Character and genesis of Proterozoic shear zone-hosted gold deposits in Borborema Province, northeast Brazil

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Synopsis
Gold mineralization in the Borborema Province of northeast Brazil is hosted by Proterozoic schists and gneisses, which were subjected first to amphibolite-facies metamorphism and subsequently to retrogressive greenschist-facies metamorphism. These units were later intruded by granitic rocks during the Brasiliano Orogeny (750–500 m.y.). The mineralization occurs in veins that are related to major shear zones. The vein mineralogy is dominated by quartz and pyrite in association with Fe–Ti oxides, bise-metal sulphides and rarer phases that contain Ag, Bi, Cd, Mo, Te and Se. Gold occurs as native Au, electrum and maldonite, as well as in solid solution in pyrite. The presence of tourmaline and K-feldspar in the veins suggests the influence of granites in the hydrothermal system.

Fluid inclusion studies have revealed the presence of a dominant fluid phase with a low salinity (ca 6 equiv. wt% NaCl) and variably enriched in CO₂ (up to 35 mole %). Temperatures of homogenization are in the range 250–350°C. The data are compatible with immiscibility of H₂O–CO₂–NaCl fluids, at a pressure of ca 2 kbar. Oxygen and carbon isotopic analysis of quartz and fluid inclusions indicates that at some localities meteoric waters were incorporated into a metamorphic or magmatic fluid-dominated hydrothermal system. Lead isotopic analysis of vein sulphides and host rocks supports the proposal that a major phase of metamorphism and Pb mobilization occurred at ca 750 m.y. and that most of the mineralization occurred after this metamorphic event.

The gold mineralization in the Borborema Province exhibits many features that are similar to those of the classic Archaean lode-gold deposits. It is proposed, however, that granite-related hydrothermal activity and the incursion of meteoric waters both played an important role in the genesis of these deposits.

Shear zone-hosted, mesothermal gold deposits are particularly abundant in many Precambrian shield areas, and many are of considerable economic importance. Because of this they have been the subject of extensive study and a wealth of published data now exists on their geological characteristics. Most of these studies, however, have concentrated on deposits in Archaean terranes—for instance, in the Abitibi Belt of Canada and the Yilgarn Province of Western Australia. Gold mineralization is much less abundant and less significant economically in Proterozoic terranes worldwide and so has usually received much less attention. This is certainly the case in northeast Brazil, where gold deposits in the Archaean terranes have been quite well studied, whereas the Proterozoic deposits are only poorly characterized.

The Borborema Province of northeast Brazil (Fig. 1) is well endowed with mineral resources and contains numerous examples of Proterozoic shear zone-hosted gold deposits, including two active mines (São Francisco and Cachoeira de Minas) and several smaller workings (garimpos) (Fig. 2). Some of the deposits have reserves in excess of 1 t Au (at grades of, typically, 2–4 g Au/t), but most are much smaller. The geological characteristics and genesis of these deposits are summarized here, mainly on the basis of unpublished work. Particular attention is paid to deposits in the central part of the province: descriptions of their form, mineralogy, wallrock alteration and geological setting are accompanied by speculation as to the source of the metals and hydrothermal fluids. The information will add to the understanding of shear-zone gold mineralization in Proterozoic terranes and will be important for the development of an efficient exploration programme in this region.

Geological setting of gold deposits
The geology of northeast Brazil is dominated by the Borborema Province, which covers an area of about 450 000 km² and consists of a mosaic of Archaean to Early Proterozoic high-grade metamorphic terranes. This province is bounded in the south by the São Francisco cratonic area and in the north, east and west by Phanerozoic fold belts (Fig. 1).

The Archaean basement consists of high-grade migmatitic gneiss, granitic–granodioritic orthogneiss, banded amphibolite and garnet–biotite schists of granulate to upper amphibolite metamorphic grade. A major post-Archaean (Trans-Amazonic) thermal–tectonic event, at around 2100–1800 m.y., can be recognized in some of the fold belts. Subsequently, a phase of rifting produced break-up of the original continental crust, and this was associated with continental sedimentation, granite emplacement and alkaline volcanism.

The basement is overlain by orthogneiss, paragneiss, schist, amphibolite, quartzite and calc-silicates, together with minor mafic volcanics and sediments intruded by granitoids. The main feature of the Proterozoic supracrustal rocks is their deformed and recrystallized nature, which resulted from amphibolite-facies metamorphic conditions. Several microplates were later accreted at around 1100–950 m.y.

The province was extensively reworked and consolidated during the 900–600 m.y. Brasiliano Orogeny. This orogeny was characterized by widespread granite emplacement and polyphase folding, which created numerous, large, northeast–southwest-, east–west- and WNW–ESE-trending ductile strike-slip faults that are elongated parallel to the trend of the fold belts. Metamorphism associated with the Brasiliano Orogeny was typically low-grade in nature (greenschist facies), and in the Borborema Province the pre-Brasiliano events have not been obliterated.

Two east-west-trending, crustal-scale lineament systems ca 150 km apart, the Patos (north) and Pernambuco (south) lineaments, crosscut the province. A complex, anastomosing network of east- to northeast-trending, dextral strike-slip shear zones is linked with the main lineaments (Fig. 2). These shear zones form many subsidiary structures, each defining a separate province. Some of the zones were infilled by syntectonic magmas. The crustal-scale lineaments were probably initiated at around 600 m.y. and continued developing until about 500 m.y., when the orogeny ceased.

Intrusive igneous rocks associated with the Brasiliano Orogeny are abundant in the fold belt, occurring as batholiths and stocks that have intruded and deformed the meta-volcanic–metasedimentary sequence. Most are K-calc-alkaline granites and contain biotite and hornblende. The earliest granites were probably formed by subduction or continent–continent collision, but the later types were extension-related.

The Brasiliano granites were formed between 760 and 500 m.y. and exhibit the following structural features. (1) Early to syntectonic granites are streaked out along shear zones (predominantly along the subsidiary shears between the Pernambuco and Patos lineaments) and are transformed to ultramylonite, with ribbons of quartz and feldspar, and remnant porphyroblasts of amphibole; these granites have been dated at 760–570 m.y. (2) Syn- to post-tectonic granites with
calc-alkaline, alkaline and peralkaline compositions (most probable age, 660–550 m.y.) either are present undeformed or have a well-developed foliation and lineation if they are within the shear zones. (3) Post-tectonic granites with a more alkaline composition (A-type granite, aplite and pegmatite) crosscut both basement and earlier granitoids and have been dated at 510 m.y.

Gold mineralization

Geological setting of deposits
The most important sites for gold mineralization are shear zones and associated structures. Most of the mineralized veins are hosted by supracrustal rocks, but a few examples are found of veins in the granites and in amphibolite lenses.
This thrust has a steep ESE dip and is located in a 4 km wide zone of shearing. The thrusting appears to be the last deformation event ($D_2/D_3$) and caused reactivation of earlier dextral shears and refolding. Gold occurs in quartz veins, which are up to 40 cm in width and extend for up to 140 m in strike length. They are situated above the thrust, but have a similar trend and are thought to have developed during the same deformation event.

_Cachoeira de Minas_

The dominant lithology in the Cachoeira de Minas mine area is an overturned syncline of muscovite schist, together with some quartzite and marble. Archaean gneiss and Brasiliano-age granites (early-, syn- and late-tectonic) are also present in the area. The dominant structure is the Jaru dextral shear zone, which has an ENE strike. Gold occurs to the south of the shear zone, in a 60 cm wide quartz vein that extends for about 1 km ENE and dips 40° northwest (parallel to the regional $S_3$ foliation). Minor gold mineralization is also found within east-west extensional fractures associated with later thrusting.

_Itapetim district_

Gold deposits are associated with development of the (sinistral) Itapetim shear zone, which trends northeast–southwest and dips steeply southeast, parallel to the regional foliation. Numerous small deposits occur and mineralization extends for about 30 km in a zone around the contact between granites (early- and syntectonic) and highly deformed supracrustal rocks (biotite gneiss and mica schist). Gold is found in quartz veins up to 0.5 m in width (Fig. 4), which are either concordant or slightly discordant to the regional $S_3$ foliation. These veins developed before and during the main shearing event. Several _garimpos_ were studied, including those at Santo Aleixo, Guilhermina, Sertãozinho, Pimenteiras, Canafistula, Ze Ferreira, Cacimba Salgada and Gurgueia.

_Garapa_

Garapa lies just to the west of the Itapetim district. Three gold-bearing quartz veins occur in the syn- to late-tectonic, undeformed Texeira granite. The veins are about 0.2 m wide and trend ENE for up to 500 m. They are not deformed and appear to have been emplaced after shearing.

_Boqueirao dos Cochos_

Gold-bearing quartz veins are hosted by amphibolite lenses in Archaean gneisses at Boqueirao dos Cochos. They have a northeast trend and a steep southeast dip and are thus parallel to foliation in the amphibolite. Veins are up to 30 cm in width and have been traced for several tens of metres along strike. The veins are associated with the northeast-striking, sinistral Cedro shear zone, which extends northwards into the Patos lineament.

The majority of the samples came from shallow underground workings or from exploration drill cores. More detailed descriptions of individual localities can be found elsewhere.\textsuperscript{11}

_Mineralogy_

Quartz is the dominant phase and makes up more than 95% by volume of the mineralized veins. It typically exhibits ribbon textures in thin section, but some crustification is also observed. Pyrite is the main associated mineral, but several additional minor phases have been noted. Overall, the majority of the veins show evidence of extensive recrystallization and are interpreted, therefore, to have formed mostly during the pre- and syn-shearing phase of vein development. However, three main stages of metallic mineralization have

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_São Francisco_

São Francisco mine is situated on an anticlinal limb made up of Proterozoic garnet-mica schists together with some quartzites, gneiss and calc-silicates. Syn- and late-tectonic granites also occur. The dominant structure is the Morro Pelado shear zone, a 50 m wide, NNE-striking thrust fault.
Fig. 4 Mineralized veins: (a) sheared vein containing quartz-tourmaline-K-feldspar alteration (looking northeast), Pimeneiras, Itapetim. Wallrocks made up of gneiss (left) and amphibolite (right). Sense of shear is strike-slip and sinistral. (b) Quartz vein (centre) surrounded by K-feldspar (light) and tourmaline (dark) alteration zones, Canaístula, Itapetim

been identified from textural relationships.

The earliest, oxide-dominated, phase of mineralization is also found disseminated in the wallrocks. The dominant Fe and Ti oxides (magnetite, ilmenite and rutile) are accompanied by some pyrite, marcasite, chalcopyrite and pyrrhotite. Spheroidal textures with rythmic zoning are common in the pyrite, but these textures have often suffered subsequent brecciation. No gold is visible, but gold can be detected in the pyrite by electron-microprobe analysis. Its distribution is heterogeneous and varies from <0.1 to 0.7 wt%.

The second stage of mineralization is typified by the presence of pyrite, marcasite, gold, chalcopyrite, molybdenite, sphalerite, bismuth, bismuthinite, maldonite (Au–Ag–Bi alloy) and unidentified Pb–Bi–S–Sc–Te phases. Pressure-solution textures (e.g. stylolites) are commonly observed in the pyrite. Gold is typically found in quartz and pyrite as grains approximately 100 μm in size.

The third stage consists of pyrite, marcasite, gold, galena, hessite (Ag3Te) and greenockite (CdS). Pyrite has developed as porphyroblasts, and textures related to annealing are also found. Gold occurs as inclusions in the pyrite and tends to be of a larger size than observed in the earlier stages of mineralization (up to several hundred micrometres). Some of this phase of mineralization could have formed after the deformation.

Besides quartz, the main gangue minerals are schorl-rich tourmaline, K-feldspar, muscovite, chlorite and fluorite. Carbonates are absent. Textural relationships of the gangue minerals indicate that whereas quartz and tourmaline were precipitated throughout the development of the veins, chlorite, muscovite and fluorite are restricted to the later parageneses.

Some evidence for the temperatures of mineralization can be obtained from the minerals present in the veins. Chemical analysis of the chlorite indicates a temperature of formation in the range 315–355°C, on the basis of the chlorite geothermometers of both Walsh24 and Cathelineau.7 The assemblage native bismuth–bismuthinite indicates a maximum temperature of 270°C.2 The significance of these results is discussed later.

Weathering of the primary minerals has been extensive and the veins contain various secondary minerals, including goethite, maghemite, covellite, chalcocite, jarosite and pyromorphite.

Wallrock alteration
Little or no visible wallrock alteration is associated with the majority of the mineralized veins. In some cases, however—in particular, in the granitoid host rocks—the alteration zones are quite distinctive. Here selvages vary typically from 4 cm to 4 m in total width and may be zoned, the widths of individual zones reaching 0.4 m (Fig. 4(b)). Where zonation is present the innermost zone is dominated by quartz, the next is tourmaline-rich with additional quartz and the outermost contains pink K-feldspar and albite with lesser amounts of quartz and sericitic mica. Accessory minerals in these wallrock alteration assemblages include epidote, ilmenite, titanite and rutile. Some gold is disseminated through the alteration assemblages, particularly in the silicified zones. Often there is evidence that the alteration assemblages have suffered deformation and a new mineral fabric has developed. In particular, ‘kinked’ tourmaline crystals and quartz with a ribbon texture are observed.

The mineralogical transformations were accompanied by marked chemical changes. On the whole these reflect the mineralogical transformations, frequent gains in K, Mg, Ti, Si, Fe and Mn being associated with the growth of quartz, K–feldspar, muscovite and tourmaline, and losses in Ca and Na ensuing from the destruction of plagioclase feldspar and amphibole.11 Trace-element changes are more variable, probably because of the varied nature of the host rocks. Instances of significant addition of Rb, Pb, Th and Ba to the altered wallrocks are, however, common.

Fluid inclusions
Because of the value of fluid inclusions in characterizing the fluids responsible for the formation of Precambrian gold deposits,20,22,24,25,40,48,56,57 the mineralized veins were subjected to a fluid inclusion study. Thermometric analysis was carried out on doubly polished wafers of quartz with the use of a Linkamp TH600 microscope stage that had been calibrated with synthetic fluid inclusions in quartz. The temperatures of the last melting of solid CO2, first melting of ice, last melting of ice or CO2–clathrate, partial homogenization of CO2 phases, total homogenization (Tc) and decrepitation were recorded wherever possible.

Fluid inclusions occur in the size range 10–30 μm and can be relatively abundant in quartz associated with gold and sulphide mineralization. They occur in several forms: randomly
distributed through the quartz grains; parallel to crystal growth zones; along grain boundaries; and as planar arrays (either in individual grains or crosscutting grain boundaries). It is often not possible to determine whether inclusions are primary or secondary, but many were clearly formed after the initial growth of quartz and during recrystallization or later fracturing events. There appears to be no difference in the fluid inclusion populations in quartz sampled from the different host lithologies.

On the basis of the fluid inclusion studies, three types of fluid seem to have been associated with the development of the quartz veins. Type (1) is a H₂O-CO₂ fluid characterized by low but variable salinity (ca 6.0 equiv. wt% NaCl) that contains varying proportions of CO₂ (up to 35 mol%) and small amounts of CH₄ (<3.0 mol%) and which displays a Tₑₑ range from 200 to 415°C; this is the dominant variety of fluid inclusion, making up about 70% of the total population. Type (2) is a non-saline, low-density phase containing dominant CO₂ together with small amounts of water and methane, which makes up about 20% of the inclusion population. Type (3) is an azeotropic phase of low to moderate salinity (2.0-14.0 equiv. wt% NaCl) with Tₑₑ mostly in the range 250-350°C, which makes up about 10% of the population.

Generally the three types of fluid inclusion occur separately in the quartz, but types (1) and (2) appear to coexist in some instances. This apparent coexistence of CO₂-rich and H₂O-rich fluids is probably due to immiscibility in the H₂O-CO₂-NaCl fluid system, although it must be stressed that there is insufficient thermometric or volumetric evidence from the vapour-rich inclusions to satisfy the accepted criteria for immiscibility. However, numerous studies of Archaean lode-gold deposits have invoked immiscibility of mixed H₂O-CO₂ fluids as an important process, so the suggestion would seem reasonable.

It is suggested, therefore, that at least fluid inclusion types (1) and (2) were closely associated, probably through vapour-phase separation and fluid immiscibility. The azeoic fluids seen in the type (3) inclusions could represent the late-stage water-rich component that remained after CO₂ loss.

All quartz samples contain mixed CO₂-H₂O inclusions with variable amounts of CO₂ and the inclusions in each sample exhibit a correlation between CO₂ content and Tₑₑ (Fig. 5). The distribution of the data points in Fig. 5 is very similar to the solvs for a 6% NaCl fluid at 2 kbar. The independent temperature data from the minerals present demonstrate that the Tₑₑ of the fluid inclusions are close to the trapping temperatures and thus support the proposition that the fluids were, or close to, immiscibility at the conditions specified in Fig. 5. The coincidence of the fluid inclusion data and the fluid solvs in Fig. 5 would indicate that changes in temperature were the most likely cause of the observed variations in fluid CO₂ content. Immiscibility and CO₂ separation could also be achieved during pressure fluctuations. Although feasible and invoked as a cause of mineralization in many gold deposits, pressure variation seems to have been of lesser importance as a control on the fluid composition in these deposits.

On the basis of the fluid inclusion study it is proposed that the mineralization was caused by low-salinity H₂O-CO₂ fluids. The major part of the gold and sulphide mineralization was formed in the temperature range 350–250°C at a pressure of around 2 kbar. The fluids were probably cooling and in consequence they experienced progressive vapour separation. At a pressure of 2 kbar and on the assumption of lithostatic conditions the thickness of the overlying rock would have been approximately 8 km.

Stable isotopes
Stable isotopes have been widely used in the study of shear zone-hosted gold deposits to elucidate the source of major components of the hydrothermal fluids. In the present study isotopic analyses of oxygen in quartz and carbon in fluid inclusions were obtained to constrain the source of the oxygen and carbon in the hydrothermal fluids that formed the quartz veins in Bamburna Province. Inclusion fluids were released by decrepitation at 1000°C and their C isotopic composition was determined by direct analysis of the evolved CO₂. Oxygen isotopic analyses of quartz were obtained by standard fluorination methods at the Natural Environmental Research Council Isotope Geosciences Laboratory (NIGL), Keyworth. The results of the stable isotopic analyses are presented in Table 1.

The O isotopic composition of quartz associated with gold mineralization exhibits a wide range, from +4.5 to +14.5‰ SMOW. There appears to be no systematic variation of the O isotopic composition of the quartz with host lithology. The isotopic composition of the quartz is a function of both temperature of formation and isotopic composition of the fluid.
Table 1  Oxygen and carbon isotopic composition of quartz and hydrothermal fluids from gold deposits in northeast Brazil

<table>
<thead>
<tr>
<th>Locality</th>
<th>Host rock</th>
<th>$\delta^{18}$O quartz, % SMOW</th>
<th>$\delta^{18}$O fluid, 250°C*</th>
<th>$\delta^{18}$O fluid, 400°C*</th>
<th>$\delta^{13}$C fluid, % PDB</th>
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</thead>
<tbody>
<tr>
<td>Garapa garrino</td>
<td>Syntectic granite</td>
<td>12.8</td>
<td>4.0</td>
<td>8.8</td>
<td>-3.2</td>
</tr>
<tr>
<td>Cacimba Salgada garrino (Itapetin)</td>
<td>Syntectic granite</td>
<td>12.8</td>
<td>4.0</td>
<td>8.8</td>
<td>-3.2</td>
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<td>Guilhermina garrino (Itapetin)</td>
<td>Early-tectonic granite</td>
<td>8.0</td>
<td>-0.8</td>
<td>4.0</td>
<td>-7.6</td>
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<td>Canafistula garrino (Itapetin)</td>
<td>Early-tectonic granite</td>
<td>7.9</td>
<td>-0.9</td>
<td>3.9</td>
<td>-7.6</td>
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<td>Ze Ferreira garrino (Itapetin)</td>
<td>Gneiss</td>
<td>10.0</td>
<td>1.2</td>
<td>6.0</td>
<td>-2.4</td>
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<td>Sertaozinho (Itapetin)</td>
<td>Gneiss and biotite schist</td>
<td>4.5</td>
<td>-4.3</td>
<td>0.5</td>
<td>-3.0</td>
</tr>
<tr>
<td>Queiroz Galvão (Itapetin)</td>
<td>Mica schist</td>
<td>12.5</td>
<td>3.7</td>
<td>8.5</td>
<td>-2.4</td>
</tr>
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<td>Cachoeira de Minas</td>
<td>Muscovite schist</td>
<td>14.5</td>
<td>5.7</td>
<td>10.5</td>
<td>-2.1</td>
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<td>São Francisco mine</td>
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<td>4.4</td>
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<td>-7.1</td>
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<tr>
<td>Boqueirao dos Cochos</td>
<td>Amphibolite</td>
<td>11.1</td>
<td>2.3</td>
<td>7.1</td>
<td>-3.4</td>
</tr>
</tbody>
</table>

SMOW, Standard Mean Ocean Water; PDB, Pee Dee Belemnite standard.

*Composition of fluid in equilibrium with quartz based on the fractionation relationship of Matsushita and co-workers.32

But the range in temperature of formation for these samples postulated from the fluid inclusion study is not sufficient to account for the observed variations. This suggests that the large range in isotopic composition of the quartz must be primarily a function of fluid composition. On the basis of the quartz-water fractionation of Matsushita and co-workers32 and a temperature range of 250–400°C derived from the fluid inclusion and chlorite studies the possible $\delta^{18}$O fluid compositions vary from -4.3 to +10.5%o (Table 1). The higher values (7 to 10.5%) are similar to those of magmatic or metasomatic fluids, but the range of compositions is too large to be ascribed solely to these sources and a significant additional component must be present. Unfortunately, no H isotopic data exist for these fluids; the low-18O fluids, however, are indicative of the presence of a substantial proportion of meteoric water in the hydrothermal system. These isotopic values could have undergone further modification by fractionation during vapour-phase separation and immiscibility, but although the $\delta^{18}$O value of the residual fluid would have increased, quantification of that increase is difficult.33 However, this process is unlikely to have been the cause of the substantial depletion in $\delta^{18}$O fluid values noted here.

Most isotopic studies of Archaean gold mineralization have favoured devolatilization by metamorphic processes (both prograde and retrograde) as the source of the aqueous portion of the hydrothermal fluid. However, the O and H isotopic data are often equivocal and the presence of a substantial magmatic component cannot always be ruled out. The O isotope data derived during the present study also support the involvement of a metamorphic or magmatic fluid in the mineralization process, but with the additional incorporation of meteoric waters at some localities. Such circumstances would corroborate suggestions that some of the more shallow shear-zone gold deposits may incorporate meteoric fluids,21 or the more extreme concept put forward by Nesbitt and co-workers36 in which Archaean and younger mesothermal gold deposits were formed from the deep circulation of highly evolved meteoric waters. This proposed influx of meteoric water could be a cause of the temperature decrease postulated for the hydrothermal systems on the basis of the fluid inclusion study (although no clear correlation has been found between fluid inclusion $T_h$ values and quartz $\delta^{18}$O values). This dilution would also have the effect of counteracting the immiscibility and restricting vapour-phase separation to higher levels in the crust for a given temperature.

The $\delta^{13}$C isotope values for fluid inclusion CO$_2$ (-7.6 to -2.1%) PDB) indicate an ultimate deep-seated source. No correlation is apparent between these values and either host-rock type, vein mineralogy, temperature of mineralization or O isotopic composition of the quartz. The $\delta^{13}$C values could have been modified by immiscibility and phase separation or by interaction of the fluid with graphite-rich lithologies during mineralization. However, the latter process seems unlikely because of the relatively low fluid methane contents and the lack of graphite-bearing lithologies in the area. The range of values is comparable with the range for fluids from other Precambrian gold deposits—typically -9.0 to -4.5.9,20,31 Such values are consistent with a mantle (or deep magmatic) derivation of the carbon. However, as magmatic and mantle fluids are closely interrelated—in particular, in subduction settings—it is possible that the hydrothermal system may contain carbon that is a mixture of magmatic and mantle-derived fluids. These fluids could have been generated directly from the mantle or from partial melting at the base of the lower crust.

Lead isotopes

Pb isotopic analysis can be used to elucidate the source of lead in shear zone-hosted gold deposits and, by inference, the source of other metals, such as gold, that exhibit similar geochemical behaviour. In addition, age relationships between sulphide mineralization and metamorphism can sometimes be deduced.12,13,33,39,42

Sixteen representative samples of the main lithologies were collected for analysis (Table 2): twelve supracrustals (two amphibolites, three gneisses and seven schists) and four granites (one early tectonic, two syntectonic and one syn- to post-tectonic). In addition, five samples of sulphide (pyrite and galena) from four widely separated gold deposits were collected for analysis.

Lead was extracted from the samples by standard ion-exchange procedures and loaded on single Re filaments with H$_2$PO$_4$ and silica gel. Lead isotope measurements were obtained with a VG354 thermal ionization mass spectrometer. All analyses were corrected using a procedural blank and for mass fractionation by repeated measurements of the SRM 981 isotope standard. Errors in the isotopic analyses are <0.005%/amu (2σ), and reproducibility, on the basis of the SRM 981 data, is estimated at better than 0.05%/amu (2σ). Th and Pb contents in the rocks were determined by X-ray
Table 2  Lead isotope ratios of rocks and sulphides from northeast Brazil

<table>
<thead>
<tr>
<th>Location</th>
<th>Lithology</th>
<th>206Pb/204Pb</th>
<th>207Pb/204Pb</th>
<th>208Pb/204Pb</th>
<th>232Th/204Pb</th>
<th>Th, ppm Pb, ppm</th>
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<tr>
<td>Sertaozinho (Itapetim)</td>
<td>Leucogneiss</td>
<td>20.706 ± 2</td>
<td>15.848 ± 2</td>
<td>40.417 ± 4</td>
<td>68.08</td>
<td>40.2 ± 41.1</td>
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<td>15.940 ± 1</td>
<td>41.743 ± 4</td>
<td>107.57</td>
<td>52.1 ± 34.9</td>
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<td>Early-tectonic granite</td>
<td>21.305 ± 2</td>
<td>15.897 ± 2</td>
<td>41.828 ± 6</td>
<td>99.21</td>
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<td>Syntectonic granite</td>
<td>18.909 ± 2</td>
<td>15.749 ± 1</td>
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<tr>
<td>Teixeira (Itapetim)</td>
<td>Syntectonic granite</td>
<td>18.700 ± 2</td>
<td>15.702 ± 2</td>
<td>38.463 ± 4</td>
<td>18.41</td>
<td>12.8 ± 48.0</td>
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<tr>
<td>Teixeira (Itapetim)</td>
<td>Syn/post-tectonic granite</td>
<td>16.237 ± 2</td>
<td>15.338 ± 2</td>
<td>36.653 ± 4</td>
<td>8.28</td>
<td>5.2 ± 39.1</td>
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<td>Sertaozinho (Itapetim)</td>
<td>Gneiss</td>
<td>19.377 ± 2</td>
<td>15.759 ± 2</td>
<td>38.731 ± 4</td>
<td>27.69</td>
<td>6.5 ± 15.7</td>
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<tr>
<td>Pimenteiras (Itapetim)</td>
<td>Schist</td>
<td>18.810 ± 2</td>
<td>15.751 ± 2</td>
<td>39.391 ± 4</td>
<td>45.37</td>
<td>15.4 ± 22.7</td>
</tr>
<tr>
<td>Sertaozinho (Itapetim)</td>
<td>Schist (altered wallrock)</td>
<td>18.115 ± 1</td>
<td>15.641 ± 1</td>
<td>38.093 ± 3</td>
<td>35.34</td>
<td>16.8 ± 30.8</td>
</tr>
<tr>
<td>Cachoeira de Minas</td>
<td>Schist (altered wallrock)</td>
<td>17.804 ± 3</td>
<td>15.633 ± 3</td>
<td>37.966 ± 8</td>
<td>34.88</td>
<td>15.9 ± 29.5</td>
</tr>
<tr>
<td>São Francisco</td>
<td>Schist</td>
<td>18.645 ± 4</td>
<td>15.648 ± 3</td>
<td>38.645 ± 9</td>
<td>27.72</td>
<td>5.3 ± 12.7</td>
</tr>
<tr>
<td>Cachoeira de Minas</td>
<td>Schist (altered wallrock)</td>
<td>18.532 ± 2</td>
<td>15.743 ± 2</td>
<td>38.907 ± 5</td>
<td>5.78</td>
<td>12.6 ± 14.9</td>
</tr>
<tr>
<td>Desterro (Itapetim)</td>
<td>Amphibolite</td>
<td>19.355 ± 3</td>
<td>15.777 ± 2</td>
<td>39.223 ± 6</td>
<td>40.64</td>
<td>3.4 ± 5.7</td>
</tr>
<tr>
<td>Boqueirão dos Cochos</td>
<td>Amphibolite</td>
<td>15.300 ± 3</td>
<td>15.181 ± 3</td>
<td>34.918 ± 6</td>
<td>9.80</td>
<td>1.3 ± 8.1</td>
</tr>
<tr>
<td>São Francisco</td>
<td>Schist (altered wallrock)</td>
<td>18.455 ± 3</td>
<td>15.670 ± 2</td>
<td>37.824 ± 6</td>
<td>53.65</td>
<td>14.0 ± 17.0</td>
</tr>
<tr>
<td>São Francisco</td>
<td>Schist (altered wallrock)</td>
<td>18.655 ± 2</td>
<td>15.704 ± 2</td>
<td>38.205 ± 3</td>
<td>0.78</td>
<td>14.0 ± 117.3</td>
</tr>
</tbody>
</table>

Model ages of sulphides calculated with use of two-stage Pb evolution model of Stacey and Kramers.50

Th and Pb contents of rocks determined by X-ray fluorescence.

The Pb isotopic analyses of the rocks and minerals are presented in Table 2 and on a standard 207Pb/206Pb 206Pb/204Pb plot in Fig. 6.

The host rocks to the mineralization exhibit a large degree of Pb isotopic heterogeneity (206Pb/204Pb ratios from 15.30 to 22.03). The higher values occur in the early granite and granitic gneiss, whereas in the schists and later granites the values are lower. Although the majority of the rock samples plot close to the average terrestrial Pb evolution curve, the amphibolite that occurs in the Archaean basement and the syn/post-tectonic granite seem to have particularly low Pb isotopic ratios. The isotopic compositions of the latter samples suggest that in these rocks at least some mixing with, or derivation of, Pb from older lithologies (Archaean or early Proterozoic basement) has been important. Certainly, the Pb isotope ratios and Th contents of the granitoids seem to be higher in the earlier granites, indicating that their genesis was

![Fig. 6 Pb isotopic plot for rocks and sulphides from Borboréma Province. See Table 2 for details. Isochron for five unaltered Itapetim supracrustal samples (672 m.y.) also shown (see text)](image-url)
from younger crustal rocks with high $\mu$ ($^{238}\text{U}/^{204}\text{Pb}$) values (e.g. mid-Proterozoic schists), whereas the source of the latest granites contained a greater component of material with lower $\mu$ values. Vanschmus et al.,51 suggested that much of the Borborema Province is underlain by middle Proterozoic crust rather than Archaean or Trans-Amazonian basement and, thus, the granites are more likely to be derived from the former lithologies.

For the five (unaltered) supracrustal rocks from the Itapetim district the linear trend in Pb isotopic values shown in Fig. 6 could approximate to an isochron and have an age significance. The slope on the plot for these samples corresponds to an age of 672 (+214/−246) m.y. An independent $^{232}\text{Th}/^{208}\text{Pb}$ age can be estimated for these rocks by use of the Th-Pb decay system. For these supracrustals an age of 755 (+52) m.y. was derived. Rather interestingly, the addition to either data set of the three Itapetim early and syntectonic granites causes no great change in the age: 771 ±52 m.y. for Th-Pb (Fig. 7) and 710 ±188/−212 m.y. for Pb-Pb.

Fig. 7  Th-Pb isotopic plot and best-fit regression line for unaltered, pre- and syntectonic lithologies from Itapetim district. See Table 2 for details

Although there is reasonable agreement between these two sets of results, the geological significance of these ages is not immediately apparent. Uranium and, to a lesser extent, thorium are both potentially mobile during amphibolite-facies metamorphism. Seeing that quite diverse lithologies were utilized, it is probable that this date represents mobilization and resetting of the Pb isotopes during metamorphism. Furthermore, the reduced errors in the Th dating, coupled with this element’s reduced geochemical mobility, indicate that the Th-derived dates are more reliable than the Pb-Pb dates. It is assumed, therefore, that the age of ca 750 m.y. represents a time of major (probably amphibolite-facies) metamorphism and lead mobilization in these Proterozoic lithologies. The earliest phase of Brasiliano magmatism in the province has also been dated at 750 m.y.11

The five sulphide samples analysed in this study exhibit only a small degree of isotopic variation by comparison with that seen in the host rocks. The sulphide data plot on or just below the Pb isotopic growth curve and appear to exhibit a linear trend similar to (although less extensive than) that proposed for the host rocks. Fig. 6 obviously represents the isotopic compositions of rocks that have continued to evolve since their formation. However, plots of the isotopic compositions of these rocks at the approximate time of mineralization (800 m.y.) (compositions derived from the present-day isotopic ratios and the U and Th concentrations of the rocks) are broadly similar to those presented here, but the spread in isotopic values is much reduced. However, the relatively tight grouping for the sulphide data compared with that for the host rock data indicates that, although the lead in the vein mineralization could have been derived from any of the Proterozoic supracrustal lithologies (granite, schist or amphibolite), it is unlikely that it was derived from the full range of lithologies found in the region.

Model ages of 860–620 m.y. were obtained for the sulphides by taking the Pb isotope ratios for the sulphides and applying the two-stage Pb evolution model of Stacey and Kramers50 (Table 2). These ages are, of course, dependent on the model adopted and the range of values has doubtful statistical significance (on account of the number of samples analysed), but overall they are quite similar to those derived for the metamorphism; thus, they support the concept that sulphide mineralization occurred during or soon after deformation and metamorphism at around 750 m.y. Although it is possible that the mineralization developed in more than one period but with a common, homogeneous parent as the source, it is more likely that there was one period and the sulphide with the youngest model age was contaminated with a more radiogenic component of lead (for example, the syntectonic granites). Thus, the linear trend in the sulphide data could be explained by invoking two end-members: a (dominant) supracrustal Pb source with radiogenic isotopic ratios and a (minor) source of Pb from presumed basement with an age of ca 2200 m.y.

Discussion

Subduction and continent–continent collision during the latter stages of the Brasiliano Orogeny in northeastern Brazil (900–600 m.y.) gave rise to a wide variety of geological processes, including the generation of major shear zones and intrusion of abundant granitoid rocks. The generation of the shear zones represents a crucial stage in the tectonic evolution of the Borborema Province, primarily by providing a structural control for the fluid pathways. Furthermore, melting associated with the calc-alkaline plutonism could have assisted the lubrication of the shear in the lower crust,26 thus also providing conduits for synkinematic pluton emplacement. (Neves and Vauchez37 have suggested, however, that the magma bodies triggered strain localization and thus promoted the nucleation of the shear zones.)

Shear faults and vein fractures probably developed under a brittle–plastic regime at a depth of around 7–10 km and would have provided microstructural conduits for fluid percolation. Although the host rocks to the mineralization have suffered amphibolite-facies regional metamorphism, in the veins only the quartz and the earliest phase of sulphides show evidence of deformation. This indicates that the majority of the mineralization was emplaced after peak deformation and during retrograde metamorphism, probably under greenschist-facies conditions (2 kbar, 250–350°C).

Although the gold deposits of the Borborema Province are found over a large area, they appear to have certain common geological characteristics. Furthermore, they exhibit many similarities to Archaean lode-gold deposits—for instance, the strong structural control on the mineralization (subsidary structures in steeply dipping, brittle–plastic shear zones), the presence of dilute, moderate-temperature (200–400°C), CO$_2$-rich fluids and the abundance of pyrite, plus local enrichments in tellurium and bismuth. Some geological features of these deposits, however, are not so commonly encountered in Archaean lode-gold deposits—as demonstrated, in particular, by those found elsewhere in Brazil (e.g. in the Rio Itapicuru greenstone belt$^{30,57,58}$). For instance, in the Borborema Province the host rocks are felsic/intermediate volcanics and metasediments (which have often been mylonitized and intruded by granitoids), rather than basic volcanics and iron formations. Furthermore, arsenopyrite and carbonates are both absent from the Borborema veins. Finally, the

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wallrock assemblages show strong K enrichments, with the development of K-feldspar, sericite and additional tourmaline and minor fluorite.

The genesis of Archaean lode-gold deposits has been the subject of a long-running debate. The most powerfully advocated view is that the hydrothermal fluids were generated by dehydration of silicates during peak or retrograde greenschist-facies metamorphism and collected along crustal-scale structures and other low mean-stress zones. Also controversial is the proposal that in some areas there may be a close genetic association between gold mineralization and calc-alkaline magmatism. There are several indications that the hydrothermal fluids responsible for the gold mineralization in the Borborema Province were not derived solely from metamorphic devolatilization and that additional fluid sources were involved. (1) Some of the gold-bearing veins also contain K-feldspar and tourmaline. Although these minerals are recorded in the classic Archaean gold-quartz veins, K-feldspar is usually restricted to the highest-temperature (amphibolite-facies) assemblages and the tourmaline is typically dravitic in composition. Tourmaline recorded in the deposits from Borborema Province is school-rich and its composition is characteristic of granitic environments. (2) The hydrothermal alteration assemblages sometimes exhibit net gains in Rb, Th, Ba and Pb—elements characteristic of felsic igneous rocks. (3) Molybdenite and fluorite have been noted, and their presence could be indicative of the involvement of granite-related fluids. (4) Most of the gold and sulphide mineralization occurred after the peak metamorphism, at a time of major granite intrusion. (5) The O isotope signature (relatively low δ18O values) of some of the hydrothermal fluids is most reasonably explained by the incursion of meteoric fluids into the hydrothermal system.

The results of this study suggest that post-peak metamorphic, granite-related hydrothermal activity played an important role in the genesis of the shear zone-related gold mineralization. The fluids could have evolved from the crystallizing plutons or could simply have interacted with them during fluid movement. In view of the abundance of granites in this terrain it would be strange if the granites had not interacted in some way with the hydrothermal fluids.

Many investigators of Archaean lode-gold deposits have noted the close spatial association between gold deposits and felsic magmatism and have been ready to accept an involvement of granites either directly in the hydrothermal system or by their interaction with extraneous fluids, or at least that the granites were generated at the same time as the hydrothermal fluids. Furthermore, several authors now stress the possibility of a spectrum of depth settings for these gold deposits based on temperature and pressure variations. Possibly the O isotopic variations noted in the present study arise from the deep incursion of meteoric fluids, and these deposits would therefore represent the shallower part of this depth spectrum. A variation in host-rock types can be incorporated into these models in a similar fashion, thus also adding slight differences to the end mineralization, as noted in the Borborema Province.

Unfortunately, the study has not shed much light on the source of the gold in these deposits. The lack of basic volcanic lithologies in the province suggests, however, that other lithologies could have been important here. Furthermore, the available information indicates that Proterozoic units were more important as a source for the gold than any underlying Archaean basement.

Several criteria for the targeting of exploration in this region of Brazil can be deduced from the genetic concepts put forward above. Gold exploration should be directed towards areas containing syntectonic, Brasiliano-age granitic rocks emplaced into Proterozoic supracrustal lithologies (especially schists). Priority must be given to areas that exhibit a high density of anastomosing shear zones, in particular where subsidiary shear zones are concentrated.

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