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Quaternary reactivation of a basement structure in the Barreirinhas Basin, Brazilian Equatorial Margin

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ABSTRACT

The Pirapemas Lineament is a remarkable 200-km-long, NE–SW trending structure in the Barreirinhas Basin, one of the several Brazilian coastal basins. This lineament splits the study area in two sectors of distinctive morphology, drainage patterns, and sedimentary covers. Terrain northward of the lineament presents a smooth topography with sub-parallel to sub-dendritic drainage patterns, whereas a dissected plateau characterized by incised valleys and rectangular drainage pattern occurs southward, suggesting a structural control by joints and faults. Geological field data, crossed with thermal luminescence (TL) and optically stimulated luminescence (OSL) dating, revealed that the surface southward of the lineament consists mostly of Miocene and late Pleistocene sedimentary deposits, represented by the Barreiras Formation and the Post-Barreiras sediments, respectively. In contrast, relatively younger sands mantle most of the northward terrain, as indicated by well-preserved paleodune deposits that grade into active aeolian dunes of the Lençóis Maranhenses National Park. Geomorphological and geological data analysis suggests that the northern sector is under the effect of subsidence, proving that the Pirapemas Lineament is an active agent modeling the landscape in the region. Geophysical data (gravity and seismic) confirm that such a structural feature is the surface expression of an active deep-seated basement fault.

Introduction

The Brazilian Equatorial Margin originates from extension and strike-slip movements related to rifting and early opening of the South Atlantic Ocean. The main rifting phase took place during the early Cretaceous and resulted in several coastal sedimentary basins (Szatmari et al., 1987). Tectonic subsidence progressively decreased, but fault reactivation might have taken place several times after rifting, affecting sediment deposition even during the Quaternary (Azevedo, 1991). An increasing amount of information has been gathered over the last decade illustrating the importance of fault reactivations to the genesis Cenozoic sedimentary succession in many of the Brazilian equatorial marginal basins (*e.g.,* Costa et al., 2001, Bemerguy et al., 2002; Rossetti et al., 2008a,b). However, the complex tectonic evolution of these basins still warrants additional data to discuss further the significance of fault reactivations during the later stages of their geologic history.

This study aims to investigate the geological nature of the Pirapemas Lineament's, in the onshore portion of the Barreirinhas Basin, State of Maranhão, northeastern Brazil. The term "lineament" is used herein as proposed by O'Leary et al. (1976), meaning "a mappable, simple or composite linear feature of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship, and which differs distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon". This NE–SW trending photogeological structure extends from the town of Pirapemas for about 200 km and ultimately disappears under the Lençóis Maranhenses National Park field dunes, in the vicinity of the town of Barreirinhas (Fig. 1). Rodrigues et al. (1986) singularly provided a broad identification of this structural feature based on visual analysis of Landsat and radar images. However, a full characterization of this lineament, with examination of its surface and sub-surface expression, remains to be carried out, specifically to investigate the possible influence of this feature on the development of Cenozoic sedimentary deposits. This focus is crucial to analyze whether the Pirapemas Lineament represents solely a surface feature, an old stable structure of the basement, or a feature that remained active throughout the Cenozoic with a possible influence on the modern landscape evolution. This study

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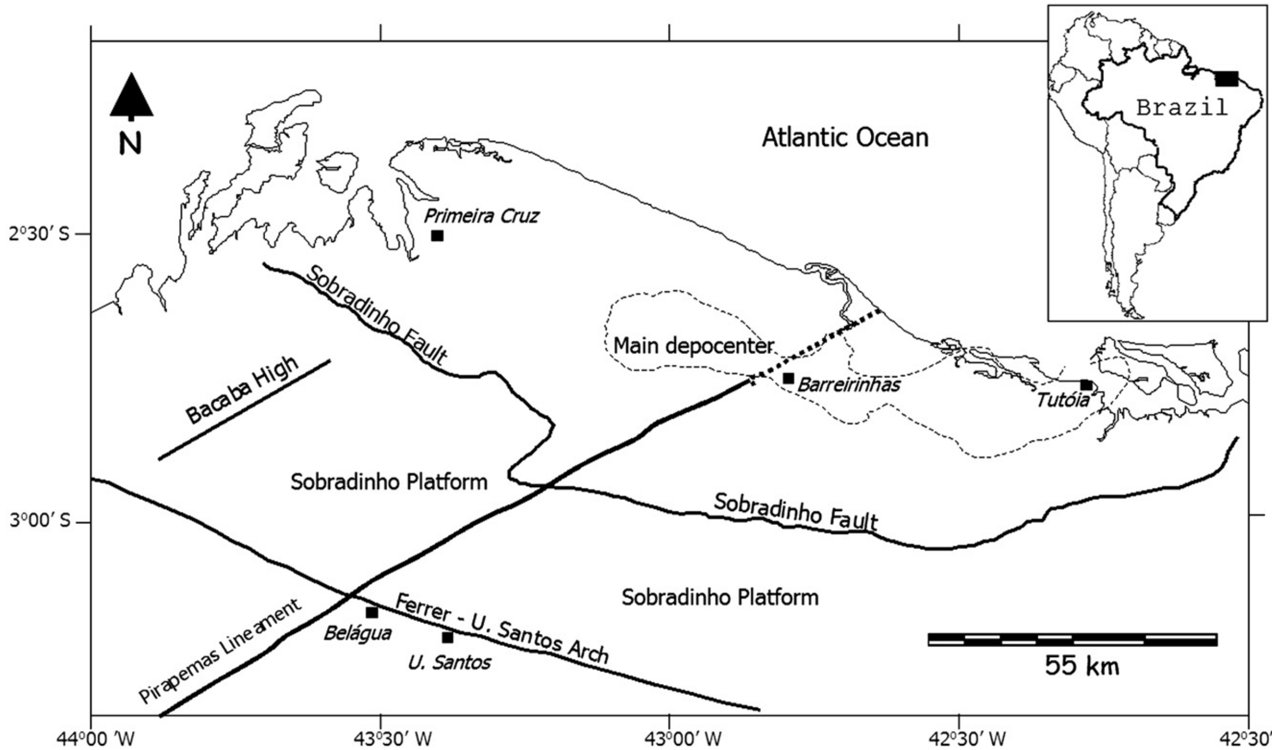

Figure 1. The Pirapemas Lineament in the tectonic context of the onshore portion of the Barreirinhas Basin (modified from Azevedo, 1991).

achieves this by crossing digital elevation model surface information, produced by the Shuttle Radar Topographic Mission (SRTM), with fieldwork and subsurface data (gravity and seismic). This dataset demonstrates the influence of the Pirapemas Lineament's on the Quaternary sedimentation of the area, thus highlighting the importance of neotectonic reactivations in areas along passive margins.

Geological setting

The Pirapemas Lineament and the main regional structural features in the onshore portion of the Barreirinhas Basin appear in Figure 1. These features form the Tutóia and Rosário Highs, which separate the Barreirinhas Basin from the Ceará and São Luis Basins, respectively, and the Ferrer-Urbano Santos Arch, which separates the Barreirinhas Basin from the Grajaú Basin. The development of the Barreirinhas Basin closely relates to the evolution of the Sobradinho Fault. This roughly E–W oriented, 200-km-long structure separates the basin's main onshore depocenter from a southern shallow area represented by the Sobradinho Platform (Fig. 1). The Sobradinho Fault structural behavior has changed throughout geologic time (Rici and Goes, 1986). From Albian, the motion on this fault varied from predominantly dextral strike-slip to extensional. The latter predominated during most of the basin evolution and was responsible for creating a set of E–W trending normal faults.

A sedimentary pile reaching 1600 m thick, ranging from Late Aptian/Early Albian to Cenozoic in age, occurs over the Sobradinho platform. These strata overlay Paleozoic rocks of the intracratonic Parnaíba Basin, which are intruded by Mesozoic sills and dikes of tholeitic nature. The Barreirinhas Basin main depocenter, located in the Sobradinho Fault downthrown block, accommodates the thickest Mesozoic–Cenozoic sedimentary piles among all the Brazilian marginal basins, exceeding 10,000 m. This sediment pile is represented by three major lithostratigraphical sequences (Azevedo, 1991; Feijó, 1994). The Canárias Group, composed of the Arpoador, Bom Gosto, Tutóia, Barro Duro, and Sobradinho formations, consists of Lower Albian continental to marine deposits. The Caju Group includes the Bonfim, Preguiças, and Periá formations and it represents an Upper Albian to Cenomanian succession that includes deep-water shales to shallow-water marls and limestones. The Humberto de Campos Group constitutes the last sedimentary succession, being composed of Turonian to Oligocene siliciclastic and carbonate rocks formed in a variety of depositional environments ranging from fan-deltas, carbonate platforms, and slope to bathyal marine settings.

The above-mentioned deposits are overlain by a thin (only a few meters thick) succession consisting of Neogene (mostly Miocene) sandstones and mudstones of the Barreiras Formation. In addition, Quaternary deposits, herein informally designated as post-Barreiras deposits, following the terminology applied from correlated strata in adjacent basins, are also present in the investigated area.

Material and methodology

SRTM elevation data (Rabus et al., 2003) opened unprecedented opportunities for regional terrain analysis, because this new class of space-borne information reveals subtle terrain features that frequently are blurred in conventional remote sensing images (Almeida-Filho and Miranda, 2007; Silva et al., 2007; Rossetti et al., 2008a,b). In vegetated terrains, the radar response at the C-band frequency (5.6 cm) results from the interaction of the radar signal with the vegetation canopy components (trunks, branches, twigs and leaves). Thus, the interferometric digital elevation model obtained by the SRTM in such areas corresponds to the mean height of vegetation canopy, which, on a regional scale, follows the terrain features below. This is the case of the study area, covered by woody savanna with diversified distribution of species that range from those adapted to aeolian deposits to riparian forests (Ledru et al., 2006). SRTM data provided the basis for the recognition of the Pirapemas Lineament real surface expression. The approach was complemented with the drainage network analysis extracted from the digital elevation model and combined with topographic charts at the scale of 1:100,000.

To support the interpretation of the SRTM data, a regional fieldwork campaign was carried out to better characterize the geological

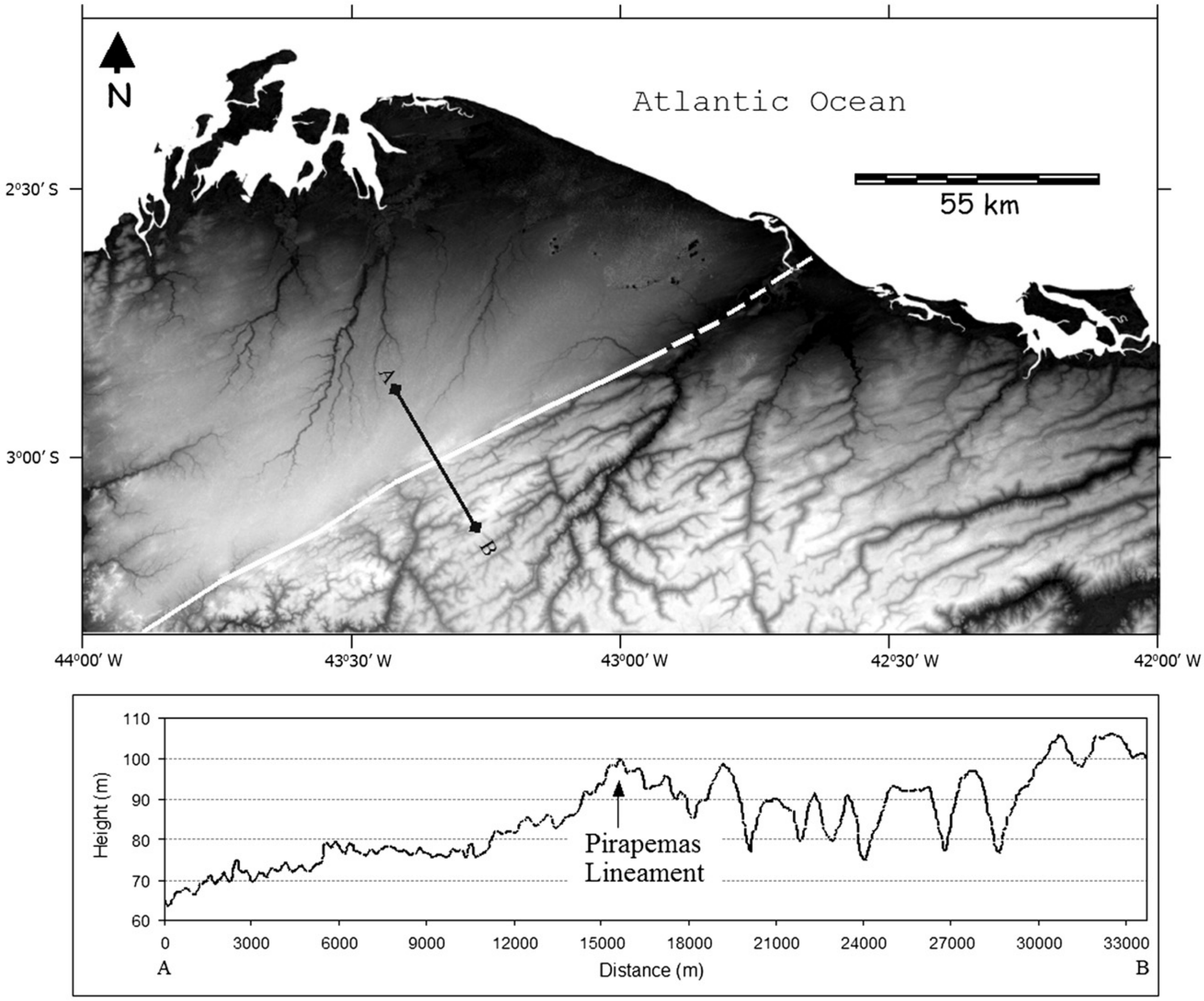

Figure 2. SRTM digital elevation model of the study area. As indicated in the profiles A–B, regional heights decrease northwards, with the Pirapemas Lineament defining a sharp contact between two sectors with contrasting morphologies: a northern sector characterized by a smooth surface, and a southern sector consisting of a deeply dissected terrain.

units in the study area. This work consisted of the broad characterization of the sedimentary deposits, correlating them with similar units that occur in nearby basins, which mostly include the Barreiras Formation (Miocene) and post-Barreiras sediments. As the latter is an informal lithostratigraphic term that encompasses several, highly oxidized Quaternary deposits, a few samples were collected for thermal luminescence (TL) and optically stimulated luminescence (OSL) dating.

To obtain TL and OSL data, pure quartz grains of 180–250 μm were separated after being treated with H_2O_2 for 4 h, 40% HF for 45 min, 20% HCl for 2 h and heavy liquid (SPT) treatments. The sediment's radioactive contents were determined with Neutron Activation Analysis (NAA). About 100 mg of two sample parcels and two standards, Buffalo River Sediment (NIST-SRM-2704) and Coal Fly Ash (ICHTJ-CTA-FFA-1), were irradiated in the swimming pool reactor, IEA-R1m, at an approximate thermal neutron flux of 5×10^{12} ncm^{-2} s^{-1} for 8 h. Gamma-radiation spectra were obtained after 7 and 15 day decay times using a Ge-hyperpure detector, model GX 2020, Canberra, FWHM 1.9 keV gamma peak of ^{60}Co and an 8192 channel S-100 Canberra MCA. Water contents in the samples were lower than 1% of dry weight. The samples were analyzed using a Multiple Aliquot Regeneration (MAR) protocol. Approximately 10–12 mg of grains, obtained after the cited treatment, was measured as an aliquot. All the natural aliquots (about 10) were bleached to near zero by sunlight exposure for 16 h and then given laboratory doses. This work was undertaken in the Glass Laboratory at the Faculdade de Tecnologia de São Paulo (FATEC), using a Daybreak Nuclear and Medical System Incorporated, Model 1100-Automated Series TL/OSL system. Dose rates were calibrated using cosmic radiation of 0.000250 Gy/yr (after Precott and Hutton, 1994).

Gravity and seismic data were qualitatively analyzed to investigate if the Pirapemas Lineament also presented some expression (if any) in the basement rocks, as well as to determine possible reflexes in the sedimentary pile. Gravity data from 45,168 field stations were Bouguer-reduced and grided to a cell size of 500 m. Due to the irregular distribution of the gravity stations throughout the area, data interpolation to produce the gravity map at this spatial resolution generated some small blank information areas. The seismic data constituted a profile (tied by two wells) that crosses the Pirapemas Lineament in the Barreirinhas Basin onshore portion.

Results

SRTM digital elevation model and drainage network

The SRTM digital elevation model showed that the study area is characterized by a flat topography, with altitudes varying gradually

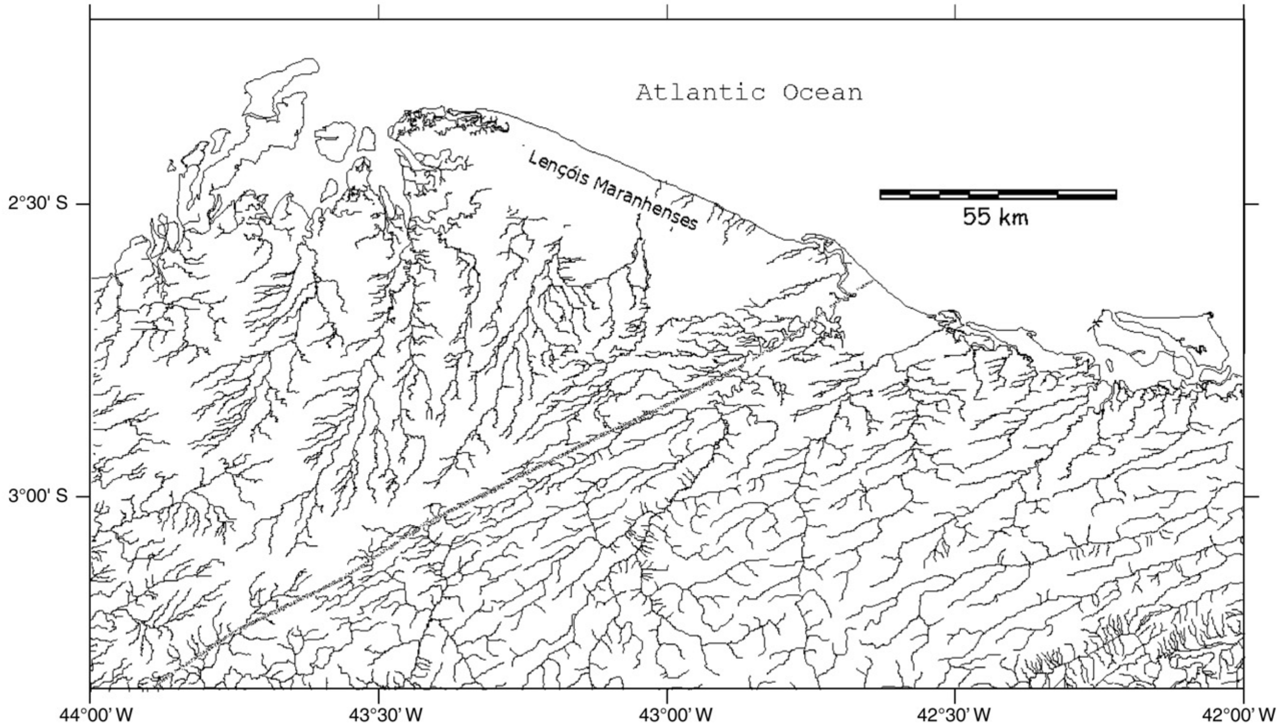

Figure 3. Drainage network of the study area illustrating the two sectors with distinctive drainage patterns separated by the Pirapemas Lineament.

from sea level up to 110 m (Fig. 2). In general, the topography decreases northward, with the Pirapemas Lineament defining two sectors with contrasting morphologies. Terrains with a smoother topography (i.e., less dissected surface) typify the area northward of the lineament. In contrast, a plateau with altitudes above 80 m, marked with deeply incised valleys, occurs south of the lineament, which suggests the action of more intense dissection processes in a surface exposed to erosion for a relatively longer time.

In addition to these morphological distinctions, the drainage networks also differ on both sides of the Pirapemas Lineament (Fig. 3). Drainage density is considerably lower northward of the lineament, constituting channels arranged into sub-parallel to sub-dendritic patterns. In contrast, a typically rectangular drainage pattern, with channels that are mostly straight and connected at high angles prevails southward of the lineament. These characteristics suggest that this area was strongly affected by tectonics, with channels

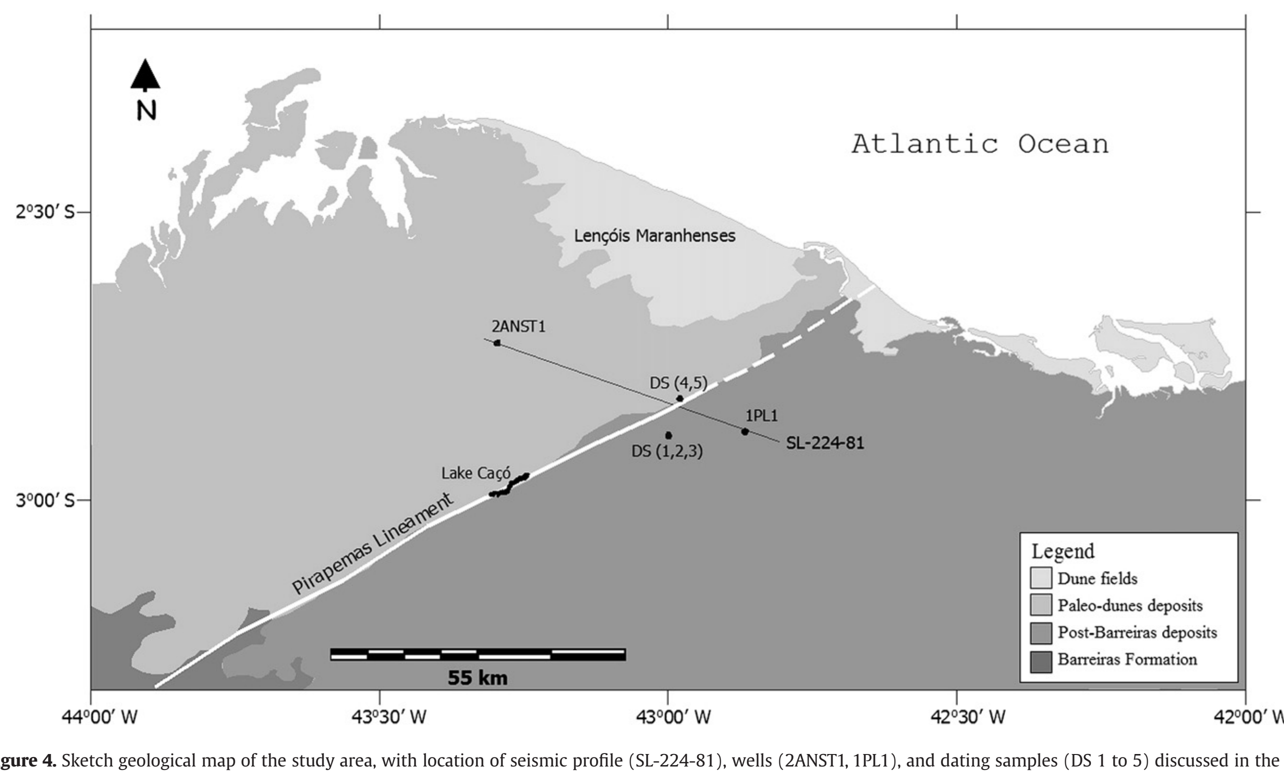

Figure 4. Sketch geological map of the study area, with location of seismic profile (SL-224-81), wells (2ANST1, 1PL1), and dating samples (DS 1 to 5) discussed in the text.

Table 1
Optically stimulated luminescence (OSL) and thermal luminescence (TL) ages of Pleistocene deposits in the study area obtained by multiple aliquot regeneration.

Coordinates	Sample #	Depth (m)	U (ppm)	K (%)	Th (ppm)	Annual dose rate (μGy/yr)	Method	Paleodose (Ma)	Age (years)
02°53.30′S 42°59.97′W	DS1	1.20	1.807 ± 0.065	0.838 ± 0.199	0.630 ± 0.091	1250 ± 150	OST	20.0 ± 1.0	16,000 ± 2720
							TL	17.0 ± 0.9	13,630 ± 2320
	DS2	5.70	3.565 ± 0.128	1.564 ± 0.269	0.219 ± 0.032	1150 ± 110	OST	30.0 ± 1.5	26,200 ± 3850
							TL	25.0 ± 1.3	21,850 ± 3250
	DS3	9.20	2.752 ± 0.099	0.870 ± 0.102	0.500 ± 0.072	1200 ± 110	OSL	40.1 ± 1.9	33,600 ± 4700
							TL	36.9 ± 1.8	30,950 ± 4350
02°50.07′S 42 °59.15′W	DS4	1.00	2.279 ± 0.082	0.961 ± 0.198	0.462 ± 0.067	1150 ± 125	OSL	110.0 ± 5.6	96,300 ± 15,400
							TL	95.0 ± 4.9	83,200 ± 13,300
	DS5	6.00	2.088 ± 0.075	0.835 ± 0.139	0.498 ± 0.072	1150 ± 115	OSL	175.0 ± 9.1	154,600 ± 23,500
							TL	185.0 ± 9.6	163,500 ± 24,800

See Figure 4 for location.

established along faults and joints. Noteworthy is that many channels are parallel to the Pirapemas Lineament, suggesting that it behaved as an active geological feature, playing a significant role in the landscape evolution. In contrast, rivers with structural control are almost absent in the northern sector. Although this area also displays channels parallel to the Pirapemas Lineament, they are rare and mostly distributed in the vicinities of the lineament, in the NE and SW portions of the sector.

Such a geomorphological context suggests a thin veneer of sedimentary deposits in the southern sector that is younger than the strata exposed in the northern sector. Most likely, the deposits accumulated in the northern sector due to tectonics gave rise to the faults and joints in the southern sector. The lower topography of the northern sector, suggests that the former might have subsided with respect to the latter. The northern sector decreased drainage density and the smoother flat lying relief reinforce this hypothesis. Therefore, the area located southward of the Pirapemas Lineament is apparently older than the area to the north. This sector would have been affected by tectonics, which gave rise to many faults and joints that have imposed a strong control on the modern drainage. In contrast, subsidence occurred to the north of the lineament. This process would have created new space to accommodate a younger and thinner sedimentary cover, not dissected yet, remaining flat and smooth. Geological field data presented in the following section sustain such an interpretation.

Field data and dating

Integration of remote sensing information, field observations, and TL/OSL dating resulted in the sketched geological map depicted in Figure 4. Cenozoic deposits entirely cover the area. The oldest mapped unit corresponds to a highly dissected plateau in the southwestern corner. The deposits are correlated with sedimentary deposits of the Miocene Barreiras Formation, which is a sedimentary unit recognized in the adjacent São Luís Basin (Rossetti, 2000). Firstly, this correlation is based on faciological similarities. The Barreiras Formation outcrops in the study area are up to 15 m thick, consisting mostly of friable, well to moderately sorted, well rounded quartz-sandstones that are interbedded with heterolithic deposits and mudstones. Likewise, the Barreiras Formation in the São Luís Basin, deposition of these lithologies is related, at least in part, to tidal processes. This interpretation is supported by an abundance of small- to medium-scale cross-stratification with foresets that are arranged into laterally alternating thicker and thinner packages defined by reactivation surfaces and/or mud drapes. Secondly, the studied deposits are related to the Barreiras Formation based on an unconformity at its top, marked by a lateritic paleosol with a regional expression throughout the northern Brazilian basins (Rossetti, 2004).

In the southern sector, the Barreiras Formation, and, where present, the lateritic paleosol, are mantled by a sandy unit hereafter named informally as post-Barreiras sediments. The terrain with the dissected morphology and rectangular drainage pattern described above characterizes this unit. These post-Barreiras sediments consist of a unit up to 8 m thick (at outcrop scale) that includes dark yellow to orange, well-sorted, well-rounded, fine to very fine-grained, massive sands. In adjacent basins, these deposits display dissipation dune structures (Rossetti, 2004), which relate them, at least in part, to aeolian processes. In the study area, it is possible to invoke a similar aeolian contribution. This suggestion is based on the textural nature of the deposits and on the dune morphology that is still recognized in several places, particularly in the eastern portion of the southern sector. TL and OSL dating of one lithostratigraphic profile entirely represented by a monotonous succession of fine- to medium-grained sand located in this area provided progressively younger upward Late Pleistocene ages, within the range of 30,950 ± 4350 to 13,630 ± 2320 yr (Table 1). However, deposition of these sands might have been initiated earlier in the Late Pleistocene, as indicated by TL and OSL dating of another sandy profile located right on the Pirapemas Lineament. This revealed an upward transition from 163,500 ± 24,800 (TL) to 83,200 ± 13,300 (OSL) and 154,600 ± 23,500 (TL) to 93,300 ± 15,400 (OSL) yr (Table 1).

The surface of the flatter and smoother (i.e., less dissected) terrain that typifies the area to the north of the Pirapemas Lineament is dominated by loose, white to light yellow, well rounded, well-sorted, massive sands that mantle the post-Barreiras sediments and, locally (to the southwest), the Barreiras Formation. These massive sands display well-preserved, vegetated paleodune morphology, vouching its deposition through aeolian processes. In the nothern portion of the study area, the paleodunes grade into the modern aeolian sand dune field that forms the Lençóis Maranhenses National Park. The prevalence of loose sands with well-preserved paleodune morphologies that grade into modern sand dunes led to the interpretation that the aeolian sands to the north of the Pirapemas Lineament are younger than the post-Barreiras sediments that cover the area to the south. Hence, the geological data reinforce the relatively younger nature of the deposits northward of the Pirapemas Lineament as suggested in the SRTM-based analysis. Aeolian sands of the Post-Barreiras sediments from the study area's southern sector recorded only Late Pleistocene ages as young as 13,630 ± 2320 yr. Furthermore, radiocarbon dating of sandy deposits in an area from the northern sector, 5 km from the Pirapemas Lineament (2°58′S, 48°20′W), recorded only Holocene ^{14}C ages ranging from 8970 (±70) to 1890 (±60) ^{14}C yr BP. (Pessenda et al., 2004).

The above-described sedimentary context leads to the proposal that the Pirapemas Lineament has imposed an important control on sediment deposition during the late Quaternary. The fact that this lineament sharply separates in surface Late Pleistocene from Holocene deposits is taken as strong evidence that this structure remained active through the Holocene. During this time, tectonic displacement might have caused a slight subsidence of the area to the north of the

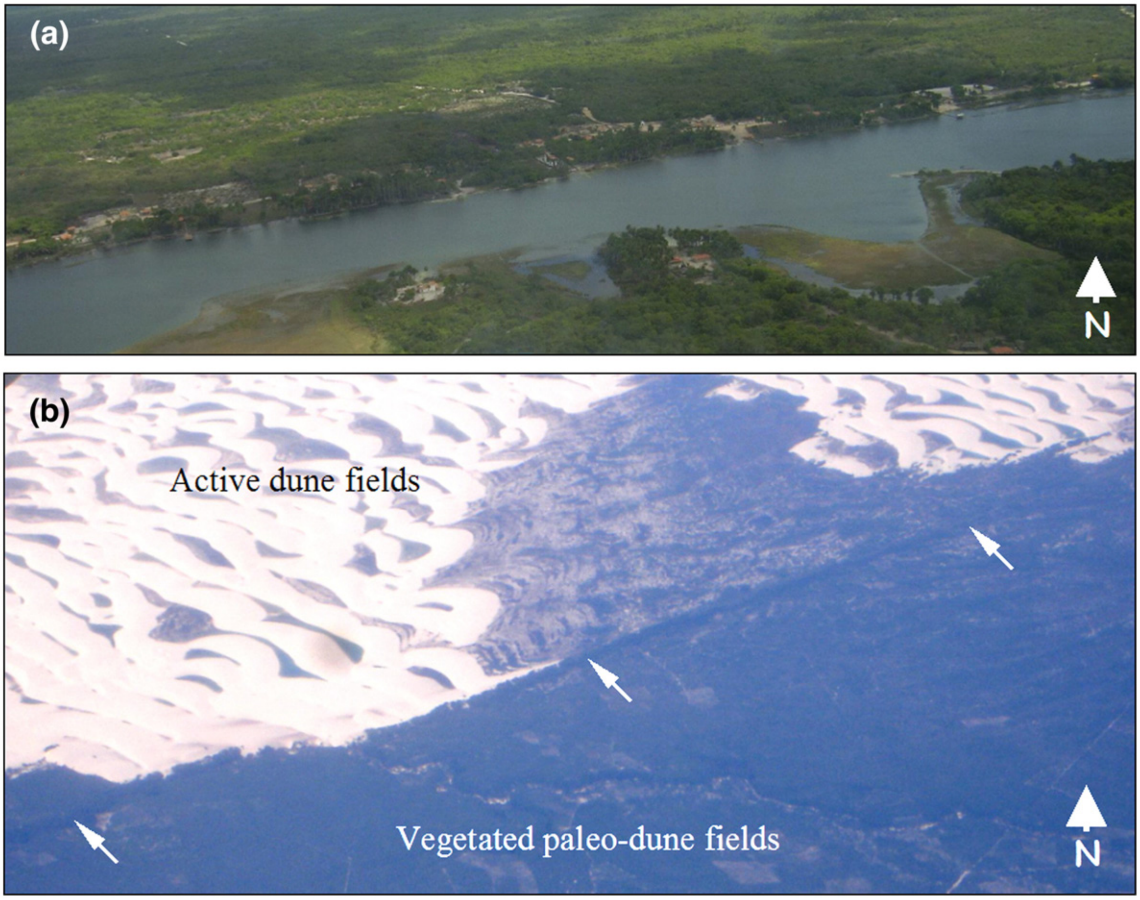

Figure 5. Examples of surface expressions of the Pirapemas Lineament: (a) low-altitude aerial view of Lake Caçó, established following the lineament; and (b) high-altitude aerial view showing that the active dune fields of the Lençóis Maranhenses National Park show straight boundaries that coincide with drainages paralleling the lineament (arrows). Pictures (a) and (b) are approximately 2 and 7 km wide, respectively.

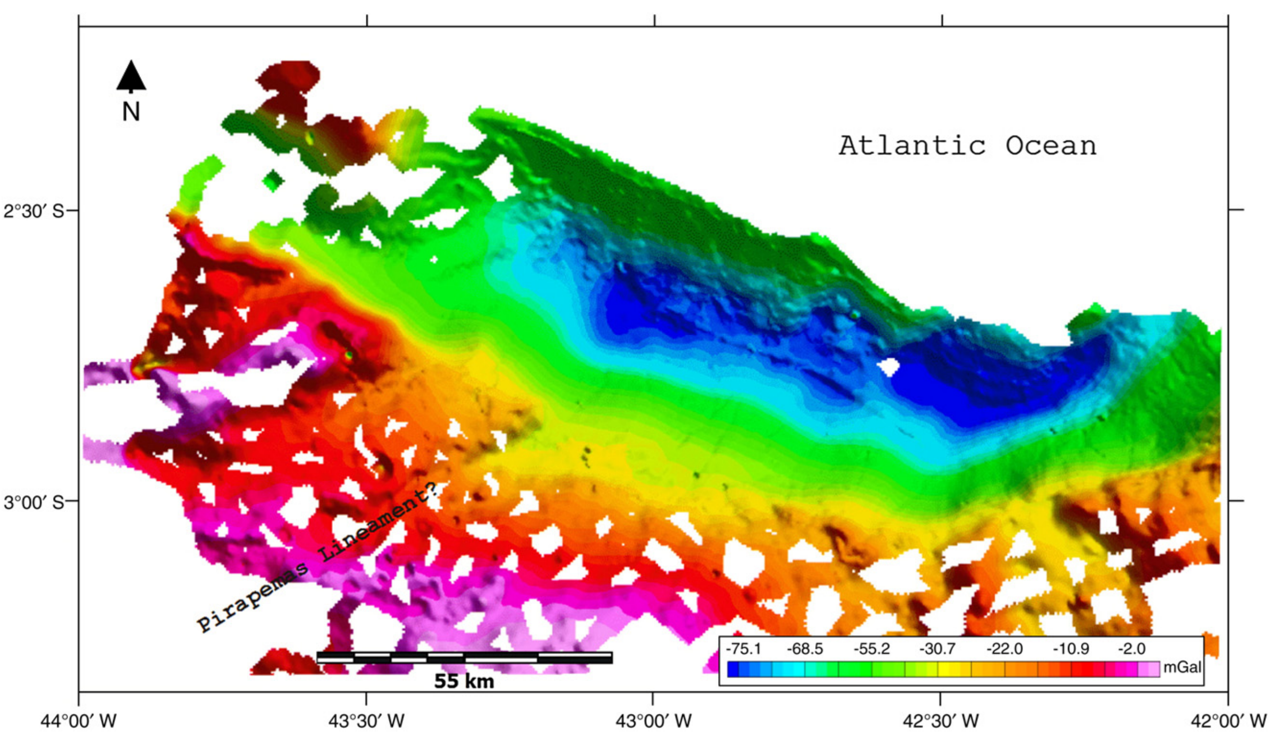

Figure 6. Gravity Bouguer map of the study area indicating a remarkable break in the border of the Sobradinho Platform suggestive of a dextral strike-slip displacement of basement rocks, which roughly coincides with the surface expression of the Pirapemas Lineament in that region.

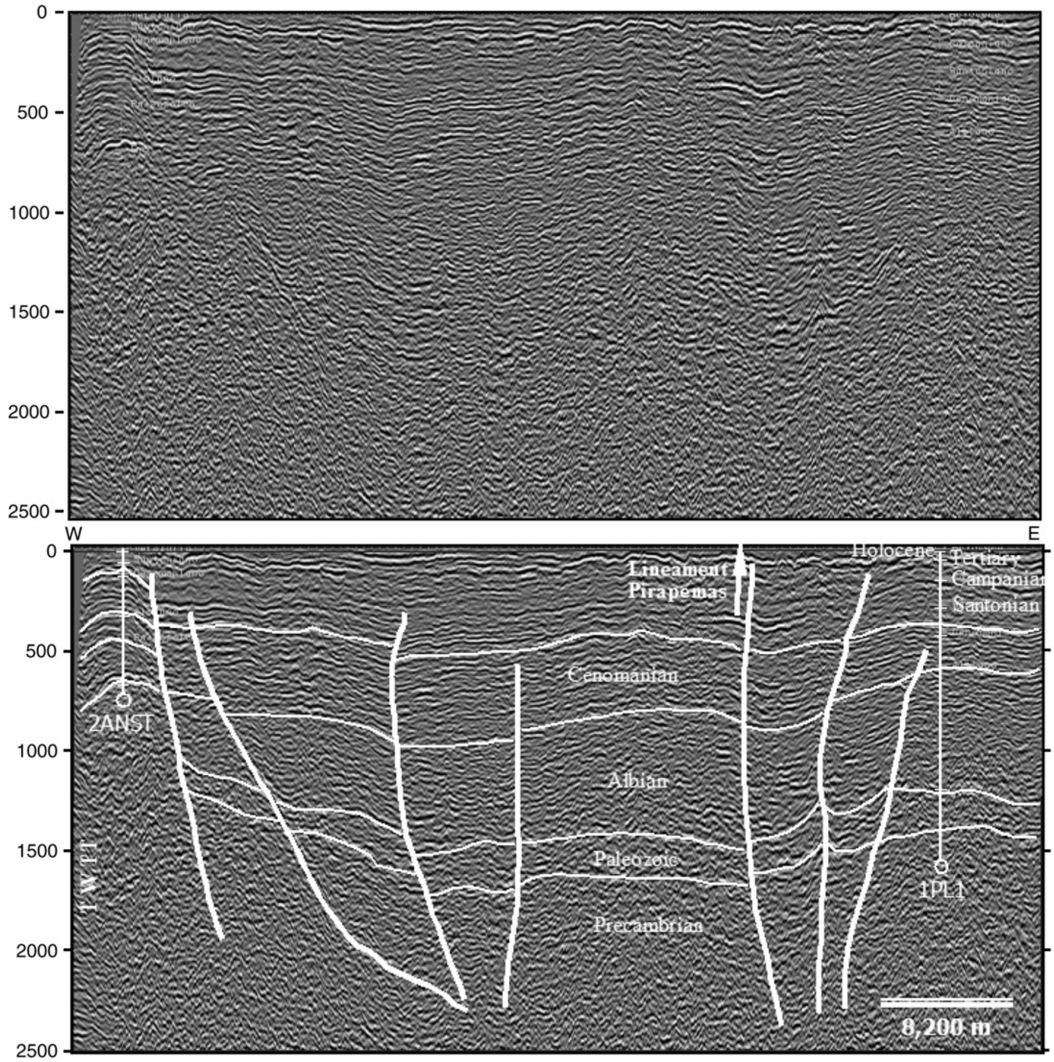

Figure 7. Seismic profile (SL-224-81) crossing the Pirapemas Lineament tied to wells 2ANST and 1PL1 (see Fig. 4 for location). A set of strike-slip faults is indicated in the area under influence of the Pirapemas Lineament (arrow). Two-way travel time is in milliseconds.

lineament, which would have promoted the creation of new space for sediment accumulation during the Holocene.

The role of the Pirapemas Lineament as an active agent modeling the landscape in the region is also witnessed by palynological studies conducted by Ledru et al. (2006) in the Lake Caçó. This consists of an elongated feature with approximately 7 km long and 0.3 km wide in the central part of the study area. Lake Caçó follows the Pirapemas Lineament (Fig. 4 and 5a), confirming its tectonic control. Those authors drilled three wells in the lake, with one (well 98-4) being of particular interest to our study. According to ^{14}C dating, a 5.7-m-thick, pollen-rich lacustrine sediment column started to be deposited over organic free sand dune deposits circa 19,000 ^{14}C yr BP. Taking into account a tectonic origin for Lake Caçó, it is compelling to claim this age as the most likely for the tectonic activity that promoted the change from sand dunes to lacustrine deposition in this area.

It is possible that tectonics continues in the study area even at the present time, exerting a remarkable control on the spatial distribution of the recent Lençóis Maranhenses National Park sand dune deposits. A high-altitude aerial view (Fig. 5b) shows that these dune fields are sharply bounded by drainages paralleling the lineament northern extension. The sharp contact of the modern sand deposits reveals that this structural feature is still active, modeling the modern geomorphological features in the region.

Subsurface geophysical data

The study area Bouguer gravity map (Fig. 6) identifies the main features that form the structural framework of the Barreirinhas Basin, which includes the Sobradinho Platform (magenta to red), the Sobradinho Fault (yellow to green), and the basin depocenter (blue). These data support that tectonic activity in the study area is ancient, with reactivation taking place on the basement structural features. The Pirapemas Lineament influence on the basement rocks is also indicated by a NE–SW trending structural feature suggestive of a remarkable dextral strike-slip displacement on the Sobradinho Platform border, which roughly coincides with the surface expression of the Pirapemas Lineament in that region. There is no apparent indication that the lineament extends toward the basin depocenter, which may indicate that it could be a pre-basin structure, without expression in the sedimentary pile. However, the lack of this lineament expression in the basin depocenter is probably related to the thick Mesozoic–Cenozoic sedimentary pile in this area (more than 10,000 m thick in the main depocenter), which could have masked the Pirapemas Lineament expression in the Bouguer gravity data. This interpretation is the most likely taking into account that other sources of information provided herein (i.e., remote sensing data, geological field data and sample dating, etc.) strongly support the Pleistocene/Holocene reactivation of the Pirapemas Lineament.

Furthermore, analysis of a seismic line that crosses the Pirapemas Lineament in the basin depocenter (Fig. 7) provided further data to deduce the structural deformation style that affected both the basement and the sedimentary pile. This seismic line indicates main reflectors related to the top of the Precambrian basement, the Paleozoic, Albian, Cenomanian, and Tertiary sedimentary sequences. As indicated, a set of strike-slip faults occurs in the area under influence of the Pirapemas Lineament, demonstrating a geologic connection with rejuvenation of basement structures. Such a fault zone, which would involve basement displacements, can be traced upward throughout the sedimentary pile, locally affecting even the Cenozoic deposits. This seismic section confirms that the Pirapemas Lineament is the surface expression of an active deep-seated basement structure in that portion of the Barreirinhas Basin.

Concluding remarks

This study shows that the Pirapemas Lineament is a remarkable linear geological feature highlighted by remote sensing data, which represents the surface expression of a major deep-seated structural feature in the basement of the Barreirinhas Basin. The deep-seated nature of this structure is confirmed by gravity and seismic data. Gravity data highlights a notable dextral strike-slip displacement on the Sobradinho Platform border, whereas seismic profiles indicate a set of strike-slip faults in the area under influence of the Pirapemas Lineament. These seismic-mapped faults show reactivation of basement faults, which propagate through the entire sedimentary pile, from the Paleozoic to the Tertiary strata.

Remote sensing and field data show that the Pirapemas Lineament splits the area in two sectors of contrasting morphology, different drainage patterns, and distinct sedimentary covers. Thus, to the north of the lineament, the terrain has a flat, smooth surface with subparallel to sub-dendritic drainage patterns. In contrast, deeply incised valleys, suggesting the action of a more intense and prolonged dissection process, characterize the sector to the south. In this sector, drainage patterns are predominantly rectangular, indicating a remarkable structural control. In addition, the northern sector displays a lower topography than the southern sector, suggesting that it might be subsiding with respect to the latter. Subsidence may explain the fact that late Pleistocene deposits mantle the area southward of the lineament, while paleodunes that grade into active sand dunes of the Lençóis Maranhenses National Park mantle the northern terrain.

While further data is needed to form a detailed tectonic history of the Pirapemas Lineament, this study presents information demonstrating that this basement structure was active in relatively recent times.

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