Deformation of a pervasively molten middle crust: insights from the neoproterozoic Ribeira-Araçuaí orogen (SE Brazil)

Alain Vauchez,1 Marcos Egydio-Silva,2 Marly Babinski,2 Andréa Tommasi,1 Alexandre Uhlein3 and Dunyi Liu4

1Geosciences Montpellier, Université de Montpellier 2 & CNRS Place E. Bataillon, 34095 Montpellier Cedex 05, France; 2Instituto de Geociências, Universidade de São Paulo, Rua do Lago, 562 Cidade Universitária, 05508-900 São Paulo, SP, Brazil; 3Instituto de Geociências Universidade Federal de Minas Gerais, Av. Antônio Carlos, 6627 Pampalhá, 31270-901 Belo Horizonte, MG, Brazil; 4Shrimp Laboratory, Institute of Geology, CAGS, Beijing 100037, China

ABSTRACT

Pervasive melting of the middle crust, as inferred in Tibet and the Altiplano, probably influences the deformation of the lithosphere. To constrain strain distribution in a pervasively molten crust, we analysed the deformation in an eroded analogue of these orogens. The Ribeira-Araçuaí orogen (SE Brazil) comprises a stack of allochthons containing large volumes of anatectic and magmatic rocks. The upper allochton (~300 km long, 50–100 km wide and >10 km thick) involves peraluminous diatexites and leucogranites resulting from partial melting of the middle crust. It overlies another allochthon containing huge early- to syn-collisional plutons intruding metasediments. Both anatexites and magmatic intrusions display a pervasive strain-induced magmatic fabric. Homogeneous strain distribution suggests inefficient localization. U–Pb ages of ~575 Ma imply that anatexite melting was synchronous to the early- to syn-collisional magmatism. Similarity in ages suggest that intrusions and anatexites deformed coherently with solid-state rocks while still molten, in response to a combination of gravity-driven and collision-driven deformation.

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Introduction

Geophysical surveys suggest that the middle crust beneath the Himalayan plateau and the Altiplano in the Andes undergoes pervasive partial melting. The middle crust beneath Tibet exhibits low seismic velocities, high attenuation and high electrical conductivity (Chen et al., 1996; McNamara et al., 1996; Nelson et al., 1996; Alsdorf et al., 1998; Unsworth et al., 2005). A pronounced satellite magnetic low supports a Curie isotherm (~550 °C) reached at ~15 km depth, i.e. a mean geotherm of 37 °C/km for which the granite solidus (600–650 °C) is achieved at 16–18 km (Alsdorf and Nelson, 1999). Through seismic detection of the quartz α–β transition, Mechie et al. (2004) suggested a temperature of ~700 °C at ~18 km depth. Altogether, these data support a >200 km wide, up to 1000 km long and >10 km thick partially molten layer in the Tibetan middle to lower crust.

A similar picture holds for the Altiplano and western Cordillera in the Central Andes. Seismic and gravimetric data suggest a 60–70 km thick crust (Wigger et al., 1994) characterized by low seismic velocities and high attenuation in the middle crust (Schmitz et al., 1997; Masson et al., 1998; Dorbath and Masson, 2000; Schurr et al., 2003). Fifteen to twenty per cent basaltic or andesitic melt are required to explain both the negative gravity anomaly and the low seismic velocities (Schmitz et al., 1997). Geoelectromagnetic measurements depict an extensive zone of high electric conductivity ≥40 km thick starting at 20 km depth (Schilling et al., 1997; Schmitz et al., 1997). Minimum temperature at the top of this zone would be ~650 °C (mean geotherm of 32 °C km−1; Schilling et al., 1997). Similar high conductivity zones further north were also attributed to partial melting in the crust (Tarits and Menvielle, 1986). These data are consistent with the high heat flow (100 mW m−2) in this area (Giese, 1994; Hamza and Munoz, 1996). They altogether suggest that the middle to lower Andean crust contain large amounts of melt as anatexites or incompletely solidified plutons.

How is strain distributed in such a hot lithosphere? Experiments support that partial melting severely weakens the rheology of crustal rocks even for <10% melt (Rosenberg and Handy, 2005). Recent models suggest that a pervasively molten middle crust is so weak that it may undergo gravity-driven channel flow and lateral extrusion (Clark and Royden, 2000; Beaumont et al., 2001). How does a partially molten middle crust affect the stress/strain transmission across the lithosphere (Royden, 1996) and thus the mechanical coupling between the seismogenic crust and the underlying ductile lithosphere?

An associated issue is the strain distribution within the hot, partially molten middle crust. At low to intermediate temperatures, strain localization is the rule; large proportions of strain are accommodated in ductile shear zones. Under high temperature conditions, strain localization becomes less efficient, large volume of rocks are deformed homogeneously and faults appear as tens of kilometres wide shear zones (Vauchez and Tommasi, 2003). The strength drop occurring at the onset of melting may cause two divergent evolutions. If
melting only affects limited volume within the crust, strain is preferentially accommodated in the partially molten domains, leading to localization (Rosenberg and Handy, 2000). On the other hand, if partial melting pervasively affects the middle crust, a homogeneous strain distribution may be expected.

Many ancient orogens display volumes of synorogenic migmatites large enough to represent analogues of the partially molten crust in active areas. Deformation analysis in these large anatectic domains and in contiguous domains where pervasive melting did not occur should provide clues on the mechanical behaviour of a pervasively molten middle crust. We present preliminary results on the kinematics and strain repartition in a segment of the neoproterozoic Ribeira-Araçuaí orogen (SE Brazil) that underwent HT-LP metamorphism, pervasive partial melting and widespread magmatism during collisional deformation. This resulted in development of a ~300 km long, 50–100 km wide and >10 km thick anatectic domain overlying allochthonous units containing abundant syn-collisional magmatism. We show that: (1) the partially molten domain as well as the early- to syn-collisional magmatic intrusions deformed coherently with solid-state rocks before complete solidification, and (2) strain is homogeneously distributed, suggesting inefficient strain localization.

Geological setting

The Ribeira, Araçuaí and Western Congo belts form an orogen >1000 km long and ~500 km wide resulting from the final amalgamation of the Gondwana super-continent (Fig. 1). The convergence between the African and South American continents during the Neoproterozoic possibly involved the closure of an oceanic basin bounded eastward by an active margin (Pedrosa-Soares et al., 1998, 2001). Dating using various geochronometers supports that collision began after 600 Ma, lasted until ~520 Ma (e.g. Silva et al., 2005), and welded together continental lithosphere of contrasted age and origin (Brueckner et al., 2000).

From north to south, the Ribeira-Araçuaí orogen displays a change in dominant deformation regime (Trompette, 1994; Vauchez et al., 1994). The southern domain is characterized by transpressional deformation involving coeval or slightly diachronous thrusting normal to the belt and dextral, orogen-parallel transcurrent movements (Trompette, 1994; Egydio-Silva et al., 2002; Schmitt et al., 2004). Deformation in the northern domain is characterized by HT thrusting of allochthonous units on the São Francisco craton margin (Cunningham et al., 1998; Oliveira et al., 2000). The change in dominant deformation regime (Fig. 1) is spatially associated with the bending of the belt around the southern termination of the São Francisco craton (Vauchez et al., 1994) where transcurrent and thrust fabrics coexist (Egydio-Silva et al., 2005).

Strain distribution in the partially molten middle crust of the northern Ribeira-Araçuaí orogen

The northern Ribeira-Araçuaí orogen underwent HT-LP synkinematic metamorphism, westward thrusting, and widespread magmatism (e.g. Oliveira et al., 2000). It comprises a variety of metamorphic rocks and magmatic
intrusives, but its most striking feature is the presence of a large anatectic unit overlying a stack of west-verging nappes. Three main allochthonous domains compose the belt (e.g. Oliveira et al., 2000): the western, central and eastern domains, which are thrust onto the HT para-autochthonous metasedimentary cover of the São Francisco craton (Figs 2 and 3). These three domains display consistent kinematics, but varying melt volumes during deformation.

**Western domain: distributed high-temperature solid-state thrusting**

The western domain of the Araçuaí belt is composed by HT mylonites (Cunningham et al., 1998), which form a >5 km thick subhorizontal shear zone (Fig. 3). These mylonites mainly derive from sedimentary protoliths. They are injected by abundant synkinematic leucocratic melts that frequently contain garnet and cordierite. Foliations dip gently eastward; lineations trend consistently close to EW (Fig. 2). Numerous centimetre to 10 m scale shear sense criteria indicate reliable top-to-West shearing (Fig. 4).

HT-LP conditions during the mylonitic deformation are attested by biotite, garnet, prismatic sillimanite, (cordierite) mineral assemblages and by the systematic absence of muscovite. PT conditions of ~750 °C and ~600 MPa were estimated from the rim compositions of biotite–garnet, garnet–plagioclase and garnet–cordierite mineral pairs (Petitgirard, 2005). These values probably represent postpeak metamorphism conditions as suggested by core-rim Fe–Mg gradients in garnet crystals and by temperature estimates (~800 °C) obtained using biotite inclusions and the host garnet core.

These mylonites overlie para-autochthonous metasediments (mainly gneiss and Al-rich quartzite) that belong to the São Francisco craton and were also mylonitized under HT-LP conditions. The transition from the para-autochthonous metasediments to the mylonitic unit is progressive and the boundary between the two domains is not sharply defined. Together the western unit and the uppermost metasediments of the craton form a HT-LP shear zone >5 km long.

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**Fig. 2** Simplified geological map modified from 'Projeto Leste' (Oliveira et al., 2000) showing the four main domains in the northern Ribeira-Araçuaí orogen. The 'eastern domain' (1) or uppermost allochton comprises a thick (210 km) layer of diatexites and anatectic granites (a) representing the partially molten middle crust, which is topped by migmatitic kinzigites (b). The 'central domain' comprises pre- to syn-collisional magmatic complexes (2 = Galiléia batholith; 3 = São Vitor Tonalite) intruded in HT metasediments (5). The 'western domain' (6) involves metasedimentary and metaigneous mylonites thrust upon the para-autochthonous metasedimentary cover of the São Francisco craton (7). A late generation of porphyritic granitoids associated with charnockites (4) intruded the stack of allochthonous units. 8 = foliation and lineation measured in the field; 9 = foliation and lineation deduced from anisotropy of magnetic susceptibility measurements (8 and 9 together summarize measurements from more than 500 localities). GV, Governador Valadares; TO, Teófilo Otoni. A–B = location of the cross section of Fig. 3. Top left insert: Location map showing the main cratonic domains (SFC, São Francisco craton; CC, Congo craton; AC, Amazon craton; WAC, West African craton) and neoproterozoic mobile belts in eastern South America (SA) and western central Africa (AF). Square East of the SFC is the area studied.

**Fig. 3** Schematic cross section from the paraautochthonous metasediments of the São Francisco craton westward, to the anatectic allochthonous unit eastward. This section shows from W to E: the dominantly granulitic (1) and metasedimentary (2) crust of the São Francisco craton; the western, the lower allochthonous domain involving dominantly metasedimentary (3) and tonalitic (4) mylonites; the central domain that comprises metasediments (5), and pre- to syn-collisional intrusives, especially the São Vitor tonalite (6) and the Galiléia batholith (7); the eastern, pervasively anatectic upper allochton, which comprises minor metasediments (8), dominant anatexites (9) intruded by syn- to late granitoids (10). The western domain is topped by kinzigitic mylonites (11). Surfaces above the topography schematically represent the dominant foliation and lineation.
zones. These observations support is limited to scarce metric-scale shear thin sections. Solid-state deformation features are not observed in to meso-scales, intracrystalline deformation marked by the alignment of mafic minerals. Coexistence of boudinaged and non-boudinaged veins suggests several generations of melt intrusion. Hammer is ~30 cm long.

thick that accommodated homogeneously the westward translation of the allochthonous middle crust over the craton, representing therefore its basal contact.

Central domain: coherent deformation of synkinematic magmatic bodies and metasedimentary host rocks

The central domain involves huge amounts of igneous rocks emplaced within metasediments (Fig.2). Two main magmatic bodies: the São Vitor Tonalite (576 ± 5 Ma; Noce et al., 2000) to the North and the Galileia batholith to the South (594 ± 6 to 576 ± 4 Ma; Nalini, 1997; Nalini et al., 2000), are in continuity, forming a domain >250 km long and ~50 km wide in which magmatic rocks and metasediments are imbricated (Figs 2 and 3). The Galileia and São Vitor plutons display a pronounced magmatic fabric (Figs 5 and 6), marked by the orientation of biotite and feldspar crystals that parallels the solid-state fabric in the metasediments. Despite a strong shape-preferred orientation at macroto meso-scales, intracrystalline deformation features are not observed in thin sections. Solid-state deformation is limited to scarce metric-scale shear zones. These observations support that the São Vitor and the Galileia plutons deformed coherently with their country rock before complete solidification.

Close to the contact with the western domain, the magmatic foliation in the São Vitor tonalite dips gently eastward. Lineations, observed in the field or deduced from anisotropy of magnetic susceptibility (AMS) measurements, trend close to EW. Eastward, the dip of the magmatic foliation and the plunge of the lineation progressively increase from gentle to moderate then to steep. Further eastward, entering the Galileia batholith, the magmatic foliation becomes subvertical (Fig. 3). Subvertical and subhorizontal lineations coexist, suggesting transpression-induced strain partitioning.

Eastern domain: thrusting in a partially molten middle crust

This domain consists of an anatectic unit ~300 km long, 50–100 km wide and >10 km thick (Figs 2 and 3). Rather homogeneous lithology ranges from peraluminous garnet–biotite diatexites to leucogranites. Garnet is ubiquitous, frequently in large proportion and locally forming elongated cumulates. Prismatic sillimanite and cordierite in equilibrium with garnet are frequent and sometimes form clusters. Muscovite is absent, except as alteration product. These anatexites display clear magmatic textures, although some feldspars and garnets display evidence of corrosion, being probably inherited from the source metasediments.

At the outcrop scale, a penetrative fabric is marked by alignment of mafic minerals (especially biotite) in the leucogranites or by alternating biotite-rich and leucocratic layers in the migmatites (Fig. 7). This well-developed fabric might be sometimes...
mistaken for a solid-state, gneissic foliation. However, quartz–feldspar aggregates have a typical granitic microstructure (Fig. 8). Quartz does not display significant intracrystalline deformation, like undulose extinction or subgrains, and systematically preserves interstitial shapes (Fig. 9). This indicates that this fabric developed in a magmatic mush before full crystallization. Evidence of HT solid-state reworking is limited to rare metric-scale shear zones.

Lineations in migmatites are usually difficult to observe (Ferré et al., 2003; Egydio-Silva et al., 2005). Where observed in the field or deduced from AMS measurements, lineations, marked by alignment of mafic minerals, span from NW–SE to NE–SW with a statistically dominant NE orientation. This dispersion is partially due to late kilometre-scale open folds, but it may also reflect a vertical pure shear (possibly gravity-driven) component of the deformation, leading to dispersion of lineation within the foliation plane.

At the regional scale, the western boundary of the anatectic unit is slightly oblique to the structural grain of the belt. As a result, the anatexites overlie the central domain to the south and are in direct contact with the para-autochthonous metasedimentary cover of the craton to the north.

Eastward, the anatectic crust sheet is topped by migmatitic kinzigites (Fig. 1) containing biotite, garnet, prismatic sillimanite and poikiloblastic cordierite suggesting metamorphic conditions of \( \sim 820 \pm 30 \,^\circ{\rm C} \) and \( 650 \pm 50 \,\text{MPa} \) (Munhá et al., 2005). Numerous shear criteria in kinzigites suggest a top to W or SW shearing. Well exposed in the southern and northern part of the studied area, they are often buried beneath coastal sediments in the central part. U–Pb dating of zircons from the kinzigites suggests a maximum age of \( \sim 630 \,\text{Ma} \) for sediment deposition (Noce et al., 2004). Thermochronology estimates (Munhá et al., 2005) suggest that temperature remained > 700 \,^\circ{\rm C} \) until 480 Ma.

**Dating anatexis**

An important issue is to determine whether partial melting in the eastern domain was coeval with granite emplacement and deformation in the central domain. The metasedimentary origin of the anatexites imposes to use in situ techniques and careful selection of the crystals. Zircon crystals from the leucocratic anatexites were separated for cathodoluminescence (CL) imaging and SHRIMP U–Pb dating. CL imaging and zircon U–Pb isotope dating were performed at the Institute of Mineral Resources, Chinese Academy of Geological Sciences, and in the SHRIMP II at the Beijing SHRIMP Laboratory, respectively. U–Pb isotope data were collected in sets of five scans throughout the masses; a reference zircon TEM (417 Ma) was analysed every fourth analysis. Measured U, Th and Pb abundances and Pb isotope ratios were normalized using the reference zircon SL13 (572 Ma) values. Common Pb was corrected using the measured 204Pb. Data were processed following Compston et al. (1992) using the ISOPLOT program (Ludwig, 2001).

The analysed zircon crystals range from 220 to 530 mm in length, are acicular and euhedral. CL imaging shows well developed oscillatory zoning; rare inherited cores were observed but not analysed (Fig. 10). Analysed zircons yielded concordant data.
A weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 574.9 ± 3.3 Ma (MSWD = 1.46; $P = 0.15$) was calculated from the 11 analyses clustered on the concordia diagram. It is interpreted as the age of the melt crystallization in the anatectic unit. This age fits the age range of the batholiths of the central domain (São Vitor and Galileia batholiths, Nalini et al., 2000; Noce et al., 2000), which were deformed before complete crystallization. This similarity in age has two important implications: (1) huge volumes of middle crust either were partially molten or contained incompletely solidified magmatic stocks at the time of the deformation, and (2) deformation in the central and eastern domains was simultaneous and occurred around 580–570 Ma.

### Strain repartition

A recurrent problem faced in the tectonic analysis of rocks deformed under HT conditions, especially in the presence of melt, is the lack of reliable methods to quantify strain. Based on field and thin section observations, a few lines of evidence may however be drawn:

There are no significant strain changes between adjacent rocks deformed in solid or magmatic state as shown by the striking continuity between the magmatic deformation in the São Vitor tonalite and the mylonitic deformation in the western domain.

No evidence of strain localization along the contacts between the three domains is observed. The units are defined on their dominant lithology rather than on the existence of strain gradients across basal faults.

The kinematics in the three units is coherent. The main peculiarities are: (1) the transpressional deformation regime in the central domain, where steeply dipping foliations dominate and horizontal and vertical lineations coexist, and (2) the more dispersed and poorly defined lineation in the anatectic unit, and its SW–NE dominant trend.

Strain appears as homogeneously distributed over the entire allochthonous pile. Temperature conditions recorded in the metasedimentary mylonites at the base of the pile (~750 °C) are close to those in the kinzigitic
Deformation of a pervasively molten middle crust  •  A. Vauchez et al.

Fig. 11  Conventional Wetherill U–Pb concordia plot of SHRIMP data for zircon grains from an anatectic leucogranite (AR548) from the eastern domain.

material that tops the anatectic unit (Uhltein et al., 1998, Munhá et al., 2005), suggesting that a large volume of crust was submitted to similar synkinematic HT conditions. The northern Ribeira-Araçuaí orogen represents therefore a case of 'weak lithosphere' similar to those documented in SW Finland (Cagnard et al., 2006b), although the large-scale kinematics (thrusting over the edge of a craton) is different.

Conclusions

The northern Ribeira-Araçuaí orogen is characterized by a HT-LP (> 700 °C, 600 MPa) metamorphism suggesting a ∼35 °C km⁻¹ geotherm, pervasive partial melting of the middle crust, and 'Himalayan-type' thrusting of the allochthonous pile onto the São Francisco craton. It may therefore represent an eroded analogue of the crust beneath the Tibet and Altiplano plateaus.

The three allochthonous domains of this collisional orogen display varying melt volumes during deformation. The western domain deformed under HT solid-state conditions, the central domain comprises a huge volume of magmatic rocks (tonalite, granodiorite, granite...) emplaced in, and deformed coherently with, metasediments before full crystallization, and the eastern domain is composed of anatectic rocks, the mineral assemblages of which suggest formation through HT melting of metasediments. SHRIMP U–Pb dating supports that partial melting in the eastern domain and intrusion of magmas in the central domain were coeval at ∼580–570 Ma. These observations suggest that, during the collision, a large volume of crust was molten (> 10% melt) and hence had a low strength. This low strength is probably the reason for the observed homogeneous strain distribution. There is no obvious strain localization, even at the contacts between the various units and sub-units that are defined on lithological rather than tectonic criteria.

The eastern, anatectic domain displays: (1) a basal contact oblique to the gross structure of the belt, (2) a sharp transition from steep foliations in the central domain to flat foliations within the anateixites, and (3) a dispersed lineation, with a statistically dominant NE orientation rather than EW as in the western domain. These differences might indicate partial decoupling at the base of the anatectic domain, perhaps due to a gravity-driven pure-shear component. Partial decoupling might have been favoured by coeval escape tectonics in the transpressive central and southern Ribeira belt, where dextral orogen-parallel wrench faulting dominated at ca. 580 Ma (e.g. Silva et al., 2005). This escape tectonics might have acted as a 'mobile boundary' substituting the 'free' boundary necessary in analogue models to generate gravity-driven lateral flow (Cagnard et al., 2006a). This suggests a model combining collision-driven and gravity-driven deformation controlled by the far-field strain regime rather than local gravity-driven lateral flow of the middle crust as invoked for Tibet (e.g. Beaumont et al., 2001).

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