by Claudio Riccomini[1] and Marcelo Assumpção[2]

Quaternary tectonics in Brazil

1 Institute of Geosciences, University of São Paulo, P.O. Box 11348, 05422-970, São Paulo, SP, Brazil. E-mail: riccomin@usp.br
2 Institute of Astronomy and Geophysics, University of São Paulo, P.O. Box 3386, 01065-970, São Paulo, SP, Brazil. E-mail: marcelo@iag.usp.br

The concept of tectonic stability has long prevailed for most of the Brazilian platform and, because of this fact, investigation of Quaternary tectonics in Brazil has begun to develop only during the last decade. From the two pioneer groups at the end of the eighties, there are now active groups studying neotectonics in almost all regions of Brazil. A clear demonstration of this progress is the fact that during the 7th Brazilian Symposium on Tectonic Studies, held in Lençóis, Bahia, in May, 1999, of the 141 papers presented more than 20% were related to neotectonics. References to faulting and other geologic features directly related to Quaternary tectonics are increasing and now available for many areas in Brazil. In this paper the geological record of Quaternary tectonics in Brazil is reviewed and a comparison with available geophysical data on stress orientations is presented.

Introduction

The South American plate encompasses four main geotectonic units: the Andean chain, the Brazilian and Patagonian platforms and the domain of oceanic crust comprising its eastern half. The Brazilian platform is composed of shield areas of Archean to Proterozoic cratons surrounded by Neoproterozoic orogenic belts, and Paleozoic to Cenozoic sedimentary basins. Reactivation of basement faults, shear zones, different types of foliations, and cratonic boundaries, among other structures, played a major role in the origin and the structural and stratigraphic development of Phanerozoic sedimentary basins (Cordani et al., 1984), including neotectonic activity (Riccomini et al., 1989; Hasui, 1990; Saadi, 1993). Recent stress models of the South American plate, calculated from finite element modeling, included plate-boundary forces (ridge push, collision with the Nazca plate and a balancing asthenospheric drag) and internal spreading stress due to large-scale lateral density contrasts along the continent/ocean transition, in order to explain the plate-driving forces (Meijer, 1995; Coblentz and Richardson, 1996). For the Brazilian territory, these models show a regional compressive stress field orientated roughly E-W to ESE-WNW.

The geological record of Quaternary tectonics in Brazil

Faults and fractures affecting dated sedimentary deposits comprise the principal indications of Quaternary tectonics in Brazil. Other evidence includes geoid anomalies related to regional uplift and seismically induced liquefaction structures.

Geoid anomalies and uplifts

Major positive geoid anomalies in Brazil are recognized in the Borborema province (+ 10 m), the southeastern part of the São Francisco craton (+ 8 m) extending eastward along the Abrolhos bank and the Vitória-Trindade chain (+ 5 m), and over the Gaúcho shield (+ 9 m) and adjoining Pelotas basin (+ 6 m) (Ussami et al., 1999). Although mainly related to thermal reactivation associated with alkaline magmatic activity during the Late Cretaceous-Tertiary, these anomalies correlate well with uplifted areas of neotectonic and seismic activity in both the Borborema province and the southeastern part of the São Francisco craton (Ussami et al., 1999). Jardim de Sá et al. (1999) associated the erosion of the Eocene-Oligocene Serra dos Martins Formation and the high sedimentary influx into the offshore Potiguar basin during Miocene-Pleistocene with the uplift of the Borborema province. The general ENE elongation of the geoid anomaly in SE São Francisco craton are in accordance with the present-day regional direction of SHmax (maximum horizontal stress) in the region. The still scarce neotectonic structures recognized near the Brazil-Uruguay international border are situated over the uplands of the Gaúcho shield.

Liquefaction features

Clastic dikes were described by Sant'Anna et al. (1997) within the Quaternary rudaceous deposits of the Chapada de Canga Formation in the southeastern part of the São Francisco craton. Convolute folds, liquefaction pillars and sand dikes were recognized in Quaternary sediments overlying the Barreiras Formation near Açu and Natal, northeast Brazil (Bezerra, 1999). In both regions these seismites have close relationship with Cenozoic faults. Etchebehere et al. (1998) recorded sand dikes, sills and blows in Late Pleistocene (27,000 yr BP) fluvial terraces along the Peixe River in the Paraná basin (São Paulo), but their relationship with major tectonic features remains unclear.

Quaternary faults

Figure 1 shows the estimated SHmax orientations obtained from geological data, mainly slickenside inversion of Quaternary faults. For each site only the youngest stress indication is represented and therefore most of data results from analysis of Holocene faults.

Amazonas basin

In northern Brazil (Amazonas basin) indications of Quaternary tectonics are mainly in the form of structural lineaments along segments of the Amazonas River valley (e.g., Costa et al., 1995). Fernandes Filho et al. (1997) described Pliocene-Pleistocene laterite profiles tilted by NE-trending listric and planar normal faults and right-lateral strike-slip faults. Analysis of a population of NNE-trending listric normal faults (with up to 5–7 m of individual vertical offset) affecting Pleistocene laterites in outcrops located between Manaus

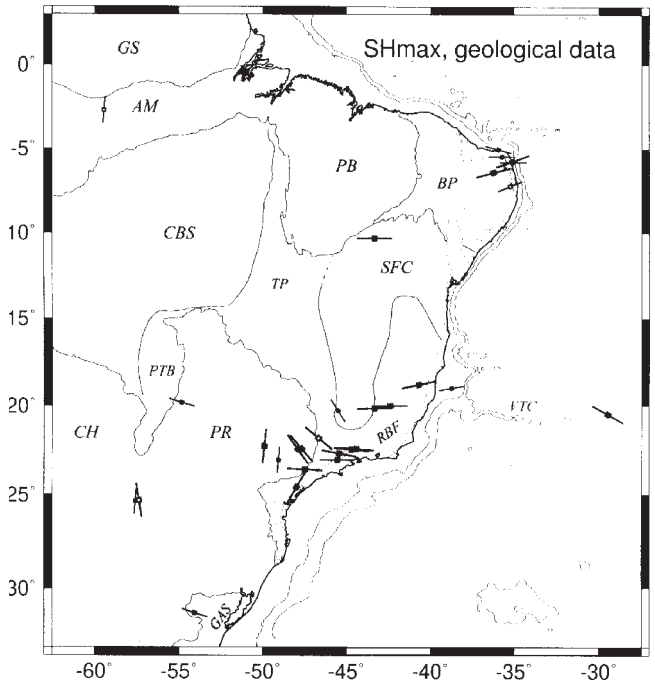

Figure 1 Maximum horizontal stresses from geological data (mainly slickenside inversion of Quaternary faults). Symbol size indicates data quality. Short bars denote preliminary determinations of SHmax. Close and open symbols indicate reverse/strike-slip and normal faulting (or stress regime), respectively. Main geological provinces: Amazon basin (AM), Guiana shield (GS), Central Brazil shield (CBS), Parnaíba basin (PB), Borborema province (BP), Tocantins province (TP), São Francisco craton (SFC), Chaco basin (CH), Pantanal basin (PTB), Paraná basin (PR), Ribeira fold belt (RBF), Gaúcho shield (GAS), Vitória-Trindad chain (VTC).

and Itacoatiara revealed an ESE direction of extension, with NNE-orientated SHmax.

Borborema province and the northern part of the São Francisco craton

Because of the relatively high seismic activity within the Borborema province and adjoining coastal areas of northeast Brazil numerous structural and tectonic studies have been carried out in an attempt to establish the relationships between tectonics and seismicity. A good number of high quality determinations of SHmax using different types of faults affecting Quaternary deposits are available for this region. Along the coast of northeastern Brazil, Holocene beachrock, with age ranging from c. 7,250 to 1,150 yr BP (Bezerra et al., 1998; Bezerra, 1999), constitute an excellent marker for dating Recent tectonic movements. This beachrock is mainly cut by ENE- to NE-trending right-lateral strike-slip faults (Coriolano et al., 1999; Dantas et al., 1999). According to Bezzera (1999), along the NW Boa Cica fault, south of Natal, beachrock dated at 7,250–5,840 yr BP was downfaulted 4 m beneath mean sea level before the accumulation of younger, undeformed beachrock dated at 5,110–4,520 yr BP. Near São Bento do Norte, associated with the ENE Carnaubais fault, a beachrock shows a rapid, possibly coseismic vertical displacement of 4 m between 4,000–2,800 yr BP (Bezerra, 1999). The ENE Jundiaí fault, which crosses the city of Natal, shows two generations of striae, the earlier ones indicating a right-lateral strike-slip and a later, dip-slip component, and contains sedimentary fill dated at 4,860–4,570 yr BP (Bezerra, 1999). Next to João Câmara the NE-trending Samambaia seismic fault, about 40 km in length, exhibits Holocene to present-day right-lateral displacement (Coriolano et al., 1999). All described cases show a consistent SHmax direction around ENE to E-W. In the inner part of the Borborema province, NE-trending right-lateral strike-slip faults near Cuité (Morais Neto and Alkmin, 1999) and normal faults with a left-lateral component of movement in São José do Pilar (Brito Neves et al., 1999) indicate an ENE direction for SHmax.

Farther to the south, in the region north of Xique-Xique (N part of the São Francisco craton, Bahia), an E-W direction of compression (SHmax) was obtained by Barreto (1993), using regional fractures affecting eolian sediments ranging from 10,990 to 2,190 yr BP in age (Barreto, 1996).

Pantanal basin and eastern Paraguay

Reverse faults affecting the Pliocene-Pleistocene sedimentary fill were recognized in seismic section across the northeastern part of the Pantanal basin (Milani et al., 1990). Along the southeastern border of this basin a population of faults and shear joints cutting Holocene colluvium deposits have furnished an WNW direction for σ_1 (Gesicki and Riccomini, 1998). Rabelo and Soares (1999) described an Holocene, probably active NE fault zone across the central Pantanal basin related to the reactivation of the Transbrasiliano lineament, in the basement. In the Asunción rift (eastern Paraguay), neotectonic strike slip-faults at the Cenozoic Ñemby alkaline plug indicate an approximate N-S direction for σ_1 (Riccomini et al., 1998), whereas Quaternary, probably Holocene oblique normal faults of the southern border of the Ypacaraí graben, with more than 40 m of vertical displacement, show an approximate E-W direction for σ_3.

Paraná basin

Quaternary faults in the eastern part of the Paraná basin indicate two orientations for SHmax. A NW orientation was obtained by the analysis of populations of NE reverse and NW normal faults, at Ipeúna and Águas da Prata, respectively (Riccomini, 1995), and strike-slip faults of the Serra de Itaqueri (Riccomini, 1997a). The same NW direction for SHmax was obtained by Saadi (1991) from reverse and right-lateral strike-slip faults near Arcos (Minas Gerais), just within Precambrian terrains, about 130 km from the NE limit of the Paraná basin. On the other hand, strike-slip faults of the Marília and Cerqueira César-Avaré regions indicate a persistent N-S direction for σ_1 (Riccomini, 1995, 1997b).

Ribeira fold belt

The best defined Quaternary tectonic features within the domain of the Ribeira fold belt are those of the Cenozoic basins of the continental rift of southeastern Brazil (Riccomini, 1989). These structures have resulted from the most recent manifestations of the successive reactivations of old ENE-orientated structural lines that have occurred intermittently ever since the Neoproterozoic Brasiliano or Pan-African Cycle, including the generation of new faults (Riccomini, 1989; 1992). Inversion of striae from Holocene faults shows different stress regimes which varies with time (Riccomini, 1989; Salvador and Riccomini, 1995; Mancini, 1995; Hiruma et al., 1997, Hiruma, 1999). The oldest movements were related to a NW-SE compressive stress field, during the Late Pleistocene-Holocene. The faults related to this phase affected a paleosol dated at 18,580 yr BP (Hiruma, 1999), colluvium and stone line deposits (Figure 2), which are often overthrust by blocks of basement rocks along faults trending NE to ENE; along the ENE Queluz fault (São Paulo-Rio de Janeiro border) right-lateral horizontal displacements of more than 20 m are observed. During the Holocene the stress regime changed to an E-W (WNW-ESE) extension (Figure 3), locally responsible for the generation of N-S-trending grabens with syntectonic sedimentary filling. Sedimentary deposits in these grabens reach more than 30 m thick, ranging from 10,240 to 8,630 yr BP in age (Salvador and Riccomini, 1995; Mello et al., 1995; Hiruma, 1999). A new change in the stress field is recorded by E-W normal and N-S reverse faults, and by conspicuous and widespread families of shear joints, systematically orientated ENE and WNW, indicating an E-W direction of compression. These structures affect colluvium, alluvium and a organic-rich deposit dated at 3,410 yr BP (Hiruma, 1999). The same

Figure 2 N-S-trending oblique-slip reverse fault related to Holocene NW-SE compression near Caçapava (São Paulo, southeastern Brazil).

variation in the stress field was reported by Silva and Ferrari (1997) and Silva (1998) in the regions of Macaé-Ponta do Retiro (Rio de Janeiro) and Pilar do Sul-Votorantim (São Paulo), respectively. In the region of the Ribeira de Iguape River valley, Melo (1990) obtained an NE direction for SHmax from normal and reverse faults cutting Quaternary sedimentary deposits.

The rapid variation of stress field during the Holocene in the region may represent the surface relaxation (with extensional faulting) within a regional compressive stress regime (Riccomini et al., 1989; Salvador and Riccomini, 1995; Assumpção, 1998).

Southeastern part of the São Francisco craton

Gallardo et al. (1987) studied short-lived geological phenomena (intermittent sounds associated with the opening of cracks and faulting in terrain) that occurred in Nova Venécia (Espírito Santo) and determined an ENE-WSW direction of compression. E-W-trending normal faults, fractures and clastic dikes described by Sant'Anna et al. (1997) in the region of the Fonseca basin (Minas Gerais) indicate an E-W direction for SHmax. Along the Doce River valley, Mello (1997) recognized a variation of stress regime similar to that of the continental rift of southeastern Brazil in faulted sedimentary deposits ranging from 9500 to 7500 yr BP in age. The N-S-trending Cedro-Rio Doce fault represents the western onshore border of the Espírito Santo basin. On the basis of seismic sections, Sobreira (1999) recognized extensional fault reactivation up to recent times.

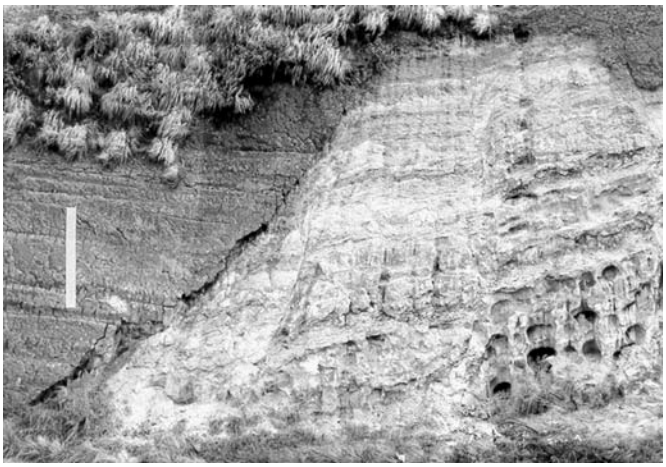

Figure 3 NNE-trending normal faults affecting colluvium (upper left and right) related to Holocene WNW-ESE extension near Taubaté (São Paulo, southeastern Brazil). Scale bar = 2 m.

Vitória-Trindade chain

Analysis of the pattern of orientation of the Pliocene-Pleistocene (0.17 to 4 Ma) dike swarm of the northeast portion of the volcanic island of Trindade pointed to a NW direction of SHmax (corresponding in this case to σ_1) during the emplacement of the intrusive bodies (Ferrari and Riccomini, 1999). The direction determined for σ_1 on the island is parallel to the larger axis of the volcanic buildup, suggesting the same tectonic control throughout its formation (Ferrari and Riccomini, 1999). In the Abrolhos bank, along the high-angle, left-lateral strike-slip Urussuquara fault (offshore Espírito Santo basin), it was possible to recognize recent deformation based on seismic sections (Sobreira, 1999), indicating an E-W direction for SHmax.

Gaúcho shield

The only available data for the Gaúcho Shield correspond to shear fractures near the town of Bagé (near the Brazil-Uruguay border), and furnished a preliminary WNW direction for σ_1.

Comparisons with geophysical data and theoretical models

Figure 4 shows maximum horizontal stresses from geophysical data, including earthquake focal mechanisms, in-situ stress measurement (hydraulic fracturing or overcoring) and average SHmax direction from breakouts in different wells (Assumpção, 1992; Lima et al., 1997; Assumpção, 1998a; b; Ferreira et al., 1998). According to Assumpção (1998a, c), away from the local flexural disturbances of the continental margin, the observed stress regime in southeastern Brazil (strike-slip with E-W SHmax) are in good agreement with theoretical stress models of the South American plate, derived from

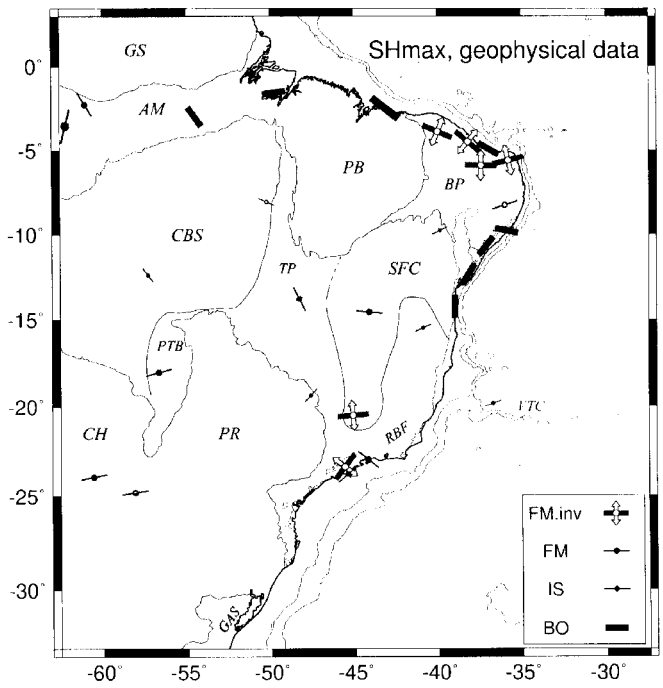

Figure 4 Maximum horizontal stresses from geophysical data. FM.inv. = stress inversion of several earthquake focal mechanisms (solid bar and open arrow denote S1 and S3 directions); FM = estimate of SHmax from a single focal mechanism. IS = in-situ stress measurement (hydraulic fracturing or overcoring). BO = average SHmax direction from breakouts in different wells. Data compiled from Assumpção (1992), Lima et al. (1997), Assumpção (1998a, b), Ferreira et al. (1998).

finite element modeling (Meijer, 1995; Coblentz and Richardson, 1996). Lima et al. (1997) proposed that flexural stresses caused by sediment load in continental shelf produced the observed coast-parallel stresses, as indicated from breakout data along the Brazilian coast. In NE Brazil, east of Parnaíba basin and north of 7˚S, the stress-field is strike-slip resulting from a superposition of a regional uniform E-W compressional stress with local extensional stresses in the upper crust (spreading stresses from the continent-ocean transition and sediment loading at the continental shelf) normal to the coast (Assumpção, 1992; Ferreira et al., 1998).

Stress directions from the youngest geological faults of Borborema province, N and SE São Francisco Craton, Ribeira fold belt, Gaúcho shield and Pantanal basin (Figure 1) also show a good agreement with theoretical models. Discrepancies between geological and geophysical data, as well as with theoretical models, may be explained by the age of analyzed geological data (Trindade island), interaction of regional and local stresses (Amazonas and Paraná basins), and even the scarcity of data (eastern Paraguay). Nevertheless, theoretical models have improved to the point that they now adequately explain stress orientations derived from geological data for most of the Brazilian geological provinces.

Concluding remarks

This summary indicates the existence of Quaternary, particularly Holocene faulting in almost all geological provinces of Brazil and a close relationship of geoid anomalies with uplifted areas of neotectonic and seismic activity. For most of the country, stress directions from Holocene faults indicate a mean E-W-trending of SHmax, in good agreement with geophysical data and theoretical stress models of the South American plate. The interaction of regional and local stresses may explain some observed discrepancies, but much more structural and geochronological data are needed for a better understanding of Quaternary tectonics in Brazil.

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Claudio Riccomini *received his PhD in Sedimentary Geology from the University of São Paulo in 1989. He is Associate Professor at the Department of Sedimentary and Environmental Geology of Institute of Geosciences of the same university since 1986. His current research is focused on Cenozoic stratigraphy, tectonics and sedimentation in Brazil, with emphasis on neotectonics. He was President of Brazilian Geological Society from 1993 to 1995 and from 1997 to 1999.*

Marcelo Assumpção *received his PhD in Geophysics from Edinburgh University in 1978. He worked at Institute of Astronomy and Geophysics of the University of São Paulo (IAG-USP) from 1974 to 1982, Seismological Observatory of University of Brasília, between 1982 and 1988, and returned to IAG-USP in 1988, where he is Associate Professor. His main research interests are intraplate seismicity, lithospheric stresses, crustal and upper mantle structure.*