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Transamazonian Orogeny in the Southern São Francisco Craton Region, Minas Gerais, Brazil: evidence for Paleoproterozoic collision and collapse in the Quadrilátero Ferrífero

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Abstract

The Paleoproterozoic Transamazonian orogeny yielded a series of discrete orogens in Brazil. The present field study in the Quadrilátero Ferrífero (QF) indicates that the southern São Francisco craton region of the Brazilian highlands preserves a portion of one of these orogens. Two sets of Transamazonian structures occur in this region. The first consists of northwest-verging folds and thrusts affecting supracrustal sequences. It is suggested that this set formed in a fold-thrust belt setting shortly after 2.125 Ga, during the closure of a passive-margin basin that had initiated along the margins of a preexisting continental mass at ca 2.5 Ga. The second set consists of structures defining the prominent dome-and-keel architecture of the QF. This set, a consequence of the emplacement of basement domes against supracrustal rocks at 2.095 Ga, may reflect the consequences of orogenic collapse. Narrow, conglomerate-filled intermontane basins may have formed coevally with dome emplacement. Formation of an ocean basin east of the present-day São Francisco craton eventually occurred in Late Mesoproterozoic. In effect, the Transamazonian orogen of the QF represents the collision and collapse stages of a Paleoproterozoic Wilson cycle. The contractional phase of the Transamazonian orogeny probably represents accretion of an offshore arc to the eastern and southeastern margin of the present-day São Francisco craton region. The arc, and an associated suture, may be traced in the Brasiliano (Pan African) orogen east of the São Francisco craton, northwards into the northeastern lobe of the São Francisco craton. Clearly, initial assembly of crustal blocks to form a larger continent involving South America occurred during the Paleoproterozoic (2.1 Ga). Post-Transamazonian rifting of this continent created the basins which were later inverted during the Brasiliano assembly of Gondwana. © 1998 Elsevier Science B.V.

Keywords: Brazil; Collision tectonics; Orogenic collapse; Orogeny; Proterozoic

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1. Introduction

Compilations of existing geochronologic data indicate that five major tectonothermal events affected South America during the Precambrian [Fig. 1; Almeida et al. (1981); Almeida and Hasui (1984); Brito Neves (1990); Brito Neves and Cordani (1991); Brito Neves et al. (1996); Schobbenhaus and Campos (1984); Teixeira (1993)]. The first, the Jequié orogeny, took place between 2.8 and 2.6 Ga (Late Archean time). The second, the Transamazonian orogeny, occurred between 2.1 and 1.8 Ga (Paleoproterozoic time); the name 'Transamazonian' was coined because these dates were first obtained in rocks from a broad belt transecting the Amazon region and Guiana shield (Hurley et al., 1967). The third, here referred to as the Espinhaço rifting event ['Estaterian taphrogenesis' of Brito Neves et al. (1996)], occurred toward the end of the Paleoproterozoic (between 1.78 and 1.70 Ga) and was associated with widespread acid and basic magmatism. The fourth, the Uruaçuano orogeny, appears to be limited to northern Brazil, where belts of metamorphic rocks yield ages between 1.5 and 1.1 Ga. Almeida (1967) postulated that some tectonic features of the central Brazil highlands may also have formed during the Uruaçuano orogeny, but this interpretation now appears unlikely. The fifth event, the Brasiliano orogeny (=Pan African orogeny of other Gondwanide continents), occurred between 0.7 and 0.45 Ga (Neoproterozoic/Early Paleozoic).

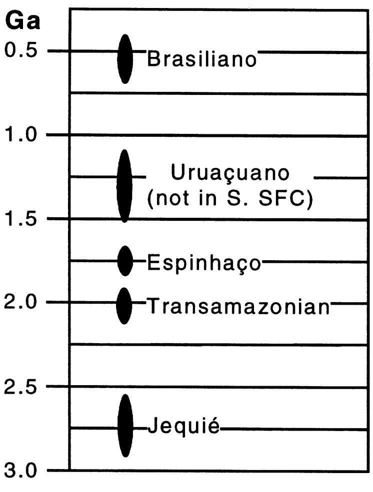


Fig. 1. Chronology chart illustrating the approximate age range of thermo-tectonic events affecting South America during the Precambrian (cf Almeida and Hasui, 1984; Schobbenhaus and Campos, 1984).

In southeastern Brazil, the overall nature of the Espinhaço and Brasiliano events is fairly clear. Rifting during the Espinhaço event broke up a large continent into smaller blocks. These blocks, plus others, reassembled to form Gondwana during the Brasiliano event. Thus, the Brasiliano orogeny created a network of collisional orogens reflecting closure of oceanic and ensialic basins. Pre-Espinhaço tectonic events, however, remain poorly understood because structures associated with these events are not well exposed or dated, have been severely overprinted by Brasiliano deformation, or have been buried by Neoproterozoic and Phanerozoic cover. As a result, questions about the older events remain incompletely answered. In what tectonic setting did the older events occur? Did geologic processes during these events resemble those that occurred during younger events? Are these events manifestations of a pre-Brasiliano continental assembly? This paper addresses these questions as they pertain to the Transamazonian orogeny.

Our structural analysis, along with results of recent geochronological studies (Romano, 1989; Machado et al., 1989a,b; Teixeira and Figueiredo, 1991; Machado and Carneiro, 1992; Machado et al., 1992; Teixeira, 1993; Babinski et al., 1991, 1993; Carneiro et al., 1995; Noce, 1995; Machado et al., 1996; Schrank and Machado, 1996a,b) indicates that the Quadrilátero Ferrífero (QF), a portion of the southern São Francisco craton in the Brazilian highlands, contains relicts of a Transamazonian orogen. We describe Transamazonian structures of the southern São Francisco craton, provide a tectonic model to explain the formation of these structures, and correlate these structures with other Transamazonian features of the Brazilian highlands. We also discuss the role that this orogen, and the Transamazonian orogeny in general, played in the assembly of South America.

2. Geology of the Southern São Francisco Craton Region

The São Francisco craton (Almeida, 1977, 1981), which was continuous with the Congo craton of Africa prior to the opening of the South Atlantic, is one of four cratons (Fig. 2), defined in South America as Archean and Paleoproterozoic crustal blocks that were not significantly affected by Brasiliano or younger orogenic remobilization. It encompasses a substantial part of the southern Brazil highlands. This craton consists of two lobes: a southern lobe and a northeastern lobe (Fig. 3). Brasiliano fold-thrust belts fringe all sides of the craton. These belts (the Brasília, the Alto Rio Grande, the Araçuaí, the Sergipano and the Riacho do Pontal) all verge toward the interior of the craton. The interior of the southern lobe includes the São Francisco basin, a continental-interior platform covered by Paleo/Mesoproterozoic to Mesozoic strata. Platform strata have been eroded from the southern tip of the craton, exposing a region of exposed Archean and Paleoproterozoic rocks (Fig. 3) including the QF, the focus of this paper, a major mining district [Figs. 3 and 4; Dorr (1969)].

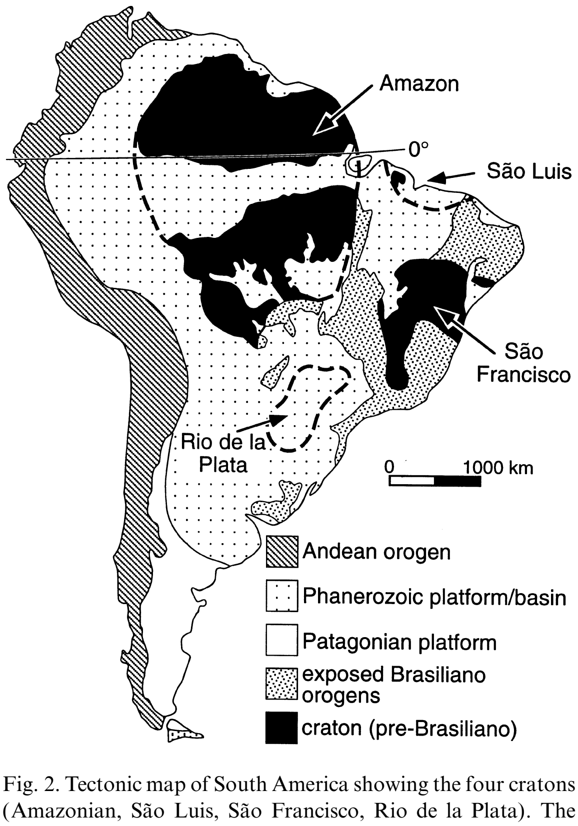


Fig. 2. Tectonic map of South America showing the four cratons (Amazonian, São Luis, São Francisco, Rio de la Plata). The Rio de la Plata craton is dashed because it is poorly exposed. Modified from Almeida et al. (1981).

2.1. Lithostratigraphic Units of the Quadrilátero Ferrífero

The QF contains five principal lithostratigraphic units: Archean crystalline basement; the Rio das Velhas Supergroup; the Minas Supergroup; post-Minas Intrusives; and the Itacolomi Group (Fig. 5).

2.1.1. Archean crystalline basement

Basement crystalline rocks include a 2.9–3.2 Ga gneiss/migmatite complex (Teixeira, 1985, 1993; Machado and Carneiro, 1992; Carneiro et al., 1995) and two generations of voluminous Late Archean plutons: 2.78–2.77 Ga calk-alkaline plutons, and 2.73 to 2.61 anorogenic granites (Carneiro, 1992; Carneiro et al., 1994; Machado et al., 1992; Noce, 1995; Romano, 1989).

2.1.2. The Rio das Velhas Supergroup

This unit consists of greenstone (basalt and komatiite), rhyolitic lava and intercalated sedimentary rock. Sedimentary units of the Supergroup include Algoma-type banded-iron formation (BIF), carbonates and siliciclastics. U–Pb dates on zircons from felsic lavas yield an age of 2.776 Ga (Machado et al., 1992), while U–Pb dates on detrital zircons and monazites from sedimentary units at the top of the Supergroup yield a maximum age of 2.857 Ga (Schrank and Machado, 1996b). Thus, the Rio das Velhas Supergroup, together with the 2.6–2.7 plutonic rocks, represent a classical Archean granite–greenstone terrane.

2.1.3. Paleoproterozoic Minas Supergroup

The Minas Supergroup is a metasedimentary unit that unconformably overlies the Rio das Velhas Supergroup (Fig. 5). Minas strata resist erosion and thus form ridges that tower above the

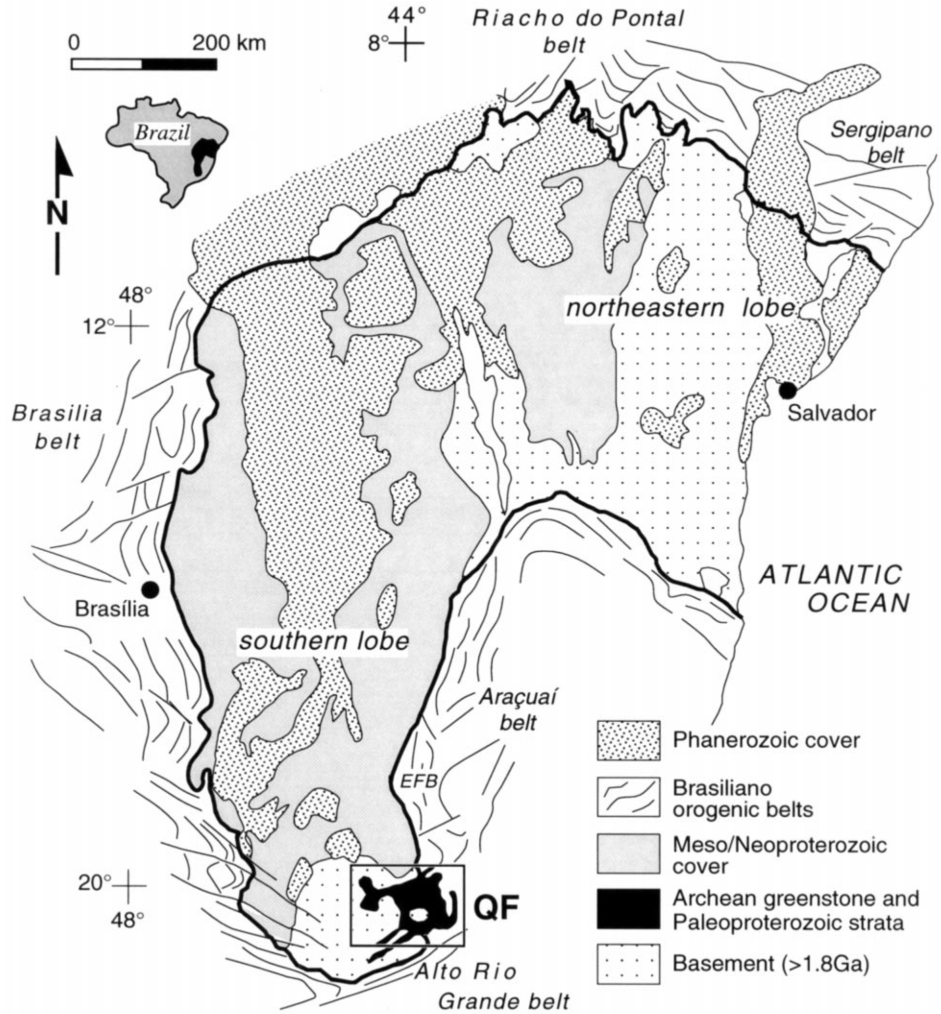


Fig. 3. Regional map of the São Francisco craton, showing the location of the northeastern and southern lobes, the bordering Brasiliano orogenic belts, the Espinhaço fold-thrust belt (EFB), and the QF. The box indicates area of Fig. 4. Modified from Alkmim et al. (1993).

regions underlain by less resistant basement or greenstone, thereby creating some of the highest relief in the southern Brazil Highlands. Minas ridges of the QF roughly outline the shape of a quadrilateral hence the name, 'Quadrilátero Ferrífero' (Fig. 4).

Basal units of the Minas Supergroup consist of alluvial conglomerate and sandstone, which grade upwards into shallow-water marine pelites (Tamanduá and Caraça Groups; Fig. 5). Pb–Pb and U–Pb dates on detrital zircons indicate that these rocks were derived by erosion of an Archean source [maximum age of 2.65 Ga; Noce (1995); Carneiro et al. (1995); Renger et al. (1995); Machado et al., 1993, 1996). Caraça metasediments are overlain by Lake Superior-type BIF (Cauê Formation), which in turn grades upwards into a carbonate sequence (Gandarela Formation; Fig. 5). Babinski et al. (1991, 1993) dated Gandarela carbonates using the Pb–Pb technique and concluded that the unit was deposited ca 2.42 Ga. These authors estimate deposition of the

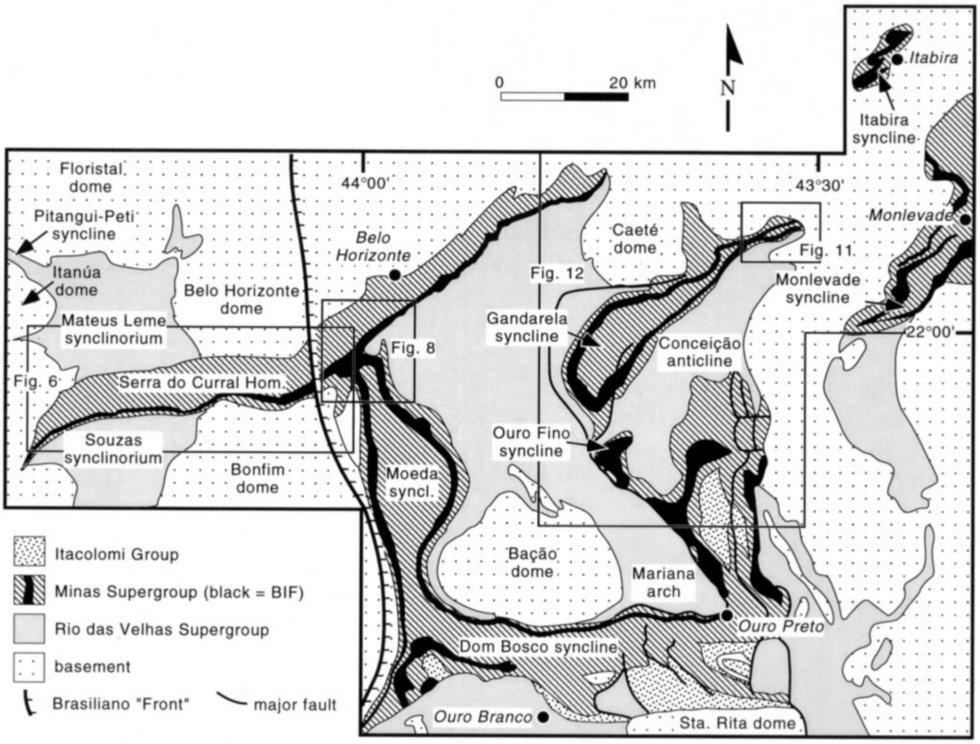


Fig. 4. Geologic map of the QF region, showing the distribution of basement crystalline rocks, Rio das Velhas Supergroup, Minas Supergroup and Itacolomi Group. Principal structures are labeled. Based on Dorr (1969) and Romano (1989). Boxes show locations of Figs. 6, 8a, 11a and 12.

underlying Cauê Formation BIF occurred ca 2.52 Ga. A thick pile of shallow-water and deltaic strata (Piracicaba Group) overlies the Gandarela Formation, locally unconformably. The Piracicaba Group contains detrital zircons in the same age range as those of the Tamanduá and Caraça groups (Machado et al., 1996).

The Sabará Group, is a 3.0–3.5 km-thick sequence of turbidites, tuffs, volcaniclastics, conglomerates and diamictites derived from a source to the east-southeast (Barbosa, 1968, 1979; Dorr, 1969; Renger et al., 1995). It unconformably overlies the Piracicaba Group. U–Pb dating of zircons from Sabará Group tuffs yields an age of 2.125 Ga, which Machado et al. (1989a, 1992) interpret to be roughly the depositional age of this unit. Thus, the Sabará is significantly younger than underlying units of the Minas Supergroup. Sabará Group metasediments in the northern QF lie in shear contact with Archean rocks of a basement dome. In 4 km-wide aureole along the contact, they have been metamorphosed to amphibolite grade (Herz, 1978; Jordt-Evangelista et al., 1992; Marshak et al., 1992). Mylonitized Sabará from the contact aureole yields a Sm–Nd garnet–muscovite–whole rock age of 2.095 Ga (Marshak et al., 1997a,b).

2.1.4. Post-Minas intrusives

Thin, undated, pegmatite veins cut Minas rocks (Herz, 1970). Similar pegmatites, which cut basement in the QF, yielded a monazite U–Pb age of 2.06 Ga (Noce, 1995). Some of the granitoids cutting metamorphic complexes of domes in the QF could be post-Minas in age, but none have yet yielded a post-Minas date. However, the Alto Maranhão granitoid pluton, which crops out just to the southeast of the QF, has yielded a U–Pb zircon date of 2.08 Ga (Noce, 1995). North- to northwest-striking mafic dikes also cut the Minas

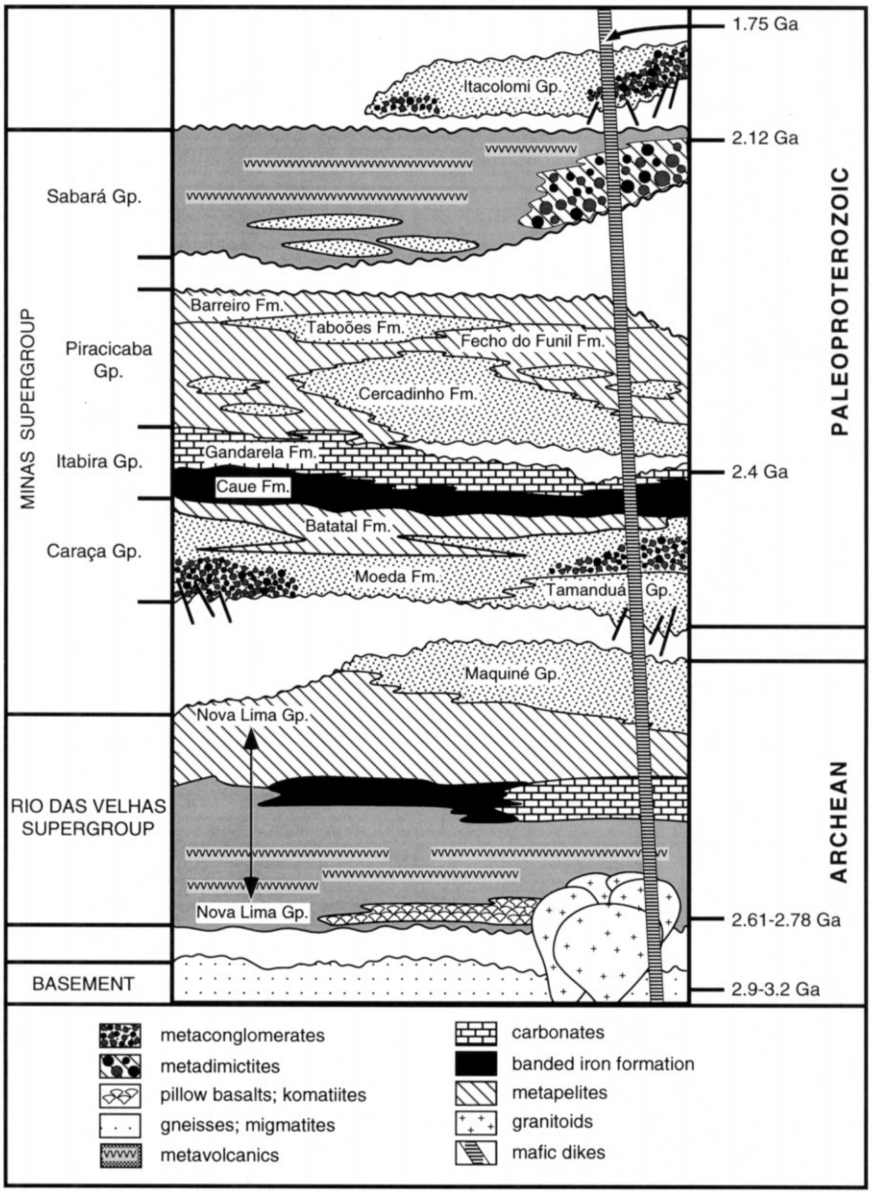


Fig. 5. Stratigraphic column of the QF. Column on the right provides radiometric dating constraints. The right-hand portion of the column represents relationships in the eastern part of the QF, while the left-hand side of the chart represents relationships in the western part of the QF.

Supergroup throughout the QF. One of these dikes yielded 1.714 Ga date (Silva et al., 1995).

2.1.5. The Itacolomi Group

The Itacolomi Group, a unit consisting of coarse sandstone and polymict conglomerate containing BIF clasts [probably Cauê; Lacourt (1935); Barbosa (1968); Dorr (1969)], crops out in narrow fault-bounded wedges at the southeastern corner of the QF (Fig. 4). Detrital zircons from the unit yielded U–Pb dates of 2.1 Ga (Machado et al., 1993, 1996). Thus, the Itacolomi Group is of the same age or a little younger than the Sabará Group, and is significantly younger that other units of the Minas Supergroup.

2.2. Geologic architecture of the QF

In the QF, Archean basement (gneiss, migmatite and granitoid) occurs in domes (e.g. Bação, Bonfim, Caeté, Santa Rita, Belo Horizonte, Florestal and Ita£na) surrounded by keels (troughs) containing the Rio das Velhas Supergroup and the Minas Supergroup (Fig. 4). Keels include large first-order synclines (e.g. Moeda, Dom Bosco, Pitangui-Peti, Mateus Leme and Souzas synclines) and a large homocline (the Serra do Curral homocline). Shear zones occur at the contact between supracrustal rocks and basement around all the domes. Rocks of the supracrustal sequence adjacent to the domes contain a distinct high-T/low-P metamorphic aureole (Herz, 1978; Jordt-Evangelista et al., 1992; Marshak et al., 1992) and intersections between keels closely resemble syncline triple points—described in other dome-and-keel provinces (see Jelsma et al., 1993; Romano, 1989). Thus, the geologic map pattern of the QF defines a dome-and-keel structure (cf Anhausser et al., 1969).

Dome-and-keel structure, though it dominates the map pattern, is not the only structural feature suggested by the map of the QF. There are two other sets of pronounced post-Minas structures. One set includes northeast-trending regional-scale folds (the Gandarela syncline, the Conceição anticline, the northeastern half of Ouro Fino syncline and the Itabira and Monlevade synclinoria; Fig. 4). The other set, generally attributed to the Neoproterozoic Brasiliano orogeny, includes a series of west-vergent thrust faults and associated structures. Penetrative tectonic fabrics (phyllitic schistosity, mylonitic foliation, crenulation cleavage, stretching lineations) related to the Brasiliano event pervasively overprint preexisting structures in the region east of a roughly north-trending line that follows the west edge of the Moeda syncline and cuts northwards across the Serra do Curral [Fig. 4; e.g. Chemale et al. (1994)]. This line, here referred to as the Brasiliano front, is the western limit of pervasive Brasiliano reactivation in the QF. East of the Brasiliano front, west-verging structures include a widespread east-southeast-dipping schistosity, north-trending folds and a north–south-trending crenulation lineation. Stretching lineations parallel the dominant set of mesoscopic fold axes in Minas strata; both plunge preferentially toward S80°E at 30°. West of the Brasiliano front, Brasiliano tectonism appears to be manifested dominantly by northeast-trending dextral strike-slip shear zones.

3. Previous models of post-Minas tectonism in the QF

Numerous publications over the years, beginning with the contributions of Guimarães (1931, 1966) and Barbosa (1961, 1968), have provided models to explain the complex map pattern of the QF. Subsequent to the first 7.5″ quadrangle mapping in the QF, Dorr (1969) attributed all post-Itacolomi structures of the QF to the 'Minas Orogeny', which he postulated consisted of two phases an early northwest-verging phase and a later west-verging phase. Dorr did not recognize the existence of basement in the region, and viewed all the domes as plutons which intruded predeformed supracrustal rocks. Subsequent structural analyses (e.g. Fleischer, 1971; Hackspacher, 1979; Pires, 1979; Glöckner, 1982; Rosière, 1981; Guba, 1982; Evangelista, 1984; Alkmim, 1985; Gomes, 1985; Chemale, 1987) have led to different interpretations, of which there have been several. For example, Drake and Morgan (1980) implied that the domes of the region represented interference structures and suggested that they were comparable to Appalachian mantled gneiss domes, while Ladeira and Viveiros (1984) considered QF structural patterns to be indicative of a very complex history of polyphase folding.

Alkmim et al. (1988) argued for the existence of two major compressional events affecting Minas metasediments, an early northwest-verging event and a later west-verging event, between which an enigmatic 'uplift' event emplaced the domes vertically into the supracrustal assemblage. They suggested that the Moeda and Dom Bosco synclines formed during the vertical uplift event, and that the northwest-vergent contraction was a manifestation of the Transamazonian event, while the west-verging contraction was a manifestation of the Brasiliano event.

Marshak and Alkmim (1989) proposed a more complex multistage history of contractional and extensional tectonic events to explain structures of the QF. They distinguished between three sets of contractional structures, one trending northeast–southwest, one trending east–west and one trending north–south. Based on cross-cutting relationships, they concluded that the northeast-trending set represented D1, the east–west set represented D2, and that the north–south set represented D3. Further, they correlated D1 with the Transamazonian orogeny, D2 with the Uruaçuano orogeny, and D3 with the Brasiliano orogeny. Based on the occurrence of younger-on-older faults, hanging-wall down shear-sense indicators, and on the occurrence of mafic dikes in the QF, Marshak and Alkmim also suggested that a major extensional event (DE) occurred between D2 and D3.

Hippertt et al. (1992) found normal-displacement shear indicators in the mylonites at the contact between the basement of the Bonfim dome and the Minas metasediments of the western limb of the Moeda syncline, providing further evidence for extension. Chemale et al. (1991, 1994), made an extensive compilation of structural and geochronological data from the QF. They proposed that post-Minas evolution of the QF was marked by two main deformational events. The first episode was a Paleoproterozoic (2.06–2.00 Ga) extensional event which the authors attributed to the Transamazonian event. The second was a Neoproterozoic (0.6–0.5 Ga) contractional event which the authors attributed to the Brasiliano event. Chemale et al. (1991, 1994) considered formation of synformal keels in the region to be a consequence of Paleoproterozoic extension. They portray the domes to be rollover anticlines above listric normal faults, and view the synformal keels as basins filling the gap between the fault and the dome surface.

Marshak et al. (1992) suggested that the doming event could best be explained as a consequence of diapiric-like movement of basement upwards into the supracrustal assemblage. As the domes rose, supracrustal units became incorporated in interdiapir synforms, thereby creating the pronounced dome-and-keel geometry. Based on cross-cutting relations, they proposed that this event postdated northwest-verging thrusting and predated west-verging Brasiliano thrusting, essentially the sequence of events proposed by Alkmim et al. (1988). Subsequent dating of metamorphic aureoles in Minas strata of dome-border shear zones has yielded a date of 2.095 Ga (Marshak et al., 1993, 1997a). Based on this age, Marshak et al. (1993, 1997a) proposed that dome emplacement occurred during orogenic collapse of the Transamazonian orogen. Marshak et al. (1997b), emphasize that dome and keel formation may better be viewed as a crustal-scale analog of boudinage. They suggest that, in this context, the keels effectively represent grabens formed during extensional collapse.

Chauvet et al. (1994) postulated a three-stage model for the tectonic evolution of the QF. According to these authors, a tectonomagmatic event during the Paleoproterozoic was responsible for the uplift of the basement domes and generation of the regional folds. During the Brasiliano event, a contractional deformation, which led to development of west-northwest-verging folds and faults, was followed by the extensional tectonism, due to the gravitational collapse of the thrust stack.

4. Evidence for Transamazonian contraction in the QF

From the above description, it is clear that the interpretation of the tectonic history of the QF remains controversial. Did the region experience a Transamazonian contractional orogeny or not? As originally defined, the Transamazonian orogeny occurred between 2.2 and 1.8 Ga. Thus, candidates for Transamazonian contractional structures in the QF are defined to be folds or faults that have the following characteristics:

(1) their development resulted in contractional (shortening) strain;
(2) they involve Minas Supergroup strata (i.e. are

certainly post-2.4 and probably post-2.125 Ga);
(3) they are overprinted by dome-border shear zones and associated metamorphic aureoles (i.e. must be pre-2.095); and
(4) in the central to eastern QF they are overprinted by west-vergent Brasiliano structures.

In this section, we describe contractional structures that meet all four criteria.

4.1. Western Serra do Curral

In the western QF, the Minas Supergroup crops out in the northeast–southwest trending Serra do Curral. Morphologically, the 80 km-long Serra do Curral defines the northwest edge of the QF (Fig. 4). Overall, the Serra do Curral is a homocline in which bedding dips steeply to the southeast, though detailed mapping studies (Pires, 1979; Hackspacher, 1979; Romano, 1989; Chemale et al., 1991, 1994; Alkmim et al., 1996) reveal local structural complexities.

The stratigraphic succession, as well as locally preserved sedimentary structures, indicate that beds comprising the Serra do Curral homocline are overturned. This observation led Pomerene (1964), Dorr (1969) and Pires (1979) to propose that the homocline represents a remnant of the overturned limb of a northwest-vergent anticline. Our observations confirm this proposal.

In the Serra do Curral, west of Sarzedo (Figs. 6 and 7), tight northwest-verging asymmetric folds and southeast-dipping mesoscopic faults were found [see also Romano (1989) and Romano et al. (1991)]. Movement on the faults accommodated hanging-wall-up (thrust) movement that resulted in stratigraphic duplication. The geometry of the folds suggests that they are parasitic folds on the overturned limb of a northwest-verging regional fold, and the geometry of the thrusts suggest that they are synthetic imbricate splays on the forelimb of a thrust-related fold. These structures are cut by the normal-sense shear zones that border basement domes. Specifically, a dome-border shear zone juxtaposes gneisses and migmatites of the Belo Horizonte dome with overturned Piracicaba Group strata on the north margin of the homocline, and a dome-border shear zone juxtaposes gneisses and migmatites of the Bonfim dome with the Moeda Quartzite along the south margin of the homocline (Fig. 6). Dome-border shear zones, in turn, are overprinted by northeast-striking dextral strike-slip shear zones, and the northwest-verging folds and faults are affected by north-trending open folds and a north-striking crenulation cleavage.

Along a transect following highway BR 381 across the south flank of the homocline in the western Serra do Curral (Figs. 6 and 7), a shear zone that dips between 35°SE and 80°SE that places Nova Lima Group schist over overturned beds of the Moeda Quartzite was observed. Kinematic indicators in the shear zone require hanging-wall-up shear (top-to-the-northwest), so the shear zone is a northwest-verging thrust. Strata of the footwall are overturned and contain cascades of asymmetric parasitic folds whose geometry suggests that they are on the overturned limb of a regional northwest-verging anticline (Figs. 6 and 7). Between BR 381 and Ponta da Serra (Fig. 6), Romano (1989) and Romano et al. (1991) mapped an array of northwest-verging thrusts.

East of Sarzedo, dextral strike-slip shear zones attributed to Brasiliano deformation increasingly overprint structures of the Serra do Curral homocline. In addition, a series of north-striking normal faults, in some cases associated with 1.75 Ga mafic dikes, crosscut the homocline.

4.2. Central and Eastern Serra do Curral

4.2.1. Junction of the Serra do Curral homocline with the Moeda syncline

About 10 km southwest of the city of Belo Horizonte, the Serra do Curral homocline intersects the north-northwest-trending Moeda syncline [Figs. 4 and 8; Pomerene (1964); Dorr (1969); Pires (1979) and Pires et al. (1993)]. The Moeda syncline is a first-order syncline that forms the keel between the Bonfim and the Bação domes (Fig. 4). Alkmim et al. (1996), utilizing the results of their own new mapping as well as results of extensive iron-mining company exploratory drilling, confirmed that at this intersection the crest of Serra do Curral is the overturned limb of a

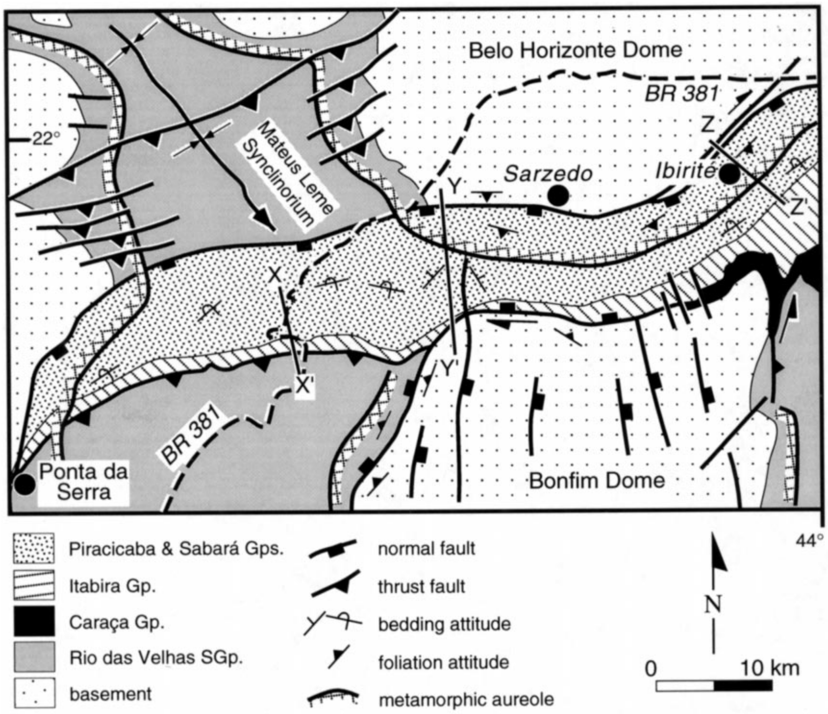


Fig. 6. Simplified geologic map of the western Serra do Curral, based on Dorr (1969) and Romano (1989). The dashed line indicates the trace of Federal Highway 381. Cross-sections are provided by Fig. 7.

northwest-verging asymmetric anticline (Figs. 8 and 9), as proposed by Pomerene (1964) and Pires (1979). But in contrast to the western Serra do Curral, the region south of Belo Horizonte also provides exposures of the right-side-up limb of this anticline. At the north end of the Moeda syncline, the Serra do Curral anticline has been refolded by the Moeda syncline, creating an interference saddle (Fig. 10). If the Moeda syncline initiated at the time of doming, then the Serra do Curral anticline must predate doming, that is, it is Transamazonian (Fig. 10). West-verging Brasiliano thrusts (the Gorduras, Mutuca, Catarina and Barreiro faults; Figs. 8–10) cut the Moeda syncline and the Serra do Curral anticline. In addition, the region contains numerous dextral strike-slip shear zones.

4.3. Serra da Piedade Syncline

A high ridge, locally known as the Serra da Piedade, forms the eastern end of Serra do Curral (Fig. 11). An overturned stratigraphic succession crops out along the ridge crest. This exposure contains pervasive asymmetric northeast-trending folds (F_1), whose attitude and vergence indicates that they are parasitic folds on the overturned limb of a northwest-verging anticline. These folds, which have been refolded around a second generation of east-trending folds (F_2), must pre-date west-verging Brasiliano deformation, for they are cut by a north-striking (i.e. Brasiliano) foliation (S_t) with an east-plunging lineation (L_{S2}; Fig. 11). To the north of the ridge, units that comprise the homocline wrap around a northeast-trending, northwest-verging syncline, the Piedade syncline (Dorr, 1969). A series of north-northeast-striking dextral shear zones (S_{sz}) crosscut the Piedade syncline [Fig. 11; Pires and Godoy (1995)]. The boundary between the northwest-limb of the Piedade syncline and the basement dome to the north is a shear zone that has been reactivated by the Brasiliano event and thus now displays reverse dextral movement. However, the syncline at this

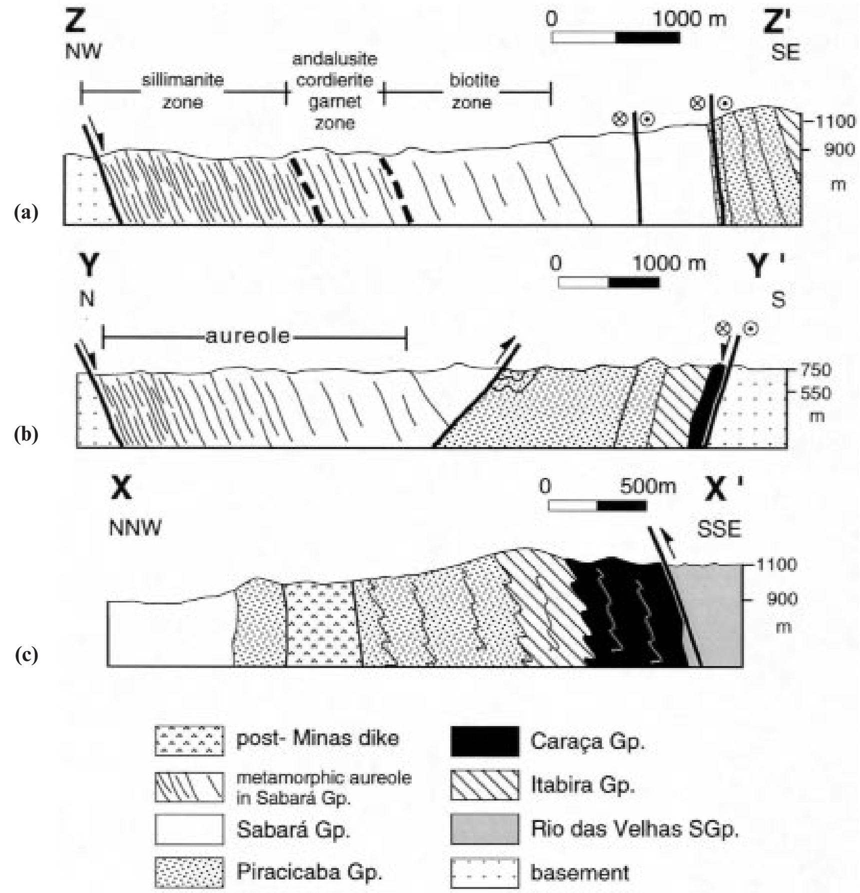


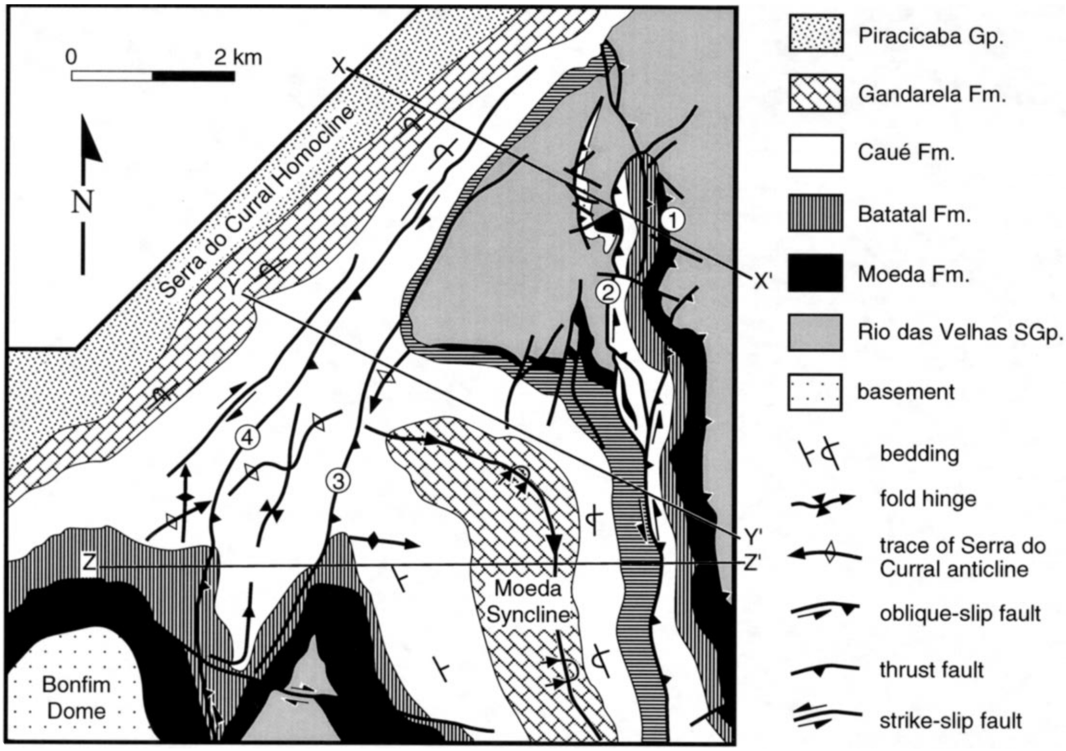
Fig. 7. Cross sections across the map area of Fig. 6. Bedding and foliation geometry are shown schematically. (a) Cross-section at ZZ′; zones of the metamorphic aureole adjacent to the dome-border shear zone are indicated; (b) cross-section at YY′; the position of the metamorphic aureole is indicated; (c) cross-section at XX′. There is no metamorphic aureole along this cross-section.

locality has been overprinted by a typical dome-border metamorphic aureole, so the development of the syncline is either pre- or syn-dome emplacement. To the south of the ridge a reverse-dextral shear zone juxtaposes Rio das Velhas schist with Minas metasediments in the overturned limb of the homocline (Fig. 11).

If the youngest generation of folds in the Serra de Piedade is Brasiliano, then their axes parallel the stretching lineation on east-dipping Brasiliano foliation. This puzzling geometry has been documented throughout the eastern QF by many authors. As shown in the block diagram of Fig. 11(b), We suggest that this geometry developed because Brasiliano deformation was superimposed on a succession of beds striking at a small angle to the west-northwest Brasiliano transport direction. The pre-Brasiliano bedding attitude reflects the large northwest-verging folds of the region.

4.4. Hanging wall of the Fundão-Cambotas fault system

According to Endo and Fonseca (1992), the Fundão-Cambotas fault system consists of two major Brasiliano west-verging thrust faults (Fig. 12). The fault system has an arcuate trace, presumably because the westward propagation of thrust sheets above the faults was confined by the



(a)

Fig. 8. Structural relations at the intersection between the Serra do Curral homocline and the Moeda Syncline. (a) Simplified geologic map based on Alkmim et al. (1996). 1, Gorduras fault; 2, Mutuca fault; 3, Catarina fault; 4, Barreiro fault; (b) equal-area, lower hemisphere stereoplots of bedding and foliation planes for the region of the junction of the Serra do Curral homocline with the Moeda Syncline.

preexisting Caeté dome to the north and Mariana basement arch to the south. The faults probably link in the subsurface to the east to the north-striking Água Quente fault (Dorr, 1969), which places a slice of basement gneiss westwards over Minas Supergroup strata (Endo and Fonseca, 1992).

The central and northern portions of the Fundão-Cambotas thrust sheet are relatively less deformed by Brasiliano shortening, and have not been affected by dome emplacement. In this portion of the thrust sheet, Minas Supergroup strata have been folded around a series of northwest-verging and northeast-trending regional-scale folds. Examples of these structures include the Gandarela syncline, the Conceição anticline, the northeastern half of the Ouro Fino syncline, and a fold train in the Serra do Caraça (Fig. 12). With the exception of the Serra do Caraça, all these folds are overprinted by north-striking phyllitic cleavage and associated mesoscopic-scale folds and shear zones. In the Serra do Caraça, Tamanduá quartzite wraps around a series of northwest-verging folds, which have been refolded around a large, roughly north-trending syncline in the west and have been cut by a family of north-striking thrust faults in the east. The northwest-verging folds in the Serra do Caraça, which are open and have a wavelength of ca 300 m, have been cut by a large number of north-striking mafic dikes (Fig. 13).

4.5. Isolated keels east of the QF

Dorr (1969) mapped isolated keels of Nova Lima and Minas supracrustal rocks, surrounded by a 'sea' of basement, in the region northeast of the QF near the towns of Itabira and João

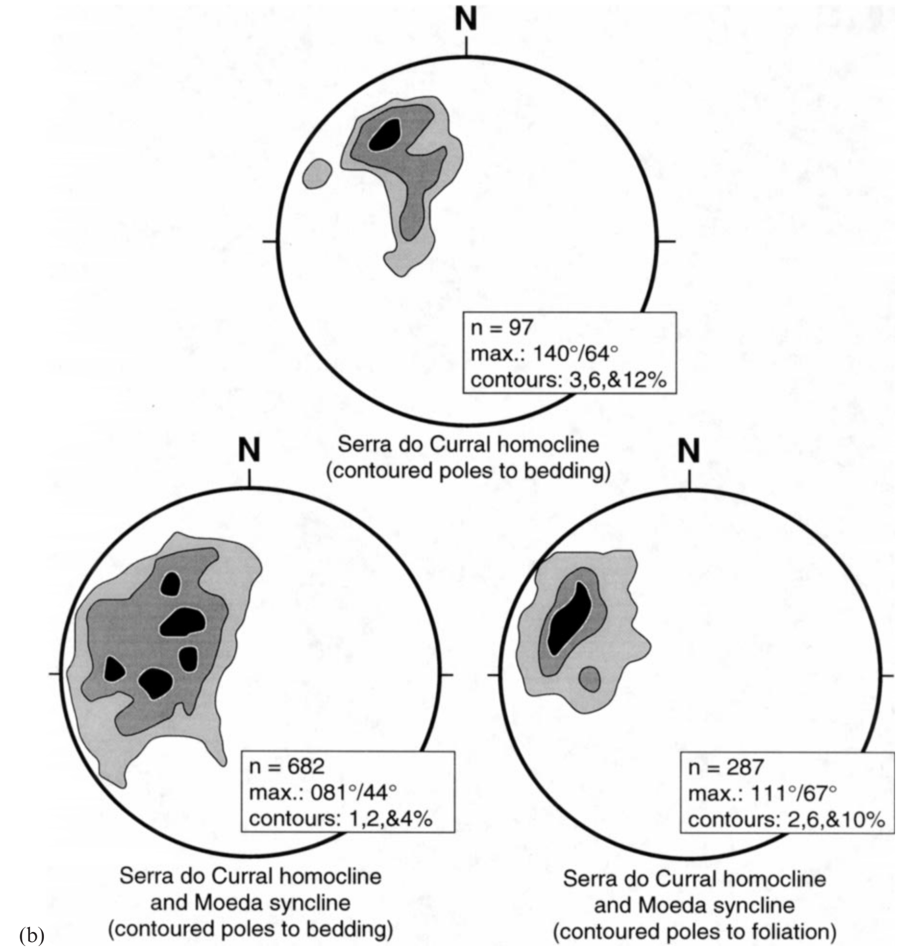


Fig. 8. (*continued*)

Monlevade (Figs. 4 and 12). These keels contain thick sections of BIF, and thus have become important mining districts. Within the keels, strata wrap around numerous northeast-trending folds. In the Itabira keel, these folds intersect the keel border at an angle of ca 15–20° (Fig. 12), and thus appear to pre-date keel formation (i.e. are pre-doming structures). Brasiliano folds, fabrics, and faults overprint the northeast-trending folds. Specifically, north-trending folds tightened and refolded pre-dome folds of the Itabira keel, and north-striking thrust-sense shear zones truncate the folds. Northeast-trending dextral/reverse shear zones also have developed in the keels (Chemale, 1987; Guba, 1982).

5. Evidence for transamazonian orogenic collapse in the QF

5.1. *The dome-emplacement event*

Cross-cutting relations indicate that emplacement of the domes and the consequent formation of present dome-and-keel structure is the second post-Minas Supergroup deformational event to affect the QF. The borders of the domes, west of the Brasiliano front, are shear zones in which kinematic indicators clearly indicate supracrustal-side-down displacement. These shear zones predate west-verging (Brasiliano) thrusting and associated dextral/reverse shear.

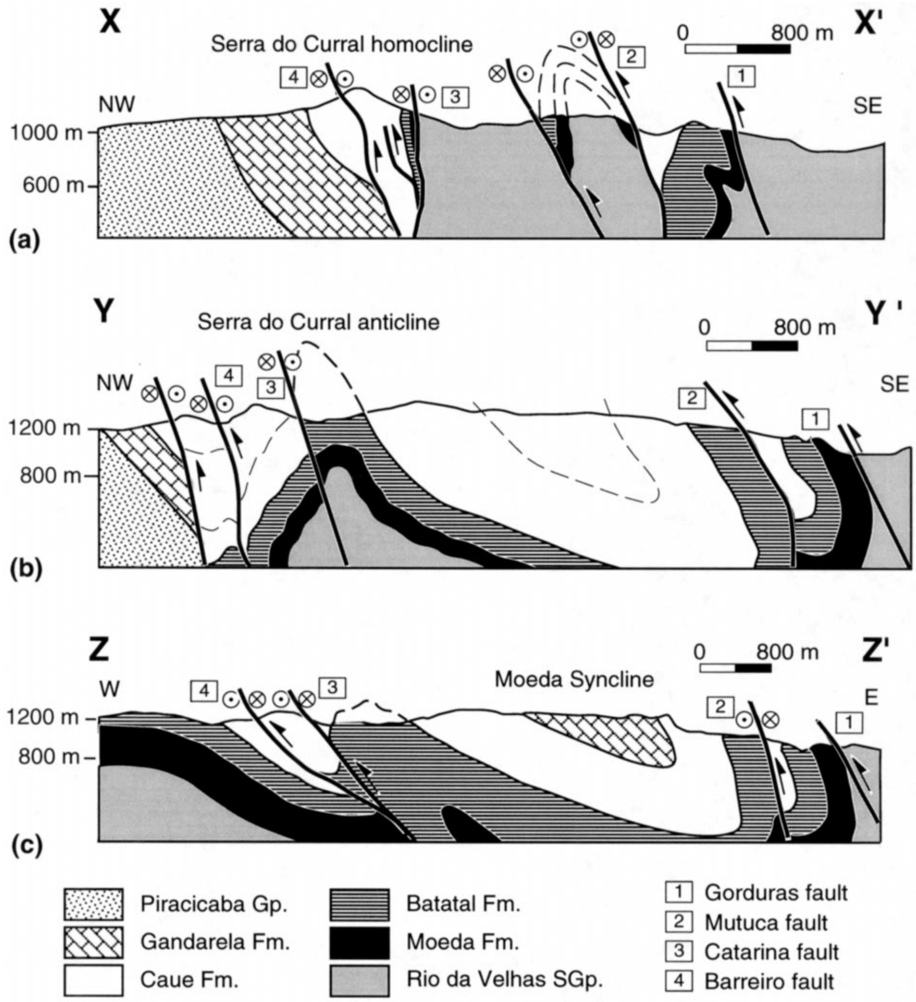


Fig. 9. Cross-sections of the map shown on Fig. 8. (a) Cross-section at XX′. (b) Cross-section at YY′. (c) Cross-section at ZZ′. Bedding is portrayed schematically.

5.1.1. Northern border of the Bonfim dome

Around the northern border of the Bonfim dome, the Moeda Quartzite is juxtaposed against the basement gneisses by a shear zone, which dips 70–85° to the north (Figs. 6 and 7). Along this shear zone, close to the contact with the gneiss, Moeda Quartzite is mylonitized and has undergone feldspathization (Pomerene, 1964). Kinematic indicators (S–C-structure, porphyroclast shadows and asymmetric foliation trajectories) indicate normal to dextral/normal shear in the zone. The dome-border shear zone overprints northwest-verging folds and faults, and is itself overprinted by weak dextral/reverse shear zones attributed to the Brasiliano event. West of the Paraopeba River Valley, the dome-border shear zone between basement gneisses and supracrustal rocks bends to the southwest and south, and is located in the Rio das Velhas schist. Here, it is associated with a 100–150 m-wide garnet–staurolite metamorphic aureole.

5.1.2. Southern border of the Belo Horizonte dome

Along the southern border the Belo Horizonte dome (Fig. 6), a normal-sense shear zone juxtaposes gneiss and granitoid to the north against

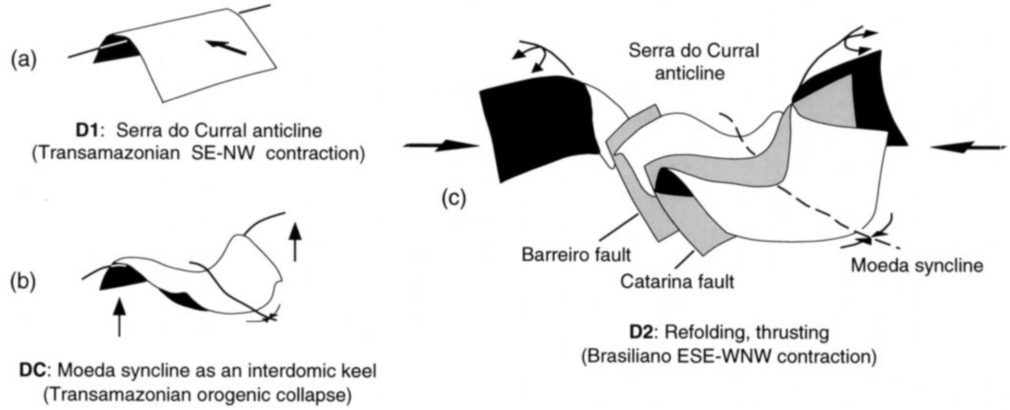


Fig. 10. Evolutionary model for the development of the junction between the Serra do Curral homocline and the Moeda syncline. The surface portrayed represents the base of the Cauê Formation (white represents the top of the surface and black represents its bottom). (a) Formation of the Serra do Curral anticline due to Transamazonian NW-contraction. (b) Bending of the Serra do Curral anticline due to the development of dome-and-keel architecture. Vertical arrows represent the displacement of basement relative to the base of the Cauê. (c) Formation of complex geometry due to Brasiliano east–west shortening (compare with the geologic map of Fig. 8). The lightly shaded surfaces are faults.

Sabará schist to the south. In map view, this contact has an arcuate trajectory as it wraps around the border of the dome. Its dip varies between 50 and 90° towards the south. Microstructural studies (Jordt-Evangelista et al., 1992; Marshak et al., 1992) show a clear hanging-wall-down sense of displacement for the contact. A metamorphic aureole in the Sabará follows the contact. Jordt-Evangelista et al. (1992) mapped sillimanite, cordierite, andalusite and biotite zones in this aureole, and further showed that blastesis of alumino-silicate polymorphs are syn- to post-shear with respect to the development of the shear zone. The dome-border shear zone is overprinted by north-trending folds, associated with a crenulation cleavage, and also by weak dextral/reverse shear zones attributed to the Brasiliano event. Sm–Nd dates on syn-shear garnets from the zone yield an age of 2.095 Ga, that is, late Transamazonian (Marshak et al., 1997a).

5.1.3. *Extensional interpretation of dome emplacement*

As indicated by the above description, west of the Brasiliano front, development of the present dome-and-keel architecture clearly postdates formation of northwest-verging (Transamazonian contractional) structures, and predates formation of west-verging (Brasiliano) contractional structures. Radiometric dating constrains dome-and-keel formation to be late or post Transamazonian (Marshak et al., 1997a). Dome-and-keel architecture of the QF has been explained by numerous different mechanisms (e.g. Barbosa, 1968; Dorr, 1969; Gomes, 1985; Chemale et al., 1991, 1994; Hippertt, 1994; Marshak et al., 1992, 1997a). More recent interpretations focus on the possibility that doming developed during extensional tectonism.

Structural features suggest that doming occurred during a regional extension, for dome emplacement involved juxtaposition of basement against supracrustal assemblages by normal-sense displacement on steeply dipping shear zones. Further, the timing of dome rise clearly indicates that it occurred at the final stage of Transamazonian tectonism, a time during which collisional orogens typically undergo extensional collapse. Marshak et al. (1997a,b) point out that in this context, dome emplacement could reflect the ductile sinking of weak, dense supracrustal rocks into grabens forming around basement blocks during progressive extension of the crust. In effect, the overall configuration of late Transamazonian dome-and-keel architecture is suggestive of crustal-scale boudinage, involving two units (basement and cover) of markedly contrasting viscosity. Considering the

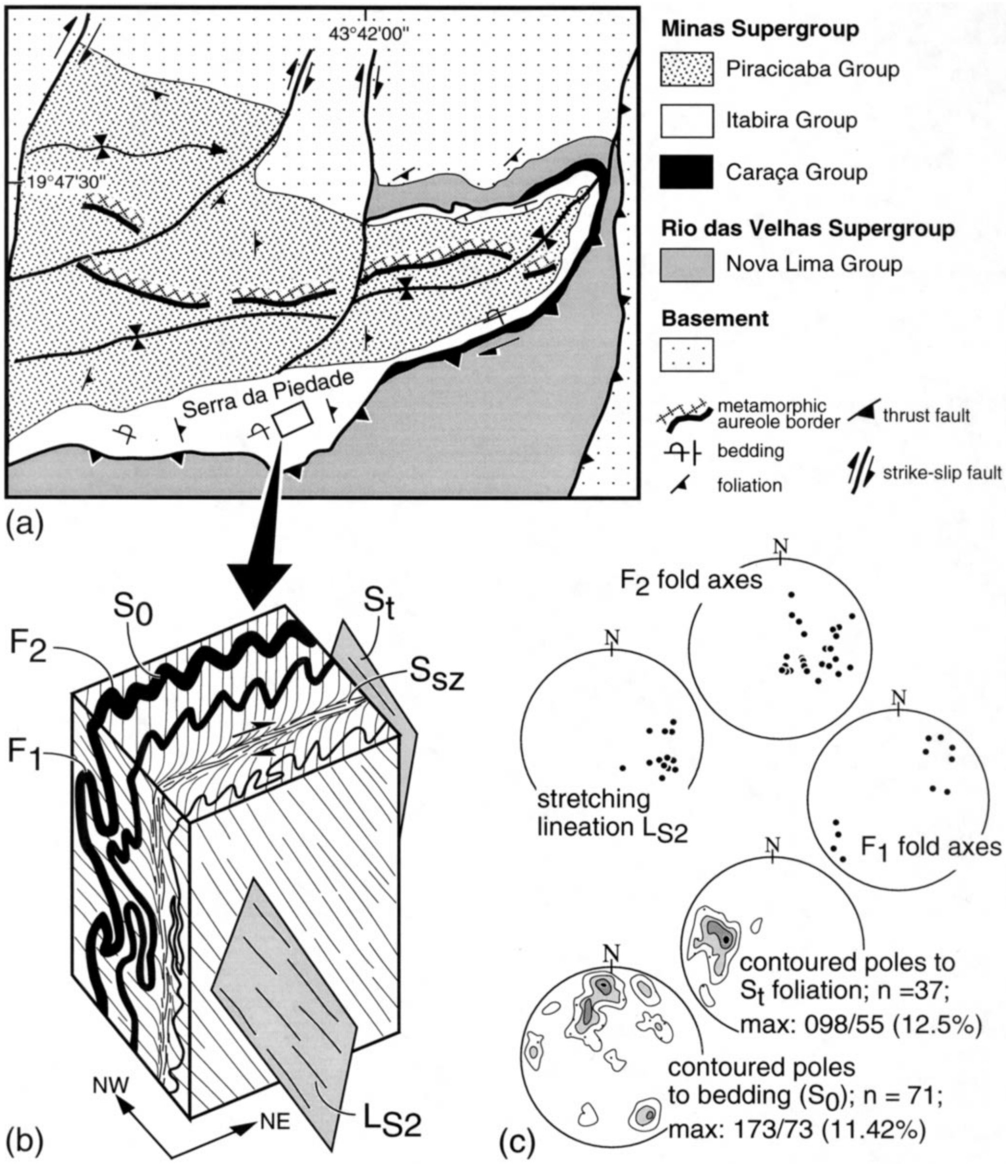


Fig. 11. Structural relations in the Serra da Piedade. (a) Simplified map of the eastern Serra do Curral, showing the Piedade ridge and the Serra da Piedade syncline [based on Alves (1969) and Pires and Godoy (1995)]. (b) Block diagram illustrating the interference of two generations of macroscopic structures in the Cauê itabirite of the Serra da Piedade S_0 is bedding. F_1 folds are parasitic folds in the vertical limb of the Transamazonian-age Piedade syncline. L_2 is the stretching lineation on the S_t foliation. F_2 folds, S_{sz} shear zones, S_t foliation and L_2 stretching lineation are younger structures, associated with west-northwest-directed Brasiliano contraction.

relatively high temperature of the basement at this time, as well as the density inversion established when Transamazonian thrusting and folding substantially thickened the iron-rich supracrustal assemblage above the intermediate/silicic basement, the rise of basement relative to supracrustal rocks may have been amplified by its relative buoyancy. Juxtaposition of hot, low-density basement beneath relatively cool high-density supracrustal assemblage could reflect transcrustal

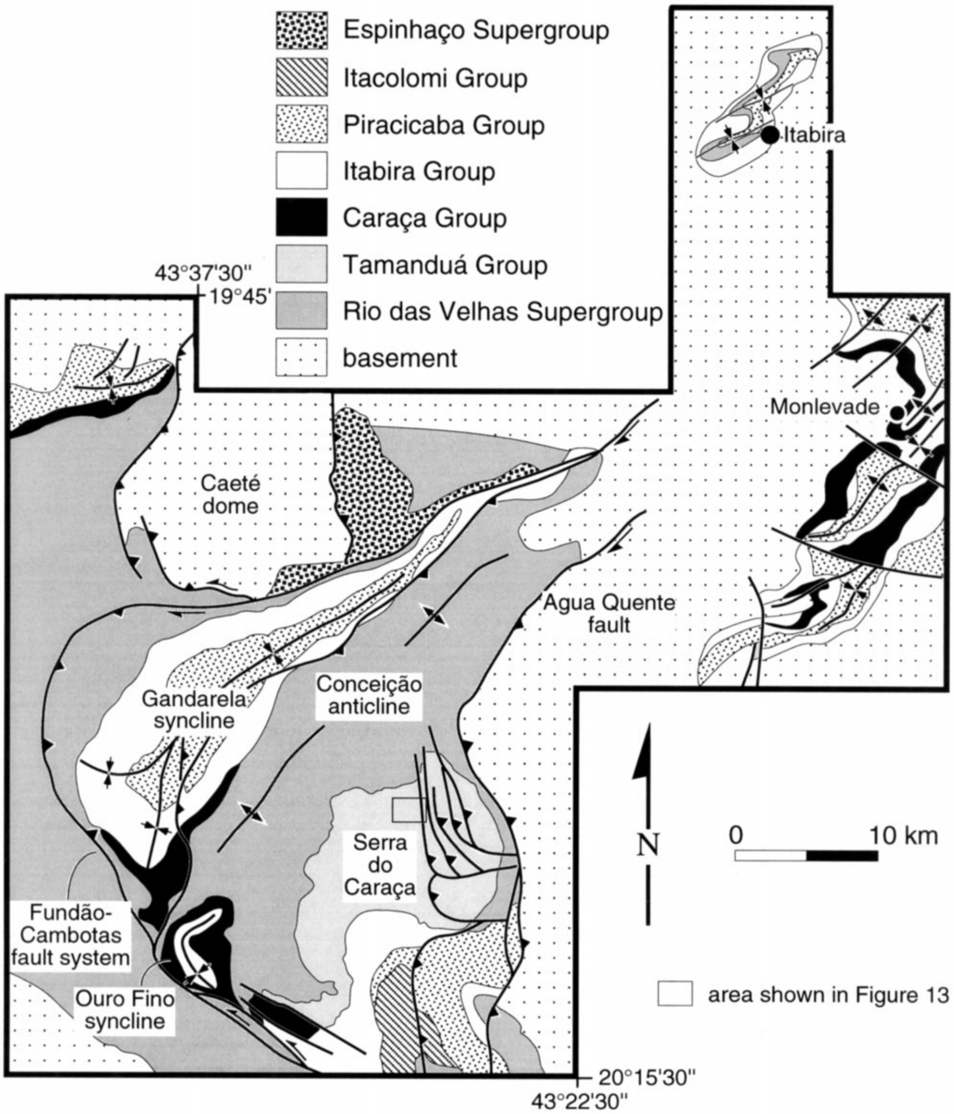


Fig. 12. Geologic map of the northeastern QF, showing the Fundão-Cambotas fault system and the isolated Itabira keel [based on Dorr (1969) and Endo and Fonseca (1992)]. This map illustrates the northeast–southwest trend of regional structures (e.g. Gandarela syncline, Conceição anticline and northeastern end of the Agua Quente fault) in the hanging wall of the Fundão-Cambotas fault system.

normal shear bringing basement up from depth, or heating by post-orogenic plutonism [see also Kusky (1993)]. The concept that dome emplacement accompanied extensional tectonism is attractive because extensional tectonism explains how space for the basement domes developed, why normal-fault-bounded keels developed, and why the region heated up.

Typically, extensional tectonism is accompanied by plutonism. Evidence for such plutonism in the QF is not abundant (no large Transamazonian plutons have yet been documented in the QF). But U–Pb dates on monazites and titanites from pegmatites, amphibolites and migmatites in the Bação and Belo Horizonte domes indicates that between 2.04 and 2.06 Ga, amphibolite-facies

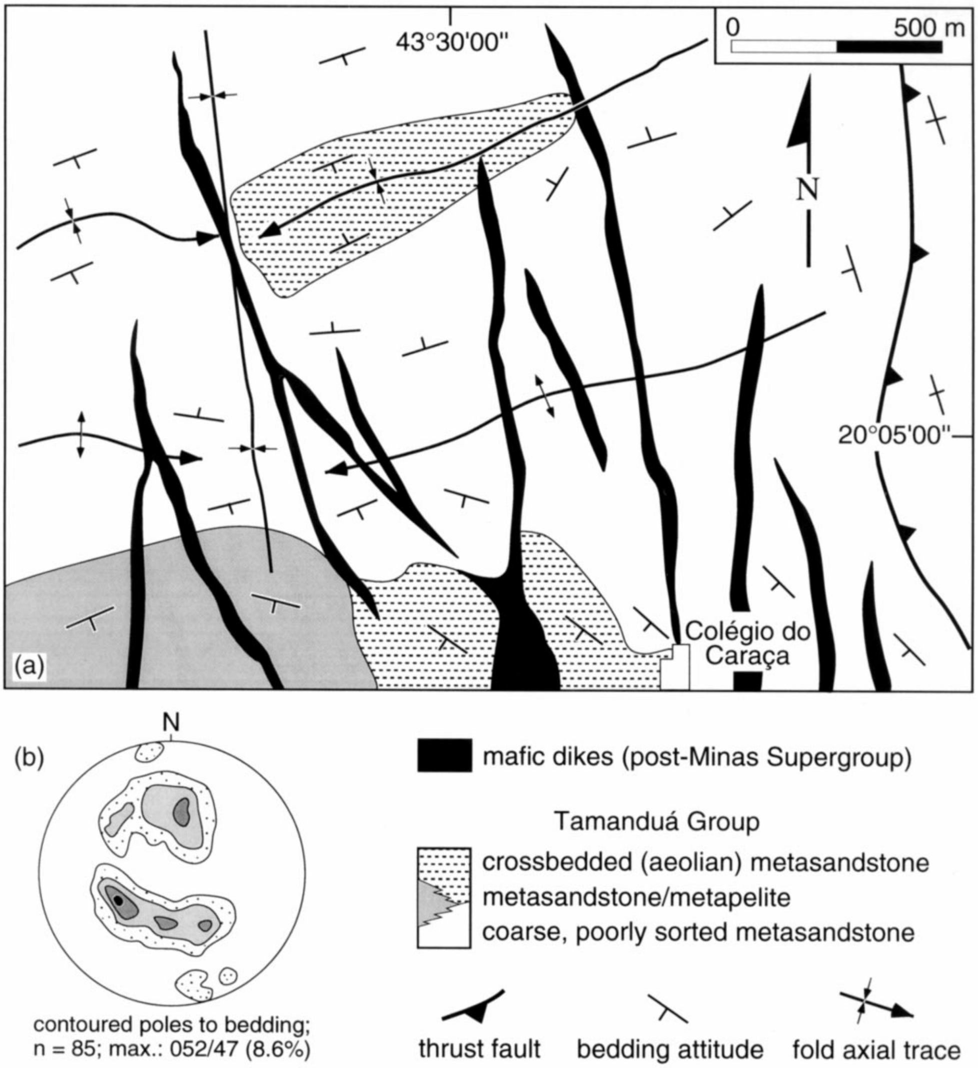


Fig. 13. Simplified structural map of the northern portion of the Serra do Caraça. Note the interference of two sets of structures east-northeast-trending folds are refolded and truncated by north–south-trending structures. Location of the map is shown in Fig. 12.

metamorphism occurred in basement along with some partial melting and generation of pegmatite (Machado et al., 1992; Noce, 1995). Also, Schrank and Machado (1996a) have recently shown that gold mineralization of the Morro Velho and Passagem mines, hosted respectively in Rio das Velhas and Minas Supergroups, formed between 2.10 and 2.06 Ga.

5.2. The Itacolomi Group—a possible record of Transamazonian orogenic collapse

If the dome-emplacement event represents extensional collapse of the Transamazonian orogen, one might expect to find a record of syn-extensional deposition. The Itacolomi Group may be the record of such deposition. As noted earlier, the

Itacolomi is post-2.1 Ga, based on dating of its detrital zircons. Further, the type Itacolomi in the southeastern QF contains clasts of Cauê-like BIF, indicating that its source terrane included rocks of the Minas Supergroup. These conglomerates do not correlate with the Espinhaço Supergroup of the Cordilheira do Espinhaço (an inverted Paleo/Mesoproterozoic rift basin fringing the east edge of the São Francisco craton north of the QF) for two reasons. First, the source terrane for the Espinhaço is the interior of the São Francisco craton, west of the Espinhaço basin (Martins Neto, 1996). Current indicators in the Itacolomi, however, indicate its source area lies to the east-northeast (Glöckner, 1982; Alkmim, 1987). Second, the Espinhaço contains diamonds, suggesting an Archean cratonic source. The Itacolomi does not contain diamonds, and thus has a different, younger, source.

It is proposed instead, following the interpretation of Barbosa (1968) and Dorr (1969), that the Itacolomi represents deposition in narrow intermontane troughs, perhaps grabens or half-grabens, after deposition of the Sabará Formation. Brasiliano contraction inverted these troughs and thrust their contents over the older rocks of their margins, thereby explaining the present younger-on-older thrust relationships observed in the southern QF, as documented by Marshak and Alkmim (1989). If this interpretation is correct, then the Itacolomi is the stratigraphic record of post-Transamazonian orogenic collapse in the uppermost crust.

It is probable that some of the extensional faults of the QF may date from the Espinhaço extension event, at ca 1.75 Ga (Brito Neves et al., 1979; Machado et al., 1989a; Dussin and Dussin, 1995; Uhlein et al., 1995), for dikes of this age occur in the QF. Further, it is possible that some extensional faults of the QF formed during post-Brasiliano extension. But the Itacolomi Group certainly predates Brasiliano contractional deformation, and may predate Espinhaço-age dikes.

6. The Brasiliano Overprint

To complete the structural picture of the QF, we briefly discuss a suite of west-verging contractional structures that cross-cut, and therefore post-date, structures that have already been described. Parallelism between this transport direction and the transport direction in the Araçuaí belt, a well dated Brasiliano thrust belt that borders the eastern edge of the QF, has led most authors (e.g. Belo de Oliveira et al., 1987; Chemale et al., 1991, 1994) to relate the last generation of penetrative contractional structures in the QF to the Brasiliano orogeny. Specifically, the Neoproterozoic Brasiliano deformation in the QF is manifested in several ways:

(1) Throughout the QF east of the Brasiliano tectonic front, supracrustal strata contain a family of structures, including mesoscopic folds, foliation (schistosity and phyllitic cleavage) and thrust-sense shear zones indicative of regional transport in the direction west-northwest. All these elements crosscut the northeast-trending folds of the QF.

(2) Throughout the QF, preexisting shear zones and major lithologic contacts have been reactivated as transpressional shear zones whose displacement is compatible with regional east–west shortening. For example, in the northeastern Serra do Curral, shear zones along the border of the supracrustal assemblage have been reactivated as dextral/reverse shear zones.

(3) Within supracrustal strata of east-trending keels (e.g. the Dom Bosco syncline), west-verging thrust faults developed. The traces of these faults curve in map view to define tight salients, convex toward the foreland. The geometry of these salients suggests that the domes existed at the time of faulting and acted as obstacles inhibiting foreland movement along the lateral boundaries of the faults so that they developed arcuate traces (see Marshak, 1988; Chemale et al., 1994).

7. Discussion

7.1. Summary of evidence for existence of a Transamazonian Orogen in the QF

This paper has presented field observations demonstrating that, prior to the development of pervasive west-verging Brasiliano structures, the region of the QF contained the remnant of a Transamazonian collisional orogen. The evidence for this event can be summarized as follows:

(1) In the western QF (west of the Brasiliano front), there are numerous northwest-verging thrusts preserved in the Minas Supergroup of the Serra do Curral.
(2) The Serra do Curral consists of the overturned limb of a regional-scale northwest verging anticline in which there are abundant mesoscopic parasitic folds. Both limbs of this anticline are preserved at the north end of the Moeda syncline, where the northwest-verging anticline was clearly refolded by the Moeda syncline, and thus must predate the doming event that created the syncline.
(3) In the eastern Serra do Curral (i.e. east of the Brasiliano front), northwest-verging regional folds have been refolded by mesoscopic folds attributed to the Brasiliano event, and thus must predate the Brasiliano event. Folds at both mesoscopic and regional scales in the hanging wall of the Brasiliano Fundão-Cambotas faults are northwest verging. Brasiliano fabrics and shear zones also clearly cut across these folds.
(4) In the western QF, cross-cutting relations between dome-border shear zones (associated with emplacement of the domes) and the northwest-verging faults are preserved. Dome-border shear zones and associated metamorphism cut across northwest-verging folds, and thus development of the present dome-and-keel architecture of the QF must postdate development of the northwest-verging folds. Because dome emplacement can be dated as 2.095 Ga, while units as young as 2.125 Ga are involved in northwest-verging folding, the northwest-verging folding must have developed ca 2.1 Ga, that is, during the Transamazonian event.
(5) The date of the dome-emplacement event requires that it occurred during the final phase of Transamazonian tectonism in the region. The fact that the dome-and-keel architecture influenced the geometry of Brasiliano structures in the region (e.g. leading to the development of local salients and to transpressionally reactivated shear zones) further requires that doming predates the Brasiliano event. Thus, the Transamazonian event consisted of two phases. The first phase generated northwest-verging regional folds, and the second phase generated the dome-and-keel architecture.

7.2. *Tectonic synthesis*

Based on the sequence of deformational events that are recognized in the QF, the following model is suggested for the tectonic history of the region (Fig. 14). This model represents an update and modification of the model proposed by Marshak and Alkmim (1989). It differs from the recent tectonic model proposed by Chemale et al. (1994).

7.2.1. *Creation of an Archean Granite-Greenstone terrane*

The earliest basement crystalline rocks of the QF region may be as old as 3.2 Ga, but little is known about these rocks. Whatever continental crustal fragments that were present served as the basement on which a roughly 2.7–2.8 Ga greenstone and sediment succession, the Rio das Velhas Supergroup, was either deposited or emplaced by thrusting, perhaps in a convergent-margin setting (Teixeira et al., 1996). Roughly coeval intermediate plutonism (2.6–2.7 Ga) into the Rio das Velhas supracrustal rocks created a classic Archean granite–greenstone belt, with domes of granite surrounded by keels of greenstone [Type-M dome-and-keel structure of Marshak et al. (1997b)], by ca 2.6 Ga.

7.2.2. *Formation of the Minas Basin*

After 2.6 Ga and prior to 2.4 Ga, the region to the east and southeast of the QF evolved into an ensialic or passive-margin basin [Fig. 14(a)]. The QF region itself became the continental-platform portion of this basin. Initiation of this basin represents an extensional event, as indicated by facies distribution and depositional environments of the Tamanduá and Caraça Groups (Renger et al., 1993).

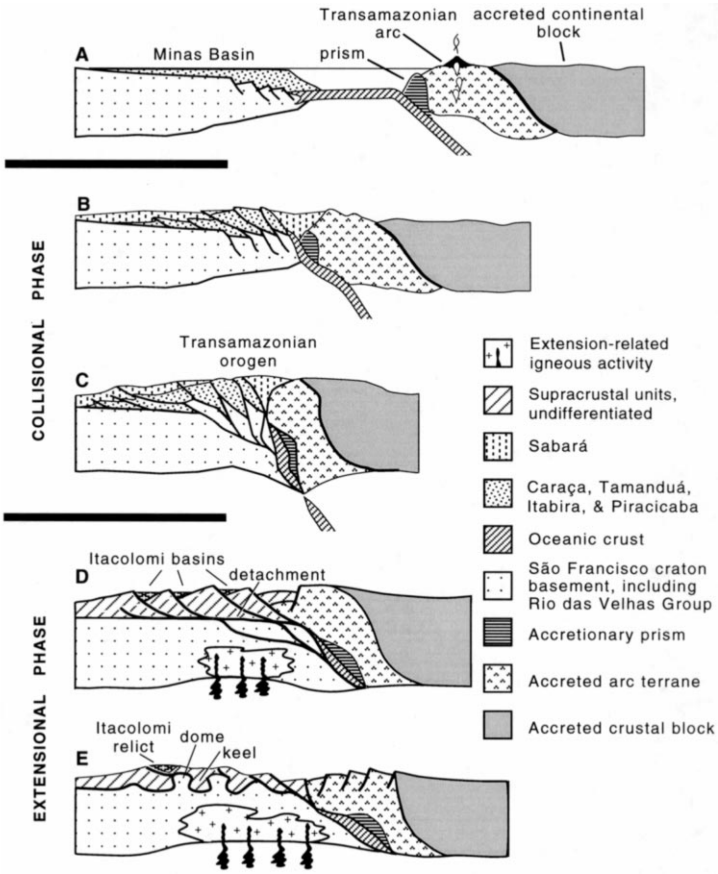


Fig. 14. Cross-sections illustrating a model for the tectonic evolution of the QF prior to and during the Transamazonian orogeny. (a) Pre-Transamazonian configuration. The Minas Supergroup represents the continental platform portion of a passive margin. (b) Initial collision with the Transamazonian arc and an accreted continental block. The Sabará, foreland basin deposit, spreads into the interior of the craton. (c) During the final stage of collision, the Sabará is also deformed. (d) Extensional collapse begins, with development of a Cordilleran metamorphic core complex-style detachment. (e) With continued extension and heating of the crust, the extending belt evolves into a dome-and-keel province. The dome-and-keel geometry effectively represents crustal-scale boudinage.

7.2.3. Transamazonian northwest-verging thrusting and folding (D1)

At ca 2.1 Ga, the QF region evolved into a northwest-verging foreland fold-thrust belt [Fig. 14(b and c)], resulting in the development of thrust-sense shear zones and regional-scale folds, as well as second-order parasitic folds. This event, however, did not generate a strong foliation. Development of the Transamazonian fold-thrust belt occurred soon after deposition of the 2.125 Ga Sabará Formation, a flysch sequence, that may represent turbidites derived from volcanic highlands to the southeast. Sabará strata spread northwest over an evolving foreland basin and onto the craton. Eventually, the fold-thrust belt propagated northwestward into its own foreland basin, as is typical of many fold-thrust belts. It is inferred that the hinterland of a collisional or convergent orogen lay to the southeast of the QF, in a region that has subsequently been completely overprinted by Brasiliano tectonism.

From information available in the QF, it is not possible to directly ascertain whether the contractional event represents collision of an offshore arc, or the formation of an Andean-type convergent margin. However, the apparent lack of large volumes of Transamazonian-age granitoids to the southeast of the QF, suggests that the event represented collision of an island arc. This interpretation is consistent with the model of the Transamazonian orogeny proposed by Figueiredo (1989) and Teixeira and Figueiredo (1991) for the northeast lobe of the São Francisco craton.

7.2.4. Transamazonian Orogenic collapse (DC)

At ca 2.095 Ga, regional extension [Fig. 14(d and e)] yielded a new dome-and-keel terrane (both reactivating and cross-cutting the Archean dome-and-keel terrane). Supracrustal rocks sank into new keels between basement domes. This event is attributed to the extensional collapse phase of the Transamazonian orogen [see Marshak et al. (1997a,b) for details of the model]. Regional extensional strain in the QF region associated with this event may be recorded by deposition of the Itacolomi Group in narrow basins.

7.2.5. Espinhaço and younger rifting (DE)

Formation of the Espinhaço rift basin to the northeast of the QF, along with intrusion diabase dikes in the QF, occurred at ca 1.75. This event created a broad ensialic basin on the eastern margin of the São Francisco craton. Renewed extension at ca 0.9–1.0 Ga succeeded in forming an oceanic basin east of the Espinhaço belt (Pedrosa Soares et al., 1992). Whether Espinhaço extension represents a continuation of Transamazonian orogenic collapse, or is a completely separate event, remains unclear. Similarly, it is not known whether some extensional structures and even dome reactivation in the QF occurred at the same time as Espinhaço rifting.

7.2.6. Brasiliano west-verging thrusting (D2)

In the model presented here, the concept of a north–south shortening event [the 'Uruaçuano' of Marshak and Alkmim (1989)] has been abandoned, for it is now clear that the east-trending synclines (e.g. the Dom Bosco syncline) of the QF, which Marshak and Alkmim (1989) attributed to the Uruaçuano are actually just keels resulting from dome emplacement, not compressional structures related to north–south shortening. The lack of a Uruaçuano event in the QF is compatible with recent geochronological studies. Thus, the only post-Transamazonian shortening event to create regional folds and associated fabrics in the QF is the Brasiliano event (0.7–0.45 Ga). This event created a west-verging thrust belt that reactivated and overprinted older structures in the QF, and represents one of the several collisional orogenies that led to the final assembly of Gondwana. It also resulted in reactivation of westerly-trending dome-border shear zones as strike-slip faults.

7.2.7. Tectonic significance of the Transamazonian event

According to Cordani et al. (1988), ca 35% of the volume of the Brazilian shield formed during the Paleoproterozoic. Many geochronological studies (Teixeira et al., 1989; Teixeira and Figueiredo, 1991; Teixeira and Silva, 1993; Barbosa, 1993; Ledru et al., 1994b) indicate that this tectonic activity was concentrated between 2.1 and 1.9 Ga, the Transamazonian event. Here, recognized manifestations of the Transamazonian event around the São Francisco craton are analyzed with and their relationship to the Transamazonian orogenic relict of the QF being discussed.

The Transamazonian orogeny in the northeastern lobe of the São Francisco craton resulted in the collision of two relatively large crustal blocks, the Gavião block on the west and the Gabon block (now exposed only in Africa) on the east, along with intervening crustal fragments (accreted terranes) known as the Jequié and Serrinha blocks, and a Paleoproterozoic magmatic arc [Fig. 15; Figueiredo (1989); Sabaté et al. (1990); Barbosa (1993); Martin et al. (1992); Marinho et al. (1993)]. Paleoproterozoic greenstone belts (the Contendas-Mirante, Itapecuru and Rio Capim belts), now displaying dome-and-keel architecture, developed in back-arc to arc environments adjacent to this volcanic arc (Schrank and Silva, 1993), and the Jacobina Group (Figueiredo, 1989; Teixeira and Figueiredo, 1991; Mascarenhas et al., 1992), a clastic wedge comparable in age and lithology to the Itacolomi Group, was deposited between 2.08 and 1.91 Ga in a molasse basin along the eastern edge of the Gavião block (Ledru et al., 1994a, 1996; Marinho et al., 1993). The orogeny

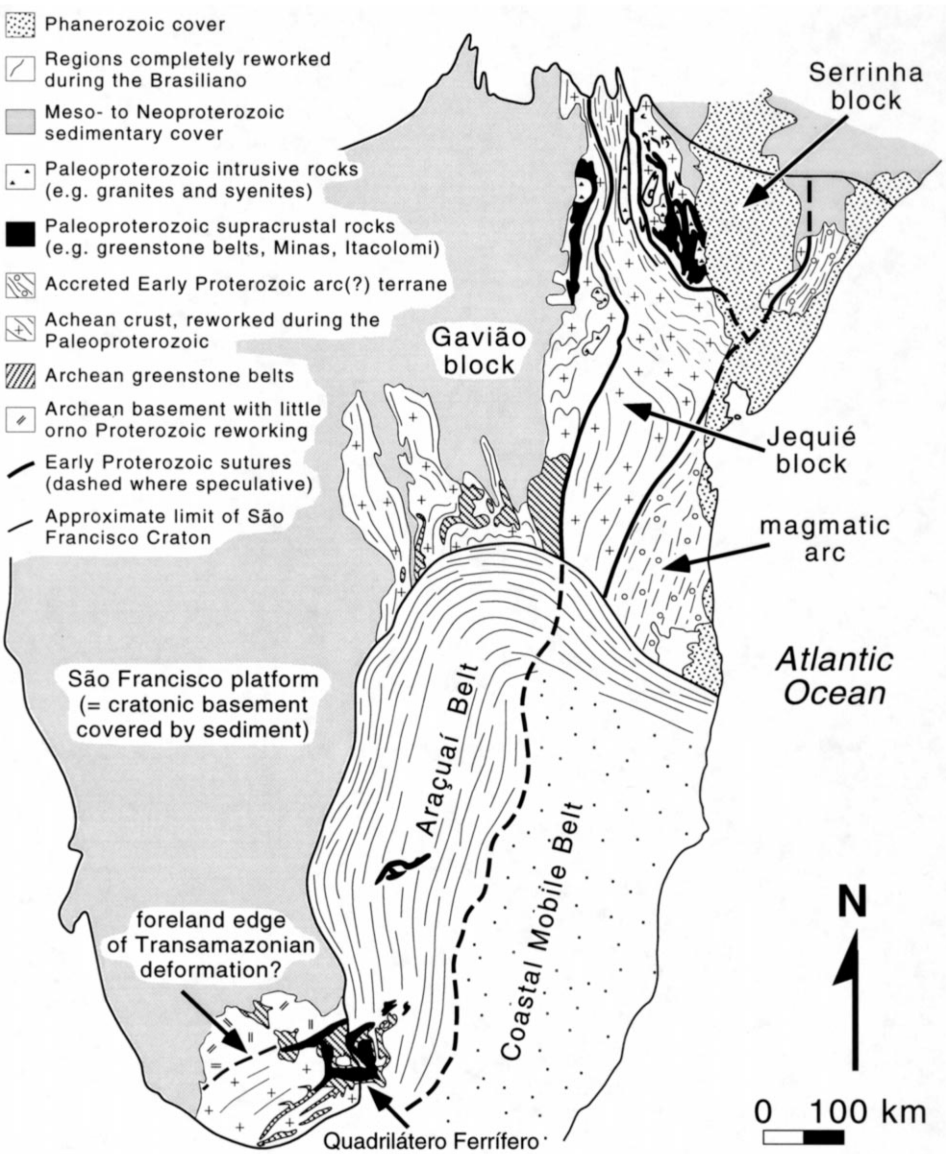


Fig. 15. Tectonic map of Transamazonian features in the São Francisco craton region, showing possible Transamazonian sutures and correlation of the Transamazonian belt in the QF with its equivalents in the northern lobe of the craton. See text for explanation. Geology of the northern lobe of the São Francisco craton is adapted from Inda and Barbosa (1978), Figueiredo (1989), Figueiredo and Barbosa (1993), Teixeira and Figueiredo (1991), Barbosa (1993), Ledru et al. (1993, 1994a,b, 1996).

also resulted in metamorphism up to granulite grade, as well as in voluminous plutonism and volcanism (Figueiredo, 1989; Teixeira and Figueiredo, 1991; Barbosa, 1993; Machado et al., 1993; Ledru et al., 1993, 1994a,b, 1996; Conceião et al., 1991). Transamazonian structural trends and sutures in this northeastern lobe strike north–south and generally verge to the west, but also display a strong sinistral strike-slip component of motion (Alves da Silva et al., 1993). These observations suggest that the principal shortening direction trended northwest during Transamazonian convergence.

Clearly, the Transamazonian orogeny of the northeastern lobe represented a complex episode of accretionary tectonics. Did this style of tectonism also affect the region to the south, a region which now comprises the Brasiliano-age Araçuaí and Coastal Mobile belts? Cordani et al. (1988) and Teixeira and Figueiredo (1991) imply that the answer is no, and thus that continental growth during the Transamazonian event south of the northeastern lobe of the São Francisco was relatively minor, for Paleoproterozoic units are sparse in this region, and tectonism appears to have occurred dominantly in an ensialic setting. As demonstrated, however, there is a record of Transamazonian fold-thrust belt tectonism in the southeastern São Francisco craton (i.e. to the west of the Coastal Mobile belt). We argue that this tectonism represents a relict of a Paleoproterozoic Wilson cycle, beginning with the formation of a continental margin, and concluding with the development of a northwest-verging frontal collisional orogen. One might expect, therefore, that the hinterland of this orogen and associated accreted terranes, lie in the region that is now the Brasiliano Coastal Mobile belt (Fig. 15), and thus that Brasiliano structures of the Coastal Mobile belt overprint crust initially attached to a continental mass by the Transamazonian assembly.

Is there evidence suggesting that Transamazonian crustal boundaries found in the northeastern lobe of the São Francisco craton track into the Coastal Mobile belt? We say 'yes', for the following reasons. First, geochronological studies carried out in this area by Söllner et al. (1991) and Figueiredo and Teixeira (1996) indicate that this region contains a record of the Transamazonian event. Second, Cunningham et al. (1996), who completed a structural transect across the region between the São Francisco craton and the Atlantic coast (i.e. across the Araçuaí and the Coastal Mobile belts), identified a possible candidate for a suture along the strike of the suture that defines the west edge of the Jequié block. This possible suture corresponds to strong linear Bouguer anomaly described in the region by Haralyi and Hasui (1982). Cunningham et al. (1996) have also found evidence for preserved Transamazonian granulites in the Coastal Mobile belt, but this proposal needs further testing. Third, recent radiometric dating suggests the occurrence of Transamazonian-age granitoids in the region southeast of the São Francisco craton [the Alto Maranhão pluton, dated at 2.08 Ga by Noce (1995)]. Further, the Coastal Mobile belt contains many orthogneisses which may have initiated as arc-related plutons.

Did even more terranes accrete to the southeast of the São Francisco craton during the Transamazonian event? So far, none have been documented, perhaps because of the severe overprint of Brasiliano tectonism in the region obscures candidates. Detailed geochronological studies using new technology may begin to see through the overprint and outline Transamazonian crustal blocks.

Fig. 16 provides a speculative reconstruction of crustal provinces along the eastern margin of the São Francisco orogeny subsequent to the Transamazonian orogeny. In this model, as also suggested by Cordani et al. (1988) and Teixeira and Figueiredo (1991), the QF lies in the foreland of the Transamazonian orogen. Magmatic arcs and accreted terranes lie to the east and southeast, together comprising the larger continent that then rifted during the Espinhaço event. South of the northeastern lobe, this region was largely reworked during the Brasiliano orogeny. Bertrand and Jardim de Sá (1990) and Ledru et al. (1994a,b) have proposed similar reconstructions.

8. Conclusions

The Transamazonian event of the QF, in the southeastern portion of the São Francisco craton, took place in two stages. First, northwest-verging contraction created a thin-skinned foreland fold-thrust belt. This belt thickened a sequence consisting of the Rio das Velhas Supergroup (an Archean greenstone belt) and the Minas Supergroup (a Paleoproterozoic platform sequence). The thrusting event, which occurred shortly after 2.125 Ga, created large northeast-

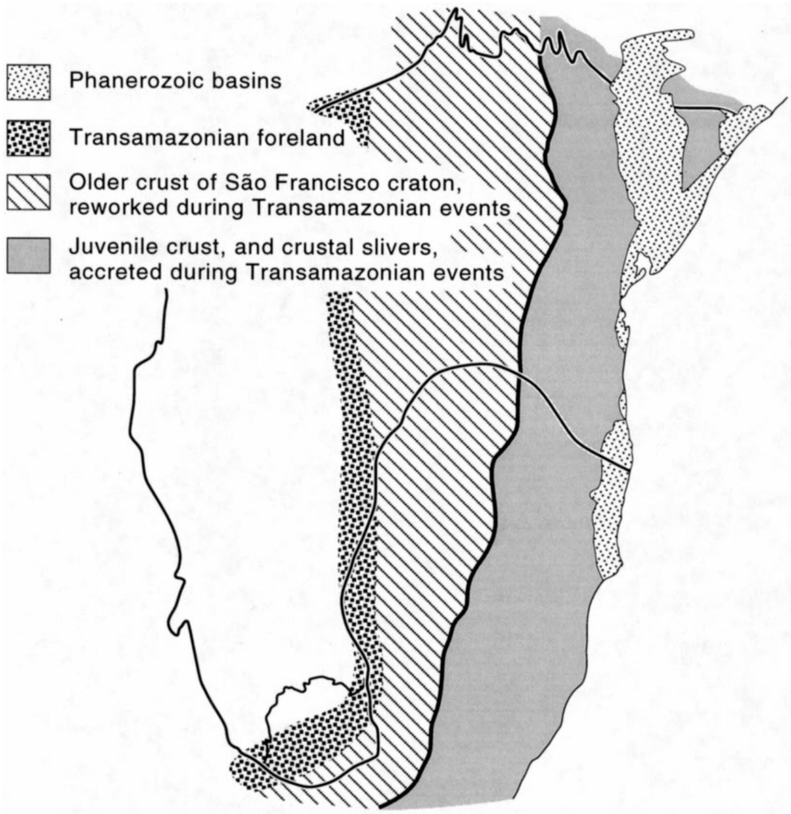


Fig. 16. Tentative reconstruction of principal belts in the Transamazonian orogen of the São Francisco craton region.

trending anticlines and synclines, along with parasitic folds and southeast-dipping shear zones. At ca 2.095 Ga, the thrust belt underwent orogenic collapse, resulting in development of a dome-and-keel province. As discussed by Marshak et al. (1997a), the dome-and-keel structure occurs in the same tectonic setting as the metamorphic core complexes of the U.S.A. Basin-and-Range, but are kinematically different, in that they are not simply warped detachment horizons. Transamazonian collapse may also have created narrow intermontane basins which filled with the Itacolomi Group sediments. Crustal extension, ultimately leading to formation of a new oceanic basin east of the São Francisco craton, did not begin until the end of the Paleoproterozoic (1.78 Ga) and may not have been totally successful until the end of the Mesoproterozoic (1.0–0.9 Ga). Effectively, the Transamazonian represents the record of the collision/collapse phase in a Paleoproterozoic Wilson-cycle tectonics, comparable to Phanerozoic collision/collapse events in terms of strain significance and tectonic setting, but different in terms of structural style. The style of Transamazonian structural features in the QF closely resemble the style of structures in other Paleoproterozoic orogens, such as the Penokean orogen along the southern edge of the Canadian Shield, in Michigan (Marshak et al., 1997a).

The collisional event leading to the Transamazonian fold-thrust belt of the QF may have involved accretion of an island arc and/or exotic terranes to the east and southeast margins of the São Francisco craton. Thus, accreted provinces and sutures exposed in the northeastern lobe of the São Francisco craton may trace into the Brasiliano Araçuaí and Coastal Mobile belts. Overall, therefore, the Transamazonian event represents the initial assembly of crustal fragments now comprising South America into a larger continental mass. This mass fragmented in the Mesoproterozoic and then ultimately reassembled during the Neoproterozoic to form Gondwana.

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