Rheology, thermal conditions and strain distribution of a hot orogenic crust: the case of the Carlos Chagas anatexite, Araçuaí belt (SE Brazil)

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Introduction

The process of continental collision and related crustal thickening typically creates conditions where the middle and the lower crust get hot enough to start melting. As a common result, large anatectic domains arise. The presence of partially molten rocks during orogeny produces a drastic change in the rheological behavior of the continental crust, decreasing dramatically the rock strength, even if only small (down to 7%) amounts of melt are present (e.g., Rosenberg and Handy, 2005).

During the Neoproterozoic collision between the South American and African protocontinents the middle crust of the Araçuaí belt underwent widespread partial melting. The Carlos Chagas anatexite, located in its eastern part, ~300 km long and 50 – 100 km wide, is the most representative result of this process. It consists of anatexites and leucogranites often associated with migmatitic kinzigites and granulites. The Carlos Chagas anatexite is composed of peraluminous migmatites containing abundant quartz, alkali feldspar, andesine, biotite, garnet, and sillimanite, plus cordierite, ilmenita and rutile as accessory minerals. The granulites and kinzigites additionally contain orthopyroxene, hornblende and magnetite.

In this work we focused on the interaction between melting and deformation during the course of the Araçuaí orogeny. We used AMS (Anisotropy of Magnetic Susceptibility) to characterize the tectonic fabric of the Carlos Chagas anatectic unit and the associated granulites and kinzigites, in order to understand the distribution of the imposed deformation, and consequently, the tectonic process actives during the collision. An additional study using the EBSD (Electron Backscatter Diffraction) technique was carried out to investigate the origin of the magnetic fabric, through a comparison between CPO (crystallographic preferred orientation) and AMS fabrics. Furthermore, characterization of thermal conditions during the deformation process was performed from modern geothermometers, such as Titanium-in-Quartz, Zr-in-rutile and Titanium-in-zircon.

Materials and methods

We studied the interaction between deformation and melting in the Carlos Chagas anatexite using a multidisciplinary approach involving field and AMS mapping, microstructural observations, CPO measurements, and TitaniQ, Zr-in-rutile and Ti-in-zircon thermometry. 153 sites of AMS produced 649 cores, which were drilled using a portable gasoline drill, and oriented with a magnetic compass coupled with a Pomeroy orienting fixture. The AMS was measured with an AGICO KLY 4CS Kappabridge susceptometer at the Paleomagnetism Laboratory of the University of São Paulo, Brazil. The mean orientation of the three principal axes of the susceptibility ellipsoid was computed with Anisoft 4.2 software using Jelinek's (1978) statistics. Magnetic mineralogy investigation was carried out through: (1) thermomagnetic experiments, acquired under argon flux to prevent excessive oxidation during heating by means of a CS-2 furnace attached to an Agico KLY 4 CS kappabridge; (2) isothermal remanent magnetisation (IRM) curves, obtained with a MMPM10 Pulse Magnetiser and; (3) anisotropy of anhysteretic remanent magnetization (AARM) using a cryogenic magnetometer 2G-760R, equipped with the 2G-600 AF demagnetizer and an anhysteretic remanent magnetizer 2G-615 to acquire and measure the ARM. Thin sections were made from 63 cores representative of the main migmatitic facies. The microstructural characterization followed the nomenclature and classification of migmatitic rocks as suggested by Sawyer (2008), Mehnert (1971), Passchier & Trouw (2005) and Vernon (2004). CPO measurements from EBSD were acquired through the indexation of diffraction patterns (EBSPs) produced in the scanning electron microscope (SEM). The diffraction bands (kikuchi bands) that form the diffraction patterns are generated by the interaction of an electron beam with the carefully polished crystalline surface, inclined at 70°. Data were collected on a JEOL JSM 5600 SEM equipped with an EBSD detector and HKL Technology's Channel 5 software package at Géosciences-Montpellier (Université de Montpellier II-France). The TitaniQ, Zr-in-rutile and the Ti-in-zircon were applied using the Wark and Watson (2006), Thomas et al. (2010), Huang and Audétat (2012) and Tomkins et al. (2007) calibration. The Ti content in quartz and the Zr content in rutile were measured using a CAMECA SX-100 electron probe instrument equipped with five wavelength-dispersive X-ray spectrometers. The Ti concentration in zircon was measured using an Inductively Coupled Plasma Mass Spectrometry (ICPMS) Neptune (Thermo) multi-colector and Excimer (Photon Machines) laser 193 nm, at Institute of Geosciences, University of São Paulo.

Results and discussion

Field observations combined with detailed microstructural study indicate that the deformation occurred when the rocks were incompletely solidified. The schlieren, nebulitc and stromatic leucosomes are rich in K-feldspar, plagioclase and garnet, and often form a network of interconnected melt. Most minerals show no evidence of intracrystalline deformation, such as subgrains, new grains, undulose extinction, mantle-and-core structure and recrystallized aggregates. Quartz is often interstitial and biotite, which is the main mineral that characterizes the field foliation, has euhedral and subhedral shapes.

The AMS fabrics reveal a complex strain pattern in which the lineation trends define three structural sectors (Fig.1). The north region (structural sector 1), which displays predominantly sub-horizontal foliations and lineation trending NW-SE, is interpreted as a region of tectonic escape that may represent a horizontal channel flow, likely driven by gravity. The southern region (structural sectors 2 and 3) with variable trending foliations (NE-SW, E-W and NW-SE) and lineation plunging to north and west, probably reflect a flow regime dominantly influenced by the E-W convergence between the African and South-American continents (collision-driven flow). CPO of rock-forming minerals show that the c-axis of biotite is oriented parallel to the pole of the magnetic foliation, and subsidiarily, parallel to the magnetic lineation. The feldspar [001] concentration is close to the orientation of the magnetic lineation.

The quartz crystallization temperatures range from 700 to 800 °C (Cavalcante et al. 2014), such as those of zircon, which are between 680 and 820 °C. These temperatures probably represent the minimum temperature over which quartz and zircon crystallized from the magma during cooling of the Carlos Chagas unit. The Zr-in-rutile temperatures ranging from 1000 to 1100 °C, suggest that rutile grains grew during the prograde stage, at peak conditions, and their compositions did not change during cooling. Such temperatures combined with bulk rock composition of neosomes suggest that the viscosity of crustal rocks was dropped to at least 10^8 Pa s. Low viscosity values associated with field and microstructural evidences are consistent with the generation of at least 30% volume of melt during the orogeny. The presence of such large volumes of melt promotes a drastic weakening of the mechanical strength of rocks.

Conclusions

Thermal investigation suggest that the minimum temperature at which partial melting of the Carlos Chagas anatexite initiated was ~700 °C and peak metamorphic conditions was ~ 1100 °C. Such high temperature heated the middle crust enough to produce large volumes of melts (at least 30%), which is consistent with field and microstructural observations. This large proportion of magma decreased the rock strength, making them prone of being deformed by gravity-driven flow.

CPO measurements reveal that the magnetic foliation result from the preferred orientation of the biotite [001] oriented normal to the flow plane, and that magnetic lineation arises from the feldspar [001] plus biotite [001].

Altogether, the characteristics of the various structural domains suggest that the deformation of the partially molten middle crust of the Araçuaí belt was the result of the combination of gravity forces due to the topographic load and tectonic forces due to the convergence between the African and South-American protocontinents.

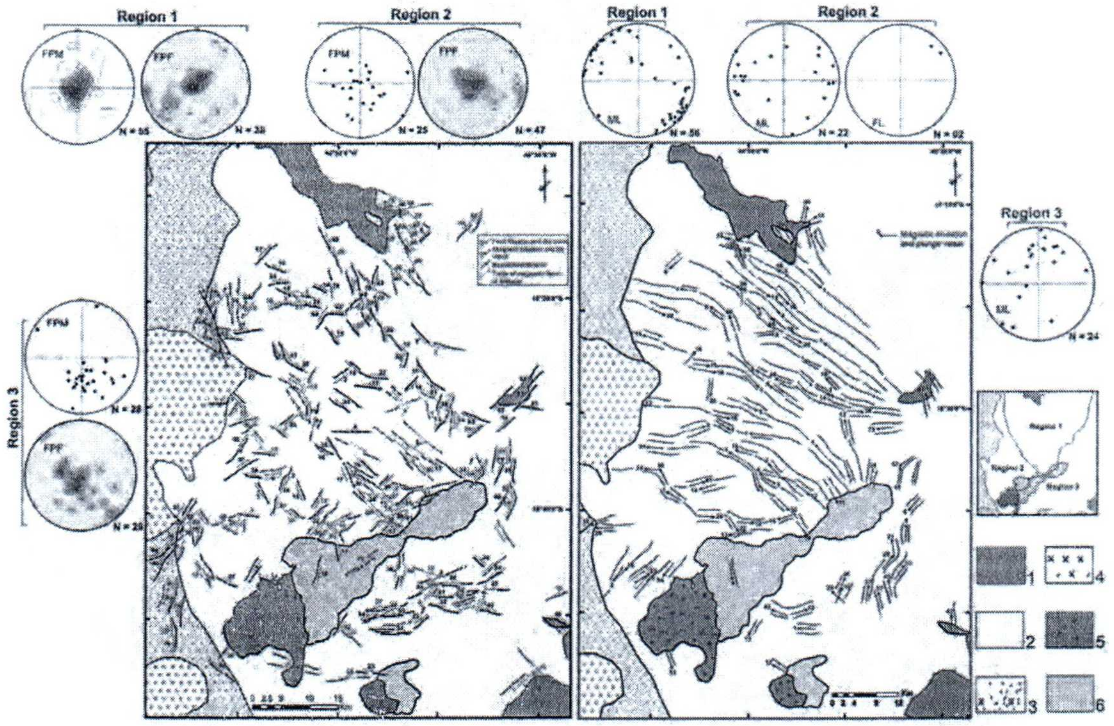

Fig. 1. Structural map showing the AMS and the field measurements across the anatectic domain. Left: foliations; small map on the right shows the 3 main structural regions as defined by their magnetic lineation pattern. The stereoplots FPM and FPF for each structural region represent the foliation poles obtained from the AMS (k_3) and measured in the field, respectively. Right: lineation and lineation traces illustrating the magmatic flow. The stereoplots ML (k_1) and FL for each structural region represent the lineation obtained from AMS and field measurements, respectively. All the stereoplots are lower hemisphere equal-area projection (Cavalcante et al. 2013).

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