Close spatial relationship between plutons and shear zones

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ABSTRACT

This paper explores the relationship between granitic plutons and transcurrent shear zones using examples from the Borborema province, northeastern Brazil. Syntectonic plutons of this province generally have en cornue shapes and were emplaced preferentially within or at the margins of wide, regional-scale transcurrent shear zones, particularly where shear zones intersect major lithological boundaries. It is argued that the plutons' shapes and their closeness to shear zones are indicative of a causal relationship between granite plutons and shear zones. With the support of numerical models, it is further argued that pluton emplacement in transcurrent terranes is controlled by low-mean-pressure magma traps at the shoulders of shear zones, resulting from strain incompatibility caused by regional variations in rheological properties.

Keywords: granites, emplacement, shear zones, rheology, transcurrent faults, Borborema.

INTRODUCTION

The common geometrical and temporal relationship between synkinematic granitic plutons and crustal-scale shear zones suggests a causative link between the two, whereby either shear zones control ascent and emplacement of granite magmas (Brown and Solar, 1998a), or magma emplacement triggers nucleation of shear zones (Neves et al., 1996).

Geophysical studies in the Armorican province, a type area for pluton and shear-zone association, determined that deep pluton roots, interpreted as magma feeders, were not sited within the shear zones but in their shoulders (Vigneresse, 1995), suggesting that the shear zones may not have been the main focus of magma ascent. Schmidt and Paterson (2000) questioned any causative link between plutons and shear zones on the basis of a perceived lack of geometrical relationship between the two in a number of terranes.

The Brasiliano-age (700–550 Ma) Borborema province, northeastern Brazil, is characterized by a conjugate pair of high-temperature transcurrent shear zones that interacted with granitic plutons of different ages (e.g., Neves et al., 1996). This paper discusses the controls exerted by the shear zones on granite emplacement in light of field relationships and numerical models.

SHEAR ZONES AND PLUTONS

Plutons associated with transcurrent shear zones have been documented worldwide (e.g., Brown and Solar, 1998b; D'Lemos et al., 1992; Guineberteau et al., 1987; McCaffrey, 1992; McNulty, 1995; Tikoff and Teyssier, 1992) and display a number of characteristic shapes (Roman-Berdiel et al., 1997), including the typical en cornue, blister, or tear shaped (e.g., Ardara pluton, Pitcher and Berger, 1972). The hypothesis that shear zones control the ascent and emplacement of granitic plutons is derived from their close spatial and temporal association, and from mesoscale structures in migmatites (e.g., Brown and Solar, 1999; Sawyer et al., 1999), and is generally ascribed to the high dynamic permeability, temperature, and strain rate in shear zones (e.g., Brown and Solar, 1998b; Leloup et al., 1999; Pe-Piper et al., 1998).

BORBOREMA PROVINCE

The Borborema province is known for its high-temperature, continental-scale shear zones (e.g., Vauchez and Neves, 1997 and references therein), and for the close spatial and temporal link between Brasiliano-age shear zones and plutons (e.g., Neves et al., 2000b). Strike-slip shear zones divide the province into domains. The Transversal domain is limited by two ~10-km-wide, 500-km-long, east-trending dextral shear zones: the Pernambuco shear zone to the south (Davison et al., 1995; Neves and Mariano, 1999), and the Patos shear zone to the north (Corsini et al., 1991; Tommasi et al., 1995).

The Transversal domain is transected by northeast-trending sinistral shear zones that generally bend into and merge with the regionally dominant and broadly contemporaneous east-trending dextral shear zones (e.g., Neves et al., 2000b). Together the shear zones define a high-temperature bookshelf-style deformation domain (Vauchez et al., 1995). We focus on part of the Transversal domain in western Paraíba state (Fig. 1). This area is traversed by four major shear zones defining a lozenge, and includes the contact between the medium- to high-grade metamorphic rocks of the Alto Pajeú terrane in the east and the low- to medium-grade metapelites of the Cachoeirinha Group of the Piancó–Alto Brígida terrane in the west, which includes the high-grade rocks of the Piancó Complex.

Four suites of Brasiliano-age plutons intruded the area (Fig. 1; Ferreira et al., 1998). The earliest suite is calc-alkaline, generally granodiorites and tonalites that intrude the metaturbiditic sequences of the Piancó–Alto Brígida terrane. These plutons are crosscut by granitic rocks of younger suites, and zircons from three plutons have yielded U-Pb crystallization ages of 644 ± 5, 638 ± 5, and 621 ± 14 Ma (Guimarães and Silva Filho, 2000; I. Guimarães, 2003, personal commun.).

This suite was followed by the intrusion of a high-K calc-alkaline suite characterized by K-feldspar megacrystic granitic rocks, mingled with K-rich dioritic rocks (Neves et al., 2000a). This suite includes the Tavares (Weinberg et al., 2001) and Itaporanga plutons (Archanjo et al., 1999) (Fig. 1). U-Pb analyses of zircons yielded crystallization ages of 581 ± 2 and 588 ± 12 Ma for plutons east of the study area (I. Guimarães, 2003, personal commun).

The third suite to intrude the area is composed of shoshonitic plutons (e.g., Solidão and Teixeira plutons; Fig. 1) and the fourth suite is composed of peralkaline plutons (e.g., Triunfo and Catingueira plutons; Ferreira et al., 1998). Rocks of both the shoshonitic and peralkaline suites yield crystallization ages of ca. 570 ± 20 Ma (Guimarães and Silva Filho, 2000), similar within error to high-K calc-alkaline plutons.

PLUTON GEOMETRY AND DISTRIBUTION

The shape and distribution of plutons of the oldest calc-alkaline suite contrast with those of younger plutons. Calc-alkaline plutons define a broad northeast-southwest belt through the middle of the area shown in Figure 1, mostly through the lower-grade metapelites (Cachoeirinha Group) of the Piancó–Alto Brígida terrane; these plutons have circular or lobed shapes, and generally crop out away from major shear zones. The only exception is the fine-grained, granodioritic Emas pluton, which, unique among all the plutons, deflects the regional trend of the Patos shear zone.

Younger plutons of all three suites are emplaced in the higher-grade rocks of the Piancó Complex and Alto Pajeú terrane, and display en cornue shapes with tails within shear zones linked to blisters intruding the shoulders of the

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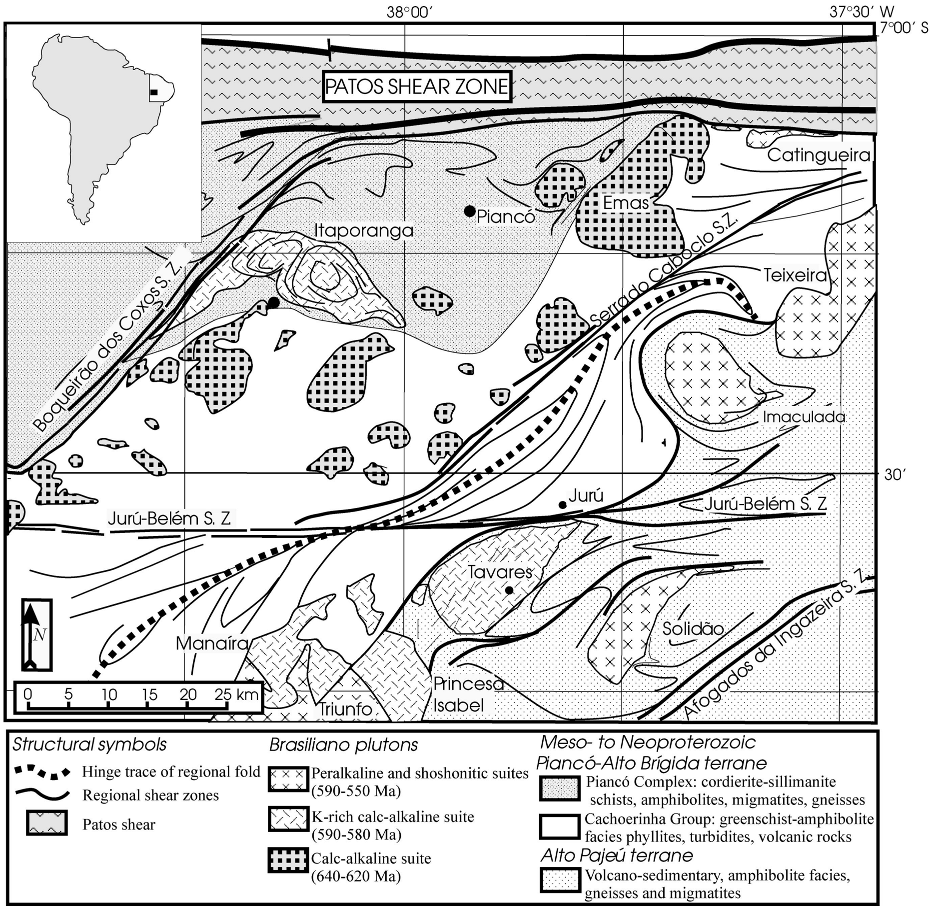

Figure 1. Simplified geological map of west Paraíba. Area is divided into Alto Pajeú terrane, and Piancó–Alto Brígida terrane, which includes Piancó Complex. Four major suites of Brasiliano-age plutons intrude area: calc-alkaline suite defining northeast-southwest belt of pluton through Piancó–Alto Brígida terrane, high-K calc-alkaline suite composed of two plutons at terrane boundaries, and peralkaline and shoshonitic suites (undifferentiated in map). Lineaments and pluton boundaries were drawn from satellite images and redrawn from Serra Talhada map (scale 1:250,000, Brazilian Geological Survey). S.Z. is shear zone.

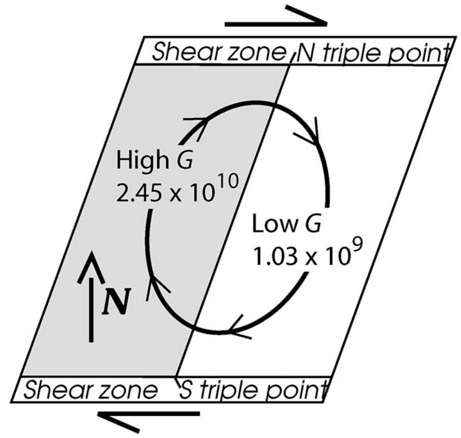

Figure 2. Elasto-plastic model after shearing, at constant shearing velocity of −0.0025 m/step (fixed strain rate), parallel to horizontal boundaries. *G* is shear modulus. Dextral shearing is imposed along northern and southern boundaries. All boundaries are rigid, no slip, and impermeable to fluid flow when pore pressure is considered.

shear zones. The tails are generally intensely sheared sheets interpreted to be magma feeders (Archanjo et al., 1999), whereas the voluminous blisters are less intensely deformed. The two large high-K calc-alkaline Itaporanga and Tavares plutons are emplaced close to triple points defined by the intersection between shear zones and terrane boundaries (Fig. 1).

The Itaporanga pluton, the largest in the area, has an en cornue shape and a tail within the sinistral Boqueirão dos Coxos shear zone (Archanjo et al., 1999). The pluton underwent pervasive solid-state deformation and its shape asymmetry supports sinistral movement along the shear zone. The pluton intrudes the vicinity of a triple point where the shear zone crosses the boundary between migmatitic cordierite-sillimanite schists of the Piancó Complex (peak temperature, $T \sim 700$ °C), and upper greenschist to amphibolite facies metapelites of the Cachoeirinha Group (peak $T \sim 500$ °C; S. Bittar, 2002, personal commun.).

The Tavares pluton also has an en cornue shape, and intruded the vicinity of a triple point where the east-trending Jurú-Belém shear zone cuts across the boundary between gneisses and migmatites of the Alto Pajeú terrane, and lower-grade metapelites of the Cachoeirinha Group. This shear zone displaces this contact dextrally by ~25 km (Fig. 1), in agreement with pluton asymmetry.

There are three noteworthy aspects of the plutons in Figure 1: (1) the early plutonic suite has an antipathetic relationship with regional shear zones and forms circular or lobate plutons, whereas plutons of the three younger magma suites are physically associated with shear zones and have en cornue shapes; (2) en cornue plutons are at the shoulders of shear zones; and (3) the two large high-K calc-alkaline plutons crop out close to triple points.

SIMPLE SHEAR NUMERICAL MODELS

The emplacement of en cornue plutons on the shoulders of shear zones, and of large plutons close to triple points, inspired numerical models designed to explore the stresses at triple points during shearing. The aim was to determine whether rheological changes across triple points give rise to conditions favorable for pluton emplacement. The finite-difference code FLAC (ITASCA, 2001) was used to model shearing of elasto-plastic materials and the code ELLIPSIS (Moresi et al., 2001) was used to model viscous materials.[1]

The model is a horizontal plane at a depth equivalent to 200 MPa undergoing simple shear, bounded north and south by vertical (into the page) dextral shear zones (Fig. 2). In the elasto-plastic models, the material block to the left has a bulk and shear modulus, *K* and *G*, of 4.09×10^{10} and 2.45×10^{10} Pa, respectively (Poisson's ratio, $\upsilon = 0.25$). All other fields, including the shear zones, have $K = G = 1.03 \times 10^9$ Pa ($\upsilon = 0.125$). The friction and dilation angles are everywhere 30° and 5°, respectively, cohesion and tensile strength are 3×10^7 and 3×10^6 Pa, respectively, and pore pressure was varied. Viscous models used a Newtonian viscosity ratio of 10.

Model Results

Simple shear deformation is asymmetric: the northern triple point accommodates the movement of a stronger material toward a weaker material, and the southern triple point accommodates the opposite (Fig. 2). This leads to different stress distribution and deformation in each triple point. In the elasto-plastic models, the material of high shear modulus, *G*, close to the northern triple point (Fig. 3; see also footnote 1), is particularly

[1]GSA Data Repository item 2004063, a brief description of the codes, Figure DR1, expanded version of Figure 3 with results for various aqueous pore pressure, and Figure DR2, viscous model results, is available online at, www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, CO 80301-9140, USA.

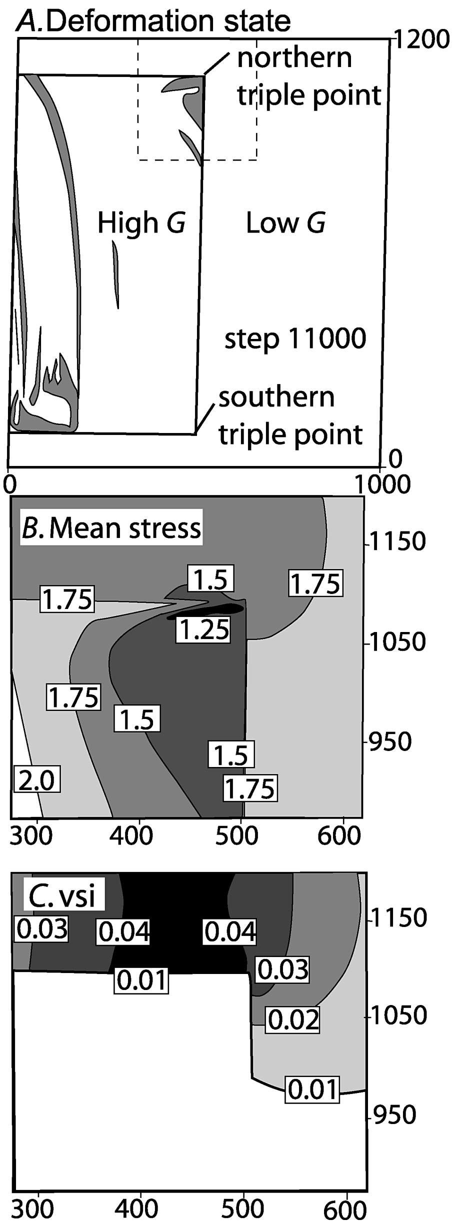

Figure 3. Results of FLAC (Fast Lagrangian Analysis of Continua) elasto-plastic model, dry case (model results including pore pressure in Data Repository; see footnote 1): A: Deformation state (box 1 km wide, 1.2 km long). Regions in gray are fracturing in this time step; regions in white are undergoing elastic deformation. Note how fractures are limited to material with high shear modulus (left half of models). Northern triple point yielded earlier than other parts. Dashed box indicates approximate position of close-up regions depicted in B and C. B: Mean stress distribution around northern triple point (numbers in 100 MPa units). C: Volumetric strain increment (vsi, dimensionless units representing ratio between change in volume and original volume; positive values = dilation). Addition of fluids and increased pore pressure leads to (1) earlier yielding, (2) decrease in mean pressure gradients, and (3) modest dilation (lower vsi). Numbers on axes are meters. Similar calculations for models 10 times larger and similar proportions produced same results, indicating that system is independent of size.

fragile, yielding before any other area and giving rise to low mean pressure and dilation (positive volume strain increment) that attract aqueous pore fluids from the surroundings (Fig. DR1; see footnote 1). The southern triple point (not shown in detail) behaves in the opposite way, developing high mean pressure, contraction, and expelling pore fluids. In the early stages of deformation, before yielding, elastic deformation leads to a similar stress distribution with low mean pressure close to the northern triple point.

The results of viscous models (Fig. DR2; see footnote 1) are essentially similar, with low mean pressure in the more viscous material close to the northern triple point, and high mean pressure close to the southern triple point.

DISCUSSION

The three most interesting aspects of the plutons in west Paraíba emphasized here raise three questions. (1) Can shear zone control on pluton emplacement be inferred from pluton shape and distribution? (2) If shear zones are conduits, why are plutons emplaced at their shoulders? (3) How do triple points control magma emplacement?

Pluton Geometry and Distribution

The oldest lobate calc-alkaline plutons define a broad northeast-southwest belt, aligned along the long axis of the lozenge defined by the regional shear zones and generally exposed away from shear zones in an antipathetic distribution. The Emas pluton is the only one to deflect the trend of the Patos shear zone. These two observations together suggest that these plutons behaved as competent bodies that inhibited the subsequent development of regional shear zones.

In contrast, younger plutons commonly have en cornue shapes, and are in the vicinity of shear zones and close to terrane boundaries. The sympathetic relationship with shear zones and the pluton shape suggest that emplacement of the younger suites was controlled by shear zones. They are therefore synkinematic, as supported by textural evidence for a gradation from magmatic to subsolidus deformation of the granitoids (e.g., Itaporanga pluton), and by the coincidence between the age of the younger suites and the suggested age of 600–570 Ma for the initiation of shearing in the province (Vauchez et al., 1995). This conclusion contrasts with that of Schmidt and Paterson (2000), who, through the use of small-scale regional maps, including a map of the Borborema province, concluded that no causal relationship between plutons and shear zones could be inferred.

Shear-zone initiation triggered by magma emplacement (Neves et al., 1996) is unlikely in west Paraíba because its plutons are much smaller than the extent of shear zones that have a consistent trend, undeflected by plutons, and a metamorphic grade independent of pluton proximity.

Control on Emplacement

Numerical models indicate that triple points develop either into a contractional, high-mean-pressure zone, or into a dilational, fractured, low-mean-pressure zone, depending on the disposition of rocks of contrasting rheology (Fig. 3). Fluids, including magmas, flow down pressure gradients toward low-mean-pressure sites. Significant gradients developed in the models around the low-mean-pressure area; for example, in Figure 3 a pressure gradient of $1–2 \times 10^5$ Pa/m formed around the northern triple point, which compares with typical magma pressure gradients of $2–5 \times 10^3$ Pa/m (equal to the magma–country-rock density difference, 200–500 kg/m^3, times gravity acceleration).

Dilatant, low-mean-pressure triple points at the shear-zone shoulders act as attractors for rising fluids, including magmas, which exploit their fragility to intrude and initiate pluton growth. Aqueous fluid pore pressure favors early development of dilational fractures and pluton emplacement, but this positive role is counterbalanced by reduced mean pressure gradients when compared to the dry case in Figure 3. The most important role of pore fluids, however, is to expand the depth in which the crust may respond in a brittle fashion. The low-mean-pressure triple points in viscous crust will also act as magma attractors, but in this case magma emplacement will be accommodated by viscous rock flow.

We postulate that in west Paraíba dilational triple points were exploited by magmas ascending in shear zones to give rise to the Itaporanga and Tavares plutons. We speculate that even other smaller plutons on shear-zone shoulders, emplaced away from obvious triple points, could have been controlled by low-mean-pressure sites related to cryptic or gradual changes in rock rheology, such as those resulting from temperature changes. We note also that the rheological contrasts in the models are moderate, and conclude that dilational triple points are likely to be a widespread feature of sheared terranes.

The evolution of low-mean-pressure triple points following magma intrusion, and the fate of a starting pluton, depend on a variety of factors not modeled here. The way the system evolves depends on the response of the country rocks to magma pressures and to its dynamic interaction with regional stresses as temperature changes. Although our results are discussed in terms of magma emplacement, they are directly applicable to processes related to hydrothermal fluid flow and explain, for example, why lithologic contacts close to shear zones are favorable sites for gold mineralization.

Magma Ascent and Emplacement

The frozen magmatic system in west Paraíba is characterized not only by the en cornue plutons emphasized here, but also by sheared granitic sheets within shear zones (e.g., Vauchez and Neves, 1997). Shear zones are likely to develop a number of dilational, low-mean-pressure sites that attract and trap magma rising as sheets in permeable shear zones, thus focusing pluton inflation. With continued deformation, new dilational sites develop elsewhere along the shear zone. We postulate that magma ascent in shear zones is intermittent and characterized by magma entrapment, ballooning, renewed escape, and deflation as the system develops into a number of dilational sites in shear-zone shoulders interconnected by magma sheets within the shear zones (see Sawyer et al., 1999).

CONCLUSIONS

We conclude that the shape and distribution of the plutons studied are clear indicators of shear-zone control and show that en cornue plutons are a direct result of synkinematic pluton emplacement. Changes in the rheological properties of rocks surrounding shear zones create fragile, dilational, low-mean-pressure triple points into which ascending magmas intrude, giving rise to plutons. Rheological changes may be either obvious, such as terrane boundaries, or subtle, such as gradual regional changes. We postulate that shear zones associated with magmatism evolve into an upward pathway characterized by a network of magma sheets within shear zones, linked to inflating and deflating chambers in shear-zone shoulders.

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