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Seismites: origin, criteria for identification and examples from the Quaternary record of Northeastern Brazil

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Abstract - Seismites are soft-sediment features produced by (paleo)earthquakes. They are formed after sediment deposition, before sediment compaction, and during sudden breakdown of a loosely packet, water saturated grain framework. Fundamental controls on seismite generation are exerted mainly by earthquake size, sediment properties, and water-table depth. Hydroplastic deformation, liquefaction, and fluidization are the three mechanisms related to seismite origin. The most common types of seismites are hydroplastic mixing layers, pillars, pockets, dikes, sills, and folds. Outcrop features are among the most valuable tools for deciphering seismic events in the past. Seismites have been described in many intraplate settings. In northeastern Brazil, earthquake swarms, including events up to 5.2 Mb, induced soft-sediment deformation in at least two historical cases. In this region, sesmites occur in the Quaternary record of the Jaguaribe, Açu, and Potengi valleys, where a great variety of types are observed. They are particularly abundant in gravelly and sandy alluvial sediments. But they also occur in deltaic and lagoonal deposits. The study of seismites is particularly useful in areas lacking structural data. Seismite investigation is also important to extent the earthquake record far beyond the instrumental period of seismic observation.

Keywords - seismite, earthquake, neotectonics.

INTRODUCTION

Instrumental seismological studies span too short a period for satisfactory analysis of regional seismotectonics or the assessment of seismic recurrence intervals. Historical and geological investigations are consequently being used to extend the record back far beyond the period of seismic observation. Additional information may be recovered from earthquake-induced structures such as seismites, which represent structures generated by earthquakes in unconsolidated sediments.

An increasing number of seismites have been identified in intraplate settings. They have been described mainly in North America and Europe, from historical reports or geological evidence. Abundant examples have been observed in central USA, including the New Madrid seismic zone (Obermeier, 1996a,b), and the Atlantic seaboard of North America (e.g., Amick & Gelinas, 1991). Other studies have reported seismites in the Quaternary of western and central Europe (e.g., Davenport & Ringrose, 1987). Seismites have also been observed in the Brazilian geological record (e.g., Saadi & Torquato, 1992; Fonseca, 1996).

Although much work has been done to date, more studies need to be conducted to describe the extension of paleoearthquake deformation in the geological record and to ascertain the meaning and importance of seismic-induced deformation in unconsolidated sediments. The present study reviews the definition of seismite, criteria for seismite identification, and the strength of paleoearthquakes to generate seismites. We conclude by describing examples of seismites in the historical and geological record of northeastern Brazil.

WHAT IS A SEISMITE ?

The term seismite, originally proposed by Seilacher (1969) to describe mud at Elwood beach, California (USA), is commonly used in the literature to describe deformation in unconsolidated sediments caused by earthquakes. Seismites occur as dikes, pockets, sills, vented sediments (sand blows or sand volcanoes), lateral spreads, and folds.

Seismite generation depends on some key-factors. The most important earthquake features that can influence seismites origin are seismic intensity, magnitude, distance between deposit susceptibility for liquefaction and earthquake source, seismic attenuation, hypocentral distance, duration of seismic shaking, amplitude of cyclic shear stress, and number of loading cycles (Allen, 1984). The most important factors related to sediment characteristics are weak grain-to-grain boundary, loose sediment packing, good sediment sorting, high permeability, low viscosity and density of water-sediment mixture, the absence of clay minerals, as well as gas bubbles and organic matter (Obermeier, 1996a,b). The age of sediment is an indirect factor which influences liquefaction as it affects the looseness of cohesionless sediment and the depth of the ground water table (Tinsley *et al.*, 1985).

Sediment depth and water table, combined with overlying sediment features, are other elements which may influence the generation of seismites. Empirical observation show that the optimal depth for seismite generation is between 2-10 m (Obermeier, 1996a) and is rarely deeper than 20 m in depth (Seed, 1979). Susceptibility to the generation of seismites decreases with low water saturation and with increasing depth to the water table (Obermeier, 1996a,b). It increases when an impermeable or semi-impermeable layer, which may elevate pore fluid pressure, caps the liquefied sediment (Lowe & LoPiccolo, 1974).

Three main sediment deformation mechanisms form seismites: (a) hydroplastic deformation, (b) liquefaction, and (c) fluidization (Lowe, 1975). The hydroplastic deformation is characterized by absence of water escape features; folds are probably the most common type of hydroplastic seismite. Liquefaction involves flowage of sediment and significant water escape processes. Liquefaction usually produces dikes, pillars, and liquefaction pockets. Fluidization is characterized by water escape, where turbulent fluid flow erases primary sedimentary structures. It generally induces layer mixing. The distinction between these three mechanisms is presented in figure 1. It should be noticed, however, that there is a gradual transition between them. Sometimes, the distinction between the features produced by these three mechanisms are not easily recognized in the field.

Deformation	**Hydroplastic**	**Liquefaction**	**Fluidization**
	I - Characteristics		
Relative pore fluid pressure	pfP < oP	pfP = oP	pfP > oP
Flow structure	laminar	laminar	turbulent
Rate of water escape	no water escape	low to high water escape	high water escape
	II - Field identification		
Viscosity of sediment/ fluid mixture	high	low-high	low
Primary structures	preserved	partially preserved	completely erased
Type of seismite	folds	dikes, sills, pockets, pillars	mixed layers, sills, dikes

Figure 1 - Principal processes of seismite generation and related features (modified from Lowe, 1975; Allen, 1984; Owen, 1987; Guiraud & Plaziat, 1993).

HOW TO IDENTIFY SEISMITES

Some studies indicate that a wide variety of unrecognized sedimentary features are lumped under the common terms 'load structures', 'synsedimentary features', 'atectonic structures', and 'periglacial ice-wedges' (permafrost) (e.g., Lowe & LoPiccolo, 1974; Allen, 1984; Amick & Gelinas, 1991). Therefore, verification of the seismic origin is very important.

Seismites can be identified both in the historical and the geological records. Seismites can be identified in historical accounts and reports from the information about the outflow of water-sand or water-mud mixtures from cracks in the soil, soil subsidence or soil collapse, and soil sinking followed by building tilting (Berardi *et al.*, 1991).

In the geological record, several features described below may help to identify seismites (Sims, 1975; Davenport & Ringrose, 1987; Obermeier, 1996a,b; Demoulin, 1996): (i) seismites usually present evidence of escape of fluids, i.e., short duration upward-directed hydraulic force; (ii) seismites should have characteristics that are similar to historically documented observations of secondary ground failure produced by earthquakes; (iii) the ground-water table, at the time of seismite generation, must have been high enough to saturate deformed sediments; (iv) seismites generally take place at multiple locations; (v) the features should be overlain and underlain by undeformed beds; (vi) dikes must cut across layers younger than the dike source; (vii) deformation involves very little limited horizontal displacement; (viii) seismites are rarely directional; (ix) they are usually restricted to single layers, which are correlated over large areas; (x) the layers are flat-lying to eliminate the possibility of slope structures; (xi) in dikes and sills, the fissure filling is commonly different from that of the host rock; (xii) the dike or sill sand should have come from below the host layer. These characteristics should be viewed collectively. Therefore, no single feature, taken alone, can be used as unequivocal evidence for seismically-induced origin (Obermeier, 1996a).

Other evidence comes from the environmental situation such as, for example, scale consideration. Megaturbidites from platform slopes exceed the ordinary thickness and lateral range to such a degree that a seismic origin is the most plausible cause (Seilacher, 1984).

THE STRENGTH OF PALEOEARTHQUAKES

Several empirical relationships between earthquake size and the generation of seismites have been developed in the last two decades. Some of the studies have associated seismites with earthquake magnitude, others with seismic intensity. Obermeier (1996a,b) insisted that not all methods for paleo-earthquake estimation are useful, and concluded that associations between seismic intensities and seismites are crude, because these phenomena do not always reflect earthquake size. He suggested that methods which take into account earthquake magnitude are more accurate, because they make it possible to estimate distance from epicenter and minimum magnitude. But methods that relate the generation of seismites to intensity can provide a first order evaluation of the paleoseismicity, and this approach is presented below.

Seismites can result from repeated small events. They can be produced by earthquakes as low as moment magnitude Mw = 5, but it becomes common in magnitudes Mw ≥ 5.5-6.0 (Ambraseys, 1988). Ambraseys & Sarma (1969) pointed out that the generation of seismites can change dramatically if a sedimentary deposit is subjected to several cycles of low stress before failure. Testing a variety of soil exposed to cyclic loading, Lee & Seed (1967) and Peacock & Seed (1968) concluded that a gradual build up of pore pressure may result in failure under small stress. Dobry (1989) concluded that the critical shear strain for seismite generation can be as small as 0.04% for earthquakes characterized by long duration and many cycles.

The empirical relationship for sedimentary response of Kuribayashi & Tatsuoka (1975) was used by Allen (1986) to derive the following equation:

$$\mathbf{Mw = 0.499 \ln (X/3.162x10^{-5})\ (a)}$$

where Mw is the moment magnitude and X is the maximum epicentral radius in kilometers. Applying the maximum distance between seismites and their nearest possible source, the paleoearthquake magnitude that generated the seismite can be found.

Ambraseys (1988) has proposed the following equation as the lower bound for the moment magnitude (Mw) and maximum epicentral distance from seismite generation (R_{max}, in cm):

$$\mathbf{Mw = -0.31 + (2.65x10^{-8} R_{max}) + (0.99 \log R_{max})\ (b)}$$

Using equations (a) and (b), for example, Mw ≥ 5.4 would be the threshold magnitude for an epicentral radius of 6 km between seismites and a contemporaneous fault.

An empirical relation between surface-wave magnitude (Ms) and maximum epicentral distance where seismites have been observed was developed by Youd & Wieczorek (1982) and is shown on figure 2. From figure 2A it can be concluded that the minimum magnitude for seismites less than 10 km from the epicenter is Ms ≥ 6.0. Another relationship between moment magnitude (Mw) and maximum epicentral distance to seismites, proposed by Munson *et al.* (1995; modified from Ambraseys, 1988; and Obermeier *et al.*, 1993), gives magnitude Mw ≥ 5.7 to seismites generated less than 10 km from an epicenter (Fig. 2B).

These relationship between magnitude and maximum epicentral distance from seismites do not take into account the texture, sorting, and composition of sedimentary deposits where seismites take place. Several studies have concluded that the generation of seismites in gravel and gravelly sand requires a much higher

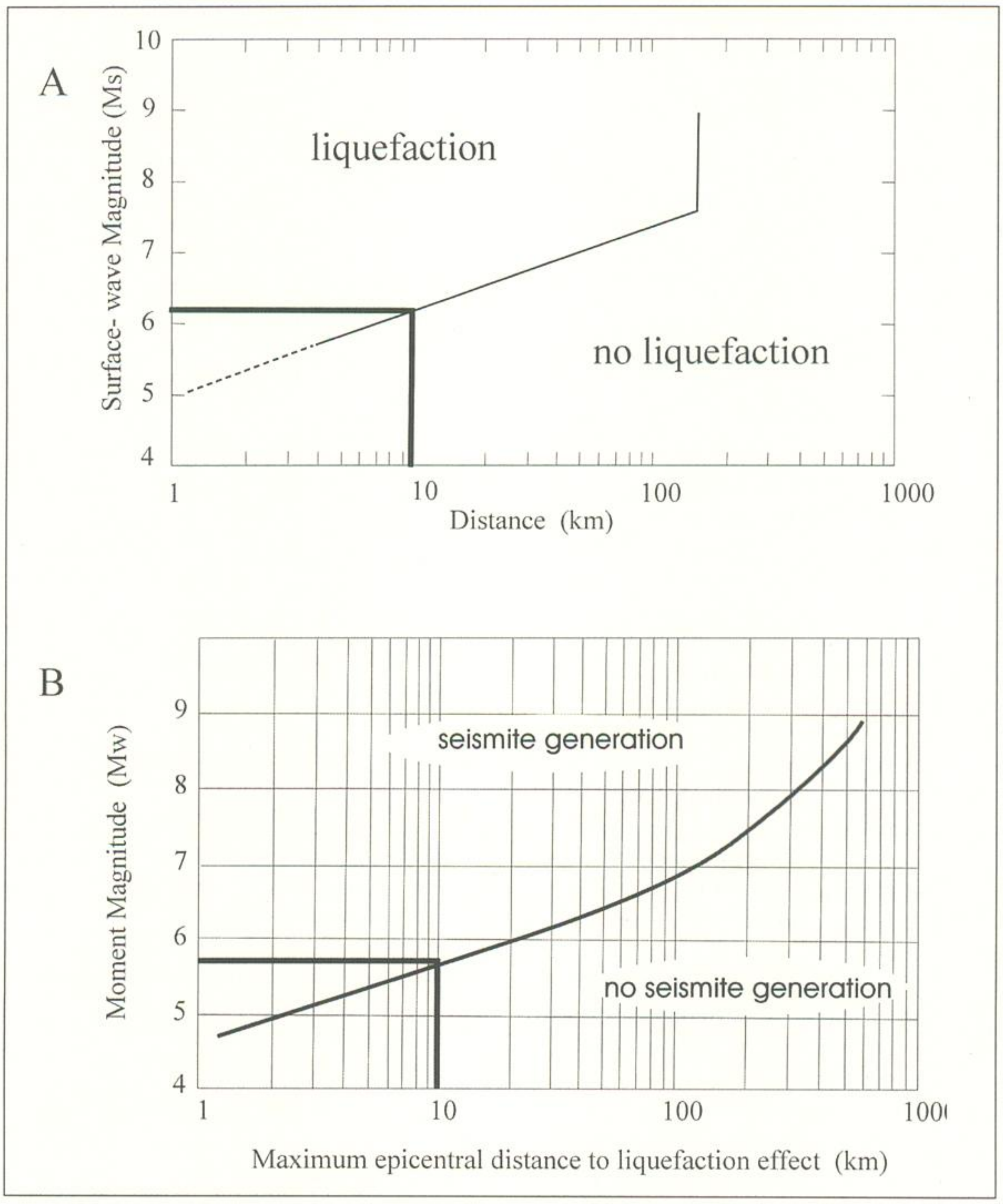

Figure 2 - Empirical relationship between earthquake magnitude and epicentral distance from seismite occurrence: (A) after Youd & Wieczrorek (1982); (B) after Munson *et al.* (1995; modified from Ambraseys, 1988 and Obermeier *et al.*, 1993). Grey rectangles stand for minimum epicentral distance quoted in text.

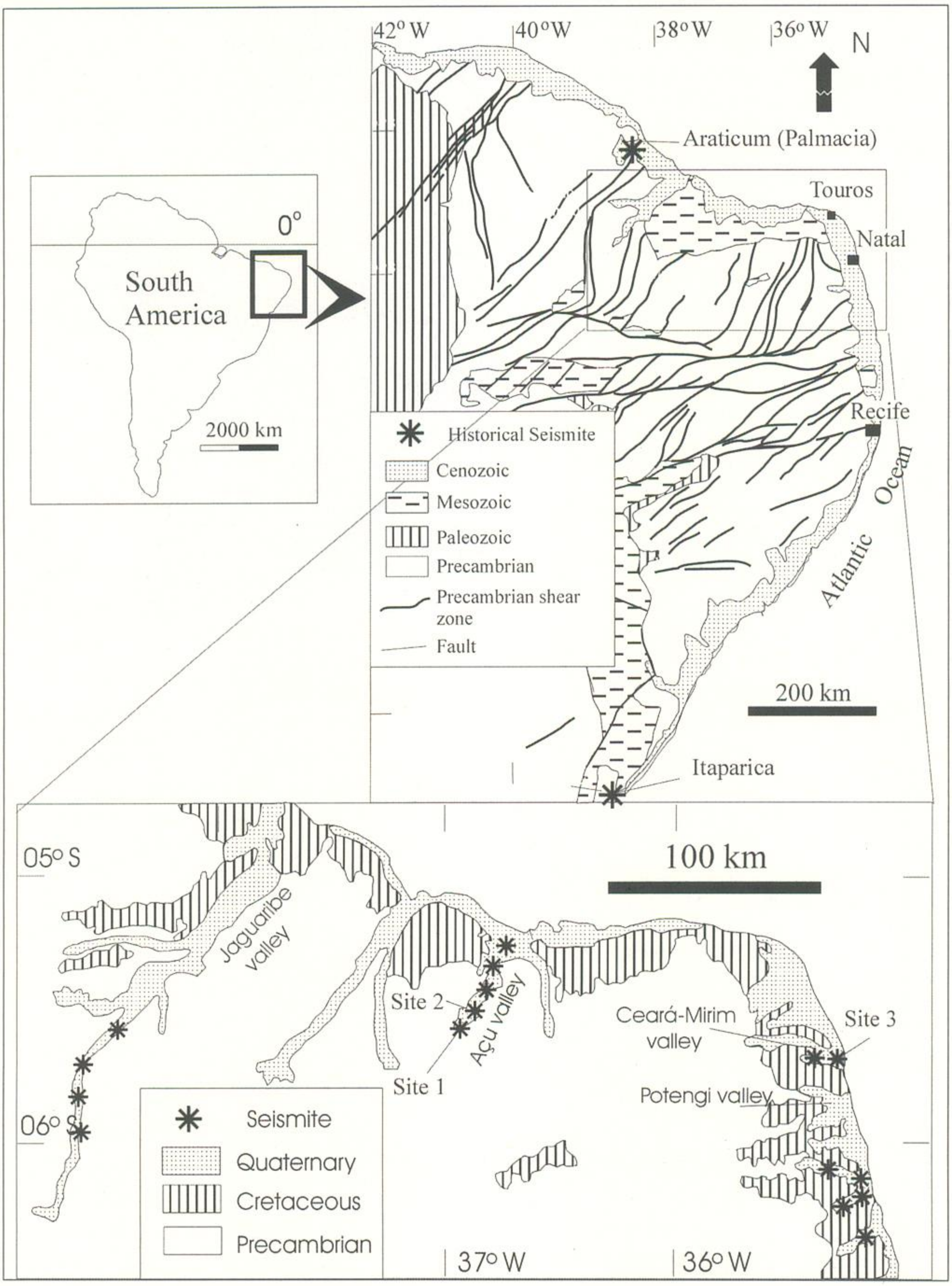

Figure 3 - Historical and geological evidence of seismites in northeastern Brazil: historical seismite according to the database by Ferreira (1983); geological map of the Rio Grande do Norte and Ceará states and seismite location.

threshold magnitude than deposits chiefly composed by sorted sand and which do not contain mud, gravel or organic matter (Tinsley *et al.*, 1985). According to Obermeier (1996a), the high gravel content of a sedimentary deposit increases the internal friction resistence, which makes seismite generation difficult. Seismites formed in gravel in modern-day earthquakes, including the 1988 Armenian Earthquake (Ms = 6.8; Yegian *et al.*, 1994); the Borah Peak-Idaho Earthquake (Ms = 7.3; Youd *et al.*, 1985) and the south-central Indiana Earthquake (Mw = 6.9; Munson *et al.*, 1995), are less common than seismites generated in sorted sand. Valera *et al.* (1994) stated that the threshold magnitude to produce seismites in gravel is 7, whereas it is reduced to about 5.5 in sand deposits. If a 30 cm impermeable layer caps the deposit, seismite generation is favored at lower ground acceleration (Yegian *et al.*, 1994).

Finally, another approach is to associate seismites with seismic intensity. Berardi *et al.* (1991) concluded that liquefaction is limited to earthquake intensity of historical Italian earthquakes MMI ≥ IX. According to Sims (1975) a MMI (modified Mercalli intensity) of about VI or over is the threshold intensity for seismite generation, but Obermeier (1996a) later insisted that these features become common at MMI intensities VII or greater.

SEISMITES IN NORTHEASTERN BRAZIL

In Northeastern Brazil, seismites have been recognized both in the historical and the geological record. Earthquake swarms in northeastern Brazil, lasting for several months or even years and composed by events equal or below magnitude of body waves Mb = 5.2 (Takeya *et al.*, 1989; Ferreira *et al.*, 1998) favor seismite generation. There is little reported evidence of seismites in northeastern Brazil because its historical record is short and patchy. The catalogue of historical seismicity by Ferreira (1983), however, presents two examples of seismites. The Itaparica-Bahia state earthquake of 22 March 1911 (modified Mercalli intensity MMI VII) was followed by soil liquefaction and localized subsidence on the coast of Itaparica, and soil collapse was observed in the epicentral area. The Araticum-Ceará state earthquake swarm in April and March 1969 also caused liquefaction. Several local newspapers described soil collapse and associated landslides; some small streams were filled by disrupted soil (Ferreira, 1983) (Fig. 3).

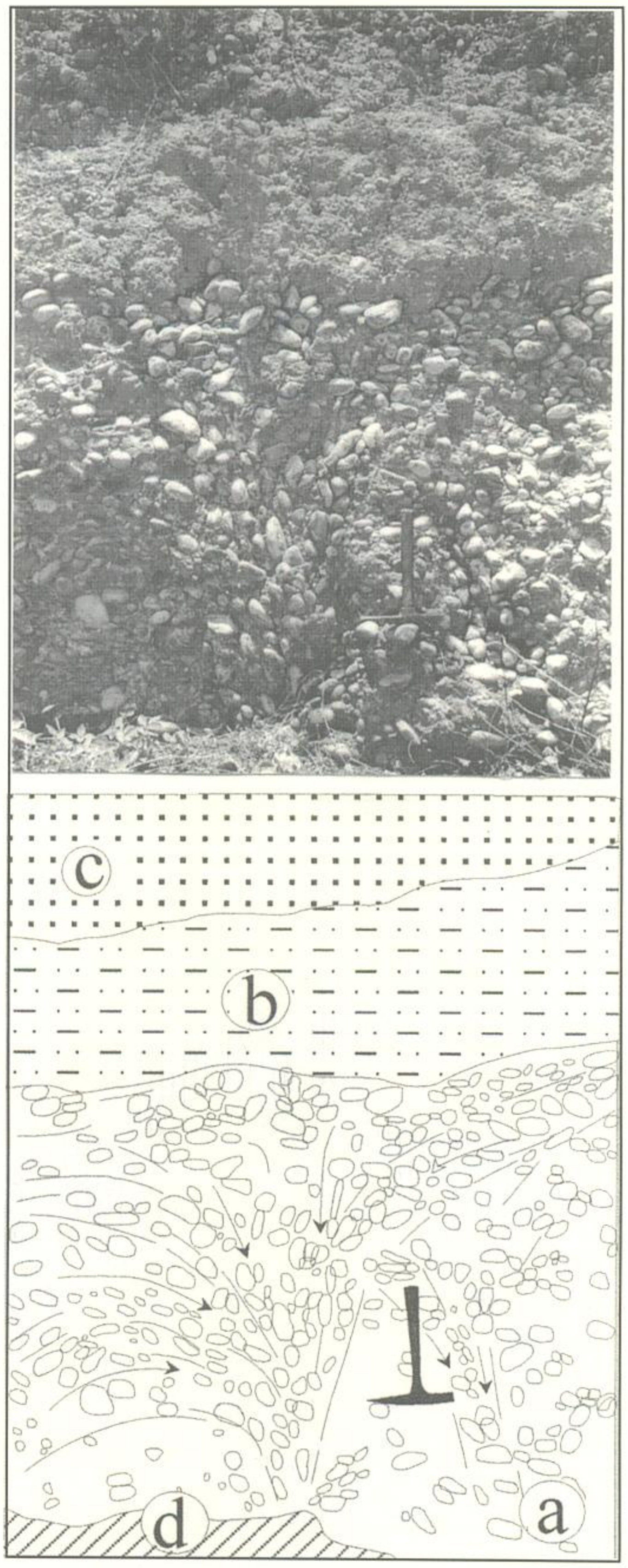

Figure 4 - Liquefaction pillar in gravelly sediment (a) capped mud-bearing sandstone (b) and soil (c); (d) represents road pavement. The arrows mark direction of pebble movement. Note that layers above the liquefied gravel are undisturbed. Scale given by hammer about 30 cm long. Location: site 1, Fig. 3.

As regarded the geological record, a few works have described soft-sediment deformation related to paleoearthquakes in the region. Clastic dikes and convolute folds have been described by Saadi & Torquato (1992) in Quaternary alluvial deposits from the Ceará State. Fonseca (1996) observed seismites in alluvial, deltaic, and lagoonal Quaternary deposits along the Açu valley, Rio Grande do Norte State. He recognized folds, liquefaction pillars and pockets as the main features affecting gravel and sand. More recently, Bezerra & Vita-Finzi (2000) and Bezerra *et al.* (2001) described seismites in Quaternary deposits that cap the Barreiras Formation between Natal and João Pessoa. Examples of seismites, mainly affecting gravelly sediments are presented in figures 4, 5, and 6.

The vast majority of seismites described in northeastern Brazil share common features. Seismites are 0.1-2.0 m wide and 0.3-4.0 m high. They are usually oblique to bedding. Some seismites form simple structures (generated by one event) or complex structures (multiple events or phases of fluid injection). Seismites in gravelly sediments tend to be associated with reorientation of clasts parallel to the margins of pillars, dikes, or pockets. Furthermore, the spatial and stratigraphic distribution of seismites in the Quaternary record suggests they were produced by different events mainly associated with strike-slip faults (Fonseca, 1996; Bezerra & Vita-Finzi, 2000).

CONCLUSION

This study has emphasized the control exerted by sediment properties, earthquake size, and water-table depth in the generation of seismites. Field criteria for seismite identification should be used collectively.

In northeastern Brazil, seismites occur mainly in gravelly alluvial sediments. Historical data indicate that seismites were generated at least in two occasions. These findings are consistent with seismological studies that indicate earthquakes large enough (up to 5.2 Mb) to produce seismites.

The investigation of seismites is an important part of the much wider research in the field of neotectonics and sedimentary geology. It follows that seismites yield valuable data on the tectonic evolution of sedimentary basins. It is, therefore, important to distinguish between tectonic features, such as seismites and atectonic features

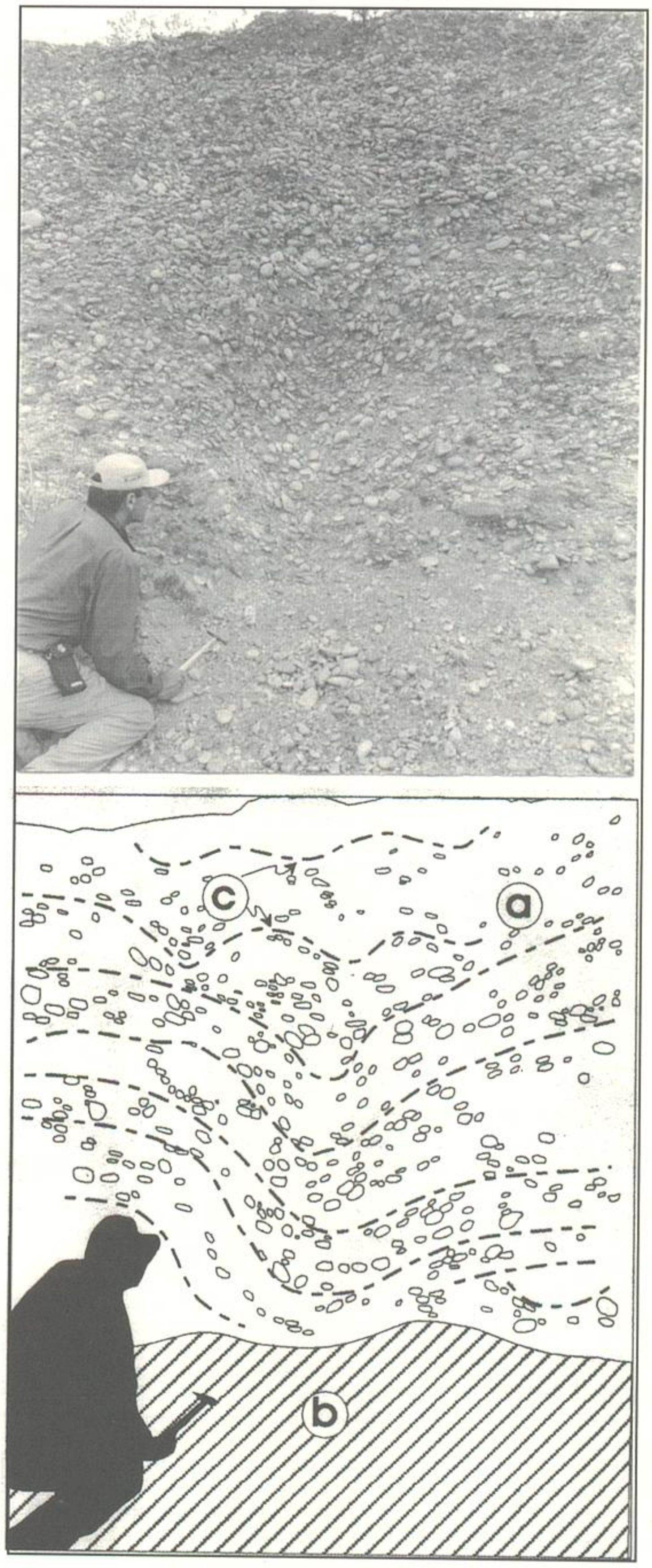

Figure 5 - Open fold formed by liquefaction in gravel: (a) gravel, (b) material collapsed from the quarry wall, (c) folded bedding. Location: site 2 in Fig. 3.

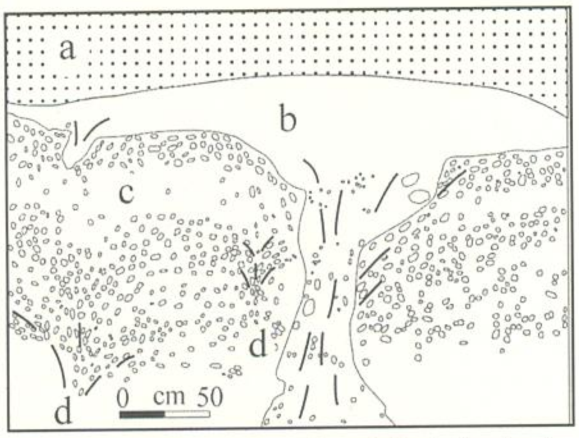

Figure 6 - Sand dike: (a) gravel, (b) sand dike, (c) bearing-clay sand bed, (d) small pillars associated with major dike. Location: site 3 in Fig. 3 (modified from Bezerra & Vita-Finzi, 2000).

such as load structures, artesian flows, and slump features. More studies are required to get a better insight into the distribution of seismites not only in northeastern Brazil, but in the Brazilian Quaternary record as well.

REFERENCES

Allen, J.R.L. 1984. **Sedimentary Structures – Their Character and Physical basis**. Amsterdam. Elsevier. 663 p.

Allen, J.R.L. 1986. Earthquake magnitude-frequency, epicentral distance, and soft-sediment deformation in sedimentary basins. **Sedimentary Geology, 46**: 67-75.

Ambraseys, N.N. 1988. Engineering seismology; earthquake engineering and structural dynamics. **Journal of the International Association of Earthquake Engineering, 17**: 1-105.

Ambraseys, N.N. & Sarma, S. 1969. Liquefaction of soils induced by earthquakes. **Bulletin of the Seismological Society of America, 59**: 651-664.

Amick, D. & Gelinas, R. 1991. The search for evidence of large prehistoric earthquakes along the Atlantic seaboard. **Sciences, 251**: 655-658.

Berardi, R.; Margottini, C.; Molin, D. & Parasi, A. 1991. Soil liquefaction: case histories in Italy. **Tectonophysics, 193**: 141-164.

Bezerra, F.H.R. & Vita-Finzi, C. 2000. How active is a passive margin? Paleoseismicity in northeastern Brazil. **Geology, 28**: 591-594.

Bezerra, F.H.R.; Amaro, V.E. & Vita-Finzi, C. & Saadi, A. 2001. Pliocene-Quaternary fault control of sedimentation and coastal plain morphology in NE Brazil. **Journal of South American Earth Sciences, 14**: 61-75.

Davenport, C.A. & Ringrose, P.S. 1987. Deformation of Scotish Quaternary Sedimentary sequences by strong earthquake motions. In: Jones, M.E. & Preston, R.M. (eds.) **Deformation of sediments and sedimentary rocks**. Geological Society of London (Geological Society, London, Special Publication n. **29**). p. 299-314.

Demoulin, A. 1996. Clastic dykes in east Belgium: evidence for upper Pleistocene strong earthquakes west of the Lower Rhine rift segment. **Journal of the Geological Society of London, 153**: 803-810.

Dobry, R. 1989. Some basic aspects of soil liquefaction during earthquakes. **Annual New York Academy of Sciences, 558**: 31-38.

Ferreira, J.M. 1983. **Sismicidade no Nordeste do Brasil**. São Paulo. 192 p. Dissertação de Mestrado em Geoffsica, Instituto Astronômico e Geofísico, Universidade de São Paulo.

Fonseca, V.P. 1996. **Estudos Morfo-tectônicos na Área do Baixo Curso do Rio Açu (Açu-Macau), Rio Grande do Norte**. Belo Horizonte. 106 p. Dissertação de Mestrado em Geociências, Instituto de Geociências, Universidade Federal de Minas Gerais.

Ferreira, J.M.; Oliveira, R.T.; Takeya, M.K. & Assumpção, M. 1998. Superposition of local and regional stresses in NE Brazil: evidence from focal mechanisms around the Potiguar basin. **Geophysical Journal International, 134**: 341-355.

Guiraud, M. & Plaziat, J.C. 1993. Seismites in the fluviatile Bima sandstone: identification of paleoseisms and discussion of their magnitudes in a Cretaceous synsedimentary strike-slip basin (Upper Benue, Nigeria). **Tectonophysics, 225**: 493-522.

Kuribayashi, E. & Tatsuoka, F. 1975. Brief review of liquefaction during earthquakes in Japan. **Soils and Foundations, 15**: 81-91.

Lee, K.L. & Seed, H.B. 1967. Cyclic stress conditions causing liquefaction of sand. **Journal of Soil Mechanics and Foundations, 93**: SM1, 47-70.

Lowe, D.R. 1975. Water escape structures in coarse-grained sediments. **Sedimentology, 22**: 157-204.

Lowe, D.R. & LoPiccolo, R.D. 1974. The characteristics and origin of dish and pillar structures. **Journal of Sedimentary Petrology, 44**: 484-501.

Munson, P.J.; Munson, C.A.; & Poud, E.C. 1995. Paleoliquefaction evidence for a strong Holocene earthquake in south-central Indiana. **Geology, 23**: 325-328.

Obermeier, S.F. 1996a. Use of liquefaction-induced features for paleoseismic analysis – An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes. **Engineering Geology, 44**: 1-76.

Obermeier, S.F. 1996b. Using liquefaction-induced features for paleoseismic analysis. In: McCalpin, J.P. (ed.) **Paleoseismology**. London, Academic Press. p. 331-396.

Obermeier, S.F.; Martin, J.R.; Frankel, A.D.; Youd, T.L.; Munson, P.J.; Munson, C.A. & Pond, E.C. 1993. **Liquefaction evidence for one or more strong Holocene earthquakes in Wabash Valley of Southern Indiana and Illinois, with a preliminary estimate of magnitude**. Washington, D.C., U.S. Geological Survey (Geological Survey Professional Paper n. **1536**).

Owen, G. 1987. Deformation processes in unconsolidated sands. In: Jones, M. & Preston, R.M.F. (eds.). **Deformation of Sediments and Sedimentary Rocks**. London, UK. Geological Society of London (Geological Society Special Publication n. **29**). P. 11-24.

Peacock, W.H. & Seed, H.B. 1968. Sand liquefaction under cyclic loading simple shear conditions. **Journal of Soil Mechanics, 94**: 689-708.

Saadi, A. & Torquato, J.R. 1992. Contribuição à neotectônica do Estado do Ceará. **Revista de Geologia UFC, 5**: 5-38.

Seed, H.B. 1979. Soil liquefaction and cyclic mobility for level ground during earthquakes. **Journal of Geotechnical Engineering, 105**: 201-255.

Seilacher, A. 1969. Fault-graded beds interpreted as seismites. **Sedimentology, 13**: 155-159.

Seilacher, A. 1984. Sedimentary structures tentatively attributed to seismic events. **Marine Geology, 55**: 1-12.

Sims, J.D. 1975. Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. **Tectonophysics, 29**: 141-152.

Takeya, M.K.; Ferreira, J.M.; Pearce, R.G.; Assumpção, M.; Costa, J.M. & Sophia, C.M. 1989. The 1986-1989 intraplate earthquake sequence near João Câmara, northeastern Brazil – evolution of seismicity. **Tectonophysics, 167**: 117-131.

Tinsley, J.C.; Youd, T.L.; Perkins, D.M.; & Chen, A.T.F. 1985. **Evaluating earthquake hazards in the Los Angeles region – An earth science perspective**. Washington, D.C., U.S. Geological Survey (Geological Survey Professional Paper, n. **1360**).

Valera, J.E.; Traubenik, M.L.; Egan, J.A. & Kaneshiro, J.Y. 1994. A practical perspective on liquefaction of gravels. In: Prakash, S. & Dakoulas, C. (eds.). **Ground failure under seismic conditions**. American Society of Civil Engineering. p. 241-257. (Geotechnical Special Publication, n. **44**).

Yegian, M.K.; Ghahraman, V.G.; Members, A.S.C.E. & Harutiunyan, R.N. 1994. Liquefaction and embankment failure case histories, 1988 Armenian Earthquake. **Journal of Geotechnical Engineering, 120**: 581-596.

Youd, T.L. & Wieczorek, G.F. 1982. **Liquefaction and secondary ground failure in the Imperial valley, California, earthquake of October 15, 1979**. Washington, D.C., U.S. Geological Survey. p. 223-246 (Geological Survey Professional Paper n. **1254**).

Youd, T.L.; Harp, E.L.; Keefer, D.K. & Wilson, R.C. 1985. The Borah Peak, Idaho earthquake of October 28, 1983. – Liquefaction. **Earthquake Spectra, 2**: 71-89.