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The influence of partial melting and melt migration on the rheology of the continental crust

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ABSTRACT

The presence of melt during deformation produces a drastic change in the rheological behavior of the continental crust; rock strength is decreased even for melt fractions as low as ~7%. At pressure/temperature conditions typical of the middle to lower crust, melt-bearing systems may play a critical role in the process of strain localization and in the overall strength of the continental lithosphere. In this contribution we focus on the role and dynamics of melt flow in two different mid-crustal settings formed during the Brasiliano orogeny: (i) a large-scale anatectic layer in an orthogonal collision belt, represented by the Carlos Chagas anatexite in southeastern Brazil, and (ii) a strike-slip setting, in which the Espinho Branco anatexite in the Patos shear zone (northeast Brazil) serves as an analogue. Both settings, located in eastern Brazil, are part of the Neoproterozoic tectonics that resulted in widespread partial melting, shear zone development and the exhumation of middle to lower crustal layers. These layers consist of compositionally heterogeneous anatexites, with variable former melt fractions and leucosome structures. The leucosomes usually form thick interconnected networks of magma that reflect a high melt content (>30%) during deformation. From a comparison of previous work based on detailed petrostructural and AMS studies of the anatexites exposed in these areas, we discuss the rheological implications caused by the accumulation of a large volume of melt “trapped” in mid-crustal levels, and by the efficient melt extraction along steep shear zones. Our analyses suggest that rocks undergoing partial melting along shear settings exhibit layers with contrasting competence, implying successive periods of weakening and strengthening. In contrast, regions where a large amount of magma accumulates lack clear evidence of competence contrast between layers, indicating that they experienced only one major stage of dramatic strength drop. This comparative analysis also suggests that the middle part of both belts contained large volumes of migmatites, attesting that the orogenic root was partially molten and encompassed more than 30% of granitic melt at the time of deformation.

1. Introduction

Experimental studies on the deformation of partially molten rocks predict that melt connectivity affects their strength, causing a drastic strength drop at melt fractions as low as ~7% (e.g., Rosenberg and Handy, 2005). Once an interconnected melt network is established, deformation is partitioned between solid and liquid components, resulting in segregation of the viscous phase in rheologically weak layers (Vanderhaeghe, 2009). These low-viscosity neosome layers widen with ongoing melting, promoting further weakening of the rock (e.g., Vigneresse and Tikoff, 1999). Due to strain partitioning, the more competent layers (paleosome/restite) may experience solid-state deformation (strain hardening) while the low-viscosity melt is sheared under high temperatures and low pressure gradients (e.g., Collins and Sawyer, 1996; Sawyer, 2008).

In the continental crust, partial melting and magma generation are common at the middle to lower levels where high temperature, decompression and/or addition of volatiles may promote pervasive melting of considerable volumes of rocks (e.g., Sawyer, 1994; Brown, 2001; Vanderhaeghe, 2009). At such depths, two factors play a key role in magma segregation/migration from its source (e.g., Vanderhaeghe, 2009, 2012): (i) gravitational instabilities and (ii) imposed deviatoric stresses. Gravity forces may trigger melt migration because the weight of overlying rock results

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in elevated pressures at depth that literally squeeze the magma upwards (e.g., Ramberg, 1980a; Burg and Vanderhaeghe, 1993; Weinberg and Podladchikov, 1994; Toé et al., 2013). However, overlying rocks may also serve as a sort of top seal or "lid", which prevents efficient vertical melt migration and further operates to facilitate the horizontal melt segregation (e.g., Weinberg and Podladchikov, 1994). The horizontal segregation leads to accumulation of magma that may later feed veins or dikes (e.g., Vigneresse and Tikoff, 1999). At deviatoric stress conditions typical of transpressive shear zones, melt segregation results from the tendency for the lower-viscosity phase to accommodate the non-coaxial deformation (e.g., Vigneresse and Tikoff, 1999). The segregation is originally horizontal and melt escapes toward shear band sites (Hall and Kisters, 2012; Vanderhaeghe, 1999). However, because strike-slip shear zones tend to be steep, the predominantly horizontal flow is accompanied or replaced by vertical flow, which results in kinematically derived vertical pressure gradients that are observed as shear-induced vertical conduits. Comparatively, this process leads to more efficient migration of melt away from its source (e.g., Vigneresse and Tikoff, 1999; Solar and Brown, 2001).

Migmatites are the most common product of in situ partial melting of solid rocks. Through the study of migmatitic petrofabrics, it is possible to understand the way melting is generated and its subsequent segregation/migration pathways between different crustal levels. A fundamental question in this scenario is how the distinct modes of melt transfer influence crustal rheology. There is general consensus that inefficient drainage of melt from the source results in the generation of large-scale molten domains that serve as weak layers within the crust (e.g., Jamieson et al., 2011; Godin et al., 2006; Beaumont et al., 2001). The accumulation of melt leads to the transition from partially molten rocks to magmas marked by loss of the continuity of the solid framework (e.g., Vanderhaeghe, 2009). On the other hand, magma generated during the nucleation and development of shear zones may be efficiently channelized and would enhance strain localization. This would result in weakening along specific crustal zones, but would prevent widespread in situ melting over large regions, i.e. development of large magmatic complexes in which diatexites and anatectic granites are commonly observed (e.g., Vanderhaeghe, 2009).

This contribution aims to illustrate two specific modes of the behavior of the crust at convergent boundaries: (1) the Carlos Chagas anatexite – a large anatectic domain which is an example of an "undrained" deep-seated partially molten/magmatic layer, and (2) the Espinho Branco anatexite – a compositionally heterogeneous partially molten rock developed within the amphibolite-facies Patos shear zone, which represents a case of efficient melt migration and channeling through the middle crust. Both migmatite terranes, located in Eastern Brazil, were formed in the Neoproterozoic during the Brasiliano orogeny in the course of the amalgamation of the Gondwana supercontinent (Van Schmus et al., 2008).

Through a comparative analysis of the migmatites/leucogranites in these two settings, we will discuss: (i) the geological record of migmatitic/magmatic terranes, (ii) the distinct modes of melt distribution, accumulation and transfer, (iii) the differences in the way magma migration influences the strength of the crust, and (iv) the overall implications for the rheology of the continental crust.

2. Geological setting of the migmatitic terranes

2.1. The Araçuaí belt and Carlos Chagas unit

The Araçuaí and the southward Ribeira belts (southeastern Brazil) were the result of collision between the São Francisco and Congo cratons in the Neoproterozoic due to the convergence between the South American and African plates (Fig. 1a; Almeida et al., 2000). The Araçuaí belt extends for more than 700 km with a N-S trend and involves thrusting of high-temperature allochthonous units onto the São Francisco craton (Cunningham et al., 1998; Oliveira et al., 2000; Vauchez et al., 2007). The belt underwent high temperature-low pressure (700–800 °C, 600 MPa) metamorphism that triggered extensive partial melting in its eastern part (Oliveira et al., 2000; Cavalcante et al., 2013, 2014).

The Araçuaí belt is separated into three lithological domains (e.g., Oliveira et al., 2000; Fig. 1b). The western, mylonitic domain constitutes high-temperature mylonites derived from metasedimentary rocks that were injected by leucogranitic veins at 577 ± 9 Ma (U-Pb on zircon, Petitgirard et al., 2009). These mylonites formed during top-to-west thrusting over the parautochthonous metasediments of the São Francisco craton (Cunningham et al., 1996; Petitgirard et al., 2009). The central plutonic domain consists of tonalite and granodiorite bodies that were deformed in the magmatic state at ~580 Ma (U-Pb on zircon, Mondou et al., 2012). The eastern part consists of a ~300 km long and 50–100 km wide anatectic domain composed of anatexites and leucogranites known as the Carlos Chagas unit (Cavalcante et al., 2013, 2014). This unit is the result of widespread partial melting of middle crustal rocks at ~600–570 Ma. Rafts of migmatitic granulites occur embedded in these anatexites. Furthermore, southeast of the Carlos Chagas unit we find migmatitic kinzigites that display a progressive increase in leucosome proportion that results in diatexites and aluminous granites (Fig. 1b). The anatexites are intruded by charnockite and biotite granite from a magmatic event lasting from 540 to 480 Ma (e.g., Söllner et al., 1991; Noce et al., 2000). Thermochronological dating suggests that the Araçuaí crust remained hot for tens of millions of years due to a very low cooling rate (5 °C/My; Petitgirard et al., 2009).

2.2. The Patos shear zone and the Espinho Branco anatexite

The Patos shear zone is part of the Borborema Province, which was formed by the collision around the Amazon, West-African, São Francisco, and Congo cratons (Vauchez et al., 1995). It is a ~600 km long E-trending strike-slip shear zone that forms part of the conjugate continental-scale Borborema shear zone system (Fig. 1c; e.g., Vauchez et al., 1995). This system is composed of Neoproterozoic crustal-scale shear zones that deform the Paleoproterozoic basement and are associated with pluton emplacement and overall partial melting of deformed lithologies.

The shear zone is divided in three main structural domains: (i) a western domain, consisting of a duplex structure that juxtaposes NE-trending lenses of high-temperature mylonitic orthogneisses, metapelites and granitoids; (ii) a central domain, mostly composed of migmatites, HT orthogneisses and a relatively thin (~5 km) low-temperature mylonite belt, and (iii) an eastern domain, characterized by progressive rotation of field foliations from an E-W to a NE-SW direction.

The orthogneisses of the central domain have leucosome veins that are mostly parallel to the foliation, with some melt pockets observed locally. Leucosome distribution in these rocks is highly heterogeneous and lesser in volume when compared with the migmatite body located in the central and eastern parts of the shear zone, and these rocks show an overall gneissic texture with no morphological features typical of migmatitic rocks (e.g., Sawyer, 2008).

Migmatites, mainly represented by the Espinho Branco and Santa Luzia anatexites (Fig. 1d), occur in the central and eastern domains and are commonly associated with the emplacement of granitic bodies (Corsini et al., 1991). U-Pb ages and structural relationships of migmatites and granites of the above mentioned domains suggest that magmatism and partial melting events span