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THE RIO ITAPICURU GREENSTONE BELT, BAHIA, BRAZIL: STRUCTURE AND STRATIGRAPHICAL OUTLINE

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Abstract

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The Rio Itapicuru greenstone belt is situated within the São Francisco craton, and is the largest of a series of N-S trending volcanosedimentary sequences surrounded by gneisses and granitoids. Pb-Pb and Rb-Sr dating of andesitic lavas within the supracrustal sequence yielded ages of 2.1 Ga, with late tectonic granitoids emplaced about the same time. The succession appears to be developed on a sialic basement represented by the Santa Luz gneiss complex. Although the actual contact between basement and supracrustals has not been observed, there is a sharp contrast in strain and metamorphic conditions near to the contact zone. A 2.9 Ga U-Pb age obtained from a gneissic raft within the intrusive Ambrosio dome is interpreted as a basement to the greenstone sequence and was plucked from a lower crustal level by the ascending magma.

The Itapicuru River section provides good exposures along an E-W profile and has been used to attempt a reconstruction of the lithostratigraphy in this area, where the supracrustals reach a maximum thickness of 9.5 km. Rare stratigraphic facing and structural data indicate that the base of the sequence is marked by an intrusive granitoid. Above this contact is a 5.0 km thick succession of tholeiitic subaqueous basalts with rare cherts, banded iron formation, pelites, andesitic lavas and tuffs. This mafic domain is overlain by a 3.5 km thick sequence of andesites, tuffs and volcanogenic sediments, with rare dacites and laminated cherts. A silica gap between 55% and 60% SiO_2 characterises the lavas as a bimodal sequence. Two small ultramafic bodies with komatiitic chemistry also occur in the andesitic volcanic domain. The uppermost 1.0 km consists of volcanogenic siltstones and shales with rare arkoses, tuffs and basalts.

Localised bedding-parallel shear zones are the earliest deformation features observed. The shear zones may be up to 200 m thick and were important in controlling subsequent lode gold mineralisation. In the north central sector of the greenstone belt these shear zones were deformed by N-S trending, east verging folds, with ~20 km wavelength. The main greenstone sequence in the Itapicuru River section lies on the overturned limb of a syncline, and the Ambrosio dome occupies the adjoining anticline.

In the southern part of the greenstone belt, the initial deformation produced a major shear zone striking E-W with a 40° S dip and a subhorizontal E-W stretching lineation. North verging folds and thrusts produced the present E-W trend. A late, upright, NE-SW trending fold phase terminated the ductile deformation.

Greenschist facies metamorphism affected the major part of the belt during deformation, with amphibolite facies assemblages developed around the margins, and thermal aureoles developed around intrusions. Metamorphic fluids transported gold to higher crustal levels via pre-existing, steeply dipping shear zones and faults and produced the large Fazenda Brasileiro deposit, along with many smaller deposits.

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Introduction

The Rio Itapicuru greenstone belt is the largest of a series of Precambrian volcanosedimentary remnants preserved along the east margin of the São Francisco craton in NE Brazil (Fig. 1). Since the discovery of the greenstone by Mascarenhas (1973) it has attracted much interest because of its metallogenic potential. A regional map and preliminary lithological descriptions were presented by Kishida (1979) and Kishida and Riccio (1980), and regional investigations culminated with the discovery, in 1976, of the Fazenda Brasileiro gold deposit (Teixeira and Kishida, 1980; Teixeira et al., 1986).

The tectonic evolution and stratigraphy of the belt are described with the aid of detailed maps produced by local mining companies operating in the area over the past ten years. The sedimentary sequence and the tectonic history of the southern E–W trending arm of the belt appears to be different from the main N–S trending arm (Fig. 2), hence, the two will be described separately.

Cross-section in the north central sector

Structural studies and way-up criteria have been used to reconstruct the lithostratigraphy of an E–W cross-section exposed along the banks of the Itapicuru River (Fig. 3). The stratigraphic column indicates outcrop control which was used in the reconstruction (Fig. 4). Kishida and Riccio (1980) postulated the same stratigraphic order presented in this paper, but without the supporting structural and stratigraphic facing data.

Mafic volcanic domain (MVD)

The mafic volcanics crop out poorly, but weather to produce a characteristic red soil, which was used to map their areal extent. They occupy ~60% of the greenstone area and are principally situated along the marginal zones of the belt, in contact with granitoids and gneisses.

Massive, greenish-grey, fine-grained basalts constitute the main lithotype. Modal estimates average about 40% actinolite, 25% plagioclase, 15% epidote, 10% chlorite, 5% calcite and 5% accessory components. In places, variolitic textures occur in irregular zones within the massive flows. Varioles consist of whitish round spots (up to 1.5 cm in diameter) filled with calcite, albite and quartz. This texture is interpreted as resulting from the rapid crystallisation of two immiscible liquids, one felsic and the other basaltic (Silva, 1984). Pillow structures were observed in only two localities (A and B in Fig. 3) and range in size from 0.15 m to 2.0 m (maximum dimension). Aphanitic chilled rims and radial cooling cracks are present and triangular tails can be used to determine the stratigraphic way-up (Fig. 5). Flow breccias of angular fragments in an aphanitic basalt matrix also occur close to the pillows (Fig. 6). Porphyritic basalts are rare and occur as irregular lenses, where igneous megacrysts can be either amphibole or plagioclase, and may reach up to 1.0 cm in length. Kishida and Riccio (1980) classified the basalts into inferior (high FeO and TiO_2) and superior (low FeO and TiO_2) groups; both have tholeiitic affinities. However, three repetitions of the inferior group along the Itapicuru River profile imply the presence of two major fold structures (wavelength 2.0 km), if such an inferior and superior stratigraphy exists. Several marker beds, with great lateral continuity, occur in the basalts. They are not repeated and we find no evidence for such folding. Hence, we believe that the inferior and su-

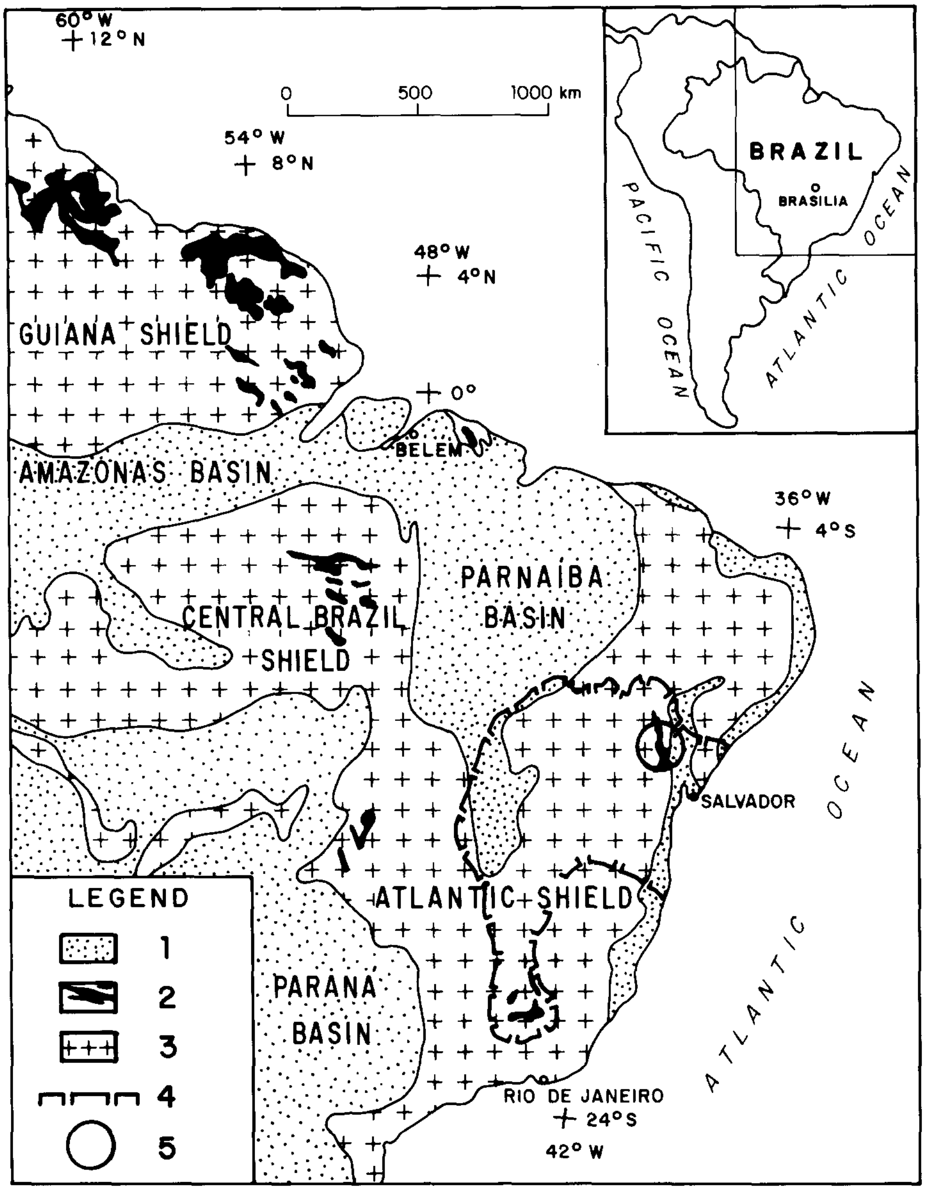

Fig. 1. Major geological units of the east-central part of South America. Simplified after Almeida (1977), Gibbs and Barron (1983), Schobbenhaus (1984) and other maps. Legend: (1) Phanerozoic cover, (2) greenstone belts, the Itapicuru and Guiana Shield occurrences are Proterozoic and the others are Archaean, (3) Precambrian terrains, (4) outline of the São Francisco craton, (5) study area (Rio Itapicuru greenstone belt).

perior terms do not have any stratigraphic significance.

Intercalations of chemical sediments and fine-grained clastics occur throughout the MVD. Fine, parallel-laminated, white and black cherts, banded iron formation (BIF), pelitic schists (in places graphitic and associated with small massive sulphide bodies) and rare carbonates are the main lithotypes. One marker horizon of pelitic sediments, ~100 m thick, can be traced along strike for ~100 km, without any change in facies, indicating that the large

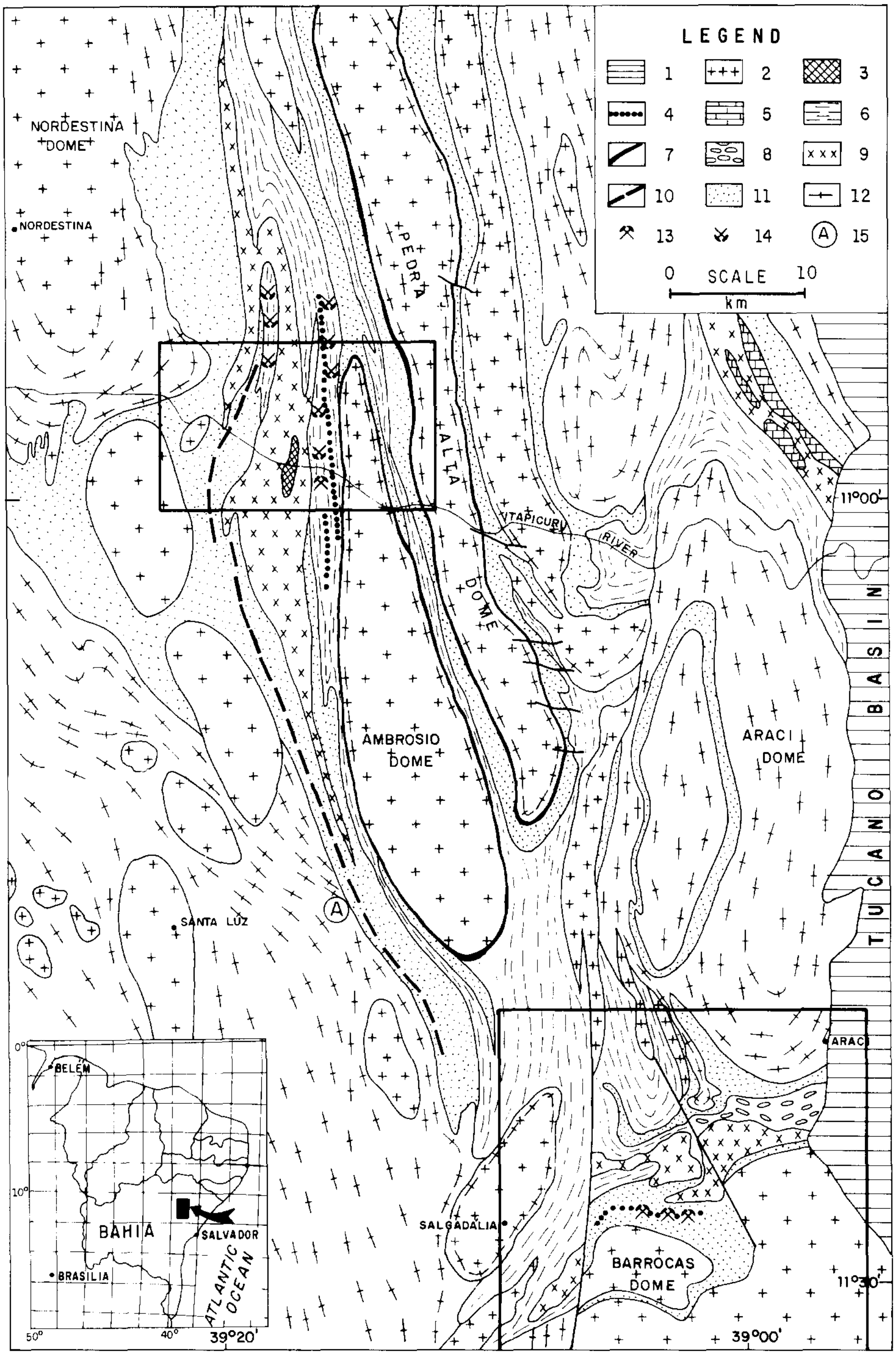

Fig. 2. Geological map of the Rio Itapicuru greenstone belt. The two thick rectangles correspond to the areas shown in Figs. 3 and 11. Legend: (1) Mesozoic sediments (Tucano basin), (2) late tectonic granitoids (mainly granodiorites), (3) metadiorites, (4) metagabbro sills, (5) metadolomites, (6) metasiltites and metapelites from the sedimentary domain, (7) banded iron formation and cherts, (8) metaconglomerates and meta-arkoses, (9) calc-alkaline metavolcanics (lavas and pyroclastics), (10) metapelites and chemical sediments in the mafic volcanic domain, (11) tholeiitic metabasalts, (12) deformed granitoids and gneisses, (13) gold mines, (14) gold deposits and occurrences, (15) locality where basement is inferred (see text).

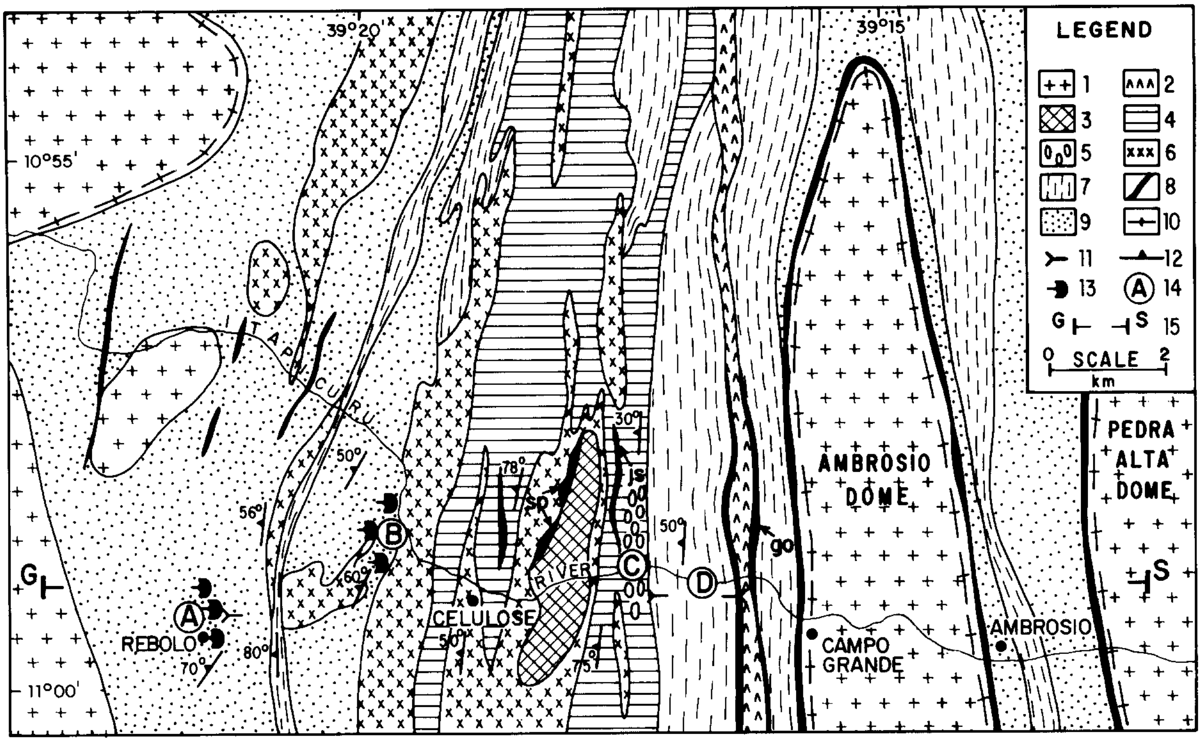

Fig. 3. Geological map of the Itapicuru River section. Legend: (1) late to syntectonic granitoids (mainly granodiorites), (2) metagabbro, (3) metadiorite, (4) felsic metatuffite, (5) andesitic meta-agglomerate, (6) meta-andesite and metadacite, (7) metapelite and metasiltite, (8) chemical metasediments (BIF and chert), (9) tholeiitic metabasalt, (10) deformed granitoid and gneiss, (11) younging direction (way-up criteria), (12) attitude of foliation, (13) pillow structures, (14) locality of photographs (see text), (15) geological section (see Fig. 9). Labels for thin units: sp = serpentinite; go = gondite (spessartine + quartz); js = jaspilite.

developing basin had a constant sedimentary environment in a N–S direction (Fig. 2). These lithologies suggest that the MVD developed in an immersed basin with very little clastic sedimentary influx, but with major subaqueous basalt effusions in tranquil water conditions. Water depth during deposition is difficult to determine, but is believed to be deeper than wave base, owing to the absence of any current-induced sedimentary structure in the intercalated sediments. Both oxidising and reducing conditions are witnessed by the intercalations of oxide facies BIF and graphitic shales with minor massive sulphides.

Felsic volcanic domain (FVD)

This domain is irregular and grades laterally into the MVD or into the sedimentary domain (SD). One localised volcanic centre is marked by andesitic agglomerates which approach 400 m in thickness; this centre lies astride the Itapicuru River (Fig. 3).

The felsic volcanic edifice has a N–S extent of 30 km. Agglomerates are surrounded by finer tuffs and andesitic lavas on all sides. The relative proportions of pyroclastics, tuffs and lavas are still difficult to determine accurately, but lavas and tuffs appear most important, occurring in approximately equal proportions.

The grey-coloured andesites can be massive or schistose, depending on the amount of strain. They are fine-grained to porphyritic with hornblende, plagioclase and, rarely, quartz phenocrysts; the matrix consists of finely saussuritised plagioclase, chlorite and quartz. Alteration products are mainly epidote, sericite and albite.

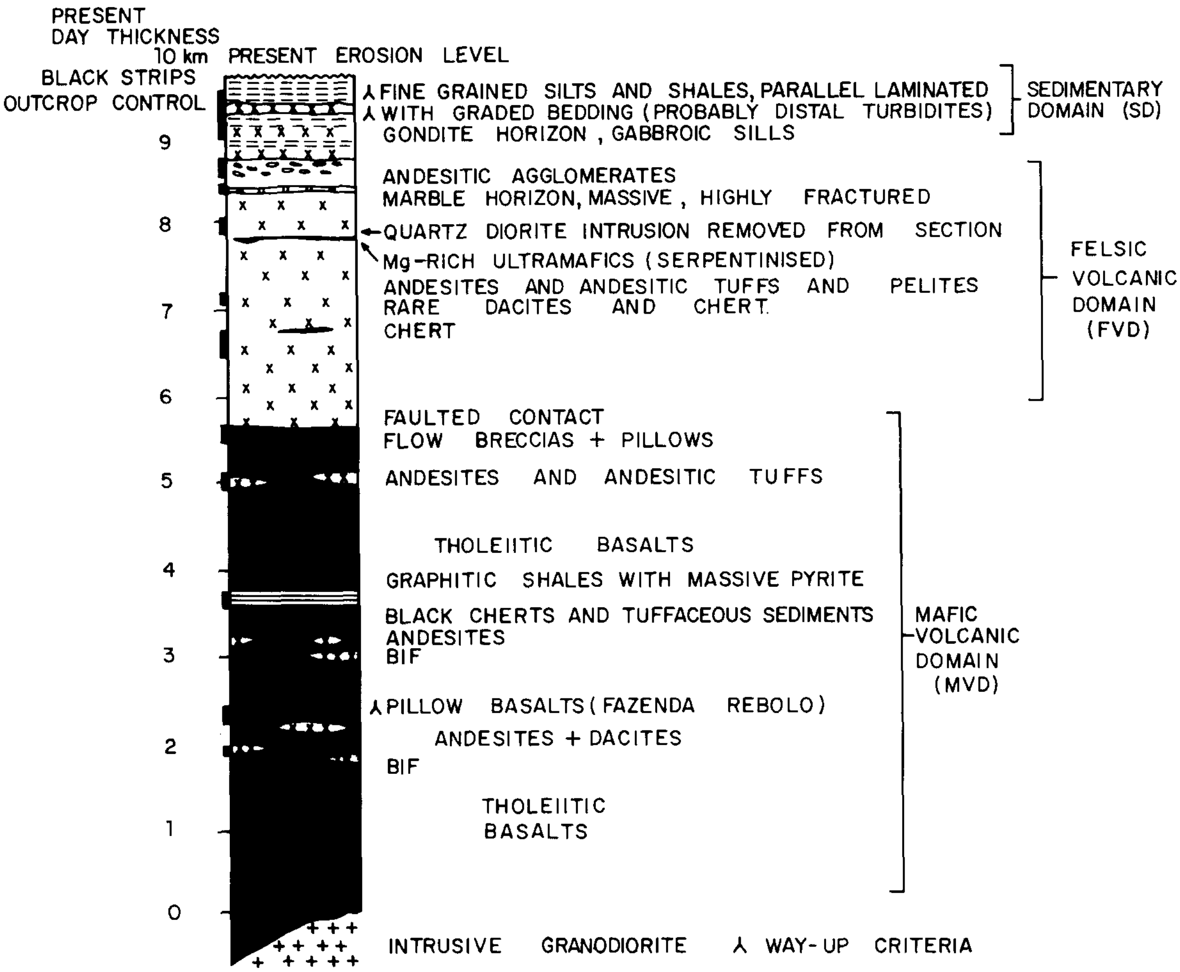

Fig. 4. Reconstructed lithostratigraphic column of the Itapicuru River section, composed along the geological profile indicated in Fig. 3. Present day thicknesses are shown along the left-hand side, and black strips show the outcrop control used in the reconstruction.

Modal estimates indicate that the andesites contain 40% plagioclase (An_{30-35}), 35% chlorite, 10% epidote, 10% quartz and 5% accessory phases (for chemical analyses see Kishida and Riccio, 1980). Lenses of spherulitic andesite, which have a rugose surface in outcrop, occur in a few places. The spherulites contain aggregates of plagioclase and quartz and measure up to 3.0 mm in diameter. These are believed to be immiscible globules which formed prior to extrusion (Silva, 1984). Minor porphyritic grey dacites also occur in this domain but their areal abundance is unknown owing to poor exposure. The andesites and dacites show a calc-alkaline affinity, and there is a bimodal silica distribution between the tholeiitic basalts (MVD) and felsic lavas (FVD), with a gap between 55% and 60% SiO_2 (Kishida and Riccio, 1980).

Felsic tuffs are schistose, with strongly oriented chlorite and sericite flakes in the matrix. The clasts are fragments of andesitic to dacitic lavas, broken plagioclase, quartz crystals and volcanic glass shards. The matrix is very fine-grained and probably composed of ash fall material with an andesitic composition. Volcanic bombs of andesitic composition which reach up to 2.0 m in length are common in the agglomerates. Some helicoidal shapes have been iden-

Fig. 5. Pillowed metabasalts near the Fazenda Rebolo, in the mafic volcanic domain, with way-up criteria well preserved due to the low strain state. Rocks young from right to left. Exposure locality labelled A in Fig. 3. The hammer is 30 cm long.

tified, indicating that subaerial eruptions occurred, although it is still debatable whether the bombs finally settled in water or not.

Epiclastic sediments occur throughout the domain, with textures and mineralogy similar to the fine tuffs, but with sedimentary structures indicating reworking. Chert layers indicate that low sedimentary deposition rates occurred between volcanic eruptions. Thus, although the felsic volcanic agglomerates and tuffs were the results of subaerial eruptions, the intercalated cherts suggest water surrounded

Fig. 6. Pillow breccia from the mafic volcanic domain. Locality B in Fig. 3. The hammer is 30 cm long.

Fig. 7. Rhythmic graded bedding in the metaturbidite from the sedimentary domain. The stratigraphic top is indicated by the arrow. Consistent younging directions with structural facing confirm the sequence was only affected by one phase of folding. Locality D, Fig. 3.

the volcanic centres, making this an ideal environment for massive sulphide deposition, but as yet only barren massive pyrite has been discovered.

The only ultramafic rocks yet found in the greenstone belt occur in the FVD near the Itapicuru River (Fig. 3). Two ellipse-shaped outcrops 1.0 km long and 200 m wide were identified. These rocks are serpentinites with euhedral, equidimensional olivine pseudomorphs, 1.0–2.0 mm long, totally transformed to serpentine, talc and carbonate, with interstitial augite and minor chromite. Chemical analyses indicate these rocks have komatiitic affiliation, although spinifex textures have not been observed (Silva, 1984).

Sedimentary domain (SD)

The main rock types in this domain are fine-grained psammites and pelites, which are rhythmically banded with planar parallel stratification (Fig. 7). Individual siltstone beds may reach up to 15.0 cm thick and contain pelite rip-up clasts. Graded bedding and rare small-scale cross-bedding provide way-up criteria, which were used in the structural interpretation (Fig.

7). White laminated chert, jaspilite, BIF and manganese-rich sediments (gondites with spessartine and quartz) also occur throughout this domain, marking periods of low clastic sediment influx. This sequence is interpreted as volcanically derived distal turbidites with intervening chemical sediments. Rare arkoses and conglomerates (with clasts up to 10.0 cm) occur near the base of the sequence, indicating more proximal conditions.

Minor basalts are intercalated with the sediments along with gabbroic sills, representing the magmatic activity which may have been involved in the production of charged hydrothermal fluids and resulting chemically precipitated sediments.

Granite gneiss domes

The Ambrosio dome is the largest body occurring within the greenstone belt sequence and is the most carefully studied to date (Fig. 8). Lithologies range from tonalite to granite and notable amounts of tourmaline-rich pegmatite occur near the contacts with the greenstone. Jardim de Sá (1982) suggested that the gneisses in the dome represent basement, based on observations that these rocks have a more complex deformation history than the greenstone sequence. Detailed mapping of the Ambrosio structure indicates that most of the body was intrusive, although large basement rafts were plucked from lower crustal levels (Matos and Davison, 1987a,b). The most striking feature of the Ambrosio dome is its highly deformed margins, which are composed of deformed granitoids, pegmatites and gneiss rafts. These appear to have deformed at temperatures high enough to produce ductile deformation of K-feldspar phenocrysts and thus deformation is thought to be synchronous with intrusion. The finite strain fabric at the dome margins, in the Itapicuru River section, is oblate, which suggests the present outcrop level is the flattened roof zone of an intrusion (Matos and Davison, 1987a,b). An 80.0 m thick BIF horizon is in contact with

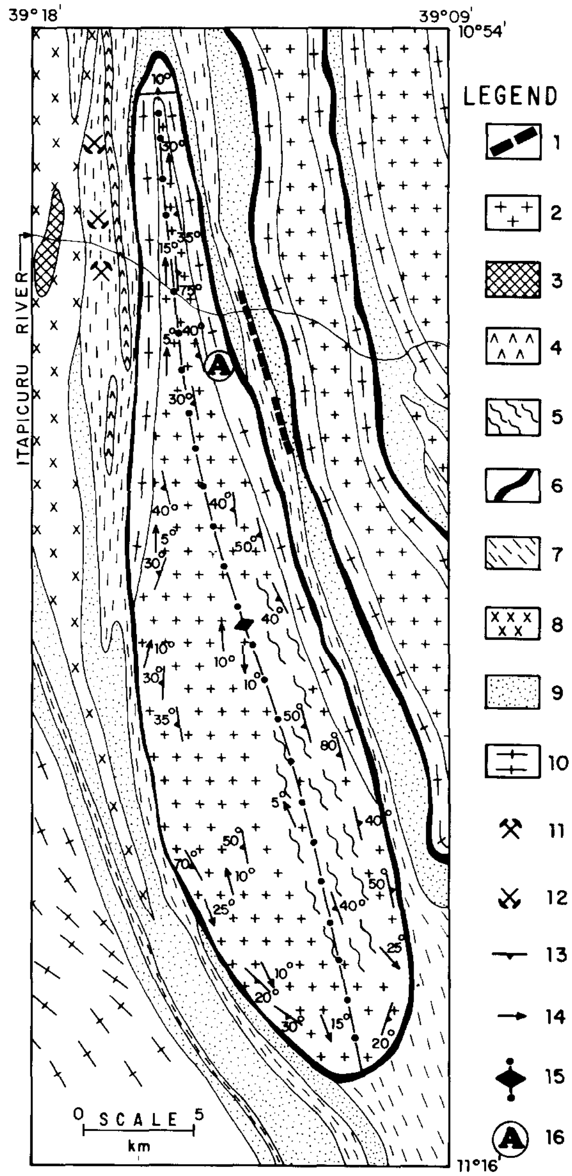

Fig. 8. Map of the geology around the Ambrosio dome. Legend: (1) pegmatite, (2) granite and granodiorite, (3) metadiorite, (4) metagabbro, (5) granitic gneiss and migmatite, (6) banded iron formation, (7) metapelite, (8) felsic metalava and pyroclastics, (9) metabasalt and amphibolite, (10) banded gneiss, (11) Maria Preta gold mine, (12) gold deposit, (13) attitude of foliation, (14) plunge of mineral lineation, (15) anticlinal axial trace, (16) locality of dated gneiss sample (see text).

the dome. Rare exposures and magnetic surveys suggest the BIF almost completely surrounds the dome and it is envisaged that the iron formation acted as a horizontal competent barrier which arrested the magma ascent and produced extensive horizontal flow. The Pedra Alta and Nordestina domes (Fig. 2) consist of similar lithologies and have similar characteristics to the Ambrosio intrusion.

Later granitoids

Smaller granitoid bodies which are clearly intrusive into the greenstone supracrustals are common (Fig. 2). They are mainly grey granodiorites without deformation textures and are presumed to be late tectonic. As yet the structures and lithologies of the granitoids have not been mapped or studied geochemically.

Gabbroic sills

Several narrow sills with gabbroic composition have been mapped in the northern sector. These are preferential sites for gold mineralisation when associated with shearing and quartz veining. Most of the gabbros were intruded near the contact between the FVD and SD. Relict ophitic textures with plagioclase and interstitial hornblende are commonly preserved.

Basement

Unequivocal evidence of the basement to the greenstone sequence does not exist and there are no data which support the hypothesis of reworking of basement fragments into the sediments of the greenstone. However, the Santa Luz gneiss complex, which lies to the southwest of the Rio Itapicuru greenstone belt is interpreted as a sialic basement to the supracrustal sequence (Fig. 2). Here, the contact between the banded gneisses and the greenstone has not been observed directly, but exposures of pelites, which lie 50.0 m above the gneisses (locality A, Fig. 2), do not show contact metamorphism. Furthermore, there is a strong structural discordance between the gneissic banding and the cleavage in the pelites, which suggests the deformation in the gneisses may be older (Fig. 2). Further indirect evidence for a pre-existing sialic basement include the megaxenoliths of banded gneiss within the highly deformed borders of the Ambrosio dome which have been dated using U–Pb on zircons at 2930 ± 32 Ma (Gaál et al., 1987).

Deformation in the northern sector

The deformation history in the N–S trending arm of the greenstone belt is best displayed in the rocks along the E–W Itapicuru River section (Fig. 3), although the exposure is far from continuous. In the MVD the cleavage dips 50–70° W with an average of 65° (Fig. 9). Bedding structures are rarely seen in the basalts. Pillow lavas (Fig. 5) at Fazenda Rebolo (Fig. 3) indicate a low strain state (X:Z=2.1:1), with the Z axis of the pillows perpendicular to a weak foliation which is only observable in the inter-pillow matrix. This suggests that the orientation of the foliation is close to that of the bedding planes, assuming the pillows had an original bedding-preferred orientation. Graphitic schists and cherts within the basalt sequence indicate the strike of the bedding is parallel to the schistosity. Minor folds in these sediments have been observed in drill cores, where an axial planar cleavage dips parallel to the cleavage in the surrounding basalts. The felsic lavas do not usually exhibit minor deformation structures. In the tuffs and volcanogenic sediments of the FVD and SD, minor folds with up to 3.0 m wavelength and interlimb angles of 10–60° have been observed. These folds have an axial planar cleavage which can be: (1) slaty, with quartz, chlorite or biotite alignment; (2) a crenulation cleavage with or without new muscovite and biotite along the axial planes; and (3) a centimetre-scale, spaced, solution cleavage with dark solution seams. The axial planes of minor folds dip 60° W and axes vary with a plunge of 0–40° towards 000–020° or to 180–200°. Where younging directions have been observed in the sediments there were no strati-

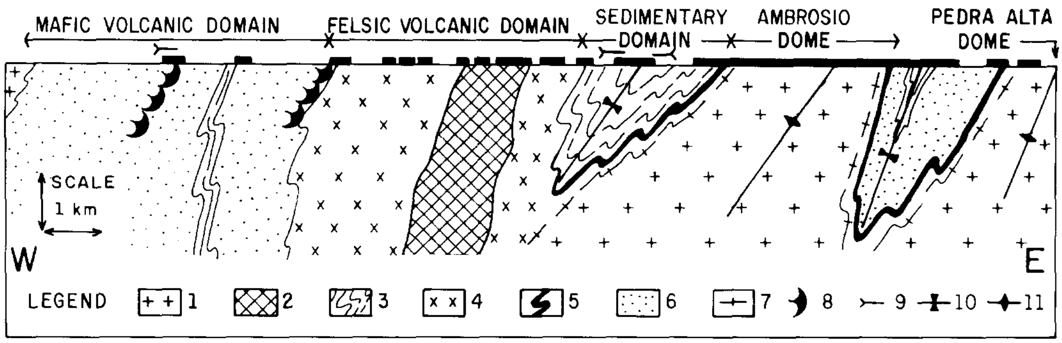

Fig. 9. E–W structural cross-section along the Itapicuru River. Location shown in Fig. 3. Legend: (1) undeformed granite and granodiorite, (2) metadiorite, (3) volcanogenic fine-grained metasediment, (4) calc-alkaline meta-andesite and pyroclastic, (5) chemical metasediment (chert and BIF), (6) tholeiitic metabasalt, (7) banded gneiss and granitic gneiss, (8) pillow structures, (9) stratigraphic younging, (10) syncline axial plane, (11) anticline axial plane. The black strips at the top of the section indicate outcrop control.

graphic inversions before this folding phase. However, localised bedding-parallel shears occur up to several hundred metres wide. During shear an intense deformation fabric developed along with a mineral stretching lineation which is affected by the first phase of folding. These shears appear to be important in controlling the localisation of lode gold–quartz veins.

There is a pre-existing mica foliation (muscovite, sericite and biotite) parallel to bedding in the sediments and which is folded by the minor folds described above. This foliation has been interpreted as having been produced by an earlier phase of recumbent folding (Teixeira, 1985). However, several field observations suggest this may be a compaction cleavage since no minor folds have been observed associated with the foliation, which is consistently parallel to bedding. If the limbs of the postulated recumbent folds are perfectly parallel to the cleavage, this implies very high strain states. However, finite strain estimates indicate that the deformation is moderate to weak (Fig. 10). Structural inversions have not been recorded and there is no observed repetition of mapped marker horizons. It is assumed, therefore, that a bedding-parallel compaction cleavage was developed which was locally sheared, metamorphosed and then refolded by first-phase folds, which have N–S axial planes and dip consistently 50–70° W. The cleavage observed in the basalts and andesites is perhaps a composite fabric of compaction and tectonic flattening.

The folds are very consistent in axial strike, and rectilinear continuity of marker horizons parallel to the axial trace of these folds, is illustrated in Figs. 2 and 3. Examination of the stratigraphic succession indicates that there are no obvious large scale repetitions along the Itapicuru River profile. However, smaller-scale repetitions cannot be discounted as the exposure is not continuous.

Younging directions indicate that the major part of this cross-section is on the overturned limb of a syncline (Fig. 9). The centre of the syncline is mapped in the SD, and to the east an anticline is occupied by the Ambrosio dome, which truncates the fold limb (Fig. 9). Minor folds (up to 10 m wavelength) of the same style and orientation affect the gneissic fabric along the margins of the dome. A penetrative biotite fabric is observed, parallel to the axial planes of these minor folds, and a mineral lineation of biotite and quartz is developed parallel to their axes. This suggests that the Ambrosio dome was intruded before, or early in the deformation phase which produced these folds. Thin sections of pelites near to the dome contact, indicate that metamorphic porphyroblasts of garnet and andalusite are syntectonic, with the axial

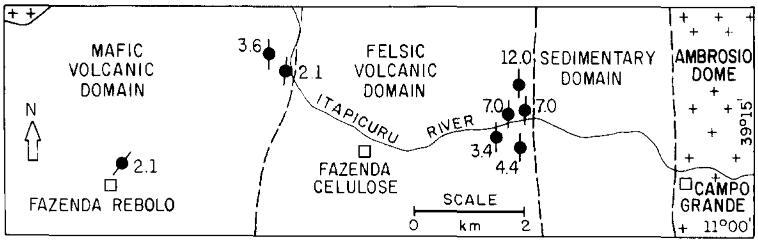

Fig. 10. Estimates of maximum flattening across the cleavage in the Itapicuru River section. Numbers are X:Z ratios and the line through the circle is the horizontal projection of the X axis. $X \simeq Y$ at all localities. X is the maximum, Y the intermediate and Z the minimum axis of the strain ellipsoid.

planar cleavage of the major folding phase wrapping around them and with internally folded inclusion trails. Minor fold asymmetry indicates the Ambrosio dome is an asymmetric periclinal fold structure rather than an original dome shape due to intrusion (Figs. 8 and 9). Earlier it was stated that the Ambrosio dome lies in contact with a BIF horizon which is interpreted to be localised near the top of the greenstone pile; if this interpretation is correct, the magma must have penetrated up through most of the greenstone succession before spreading laterally below the BIF horizon.

A second phase of deformation was observed in the tuffs and sediments, but not in the lavas. This is a crenulation phase, with maximum fold amplitude up to 30.0 cm and wavelengths of a similar scale. There is no mineral growth associated with this deformation phase. Crenulation axes generally dip 60–280° with variably oriented axial planes. Detailed mapping at a scale of 1:10 000 does not reveal any larger-scale structures associated with these crenulations. It is significant that these structures are only developed in less competent units, and crustal shortening is thought to be minimal.

Strain measurements indicate that the finite fabric is oblate, with X being approximately equal to Y in the majority of cases. The flattening across the cleavage (X:Z in Fig. 10) is considered to be a maximum value for the tectonic deformation, as bedding is subparallel to cleavage in all of the samples studied. Thus, any sedimentary fabric is also included in the measurement (see Ramsay and Huber, 1983). Measurements were made using pyroclastic fragments, pillow lavas (Figs. 5 and 6), detrital quartz grains and conglomerate pebbles. Very little long-axis angular variation was observed in the deformed objects, presumably because a tectonic fabric was superimposed on an initial bedding plus compactional fabric. The harmonic mean method of Lisle (1977) was used to estimate the axial ratios of the 'sedimentary fabric + compaction + deformation' ellipse. Measurements which were made in basalts (X:Z = 2.1:1) are considered to be the closest to a true tectonic flattening strain across the cleavage, but these are still maximum estimates. The pyroclastics and intercalated sediments show much higher X:Z ratios (up to 12:1) because of original sedimentary preferred orientations and higher compaction, as well as larger tectonic strains (Fig. 10).

The possibility of any minor folds producing tectonic thickening where there is no exposure could result in a reduction of the estimate of the original thickness of the greenstone succession. However, exposed minor folds are rare in the basalts and andesites and therefore fold repetition is not thought to be important, except in the sediments and tuffs. This relatively simple deformation scheme facilitated the reconstruction of the greenstone succession using the overturned limb of the megasyncline. The total thickness of the succession is 9.5 km (Fig. 4). This is considered an approximate value since an intrusive granitoid marks the base of the greenstone sequence and greenschist facies sediments occur at the top, suggesting that a

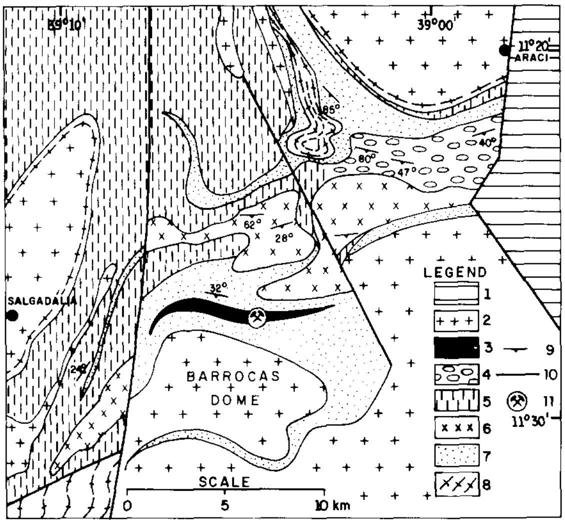

Fig. 11. Geological map of the southern sector of the Rio Itapicuru greenstone belt. After Teixeira (1985). Legend: (1) Phanerozoic cover (Tucano basin), (2) intrusive granodiorite and tonalite, (3) differentiated mafic sill (Weber belt), (4) sedimentary domain; polymictic metaconglomerate, (5) sedimentary domain; metapelite, meta-arkose and metagreywacke, (6) felsic volcanic domain: calc-alkaline metadacite and metarhyodacite associated with metatuffaceous and metasedimentary layers, (7) mafic volcanic domain: tholeiitic metabasalt interbedded with metasedimentary layers, (8) banded gneiss, (9) attitude of S_2 foliation, (10) fault/shear zone, (11) Fazenda Brasileiro gold mine.

considerable amount of erosion has occurred to expose these metamorphic rocks at the surface. There is also an offsetting effect of flattening and, hence, a thinning of the volcanosedimentary pile caused by compaction and tectonic deformation.

Lithologies and deformation in the southern sector

The area which was studied in detail in the southern sector of the Rio Itapicuru greenstone belt is outlined in Fig. 2 and shown in more detail in Fig. 11. Regional mapping is not as advanced in the southern domain as it is in the northern domain, except in the Faixa Weber gold district and along principal road and rail sections. The complexity of the structure in this area also makes it difficult to reconstruct the stratigraphy. Tholeiitic basalts and calc-alkaline felsic volcanics and sediments are represented, although there is a predominance of coarser-grained clastics at the top of the sedimentary sequence. Polymictic matrix-supported conglomerates, with volcanic-derived detritus, are well developed south of Araci (Fig. 11).

Five deformation phases have been recognised in the Fazenda Brasileiro mine area (Teixeira, 1985; Gaál and Teixeira, 1988). The first tectonic phase was an intense shearing accompanied by isoclinal folding. This shear zone extends for at least 8.0 km E–W along the Weber belt (Fig. 11). A strong ductile fabric produced in the sediments and igneous rocks destroyed most of the primary textures. An E–W, subhorizontal stretching lineation was produced on the S_1 shear planes and is interpreted as the main movement direction. An F_1 antiform which folds the shear fabric is inferred from repetition of the differentiated units of a layered mafic sill in the Fazenda Brasileiro mine area (Fig. 12; Teixeira, 1985). Further evidence of localised F_1 folding lies in stratigraphic inversions identified in the sediments. The isoclinal folding (F_1) and shearing events are classified as the D_1 deformation in this paper. The D_1 event is not penetrative outside the Weber belt, and the D_2 event is the first recognised regional phase in the southern sector.

The D_2 event produced E–W trending, tight to isoclinal folds, with axial planes dipping 40° S and subhorizontal undulating axes. The folding produced an axial planar slaty cleavage outside the areas affected by D_1, and a finely spaced crenulation cleavage in the mine area. Chlorite and white mica are the main fabric-forming minerals. The F_2 folds have $\geqslant 500$ m amplitude in the mine area (Fig. 12). The D_3 event represents a continuation of the same south to north movement pattern indicated by the D_2 structures. The D_3 phase produced subvertical, E–W trending folds which are open, asymmetric monoclines with a spaced mica crenulation

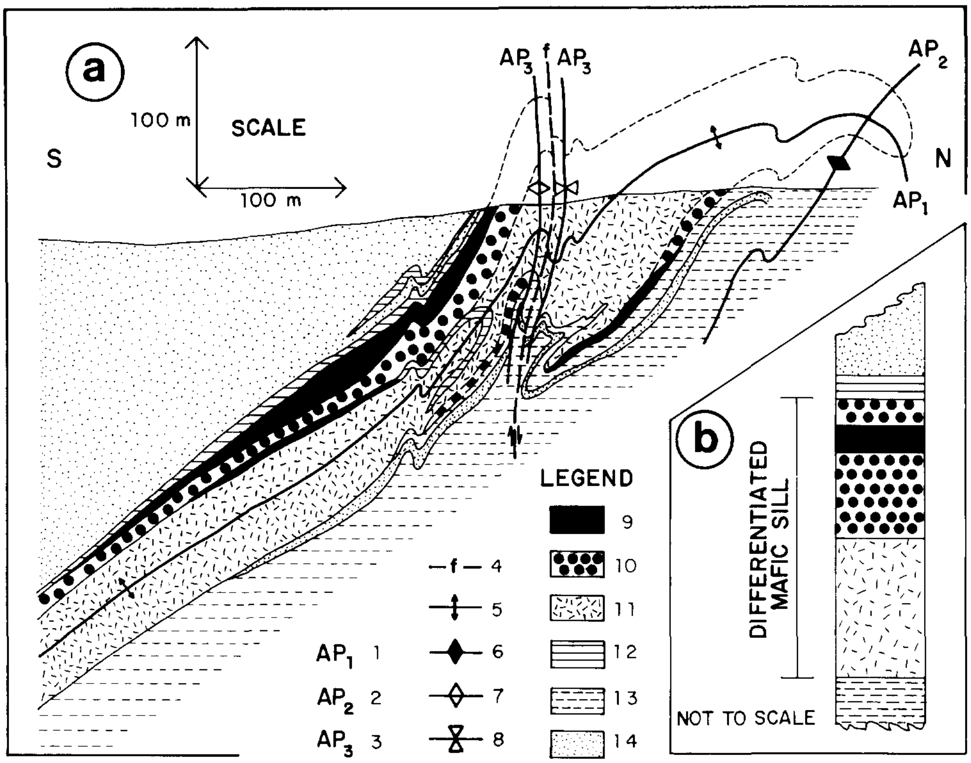

Fig. 12. Geologic section (a) and stratigraphic column (b) of the Fazenda Brasileiro gold mine. After Teixeira (1985). Legend: (1) axial plane trace of F_1 folds, (2) axial plane trace of F_2 folds, (3) axial plane trace of F_3 folds, (4) fault, (5) F_1 antiform, (6) F_2 antiform, (7) F_3 antiform, (8) F_3 synform, (9) orebodies (gold-quartz vein network), (10) Fe-rich metagabbro, (11) metagabbro, (12) graphitic metapelite, (13) metaturbidite, (14) tholeiitic metabasalt. The gold-quartz veins are hosted by the Fe-rich gabbroic horizon which is part of the differentiated mafic sill (see text).

cleavage. These folds refold the axial planar D_2 cleavage. Northward-directed thrusting which is also correlated with the D_2–D_3 events occurred in the Fazenda Brasileiro area (Fig. 13).

The maximum shortening direction changed during the D_4 event, when open, upright NE–SW trending folds developed, with an axial planar crenulation cleavage. F_4 fold axes generally plunge 55° towards 225°. As yet the amplitude and wavelength of these late folds have not been determined.

Finally, NE–SW and NW–SE trending brittle faulting occurred which produced kilometre scale horizontal offsets of lithological contacts, but net slip of these faults is not known.

Structural correlations between the northern and southern domains are still not clear and a change in principal shortening direction from E–W in the north to N–S in the south is poorly understood. The southern domain appears to be an anomalous area, as all the greenstone remnants further north show a well-defined N–S orientation.

Metamorphism and structural relationships

Detailed metamorphic studies undertaken in the northern sector and field observations in the southern sector indicate that the greenstone is generally in greenschist facies, except near to granite–gneiss domes where amphibolite facies metamorphism developed.

Contact metamorphism is observed around all the granitoid intrusions, with development

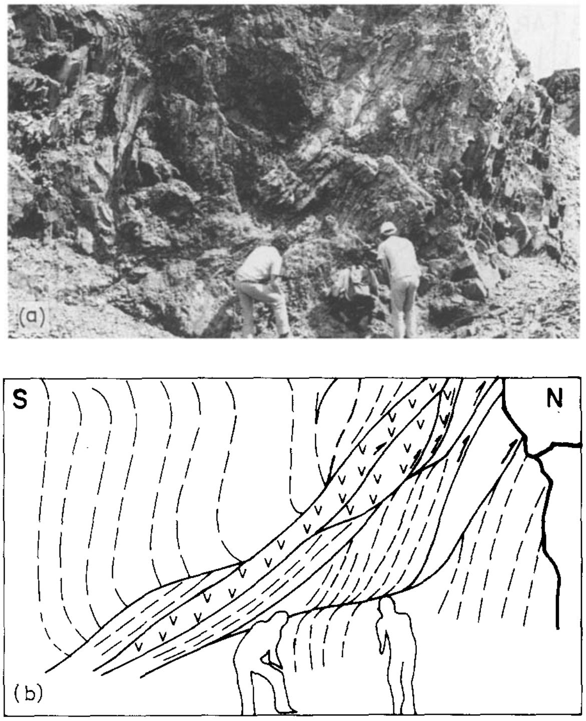

Fig. 13. (a) Northward directed thrusting producing a duplex structure in the Fazenda Brasileiro gold mine. (b) Line drawing of (a). Broken lines represent S_2 foliation traces, solid lines are thrust contacts and the V-pattern is a quartzofeldspathic marker horizon.

of hornblende hornfels in the basalts and andalusite and garnet porphyroblasts in the pelites. Where the granitoids are not deformed and appear to be late-tectonic, supporting mineral textures can be found. Porphyroblasts from the thermal aureole overprint earlier minerals defining the regional schistosity produced during the regional metamorphism.

The textures in the sediments allow the timing of metamorphism to be related to deformation. All the sediments exhibit a bedding-parallel mica fabric of sericite and chlorite. As outlined in the structural section, this fabric is believed to be caused by deep burial metamorphism during basin subsidence and is a 'compactional' cleavage. This cleavage was folded by F_1 folds which produced an S_1 axial planar cleavage consisting of mica and quartz grains reoriented by mechanical rotation and pressure solution along with new mica growth (sericite, biotite and chlorite). The F_1 folds were thus produced during greenschist facies metamorphism, although mica growth had already commenced before the D_1 phase.

Along the Ambrosio dome margins the higher temperatures produced hornblende-hornfels facies assemblages (Matos and Davison, 1987b). The pelites show a rapid increase in metamorphic grade near the eastern border of the dome where, 500 m from the dome contact, biotite-grade sediments occur. These same sediments undergo partial melting to produce a coarse-grained muscovite + quartz assemblage along the dome margin. This zonation suggests that within 500 m of the dome contact the thermal gradient during intrusion exceeded 200°C km^{-1}. The porphyroblastic textures of garnet and andalusite indicate that peak metamorphism was syntectonic during intrusion of the dome. The porphyroblasts have tectonic inclusion fabrics which may or may not be deformed, and also exhibit pressure shadows and 'wrap around' cleavages. A syntectonic metamorphic peak is supported by evidence of pegmatite injection into the high-grade zone during deformation, with the pegmatites deformed to varying degrees depending on the time of injection (Matos and Davison, 1987a,b).

Because the major part of the greenstone belt appears to be greenschist facies it may be argued that a simple megasyncline in the Itapicuru River section is unlikely, since metamorphic grade should progressively increase towards the base of the sequence. The mapped vertical distance (normal to bedding) between the uppermost and lowermost exposures of greenschist assemblages is 7.0–8.0 km. However, deformation occurred during metamorphism and, perhaps, uplift of the synclinal limbs occurred at the same time as subsidence in the hinge. This would allow rocks of similar metamorphic grade to crop out over apparently large vertical profiles, if metamorphic reaction rates could keep pace with subsidence rates.

Geochronology

Brito Neves et al. (1980) dated the felsic volcanics in the southern part of the belt at 2080 ± 90 Ma, with a five point Rb–Sr whole rock isochron, with an initial ratio of 0.7017 ± 0.0014. This age is corroborated by a three point Pb–Pb mineral isochron on andesites taken from the Itapicuru River section which gave a tentative age of 2178 ± 12 Ma (Gaál et al., in preparation). These ages are interpreted as the original magma crystallisation event in the FVD.

Brito Neves et al. (1980) also published a 13 point Rb–Sr whole rock isochron on intrusive granites and migmatites from the western and southern parts of the belt which gave an age of 2090 ± 27 Ma, with an initial ratio of 0.704 ± 0.0008. Recent U–Pb zircon ages of syntectonic granites in the western part of the belt (5.0 km north of Santa Luz; Fig. 2) also gave a similar age of 2107 ± 23 Ma (Gaál et al., 1987; Gaál et al., in preparation).

Gaál et al. (1987) also presented an age of 2930 ± 32 Ma from a highly deformed gneiss in the marginal zone of the Ambrosio dome (locality A; Fig. 8) which we interpret to be a xenolith plucked from a lower crustal level. The geochronological data point to a Proterozoic age for deposition, deformation and intrusion within the greenstone succession, with a probable Archaean basement already in existence before greenstone formation. The isochron and concordia plots will be presented in more detail elsewhere (Gaál et al., in preparation; Silva et al., in preparation).

Gold mineralisation

The principal gold districts presently known in the Rio Itapicuru greenstone belt are shown in Fig. 2. The dominant geological feature in the Fazenda Brasileiro (the largest deposit) is an E–W trending, 8.0 km long differentiated mafic sill which is bounded by basalts and turbidites (Figs. 11 and 12; Teixeira, 1985). Gold deposition is associated with hydrothermal alteration processes which overprint greenschist facies regional metamorphism and caused carbonation, albitisation and sulphidation, along with quartz veining (Marimon et al., 1986). The main host rock to gold mineralisation is an Fe-rich differentiated gabbroic horizon which is part of the sill (Fig. 12). The main orebodies are localised within a shear zone (Teixeira, 1985). However, mineralisation occurred after shearing, when the shear zone had been rotated to a 45° S dip by later folding.

The presence of mafic rocks is not a prerequisite for gold deposition in the belt, since most of the other smaller deposits occur in felsic tuffs, andesites, pelites and intrusive diorites, frequently associated with steeply dipping shear zones which are cross-cut by quartz veins produced by hydraulic fracturing. The major quartz veins occur along lithological contacts which dip parallel to the shear planes. Pervasive small-scale fracturing in the more competent lithologies was responsible for providing the necessary surface area for effective fluid–wall rock reactions to produce economic gold concentrations. These deposits appear to be very similar to Australian Archaean gold deposits described by Groves et al. (1984).

Conclusions

The Rio Itapicuru greenstone belt is considered to be the remnant of an Early Proterozoic lava and volcanoclastic filled basin, which was subsequently metamorphosed and deformed within ~ 200 Ma of formation.

Unequivocal sialic basement has not been observed, but indirect evidence suggests that granodioritic gneisses did exist before greenstone deposition. Exposures along the Itapicuru River section permit a crude restoration of the stratigraphic pile in the thickest part of the greenstone, but rapid lateral variation in thickness and sedimentary facies do not allow extrapolation of this stratigraphy to other parts of the belt. Subaqueous tholeiitic basalts with intercalated chemical sediments occupy the lowermost 5.0 km of the pile, followed by 3.0 km of calc-alkaline andesitic lavas, pyroclastics and epiclastic sediments. A localised felsic volcanic centre occurs in the Itapicuru River section, which is marked by a 400 m thick agglomerate unit and a subvolcanic intrusion of dioritic composition. Finally, 1.0 km thick distal turbidites terminate the sequence. However, these sediments may have been much thicker as erosion has exhumed greenschist facies sediments. The sediments are much coarser in the southern portion of the belt where polymictic conglomerates occur, but the more complex structure and paucity of exposures does not permit a stratigraphic reconstruction in this area.

The basin was compressed in an E–W direction along most of its present length which produced localised bedding-parallel shearing and eastward-verging, large-scale folding with a 000–020° trend. Farther south, in the Weber gold district, the predominant structures are E–W striking folds which have a northerly vergence. This change in movement pattern is still poorly understood and structural correlations between the N–S domain and E–W domain are not clear, the two being separated by a late N–S fault, the displacement on which is not known. E–W shortening in the N–S trending domain was accompanied by intrusion of massive granodiorites. These syntectonic intrusions assumed elongated domal shapes due to E–W compression.

Most of the greenstone belt was metamorphosed to greenschist facies, except at the marginal contacts with the granite–gneiss domes where amphibolite facies metamorphism and partial melting occurred.

Gold deposits are important in the greenstone, with >50 t of proven Au reserves and >100 t of probable Au reserves. Annual production from opencast mines currently stands at 2.0 t, with underground production scheduled to start in 1988 which will boost production to 6.0 t of Au per annum. The main deposits were controlled by steeply dipping shear zones, but mineralisation occurred in hydrothermally altered zones after shearing. Host rocks to the gold–quartz veining are variable, with gabbro, dacite, andesite, tuff and pelite recorded.

The large-scale tectonic significance of the relatively narrow greenstone sandwiched between extensive granulite and granite terranes of the São Francisco craton (Fig. 1) is still not fully understood. We intend to discuss the general crustal evolution of this region with the aid of more laboratory data (Gaál et al., in preparation; Silva et al., in preparation).

The Rio Itapicuru greenstone succession has many features in common with Archaean greenstones, and constitutes another example of the growing number of Proterozoic occurrences identified in South America.

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