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Autochthonous and allochthonous strata of the El Callao greenstone belt: Implications for the nature of the Paleoproterozoic Trans-Amazonian orogeny and the origin of gold-bearing shear zones in the El Callao mining district, Guayana shield, Venezuela

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Abstract

The tectonic style of the Paleoproterozoic Trans-Amazonian orogeny in the Guayana shield was considered by previous workers to represent non-actualistic tectonics in which rising masses of granitoid magma of the Supamo complex deformed 2.1–2.0 Ga supracrustal belts of volcanic and sedimentary rocks to form greenstone belts. Subsequent collision with the dominantly granulite-grade Imataca complex deformed the greenstone belts. However, the base of the greenstone belts is everywhere marked by a major mylonitic shear zone that placed rocks of the greenstone belts atop a regional unit of quartzite that sits unconformably upon both the Imataca and Supamo complexes. The simplest interpretation of these relationships is that the greenstone belts are allochthonous with respect to the Imataca and Supamo complexes. As the quartzite oversteps the contact between the Imataca and Supamo complexes, juxtaposition of the two complexes must predate deposition of the quartzite and deformation of the Trans-Amazonian orogeny.

The quartzite and the thrust fault are used as paleohorizontal markers to unfold the greenstone belt in the El Callao area where auriferous shear zones, which clearly predate the thrusting, show reverse sense of movement. When restored to their pre-folding orientation they are normal faults. This, and the tholeiitic to calc-alkaline volcanic packages, are compatible with an extensional forearc to arc setting for both the mineralization and the volcano-sedimentary sequences.

East–northeasterly trending folds of both the allochthon and the autochthon, coupled with the northerly thickening of the quartzite, suggest that the allochthon was part of an unknown craton that formerly lay to the north. A second regional fold set, which trends northerly, refolds the earlier structures. It is possibly related to collision of the San Carlos terrane with the amalgamated Imataca–Supamo–Pastora terranes. The unconformably overlying 1.98 Ga Cuchivero arc terrane provides a minimum age for the two collisional events.

Keywords: Gold mineralization; Plate tectonics; Paleoproterozoic; Trans-Amazonian orogeny; Guayana shield; Venezuela

1. Introduction

Gold was discovered in the Guayana shield of Venezuela by natives some time ago, but it was in the 1850s that a Brazilian prospector traced gold nuggets to the El Callao area. Since then the El Callao mining district has been Venezuela's most prolific producer of gold with over 200 metric tonnes produced. Ore within the district is localized in quartz veins and stringers within shear zones. Previous workers (Mendoza, 2000; personal communication, 2004; Teixeira et al., 2003) suggested that the gold deposits were syn-collisional and localized

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in shear zones related to thrusting. However, the exact nature of these zones is unresolved, in large part because they are the oldest faults in the district and the subsequent structural evolution of the area is poorly understood.

The rocks of the El Callao greenstone belt—and others of the Guayana shield deformed during the Trans-Amazonian orogeny—were considered by previous workers (Sidder and Mendoza, 1995; Mendoza, 1977, 2000; Cox et al., 1993) to represent Paleoproterozoic greenstone belts in which rising masses of dome-like intrusions metamorphosed and deformed the older volcano-sedimentary succession. However, new geological mapping and observations by the author demonstrate that the volcano-sedimentary successions within the Guayana shield were thrust over a stable craton comprising granitoid and gneissic rocks covered by a veneer of quartzite and are now preserved in a series of synclinal klippe, collectively termed the Pastora allochthon. Thus, rather than a mysterious—non actualistic—tectonic style, the rocks are amenable to a modern, plate tectonics-style interpretation. This new interpretation resolves many problems and provides a modern, actualistic framework for understanding the evolution of the Guayana shield and the origin of its gold deposits.

2. Regional setting

The Guayana shield forms the northernmost part of the Amazonian craton (Fig. 1). Within Venezuela, the Guayana shield comprises six lithotectonic domains: (1) the Imataca complex, dominated by Archean granulite

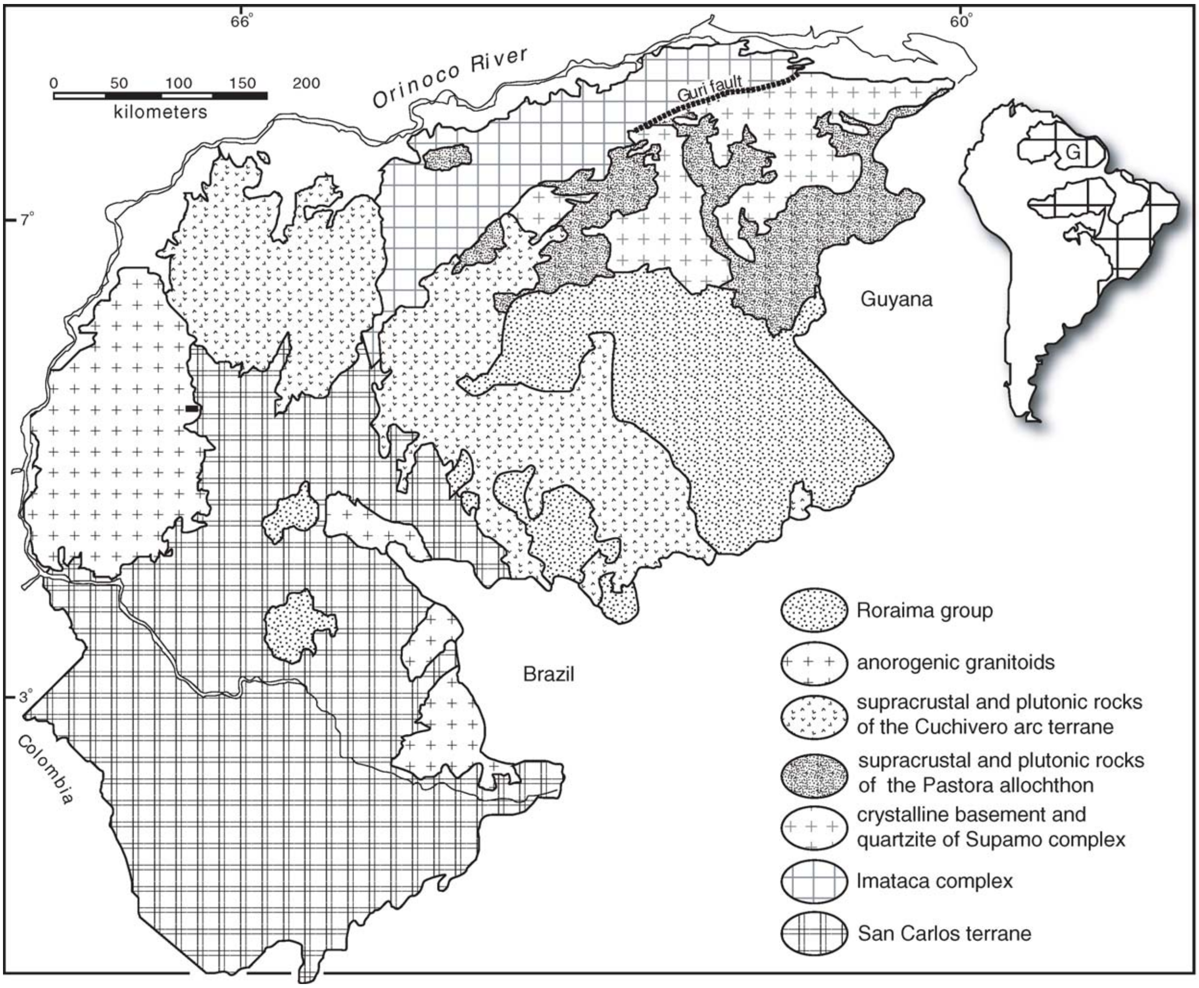

Fig. 1. Regional geological map showing the location of the Guayana shield (G) with respect to the Amazonian craton (patterned) and the large-scale lithotectonic domains of the Venezuelan portion of the Guayana shield.

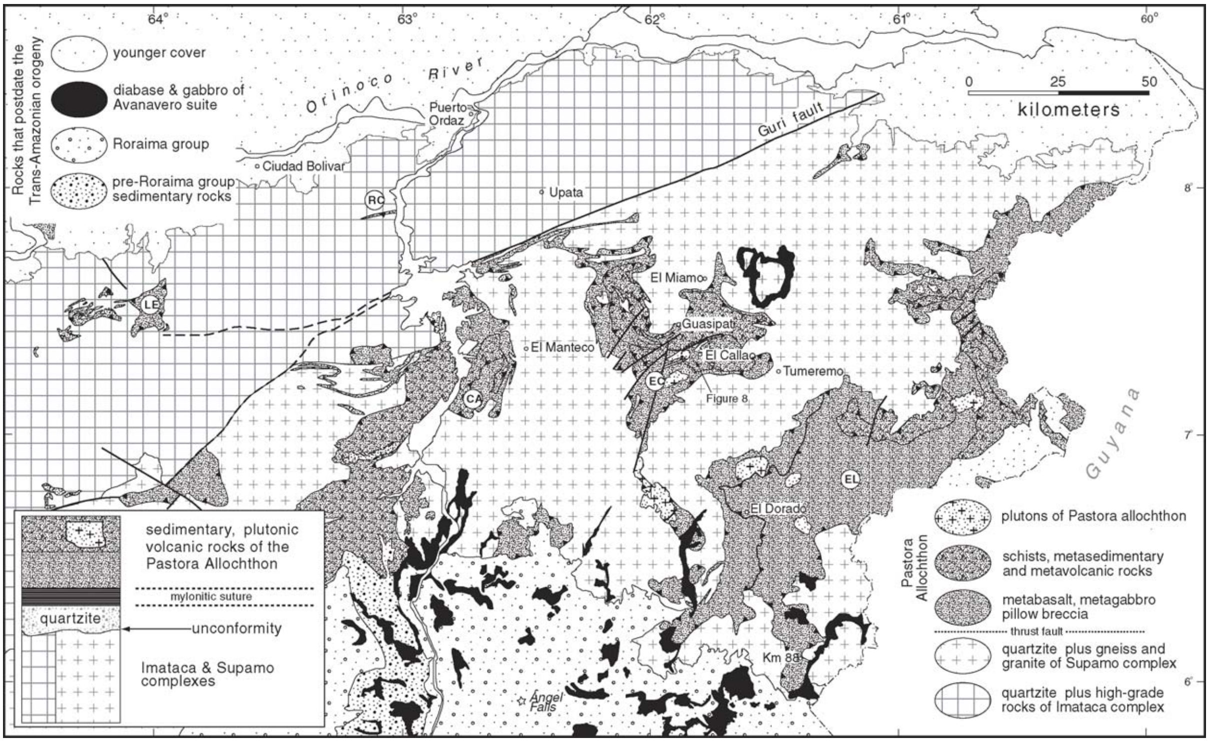

Fig. 2. Geology of the northeastern part of the Venezuelan Guayana shield, showing the relationships between the Imataca terrane, the Supamo terrane, and the Pastora allochthon. Individual greenstone klippe: LE = La Esperanza; RC = Rio Claro; CA = Caroni; EC = El Callao-Guasipati; EL = El Dorado-Introduccion. Modified from Wynn et al. (1993).

to amphibolite facies gneisses; (2) the Pastora–Supamo terrane, a Paleoproterozoic granite-greenstone terrane in which volcano-sedimentary successions of the Pastora supergroup were thrust over crystalline basement of the combined Imataca–Supamo complexes and its sedimentary cover; (3) another Paleoproterozoic basement assemblage of granitoids, gneisses and minor volcanic rocks called the San Carlos terrane; (4) a northwesterly-trending, Paleoproterozoic, calc-alkaline, volcano-plutonic complex, the Cuchivero, that sits unconformably upon both the San Carlos and Imataca–Pastora–Supamo terranes; (5) the Roraima group, a 1.87 Ga succession of continental sedimentary rocks that form the spectacular flat-topped mountains locally called tepuis; (6) a Mesoproterozoic suite of anorogenic rapakivi granites. Gabbroic and doleritic intrusions, known as the Avanavero suite, intruded rocks of the Roraima group and its basement at 1.79 Ga. The study area is located within the Pastora–Supamo terrane near the towns of Guasipati, El Callao and Tumeremo (Fig. 2); however, the author visited key locales throughout the Venezuelan portion of the Guayana shield to broaden the results of the more localized mapping.

3. Autochthon

3.1. Basement

There are two main complexes of basement rocks in the northeastern Guayana shield: the Imataca complex, a dominantly Archean granulitic gneiss terrane, and the Supamo complex, an amalgamation of Paleoproterozoic granitoid rocks, gneisses, and migmatites.

The Imataca complex comprises mostly quartzofeldspathic gneisses—commonly migmatitic and garnetiferous—and felsic granulite along with moderate amounts of intermediate to mafic orthogneiss, granulite, and charnockite (Cox et al., 1993). Small quantities of banded iron-formation, manganiferous sedimentary rocks, dolomitic marble, and anorthosite occur locally. The age of rocks in the Imataca complex is reported as 3.25–3.0 Ga (Teixeira et al., 1999, 2002; Montgomery, 1979) with possible younger metamorphic overprints at 2.8–2.7 and 2.15–2.0 Ga (Hurley et al., 1976).

The Supamo complex is an assemblage of gneisses, schists, migmatite, tonalite, granodiorite, and trondjemite formerly considered intrusive into rocks of the

Pastora supergroup (Mendoza, 2000; Menéndez, 1995; Cox et al., 1993). However, recent fieldwork demonstrates that rocks of the Supamo complex are unconformably overlain by quartzites, which are in turn structurally overlain by 5–10 m of amphibolitic ultramylonite and the main volcano-sedimentary sequences of the Pastora supergroup (Fig. 2 inset). U–Pb ages are sparse but ages of plutons within the Supamo complex appear to be 2.2 Ga and older (Klar, 1979).

3.2. Cover

A new stratigraphic term, the El Miamo formation, is used here for a formation of sedimentary rocks that were formerly unrecognized in the area and unconformably overlie rocks of the Supamo and Imataca complexes throughout the Guayana shield of Venezuela. The dominant lithology is quartzite, with minor quartz-pebbly conglomerate. This unit occurs beneath the allochthonous Pastora supergroup in the area and occurs locally within the cores of synclines within the Supamo complex. Where the unconformity is best exposed it is a planar surface with quartzite or quartz pebbly conglomerate abruptly overlying strongly foliated trondjemitic gneiss or massive to foliated granitoid rocks. More typically, the quartzite forms rubbly piles of blocks and debris (Fig. 3) due to intense tropical weathering of the subjacent basement granites and gneisses.

The quartzite is mature to supermature, locally cross-bedded, and is variably deformed. The unit is thicker to the north–northwest where it unconformably overlies gneisses of the Imataca complex. Near the unconformity in all locations strain is low, but adjacent to the overlying allochthon the quartzite is partially to completely recrystallized and strongly lineated (SSW). Lenses of strongly-modified quartzite occur within the mylonitic basal thrust and probably represent fragments of quartzite incorporated within the suture zone.

The Imataca and Supamo complexes are separated in many places by the Guri fault (Figs. 1 and 2), which was formerly considered to be the suture along which rocks of the Imataca terrane were thrust southward over the greenstone belts and associated plutons of the Supamo complex (Sidder and Mendoza, 1995; Cox et al., 1993; Mendoza, 2000). However, rocks of the El Miamo formation sit unconformably on both the Imataca and Supamo complexes (Fig. 2 inset), which negates this hypothesis and requires that substantial vertical movement on the Guri fault predate sedimentation. Furthermore, because the quartzite is everywhere structurally overlain along a major thrust fault at the base of the overlying volcano-sedimentary successions, the Guri fault cannot be a suture juxtaposing the Imateca complex and Pastora–Supamo terranes during the Trans-Amazonian orogeny.

4. Mylonitic thrust fault

Abruptly overlying quartzites of the El Miamo formation are 5–10 m of mafic mylonite and ultramylonite (Figs. 4–6). The mylonites are well-foliated rocks of basaltic composition and in places contain small elongate and/or rotated clasts of granitic rocks, and locally much larger lenses up to a meter thick of recrystallized and strongly lineated quartzite. Slices of talc-carbonate rocks, possibly derived from ultramafic rocks, also occur

Fig. 3. Typical rubbly appearance of quartzites of the El Miamo formation. The quartzite beds collapse and disaggregate in situ due to deep tropical weathering of the subjacent granites and granitic gneisses.

Fig. 4. Partial cross-section of basal mafic mylonite showing typical appearance of the interior portions of the mylonite zone. Note dismembered and attenuated granitic fragments.

Fig. 5. Contact of mylonite with quartzites of the El Miamo formation in the lower foreground.

Fig. 7. Strongly-folded pillow basalts of the El Callao formation a few meters above basal mylonite, showing extreme attenuation of folds (outlined).

in the mylonitic zone. The metamorphic grade of the mylonitic zone is amphibolite.

Exposures of the zone are generally poor due to tropical weathering and the flaggy or slate-like nature of the rocks; however, the stone is used throughout the region as flagstones in town plazas or as facing for buildings and walls. Thus, there are abundant small quarries in which exposures are excellent. In fact, the author consistently located the best exposures of this zone simply by inquiring locally as to the source of their building stone.

The mylonitic rocks grade upwards into massive basaltic pillow lavas at greenschist grade. Immediately above the mylonite, the pillow basalts are typically intensely-folded with attenuated fold limbs (Fig. 7). Still higher in the section all primary volcanic textures, such as pillows, are well-preserved and strain is low, except within smaller-scale shear zones or axial zones of folds. Menéndez (1995) analyzed samples from the amphibolitic mylonite and they show about the same range and variation in composition as those from basalts above the mylonitic zone.

Fig. 6. Detail of mylonite 50 cm above the contact in Fig. 5. Note dismembered, rotated and attenuated granitic fragments.

5. Allochthon

Sedimentary and volcanic rocks structurally above the basal thrust are termed the Pastora supergroup (Korol, 1965; Menéndez, 1968, 1972, 1995; Mendoza, 1977) and in the study area are preserved in a multiply folded klippe. The older set of folds trends east–northeast whereas the younger set trends north–northwest to northerly (Fig. 2). Rocks of the underlying autochthon are folded along with those of the overlying allochthon.

Traditionally, rocks of the Pastora supergroup were considered to be intruded by plutonic rocks of the Supamo complex: basement was unrecognized. However, in a few places the author discovered 3–15 m of strongly tectonized augen gneiss lying beneath rocks of the Pastora supergroup and above mylonites of the basal thrust. The age of this crystalline basement is unknown.

As originally defined, the Pastora supergroup comprises the Carichapa group and the overlying Yuruari formation (Menéndez, 1968). The Carichapa group consists of the El Callao and Cicapra formations. Thickness estimates for formations are unreliable due to high penetrative strain, faults and folds. Contacts between formations are dominantly structural, not stratigraphic. Thus, it is entirely possible that rocks of the Yuruari formation are the same age as, or older than, rocks of the El Callao formation.

The El Callao formation (Korol, 1965; Menéndez, 1968) occupies the structurally lowest thrust slices and is dominated by pillowed and massive tholeiitic basalt–basaltic andesite with associated pillow breccias and minor chert. The rocks were metamorphosed to greenschist facies assemblages of biotite–chlorite–albite–epidote–actinolite but within the mylonitic rocks of the basal thrust the rocks reach the amphibolite facies. Seventeen samples of the basal mylonitic amphibolite show about the same range and variation in composition as those from the El Callao formation (Menéndez, 1995). As stated earlier, slices of talc-carbonate rocks, possibly derived from ultramafic rocks, also occur in the mylonitic zone. Metagabbro and siliceous dikes and sills intrude the section.

An additional formation, the Florinda, was proposed by Menéndez (1995) for mafic to possible ultramafic lavas that occur at the base of the belt within the El Callao formation. However, except for one of more than 15 samples analyzed from this formation the rocks are chemically indistinguishable on a Jensen diagram from those of the El Callao formation (Menéndez, 1995). For these reasons, and because it occurs in the same stratigraphic-structural position as rocks of the El Callao formation, rocks of the proposed Florinda formation are probably better designated a member of the El Callao formation.

Menéndez (1968, 1995) defined the Cicapra formation for sections of amphibolitic slate with minor mudstone, arenite and conglomerate; but the rocks occur only in a structurally complex area of tight basement-involved folds: the amphibolitic slates are mylonites of the basal thrust and the arenites are quartzites beneath it. The muddy rocks and conglomerates are schists that occur structurally above the basalts and are better placed within the Yuruari formation. From the author's perspective, the term Cicapra formation should be abandoned.

The Yuruari formation (Korol, 1965) is dominated by epiclastic and volcanic rocks metamorphosed and deformed to schists with greenschist facies assemblages of chlorite–sericite–calcite. Original lithologies were feldspathic sandstone, siltstone and shale with minor chert, tuff breccia and intercalated intermediate to mafic tuffs, intrusions, and lavas. In places, polymictic breccia and conglomerate dominate the section. Foliation is crudely parallel to bedding except in the axial zones of folds. A dacitic tuff from the formation yielded a U–Pb zircon age of 2131 ± 10 Ma (Day et al., 1995).

The rock types of other supracrustal belts within the Guayana shield are crudely similar, with tholeiitic and calc-alkaline basalt–basaltic andesite generally structurally overlain by siliciclastic sedimentary rocks and calc-alkaline volcanic successions ranging from basalt to rhyolite (Gibbs, 1987; Gibbs and Barron, 1993; Menéndez, 1995; Ledru and Milési, 1995; Salazar and Franco, 1995; Biagi, 2002). Intermediate composition plutons intrude the sequences and predate the thrusting. Thick sections of dacitic ash-flow tuff attest to the presence of continental basement during generation and eruption.

6. Age of thrusting

There are no direct age determinations on the age of thrusting but it must be younger than 2131 ± 10 Ma, the age of the dacitic tuff in the Yuruari formation (Day et al., 1995). Slightly younger ages of 2120 ± 2 Ma for a siliceous volcanic rock and 2094 ± 6 Ma for zircons in a pre-thrusting diorite, come from the correlative Barama-Mazaruni belt in Guyana (Norcross et al., 2000). The author has examined the western margin of this belt in Venezuela, where it is called the El Dorado-Introduccion (Fig. 2), and found the quartzite and the basal thrust, so it is likely that rocks in this belt are also part of the Pastora allochthon.

Indirect evidence on the maximum age might come from the Imataca complex where $^{40}Ar/^{39}Ar$ plateau ages from minerals in the complex indicate that uplift had ceased by 1.962 Ga (Swapp and Onstott, 1989). Since both the Imateca and Pastora–Supamo terranes are overlain by quartzites of the El Miamo formation, this would imply that the emplacement of the overlying allochthon must be younger than 1.962 Ga.

The minimum age of thrusting is constrained by rocks of the unconformably overlying Cuchivero group, a non-metamorphosed assemblage of continental volcanic and sedimentary rocks intruded by a variety of intermediate to siliceous plutons. Although these rocks are undated by reliable methods at present, rocks correlative with them in Brazil, where they are known as the Surumu group, are dated at 1984 ± 9 and 1966 ± 9 Ma (Santos et al., 2001, 2003). If the correlations are incorrect then the best minimum age comes from 1873 ± 3 Ma zircons within ash beds of the Roraima group, which unconformably overlies rocks in both the Cuchivero group and the Pastoro-Supamo terrane (Santos et al., 2003).

It is obvious that there is a conflict between the $^{40}Ar/^{39}Ar$ plateau ages from the Imataca terrane and the U–Pb zircon ages from rocks of the Surumu group. The simplest way to resolve the differences is for the $^{40}Ar/^{39}Ar$ plateau ages from the Imataca terrane to reflect final denudation after the collisional event that juxtaposed the Pastora allochthon with the Supamo–Imataca terranes. If correct, then the best estimate for the age of thrusting is between 2094 ± 6 and 1984 ± 9 Ma.

7. Implications for gold veins in the El Callao district

Numerous active and inactive gold mines, such as Chile, Laguna, Panama, San Antonio, and Columbia occur just south of El Callao in a section of pillowed and massive basalts of the El Callao formation (Fig. 8). The gold occurs in quartz veins and pods within east–northeast and west–northwest trending shear zones as native gold and as microinclusions within pyrite. While the quartz veins themselves generally contain few sulfides, rocks of the shear zones contain up to about 10% pyrite. The shear zones are up to 10 m thick and span the transition from brittle to ductile as they commonly contain fragments of wall-rock breccia deformed in ductile fashion. Wall-rock alteration includes carbonitization, silicification, seritization and propylitization.

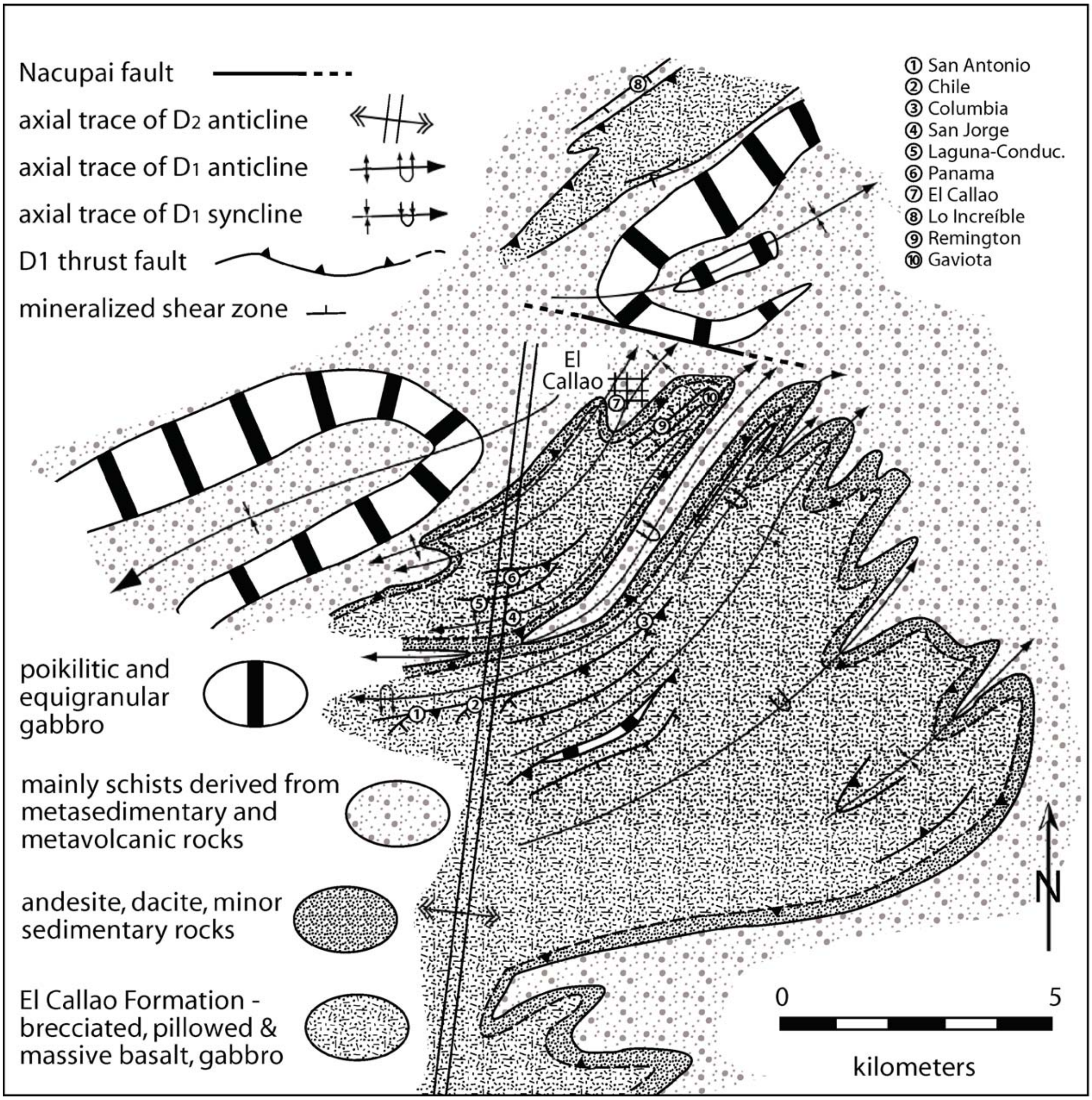

Fig. 8. Geological sketch map of the El Callao area showing the location of some important gold-bearing shear zones and illustrating the relationships between D1 folds and thrusts and D2 folds. Based on geological mapping by the author in 2004. Location of this map shown in Fig. 2.

Many of the known deposits in the immediate area dip 40–60° to the south in a series of east–northeasterly-trending reclined folds (Fig. 3) with southeasterly-dipping axial planes. The veins and shear zones are clearly cut by younger sets of faults, including a set of thrust faults, which dip more steeply and locally imbricate the veins. The thrust faults, which are continuous along strike for many kilometers, are folded along with the strata and, therefore, likely formed during imbrication of the allochthon. Because the mineralized shear

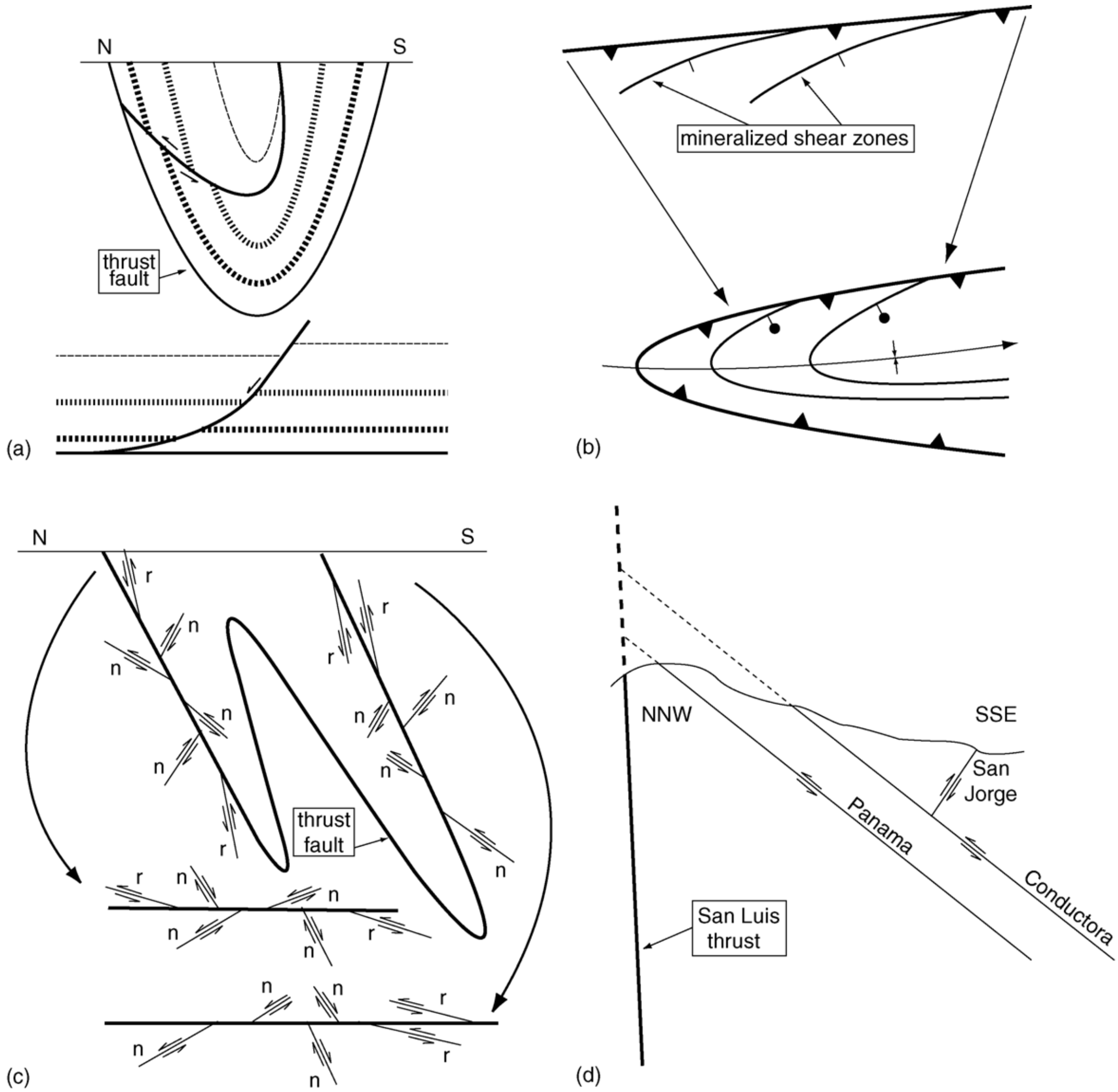

Fig. 9. (a) Cross section illustrating the relationship of a gold-bearing shear zone and younger thrust fault. The shear zone exhibits reverse sense of movement in this orientation; but when effects of the fold are removed it is a normal fault as shown below. (b) A map view of the fold shown in a, but with two normal faults. (c) Folds with overturned limbs have similar geometries to the more simple cases. Only faults showing a reverse sense of separation in their present-day orientation are shown. Note that it does not matter which limb of a fold you are on, nor the relative dip direction, because as long as the early faults show reverse sense of separation today and are less steeply-dipping than the thrusts, they have normal displacement when rotated back to their pre-folding orientation. Only in cases where the early faults are more steeply dipping than the thrusts will reverse faults remain reverse faults. Note that these geometries hold even if the fold limb is overturned, except that early faults, which show reverse sense and are more steeply-dipping than the thrusts have a reversal in that the present-day footwall block is the hanging wall when restored to its pre-thrusting position. These geometric relationships can easily be extended to families of pre-thrusting faults as shown in example (d), which is a schematic cross section, with younger gabbros and faults removed, from the El Callao district. San Jorge, Panama, and Conductora are mineralized shear zones, whereas the San Luis thrust is a regional thrust fault. The three mineralized shear zones contain small-scale structures that indicate reverse sense of movement in their present-day orientation, but are normal faults when restored to their pre-folding orientation.

zones are cut and displaced by the thrust faults, and are not known to transgress the mylonite at the base of the allochthon, the age of mineralization must predate the emplacement of the allochthon.

As many of the deposits occur within the basalt pile there are few, if any, marker horizons to resolve structural complexities. Furthermore, even though the basalts are topographically high standing, deep tropical weathering and vegetation obscure most of the bedrock. Nevertheless, subcrops in mines, as well as in hundreds of exploration pits and glory holes, have small-scale structures in the gold-bearing shear zones that indicate the sense of movement to be hanging wall up to the north, that is, they appear to be thrust or reverse faults. This has presented problems in understanding the origin of the mineralization because, not only is it difficult to create extensive open-space for veins along thrust and reverse faults except along bends in fault strands, but also because it is hard to generate the heat flow necessary to drive hydrothermal circulation in compressional regimes. This conundrum can be resolved rather simply when one realizes that the shear zones are cut by the thrust faults and, therefore, folded—they must be rotated back to their pre-folding orientation in order to resolve their original sense of movement. The discovery of the basal quartzite of the El Miamo formation, the unconformably between the quartzite and the Supamo complex, and the major thrust fault between the quartzite and the greenstone belt, provide markers to resolve pre-folding geometries, because the unconformity, the quartzite veneer, and thrust were all very gently inclined prior to folding. When the effects of the younger folding are removed (Fig. 9) it is clear that the shear zones, which presently display reverse sense of movement, are normal faults.

A major problem, and often a source of confusion for those working only at the mine scale, is that immediately adjacent to the thrusts the foliation within the earlier shears is typically over-steepened or rotated more or less parallel to the plane of the thrust. However, this difficulty can usually be overcome by noting the larger-scale geometries and the angular divergence in plan view between the two sets of faults (Fig. 9b).

Based on the rock types found within the allochthon and the abundant pre-thrusting normal faults, the overall tectonic setting for the allochthon and its mineralized shears is probably an extensional arc to forearc region (Fig. 10). This simple modern analog, known from nearly every modern subduction zone in the circum-Pacific region, generates its magmatism coincident with roll-back of the subduction hinge in the fashion originally proposed by Elsasser (1971) and amplified by others more recently (Kincaid and Olson, 1987; Garfunkel et al., 1986; Uyeda and Kanamori, 1979; Carlson and Melia, 1984; Royden, 1993; Royden and Burchfiel, 1989). Lateral migration, or retrograde slab motion as it is sometimes called, is the typical case in modern subduction zones and is a natural consequence of the simultaneous opening and closing of oceans (Garfunkel et al., 1986). As older, colder, and denser oceanic lithosphere adjacent to the ancient passive margin is subducted, the dip angle of the subducting slab steepens and the subducting slab migrates laterally. The lateral migration causes extension in the overriding plate and trenchward migration of the arc front such that most arcs

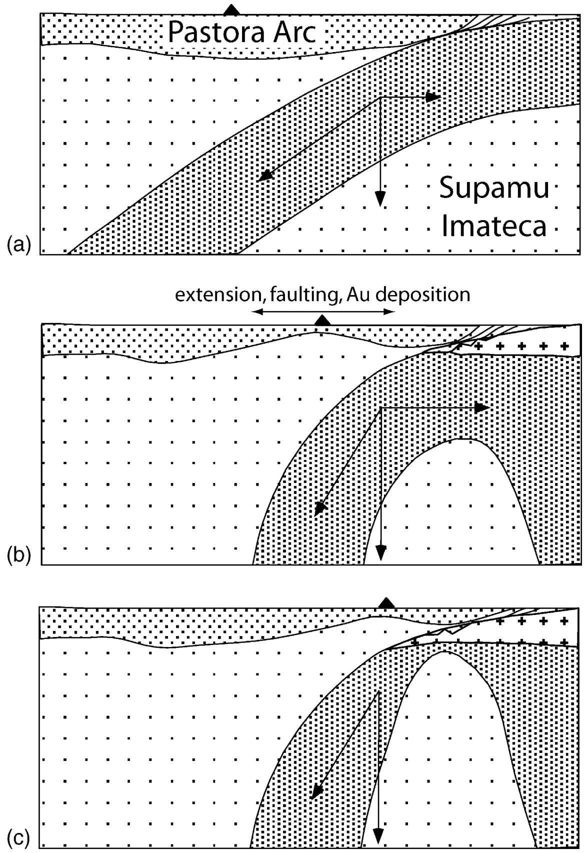

Fig. 10. General tectonic model for the development of the Trans-Amazonian orogeny. (a) Arc magmatism in Pastora arc; (b) as Supamo–Imataca plate approaches, the increasing age, density and thickness of the oceanic portion of the plate causes it to dip progressively more steeply. This leads the arc to migrate trenchward, which causes extension within the arc. It is this extension that provided the likely environment for normal faulting and high heat flow that led to gold deposition. (c) Ultimately, the subducting slab likely fails and large-scale folds (not shown) are formed as the collision zone buckles. The Trans-Amazonian orogeny is the thrusting and subsequent folding that relates to the collision of the Pastora arc with the Supamo–Imataca plate.

are erupted in extensional regimes that migrate trenchward with time (Hamilton, 1988, 1995; Apperson, 1991). This setting has all of the prerequisites for generation of the gold deposits, including high heat flow, extension, and plenty of hot saline water to transport metals.

8. Regional considerations

The discovery of the quartzite sequence lying unconformably on crystalline basement of the Supamo and Imataca complexes and structurally beneath rocks of the Pastora supergroup allows the geology of the Guayana shield to be placed within an actualistic plate tectonics-style framework. They also constrain any major vertical movement between the Supamo and Imataca complexes to predate deposition of the quartzite, which in turn, precludes the possibility that the Trans-Amazonian orogeny was caused by collision between the two complexes. The suture between the two collided plates is actually the major mylonitic shear zone at the base of the Pastora supergroup—rocks of the Pastora supergroup were derived from the upper plate during the collision whereas those of the combined Imataca–Supamo terranes formed the lower plate.

There are only a few outcrops of continental-type basement to the Pastora supergroup known, but based on the presence of large volumes of intermediate ash-flow tuff, an exhaustive search would probably reveal others. The age and provenance of this basement are unknown but the east–northeast trend of D_1 folds in the Supamo–Imataca terrane, the observation that they are much tighter to the north, and the northward thickening of the El Miamo formation all suggest that the main mass of the upper plate lay more or less to the north of the Imataca complex. Unfortunately, the Precambrian rocks to the north were rifted away and reconstructions of this part of the former Atlantica paleocontinent are not convincing (see for example: Teixeira et al., 2003; Condie, 2002).

Some information on the upper plate can be gleaned from the structural stacking order of the thrust sheets within the greenstone belts. In typical thrust belts, the upper slices are, in part, carried piggy-back on the lower slices. If correct, then the stacking order reflects their former lateral distribution, with the lowest sheets of tholeiitic pillow basalts derived from a more trenchward setting than the calc-alkaline rocks and associated sedimentary rocks. In the model presented here magmatism migrated trenchward with time, so precise U–Pb dating of zircons and/or baddleyite should show the basalts to be slightly younger than the calc-alkaline rocks of the upper slices.

The first set of regional folds is a set that trends east–northeast and involves rocks of both the allochthon and autochthon. The folds are most likely related to the terminal stages of collision much as large-amplitude basement-involved folds in Wopmay orogen and the Cape Smith belt reflect progressions from thin-skinned to thick-skinned deformation during their collisional events (Hoffman, 1989; St-Onge and Lucas, 1990; Lucas and Byrne, 1992). Probably, when the subducting slab fails due to competing bouyancies and the oceanic crust lithosphere is torn from the continental portion of the plate (Hildebrand and Bowring, 1999), horizontal compression does not stop instantaneously, perhaps in part due to diachronous slab break-away (Hoffman, 1989) or possibly just due to plate momentum. Whatever the cause, it is likely that progressive steepening and locking of the suture due to rapid uplift is followed by large-scale buckling of the collision zone as the final contraction is distributed over the entire thickness of the orogen.

The second set of folds trends more or less northerly and the folds are generally tighter to the west–southwest (Fig. 2). The western–southwestern edge of the Imataca–Pastora–Supamo terrane lies unconformably beneath the 1.98 Ga Cuchivero-Surumu calc-alkaline volcano-plutonic terrane, which trends northwest and overlies the poorly-known and jungle-covered San Carlos terrane to the southwest (Fig. 1). A common scenario following arc-continent and continent–microcontinent collisions is for a new subduction zone to start outboard of the collision zone and dip beneath the previously amalgamated continental plates. A well-studied example occurs in the Paleoproterozoic Wopmay orogen of northern Canada, where following attempted subduction of Slave craton beneath Hottah terrane, a new volcano-plutonic arc known as the Great Bear magmatic zone rapidly formed atop the newly amalgamated block (Hildebrand et al., 1987; Hoffman, 1989). The second set of folds could thus be related to collision between the Imataca–Pastora–Supamo and San Carlos terranes (Fig. 1).

9. Conclusions

The recognition of a regional quartzite unit sitting unconformably above both the Imataca and Supamo complexes, but beneath a major mylonitic shear zone at the base of the structurally overlying greenstone belts, indicates that the rocks of the Imataca and Supamo complexes were juxtaposed prior to the Trans-Amazonian orogeny, and that the main event of the orogeny was the imbrication and emplacement of the Pastora allocthon upon the quartzite and its basement during attempted subduction beneath an arc bearing continent–microcontinent that formerly lay to the north. Two periods of basement-involved folding—the oldest of which probably constituted the terminal phase of the collision, and the younger likely the effect of a collisional event to the southwest—deformed the collision zone to form klippe of the greenstone belt rocks. The term Trans-Amazonian orogeny should be restricted to the imbrication, emplacement, and first period of basement involved folding.

Auriferous shear zones in the El Callao mining district do not transgress the sole thrust and are cut by the thrust faults, so they formed prior to the collisional event. They, along with their wall-rocks, were transported and emplaced atop the Imataca–Supamo plate during the collision. Although the shear zones typically display a reverse sense of separation, when they are rotated to their pre-folding orientation, they are normal faults. This is compatible with their formation in an extensional arc-forearc setting prior to the collision.

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