and joints (Calegari et al. 2016; Santiago et al. 2020).

Dike emplacement can result from dilational and non-dilational mechanisms, which means, propagating through preexisting cracks or developing their pathway by hydraulic fracturing and/or regional stress (Delaney et al. 1986). Thus, dikes propagation depends on tensile balance between magma pressure, preexisting weakness planes, host rocks stress, and rheological proprieties (see section 5). The intrusions will be generated when the magma pressure exceeds the least compressive stress + tensile strength of the host rocks (Gudmundsson 1984).

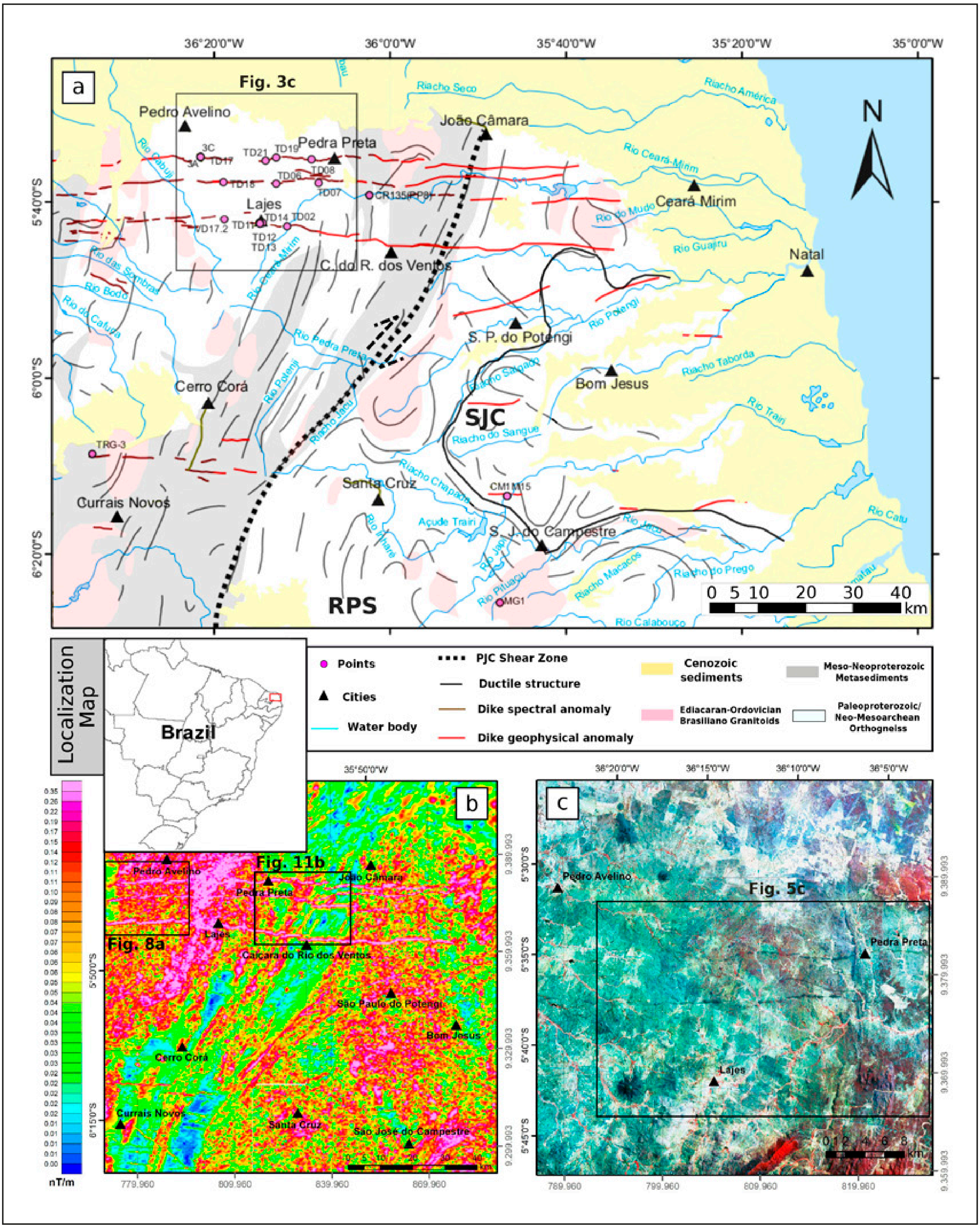

FIGURE 2: Remote sensing products of the study area, compiled from Vasconcelos (2018). (a) Simplified geological and localization map, adapted from Angelim et al. (2006) (SJC - São José do Campestre Domain; RPS - Rio Piranhas-Seridó Domain; SG – Seridó Group; PJC - Picuí-João Câmara); (b) CPRM (2008, 2010) aerogeophysical (Analytic Signal) map showing evidence of dikes as highly magnetic E-W anomalies; (c) Spectral map highlighting well-preserved and fresh E-W dikes around Lajes-RN (Landsat 8, 5/4/1 – RGB).

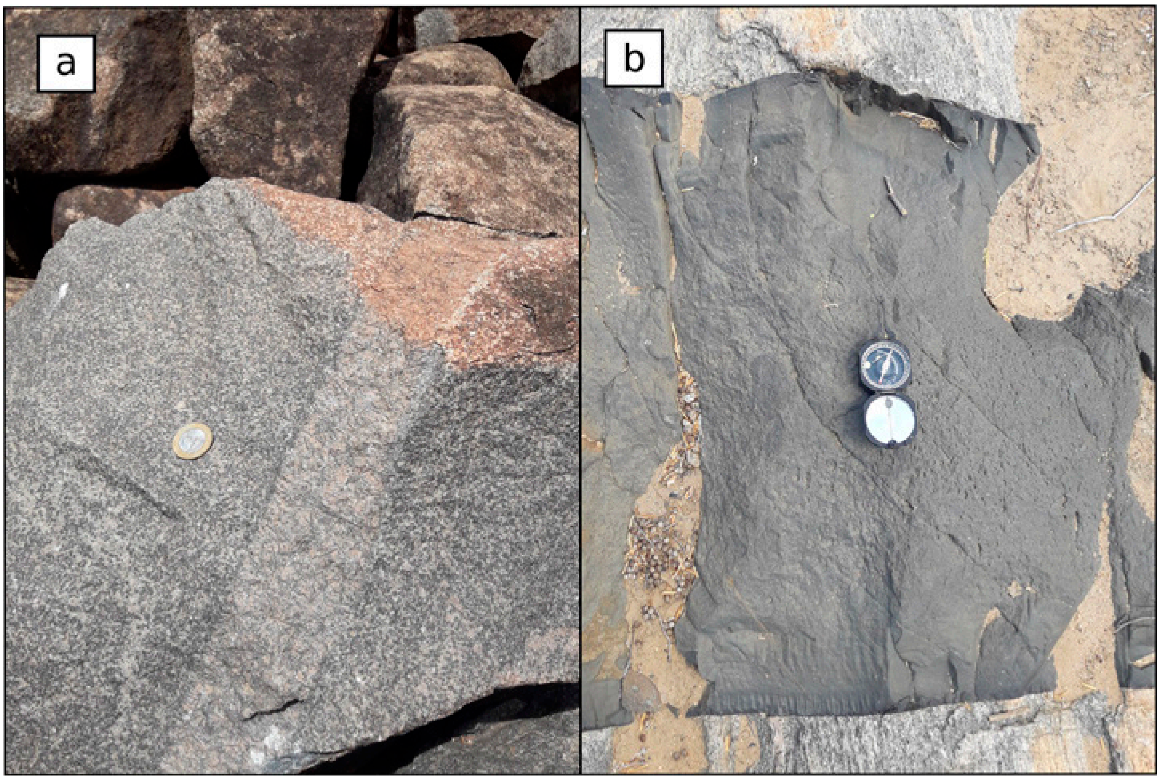

FIGURE 3: RPetrographic aspects of the eastern RCMDS dikes. Compiled from Vasconcelos (2018). (a) Unchilled leucocratic vein crosscutting medium-grained diabase; (b) Dike with aphanitic borders grading towards the amygdaloidal phaneritic center.

Dikes indicate the active stress fields during their intrusion. There is a consensus that dikes strike perpendicular to the least compressive axis (σ3) (Anderson 1951), also syn-emplacement variation in the stress orientation may promote slip movements on the dike's walls. Pollard (1987) distinguished three modes of dike propagation regarding the stress axes attitudes, which results in different geometries as illustrated in Figure 4a.

Segmentation structures along dikes indicate important parameters for stress fields evolution, propagation direction, and magma pressure (Figure 4) (Rubin 1995; Nicholson and Pollard 1985; Pollard 1987; Rickwood 1990; Hoek 1991; Correa-Gomes et al. 2001; Clemente et al. 2007; Ghodke et al. 2018). Hoek (1991) classified irregular and anastomosing/braided geometries, respectively, linked to the predominance of regional stress and high rates of magma flow during fractures development. This paper considers steps, bridges, and horns among morphological criteria of slip displacement (mode I / mode I-III), according to the classic interpretation of Pollard (1987) and Rickwood (1990) (Figure 4b). It is important to highlight that Schofield et al. (2012) and Magee et al. (2019) observed that some of these structures can be formed exclusively by pure shear (mode I) due to the coalescence of fractures. The *en echelon* pattern can be associated with variations in the syn-emplacement stress fields (Hoek 1991) (Figure 8c), steps and bridges generated due to this mechanism would have a consistent stepping direction (Magee et al. 2019) (Figure 4d).

In the study area, the RCMDS crosscut orthogonally to obliquely the host rocks' foliation and reactivation of preexisting weakness planes were observed only in meter-scale. An example of this latter process is shown by metric basement shear zones influencing the local striking in a few dikes (Figure 6b).

The attitude of the stress axes (σ1, σ2, σ3) were determined using Bingham statistics on the Stereonet 9 software. 36 dikes from remote sensing techniques indicate a sub-horizontal NNE-SSW least compressive axis (σ3 = 005 Az) (Figure 5c). Whilst, 145 measures from the Rio Salgado occurrences reconstruct a σ3 = 010 Az (Figure 5a), which agrees with their WNW-EWE prolongation (Figure 5c). In a few places where vertical sections had been available, dips around 80° and 60°, respectively, were observed to the north and south quadrant.

Non-filled joint systems near the dikes observed at Rio Salgado show similar stress axes position (Figure 5B). In addition, the framework of kilometer-scale fracture sets around Lajes-RN agrees with a least compressive axis from NNW-SSE to N-S (Figure 5b, c). On both scales, it is not possible to attest to their simultaneous generation, but they present notable correlations (Figure 5c). Preexisting fractures have key roles on magma intrusion, although there is no adjacent brittle structure controlling dikes emplacement in this case.

Determination of brittle fracturing phases is difficult due to structures overlapping, especially in the basement rocks. The RCMDS can be a good temporal marker to understand the successive stress regime in the Potiguar Basin, examples of brittle structures affecting the dikes occur as joints systems, strike-slip fractures, and brecciation zones (Oliveira and Gomes 1996; Bezerra et al. 2020).

Detailed mapping in the well-preserved dikes from Rio Salgado was performed to better understand the RCMDS' centimeter-scale patterns and their relationships with the basement fabric (Figure 6). These occurrences are the best

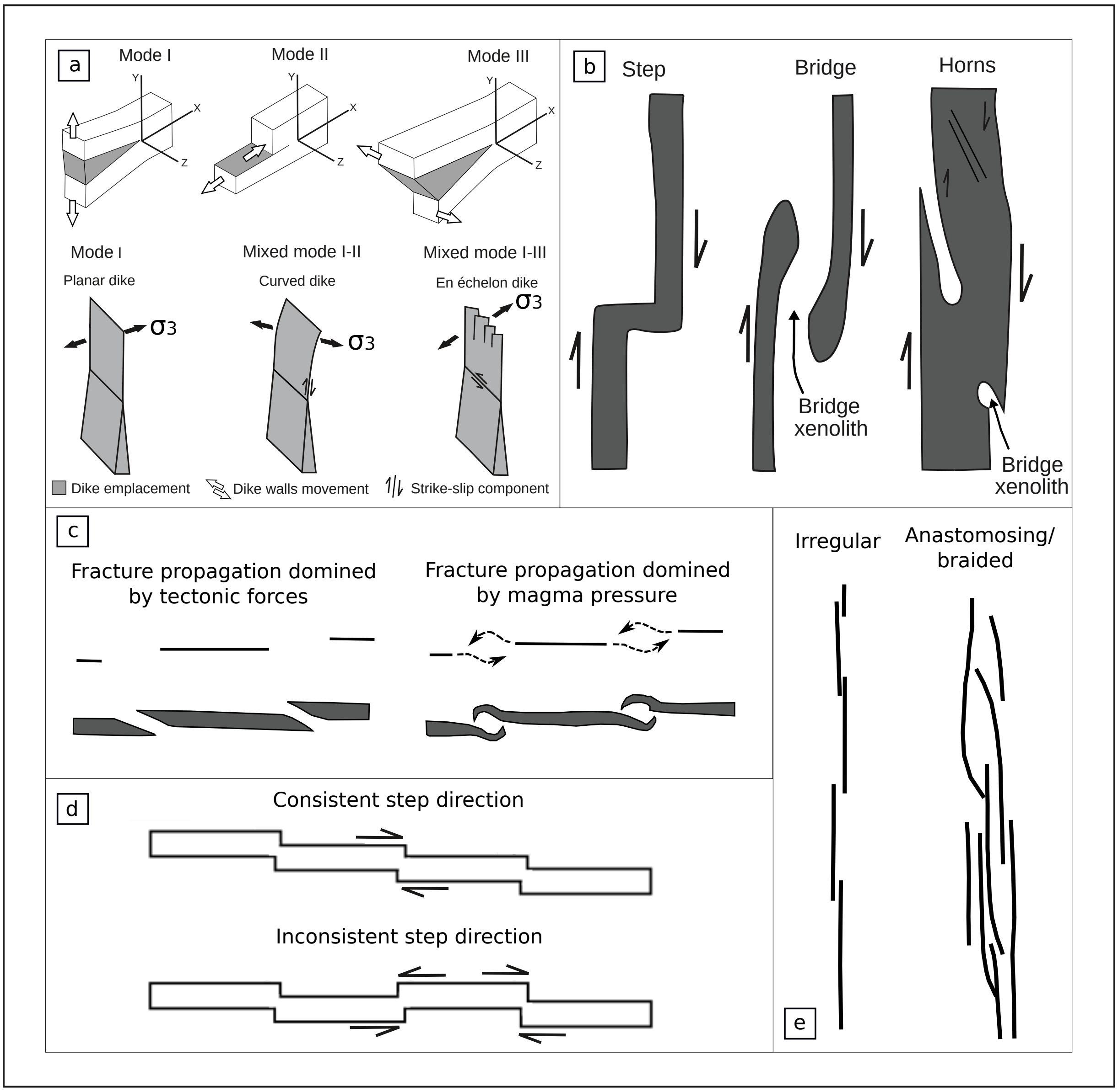

FIGURE 4: Dike morphological markers and their interpretation. Compiled from Nicholson and Pollard (1985), Pollard (1987), Hoek (1991), Rickwood (1990), Correa-Gomes et al. (2001), Clemente et al. (2007), Tomba (2012), Ghodke et al. (2018), Vasconcelos (2018), Magee et al. (2019). (a) Modes of dike fracturing and resulting geometries according to the stress fields attitude; (b) Morphological markers indicating slip components in dikes; (c) Fractures propagation by regional stress and influenced by fluid pressure; (d) Scheme of consistent and inconsistent stepping directions in *en echelon* dikes; (e) Classification of dike geometry.

exposition showing fresh contacts between the RCMDS dikes and orthogneissic host rocks, which present a complex kinetic interpretation.

The dikes' morphological styles vary from symmetrical to asymmetrical, from sharp and straight to anastomosing/ braided dikes with diverse shapes of *en echelon* patterns, steps, horns, bridges, and bridge xenoliths. Shifts in the syn-magmatic stress fields induced some fractures to an active simple shear regime (mode I-III). Also, the asymmetric fabric (variable thickness) observed along the RCMDS can be attributed to slip displacements on the dikes' walls (Clemente et al. 2007). Figure 7 shows examples of syn-emplacement strike-slip morphologies in the Rio Salgado dikes. Dextral markers are more recurrent, including *en echelon* dikes, steps, horns, and bridges, which characterize a prevalent dextral component (Figures 7a, b, c). Late fractures within some dikes also support a dextral component in the final stages of magma crystallization (Figure 4b, 7d, 8b). Oliveira (1993) have already interpreted a main N-S extension with a dextral strike-slip rate for the RCMDS propagation. Sinistral markers are present in a minor proportion, such as *en echelon* patterns, bridges, horns, and bridge xenoliths rotation (Figures 7e, f).

Excellent examples of *en echelon* dikes can be found affecting the basement rocks and preexisting E-W dikes (Figure 8a and b, respectively). Based on the most recurrent *en echelon* pattern observed from remote sensing techniques and fieldwork (Figure 8a, b), it is possible to deduce the least compressive axis repetitively deviating from NW-SE to N-S (Figure 8b).

A punctual occurrence of *en echelon* dikes expresses three main orientations in the stress fields during their intrusion, which imposed the structure evolution illustrated in Figure

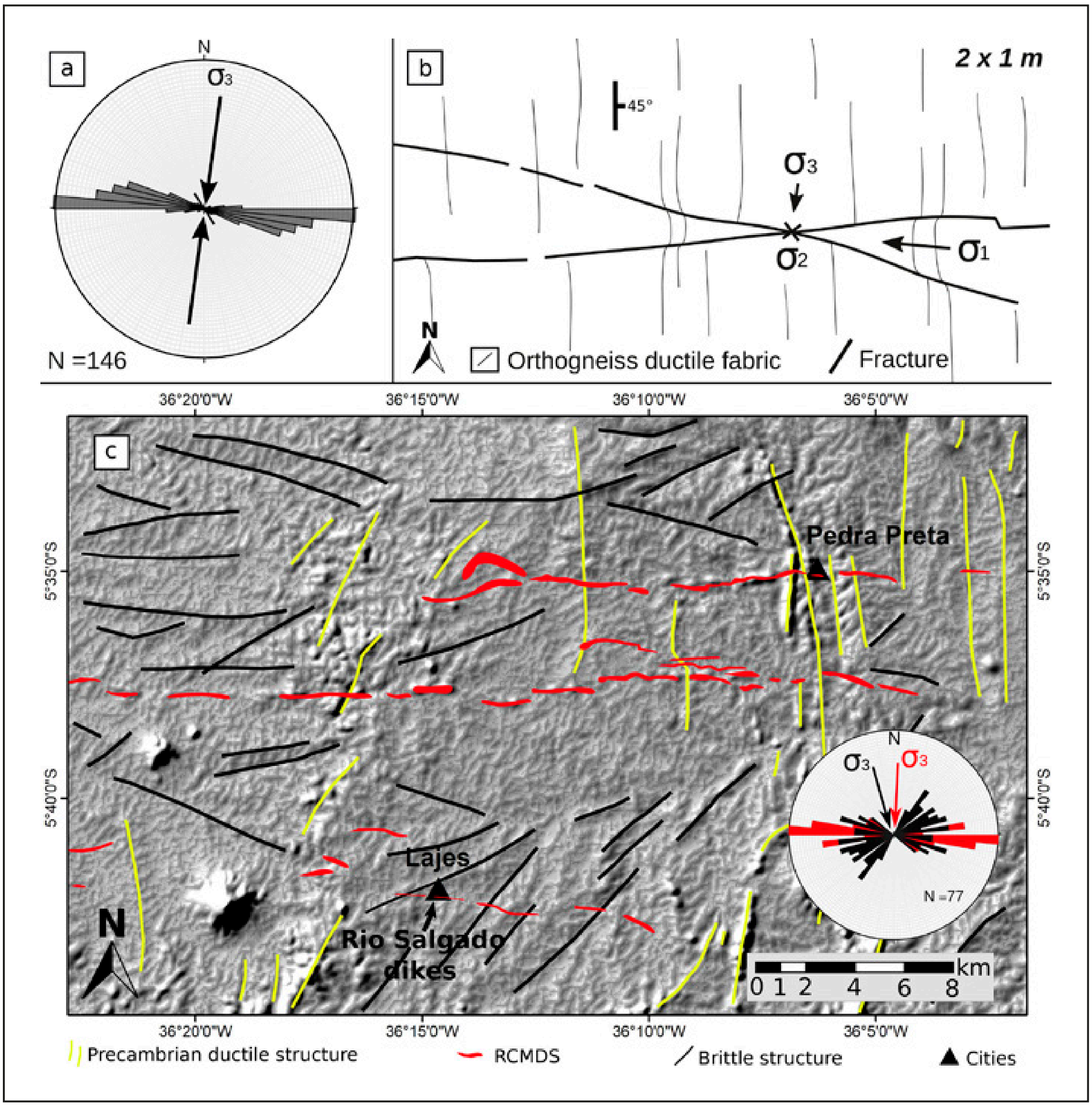

FIGURE 5 : Relationships between Rio Ceará Mirim Dike Swarm (RCMDS) syn-magmatic stress fields and the brittle and ductile structures. (a) Rosette diagram illustrating the orientation and average least compressive axis from the Rio Salgado dikes (σ3) (N = number of measurements); (b) Schematic illustration of fracture sets found near the Rio Salgado dikes presenting the stress axes interpretation; (c) Digital elevation map outlining the RCMDS dikes, brittle fracture sets and ductile structures around Lajes-RN. The outcropping dikes were extracted from spectral maps (figure 2c).

9a. The kinetic interpretation from these *en echelon* dikes indicates that they were formed by an active NW-SE extension in the early fracturing stages (Figure 9b). After changing the least compressive axis from NW-SE to N-S, fractures grew up and triggered the most recurrent stairs patterns observed in the eastern RCMDS tip (Figure 9c). Finally, the σ3 oriented towards NNW-SSE, impressing the dextral strike-slip markers observed in the Rio Salgado dikes and across Lajes-RN (Figure 9a, d). Also, late fractures within some dikes agree with a dextral displacement in the final stages of crystallization (Figure 7d, 8b).

Subvertical straight dikes with irregular patterns and sharp offsets are the most abundant styles in the eastern RCMDS, attributing predominance of host rocks stress as fractures propagator (Hoek 1991; Gudmundsson 2012). Nevertheless, some structures linked to magma pressure suggest hydraulic fracturing contribution for the RCMDS development, such as anastomosing/braided dikes and centimeter- to kilometer-scale rounded offsets (Figures 10a, b) (Nicholson and Pollard 1985; Hoek 1991). Also, the absence or erosion of the Potiguar Basin pre-rift sequences and some curvilinear dikes (Figure 5) evoke domal uplifts due to an overpressurized magma intruding into the crust (Oliveira 1993; Araripe and Feijó 1994; Ernst and Buchan 1997, 2001; Campbell 2001; Pessoa Neto et al. 2007). Thin sections from the edges of superimposed dikes exhibit microapophysis (Figure 10c, d). Considering the host dike (H) in a viscous-plastic physical state, the texture might be evidence of a greater internal magmatic pressure in the emplacing dike (E).

5. Mechanical model for fractures development

Fracture development and reactivation involve a combination of regional stress field (σ1, σ2, σ3), given by stress ratio (ϕ = σ2-σ3 / σ1-σ3 = 1+cos2θ2 / 1+cos2θ1), and driving pressure ratio (R' = Pf-σ3 / σ1-σ3 = 1+cos2θ2 / 2) (Delaney et

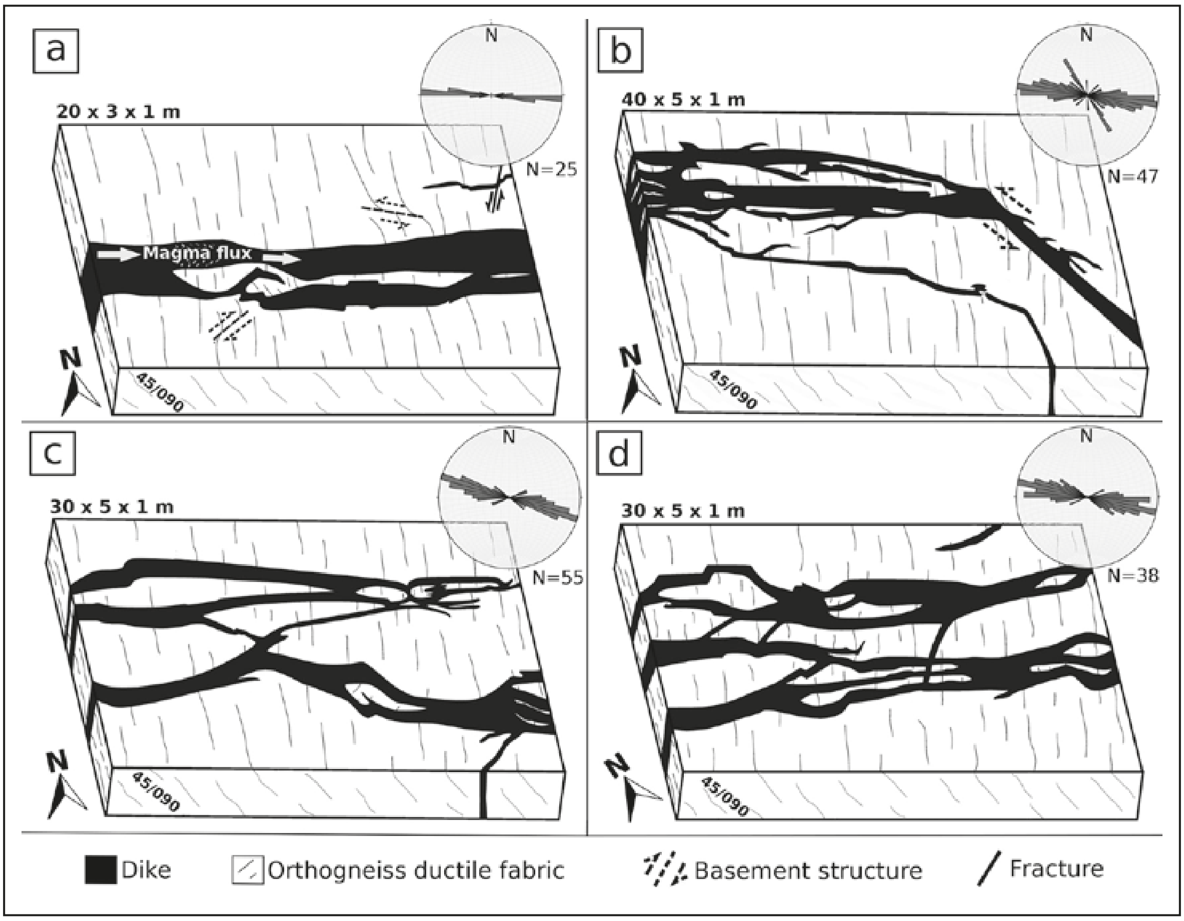

FIGURE 6: Schematic block diagrams for the Rio Salgado dikes. Compiled from Vasconcelos (2018) (N = number of measurements). (a) Straight dike with imbrication of plagioclase crystals indicating local magma flow from W to E; (b) Anastomosing dike. The eastern offset deflects to NW-SE due to a meter-scale secondary basement shear zone reactivation; (c) Anastomosing dike reassembling curvilinear shapes; (d) Anastomosing dike sometimes forming curvilinear shapes.

al. 1986; Baer et al. 1994; Jolly and Sanderson 1997). Stress ratio (ϕ) is a non-directional value that describes the relative magnitudes of the stress axes, while the driving pressure ratio (R') corresponds to the relative proportion between fluid pressure (Pf) and stress (Martínez-Poza et al. 2014; Stephens et al. 2018). Dilation tendency (Td) demonstrates the propensity of potential fracture planes to reactivate through pure shear, and slip tendency (Ts) depends on the frictional characteristics of the host rocks and determines the propensity of any fracture orientation to reactivate by strike-slip displacements (Ferrill et al. 1999). While a high dilation tendency presumes reactivation through normal dilation, a high slip tendency indicates opening through simple shear. Fracture susceptibility (Sf) represents the potential planes that can lead to fluid-induced reactivation in a particular stress condition (Mildren et al. 2002; Stephens et al. 2018; Bhowmick and Mondal 2021).

We used the Rio Salgado occurrences to calculate the stress states influencing dikes emplacement, because they show a vast number of measures and greater strike variation compared to the regional frame. Due to the poor exposition of the vertical section, we randomly distributed the dikes' dips between 90° and 60°, as observed in a few examples in field. Girdle distributions using Kamb's method were applied in the Stereonet software to obtain the θ angles from dikes' poles clusters ($\theta1$ = 51°, $\theta2$ = 57°) (Figure 11a). $\theta1$ and $\theta2$ are, respectively, the angle between the σ2 and σ1 in relation to the perimeter of the dilational ellipse (Jolly and Sanderson 1997). Since the range of dikes attitude is known, it is possible to determine the relative stress and fluid pressure using the ϕ and R' parameters according to the method of Jolly and Sanderson (1997). For modeling, we have considered 1.0 km depth to determine the magnitude of the subhorizontal intermediate compressive axis (σ2) during fracture formation. If σv = σ2 = hρg (h = depth of fracturing in orthogneiss, ρ = approximate bulk density of crust (2,700 kg/m3) and g = 9.8 m/s2), σ2 is approximately 26.4 MPa. The development of extensional fractures requires a low differential stress (σD = σ1 - σ3) (4T < σD < 5.66T). Considering σD = 5T (T is the host rock tensile strength; Sibson 2003), we estimate the tensile strength of the host rock at 1.0 km depth to be 3 MPa, giving σD = 15 Mpa. Host rock rheological proprieties such as cohesion (C = 0) and static coefficient of friction (μs = 0.6) were considered according to Fossen (2010).

Knowing these parameters, the Fractend code (Healy 2017) has been used to obtain the lower-hemisphere equal-area projections of dikes' pole data from 145 dikes at Rio Salgado, accentuating the slip tendency (Ts), dilation tendency (Td), and fracture susceptibility (Fs). The stress ratio (ϕ = 0.74) and driving pressure (R' = 0.29) derived in the model indicate a NNE-SSW vertical extension with σ1= 30.4 MPa; σ2 = 26.4 MPa; σ3 = 15.4 and Pf = 19.8 MPa. Figure 11 was

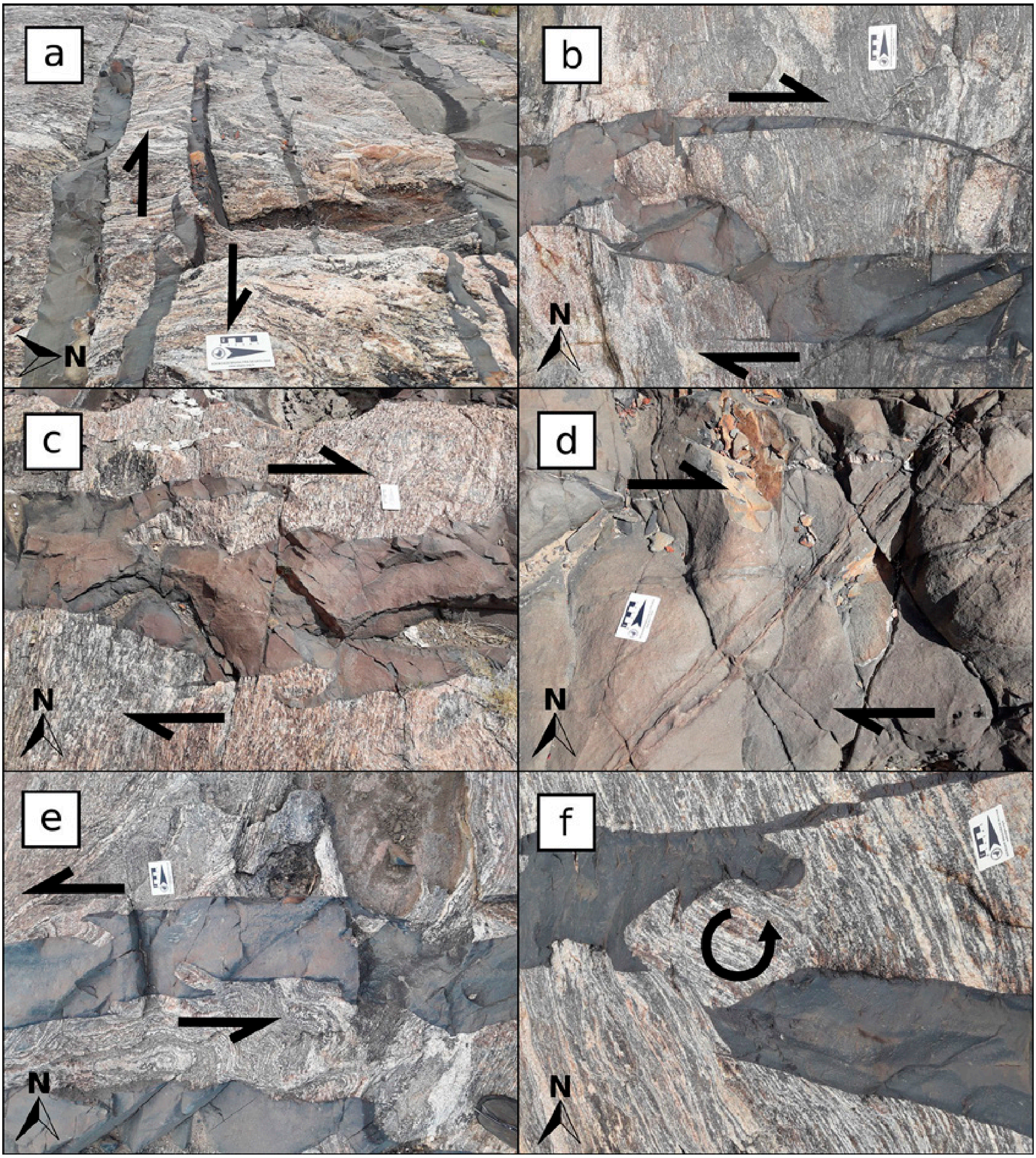

FIGURE 7: SMorphological strike-slip markers in the well-preserved dikes from Rio Salgado. (a) *En echelon* dikes with dextral horns. Notice the vertical sections showing nearly vertical dips; (b) Dextral horns; (c) Dextral horns; (d) Late fractures indicating dextral shear; (e) Sinistral horns; (f) Counterclockwise rotation of bridge xenolith.

constructed using the stress state conditions influencing dikes emplacement as discussed above.

Normalized Ts and Td can be used to predict the potential failure planes that reactivate under the specific stress state (Figure 11 b,c). The warm zones consistent for high dilation tendency (Td = 0.8-1.0) values in part overlap the warm zones for high slip tendency values (Ts = 0.8-1.0). Dikes' pole data within the warm zone consistent with high dilation and moderately high slip tendency will certainly encounter high fracture susceptibility (Figure 11d) (Bhowmick and Mondal 2021). Notably, the dikes' poles clusters are majorly located in zones of high dilatation, suggesting a greater participation of normal dilatation rather than strike-slip as observed in the morphological analyses.

These occurrences indicate Pf < σ2, which predicts a limited range of fracture orientations that can be reactivated (Jolly and Sanderson 1997; Stephens et al. 2018). In case

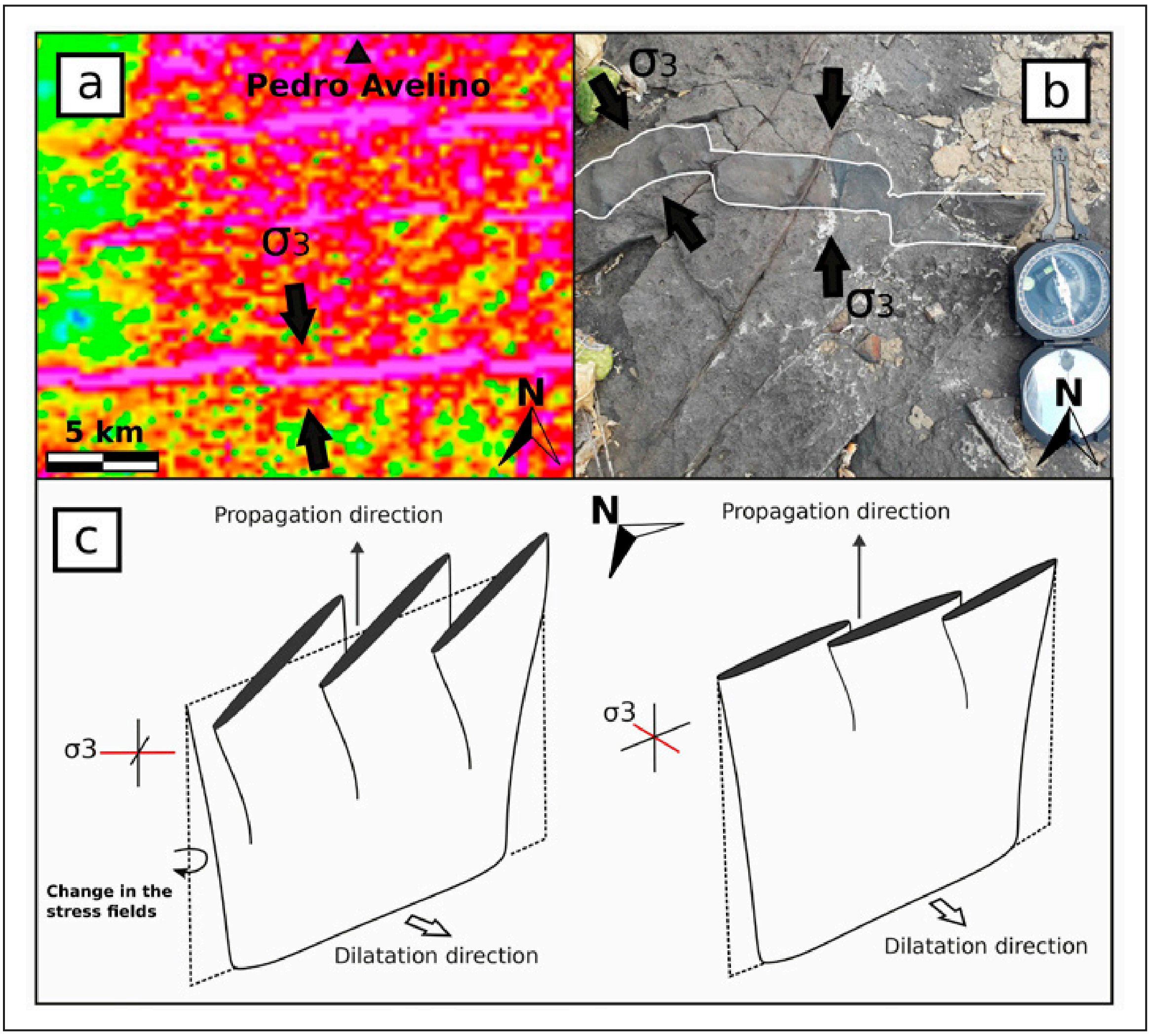

FIGURE 8: *En echelon* dikes in the study area. (a) *En echelon* dikes showing an NNW-SSE least compressive axis (σ3); (b) *En echelon* dikes crosscutting a preexistent E-W dike from Rio Salgado. Notice the apparent σ3 variation. The compass points to the north; (c) Interpretation of the stress field evolution in *en echelon* dikes according to Hoek (1991).

of fractures generated under conditions of σ3 < Pf ≤ σ2, the dilation zone outline the dikes' poles forming an ellipse near the σ3 axis, and mode I opening are favored parallel to the σ3 axis. Almost all of the considered dikes could intrude in this condition. Just a few dikes are not predicted due to the reactivation of preexisting fractures (Figure 11e). In a low-deviatoric environment, restricted variations in intrusion orientation are traditionally interpreted as local rotations of the stress axes, which may be caused by the effects of mechanical layering (Gudmundsson 2011), or preexisting faults and fractures (Fossen 2010; Magee et al. 2013). A similar investigation across intrusions associated with the EQUAMP could reveal stress states phases for this Early Cretaceous magmatic activity in Northeast Brazil.

6. Geodynamic significance of the RCMDS

The Northeast Brazilian Rift System (NBRS) comprises a series of continental rifts throughout a thousand kilometers, from the Potiguar to the Reconcavo Basins. Precambrian rocks host them along a main N-S direction, which is deflected northward to NE-SW in the Cariri-Potiguar trend (Matos 1992; Castro 2011). This region experienced a mechanical balance between the opposite propagating rift tips of the South and Equatorial Atlantic (Matos et al. 2021).

Magmatism was an active factor for the Potiguar Basin from Early Cretaceous to Middle Miocene (Bezerra et al. 2020; Matos 1992, 2000). Temporal association between the Potiguar Basin and RCMDS have been widely discussed, being the dikes useful for tectono-structural reconstruction in the initial rifting phase (Matos 1992; Bellieni et al. 1992). Oliveira (1993) found NE-SW reactivated Precambrian shear zones overlapping dikes and established a temporal correlation between the Potiguar Rift installation and the RCMDS intrusions. Melo et al. (2021) detected dikes with displacements of a few kilometers when they crosscut some N-S shear zones, suggesting that the shear zone was reactivated at some moment after the intrusion. Furthermore, volcanoclastic rocks had been described in the basal Pendências Formation. These relationships evoke magmatic activity in the northern Cariri-Potiguar rift valley from pre- to syn-rift phase of the Potiguar Basin.

The Potiguar Basin rift phase, from Eobarresian to Eobarremian (140-125 Ma), involves a tectonic regime with high NW-SE crustal stretching and basement subsidence (Matos 1992; Melo et al. 2016). The Carnaubais and

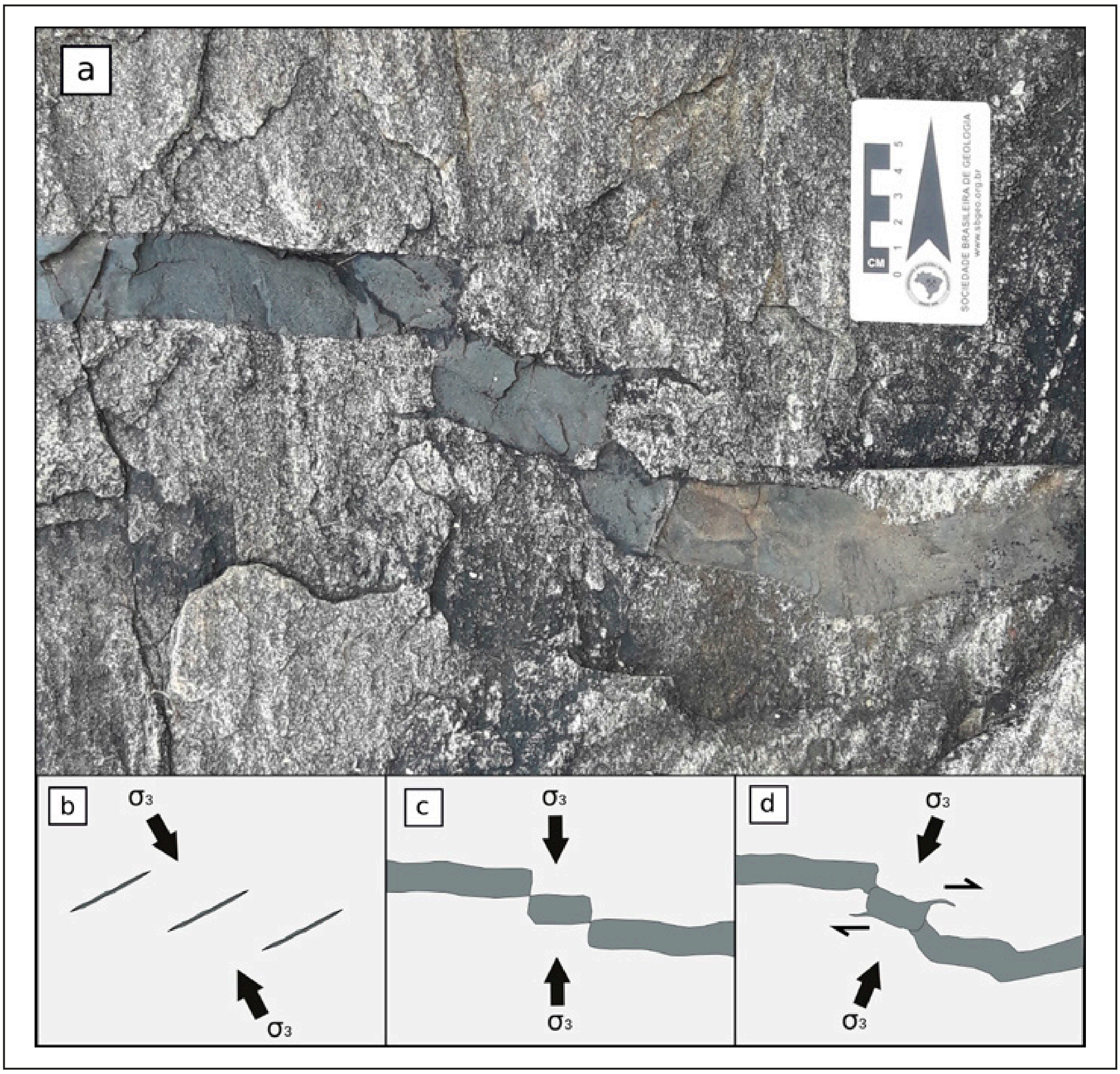

FIGURE 9: Interpretation of syn-emplacement variations in the least compressive axis from a punctual case of *en echelon* dikes at Rio Salgado. (a) Aspects of the interpreted *en echelon* dikes in the field. The card points to the north; (b) Early fractures formed by an active NW-SE extension; (c) Classic geometry of *en echelon* dikes after changing the least compressive axis from NW-SE to N-S; (d) Current disposition from the illustrated *en echelon* dikes, indicating a final NE-SW extension with dextral displacements.

Apodi Fault Systems controlled the onshore rift (Figure 1c), producing half-grabens divided by NE-SW oriented basement highs and transfer faults accommodating displacements between NE-SW rift sections (Matos 1992; Castro et al. 2012). The main depocenters achieve 6000 meters of depth, and the Pendências Formation was deposited at continental environments (Araripe and Feijó 1994; Pessoa Neto et al. 2007).

Subsequent lower thermal subsidence allowed the deposition of transitional-drift sequences, and post-rift reactivation took place in the NE-SW rift structure and basement rocks (Lopes et al. 2018). Matos (1992) recognized that the NW-SE extension ceased during the Aptian, dropping an aborted continental rift system in the Potiguar region; the regional NBRS stress fields evolved from NW-SE (145 - 130 Ma) to E-W (129 - 125 Ma).

Following the Potiguar Basin rift phase, a slight E-W dextral strike-slip regime was installed along the Brazilian equatorial margin from Eo-Barremian to Eo-Aptian (125-115 Ma) (Matos 2000). Castro et al. (2012) detected anomalous gravity lineaments at the Potiguar Rift boundaries, which indicate a dextral component for the onshore Potiguar Rift development. Moreover, the syn-rift *en echelon* Bica, Algodões, and Apodi grabens agree with dextral displacements (Castro and Bezerra 2015).

According to Matos (1992), the mismatch between the eastern RCMDS E-W dikes and the northern NBRS' NW-SE extension represents the tectonic behavior inherited at the north of Patos shear zones (Figure 12). Françolin and Szatmari (1987) suggested that the Patos and Senador Pompeu shear zones mitigated a pre-Aptian clockwise rotation in the South America plate, imposed because the South Atlantic drift was greater than the Equatorial sector (Peate 1997). Thus, the RCMDS E-W dikes have been explained due to this interaction with preexisting regional E-W discontinuities, which changed the main NE-SW extension to N-S.

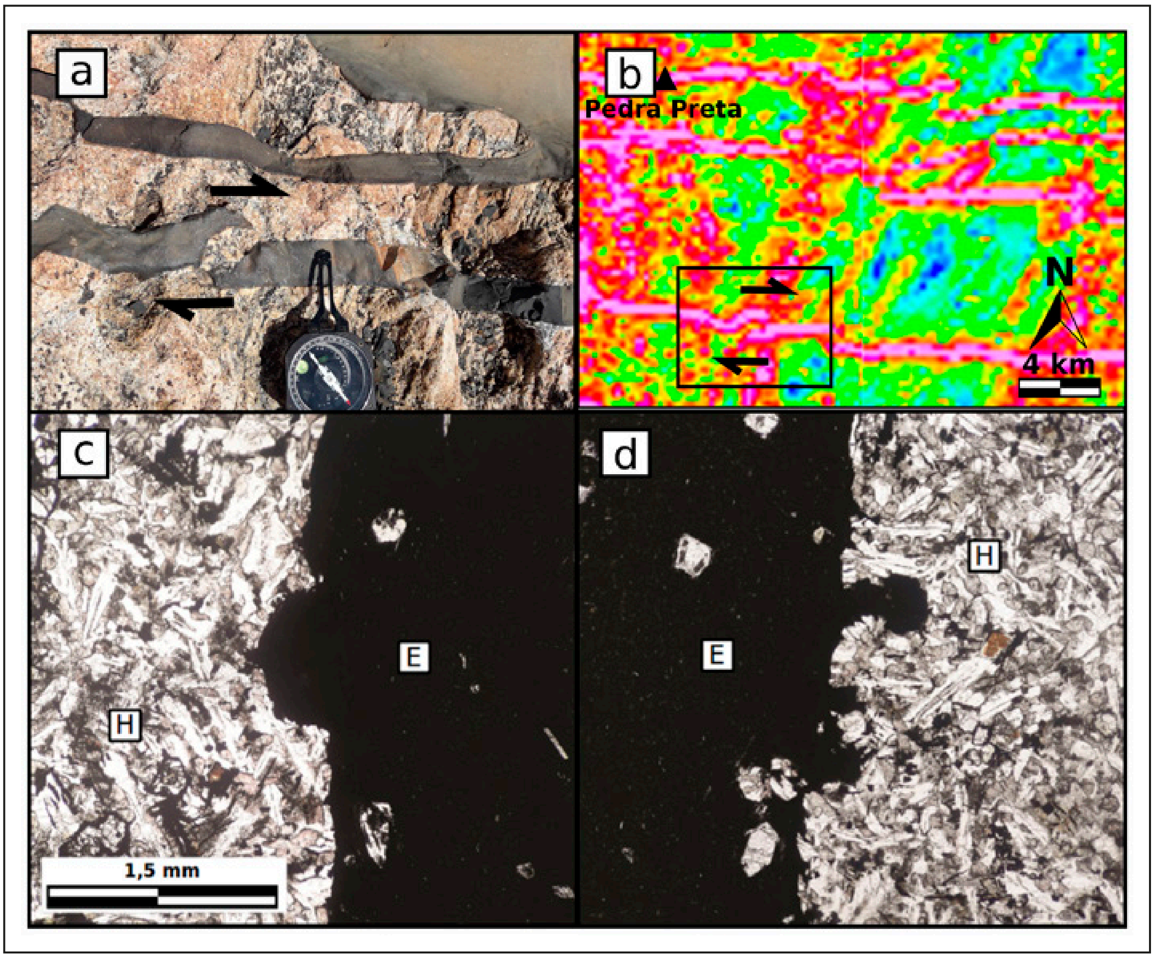

FIGURE 10: Structures indicating the contribution of magma-induced hydraulic fracturing for the dike propagation. (a) Centimeter-scale rounded offsets in the Rio Salgado dikes. The compass points to the north; (b) Kilometer-scale rounded offsets; (c,d) Microapophysis at the contact of an aphyric dike (E: emplacing) crosscutting preexisting phaneritic hipocrystalline dike (H: host) - parallel nicols.

Ernst and Buchan (2001) described different geometries for large dikes swarms, where linear shapes are associated with rifting processes and radial orientations form under the influence of mantle plumes. A continuous giant arcuate dikes swarm, up to 1000 kilometers in length, were mapped across the Borborema Province and Parnaíba Basin (Figure 12) (Hollanda et al. 2019; Melo et al. 2021). The great size and short span of magmatic activity fit these occurrences as a Large Igneous Province triggered by the Santa Helena plume (Hollanda et al. 2019; Matos 2021). The spatial geometry of such giant swarms interacts with thermomechanical proprieties of the crust within they intrude, including preexisting weakness planes, regional stress fields, and isostatic accommodations caused by domal uplifts related to a mantle plume attachment in the base of the lithosphere (Ernst and Buchan 1997, 2001; Ernst 2014).

O'Connor et al. (2012) proposed a plate-tectonic-controlled cycle for the Atlantic Ocean opening, where hotspot trails are regulated by deep-sourced mantle plumes and plate dynamics; Santa Helena in the equatorial portion and Tristan da Cunha in the southern. According to Peace et al. (2020), tectonic forces led the South Atlantic rifting and it is not an example of a plume-centered breakup. Some arguments used by the authors include the short evidence of LIP uplift, the high Ti content of volcanic rocks suggesting lithospheric mantle sources, the rifting driven by regional stress, and the magmatism probably not derived from a single volcanic center. Although, for Matos et al. (2021) there are spatial and temporal relationships from the Santa Helena and Tristan da Cunha hotspots that challenge the idea of passive rifting, even showing a strong influence of shallow crustal processes, such as thermal and structural inheritance.

The participation of mantle plumes has been proposed to support the NBRS and RCMDS development, also playing an important role in plate drifting (White and McKenzie 1989; O'Connor and Duncan 1990; Matos 2000; Ngonge et al. 2016; Hollanda et al. 2006, 2019). Isotopic and trace element models indicate lithospheric sources for the RCMDS and EQUAMP, but some OIB-dikes would indicate the contribution of mantle plumes (Hollanda et al. 2006, 2019). Ngonge et al. (2016) suggested that tectonic forces promoted passive rifting and the resulting asthenospheric up-welling was responsible for the RCMDS magmatism. However, they do not exclude a rifting process induced by edge-driven convection, or due to the combination of both mechanisms. Resorting of several isotope data, Macêdo Filho and Hollanda (2022) observed that both High Ti (HT) and Low Ti (LT) tholeiites from EQUAMP require the involvement of variable proportions of an enriched component that can be either the metasomatized upper mantle itself (case of LTs) or a deep plume (case of HT), with some crustal contamination. Also, these authors emphasize

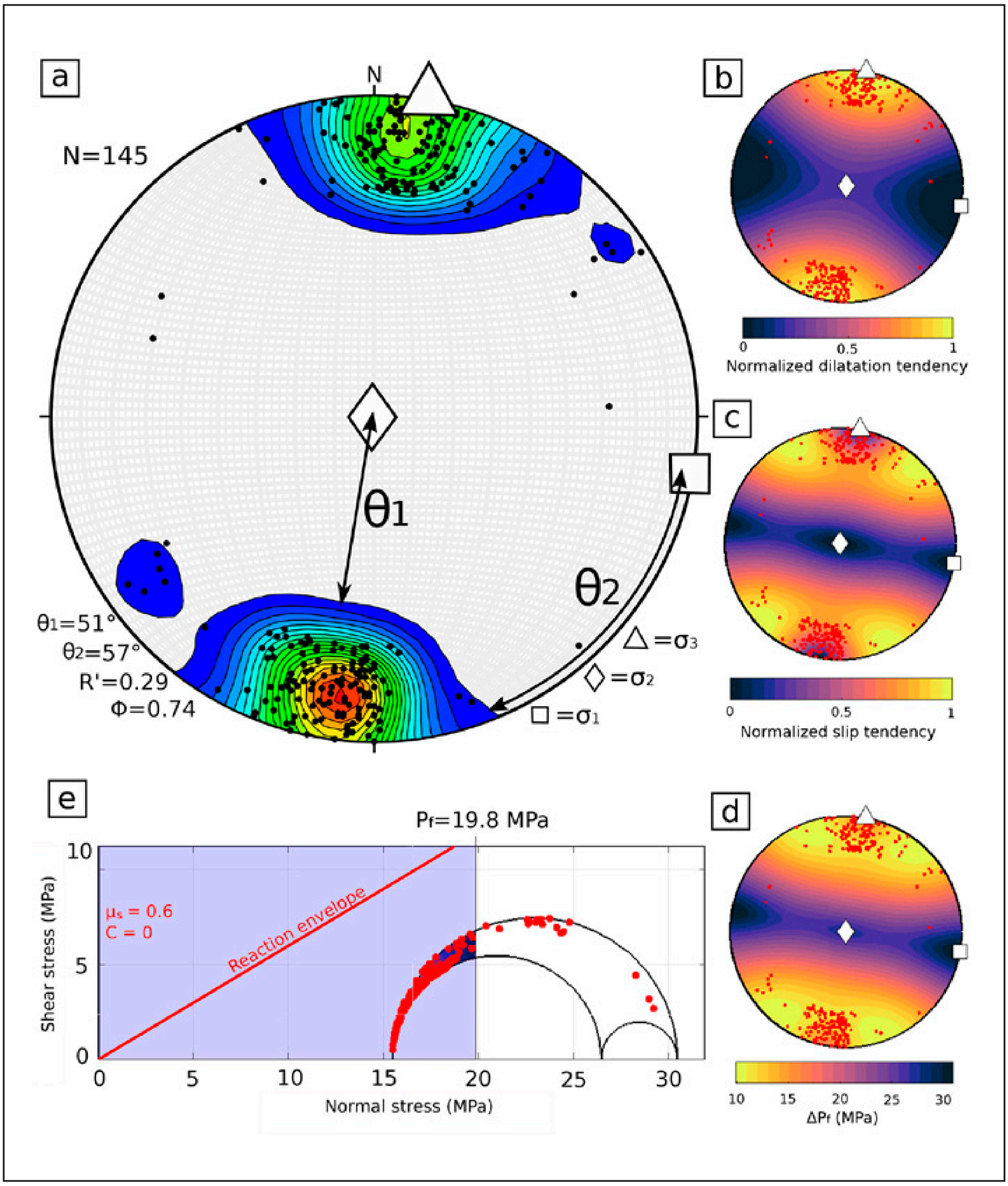

FIGURE 11: Stress states obtained from the Rio Salgado dikes' orientation data. (a) Lower hemisphere equal-area projection of the dikes' poles clusters according to Kamb's methods; Lower hemisphere equal-area projection for dilation tendency (b), slip tendency (c) and fracture susceptibility (d) in the specified conditions; (e) 3-D Mohr circle diagram. Red dots represent dike poles data and the red line forms the reactivation envelope for cohesionless fractures.

the role of tectonomagmatic activity in the South Atlantic rifting and demonstrate strong geochemical similarities between the EQUAMP and the Paraná-Etendeka LIP. In both mantle plume and asthenospheric convection models, a long-lived thermal anomaly should have influenced the base of the lithosphere to cause the extensive mantle melting (Hollanda et al. 2006).

Oliveira (1993) associated the RCMDS magmatism as a thermomechanical factor for the Potiguar Rift installation. Mello (1987) calculated insufficient alpha (α) and beta (β) crustal stretching for the onshore Potiguar Rift development. Buck et al. (2006) demonstrated experimentally that sublithospheric magma facilitates the rifting process decreasing the necessary yield stress for lithosphere failure. As reported by the authors, dikes represent a type of accretion in divergent environments, where intrusive magmatism contributes to the extension process. Perhaps this process could explain the low crustal stretching locally found and is validated by the low/intermediate contribution of fluid pressure for the eastern RCMDS dikes propagation.

Knowing the NBRS geological setting in the Early Cretaceous, the tectonic processes influencing the obtained stress states condition can be proposed; despite the short lack of geochemical, geochronologic, and structural study along the EQUAMP dikes and the difficult acquisition of precise

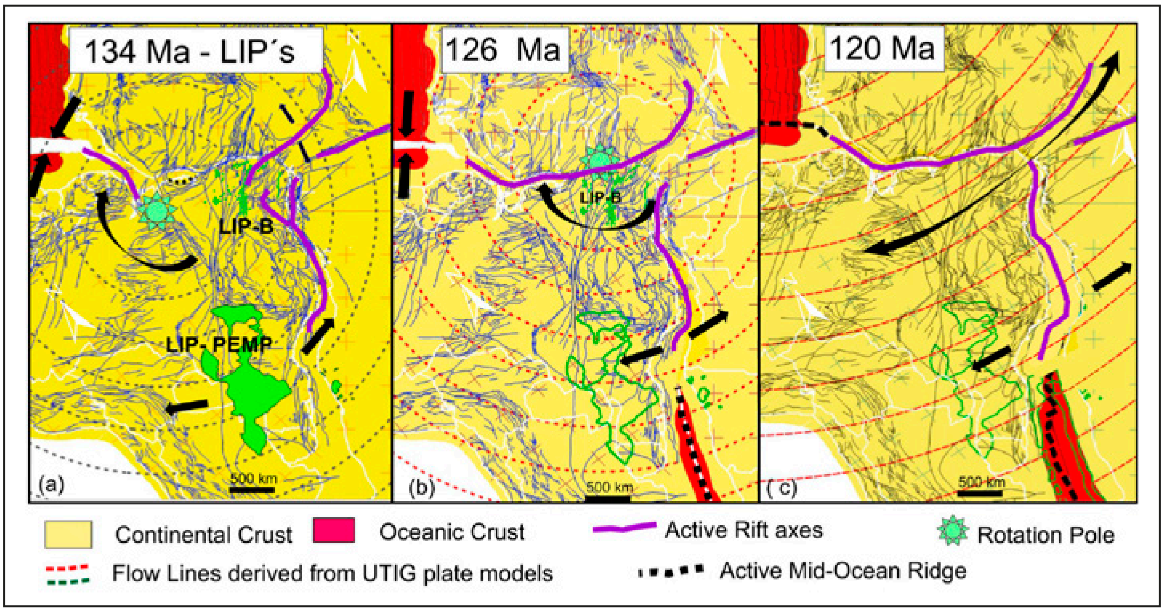

FIGURE 12: Reconstructions of the pre-Aptian clockwise rotation in the Atlantic Ocean opening at 134, 126, and 120 Ma. Compiled from Matos et al. (2021). The black arrows indicate regional movements. (a) Plate reconstruction during the development of Cretaceous LIPs: Paraná-Etendeka Magmatic Province (LIP-PEMP) and the EQUAMP, or Borborema Magmatic Province (LIP-B) according to Matos (2021); (b) Variation in the rotation pole to Northeast Brazil. The EQUAMP seems to be still be active at this moment; (c) Plate reconstruction at 120 Ma., when Africa and South America assume a straight divergent movement.

chronostratigraphic correlation between sedimentary sequences and associated magmatism. Using airborne magnetometry and gamma-spectrometry data, Melo et al. (2021) mapped the EQUAMP toughly and observed that the western RCMDS dikes present an active NW-SE least compressive axis, rather than exploit crustal weakness planes for magma propagation. These authors observed that the NE-SW striking dikes from the western RCMDS extend hundreds of kilometers across the Borborema Province and, contrary to what was thought, they crosscut shear zones at high angles, demonstrating a great influence of an active stress field during their emplacement. In addition, Fernandes et al. (2020) described NE-SW trending dikes crosscutting the E-W Pernambuco shear zones in the Parnaíba Basin eastern border. Therefore, the upper crustal inherited structure has been shown to have little control over the emplacement of this arcuate giant dike swarm, reinforcing the idea of matle processes. An active NW-SE extension seems to repetitively influence the extension in the eastern RCMDS, depicted by *en echelon* dikes affecting the basement rocks and preexisting E-W dikes. Although, this variance can not explain the NNE-SSW least compressive axis and dextral displacement in the Rio Salgado dikes, reassembled by their average orientation and the most expressive occurrences of morphological markers. Some mechanisms can be proposed to support this late dextral phase in the eastern RCMDS: (I) Local behavior from host rocks facing the main N-S extension; (II) Effect of the dextral displacement along the Brazilian equatorial margin after the Potiguar Basin rift phase (Matos 1992, 2000); (III) Response to the pre-Aptian clockwise rotation of South America during Atlantic Ocean opening (Françolin and Szatmari 1987; Matos et al. 2021); (IV) Isostatic accommodation from regional uplifts associated to mantle plumes (Ernst and Buchan 1997, 2001; Ernst 2014; Hollanda et al. 2019).

7. Conclusions

The eastern RCMDS E-W dikes truncate the regional NE-SW Precambrian foliation, ranging from a few centimeters to 150 meters thick, in some cases, achieving tens of kilometers in length. The dikes are composed of basalt-diabase with aphyric chilled rocks near the dikes' walls, grading to medium-grained amygdaloidal phaneritic centers. Morphological styles vary from symmetrical to asymmetrical, from sharp and straight to anastomosing dikes with several shapes of *en echelon* patterns, steps, horns, bridges, and bridge xenoliths.

The RCMDS provides an excellent opportunity for syn-magmatic structural analysis, especially due to their weathering preservation, attitude homogeneity, and fresh relationships with the host rocks. It is possible to discern three extensional phases due to syn-emplacement reorientation in the stress fields. The early fractures were formed by a predominant NW-SE least compressive axis, which afterward changed to N-S. *En echelon* dikes imply that the main N-S least compressive axis has repetitively oriented to NW-SE, even after the intrusion of E-W dikes. The final stage was interpreted as an NNE-SSW least compressive axis, corroborating with the predominance of dextral strike-slip markers in the Rio Salgado dikes and their average orientation.

Fractal morphological patterns indicate that the propagation mode in the eastern RCMDS is predominantly linked host rocks stress, however, there is evidence of magma-induced hydraulic fracturing contribution. Mechanical models indicate that the Rio Salgado dikes were emplaced in deviatoric stress with low/intermediate fluid pressure ($P_f < \sigma 2$), which is in agreement with the described morphological patterns.

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Authorship credits

Author	A	B	C	D	E	F
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MMMS						
JLO						

A - Study design/Conceptualization **B** - Investigation/Data acquisition
C - Data Interpretation/Validation **D** - Writing
E - Review/Editing **F** - Supervision/Project administration

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