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The Araripe Basin in NE Brazil: An intracontinental graben inverted to a high-standing horst

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ABSTRACT

The Mesozoic sediments of the Araripe Basin peak at ca. 1000 m, more than 500 m above the host Precambrian basement. This means that an intracontinental graben has been inverted to a topographically high-standing horst, which raises four fundamental questions: (1) Where are the inversion structures? (2) What is the age of the inversion? (3) How can inversion occur in a thick lithosphere? (4) What forces are responsible for the inversion? Here we show that displacement on inverted normal faults increases towards the core of the horst, and new reverse faults thrust basement over basin. Field observations indicate that inversion has occurred on faults striking between NNE–SSW and E–W, following the structure of the host basement. Inversion is reverse/dextral in the NNE–SSW system, and reverse/sinistral in the ENE–WSW system. This is consistent with the Mid-Atlantic Ridge and Andean pushes. From the tectonic analysis of topography and gravity anomaly, the NW–SE faults seem critical to the inversion, although not clearly recognized in the field. The inversion of high-angle normal faults occurred by oblique slip and injection of clay-rich breccias, which apparently reduced friction sufficiently to allow for major inversion. Fault scarps with a prominent topographic expression and faults cutting through colluvium indicate that the latest stage of inversion is Quaternary, although older inversion episodes are likely. The new tectonic data, the timing, and the stress field altogether indicate that inversion was due to plate-wide compression, which preferentially concentrated along inherited shear zones and reactivated them to form the main inversion faults of the Araripe Basin. The high degree of inversion in the Araripe Basin is most likely due to its position at a bend in the major Patos shear zone, which worked as a restraining bend under the maximum compressive stress acting in NE Brazil.

1. Introduction

Intracontinental basins are common in NE Brazil (Fig. 1), but, in most cases, inversion has been disregarded, and therefore the age and extent of inversion are not constrained. In the Cretaceous, continental rifting was widespread in NE Brazil. Later, rifting evolved to drifting, and the Mid-Atlantic Ridge (MAR) formed further to the east, leaving in the west a series of intracontinental basins sealed with post-rift sediments. The added velocities of the MAR (towards the W) and Nazca (towards the E) inverted the western margin of South America (from extension to compression — e.g. Cobbold and Rossello, 2003), and the Andes started to rise. The topographic gradients of both MAR and Andes have kept the South America plate under compression (e.g. Assumpção, 1992; Coblentz and Richardson, 1996; Cogné et al., 2012; Marques and Moulin, 2011), which caused intracontinental rifting to cease and provided the stresses necessary for inversion. In order to investigate the inversion, we chose the most spectacular and unique (inverted) basin, the Araripe Basin (AB) in NE Brazil.

The stresses born at the Andes and MAR can be transmitted into Brazil and the Brazilian Atlantic margin if the lithosphere in between behaves as effectively elastic. The “effective elastic thickness” (*Te*) can be defined as the depth of lithosphere over which the response can be likened to the deformation of an elastic plate under load. It is best conceptualized as the thickness of a perfectly elastic infinite plate composed of lithospheric material located on top of an essentially fluid (at least on geological time scales) mantle. It is therefore a proxy for the long-term (>1 Ma) strength of the lithosphere, which measures the lithosphere's complex strength distribution by analogy to the thickness of a purely elastic beam or plate. Several publications have reported on the estimations of South America's T_e: (1) using the ca. 600 °C isotherm as the T_e's lower bound (e.g. Burov and Diament, 1995), then the T_e in the AB region is ca. 50 km according to the thermal data in Artemieva and Mooney (2001) and Artemieva (2006). (2) In Tassara et al.'s (2007) T_e map, the AB falls in a region with T_e between 30 and 40 km. (3) In Perez-Gussinyé et al.'s (2007) T_e map, the AB falls on the boundary between $T_e > 70$ km and rapid decrease to $T_e = 20$–30 km

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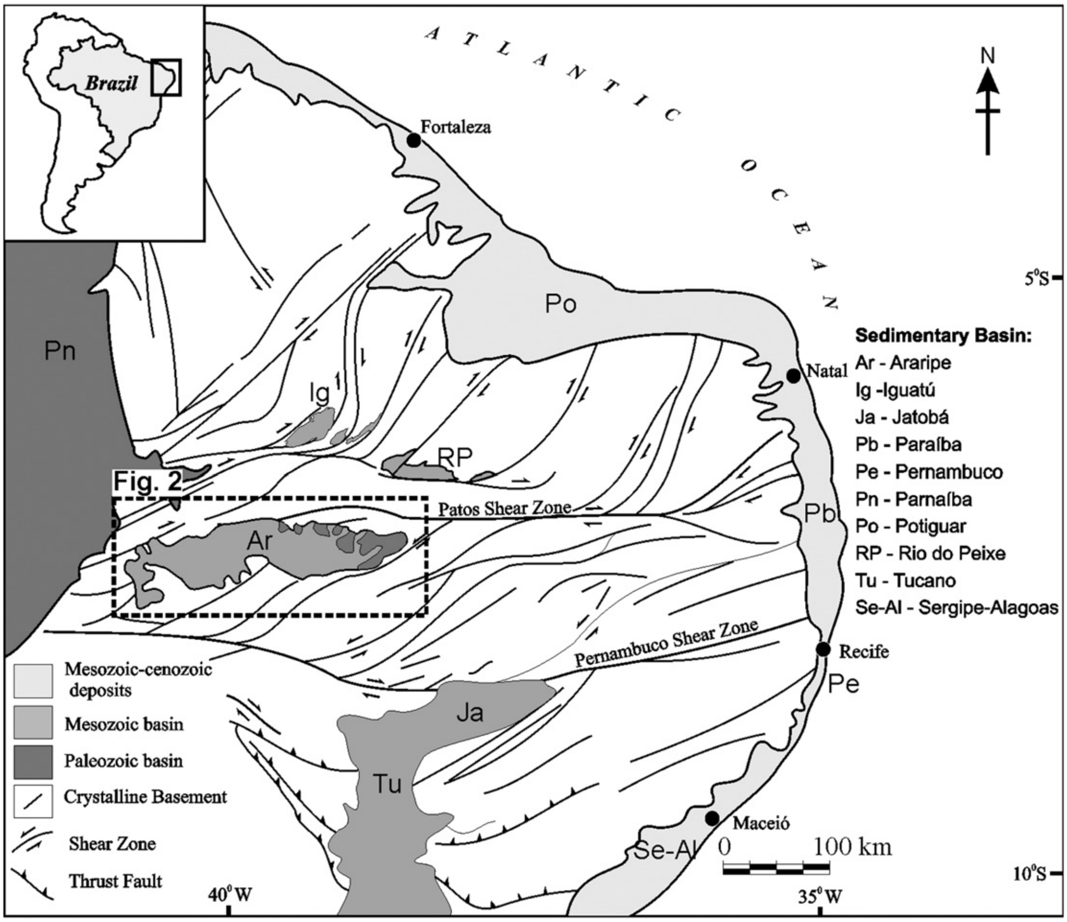

Fig. 1. Sketch map of NE Brazil with main E–W and NE–SW shear zones, and the localization of the main coastal and interior basins. Modified from De Castro and Branco (1999).

to the NE. (4) In Tesauro et al.'s (2012) T_e map, the AB falls in a region with *Te* between 60 and 80 km, and also decreasing to the east, towards the Atlantic margin. (5) In Pascal and Bürgmann's (2011) T_e map, the AB falls in a region with *Te* between 60 and 40 km, and also decreasing to the east, towards the Atlantic margin. Taking into account all these estimates, the average elastic thickness of the lithosphere is around 50 km in NE Brazil, which poses major mechanical problems regarding inversion under compression.

Assumpção et al. (2013) used a compilation of data published in the literature as well as new measurements to produce a map of the crustal thickness in Brazil. They used mostly seismic datasets, such as deep seismic refraction, receiver function analyses, and surface-wave dispersion velocities. The thickness estimated for the crust below the AB is around 35–40 km.

The inversion of an intracontinental basin is not a trivial problem, because: (1) the stresses are exerted in, and transmitted by, the elastic lithosphere, which is thick below the studied AB. Even if there were a ductile and weak lower crust, which could work as a detachment, the stresses would concentrate, at least, in the entire brittle upper crust. We do not know of any source of stress in South America (i.e. horizontal maximum compressive stress) that can be exerted exclusively on the top 2–3 km of the crust, where we see the tectonic effects, to invert the basin without involving the thick and strong underlying lithosphere (or at least the crust). Therefore, one cannot dissociate the observed tectonics from the lithospheric stresses. (2) Hansen and Nielsen (2003) noted that the phenomenon of basin inversion is non-trivial from the point of view of rheology, because rifting and subsequent thermal re-equilibration can alter the long-term mechanical state of the lithosphere.

What we observe at the surface must reflect what has happened at depth. This is the reason why inversion in eastern Brazil (e.g. Cogné et al., 2012), and in particular in the AB (this work), has occurred along major inherited discontinuities, which must therefore be lithospheric scale (at least crustal scale). We cannot imagine shallow tectonics (except salt tectonics) completely dissociated from the underlying lithosphere where the stresses are applied and can propagate (elastic lithosphere). It is now consensual that inversion represents the response to horizontal maximum compressive stress, probably originating at the plate-scale (e.g. Hillis, 1995; Lowell, 1995; Sandiford, 1999). Sandiford (1999) noted that, from the mechanical point of view, inversion in response to a horizontal maximum compressive stress implies that the lithosphere on which the basin is developed remains sufficiently weak to localise regional contraction long after the extensional episode. We conclude that the whole elastic lithosphere (or at least the crust) must be involved, which is a major tectonic/mechanical problem.

At shallower levels, inversion of normal faults is a major mechanical problem (e.g. Sibson, 1985), because inversion of the typical ca. 60° dipping normal faults requires much more work than that needed to create a new reverse fault at an angle of ca. 30° to the maximum compressive stress. Therefore, our main objective is to understand the mechanisms responsible for basin inversion in intracontinental settings,