July 2010 LIP of the Month

The Avanavero Large Igneous Province: A Paleoproterozoic LIP In The Guiana Shield, Amazonian Craton

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Introduction

The Avanavero mafic magmatism lies within the Guiana Shield, northern Amazonian Craton, and represents one of the largest igneous provinces (LIPs) of the South American Platform. It comprises voluminous mafic dikes and sills, the latter intrusive into the Roraima Supergroup that crops out over a wide continuous sedimentary area (c.a. 73,000 km^2, Gibbs & Barron 1983) of Venezuela, Brazil and Guyana known as Pakaraima Sedimentary Block – PSB (Reis & Yánez 2001, Figures 1 and 2). The PSB cover sequences correlate with a lot of minor and surrounding sedimentary cover outliers, sometimes referred as Roraima-like cover, such as Tafelberg in Suriname, Tepequém, Uafaranda, Urutanim and Urupi in Brazil, Makari in Guyana and Ichún, Jaua and Cacaro in Venezuela (Figure 1).

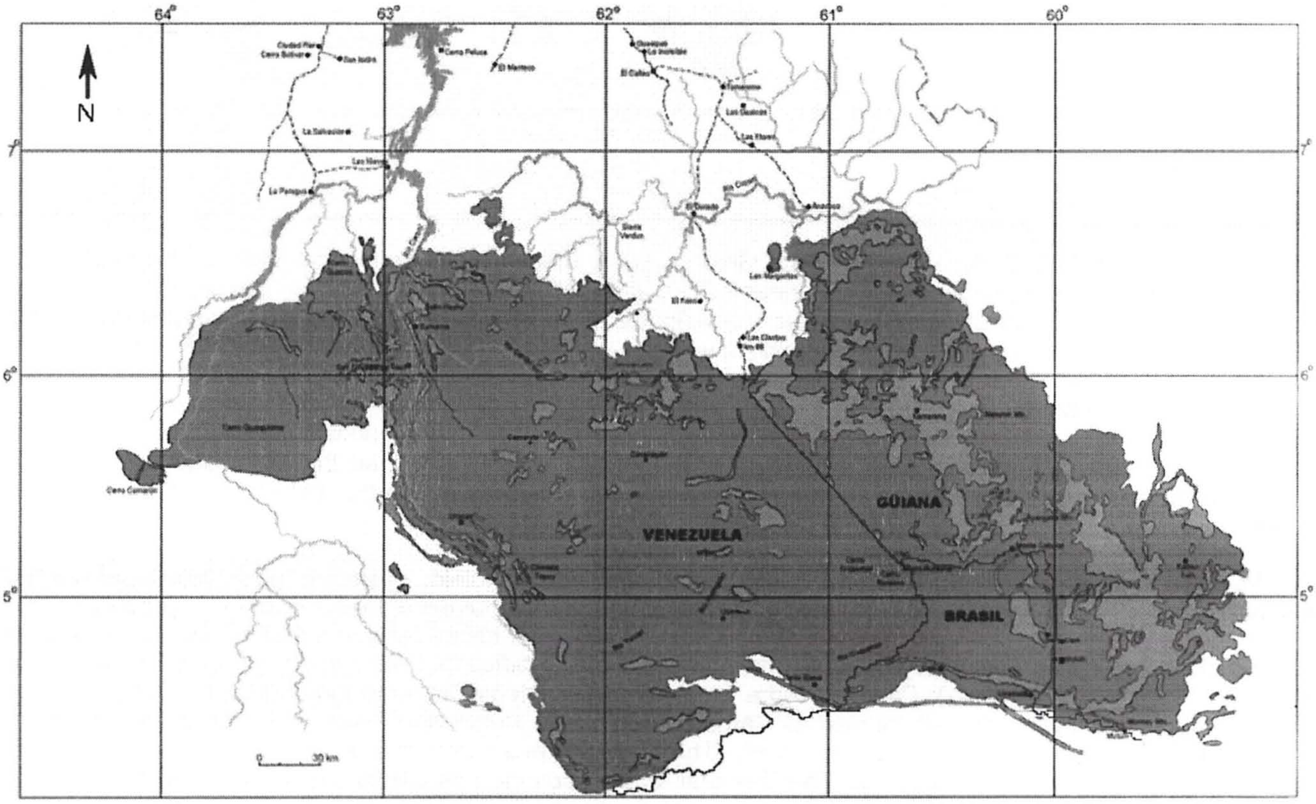

__Figure 1.__ The Pakaraima Sedimentary Block (PSB) and surrounding outliers in Guiana Shield: 1 – Tafelberg; 2 – Makari; 3 – Tepequém; 4 – Urutanim; 5 – Uafaranda; 6 – Ichún; 7 – Jaua; 8 – Cacaro; 9 – Urupi/Quarenta Ilhas. Modified from Santos et al. (2003).

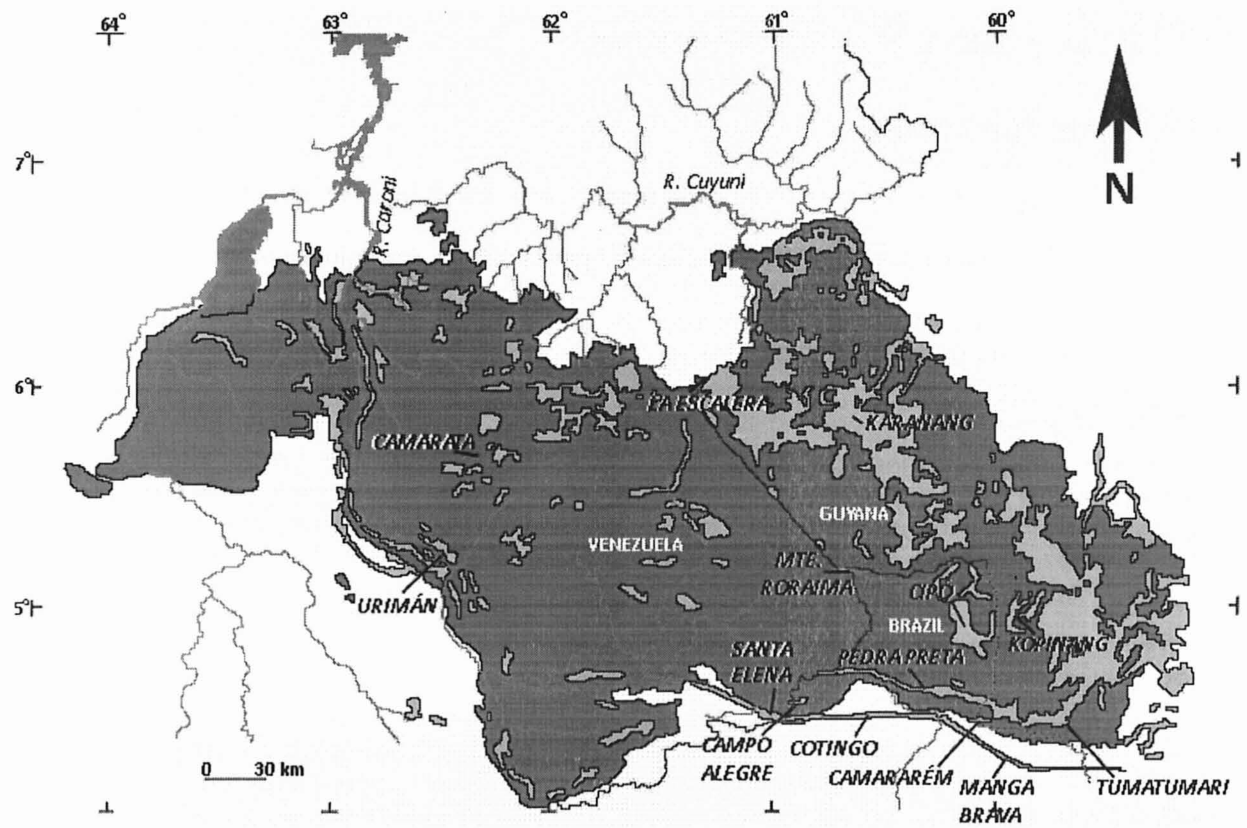

Figure 2. The Pakaraima Sedimentary Block (brownish color) along the Venezuela, Brazil and Guyana borders. The Avanavero dikes and sills are shown in light greenish color. After Reis et al. (2000). The red lines indicate the country boundaries.

The term *Avanavero Dolerite* was first used by Groeneweg & Bosma (1969) for large dikes and irregular sills in the Avanavero region and surrounding areas in Suriname. The association of this mafic magmatism around the Guiana Shield with the Roraima Supergroup sedimentary cover was reflected in the original name, *Roraima Magmatic Province* given by Bellizzia (1957). In the 1970's Avanavero magmatism was used to establish the minimum age of the Roraima Supergroup, and a series of K/Ar and Rb/Sr age determinations of such mafic rocks was reported by Snelling & Berrangé (1970), Priem *et al.* (1973) and Hebeda *et al.* (1973). An age around 1.6 Ga was inferred for the Avanavero magmatic event. Subsequently, a minimum age of 1.78 Ga was determined by U/Pb SHRIMP using baddeleyite and zircon from two levels of Avanavero sills emplaced into the Brazilian portion of the PSB, which also defined the lower age limit of the Roraima Supergroup (Santos *et al.* 2003). These U-Pb ages remain the best constraints on the age of Avanavero magmatism (see discussion below).

Apart from the widespread use of the term Avanavero in the Guiana Shield, numerous geologists have described this magmatism under various local names. Hawkes (1966) recognized three levels of mafic rocks in Guyana (lower to upper): the Tumatumari sill, the Kopinang sill (Main Sill) and the high level sill below the summit of Mount Roraima. In Roraima State, Brazil, the so-called Avanavero Diabase comprises four main bodies that are intruded into the Roraima Supergroup (Reis *et al.* 1990) (lower to upper): Cotingo, Pedra Preta, Cipó and Monte Roraima (see figure 2). Other small outcrops, commonly sills, have been informally named as Camararém, Campo Alegre and Paiuá. The first two sills extend through the border with Guyana and Venezuela respectively. The Manga Brava name was applied by Santos *et al.* (2003) to the easternmost extension for the Cotingo sill. The Tumatumari and Cotingo sills are usually concordant in both sedimentary and volcanic rocks (Surumu Group in Brazil and Iwokrama Formation in Guyana), passing to a different horizon by way of an inclined sheet (feeder dikes). In the Venezuelan portion of the PSB several authors have described Avanavero mafic sills under local names as such Uriman, Gran Sabana, Luepa, Aprada and La Escalera, although no specific stratigraphic unit into Roraima Supergroup has been mentioned. A brief and speculative correlation between the several levels and proposed local sill names from across the PSB is presented in the Table 1.

	PSB - sill level / local name			
Country	***Upper 2***	***Upper 1***	***Middle***	***Lower***
BR	*Monte Roraima*	*Cipó*	*Pedra Preta*	*Cotingo – Manga Brava*

VZ	*Monte Roraima*	*Camarata?*	*Urimán - La Escalera?*	*Luepa - Sta. Elena*
GUY	*Mount Roraima*	*Upper Kopinang*	*Lower Kopinang*	*Tumatumari*
Unit	*Mataui Fm.*	*Uaimapué Fm.*	*Suapi Gr.*	*Arai Fm.*

Table 1. *Speculative correlation of local sills to the Avanavero sill level into PSB and related sedimentary units according Reis & Yánez (2001): BR – Brazil; VZ – Venezuela; GUY – Guyana.*

Figure 3. *The Cotingo sill (Avanavero first level into Roraima Supergroup and Surumu volcanics) cut by Mesozoic dike (on which is a hammer for scale). Tamanduá - Laimã area, northern portion of Roraima State, Brazil (GPS N 0795796/ W 0502503).*

According to Hawkes (1966) the higher levels of mafic rocks vary in composition, suggesting variable differentiation before intrusion. Differentiation may also occur within a single sill (i.e., in situ). Norite often constitutes the uppermost levels in a sill while lower levels are mainly gabbro.

The Avanavero rocks are medium to coarse-grained. The differentiation processes increases to the center of the bodies, indicated by micrographic intergrowth and pyroxene uralitization, i.e., replacement by amphibole, chlorite and opaque minerals. In thin section Avanavero rocks are composed of plagioclase, pyroxene, amphibole and accessory minerals (magnetite and ilmenite). The plagioclases are calcic (andesine) and occur as short prismatic crystals, with albite or albite-Carlsbad twinning. The pyroxenes are divided into two groups: augite (Ca-rich) and pigeonite (Ca-poor), and the latter is frequently inverted to orthorhombic forms; augite is more abundant than pigeonite. Late hydrothermal processes are common, as indicated in petrographic descriptions where plagioclases are altered to clay minerals and/or albite (Pinheiro *et al.* 1990). The diabase dikes generally show an ophitic texture and are composed of plagioclase (labradorite), pyroxene (augite and occasionally pigeonite), hornblende and accessory minerals (chlorite, sericite, and epidote).

Outside the Roraima Supergroup domain the Avanavero dikes (Gibbs 1987; Sial *et al.* 1987) show different strikes and are difficult to distinguish in the field from Mesozoic dikes (Taiano in Roraima, Apoteri in Guyana, Apatoe in Surinam) and Mesoproterozoic dikes (Käyser in Surinam) dikes. WNW-striking structures are the most common in the crystalline basement and the Avanavero dikes frequently follow these trends, although the Aro swarm in western Venezuela differs from most Avanavero intrusions, where both fault and most dikes strike NE. The Avanavero dikes are normally more extensive and more irregular in shape than those of Mesozoic age (ca. 200 Ma.) age. Many of the Avanavero sills are connected with basement dikes. The Avanavero dikes are typically tens of kilometers in length, sometimes exhibit branching and also can change in trend (Gibbs 1987).

Chemistry of the Avanavero sills and dikes

The chemistry of the Avanavero sills and dikes remains poorly studied with the great majority of geochemical results based only on major elements and some trace elements. The Avanavero magmatism is classified as continental tholeiitic as was demonstrated by Pinheiro *et al.* (1990). These authors showed that a group of Avanavero' samples from many parts of the Guiana Shield plot together in the tholeiitic field on the AFM diagram (figure 4).

In Guyana, the Avanavero rocks show generally low Ti, P and Zr, with relatively high lithophile elements (LILE) and rare-earth elements (REE). This suggests a mantle source previously depleted in Ti, P and Zr and later enriched in LILE elements. Ti/Zr for Avanavero dikes is slightly high (Choudhuri 1978).

Otherwise, high LILE, low Nb, low Ti and high $^{87}Sr/^{86}Sr$ ratios, interpreted as evidence of crustal contamination have been found for the Cotingo and Pedra Preta sills in Roraima (Leal *et al.* 2001). Typically Avanavero magmatism shows high enrichment in LREE related to HREE.

The Tumatumari – Kopinang sills in Guyana show the iron-enrichment typical of tholeiitic magma (Hawkes 1966) (Figure 4).

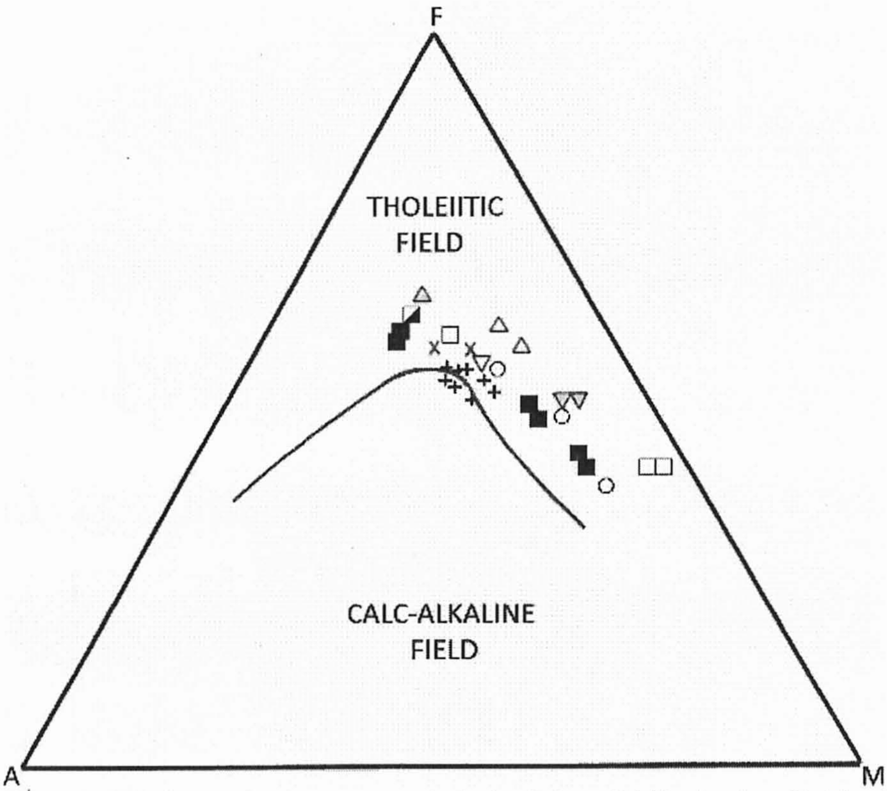

Figure 4. *AFM diagram for Avanavero rocks in the Guiana Shield: triangle – Cipó level (Roraima State, Pinheiro et al. 1990); cross – Pedra Preta level (Roraima State, Pinheiro et al. 1990); x – Cotingo level (Roraima State, Pinheiro et al. 1990); circle – Monte Roraima level (Roraima State, Pinheiro et al. 1990); inverted triangle – Kamarata sill (Venezuela, Bellizzia 1957); open square – Canaima sill (Venezuela, Bellizzia 1957); full square – Kopinang sill (Guyana, Hawkes 1966); semi-full square - Tumatumari sill (Guyana & Hawkes 1966).*

Geochronology

Avanavero magmatism has been the focus of intensive geochronological studies since the 1960's, and there have been two goals: firstly to establish indirectly the minimum age of the Roraima Supergroup and secondly to date this important widespread mafic magmatic event in the Guiana Shield.

The available K/Ar determinations for the Avanavero magmatism yield a broad range of ages from 1.2 – 2.7 Ga (McDougall *et al.* 1963; Hargraves 1968; Snelling & McConnell 1969; Hebeda *et al.* 1973; Priem *et al.* 1973; Frick & Steiger 1974, Basei & Teixeira 1975, among others). According to K/Ar systematics the oldest ages in western Suriname can be explained by an excess of radiogenic ^{40}Ar (Hebeda *et al.* 1973). K-Ar measurements were made on 61 samples from Avanavero Dolerite by the authors and 93% of all dates were older than the 1603 Ma Rb-Sr isochron age. Santos *et al.* (2003) point to an opposite effect, that is Rb/Sr ages exhibit radiogenic ^{87}Sr loss, which produces lower $^{87}Sr/^{86}Sr$ ratios and thereby ages which are too young. In addition, the Avanavero magmatism shows reset K-Ar ages around 1.2 Ga, attributed to the K'Mudku Episode (Barron 1962). Table 2 summarizes the previous K/Ar and Rb/Sr results.

Level (sill)/dike	*State/Country*	*Age*	*Method*	*Reference*

Aprada Ambituir; Lower Kopinang	*Venezuela, Guyana*	*1490-2070 Ma*	*K/Ar (plag.;pyrox.)*	*McDougall 1968*
hornfels	*Guyana*	*1640 ± 30 Ma*	*Rb/Sr (isochron)*	*Snelling & McConnell 1969*
unknown	*Guyana*	*1695 ± 65 Ma*	*Rb/Sr (isochron)*	*Snelling & McConnell 1969*
Tafelberg	*Suriname*	*1593 ± 66 Ma*	*Rb/Sr (isochron)*	*Snelling & McConnell 1969*
sill	*Guyana*	*1965 ± 66 Ma*	*Rb/Sr (isochron)*	*McConnell & Williams 1970*
Avanavero type-area	*Suriname*	*1603 ± 27 Ma*	*Rb/Sr (isochron)*	*Hebeda et al. 1973*
Tafelberg	*Suriname*	*1544 ± 50 Ma*	*Rb/Sr; K/Ar*	*Priem et al. 1973*
second level into Roraima Supergroup (P.Preta)	*Roraima, Brazil*	*1647 ± 45 Ma*	*K/Ar (whole rock)*	*Frick & Steiger 1974*
second level into Roraima Supergroup (P.Preta)	*Roraima, Brazil*	*1712 ± 45 Ma*	*K/Ar (whole rock)*	*Frick & Steiger 1974*
second level into Roraima Supergroup (P.Preta)	*Roraima, Brazil*	*1807 ± 47 Ma*	*K/Ar (biotite)*	*Frick & Steiger 1974*
second level into Roraima Supergroup (P.Preta)	*Roraima, Brazil*	*1805 Ma*	*K/Ar (hornfels)*	*Basei & Teixeira 1975*

Table 2. *Previous K/Ar and Rb/Sr ages for Avanavero sills and dikes*

More recently Santos *et al.* (2003) used U/Pb (baddeleyite) geochronology to precisely date the Cipó and Cotingo sills which are intrusive into the Roraima Supergroup in two different stratigraphic levels. Both yielded similar ages: 1787 ± 14 and 1782 ± 3 Ma respectively. These ages provided a minimum age for the Roraima cover, and they correlate well with that of other Avanavero intrusions (1794 ± 4 Ma) in Guyana one of which was dated by Norcross *et al.* (2000) using the same method. Aditional U-Pb baddeleyite ages were obtained by Santos *et al.* (2002) for the Crepori sill (1780 ± 7 Ma) in southwestern Pará State and for the Quarenta Ilhas sill (1780 ± 3 Ma) in northeastern Amazonas State. These similar U-Pb baddeleyite ages confirm that Avanavero magmatism can also be recognized far away from the Surinam type-area, albeit the largest volume of magma has been concentrated into the PSB and surroundings. The Ar-Ar age (1798 ± 2 Ma) in biotite obtained by Onstott *et al.* (1984) remains the best age estimate, using that method, for emplacement of the Guaniamo dike. Table 3 presents the available U-Pb and Ar/Ar results.

Level (sill)/dike	***State/Country***	***Age***	***Method***	***Reference***
third level into Roraima Supergroup (Cipó sill)	*Roraima, Brazil*	*1787 ± 14 Ma*	*U-Pb (baddeleyite)*	*Santos et al. 2003*

first level into Roraima Supergroup (Cotingo sill)	*Roraima, Brazil*	*1782 ± 3 Ma*	*U-Pb (baddeleyite)*	*Santos et al. 2003*
(Crepori sill)	*Pará, Brazil*	*1780 ± 7 Ma*	*U-Pb (baddeleyite)*	*Santos et al. 2002*
(Quarenta Ilhas sill)	*Amazonas, Brazil*	*1780 ± 3 Ma*	*U-Pb (baddeleyite)*	*Santos et al. 2002*
Omai Mine (dike)	*Guyana*	*1794 ± 4 Ma*	*U/Pb (baddeleyite)*	*Norcross et al. 2000*
Guaniamo (dike)	*Venezuela*	*1798 ± 2 Ma*	*Ar-Ar (biotite)*	*Onstott et al. 1984*

Table 3 *– U-Pb and Ar/Ar ages for Avanavero sills and dikes*

Paleomagnetism

A paleomagnetic study on 110 oriented cores collected from 16 sites of sills exposed in northern Roraima State, are presently in progress at the laboratory of paleomagnetism of the University of São Paulo (IAG-USP). AF treatment was efficient in isolating a characteristic southeastern, low inclination direction after removal of low coercivity components (Figure 5). Thermal and AF demagnetization associated with thermomagnetic curves and IRM acquisition curves suggest Ti-poor titanomagnetite as the main magnetic carrier of this characteristic component.

Preliminary site mean directions are shown in Figure 6a. These directions are very different from the present geomagnetic field, and also from the northern, low downward inclination directions found in the ~200 Ma mafic dikes of the Central Atlantic Magmatic Province that are widespread in the Guiana Shield basement (Théveneaut *et al.* 2006). It is also very different from the northern, steep upward inclination directions found for the ~1.79 Ga Colider acid volcanic rocks that belong to the southernmost part of the Amazonian Craton (Bispo-Santos *et al.* 2008). This implies either, that the paleomagnetic directions from Colider Suite and Avanavero mafic rocks were acquired at different times or that relative movement occurred between the Guiana Shield and the Central-Brazil Shield after 1.78-1.79 Ga ago.

The characteristic directions from the Avanavero sills and dikes are similar to those found in the Guaniamo and Rio Aro dikes from Venezuela (Figure 6b), and ascribed to the component II by Onstott *et al.* (1984). These authors suggest an age between 1.80 and 1.84 Ga for this component based on ^{40}Ar-^{39}Ar analysis on biotite and plagioclase from a diabase. However, as summarized above, Avanavero magmatism is now well-dated at 1.78-1.79 Ga.

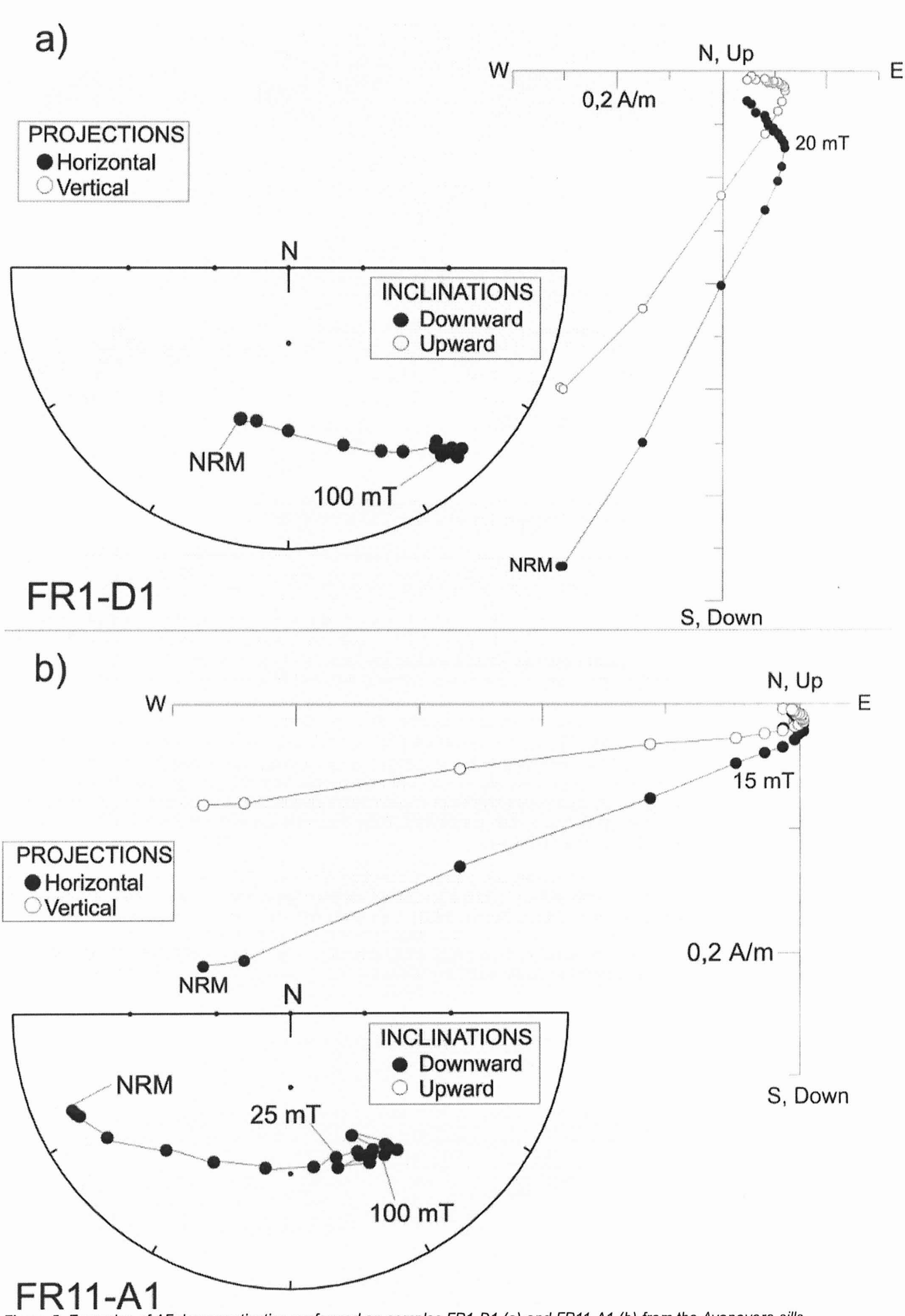

Figure 5. *Examples of AF demagnetization performed on samples FR1-D1 (a) and FR11-A1 (b) from the Avanavero sills.*

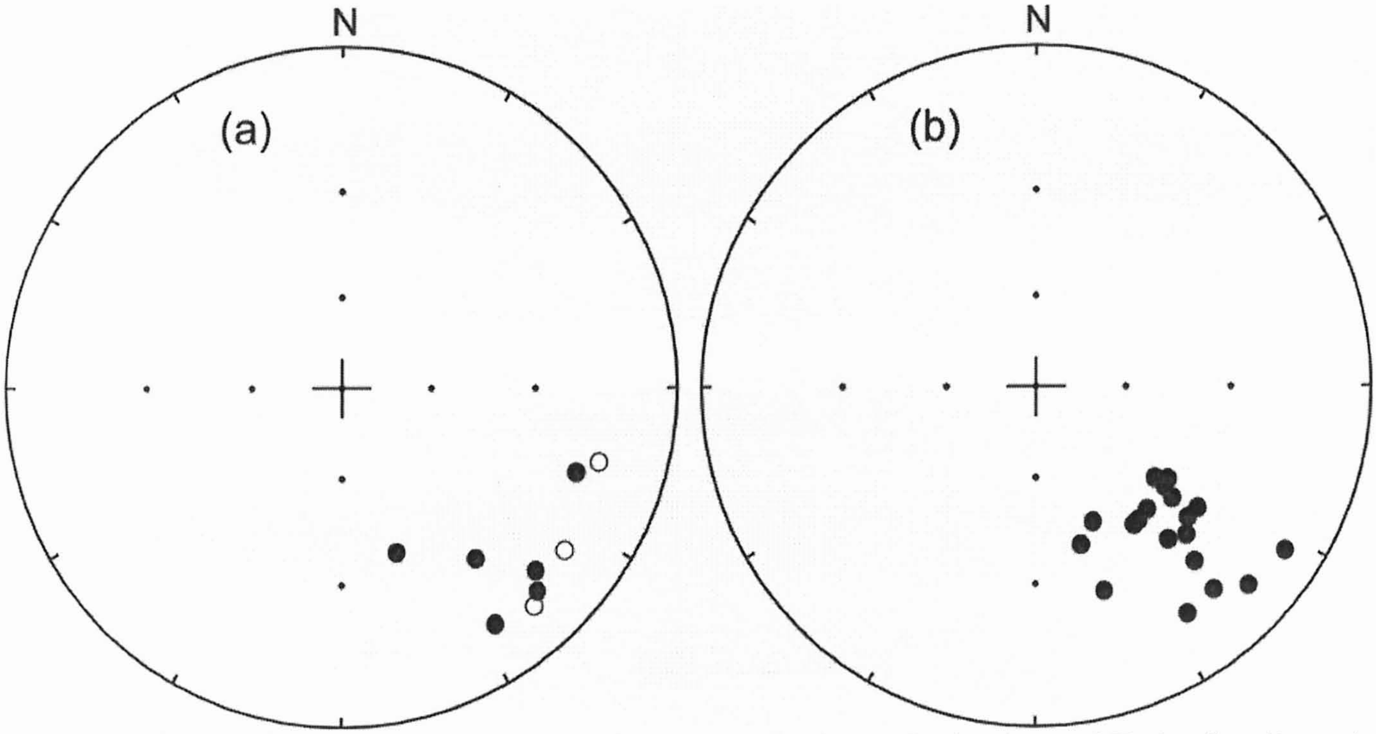

Figure 6. (a) Site mean directions for the Avanavero sills. (b) Site mean directions for the Guaniamo and Rio Aro dikes, Venezuela (component II of Onstott et al. 1984). Open (full) symbols represent upward (downward) directions.

Final Remarks

According to Gibbs (1987) the Guiana Shield hosts one of the most significant anorogenic magmatic provinces of Paleoproterozoic age on the Earth. This province includes plutonism, volcanism and the Avanavero mafic intrusions. The Avanavero mafic rocks (1.79 – 1.78 Ga) occur as dikes intruding the basement or as sheets intruded into the Roraima Supergroup or into isolated sedimentary cover sequences, pointing to a within-plate setting for emplacement. This voluminous igneous episode must be on the order of at least 30,000 km^3. The Avanavero ages for mafic sills obtained far away from the northern portion of the Guiana Shield as Quarenta Ilhas and Crepori, permit to postulate an areal surface bigger than that previously inferred (Figure 7), and the overall distribution (including dikes, sills and volcanics) extends over an area of at least 300,000 km^2 (p. 508 in Ernst and Buchan 2001). Avanavero magmatism has tholeiitic chemical affinity, and differs in structural style, chemical composition and geological relationship from the younger 200 Ma Central Atlantic Magmatic Province which belong the Apoteri Formation from Guyana and Taiano Diabase from Brazil (Reis *et al.* 2008) near the border area. Avanavero magmatism is also distributed along the northern and southern border of the Guiana Shield but does not appear present on the eastern side.

Avanavero magmatism was associated with continental rifting (Choudhuri & Milner 1971). The irregular distribution of the intrusions has been more recently interpreted as a reflection of an emplacement into a weak juvenile crust that was simultaneously undergoing partial melting (Gibbs & Barron 1993). Under an extended period of melting from a huge mantle source both chemical differentiation of the crust and gradual loss of radiogenic heat sources may have contributed to a change in the craton's response to extensional stresses and mafic intrusion. This magma was not propagated uniformly over large areas, impeding the development of swarms (Gibbs 1987).

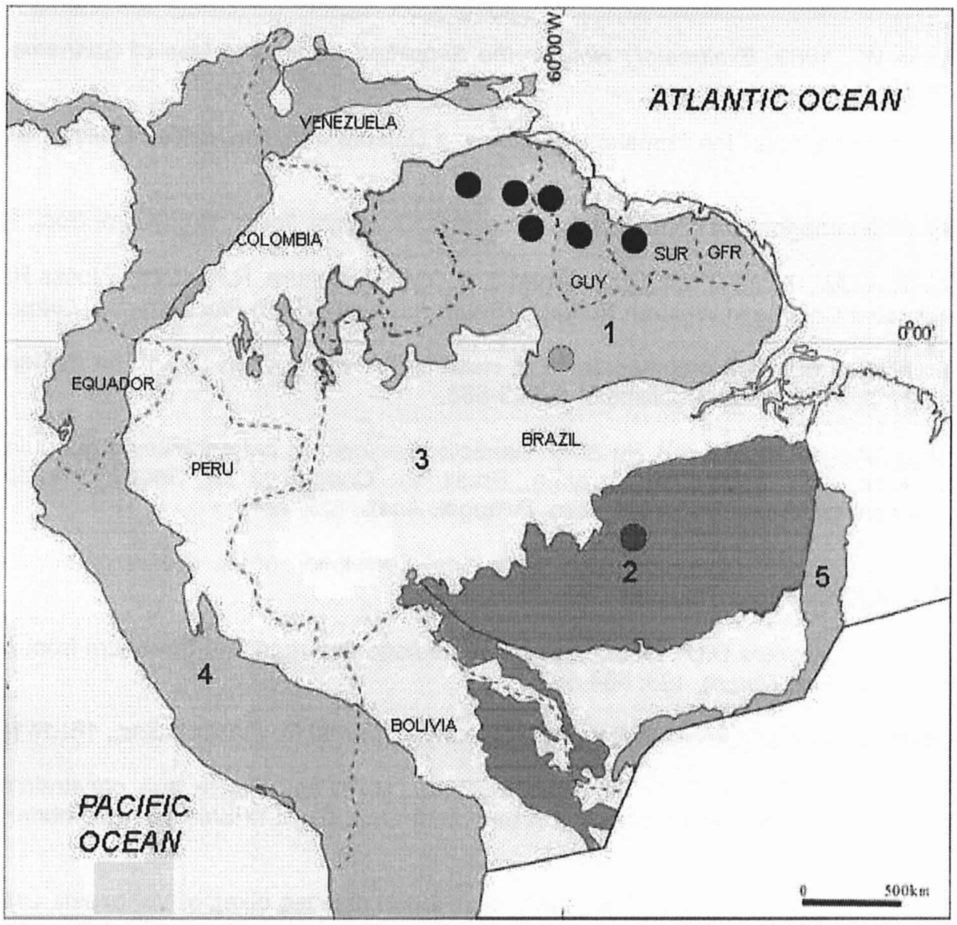

Figure 7. Locations of Avanavero sills and/or dikes. Legend: 1 – Guiana Shield; 2 – Central Brazil Shield; 3 – Phanerozoic Cover; 4 – Andean Belt; 5 – Araguaia Belt. Black points – typical Avanavero magmatism; green point – Quarenta Ilhas magmatism; purple point – Crepori magmatism.

Acknowledgements

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