Dome emplacement and formation of kilometre-scale synclines in a granite–greenstone terrain (Quadrilátero Ferrífero, southeastern Brazil)

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Abstract

The Quadrilátero Ferrífero is a portion of the Brazilian Precambrian shield containing a granite–greenstone terrain characterized by granite–gneiss domes encircled by kilometre-scale synclines. Integration of porphyroblast-matrix microtextures, c-axis fabrics analysis and strain analysis with outcrop-scale structural relationships indicates that the main phase of domes and synclines evolution occurred during the westerly directed 0.8–0.6 Ga Pan-African-Brasiliano regional shortening. This tectonic event has produced the single pervasive foliation observed in the folded supracrustal sequences of the Quadrilátero Ferrífero. Dip-slip ductile shear zones developed at the dome–supracrustal interface are synchronous with dome evolution during the Pan-African-Brasiliano deformation, as indicated by contemporaneous growth of aureole porphyroblasts in the shear planes. These shear zones facilitated steeply directed downward flow of country rock material around the granite–gneiss domes. The marked density contrast between granite–gneiss material and the iron-rich supracrustals provided a gravitationally favourable environment for downward wallrock flow. Variations in shear zone kinematics away from the domes, combined with kilometer-scale viscous drag, contributed to produce kilometre-scale synclines in the supracrustal rocks constrained between upward moving domes. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Kilometre-scale synclines; Granite–greenstone terrain; Dome emplacement

1. Introduction

A number of kilometre-scale, generally sub-circular or elliptical granite–gneiss massifs display development of kilometre-scale synclines in their surrounding country rocks. Such structures include intrusive granite plutons (e.g. Brun et al., 1990; Veenhof and Stel, 1991), mantled gneissic
domes (e.g. Jelmsa et al., 1993), and core complex structures (e.g. Holm and Lux, 1996). The formation of kilometre-scale synclines is commonly interpreted to result from the emplacement of diapiric plutons. Integral to this interpretation is a model involving return flow of the material surrounding and overlying the diapir during its ascent and emplacement within the upper level of the crust. Such processes have been invoked to explain the geometry of the surrounding synclines, which are commonly interpreted to be a reflection of mass-transfer processes that operate to provide room for the intruding pluton (see reviews by Paterson and Fowler, 1993; Paterson et al., 1996). Consequently, formation of the synclines in these models is proposed to occur synchronously with emplacement and can be independent of any congruous regional deformation.

Alternatively, similar geometries comprising granitic plutons surrounded by synclines have also been proposed as having formed by subsequent deformation of country rocks around the plutons during contractional deformation (e.g. Davis, 1993). However, the axial surfaces and fold axes of the synclines in these cases commonly anastomose around the plutons and taper off in directions at a high angle to the maximum compression direction of regional deformation. Commonly, the plutons are considered to have acted as relatively rigid objects within the regional stress field, thereby causing strain accumulation against their margins that results in enhanced deformation in the vicinity of the contacts (e.g. Meneilly, 1983; Davis, 1993).

However, it is difficult to tell which model has operated in cases where the synclines do not define continuous encircling geometries around the plutons. Contention as to which model is most applicable has been prevalent recently in the literature, particularly for plutons that were considered to be classic examples of ballooning granitoids (e.g. Ramsay, 1989). Crucial to determining which model is most appropriate is an integration of the deformation history in aureole country rocks with that recognized regionally, as the porphyroblasts grown in the aureoles can preserve foliations that have been destroyed in the matrix during subsequent deformation.

The Quadrilátero Ferrífero is dominated by granite–gneiss domes with diameters in the order of a few to several tens of kilometres that are typically surrounded by kilometre-scale synclines. These structures are well exposed, including their contact with the granite–gneiss domes, and they show development of metamorphic minerals in the contact metamorphic aureoles. In this paper, microstructural and field-based information are used to interpret the deformation processes responsible for syncline development associated with dome emplacement, using as an example the dome-and-keel structure of the Quadrilátero Ferrífero. A model is then proposed for dome emplacement and syncline development that integrates field information with microstructural data from spatially oriented thin sections.

2. Geologic and structural setting

The Quadrilátero Ferrífero, one of the most important regions of the Brazilian Precambrian shield for its reserves of Fe, Mn and Au, is a granite–greenstone terrain (Schorscher, 1978) located in the southern portion of the São Francisco craton in southeastern Brazil (Fig. 1). It comprises a supracrustal sequence of Archaean metavolcanic rocks (the Rio das Velhas greenstone unit, 2.9–2.7 Ga) and Lower Palaeoproterozoic metasedimentary rocks (the Minas supergroup, 2.1–2.5 Ga), which have been regionally metamorphosed to greenschist to lower amphibolite facies (Herz, 1978) during the Transamazonian (2.1–2.0 Ga) and Pan–African–Brasiliano (0.8–0.6 Ga) orogenies. Available U–Pb zircon dating (Machado and Carneiro, 1992) indicates that the Rio das Velhas greenstone unit was deposited on an Archaean granitic–gneissic basement. Reactivation of this basement in subsequent orogenic events (cf. Marshak et al., 1997) has produced the dome-and-keel structure of the Quadrilátero Ferrífero.

The greenstone unit consists mainly of chlorite schists produced during low-grade metamorphism of basic and ultrabasic volcanic rocks. Locally, the primary igneous microstructure of these rocks is preserved in the form of spina...
Mica schists, carbonatic rocks, quartzites and banded iron formations (BIFs) also occur in variable proportions as a result of low-grade metamorphism of chemical and clastic sediments, as well as volcanic rocks of intermediate-acid composition. The overlying Palaeoproterozoic metasedimentary sequence, which is separated from the greenschist sequence by an erosional unconformity, is mainly composed of quartzites, mica schists, phyllites and carbonatic rocks. These lithologies are interpreted to represent infill of a platformal basin with a basal rift sequence overlain by marine sediments (Chemale et al., 1994). This sequence also includes a several hundred metres-thick unit of BIFs (Itabira Group) composed of quartzites with variable proportion of carbonates and Fe oxide (hematite and magnetite), which host the Fe reserves of the Quadrilátero Ferrífero.

The supracrustal sequences have been folded within interconnected kilometre-scale synclines and anticlines that surround the granitic domes of the Quadrilátero Ferrífero (Fig. 2). These domes generally have a complex internal structure (e.g. Hippertt, 1994a) and comprise a number of plutonic granitoids of granitic, granodioritic and trondjemitic composition, as well as gneisses and migmatites. Available U/Pb zircon dating indicates an Archaean age (2.7–3.2 Ga) of crystallization for these granitic rocks (e.g. Machado and Carneiro, 1992; Machado et al., 1992). However, the significance of these results is still uncertain as some of these ages were obtained in zircon cores, which may represent detrital zircons that do not necessarily reflect the crystallization age of the host granitoid (Hippertt, 1996). The contacts between domes and supracrustals are generally marked by low to medium metamorphic grade shear zones with variable kinematics.

Fig. 1. Location and simplified geologic map of the Quadrilátero Ferrífero in southeastern Brazil.
Fig. 2. Map showing the kilometer-scale synclinal-homoclinal keel and shear zones in the dome/supracrustals contacts. Locations of cross-sections shown in Figs. 3–5 are indicated. Stereograms show orientation of mylonitic foliation (Sm) and stretching lineation (L) in different domains of the contact shear zones (circled numbers).
The ascent and emplacement mechanism of the granitic domes of the Quadrilátero Ferrífero is a controversial topic that has already been the subject of discussion in the literature (Chemale et al., 1996; Hippertt, 1996). Classical views generally favor a model involving emplacement in the magmatic state (e.g. Herz, 1970), whereas emplacement of dome material in a predominantly plastic state was proposed by Hippertt (1994a). Other recent papers (e.g. Marshak et al., 1992), however, claim that solid state uplift of the domes occurred during a regional extensional tectonic event during the Transamazonian orogeny (2.1–2.0 Ga). Emplacement of the granitic–migmatitic domes into the relatively cooler supracrustal sequences has induced the development of porphyroblastic thermal aureoles around the domes (Marshak et al., 1992). These aureoles, firstly recognized and mapped by Herz (1978), are a crucial feature to elucidate the development of the dome-syncline architecture of the Quadrilátero Ferrífero. Metamorphic porphyroblasts within these aureoles contain preserved foliations which have enabled study of the interrelationships between deformation and granite emplacement via microstructural analysis of inclusion trails and porphyroblast-matrix relationships (discussed below).

Recent studies (e.g. Marshak et al., 1992; Marshak et al. 1997; Chemal et al., 1994; Alkmim and Marshak, 1998) have summarized the tectonic evolution of the Quadrilátero Ferrífero into two main tectonic cycles. The first event (2.1–2.0 Ga Transamazonian orogeny) has been interpreted as a period of predominant crustal extension, with some authors (e.g. Marshak et al., 1992) invoking synchronous dome emplacement and development of kilometre-scale synclines. The second major event, which has been attributed to the Pan-African-Brasiliano orogeny (0.8–0.6 Ga), was contractional and produced west-verging thrusts in the east margin of the Quadrilátero Ferrífero. Alternatively, Chauvet et al. (1994) interpreted all the main structures and metamorphic paragenesis of the Quadrilátero Ferrífero region as related to the Pan-African-Brasiliano deformation and metamorphism.

2.1. Kilometre-scale synclines

The axial traces of the kilometre-scale synclines anastomose around the granitic domes (Fig. 2), forming a discontinuous keel that is approximately 240 km in length and 20 km in width. In the eastern portion of the Quadrilátero, several segments of this keel appear to be isolated at the present erosional level, but were probably originally connected (Chemal et al., 1994), as suggested by their identical stratigraphic sequences.

Both the Archaean greenstone unit and the overlying Palaeoproterozoic metasedimentary sequences are folded within this keel, forming tight synclinoria or, locally, overturned homoclines. The geometry of the interconnected kilometre-scale synclines varies greatly from one point to another. For example, the Moeda Syncline, west of the Baçá complex, has its east limb progressively overturned towards the south where the Baçá complex lies on the overturned supracrustal sequences (Fig. 3). In contrast, the Dom Bosco syncline on the southern margin of the Baçá complex (Fig. 4), which was strongly affected by westward tectonic transport during the Pan-African-Brasiliano orogeny, has suffered superimposition of a strike-slip component. North of the Bonfim Complex, the surrounding keel is a truncated, overturned syncline that would be better described as a steeply dipping homocline (Fig. 5). In the following section, the structural/microstructural framework is described as observed in representative profiles across some sectors of the synclinal-homoclinal keel.

3. Structures and microstructures

3.1. Shear zones

Several tens of metres-thick, dip-slip shear zones, which generally dip at a high angle outward from the domes, typically occur at the contact between the domes and supracrustals in the western portion of the Quadrilátero, which was relatively more protected from the pervasive Pan-African-Brasiliano deformation. The sense of shear in these zones is consistent with a relative
upward movement of the domes. The downward movement of encompassing supracrustal material appears to have been steeply directed, rather than accommodated by strike-slip movements, as indicated by stretching lineations that generally pitch steeply (70–90°) in the shear planes (Fig. 2). Thus, these marginal shear zones are extensional (normal) where the syncline limbs are not overturned, but record a reverse sense of movement where the contact plane dips towards the domes (Fig. 3). Strike-slip and thrust components have also been detected at other contacts (e.g. around the Baçao and Caetés domes, respectively; Fig. 2). These variations in the kinematics of the granite–supracrustals contact have been previously interpreted either as post-emplacement tectonic effects (e.g. Chemale et al., 1994) or aureole effects during dome ascent (Hippertt, 1994a).

Metamorphic assemblages in these shear zones (e.g. muscovite–chlorite–epidote; muscovite–biotite–garnet) are compatible with deformation under greenschist/lower amphibolite facies conditions, suggesting that these shear zones were active during imposition of regional low to medium grade metamorphism that affected most of the Quadrilátero Ferrífero region during the 0.8–0.6 Ga Pan-African-Brasiliano orogeny (Chemale et al., 1994). The shear zones affect both supracrustals and granitic rocks and were the locus of intense fluid activity that induced volume loss via dissolution of quartz and carbonates and consequent phyllonitization (Hippertt, 1994b).
the granitic rocks, deformation was principally accommodated via crystal-plasticity and solution-transfer processes in quartz and retrograde softening reactions in feldspar (Hippertt, 1998). In the supracrustal rocks, crystal plasticity of carbonates and slip on basal planes of mica were also important, and accommodated much of the shearing component of the deformation (Davis, 1993, 1995).

Bedding-parallel ductile shear zones occur throughout the synclines. These shear zones vary in width from millimetres to a few decimetres in width, and generally occur at the interface between beds of contrasting composition and rheol-

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**Fig. 4.** S–C fabrics and XZ finite strain ellipses across the normal Dom Bosco syncline (see Fig. 2 for location). The southern limb was strongly affected by a later strike-slip deformation that partially obliterated the S–C fabrics and the strain ellipses related to the syncline development. Note shear sense reversal in the northern limb (see text).

**Fig. 5.** S–C fabrics and XZ finite strain ellipses across the Serra do Curral homocline (see Fig. 2 for location). Fold traces and cleavage traces are indicated.
ogy. The sense of shear in these interlayer shear zones is in most cases consistent with a downward movement of the older beds. Thus, the kinematics of this internal shear zones is opposite to the contact shear zones, which has commonly produced an abrupt reversal in sense of shear a few tens of metres away from the dome–supracrustals interface, as observed in the west margin of the Moeda Syncline (Fig. 3).

3.2. Cleavages, S–C fabrics, oblique fabrics and strain ellipses

There is a single pervasive cleavage developed in the supracrustal rocks all over the synclinal keel of the Quadrilátero Ferrífero. This cleavage is generally parallel to, or maintains a low angle obliquity to bedding (<15–20°), suggesting continued bedding-parallel shear during folding. In the hinge zones of the kilometre-scale synclines, however, the plane axial character of this cleavage is revealed in some outcrop scale folds.

S–C fabrics and oblique grain shape fabrics are also common in the folded supracrustal sequences. S–C fabrics of microscopic, hand specimen and outcrop scales are dominant in both the internal and marginal shear zones (Fig. 6), and possess unambiguous asymmetries consistent with the shear sense inferred from independent criteria such as shear bands and displacement of quartz veins. Oblique fabrics, generally defined by a discontinuous mica foliation or grain shape fabrics in quartz aggregates are widespread in domains between consecutive shear zones. The asymmetry of these shape fabrics provides reliable shear sense indicators (Simpson and Schmid, 1983). The shape fabrics show opposite geometries on different synclinal limbs with reversals in asymmetry occurring generally close to the syncline axis.

XZ finite strain ellipses were determined by the Fry (1979) method in oriented thin sections of porphyroclastic quartzose horizons with low degrees of recrystallization in all the main stratigraphic units across the profiles shown in Figs. 3–5. The ellipses generally show opposite obliquities in the different syncline limbs, consistent with the variation in the asymmetry of S–C fabrics. The most elongate finite strain ellipses were determined in the contact shear zones between domes and supracrustals. In addition, inverted syncline limbs, such as the east limb of the Moeda syncline, tend to record smaller degrees of finite strain than the normal limbs (Fig. 3).

3.3. Quartz c-axis fabrics

Quartz c-axis fabrics in sheared granitoids and supracrustals have been investigated with variable degrees of finite strain throughout the profile that crosscuts the Moeda syncline (Fig. 7). Both marginal and internal shear zones show predominant asymmetric single girdle c-axis fabrics, which typically form during progressive simple shear (Schmid and Casey, 1986). The asymmetry of this fabric, however, is not always coincident with that indicated by S–C fabrics, oblique fabrics and other independent criteria. This is a common problem in shear zones, which generally prevents utilization of c-axis fabrics as a reliable shear sense indicator (Hanmer and Passchier, 1991). The important inference, however, is that these single girdle fabrics reflect a predominant non-coaxial deformation in both the contact zone and between the sedimentary beds in the interior of the synclines. In contrast, the less deformed domains between pairs of consecutive shear zones, i.e. the interior of the sedimentary beds, show weaker asymmetric cross girdle fabrics (Fig. 8), which are currently interpreted to be a product of general strain regimes with components of both pure shear and simple shear (Lister and Hobbs, 1980). Occasionally, near-symmetric cross girdle fabrics have also formed in these domains, reflecting a local strain regime close to ideal pure shear.
Fig. 6.
These variations in $c$-axis fabrics are also detectable at the thin-section scale in metasediments that are finely laminated. In these rocks, domains that are only a few millimetres thick in the limiting zone between two sedimentary beds show an asymmetric single girdle fabric, while the quartzose matrix inside the beds shows a more symmetric fabric. These crystallographic fabrics are

![Diagram](image)

Fig. 7. Quartz $c$-axis fabrics determined across the overturned Moeda syncline. Numbers between parenthesis indicate number of grains measured in each diagram. The two larger diagrams represent overall $c$-axis fabrics for each syncline limb. Density contours are 1.25 and 2.75% per 1% area.

![Diagram](image)

Fig. 8. (a) Outcrop view of Moeda quartzites in the east limb of the Moeda syncline. The fractures correspond to millimetre-scale shear zones, that developed on relatively more micaceous horizons between the decimetric quartzose strata. The approximate location of the thin sections show in 'b' and 'c' are indicated. Width of view is 1.6 m. (b) Representative microstructure and corresponding $c$-axis fabric of a quartzose layer. An important component of coaxial deformation is reflected in the low asymmetry of the $c$-axis fabric skeleton. Strain is accommodated through pressure solution in grain boundaries that face the maximum shortening direction (Ps) plus opening of tension fractures (Te) at high angle to the maximum extension direction. Large dimension of photo is 1.2 mm. Density contours are 1.25 and 2.5% per 1% area. $N = 123$. (c) Microstructure and $c$-axis fabric of the sheared micaceous horizons. The $c$-axis fabric skeleton is an asymmetric single girdle indicative of non-coaxial deformation. Width of view is 550 µm. Density contours are 1.25, 2 and 3% per 1% area. $N = 200$. 
Fig. 8.
consistent with the overall distribution of shear zones and S–C fabrics within the synclines and reflect well-organized strain partitioning between interlayer and intralayer domains during syncline development (discussed below).

3.4. Folds

Numerous parasitic folds are represented on the limbs of the first-order folds that define the kilometre-scale synclines, with fold geometries evident down to the thin-section scale. Metasedimentary lithologies with different rheologic properties show contrasting folding patterns. The hematite-rich layers in the BIF unit show the most complex and tight fold geometries (Fig. 6d), whereas folds in the quartz-rich units are much more open and regular. Folds in the hematite-rich layers, and also in some phyllic horizons, are intrafolial and commonly grade into kinks (see below), their asymmetry being generally opposite to the bed- ing-parallel shear inferred from S–C fabrics and other criteria.

Outcrop scale, open to moderately tight folds showing a plane axial cleavage are also common in the hinge zones of the kilometre-scale synclines, principally in the more pelitic lithologies. The geometry and orientation of the majority of these folds, with fold axis generally subparallel to the syncline keel axis, suggest they are also smaller scale folds related to development of the kilometre-scale synclines. However, a minor proportion of tight folds with fold axis oblique or perpendicular to the syncline axis, suggest they are also smaller scale folds related to development of the kilometre-scale synclines. Porphyroblast growth represented by muscovite and, more locally, kyanite porphyroblasts are common throughout the metasedimentary sequences of Quadrilátero Ferrífero. In domains adjacent to the granitic domes, however, a metamorphic aureole, whose width varies between a few to several hundred metres, is generally present and is characterized by the presence of staurolite and biotite porphyroblasts. These aureoles reflect a higher temperature of metamorphism in domains adjacent to domes. In this section, porphyroblast textures observed in these aureoles are described.

Rocks from the aureole of the Bonfim and Belo Horizonte domes locally exhibit well-developed staurolite/biotite porphyroblast growth, particularly within pelitic horizons. Best exposures of
Fig. 9. (a) Kink band in a hematite-rich banded iron formation (BIF) layer (He). Note how the kink band does not propagate into adjacent quartzite layer (Q), indicating the intrafolial character of this structure. Width of view is 65 cm. (b) Overturned and intensely kinked BIF strata in the west end of the Serra do Curral homocline. Note relative downward movement of younger strata and the brecciated zone adjacent to it (see text). The main kink plane is also indicated (dotted line). (c) Complex pattern of kinks and fractures in BIF layers of the west limb of the Moeda Syncline. Note that some kink bands modify into breccia zones (Br). Small arrows indicate the relative movements on individual kink planes. Width of view is 1.6 m. (d) Detail of a brecciated zone in BIF layers. The white matrix is carbonate-rich. Width of view is 25 cm.

These rocks occur on the northern end of the Bonfim dome near the townships of Brumadinho and Ibirité (see Jordt-Evangelista et al., 1992; Marshall et al., 1992). Porphyroblasts at these localities are several millimetres across. A pervasive schistosity is evident in outcrop and is sub-parallel to lithological layering (bedding), which is commonly defined by porphyroblast-poor quartzose layers and porphyroblast-rich pelitic horizons. Elongate porphyroblasts, in particular biotite, commonly define a well-developed down-dip stretching lineation.

Spatially oriented thin sections from the aureole of the Bonfim dome commonly show preservation of bedding in staurolite and, more rarely, biotite porphyroblasts (Fig. 11a,b). Bedding preserved in porphyroblasts is continuous with bedding in the matrix, and evidence for porphyroblast growth during the main fabric-forming deformation event is clear. This deformation has produced the single
pervasive foliation evident in outcrop all over the Quadrilátero Ferrífero and defined by the shape-preferred orientation of mica and quartz grains. This foliation is generally subparallel to bedding but attains angles of approximately 10° to it in zones where the percentage of quartz dominates over that of biotite. Inclusion trails defined by quartz and opaques (ilmenite and magnetite) are continuous with the dominant matrix foliation, and porphyroblasts commonly preserve an angular relationship between bedding and this fabric that is greater than that in the matrix (Fig. 10b). This is suggestive of continued shearing in an orientation subparallel to bedding, which occurred after growth and preservation of original foliation bedding asymmetries.

A more local deformation is expressed as crenulations, which are locally differentiated and generally restricted to mica-rich pelitic horizons. The best development of crenulations in the pelitic horizons is largely due to the presence of porphyroblasts, which have acted as rigid objects against which accumulation of shortening strain has occurred. This strain intensification has produced local zones of phyllosilicate concentration on the porphyroblast margins (Fig. 10c).

Both staurolite and biotite porphyroblasts have overgrown the pervasive matrix foliation associ-

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**Fig. 10.** Frequency diagram showing orientation of kink planes relative to lithological layering in different sectors of the synclinal keel. The two sketches in the bottom illustrate the different relationships (positive and negative obliquities) between kink plane and bedding. Note that most kinks are 30–50° oblique, and in a orientation consistent with a downward movement of the upper strata (positive obliquity).
Fig. 11. Photomicrographs of aureole porphyroblasts from the Quadrilátero Ferrífero. (a) Biotite porphyroblast bordered by staurolite porphyroblasts, both of which include bedding as inclusion trails parallel to the long edge of the photo. Note that inclusion trails in the biotite display more pronounced curvature than those in staurolite, which is consistent with progressive low-medium grade metamorphism (i.e. biotite after staurolite) concurrent with progressive deformation. Sample is from northern end of Bonfim dome. Long edge of photo is 4.0 mm. (b) Staurolite porphyroblast that has grown along a phyllosilicate-rich layer defining bedding. Opaques and quartz inclusions define inclusion trails with an angular relationship with bedding, which are continuous with the matrix foliation. Sample is from northern end of Bonfim dome. Long edge of photo is 1.0 mm. (c) Intensification of cleavage on the margin of the staurolite porphyroblast where strain accumulation has occurred. Matrix comprised of muscovite and quartz. Sample is from northern end of Bonfim dome. Long edge of photo is 2.0 mm. (d) Garnet porphyroblast including a small biotite porphyroblast and displaying sigmoidal inclusion trails that are continuous with a weakly curved foliation in the matrix. Progressive deformation has caused strain accumulation against the porphyroblast margin resulting in phyllosilicate concentration. Matrix is comprised of muscovite and quartz. Sample is from location adjacent to contact of the Baçao complex. Long edge of photo is 2.0 mm. Polars partly crossed in all photos.

ated with the main deformation event. The greater degree of curvature preserved in biotite relative to that in staurolite porphyroblasts (e.g. Fig. 11a), combined with further intensification of matrix crenulations against the porphyroblast margins, suggests growth of the biotite during the main deformation but after staurolite. Relative overgrowth textures confirm these microstructural relationships.

Similar porphyroblast–matrix relationships occur between biotite and staurolite porphyroblasts from the aureole of the southern margin of the Baçao complex (e.g. Gomes, 1989). Samples collected from country rocks adjacent to this contact contain a pervasive crenulation cleavage and garnet porphyroblasts with well-developed sigmoidal inclusion trails and including biotite and staurolite (Fig. 11d). This relationship is consistent with growth of the garnets during the main deformation event but after staurolite and biotite, as expected to occur during progressive low to medium grade metamorphism.
4. Interpretations and discussion

4.1. Gravitational structures

The complex kink pattern that typically occurs in the BIF layers of the Quadrilátero Ferrífero has been interpreted by previous workers (e.g. Chemale et al., 1994) to result from a polydeformational tectonic evolution that could have occurred in this region. Kink distributions and geometries have been investigated in different sectors of the syncline keel (Fig. 10), and the conclusion is that their geometry is extremely variable and is not consistent with those present in other lithologies. The critical point in understanding the origin of these kinks is that they are more abundant in syncline sectors where the BIF layers are steeply dipping (> 60°). In addition, BIF layers in inverted syncline limbs typically host the most complex kink patterns. The intensity of kinking is also directly related to the local hematite/magnetite content in the individual BIF layers. These relationships, combined with the observation that the kinks are nearly always in an orientation that reflects slip downwards of the overlying younger strata over the older ones (even when the strata are inverted as in Fig. 9b), is herein interpreted as being indicative of gravitational collapse of denser BIF layers [density \(D\) varies between 3.4 and 4.8, depending on the Fe oxide content] relative to the adjacent, less dense lithologies (e.g. quartzite, phyllites, carbonatic rocks; with \(D < 2.9\)), as shown schematically in Fig. 12.

4.2. Kinematic framework during syncline development

The single pervasive foliation present in the folded supracrustal sequences is subparallel or has a low angle obliquity to bedding all over the synclinal-homoclinal keel. The opposite sense of shear in each syncline limb, as indicated by all meso- and microstructural shear sense indicators, and the pronounced strain partitioning between intralayer domains (with predominant coaxial deformation) and interlayer domains (with predominant simple shear), as indicated by \(c\)-axis patterns, are all consistent with a general kinematic framework with local and regional strain components. This is particularly clear in inverted synclines such as the Moeda syncline (Fig. 3). The existence of opposite senses of layer-parallel shear in different limbs is interpreted to reflect the operation of flexural slip/flow (Tanner, 1989) during syncline development at low/medium metamorphic grade conditions. This is corroborated by the fact that most of the slip is accommodated between the sedimentary strata (where a strong rheologic contrast occurs) via bedding parallel, interlayer shear. In contrast, the interior of the strata have been important for localizing the pure shear component (indicated by the existence of cross-girdle \(c\)-axis fabrics; Fig. 8), which reflects the bulk shortening direction of finite strain during the syncline closure. Evidence for brittle deformation of quartz (Fig. 8b) indicates that deformation occurred at temperatures below 300–350°C and/or at relatively fast strain rates (Passchier and Trouw, 1996), therefore preventing pervasive ductile flow in the supracrustal rocks. At these rheologic conditions, flexural slip/flow appears to be a suitable mechanism to accommodate folding (Tanner, 1989).

The overall kinematic pattern has been largely influenced by the regional tectonic transport from east to west, which has determined the progressive closure and ultimate inversion of some syncline sectors. Thus, two distinct situations have been produced, which are functions of the relative roles of local (derived from flexural slip/flow) and regional strain components (ultimately responsible for syncline closure and inversion). These relationships are sketched in Fig. 13. During the initial stages of syncline development (or in cases where no syncline limb inversion has occurred) with two ascending domes symmetrically disposed relative to the syncline axis, no difference in the magnitude and distribution of finite strain across the syncline is expected to occur (Fig. 13a). Geometries in syncline sectors without limb inversions are consistent with this (e.g. the western portion of the Dom Bosco syncline; Fig. 4). In contrast, a totally different situation should have been produced in inverted synclines (e.g. Serra do Curral and Moeda synclines), where the regional tectonic transport responsible by the limb inver-
sion induced a non-coaxial strain component that interacted in different ways in each limb with the non-coaxial component derived from flexural slip (Fig. 13b). Thus, in overturned limbs, the regional simple shear component derived from the dome movement that caused the syncline inversion opposed the simple shear derived from flexural slip, so that a smaller finite strain was produced in these domains. In contrast, in the normal, non-inverted limbs these two non-coaxial components were synthetic, leading to a higher finite strain in these domains. This scenario is consistent with all microstructural and kinematic information collected across the asymmetric Moeda syncline.

Fig. 12. Sketch illustrating kink development due to intrafolial gravitational collapse of denser hematite-rich layers during progressive syncline closure. More complex kink patterns and intense brecciation along layer boundaries are produced in locations where banded iron formation (BIF) layers are steeply dipping (see text).
Fig. 13. Suggested kinematic frameworks during evolution of the dome/syncline structure of the Quadrilátero Ferrifero in a compressive regional stress field. (a) Symmetric syncline closure associated with vertical dome ascent. There is a pronounced strain/deformation partitioning between intralayer domains, where coaxial deformation is predominant, and interlayer domains, where flexural slip induces opposite shears in each limb. Note that the shear sense in the contacts with domes is opposite to the flexural shear in the corresponding syncline limb. (b) Syncline closure with overturning. Rs is the regional shear component associated with the horizontal dome transport that induced the syncline inversion. Note that Rs is synthetic to flexural shear in the normal limb, but it is opposite to it in the overturned limb. As a consequence, finite strain produced in the overturned limb should be smaller than in the normal limb, as occurs in the overturned Moeda syncline.
4.3. Granite emplacement, syncline development and aureole structures

Explanation of processes involved in the development of the different types of dome–supracrustal structures such as intrusive plutons and core complexes invokes the necessity to consider mass transfer processes that must occur to make space available, as deformation in the structural aureoles only provide accommodation of 15–35% of the country rock material that had to be displaced to allow granitic plutons to be emplaced (Paterson and Fowler, 1993). As a consequence, mass transfer processes necessarily involved a downward movement of the country rock. Similarly, published studies of Archaean granite–greenstone terrains have invoked the process of diapirism, with upwelling of relatively less dense granitic material through surrounding greenstones (e.g. Anhaeusser, 1984; Hickman, 1984; Bouhallier et al., 1993; Jelmsa et al., 1993; Pons et al., 1995; Chardon et al., 1998). Although these examples involve emplacement of igneous plutons, the same space problems and mass transfer considerations must be taken into account during development of dome–supracrustal structures by solid-state processes during basement reactivation, such as occurs in the Quadrilátero Ferrífero dome-and-keel structure and in other mantled gneisses and core complexes (Marshak et al. 1997).

The pervasive development of shear zones at the dome–supracrustal contacts, which generally display steep down-dip lineations and dome-side-up senses of shear, is consistent with downward flow of supracrustal sequence. This would appear to be a mechanically viable process because no work need be done against gravity (e.g. Paterson and Miller, 1998) during downward transfer of the relatively more dense supracrustals. The gravitational collapse of the denser BIF layers and the solution transfer mechanisms in the marginal shear zones (e.g. Hippertt, 1994b), along with attenuation of syncline limbs closest to the domes, provide examples of such mass transfer processes in the Quadrilátero Ferrífero dome-syncline architecture.

Kilometre-scale synclines display close spatial relationships to the domes, and pronounced staurolite/biotite porphyroblast growth is spatially restricted to the margins of the domes. This suggests that dome formation is linked both to syncline development and porphyroblast growth. This contention is further supported by the steep down-dip preferred orientations of metamorphic minerals in the shear zones, which represent stretching lineations on the foliation that has accommodated the shearing strain.

Previous authors (e.g. Marshak and Alkmin, 1989; Chemale et al., 1994) have suggested that the earliest deformation in the Quadrilátero Ferrífero was represented by a Palaeoproterozoic extensional event that was also responsible for formation of the granite–gneiss domes and nucleation of the regional synclines. Alternatively, Chauvet et al. (1994) have attributed the development of these structures to the Pan-African-Brasiliano contractional deformation. The intensification of foliation development adjacent to porphyroblasts during the event in which they grew is also more suggestive of contractional deformation (e.g. Bell and Cuff, 1989; Vernon, 1989; Davis, 1993, 1995), the critical criterion for syntectonic growth being that inclusion trails are continuous with the matrix foliation (e.g. Johnson and Vernon, 1995). In addition, porphyroblast growth (staurolite, biotite, garnet) restricted to the margins of the domes and occurred during the main fabric-forming deformation expressed by pervasive foliation development in the country rock of both the Bação and Bonfim domes. In summary, the above observations are found to be consistent with interpretations such as those of Chauvet et al. (1994), who suggested that the main structures of the Quadrilátero Ferrífero are related to contractional deformation during the Pan-African-Brasiliano orogeny. Therefore, formation of the synclines was interpreted to have occurred synchronous with emplacement of the domes and staurolite/biotite porphyroblast growth in the aureoles during the Pan-African-Brasiliano orogeny.
4.4. Model for dome emplacement and syncline development

Given the above relationships and interpretations, a model for formation of the domes was suggested (Fig. 14) which is compatible with the geometry of the surrounding synclines, timing of porphyroblast growth in the aureoles, kinematics of the shear zones, and structures at all scales. Initiation of dome formation could have occurred early during the Palaeoproterozoic extensional event, with development of basement heterogeneities that acted as dome precursors as suggested by Marshak et al. (1992) and Chemale et al. (1994).

This extensional tectonics was synchronous with pronounced anatexis and granite formation (e.g. Machado et al., 1992) probably due to stress release and associated water access into the Archaean basement. However, there is no evidence that this Palaeoproterozoic event has produced any pervasive cleavage, there being a single pervasive foliation defined by muscovite–quartz–(chlorite) all over the Quadrilátero Ferrífero region which is most likely 0.8–0.6 Ga old (Chauvet et al., 1994). Subsequent to this earliest extensional deformation, there was a change in deformation regime to one of west-directed compression during the 0.8–0.6 Ga Pan-African-Brasiliano.

Fig. 14. Suggested model for the development of the dome/syncline architecture of the Quadrilátero Ferrífero. Stage 1 represents original basement/supracrustals structure prior to Proterozoic orogenies. Stage 2 illustrates the 2.1–2.0 Ga Transamazonian extensional tectonic event (cf. Marshak and Alkmim, 1989), when normal faults and dome/syncline precursors may have formed. Downward H₂O flow through normal faults favoured partial melting and granite magmatism in this period. Stage 3 represents the westerly-directed 0.8–0.6 Ga Pan-African-Brasiliano compression which is synchronous with low to medium grade regional metamorphism, basement reactivation and return flow in the supracrustal rocks. Shear zones are developed on dome–supracrustal contacts. The ascending 'hot' domes induce development of thermal aureoles characterized by staurolite/biotite porphyroblasts in the surrounding supracrustals (black objects). Thrusts are developed in the eastern portion of the Quadrilátero. Progressive shortening tightens the synclines and enhances the dome/syncline architecture. A moderate to steeply dipping foliation is produced in the supracrustal rocks.
orogeny, which accentuated the kilometre-scale basement heterogeneities and caused nucleation and amplification of synclinal structures in parallel with basement reactivation and dome ascent (Hippertt, 1994a). The enhanced development of cleavage synchronous with porphyroblast growth in the structural aureoles around the domes suggests that dome-induced deformation processes may have been important and operated in parallel with this regional compression. Alternatively, this can be explained as an effect of strain localization around the developing domes, which would have behaved as comparatively rigid objects relative to the country rocks in a compressive regional stress field.

Progressive shortening induced upward movement and amplification of domal structures through solid state deformation (Hippertt, 1994a), with mass transfer processes causing return flow of supracrustal material on the dome margins, thereby accentuating synclinal geometries. Similar processes have been invoked by Bloem et al. (1997) who suggested that kilometre-scale structures in the granite–greenstone terrain of the Bullfinch–Parker Dome area, Western Australia, occurred due to regional shortening broadly simultaneous with upward movement of granitoids by solid-state diapirism and/or ballooning plutonism.

Synclinal development in the Quadrilátero Ferrífero was enhanced on the eastern and western margins of the domes due to the concentration of strain resulting from WNW-directed shortening and synchronous downward movement of supracrustal rocks. Porphyroblast growth associated with dome development occurred early in the compressional stages of the 0.8–0.6 Ga Pan-African-Brasiliano deformation. Continued progressive deformation caused strain accumulation on porphyroblast margins, resulting in zones of enhanced phyllosilicate concentration and local cleavage differentiation. Shear zones marginal to the domes formed progressively during this deformation and aided movement of the supracrustal material around the flanks of the dome, developing syn-kinematic metamorphic assemblages compatible with the greenschist/lower amphibolite facies metamorphism responsible for porphyroblast growth in the structural aureoles. These shear zones were operative at this stage and accommodated downward flow of supracrustal material in tandem with relative upward movement of the domes, as indicated by shear zone kinematics and the preferred growth of metamorphic minerals along the shear planes. Progressive shortening would have enhanced cleavage and shear zone development, with further tightening of the synclines.

5. Conclusions

1. The main processes for dome emplacement and syncline formation were operative during de Pan-African-Brasiliano crustal contraction. Important processes were steeply directed supracrustal wall-rock flow around the domes, accommodated largely by synchronous development of high-strain shear zones coincident with the dome–supracrustal contacts and spaced bedding-parallel shear related to flexural slip/flow. The relative movements of supracrustals and dome material, and the changes in shear zone kinematics away from the domes, caused kilometre-scale variations in viscous drag of the country rocks, producing kilometre-scale synclines. Heat supplied by the ascending granite–gneiss domes, as they came from deeper (and heater) crustal levels due to basement reactivation (cf. Marshak et al., 1992), induced development of thermal metamorphic aureoles with staurolite and biotite porphyroblasts. Strain accumulation at the supracrustal–dome interface, the density contrast between supracrustals and granite–gneisses, and contractional deformation during westerly-directed Pan-African-Brasiliano shortening all aided in formation of the synclines, with the downward flow of denser supracrustals being a gravitationally favourable process.

2. The integration of microscale textural and kinematic relationships with meso- and kilometre-scale documentation of tectonites and large-scale geologic structures play a crucial role in the development of tectonic models. Syn-kinematic biotite and staurolite porphyroblasts in the contact metamorphic aureoles around the domes have revealed
the pervasive nature of the Pan-African Brasiliano foliation and providing structural timing criteria for emplacement of the domes, contact-parallel shear zones and kilometre-scale synclines.

3. Kilometre-scale structures such this domes-synclines architecture in the Quadrilátero Ferrífero are a good natural laboratory for studying how local and regional stress–strain components may interact and influence the resulting structural geometries. Kilometre-scale folding of very heterogeneous sedimentary sequences containing layers with a higher density than the surrounding lithologies (such as the BIFs in the syncline keel) may be an ideal situation for gravitational collapse of the denser lithologies, giving rise to complex structures and geometries that do not necessarily reflect the regional tectonic stress field. Such gravity-impelled processes contribute to the global mass transfer during syncline development in low to medium grade metamorphic ambients, but should exert a decreasing role downward in the crust where more cohesive deformation processes such as dislocation- and diffusion-assisted deformation gain importance.

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