Magma-assisted strain localization in an orogen-parallel transcurrent shear zone of southern Brazil

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Abstract. In a lithospheric-scale, orogen-parallel transcurrent shear zone of the Pan-African Dom Feliciano belt of southern Brazil, two successive generations of magmas, an early calc-alkaline and a late peraluminous, have been emplaced during deformation. Microstructures show that these granitoids experienced a progressive deformation from magmatic to solid state under decreasing temperature conditions. Magmatic deformation is indicated by the coexistence of aligned K-feldspar, plagioclase, micas, and/or tourmaline with undeformed quartz. Submagmatic deformation is characterized by strain features, such as fractures, lattice bending, or replacement reactions affecting only the early crystallized phases. High-temperature solid-state deformation is characterized by extensive grain boundary migration in quartz, myrmekitic K-feldspar replacement, and dynamic recrystallization of both K-feldspar and plagioclase. Decreasing temperature during solid-state deformation is inferred from changes in quartz crystallographic fabrics, decrease in grain size of recrystallized feldspars, and lower Ti amount in recrystallized biotites. Final low-temperature deformation is characterized by feldspar replacement by micas. The geochemical evolution of the synkinematic magmatism, from calc-alkaline metaluminous granodiorites with intermediate $^{87}$Sr/$^{86}$Sr initial ratio to peraluminous granites with very high $^{87}$Sr/$^{86}$Sr initial ratio, suggests an early lower crustal source or a mixed mantle/crustal source, followed by a middle to upper crustal source for the melts. Shearing in lithospheric faults may induce partial melting in the lower crust by shear heating in the upper mantle, but, whatever the process initiating partial melting, lithospheric transcurrent shear zones may collect melt at different depths. Because they enhance the vertical permeability of the crust, these zones may then act as heat conductors (by advection), promoting an upward propagation of partial melting in the crust. Synkinematic granitoids localize most, if not all, deformation in the studied shear zone. The regional continuity and the pervasive character of the magmatic fabric in the various synkinematic granitic bodies, consistently displaying similar plane and direction of flow, argue for accommodation of large amounts of orogen-parallel movement by viscous deformation of these magmas. Moreover, activation of high-temperature deformation mechanisms probably allowed a much easier deformation of the hot synkinematic granites than of the colder country rock and, consequently, contributed significantly to the localization of deformation. Finally, the small extent of the low-temperature deformation suggests that the strike-slip deformation ended approximately synchronously with the final cooling of the peraluminous granites. The evolution of the deformation reflects the strong influence of synkinematic magma emplacement and subsequent cooling on the thermomechanical evolution of the shear zone. Magma intrusion in an orogen-scale transcurrent shear zone deeply modifies the rheological behavior of the continental crust. It triggers an efficient thermomechanical softening localized within the fault that may persist long enough for large displacements to be accommodated. Therefore the close association of deformation and synkinematic magmatism probably represents an important factor controlling the mechanical response of continental plates in collisional environments.

Introduction

The mechanical behavior of continental plates during orogenesis and therefore strain distribution throughout orogenic belts depends on many extrinsic (e.g., convergence rate and thermal flow) and intrinsic (e.g., crust thickness, rheological stratification of the lithosphere and preexisting heterogeneities) factors. During mountain building, some of these factors and their relative importance may vary, resulting in significant changes in the tectonic/mechanical system. Partial melting at different lithospheric levels and resulting magma emplacement undoubtedly represent important processes through which modifications of the initial physical properties of the system may occur during orogenesis. Not only the thermal field and therefore the rheological properties of the crust are altered by the intrusion of hot magmas in colder country rocks, but the introduction of even a small amount of melt in solid rocks drastically lowers their strength [Arzr, 1978]. As magma intrusion is not homogeneous throughout orogenic belts, it certainly results in local softening of the crust and strain localization.

Several mechanisms have been advocated during the last decades to explain magma circulation through the crust (see review by Miller et al. [1988]), and recent studies have highlighted the importance of crustal-scale or lithospheric-scale faults as providing easy channels for magmas to circulate [e.g., Clemens and Mawer, 1992]. Many examples of spatial
and temporal association of a large volume of magmas with regional-scale extensional [e.g., Hutton et al., 1990; Quick et al., 1992], compressional [e.g., Davidson et al., 1992], and transcurrent [e.g., McCaffrey, 1992; Pacheco Neves, 1989] faults have been reported. Lithospheric-scale transcurrent shear zones are undoubtedly good candidates to tap and channel melt at different depths because deformation induces a continuous transformation of the rocks fabric that may enhance the vertical permeability of the crust. This ability may still be increased in an extensional stress regime owing to global transtension or local opening due to geometric irregularities.

In this paper we aim to show that granitoids intruded and were deformed in a lithospheric-scale, orogen-parallel strike-slip shear zone of the Dom Feliciano belt, southern Brazil. To investigate the relationship between magmatism and deformation, we consider a key area located in the central domain of the shear zone, where deformation was entirely accommodated by synkinematic granitoids. A detailed analysis of the fabric and microstructure developed in these synkinematic granitoids shows that they have suffered a progressive deformation, beginning with their emplacement (i.e., in a magmatic state) and continuing under decreasing temperature after solidification. Petrological evolution of the synkinematic magmatism is used to discuss possible sources for magmas with respect to thermomechanical models for melt production during collisional processes. Finally, on the basis of the close relationship between successive intrusion, solidification, and cooling of granites and strain localization, we suggest that melt production and migration along lithospheric shear zones may shape the rheological behavior of the continental crust during continental collision.

Geological Setting

The Pan-African Dom Feliciano belt of southern Brazil and Uruguay (Figure 1) results from a long-lasting convergence of the Kalahari and Rio de La Plata cratons, involving west-directed subduction and continental collision. This tectonic evolution induced the formation, from southeast to northwest, of an early magmatic arc, a marginal basin, and a late magmatic arc over the trans-Amazonian age basement of the Rio de La Plata craton. The continental collision resulted in early orogen-normal thrusting that accommodated crustal thickening, followed by dominant orogen-parallel motions in the internal domains of the belt [Fernandes et al., 1992].

Orogen-parallel movements are largely accommodated by a

Figure 1. Schematic map of the Dom Feliciano belt (location in insert), showing the Dorsal de Canguçu shear zone and associated synkinematic granitoids. Data in Uruguay are from Preciszi et al. [1993].
continental-scale strike-slip fault zone, the Dorsal de Canguçu shear zone, which runs from southeast Uruguay to south Brazil over several hundreds of kilometers and marks roughly the limit between magmatic arc and marginal basin rocks [Tommasi, 1991]. A 2-km-thick mylonite belt underlines the curvilinear trend of the shear zone from approximately N-S in Uruguay, to N40°E in the central domain, and, finally, to N60°E in the northeastern portion, following the trend of the Dom Feliciano belt.

A closer examination of the shear zone and its surrounding rocks (diorite to granodioritic gneisses and metapelites) reveals several important observations. The shear zone is almost entirely developed within granitoids belonging to two successive generations of magmas of different composition: early coarse-grained granodiorites subsequently intruded by peraluminous leucogranites. These granitoids are only present along the shear zone and define a narrow (10 to 20 km wide) and elongated magmatic line. Both granodiorites and leucogranites consistently display a magmatic fabric. Magmatic and mylonitic fabrics present a similar geometry: a steeply northwestward dipping foliation trend parallel to orogen strike and a subhorizontal lineation. Transition between both fabrics is progressive; it shows a succession of microstructures suggesting deformation under decreasing temperature conditions. In addition, along-strike changes in deformation pattern of the shear zone can be correlated to local variations in volume of synkinematic granitoids; hence reworking of the country rocks in decametric-scale discrete mylonitic zones is restricted to domains with lower volumes of granitoids [e.g., Tommasi et al., 1992].

Sinistral sense of shear in moderate-temperature to low-temperature mylonites was inferred from various kinematic indicators. Shear bands, asymmetric recrystallization tails of feldspar porphyroclasts (Figure 11), mica fish, crystallographic fabric of quartz (Figure 9), as well as local rotation of high-temperature mylonitic foliation in late low-temperature shear zones [Fernandes et al., 1993a], are the most frequently observed. A sinistral sense of shear is also consistent with the volume distribution of synkinematic granitoids, lower in the domains where the shear zone trends ENE (see the location south of the study area shown Figure 1), which would represent transpressional bends.

Synkinematic Magmatism

In the study area (Figure 2) the earliest granitoid emplaced in the shear zone is a porphyritic granodiorite to monzogranite. It is mostly composed of prismatic K-feldspar porphyroclasts up to 7 cm long in a coarse-grained matrix of andesine (An29-32), quartz, and reddish-brown biotite. Almandine garnet and muscovite occur as accessory minerals in some locations. Locally, K-feldspar cumulates are also observed. Xenoliths of the gneissic host rocks frequently occur in the outer part of the magmatic body.

In the cationic classification of Debon and Le Fort [1988] the early granitoids are metaluminous granodiorites to adamellites, belonging to the calc-alkaline association (Figure 3). The granodiorite has an intermediate 87Sr/86Sr initial ratio (R0=0.71629). This initial ratio is too high for mantle-derived calc-alkaline magmas (~0.703-0.706), and crustal contamination of a mantle-derived magma seems improbable since it would require a too high crustal assimilation [e.g., Wilson, 1989, p. 90-91]. However, either mixing of magmas of mantle and crustal origins or melting of lower crust rocks could account for the observed 87Sr/86Sr initial ratio. High-temperature fluid-absent melting of metaluminous rocks may generate metaluminous magmas, like granodiorite, that would be highly mobile due to their high temperature (~850°C [Clemens and Vielzeuf, 1987]).

The granodiorite to monzogranite suite was then intruded by leucogranites accompanied by extensive late greisen and pegmatite veining. The leucogranites are equigranular, coarse-grained to sienogranites to monzogranites composed by K-feldspar, oligoclase (An25-30), quartz, reddish-brown biotite, and muscovite. Tourmaline and, in lesser proportion, garnet are important accessory minerals.

Large xenoliths of the porphyritic granodiorite with rectilinear boundaries and angular shapes (Figure 4) are widespread in the leucogranites; this probably indicates that the former solidified before the intrusion of the latter. Locally, xenoliths of mylonitic leucogranite occur in undeformed leucogranites, suggesting episodic emplacement of granodioritic magma during shearing. In the northwestern boundary of the leucogranites, xenoliths of high-grade pelitic gneisses are also observed.

The leucogranites are sodic-potassic to sodic peraluminous granites and plot in fields 1 and 2 of the aluminous balance diagram of Debon and Le Fort [1988]. They have a very high 87Sr/86Sr initial ratio (R0=0.7329) that clearly suggests a crustal source. Presence of tourmaline prompts to a pelitic source rock, since pelitic rocks generally contain significant amounts of B due to substitution of Al by B in clay minerals [Bernard et al., 1985]. According to Clemens and Vielzeuf [1987], these peraluminous magmas could be produced in the middle crust, either by relatively low-temperature, fluid-present melting or by fluid-absent melting of pelitic material by muscovite breakdown, but the later process is unlikely to produce large amounts of melt, unless very high crustal pressures (~1 GPa) are reached, allowing the onset of more fertile reactions such as muscovite + biotite + quartz + plagioclase = garnet + K-feldspar + melt. High volatile content inferred from crystallization of tourmaline and extensive late greisen and pegmatite veining suggests low mobility of the peraluminous melt. This low mobility associated with the relatively shallow level of emplacement (~10-12 km), supported by low-pressure high-temperature conditions determined on mylonitized pelitic xenoliths (see our section on PT estimates), favors an origin by fluid-present melting in the middle to upper crust for these magmas.

Syncrystallization and Postcrystallization Deformation

Northwestward across the shear zone (Figure 2), the leucogranite displays a transition from a magmatic and/or submagmatic fabric to solid-state mylonitic fabrics formed under retrogressive temperature conditions. The granodiorite does not show the same straightforward geographic distribution of deformation facies. However, a similar evolution of the microstructures in both granitoids suggests that each generation of magma was progressively deformed with decreasing amounts of melt and then, after total
Figure 2. Schematic geological map of the central domain of the Dorsal de Canguçu shear zone (location in Figure 1), modified from Fernandes et al.'s [1993b] map. The blowup shows the area studied in detail.
solidification, under decreasing temperature. Progressive localization of strain in narrower zones allowed preservation of textures indicative of the various thermal stages of the deformation.

Although solid-state deformation produced a 2-km-thick ultramylonitic belt in the peraluminous leucogranite (Figure 2), the porphyritic granodiorite it is recorded only in discrete shear zones of decametric width (Figure 5). Most high-temperature mylonites were extensively reworked under middle to lower amphibolite facies metamorphic conditions. However, in the external domains of both the large- and small-scale shear zones, evidence of deformation under upper amphibolite facies metamorphic conditions is locally preserved. A few metric-scale zones of mylonites deformed under greenschist facies conditions recorded the latest shearing. Thus the shear zone width evolves from a 15- to 10-km-wide belt during the magmatic flow to discrete shear zones a few tens of meters wide during the latest, low-temperature deformation.

**Figure 5.** Granodiorite (G) with a well-developed magmatic fabric affected by a discrete mylonitic zone (indicated by arrow parallel to stretching lineation). Microstructures in the shear zone (moderate-temperature solid-state deformation) are shown in Figure 1b.

**Magmatic Deformation**

Magmatic deformation, that is, deformation of a crystal mush containing an amount of melt high enough to minimize grain interaction and avoid formation of a solid framework, is evidenced in the granodiorite by a foliation defined by aligned K-feldspar porphyroclasts, plagioclase, and/or micas in an undeformed quartz-rich matrix. This foliation (Figure 5) is often associated with a magmatic lineation defined by preferred orientation of the long axis of prismatic K-feldspar megacrysts. In the leucogranites the magmatic fabric is less ubiquitous; locally, it is marked by orientation of tourmaline and/or micas. Crystallographic preferred orientation of plagioclase (Figure 6) displays [100] lying in the foliation with a maximum perpendicular to the lineation, [010] defining a plane normal to the Y axes with two maxima, respectively, normal and at low angle to the lineation, and more dispersed [001]. This fabric likely originated in the flow of anisometric rigid particles in a deforming magma and therefore corresponded to a shape-preferred orientation fabric, with [100] representing a rotation axis. The flattening of plagioclase crystals parallel to [010] would induce the observed concentration of [010] normal to the foliation, while stacked crystals (tilting effect, as discussed by Hédon et al. [1992]) may be responsible to the [010] maximum near the lineation.

**Submagmatic Deformation**

Continuation of shearing during crystallization (submagmatic deformation, i.e., in presence of an amount of melt sufficient to avoid formation of a continuous solid framework but not grain interaction) is recorded by both granitoids in domains that escaped subsequent solid-state
Figure 6. Plagioclase crystallographic fabric in leucogranite. (For discussion, see the text.)

deformation. It is suggested by the coexistence of undeformed interstitial quartz grains, sometimes filling fractures in feldspars (Figure 7a), and microstructures indicative of high-temperature deformation of feldspars. Plagioclase shows corroded boundaries, mechanical twins (Figure 7b), lattice bending, and kinks that are sometimes accompanied by en echelon cracks filled by quartz. Interpenetrating grain boundaries are also observed locally, suggesting grain boundary migration. Although K-feldspar also displays deformational features such as lattice bending and crosshatched twinning suggesting triclinic (microcline) structure, it is more commonly replaced by plagioclase and quartz in the form of myrmekites and granoblastic aggregates of plagioclase with quartz at triple junctions (Figure 7c). This fluid-assisted replacement reaction [Vernon, 1991] was probably favored by the remaining melt fraction. Preferential location of myrmekites at porphyroclast-porphyroclast contacts suggests that local stresses induced by grain interactions may have favored the substitution process [La Tou and Thompson, 1988; Simpson and Wintsch, 1989]. This process can evolve up to formation of a “matrix” composed of polymineralic aggregates of plagioclase and quartz that surrounds the K-feldspar crystals. This evolution, associated with the deformational features, suggests an active role of shearing on the replacement process. Igneous muscovite and biotite are frequently kinked or bent and show incipient recrystallization limited to deformed domains.

High-Temperature Solid-State Deformation

Deformation under subsolidus temperature conditions occurs locally in the outer part of the mylonitic zones in both granites. It is characterized in coarse-grained mylonites (Figure 8a) by microstructures suggesting extensive grain boundary migration in quartz and K-feldspar replacement by plagioclase and quartz. Protracted replacement process during this stage is suggested by (1) coexistence of elongated and

Figure 7. Characteristic microstructures of submagmatic deformation in both granites. (a) Quartz infilling a fracture in plagioclase in optical continuity with an interstitial quartz grain. (b) Mechanical twins and deformation bands in plagioclase with highly interpenetrating boundaries. (c) K-feldspar replacement by myrmekites and plagioclase-quartz aggregates at the contact between two K-feldspar crystals. Scale bar is 1 mm in Figure 7a and 0.1 mm in Figures 7b and c.
undeformed quartz grains within the myrmekites and granoblastic aggregates and (2) preferential location of myrmekites on the K-feldspar crystal boundaries parallel to the foliation. In some samples, widespread replacement results in a granoblastic plagioclase-quartz matrix surrounding corroded elongated K-feldspar relics (Figure 8b). Plagioclase grains display incipient evidence of plastic deformation such as undulose extinction and mechanical twins that may be inherited from the submagmatic deformation. Quartz forms single crystals or polycrystalline ribbons with large grains showing a mosaic structure characterized by highly interpenetrating grain boundaries, often with polygonal shapes (Figures 8c and 8d), suggesting extensive grain boundary migration. Quartz crystallographic orientation (Figure 9b) is characterized by \(<\angle\)> axis oriented in the XZ plane with a well-defined maximum near the extension direction (\(X\)). As the quartz grains display only weak evidence of internal deformation and especially no basal subboundaries, characteristic of high-temperature prismatic \(<\angle\>) glide [e.g., Mainprice et al., 1986], it seems more justified to consider the crystallographic fabric and microstructure of quartz to have resulted from oriented growth [e.g., Gapaï and Barbarin, 1986] rather than prismatic \(<\angle\>) glide. This hypothesis is strengthened by the observation of a preferred crystallographic orientation of quartz in rocks deformed in the
Figures 9. Quartz [0001] axis fabrics of leucogranite samples deformed under decreasing temperatures. (a) Magmatic (no solid-state deformation). (b) High-temperature mylonite. (c) Intermediate-temperature mylonite. (d) Low-temperature mylonite. For discussion, see the text.

Magmatic state only (Figure 9a). Igneous biotite is recrystallized, producing fine-grained reddish-brown biotite with (001) oriented parallel to the foliation.

Moderate-Temperature to Low-Temperature Solid-State Deformation

Deformation under moderate-temperature conditions (~450°C) produced fine-grained mylonites to ultramylonites (Figure 10) that constitute the main shear zones in both granitoids. However, coarser-grained lenses that have recorded slightly higher temperature deformation are locally preserved in the mylonitic belt. In these lenses, higher temperature conditions are particularly suggested by synkinematic crystallization of reddish-brown biotite and by the high density of bulges and recrystallized neoblasts of similar size and shape along feldspar porphyroclast boundaries. Bulging indicates a high mobility of grain boundaries due to the activation of diffusion processes [Poitier, 1985]. The predominant deformation under moderate-temperature conditions is consistently suggested by the microstructure of quartz and feldspars, the crystallographic fabric of quartz (Figure 9c), and the crystallization of low-temperature (green) biotite. Dynamic recrystallization of feldspar probably occurred through nucleation and growth, since the new grains are tiny (a few millimeters) and subgrains are lacking in the parent crystal. In mildly deformed facies, recrystallization starts over the myrmekitic reaction rims on K-feldspars (Figure 11a) and kinks and fractures in plagioclase; then, in severely deformed mylonites, it becomes extensive and generates a very fine-grained feldspathic matrix (Figure 11b). This recrystallization process may have induced an intense strain softening in the feldspar-rich domains and the transposition of quartz and feldspar aggregates in the foliation (Figure 11c), due to the difference in rheological behavior for the two minerals. This strain softening in the very fine-grained feldspathic bands may be due to activation of mechanisms like cyclic recrystallization or grain boundary sliding [Tullis and Yund, 1985; Vayuch, 1987]. Lithoclasts in the fine-grained mylonites frequently preserve microstructures, like myrmekites developed over K-feldspar or undulose extinction of plagioclase, suggesting they have experienced an earlier, higher-temperature deformation. Quartz is largely to totally recrystallized, probably through subgrain rotation, and forms polycrystalline ribbons. Its composite crystallographic preferred orientation suggests activation of both prismatic and basal slip (Figure 9e). Muscovite porphyroclasts occurs as mica fish that display evidence of slip on (001) and recrystallization tails.

The last stage of deformation, under greenschist facies conditions, is of small extent. It is recorded by phyllonites and quartz-mylonites in some discrete shear zones of metric width, reworking early mylonites. This low-temperature deformation is evidenced by fracturing and replacement of feldspars by micas, synkinematic crystallization of low-temperature biotite, and formation of monocristalline ribbons of quartz with prismatic subgrains, as well as few recrystallized new grains concentrated along ribbon boundaries (Figure 12). The crystallographic preferred orientation of the quartz ribbons suggests activation of basal slip (Figure 9d).
PT Estimates

Preliminary estimates of the PT conditions of deformation have been inferred from metapelitic xenoliths within the coarse-grained mylonitic leucogranite. In these xenoliths the early coarse-grained granoblastic fabric and compositional banding that characterize the metapelitic gneisses outside the shear zone are completely reworked by mylonitic foliation and lineation concordant with the high-temperature mylonitic fabric of the leucogranites. This mylonitic foliation is marked by Ti-rich biotite, muscovite, albite, and quartz. Poikiloblastic andalusite and, in smaller amounts, staurolite crystals oriented parallel to the lineation overgrow the foliation. Andalusite porphyroblasts have small overgrowths of fibrous sillimanite (Figure 13), and prismatic sillimanite also occurs lying in the foliation (with extensional fractures transverse to elongation). This suggests that deformation experienced a prograde PT path across the andalusite-sillimanite transition. Occurrence of andalusite sets an upper limit of 375 MPa for pressure [Holdaway and Mukhopadhyay, 1993], and the coexistence of sillimanite, staurolite and muscovite agrees with a temperature in the range 500°-620°C [Spear and Cheney, 1989]. The upper temperature conditions agree with the evidence for diffusion-assisted deformation processes observed in the surrounding granite and suggest very high temperatures at a relatively shallow crustal level probably due to the emplacement of a large volume of magma. In addition, these temperatures are similar to crystallization temperatures for hydrated granitic magmas under pressures over 300 MPa [Philpotts, 1990, p. 201]. Together these data point to a moderate depth (10-12 km) for the leucogranites emplacement and deformation, and the microstructural evolution suggests a temperature decrease from 700°-650°C (hypersolvus) to 450°-400°C (middle to lower greenschist facies) during shearing.

Discussion

Similarity of structural directions and continuity of evolution of fabrics formed in the magmatic and solid states

Figure 11. Characteristic microstructures of the moderate-temperature mylonites from both granitoids. (a) Partial recrystallization of a myrmekitic replacement rim on K-feldspar displayed by a mildly deformed sample. (b) Mylonite (shown in Figure 5) displaying a very fine grained matrix due to the dynamic recrystallization of feldspars and micas, recrystallized quartz ribbons, and feldspar porphyroclasts with earlier high-temperature microstructures (myrmekites indicated by arrow). (c) Ultramylonite (from Figure 10) showing transposition of quartz and feldspathic aggregates in the foliation. Scale bar is 0.1 mm in Figure 11a and 0.5 mm in Figures 11b and 11c.
support a synkinematic emplacement and cooling of both granites [Blumenfeld and Boucher, 1988; Paterson et al., 1989]. This close relationship between deformation and magmatism raises two major problems: the origin of synkinematic magmatism and the rheological effects caused by local emplacement of large volumes of magmas in the continental crust.

Origin of Synkinematic Magmatism

In the present study area, synkinematic magmatism evolves from an early metaluminous granodiorite belonging to the calcalkaline association to peraluminous leucogranites. The \(^{87}\text{Sr}/^{86}\text{Sr}\) initial ratios suggest a clear crustal source for the latter, and a lower crustal or a mixed mantle/crustal source is probable for the early granodiorite.

Synkinematic magmatism in convergent plate boundaries may be produced by either shear heating of the upper mantle within a lithospheric-scale shear zone inducing melting in the lower crust [Fleet and Frohlich, 1980; Leloup and Kienast, 1993] or crustal melting due to thermal relaxation [De Yoreo et al., 1989; England and Thompson, 1986] and/or mantle delamination [Houseman et al., 1981] following an episode of crustal thickening.

In thermal relaxation models, crustal thickening in absence of advective heating would result in very limited amounts of melt, unless significant amounts of water were introduced in the
lower crust [England and Thompson, 1986]. Even when a hot plate overthrusts a plate containing wet, pelitic rocks, the resulting fluid-present melting would result in a predominant peraluminous magmatism [Clemens and Vielzeuf, 1987]. Thus thermal relaxation alone cannot account for the compositional evolution of synkinematic magmas in the Dorsal de Canguçu shear zone.

Mantle delamination would provide an enhanced heat supply into the lower crust [Houseman et al., 1981], which would attain temperatures sufficient for fluid-absent biotite breakdown and production of metaluminous melts [Clemens and Vielzeuf, 1987]. However, mantle delamination process would have a larger wavelength than the deformation of the crust in the studied shear zone, and evidence of a large-scale perturbation of the thermal field is lacking outside the shear zone.

Shear heating in the upper mantle may generate the observed magmatic evolution and location, as heat conduction from the upper mantle to the crust would allow melting in the lower crust (calc-alkaline melts) and later, by heat advection through the

Figure 12. Low-temperature quartz-mylonite displaying elongated quartz grains with few recrystallized new grains concentrated on the grain boundaries. Scale bar is 0.1 mm.

Figure 13. Synkinematic andalusite porphyroblast with sillimanite overgrowths in a mylonitic pelitic xenolith. Scale bar is 0.5 mm.
shear zone, melting in the middle to upper crust (peraluminous melts). This model requires a shear zone cutting through the entire lithosphere to produce the necessary heating of the upper mantle. The inference that the Dorsal de Canguçu shear zone is a lithospheric-scale shear zone agrees with Vauchet and Nicolas's [1991] suggestion that large displacements parallel to mountain belts occur along lithospheric faults rooted in the upper mantle. Moreover, according to Vauchet and Nicolas, such lithospheric shear zones should be marked by an intimate association of metamorphic-magmatic activity and shearing, in contrast to crustal shear zones that would be devoid of significant thermal effects because of shear heating buffering [Turcotte and Oxburgh, 1968].

However, lithospheric shear zones may also collect and channel mantle melts derived through other processes. Resulting advection of heat in the crust would induce a vertical progression of melting similar to the one produced in the shear heating model. Therefore initiation of melting is not necessarily related to shearing, but further evolution of the magmatism should depend on the heat transfer capacity of the shear zone.

Mechanical Properties of the Crust

The introduction of large volumes of melt in the continental crust modifies its mechanical properties. In magma-rich zones, shear strength of the crust is lowered, favoring an intense localization of deformation. Many natural examples clearly show a concentration of the deformation in partially melted (or solidified) zones [e.g., Davidson et al., 1992; Hollister and Crawford, 1986; Mogk, 1992; Quick et al., 1992].

Experimental deformation of olivine-basalt, olivine-granitic rock, and granitic aggregates consistently shows a dramatic weakening at the onset of melting [Cooper and Kohlstedt, 1984; Dell'Angelo and Tallis, 1988; Dell'Angelo et al., 1987; Ji and Mainprice, 1986]. In these works, strain softening is related to a change in deformation mechanism induced by the presence of melt films along grain boundaries.

According to Dell'Angelo and Tallis [1988] and Dell'Angelo et al. [1987], partial melting may enhance several deformation mechanisms, especially: (1) faulting, at high temperatures and pressures (where thermally activated mechanisms normally operate), by increase of the pore fluid pressure due to the inability of the interconnected melt to flow at a rate equal to the imposed strain rate; and (2) diffusion creep, at low to moderate experimental temperatures and pressures. Melt-enhanced diffusion could increase the strain rate by orders of magnitude, if melt totally wets grain boundaries, or much less, if melt occurs in interconnected grain boundary channels. As this mechanism shows linear dependence of stress on strain rate and inverse dependence on grain size, the switch from dislocation creep to diffusion creep would be marked by a change of the constitutive equations from a power law to a Newtonian creep.

Cooper and Kohlstedt [1984] studied the effects of small amounts of basaltic melt on the diffusion creep of olivine aggregates. They showed that melt in triple-junction grain channels increased the creep rate by a factor of 2-5, by reducing the diffusive pathlength, and that the creep rate enhancement was proportional to the fractional grain boundary area wetted.

Similar results were obtained by Ji and Mainprice [1986]. They report a transition from a power law creep to a Newtonian viscous flow induced by partial melting in a fine-grained dry olivine rock experimentally deformed at 1060°C and 40 MPa. They interpreted this effect as resulting from a change in deformation mechanism from dislocation creep to melt-enhanced grain boundary sliding and/or melt-enhanced diffusion creep. They also calculate for melt enhanced grain boundary sliding that the loss of cohesion by the presence of melt films on grain boundaries could enhance the bulk strain rate by a factor of 2.

Experimental melting during deformation of analog materials conducted by Mawer [1989] indicates that deformation induces a lowering of wetting angles, therefore a higher connectivity of melt. This suggests that even very small melt amounts could have an important effect on diffusional processes.

Finally, from analog experiments on particle suspensions, Nicolas et al. [1993] suggest that viscous deformation may be accommodated by displacement of neighbor grains on a thin film of melt, even for melt amounts as low as 20-25%, as far as the molten material has a well-developed planar fabric.

In the Dorsal de Canguçu shear zone, the synkinematic granites localize most, if not all, of the strike-parallel motions in the eastern, more internal domains of the orogen. Reworking of the country rocks is only observed along limited segments of the shear zone, where the volume of synkinematic granites is smaller. Moreover, the regional continuity and the pervasive character of the magmatic fabric in the various synkinematic granitic bodies, consistently displaying similar plane and direction of flow, argue for accommodation of large amounts of orogen-parallel movement by viscous deformation of these magmas.

In addition to the evident softening of the crust represented by accommodation of the movement by Newtonian or Bingham (by higher crystal proportions) viscous flow on partially crystallized magmatic bodies, softening by activation of high-temperature deformation mechanisms is well documented during the solid-state deformation of the studied synkinematic granites. These processes probably allowed a much easier deformation of the hot synkinematic granites than of the colder country rock and, consequently, contribute significantly to strain localization.

Likewise, the restricted extension of the solid-state deformation in the porphyritic granodiorite suggests that the intrusion of leucogranitic magmas induced further localization of the deformation, due to easier accommodation of the deformation, first, by viscous flow in the newly emplaced melt and, second, by activation of high-temperature deformation mechanisms in the leucogranite after solidification. Finally, the small extent of the low-temperature deformation suggests that shearing ended as the leucogranite cooled down.

The tight correlation between magmatic evolution and deformation strongly support that magma emplacement has controlled the thermomechanical behavior of the shear zone.

Thermal Modeling

Synkinematic granites undoubtedly represent important mechanical heterogeneities; their efficiency to accommodate strain is, however, dependent on the time span they remain molten and/or significantly hotter than the country rocks. This is mainly controlled by the temperature of the surrounding rocks and thus by the depth of emplacement. However, the
Figure 14. Thermal modeling of cooling plutons emplaced into country rocks at different temperatures. (a) One-dimensional model used for computation (after Peacock [1990]). The finite-difference array consists of 100 points and is oriented normal to the intrusive contact. The left-side boundary is located at the center of intrusion, and symmetry requires that temperature at this point will always be a local maximum, thus $dT/dx = 0$, and Fourier's law requires absence of heat flow across this boundary. The right-side boundary is located significantly far away from the center of the intrusion, such that the constant temperature boundary condition will not significantly affect the thermal evolution of the intrusion. Enlargement shows points for which time-temperature curves were calculated. (b) Time vs. temperature curves for different points of a 12-km-wide granodiorite and a 10-km-wide granite emplaced at moderate depths in the crust. Symbols on the curves correspond to points shown in the blowup of Figure 14a.
initial temperature of the melt, the thermal diffusivity, and, especially, the shape and size of the magmatic body and the duration of magma emplacement also play important roles. Paterson and Tobisch [1992], taking into account the size and shape of plutons, suggest that the duration of cooling may vary from a few years for small dikes at shallow levels to millions of years for moderately sized batholiths at midcrustal levels.

Accommodation of the whole deformation by the granitoids suggests that their intrusion produced an efficient thermal softening. Moreover, assuming a continuous deformation, the absence of any evidence of low-temperature deformation in the numerous xenoliths of the granodiorite observed in the leucogranite supports that the movement zone did not experience significant cooling in the time interval between the emplacement of the two granitoids. However, lack of consistent geochronological data, especially for the leucogranites, prevents any quantitative evaluation of how long the thermal anomaly in the shear zone was preserved.

The persistence of the thermal anomaly caused by granite emplacement in the middle crust may be evaluated by one-dimensional finite difference modeling [Peacock, 1990], which simulates the thermal adjustment between an instantaneously emplaced tabular intrusion and its country rock. In the present model, boundary conditions (Figure 14a) and adjustment of thermal diffusivity to take into account the enthalpy of crystallization are similar to those of the original model. In spite of evident simplifications implied in such a modeling, it can be used to investigate the limiting case, giving a hint of the minimum time span that the granites and, consequently, the shear zone remained softer than the country rocks.

The tabular geometry of both granites is inferred from their elongate geometry and magmatic fabrics. The across-strike widths in map view were used, 12 and 10 km for the granodiorite and the leucogranite, respectively, since they represent minimum widths that do not take into account the possible symmetry of the shear zone before the intrusion of the postkinematic granites in its northwestern boundary. Petrogenetical PT determinations on mylonitized pelitic xenoliths of the leucogranite suggest a shallow to moderate level of emplacement of the leucogranites (less than 15 km), therefore temperature of the country rocks was set to a value of 400°C. Since the emplacement level of the granodiorite is poorly constrained, a temperature of 450°C was arbitrarily chosen for the country rocks in order to obtain a minimum time estimate. Other model parameters are presented in Table 1.

Modeling for the granodiorite yields crystallization times of 2 m.y. for the center of the pluton and shows that 10 m.y. after its emplacement the entire massif is still at temperatures higher than 550°C. Similar modeling performed for a leucogranitic intrusion emplaced at higher crustal levels shows that the core remains molten during 1 m.y. and that cooling of the entire intrusion to 500°C is reached 5 m.y. after emplacement.

Assuming a continuous deformation and no important cooling between the emplacement of the two granitoids, these results indicate that the shear zone may be maintained at temperatures significantly higher than the surrounding rocks (outside the contact aureole), for at least 15 m.y. Multiple intrusions of leucogranites, as suggested by field data, would imply heat advection into the shear zone during a longer time span, increasing the duration of the thermal anomaly.

Table 1. Model Parameters for Thermal Simulations

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Granodiorite</th>
<th>Leucogranite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half width, m</td>
<td>6,000.00</td>
<td>5,000.00</td>
</tr>
<tr>
<td>Country rock temperature, °C</td>
<td>450.00</td>
<td>400.00</td>
</tr>
<tr>
<td>Temperature of intrusion, °C</td>
<td>850.00</td>
<td>750.00</td>
</tr>
<tr>
<td>Solidus temperature, °C</td>
<td>750.00</td>
<td>650.00</td>
</tr>
<tr>
<td>Heat of crystallization, J kg⁻¹</td>
<td>200,000.00</td>
<td>100,000.00</td>
</tr>
<tr>
<td>Thermal conductivity, W m⁻¹ K⁻¹</td>
<td>2.51</td>
<td>2.93</td>
</tr>
<tr>
<td>Heat capacity, J kg⁻¹ K⁻¹</td>
<td>1,000.00</td>
<td>1,000.00</td>
</tr>
<tr>
<td>Density, kg m⁻³</td>
<td>2,800.00</td>
<td>2,650.00</td>
</tr>
</tbody>
</table>

Therefore calculated minimal estimates highlight that an anomalously high thermal gradient may have persisted in the studied shear zone over a large time span.

Conclusions

The petrological, structural, and microstructural data in the Dorsal de Cangué shear zone point to a scenario in which an early, metaluminous granodiorite, probably resulting from melting of the mantle and/or lower crust, was emplaced in the shear zone and deformed while still molten. Then, the magma solidified, still deforming, and thus recorded a transitional to high-temperature deformation path. Subsequently, a peraluminous leucogranite produced by partial melting in the middle crust was emplaced in the shear zone. The addition of large volumes of magma triggered localization of the deformation in the newly emplaced granites, inducing the development of a magmatic fabric. Then, the magma began to cool in the active shear zone and experienced a transition from magmatic to solid-state deformation under decreasing temperature. Subsequently, as the leucogranites cooled down to the temperature of the country rocks (relatively low, owing to the level of emplacement), the shear zone was reactivated under lower temperatures, generating increasingly localized mylonitic zones. Finally, the small extent of the greenschist facies deformation suggests that the strike-slip motion ended approximately synchronously with the final cooling of the peraluminous granites.

The large extent of synkinematic magmatism suggests that lithospheric shear zones may act as important conduits for magma production and emplacement. The observed petrological evolution may be produced either by shear heating in a fault zone rooting in the upper mantle or by collection of mantle melts by such a shear zone. In any case, conduction and/or advective heat in the lower crust may allow an upward progression of melting in the crust.

The thermal evolution of the shear zone was probably controlled by the synkinematic magmatism. The deformation history reflects the effect of magma emplacement and subsequent cooling on the rheological behavior of the continental crust. As cooling rates are relatively slow compared to strain rates, the important localized softening of the middle to upper crust induced by the introduction of large amounts of melt in transcurrent shear zones may persist during large time spans, allowing large displacements to take place.
This should be taken into account in the evaluation of the balance of forces controlling the activation of different kinematic responses to a continental collision and, in the case of the Dom Feliciano belt, may have played a major role in the transition from orogen-transverse to orogen-parallel motion.

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