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How active is a passive margin? Paleoseismicity in northeastern Brazil

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ABSTRACT

The seismicity of intraplate areas reflects both far-field plate-boundary stresses and local effects, including dormant structures. In northeastern Brazil, within the passive margin of the South American plate, a short instrumental seismic record yields a pattern consistent with east-west plate push via events that do not exceed m_b = 5.2. Paleoseismic evidence from remote sensing, well records, earthquake-induced liquefaction, and radiocarbon dating of beachrock, coastal peats, and fault-filling sediment indicates the occurrence of larger prehistoric Holocene earthquakes, including some of Ms ≥ 6.8. The finding is of obvious significance for seismic hazard assessment, but because the azimuth of the maximum horizontal stress (S_{Hmax}) may be a poor guide to the present stress field, intraplate events on reactivated structures are of limited value for testing deformation models.

Keywords: Brazil, intraplate, paleoseismicity, neotectonics, radiocarbon.

INTRODUCTION

In intraplate areas, the magnitude and location of seismicity reflect far-field stresses, and hence the nature of the plate-driving forces, as well as local sources of deformation and zones of weakness (Sykes, 1978). The quality of an analysis of intraplate seismicity is thus governed by that of the seismic record and the ease with which inherited structures can be distinguished from those that have resulted from the modern tectonic configuration.

In coastal northeastern Brazil, within the passive margin of the South American plate (Fig. 1, inset), focal mechanisms indicate a strike-slip regime with compression parallel to the west-to west-northwest–trending coastline. This regime is consistent with the stress field produced by ridge push and plate-boundary resistance combined with local extension resulting from flexural bending and spreading at the coast (Assumpção, 1992).

In the instrumental catalogue for the area, the number of events of m_b > 5.0 is small. In 1986–1989, a seismic sequence recorded near João Câmara included more than 14 000 events; 15 had m_b > 4.0, and a single event had m_b > 5.1. The events were concentrated mainly in a >25-km-long belt bearing 040° (Takeya et al., 1989). This kind of swarm activity has been observed elsewhere in northeastern Brazil since 1968; the earliest individual event for which there are records was west of Açu (Fig. 2) in 1808 and was estimated to have been of m_b = 4.8 (Ferreira et al., 1998).

Assessment of the relative importance of plate-driving forces and local tectonic factors is hampered by scanty evidence. Although radiocarbon dating of coastal deposits points to late Quaternary tectonic activity in the region (e.g., Bezerra et al., 1998), no coseismic surface rupture has hitherto been reported for any of the historical events. In an attempt to extend the record back into the Holocene and improve its areal coverage, we here explore the evidence provided by remote sensing, boreholes, and deformed Pliocene to Holocene continental and coastal deposits. Empirical relationships are used to estimate paleomagnitudes from the evidence of surface faulting and seismically induced liquefaction.

LATE QUATERNARY FAULTS

Brazil occupies a substantial part of the South American plate, which is subject to compressional displacement at velocities from east and west of 34 and 84 mm/yr, respectively (Fig. 1) (DeMets et al., 1990). The region is underlain mainly by Precambrian granites and gneisses deformed by steep-dipping, transcurrent shear zones

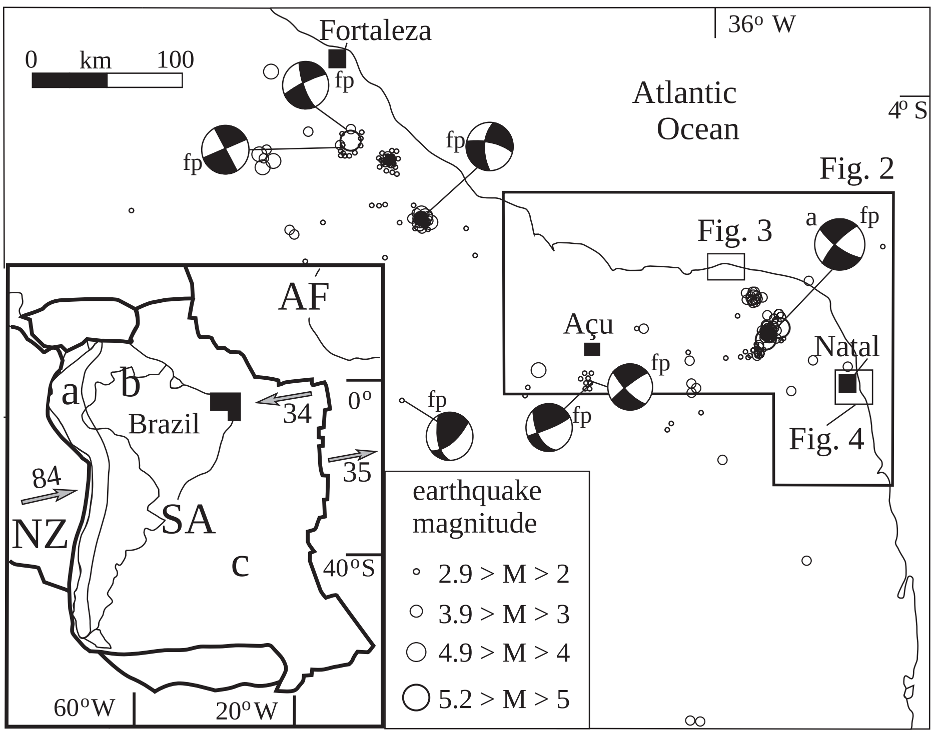


Figure 1. Seismicity of northeastern Brazil showing focal mechanisms and instrumental and historical epicenters (after Berrocal et al., 1984; Ferreira et al., 1998). Inset: location of study area (black). NZ—Nazca plate, AF—African plate, SA—South American plate, a—Mesozoic-Cenozoic orogenic belt, b—Precambrian shield and Paleozoic-Cenozoic platform, c—oceanic crust, fp—fault plane. Hollow arrows indicate plate vectors (in mm/yr) after DeMets et al. (1990).

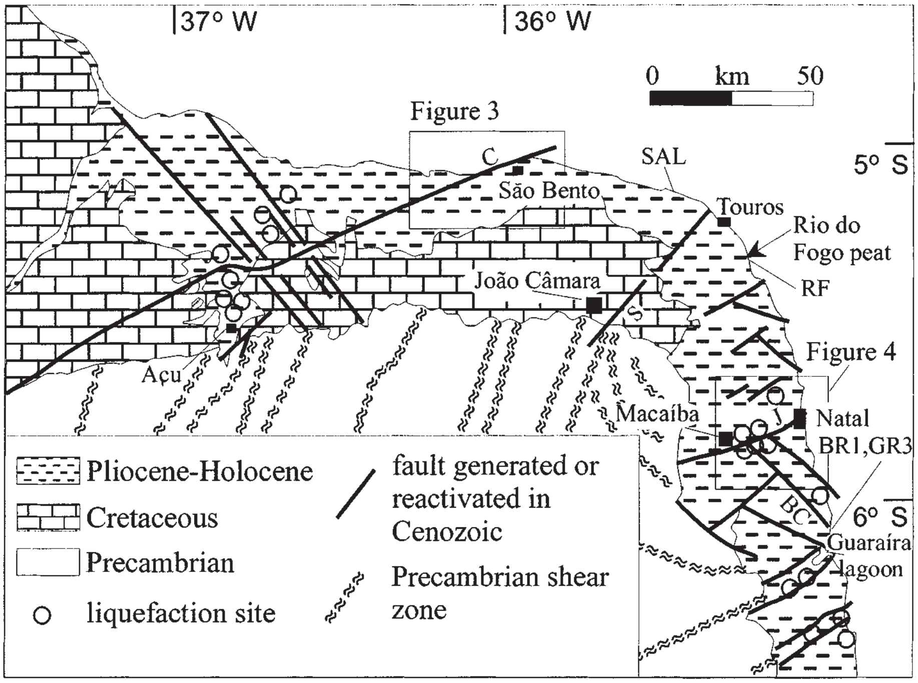


Figure 2. Geologic evidence of late Cenozoic deformation and location of faults and shear zones. Faults discussed in text: S—Samambaia, J—Jundiaí, BC—Boa Cica, C—Carnaubais. BR1, GR3, SAL, and RF are sample numbers (see Table 1).

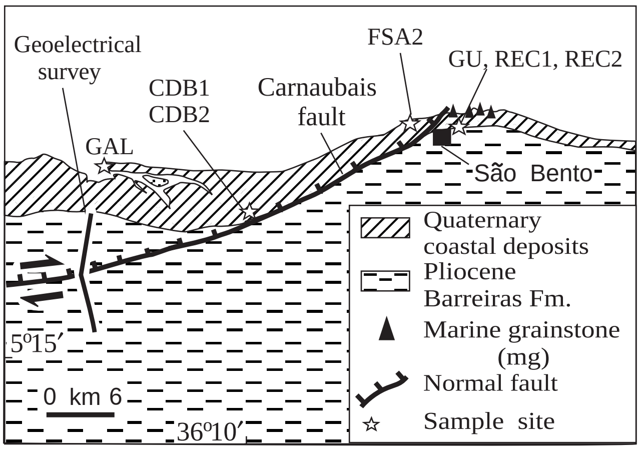


Figure 3. Geologic map of São Bento littoral zone showing locations of dated samples near and on Carnaubais fault and of electromagnetic survey by Caldas et al. (1997).

TABLE 1. RADIOCARBON AGES FOR FAULTS DISCUSSED IN TEXT

Sample	Elevation (m)	Corrected elevation* (m)	Lab. number	Dated material	^{14}C ages (yr B.P.)	δ^{13}C (‰)	Calibrated age (yr B.P.)
MAC	n.a.	n.a.	Beta 10907	charcoal	4200 ± 50	–26.4	4860–4570†
RF	n.a.	n.a.	Beta 04723	wood	3540 ± 60	–28.9	4040–3690†
GAL	+1.10	+0.60	UCL-416§	shell	3550 ± 100	0.30	3670–3210
CDB1	+0.30	–0.50	UCL-433§	shell	3950 ± 110	–1.49	4250–3640
CDB2	+0.30	+0.60	UCL-434§	shell	4500 ± 130	–1.32	4990–4370
FSA2	+0.50	+2.20	UCL-411§	shell	6550 ± 210	–0.73	7430–6580
GU	+0.60	+0.20	UCL-431§	shell	3050 ± 90	n.d.	2990–2650
REC1	+3.90	+3.00	UCL-397§	shell	5100 ± 140	n.d.	5740–5060
REC2	+5.40	+5.00	UCL-393§	shell	4050 ± 110	n.d.	4390–3790
SAL	+1.20	+0.30	UCL-417§	shell	3950 ± 110	–0.19	4250–3940
GR3	+0.70	–0.50	UCL-405§	shell	5950 ± 170	–0.50	6740–5980
BR1	+2.20	–0.20	UCL-403§	shell	4700 ± 140	–1.32	5300–4560

* Elevations corrected after sea-level curve by W. R. Peltier (in Bezerra et al., 1998).
† Accelerated mass spectrometry age, calibration at 2 σ after Pearson et al. (1986).
§ ^{14}C ages from Bezerra (1998) and Bezerra et al. (1998) calibrated at 2 σ after Stuiver et al. (1986).

dating from the Brazilian–Pan African orogeny (Jardim-de-Sá, 1994). These shear zones were reactivated in the Cretaceous during the South America–Africa breakup, when a number of passive-margin basins were formed (Matos, 1992).

The crystalline basement and the Cretaceous basins are locally capped by Pliocene continental siliciclastic deposits (Barreiras Formation), for which paleomagnetic ages of 4.5 and 5.0 Ma have been obtained in the coastal zone ~900 km to the south of the study area (Suguio et al., 1986). Quaternary units are concentrated near the coast and include beachrock, peat, and alluvium.

Faults that cut across Quaternary and Tertiary rocks have generated variations in the thickness of sedimentary deposits over the main bounding faults, as well as fault scarps, fault-line scarps, and fault-controlled drainage patterns. Radar and Landsat-5 TM imagery makes it clear that northeast- and northwest-trending faults from the dominant sets have acted as conjugate faults. Although the horizontality of most of the sedimentary strata makes it difficult to establish the amount of offset, numerous low-rake striae along fault planes show that an important strike-slip component of movement is associated with minor oblique slip. Some of the associated fault scarps attain heights of 30–40 m but are covered by debris slopes, vegetation, and soil.

The Carnaubais fault (Fig. 2) strikes 065° on the coast near São Bento (Matos, 1992) and forms cliffs to 7 m high southeast of the fault in a marine bioclastic grainstone that interfingers with the Pliocene Barreiras Formation. Electromagnetic surveys show that the base of this sequence was downfaulted by about 60 m southwest of São Bento (Caldas et al., 1997). Part of the movement took place in the Holocene: ^{14}C dating of a marine bivalve fauna in growth position and of redeposited shells in beachrock and tidal flats, after allowing for sea-level change (Bezerra et al., 1998), indicates that the southeastern block was uplifted 1–3 m more than the northwestern block between ca. 4000 and 2800 yr B.P., when vertical displacement apparently ceased (samples CDB1, CDB2, GAL, FSA2, REC1, REC2, GU, and SAL; Figs. 2 and 3; Table 1). Within the fault zone, a deformed beachrock dated as 7430–6580 yr B.P. (sample FSA2, Table 1) (Bezerra et al., 1998) indicates dextral strike-slip motion with a transtensional component (Caldas et al., 1997).

The Jundiaí fault (Fig. 4), which strikes 060°, cuts across Precambrian granites and shear zones and displaces the base of the Barreiras Formation vertically by as much as ~260 m (Bezerra, 1998). Within the fault zone, sediment-filled fractures 2–30 m deep are exposed in granite quarries near Macaíba (Figs. 4 and 5A). The fractures, like the Jundiaí fault, are oriented 060° and display slickensides indicating right-lateral strike slip and a later dip-slip component of movement. Crushed pebbles in the infilling sediment display striae,

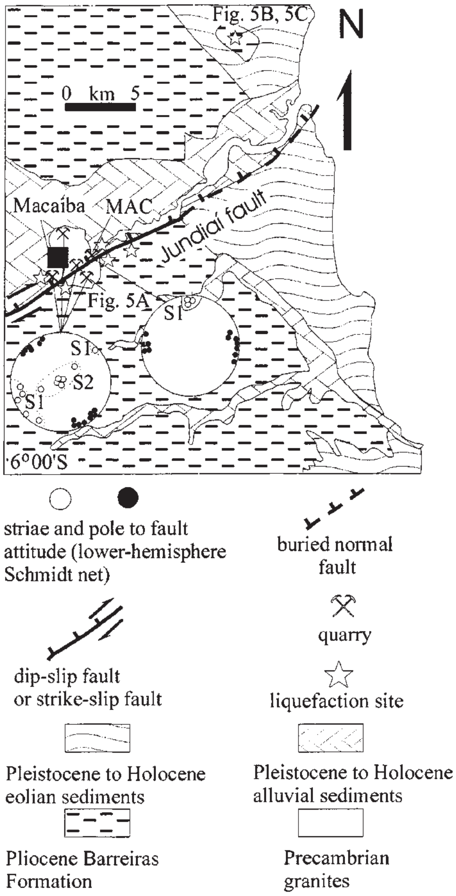
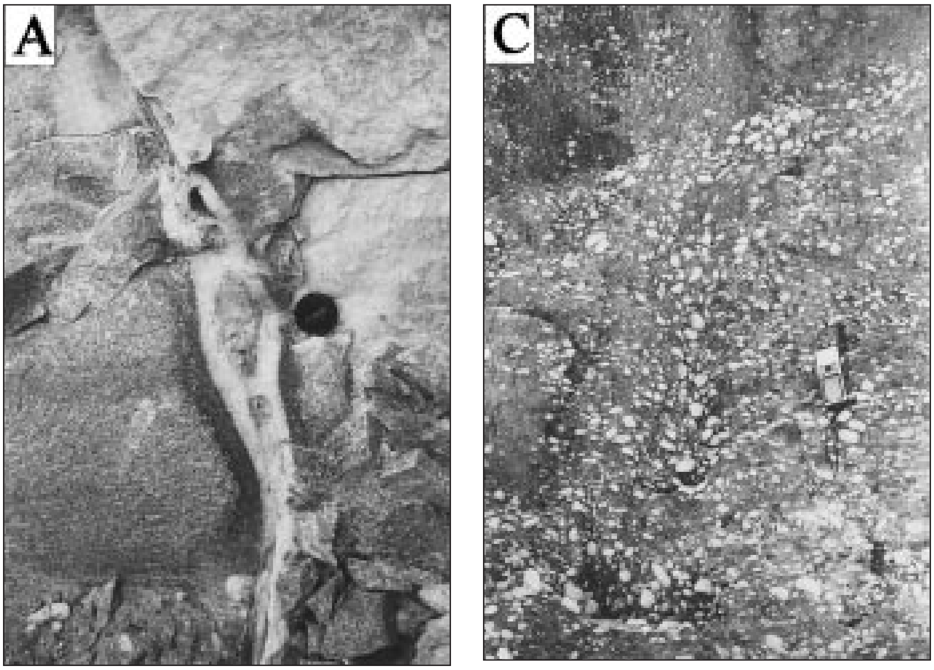


Figure 4. Jundiaí fault and attitude of two slickenline generations measured in outcrops and quarries: S1—low-rake striae, S2—high-rake striae. Earthquake-induced liquefaction sites in alluvium and soil are also shown. City of Natal is omitted for sake of clarity. MAC is sample number (see Table 1).



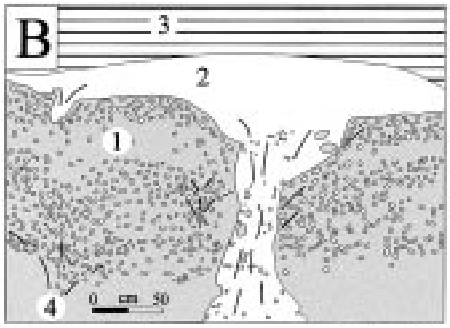


Figure 5. Paleoseismic structures of study area. A: Detailed view of fracture in Precambrian granite filled with sediments (Fig. 4) (cross section, scale given by lens cap, ~6 cm in diameter). B: Sand dike in gravelly sediments: (1) gravel, (2) sand dike, (3) clay-bearing sand bed, (4) small liquefaction pillars associated with major dike. C: Liquefaction pillar in adjoining location. Scale given by global positioning system receiver, ~13 cm long. Location of sites shown by stars in Figure 4.

and fault planes in the granite display polished surfaces. Such features are thought to result from seismic faulting (Hancock and Barka, 1987). We obtained an AMS (accelerator mass spectrometer) ^{14}C age of 4860–4570 yr B.P. (sample MAC, Table 1) on charcoal fragments from sediment within a gap in one of the fractures sealed by subsequent transpressive movement.

Late Cenozoic faults also cut across coastal peats and beachrock. Near Guaraíra, echo-sounding results suggest that a beachrock dated to 6740–5980 yr B.P. (sample GR3, Table 1; Fig. 2) (Bezerra et al., 1998) was downfaulted by 4 m below mean sea level prior to the accumulation of a younger, undeformed beachrock dated to 5300–4560 yr B.P. (sample BR1, Table 1) (R.F. Amaral, cited by Bezerra, 1998; Bezerra et al., 1998). The offset coincides with the 140° Boa Cica fault (BC, Fig. 2), which displaces the Barreiras Formation vertically by about 25 m (Bezerra, 1998). A peat exposed in the intertidal zone at the mouth of the Rio do Fogo (Fig. 2) is cut by two sets of strike-slip faults; their offsets average ~1 m and ~10 cm, and they strike 015°–060° and 120°–150° (Gusso and Bagnoli, 1989). We obtained a ^{14}C age of 4040–3690 yr B.P. for the peat (sample RF, Table 1).

A number of sedimentary structures in post-Barreiras alluvial, deltaic, and lagoonal deposits provide additional evidence of Quaternary seismic activity. These earthquake-induced liquefaction features occur at depths of 1–5 m and include convoluted folds, liquefaction pillars, and sand dikes (Fig. 5B and 5C); they are found close to the major Cenozoic structures, notably north of Açu (Fonseca, 1997) and south and north of Natal (Fig. 2).

In the absence of present-day counterparts, reliance has to be placed on parallels in analogous settings. We observed pillars, dikes, and pockets that, viewed collectively, point to liquefaction in a variety of lithologies and textures. The features show evidence of short-lived, upwardly directed migration of fluid that we interpret as indicative of seismicity, because the sand dikes cut across sedimentary strata younger than the sand-dike source, which rules out syndepositional processes, and all the features occur at several locations and are both overlain and underlain by undeformed beds.

Predominantly strike-slip faulting has affected strata having ages that span slate Cenozoic; faults with throws to 260 m cut Pliocene strata, and some fault throws average as high as 4–5 m for the past 10 k.y. Coseismic displacement, as opposed to creep, is indicated in the majority of faults that cut sedimentary rocks by the presence of fault breccia, in places associated with unconsolidated gouge or earthquake-induced liquefaction.

DISCUSSION

The present investigation shows that northeast- and northwest-trending faults have been active in northeastern Brazil during the Holocene. To judge from the criteria discussed by Bonilla (1988) and dePolo (1994), earthquakes of M_L = 5.5 and M_s = 5.6 or greater have occurred in the area as recently as 4860–4570 yr B.P. (sample MAC, Table 1). There is no evidence of events of such magnitude in eastern Brazil during the past 200 yr (Assumpção, 1992).

In addition, all the earthquake-induced liquefaction features recognized in the study area are located <6 km—some <1 km—from a late Cenozoic fault. On the assumption that the observed liquefaction effects were induced by the nearest fault, the empirical relationships (Kuribayashi and Tatsuoka, 1975; used by Allen, 1986) for sedimentary response indicate a magnitude $M_L \geq$ 5.4 for a maximum distance of 6 km between earthquake-induced liquefaction and the Quaternary fault in question. A similar empirical relationship, but expressed by moment magnitude M_w, was obtained by Ambraseys (1988). If we consider the liquefaction of gravel today (e.g., Youd et al., 1985; Yegian et al., 1994), the threshold magnitude is $M_s = 6.8$–7.0.

The new data indicate that some faults in the region represent the reactivation of existing structures whereas others are discordant to those structures. The parallelism of the faults with steep gravity gradients and structures such as Precambrian shear zones (Matos, 1992) may also indicate that part of the reactivation process has reached deep crustal levels, in agreement with focal mechanisms published by Ferreira et al. (1998; see Fig. 1) and the seismicity they described south of Açu, which coincides with a northeast-trending shear zone. In contrast, other fault planes cut across existing structures (Jundiaí, Fig. 2), as do fault planes identified by their seismic activity (Samambaia, Figs. 1 and 2) (Takeya et al., 1989).

At least two of the late Quaternary faults (Carnaubais, Jundiaí) are in the range of optimum orientation for strike-slip reactivation by the local stress field, i.e., an angle of 22°–32° between fault strike and S_{Hmax}, (Sibson, 1985; Assumpção, 1992; Ferreira et al., 1998). The fault planes of one late Quaternary fault (Boa Cica) and of one seismogenic fault (Samambaia, focal mechanism a, Fig. 1) depart by more than ±45° from S_{Hmax}, which for fault initiation and reactivation would require either low-friction material in the fault zone or high fluid pressure (Sibson, 1985). The latter has been identified in the Samambaia fault by Henderson et al. (1995). In other words, apart from new structures, there are several ancient faults that are correctly placed for renewed activity of at least $m_b = 5.2$.

This conclusion is evidently important to the realistic assessment of seismic hazard because it reveals the location and to some extent the potential level of activity of dormant faults as well as greatly extending the earthquake data sequence. However, the results are of limited value in the interpretation of intraplate seismicity in terms of the stress field. It is well known that focal-plane solutions are influenced by the geometry of existing structures.

The S_{Hmax} recovered from reactivated structures is likewise compromised, but so is some evidence from which the resultant azimuths of present-day plate convergence are derived, so that any match between them may be coincidental. It follows that testing finite-element and other models of intraplate deformation will be all the more demanding where much of the plate is buried or submerged, as the distinction between fossil and current structures is all the more problematic.

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