Precambrian Research, 65 (1994) 25–54
Elsevier Science B.V., Amsterdam

The tectonic evolution of the Quadrilátero Ferrífero, Minas Gerais, Brazil

Farid Chemale Jr.[a], Carlos A. Rosière[b] and Issamu Endo[c]
[a]*Departamento de Geologia, Universidade do Vale do Rio dos Sinos, 93023-000 São Leopoldo, RS, Brazil*
[b]*Centro de Pesquisas M.T. da Costa/IGC, Universidade Federal de Minas Gerais, Pampulha, 31270-000 Belo Horizonte, MG, Brazil*
[c]*Departamento de Geologia, Universidade Federal de Ouro Preto, Morro do Cruzeiro, 35400-000 Ouro Preto, MG, Brazil*

Received February 3, 1992; revised version accepted March 24, 1993

ABSTRACT

The structural framework of the Quadrilátero Ferrífero is the result of two main deformational events. The first is an extensional event of Palaeoproterozoic age (between 2100 and 1700 Ma, the Transamazonian Event), which resulted in the formation of Archaean granite–gneiss domes and the nucleation of regional synclines in the overlying Rio das Velhas and Minas supergroups strata. Such regional synclines are continuous with each other and are bordered by structural granite–gneiss highs. At the contact between these units, ductile–brittle to ductile extensional shear zones are developed, representing the dislocation surfaces of Archaean blocks. This tectonism is probably related to the evolution of a metamorphic core complex, formed in the hinterland to the west of a Transamazonian collision zone, which structured the Paramirim Craton. The second event is compressive and associated with the closure of the Pan-African/Brasiliano proto-ocean (650–500 Ma), situated to the east of Quadrilátero Ferrífero (QF). During this event, a west-verging fold-and-thrust belt (FTB) developed, causing inversion, amplification, translation and rotation of the basinal synclines. The FTB affected mainly the eastern portion of QF and obliterated many of the tectonic features of the extensional event.

Introduction

The Quadrilátero Ferrífero/Iron Quadrangle is one of the most intensively investigated geological areas in Brazil. Many studies on its stratigraphy, structural geology, metallogeny, geochemistry and geochronology have been published as individual contributions. Only a few authors such as Dorr (1969), Ladeira and Viveiros (1984), and Marshak and Alkmim (1989), however, published interpretative papers on the geological/tectonic evolution of this complex and enigmatic area. Most of the published papers regarded the quadrangular shape of the area as the result of a multiple deformational evolution, with acute variations of the stress field during distinct periods of time.

The purpose of this work is to present a tectonic evolutionary model of the QF and surrounding terrains (Fig. 1), based on detailed structural analysis. Our model incorporated two main episodes: the first is one of extensional tectonics, affecting the supracrustal and granite–gneissic units of QF during the Transamazonian (Eburnean) Cycle of Palaeoproterozoic age; and the second involves collisional tectonics, affecting all earlier units and also the supracrustal rocks of the Espinhaço Meridional and São Francisco Basin during the Brasiliano (Pan-African) Cycle of Neoproterozoic age.

The data presented are the culmination of several structural-geologic studies carried out at different scales (1:25,000 to 1:1,000) dur-

Correspondence to: Farid Chemale Jr., Departamento de Geologia, Universidade do Vale do Rio dos Sinos, 93022-000 São Leopoldo, RS, Brazil.

SSDI 0301-9268(93)E0013-3

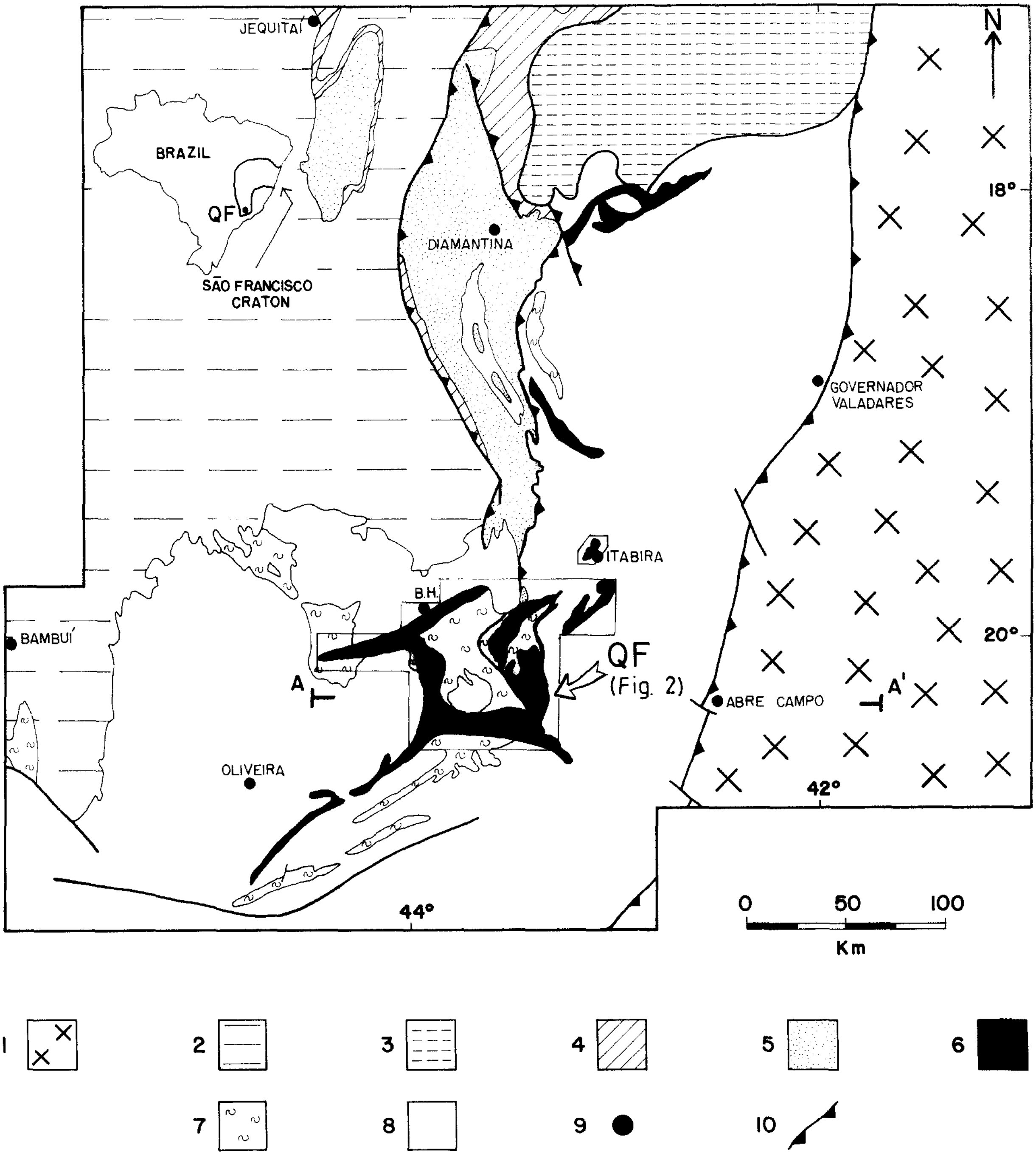


Fig. 1. Simplified geological map of the southern portion of the São Francisco Craton and northwestern Mantiqueira Belt (adapted from Inda et al., 1984; Mascarenhas et al., 1984). *1*=Mantiqueira Belt with Brasiliano Granites, *2*=Neoproterozoic Bambuí Group, *3*=Neoproterozoic Salinas Group; *4*=Neoproterozoic Macaúbas Group, *5*=Mesoproterozoic Espinhaço Supergroup, *6*=Palaeoproterozoic Minas Supergroup, *7*=Archaean Greenstone Belt, *8*=granite–gneiss terrains, *9*=city, *10*=thrusts.

ing the 80's by the authors, integrated with a compilation of other relevant publications. Over 40,000 linear and planar data have been used to construct the structural-geologic maps.

Geologic setting

The QF, which quadrangular shape is defined by the distribution of Palaeoproterozoic metasedimentary rocks (Minas Supergroup), is exposed in the southeastern part of the São Francisco Craton (SFC) (Almeida 1977, Fig. 1). This region is composed of (1) Archaean to Palaeoproterozoic granite–gneiss terrains, (2) Archaean greenstone belts, (3) Palaeoproterozoic supracrustal sequences, (4) Mesoproterozoic supracrustal sequences, and (5) Neoproterozoic sequences.

The supracrustal units of the QF surround and are surrounded by commonly dome-like granite–gneiss terrains (GGTs; Fig. 2a). The QF and adjacent regions consist mainly of GGTs, the Rio das Velhas greenstone belt (or Supergroup, RVSG), the Palaeoproterozoic Minas Supergroup (MSG), and Mesoproterozoic Espinhaço Supergroup (ESG) (Fig. 3). The GGTs are composed of polydeformed gneisses, metatonalites to metagranites, amphibolites, meta-ultramafic rocks and pegmatites formed during the Archaean and Palaeoproterozoic (Transamazonian) Eras (Cordani et al., 1980, 1989; Machado et al., 1989; Romano, 1990; Machado and Carneiro, 1992). The RVSG represents an Archaean greenstone belt in the QF region (Schorscher et al., 1982), and is divided into the Nova Lima and Maquiné Groups. A lower ultramafic unit, an intermediate felsic–mafic unit, and an upper chemical–clastic unit comprise the Nova Lima Group (Ladeira, 1980, 1985). These rocks are overlain by quartzites of the Maquiné Group (Dorr, 1969). Both GGTs and the RVSG constitute the basement of the QF (Cordani et al., 1980, 1989; Ladeira and Viveiros, 1984).

The overlying MSG comprises a basal clastic unit (Caraça Group), a middle clastic–chemical unit (Itabira Group), and an upper chemical–clastic unit (Piracicaba Group). The Itabira Group contains extensive banded iron formations of the Lake Superior type. In the Serra das Cambotas, NE of the QF (Fig. 2a), quartzites, metaconglomerates, and metabasic rocks of the Mesoproterozoic Espinhaço Supergroup (ESG) are exposed (Schorscher et al., 1982; Marshak and Alkmim, 1989). Palaeo- to Neoproterozoic deformed and non-deformed basic dykes occur in the GGT west of the QF (Teixeira, 1985).

Both Archaean and Palaeoproterozoic units display a complex metamorphic and deformational history (Dorr, 1969; Ladeira and Viveiros, 1984; Marshak and Alkmim, 1989). The GGTs show prograde metamorphic parageneses of amphibolite to granulite facies (Herz, 1978; Cordani et al., 1980; Jordt-Evangelista, 1984), and also of retrograde greenschist facies. The supracrustal rocks of the RVSG and MSG have been metamorphosed in the greenschist to lower amphibolite facies (Herz, 1978; Hoefs et al., 1982; Ladeira and Viveiros, 1984; Marshak and Alkmim, 1989), but locally they display only anchimetamorphism. Near the contact to intrusive granitic bodies, typical progressive contact metamorphic parageneses in the schists of the RVSG and of the MSG are developed (Herz, 1978; Jordt-Evangelista et al., 1992).

Structural framework of the Quadrilátero Ferrífero

The Quadrilátero Ferrífero is a tectonic feature which is the result of the superposition of structures developed during two main tectonic events, the first represented by a regional extensional event, and the second by a west-vergent compressional event.

Structures related to a regional extensional event

The first group of continuous structures comprises the megasynclines of the Serra do

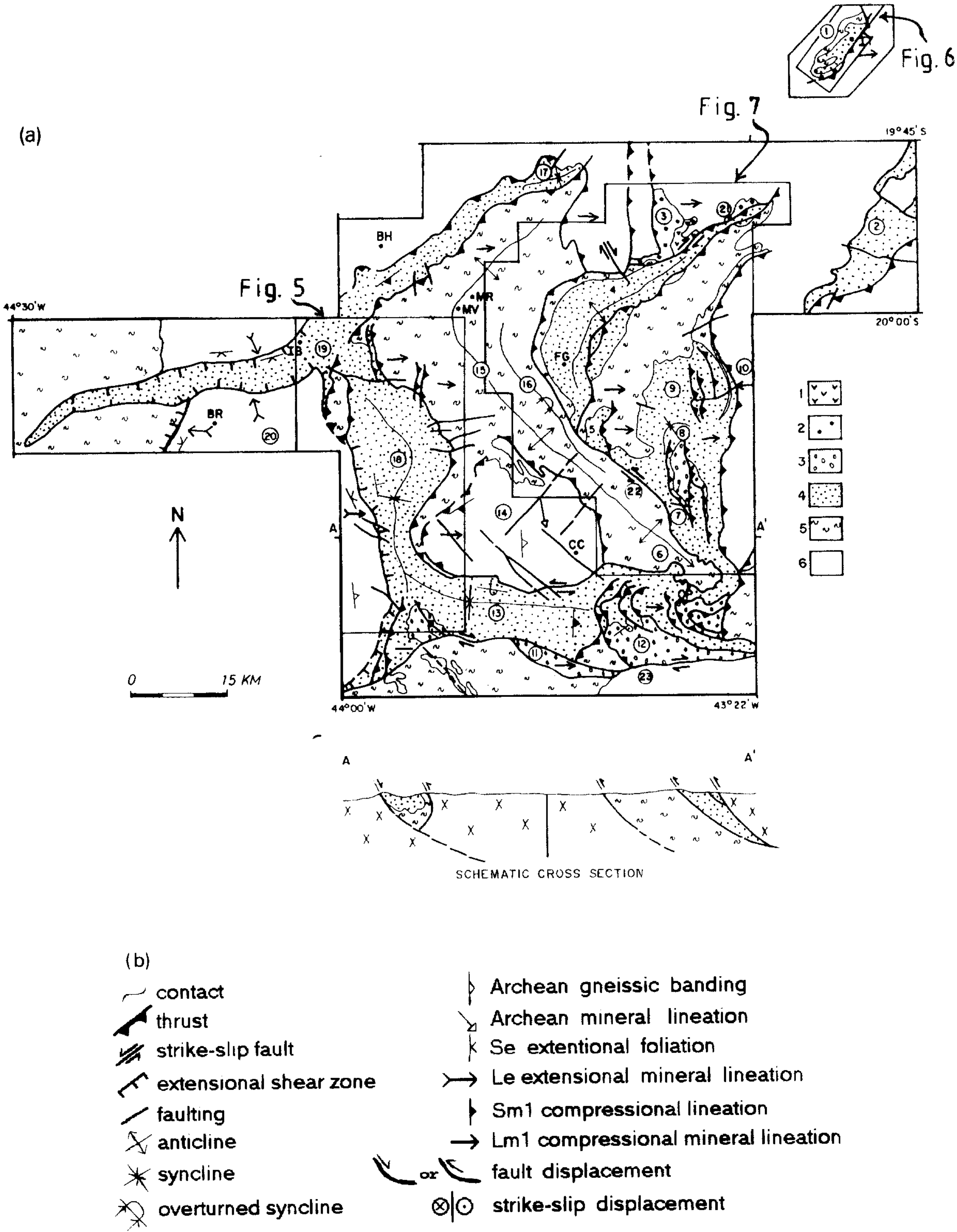


Fig. 6
Fig. 7
(a)
19°45' S
Fig. 5
44°30' W
BH
MR
MV
FG
TB
BR
CC
20°00' S
N
A
A'
0 15 KM
44°00' W
43°22' W
1
2
3
4
5
6
A
A'
SCHEMATIC CROSS SECTION
(b)
contact
thrust
strike-slip fault
extensional shear zone
faulting
anticline
syncline
overturned syncline
Archean gneissic banding
Archean mineral lineation
Se extentional foliation
Le extensional mineral lineation
Sm1 compressional lineation
Lm1 compressional mineral lineation
or
fault displacement
strike-slip displacement

Curral (NW–SE), Moeda (N–S), Dom Bosco (E–W), and Santa Rita (N–S), all bordered by structural basement highs (see Fig. 1). The synclines of Gandarela, João Monlevade and Itabira, all trending NE–SW, are presently isolated from the other megastructures, but were probably generated during the same event (Rosière et al., 1990).

The synclines contain relicts of a widespread platformal basin with a basal rift sequence overlain by shallow to deep water marine sediments deposited in an intracratonic environment. This basin was segmented during a regional extensional event. This extension is recorded by discontinuous, ductile–brittle to ductile extensional shear zones, affecting both supracrustal and infracrustal rocks. Kinematic shear sense criteria, such as asymmetric, sigma-type porphyroclasts and S-C structures attest to the eastward (at the western margin of the Moeda Syncline) and southeastward (at margins of segment I of the Serra do Curral) extensional movement of the shear zones. Associated uplift of the underlying crystalline basement and subsidence of the supracrustal strata, resulted in the formation of wide synclines and anticlines (Fig. 3, Table 1). The effects of the extensional tectonics are well preserved in the western portion of the QF, where the structures are autochthonous to para-autochthonous, and were less deformed during the younger collisional event than in the eastern portion. The regional vectorial field during the extensional event, that is registered by geometric and kinematic data from extensional shear zones and the shape of megastructures, is oriented WNW–ESE.

In ductile extensional shear zones, paragenesis of low greenschist facies (chlorite + quartz + sericite + opaques) occurs, suggesting that at least 10 to 12 km of the section have been eroded. In addition, there are contact aureoles in the pelitics units of the MSG and the RVSG around the Bonfim and Bação Complexes, from greenschist to amphibolite facies metamorphic conditions (Herz, 1978; Jordt-Evangelista et al., 1992), associated with the metamorphic complex uplift.

Structures related to a west-vergent compressional event

The second group of structures is related to a west-vergent thrusting event of Brasiliano age. Three phases of deformation have been recognized (D1–D3).

D1. This phase displays the most pervasive effects. Rocks were deformed under ductile conditions in the greenschist to amphibolite facies, with the development of shear zones related to thrusts, tear faults and conjugate transcurrent zones. In the shear zones, the most consistent features are a penetrative mylonitic foliation, Sm1, associated with variable plunging mineral stretching and mineral lineations, Lm1, trending east or, locally, southeast with variable plunges (Table 2).

D2. This phase developed under low greenschist facies conditions. It is associated with the nucleation of mesoscopic F2-folds and

Fig. 2. (a) Structural map of the Quadrilátero Ferrífero showing its main structures (modified after Dorr, 1969). *1* = metabasic rocks, *2* = Espinhaço Supergroup, *3* = Itacolomi Group, *4* = Minas Supergroup, *5* = Rio das Velhas Supergroup, *6* = granite–gneiss terrain. Cities and localities: *BH* = Belo Horizonte, *BR* = Brumadinho, *CC* = Congonhas do Campo, *FG* = Fazenda Gandarela, *IB* = Ibirité, *IT* = Itabira, *MR* = Mina Raposos, *MV* = Morro Velho, *OP* = Ouro Preto. Megastructures and geographic features: *1* = Itabira Synclinorium, *2* = João Monlevade Synclinorium, *3* = Serra das Cambotas, *4* = Gandarela Syncline, *5* = Ouro Fino Syncline, *6* = Mariana Anticline, *7* = Conta História Syncline, *8* = Alegria Syncline, *9* = Serra do Caraça, *10* = Fazendão Thrust Front, *11* = Serra de Ouro Branco, *12* = Serra de Itatiaia, *13* = Dom Bosco Syncline, *14* = Bação Complex, *15* = Rio das Velhas Uplift, *16* = Vargem do Lima Syncline, *17* = Piedade Syncline, *18* = Moeda Syncline, *19* = Serra do Curral, *20* = Bonfim Complex, *C* = Cambotas Fault, *E* = Engenho Fault, *F* = Fundão Fault. The Lm1 compressional mineral lineations (syntectonic kyanite needles, stretched pebbles and recrystallized minerals parallel to the kinematic vector) correspond to average value of populations over 100 measurements. (b) Structural legend to all figures.

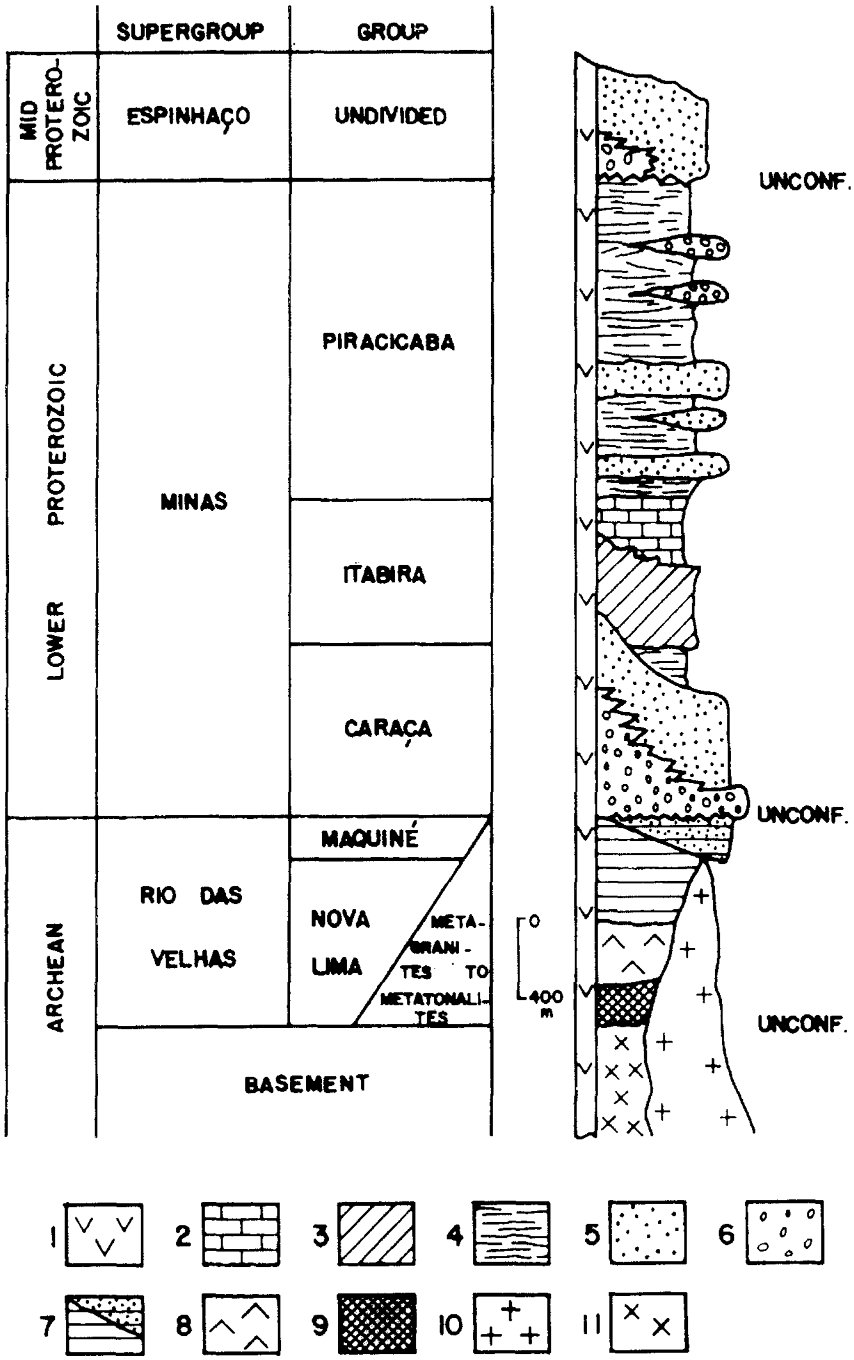


Fig. 3. Stratigraphic column of the Quadrilátero Ferrífero (modified after Marshak and Alkmim, 1989). *1* = metabasic rocks, *2* = marble, *3* = banded iron formation, *4* = metapelitic rocks, *5* = quartzite, *6* = metaconglomerate, *7* = chemical–clastic unit, *8* = felsic to mafic unit, *9* = ultramafic unit, *10* = metagranitic rocks, *11* = granite–gneissic basement rocks.

TABLE 1

Structural elements and styles related to the post-Minas depositional extensional tectonics

Megascopic structures: Synclines	Basement highs	Faulting
Dom Bosco Syncline (E–W?/horiz.)	Bação Complex and Santa Rita Complex	Dextral transcurrent SZ (Engenho Fault) and normal faulting (?)
Moeda Syncline (N–S/horiz.)	Bonfim and Baçao complexes	Normal faulting (?)
Serra do Curral Homocline	Caeté, Belo Horizonte and Bonfim complexes	Normal faulting (?)
Itabira Synclinorium (NE–SW/horiz.)	Belo Horizonte Complex	Inverted normal faulting (?)
Gandarela Syncline (NE–SW/horiz.)	Rio das Velhas Uplift and Caeté Complex	Inverted normal faulting (?)
Ouro Fino Syncline (NE–SW/syncline)	see above	see above
Santa Rita Syncline (N–S/horiz.)	Serra do Caraça	Inverted normal faulting (?)
Mesoscopic structures: Domain	Extensional SZ[a]	Lineation
Bonfim Complex (eastern border)	080-120/50-75	Down dip
Bonfim Complex (western border)	275-292/74	Down-dip and 335/35
Bonfim Complex (northern border)	000-030/70	40-60/40-60
Bonfim Complex (interior)	90/75-86	Down-dip
Belo Horizonte Complex	120/50-75	Down-dip
Moeda Syncline	080-120/50-75	Down-dip

[a]SZ = shear zone.

crenulations with E–W-trending axes, and the development of a spaced, subvertical axial planar cleavage, S2, and strike-slip faults (Table 3).

D3. This phase developed under metamorphic conditions similar to Phase 2, with the development of N–S-trending, mesoscopic F3-folds and crenulations, together with a subvertical spaced cleavage, S3, and N–S-trending, steep, reverse faults (Table 3).

Structural analysis

In order to simplify the understanding of the tectonics of the QF, the area has been subdivided in domains according to the trend of the main megascopic structures (Fig. 2a). These domains are: (1) the Dom Bosco Syncline and Engenho Fault System; (2) the Moeda Syncline; (3) the Bonfim and Bação complexes; (4) the Serra do Curral; (5) the Itabira Synclinorium; (6) the Fundão–Cambotas Thrust System.

The structural analysis is based on geometric and kinematic criteria, and considers the influence of two factors as critical in the development of the complex present day geometry, viz. (1) the basement relief, with several structural highs acting as rigid buttresses, obstructing and "channelling" the overthrust supracrustal sheets, and (2) the current erosional level, allowing the observation of such "low level" structures.

The structural data for each of the domains are summarized in Tables 1, 2 and 3 and graphically represented in Figs. 2a and 4 for constant reference to 10. The structural legend which is common to all figures is given in Fig. 2b

Each domain is described below, in terms of its broad geometry, structural imprint and kinematic history. In order to simplify descriptions, planar and linear tectonic features associated with compressional events are separated into D1 (Sm1, S1, Lm1, F1, b1), D2 (S2, Lm2, F2, b2), and D3 (S3, Lm3, F3, b3).

The Dom Bosco Syncline and the Engenho Fault System

The *Dom Bosco Syncline* is defined by bedding surfaces folded along an E–W-trending axis (Figs. 4 and 5, Table 1). It is structurally

TABLE 2

Structural elements and styles related to the compressional event (after extensional tectonics)—Phase 1

Domain	D1 Phase					
	faults	folds	B1	SM1	LM1	metamorphism
Dom Bosco Syncline and Engenho Fault (1)	Arcuate thrusts (N–S), strike-slip SZ (E–W, 60-240 to 120-300)	B and A-folds tight, isoclinal sheath folds	066/45 to 120/25 rotation towards E in SZ	90/10-40 (frontal thrusts)	Down-dip[a]	Low greenschist (W) to low amphibolite (E)
Moeda Syncline (2)	Thrust (N–S), S-S S-Z, bedding shears	same as above	045/20 to 092/60	87-90/ 60-90	Down-dip	Mostly low greenschist
Baçao Complex	Reverse and S-S faults	Upwarping of metasediments. Steep beds and some overturned	Variable	Around the complex	N, S and E= 90-130/15-50 W=220-270/ 70-90	Retrograde metamorphism of old assemblage (amphib. to greens.)
Serra do Curral seg. I (trend 070)	Reverse N–S/60-80 S-S faults NE–SW/50	Open cylindric high amplitude folds	NE–SW	In some shear zones	90/subhz	Regional low grade
Serra do Curral seg. II (trend 045) (3)	Thrusts 130/30 and S-S SZ (E–W, 60-240, to 120-310)	Inverse folds tight to isoclinal sheath folds	Rotation of axis toward E in high strain regions 045 to 080/10-30	Axial planar position 120/30	90/10[b]	Very low to low greenschist
Itabira Synclinorium (4) (40/20)	Thrusts with eastward rotation of megafold axes	Open to isoclinal sheath folds	045-110/1-53	114-132/ 29-33	40-90/ 5-52	Low greenschist
Caeté Complex (5)	Thrusts (N–S, NE–SW) with quartzite slivers and S-S SZ	Tight to isoclinal	Variable	90/18-30 and 120/50	78-102/ 15-48	Greenschist (SW) to low amphibolite (NE)

Serra das Cambotas (5)	Frontal (N–S) and oblique (NE–SW) thrusts	B- and A-folds open to isoclinal	Variable	90-144/18-30	87-90/9-27 rotated = 120-30/50	Greenschist
Gandarela Syncline (6)	Lateral to frontal ramps of NE–SW-trending thrusts and S-S SZ	Open to tight isoclinal overturned	Variable axis 18-93/12-51	90-108/40-60	75-119/10-52	Greenschist with kyanite
Ouro Fino (7)	Frontal to lateral	Open to isoclinal	90-117/36-54	50-96/50-53	66-93/45-49	Greenschist with kyanite
Conta Historia Syncline (8)	Oblique ramps	Tight to isoclinal,	117/27[b]	SM1//S1 20/42	99/18[b]	Greenschist with kyanite
Alegria Syncline (9)	Folded and rotated thrust surface	Megascopic horseshoe-shaped syncline (160/30-50)	Rotation towards E of mesofolds 045/25 to 099/30	12/75	93/42[b]	Greenschist with kyanite
Fazendao Thrust (10)	Frontal thrust, S-S faults (E–W, 60-240, 120-300)	A-folds, open to isoclinal sheath folds	84/45[b]	94/52	84/48[b]	Greenschist with kyanite

[a]Average value corresponds to 107/20.
[b]Average value of populations over 100 measurements.
Average value for all L1 mineral lineation (mostly parallel to the kinematic vector) is around 90.
SZ = shear zone, S-S SZ = strike-slip SZ, HZ = horizontal, VT = vertical.
(1) Structural data after Gloeckner (1981), Alkmim (1985) and this work. (2) Structural data after Rosière (1981), Evangelista (1984) and this work. (3) Structural data after Hackspacher (1979). (4) Structural data after Chemale et al. (1987). (5) Structural data after Croco-Rodrigues et al. (1989). (6) Structural data after Endo and Chemale (1991b). (7) Structural data after Fonseca (1990). (8) Structural data after Endo (1988). (9) Structural data after Januzzi and Alkmim (1989) and Chemale and Endo (1990). (10) Structural data after Silva and Gibotti (1989) and Castro Alves (1991).

TABLE 3

Structural elements and styles related to the compressional event (after extensional tectonics)—Phases 2 and 3

	D2 Phase[a]				D3 Phase[a]			
Domain	faults	folds	B2//LCR2	S2	faults	folds	B3//LCR3	S3
Dom Bosco Syncline and Engenho Fault (1)	Transcurrents, sinistral reactivation of Engenho F.	Open to tight, crenul.	121/ 11	180/ 75	Reverse brittle faults	Open kink crenul.	NS/ subhz	90/ or 270/ subvt
Moeda Syncline (2)	Transcurrents	Open to tight, crenul.	E–W		Reverse faults	Open kink crenul.	NS/ subhz	90/ vt to subvt
Serra do Cur- ral seg. I	No main structure is recognized							
Serra do Curral seg. II (3)		Open to tight, crenul.	E–W		Reverse brittle faults	Open kink crenul.	N–S/ 0-30	90/ subvt
Itabira Synclinorium (4)	Transcurrents	Open to tight, crenul.	35-110/ 1-53	170/ 50-85	Reverse brittle faults	Open kink crenul.	NS/ subhz	291/ 70
Serra das Cambotas (5)	Transcurrents E–W, NE–SW NW–SE	Open to tight crenul.	117/ 10-17	135/ 45	Reverse brittle faults	Open kink	NS/ subhz	162/ 78
Gandarela Syncline (6)	same as above	Open crenul.	E–W and 80-160/ 20-40	180/ 80/90	Reverse brittle faults	Open kink crenul.	NS/ 05	80-90/ 75-90
Ouro Fino Syncline (7)	Reactivation of thrusts and strike-slip	Open to tight crenul.	096/54	357/ VT to subvt	Reverse faults	Kink crenul.	003/ 06	273/ 73-84
Conta Historia Syncline (8)		Assym. open	108/ 36	18/84		Kink crenul.	351/ 56	284/ 48
Alegria Syncline (9)		Open crenul.	120/30	174/54 120/36	Reverse faults	Open kink	174/ 42	81/ 75
Fazendao Thrust (10)	Transcurrents E–W, NE–SW NW–SE	Open to tight crenul.	E–W	15/75 and 357/87	Reverse faults	Open kink crenul.	NS/ 15-17	90 or 270/ subvt

[a]Metamorphic assemblage is represented by ± chlorite ± sericite ± quartz ± opaques
For (1) to (10) see Table 2.

continuous with the Moeda Syncline at its western extremity. The southern limb of the syncline is intensely disrupted, while the northern limb is less deformed. Primary sedimentary structures are present, locally being obliterated by a mylonitic foliation in shear zones (Fig. 4).

This synclinal megastructure is cut by an arcuate thrust system, with a N–S-trending frontal ramp along its axial extension from the

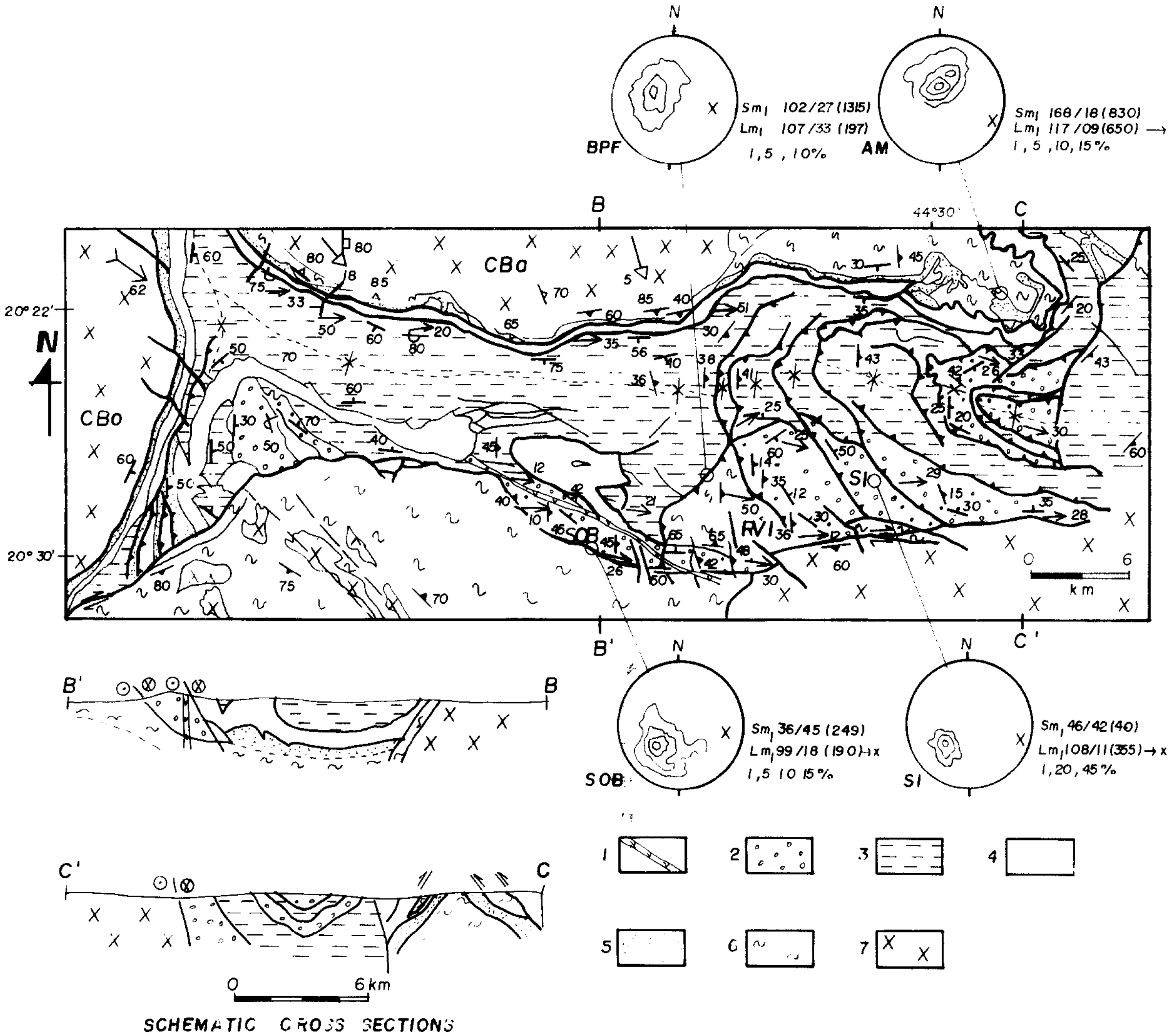


Fig. 4. Geologic-structural map of the Dom Bosco Syncline (modified after Dorr, 1969) with schematic cross-section. *1*=basic dyke, *2*=Itacolomi Group, *3*=Piracicaba Group, *4*=Itabira Group, *5*=Caraça Group, *6*=RVSG, *7*=GGT. *CBa*=Bação Complex, *CBo*=Bonfim Complex, *SI*=Serra de Itatiaia, *SOB*=Serra de Ouro Branco. Stereograms with Sm1 foliation (contour lines) and Lm1 mineral lineation. Structural data of *BPF* (Bico de Pedra Fault) and *MA* (Mariana Anticline), this work; *SOB* after Alkmim (1985); *SI* after Gloeckner (1981).

Serra do Itacolomi to the Serra do Mascate (Fig. 4). All thrusts have characteristic flat and ramp geometry. Tear faults connect individual fault planes. The deformational event associated with the thrusts produced three structural assemblages: one under ductile conditions (Table 2), and the other two respectively under brittle–ductile and ductile–brittle conditions (Table 3).

The first assemblage of structures is represented by ductile shear zones, whose kinematic indicators such as S-C structures, porphyroclasts, and the geometry of the thrust planes record a westward tectonic transport direction. In the vicinity of the limbs of the Dom Bosco Syncline and most notably at the northern limb, the thrust planes inflect progressively to the east, while the mineral and

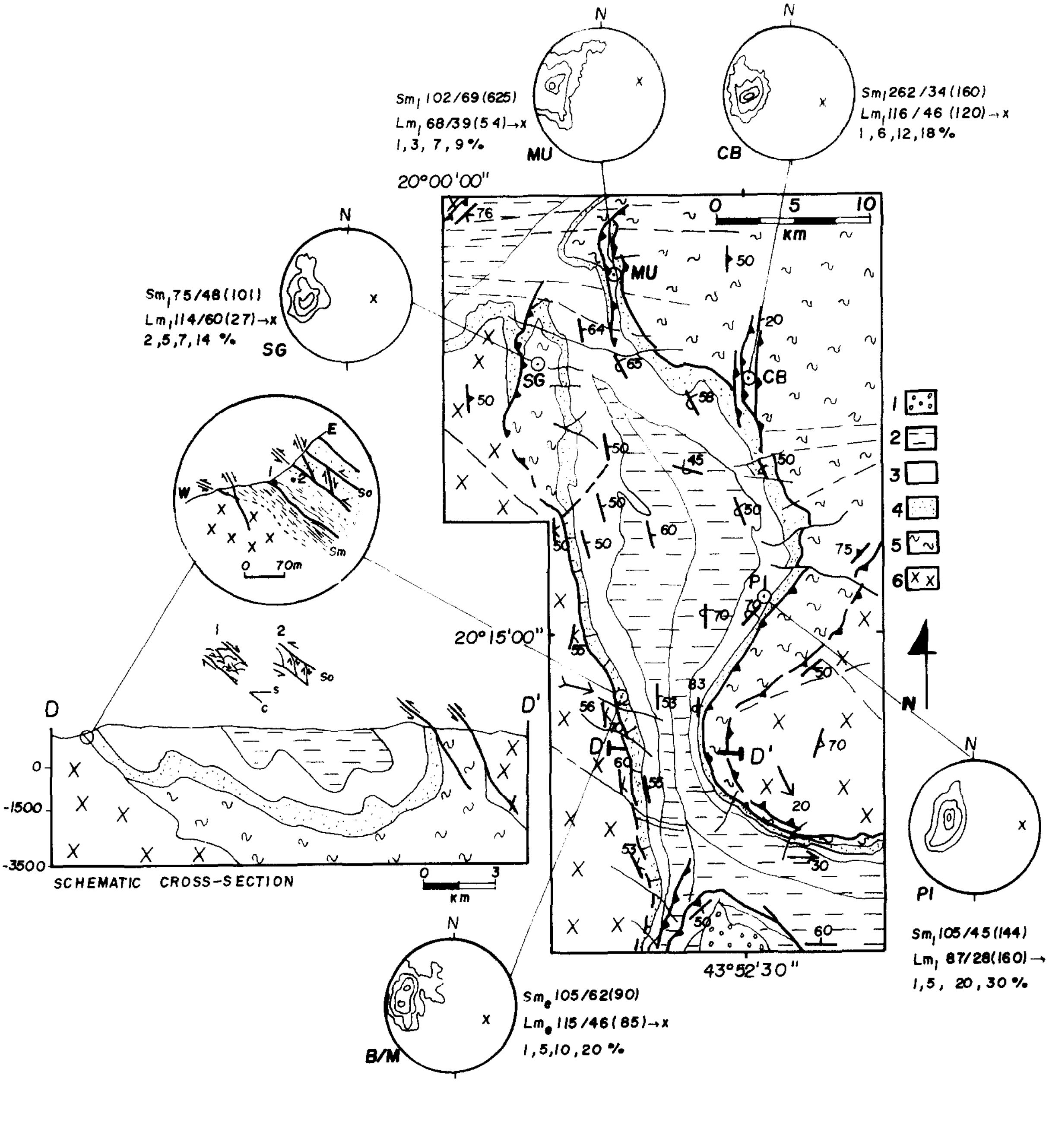


Fig. 5. Geologic-structural map of the Moeda Syncline (modified after Dorr, 1969). *1* = Itacolomi Group, *2* = Piracicaba Group, *3* = Itabira Goup, *4* = Caraça Group, *5* = RVSG, *6* = GGT. Schematic E–W cross-section looking north across the Moeda Syncline and Bonfim and Baçao complexes, with inset of the Moeda Syncline western limb and detail of its internal structures (*1* and *2*). Stereograms with Sm1 foliation (contour lines) and Lm1 mineral lineation (cross). Structural data of *CB* (Córrego dos Boiadeiros) this work, *MU* (Mutuca Mine) after Evangelista (1984), *SG* (Serra da Gaivota) after Noce and Ladeira (1989), *B/M* (contact Bonfim Complex/Moeda Syncline) this work, *PI* (Pico do Itabirito) after Rosière (1981).

stretching lineation remain consistently shallow plunging (between sections lines *A–A'* and *B–B'*, Fig. 4). In the intensely deformed parts of the shear zones, sheath folds and intrafolial F1 structures with axes parallel to the stretching lineation (a-type folds) are common. With decreasing strain, the folds are west-vergent and display a tight to isoclinal profile with their axes oblique to the tectonic transport direction (oblique folds).

F2 buckle-folds both in micro- and megascopic scale superpose these structures. They are most commonly preserved in the pelitic compositional bands where they deform the earlier S1 and Sm1 foliations.

D3 comprises mesoscopic F3-folds and crenulations that refold S2.

The *Engenho Fault* was defined by Guild (1957) as a strike-slip fault. It strikes essentially E–W (Fig. 2a) along an extension of approximately 70 km from the Serra do Itacolomi at the east to the town of Bom Sucesso at the west, where the fault deviates to the southwest (Fig. 4). The Engenho Fault has a transcurrent, right-lateral displacement, resulting from the translative dislocation of tectonic slices of the RVSG, the gneissic Basement Complex, and the quartzites of the Itacolomi Group, that constitute the Serra do Ouro Branco (Fig. 4). The displacement along the strike can be estimated to be at least 25 km, and probably occurred during the extensional event. A superimposed left-lateral movement and the tightening and amplification of the Dom Bosco Syncline, resulting of the younger west-verging belt, indicate that this fault might be at least of Palaeoproterozoic age, and that significant reactivation occurred during the Brasiliano Event.

The Moeda Syncline

Similarly to the Dom Bosco Syncline, this megastructure was nucleated very early during the tectonic history of the QF (Table 1). It is a N–S-trending syncline (Fig. 5), tightened and deformed around the Bação Dome, continuous to the south with the Dom Bosco Syncline and truncated by the Engenho Fault. To the north, the syncline is continuous with the structure of the Serra do Curral where it is attenuated by younger thrusts (Fig. 5).

Bedding and other sedimentary structures are well preserved in the syncline. Late ductile shear zones, best-developed on the eastern limb of the Moeda Syncline, truncate all lithologies of the supracrustal sequences and the underlying talc-schists and serpentinites of the Córrego dos Boiadeiros Ultramafic–Mafic Complex, or alternatively being parallel to subfjparallel to the bedding of the MSG strata, as in the Serra do Itabirito.

Several strike-slip faults cut both limbs of the Moeda Syncline. N–S-trending D3 structures similar to those described in the Dom Bosco Syncline described above, are superimposed over all pre-existing structures.

Bonfim and Bação complexes

The Bonfim Complex comprises multiply deformed gneisses, amphibolites, meta-ultramafic rocks, pegmatites, migmatites, Archaean foliated granites (Machado and Carneiro, 1993), and N–S- and NW–SE-trending mafic dykes. The gneissic layering is sub-vertical and trends N–S, displaying a very low pitch mineral lineation. These fabrics are truncated by a 2703^{+20}_{-24} Ma granitic intrusion which itself is affected by all later deformation events of the QF (Machado and Carneiro, 1992).

East-dipping ductile–brittle to ductile extensional shear zones (Table 1) deform rocks of the Bonfim Complex, the surrounding units of the RVSG, and locally the basal formations of the MSG at the western limb of the Moeda Syncline (see detail in Fig. 5) (J. Hippert, pers. commun., 1990; Rosière et al., 1990). These shear zones predate N–S thrust faults which affect all rocks of the QF. They are very discrete and east-dipping, with the development of a foliation associated with greenschist facies metamorphism and a stretching lineation defined by oriented feldspar porphyroclasts. Extensional and compressional shear zones alternate and the older extensional structures are locally entirely obliterated by later compressive features (Fig. 5, inset).

The Bacão Complex is a domal structure with similar characteristics as the Bonfim Complex. This complex displays a bordering mylonitic foliation which dips away from its centre, with a compressional character. Intern to the complex, compressive shear zones, the most common ones, are also described. We assume that the bordering foliation as well as internal faulting formed in the extensional event and then inverted by the younger compressional event.

In the rocks of the RVSG biotite, plagioclase, epidote, garnet, hornblende and tremolite occur in assemblages as a contact aureole around the Bação Complex (Herz, 1978).

The Serra do Curral

The Serra do Curral is an overturned southeastern limb of a truncated syncline (Fig. 2a) (Pomerene, 1964). In this structure, the Caraça, Itabira and Piracicaba groups of the MSG crop out along most of its extension as an inverted sequence without repetition. The synclinal closure is mapped at the northeastern end of the range, where it has been named the Piedade Syncline, and also at its southwestern extremity (Romano, 1990). Elsewhere, megascopic parasitic synclines occur at several outcrops along the range.

The Serra do Curral can be divided into two segments (Fig. 2a): I, between its western end and the western limb of the Moeda Syncline; II, between the Moeda Syncline and its eastern end. *Segment I* is not significantly deformed by the thrust tectonics while *Segment II* is highly strained and sinistrally rotated approximately 25° from its original position (Fig. 2a).

Segment I is defined by a homoclinal structure which contains the MSG in normal position. As the oldest tectonic register in the range, early, extensional ductile to brittle–ductile shear zones are present both in the surrounding basement gneiss (Bonfim and Belo Horizonte complexes), and in the supracrustal rocks of the Itabira and Piracicaba groups near Ibirité and Brumadinho (Table 1). Kinematic indicators record down-dip and oblique extensional movement (Alkmim, pers. commun., 1991; Endo and Chemale, 1991a) (Table 1). Such features are related to regional extensional tectonics that induced the uplift of granite–gneissic blocks and the downwarping of the sediments of the MSG resulting in open synclines surrounded by basement blocks. The occurrence of undeformed Mesoproterozoic basic dykes and bodies cutting units of the GGT's and of the MSG near the localities of Pará de Minas and Ibirité (Fig. 2a), in an area where extensional structures are common, suggests that extensional processes took place before the Mesoproterozoic. On the northern side of the Serra do Curral, phyllites and schists of the Sabará Formation (Piracicaba Group) contain porphyroblasts of sillimanite, cordierite, staurolite, kyanite, garnet, biotite, and chlorite developed by contact metamorphism (Herz, 1978; Jordt-Evangelista et al., 1992). The contact metamorphic aureole may be related to the extensional tectonics (Jordt-Evangelista et al., 1992)

Discrete, younger, east-dipping, N–S-trending reverse faults, and NE–SW-trending transcurrent faults deform all previous structures.

In Segment II, the northwestward-inverted limb of the syncline is truncated near the contact of the MSG with the RVSG by wide, compressive D1 ductile shear zones. These shear zones deform Mesoproterozoic mafic dykes. In high strain zones D1 fold axes occur parallel to the westward direction transport along the shear zones. We interpret these shear zones as representing oblique ramps of arcuate, approximately N–S-trending thrusts, truncating and deforming the older NE-trending syncline (Fig. 2a).

We interpret the junction between the Serra do Curral structure and the Moeda Syncline as a structure similar to the junction between the Dom Bosco and Moeda Synclines. NE–SW-trending thrust planes, connected by an ESE–WNW-trending tear fault (Figs. 2a and 5) perhaps popped out the upper formations, particularly the Piracicaba Group units, that are absent and probably eroded in the area.

The Itabira Synclinorium

This structure is an isolated allochthonous outlier in the GGTs, 20 km to the northeast of the QF. It is rimmed by iron formations apparently conformable with the schists of the RVSG; the core of the structure comprises quartzites of the Piracicaba Group (Fig. 6).

The variations of synclinal axis orientation indicate a progressive dextral rotation towards the east, similar to the mesoscopic folds in Segment II of the Serra do Curral. The increase in intensity of deformation in this area is accompanied by an increase in metamorphic grade, varying from very low greenschist facies at the southwest (Conceição Syncline) to lower amphibolite at the northeast (Cauê Syncline) (Fig. 6).

All the rocks contain a pervasive mylonitic foliation (Sm1) and a stretching lineation Lm1. D2 and D3 structures are also well developed in the Itabira region (Table 3).

The Cambotas–Fundão System

The Cambotas–Fundão Thrust System (Fig. 7) is the most conspicuous structural feature of the eastern QF. It comprises several arcuate thrusts. The main thrust, the Cambotas Fault, truncates the Serra das Cambotas at its northeastern end, where it has a NE–SW trend (Simmons and Maxwell, 1961). At its southeastern end the thrust borders the Caeté Granitic Gneissic Dome (Fig. 7). Near the Ouro Fino Syncline, the trace of the thrust trends NW–SE, parallel to the Conta-História Syncline, where it coincides with the Fundão Fault (defined by Dorr, 1969). Several major and minor thrust splays are probably the result of duplexing. Further east, the thrusts have increasingly linear N–S trends.

Metamorphism in the area varies from greenschist facies on the west, increasing eastwards to the formation of a kyanite + chloritoid paragenesis near the Fazendão Thrust. In the shear zones related to the Cambotas–Fundão System, syn- and post-tectonic kyanite occurs defining a mineral stretching lineation Lm1.

The Cambotas–Fundão System comprises the following megastructures: the Cambotas Fault, Caeté Complex, and the Gandarela, Ouro Fino and Santa Rita synclines (Fig. 7). The latter syncline includes the Conta-História and Alegria synclines, and the Fazendão Thrust front. The main structural characteristics of each structure are presented in Tables 1, 2 and 3.

The Cambotas Fault corresponds to the northern oblique ramp of the main fault of the Cambotas–Fundão Thrust System (Fig. 7). It trends NE–SW and has a dextral transpressive character, thrusting the NE–SW-striking metasediments of the RVSG and MSG over the Cambotas quartzites of the ESG and the granite–gneissic rocks of the Caeté Dome, which structure is dominated by the N–S-trending thrusts of the Córrego do Garimpo System (Crocco-Rodrigues et al., 1989) (Fig. 8).

The Gandarela Syncline is an allochthonous, overturned, northwest-vergent structure, where the MSG strata are folded around a NE–SW-trending axis (Fig. 7, Table 1). It can be divided into three structural domains: (1) the NE area with axis trending at N60°E, delimited by the Cambotas and Fundão Faults; (2) the central area with the axis trending at N40°E, representing the less-deformed part of the syncline; and (3) the southern area with

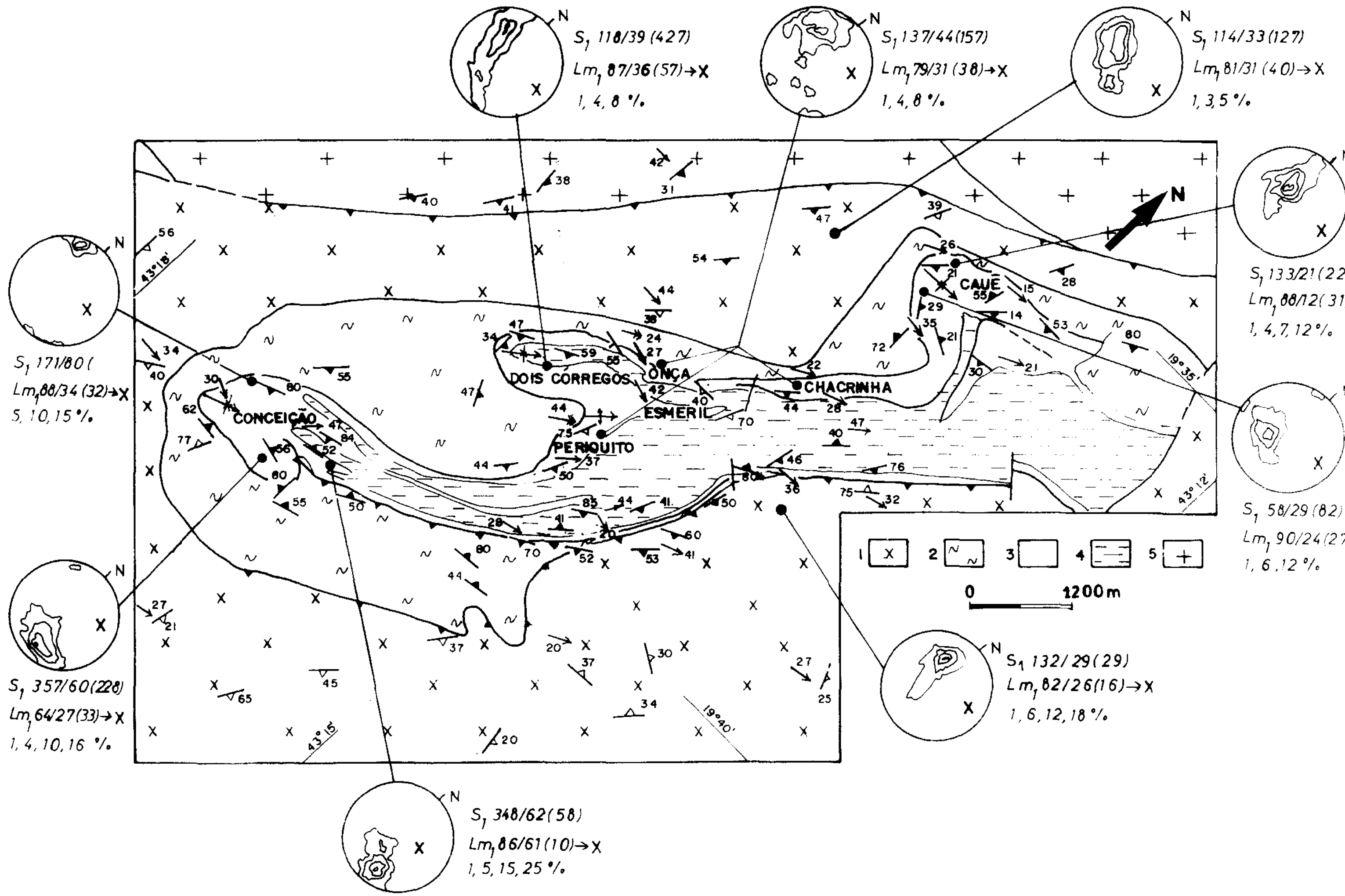


Fig. 6. Geologic-structural map of Itabira Synclinorium (adapted from Chemale et al., 1987). *1*=GGT, *2*=RVSG, *3*=Itabira Group, *4*=Piracicaba Group, *5*=Borrachudo Metagranite. Stereo-grams with Sm1 foliation (contour lines) and Lm1 mineral lineation.

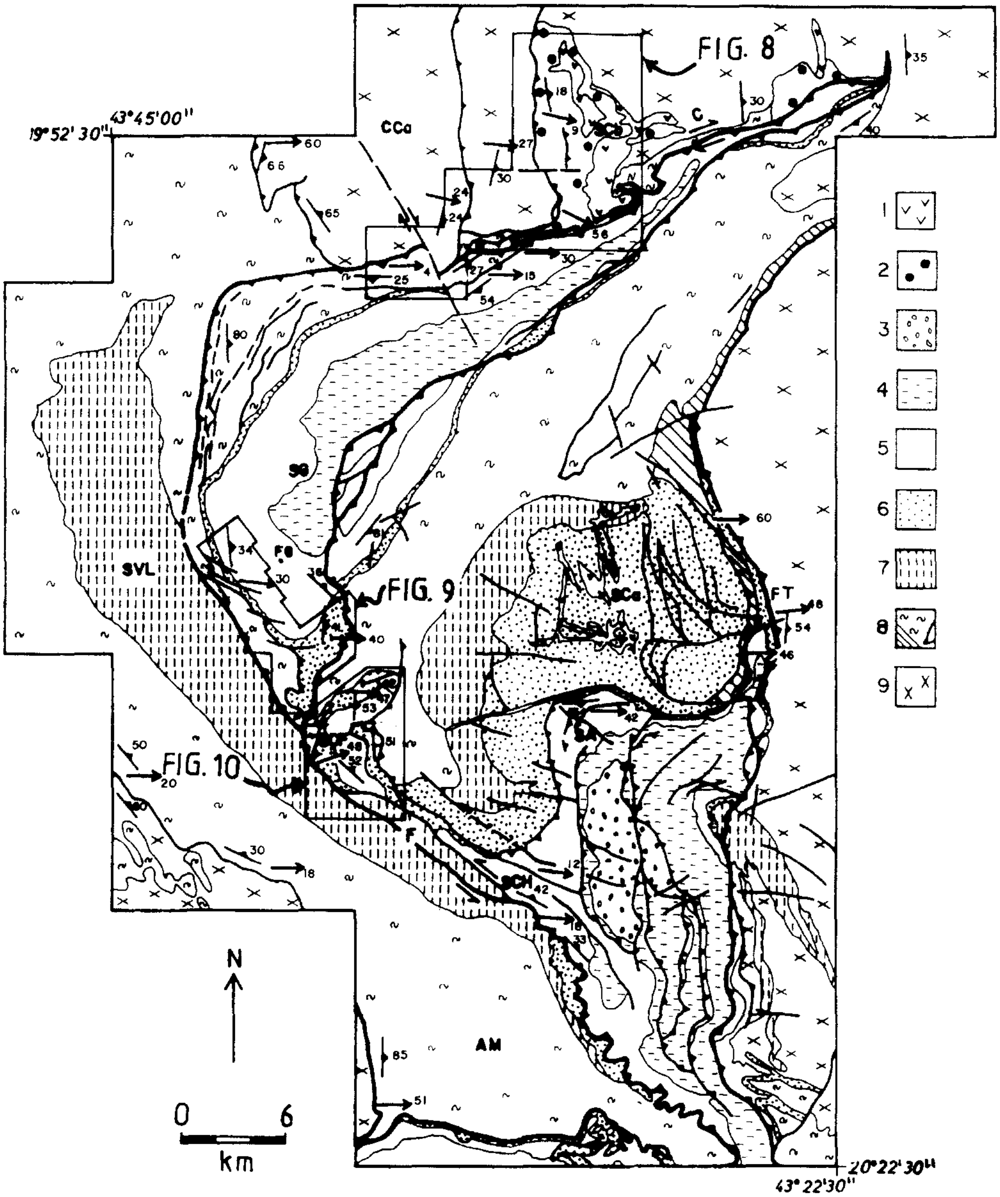


Fig. 7. Geologic-structural map of the Cambotas–Fundão System. *1* = metabasic rocks, *2* = Cambotas Fm., *3* = Itacolomi Group, *4* = Piracicaba Group, *5* = Itabira Group, *6* = Caraça Group, *7* = Maquiné Group, *8* = Nova Lima Group, *9* = GGT. *F* = Fundão Fault, *C* = Cambotas Fault, *AM* = Mariana Anticline, *CCa* = Caeté Complex, *FG* = Fazenda Gandarela, *SA* = Alegria Syncline, *SCa* = Serra do Caraça, *SCb* = Serra das Cambotas, *SCH* = Conta História Syncline, *SG* = Gandarela Syncline, *SOF* = Ouro Fino Syncline, *SVL* = Vargem da Lima Syncline, *FT* = Fazendão Thrust

the axis trending approximately N–S, interpreted as an appendix of the Gandarela Syncline and denominated the Palmital Homocline (Rosière et al., 1991).

In the northeastern area of the Gandarela Syncline, the normal limb tectonically overlies the Cambotas quartzite, the rocks of the RVSG and the Caeté Complex (Fig. 7), with development of the Cambotas Fault and several minor thrusts. The central area of the syncline represents the least deformed part of the structure. It is about 12 km wide and in this do-

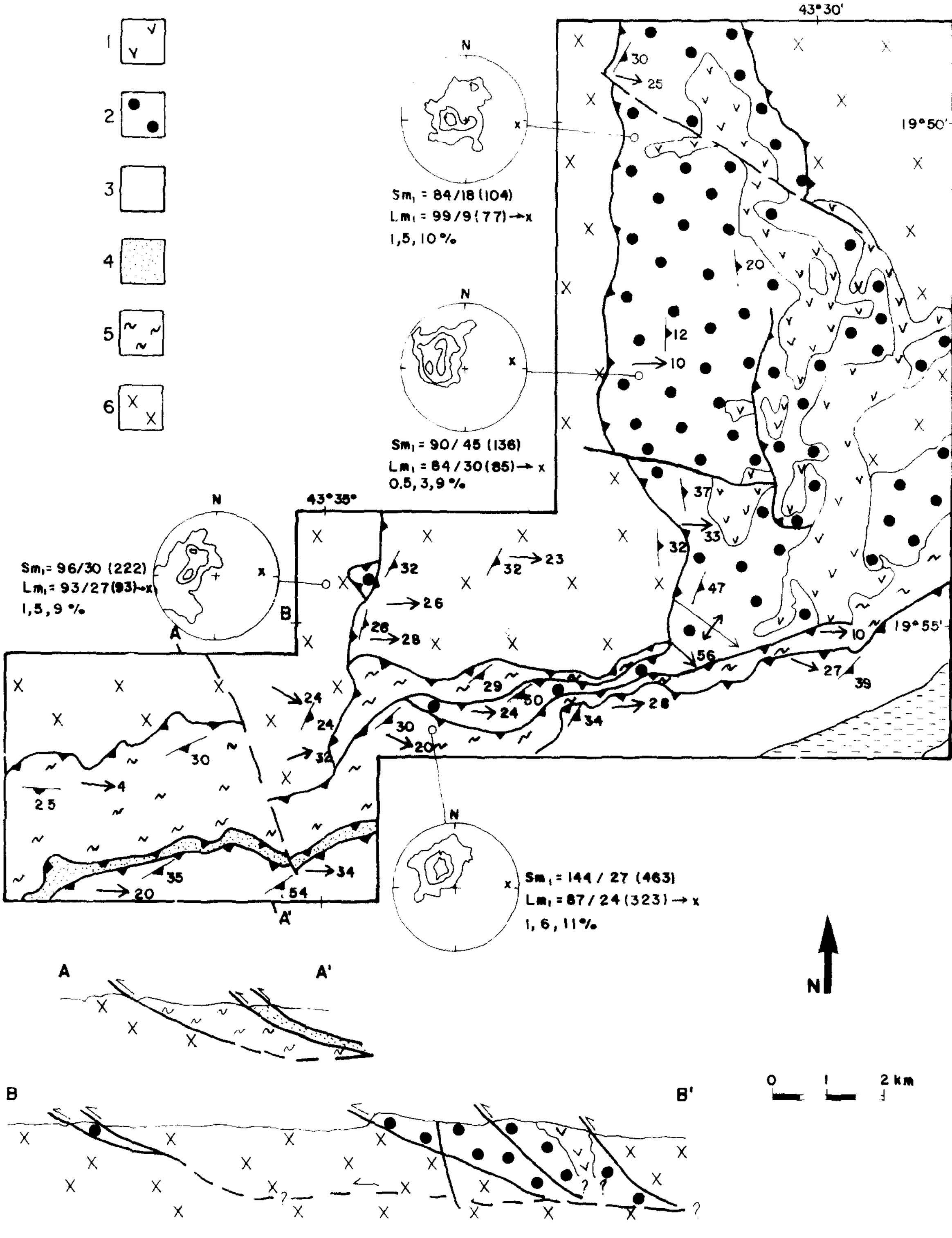


Fig. 8. Geologic-structural map of the Serra das Cambotas (after Crocco-Rodrigues et al., 1989). *1*=metabasic rocks, *2*=Cambotas Fm., *3*=Itabira Group, *4*=Caraça Group, *5*=SGRV, *6*=TTG. Cross sections *A–A'* and *B–B'*. Stereograms with Sm1 foliation (contour lines) and Lm1 mineral lineation (cross).

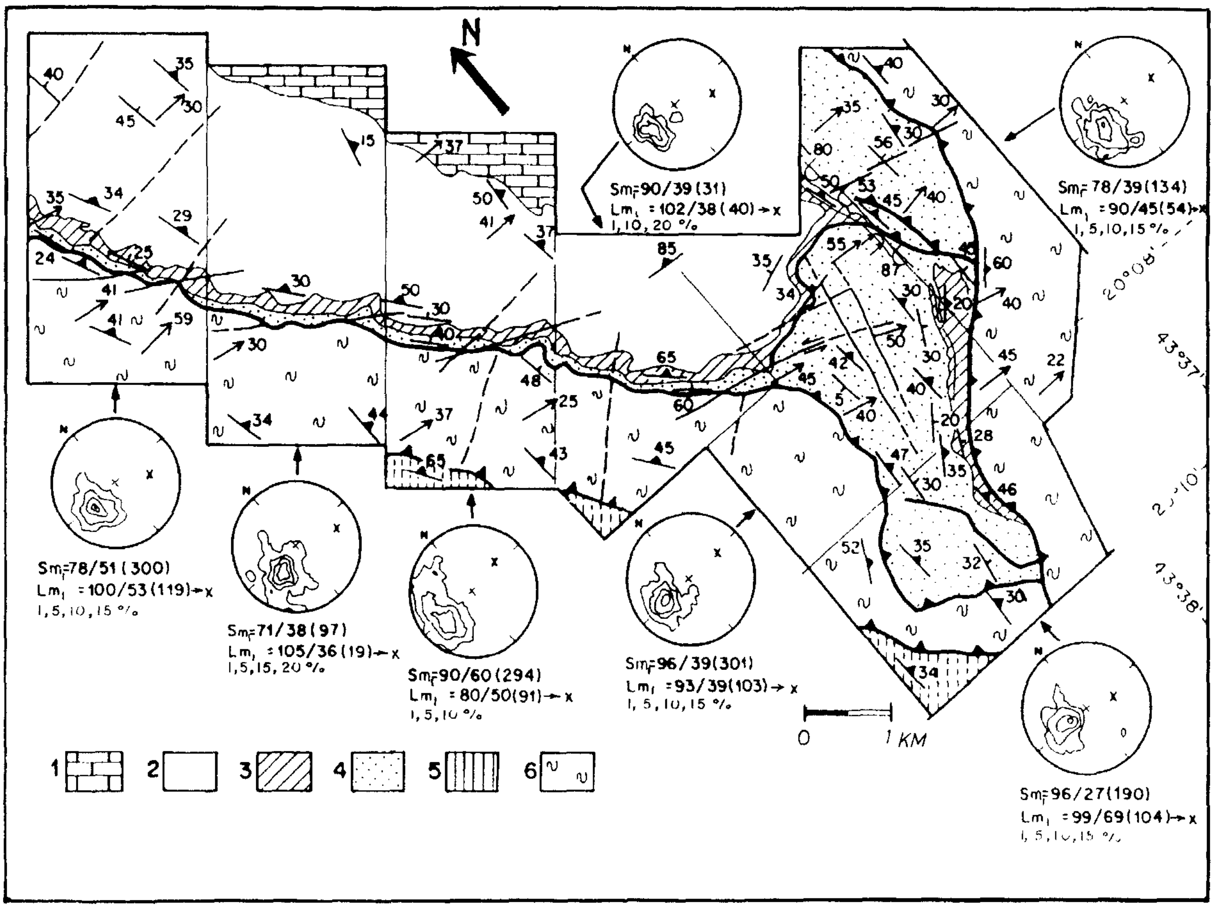


Fig. 9. Geologic-structural map of the Palmital Homocline and SE portion of the central segment of the Gandarela Syncline (after Endo and Chemale, 1991b). *1*=Gandarela Fm., *2*=Cauê Fm., *3*=Batatal Fm., *4*=Moeda Fm., Maquiné Group, *6*=Nova Lima Group. Stereograms with Sm1 foliation (contour lines) and Lm1 mineral lineation (cross).

main, the MSG strata show well-preserved sedimentary structures such as bedding, cross-bedding, flaser structures and fossil cyanobacteria (stromatolites) (Souza and Müller, 1984). The southern area of the syncline has an elongated shape, roughly resembling a boot (Fig. 9). There, only the basal, clastic formations of the MSG (Caraça Group) crop out, building a weakly folded synformal structure with medium to low strain features in its interior surrounded by shear zones, developed during the W-vergent belt (Tables 2 and 3).

The Ouro Fino structure is a refolded syncline, that on map scale displays a shape similar to a "mushroom" interference pattern. Like other megascopic folds of the QF, it is the result of the superposition of the thrust tectonics related to the development of the Cambotas–Fundão System, on folded strata of the MSG (Tables 1, 2 and 3). It can be divided into two segments according to its axial orientation (Figs. 7 and 10), viz. the northern and southern segments, respectively with NE–SW- and NW–SW-trending axes, and northwestward and southwestward vergence.

The analysis of both segments indicates a major E–W-trending refold axis. The northern segment trends parallel to the central part of the Gandarela Syncline and it probably lies on its original position after an extensional event. The southern segment has been sinistrally rotated along the southern, oblique ramp of the

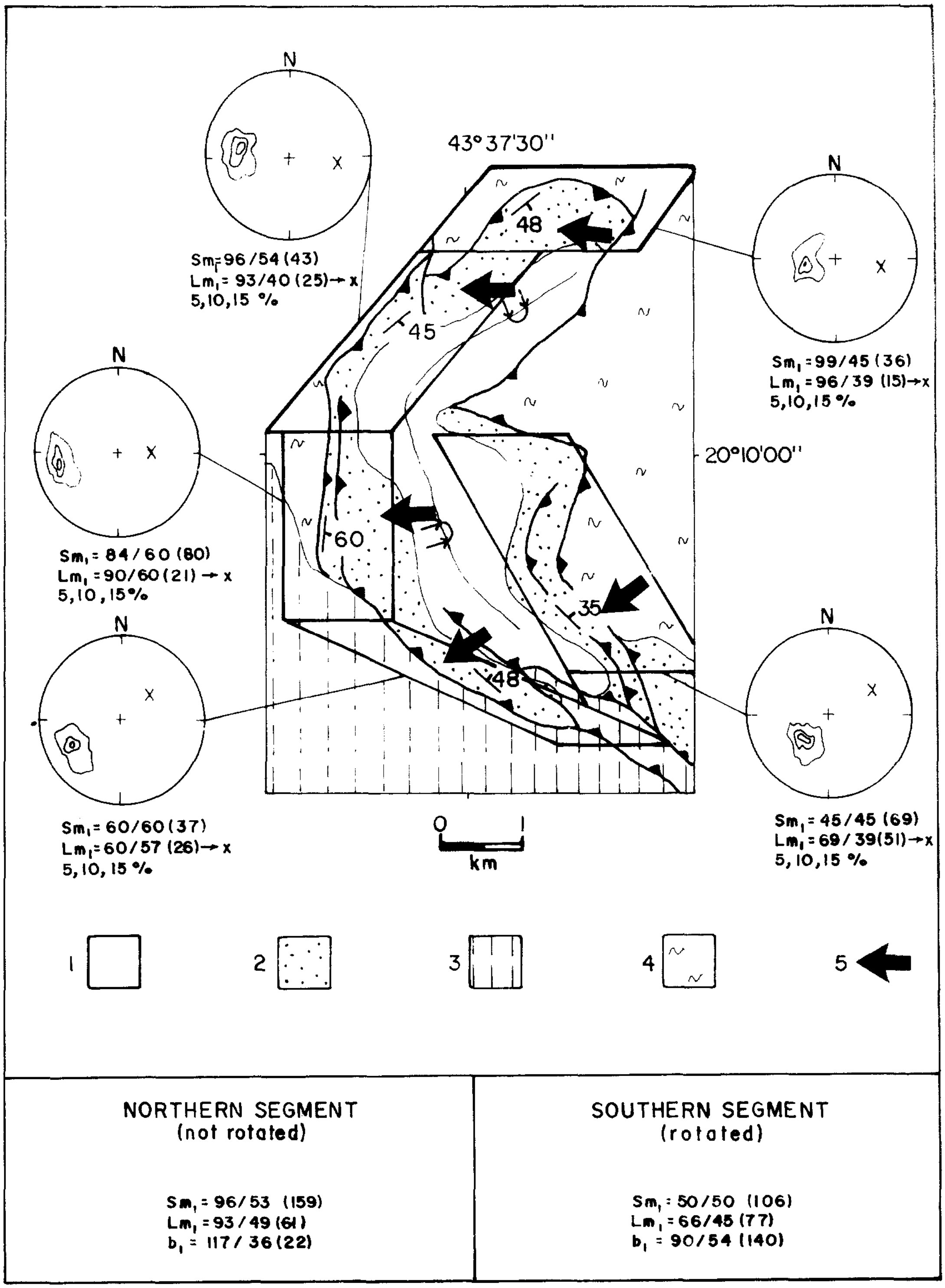


Fig. 10. Geologic-structural map of the Ouro Fino Syncline showing five structural domains (after Fonseca, 1990). *1*=Itabira Group, *2*=Caraça Group, *3*=Maquiné, *4*=Nova Lima Group, *5*=Brasiliano tectonic transport. Stereograms with Sm1 foliation (contour lines) and Lm1 mineral lineation (cross).

Cambotas–Fundão System, that has been reactivated during compressional tectonics (Fig. 10).

The Santa Rita Syncline was also nucleated early during the tectonic history of the QF (Table 1). Its continuity with the Dom Bosco Syncline has been strongly disrupted by the intense thrust tectonics related to the development of the Cambotas–Fundão Thrust System at the eastern margin of the QF. The thrusts compressed the folded strata of the MSG against the structural high of the Serra do Caraça, resulting in the synclines of Conta História and Alegria, and the Fazendão Thrust (Fig. 7).

Structural model

We believe that much of the Proterozoic tectonic history of the QF can be best explained in terms of heterogeneous regional deformation, due to the interference of old structures with later tectonism. Clearly the E–W compressional events were superimposed onto an earlier complex arrangement (Fig. 11B), with prominent structural highs between synclines, that display a wide array of axial planar orientations. We believe that the effects of this previous framework were particularly significant during D1, when the location and nucleation of thrust faults were conditioned by the older structures. The E–W-trending Dom Bosco Syncline favoured the effects of the thrusts by "channelling" their trajectories along its hinge line. The thrusts sliced the Dom Bosco Syncline, resulting in the transection of the primary surfaces by N–S-striking faults. In the limbs of the synclines the thrusts were controlled by the morphology of the structural basement, resulting in curved fault planes and mylonitization parallel to the contact between the supracrustal and infracrustal rocks.

The Bação Complex, to the north (Figs. 2a and 11B), acted as a rigid buttress, displaying a mylonitic foliation along its borders, parallel to the contact with the supracrustal rocks. It obstructed the trajectory of the thrusts in the Dom Bosco Syncline and the southern thrust ramps related to the Cambotas–Fundão System. The westward compression also forced the rocks of the Bação Complex against those of the Moeda Syncline, attenuating its southern extremity at the junction with the Dom Bosco Syncline (Figs. 2a and 12).

The oroclinal shape of the Cambotas–Fundão System is believed to be due to its obstruction in the north by the Caeté Complex and in the south by the Bação Complex, associated with the development of two conjugate, transpressive shear zones, respectively with dextral and sinistral sense of rotation (Figs. 2a and 12), probably reactivating earlier major basement structures. The arcuate trajectory of the thrusts reshaped all previous structures, deforming the megasynclines formed during the previous extensional event. At the junction between the Santa Rita and Dom Bosco synclines, the arcuate shape of the Cambotas–Fundão System gave origin to the Mariana Anticline.

Another important rigid buttress in the QF is the Serra do Caraça, that partially obstructed the westward trajectory of the Santa Rita Syncline during compression, and conditioned the present shape of the structure, with the development of the Alegria (ESE-trending axis), and Conta História (SE-trending axis) synclines, and the N–S-striking Fazendão frontal ramp. These structures are all strongly deformed segments of the Santa Rita Syncline. The Serra do Caraça also partially protected the central segment of the Gandarela Syncline from the deformational effects of the compressive event, that produced an intense mylonitization at the northeastern segment along the Cambotas transpressive zone.

E–W-striking tear faults also developed during the compressive tectonism. The most important is the Engenho Fault that defines the southern limit of the QF. It is an old structural discontinuity of the basement that has been successively reactivated during the Protero-

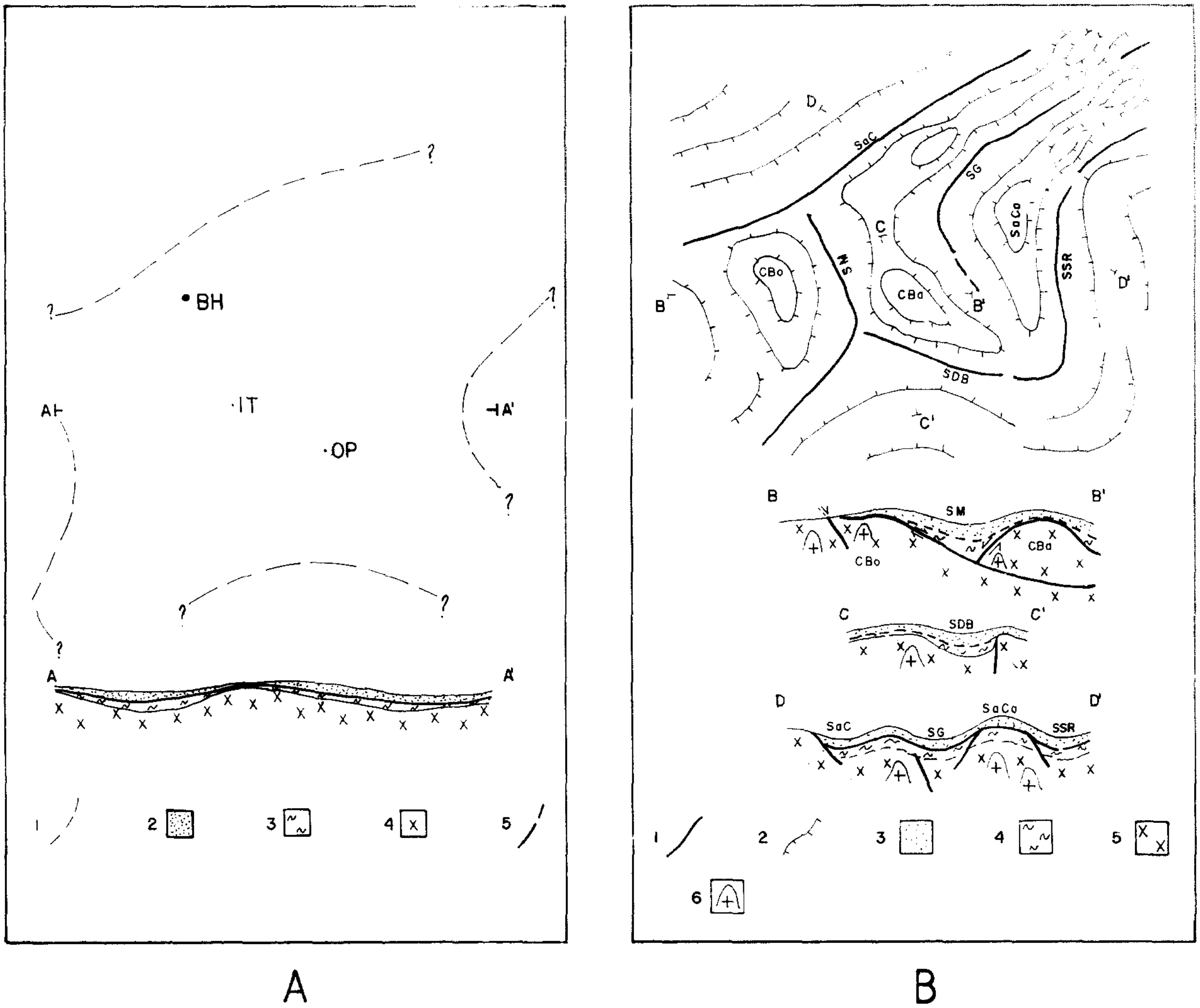
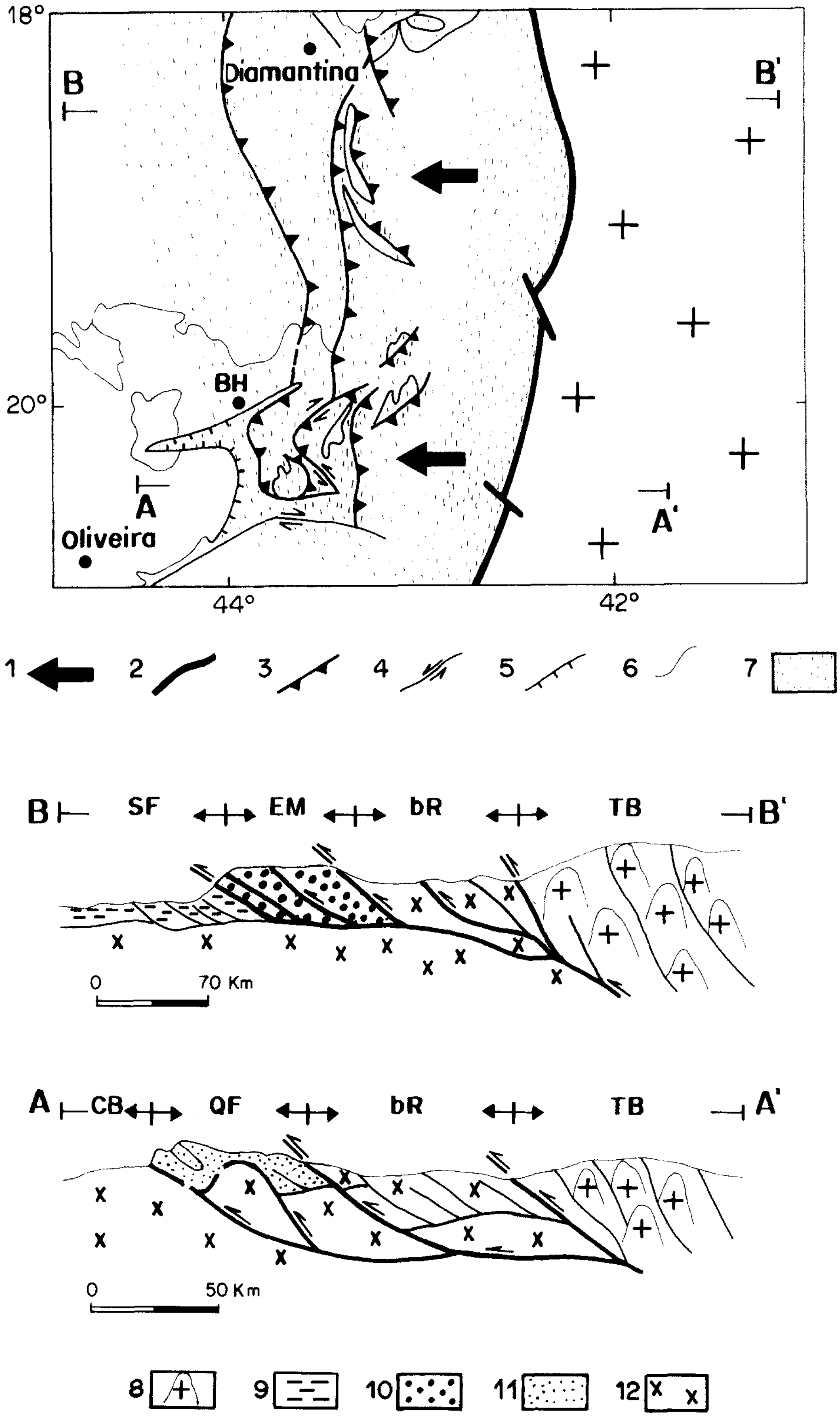


Fig. 11. Sketch maps illustrating the Palaeoproterozoic evolution of the Quadrilátero Ferrífero. (A) The Minas Basin after its deposition. *1* = minimum basin limit based on present MSG distribution, *2* = Minas sediments, *3* = deformed RVSG units, *4* = Archaean TGG. (B) The Minas Basin after the first extensional event. *1* = structural low, *2* = structural high, *3* to *5* as in (A). *SaC* = Serra do Curral, *SM* = Moeda Syncline, *SDB* = Dom Bosco Syncline, *SSR* = Santa Rita Syncline, *SG* = Gandarela Syncline, *SaCa* = Serra do Caraça, *CBa* = Bação Complex, *CBo* = Bonfim Complex.

zoic era. In the Brasiliano Event this fault is reactivated by several parallel sinistral shear zones resulting in translation and rotation of blocks.

The E–W-trending D2 structures resulted from transpressive deformation, developing in non-planar deformation conditions. The N–S-trending D3 structures are interpreted to be due to the development and reactivation of frontal ramps as the thrusts reached shallower levels

Fig. 12. Schematic map of the southeastern portion of the São Francisco Craton with main structural features. *1* = Brasiliano tectonic transport, *2* = limit of Brasília (W) and Vitória (E) blocks, *3* = frontal and oblique thrusts, *4* = strike-slip shear zone, *5* = Palaeoproterozoic, extensional shear zone, *6* = contact, *7* = influence zone of Brasiliano Orogeny in the Brasília Block, *8* = gneissic terrain with Brasiliano granites, *9* = São Francisco Supergroup, *10* = Espinhaço Supergroup, *11* = Minas and Rio das Velhas Supergroup, *12* = Palaeoproterozoic and Archaean granite-gneiss terrain. *TB* = 8, *bR* = reworked basement, *EM* = Espinhaço Meridional, *SF* = São Francisco basin.



in the crust. The ambiguous relationship of superposition between the structures of these last phases suggests their contemporaneity.

The tectonic transport during the compressive Brasiliano Event is unambiguously westward, as registered by the kinematic shear sense indicators in all analysed domains. Northwest- and southwestward movements are also recorded in the QF, but are related to local oblique ramps, conditioned by the pre-existing structural topography. The conjugate transpressive zones that limit the Cambotas–Fundão System (Fig. 7) also indicate a compressive component.

Tectonic evolution

Relating the results of the structural analysis and available geochronological and gravimetric data we suggest the following evolutionary model for the QF, which is summarized in Table 4.

The GGTs older than 2920 Ma, possibly as old as 3080 Ma (U/Pb on zircon) (Machado et al., 1989a) are the most complex and little can presently be asserted about their early history. The 2.7–2.8 Ga metagranites and gneisses (Cordani et al., 1980, 1989; Teixeira, 1985; Teixeira et al., 1987; Machado et al., 1989a; Romano, 1990) often display a N–S-striking banding, and a mineral lineation displaying subhorizontal pitches. Machado and Carneiro (1992) indirectly dated the deformation of the gneiss between 2772 Ma and 2703 Ma, based on the fact that a 2703^{+20}_{-25} Ma old aplitic dyke from the Bonfim Complex intersects the N–S-trending fabric of the gneissic country rock whose age was determined as 2772 ± 6 Ma (U/Pb on zircon).

The RVSG comprises an Archaean greenstone belt sequence, older than 2.76 Ga, with deformation and metamorphism developed at about 2.7–2.8 Ga (Herz, 1970; Thorpe et al., 1984; Machado et al., 1989a), together with granitic intrusions as at the Serra do Itatiaia and Serra do Ouro Branco (outcrop RV1 in Fig. 4), where they are preserved from the events that deformed the MSG. As the surrounding granite–gneiss rocks the old fabric of the RVSG attests to transcurrent tectonics. U/Pb in zircon data for felsic volcanic rocks from the RVSG and some granite–gneiss rocks yield ages of 2.7–2.8 Ga (Machado et al., 1989a) which is interpreted as the main deformational event affecting the RVSG and surrounding GGTs. The superimposition of younger fabrics that obliterates the older structures in most outcrops, makes it difficult to give a complete interpretation of the Archaean tectonics.

The sedimentation of the MSG occurred mainly upon units of the RVSG, since its basal formation comprises conglomerates with fragments from the greenstone belt sequence, while granitic clasts are absent. The stratigraphy of the MSG indicates a long, quiescent period of stabilization of the Archaean crust, with the development of platformal or wide intracratonic basin >10000 km^2 (see Fig. 11A), in which thick layers of BIF were extensively deposited. The extent of the Minas Basin is not, at this stage, reconstructable. The Pb/Pb date of undeformed to weakly deformed carbonatic rocks indicates ages of 2420 ± 25 Ma for the Itabira Group (Babinski et al., 1991) and the U/Pb date from detrital zircon grains of metagraywacke indicates a minimum age of 2125 ± 4 Ma for the Sabará Formation (Piracicaba Group), uppermost formation of the MSG (Machado et al., 1989a). The basal group of MSG, the Caraça Group, is older than 2420 ± 25 Ma (age of Itabira Group) and younger than 2703^{+20}_{-25} Ma (the youngest granitic rock of basement). Metamorphic age of 2059 ± 6 determined on sphene from granite–gneiss terrain (Machado et al., 1989a) and Pb/Pb data for deformed marble of the Piracicaba Group yielding an isochron age of 2110 ± 110 (Babinski et al., 1991) are considered as minimum deposition age of MSG rocks.

The units of the MSG were first affected by regional, extensional tectonics, that resulted in the uplift of blocks of the basement, with development of shear zones along the contact between supracrustal and infracrustal rocks and downwarping of the overlying strata (Fig. 11B). This downwarping movement resulted in a series of wide megasynclines that may have been nucleated continuously or individually, in

TABLE 4

Tectonic evolution synthesis of the Quadrilátero Ferrífero and adjacent regions (see text)

Lithological groups of rock formation	Age (Ma)	Tectonic regime and other characteristics
(1) Generation of older granite–gneiss terrains	>2920	Compressive tectonics with production of a complex structural arrangement
(2) Initial phase of the greenstone belt Rio das Velhas	>2880	Extensional tectonics with generation of komatiites and tholeiites
(3) Acid to intermediate magmatism associated with deformation and metamorphism of the RVSG as well granite–gneissic rocks formation	2780 to 2703	Compressive tectonics with a dominant strike-slip deformation which produced a horizontal to subhorizontal mineral lineation at N–S-trending foliation with vertical dip (Rio das Velhas Orogeny)
(4) Minas Supergroup deposition (intermediate unit, Itabira Group, deposited ~2400 Ma)	<2703 to >2060	Initial rift phase followed by a platform deposit (somewhat like an intracratonic basin)
(5) Isotopic remobilization of Archaean rocks. Pegmatites and amphibolites (probably granites?) in the GGT and RVSG, and low-grade and contact metamorphic rocks in the MSG, were formed	2060 to 2000	Extensional tectonics with development of ductile–brittle to ductile shear zones, resulting in the uplift of GGTs and formation of interconnected regional synclines
(6) Mafic dyke intrusions	1700 to 1500	Extensional tectonics associated with the Mesoproterozoic rifting of the SF Craton
	1200 to 900	Extensional tectonics during the opening of the Brasiliano/Pan-African proto-ocean
(7) Generation of low-grade rocks (locally in amphibolite facies)	650 to 500	Compressive tectonics related to the Brasiliano fold-and-thrust belt (Brasiliano Orogeny)
(8) Mesozoic tectonism with formation of basic dykes and sedimentary basin	<130	Extensional tectonics during the drift of South America and Africa continents

accordance with the vertical movement of underlying blocks. Such a peculiar tectonic event could be interpreted as a response to the collision of continental blocks with a west-dipping subduction during the Transamazonian Event at 2.1–1.7 Ga, involving the eastern portion of the Paramirim Craton. The region could correspond to metamorphic core terrains of Archaean age that have been uplifted during extensional tectonism related to a subduction event similar to the Phanerozoic West Cordilleran Pan-American coast (Davis and Coney, 1979; Coney and Harms, 1984; Parrish et al., 1988). As alternative explanation, the extensional event could be related to a regional process during continental drift with development of basement uplift, as proposed by Wernicke (1990) for Phanerozoic sequences.

The shear zones represent the consequent dislocation surfaces developed during the uplift, and together with the megafolds, are the main tectonic features of the Transamazonian Event in the QF. Whole rock Rb/Sr, Pb/Pb in monazite and U/Pb in sphene data record a 2.0 Ga crustal remobilization in the GGTs (Cordani et al., 1980, 1989; Teixeira, 1985;

Machado et al., 1989a; Romano, 1990) and radiometric age K/Ar data indicate mineral cooling in the western portion of the QF at 1.7 Ga (Romano, 1990; Carneiro, in prep.) which region is not affected by younger compressional events.

During the extensional event, the metamorphic conditions reached the greenschist facies in the extensional ductile to ductile–brittle shear zones at the contact between the GGTs and the overlying supracrustal rocks. Distant from the shear zones, in the core of the megasynclines almost very low greenschist facies metamorphism related to this event can be detected. The existing contact metamorphism aureoles, syntectonic to post-tectonic with respect to the development of the extensional shear zone (Jordt-Evangelista et al., 1992), can be interpreted as the result of intrusion of igneous during the crustal remobilization associated to the development of the metamorphic core complexes or the juxtaposition of hotter crustal material against cooler supracrustal rocks.

During Mesoproterozoic times this region behaved as a cratonic area in which different extensional pulses through mafic dyke generations have been identified (Table 4). In contrast to Cordani et al. (1980, 1989), Teixeira (1985), Marshak and Alkmim (1989), a Mesoproterozoic (Uruaçuano) orogeny is not recognized in the QF.

At the end of the Mesoproterozoic and the beginning of the Neoproterozoic, a broad extensional event affected the São Francisco Craton when the first stages of the Brasiliano/Pan-African Cycle took place.

Undeformed mafic dykes and other intrusive bodies that crop out in the western parts of the QF, similar to those occurring in the Serra do Espinhaço which are about 1.0 Ga old (Machado et al., 1989b), truncate the Archaean and Transamazonian terrains (GGTs, RVSG and MSG), as for instance, in the Ibirité region (IB in Fig. 2a). In the eastern portion of the QF, they are deformed by the E–W compressive event, as at the Raposos Mine (MR in Fig. 2a) and Serra das Cambotas (Fig. 8).

A comparison between data from the Serra do Espinhaço, eastern São Francisco Basin and the QF area, indicates that all these regions were affected by similar tectonism, under the same westward kinematic vector (Fig. 12). In the Serra das Cambotas region, where ESG and MSG are juxtaposed, it is clear that the latter is thrust over the former along the Cambotas–Fundão System (Fig. 8). Both geological facts attest that this compressive event developed during the Brasiliano as a part of the Espinhaço FTB, related to the closure of the eastern margin of the São Francisco Craton. K/Ar data from biotite, hornblende and whole rock analysis of amphibolites and granitic rocks from the eastern border of the QF range from 1.0 and 0.43 Ga, with most data between 0.55 and 0.45 Ga, which reflect the thermal overprint associated with this compressive event (Teixeira, 1985; Cordani et al., 1989).

The infracrustal blocks acted as barriers to the collisional deformation in the QF, resulting in amplification, translation and rotation of the megasynclines. Pre-existing structures were reactivated and new features, typical of fold-and-thrust belts, developed. In the QF, the collisional deformation affected mainly the supracrustal rocks, particularly along their contact with the crystalline basement. Significant Brasiliano crustal accretion occurred only in the Mantiqueira Province to the east of the QF (Siga et al., 1987), in response to the closure between the Vitória and the Brasília Blocks (Fig. 12). Along the contact of these blocks, a gravimetric anomaly is detectable in the Acaiaca (Haraly et al., 1985) and western Itabira regions (Ortu, 1990), which is interpreted as the result of crustal thickening due to the Brasiliano tectonics (see simplified cross-sections *A–A′* and *B–B′* of Fig. 12).

Conclusions

The QF area is a regional interface structure as a result of the following tectonic history: extensional tectonics, of Transamazonian age (2100–1700 Ma) and compressional tectonics with the development of a fold and thrust belt of Brasiliano age (650–500 Ma). The structural data allow us to define two main structural regions in the QF: the western region which displays mainly extensional records, and the eastern region which has been affected in different magnitude of deformation by the younger Brasiliano FTB (Fig. 12).

The uplift of the Archaean granite–gneiss domes and the formation of interconnected regional synclines took place during the Palaeoproterozoic extensional tectonics, generating a dome and basin architecture for the QF region. The regional synclines of the QF, such as the Gandarela, are also originally extensional in origin and are not only compressive in origin as proposed in other models. The extensional tectonics may be related to the development of a core complex in the hinterland of a collisional area to the east of the QF. This would imply in a subduction zone dipping westwards under the Transamazonian Paramirim Craton. Alternatively, the extensional event could be related to a more extensive continental fragmentation process.

During this extension, metamorphic conditions reached the greenschist facies in the extensional shear zones at the contact between the GGTs and the overlying supracrustal rocks. Syn- to post-tectonic metamorphic aureoles (Jordt-Evangelista et al., 1992) can be interpreted as the result of granitic intrusion, or the juxtaposition of older, hotter crustal material against cooler supracrustal rocks. The kinematic field of the extensional tectonics is strongly variable, being controlled by the shape of GGTs and their contacts with the supracrustal rocks; however, the regional vectorial field is oriented WNW–ESE.

Compressional tectonics is believed to be associated with the closure of the Brasiliano/Pan-African basins. It resulted from the development of a west-vergent Brasiliano FTB, as is partially described by Belo de Oliveira and Vieira (1987) and Marshak and Alkmim (1989), where the QF represents its intermediate to distal portion without magmatism activity. Related deformational structures developed in three deformational phases, and are continuous with the Brasiliano age structures of the São Francisco Basin and Espinhaço Meridional. During ductile D1, the metamorphic conditions varied from anchimetamorphism to low amphibolite facies, while during ductile–brittle D2 and D3 retrograde conditions prevailed as the result of a progressive uplift of thrust blocks/wedges during the tectonic transport. The uplifted granite–gneiss blocks acted as obstacles during the collisional tectonics, resulting in amplification, translation and rotation of the regional synclines. The intensity of deformation and metamorphism decrease from east to the west as already stated by Almeida (1977).

Acknowledgements

Grateful acknowledgments are made to the iron mining companies Companhia do Vale do Rio Doce (CVRD), Mineraçoes Brasileiras Reunidas (MBR) and Samitri for support of much of the field work; and to the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and the Financiadora de Estudos e Projetos (FINEP/PDACT), respectively for Grants 404983/88.0 and 4.286.0337. We thank Francy Jacobus Baars for helpful discussions, many suggestions and improvement of the manuscript. Maarten J. de Wit is also thanked for extensive reviewing and critical comments.

References

Alkmim, F.F., 1985. Sedimentologische, lithostratigraphische und tektonische Untersuchungen in der Serra de Ouro Branco, Minas Gerais, Brasilien. Unpubl. D.Sc. Thesis, Tech. Univ. Clausthal, Clausthal-Zellerfeld, 217 pp.

Almeida, F.F.M., 1977. O Cráton de São Francisco. Rev. Bras. Geocienc., 7 (4): 349–364.

Babinski, M., Chemale, F. Jr. and Van Schmus, W.R., 1991. Geochronologia Pb/Pb em rochas carbonáticas do Supergrupo Minas, Quadrilátero Ferrífero, Minas Gerais, Brasil. An. III Congr. Bras. Geoqim., São Paulo, Soc. Bras. Geoquim., 2: 628–631.

Belo de Oliveira, O.A. and Vieira, M.B.H., 1987. Aspectos da deformação dúctil e progressiva no Quadrilátero Ferrífero. In: Bol. Res. I. Simp. Nac. Est. Tect., Salvador, Soc. Bras. Geol., pp. 74–76.

Carneiro, M.A., in prep. Geocronologia e Geoquímica do Complexo Bonfim. Ph.D. thesis, Univ. Sao Paulo, São Paulo.

Castro Alves, J.A., 1991. Reconstrução Estocástica da Mina São Luiz, Complexo Fazendão, MG. M.Sc. Thesis, Univ. Fed. Ouro Preto, Ouro Preto, 211 pp.

Chemale, F., Jr. and Endo, I., 1990. Projeto Sinclinal Gandarela, Parte II. Conv. MBR/UFOP, Unpubl. Int. Rep., 39 pp.

Chemale, F., Jr., Quade, H. and Santana, F.C., 1987. Economic and structural Geology of the Itabira Iron District, Minas Gerais, Brazil. Zentralbl. Geol. Palaeontol., VI (7/8): 743–752.

Coney, P.J. and Harms, T.A., 1984. Cordilleran metamorphic complexes: Cenozoic extensional relics of Mesozoic compression. Geology, 12: 550–554.

Cordani, U.G., Kawashita, K., Müller, G., Quade, H., Reimer, V. and Roesler, H., 1980. Interpretação tectônica e petrológica de dados geocronológicos do embasamento na borda sudeste do Quadrilátero Ferrífero. An. Acad. Bras. Cienc., 52(4): 785–799.

Cordani, U.G., Teixeira, W. and Siga, O., Jr., 1989. Geocronologia do Quadrilátero Ferrífero. Bol. XXI Sem. Estudos, Soc. Interc. Cult. Est. Geol., Ouro Preto, 21: 27–44

Costa, C.S., in prep. Geologia Estrutural e Petrologia do Córrego dos Boiadeiros. M.Sc. Thesis, Univ. Fed. Minas Gerais.

Crocco-Rodrigues, F.A., Costa, A.F., Souza, F.A.C. and Rosière, C.A., 1989. Sistemas de Cavalgamento do Nordeste do Quadrilátero Ferrífero-MG. An. V Simp. Geol. Minas Gerais, Belo Horizonte, Soc. Bras. Geol., Bol., 10: 6–10.

Davis, G.H. and Coney, P.J., 1979. Geologic development of the Cordilleran metamorphic core complexes. Geology, 7: 120–124.

Dorr, J.N. 2nd., 1969. Physiographic, stratigraphic, and structural development of the Quadrilátero Ferrífero, Minas Gerais. U.S. Geol. Surv. Prof. Pap., 641-A: 1–110.

Endo, I., 1988. Análise Estrutural Qualitativa do Minério de Ferro e encaixantes da Mina de Timbopeba–Borda Leste do Quadrilátero Ferrífero, Mariana, MG. Unpubl. M.Sc. Thesis, Univ. Fed. Ouro Preto, Ouro Preto, 130 pp.

Endo, I. and Chemale, F., Jr., 1991a. Implicações tectônicas das estruturas extensionais no Quadrilátero Ferrífero, MG. Bol. III. Simp. Nac. Est. Tect., Rio Claro, pp. 51–53

Endo, I. and Chemale, F., Jr., 1991b. Projeto Sinclinal de Alegria–Aba NE. Unpubl. Int. Rep., SAMITRI, Mariana, 16 pp.

Evangelista, M.T.R., 1984. Strukturelle und texturelle Untersuchungen in der Eisenerzlagerstaette "Mutuca" bei Belo Horizonte, Minas Gerais, Brasilien. Unpub. Dr.Sc. Thesis, Tech. Univ. Clausthal, Clausthal-Zellerfeld, 171 pp.

Fonseca, M.A., 1990. O Sinclinal de Ouro Fino: Análise Descritiva e Cinemática de um segmento do Sistema Fundão, Quadrilátero Ferrífero, Minas Gerais. Unpubl. M.Sc. thesis, Univ. Fed. Ouro Preto, Ouro Preto, 102 pp.

Gloeckner, K.H., 1981. Lithostratigraphie, Sedimentologie, Tektonik und Metamorphose der proterozoischen Itacolomi-Serie bei Ouro Preto, Minas Gerais, Brasilien. Claust. Geowiss. Diss., 10: 1–221.

Guild, P.W., 1957. Geology and Mineral Resources of the Congonhas District, Minas Gerais, Brazil. U.S. Geol. Surv. Prof. Pap., 290: 1–90.

Hackspacher, P.C., 1979. Strukturelle und texturelle Untersuchungen zur internen Deformation des Eisenreicherzkoerpers der Grube "Aguas Claras" bei Belo Horizonte/Minas Gerais, Brasilien. Claust. Geol. Abh., 34: 1–164.

Haraly, N.L.E., Hasui, Y., Mioto, J.A., Hamza, V.M. and Rodrigues, C.V.R., 1985. Ensaio sobre a estruturação crustal do Estado de Minas Gerais com base na informação geofísica e geológica. Contribuições à geologia e petrologia. Belo Horizonte, Bol. Esp. Soc. Bras. Geol. Minas Gerais, pp. 71–93.

Herz, N., 1970. Gneissic and igneous rocks of the Quadrilátero Ferrífero, Minas Gerais, Brazil. U.S. Geol. Surv. Prof. Pap., 641-B: 1–58.

Herz, N., 1978. Metamorphic rocks of the Quadrilátero Ferrífero, Minas Gerais, Brazil. U.S. Geol. Surv. Prof. Pap., 641-C: 1–78.

Hoefs, J., Müller, G. and Schuster, A.K., 1982. Polymetamorphic relations in iron ores from the Iron Quadrangle, Brazil: the correlation of oxygen isotope variations with deformation history. Contrib. Mineral. Petrol., 79: 241–251.

Inda, H.A.V., Schorscher, H.D., Dardenne, M.A., Schobbenhaus, C., Haralyi, N.L.E., Branco, P.C.A. and Ramalho, R., 1984. O Cráton Sao Francisco e a Faixa de Dobramentos Araçuaí. In: C. Schobbenhaus, D.A. Campos, G.R. Derze and H.E. Asmus (Editors), Geologia do Brasil. DNPM, Brasília, pp. 193–248.

Januzzi, A. and Alkmim, F.F., 1989. Geologia Estrutural da Mina de Alegria (SAMITRI), Município de Mariana (MG). Unpubl. Int. Rep., SAMITRI, Mariana, 13 pp.

Jordt-Evangelista, H., 1984. Petrologische Untersuchungen im Gebiete zwischen Mariana und Ponte Nova, Minas Gerais, Brasilien. Unpubl. Dr.Sc. thesis, Tech. Univ. Clausthal, Clausthal-Zellerfeld, 183 pp.

Jordt-Evangelista, H., Alkmim, F.F. and Marshak, S., 1992. Metamorfismo progressivo e a ocorrencia dos 3 polimorfos $Al_2O_3SiO_5$ (cianita, andaluzita e silimanita) na Formação Sabará em Ibirité, Quadrilátero Ferrífero, MG. Rev. Esc. Minas, Ouro Preto, 45 (01/02): 157–160.

Ladeira, E.A., 1980. Metallogenesis of Gold at the Morro Velho Mine, and in Nova Lima District, Quadrilátero Ferrífero, Minas gerais, Brazil. Unpubl. Ph.D. thesis, University of Western Ontario, London, 272 pp.

Ladeira, E.A., 1985. Metalogênese do ouro da mina de Morro Velho e no distrito Nova Lima, Quadrilátero Ferrífero, Minas Gerais, Brasil. Contrib. Geol. Petrol., Soc. Bras. Geol. Minas Gerais, pp. 95–151.

Ladeira, E.A. and Viveiros, J.F.M., 1984. Hipótese sobre a Estruturaçao do Quadrilátero Ferrífero com Base nos Dados Disponíveis. Bol. Soc. Bras. Geol. Minas Gerais, 4: 14 pp.

Machado, N. and Carneiro, M., 1992. U–Pb evidence of late Archean tectono-thermal activity in the southern São Francisco shield, Brazil. Can. J. Earth Sci., 29 (11): 2341–2346.

Machado, N., Noce, C.M., Belo de Oliveira, O.A. and Ladeira, E.A., 1989a. Evolução geológica do Quadrilátero Ferrífero no Arqueano e Proterozóico Inferior, com base em geocronologia U–Pb. An. V Simp. Geol. MG, Belo Horizonte, Soc. Bras. Geol., 10: 1–5.

Machado, N., Schranck, A., Abreu, F.R., Knauer, L.G. and Abreu, P.A.A., 1989b. Resultados preliminares da geocronologia U/Pb na Serra do Espinhaço Meridional. An. V Simp. Geol. MG, Belo Horizonte, Soc. Bras. Geol., 10: 171–175.

Marshak, S. and Alkmim, F.F., 1989. Proterozoic extension/contraction tectonics of the southern São Francisco Craton and adjacent regions, Minas Gerais, Brazil: a kinematic model relating Quadrilátero Ferrífero, São Francisco Basin and Cordilhera do Espinhaço. Tectonics, 8(3): 555–571.

Mascarenhas, J.F., Misi, A., Motta, A.C. and Silva Sa, J.H., 1984. Província Sao Francisco. In: F.F.M. Almeida and Y. Hasui (Editors), O Pré-Cambriano do Brasil. E. Blücher, São Paulo, pp. 46–122.

Nalini, H.A., in prep. Análise Geométrica e Cinemática do Anticlinal de Mariana. M.Sc. Thesis, Univ. Fed. Minas Gerais.

Noce, C.M. and Ladeira, E.A., 1989. Geologia Estrutural da Região de Paraopeba, Minas Gerais. Unpubl. Int. Rep., Univ. Fed. Minas Gerais, 34 pp.

Ortu, J.C., 1990. Modelagem tectono-geofísica da porção sul da Bacia do São Francisco, Minas Gerais. Unpubl. M.Sc. thesis, Univ. Fed. Ouro Preto, Ouro Preto, 149 pp.

Parrish, R.R., Carr, S.D. and Parkinson, D.L., 1988. Eocene extensional tectonics and geochronology of the southern Omineca belt, British Columbia and Washington. Tectonics, 7: 181–212.

Pomerene, J.B., 1964. Geology and Ore Deposits of the Belo Horizonte, Ibirité and Macacos Quadrangles, Minas Gerais, Brazil. U.S. Geol. Surv. Prof. Pap., 341-D: 1–84.

Romano, C., 1990. La Évolution Tectonique de la region du Quadriláter Ferrifer, Minas Gerais, Brésil. Unpubl. Ph.D. Thesis, Université de Nancy I, Nancy, 259 pp.

Rosière, C.A., 1981. Strukturelle und texturelle Untersuchungen in der Eisenerzlagerstätte "Pico de Itabira" bei Itabirito/Minas Gerais, Brasilien. Claust. Geowiss. Diss., 9: 1–302.

Rosière, C.A., Chemale, F., Jr. and Endo, I., 1990. Der tektonische Aufbau des Eisernen Vierecks—Ein Modellversuch. Abstr. XII Geowiss. Lateinamerika Kolloquium, Munich, p. 14.

Rosière, C.A., Chemale, F., Jr. and Crocco-Rodrigues, F.A., 1991. Geologia estrutural da sinclinal de Gandarela. An. III Simp. Est. Tect., Rio Claro, Soc. Bras. Geol., pp. 14–16.

Schorscher, H.D., Carbonari, F.C., Polonia, J.C. and Moreira, J.M.P., 1982. Quadrilátero Ferrífero—Minas Gerais State: Rio das Velhas greenstone belt and Proterozoic rocks. Intern. Symp. Early Arch. Prot., Salvador, Excur. Annex, 46 pp.

Siga, O., Jr., Cordani, U.G., Basei, M.A.S., Teixeira, W., Kawashita, K. and Van Schmus, W.R., 1987. Contribuição ao estudo geológico-geocronológico da porção nordeste de Minas Gerais. An. IV Simp. Geol. Minas Gerais, Belo Horizonte, Soc. Bras. Geol., 7: 29–44.

Silva, A.M. and Gibotti, M., 1989. Petrografia, Geoquímica e Geologia Estrutural das Minas de Fazendão e adjacências. Unpubl. Int. Rep., Univ. Fed. Ouro Preto, 126 pp.

Simmons, G.C. and Maxwell, C.H., 1961. Grupo Tamanduá da Série Rio das Velhas. Dep. Nac. Prod. Min., Div. Geol. Min., Bol., 211, 31 pp.

Souza, P.C. and Müller, G., 1984. Primeiras estruturas algais comprovadas na Formação Gandarela, Quadrilátero Ferrífero. Rev. Esc. Minas, Ouro Preto, 2: 161–198.

Teixeira, W., 1985. A evolução geotectônica da porção meridional do Cráton do São Francisco, com base em interpretações geocronológicas. Unpubl. Ph.D. Thesis, Univ. São Paulo, São Paulo, 207 pp.

Teixeira, W., Jordt-Evangelista, H., Kawashita, K. and Taylor, P.N., 1987. Complexo granulítico de Acaiaca, MG: idade, petrogênese, e implicações tectônicas. An. IV Simp. Geol. Minas Gerais, Belo Horizonte, Soc. Bras. Geol., 4: 58–71.

Thorpe, R.I., Cumming, G.L. and Krstic, D., 1984. Lead isotope evidence regarding age of gold deposits in the Nova Lima district, Minas Gerais, Brazil. Rev. Bras. Geocienc., 14(3): 147–152.
Wernicke, B., 1990. The fluid crustal layer and its implications for continental dynamics. In: M.H. Salisbury and D.M. Fountain (Editors), Exposed Cross-Sections of the Continental Crust. Blackwell, London, pp. 509–544.