FRACTURE CHRONOLOGY AND NEOTECTONIC CONTROL OF WATER WELLS LOCATION IN CRYSTALLINE TERRANES: AN EXAMPLE FROM THE EQUADOR REGION, NORTHEASTERNMOST BRAZIL

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ABSTRACT The brittle deformation in the Equador area, in the center-south domain of the Rio Grande do Norte State, NE Brazil, was analyzed to establish the chronological sequence of the different tectonic episodes and their stress fields, emphasizing the neotectonic activity by structural and morphotectonic criteria. The aim of this study was to test the relationship between local and/or regional neotectonic stress field and the yield of water wells drilled in the region. The local neotectonic structures and morphotectonic features agree with the regional stress field, defined by E-W compression (s_1 or S_H) and N-S extension (s_3 or S_h). The current kinematics of the fracture sets, with an "open" or "closed" behavior, seems to be related to the neotectonic stresses and to be highly influential upon the water-yielding potential of the fissural aquifer. Besides other controls, water wells located along roughly E-W trending fractures that act as extension joints have a higher hydrological potential than those along N-S fractures, which tend to be "closed". NE-or NW-trending old fractures tend to reactivate by shearing. In this region, E-W tension joints generated at end of the Brasiliano Cycle (filled with pegmatite or quartz veins), were reactivated under the N-S to NNW extensional deformation related to rifting and development of the Cretaceous basins. The same N-S extension direction is once again active as part of the Holocene stress field. In the Caiçara area, 2 km NW of Equador, the wells drilled in quartzite and metaconglomerate, located along E-W (± 20°) extension fractures and NE or NW shear fractures have been pumped in a full-time regime since the last 20 years, without major variations in their dynamic levels. On the other hand, wells located along longitudinal, N-S fractures or in poorly fractured sites frequently have very low yields.

Keywords: brittle structures, neotectonic deformation, crystalline fissural aquifers, NE Brazil

INTRODUCTION

In crystalline basement terranes, underground water flow and storage is essentially controlled by fractures. The most important fractures are those with high porosity and/or permeability which, in fact, correspond to extension joints and to multi-fractured fault zones. Therefore, the basic problem in the location of water wells in such terranes rests essentially in the identification of these fracture sets. Fracture recognition becomes more difficult when the bedrock is hidden below thicker soil, alluvial or colluvial covers, although recharge may be favored in that way.

The criteria currently used for hydrogeological exploration remain attached to old structural concepts established in the 1950' and 1960's (Siqueira 1967), including the association of straight-line drainage to fracture zones. The best sites for well drilling correspond to the more intensely fractured zones; the influence of fracture chronology, crustal depth and kinematics were not considered at that time.

It is now known that fracture sets usually represent brittle structures generated during different tectonic events and their respective stress fields. The chronological sequence of the fracture systems, established on the basis of structural, morphotectonic and seismological criteria, constrains the neotectonic stress fields, represented by the latest structures. Subjected to the neotectonic stress regime and depending on their angular relations, some fractures tend to be "open" (acting as extension joints, normal to σ_3 or S_h), others tend to be "closed" (normal to σ_1 or S_H), and those at an intermediate position will be reactivated with a shear component. Therefore, the "water yielding potential" (depending on the porosity and permeability) of the fracture systems will be a function of their original geometry and of the neotectonic stress regime. A critical reappraisal of structural concepts and the development of a practical methodology for location of water wells are part of an ongoing research project in the semi-arid basement crystalline terranes of Rio Grande do Norte State.

The Equador area, located in the center-south portion of this State, along the border with the State of Paraíba (Fig. 1a), provides an excellent case study to test the hypothetical correlation between neotectonic fracture reactivation and the water yield of wells drilled in crystalline terranes. The preliminary results of this study are reported below.

REGIONAL FRAMEWORK

The regional geological framework

The study area is located in the northeast part of the Borborema Province (Almeida *et al.* 1977), known as the "Seridó Belt", and more precisely in its central domain, immediately to the north of the E-W-trending Patos Shear Zone. The Seridó Belt comprises a Proterozoic supracrustal sequence (the Seridó Group, including the Jucurutu, Equador and Seridó formations), which overlies a Paleoproterozoic gneissic-migmatitic basement (the Caicó Complex). These rocks were strongly deformed and intruded by granitoid plutons during the late Neoproterozoic Brasiliano orogeny. The Precambrian units are covered by the Meso-Cenozoic sediments of the coastal basins and, inland, by the subhorizontal, Early Tertiary sandstones of the Serra do Martins Formation. The latter is currently undergoing dissection after a regional uplift (the Borborema Plateau) which started in the Late Tertiary, producing siliciclastics that were transported to the coastal basins. In the coast, these siliciclastic units correspond to the Barreiras Formation (Miocene to Pleistocene) and to other, younger units.

The Phanerozoic brittle deformation

Several phases of Phanerozoic brittle deformation are recorded in the rocks of the Seridó Belt (Jardim de Sá *et al.* 1999). An older set includes brittle-ductile and brittle structures developed at the end of the Brasiliano Cycle, related to E-W compression, regional uplift, cooling and late movement of the shear zones (Jardim de Sá 1994, Coriolano *et al.* 1997, Jardim de Sá *et al.* 1999). The Potiguar and other coastal basins are related to another tectonic episode that lasted from the late Jurassic to the Cretaceous, due to the rifting between South America and Africa (known as the "Gondwanic Reactivation"; Almeida *et al.* 1977). According to Matos (1992), this period is marked by extensional deformation along N- to NW-trending (s_3) axes, reactivating the Precambrian structures. An E-W-trending swarm of diabase dikes, named the Rio Ceará-Mirim Volcanism, was emplaced between 140 and 120 Ma (Martins and Oliveira 1992). During the Late Tertiary to the Pleistocene, a new tectonic episode controlled by N-S compressive stresses (Dantas 1998) created and reactivated strike-slip fault zones. A regional dome, associated with alkaline basic volcanism, uplifted the Borborema Plateau (Jardim de Sá *et al.* 1999).

During the Holocene, the neotectonic regime is dominated by E-W compression and N-S extension, as shown by the important seismic activity in several areas, such as João Câmara (Ferreira *et al.* 1998, Coriolano *et al.* 1997). The neotectonic structures are also recognized in stratigraphic markers such as the Barreiras Formation, gravel deposits and younger holocenic covers (Caldas *et al.* 1997, Coriolano *et al.* 1999, Jardim de Sá *et al.* 1999), as well as by a number of morphotectonic features (i.e., Dantas 1998).

GEOLOGY OF THE EQUADOR AREA

Stratigraphic and structural framework

The following stratigraphic units crop out in the Equador area: a) migmatitic gneisses related to the Caicó Complex; b) paragneisses, quartzites and micaschists respectively correlated to the Jucurutu, Equador and Seridó formations of the Seridó Group; c) late-Brasiliano acid dikes; d) ferruginous sandstones (Serra do Martins Formation) and e) Holocene sandy cover and more

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localized alluvial and colluvial deposits. The macro-scale structures were produced mostly during the main high temperature, Brasiliano ductile event, named as D_3 (Jardim de Sá 1994). This event was responsible for the development of the dextral, transcurrent Serra dos Quintos Shear Zone, located in the western portion of the area, and for the alternating antiforms and synforms along the Serra das Queimadas, folding an earlier, D_2 fabric (Fig. 1b).

The brittle structures The determination of the relative age of the fracture systems (Fig. 1c), combined with the morphotectonic framework, is the first step in investigating the effect of the neotectonic stress field upon potential structures for water storage. The chronological criteria used to determine the relative formation and/or reactivation of the fractures were: a) type of affected markers and filling materials, the latter also used to interpret the crustal level of fracturing; b) kinematics; c) cross-cutting relationships between different fracture sets; d) geomorphologic features which are associated to the youngest structures, being consistent with other neotectonic and regional seismotectonic data (Jardim de Sá *et al.* 1999).

In chronological order, the structures were grouped as:

a) Late-Brasiliano, Cambrian-Ordovician Structures: these occur in kinematic continuity with structures generated during the high temperature deformation stage of the Brasiliano Cycle, and were developed during a brittle to ductile-brittle regime consistent with tectonic denudation and regional cooling. The structures of this system result from an E-W main compression (σ_1) with N-S extension (σ_3), coupled with dextral shearing along NNE-trending zones (*i.e.*, a transpressional environment). They include E-W extensional joints, sometimes filled by pegmatitic, quartz or aplite veins, besides dextral N to NNE longitudinal (shear) fractures and conjugate NE dextral and NW sinistral shear fractures.

b) Jurassic-Cretaceous Structures: these structures comprise roughly E-W trending faults displaying low-temperature slickensides with a down-dip movement, indicative of a N-S extensional deformation. They reactivated the late-Brasiliano extension joint set, generating cataclastic zones and may be occasionally filled with basic dikes.

c) Late Tertiary-Pleistocene Structures: these structures are not kinematically compatible with any of the other groups, consisting of NE sinistral and NW dextral shear fractures sets, and N-S extensional joints or normal faults. Regional N-S compression and E-W extension axes may be inferred for this system. Their regional tectonic setting has been related to the thermal doming effect which uplifted the Borborema Plateau since Miocene times, overprinting the regional E-W compressional regime currently in operation (see below). With regard to the geomorphologic evolution, it is noteworthy the structural control of the sandstone occurrences of

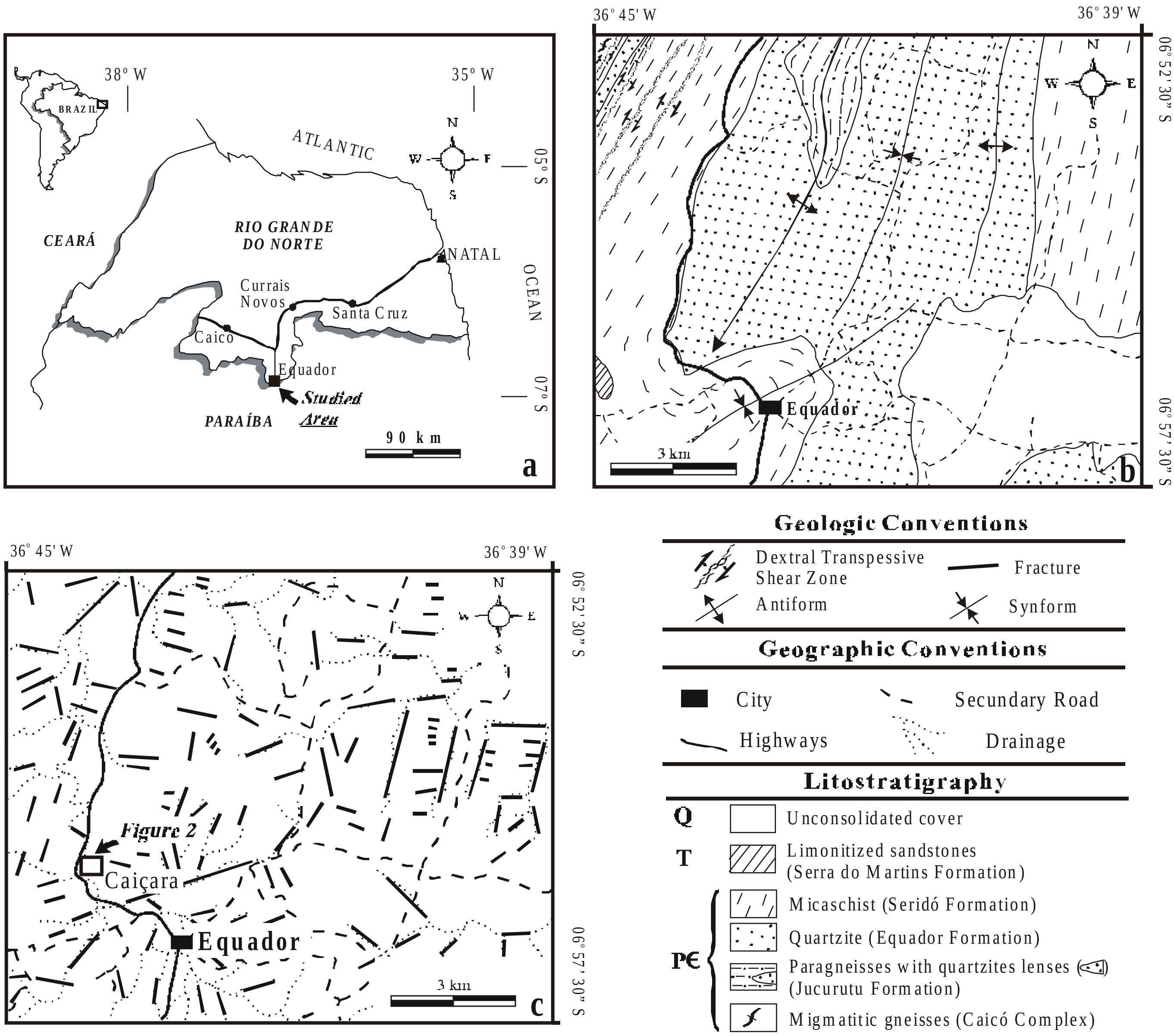

Figure 1 – Geographical (1a), geological (1b) and lineament (fracture) (1c) maps of the Equador area.

the Serra do Martins Formation, preserved as down-faulted blocks due to the E-W extension, which reactivated the NNE-trending Serra dos Quintos shear zone.

d) Holocene Structures: these correspond to reactivated late-Brasiliano (or Cretaceous) fractures, especially those trending E-W ± 20°, which show low temperature slickensides defined by clay-minerals. This group has a normal fault kinematics, sometimes with a subordinate strike slip component, or simply correspond to extension joints, being systematically more open as compared to the other sets. The morphotectonic expression of N-S extension includes the tilting of the pediplane built on the top of quartzite ridges of the Serra das Queimadas, along the E-W fracture planes. These fracture surfaces are also well marked by gorges, bearing dense vegetation, crosscutting the quartzite ridges.

CRITERIA FOR LOCATION OF WATER WELLS IN CRYSTALLINE TERRANES The choice of location of water wells in crystalline terranes is still based on criteria defined in the 1950's and 1960's decades (Costa 1965, Siqueira 1967). These criteria include the widely used association between drainages and fracture zones. "Extensional fractures" are often determined as such using Precambrian markers (!); densely fractured zones (such as fracture intersection zones) are prospected through the examination of aerial photographs and outcrops. However, in many cases, these fractures are old structures, generated at depth under an old stress field, different from the present one. These structures would not necessarily present an "open" behavior, even if they originally correspond to extensional fractures. Besides generating a network of discontinuities, these old stress fields cannot, by any chance, control the water flow and storage, either nowadays or in very recent geological times.

It is very likely that the relationship between the neotectonic stress field and the trend of the fracture (whether old, generated at a relative depth, or younger, developed at near-surface conditions) will influence their "open" or "closed" behavior and, thus, the water flow regime. Relatively to this stress field, fractures that are roughly perpendicular to the main tensional stress (σ_3) will have, in theory, higher hydraulic potential. On the other hand, fractures which are perpendicular to the main compression direction (σ_1) will tend to the closed. At intermediate angles, shear fractures tend to be somewhat closed but do present other possibilities for opening, such as conjugate or intersecting sets, and transtensional sites.

The structural analysis of crystalline terranes identifies several fracture systems which, when individually analyzed, indicate their parent stress field. The chronological ordering of these structures and their corresponding stress fields may help identifying the youngest structures, *i.e.*, those related to the neotectonic regime, as previously discussed. The local neotectonic stress field may be quite difficult to determine in crystalline rocks, at a given place. It may be the same as the regional scale one or it may vary, due to local anisotropy (topographical anomalies or major geological discontinuities). Due to the general lack of appropriate markers in crystalline rocks, it is the regional stress field that is usually taken for comparisons.

Another useful criteria are the morphotectonic analysis of the area, especially those with diversified topography, determining areas of uplift, depression or tilting. Furthermore, regional and (less frequently available) local seismological data may give the best clues to the corresponding present stress field.

Other important criteria for water productivity, such as regional and local drainage and superficial runoff patterns, availability of recharge zones, allochthonous or autochthonous covers, etc., are beyond the scope of this contribution.

CORRELATION BETWEEN THE NEOTECTONIC FRAMEWORK AND WATER WELL LOCATION IN THE EQUADOR AREA In this work, emphasis was given to the set of water wells that supply, almost entirely, the Equador city. The wells are located in the area called Caiçara, approximately 2 km NW of Equador (Fig. 2). At this place, 8 wells were drilled at the beginning of 1980's, located in quartzite and metaconglomerate, with depths ranging from 33 to 60 meters. Their location followed the traditional method including analysis of aerial photographs and investigation of outcrops. 3 out of the 8 wells are not productive, one of them due to mechanical obstruction (well 02). The remaining 5 wells currently yield from 2000 to 6000 l/h; two of them are pumped by weather vane (wells 03 and 04) and three by electric pumps (wells 06, 07 and 08).

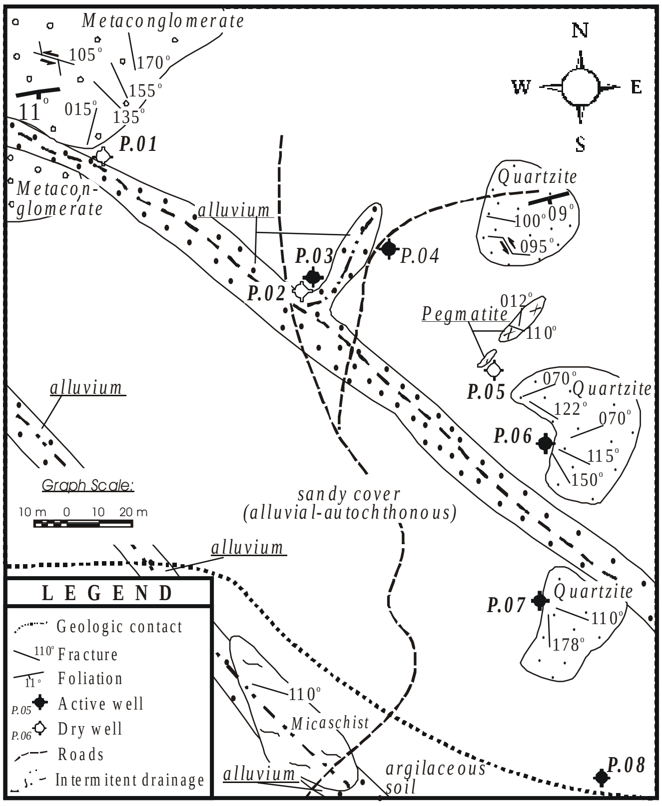

Figure 2 – Simplified geologic and structural map of the Caiçara area, Equador (location in Figure 1c).

In the area, there is a white, quartz-sand sedimentary cover, partly aluvionar, partly autochthonous, with a maximum thickness of approximately 1,5 m, which must be acting, at least partially, as a recharge zone for the fracture systems. The streams are intermittent and flow from the quartzite hills to the east, minimizing water salinization due to the low content of clays in these rocks.

The data obtained through the geologic-structural and morphotectonic analyses attest the neotectonic compression and extension directions as E-W and N-S, respectively. These directions are in agreement with the regional stress field. In this way, the structures with higher water potential are those with E-W (± 20°) trend, presently working as extension fractures, followed by NE and NW-trending fractures, which reactivate as shear surfaces (with a more closed behavior, although still able to channel flow and retain water).

At Caiçara, the main drainage is controlled by NW-trending fractures, flowing in that direction, with small tributaries coming from NE. The main fracture zones observed at the outcrop scale have ENE, NNW and WNW directions. Longitudinal, NNE fractures are also observed. The spacing between fractures varies from centimetric to metric. The E-W (± 20°) fractures correspond to late-Brasiliano extension joints (filled with quartz and pegmatite, *e.g.*) and presently display a distinctly open behavior, as also shown by the regional (gorges) and outcrop scale microtopographic features.

The wells located around E-W (± 20°), NE and NW structures still present good yields after nearly 20 years of exploitation. On the other hand, the "dry" wells yield 320 to 600 l/h, were located according to the "closed", N-S (± 20°) structures, or in less fractured sites.

DISCUSSIONS The geological, structural and morphotectonic analyses of the Equador area, in the light of modern techniques, provide some new insights to improve the hydrogeological prospecting in semi-arid crystalline terranes.

The correlation between fracture trends and the local or regional neotectonic stress fields, may allow the prediction of an "open" or "closed" behavior of the structures and their capability of storing groundwater resources.

This hypothesis is being tested at different areas in the Rio Grande do Norte State. The wells controlled by E-W trending fractures (thus perpendicular to the current extension vector, σ_3), that usually display an open behavior, tend to present relatively high yields. At the opposite side, N-S trending fractures tend to be closed and, as such, "dry." The higher hydrogeological potential of the "transverse", E-W structures was noticed some time ago (Costa 1965, for instance). The neotectonic approach improves our knowledge on the controls of the fracture systems upon water flow and storage.

It should be emphasized that the correlation between the current stress field and the preexisting fracture zones alone will not necessarily arrive at high yield water well. This is only one though important criterion, to which others must be added in order to obtain a complete evaluation of the best location site for a given water well. We hope that with an increasing number of case studies, a sounder statistical basis will support and improve this model.

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References

Almeida F.F.M., Hasui Y., Brito Neves B.B., Fuck R. 1977. Províncias estruturais brasileiras. In: Simp. Geol. Nordeste, 8, Campina Grande, *Atas*, 363-391.

Caldas L.H.O., Coriolano A.C.F., Dantas E.P., Jardim de Sá E.F. 1997. Os Beachrocks no litoral do Rio Grande do Norte: potencial como marcadores neotectônicos. In: Simp. Geol. Nordeste, 17, Fortaleza, *Resumos Expandidos*, **15**:369-376.

Coriolano A.C.F., Jardim de Sá E.F., Cowie P.A., Amaral C.A. 1997. Estruturas frágeis no substrato da região de João Câmara (RN): correlação com a falha sísmica de Samambaia? In: Simp. Geol. Nordeste, 17, Fortaleza, *Resumos Expandidos*, **15**:325-329.

Coriolano A.C.F., Lucena L.F., Jardim de Sá E.F., Saadi A. 1999. A deformação quaternária no litoral oriental do Rio Grande do Norte. In: Simp. Nac. Estudos Tectônicos e Simp. Intern. Tectônica da SBG, 7, Lençóis, *Anais*, 67-72.

Costa W.D. 1965. Análise dos fatores que influenciam na hidrogeologia do cristalino. *Água Subterrânea*, **4**:14-47.

Dantas E.P. 1998. Gravimetria e sensoriamento remoto: uma aplicação ao estudo da tectônica recente entre Macau e São Bento do Norte (RN). M. Sc. Thesis, Pós-Grad. Geodinâmica e Geofísica, UFRN, Natal, 97p.

Ferreira J.M., Oliveira R.T., Takeya M.K., Assumpção M. 1998. Superposition of local and regional stresses in northeast Brazil: evidence from focal mechanisms around the Potiguar marginal basin. *Geophysics*, **134**:341-355.

Jardim de Sá E.F. 1994. *A Faixa Seridó (Província Borborema, NE do Brasil) e o seu significado geodinâmico na cadeia Brasiliana/Pan-Africana*. UnB, IGeo, Brasília, Ph. D. Thesis, 804p.

Jardim de Sá E.F., Matos R.M.D., Morais Neto J.M., Saadi A., Pessoa Neto O.C. 1999. Epirogenia Cenozóica na Província Borborema: Síntese e Discussão sobre os Modelos de Deformação Associados. In: Simp. Nac. Estudos Tectônicos e Simp. Intern. Tectônica da SBG, 7, Lençóis, *Anais*, 58- 61.

Martins G. & Oliveira D.C. 1992. O enxame de diques Rio Ceará-Mirim (EDCM) no contexto da abertura do Oceano Atlântico. *Rev. Geol. Fortaleza*, **5**:51-78.

Matos R. M. D. 1992. The northeast brazilian rifte system. *Tectonics*, **1**:766-791.

Siqueira L. 1967. Contribuição da geologia à pesquisa de água subterrânea no cristalino. *Água Subterrânea*, **9**:1-29.

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