NEOTECTONIC MOVEMENTS IN NORTHEASTERN BRAZIL: IMPLICATIONS FOR A PRELIMINARY SEISMIC-HAZARD ASSESSMENT

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ABSTRACT Northeastern Brazil is located on the Brazilian passive margin within the intraplate part of South America. The region comprises a Precambrian crystalline basement deformed mainly by shear zones, overlain by Cretaceous sedimentary basins formed during the South America-Africa breakup and by Cenozoic units. There are two main sets of faults in the region, trending NE and NW. The maximum horizontal compression deduced from focal mechanisms is oblique to the NE- and the NW-trending faults, in a compressive direction which favors right-lateral and left-lateral strike-slip movement respectively. Widespread faulting from the beginning of the deposition of Barreiras Formation to the Quaternary indicates that the neotectonic period in northeastern Brazil started in the Miocene. Judging from the historical and instrumental seismicity, surface rupture and liquefaction is unlikely anywhere in the region. But the neotectonic record shows widespread evidence of liquefaction, surface faulting and coseismic uplift. Liquefaction in Quaternary alluvial sediments, for example, points to strong paleoearthquakes. The recognition of strong and pervasive seismic faulting from the Miocene to the Holocene indicates that the seismic hazard in northeastern Brazil has been underestimated.

Keywords: northeastern Brazil, seismic hazard, seismicity

INTRODUCTION Most surface-faulting earthquakes in intraplate settings have taken place at “unexpected locations”, regarded as essentially aseismic or considered to display low seismicity (Crone *et al*. 1997). Because intraplate earthquakes are less frequent than those occurring at plate margins, both the population and the building structures are less prepared to cope with them. Earthquakes in northeastern Brazil, known since the beginning of the nineteenth century, are as strong as 5.0 to 5.2 m_b (Ferreira *et al.* 1998). The 1986-1989 earthquake swarm along the Samambaia fault, for instance, damaged more than 30,000 buildings and caused significant panic in the population, which was displaced during the events. Even so, public awareness regarding potentially active faults in northeastern Brazil, as in many other intraplate settings, is relatively low.

The brevity of the period covered by historical and instrumental investigations, coupled with the small number of radiocarbon ages appears grossly inadequate for any secure inference about important seismic-hazard parameters such as recurrence. Nevertheless, although the historical and instrumental data suggest that surface rupture has not taken place in northeastern Brazil in the last 200 years, the neotectonic evidence indicates much stronger seismicity in the past causing not only surface rupture but also coastal coseismic uplift and widespread liquefaction (Bezerra 1998). Thus, the recognition of strong and pervasive seismic faulting in the neotectonic record of northeastern Brazil has far-reaching implications.

The objectives of this paper are (a) to establish what should be considered neotectonics in northeastern Brazil; (b) to present a brief review of the main hypothesis advanced to account for the neotectonics and seismicity in the region; and (c) to use the data gathered during the present research to assess, on a preliminary basis, the regional seismic hazard. The study area includes the Potiguar Mesozoic basin and its basement, which have a high level of historical and instrumental seismicity when compared with other areas in Brazil.

WHAT SHOULD BE CONSIDERED NEOTECTONICS IN NORTHEASTERN BRAZIL? The term neotectonics was first proposed by Obruchev (1948) to denote active geological processes. At first, neotectonic was viewed as the equivalent of Cenozoic or Quaternary deformation. Increasingly, however, there is a tendency to abandon precise definitions of the period encompassed by neotectonics. Hancock (1986), for example, proposed that the neotectonic period in a certain region started when the present-day configuration of relevant plate boundaries and motions was established. This is in agreement with the concept of Slemmons (1991), who defined neotectonics as the period of time when the present stress field and tectonic processes came to place.

Saadi (1993) made an early attempt to integrate all the available data in the literature in order to define the beginning of the neotectonic period in Brazil. Having correlated neotectonic deformation in the intraplate portion of South America with orogenic events in the Andean Cordillera, he placed the onset of the neotectonic period in Brazil during the Incaic II tectonic event in the Andes, which took place in the Eocene-Oligocene.

In northeastern Brazil, this period coincides with the Macau volcanism (Mizusaki 1989). But it was not until the Miocene that widespread faulting took place and allowed deposition of the Barreiras Formation in fault-controlled troughs. Several tectonic pulses favored the development of strike-slip and normal faulting, showing geometric and kinematic continuity from the start of the Barreiras Formation deposition to the Quaternary (Bezerra 1998).

This continuity is consistent with the E-W-oriented maximum compression and N-S oriented extension (Assumpção 1992, Ferreira *et al*. 1998) implicit in the shape and direction of movement of the South America plate since the Miocene (Bezerra 1998). It is therefore reasonable to propose that the beginning of the neotectonic deformation in the region coincided with the beginning of the Barreiras Formation deposition in the Miocene. At least in northeastern Brazil, there is no other widespread, post-Cretaceous stratigraphic unit that records Tertiary to Quaternary deformation so well.

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The most important neotectonic structures formed since the Miocene have been the NE- and NW-trending faults, which locally assume characteristics of conjugate faults and have reactivated pre-existing structures, including Cretaceous faults and Precambrian shear zones (Fig. 1). Most of the faults that affect the Barreiras Formation show structures that are consistent with syn-sedimentary deformation (*e.g.*, Souza *et al*. 1999). Both sets of faults are characterized by strike-slip and normal movement and have produced strong liquefaction in alluvial deposits that cap the Barreiras Formation (Fig. 1) (Bezerra *et al*. 1998). The cumulative offset along both sets of faults has made possible the deposition of several stratigraphic units including the Barreiras Formation in the Miocene to Pliocene, and alluvial and aeolian sediments from the Pleistocene to the Holocene (*e.g*., Bezerra *et al*. 1998).

The area’s tectonic evolution from the late Pleistocene to the Holocene can be described more precisely thanks to U-series and radiocarbon ages. Menezes and Jardim-de-Sá (1999) presented $^{230}Th/^{234}U$ ages, which range from ~300 Ka to 1.6 Ka, of N-S to NE-SW and E-W to WNW-ESE-oriented calcite veins filling alluvial terraces to the south of Lajes. They suggested that variation of vein trend is associated with reactivation of local weakness zones. In the Macau area (Fig. 1), faults controlled the late Pleistocene-Holocene sedimentary evolution. Silva (1991) concluded those deltaic and other coastal deposits as old as 30,190-2,340 yr BP have their thickness and location associated with normal faults. Another example of Holocene reactivation is provided by the NE-trending Carnaubais fault (Fig. 1), which moved in the Pleistocene and again at 4,240-2,740 cal. yr BP. The latter movement amounted to 4-5 m and displaced Holocene coastal deposits (Bezerra *et al.* 1998).

Several geophysical studies have correlated mapped faults and seismicity. Ferreira *et al*. (1997, 1998) showed that the focal mechanism solution in the Assu area (focal mechanism a, a’) coincides

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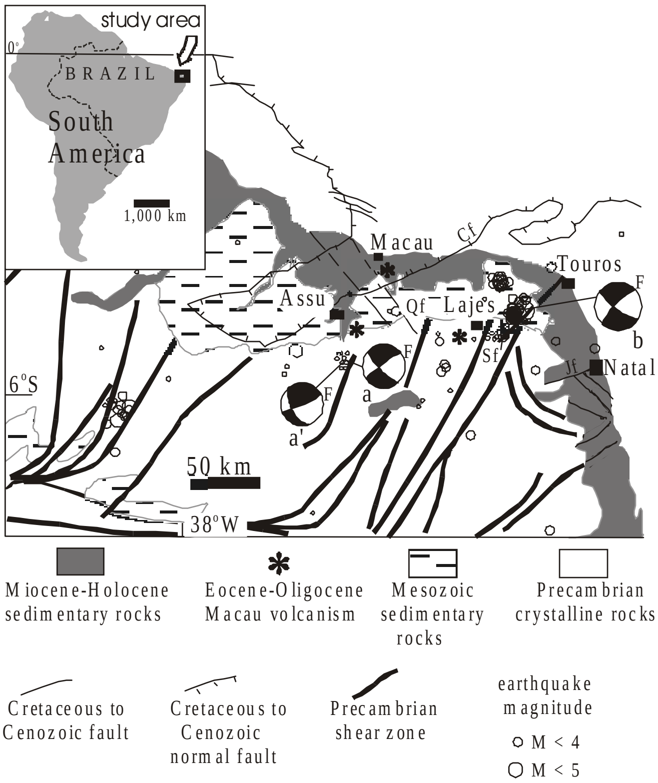

Figure 1 – Simplified geological map of the study area. Main faults dated by Silva (1991 and, Bezerra et al. (1998): Cf, Carnaubais; Jf, Jundiaí; Qf, Queimado. Sf, Samambaia seismogenic fault. Modified from Ferreira et al. (1997, 1998) and Bezerra (1999).

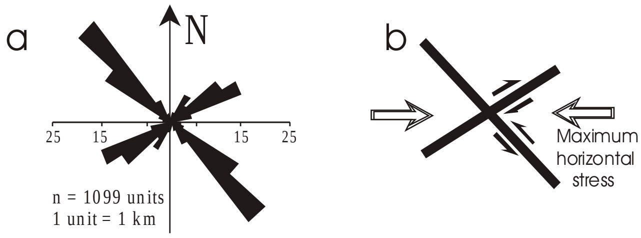

Figure 2 – a) Rose diagram of neotectonic faults presented in Fig. 1, and from Bezerra (1998, 1999); b) relationship between the current stress field and fault trends, which favors strike-slip reactivation.

with the main shear zones nearby. This may be a clear case of where seismic faulting is primarily influenced by zones of weakness. But Takeya *et al.* (1989) pointed out that the Samambaia seismogenic fault, located to the east of Assu (Fig. 1), is not consistent with the direction of shear zones in the area. However, Ferreira *et al.* (1997), analyzing the relationship between focal mechanisms and the major Cretaceous faults that limit the Potiguar rift, drew attention to the parallelism between the Samambaia fault (focal mechanism b) and the orientation of the rift margins offshore, to the northeast of Touros city (Fig. 1). In addition, some geological features at the surface may not correspond to faulting processes at deeper crustal levels, as indicated by the gravity study of Moreira *et al*. (1990). These authors suggested that, although the Samambaia fault is oblique to Precambrian shear zones at the surface, it is parallel to strong Bouguer gradients reflecting the alignment of a deeper structural and lithological framework.

If the angular relationship between the vast majority of NE- and NW-trending faults (Fig. 2) and the current stress field are taken into account, it can be inferred that both fault sets are likely to have undergone reactivation under the present E-W-oriented maximum horizontal stress. The fault orientation in the study area would favor strike-slip reactivation of 58^o-72^o and 292^o-302^o-trending faults (Bezerra 1998) (Fig. 2). The lithology and age of the Precambrian crust of northeastern Brazil are not the most important controls of fault reactivation and seismicity. Rather, it is probably the stress field orientation, its magnitude, and the orientation of existing faults that appear to determine Miocene to Holocene faulting and seismicity (*e.g.*, Assumpção 1992, Ferreira *et al*. 1998, Bezerra 1998).

DISCUSSION AND SEISMIC-HAZARD IMPLICATIONS

Several approaches can be used to estimate earthquake size generated in the past or likely to occur along active faults in the future. Assessing the seismic hazard where the historical record is short is more a matter of judgement than knowledge (Johnston and Nava 1990). The historical record for northeastern Brazil is too short to provide a realistic evaluation of the past seismic activity. Likewise, the instrumental record is not sufficient for dependable seismic-hazard analysis. Therefore, this approach is likely to yield controversial results. It follows that the most reliable approach for seismic-hazard assessment in the region is one based on neotectonic evidence, as this can easily be integrated with historical and instrumental seismic data.

In the historical data set of Wells and Coppersmith (1994), the minimum surface rupture associated with normal faults is about M = 5.2, whereas in strike-slip faults it is M= 5.8. Surface faulting has not occurred in the last 200 years in northeastern Brazil. However, there is clear evidence for surface faulting in the Quaternary (*e.g.*, Bezerra *et al*. 1998).

Moreover, the amount of liquefaction and hydroplastic deformation in alluvial sediments, which cap the Barreiras formation, point to higher levels of seismicity in the Quaternary (Bezerra 1998). Empirical studies clearly indicate that earthquakes which cause liquefaction in gravelly sediments, such as the Quaternary alluvial deposits in northeastern Brazil, have magnitudes Ms ³ 6.8 (Yegian *et al*. 1994). There is no reason to rule out events as strong as those in northeastern Brazil in the future.

An essential step in seismic-hazard assessment is the recognition of active faults. According to the U.S. Regulatory Commission (1982), an active fault is one that has moved during the last 10,000 years. From this point of view, several faults dated by Silva (1991) and Bezerra *et al*. (1998) should be considered active (Fig. 1). But if we concede that a fault should be designated active or extinct in terms of local parameters (Muir-Wood and Mallard 1992), several other faults across the region which are optimally oriented for reactivation should also be regarded as potential zones for earthquake generation (Fig. 2). If we accept, with Muir-Wood and Mallard (1992) that a fault which has moved in the current tectonic regime should be considered active, all the faults described by Bezerra (1998) should be regarded as active (Fig. 1).

Some kind of assessment can also be made by comparison with examples in similar settings elsewhere. Like the passive margin of North America, areas of relatively high and of relatively low seismicity characterize the passive margin of South America. The relatively high seismicity of northeastern Brazil is not exceptional: several other intraplate regions across the world show similar or even higher activity. Earthquake as high as 6.0-6.5 have occurred in continental rifts under compression. Examples include the Rhine graben (Europe), the Cawbay and Godava grabens (India), the St Lawrence rift and the New Midrid seismic zone (North America), the Adelaide and Fitzroy troughs (Australia), and the Sirte graben Africa (Johnston and Nava 1990, Zoback 1979).

But one of the most striking parallels with northeastern Brazil is found in West Africa, where the 1983 Guinea earthquake (m_b =6.4) produced at least 9 km of surface rupture (Crone *et al.* 1997). The region was part of the South American plate before the South Atlantic opening. Thus, the earthquake took place in a Precambrian crust that extended to northeastern Brazil, which has rifted margins that were subjected to a relatively similar Cretaceous evolution, and is under a similar compressional stress field.

The above, taken in conjunction with the neotectonic data gathered in this paper, would seem to indicate that the potential for large earthquakes in northeastern Brazil has been underestimated largely because it is much greater than that represented in the historical and instrumental seismic record. This is a fact of concern, as the region displays a high concentration of large dams, and some important pipelines and oil fields. In addition, the coastal area is densely populated, including urban areas with more than three million inhabitants. The recognition of a real seismic hazard in intraplate regions could at the very least lead to measures that can mitigate the impact of the seismicity in the more densely populated areas.

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Comtribution IGC-139
Received March 1, 2000
Accepted for publication April 30, 2000