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Solid Earth Discussions

Interactive comment on "Thermal conditions during deformation of partially molten crust from TitaniQ geothermometry: rheological implications for the anatectic domain of the Araçuaí belt, Eastern Brazil" *by* G. C. G. Cavalcante et al.

G. C. G. Cavalcante et al.

geanecarol@gmail.com

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Anonymous Referee #1

1. "The authors state the viscosity of 1019 Pa s as the one required for a channel flow to operate citing Beaumont et al. (2004). However, it should be noted that there are several parameters that determine the conditions for the channel flow"

Answer: We agree with the reviewer that several parameters physically determine channel flow triggering. Indeed, we did not state that viscosity is the only parameter

required for the development of the channel flow. A major aspect, which was probably not clear enough in our original manuscript, is that we do not suggest a pure channel flow model, but a deformation that results from a combination of boundary forces due continent-continent collision and gravitational loading due to topography. Several parameters are difficult to estimate reliably from field studies, such as the thickness of the weak layer. We have suggested it to be several tens of kilometers thick (∼60 km thick; Cavalcante et al., 2013) considering the dimension of the anatectic domain (>300 km long and 50-100 km wide; Vauchez et al., 2007). The relative velocity of the bounding plates is another important parameter, but rather difficult to determine for ancient natural geological cases. What we can say is that the viscosity was low, below 1017 Pa s, that the volume of molten rocks was large and that the flow field is characterized by a spatial variation in flow direction associated with a dominantly subhorizontal foliation (see new Fig. 2b with stereoplots), that may be reasonably well explained by a contribution of topographic loading. In the revised manuscript, we have made this clear so that it should be apparent to the reader that viscosity is not the only controlling parameter in the context of the channel flow.

2. Considering the potential geometry of the studied orogen was there a potential plateau area or thickened crust area? where was the respective foreland with the normal crustal thickness towards which would mid crustal flow be directed? Is this consistent with the observations of the kinematics?

Answer: The migmatitic area probably was a plateau and a thickened crust area. The evidence of this is the dominantly subhorizontal character of the magmatic foliation. As stated in our original manuscript (page 14; line 7-14) the current crustal thickness of the Araçuaí belt is ∼32-41 km (Assumpção et al., 2013). Thickness variation is correlated with the proximity of the South Atlantic Ocean and is likely due to its opening. Pressure estimates (650 – 700 MPa) in different tectonic units suggest that ∼25 km of crust has been eroded. Even considering that part of the exhumation of the rocks currently outcropping is due to tectonics, the homogeneity of metamorphic conditions in the various tectonic units supports the model that the current level of erosion corresponds to the middle part of an over thickened orogenic crust. Therefore, during the continent-continent collision the crust reached a thickness of at least 60 km, which can be considered to be similar to the present-day Himalayan situation (63 - 73 km). The foreland of the Araçuaí orogen likely corresponds to the São Francisco craton, both to the West and the North of the orogen. The external part of the craton was deformed during the Araçuaí orogeny, both in the west and the north. The strain decreases both westward and northward respectively. However, as in several "hot orogens" the foreland is not characterized by the development of large sedimentary basins. The kinematics inferred in the Araçuaí belt is top-to-West in the study area (Vauchez et al., 2007), and it was determined as top-to-North in the northernmost part of the belt (Uhlein et al., 1998), which is consistent with the cratonic domains representing the foreland of the belt and with the anatectic domain representing an unit which propagated toward the front of the belt, both westward and northward, crosscutting the general trend of the belt. In order to make it clearer we have inserted some statements in the geological setting section of our revised manuscript.

3. Only one calibration of the Ti-in-quartz geothermometer has been used, the original one. Although there is not yet an agreement on the exact calibration there is solid evidence for the pressure sensitivity of the Ti concentration in quartz (Huang and Audétat, 2012; Thomas et al., 2010), making therefore this technique a geothemobarometer. Therefore another two calibrations should be applied as well. As the authors state the pressure at the peak temperature has been estimated to 600-800 MPa while the used calibration of the Ti-in-quartz thermometer has been calibrated at 1 GPa. Accordingly, the calibrations using pressure sensitivity would yield about 80-100 °C lower temperatures. Taking this in account might make the Ti-in-quartz temperatures more consistent with the biotite-garnet geothermometry, which yields lower temperatures for the mineral rims.

Answer: We agree with the two reviewers that temperature estimates using calibrations

from Thomas et al., 2010 and Huang and Audétat (2012) are lacking in the submitted version of our manuscript and we have now included these methods in the revised version. We however disagree with reviewer #1 on the fact that these new experimental calibrations consistently suggest temperatures 80-100°C lower than the ones calculated using Wark and Watson (2006). Following the suggestions of the reviewers we have estimated the TitaniQ temperatures using Huang and Audétat, 2012 and Thomas et al., 2010 calibration in order to check the pressure effect and to compare with our previous results. These results were inserted in a new Table 1 of our revised version. In our case, pressures estimated from thermobarometers range between 650 – 700 MPa. For such pressure values, temperatures calculated using Thomas et al., (2010) calibration are 50 - 80°C lower than those initially computed with Wark and Watson (2006) and they are 50 - 100°C higher using Huang and Audétat's (2012) method. According to Huang and Audétat (2012), the misfit between the two new calibrations is likely due to quartz grains growing too fast during Thomas et al.'s, (2010) experiments, limiting Ti incorporation. If we assume that the Huang and Audétat (2012) calibration is more reliable, our initial estimates represent a conservative values for the minimum peak temperatures to which the anatectic unit of the Araçuaí belt was exposed. Using temperature estimates from the Huang and Audétat (2012) calibration, Rhyolite-MELTS (Galda et al., 2012) suggests >40% liquid-phase and thus viscosities even lower than the ones we have calculated. Some comments about these new temperature values and its implications for our interpretations are being incorporated in the discussion section of our revised version.

Specific Comments: 1. The authors mention in the geological setting that the magmatic flow direction progressively changes within the study area, but there is no clear evidence if this flow pattern was achieved during the magmatic flow or was the initial flow direction deformed in a successive (or progressive) deformation.

Answer: Regarding the conditions of deformation (solid- or magmatic-state), more details are given in a previous paper (Cavalcante et al., 2013) in which we included many pictures (Figs. 3 and 5) that clearly show the magmatic character of the foliation (quartz grains are dominantly interstitial or occur as quartz films along feldspar and/or biotite grain boundaries). We have systematically studied the microstructure of the rocks on which magnetic measurements have been done. Only few of them display evidence of incipient solid-state deformation (faint undulose extinction and subgrains in some quartz crystals); however it did not erase the interstitial habitus of quartz. These samples are located in the central part of the studied area (Cavalcante et al., 2013). Most studied samples display microstructural evidence that they were partially melted during deformation. We thus concluded that the flow pattern was achieved through deformation in the magmatic state (Cavalcante et al 2013). These previous results are summarized in the "geological settings" section of the submitted manuscript. In addition, the transition from one direction of flow to another is progressive and there is no evidence of superimposed deformation. This rather supports a heterogeneous deformation resulting in a 3D flow. As explain in the manuscript, this is also supported at larger scale by the predominance of north-trending lineations both magmatic and solid-state in the northern termination of the Araçuaí belt against the São Francisco craton. A variation of the flow direction is therefore also recorded at the scale of the orogen. In our revised version we added some words (geological setting section) to make it clearer.

How is this pattern of flow related to the tectonic setting as shown in figure 1 where the Neoproterozoic belts wrap around cratons? Related to this the authors briefly describe and show in the figure 2c the magnetic (AMS) lineation. However, it is crucial to have information on kinematics (top-to-the-direction of the flow). How is this flow pattern related to the tectonic model?

Answer: As already published in several papers (e.g., Vauchez et al. 1994, Egydio-Silva et al. 2005, Vauchez et al. 2007), the Araçuaí belt is part of a larger orogen that was built as a result of the collision between the proto-Africa and -South America continents. The Araçuaí belt, located in the northern part of this orogen, was confined along the boundaries of the São Francisco craton (both to the West and the North)

and is characterized by thrusting of various allochtonous units toward the craton. The southern part of this orogen, the Ribeira belt is characterized by transpressive deformation that accommodated kind of "escape" tectonics (Vauchez et al. 1994). This large-scale pattern is clearly related to the southern termination of the São Francisco craton. The studied area is representative of the domain constrained by the craton, where westward thrusting dominates. It should be noticed however, as already stated, that the northernmost part of the Araçuaí belt is itself characterized by NS-trending lineations due to thrusting on the São Francisco craton (Uhlein et al., 1998). The figure 2b (from Cavalcante et al 2013) was inserted in the manuscript to show how the deformation is distributed in the study area. Since the flow pattern was intensively discussed in Cavalcante et al (2013), our submitted manuscript focus on temperature estimates and evaluation of melt content in order to check if the tectonic interpretation presented in that previous publication is consistent with temperature and rheological conditions. In Cavalcante et al., 2013 as well as in Vauchez et al., 2007, Petitgirad et al., 2009 and Mondou et al., 2012, it is mentioned that several kinematic indicators observed in the Central and Mylonitic domain (Fig 2a) are indicative of a top-to-west thrusting. In the studied anatectic domain, the flow pattern characterizes a complex kinematic distribution: from North southward, the lineation, associated to a dominantly low-angle foliation, progressively rotate from NW-SE to E-W and NE-SW. Flow in various directions is expected in channel flow models of weakened crust that cannot support the topographic load; such deformation pattern "is analogous to pressing on an egg sandwich: the soft filling is squeezed out and emerges at the edge of the sandwich and through any holes in the bread" (Jamieson et al., 2011).

2. In the large-hot orogens the mid and lower crustal channel flow occurs along a horizontal crustal layer, resulting in a subhorizontal foliation. However in the study area the foliation is moderately to steeply dipping while the lineation is more gently plunging suggesting a strike rather than dip directed flow. How is this reconciled with the Himalayan-type channel flow models?

Answer: We agree with the reviewer that channel flow is expected to occur along a horizontal crustal layer. However, this does not mean that vertical flow cannot occur. For instance, Godin et al., 2006 in their description of the characteristics of channel flow stated: "There is more lateral transport of material in the channel than vertical". A second point is that we do not suggest a pure channel flow model, but a deformation that results from a combination of boundary forces due to the continent-continent collision and gravitational loading due to topography. Indeed, in the study area, the foliation is dominantly sub-horizontal (see the new Fig. 2b with stereoplots), but undulatory. Moderately to steeply dipping foliation that are not dominant were interpreted as due small open folds (Cavalcante et al., 2013). Therefore, in accordance with the foliation pattern, the studied anatectic sector would be thoroughly reconciled with the Himalayan-Tibetan system. In the figure 2b of our revised manuscript we have inserted the stereplots for foliations and lineation in order to highlights the predominant sub-horizontal pattern of these structures.

3. Please explain what is the relationship between the field foliation and the magnetic foliation (Figure 2 b)? Are there different types and generations of the foliation and is there any deformation foliation, e.g. mylonitic foliation?

Answer: "Field" and "magnetic" foliation designate the same magmatic fabric either observed in the field and in thin sections. AMS (Anisotropy of magnetic susceptibility) measurements have been performed because the lineation is usually difficult to determine precisely in the field. The AMS fabric, due to the preferred orientation of specific minerals responsible for the anisotropic behaviour of the rock, is considered a good proxy of the tectonic fabric (e.g., Bouchez et al., 2000). The field foliation fits with the magnetic foliation (see the steroplots of the new Fig. 2b of our revised version). Anatexites and leucocratic granites usually do not show evidence of solid-state deformation (e.g., mylonitic foliation), except very locally and for limited volume of rocks. The foliation is almost everywhere magmatic (gneissic banding associated with stromatic leucosome and preferred orientation of biotite and feldspar, especially,

without evidences of intracrystalline deformation). There is no evidence of a superimposed deformation, except locally. In the geological setting of our revised manuscript we have informed the reader that more detailed information about AMS measurements and their interpretation can be seen in Cavalcante et al., 2013. Furthermore, in the section 3 (Samples: location and description) we have inserted more details on the magmatic fabric of the anatextites.

4. In the model and field examples of a mid crustal channel flow the weak crustal layer flowing laterally is bounded by two coeval, sub parallel, opposite-sense shear zones. Are such shear zones observed in the study area?

Answer: As already stated in the first part of these answers to reviewer, we do not suggest a "true" channel flow model (in the physical sense, e.g., Klemperer 2006) for the anatectic domain of the Araçuaí belt, but a deformation that results from a combination of far-field forces due to continents convergence and gravitational loading. We think that in our revised version this is clearer. In models of mid crustal channel flow suggested for the Himalayan-Tibetan system, the normal and thrust faults that bound the “channel zone” are mostly observed in the upper crust because the “pure channel zone” is not exposed. These faults however cannot be traced through the channel (from the upper crust, through the channel and into channel footwall rocks; Godin et al., 2006). The strain pattern is more complex in the middle crust, especially when heterogeneities are included in the model (Jamieson et al., 2006). Indeed, the upper normal faulting is particularly well expressed when the upper plate is significantly stiffer than the partially melted crustal layer. In the study area the upper crust was totally eroded and we are looking rather deep into the orogenic crust (say $\sim$25km). Migmatites and leucogranites are dominant and the rocks in contact with the anatectic domain are also, although significantly less, partially melted.

5. With such high temperatures and so slow cooling rates as reported in the manuscript and combined with the long geological time-scale, some fort of solid-state Ti diffusion should be expected (Cherniak and Watson, 2007). Are any such features observed?

These could be measured and quantified (e.g. Nachlas et al., 2014).

Answer: We agree with the reviewer. Ti diffusion is significant at high temperature (e.g., 16 – 1600 μm at 800°C; Cherniak and Watson, 2007). However, Ti diffusion is characterized, especially, by the presence of zoning in quartz grains. The zoning may be observed in the CL (cathodoluminescence) images through the presence of different intensities of brightness. Observed variations in CL intensity are also correlated with the Ti content (e.g., Wark and Spear, 2005). As showed in our original manuscript no zoning was observed in the CL images we made on our samples (Fig. 6). All the analyzed quartz grains showed an intense homogeneous dark blue brightness (Page 8 - line 3). This homogeneity is also reflected in the Ti content of the quartz grains that exhibit a homogenous distribution (Fig. 7 and table 1).

Formatting (a) Please explain all the acronyms in the figure 1. (b) There is no lithological legend for the subfigure 2b and c. In general the caption of the figure 2 is inconsistent with the subfigures b and c. (c) What are the thick red and black lines in figure 2b? These obscure the structural measurements. (d) Instead of figure 8 it is suggested to construct frequency plots of the measured temperatures. The data shown in the figure 8 (measurement number/temperature) can be read from the corresponding table. (e) Manuscript is well written but there are scattered minor typos and grammar errors. It is suggested to revise the final version of the manuscript by a professional language and style editor. There are several affordable services.

Answer: In order to make the manuscript clearer we have improved some figures and captions.

Please also note the supplement to this comment:
http://www.solid-earth-discuss.net/6/C695/2014/sed-6-C695-2014-supplement.pdf

Interactive comment on Solid Earth Discuss., 6, 1299, 2014.

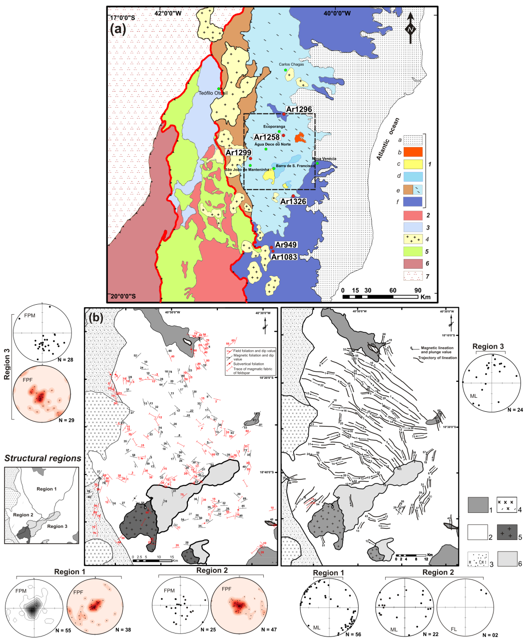

Fig. 1. Figure 2