Self-indentation of a heterogeneous continental lithosphere

Alain Vauchez  
Andréa Tommasi  
Marcos Egydio-Silva

Laboratoire de Tectonophysique, Université de Montpellier II, F34095 Montpellier cedex 5, France  
Instituto de Geociências, Universidade de São Paulo, BRD1498 São Paulo, Brazil

ABSTRACT

The Neoproterozoic Ribeira-Araçuaí belt stretches along the southeastern edge of the São Francisco craton of southeastern Brazil and extends south of the cratonic domain for >1000 km. The termination of the craton is spatially correlated with a significant modification of the deformation pattern in the belt: (1) the structural trend bends from north to northeast, (2) the dominant tectonic flow shifts from orogen-transverse to orogen-parallel, and (3) the metamorphic conditions of deformation decrease southwestward from high to medium grade. Finite-element modeling suggests that the presence of a craton within a continent favors strain localization, initiation of continental-scale shear zones, and differential vertical deformations. The southward termination of the São Francisco craton may have triggered the development of the complex deformation pattern that characterizes the Ribeira-Araçuaí belt.

INTRODUCTION

Because its lithosphere is colder and thicker than the lithosphere of the more recently accreted surrounding terranes (e.g., Vitorello and Polack, 1980; Lowe and Ranaill), 1993), a craton within a continental plate represents a major rheological heterogeneity. It may be expected that, during a continental collision, the presence of a stiffer cratonic block significantly modifies the mechanical behavior of the plate in which it is included and thus the resulting deformation field. Indeed, in transpression belts, the limit of the cratonic lithosphere is frequently correlated with the transition between an external domain in which orogen-parallel motions dominate and an internal domain in which most of the convergence is accommodated by orogen-transverse thrusting (Tommasi and Vauchez, 1992).

The perturbation of the plate-tectonics-induced strain field by a stiff inclusion in a continental plate during a collisional orogeny was already highlighted by Viot et al. (1984). Besides the stiffness contrast between the cratonic and surrounding lithospheres, the size of the heterogeneity relative to the tectonic system certainly represents a major factor. For large heterogeneities, it may be expected that the resulting strain field should be especially complex at the terminations of the stiff domain. This latter point is well illustrated by along-strike variation of the deformation pattern in the neoproterozoic Ribeira belt, which developed at the southern end of the São Francisco craton (southeastern Brazil). This paper presents (1) geologic evidence suggesting that the deformation pattern in the Ribeira belt is strongly modified approaching the southern termination of the craton, and (2) preliminary numerical models of the deformation pattern produced at the termination of a large-scale stiff domain included

in a continental plate undergoing margin-normal compression.

GEOLOGIC SETTING

The São Francisco craton of Brazil (Fig. 1) is formed by Archean to Paleoproterozoic high-grade metamorphic and magmatic rocks (e.g., Cardani et al., 1988; Teixeira and Figueiredo, 1991). The cratonic domain is surrounded by late Precambrian orogenic belts in which it was partially reworked (e.g., Brito Neves and Cardani, 1991; Trompette et al., 1992). Preliminary seismic data suggest a continental root between 200 and 400 km thick beneath the craton (James et al., 1994). Average heat flow is significantly lower in the craton than in the surrounding belts (42 ± 5 and 55 ± 4 mW·m⁻², respectively; Vitorello et al., 1980).

The Ribeira-Araçuaí belt (see review in Trompette, 1994), >1500 km long, comprises tectono-stratigraphic domains of different natures and ages. It was formed east and southeast of the São Francisco craton, probably in response to the convergence between the São Francisco and the Congo cratons. The northern part of the belt trends almost due north and borders the São Francisco craton. Deformation and metamorphism are moderate in the external domain overlying the craton but increase rapidly eastward from the craton. The more internal domains of the belt have undergone a polyphase deformation under metamorphic conditions decreasing from the granulite to the amphibolite facies. Although they are still few, reliable kinematic data collected by various authors consistently indicate a westward tangential transport (e.g., Pedrosa-Soares et al., 1992; Trompette et al., 1992).

Approaching the termination of the craton southward, the deformation pattern changes progressively. The structural trend rotates from due north to northeast; narrow ductile strike-slip faults parallel to the belt begin in the north, then widen and merge southward to form several mylonite zones ~10 km thick. South of the craton, those

![Figure 1. Schematic map of Ribeira-Araçuaí belt (light shading) showing dominant kinematics for its southern and northern domains. Inset shows location of belt among Neoproterozoic belts (black lines) and cratonic regions (dark shading) of western Gondwana.](image-url)
mylonite zones are concentrated within an elongated domain 100 km wide in which orogen-parallel motions dominate (e.g., Hasui and Oliveira, 1984; Trompette, 1994). Mylonites in the shear zones display a vertical foliation, a subhorizontal mineral-stretching lineation, and kinematic indicators in agreement with a dextral sense of shear. Northward, the mylonitization occurred under granulate to upper-amphibolite facies metamorphic conditions. Although largely annealed, the mylonites display evidence of a high-temperature quartz fabric and of plastic deformation and dynamic recrystallization of plagioclase. Preliminary garnet-biotite thermometry calculations suggest synkinematic temperature conditions of \( \pm 720 \) \( \pm 30 ^\circ \) C, depending on the calibration, and subsequent retrogression conditions of \( \pm 720 \) \( \pm 30 ^\circ \) C. The shear zones clearly reworked higher-grade granulites under slightly retrogressive conditions (Campagna, 1981). Between the shear zones, the granulites are locally well preserved and display a flat-foliation foliation locally bearing an east-trending lineation that suggests early orogen-transverse tectonics. Southward along with the shear zones, the metamorphic conditions of mylonitization decrease progressively down to the upper-green schist facies in the southernmost part of the belt. A similar variation in metamorphic grade is displayed by the blocks bounded by the transcurrent shear zones. This suggests that shallower crustal levels are exposed within the Ribeira belt away from the termination of the craton. The southernmost domain of the belt, buried beneath the Paraná basin, remains unknown.

**CONCEPTUAL MODEL**

The late Precambrian orogeny in the Ribeira-Araquá domain resulted in changes, from north to south, (1) structural trend, from due north to northeast, (2) tectonic flow, from dominantly orogen-transverse to dominantly orogen-parallel, and (3) metamorphic conditions of mylonitization in the shear zones, from high to medium grade. All these changes are spatially correlated with the termination of the São Francisco craton.

Along-strike differential vertical motions suggested by southwestward-decreasing metamorphic grade within the shear zones may result from a longitudinal variation of crustal thickening and related exhumation rate, due to the presence of a stiffer lithosphere at the front of the belt in the northern domain. Similarly, both changes in tectonic flow and structural trend may be related to the considerable variation in rheological properties of the lithosphere induced by the termination of the craton. We suggest a tectonic model in which the continental convergence is assumed to have been normal to the eastern boundary of the São Francisco craton (Fig. 1). In the northern part of the belt, the inland propagation of the deformation was limited by the cratonic lithosphere; this confinement effect—absent in the southern domain—resulted in significant shortening accommodated by nappe stacking and crustal thickening in the northern domain. At the tip of the craton, a transpressional deformation regime certainly prevailed, associating limited orogen-transverse motions, which probably represent the earliest deformation, and a tendency for the lithospheric material to move laterally along southwest-trending transcurrent shear zones (Vauclain et al., 1992). Southward, the effect of the stiff domain lessened, resulting in decreasing crustal thickening.

**NUMERICAL MODELING**

Numerical modeling was undertaken to analyze the influence of a continental-scale stiff heterogeneity in a continental plate undergoing compression. We used a finite-element program developed by Daudré (1991), in which a Lagrangian formulation of the equations of continuum mechanics is solved for plane-strain or plane-stress approximations. The deformation of the lithosphere is modeled by a Stokes flow of a nonlinear incompressible viscoplastic material that follows a Norton law and a Von Mises plasticity criterion (see Appendix 1). Deformation is driven by an imposed velocity along one boundary of the model, and elastic deformations are assumed to be negligible when compared to plastic finite deformations.

Two-dimensional modeling of large horizontal displacements (strike-slip motions) requires severe simplifications of the lithosphere rheology, which varies with depth owing to geothermal gradient and lithologic layering. Considering that the long-term deformation of the lithosphere is controlled by its most resistant layer (Vilotte et al., 1982; England, 1983), the mechanical behavior of the lithosphere is approximated by a constitutive relation for a homogeneous lithosphere. For a wide range of geothermal gradients, the uppermost mantle has the highest strength (Fig. 2). We therefore used the material constants of the wet Ania Bay dunite (Appendix 1), experimentally determined by Chopra and Paterson (1981).

The purpose of our models is to investigate the mechanical behavior of a heterogeneous continental lithosphere rather than to reproduce the tectonic evolution of the Ribeira belt. Consequently, the geometry of the problem and the boundary conditions were simplified to minimize the number of free parameters. A rectangular plate, 2500 by 2000 km, is modeled by a mesh of 1136 seven-noded isoparametric elements (Fig. 3). A westward displacement at a constant velocity of \( 2 \times 10^{-5} \) m/s is set on the eastern boundary of the plate, simulating the convergence of a rigid plate. The northern and western boundaries are free to glide laterally (reflective conditions), with the exception of the northern limit of the stiffer block, which remains fixed so as to prevent a rigid block translation, an unlikely process considering the extension of the craton to the north. Geologic constraints on the boundary conditions at the western limit of the model are lacking because there the belt is buried beneath the Phanerzoic Paraná basin. Consequently, the western boundary of the model was located far from the domain of interest and did not affect the solution. The southern boundary is located 1000 km away from the end of the craton and is set totally...
free, simulating the conditions of an active margin.

The stiffer craton is modeled as a 1000 × 500 km quadrilateral block (Fig. 3) having a higher viscosity than the surrounding material. The rheological contrast between the craton and the surrounding terranes may be schematically considered as resulting mainly from the lateral variation in the geotherm. Using classical geotherms for both cratonic and orogenic areas (Fig. 2), we computed a contrast in Moho temperatures of ~200 K. For a constant strain rate, such a temperature contrast would induce an effective viscosity variation of one order of magnitude.

Series of runs were performed with either plane-strain or plane-stress approximations to investigate the two extreme cases: an infinitely thick and an extremely thin plate. The plane-strain approximation implies no vertical deformation and therefore favors lateral escape. Consequently, we have focused on plane-stress experiments, in which flow may involve both horizontal and vertical displacements.

The results (Fig. 4) show that the presence of a stiff block deeply modifies the otherwise homogeneous deformation field. An important strain localization occurs in two domains characterized by higher strain rates (Fig. 4A): a northern domain squeezed between the converging boundary and the stiff block, in which the strain is quite homogeneous, and a wide zone starting at the southeastern corner of the stiff block and propagating southwest. Although they are in continuity, these two domains present different mechanical behaviors. The northern domain undergoes a roughly coaxial strain (Fig. 4B), characterized by dominant shortening almost parallel to the displacement imposed at the model boundary and significant upward displacements that represent a thickening of the model (Fig. 4C).
domain to the southwest displays a large rotational component of strain (Fig. 4B) in agreement with lateral escape of the material at the free boundary by dextral shear. In the southern domain, the principal strain directions are rotated, the extension axis trends northeast, and the vertical deformation in the shear zone decreases rapidly away from the stiff block (Fig. 4C).

To test the influence of the southern free boundary, runs have been performed with a configuration without any free boundary. Although it strongly modifies the strain repartition, this configuration does not significantly change the effect of the stiff heterogeneity: a shear zone is initiated at the termination of the stiff block, but its propagation is limited by the hindrance of displacement normal to the southern boundary.

CONCLUSIONS

The modeled result of a deformation field produced by a lithospheric plate containing a stiff block undergoing normal compression displays considerable similarity to the deformation pattern in the Ribeira-Araquã belt. The change in dominant kinematics, in structural trend, and in exposed crustal level in the Ribeira-Araquã belt correlates well with the switch in the models from a dominant east-west shortening accompanied by significant crustal thickening in northeastern-oriented dextral shearing associated with a limited thickening that decreases rapidly southwestward along the shear zone. These results strengthen the hypothesis that the termination of the São Francisco craton may have largely controlled the deformation field in the belt. Moreover, the good agreement between the modeled uppermost mantle deformation and the observed deformation of the lower to middle crust supports the crust-mantle coupling implicitly assumed by the model formulation.

During a continental collision, the rheological contrast between a stiffer craton and surrounding terranes may control the extent of strain and the type of kinematic field over a large continental area. The termination of a cratonic block especially represents a first-order heterogeneity that may provoke a kind of self-indentation of the continental lithosphere, which is then responsible for the localization of strain in a narrow belt along the boundary of the craton but in a wide shear zone beginning at the craton’s termination. From one domain to the other, the strain regime and the orientation of the principal strain axes change significantly. This complex mechanical behavior also highlights the fact that, during a single orogenic event, the tectonic regime and vertical deformation may vary from place to place because of the presence of continental-scale heterogeneities within the lithosphere.

APPENDIX I. CONSTITUTIVE RELATION AND MODEL PARAMETERS

The constitutive relation used in CREEP to model the lithosphere behavior is (Daudré, 1991)

\[ \sigma = 2\mu (\dot{\varepsilon}_S - \dot{\varepsilon}_T) + \dot{\varepsilon}_P, \]

where \( \sigma \) is the Cauchy stress tensor, \( \dot{\varepsilon}_S \) is the strain-rate tensor, \( \dot{\varepsilon}_P \) is the pressure, and \( \dot{\varepsilon}_T \) is the Kronecker delta. The effective viscosity \( \mu \) is defined by

\[ \mu = \left( \alpha_\gamma \left( \frac{\epsilon}{T} \right)^{1/3} \right)^{1/2} \rho_1 \beta, \]

where \( \alpha_\gamma \) is the plasticity limit defined by the Von Mises criterion, \( \epsilon \) is the second invariant of the strain-rate tensor, \( \rho_1 \) is the stress exponent, and \( \gamma \) is the fluidity. The fluidity depends on the temperature \( T \) according to

\[ \gamma = \gamma_0 \exp \left( \frac{Q}{RT} \right), \]

where \( R \) is the universal gas constant, \( \gamma_0 \) is a material constant, and \( Q \) is the activation energy, both experimentally defined.

In the models, the preexponential parameter, \( \gamma_0 \), is 7.59 \times 10^{-17} Pa \cdot m^{-n} \cdot s^{-1}. The activation energy, \( Q \), is 444 kJ mol^{-1} K^{-1}. The stress exponent, \( n \), is 3.55, and the yield stress, \( \sigma_0 \), is 30 MPa. All material parameters are from Chopra and Paterson (1981).

ACKNOWLEDGMENTS

We thank Bertrand Daudré for providing us with the CREEP program and for discussions, and Marc Daiglères, David Mainprice, and John Oldow for helpful reviews and constructive criticism. Tommasi thanks Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for a Ph.D. fellowship. This work is a contribution to the Centre National de la Recherche Scientifique-CNPq project "Crust-Mantle Coupling in Transpressional Belts."

REFERENCES CITED


Manuscript received February 23, 1994
Revised manuscript received August 1, 1994
Manuscript accepted August 16, 1994