Metamorphism and tectonics in the Neoproterozoic nappe system south of São Francisco Craton, SE Brazil: thermobarometric and oxygen isotope constraints

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Introduction

The inverted metamorphic zonation observed in many orogenic systems has been investigated by several models that search for plausible mechanisms to explain this inversion. The construction of evolutionary P-T paths resulting from the burial and exhumation of rocks during continental thickening is strongly based on rocks such as eclogites and high-pressure granulites, normally taken as key pieces in these geodynamic reconstructions. In high-pressure terrains, commonly characterised either by thrusting or magma addition in convergent plate margins; contrasted P-T trajectories have been frequently documented, and possible explanations include variations in the burial initial conditions, discrepancies in the uplift rates, and distinct tectonic histories. Opposite P-T paths may be, for instance, the result of the normal evolution of domains such as subduction zones, where the controlling parameters may vary in space and time. The type of these paths may therefore result from their position relative to the main suture.

In the area under investigation an increase in the metamorphic grade from the lowest to the topmost units has been already described by several authors (Trouw *et al.*, 1986, Ribeiro *et al.*, 1995), being the inverted high-pressure metamorphic pattern defined by Campos Neto & Caby (1999). In this research cationic thermobarometric calculations and oxygen isotope analyses were applied in order to obtain more detailed data in the Varginha region regarding this inversion, as well as the P-T trajectories of the main units and the nature of the metamorphism.

Tectonic units

The area studied is characterised by a set of structurally related units roughly transported to E-NE towards the southern edge of the São Francisco Craton (Fig. 1). The Socorro-Guaxupé Nappe (SGN) represents the western and uppermost high-temperature magmatic arc terrain (Campos Neto & Figueiredo, 1995). Its basal portion shows as a conspicuous feature a deformation-produced compositional layering made up of both amphibolite and granulite facies mineral assemblages such as enderbitic and charnockitic gneisses, garnet granulites, mafic granulites, and quartz-feldspatic granulites, and Sill-bearing metapelites to a less extent. The main foliation is homogeneously low- to medium- southeastward dipping, being associated with strong E-ENE plunging mineral and stretching lineations. Kinematic indicators reveal a top movement predominantly towards ENE.

The underlying units occur as a large metasedimentary pile structurally organised as an upper Ky-bearing granulitic Três Pontas-Varginha Nappe (TPVN) and a lower Ky-bearing schistose and gneissic Carmo da Cachoeira Nappe (CCN) - Campos Neto & Caby (2000), separated by a tectonic discontinuity. In the former, from base to top, Ky-bearing assemblages grade to Sill-bearing types, which correspond to an inverted metamorphic pattern observed throughout a 5 km-thick allocthon, already reported by Campos Neto & Caby (1999). The foliations dip gently southeastward forming a half synformal crosscut by a NE-oriented dextral shear zone. The distribution of the lineations shows a medium value of S80°W, being associated with ductile kinematic indicators showing top transport towards ENE/NE. The latter is a 3 km-thick sequence composed of Ky/Grt-bearing metapelitic schists, gneisses, metabasic rocks and gondites. The basal contact is a thrust surface characterised by a major metamorphic jump over the underlying rocks.

To the north, occurs a metapelitic sequence composed of a narrow strip of quartzites and graphytic phyllites in the base, grading to Bt-bearing and rhythmic schists to the top. This sequence is part of the Luminárias Nappe and Carrancas Klippe as defined by Trouw *et al.* (2000). The main foliation is a differential layering superposed by a low-angle mylonitic foliation. Kinematic indicators reveal a shear sense towards the E. In the eastern portion of the sequence, the schists and phyllites are superposed on low-grade metasediments, whilst in the west they are thrusted over orthogneisses and ultramafic rocks from the basement. The former are composed of micaceous quartzites predominating in the base, grading to aluminous and graphytic metapelites towards the top (Três Pontas, Faria, and Bocaina mountains) and tectonically settled onto the northern basement. The sequence shows a polyphasic deformation history in which kinematic indicators give a top transport direction towards the N/NNW. The basement is part of the São Francisco Craton, being

characterised by nearly continuous mafic-ultramafic sequences associated with intrusive granitic and granodioritic orthogneisses and hornblende-bearing gneisses.

Metamorphism and cationic thermobarometric data

Results corresponding to the centre of the ellipse built into the geometric P-T space are shown in Fig. 2. In the SGN peak temperature was calculated from rim Hd-Amp-Hy-Prp-Pl assemblages preserved in garnet cores in granulite samples (865°C for P=11.2Kb). The maximum pressure was obtained in Hy-Amp-Pl matrix assemblages (12.2Kb for T=848°C). The Sill-bearing metapelite calculations furnished information about early St and Sill zones conditions, being its temperature and pressure conditions lower than those attained by the orthogranulites. The St-bearing assemblage registered in the garnet cores was stable at 627°C and 5.3Kb, whereas Sill-bearing rim assemblage yielded temperatures and pressures of 705°C e 6.2 Kb. In the TPVN two different kinds of paths were defined. The highest temperatures were obtained from the Sill-granulites, in a calc-silicate Di-Grt-Pl assemblage (923°C for 12.1Kb). The most extreme pressures were provided by core thermobarometry in Ky-bearing granulites, using the assemblage Ky-Bt-Grt-Pl (12.9Kb for 835°C). Estimations of the retrograde path were obtained from Sill-rich matrix and rim, in which the thermobarometric calculations produced considerably lower pressure results for similar temperature values. For the CCN results from both metapelite and gneiss samples are compatible with a prograde metamorphic path characterised by lower-temperature, higher-pressure Ms-bearing mineral associations (657°C for 12.1Kb) and higher-temperature, lower-pressure Bt-bearing assemblages (688-698°C for 11-11.8Kb). The most extreme baric conditions were obtained from a Cpx-bearing assemblage in a garnet amphibolite sample (782° and 16.3Kb for temperature and pressure). Additionally, thermobarometric data obtained by Campos Neto & Caby (1999) in Alm-rich garnet and Ms assemblages from the Aiuruoca-Andrelândia Nappe gave temperature conditions of 620°-636°C for a 6.5Kb reference pressure. For the parauthoctonous unit, calculations based on Phg Si contents (3.25 PFU) from St-bearing metapelites resulted in a 7-Kb pressure value for 500°C.

Oxygen isotope data

Oxygen isotope geochemistry and geothermometry were carried out in rocks metamorphosed under granulite to green schist facies from a NE-SW traverse along the several units that compound the nappe system (Fig. 3). The SGN granulite samples show $\delta^{18}O$ values that lie within the normal I-type granitoid rock range (9.266-10.078‰). The internal oxygen isotope distribution is normally coherent with petrographic observations, being the most homogeneous values obtained in the most equilibrated samples. Although somewhat below than those expected for such a high-grade metamorphism, the most reliable temperature estimates were taken from the most refractory phase, garnet. Qtz-Mag temperatures are significantly lower than those yielded by other Qtz-Min pairs, as this mineral is highly fast diffusing and not therefore ideal for high-temperature thermometry. Similarly, the Qtz-Pl fractionations show frequently spurious results. For the TPVN, although the whole-rock compositions (12.979 and 13.769‰) are compatible with a sedimentary protolith and the $\delta^{18}O$ values for the individual minerals show internal consistency within samples, they are significantly different when compared across samples. The values obtained from the Qtz-Grt and Qtz-Ky fractionations for these metapelites are highly compatible with the results predicted by cationic thermobarometry and reproduce probably the true metamorphic conditions. Calc-silicate samples from this unit produced $\delta^{18}O$ values considerably different from the metapelites associated. The oxygen isotopic temperatures achieved for the Grt-Bt schist from CCN, as well as for the underlying units are considerably lower than those verified in cationic thermometric calculations. Data from Qtz-Bt fractionation for the two basement samples seem to agree with the temperature conditions expected for biotite formation. The most interesting fact, however, is the notable increase in these temperatures from the parauthoctonous unit to the northern basement (from 319°C in Qtz-Ms to 522° and 565°C in Qtz-Bt).

Discussion and conclusions

P-T path reconstructions based on cationic thermobarometric calculations, carried out for three of these units (SGN, TPVN, and CCN), indicate considerably different metamorphic histories associated with distinct tectonic environments. For the SGN a P-T trajectory compatible with an initial metamorphic evolution involving magmatic heating of the lower crust before and during its burial was established. This anomalous thermal gradient was responsible for the generation of water-absent granulitic metamorphism, a suggestion also indicated by the heterogeneous oxygen isotopic compositions. The retrograde portion of this path was registered by reequilibrated mylonitic textures probably related to the extrusion of the unit. In the TPVN, clockwise, IBC-type P-T paths that seem to be typical in many collisional settings were defined for both Ky- and Sill-type granulites, characterised by both heating and cooling occurring in a nearly

isobaric way. The entire basal Ky granulites trajectory lies in the Ky stability field, whilst data from the upper Sill granulites suggest an evolution towards the Sill/Ky boundary. These distinct paths testify the differences between the metamorphic evolution of the two types of granulites, and demonstrate the decreasing temperature conditions towards the base of the unit. Loading and uplift of the package follow similar evolutionary trajectories in which maximum P and T were reached at points close to each other, which implies a heating-absence uplifting in which erosion processes were significant. In the CCN ITD-type P-T path the highest pressures were attained under relatively low temperature conditions, being compatible with fast rates of exhumation. The whole path exhibits a tendency for the depression of the paleogeotherm pattern toward lower temperatures related to underthrusting of cold lithosphere in subduction zones. The differences verified between the TPVN and CCN P-T paths may result from the normal thickening event that follows a subduction episode.

Oxygen isotope thermometry shows a temperature decrease towards the base of the whole system, which is consistent with the previously recognised inverted metamorphic pattern. The tectonic contact of the most basal unit and the basement is characterised by a steep temperature gradient suggesting low-temperature thrusting acting as a dominant tectonic process. The best temperature estimates were obtained from the most refractory phases, garnet and kyanite, whose calculated values are in agreement with those given by means of cationic thermometry. The contrasts between the $\delta^{18}O$ values from TPVN and CCN, as well as the internal differences among both samples and mineral phases, are consistent with a general preservation of isotopic composition prior to metamorphism, and argue for a highly heterogeneous source for these rocks. The low W/R ratios (0.6-0.9) estimated for the calc-silicate samples from TPVN indicate that mylonitisation occurred under prevalent rock-dominated conditions, and fluid-related processes played only a minor role. Also, the relatively small differences observed in the $\delta^{18}O$ values from the undeformed to the deformed calc-silicate specimen (~1.6‰) suggest that the $\delta^{18}O$ composition of the fluid associated with the mylonitisation processes was close to that in equilibrium with the metamorphic assemblage. In addition, the extremely distinct $\delta^{18}O$ values showed by the metapelitic and associated calc-silicate samples, as well as the great drop observed in the temperatures calculated from one rock type to the other, indicate that no large-scale fluid-interaction processes occurred during the high-grade metamorphism. Oxygen isotopic exchange is therefore more likely to result from restricted diffusion-related processes than from extensive fluid flow. Estimation of the oxygen isotopic composition of both TPVN undeformed and CCN unaltered equivalents points to $\delta^{18}O$ values of up to 18‰. Comparison between these values and those achieved from the basement granitoid rocks (8.267-8.490‰) argues against the latter as possible sources for the metapelites.

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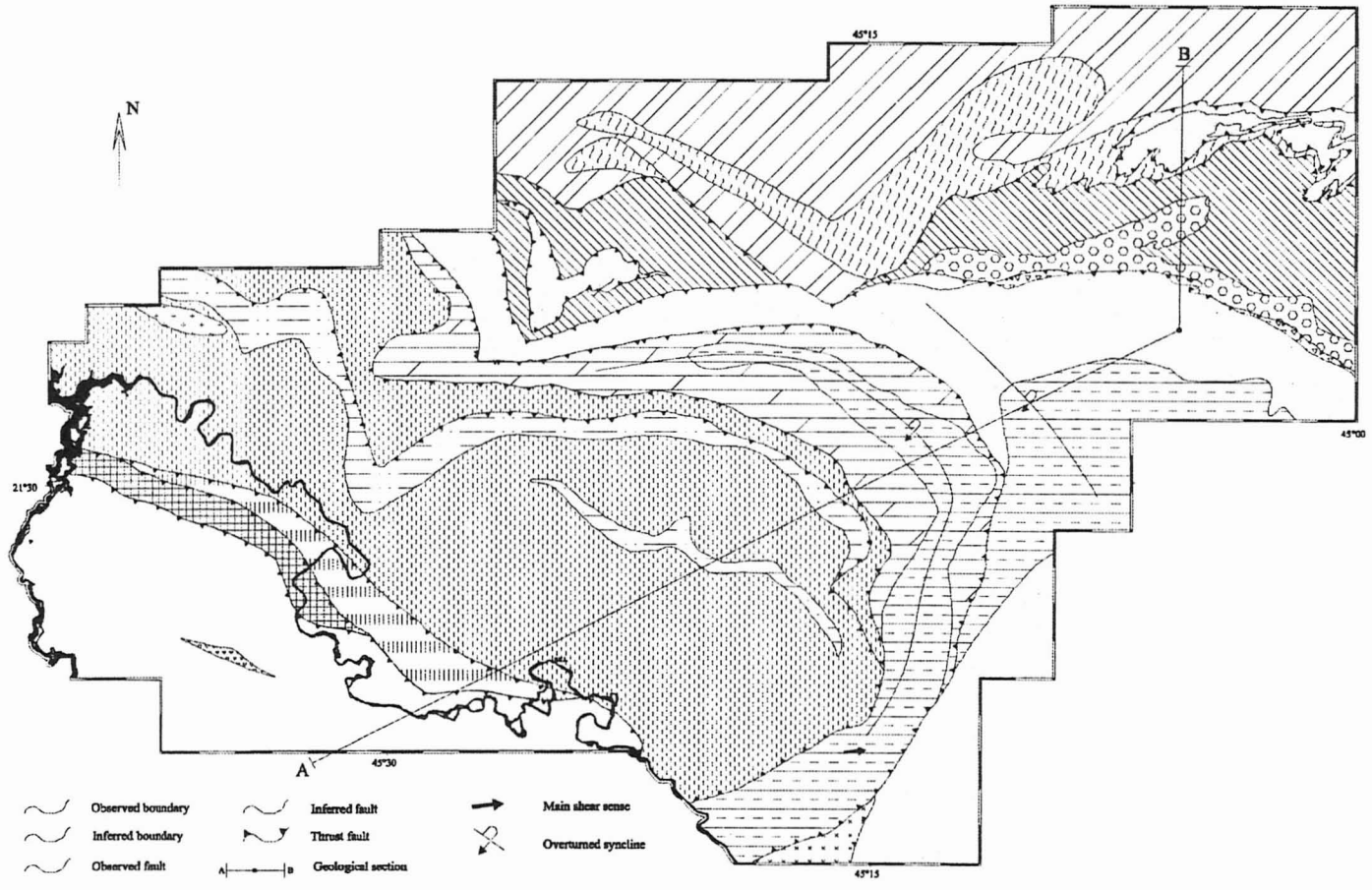

Fig. 1. Geological map.

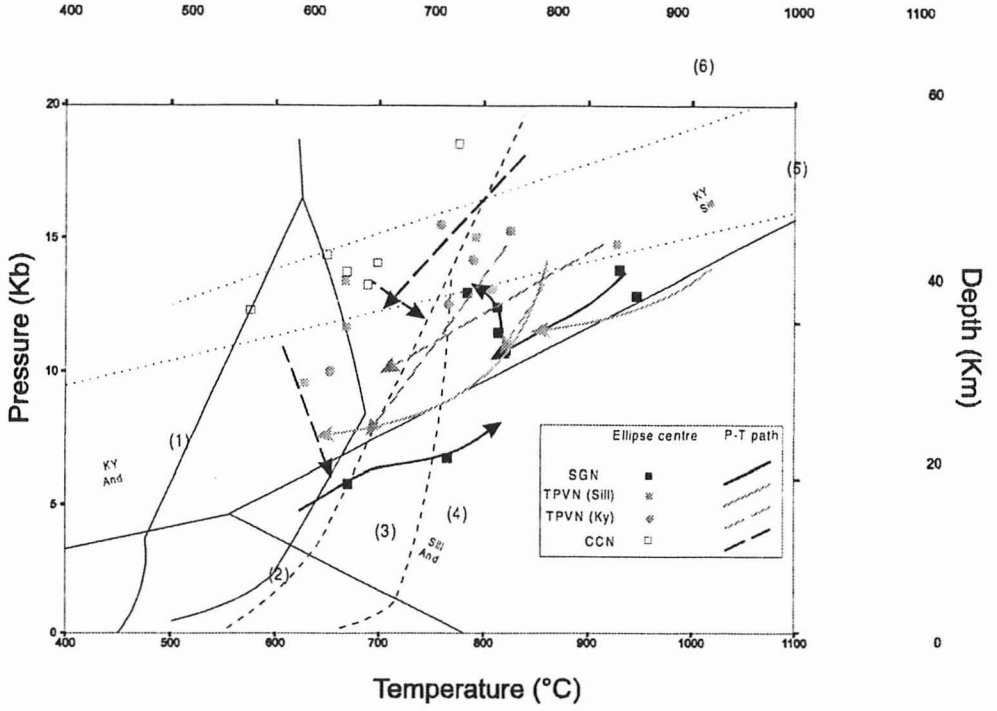

Fig. 2. Summary of cationic thermobarometry and P-T paths.

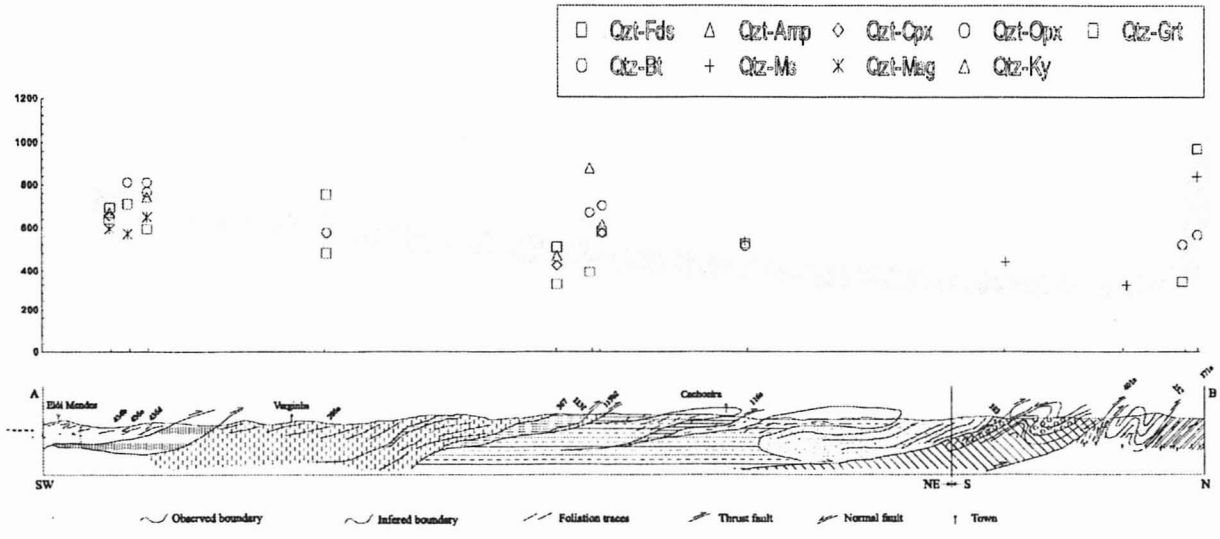

Fig. 3. Geological section and oxygen isotope thermometry results.