GEOLOGICAL AND GEODIVERSITY MAPPING PROJECT ON THE BRAZIL–SURINAME BORDER

EXPLANATORY NOTE FOR THE GEOLOGICAL AND MINERAL RESOURCES AND GEODIVERSITY MAPS

July 2017

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GEOLOGICAL AND GEODIVERSITY MAPPING ON THE BORDER BRAZIL – SURINAME PROJECT

EXPLANATORY NOTE FOR THE GEOLOGICAL AND MINERAL RESOURCES AND GEODIVERSITY MAPS

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Appendix

1. INTRODUCTION.

The **GEOLOGICAL AND GEODIVERSITY MAPPING PROJECT ON THE BRAZIL – SURINAME BORDER** (Fig. 1) was carried out at the framework of the Supplementary Agreement to the Basic Agreement for Technical and Scientific Cooperation (BR / 04/043) signed between the Republic of Suriname and the Federative Republic of Brazil and was developed under the coordination of the Brazilian Cooperation Agency - ABC of the Ministry of Foreign Affairs of Brazil and the Ministry of International Affairs of Suriname. The project intensified intergovernmental cooperation through the joint action of the executing institutions, the Geological Survey of Brazil - CPRM and the Geological and Mining Service of Suriname - GMD, with the participation of Anton de Kom University of Suriname and the Environment and Mining Foundation of the Ministry of Mineral Resources of the Government of Suriname.

The focus of the project was the improvement and harmonization of the geological knowledge of the Brazil-Suriname border region, as well as the identification and spatialization of occurrences of mineral resources and the characterization of the geodiversity of this portion of South America, with the elaboration of maps in the 1: 1,000,000 scale and GIS. These products are important tools for territorial management. The geological integration of the Brazil Suriname border area is also part of the GIS program of South America in the 1: 1,000,000 scale carried out by the Commission for the Geological Map of the World (CGMW).

The work was developed through technical meetings, field activities and laboratory investigations, and involved the on-the-job training of Surinamese technicians with transfer of GIS-Geographic Information System technology applied to geological mapping (Fig.2).

Considering the scale of the work, 1: 1,000,000, the adopted methodology was to integrate and reinterpret all the available data, as fieldwork was only carried out in a restricted area of Suriname.

The Geological and Mineral Resources Map of the Brazilian portion of the area was elaborated through the interpretation of aerogeophysical maps and images of remote sensors and their integration with available geological data. The magnetometry and gamma spectrometry maps of the Trombetas, Paru do Oeste and Mapuera aerogeophysics projects, spacing 1,000 meters between the flight lines, and the Tumucumaque project, with a spacing of 500 meters between flight lines, were used. The interpretation was made with the support of the shaded relief image of the SRTM, and based on the integration of available geological data. These data include regional geological maps (CPRM 2004, Vasquez et al. 2008), which have been reassessed, and descriptions of outcrops and petrographic thin sections of historical projects (Oliveira et al. 1975, RADAM), which have been properly recovered and reinterpreted.

With regard to the Surinamese part of the area, the available geological maps were digitilized and georeferenced in relation to GEOCOVER, with the preparation of shapes of geology and outcrops and the retrieval of the available data in the GIS environment. Unfortunately, the information concerning the outcrops could not be systematically recovered.

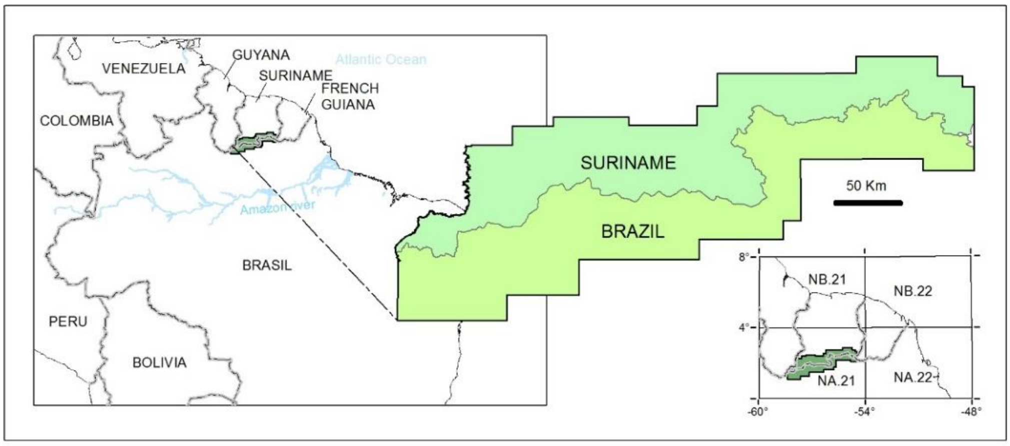


Figure 1. Location of the project area.

Figure 2. Technicians from the Suriname and Brazil teams during the training in June 2011 (a) and technical meeting with geologists representing the Suriname delegation in October 2011 (b) both activities held in the Belém office of the Geological Survey of Brazil-CPRM; Minister of Natural Resources of Suriname Mr. Jim Hok and the Ambassador of Brazil in Suriname Marcello Baumbach, and Dr Telma Faraco, head of the Brazilian delegation at a meeting in Paramaribo, October 2013 (c); Presentation of a lecture on the Geology of the Guiana Shield, by Dr Lêda Maria Fraga, at the Anton de Kom University of Suriname in Paramaribo in October 2013 (d); Binational team on the Sipaliwini river field work in October 2013 (f).

Improvements to the geological map of the Surinamese area were made as a result of the field works in the region of the Sipaliwini River (Fig. 1) and on the base of the interpretation of the SRTM images. During field activities, lasting ten days, 33 outcrops were described and 61 rock samples were collected for laboratorial studies at the Geological Survey of Brazil. Fifty-one thin sections were prepared and studied by the Brazilian team and the results were discussed with the Suriname delegation. Geochemical analyses could not be obtained; however, the results of geochronological analyses carried out on 4 of the samples collected by the binational team in the Sipaliwini River region and one from the GMD sample collection are discussed in this explanatory note. The analyses were performed through collaboration with Prof. Umberto Cordani, from the Laboratory of Geochronology and Isotopic Geology of the University of São Paulo (USP), and Lêda Maria Fraga (unpublished data summarized by Kroonenberg et al., 2016). The new geological data obtained for the Sipaliwini River region together with the reinterpretation of images and the laboratory data allowed the geology of the southern portion of Suriname to be updated in a scale of 1: 1,000,000.

The data obtained in this project contributed to the improvement of the regional knowledge, but were not enough to solve some important geological issues. Therefore, as the reader may perceive, at several points in this explanatory note two possible interpretations for the described geological features are presented. These sometimes antagonistic interpretations are based on the experience of the various researchers who participated in the project and it is hoped that they will contribute to the scientific debate and guide future geological investigation in the region.

The geodiversity aspects of the studied area are also addressed in this explanatory note. The aim of the geodiversity studies is the reclassification of geological information, grouped in the form of domain and geological-environmental units in order to gather lithological or lithostratigraphic units that present similar characteristics concerning the use and occupation of the land (CPRM, 2006). The information presented in this topic is complementary to the geodiversity map produced for the area, which provides information for engineering work, agricultural use, polluting sources, and mineral potential and for groundwater and sites favorable to geotourism.

2. REGIONAL GEOLOGICAL SETTING

The Amazonian Craton in the north of the South American Continent (Fig. 3, inset) is one of the largest cratonic areas of the planet and was stabilized during the Brasiliano Cycle in the Neoproterozoic. The Amazon Basin splits the craton in two parts, the Guiana Shield in the north and the Central-Brazil Shield in the south (Fig. 3). The study area is situated in the central-eastern part of the Guiana Shield, which will be shortly described below, with emphasis on its the central and eastern parts.

Archean rocks or rock units with Archean heritance were only identified in the Amapá Block (Rosa-Costa et al. 2006) in the south-eastern part of the Guiana Shield, and in the Imataca Complex, in its north-western extremity (Swapp & Onstott, 1989, Tassinari et al. 2004). These two Archean segments were strongly reworked during the Trans-Amazonian Cycle, and between these units Proterozoic lithological units of varying ages, compositions and geodynamic significance crop out. The limits of the Trans-Amazonian Cycle are still being debated in the geological literature (see discussion in Santos, 2003). Some authors consider an age range of 2.2-2.0 Ga, the main period of juvenile crustal growth in the South American Platform (Cordani & Sato, 1999), while other researchers prefer younger minimum ages for the Trans-Amazonian Cycle, down to 1,95 (Tassinari & Macambira, 1999) or 1,93 (Delor et al. 2003a).

The north-eastern part of the shield is dominated by Rhyacian granite-greenstone terrains, with volcano-sedimentary sequences (Marowijne Greenstone Belt in Suriname), TTG complexes and associated granitoids, showing ages between 2.26 and 2.11 Ga (Teixeira et al. 1985; Gruau et al. 1985; McReath & Faraco, 1997; Vanderhaeghe et al. 1998; Delor et al. 2003b), which extend continuously across the boundaries between Suriname, French Guiana and Brazil (Fig.3) (Bosma et al. 1983; Gibbs & Barron, 1993; McReath & Faraco, 1997; De Vletter et al. 1998). The isotopic data indicate a predominantly juvenile character, without contributions of older continental crust, for the granite-greenstone belts of the north-eastern part of the shield (Gruau et al. 1985; Ledru et al. 1994; Vanderhaeghe et al. 1998; Delor et al. 2003b). This scenario contrasts with the situation observed in the Amapá Block, where the granite-greenstone terrains record an important contribution of Archean crust (Avelar et al. 2003). Several authors considered the granite-greenstone belt of the Guiana Shield to have evolved as an island arc (Gruau et al 1985; Ledru et al. 1994; McReath & Faraco 1997; Vanderhaeghe et al. 1998; Delor et al. 2003b) or continental magmatic arc, along the border of the Amapá Block (Avelar et al. 2003; Rosa- Costa et al. 2006). The origin and development of the magmatic arcs and islands arcs would be related to the approaching of two Archean paleoplates, that are now incorporated in the Amazonian and West-African Cratons. The collision of those plates in the period between 2.11 and 2.08 Ga resulted in the closure of the oceanic basins and marginal basins, and culminated in the migmatization of the TTG complexes, the development of important sinistral shear zones, and the opening of pull-apart-basins in the north-eastern part of the shield (Delor et al. 2003b). In the southeast portion, characterized by the presence of a thicker Archean crustal block, the collision between the Archaean paleoplates resulted in intense deformation and metamorphism in amphibolite to granulite facies with a fast cooling path related to the tectonically controlled exhumation (Rosa-Costa et al. 2008).

The prolonged shearing of the juvenile, dominantly Rhyacian crust in the north-eastern part of the

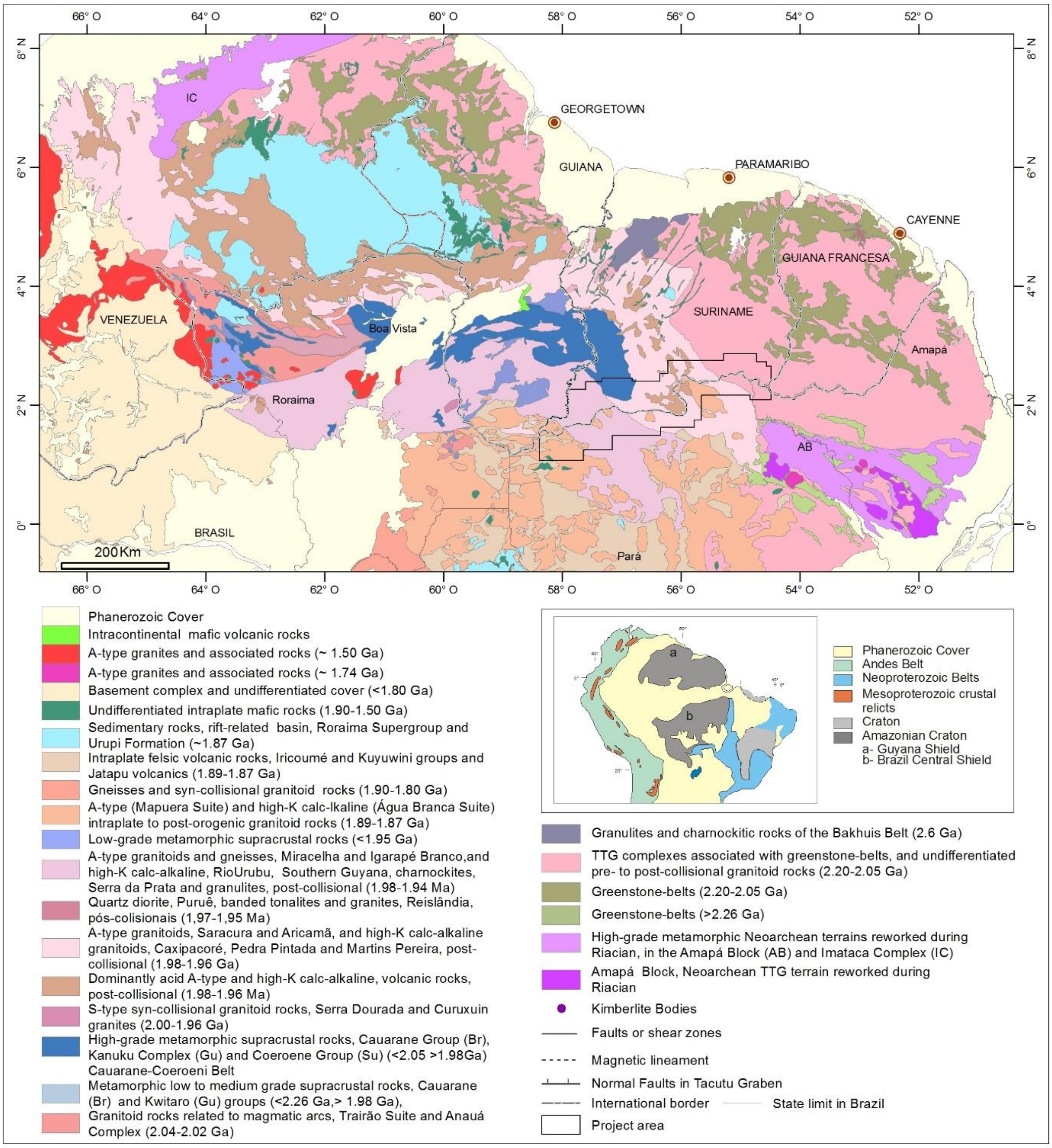


Figure 3. Simplified geological map of the Guiana Shield according to Fraga et al (2009b) indicating the study area and, in the inset, the position of the Amazonian Craton in the main tectonic features of South America (modified after Almeida et al. 1978).

shield after the collisional phase, stimulated the closure of the pull-apart basins, leading to low-pressure high-temperature metamorphism (steep geothermal gradient) of the rocks in the basins during the burial and isobaric cooling (anti-clockwise PT path) in the period between 2.07 and 2.05 Ga (Delor et al. 2003a). Mantle upwelling and crustal overheating in this period of the geodynamic evolution of the shield allowed the generation of ultra-high temperature (UHT) granulites in the Bakhuis Granulite Belt in western Suriname (De Roever et al. 2003a; Klaver et al 2015). In the Amapá Block granitic and charnockitic bodies were emplaced in the, 2.07-2.05 Ga, and the basement was migmatized along transcurrent shear zones.

Eo-Orosirian Crustal fragments with ages between 2.04 and 2.03 Ga occur in the central part of the Guiana Shield and consist of TTG complexes and calc-alkaline granitoids with an important juvenile contribution (Anauá Complex and Trairão Suite). They are situated close to a high-grade metamorphic belt and are interpreted as representatives of continental magmatic arcs and/or island arcs (Faria et al. 2003; Almeida et al. 2007; Fraga et al. 2009a). The high-grade metamorphic belt combines the outcrops of the Cauarane Group (Brazil), Kanuku Complex (Guyana) and Coeroeni Group (Suriname), and forms a sinuous structure, very well characterised in aeromagnetic maps, and collectively designated as Cauarane-Coeroeni Belt (Fraga et al. 2008, 2009a) (Fig. 3). The supracrustal rocks of these units comprise migmatitic aluminous paragneisses, with subordinate calcsilicate rocks, amphibolites, metacherts, quartzites, gondites and mafic schists, deformed and metamorphosed in the amphibolite to granulite facies at low pressures, with superimposed static metamorphism in the amphibolite facies (Kroonenberg 1976; Berrange 1977; Riker et al. 1999; Dreher et al. 2009).

The structure of the Cauarane-Coeroeni Belt had already largely been defined by Kroonenberg (1976) as Central Guiana Granulite Belt, which also included a bifurcation towards the NE to include the Bakhuis Granulite Belt (Fig. 3). The original concept of Kroonenberg (1976) was changed by Gibbs and Barron (1993), defining the Central Guiana Granulite Belt as a NE-SW structure including the Bakhuis Belt and the Kanuku Complex, but leaving apart the Cauarane and Coeroeni Group outcrops. This vision prevailed many years in the literature on the Guiana Shield, until Fraga (2002) and Delor et al. (2003a) outlined sinuous structures partly similar to the original proposal. Fraga (2002) presented a map extending them across the Cauarane, Kanuku and Coeroeni Groups, but defined it later as Cauarane-Coeroeni Belt, and Delor et al (2003a) in a similar way grouped gneisses in the amphibolite and granulite facies, charnockites and granulites in one structure.

With respect to the Cauarane Coeroeni Belt, Fraga et al. (2008; 2009a), defend an evolution from a series of basins installed in an orogenic environment, associated with the Trairão and Anauá arcs, which were closed during the agglutination of these eo-Orosirian magmatic arcs and older juvenile Rhyacian crustal blocks. The authors mention the presence of detrital zircon crystals younger than 2,05Ga, derived from the magmatic arcs, and propose the value of 1995 Ma (U-Pb SHRIMP in monazite) obtained for an S-type granite cutting the Cauarane Group to represent the peak of the metamorphism associated with the agglutination phase, interpreted as the M1 metamorphic phase (Dreher et al. 2009) in these rocks. A static metamorphism, M2, under medium to low amphibolite facies was described (Dreher et al. 2009) and interpreted as a result of heating (and contribution of fluids) caused by intense post-collisional magmatism at around 1.98 Ga (Fraga et al. 2009 a, b).

Kroonenberg et al. (2016) in a different point of view suggest a common evolution for the units that define the Cauarane-Coeroeni and Bakhuis belts (Fig. 3). They contend that the two belts underwent a single phase of metamorphism, with an initial prograde path between 2.07 and 2.05 Ga, and another retrograde path around 1.98 Ga, defining in this way an anticlockwise path with isobaric cooling. As to the period between 2.07 and 2.05 Ga, Kroonenberg et al. (2016) interpret the ages around 2.05 Ga (obtained by U. Cordani and L.M. Fraga, unpublished data) for zircon nuclei from metasedimentary rocks of the Coeroeni Group as recording a metamorphic event, and correlate this event with the metamorphic phase in the Bakhuis granulites described by De Roever et al. (2003a). This interpretation contrasts with that of U. Cordani and L.M. Fraga (verbal communication) who consider these ages, as well as other ages obtained for nuclei of zircon crystals from the Cauarane-Kanuku-Coeroeni supracrustal rocks in the interval 2.07-2.02 Ga, as recording the provenance area of detritic zircon crystals. The geochronological researches are in their final phase and it is hoped that they can elucidate the discrepancy in interpretation. The age of 1.98 Ga for a static metamorphic event proposed by Kroonenberg et al. (2016) is in agreement with that suggested by other authors. However, Klaver et al. (2015) and Fraga et al. (2009 a, b) do not agree that this metamorphism around 1,98 Ga corresponds to the retrograde phase of a metamorphic event that had its first phase around 2.07-2.05 Ga, and proposed that it is related to another geodynamic scenario recording intense magmatism (Klaver et al. 2005; Fraga et al. 2009 a, b) at around 1.98 Ga.

A huge igneous belt including high crustal level granitoids and volcanic rocks with ages ranging from 1.99 Ga to 1.96 Ga interpreted as post-collisional magmatism by Fraga et al. (1997, 2009 a, b) extends from Venezuela to Suriname along the northern border of the Cauarane-Coeroeni belt. In a different tectonic interpretation, Santos (2003) proposes for this magmatism an evolution along magmatic arcs.

In Brazil a considerable data base of field, petrography, geochemistry and isotope data has been obtained, for this 1.99-1.96 Ga igneous belt and allowed the characterisation of the high-K calc-alkaline granitoid and volcanic rocks included in the Pedra Pintada Suite and Surumu Group and the coeval A-type granitoids of the Aricamã and Saracura suites and volcanics the Cachoeira da Ilha Formation (Fraga et al. 1997; Reis et al. 2000; Reis et al. 2003; Fraga et al. 2009c). The granitoids are usually isotropic and the volcanics may show gentle folds. 1.97 Ga high-K calc-alkaline granitoids showing compositional banding and magmatic foliation were identified recently in the proximities of the high-grade supracrustals of the Cauarane-Coeroeni Belt in Roraima and included in the Reislândia Suite and Mixiguana Granite units (Fraga et al. 2013). In Guyana the volcanic rocks (Iwkorama Formation) and the associated granitoids are collectively designated as Burro-Burro Group (Gibbs & Barron, 1993; Berrangé, 1977), while in Suriname the volcanites are named Dalbana Formation and the associated granitoids received various names. Nadeau et al (2013) reports the presence of inherited Hadean zircon xenocrysts in the Iwokrama volcanic rocks, which show ages around 1.99-1.96 Ga. In Guyana and Suriname, a lower greenschist facies metamorphism has been described by various authors for the 1.99-1.96 Ga volcanic rocks (Gibbs & Barron 1993; De Vletter et al. 1998).

High-K calc-alkaline granitoids and volcanics (Caxipacoré Suite, Igarapé Paboca Formation, Castro et al. 2014; Martins Pereira Suite, Almeida et al. 2007), and S-type granitoids (Serra Dourada Granite, Almeida et al. 2007) correlated with the 1.99-1.96 magmatism also occur further south, not in contact with the Cauarane-Coeroeni Belt (Fig. 3).

The southern border of the Cauarane-Coeroeni Belt was also affected by intense magmatism but with different characteristics. Contrasting with the higher crustal level magmatism preserved in the northern igneous belt, to south 1.94-1.93 Ga granitoids, in part syn-kinematically emplaced, gneisses, charnockites and granulite lens crop out. High-K calc-alkaline granitoids and gneisses of the Rio Urubu Suite, A-type granitoids and gneisses of the Miracelha and Igarapé Branco units as well as charnockites of the Serra da Prata Suite (Fraga et al. 2009 a, b) and Barauana granulites are the main rock units in Brasil. The Southern Guyana Granite Complex (Berrangé, 1977) is the prolongation of the Rio Urubu Suite to east in Guyana. Fraga et al. (2009 a, b) envisage that in 1.94-1.93 Ga time interval magmatism, deformation and metamorphism has been concentrated to south of the Cauarane-Coeroeni Belt in an intracontinental post-collisional site.

A meta-volcanosedimentary unit in the greenschist facies occurs in the central part of the shield, in the western part of Roraima State, incorporated in the Parima Group. Santos et al. (2003a) report a maximum age of 1949 ± 6 Ma for a meta-andesite of this sequence. According to Fraga et al. (2009 a b) the Parima Group was developed in sedimentary basins, which were formed, and afterwards closed and metamorphosed in response to continuing shear stresses in a post-collisional setting. Santos et al. (2003a) suggest that these rocks evolved in relation to a collisional orogeny between 1960 and 1900 Ma.

A-type and high-K calc-alkaline granites, and charnockitic bodies as well as a vast cover of predominantly acidic volcanic rocks (Iricoumé Group) are related to the Uatumã Magmatism which obliterated the basement of the south-central part of the Guiana Shield between 1.90 Ga and 1.86 Ga, with a maximum of ages in the range of 1.89-1.87 Ga (Valério et al. 2009; Klein et al. 2012; Barreto et al. 2014). Klein et al. (2012 and references therein) proposed that the Uatumã Magmatism represents a Silicic Large Igneous Province (LIP). High-K calc-alkaline volcanic rocks (Jatapu Volcanics, Almeida 2006) with age in the same range of the Iricoumé Group also occur in the region, and although they have not been cited by Klein et al. (2012) are also related to LIP Uatumã. The 1.88 Ga Uraricaá Mafic-Ultramafic Suite (Fraga et al. 2013) described in the northern portion of the state of Roraima records mafic-ultramafic magmatism coeval with the Uatumã Silicic LIP.

A thick sequence of sedimentary rocks with tuff intercalations dated at 1.87 Ga, related with the Roraima Supergroup (Santos et al. 2003b) covers part of the older basement and is well preserved in 'mesas' in the central part of the shield. The Avanavero magmatism around 1.79-1.78 Ga (Norcross et al. 2000; Santos et al. 2003 b; Reis et al. 2013) affected the shield in the form of dolerite dykes, cutting the older basement, and forming sills in the sedimentary sequence of the Roraima Supergroup.

In the central part of the shield, in the state of Roraima, Brazil, an Anorthosite - Mangerite – Rapakivi Granite association, with ages around 1.52 Ga (Fraga et al. 2009d) as well as rapakivi granite bodies and charnockites dated at 1.43 Ga (Santos et al. 2011) were identified. A swarm of 1.50 Ga alkaline dolerites dykes (Käyser Dolerite) occur in Suriname (De Roever et al. 2003b) and has been interpreted by Fraga et al. (2009b) as a record of the extensional setting associated to the AMG association.

An important deformational episode, called K'Mudku or Nickerie (Gibbs & Barron 1993; De Vletter et al. 1998; Fraga 2002; Cordani et al. 2010) generated mylonitic zones at low temperature conditions with a predominant NE-SW and NE-SW strike.

Alkaline plutons in Brazil and along the Brazil-Suriname Border received various names, like Muri or Mutum, and were dated at 1028 ± 28 Ma (K-Ar, Issler et al. 1975) and 1090 Ma (Nadeau, 2014).

Narrow dolerite dykes of 0,8 Ga occur in French Guiana (Delor et al. 2003 b) and in Brazil. Apatoe (CAMP) Early Jurassic dolerite dykes mark the break-up of Pangea.

3. GEOLOGY OF THE SURINAME-BRAZIL FRONTIER AREA

Figure 4 illustrates the simplified geological map of the project area. In the eastern part of the region predominantly Rhyacian units related to the granite-greenstone belt crop out as well as a possible Archean fragment. In the central part of the area predominantly eo-Orosirian units occur, whereas in the western part younger, late-Orosirian granitoid and volcanic rocks predominate. Alkaline plutons and Mesoproterozoic and Mesozoic dykes cut the older units.

In a general way the units are affected by WNW-ESE shear zones and faults in the eastern and western part of the studied area and by NW-SE structures in its central part. Below a short description of the mapped units is given.

The geochronological information available for the area studied or relevant for the discussion of the area are listed in table 1.

3.a. Undifferentiated complex (*Br*) APPmgnmg

This unit comprises gneisses, migmatites, tonalities, trondhjemites and granodiorites, of uncertain ages, distributed in an elongated NW-SE striking body in the eastern part of the area and limited in the NE by a shear zone.

The complex is mainly characterised by high magnetic gradient with linear high-amplitude NW-striking anomalies. The spectral characteristics with different radiation intensities show a heterogeneous physical pattern, which may reflect the compositional diversity of the Undifferentiated Complex rocks.

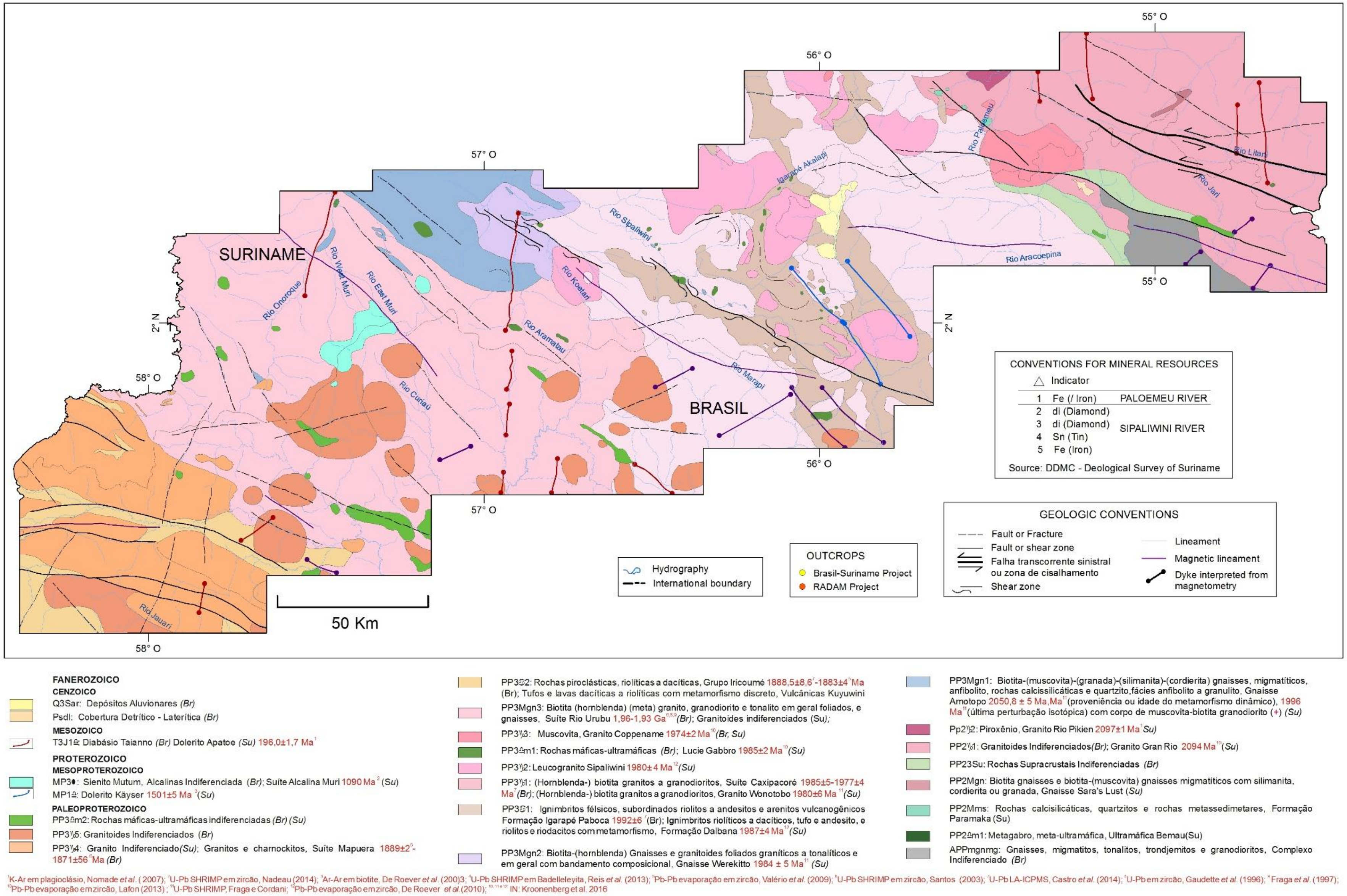


Figure 4. Simplified geological Map of the Suriname-Brazil Frontier area.

3.b. Paramaka Formation (*Su*) P2Mms

The Paramaka Formation forms part of the Marowijne Greenstone Belt sequence, of Rhyacian age, which dominates the north-eastern part of the Guiana Shield. The formation includes predominantly metasedimentary rocks, calcsilicate rocks with diopside and grossular, spessartite quartzite, itabirite and metapelites, which are designated with number 36 on the Geological Map of Suriname (GMD, 1977).

In the project area these rocks occur as rounded outcrops, possibly megaenclaves within the Gran Rio Granite. Ages obtained by Delor et al. (2003a) for a metaquartzandesite of a correlated sequence in French Guiana are 2137 ± 6 Ma (Pb-Pb evaporation on zircon) and 2156 ± 6 (U-Pb on zircon, microprobe).

Table 1. Results of Pb-Pb zircon evaporation and U-Pb SHRIMP zircon ages available for the project area, including the KG 826 * sample from an outcrop north of the study area, which will be discussed in the text (see Kroonenberg et al., 2016).

SAMPLE	METHOD	AGE	LITHOSTRATIGRAPHIC UNIT	SOURCE
CP806/2192-ED-R-806	Pb–Pb	2090 ± 2	Granito Gran Rio	Lafon (2013, apud Kroonenberg *et al.,* 2016)
HK1697/2192-ED-R-697	Pb–Pb	2085 ± 5	Granito Gran Rio	Lafon (2013, apud Kroonenberg *et al.,* 2016)
KG826*	SHRIMP	2050.8 ± 5.0	Amotopo Gnaisse núcleo do cristal	Cordani e Fraga Inf. Verbal
KG826*	SHRIMP	1986 ± 15	Amotopo Gnaisse borda metamórfica do cristal	Cordani e Fraga Inf. Verbal
SB-24 A	SRIMP	1983.9 ± 5.4	Gnaisse Werekito	Cordani e Fraga Inf. Verbal
SB-31	SRIMP	1993.9 ± 3.7	Gnaisse Werekito	Cordani e Fraga Inf. Verbal
Sur40	Pb–Pb	1987 ± 4	Formação Dalbana	De Roever *et al*. (2015)
SB-21A	SHRIMP	1980.2 ± 5.8	Granito Wonotobo	Cordani e Fraga Inf. Verbal
SB-21B	SHRIMP	1961 ± 20	Xenólito no Granito Wonotobo	Cordani e Fraga Inf. Verbal
SB13	SHRIMP	1973.6 ± 3.8	Granito Wonotobo	Cordani e Fraga Inf. Verbal
ED 631/OB3631	SHRIMP	1956.2 ± 6.4	Granito Wonotobo	De Roever et al. (2015)
ED 820/OB3820	SHRIMP	1982.9 ± 9.	Granito Wonotobo	De Roever et al. (2015)
Sur48	Pb–Pb	1980 ± 4	Leucogranito Sipaliwini	De Roever et al. (2010)
MW1225/DDZ031	Pb–Pb	1974 ± 2	Muscovita Granito Coppename	Lafon (2013, apud Kroonenberg *et al.,* 2016)

3.c. Sara’s Lust Gneiss (*Su*) - PP2Mgn

Sara’s Lust Gneiss occurs in an elongated NE-striking body on Surinamese territory, probably corresponding to a mega-enclave in the Gran Rio Granite.

The term Sara’s Lust Gneiss was proposed by Kroonenberg et al. (2016) to comprise migmatitic biotite gneisses of granitic to tonalitic composition, migmatitic biotite-(muscovite) gneisses with sillimanite, cordierite or garnet. On the Geological Map of Suriname (GMD 1977) these lithologies were correlated with the high-grade metamorphic rocks of the Coeroeni Group, but at present they are recognised as being older, and correlated with the Tamouri Complex defined in French Guiana, with ages between 2165 ± 6 Ma and 2055 ± 3 Ma (Pb-Pb evaporation on zircon, Delor et al. 2003a).

3.d. Undifferentiated Supracrustal Rocks (*Br*) - PP23Su

NW-trending elongated bodies, interpreted as possible lenses of supracrustal rocks are aligned with the occurrence of the Paramaka Formation in Suriname, and may correspond to the continuation of these sequences into Brazil. The geophysical pattern of the Undifferentiated Supracrustal Rocks is characterised by elongated units with low magnetisation associated with medium and high radiometric values.

3.e. Gran Rio Granite (Su) and Undifferentiated Granitoids (*Br*) - PP2γ1

The Gran Rio Granite comprises medium-grained biotite-(hornblende) granites, locally with megacrysts and inhomogeneous, in the eastern part of the area, which are indicated with the codes 23 and 24 on the Geological Map of Suriname (GMD, 1977). The name was proposed by Kroonenberg et al. (2016), following the historic terminology of IJzerman (1931, *apud* Kroonenberg *et al.*2016). Lafon (2013, *apud* Kroonenberg et al. 2016) obtained ages between 2102 ± 2 and 2085 ±5 Ma (Pb-Pb-evaporation on zircon) for this unit.

The continuity of the Gran Rio Granite in Brazilian territory coincides with an area where granodiorites and tonalities predominate (CPRM 2004). The area is characterised by a strongly accentuated magnetic relief, high gradient, linear high-frequency and high-amplitude anomalies in NW and E-W directions and high radiometric values.

3.f. Pikien Rio Pyroxene Granite (Su) - PP2γ2

This unit (code 25 on the Geological Map of Suriname, GMD, 1977) comprises hornblende biotite granite, granodiorite and tonalite with pyroxene, generally corresponding to clinopyroxene, which crop out in the eastern part of the project area, north of the locality of Majoh. An age of 2097±1 Ma was obtained for the Pikien Rio Granite (Pb-Pb evaporation on zircon, Lafon 2013, *apud* Kroonenberg et al. 2016).

3.g. Gnaisse Amotopo (Su) - PP3Mgn1

The Amotopo Gneiss was defined by Kroonenberg et al. (2016) to comprise migmatitic pelitic gneisses, amphibolites, quartzites, marbles and calc-silicate rocks, predominantly of metasedimentary origin, metamorphosed in the amphibolite to granulite facies, which together with the Werekitto Gneiss (see below) is assumed by the authors to form part of the Coeroeni Gneiss Belt in the south-western part of the country. On the Geological map of Suriname (GMD, 1977) this unit was indicated with code 45, forming part of the Coeroeni Group, lithostratigraphic terminology that has been abandoned by Kroonenberg et al. (2016). The Amotopo Gneiss crop out in a large body, with a general NW-SE strike.

De Roever et al. (2015) give Pb-Pb evaporation ages between 2080 and 2890 Ma for a cordierite tonalite from this unit, the latter value pointing evidently to detrital zircons. U. Cordani and L.M. Fraga (*in* Kroonenberg et al., 2016) obtained a SHRIMP age of 2079 ± 19 Ma for a granulite-facies metapelitic gneiss from the Coeroeni Gneiss Belt, and 2050.8 ± 5 and 1986 ± 5 Ma ages for an amphibolite-facies metapelitic gneiss sample from the Lucie River in the northern part of the area. U. Cordani and L.M. Fraga (verbal communication) regard the older age in the latter sample, referring to the core of the crystal, as recording the age of the provenance area of the sedimentary protolith, and the younger age as the ultimate isotopic perturbation of the system, associated with the ~1.98 magmatism that affected the area. Kroonenberg et al., (2016) contend the two values to reflect the two phases M1 and M2 of a single metamorphic event that these rocks experienced, according to the authors (see discussions above).

3.h. Werekitto Gneiss (Su): PP3Mgn2

This unit was proposed by Kroonenberg et al. (2016), and comprises granitic to tonalitic or trondhjemitic (hornblende-) biotite gneiss and foliated hornblende-biotite tonalite, generally with compositional banding. In the Geological Map of Suriname (GMD, 1977) this unit is designated with code 43.

The Werekitto Gneiss was envisaged by Kroonenberg et al. (2016) as an integral part of the Coeroeni Gneiss Belt, and interpreted as being of supracrustal origin, sharing the same metamorphic evolution with the Amotopo Gneiss. However, field and petrographic, and geochronological data have cast some doubt about the supracrustal origin of these rocks, as will be discussed in more detail in the description of the geology of the Sipaliwini area below (Chapter 4).

From the studies carried out in the region of the Sipaliwini river, in the present work, biotite (-hornblende) gneisses and granitoids of monzogranitic to tonalitic composition (or quartz-dioritic), usually with compositional banding, sometimes exhibiting mylonitic fabric were included in the Werekitto unit.

Ages of 1983±5,4 Ma (foliated hornblende-biotite tonalite or tonalitic gneiss, sample SB-24), and 1993,9±37 (Sample SB 31, mylonitic biotite monzogranite) were obtained using U-Pb SHRIMP on zircon by U. Cordani and L.M. Fraga (unpublished data in Kroonenberg et al. 2016) for the granitoids of this unit. U. Cordani and L.M. Fraga (verbal communication) emphasize that in contrast to the analyses of the zircon crystals of the high grade paragneiss, the Werekitto granitoids provided only one group of ages, interpreted as the age of crystallization of the igneous body. There are still important differences in both the Th / U ratio and the internal structure of the zircon crystals of the granitoids dated in the Werekkito unit (higher Th / U ratios and absence of edges or metamorphic perturbations) relative to the crystals of the Amotopo high grade paragneisses (U. Cordani and L.M. Fraga, verbal communication). In the view, of Lêda Maria Fraga the Werekitto Gnaisse may correlated with the Reislândia Suite described in Brazil (Fraga et al. 2013).

3.i. Dalbana (Su) and Igarapé Paboca (Br) Formations- PP3α1

These volcanic formations crop out in the central part of the project area. The Dalbana Formation received codes 29 and 30 on the Geological Map of Suriname (GMD, 1977) respectively referring to slightly metamorphosed rhyolites and rhyodacites, and more strongly recrystallized rhyolites and dacites. However, the latter rock types have not been observed in the Sipaliwini River area (see chapter 4) and have therefore been omitted in map and legend. In the project area rhyolitic to dacitic ignimbrites, tuff and andesite have been identified, apart from low grade metamorphosed rhyolites and rhyodacites.

The Igarapé Paboca Formation (Castro et al. 2014) was defined in the Trombetas river area (Sheet SA.21-X-A), south of the project area, and comprises intermediate to felsic volcanic and pyroclastic rocks with high-K calc-alkaline affinities. Andesites and dacites predominate, with subordinate trachyandesites, trachytes, latites, andesitic ignimbrites, lamprophyres, tuffs and breccias (Barreto et al. 2014; Castro et al. 2014). The ages obtained are 1992 ± 3 (Pb-Pb on zircon, Barreto et al. 2014) and 1948 ± 6 Ma (U-Pb on zircon Castro et al. 2014).

In the project area the Igarapé Paboca Formation presents a high magnetic gradient with very high-amplitude linear anomalies. In general, the radiometric signals of the formation are characterised by low radiometric values, however, with a clear relative contribution of the potassium channel.

3.j. Wonotobo Granite (Su) and Caxipacoré Suite (Br) - PP3γ1

The Wonotobo Granite unit was proposed by Kroonenberg et al. (2016) to comprise the widely distributed granitoids of western Suriname, including units with code 22 and 23 of the Geological Map of Suriname (GMD, 1977), consisting of fine and fine to medium grained granites, and medium to coarse-grained granites, respectively. On the basis of observations along the Sipaliwini River and suggestions by the geologists Salomon Kroonenberg and Emond de Roever these two units 22 and 23 were taken together in the project area.

In the present project medium- to coarse grained, locally porphyritic (hornblende-) biotite granites to granodiorites, and locally some finer grained varieties, were mapped as Wonotobo Granite. Locally these granitoids are affected by shear zones and moderate to low-temperature mylonites are present.

The Caxipacoré Suite comprises granitic rocks and subordinate granodiorites, quartz monzonites, quartz syenites, alkaliquartz syenites and alkaligranites, with high-K calc-alkaline affinities in the age range 1985 ± 5-1977 ± 4 Ma (Castro et al. 2014; Leal et al. 2013). The unit was defined in the Trombetas river area (Sheet SA.21-X-A) south of the project area. The magnetic features of the Caxipacoré Suite show medium to high magnetic gradient, characterised by the occurrence of high-amplitude E-W striking magnetic anomalies. At the same time, it has also magnetic anomalies with low magnetisation. The radiometric signals of the suite characteristically show a predominance of low and high radiometric values, reflecting the compositional diversity of the rocks.

3.k. Sipaliwini Leucogranite (Su, Br) - PP3γ2

This designation proposed by Kroonenberg et al. (2016) comprises leucogranites, granophyric granites and fine-grained granites indicated with codes 20 and 21 in the Geological Map of Suriname (GMD, 1977). An age of 1980 ± 4 (Pb-Pb zircon evaporation) was obtained by De Roever et al. (2015).

The continuation of these granitoids into Brazil was mapped based on geophysics.

3.l. Lucie Gabbro (Su) –Undifferentiated mafic-ultramafic rocks (Br) - PP3δm1

Metagabbronorites, norites and troctolites, pyroxenites and peridotite which received code 31 on the Geological map of Suriname (GMD, 1977) were designated as Lucie Gabbro, dated at 1985 ± 2 Ma, by Kroonenberg et al. (2016).

In Brazil, undifferentiated mafic and ultramafic rocks, possibly correlated with the Lucie Gabbro, are characterised by very high amplitude magnetic anomalies, associated with low concentrations of radioelements.

3.m. Coppename Muscovite Granite (Br, Su) PP3γ3

Granites with primary or secondary muscovite and locally feldspar megacrysts were included in the Coppename Muscovite Granite with an age of 1974 ± 2 Ma (Kroonenberg et al. 2016). The prolongation of this unit into Brazil was mapped using geophysical data.

3.n. Undifferentiated medium to coarse biotite-(hornblende) granites (Su), Rio Urubu Suite (Br) PP3Mgn

The undifferentiated medium- to coarse grained biotite-(hornblende) granites, cropping out SW of the Coeroeni Gneiss Belt (code 23 on the Geological Map of Suriname, GMD, 1977), are the continuation of the granitoids and metagranitoids of the Southern Guyana Granite Complex (Berrangé, 1977) of Guyana, and the Rio Urubu Suite (Fraga et al. 1999) in Brazil, units that are bordered to the north by the Cauarane-Coeroeni Belt supracrustals. Therefore, it was chosen to map these biotite-(hornblende) granites in the SW of the study area as being correlated to the Rio Urubu and Southern Guyana granitoids. For the Rio Urubu Suite zircon U-Pb SHRIMP and Pb-Pb ages between 1.94 and 1.93 Ga were mentioned (Gaudette et al. 1996, Fraga et al. 1999).

The magnetic domain of the Rio Urubu suite in Brazil shows moderate magnetic relief, characterised by medium-amplitude E-W-striking linear magnetic anomalies; moreover, is shows high-frequency and high-amplitude linear and subcircular magnetic anomalies. The radiometric signals of the Rio Urubu Suite are characteristically a domain of low and moderate radiometric values.

3.o. Iricoumé Group (Br), Kuyuwini Group (Su) – PP3α2

Whereas slightly metamorphic volcanites NE and SW of the high-grade metamorphic Coeroeni Gneiss Belt were correlated with the Dalbana Formation (numbers 29 and 30 on the Geological map of Suriname, GMD, 1977; De Vletter et al. 1998), the volcanic rocks exposed SE of the Coeroeni Gneiss Belt were reinterpreted as being correlated with the Kuyuwini Group in Guyana (Berrangé, 1977) and the Iricoumé Group in Brazil, and not with the Dalbana Formation. This reinterpretation is relevant, because geochronological data obtained in Brazil showed that the volcanic rocks in this part of the shield are 100 Ma younger than those related to Surumu Group (Brazil) and Iwokrama (Guyana) and Dalbana (Suriname) formations.

The Kuyuwini Group includes felsic and intermediate, 'slightly' metamorphosed volcanic rocks with subordinate sedimentary rocks and subvolcanic intrusions (Berrangé, 1977).

The Iricoumé Group comprises effusive, pyroclastic and some hypabyssal rocks of felsic to intermediate composition, with a predominance of rhyolitic to dacitic types. The group exhibits affinity with A-type magmatism (Barreto et al. 2014) and ages in the range of 1.89-1.88 Ga (Castro *et al.,* 2014; Valério *et al*., 2009; Macambira *et al*., 2002; Costi *et al*., 2000).

The Iricoumé Group shows a medium to high magnetic gradient, characterised by the occurrence of high-frequency E-W striking linear anomalies, and, moreover, by small isolated subcircular magnetic anomalies. The radiometric signals are characterised by high radiometric values, mainly in the potassium channel.

3.p. Undifferentiated granite (Su), Mapuera Suite (Br), PP3γ4

Granites in the extreme SW of Suriname, indicated with the code 21 on the Geological Map of Suriname (GMD, 1977), are in this study correlated with the subvolcanic granitoids of the Kuyuwini Group, described by Berrangé (1977) in Guyana, and with granite bodies of the Mapuera Intrusive Suite defined in Brazil. This reinterpretation is based on the fact that the mentioned units show physical continuation into the territory of Suriname.

The Mapuera Suite comprises syenogranites and monzogranites with subordinate monzonites, syenites and alkali feldspar granites, generally reddish or greyish, with A-type affinity (Haddad & Faria 2000; Almeida et al. 2007), apart from charnockitic bodies (Santos, 2003). For the Trombetas river area (Sheet SA.21-X-A) south of the project area, Castro et al (2014) obtained zircon Pb-Pb ages of 1889 ± 2 and 1861 ± 20 Ma, which is compatible with the Uatumã volcano-plutonism (Klein et al. 2012, and references therein).

The geophysical pattern of the Mapuera Suite shows moderate magnetic relief, characterised by medium amplitude linear anomalies and flat magnetic surfaces (gentle magnetic relief). The radiometric anomalies of the Mapuera Suite present elongated belts in NW direction, with lenticular forms, reflecting the geometry of the bodies, and a predominance of high radiometric values.

3.q. Undifferentiated granitoids (Br) – PP3γ5

Granitoid bodies interpreted on the basis of their geophysical characteristics and relief patterns were grouped in this unit.

Some bodies are elliptical or circular, clearly intrusive in neighbouring units, with low magnetisation and high radiometric values, possibly corresponding to A-type granitoids. These bodies show strongly magnetic borders.

There are also bodies, without such a characteristic circular aspect, characterised by low magnetic gradient, gentle magnetic relief (flat magnetic surfaces), while some bodies show high values of magnetic susceptibility. The radiometric signals indicate high concentration of radioelements.

3.r. Undifferentiated mafic-ultramafic rocks (Br, Su) – PP3⍰m2

Bodies of undifferentiated mafic-ultramafic rocks distinguished in Brazil in the area affected by the Uatumã magmatism and south western Suriname were tentatively grouped in this unit and considered coeval with this magmatism.

3.s. Käyser Dolerite (Su): MP1δ

Narrow dykes oriented NW-SE occur in the SW part of Suriname and show chemical and mineralogical characteristics differing from those of the Avanavero and Apatoe Dolerites (Bosma et al. 1984). De Roever et al. (2003b) obtained an Ar-Ar age on biotites of 1501±5 Ma for one of these dykes, designated as Käyser Dolerite.

In the project area, dykes with NW-SE orientation were correlated with this unit.

3.t. Mutum Syenite (Br), Muri Alkaline Complex (Su), MP3λ

Alkaline rocks occur in bodies associated with more or less circular relief anomalies, while the most conspicuous one, situated across the Suriname-Brazil boundary was originally identified by Issler et al (1975) during the RADAM project and called Mutum Syenite.

In Suriname it is called Muri Alkaline Complex. As Kroonenberg et al (2016, and referenced cited therein) mentions, this occurrence in the Muri Mountains is composed of two nepheline syenite and tinguaite bodies. Nadeau (2014) recently obtained an age of 1090 Ma for rocks of the Muri Alkaline Complex.

One conical hill in the neighbourhood of the Muri Mountains is interpreted as a possible carbonatite, being capped by laterite with high Nb and Sr values. The soil is characterised by high radioactivity and rich in REE and phosphates, and various authors mention fenitisation (sodium metasomatism) in the surrounding rocks (see Kroonenberg et al. 2016 and cited references).

3.u. Apatoe Dolerite (Su), Taiano Diabase (Br), T3J1δ

Pigeonite dolerite dykes with N-S to NNE-SSW orientation (code 15 on the Geological Map of Suriname, GMD 1977) cut older units in Suriname and Brazil, being probably related to the opening of the Atlantic Ocean. These dykes are collectively designated as Apatoe Dolerite in Suriname and Taiano Diabase (Reis et al. 2008) in Brazil. An age of 196.0±1.7 Ma was obtained for this unit in French Guiana (Nomade et al. 2000).

3.v. Detritic-Lateritic Cover (Br –Q3Sar) and Alluvial Deposits (Br-PSdl)

Areas mapped as Detritic-Lateritic Cover or as Alluvial Deposits were individualised through interpretation of remote sensing imagery.

4. GEOLOGY OF THE SIPALIWINI RIVER AREA

As stated in the introduction of this explanatory note, the Sipaliwini River area was the goal of a 10 days' field campaign between October 2 and 12 of 2013, with participation of Suriname and Brazil teams, and resulted in a revised geological map for the area.

Thirty-three outcrops were described and sixty-one rock samples were collected for further studies including petrographic analyses at the Brazilian Geological Survey. Fifty-one thin sections were prepared and studied by Ana Maria Dreher, with collaboration of Lêda Maria Fraga in microtectonic. The results were discussed with the Suriname delegation, represented by Salomon Kroonenberg and Emond De Roever, during our last meeting in Paramaribo (October 2015).

The integration of the field and analytical data for the mapped rock units is shown below as well as the proposed correlations with recognised lithostratigraphic units in northern Brazil and central Guyana (Fig.3).

Figures 5 and 6 show the Geological Map of Suriname (GMD, 1977) and the Geological Map of the project reduced to the area of the Sipaliwini River.

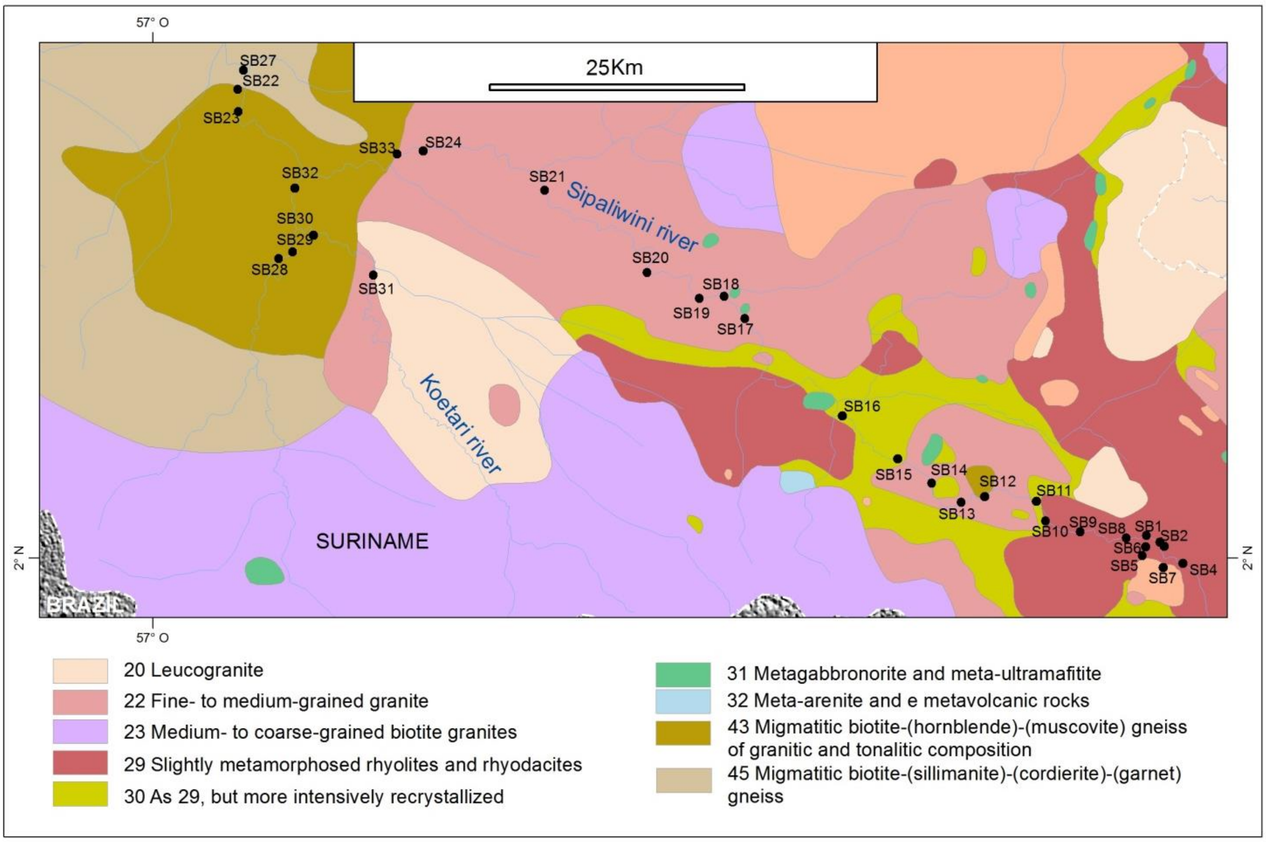


Figure 5. Geological map of Suriname (GMD, 1977), with the location of the outcrops described by the binational team in the Sipaliwini River area

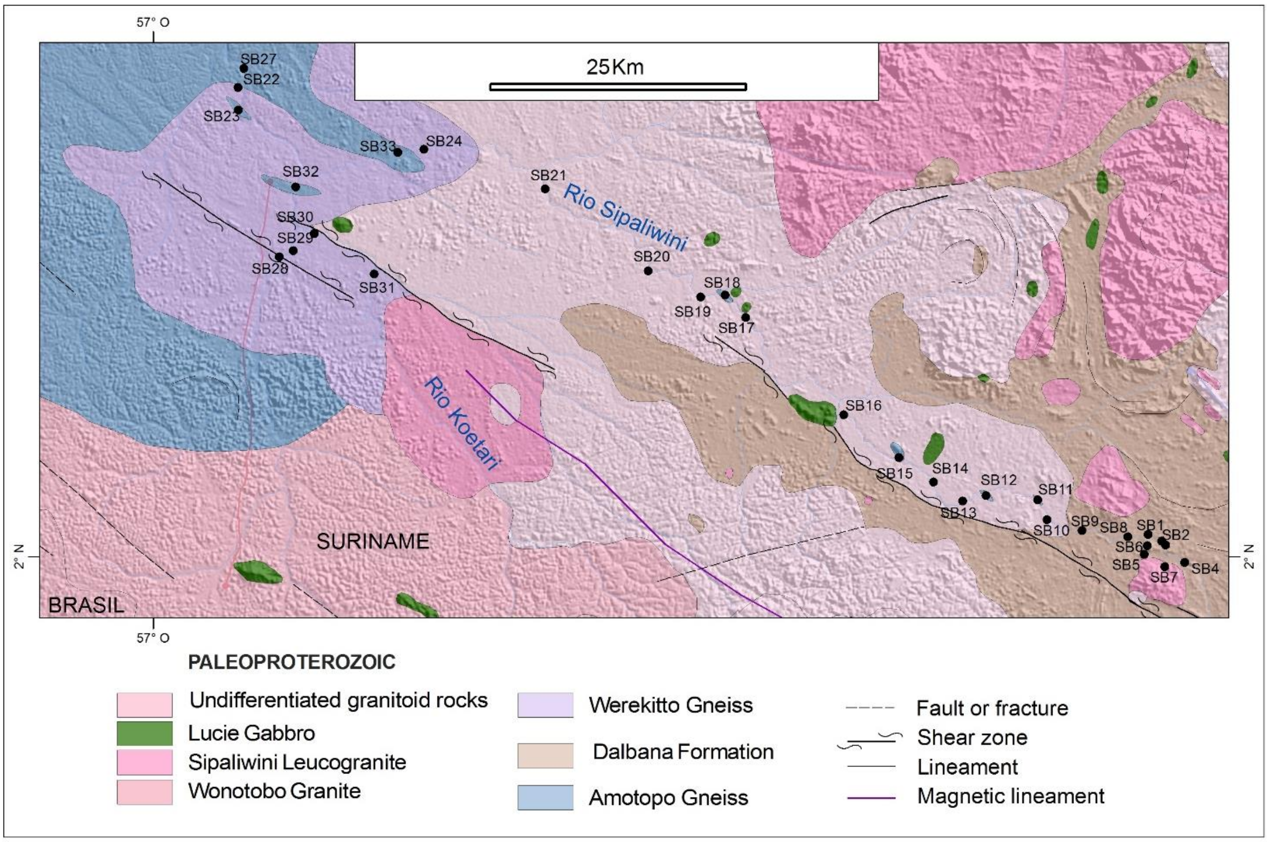


Figure 6. Simplified geological Map of the Suriname-Brazil Frontier area, with location of the outcrops described by the binational team in the Sipaliwini River area.

Figure 7. Field aspect of Amotopo Gneiss rocks (a) Banded paragneiss (outcrop SB-23; (b) Centimetre to decimetre-sized leucosome veins cut the metamorphic banding at a high angle (outcrop SB-32). (c) Pegmatite vein (P) more than 4 metres thick, cutting the paragneiss (outcrop SB-26); (d) Centimetre-sized banding in calcsilicate rock (outcrop SB-25).

4.a. LITHOSTRATOGRAPHIC UNITS

4.a.1. Amotopo Gneiss. High-grade metamorphic metasedimentary rocks

The designation Amotopo Gneiss is used, as explained in paragraphs 2 and 3 to describe high-grade metamorphic rocks of undoubtedly metasedimentary origin. These rocks crop out in areas indicated on the Geological Map of Suriname (GMD, 1977) as units 43 and 45, (Coeroeni Group), but we observed them also in areas mapped as fine-grained granites (unit 22), and slightly metamorphosed rhyolites and rhyodacites (Dalbana Formation, units 29 and 30) (Figs. 5 and 6).

Macroscopic aspects

The aluminous gneisses are represented by quartz-feldspar-biotite-(garnet) gneisses, varying in grain size from fine to coarse, with greyish colours, generally migmatitic, with a millimetre-to centimetre-sized banding as a result of the presence of 1-2 cm thick leucosome veins (Fig. 7a). There are also leucosome veins cutting at high angle through the foliation and the metamorphic banding, indicating the presence of at least two generations of these veins (Fig. 7b). Pegmatitic veins are very common in outcrops SB-26 and SB-32 (Fig. 7c). Another rock type considered as part of the Amotopo is a greyish, medium-grained muscovite-biotite granodiorite, (SB-33) showing a compositional banding, conferred by the variation in the content of mafic minerals and containing amphibolite enclaves (xenoliths ?).

Within the Amotopo Gneiss banded rocks with centimetre to decimetre thick bands have also been identified, characterised by dark grey bands, consisting of iron-rich metachert, finer, greenish bands, consisting of amphibolite and lighter coloured calcsilicate bands (Fig. 7d). These rocks were collectively described as calcsilicate rocks.

Petrography and microtectonics

The classification and mineralogical composition of 17 samples are given in Table 2.

The aluminous paragneisses are generally fine-grained, of granolepidoblastic texture, composed mainly of feldspars, quartz and biotite (Fig. 8a), and locally also muscovite. In some gneisses the dominant feldspar is plagioclase, in others microcline predominates, while there are types that show alternating bands of different composition, including in the biotite contents (see sample SB-32 A, Table 2). The biotite in the paragneisses is dark brown or more commonly, greenish brown, and makes up between 7% and 20% of the rock volume. Muscovite, when present, is usually associated with biotite, but tends to form larger, generally poikiloblastic crystals that do not follow the same orientation as the biotite, or even transect it (Fig. 8b). Apatite, zircon, allanite, epidote and opaque minerals are accessory components in these rocks.

Table 2. Petrographic classification and estimated mineral content (%) of the Amotopo Gneiss rocks (mineral abbreviations according to Siivola & Schmid 2007).

Sample	Classification	Qtz	Pl	Afs	Bt	Ms	Hbl	Act	Cpx	Op	Ser	Chl	Ep	Brt	Grt	Cal	Ttn	Ap	Aln	**Zrn**
SB-18	Bt-qtz-afs-pl gneiss	20	51	20	7					1	tr		1					tr		
SB-26 A	Ms-bt-qtz-pl-afs gneiss	22	20	34	20	4				tr	tr							tr		tr
SB-32 A	Bt-qtz-pl-afs banded gneiss	25 20	15 39	52 20	7 20					1 1	tr tr						? tr	tr -	tr tr	tr tr
SB-32 B	Bt-qtz-afs-pl gneiss	20	40	25	13					1		tr	tr				1	tr	tr	
SB-32 C	Bt-pl-qtz-afs gneiss	22	20	48	9					1	tr	tr	tr					tr	tr	tr
SB-22 B	Granitic pegmatite	13	5	80		2														
SB-27 C	Granitic pegmatite	20	20	60		Tr														
SB-33 A	Ms-bt granodiorite	20	41	7	20	12				tr										
SB-33 B 1	Qtz-bt amphibolite	6	30		8		40			4		3	8				1		tr	
SB-33 B 2	Qtz amphibolite	5	28		3		47			5	tr	2	10				tr	tr	?	
SB-23	Qtz-bt amphibolite	10	40		15		30				tr		4			tr	1	tr		
SB-25	Cpx-qtz amphibolite	25	10				50		6	tr	tr		5				4	tr		
SB-25 A 1	Cpx banded amphibolite	8	2				25	15	33				15	tr	tr	tr	2			
SB-26 B	Qtz amphibolite	20	10				66				tr		tr				4	tr		
SB-27 B	Qtz-cpx amphibolite	15	8				53		18	tr	tr						3	tr	tr	
SB-25 A	Cpx-qtz granofels	51					4		40	4				tr		1	tr	tr		
SB-27 A	Act-pl-cpx-qtz granofels	35	17					16	28	tr	tr		tr				tr	4	tr	

Qtz = quartz; Pl = plagioclase; Afs = alkali feldspar; Bt = biotite; Ms = muscovite; Act = actinolite; Cpx = clinopyroxene; Op = opaque mineral; Ser = sericite; Chl = chlorite; Ep = epidote; Brt = barite; Grt = garnet; Cal = calcite; Ttn = titanite; Ap = apatite; Aln = alanite; Zrn = zircon; tr = traces (< 1%).

Petrographically the muscovite-biotite granodiorite (SB33) exhibits granular texture and is not foliated. Its felsic components are idio to subidiomorphic oligoclase plagioclase and xenomorphic quartz and microcline. The mafic minerals are greenish brown biotite and muscovite, the last one found associated to the biotite, covering the microcline or forming rounded aggregates that suggest pseudomorphic replacement of ancient cordierite crystals (Fig. 8c). Zircon and opaque minerals are rare. The amphibolite enclave (xenolith?) observed in the muscovite-biotite granodiorite shows fine granolepidoblastic texture, with evident foliation, containing dark bluish green hornblende and masses of sericite and epitote substituting plagioclase crystals. Chloritized biotite and quartz are rarer components. The accessory minerals are opaque minerals with borders of titanite, apatite, and scarce allanite.

The calcsilicate rocks were classified either as amphibolites or granofelses (see Table 2) as a function of their compositions and textures. They are in general banded, fine- to coarse-grained rocks, with granoblastic to granonematoblastic textures.

The amphibolites are very rich in amphibole, usually represented by a dark blue-green hornblende, with plagioclase and quartz in between. Part of the amphibolites also contains a light- green amphibole of the tremolite-actinolite group, as well as chloritized biotite and a plagioclase strongly altered to sericite and epidote. The most common accessory is titanite, followed by apatite, opaque minerals, usually ilmenites with borders of titanite, and scarce allanite. Some amphibolites are strongly banded, with thicker levels containing hornblende and plagioclase, alternated with fine layers of quartz and clinopyroxene (Fig. 8d). These amphibolites are considered as paraderived rocks by Ana Dreher (this report). However, in the view of Salomon Kroonenberg (this report) they could correspond to metabasites. The granofelses are mainly composed of quartz and colourless or light green clinopyroxene, of the diopside or diopside-hedenbergite varieties (Fig 8e) besides calcic plagioclase, bluish-green hornblende, pale green tremolite-actinolite, epidote, apatite, titanite, and opaque minerals. Some of these granofelses contain additionally calcite, barite and brown garnet along certain bands (Fig. 8f).

The pegmatites are typically hololeucocratic and of granitic composition, consisting of well-formed centimetre-sized crystals of microcline perthite, anhedral quartz, subidiomorphic sodic plagioclase and muscovite books generally situated between the feldspars and quartz, apart from greenish apatite.

Metamorphism

In the mapped area, the aluminous paragneisses of the Amotopo Gneiss do not contain metamorphic key mineral such as sillimanite or cordierite. In addition to quartz and feldspar, only biotite and occasionally muscovite occur as varietal minerals (Figs 8 a, b) in these rocks. However, in other portions of the Guiana shield a low pressure high amphibolite facies main metamorphic phase has been characterized for similar rock types (Kroonenberg 1976; CPRM 2010). The presence of rounded muscovite aggregates suggestive of pseudomorphosis on cordierite in the muscovite-biotite granodiorite from outcrop SB-33 led Salomon Kroonenberg (this report) to suggest that this possible cordierite would reflect this main metamorphic phase (of low pressure high amphibolite facies) in the project area.

In the meantime, the gneissic banding and the presence of pegmatites and leucocratic veins, indicative of partial melting as observed in the paragneisses in the field, are evidencing that metamorphism in the Amotopo Gneiss certainly attained the highest temperature amphibolite facies. In addition, in calcsilicatic rocks, a calcium pyroxene of the diopside-hedenbergite series (Figs. 8c, d, e) is also frequent, also demonstrating that the metamorphism reached the highest temperature in the amphibolite facies.

On the other hand, muscovite occurs in the paragneisses in well-developed poikilitic crystals that replace and crosscut biotite flakes without following the same orientation of the dark mica (Fig 8 b). This feature suggests a second event or phase of metamorphism of static character and of a lower temperature in the amphibolite facies, possibly related to the thermal effect produced by granitic intrusions of the Wonotobo Granite unit on the Amotopo Gneiss.

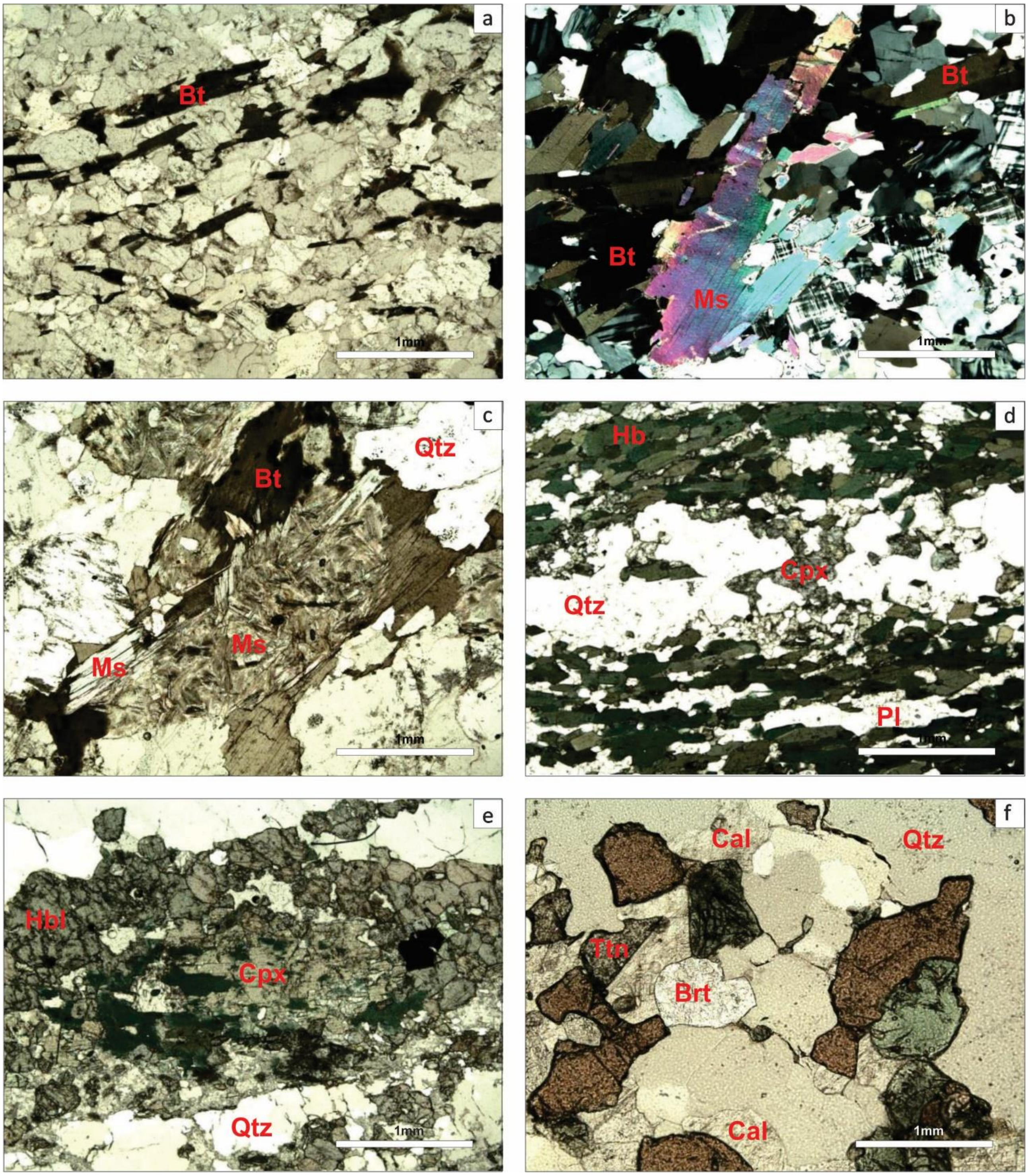


Figure 8. Microscopic aspects of the Amotopo Gneiss rocks. (a) fine aluminous paragneiss, consisting of feldspars (microcline, plagioclase), quartz and biotite (Bt). Thin section SB-32B, plane-polarized light, scale = 1 mm. (b) Muscovite-biotite gneiss with large muscovite flakes (Ms) that cross the biotite (Bt). Thin section SB-26A, crossed polarizers, scale = 1 mm; (c) Muscovite-biotite granodiorite with fine muscovite aggregates suggesting pseudomorphs of original cordierite crystals. Thin section SB-33A, plane-polarized light, scale 1 mm; (d) Amphibolite consisting of laminae rich in dark bluish-green hornblende (Hbl) and plagioclase (Pl) alternating with laminae with quartz (Qtz) and clinopyroxene (Cpx). Thin section SB-25, plane-polarized light, scale = 1 mm; (e) Calcsilicate granofels consisting mainly of diopside-hedenbergite (Cpx) and quartz (Qtz) with smaller quantities or bluish-green hornblende (Hbl). Thin section SB-25A, plane-polarized light. Scale 1 mm; (f) Detail of a quartz-rich band in granofels, showing an association of green diopside-hedenbergite (Cpx), titanite (Ttn), light-brown garnet (Grt), calcite (Cal) and barite (Brt). Thin section SB-25 A, plane-polarized light, scale = 0.5 mm.

Ages and correlations

As described in the 3.b paragraph, Pb-Pb zircon evaporation ages between 2080 and 2890 Ma (De Roever et al. 2015) were obtained for a cordierite tonalite and U-Pb zircon SHRIMP ages of 2079 ± 19 Ma, 2050.8 ± 5 and 1986 ± 5 Ma (U. Cordani and L.M. Fraga, unpub. data, in Kroonenberg et al. 2016) were calculated for metapelitic gneisses of amphibolite to granulite facies. The last two values are related respectively to the crystal core, and its metamorphic edge, having been interpreted as a record of the basin source (core), and the last isotopic perturbation of the system (border), associated with the 1.98Ga magmatism (U. Cordani and L.M. Fraga, verbal communication), or as a related to metamorphic phases M1 and M2 of a single metamorphic event (Kroonenberg et al. 2016) (see discussions in items 2 and 3).

These rock types can be correlated with the Cauarane Group in Brazil and the supracrustal part of the Kanuku Complex in Guyana.

4.a.2. Werekitto gneisses and granitoid rocks

Three groups of granitoid and gneisses with different textures/structures were distinguished within the Werekitto Gneiss.

(a) Compositionally banded granitoid gneisses with magmatic foliation and preserved igneous textures (outcrop SB-24);

(b) Gneisses and granitoids with well-developed foliation (outcrops SB-22 and SB-28) and microtectonic features indicating solid-state deformation at high temperatures;

(c) Foliated granitoids, without evidence of solid-state deformation at high temperature, but with mylonitic bands compatible with low to intermediate temperatures.

In the framework of this study, at scale 1: 1,000,000 it was not possible to distinguish groups of rocks with different textural and structural features in specific units, and therefore they have all been included into the Werekitto unit.

These granitoid rocks crop out in areas represented on the Geological Map of Suriname (Figs 5 and 6, GMD, 1977) as fine-grained granite (unit 22) and migmatitic biotite gneisses of granitic and tonalitic composition, unit 43, Coeroeni Group.

Macroscopic aspects

In general terms, the Werekitto gneisses and granitoids vary compositionally from biotite-(hornblende) monzogranites to tonalites (or quartz diorites), and present commonly greyish colours and a magnetic character (Figs 9, 10).

At site SB-24 there is a fantastic outcrop showing compositional banding on centimetre- to decimetre scale, and several mafic enclaves forming occasionally lensoid bodies. Analysed in three dimensions it was verified that the enclaves show the geometry of L-S tectonites, and what is observed in Figures 9a and 9b is the effect of the low-angle intersection of the banding. The bands consist of granodiorites and tonalites with differing contents of mafic minerals and different grain size, (Fig. 9d), while the contact between them is diffuse to sharp. A relevant aspect is that the rocks types of the different bands, do not seem to show important solid-state deformation, which could be responsible for the structure of the outcrop. Internally these bands occasionally show tabular feldspar crystals, with preferential orientation, which indicate magmatic foliation (Fig 9c). In the upper part of Figure 9c a coarse granitoid band without traces of foliation is observed, in contact with medium-grained granitoid band with diffuse banding. This banding is interpreted as inherited from igneous processes related to the emplacement of the magmatic body.

It has to be stated that in the concept of Salomon Kroonenberg (this report) features such as the oriented plagioclase crystals and compositional banding may occur in greywackes of metavolcanic and plutonic provenance. This researcher interprets the banded lithological varieties observed in SB-24 as of supracrustal origin and emphasizes that the textures of the rock samples collected from this outcrop are in harmony with its metamorphic origin.

Figure 9. Macroscopic aspect of Werekitto gneiss with compositional banding at outcrop SB-24. (a) Compositional banding and mafic boudins in a section subparallel to de banding; (b) Detail of the compositional banding; (c), (d) Details of the different granitoid bands that shows no internal foliation.

In the outcrops SB-22 and SB-28 greyish coarse-grained biotite (hornblende) gneisses occur (Fig. 10a, b, c). In the first outcrop centimetre-sized lenticular enclaves were observed, consisting of fine-grained mafic rock as well as a pegmatite vein about 3 m thick with quartz graphically intergrown with alkalifeldspar, and booklets of centimetre-sized biotite and muscovite crystals, cutting the biotite-hornblende gneiss (Fig. 10b).

The protomylonitic granitoids observed at outcrops SB-30 and 31 correspond to grey to crème-coloured biotite-(hornblende) monzogranites to granodiorites, showing some magnetism, with mafic minerals (between 10% and 15%) arranged in oriented lenticular aggregates. In outcrop SB-29 the rock is pink and the foliation is well-developed (Fig. 10d).

Petrography and microtectonics

In Table 3 the classification and approximate mineralogical composition of 9 samples of the granitoids and gneisses attributed to the Werekitto unit and of two enclaves is given.

Among the compositionally banded granitoids of outcrop SB-24 coarse to fine tonalitic rocks with granular textures predominate. In the coarsest type a foliation defined by the orientation of tabular idiomorphic plagioclase crystals and of the mafic components such as greenish biotite and bluish-green hornblende has been discerned and interpreted as a magmatic foliation (Fig. 11a, b). In this rock plagioclase shows Carlsbad-albite twinning, some antiperthite and a pronounced zoning. Quartz occurs in rather elongate grains, internally divided in subgrains and new grains that together with microcline and the mafic

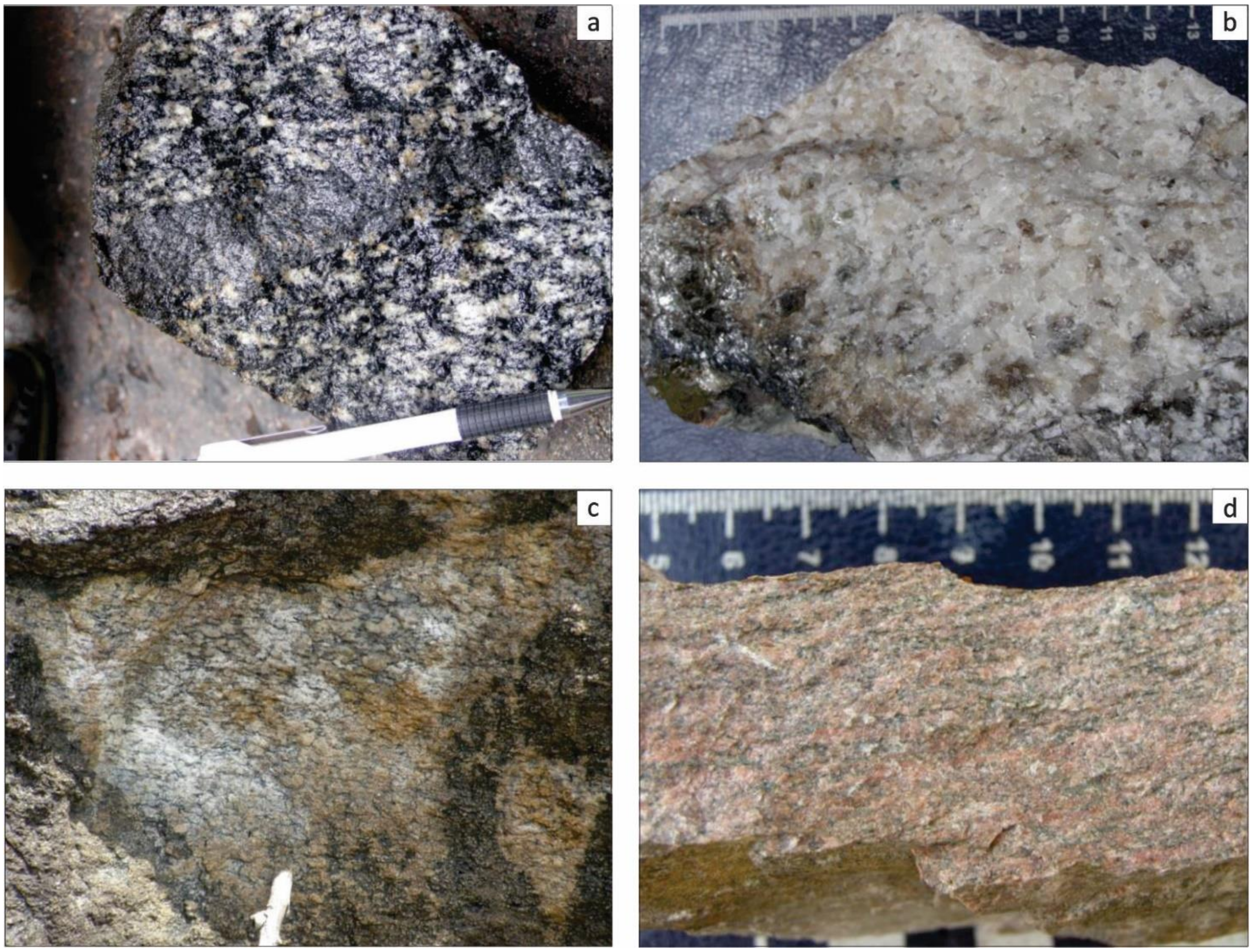


Figure 10. Macroscopic aspects of the Werekitto gneisses and granitoids (a) biotite-hornblende gneiss (outcrop SB-22); (b) detail of pegmatite cutting the biotite-hornblende gneiss (outcrop SB-22). (c) Biotite gneiss (outcrop SB-28); (d) pinkish mylonitic granitoid (outcrop SB-29).

Table 3. Classification and estimated mineral composition (%) of gneisses and granitoids of the Werekitto unit (mineral abbreviations according to Siivola & Schmid 2007).

Sample	Classification	Qtz	Pl	Afs	Bt	Hbl	Op	Ser	Chl	Ep	Cal	Fl	Aln	Ttn	Ap	Zrn
SB-28	Gneissic bt monzogranite	20	23	41	14		1	tr					tr	1		tr
SB-31 A	Protomylonitic bt monzogranite	18	33	40	8		tr	1		tr			tr	tr	tr	
SB-30	Protomylonitic bt-hbl granodiorite	20	40	18	4	16	tr	tr		2				tr	tr	tr
SB-29	Protomylonitic bt-chl granodiorite with a monzogranitic band	18 30	45 30	25 40	2		2		10 tr	tr tr			tr	2 tr	tr	tr
SB-29 A	Protomylonitic chl granodiorite	20	44	23			2	tr	9	tr		2	tr	tr	tr	tr
SB-24 B 1	Banded bt-hbl granodiorite	21	33	5	18	22	tr			1					tr	tr
SB-24 A	Foliated hbl-bt tonalite	23	60	4	10	4	1	tr		2	tr			1	tr	
SB-24 B 2	Foliated hbl-bt tonalite	20	47	3	20	7	tr			3	tr			tr	tr	
SB-22 A	Gneissic bt- hbl quartzdiorite	5	48		9	35	3	tr					tr		tr	
SB-15 (Enclave)	Foliated porphyritic hbl qtz diorite	5	52		3	40	tr	tr	tr						tr	
SB-24B(Enclave)	Foliated porphyritic bt-hbl diorite		52		17	28	tr	tr		3			?	tr	tr	

Qtz = quartz; Pl = plagioclase; Afs = alkali feldspar; Bt = biotite; Hbl = hornblende; Op = opaque mineral; Ser = sericite; Chl = clorite; Ep = epidote; Cal = calcite; Fl = fluorite; Aln = allanite; Ttn = titanite; Ap = apatite; Zrn = zircon; tr = trace (< 1%)

minerals occupy the spaces between the plagioclases. Epidote, opaque minerals, titanite, apatite and calcite are accessory phases. In the same outcrop SB-24 a granodioritic band of medium to fine grain size and a xenomorphic granular texture was studied (SB-24B). In this rock plagioclase generally does not show clear igneous zoning. Quartz and microcline are xenomorphic, the first showing undulous extinction and signs of recrystallisation. Brown biotite and bluish-green hornblende tend to have a preferential orientation. Epidote, apatite, zircon and allanite are present in accessory amounts.

The biotite-hornblende quartz-dioritic gneiss of sample SB-22A shows an irregular coarse to fine grain size and a foliation resulting from the preferential orientation of the mafic minerals and their concentration in fine laminae that surround more felsic almond-shaped parts containing plagioclase, quartz and subordinate mafics (Fig. 11c). The plagioclase is andesine (An30-34) with igneous zoning still present in some crystals. Some of these plagioclase grains show undulatory extinction, subgrains and new grains of varying size and irregular forms with irregular borders, or subgrains and new grains with rectilinear up to polygonal boundaries. These microtectonic observations suggest that recrystallisation processes were active by migration of the grain boundaries and rotation of subgrains, respectively. These processes act on plagioclase at temperatures higher than 500°C (Passchier and Trouw, 1996). The hornblende is bluish green, occasionally twinned, and contains inclusions of quartz, opaque minerals, biotite and apatite. Biotite is brown and tends to occur associated with hornblende. Quartz is recrystallized.

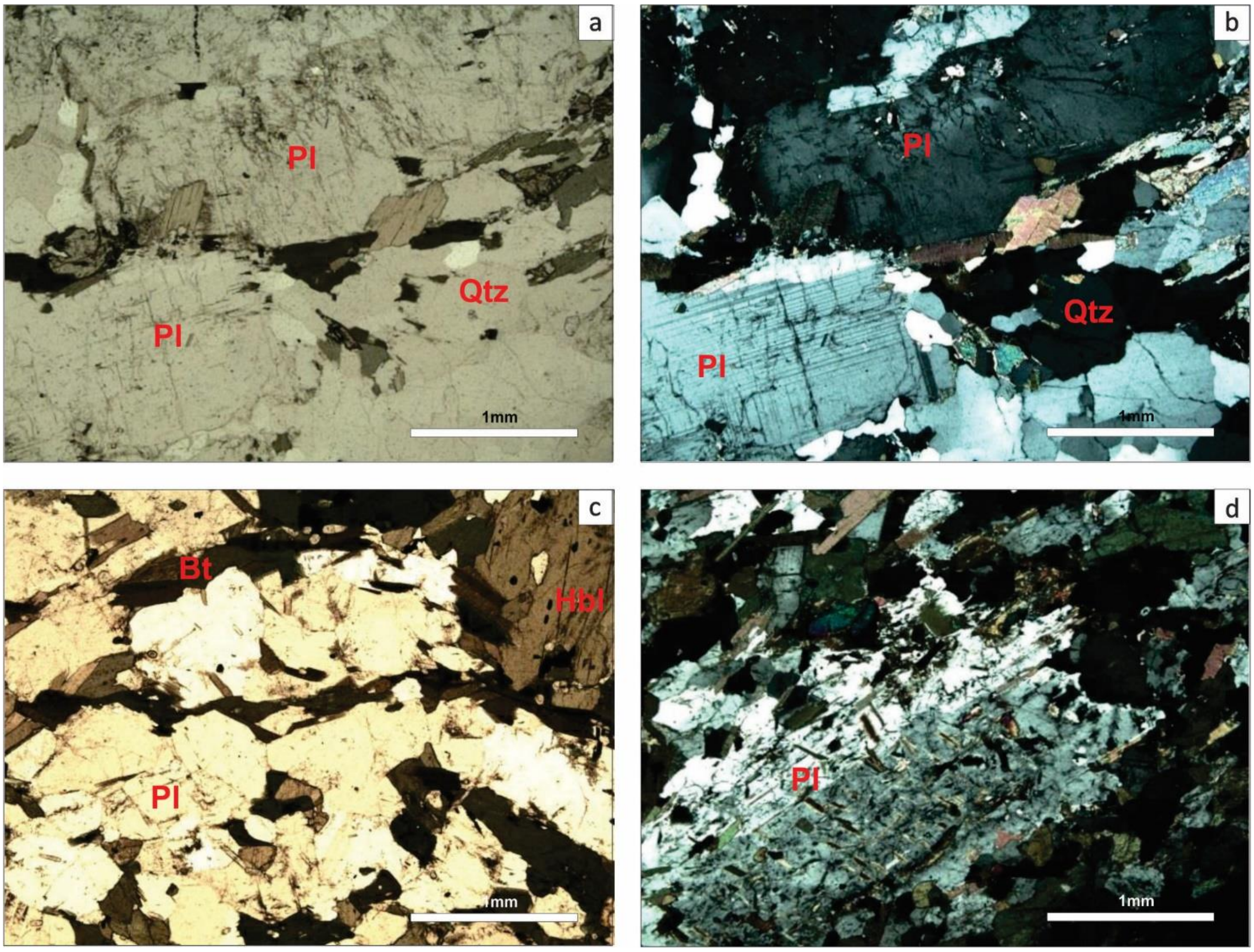


Figure 11. Microscopic aspects of the Werekitto gneisses and granitoids. (a) coarse-grained hornblende-biotite tonalitic rock, with a foliation defined by the orientation of the mafic components, such as biotite (Bt), and hornblende and tabular zoned plagioclase crystals (Pl). Thin section SB-24A, plane-polarized light. Scale = 1 mm. (b) Same image as previous under crossed polarizers. Thin section SB-24A. Scale= 1 mm. (c) Biotite (Bi) – hornblende (Hbl) quartz dioritic rock showing a gneissic structure. Thin section SB-22A plane-polarized light. Scale= 1mm. (d) Plagioclase (Pl) phenocryst with Carlsbad-albite twins in dioritic enclave. Thin section SB-24 B, crossed polarizers. Scale = 1 mm.

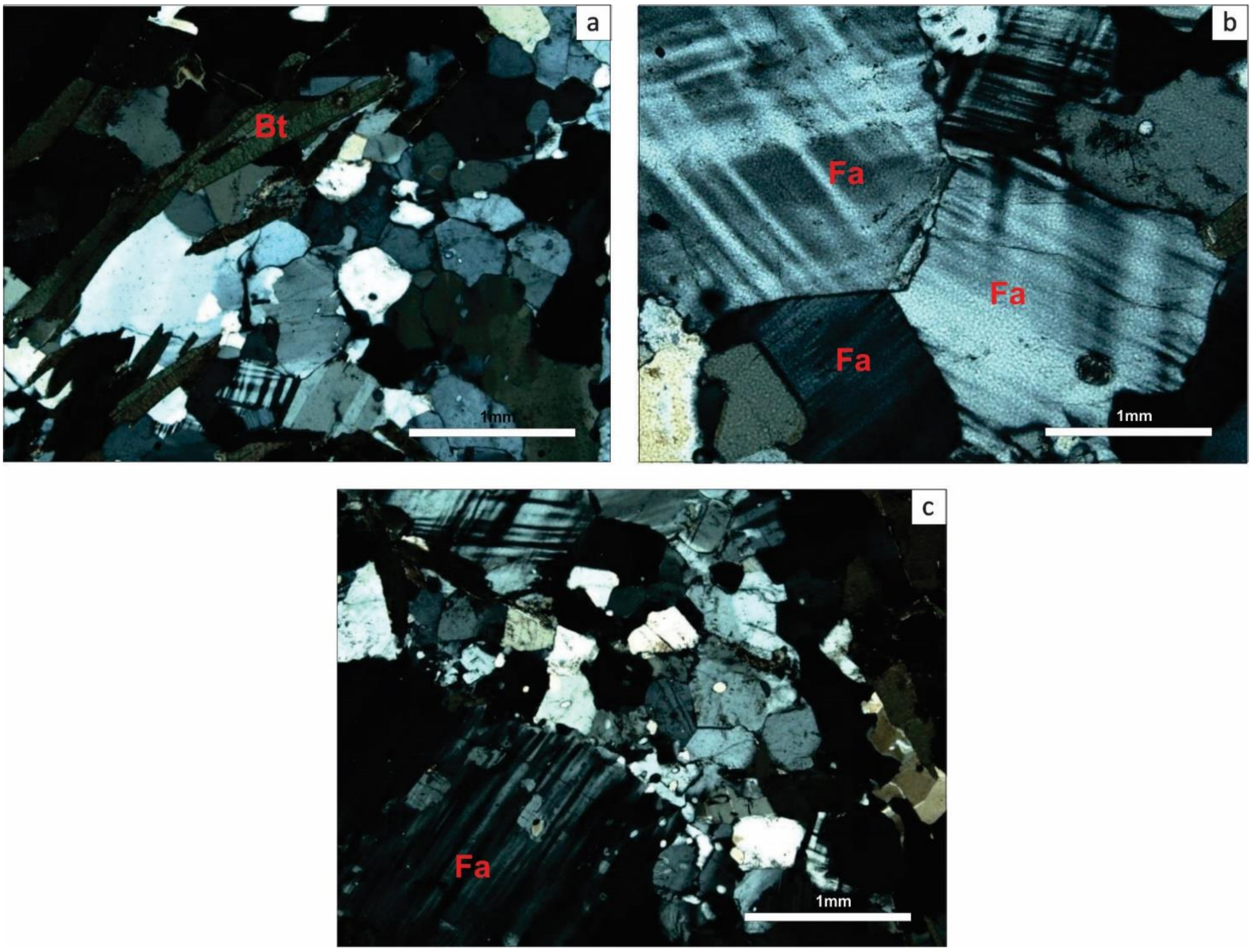


Figure 12. Microtectonic aspects of the monzogranitic gneiss of the Werekitto Gneiss unit from outcrop SB-28. (a) Biotite (Bt) flakes deviate from the partly granoblastic felsic parts. Crossed polarizers. Scale = 1 mm. (b) Evidence of recrystallization in alkali feldspar (Fa) in part polygonised, partly with lobate boundaries. Crossed polarizers. Scale = 0.4 mm. (c) Large alkali feldspar crystals with very little internal deformation. Crossed polarizers. Scale = 1 mm.

In sample SB-28, of monzogranitic composition and well-developed foliation, quartz, alkali feldspar, plagioclase (An25) without clear zoning and brown biotite are the main constituents. Opaque minerals, allanite, titanite and zircon occur in accessory amounts. The grain size is fine to medium. Quartz occurs in partially recrystallized elongated crystals, tending to rectangular, and show a preferential orientation parallel to the brown biotite flakes. These biotite flakes tend to be oriented surrounding felsic portions of the rock consisting of feldspar megacrysts/porphyroclasts distributed in a xenomorphic, partly granoblastic groundmass (Fig. 12a). The groundmass consists of quartz, alkali feldspar and some plagioclase, in which quartz and less frequently alkali feldspar are poligonized (Fig. 12b) suggesting recrystallization by Rotation of Subgrains. This deformational mechanism starts to be important in quartz under intermediate temperatures and in alkali feldspar, under temperatures higher than 500°C (Passchier and Trouw, 1996). It has to be highlighted that in this rock (SB-28) there are large alkali feldspar crystals with very little internal deformation in spite of the indications of recrystallization in the groundmass (Fig. 12c), suggesting low strain conditions under high (>500°) temperatures for the observed microstructural features. Locally flame perthites, myrmekites and transcrystal fractures occur, suggesting solid-state deformation at low to intermediate temperatures. It is possible that these features superimposed upon the higher-temperature zones are related to the episode that generated mylonitic textures in other granitoids in the area.

As mentioned before, a group of granitoids without any sign of high-temperature solid-state deformation, but showing low- to medium temperature mylonitic textures will be described below.

The granitoids of the sites SB-29 and SB-31A show hypidiomorphic to xenomorphic granular textures, partly obliterated by deformational fabrics. The compositions vary from granodioritic to monzogranitic, with quartz, plagioclase, alkali feldspar and brown biotite as essential minerals, and additionally bluish green hornblende in sample SB-30 (Table 3). Opaque minerals, allanite, titanite, apatite and zircon are accessory minerals. In these granitoids the feldspars occur as porphyroclasts or in the groundmass. The porphyroclasts show fractures, undulatory extinction and some comminution into fine-grained feldspar aggregates, with irregular contacts, occasionally forming an incipient groundmass (Fig. 13a). The plagioclase shows deformation twins and kinked polysynthetic twins with clear boundaries. The alkali feldspar shows flame perthites, and myrmekites may occur at the contact with plagioclase. Quartz is recrystallized in irregular grains with lobate contacts or more in polygonal aggregates. The mylonitic fabric is best developed in sample SB-29 where a mylonitic foliation is marked by grain orientation and fairly elongated quartz aggregates, tending to bands, arranged parallel to films where the original mafic minerals were destabilised to an assemblage dominated by chlorite (Fig. 13b). Fine streaks of fine-grained comminuted material with fairly irregular contacts occur side by side to the foliation films in some parts of the rock. In this mylonitic granitoid (SB-29) the porphyroclasts are more strongly affected, fractured and fragmented. These microstructural features suggest the occurrence of an episode of inhomogeneous deformation at low to intermediate temperatures of the order of 400°-500°C.

Ages and Correlations

In the concept of Kroonenberg et al. (2016) (see discussion on item 3.h) the Werekitto Gneiss is part of the Coeroeni Gneiss Belt and shares the same supracrustal origin and metamorphic evolution of the Amotopo paragneisses. On the other hand, Lêda Maria Fraga and Ana Maria Dreher believe that the granitoids of the Werekitto unit are of clear igneous plutonic nature with crystallization ages in the range of 1993,9 ± 37 (Sample SB 31, mylonitic biotite monzogranite) – 1983 ± 5,4 Ma (foliated hornblende-biotite tonalite or tonalitic gneiss, sample SB-24) (U-Pb SHRIMP on zircon by U. Cordani and L.M. Fraga, unpublished data in Kroonenberg et al. 2016).

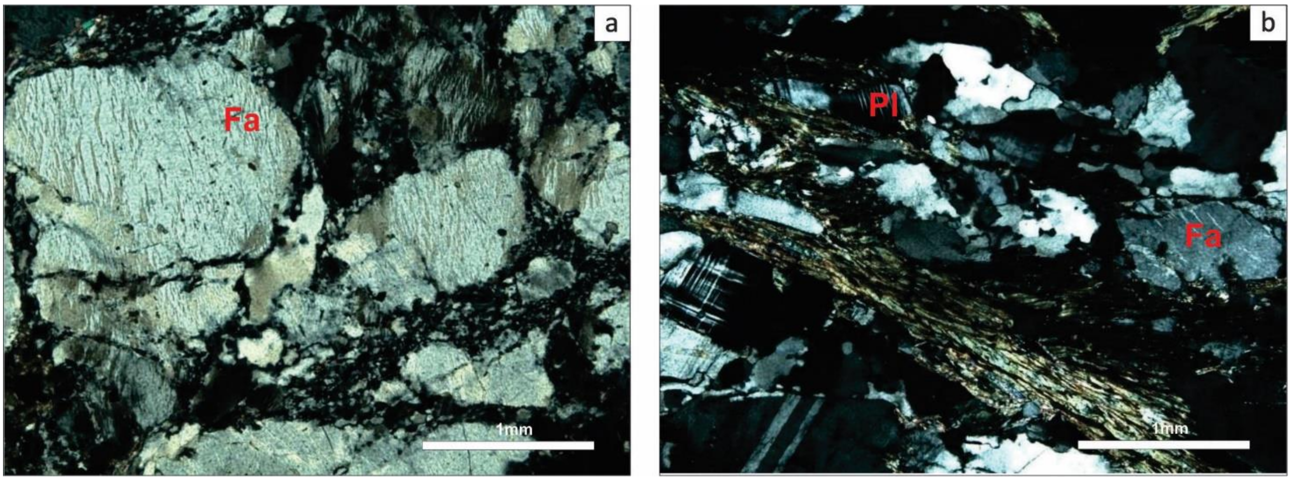


Figure 13. Microtectonic aspects of the Werekitto granitoids. (a) Alkali feldspar porphyroclast I(Fa) with undulatory extinction, fragmented and separated by aggregates of very fine grains with irregular forms. Protomylonitic biotite monzogranite. Thin section SB-31, crossed polarizers. Scale = 1 mm. (b) Mylonitic foliation highlighted by the orientation of chlorite flakes and arrangement of very fine grains of irregular forms. Flame perthites in alkali feldspar crystal (Fa), and tapering deformational twin in Plagioclase (Pl). Protomylonitic granodiorite. Thin section SB-29, crossed polarizers. Scale = 1mm.

4.a.3. Dalbana Formation

The outcrops of volcanic and volcaniclastic rocks occur in the area that is indicated on the Geological Map of Suriname (Figs. 5 and 6, GMD, 1977) as Dalbana Formation (codes 29 and 30). It has to be remarked, however, that in part of the area mapped as volcanic rocks recrystallized by contact metamorphism (unit 30) a variety of plutonic and high-grade metamorphic supracrustal rocks crops out (Figs 5 and 6).

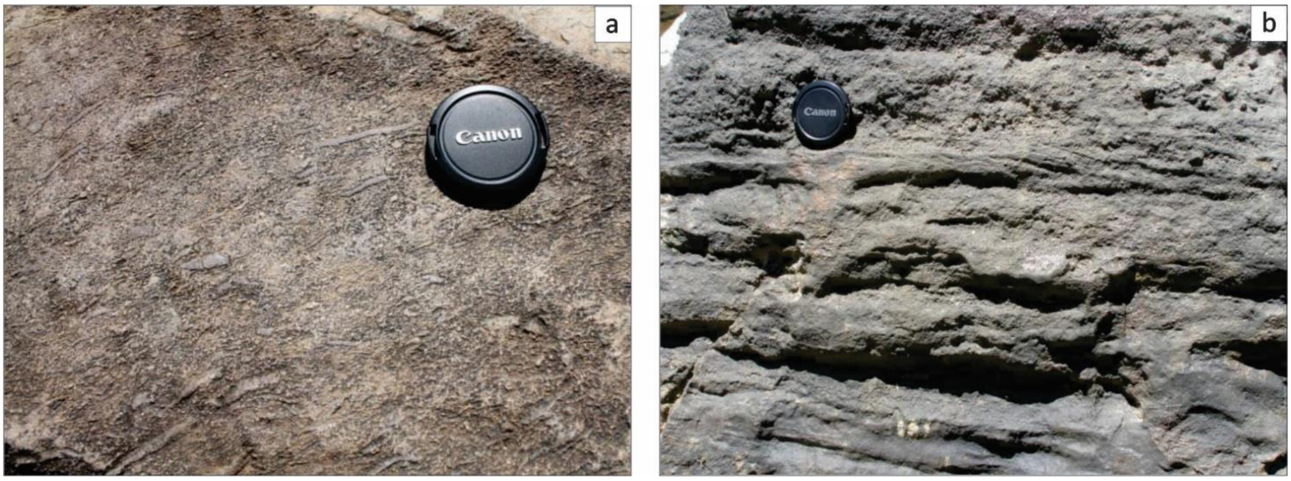


Figure 14. Macroscopic aspect of the Dalbana Formation Rocks. (a) Lensoid fragments, possibly of flattened pumice, marking the volcaniclastic S0 (SB-01). (b) Layered volcaniclastic rock. There are massive beds, cross-bedding layers and beds containing probable accretionary lapilli. (SB-03C).

Macroscopic aspects

The Dalbana Formation in the studied area is consists dominantly of welded rhyolitic to dacitic ignimbrites of dark-grey colour, with scarce feldspar and locally also quartz phenocrysts. Pumice fragments are very common (Fig. 14a), and less frequently, fragments of dark-grey volcanic rock are observed (outcrop SB-3A). A 'volcaniclastic' foliation (or eutaxitic structure), marked by flattened pumice fragments is common in welded ignimbrites. The rocks are generally cut by many fault surfaces to which quartz veins may be associate. Some volcanoclastic varieties rich in rounded particles, measuring in general between 0.5 and 1 cm in diameter were observed. These rocks probably correspond with tuffs with accretionary lapilli (outcrop SB- 3-B). A rock with centimetre- to decimetre-sized layering marked by the presence of beds rich in accretionary lapilli, beds with channel cross-bedding/lamination and massive beds was observed in outcrop SB-3C (Fig. 14b), indicating that these rocks may result from pyroclastic flows or subaqueous reworking of tuffaceous material.

An andesite was described from outcrop SB-09. The rock is greenish-grey, with few plagioclase crystals and many fine crystals of mafic minerals, distributed in a very fine to aphanitic groundmass, and includes fragments of dark grey volcanic rocks with angular forms, between 2 and 9 cm in size. In this outcrop fault surfaces are filled with quartz veins together with a greenish mineral, possibly tourmaline.

Petrography and microtectonics

The rocks belonging to the Dalbana Formation are mainly felsic ignimbrites of dacitic to rhyolitic composition, with lesser andesites and felsic subvolcanic rocks. Table 4 presents the mineralogy and petrographic classification of 9 samples of rocks included in the Dalbana Formation are given.

The dactic and rhyolitic ignimbrites show dispersed crystals, 1 to 4 mm in length, and fragments of pumice of varied size, immersed in a very fine matrix. The crystals are idiomorphic to fragmentary and generally of plagioclase, potassic feldspar and rounded and corroded quartz (Fig. 15a, b). Minor crystals (≤ 1mm) of opaque minerals and biotite are also present.

The pumice fragments are cryptocrystalline and dark in a few thin sections, preserving frayed ends and a vesicular internal structure (Fig. 15 b), with little round vesicles filled with quartz, which suggests that the rocks suffered only weak welding. In other thin sections the presence of pumice is indicated by strongly stretched lenses, of somewhat larger grain size than the groundmass, and that point to considerable welding. Small lithic fragments, up to 2 mm of other felsic tuffs and andesites also have been observed in some ignimbrites.

The groundmass of these pyroclastic rocks is felsic, crypto- to microcrystalline, showing weak to clear flow structure (Fig. 15c), and locally, the presence of stylolites and micropoikilitic textures. These features point to an original vitroclastic nature of the groundmass, affected by welding and devitrification, although glass shards are no longer visible in these rocks.

Table 4. Petrographic classification and mineral content of the Dalbana Formation rocks (mineral abbreviations according to Siivola & Schmid 2007).

Sample	Classification	Qtz	Pl	Afs	Bt	Am	Opx	Cpx	Op	Ser	Chl	Ep	Cal	Ttn	Ap	Zrn
SB-01	Dacitic ignimbrite	X	X		tr				X	tr		tr		tr	tr	
SB-02 C	Slightly welded rhyolitic ignimbrite	X	X	X	tr				X	tr				tr		
SB-03 A	Dacitic ignimbrite	X	X		tr				X	tr					tr	tr
SB-03 B	Altered dacite or dacitic tuff	X	X		X				tr	X	tr				tr	
SB-06 A	Slighly foliated dacitic ignimbrite	X	X		tr				X	X		tr		tr	tr	tr
SB-06 B	Dacitic ignimbrite	X	X		X				X	X		tr		tr	tr	tr
SB-08	Dacitic ignimbrite	X	X		X				X	X	X	tr	tr	tr	tr	
SB-09	Altered vesicular andesite	X	X		X	X			tr	tr				tr		
SB-05	Porphyritic opx-cpx-am qtz monzonite	X	X	X	X	X	X	X	X	tr	tr	tr			tr	tr

Qtz = quartz; Pl = plagioclase; Afs = alkali feldspar; Bt = biotite; Am = amphibole; Opx = orthopyroxene; Cpx = clinopyroxene; Op = opaque mineral; Ser = sericite; Chl = chlorite; Ep = epidote; Cal = calcite; Ttn = titanite; Ap = apatite; Zrn = zircon; X = main component (> 1%); tr = traces (< 1%)

The minerals present in the groundmass are mainly quartz, feldspars and sericite, apart from disseminated minute grains of opaques, extremely fine biotite, epidote, titanite, chlorite, apatite and carbonate. This mineral association most probably developed in these rocks by processes of devitrification and diagenetic and hydrothermal alteration (McPhie et al. 1993). However, this mineral assemblage has been interpreted by various authors as reflecting incipient metamorphism (Kroonenberg et al. 2016).

Andesites are rarer in the Dalbana Formation and show strong alteration. They show phenocrysts up to 2 mm of tabular plagioclase (Fig. 15d) and of amphibole. The groundmass is rather fine, formed by disseminated plagioclase laths, amphibole, greenish brown biotite, epidote, sericite and titanite. Small round vesicular cavities (Fig. 15d), filled mainly by quartz, with biotite and amphibole in the cores, occur throughout the groundmass.

A porphyritic subvolcanic rock, of quartzmonzonitic composition, collected within the area occupied by the Dalbana Formation, was also included into this unit. This rock contains medium to fine-sized phenocrysts of plagioclase, microcline, quartz, hornblende, clinopyroxene and opaque immersed in a fine to very fine saccharoidal to granophyric groundmass consisting mainly of quartz and alkali feldspar.

Correlations

The Dalbana Formation can be correlated with the Igarapé Paboca Formation and the Surumu Formation in Brazil, the latter unit crops out outside the project area.

4.a.4. Wonotobo Biotite-(hornblende) granodiorites and monzogranites

This unit, named on the base of a proposal by Kroonenberg et al. (2016) crops out in areas which on the Geological Map of Suriname (Figs.5 and 6, GMD, 1977) units 22, Fine-grained granite and 29 and 30, Dalbana Formation are represented.

Macroscopic aspects

The Wonotobo granites correspond mainly to biotite- (hornblende) monzogranites and granodiorites (Figs. 16a, b). They are greyish, magnetic rocks of medium- to coarse grain size, generally equigranular, whereas porphyritic types also occur (Fig 16c). They are frequently isotropic, but in the outcrops SB-13, SB-14, SB-16B and SB-19 foliated, protomylonitic varieties also occur.

Centimetre-sized round enclaves of fine mafic rocks are common, and some of them contain alkali feldspar crystals, probably dropped from the surrounding rock, suggesting the coexistence of granitoid with mafic magmas during the emplacement of the bodies. Locally an arrangement of aligned lenticular enclaves

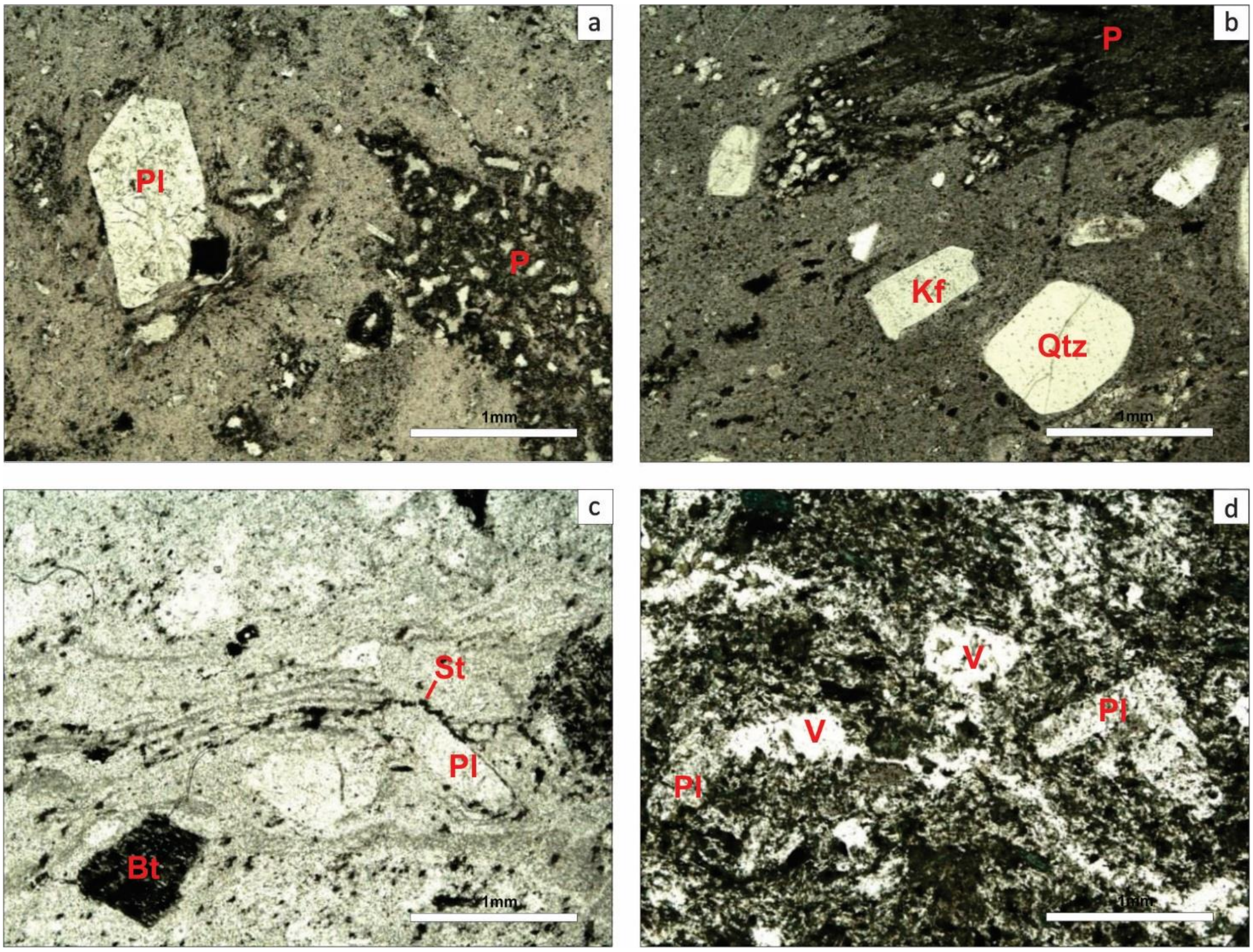


Figure 15. Microscopic aspects of Dalbana Formation Rocks. (a) Dacitic ignimbrite showing a larger plagioclase crystal (Pl) and dark pumice fragments (P) with irregular borders and vesicular internal structure suggesting moderate welding. The groundmass is felsic, microcrystalline. Thin section SB-01, plane-polarized light. Scale = 1 mm. (b) Rhyolitic ignimbrite formed by quartz crystals (Qz), K-feldspar (Kf) and dark pumice fragments (P) with frayed borders and vesicles. The groundmass is felsic with weak flow structures. Thin section SB-02C, plan-polarised light. Scale= 1mm (c) Dacitic ignimbrite, showing larger plagioclase crystals (Pl) and altered biotite (Bt), amidst a felsic groundmass with strong flow structure and stylolites (St). Thin section SB-06B, plane-polarized light. Scale = 1 mm. (d) Altered andesite with larger plagioclase crystals (Pl) and vesicular cavities (V) filled with quartz, amidst a fine groundmass rich in plagioclase, amphibole and biotite. Thin section SB-09, plane-polarized light. Scale = 1 mm.

was observed, suggesting broken synplutonic dykes (SB-19). There are also centimetre- to decimetre-sized xenoliths with angular forms consisting of fine-grained mafic rock (Figs. 16d, e) as for instance the foliated quarzdiorite of SB-21 and the probable amphibolite of SB-10, and fine, sometimes foliated quartzdiorite (SB-21). Finally, it should be mentioned that the Wonotobo granitoid is the dominant lithology at the archeological site Werehpai (Fig. 16f).

Petrography and microtectonics

The Wonotobo granitoids vary from monzogranites to quartz diorite, with a predominance of granodiorites over other varieties. They are medium- to coarse-grained rocks, generally equigranular and massive, apart from a few porphyritic types. Protomylonitic to mylonitic granitoids were also observed and will be described at the end of this section.

Table 5 illustrates the classification and mineralogical composition of 8 granitoids and 3 xenolith samples.

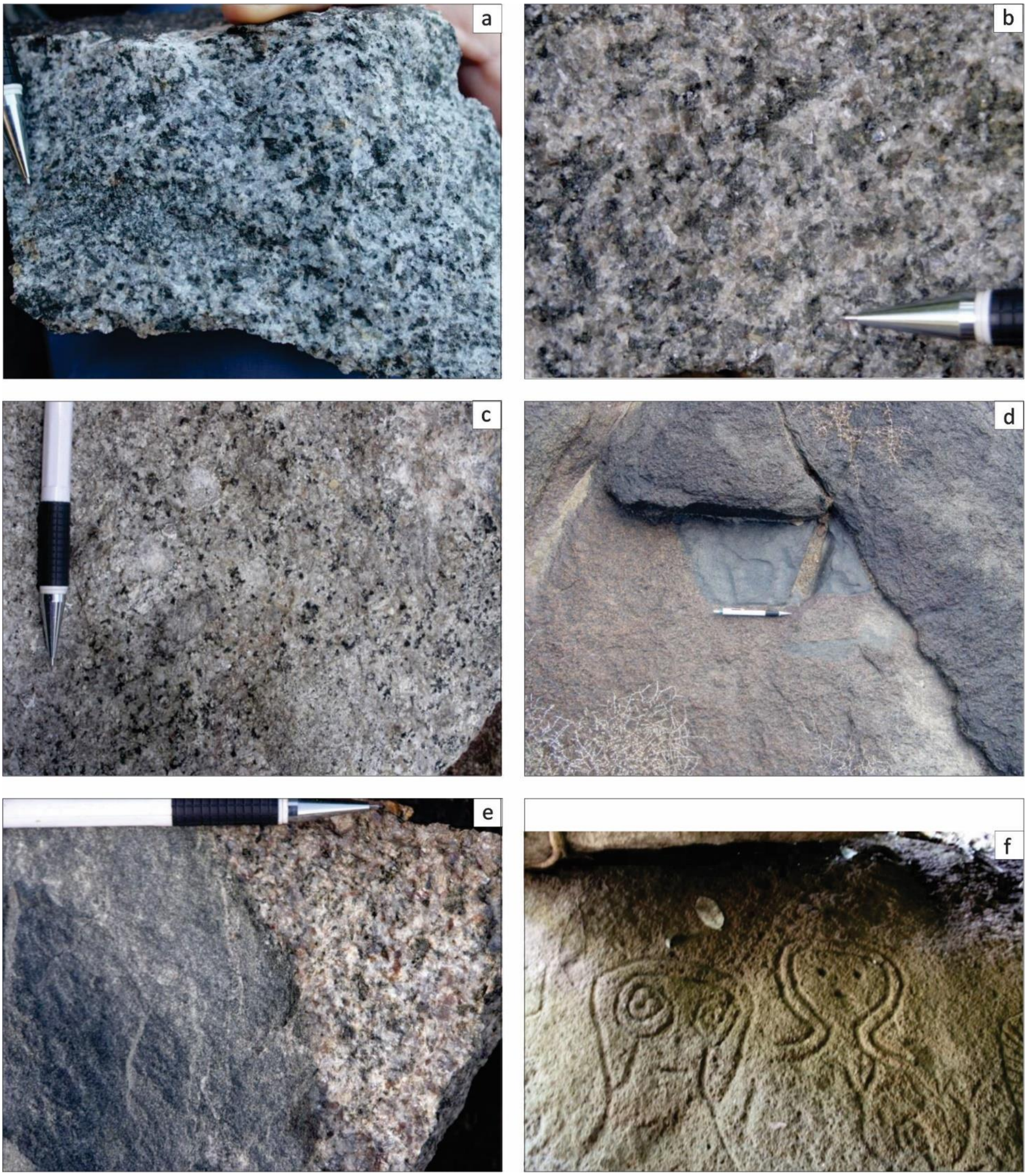


Figure 16. (a) Medium-grained equigranular granodiorite with fine mafic enclave (outcrop SB-17); (b) Medium-coarse grained monzogranite (outcrop SB-16); (c) Porphyritic granodiorite (outcrop SB-20); (d) Amphibolite xenolith in monzogranite (outcrop SB-20); (e) detail of contact of granite with amphibolite (outcrop SB-20); (f) Werehpai petroglyphs, one of the most fantastic archeologic sites of Amazonia, carved in monzogranite of this unit (see chapter 6 below).

The monzogranites and granodiorites present hypidiomorphic granular textures and consist of idiomorphic plagioclase, subidiomorphic microcline and xenomorphic quartz (Figs. 17a, b). The main mafic component is biotite, accompanied by hornblende in a few samples. Opaque minerals, epidote, titanite in large and generally well formed crystals (Fig. 17c) besides apatite, acicular rutile and zircon are present in accessory amounts. The plagioclase shows Carlsbad-albite twinning, well developed concentric zoning, rare antiperthites, and strong alteration to sericite and epidote in the most calcic cores of the crystals (Fig. 17d).

Table 5. Classification and estimated mineral content (%) of rocks of the Wonotobo unit (mineral abbreviations according to Siivola & Schmid 2007).

Sample	Classification	Qtz	Pl	Afs	Bt	Hbl	Op	Ser	Chl	Ep	Aln	Ttn	Rt	Ap	Zrn
SB-13	Protomylonitic bt monzogranite	20	35	25	16		1	tr		2	tr	1		tr	tr
SB-16	Bt monzogranite	18	35	32	12		1	tr	tr	tr		2	tr	tr	tr
SB-14	Mylonitic bt-hbl granodiorite	15	48	12	6	15	2				tr	tr		tr	tr
SB-17	Bt-hbl granodiorite	15	40	20	10	12	2	tr		tr		1		tr	
SB-20	Bt granodiorite	25	45	20	8		1	tr	tr	tr		1	tr	tr	tr
SB-20 A	Bt granodiorite	22	46	22	9		1	tr		tr		tr	tr	tr	tr
SB-21 A	Bt tonalite	18	49	3	25		3	tr		1		1	tr	tr	?
SB-10	Porphyritic hbl qtz diorite	12	58	4	8	15	1	tr		2	tr	tr		tr	
SB-21 (xenolith)	Foliated porphyritic ep-bt micro qtz diorite	10	46	3	26	tr	tr			15	tr	tr		tr	tr
SB-21 B (xenolith)	Foliated porphyritic ep-bt micro qtz diorite	8	53	2	28		tr			9	tr			tr	tr
SB-11 (xenolith)	Foliated chl-hbl micro monzo diorite	tr	60	6		16	2	tr	10	6		tr			

Qtz = quartz; Pl = plagioclase; Afs = alkali feldspar; Bt = biotite; Hbl = hornblende; Op = opaque mineral; Ser = sericite; Chl = chlorite; Ep = epidote; Aln = allanite; Ttn = titanite; Rt = rutile; Ap = apatite; Zrn = zircon; tr = traces (< 1%)

Its composition varies from oligoclase to andesine (An27-35) in the monzogranites to andesite (An 33) in the granodiorites. The microcline is slightly perthitic and shows Carlsbad and albite-pericline twinning. Biotite is green to greenish brown and is slightly altered to chlorite. Hornblende is olive-green. Both mafic minerals occur in aggregates together with opaque minerals and epidote, well-developed titanite, apatite and zircon (Fig. 17e).

The quartz diorite SB-10 (Table 6) is porphyritic with medium-sized plagioclase and hornblende phenocrysts set in a fine groundmass with biotite, hornblende, rare alkali feldspar and graphic quartz. The plagioclase phenocrysts are idiomorphic to subidiomorphic of andesine (An35) composition, showing strong zoning and pronounced alteration to epidote and sericite. The hornblende phenocrysts are idiomorphic to xenomorphic bluish-green crystals, twinned and slightly altered to biotite. Opaque minerals, allanite, zircon and titanite are accessories.

The xenoliths observed in the Wonotobo granitoids are dark, fine-grained foliated rocks, almost always porphyritic, with quartz dioritic to monzodioritic composition. The quartz diorite enclaves contain grouped phenocrysts of idiomorphic to xenomorphic plagioclase (Fig. 17f, Table 5), up to 1 mm long, of the Andesine variety (An35). The matrix is fine to very fine-grained, with a granolepidoblastic on texture, composed of plagioclase, brown-green oriented biotite, epitope, quartz and rare microcline and hornblende. Opaque minerals, apatite, allanite, zircon and titanite are accessories. The monzodioritic xenolith has a microcrystalline texture, and consists of sericite- and epidote-altered plagioclase, green hornblende and oriented dark green chlorite, epidote, microcline, opaque and rare quartz and titanite.

In the protomylonitic and mylonitic Wonotobo types (Fig. 18 a, b, c) (SB-13 and SB-14) the original texture of the rocks was affected by deformational features.

In sample SB-13 a small proportion of comminuted material, consisting of very fine grains with irregular boundaries is locally present, quartz is partly recrystallized and the feldspars show undulatory extinction. The alkali feldspar shows flame perthite (Fig. 18a), and the plagioclase locally shows tapering deformational twin lamellae. In sample SB-14, which is more deformed, feldspar porphyroclasts are set in a finer

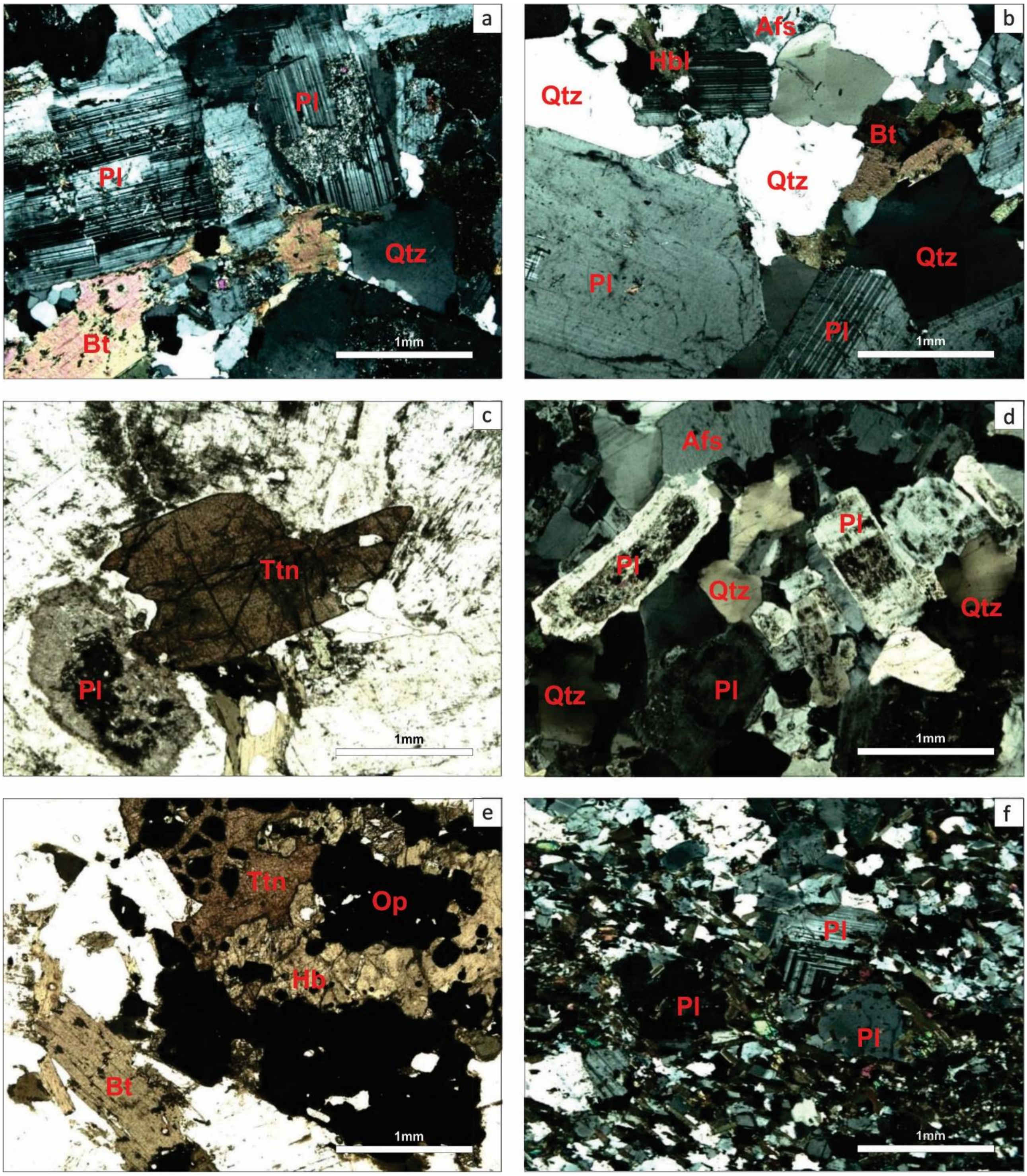


Figure 17. Microscopic aspects of the Wonotobo granitoids. (a) Biotite monzogranite with a granular texture, showing idiomorphic, twinned and strongly zoned plagioclase crystals (Pl), anhedral quartz (Qtz) and biotite (Bt). Thin section SB-16, crossed polarizers. Scale = 1 mm. (b) Biotite-hornblende granodiorite consisting of euhedral plagioclase (Pl) and anhedral quartz (Qtz) and microcline (Afs) crystals next to biotite (Bt) and hornblende (Hbl). Thin section SB-17, crossed polarizers. Scale = 1 mm. (c) Large idiomorphic to subidiomorphic titanite crystal (Ttn) next to strongly zoned and altered plagioclase in monzogranite. Thin section SB-16, plane-polarized light. Scale = 1 mm. (d) Tabular, strongly zoned and altered plagioclase crystals (Pl), anhedral quartz (Qtz) and microcline (Afs) in biotite granodiorite. Thin section SB-20, crossed polarizers. Scale = 1 mm. (e) Mineral aggregate in granodiorite, formed by hornblende (Hbl), biotite (Bt), magnetite (Op) and apatite. Thin section SB-17, plane-polarized light. Scale = 1 mm. (f) Porphyritic quartz diorite belonging to a xenolith, containing grouped phenocrysts of plagioclase amidst a fine-grained and foliated groundmass. Thin section SB-21 B, crossed polarizers. Scale = 1 mm.

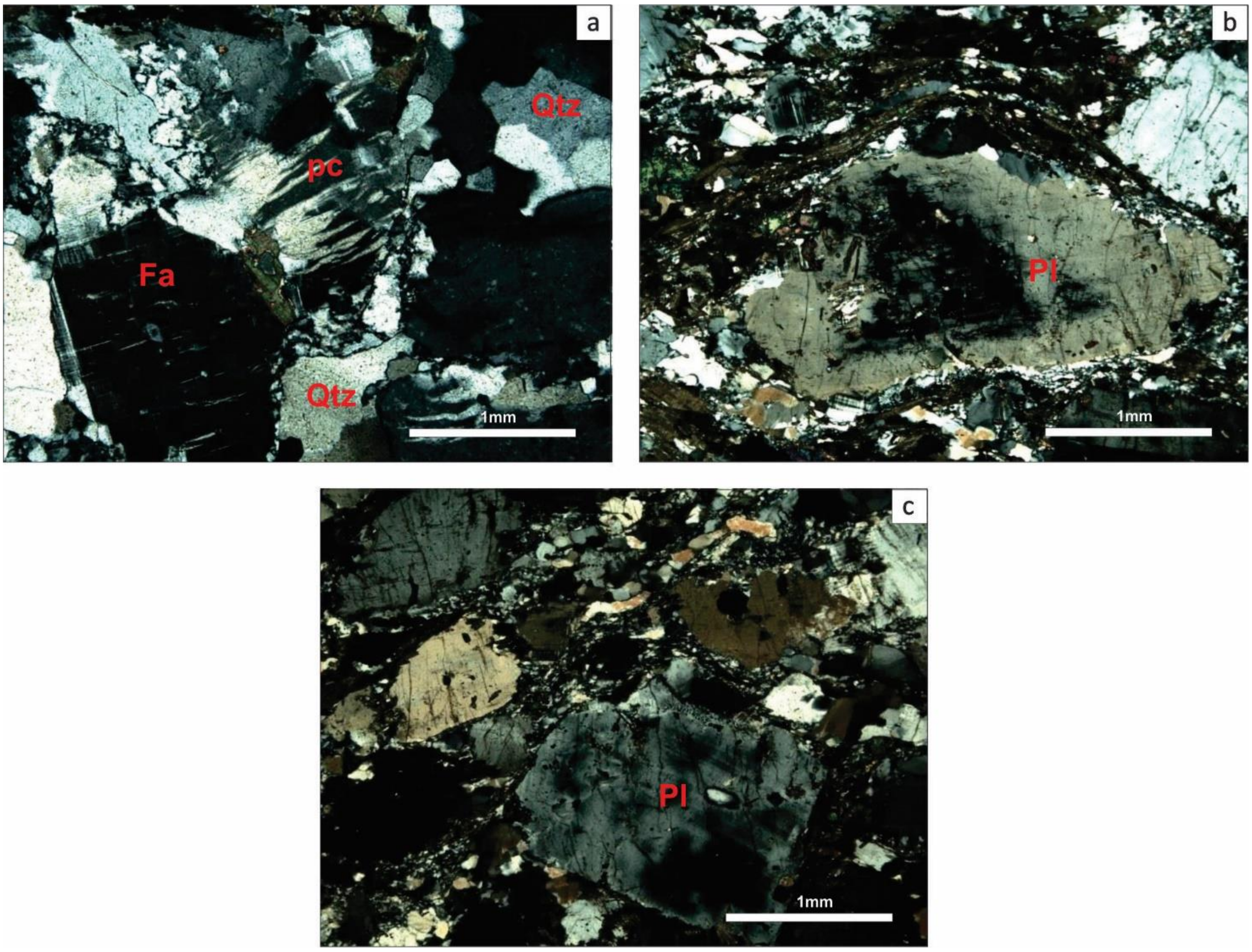


Figure 18. Microtectonic aspect of the Wonotobo granitoids. (a) Protomylonitic biotite monzogranite with alkali feldspar crystals (Fa) showing flame perthite (pc), and recrystallized quartz (Qtz). Thin section SB-13, crossed polarizers. Scale = 1 mm. (b) Protomylonitic biotite-hornblende granodiorite, with plagioclase porphyroclasts (Pl) and films or fine comminuted material. Thin section SB-14, crossed polarizers. Scale = 1mm. (c) Protomylonitic biotite-hornblende granodiorite, showing plagioclase crystals (Pl) largely preserving their igneous outlines. Thin section SB-14. Crossed polarizers. Scale = 1mm.

groundmass where foliation films (Fig. 18b) are outlined by fine biotite, associated with epidote, opaque minerals, titanite and fine sericite, originated from the destabilization of the original mafic minerals of the rock (biotite and hornblende) at moderate to low temperatures. These foliation films are bordered by bands of aggregates with very fine irregular grains of feldspars and quartz (Fig.18b). Plagioclase in this rock occurs as porphyroclasts with igneous outlines partially preserved (Fig. 18c) or in the groundmass of the rock. It shows moderate to strong undulatory extinction and occasional deformational twinning. Some porphyroclasts present subgrains with irregular boundaries or new grains divided by fine bands of aggregates of very fine grains with saw-toothed boundaries occur. These aggregates also occupy parts of the borders of the porphyroclasts. The alkali feldspar shows undulatory extinction, flame perthites, and myrmekites at the contact with plagioclases, and may contain subgrains and new grains with saw-toothed boundaries and irregular outlines. The observed features suggest incipient recrystallization by migration of the boundaries between the grains in the alkali feldspar and nucleation of very fine newly formed grains in the plagioclase.

Quartz is crystallised in irregular grains with saw-toothed boundaries or in polygonal grains suggesting recrystallization by migration of the grain boundaries and rotation of subgrains (Passchier and Trouw, 1996).

The observed microstructural features indicate that the granitoids underwent heterogeneous solid state deformation at low to intermediate temperatures, lower than those during which recrystallization by eminently plastic processes can occur in feldspar (Passchier and Trouw, 1996), and in harmony with the recrystallization of quartz. This deformation occurred along restricted shear zones, as the largest part of the Wonotobo granite samples do not show major signs of deformation. The presence of flame perthites, deformational twinning, myrmekites and groundmasses with fine aggregates of irregular grains (possibly by nucleation of new grains), apart from indications of recrystallization by boundary migration processes between the grains of alkali feldspar, suggest temperatures in the order of 400°-500°C for the deformational episode.

Correlations

Granitoids with such macroscopic and microscopic features and similar ages were identified in Brazil in the Caxipacoré Suite, and outside the study area in the Pedra Pintada Suite.

4.a.5.Sipaliwini Leucogranite

This lithology, named as such on the basis of the proposal by Kroonenberg et al. (2016) occurs in the vicinity of the Sipaliwini village, in a body mapped as Granophyric Granite, unit 21, on the Geological Map of Suriname (Figs 5 and 6). The rock corresponds to a medium-grained, whitish equigranular leucogranite, with irregular clots of greenish minerals (epidote?). Petrographically the sample was classified as hololeucocratic albite syenite, consisting almost exclusively of mesoperthite and sodic plagioclase of albite composition. Table 6 shows the estimated composition of sample SB-07 which belongs to this unit.

Table 6. Classification and mineral content (%) of the Sipaliwini leucogranite (mineral abbreviations according to Siivola & Schmid 2007).

Sample	Classification	Ab	Afs	Ser	Ep	Aln	Ttn
SB-07	Protomylonitic albite syenite	55	40	2	tr	1	2

Ab = albite; Afs = mesoperthitic alkali feldspar; Ser = sericite; Ep = epidote; Aln = allanite; Ttn = titanite; tr = traces (< 1%)

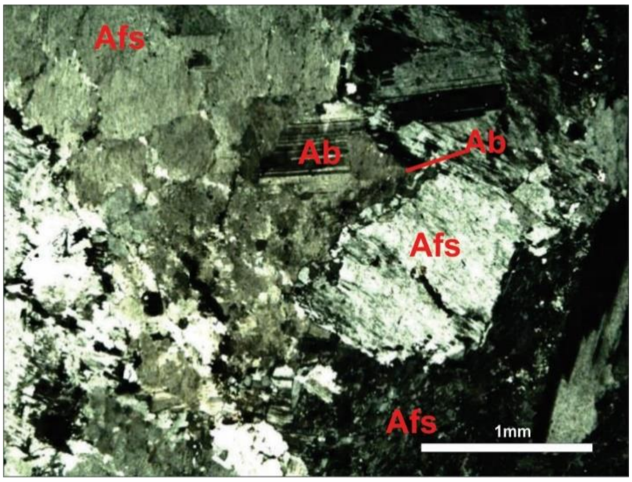


Figure 19. Microscopic aspect of the Sipaliwini Leucogranite. Albite syenite, formed by mesoperthitic feldspar (Afs), with undulatory extinction and partial disintegration, and albite (Ab), in the form of inclusions and also forming a fine rim between adjacent grains of mesoperthite (see arrow). Thin section SB-07, crossed polarizers. Scale = 1 mm.

The grain size of the albite syenite is fine to medium and the texture is protomylonitic, with preservation of granular parts. Mesoperthite is xenomorphic or idiomorphic, shows undulatory extinction, and is partly comminuted, with subgrains and new grains with saw-toothed boundaries and irregular shapes. Albite occurs either amidst mesoperthite crystals or as inclusions within its crystals, or also as fine crystals concentrated between adjacent crystals of mesoperthite (Fig. 19). It shows undulatory extinction and vanishing or interrupted polysynthetic twins, and borders of subgrains and new grains with saw-toothed boundaries and irregular shapes. Fine streaks of sericite, associated with leucoxene, epidote and allanite are the other mineral components present.

The microstructural features suggest, in the same way as proposed for the Wonotobo granitoids, an episode of solid-state deformation, at conditions of low to intermediate temperatures. Granitoids with these same field and petrographic characteristics and similar ages were identified in Brazil in the Aricamã and Saracura Suites that crop out outside the study area.

4.b. STRUCTURAL GEOLOGY

On the basis of the field information, petrography and microtectonics 4 groups of structural features (Table 7) were identified in the Sipaliwini River area

4.b.1. Polyphase folding at high temperatures in the Amotopo Gneiss

Solid-state deformation under high-grade metamorphic conditions, with more than one folding phase, were only recorded in the Amotopo Gneiss. In this unit the main foliation is parallel to a metamorphic banding which is highlighted by the presence of light-coloured bands of leucosomatic material, which records the migmatitic character of the aluminous gneisses of the Amotopo Gneiss in the study area. The metamorphic banding is parallel to a well-developed foliation oriented according to 220/70 (SB-11A); 245/85 (SB-12), 060/55 to 060/70 (SB-18); 072/70 (SB-32).

In the paragneisses an older Sn foliation is affected by closed and isoclinal folds (outcrop SB-23), related to a folding phase Dn+1 and associated with a strong axial plane foliation, Sn+1, probably the main planar feature in these gneisses. Open to closed folds (Dn+2), without developed axial plane foliation, were observed in various outcrops (SB-12; SB-23; SB-25; SB 26 and SB- 32) and are best developed in outcrop SB-12, where the axial surface and axis of those folds are oriented 030/87 and 140/52, respectively.

As mentioned under 4.1.1 there are also leucosome veins cutting the foliation and metamorphic banding at high angle (Fig. 7b), suggesting that a second event of migmatization and injection of post-kinematic veins was affecting the area.

4.b.2. Structural features of uncertain origin in Werekitto gneisses and granitoids – inheritance of emplacement of magmatic bodies or result of metamorphic processes

As described before (4.a.2) the granitoid rocks and gneisses at outcrop SB-24 show a centimetre- to decimetre-sized compositional banding granodioritic to tonalitic bands, with diffuse of sharp contacts, oriented 160/50. In this outcrop mafic enclaves occur, arranged in lenticular sometimes boudinaged bodies, with the geometry of L-S tectonites. Internally the compositional bands show preserved igneous textures and locally preferential orientation of tabular feldspars marks a foliation which is interpreted as magmatic (Fig. 9 c). The structural features observed at the outcrop SB-24 should be an inheritance of igneous processes related to the emplacement of magmatic bodies, possibly in a syn-kinematic environment. In another opinion about the outcrop, (spite the plutonic igneous character of the granitoids), Salomon Kroonenberg (this report) interpret the observed features, including the banding, and the orientation of the feldspar crystals as related to the metamorphism of supracrustal rocks.

4.b.3. Structural features developed in solid state at high temperatures in the Werekitto gneisses

In the gneisses and granitoids with well-developed foliation observed at the outcrops SB-22 and SB-28, the feldspars are partially recrystallized, with subgrains and new grains with rectilinear boundaries and polygonal shapes, suggesting subgrain rotation processes have been active (Passchier and Trouw, 1996), above 500°C (see paragraph 4.a.2). In spite of the record of solid-state deformation at higher temperatures, parts with preserved igneous textures can be found in the described thin sections, suggesting a situation of low strain and high temperature for the studied rocks.

Table 7 – Structural observations

Outcrop	Unit	Structure	Dip Direction	Dip	Observations
SB-11A	Amotopo Gneiss	Metamorphic banding	220	70	
SB-12	Amotopo Gneiss	Metamorphic banding	245	85	
SB-12	Amotopo Gneiss	Close Folds axial surface	030	87	
SB-12	Amotopo Gneiss	Axis of close folds	140	52	
SB-18	Amotopo Gneiss	Metamorphic banding	060	70	
SB-18	Amotopo Gneiss	Shear zone	330	80	
SB-23	Amotopo Gneiss	Shear zone $S_n//S_{n+1}$	050	85	Close to isoclinal folds with axial plane foliation (D_{n+1}) affecting metamorphic foliation (S_n)
SB-23	Amotopo Gneiss	Shear zone	080	70	Dextral shear zone
SB-25	Amotopo Gneiss	Metamorphic banding	350 040	60 60	Open folds without axial plane foliation (Dn+2) affect the metamorphic banding
SB-26	Amotopo Gneiss	Axial Surface Axis	352 052	78 72	Open folds without axial plane foliation (Dn+2
SB-32	Amotopo Gneiss	Metamorphic banding	088	60	Open folds without axial plane foliation (Dn+2) affect the metamorphic
SB-29	Werekitto Gneiss	Mylonitic Foliation	030	75	
SB-31	Werekitto Gneiss	Mylonitic foliation	030	75	
SB-24	Werekitto Gneiss	Compositional banding	160	50	Magmatic
SB-14	Wonotobo Granite	Mylonitic foliation	350	74	
SB-01	Dalbana Formation	Faults	000 (Main) 258	70 55	
SB-01	Dalbana Formation	S_0 vulcaniclastic	118	18	
SB-02	Dalbana Formation	Faults	348 (Main) 110 330	85 70 87	
SB-04	Dalbana Formation	Faults	218 346	84 68	
SB-09	Dalbana Formation	Faults	350 (Main) 210 060 320	87 60 78 75	

4.b.4. Mylonitic features developed at moderate to low temperatures

Along WSW-ENE oriented shear zones mylonitic features are superimposed upon the igneous textures of the Wonotobo granitoids (outcrops S B-13 and SB-14) and Werekitto gneisses (outcrops SB-29 and SB-31A) (Fig. 18 and 13). There are protomylonites and mylonites with microtectonic features as flame perthites, deformational twinning, myrmekites and groundmass of aggregates of irregular grains, recording a heterogeneous solid-state deformation at temperatures around 400°-500°C.

4.b.5. Faulting features

Important fault tectonics is recorded especially in the rocks of the Dalbana Formation. There are many faults, with main orientations about 000/70 (SB-01), 348/85 (SB-02) and 350/87 (SB- 09), i.e. with directions close to E-W and very steep dips to the north.

The deformation observed in the Dalbana Formation rocks along the Sipaliwini River does not deviate from the pattern substantiated in the volcanics of the Surumu Group in the northern Roraima State and continues through Guiana in the Karasabai region. It should be stated that the rocks of the Dalbana Formation have been described in the literature as greenschist-facies metavolcanics.

4.c. GEOLOGICAL/STRUCTURAL EVOLUTION

By comparison with similar terrains in Brazil and Guyana (see discussions under paragraph 2) and on the basis of the data collected here, and those available about the geology of Suriname, a few considerations on the evolutionary picture of the area can be given.

The oldest litostratigraphic unit in the Sipaliwini River area is the Amotopo Gneiss, which preserves a structural characteristic of polyphase folding under high-grade metamorphic conditions, which have not been observed in the other mapped units. Two metamorphic phases were recognised in these supracrustal series in various parts of the Cauarane-Coeroeni Belt and particularly in this area considered by Kroonenberg et al. (2016) as part of the Coeroeni Gneiss belt (see paragraph 2 and Kroonenberg, 1976). The first phase, of syn-kinematic character, is related to the closure of the Cauarane-Kanuku-Coeroeni basins in a collisional setting (Fraga et al. 2009), or in an intracontinental setting (Kroonenberg et al. 2016). The second, static, metamorphic phase is associated with an intense volcano-plutonism around 1.98 which affected the area. With reference to this volcano-plutonism, it is suggested, on the basis of well-studied areas in Brazil, that the Wonotobo Granite (1980.2 ± 5.8 Ma, 1973,6 ± 3.8 Ma) and the Dalbana Formation represent a high-K calc-alkaline magmatism, and that the Sipaliwini Granite has affinities with A-type granites. These high-K calc-alkaline and A-type magmatisms with ages around 1.98 Ga were interpreted by Fraga et al. (2009 a, b, c) as post-collisional and supposed by Kroonenberg et al. (2016) as related to the third phase of the Trans-Amazonian Cycle. The foliated granitoids and gneisses in the Werekitto Gneiss (1983.9 ± 5.4 Ma, 1993.9 ± 3.7 Ma) of similar ages as the Wonotobo and Sipaliwini granitoids were interpreted by Kroonenberg et al. (2016) as metamorphic products of a supracrustal sequence within the Coeroeni Gneiss Belt. In the meantime, the geochronological and petrographic data suggest that these rocks represent igneous bodies, which possibly can be related to the Suite Reislândia, which includes synkinematically emplaced granitoids, in a deeper environment, along shear zones, which would explain at least in part the structural framework identified in the Werekitto unit. However, this question of the significance of the structural characteristics of the Werekitto gneisses and foliated granitoids, needs to be investigated in more detail.

WNW-ESE oriented shear zones, developed at moderate to low temperatures, cut the Paleoproterozoic units of the area, as mylonitic streaks have been identified in the Wonotobo and Werekitto granitoids. These shear zones are probably related to the Nickerie/K'Mudku Episode which reactivated part of the older structures of the Guiana Shield around ~1.2 Ga.

Faults and fractures especially observed in the volcanic rocks are possibly related to the Mesozoic evolution of the Guiana Shield with the opening of the Central Atlantic, when dyke swarms and brecciated zones developed, and deep basins such as the Takutu Graben were formed in the central part of the shield.

5. MINERAL OCCURRENCES

In the project area several mineral indications are known to occur, such as for itabiritic iron at Tapajé Creek in the Paloemeu area and manganese in the Lada Soela area in the Upper Tapanahony River, both in the eastern part of the map area not visited during the joint expedition. These small indications figure on the Metallogenic Map of Suriname by Dahlberg (1976). A possible carbonatite in the Muri Alkaline Complex in the extreme western part of the area is capped by a laterite high in Nb and Sr, the soil below it shows a high radioactive anomaly and is rich in REE-phosphates (Fozzard, 1986; Gibbs & Barron, 1993).

Because of rumours of the occurrence of diamonds in the Sipaliwini area an expedition has been organized by GMD and the Sipaliwini Development Co. in May 1974. At six locations along the Linker and Rechter Sipaliwini river upstream from the airstrip, gravel has been sieved and panned to get a high concentration of heavy minerals. At two sites a diamond was found, of 4.7 and 27.3 mg respectively. Geikielite, gorceixite and goyazite, common fellow travellers of diamond were found in four pits. Cassiterite, a tin mineral, was found in two pits (Schönberger, 1974). Also these indications figure on the map by Dahlberg (1976). The present field trip did not encounter any mineralisations.

6. GEODIVERSITY

The concept of geodiversity is relatively recent and according to CPRM (2006), geodiversity is the study of the abiotic nature (physical environment), comprised by various geological environments, compositions, phenomena and processes; which originate the landscapes, rocks, minerals, fossils, soils, climate and other superficial deposits that provide the life development in Earth, as intrinsic value are the cultural, aesthetical, economical, scientific, educational and touristic development. According to Silva et al. (2008) the use of geodiversity studies towards territorial management could work as an index for suitability or restriction on land use, as well as provide a geological perspective of potential environmental impacts due to inappropriate land use.

Since 2006, systematically, many regional geodiversity studies have been realized by CPRM in Brazil (http://www.cprm.gov.br/publique/Gestao-Territorial/Geodiversidade-162), which aims to provide an interpretation of the scientific-geological knowledge of the Brazilian territory to various segments of the society, in order to contribute to the elaboration of major guidelines of land use planning, among other applications (Fig. 20).

The presented BRAZIL-SURINAME FRONTIER GEODIVERSITY MAP provides information for major regional policies aiming territorial planning, management and ordainment, based in the geology diversity influence (Environmental-geological domains and units). The characteristics of each environmental-geological unit are described in the map along with their adequacies/favourability and limitations against civil engineering projects, agriculture, sources of pollution, underground water; and also according to mineral potential and their geosites favourable to geotourism.

Additionally, there are presented thematic cartograms related to the subjects: a) Infrastructure and Citizenship Territory; b) Relief Patterns; c) Special Protected/ Restricted Areas; d) Hydrological Favourability. The objective of presenting these cartograms is to provide a spatial visualization and acknowledgement of natural or legal potential and restrictions to development, above all related to the economic activities in the frontier region.

6.a. Metodology

The Brazil-Suriname frontier region geodiversity survey was based on the reclassification of the lithologic units presented in the Mineral Resources and Geology Map of the Brazil-Suriname Frontier Region (present project). The result obtained it is not a geological nor tectonic map, but a new product denominated BRAZIL – SURINAME FRONTIER REGION GEODIVERSITY MAP, in which was inserted environment related information, based in the available information interpreted for the area, such as the Amapá State (Jorge João et al., 2011) and Pará State (Jorge João et.al, 2013) Geodiversity Maps.

The criteria adopted were the same as in the surveys previously done in Brazilian territory, the lithologic units were grouped in stratigraphic sets (lithologic or lithostratigraphic units) of similar response against land use, which were denominated as environmental-geological units and domains. The environmental-geological domains and its subdivisions were analysed regarding the environmental implications of their physical-chemical properties, geometry and genesis of the rock bodies which are applicable for territorial planning, and also the information of the geomorphological relief pattern compartmentalization (Ramos et al., 2010; Ramos et al. 2005; Theodorovicz, 2005). The main objective of such compartmentalization is to reach for a wide range of users interested to know the environmental implications arising from the interaction of land use and the geologic basement.

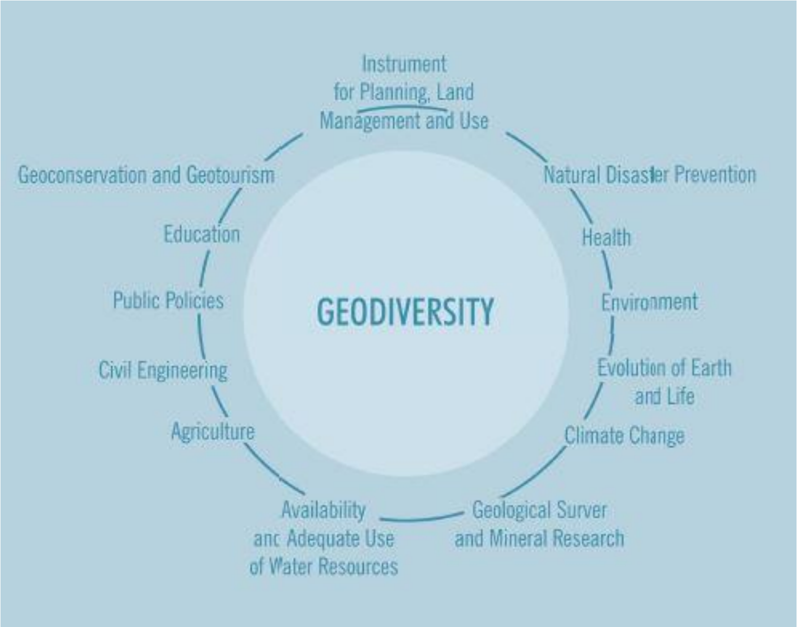


Figure 20. Multiple applications of the geodiversity knowledge. Source: Silva et al. (2008).

The figure 21 contains a synthesis of the methodology stages used in the elaboration of the geodiversity map. In some cases stratigraphic units of different ages were grouped in the same domain, as long as they match a set of criteria such as: tectonic setting, crustal level, rock class (igneous, sedimentary or metamorphic), cohesion degree, texture, composition, type and grade of deformation, relevance of the rock body, type of metamorphism, geomorphological expression or special lithotypes.

In the Brazil-Suriname Frontier Geodiversity Map, each environmental-geological unit has a graphic representation defined by a composition of colour and numeric identification (ex: 1- Alluvial plains environment). The same colour tone variations were used to represent units of the same environmental-geological domain. Each environmental geological unit, subdivided according to its relief pattern, is represented in the map by letters (ex: a-Fluvial or Fluvial-Lacustrine Plains – Flood plains, lowlands and basins).

6.b. Geodiversity Aspects

The Brazilian portion of the study area has restricted usage due to the presence of indigenous protected areas (*Área Indígena do Tumucumaque*) and of conservation units (*Área Ecológica Grão-Pará* and *Parque Nacional do Tumucumaque*). In Suriname, part of the region is occupied by the *Sipaliwini* Ecological Area (*Área Ecológica Sipaliwini)*.

The Brazil-Suriname frontier region is characterized by equatorial rainforest climate, which is under the intense influence of the Intertropical Convergence Zone (ITCZ) and by the Equatorial Continental Mass (cE);

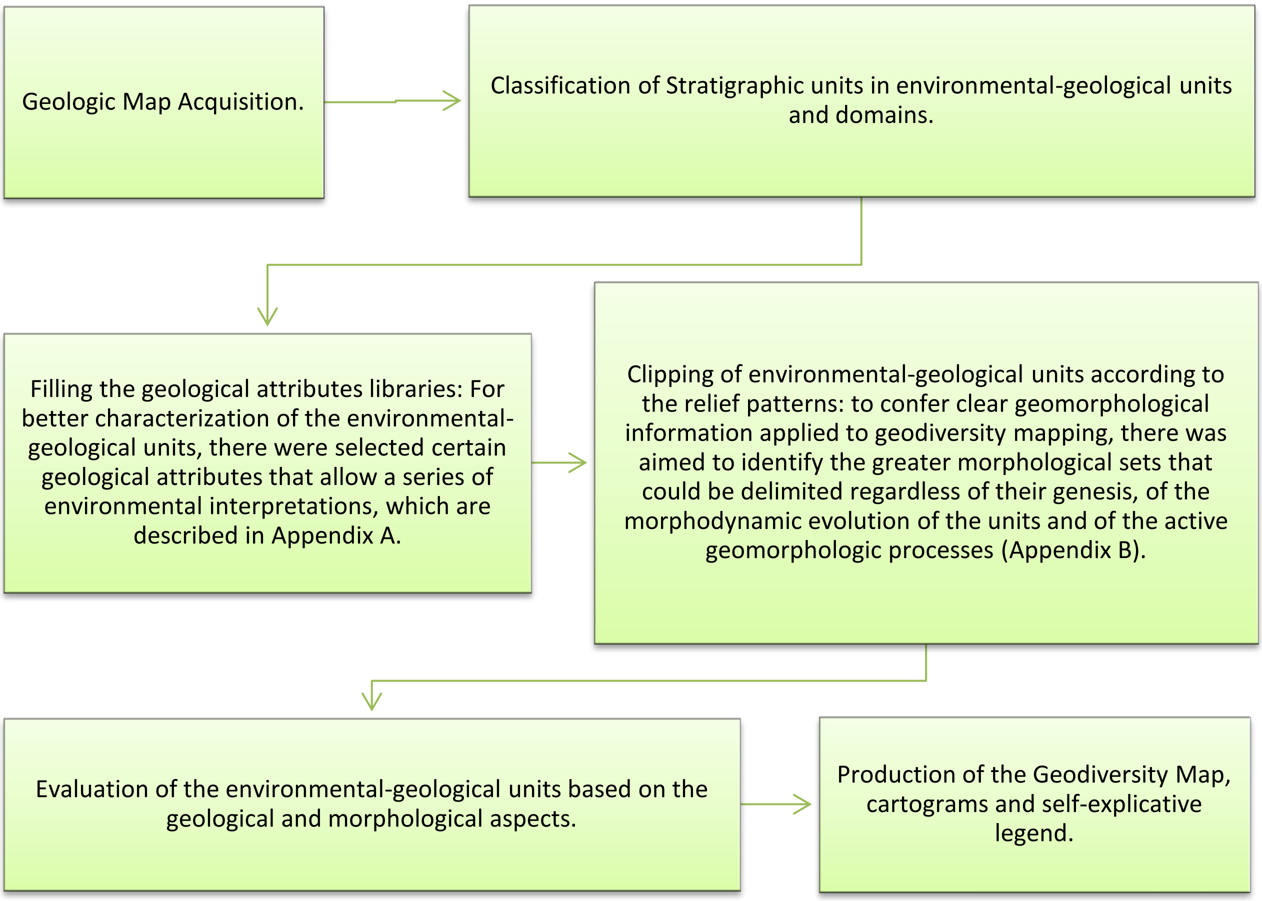


Figure 21. Stages of the methodology used in the production of the Brazil Suriname Frontier Geodiversity Map. The satellite imagery from GEOCOVER and products extracted from the TOPODATA (2011) digital elevation model, such as shaded relief, contour lines and declivity were used as complementary material.

the annual rainfall of the north and northeast region reaches 2,200 to 2,500mm/year (Nimer, 1989); the region is mostly covered by the amazon biome's dense equatorial forest. There is, however, an expressive region covered by Cerrado vegetation, along the Suriname borderline (IBGE, 2014), covering a vast territory of the high Paru do Oeste River and Cuminá River valleys.

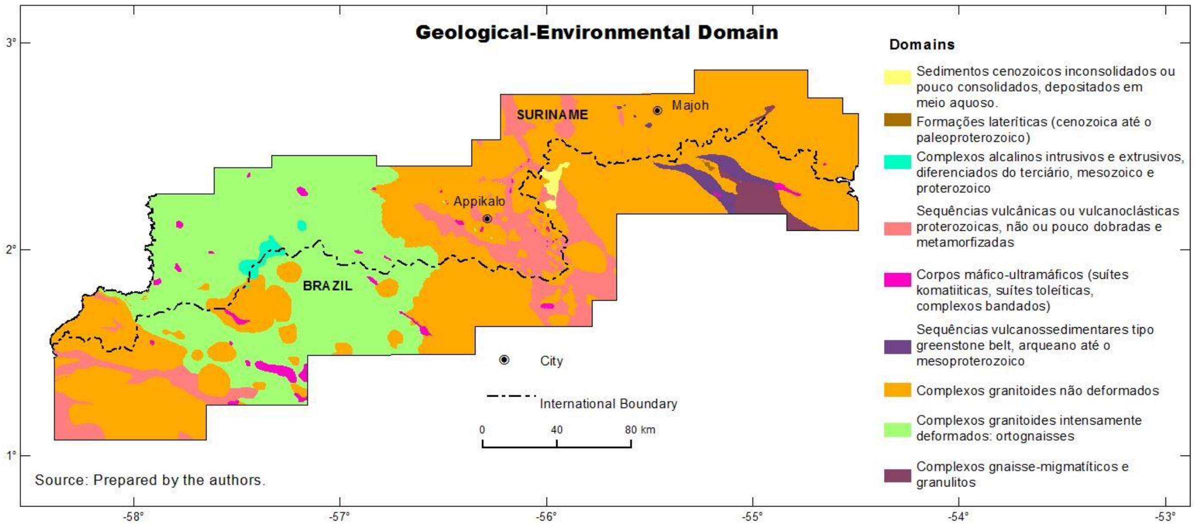
The general relief pattern characterization reflects vast planed terrains, positioned at moderate elevations, between 250 and 400 meters. Mostly of these terrains are in sets of Degraded Planation Surfaces (R3a2) or undone in Broad Gentle Hills (R4a1) or Low Hills (R4a2). Those terrains are set on an igneous-metamorphic basement, predominantely of Paleoproterozoic age and have a predominance of granitoids rocks. On these planation surfaces, a wide range of residual relief patterns (from isolated hills to buttes and small ridges) (R3b) sporadically arise, associated to more erosion resistant lithologies. Residual plateaus stand up in the landscape as the highest elevations along the frontier, the summits reach from 450 to 900 meters high. There is an extensive set of Hills and Low Sierras (R4b) and Mountainous regions (R4c), composed of Paleoproterozoic undeformed plutonic rocks. These set of relief patterns belongs to two sculpted geomorphological units: the North Amazon (*Norte da Amazônia*) Planation Surface and the North Amazon (*Norte da Amazônia*) Residual Plateaus (Costa & Melo, 1975; Dantas & Teixeira, 2013).

The geologic substratum of the Brazil Suriname frontier region presents a diversified lithological composition. The geodiversity of these substratum results in occurrences of diamond and cassiterite scattered over the project area. The mineral resources represent a natural heritage, or a non-renewable resource of the study area geodiversity, which may lead to sustainable development and as a consequence to the improvement of citizen well-being for the communities of the region.

Considering the mineral occurrences of the area and on the geological context analysis, it is possible that areas potentially favourable to economically interesting mineral deposits can still be found. However, in the study area, the mineral development can be restrained or even prevented by the existence of restrictive or impeditive areas, which may create a land use conflict.

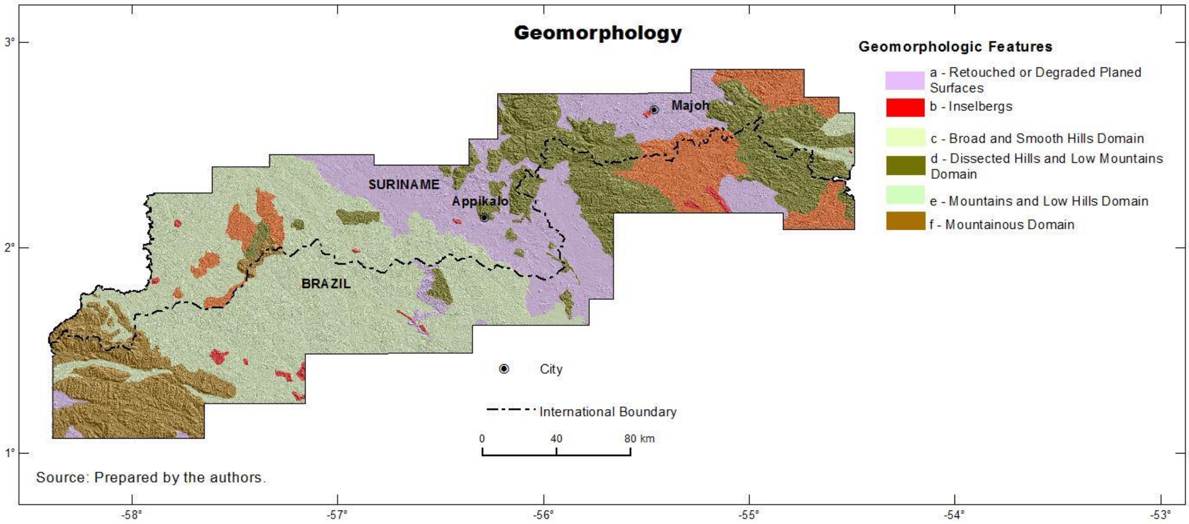
From the geoturistic perspective, the narrative from Kroonemberg, S. B., about the study area geodiversity, deserves to be highlighted; it registers a visitation to the Werehpai Cavern, located approximately 40 Km east of Kwamalasamutu and nearly 4 Km from the Sipawilini River. This cavern is considered a monument with great geodiversity and contains about 300 carvings and petroglyphs. Archaeological excavations in the cavern floor allowed to find pottery dated to be 5000 to 4200 years old. This site deserves to be classified as Heritage of Humanity; it is regularly visited as a geoturistic attraction and is in urgent need for protection policies. Aside from the Werehpai Cavern, there are numerous other sites containing petroglyphs in the Sipaliwini area. Another aspect of geodiversity is the presence of striation, scratches and polishing in a great variety of narrow forms both shallow and deep.

Towards the information presented, the frontier region territory was divided in 09 domains and 10 environmental-geological units, subdivided according to the main relief pattern (Figs. 22 and 23).



Source: Prepared by the authors.

Figure 22. Environmental-geological domains in the Brazil-Suriname frontier region.



Source: Prepared by the authors.

Figure 22. Relief Pattern Compartments in the Brazil-Suriname frontier region.

7. CONCLUSIONS AND RECOMMENDATIONS

The low level of geological knowledge of the area mostly results from the infrastructural deficiency, which requires more expensive logistic operations for field works; also there are no high resolution aerogeophysical surveys for the Suriname side of the region. However the integration of geology along the Brazil-Suriname frontier region was extremely productive and allowed and update on the geological mapping of the northern Brazil and southern Suriname, as well as an enriching contact between researchers from Suriname and from the Geological Survey of Brazil.

The execution of field works in the Sipawilini region, even though brief in duration, allowed an excellent observation of the main lithological units outcrops near the Brazil-Suriname frontier. With the support of the field works of the binational team and the laboratorial analysis executed by CPRM, it was possible to identify and fix some discrepancies in the Geological Map of Suriname (*Mapa Geológico do Suriname*, GMD, 1977) and, therefore, in the spatial distribution of the lithostratigraphic units that enter the Brazilian territory. In Brazil the integration of available data and geophysical imagery interpretation allowed as well an improvement in the geologic cartography of these remote areas of the national territory. Regarding the geodiversity, the study area comprises one of the most remote regions of the planet, as well as one of the most well conserved and protected areas of the Amazon Forest in its climax stage. The region is a true hotspot of world biodiversity considering tropical forests. In a general manner, the areas are difficult to access and there is low knowledge of the physical environment, which does not allow clearly pointing out the adequacies and limitations regarding agriculture, engineering projects, hydric resources and pollution sources.

Finally, we acknowledge the importance of the executed project to the advance of the geodiversity and of the geological knowledge of the central-eastern portion of the Guiana Shield and we recommend that new cooperation projects are stablished between CPRM and the institutions from Suriname, which may further improve the information details.

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Appendage

Appendage A – **Attribute library for geodiversity**

GEODIVERSITY THEME DATABASE DICTIONARY

Below is the description of the attribute fields which are in the shapefile of the Geological-Environmental Unit.

SIGLA_UNID – UNIT ABBREVIATION: the unique lithostratigraphic unit identity. It is the primary key field which links the attribute table to the map polygons.

NOME_UNIDA – UNIT NAME: formal or informal denomination of the lithostratigraphic unit.

HIERARQUIA: hierarchy to which the lithostratigraphic unit belongs.

LITOTIPO1: lithotypes that represent more than 10% of the lithostratigraphic unit or which have undetermined representativeness.

LITOTIPO2: lithotypes that represent less than 10% of the lithostratigraphic unit.

CLASSE_ROC – ROCK CLASS: class of the lithotypes that represent more than 10% of the lithostratigraphic unit or which have undetermined representativeness.

COD_DOM – ENVIRONMENTAL-GEOLOGICAL DOMAIN CODE: abbreviation of the environmental-geological domain.

DOM_GEO – ENVIRONMENTAL-GEOLOGICAL DOMAIN DESCRIPTION: – Reclassification of the geological unit accord to the larger geological domains.

COD_UNIGEO – ENVIRONMENTAL-GEOLOGICAL UNIT CODE: abbreviation of the environmental-geological unit.

UNIGEO – ENVIRONMENTAL-GEOLOGICAL UNIT DESCRIPTION: the environmental-geological units were grouped according to similar characteristics regarding environmental response, from the subdivision of the environmental-geological domains.

DEF_TEC – TECTONIC DEFORMATION / FOLDING: Deformation related to the internal dynamics of the planet. The interpretation is based on tectonic and lithological ambient and on the structurally controlled relief and drainage interpretation.

Library

Absent

Not folded

Slightly to moderately folded

Intensely folded

Moderately to intensely folded

Slightly to intensely folded

CIS_FRAT – TECTONIC FRACTURING (joints and faults)/ CISALLING : Related to the planet internal dynamics. The interpretation is based on tectonic and lithological ambience and on the structurally controlled relief and drainage patterns interpretation.

Library

Not fractured

Slightly to moderately fractured (regularly distributed).

Slightly to moderately fractured (irregularly distributed).

Moderately to intensely fractured (regularly distributed).

Moderately to intensely fractured (irregularly distributed).

Slightly to intensely fractured (regularly distributed).

Slightly to intensely fractured (irregularly distributed).

Intensely fractured (regularly distributed).

Intensely fractured (irregularly distributed).

TIPO_DEF – TYPE OF DEFORMATION

Library

Not applicable

Brittle deformation

Ductile / brittle deformation

Brittle/ductile deformation

Ductile deformation

COMP_REOL – RHEOLOGICAL CHARACTERISTICS (response to mechanical stresses). According to Oliveira & Brito (1998), the rocks can present the following rheological characteristics (response to mechanical stresses):

Library

Isotropic – Case of granites with homogeneous granulation and texture.

Anisotropic – Case of units composed by various lithologies and/ or heterogeneous deformations.

ASPECTO – TEXTURAL AND STRUCTURAL ASPECTS

Library

Not structured

Stratified/Biogenic

Massive/Vesicular

Massive/Layered

Massive/Laminated

Massive

Layered

Layered/Phyllitic

Layered/Schistose

Schistose / Massive

Phyllitic / Schistose

Magmatic Layered

Gneissic

Banded

Concretionary

Concretionary / Lumpy

Biogenic

Dissolution Features

Collapse Features

INTEMP_F – RESISTANCE TO PHYSICAL WEATHERING: inferred from analysis of the mineral composition of the rock or rocks that compose the geologic unit.

Library

- If the geological unit comprises only one lithotype or if it is a plutonic complex of various lithotypes:

Low

Moderate to High

- If the geological domain comprises various lithologies:

Low to moderate vertically

Low to high vertically

Low to high horizontally and vertically

INTEMP_Q – RESISTANCE TO CHEMICAL WEATHERIN: inferred from analysis of the mineral composition of the rock or rocks that compose the geologic unit.

Library

- If only one lithotype supports the geological unit or if it is a plutonic complex of various lithotypes:

Low

Moderate to high

Not applicable

- If the geological domain comprises various lithologies:

Low to moderate vertically

Low to high vertically

Low to high horizontally and vertically

GR_COER – COHERENCE DEGREE

The rock resistance to cutting and penetration; classification based on the Weathering Classes and Uniaxial Compression Resistance Chart (Vaz, 1996).

Library

- If the geological unit comprises only one lithotype or if it is a plutonic complex of various lithotypes:

Very Soft

Soft

Average

Hard

From very soft to hard

- If the geological domain comprises various lithologies:

Variable horizontally

Variable vertically

Variable horizontally and vertically

Not applicable

TEXTURE – CHARACTERISTICS OF THE WEATHERING CAPE (residual soil): inferred from the analysis of the mineral composition of the rocks.

Library

Mainly sandy

Mainly clayey

Mainly clayey-silty

Mainly clayey-silty-sandy

Variable from sandy to clayey-silty

Mainly silty

Not applicable

PORO_PRI – PRIMARY POROSITY: the volume of voids in relation to the total volume of the rock (based in Diverse Rock Materials Total Porosity Table – Chapter 3).

Library

- If the geological unit is comprises only one lithotype:

Low – 0 a 15%

Moderate – 15 a 30%

High – >30%

- If the geological unit is comprises various lithologies:

Variable – 0 a >30%

LITO_HIDRO – Lithologic-hydrogeologic unit characteristics

Library

Granular

Fissure

Granular/Fissure

Karstic

Not applicable

COD_REL – RELIEF COMPARTMENT CODE: abbreviation of the major relief compartments division. See Annex B.

RELEVO – MAJOR RELIEF COMPARTIMENT: major relief compartments description. See Annex B.

DECLIVIDAD – DECLIVITY: declivity intervals of relief compartments.

AMPL_TOPO – AMPLITUDE: topographic amplitudes. See Annex B.

GEO_REL – ENVIRONMENTAL-GEOLOGIC UNIT CODE + RELIEF CODE: abbreviation of the new environmental-geological unit, classified from the geological unit and relief pattern. It is the index attribute field that links the table to the map polygons and the database. The classification comprises the fields COD_UNIGEO + COD_REL.

Appendage B – **Simplified methodology for classifying the relief patterns**

RELIEF ATTRIBUTES

Mapping relief patterns is essentially a morphologic terrain analysis based on imagery interpretation from multiple remote sensors.

With this approach, the relief patterns were selected considering essentially:

- Morphological and morphometric parameters that could be evaluated through technological instrumentation available in the digital *kits* (Landsat Geocover Imagery and Digital Terrain Model and Hillshade Relief (SRTM); hypsometry classes map; slope classes map).
- Reinterpretation of existent information available in geomorphologic maps produced by various institutions, especially the maps produced under the scope of RadamBrasil Project, in scale 1:1000,000,000.
- Execution of a series of field cross sections, in order to calibrate the executed classifications.

To each of the relief attributes, with each respective library, there is an explanation legend (– Relief Patterns Library), that groups general geomorphological and morphometric characteristics, as well as elementary and simplified information about formation processes and vulnerability toward geomorphological processes (weathering, erosion and depositional).

Evidentially, considering the vastness and huge geodiversity of the borderline territory of Brazil/ Suriname, as well as the diversified bioclimatic landscape set and geological-geomorphological conditioners; the topographic amplitude and slope information are to be considered standard values, not to be applied indiscriminately in all regions. Adjustment suggestions and improvements on Chart 1 and Appendix II are not discarded and are welcome.

Chart 1 – Attributes and relief patterns library

Symbol	Relief Pattern	Declivity (degrees)	Topographic Amplitude (m)
R1a	Fluvial or Fluvial-Lacustrine Plains	0 a 3	zero
R1b1	Fluvial Terraces	0 a 3	2 a 20
R1b2	Marine Terraces	0 a 3	2 a 20
R1b3	Lagoon Terraces	0 a 3	2 a 20
R1c1	Colluvium Covered Hillslopes	5 a 45	Variable
R1c2	Alluvial Fans	0 a 3	2 a 20
R1d	Fluvial-Marine Plains	0 (flat)	zero
R1e	Coastal Plains	0 a 5	2 a 20
R1f1	Dune Fields	3 a 30	2 a 40
R1f2	Loess Fields	0 a 5	2 a 20
R1g	Reefs	0	zero
R2a1	Tablelands	0 a 3	20 a 50
R2a2	Dissected Tablelands	0 a 3	20 a 50
R2b1	Short Plateaus	0 a 5	0 a 20
R2b2	Short Dissected Plateaus	0 a 5	20 a 50
R2b3	Plateaus	0 a 5	20 a 50
R2c	Mesas and Plateaus	0 a 5	0 a 20
R3a1	Preserved Planation Surfaces	0 a 5	0 a 10
R3a2	Degraded Planation Surfaces	0 a 5	10 a 30
R3b	Buttes	25 a 60	50 a 500
R4a1	Broad Gentle Hills Domain	3 a 10	20 a 50
R4a2	Dissected Hills and Low Hills	5 a 20	30 a 80
R4a3	Domes in Elevated Structures	3 a 10	50 a 200
R4b	Hills and Low Sierras Domain	15 a 35	80 a 200
R4c	Mountainous Domain	25 a 60	300 a 2000
R4d	Sierra Escarpments	25 a 60	300 a 2000
R4e	Fault Blocks and Erosive Ridges	10 a 45	50 a 200
R4f	Entrenched Valleys	10 a 45	100 a 300

Source: DANTAS, M.E. Biblioteca de relevo do território brasileiro. In: BANDEIRA, I.C.N. (Org.). **Geodiversidade do estado do Maranhão**. Teresina: CPRM, 2013. p. 133-140.

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