DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2016/66

Suriname – Brazil. Fieldwork November 2016

Establishing a chronology of burial, uplift and denudation of the South American Equatorial Atlantic Margin (SAEAM Uplift)

Peter Japsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF ENERGY,UTILITIES AND CLIMATE

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Released 01.10.2020

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Contents

1. Summary

Three weeks of fieldwork was carried out in Suriname and Brazil in November 2016 as part of the project “Establishing a chronology of burial, uplift and denudation of the South American Equatorial Atlantic Margin” (SAEAM Uplift) which is carried out under the umbrella of the BRGM-Total Source-to-Sink programme.

The overall aim was to sample rocks and to get an impression of the geology, landscapes and structural relations across the Guiana Shield. For this purpose, the route chosen provided a regional north to south cross section over the Guyana Shield and the northern limit of the Brazilian Shield of almost 1200 km. In particular, to sample rocks for apatite fission-track analysis (AFTA) and vitrinite reflectance (VR) as reported here.

Along the northern margin of the Guiana Shield, in Suriname, the coastal plain with bauxite deposits and basement terrains were visited. In particular, the samples were collected from the Palaeoproterozoic Tafelberg Formation (Roraima Supergroup) and the underlying basement, 250 km from the coast. In total, 19 samples of Palaeoproterozoic rocks were collected for AFTA.

From the southern margin of the Guiana Shield to the northern margin of the Brazilian Shield, samples were collected along a 450 km long transect north and south of the Amazon. The Paleozoic strata of Amazon Basin crop out along these margins and a total of 26 samples of Late Ordovician to Pennsylvanian age were collected for AFTA and VR. Five samples of the underlying Precambrian basement as well as 8 samples of the overlying Cretaceous Alter do Chão Formation were also collected.

The samples from the post-Palaeozoic Monte Alegre Dome are of particular interest because AFTA data from these samples may provide insight into younger thermos-tectonic events than those from the surrounding Amazon Basin.

Georeferenced databases (kmz and ArcGis format) with sample details and photos are available.

2. Introduction

The project "Establishing a chronology of burial, uplift and denudation of the South American Equatorial Atlantic Margin" (SAEAM Uplift) is aimed at understanding the regional history of burial, uplift and denudation of the South American Equatorial Atlantic Margin to provide a framework for investigating the hydrocarbon prospectivity of the offshore region. The study combines apatite fission-track analysis (AFTA) and vitrinite reflectance (VR) data from samples of outcrops and drillcores, sonic velocity data from drill holes and stratigraphic landscape analysis (mapping of peneplains) – all constrained by the available geological information (Figure 2-1). The study will thus continue the approach undertaken in previous uplift studies by combining the thermal history from AFTA data with the denudation history from stratigraphic landscape analysis to provide magnitudes and timing of vertical movements (Japsen *et al.* 2012b; Japsen *et al.* 2012a; Green *et al.* 2013). In this way the study can provide a framework for anticipating possible effects from uplift on the petroleum system along the margin.

The area investigated by the study covers onshore and offshore areas along the equatorial, Atlantic margin of South America reaching from Suriname, French Guyana to the Brazilian state of Para (Figure 2-2). The study will thus be focussed in the area between 46 and 57ºW. The Guiana Shield and the adjacent basins onshore and offshore are the primary study area because it constitutes a major and coherent geological entity within the study area.

The study is part of the Source-to-Sink program funded by Total and BRGM (Geological Survey of France), and the outline of the study is defined by a contract between BRGM and GEUS. Furthermore, GEUS has signed subcontracts with Geotrack International (Paul F. Green, Australia) and with Geovisiona AB (Johan Bonow, Sweden) about parts of the investigations foreseen in the BRGM-GEUS contract. Geotrack will carry out low-temperature thermochronology based on AFTA and VR and Geovisiona will carry out stratigraphic landscape analysis.

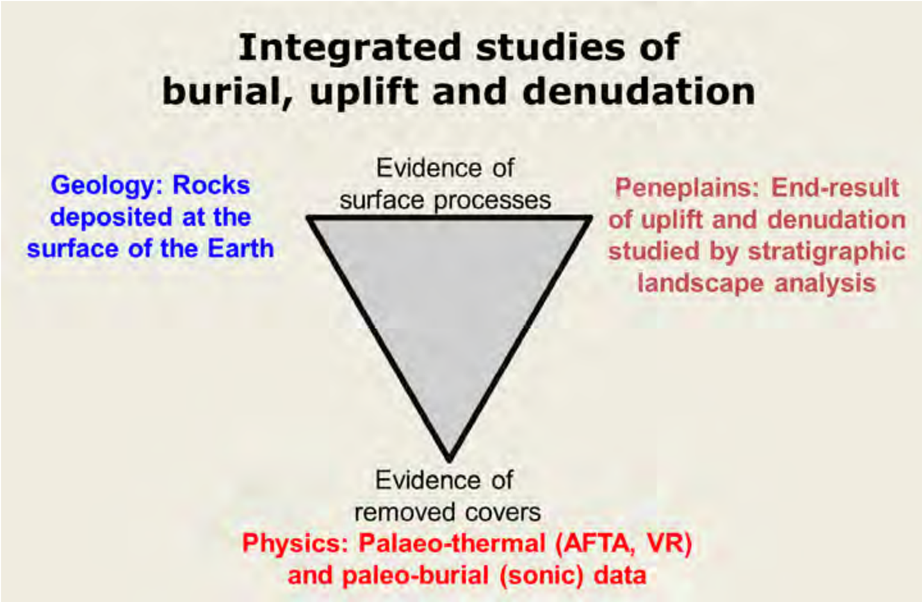


Figure 2-1. Sketch illustrating the components of integrated studies of burial, uplift and exhumation.

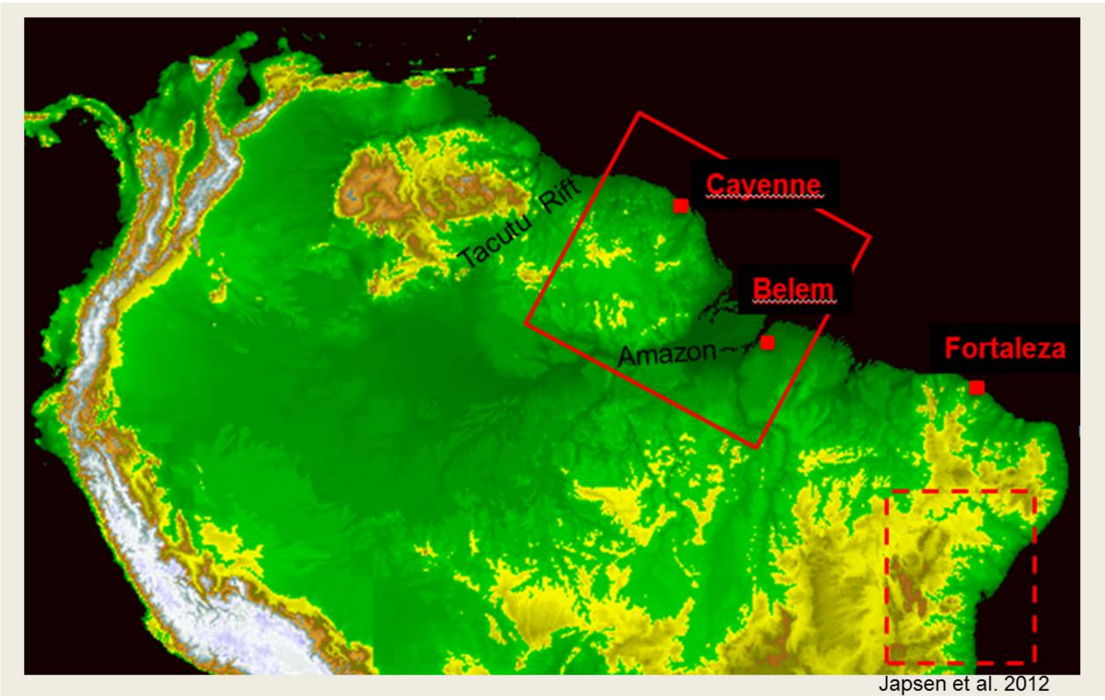


Figure 2-2. Outline of the study area, onshore and offshore along the equatorial, Atlantic margin of South America reaching from Surinam, French Guyana to the Brazilian state of Para. The extent of the area investigated by Japsen *et al.* (2012b) is indicated for reference.

3. Outline of the fieldwork

The fieldwork was discussed and planned during meetings in France in 2016; in particular at a meeting in Paris in September with participation of Jean-Yves Roig and Renauld Coueffe (BRGM), Johan Bonow (Geovisiona), Massimo dall'Asta (Total) and Peter Japsen (GEUS). At this meeting it was decided to focus fieldwork during 3 weeks in November on Suriname and Brazil. To avoid logistical complications, French Guiana was not included in this campaign. Jean-Yves Roig was in charge for solving the final logistic challenges. Our day-to-day program is summarized in Table 3-1.

Many different aspects were in focus during the fieldwork, but the overall aim was to get an overall impression of the geology, landscapes and structural relations across the Guiana Shield. For this purpose, the route chosen provided a regional north to south cross section across the Guyana Shield and the northern limit of the Brazilian Shield of almost 1200 km (Figures 3-1, 3-2).

Four persons took part in entire field campaign:

- Jean-Yves Roig (structural geologist) and Renaud Coueffe (sedimentologist), both BRGM, had their main focus on the sedimentary sequences and the structural relations as part of the source-to-sink study of BRGM. The results of these investigations will be presented in report BRGM/RP-66566-FR
- Johan Bonow (geomorphologist, Geovisiona) focussed on the landscapes and their relation to exposed strata and these results will be presented in Geovisiona Report 2016/2.
- Peter Japsen (GEUS) was specifically focussed on sampling rocks for AFTA and VR as reported here.

The latter two efforts are part at the SAEAM uplift study.

Several other persons assisted our work in various ways and were crucial for the success of the field campaign:

- Salomon B. Kroonenberg, professor emeritus, Delft University of Technology; invited to take part in the fieldwork in Suriname.
- Theo E. Wong, professor, Anton de Kom University, Suriname.
- Ernesto Goldfarb Figueira, professor, UFPR - Universidade Federal do Paraná (Curitiba), guide and practical coordinator of our work in Brazil.
- Nelsi Sadeck, retired engineer, assisted us during the fieldwork in the Monte Alegre area.

Some of the main aspects covered by the fieldwork were the following:

Coastal plain and Precambrian terrain, Suriname:

- Bauxite deposits; in Paleogene sediments and Precambrian rocks
- Coastal plain with Holocene to Pliocene deposits
- Outcrops of fresh basement
- Rosebel goldmine where IamGold generously provided us access to drillcore samples

- Discussions with staff at the Geological Survey of Suriname (Geologishe mijnbouwkundige dienst Suriname, GMD)

Tafelberg, Suriname

- Paleoproterozoic sandstone of the Roraima Group resting on Paleoproterozoic basement. Sampling for AFTA over an elevation difference of ~700 m between the summit and the base of the mountain. Landscape observations.

North-south transect across the Amazon, Brazil (450 km)

- Precambrian, Paleozoic and Cretaceous rocks at outcrop north and south of the Amazon; north of Monte Alegre and along Rio Tapajós, respectively. Relation between landscape and lithology.

Monte Alegre Dome

- An anticlinal, post-Paleozoic structure (Figueira 2011; Figueira *et al.* 2012).

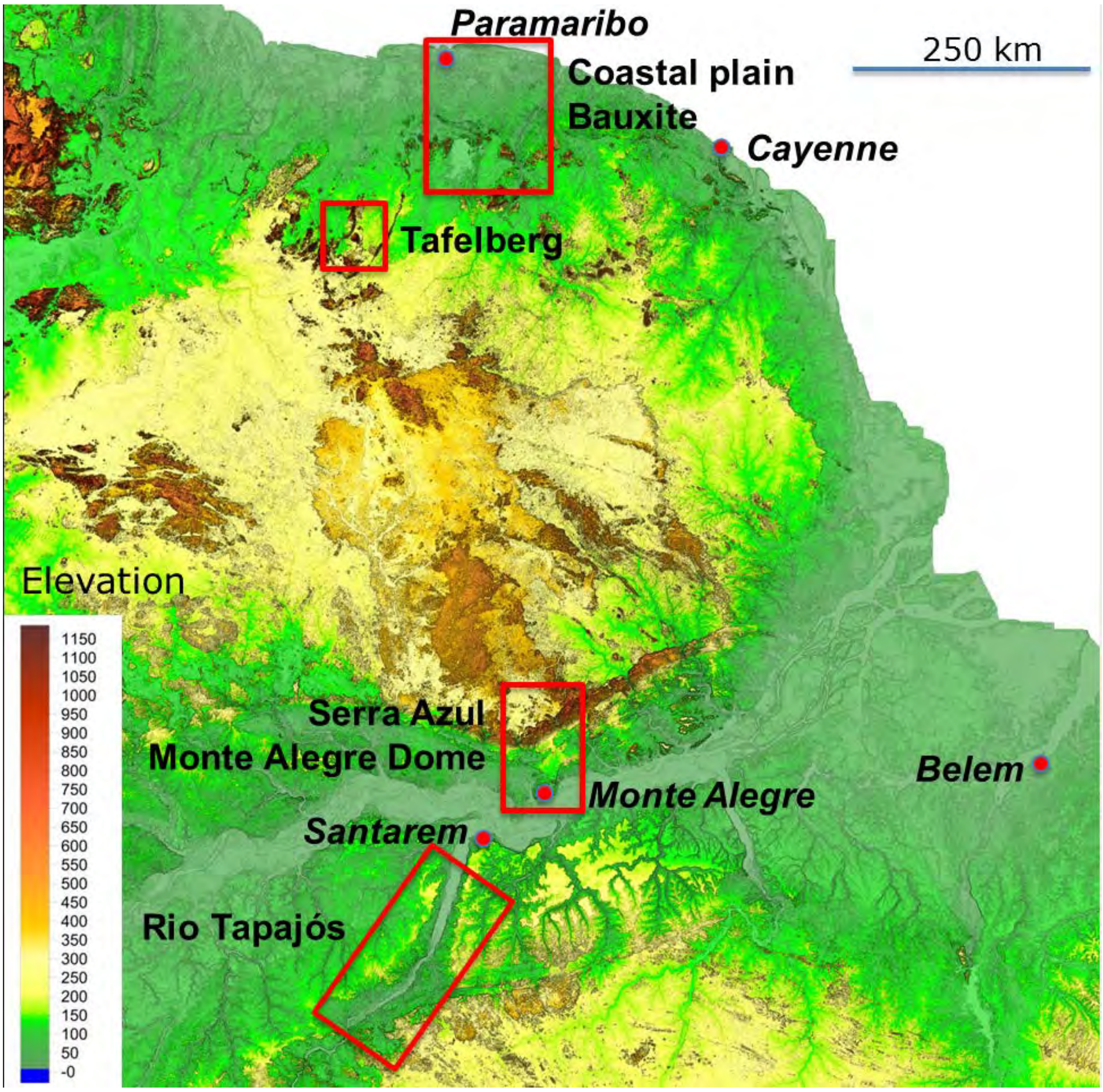


Figure 3-1. Elevation of the study area with indication of the areas visited during the field-work.

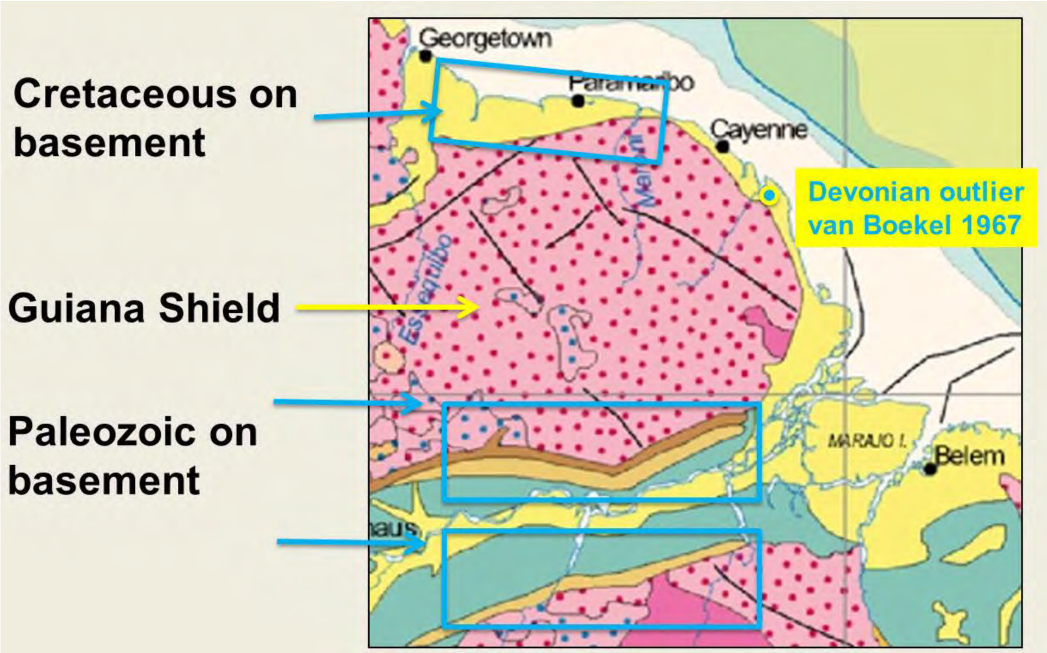


Figure 3-2. Geological outline of the study area. Cretaceous sediment rest on Paleoproterozoic basement along the Atlantic margin. Along the Amazon, Paleozoic strata (brown colors) rest on basement whereas Cretaceous sandstone (green color) overlie the Palaeozoic strata along the Amazon River. Note the location of the marine Devonian deposits in northernmost Brazil (Amapá), near the border to French Guiana (Sommer & van Boekel 1967; van Boekel 1967). Marine Devonian strata are also present in the offshore Maranhão Basin, NE of Belem (Soares *et al.* 2007).

Table 3-1: Day-to-day program and main activities.

Day	Date	Flight	Focus	Night	Accomodation	Team
Thursday	3-11-16	Bonow/ Japsen: ARN/CPH-CDG CDG-PBM (11:20-16:35)	**Flying**	Paramaribo	Eco Resort	
Friday	4-11-16		Talks with Theo Wong and the GMD	Paramaribo	Eco Resort	+SBK
Saturday	5-11-16		Coastal plane, granite quarry, Brokopondo	Paramaribo	Eco Resort	+SBK, ThEW
Sunday	6-11-16		Mungo, bauxite	Paramaribo	Eco Resort	+SBK, ThEW
Monday	7-11-16	Zorg en Hoop airport - Rudy Kappel airstrip	Tafelberg	Paramaribo	Eco Resort	+SBK, GMD
Tuesday	8-11-16		Brownberg and surroundings	Brownsberg	Berg en Dal Resort	+SBK, GMD
Wednesday	9-11-16		Rosebel goldmine	Brownsberg	Berg en Dal Resort	+SBK, GMD
Thursday	10-11-16		Atjoni/Pokigron, Suriname River	Brownsberg	Berg en Dal Resort	+GMD
Friday	11-11-16		Sample packing and shipping	Paramaribo	Eco Resort	
Saturday	12-11-16		Practical arrangements Talks with Theo Wong	Paramaribo	Eco Resort	+ThEW
Sunday	13-11-16	PBM-BEL (09:00-11:55) BEL-STM (15:25-16:50)	**Flying**	Santarem	Sandis Mirante	+EG
Monday	14-11-16		Driving to boat, Itaituba	Boat	Boat (name?)	+EG
Tuesday	15-11-16		Rio Tapajós, south of Itaituba	Boat	Boat	+EG
Wednesday	16-11-16		Rio Tapajós, near Itaituba	Boat	Boat	+EG
Thursday	17-11-16		Rio Tapajós, north of Itaituba	Boat	Boat	+EG
Friday	18-11-16		Ferry, car to Monte Alegre	Monte Alegre	Hotel Shekinah	+EG
Saturday	19-11-16		Monte Alegre Dome	Monte Alegre	Hotel Shekinah	+EG, Nelsie
Sunday	20-11-16		Serra Azul, N-S transect	Monte Alegre	Hotel Shekinah	+EG, Nelsie
Monday	21-11-16		Serra Azul, N-S transect	Monte Alegre	Hotel Shekinah	+EG, Nelsie
Tuesday	22-11-16		Monte Alegre Dome, half day Transfer to Santarem	Santarem	Sandis Mirante	+EG, Nelsie
Wednesday	23-11-16	STM-BEL (21:00-22:20)	Practical arrangements, Santarem Shipping samples to Curitiba (BR)	Belem	Ibis Belem Aeroporto	+EG
Thursday	24-11-16	BEL-GIG (11:50 - 16:20) GIG-CDG (17:40 - 07.40 +1)	**Flying**	Airplane		
Friday	25-11-16	Bonow/Japsen: CDG-ARN/CPH	**Flying**			

GMD: Geologishe mijnbouwkundige dienst Suriname (Geological Survey of Suriname).

SBK: Salomon B. Kroonenberg. ThEW: Theo E. Wong. EG: Ernesto Goldfarb Figueira. Nelsi Sadeck: Local guide in the Monte Alegre area.

4. Suriname

4.1 Aspects of the geology of northern Suriname

4.1.1 Precambrian terrain

The Precambrian terrain in Suriname is part of the Guiana Shield that stretches from Venezuela, Guyana, Suriname and French Guiana to Brazil (north of the Amazon). The Guiana Shield thus extends both west and east of the Jurassic Tacutu Rift (Eiras & Kinoshita 1990; Vaz *et al.* 2007) whereas the Brazilian Shield is south of the Amazon (Kroonenberg *et al.* 2016). The Precambrian rocks in Suriname (Palaeoproterozoic age) are cut by Jurassic Apatoe intrusives (~200 Ma; Central Atlantic Magmatic Province, CAMP;Kroonenberg *et al.* 2016) (Figures 4-1, 4-2).

The youngest sedimentary rocks within the Precambrian terrain is the sandstone of the Tafelberg Formation (part of Palaeoproterozoic Roraima Supergroup). Kroonenberg *et al.* (2016) assigned an age of 1.9 Ga to these sandstones based on a correlation with similar rocks in Brazil. It is interesting that top basement at Tafelberg is at ~300 m above sea level (a.s.l. whereas this surface reaches ~1300 m a.s.l. at the Wilhelmina Mountains only ~50 km SW of Tafelberg.

4.1.2 The coastal plain

The coastal plain of Suriname (Figured 4-3, 4-4) contains the southern part of the offshore Guyana–Suriname Basin where the Cretaceous – Neogene succession can attain considerable thickness; e.g. 1368 m in the Burnside-1 well where the Cretaceous Nickerie rests on basement (see also Figure 4-5). The Cenozoic overburden consists of (Wong *et al.* 1998; Verreussel *et al.* 2011; Wong 2014; Monsels 2016; Wong 2016):

- Holocene deposits, the Pleistocene Coropina Formation (silty clays and fine to medium sands) and the Pliocene Zanderij Formation (poorly sorted sands, kaolinitic sands and loams).
- Miocene sediments.
- A pronounced ~Oligocene hiatus, the so-called bauxite hiatus. At Tambaredjo this hiatus spans Eocene – earliest Miocene.
- Late Paleocene to earliest Eocene sediments that partly overlie the Nickerie Formation partly the Precambrian basement. Intense weathering resulted in bauxitization of he upper part of the Paleocene–Eocene Onverdacht Formation.

Wong (1994) used biostratigraphic and lithostratigraphic well data to demonstrate that, in addition to the Cretaceous–Tertiary boundary and the bauxite hiatus, the Paleocene–Eocene boundary is a well-defined unconformity.

4.1.3 Bauxite deposits

In Suriname, bauxite deposits formed on two different types of parent rocks (Figure 4-3) (Monsels 2016):

- Sedimentary parent rocks in the coastal area (coastal plain or lowland bauxites; e.g. at Mongo and Onverdacht; Figure 4-8). These bauxites formed at the expense of Paleocene–Eocene sediments in a belt running subparallel to the 'Old coastal plain' where the Pleistocene Coropina Formation constitute the unconsolidated overburden of the bauxites (Wong *et al.* 2009). The bauxites have an average thickness of 6 m and they are either within 5 m from the surface or buried below an overburden of up to 40 m (Figure 4-7).

- Crystalline parent rocks in the hinterland (plateau or highland bauxites; e.g. at Bakhuis, Nassau and Brownsberg).These bauxites are mostly developed on intermediate to basic Precambrian igneous or metamorphic rocks. They are found on plateaus (250–650 m a.s.l.) and have an average thickness of 4 m with little or no overburden.

The bauxites in Suriname are Palaeogene in age as most bauxites on both sides of the Atlantic and formed during a bauxitisation phase when climatic conditions were favourable worldwide (Bárdossy & Aleva 1990; Monsels 2016). Different approaches have been applied to date the formation of bauxite in Suriname and French Guiana.

Theveniaut and Freyssinet (2002) studied paleomagnetic properties on duricrust paleosurfaces in French Guiana (Cayenne region and Kaw Mountain) and Suriname (Mongo and Bakhuis Mountains). They estimated the age of weathering of ferruginous and bauxitic duricrusts from comparison of paleomagnetic poles determined from these duricrust horizons with the South American apparent polar wander path. They

- attributed the `Sul Americano' lateritization cycle of Paleocene–Eocene age to the bauxitic surfaces of Bakhuis Mountains (400 m a.s.l.), Kaw Mountain (upper surface, 300 m a.s.l.) and probably the Cayenne Unit 1 (75–200 m a.s.l.) with respectively average relative ages of 60, 50 and 40 Ma.

- attributed the `Late Velhas' lateritization cycle of Miocene age to the bauxitic paleosurface of Kaw Mountain (lower surface, 220 m a.s.l.), the coastal Moengo deposit (40 m a.s.l.) and the ferruginous surface of Cayenne Unit 2 (20–50 m) with relative average ages of 13 and 10 Ma.

- related a late Miocene lateritization event (5–13 Ma) to the formation of the Fe-duricrust of Cayenne Unit 3, close to sea level and occupying most of the coastal plain.

Theveniaut and Freyssinet (2002) found the Oligocene to represent a major break in the development of weathering profiles, with erosion as the predominant process which stripped 50–80 m from the landscape between the two main lateritization phases of Paleocene–Eocene and Miocene.

Monsels (2016) also related the bauxite deposits in Suriname to five planation levels on the Guiana Shield (Figure 4-4) (e.g. Bárdossy & Aleva 1990):

1. Summit Level, Jurassic to Cretaceous,
2. Main Aluminous Laterite Level, Early Tertiary,
3. Foothill Level, Oligocene to early Miocene,
4. Pediplane Level, Pliocene and
5. Valley Floor Level, Pleistocene to recent.

Monsels (2016) noted that the major bauxite and aluminous laterite horizons on the Guiana Shield are related to the well-developed and widespread Main Aluminous Laterite Level.

According to Monsels (2016), the age of Main Aluminous Laterite Level is documented by Paleocene pollen from unconsolidated sediments (arkosic sands or kaolin) below, and Miocene sediments on top of some of the bauxite deposits. A long period of non-deposition during the late Eocene to Oligocene is known as the 'Bauxite hiatus', durin which intense weathering resulted in bauxitisation of the upper part of the Onverdacht Formation (Wong *et al.* 2009). Clearly, this dating only applies to the coastal plain bauxites.

Consequently, there is a broad agreement between the results of Theveniaut and Freyssinet (2002) and the summary presented by Monsels (2016), in particular because both studies relate the bauxites to supposedly Palaeogene planation surfaces on the Guiana Shield (the 'Sul Americano' cycle, sensu King). However, in the details the results do not seem to be in perfect agreement. Monsels (2016) reported that the bauxitisation of Paleocene–Eocene sediments on the coastal plain took place in the late Eocene to Oligocene (in the interval 40–25 Ma). Theveniaut and Freyssinet (2002) found that the bauxites in the Bakhuis Mountains developed in the Paleocene ('average relative age' of 60 Ma) and assigned a Miocene age to the Mongo deposits (13–10 Ma).

4.2 Localities visited

4.2.1 Outcrops of Palaeoproterozoic basement, metasediments and sandstone

Around Brownsberg and Lake Brokopondo, 50–150 km from the coast (Paramaribo):

- North of Brokopondo (in a quarry near the Suriname River (GC1196-64 at Saras Lust), at Brownsberg (e.g. GC1196-73) and south of Brokopondo (GC1196-78, 79).
- Rosebel goldmine (GC1196-74–77) across a vertical range of 683 m (including outcrop sample GC1196-73).

Tafelberg, 230 km from the coast (see Figure 4-9):

- We visted an outcrop exposing the basal part of the Tafelberg Sandstone (GC1196-67), the underlying basement (GC1196-65) as well as of the palaeosol separating these two units (GC1196-66). The outcrop occurs in a waterfall (290 m a.s.l.) at the scarp below the plain with the air strip.
- We visited the top surface of Tafelberg at two locations (GC1196-68, -69). The elevation at these locations are 1010 and 600 m a.s.l., at the eastern and western edge, respectively. The top surface is thus dipping towards the west.

The Tafelberg sandstone samples cover an elevation range of 720 m.

We saw very different degrees of weathering of these Precambrian rocks (Figure 4-10), ranging from saprolites tens of meters thick at the Rosebel goldmine and at the illegal goldmines near Brownsberg to fresh outcrops with little sign of weathering at the quarry at Saras Lust and on and near Tafelberg.

4.2.2 Outcrops of young sediments and of bauxite

Within the coastal zone, we saw an outcrop of the the Pliocene Zanderij Formation with poorly sorted sands of almost pure quartz.

We visited bauxite deposits in Paleogene sediments around Mungo (Figure 4-11) and in Precambrian rocks around Brownsberg (e.g. Theveniaut & Freyssinet 2002; Monsels 2016). We did sample rocks at Brownsberg, but not around Mungo. At Mungo, Theo Wong reported that fossil wood encountered below the bauxite had been dated to be of Eocene age.

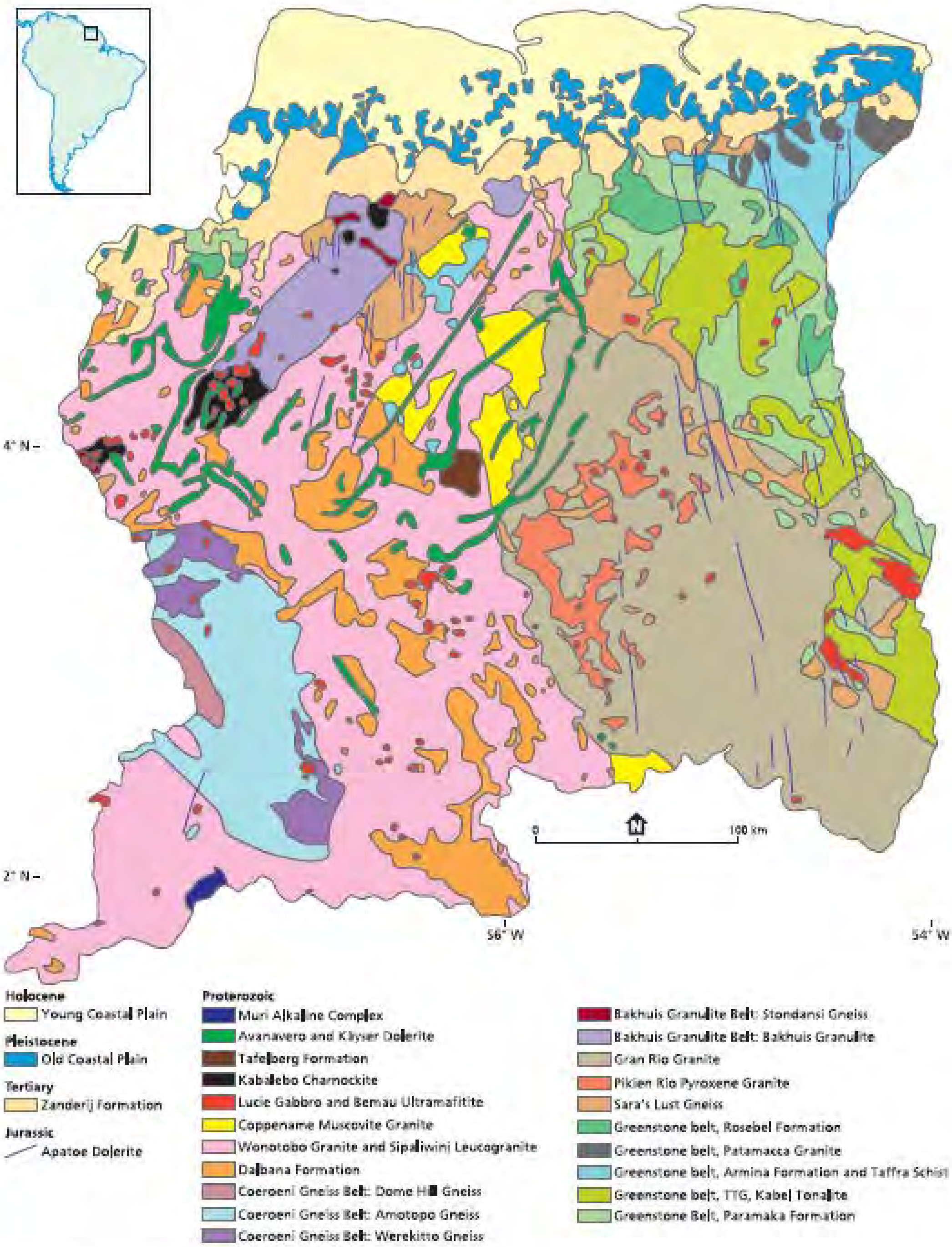


Figure 4-1. Geological map of Suriname (Kroonenberg *et al.* 2016).

Epoch	Main unit	Subdivision	1977 nr.	Rocks	Age	Events
Jurassic	Apatoe Dolerite		15	Pigeonite dolerite	196.0±1.7Ma	
Meso-proterozoic	Muri Alkaline Complex		20	Alkali syenite, carbonatite (?)	~ 1090 Ma	
	Nickerie Mylonite		16	Mylonite	~ 1200 Ma	
	Kayser Dolerite		17	Olivine dolerite	~1500 Ma	
Paleo-protero zoic	Avanavero Dolerite		18	Hypersthene dolerite	1787 Ma (BR)	
Orosirian	Tafelberg Fmn		19	Sandstone, conglomerate, volc. ash	1873 Ma (BR)	
	Younger intrusives	Coppename Muscovite Granite	26	Muscovite granite	1974±2 Ma	Trans-Amazonian Orogeny, Collision Guiana Shield -West-African Craton; <- First phase -> | <- Second Phase -> | <- Third Phase ->
		Lucie Gabbro	31	(Meta)gabbro, ultramafitite	1985±2 Ma	
		[illegible]	25	Charnockite, pyroxene granite	1988.5 (avg N=5)	
		Wonotobo Granite	23	Biotite granite	1980±6Ma	
		Sipaliwini Leucogranite	20, 21, 22	Leuco-, fine-gr., granophyric granite	1980±4 Ma	
	Younger felsic volcanites	Dalbana Formation	29, 30	(Meta)rhyolite, dacite	1987±4Ma	
Rhyacian	Coeroeni Gneiss Belt (Coeroeni Group)	Werekitto Gneiss	43	Quartzofeldspathic gneiss	1984±5, 1994±4 Ma	
		Amotopo Gneiss	45	Amphibolite-facies metapelite	2053±9, 1986±15	
		Dome Hill Gneiss	46	Granulite-facies metapelite	2079±17	
	Bakhuis Granulite Belt (Falawatra Group)	Bakhuis Granulite	47	Intermediate-mafic granulite	2065±2 Ma	
		Stondansi Gneiss	46	Metapelitic granulite	2072±4, 2055±3Ma	
	Older granites	Gran Rio Granite	24	Biotite granite	2094 (avg N=5)	
		Pikien Rio Pyroxene Granite	25	Pyroxene granite	2097±1 Ma	
	Marowijne Greenstone Belt (Marowijne Group)	Rosebel Formation	32	Quartz sandstone, conglomerate	<2115 Ma? (FG)	
		Potamacca Granite	27	Two-mica granite	2060±4(FG)	
		Taffra Schist	34	Staurolite schist		
		Armina Formation	33	Metagreywacke, phyllite	<2127 Ma?(FG)	
		Sara's Lust Gneiss	43, 44	Migmatitic gneiss	2155-2165 Ma (FG)	
		Kabel Tonalite	28	Tonalite, trondhjemite, granodiorite	2180-2130 Ma (FG)	
		Paramaka Formation	35-36	Phyllite, metachert etc		
		Paramaka Formation	37-38	Metaquartzandesite, metadacite etc	2137±6, 2156±6 Ma (FG)	
		Bemau Ultramafitite	41, 42, 31	(Meta)gabbro, meta-ultramafitite	2147-2144 Ma (FG)	
		Paramaka Formation	39-40	Metabasalt, amphibolite		

Figure 4-2. Stratigraphy and sequence of events in the Suriname basement from Kroonenberg *et al.* (2016).

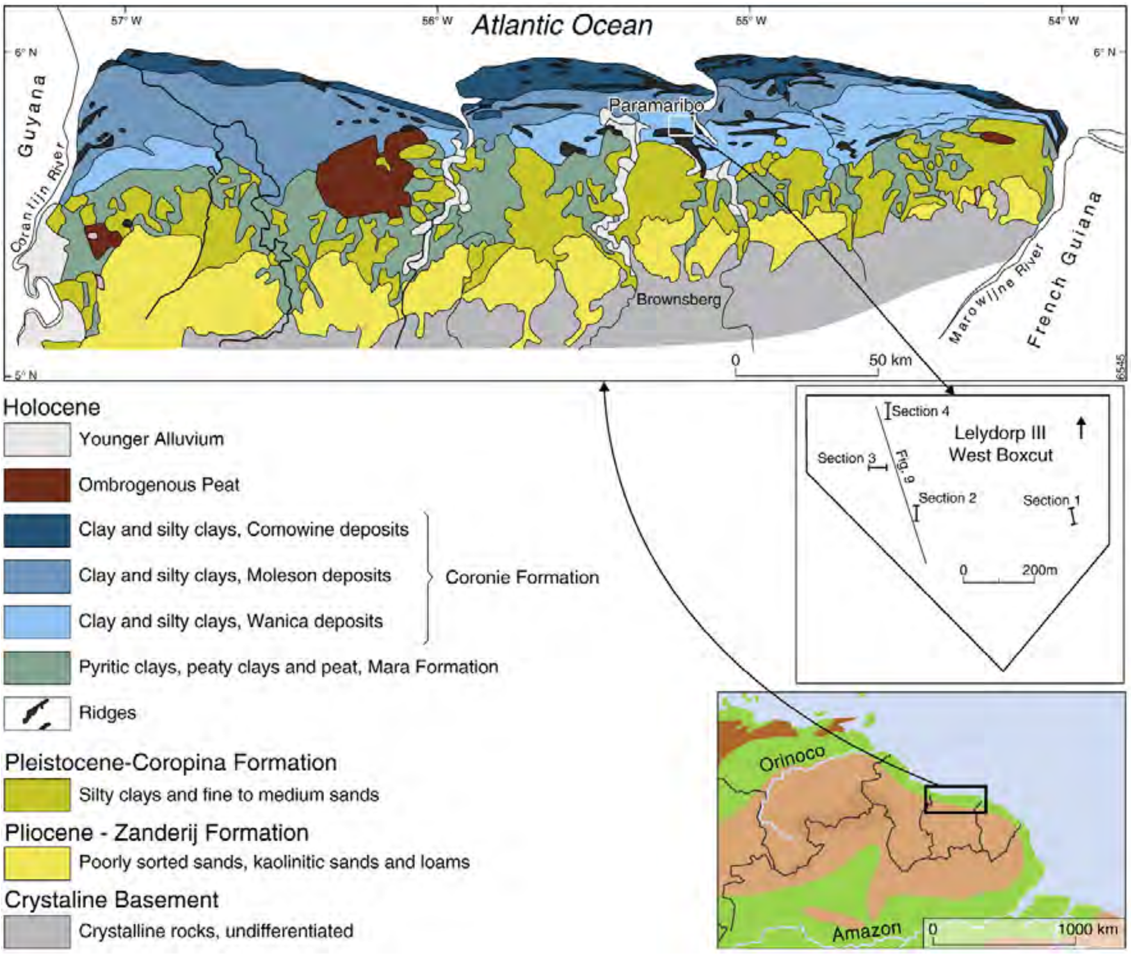


Figure 4-3. Geological map of the coastal plain of Suriname where the old coastal plain is defined by the extent of the Pleistocene Coropina Formation (Wong *et al.* 2009). Note that the Pliocene Zanderij Formation onlap basement.

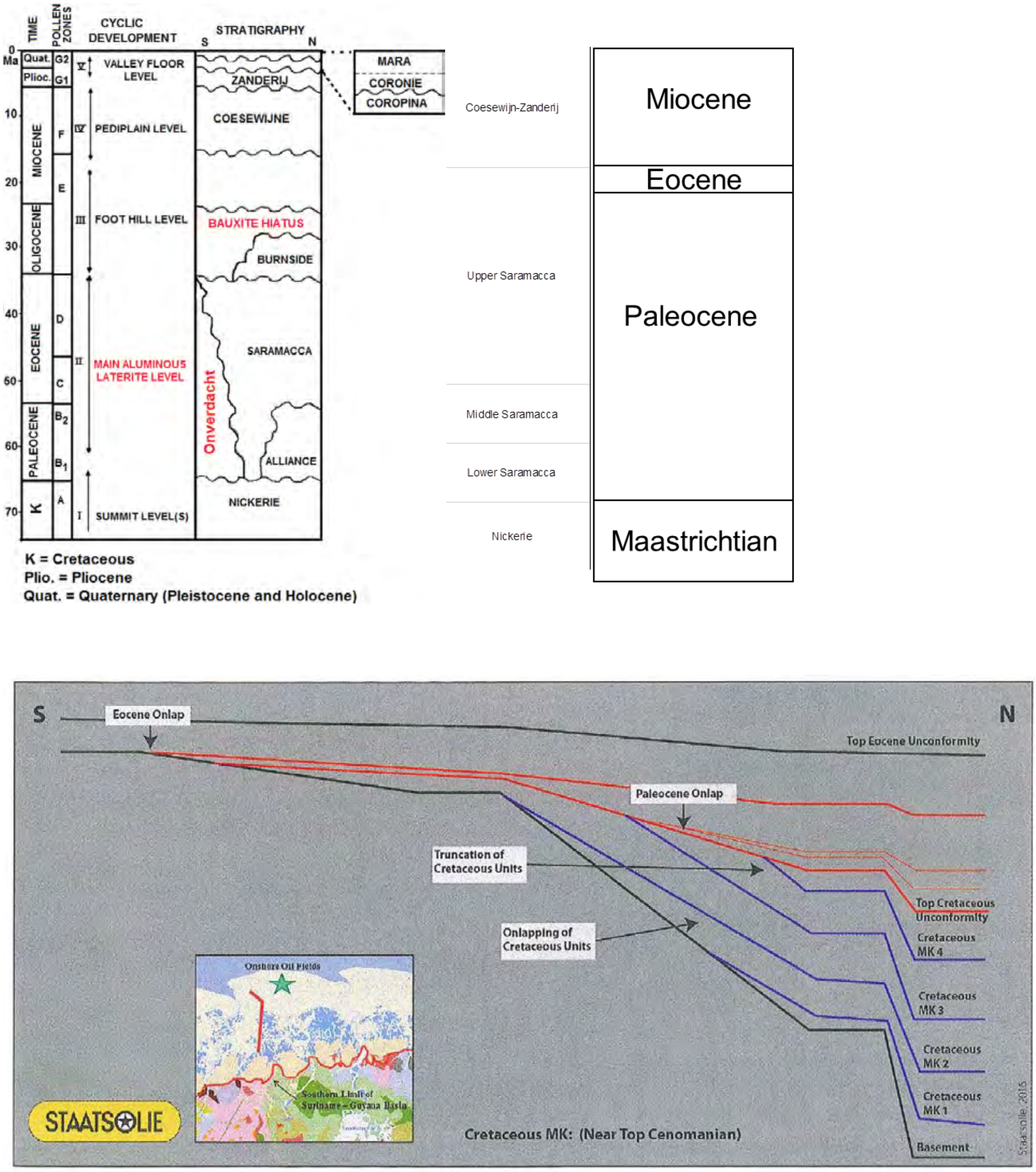


Figure 4-4.

Upper. Left: The planation levels, stratigraphy and pollen zones of Suriname (Monsels 2016). Note the Oligocene ‘bauxite hiatus’. **Right:** Composite stratigraphic log covering 900 m penetrated by the Tamparedjo wells near Paramaribo (Verreussel *et al.* 2011). Note the absence of Oligocene strata and the thin Eocene unit.

Lower. S-N stratigraphic section across the coastal plain (Griffith et al, 2016). Note the truncation of the Cretaceous strata below the Palaeogene and that the Eocene units rest on basement at some distance from the coast. Further south, Pliocene sands of the Zanderij Formation rest on basement

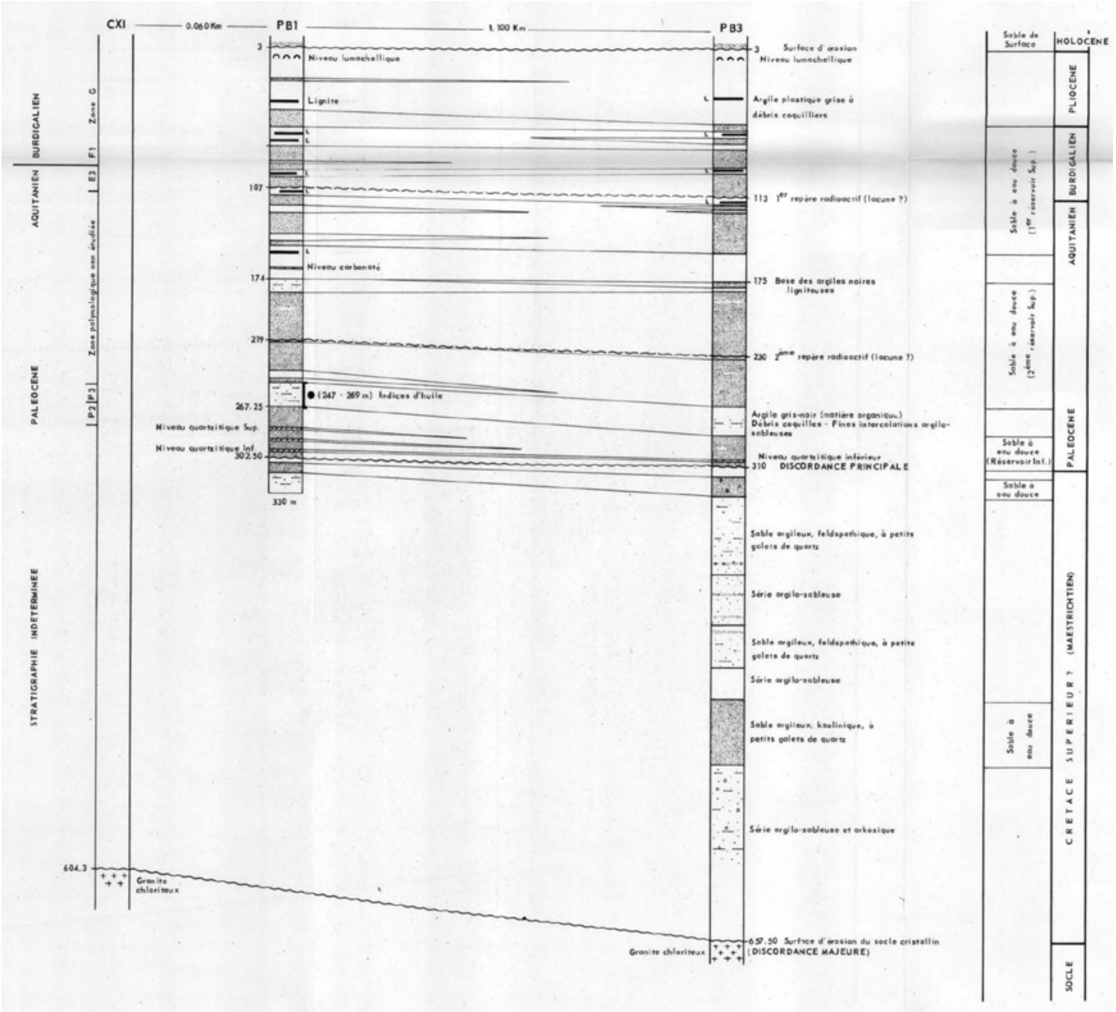


Figure 4-5. Examples of the stratigraphy of the onshore part of the Guyana-Suriname Basin. Siliciclastic sediments of ?Late Cretaceous age rest on granitic basement and are covered by Tertiary strata (sand-shale and lignite and a minor carbonate units) of Paleocene, Miocene and Pliocene age. Stratigraphic logs for the Paramaribo-1 and -3 wells (ELF, 1968).

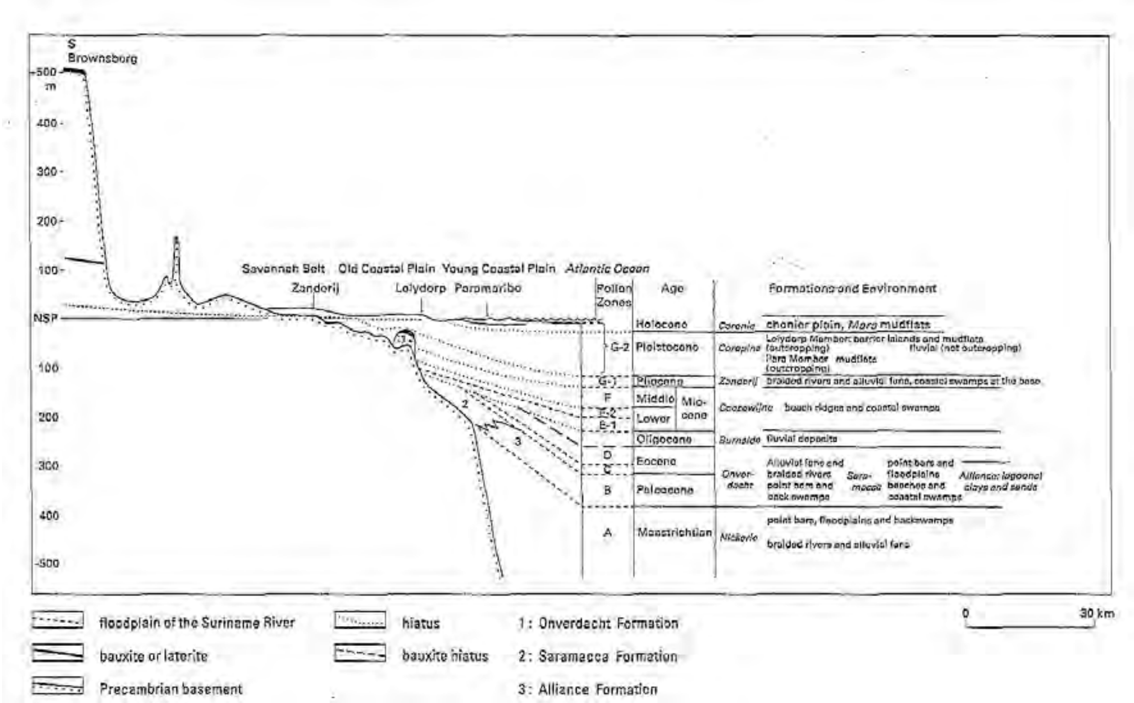


Figure 4-6. S-N cross-section through the northern part of Suriname (Wong *et al.* 1998). Note the difference in elevation between the bauxite deposits at Brownsberg and at Lelydorp.

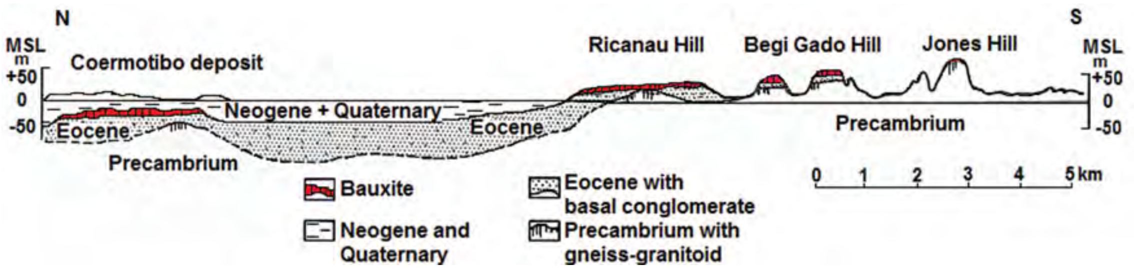
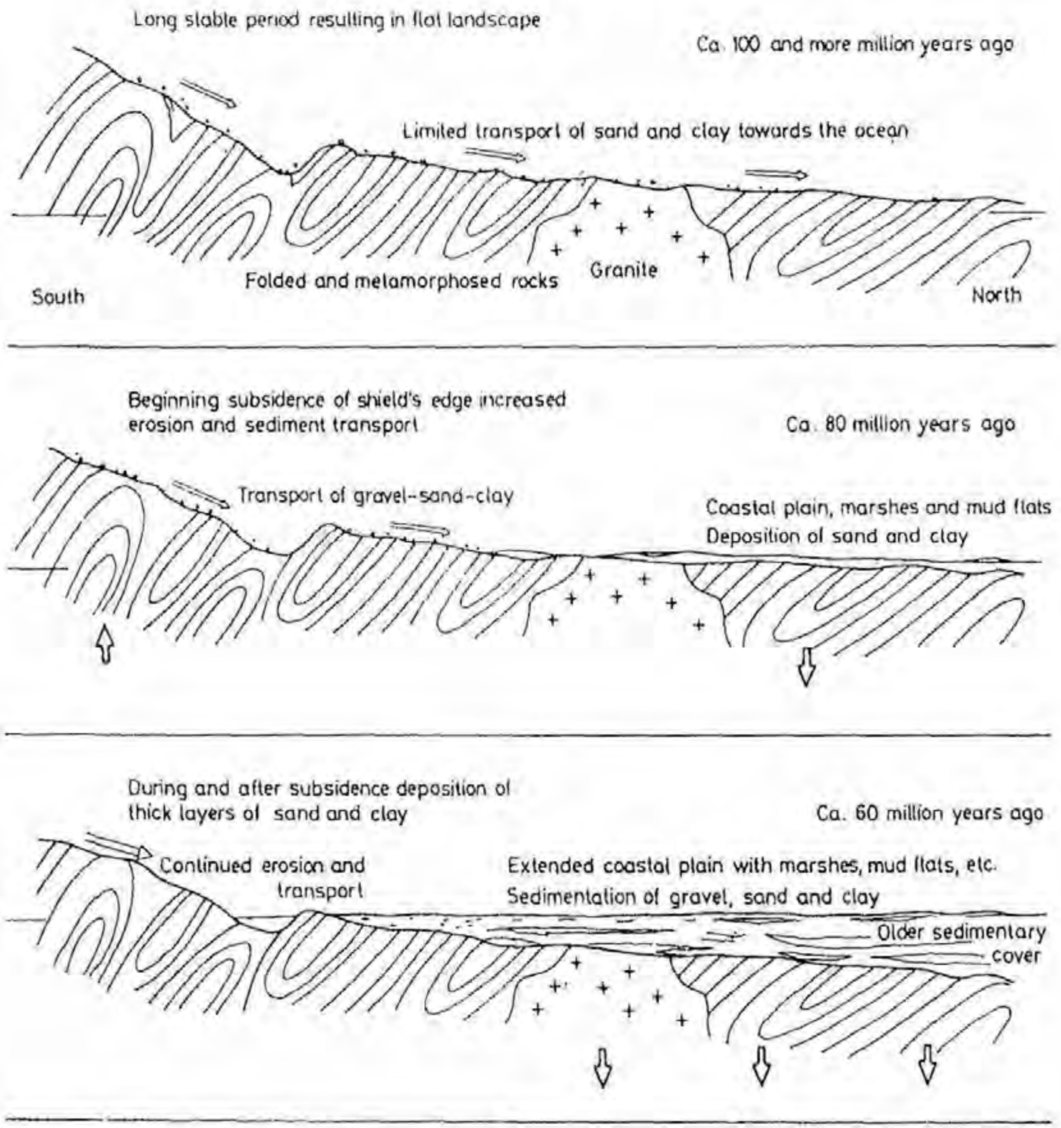


Figure 4-7. N-S cross section through the bauxite deposits in the Mongo district (Monsels 2016). Note that Eocene sediments rest on basement in contrast to the coastal zone where Cretaceous rest on basement (Figure x2).



During Mesozoic time, the whole of the present Coastal Plain was already well above sea level for a long time, resulting in a flat landscape with quietly flowing rivers.

In Upper Cretaceous time, start of subsidence and deposition of sand and clay in the area of the present Coastal Plain.

In Paleocene time, continuous slow subsidence and transgression resulted in deposition of thick layers of sand and clay in a landscape of tidal flats, sand bars, mud flats and marshes; tropical climate with palms, mangrove, ferns, etc.

Figure 4-8A. Illustration of the geological history of the Coastal Plain bauxite deposits in the Paranam-Onverdacht-Lelydorp area (Bárdossy & Aleva 1990).

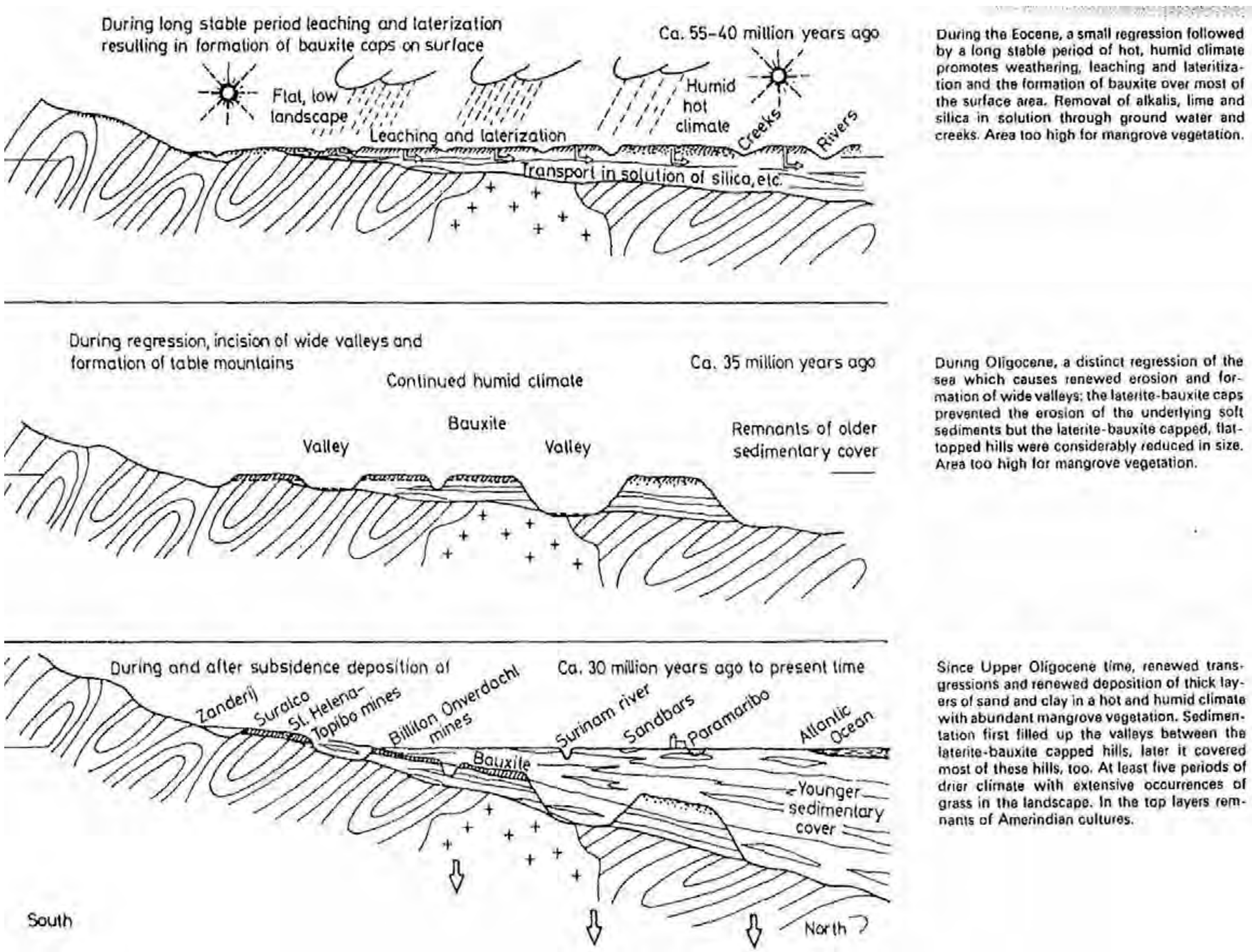


Figure 4-8B. Illustration of the geological history of the Coastal Plain bauxite deposits in the Paranam-Onverdacht-Lelydorp area (Bárdossy & Aleva 1990).

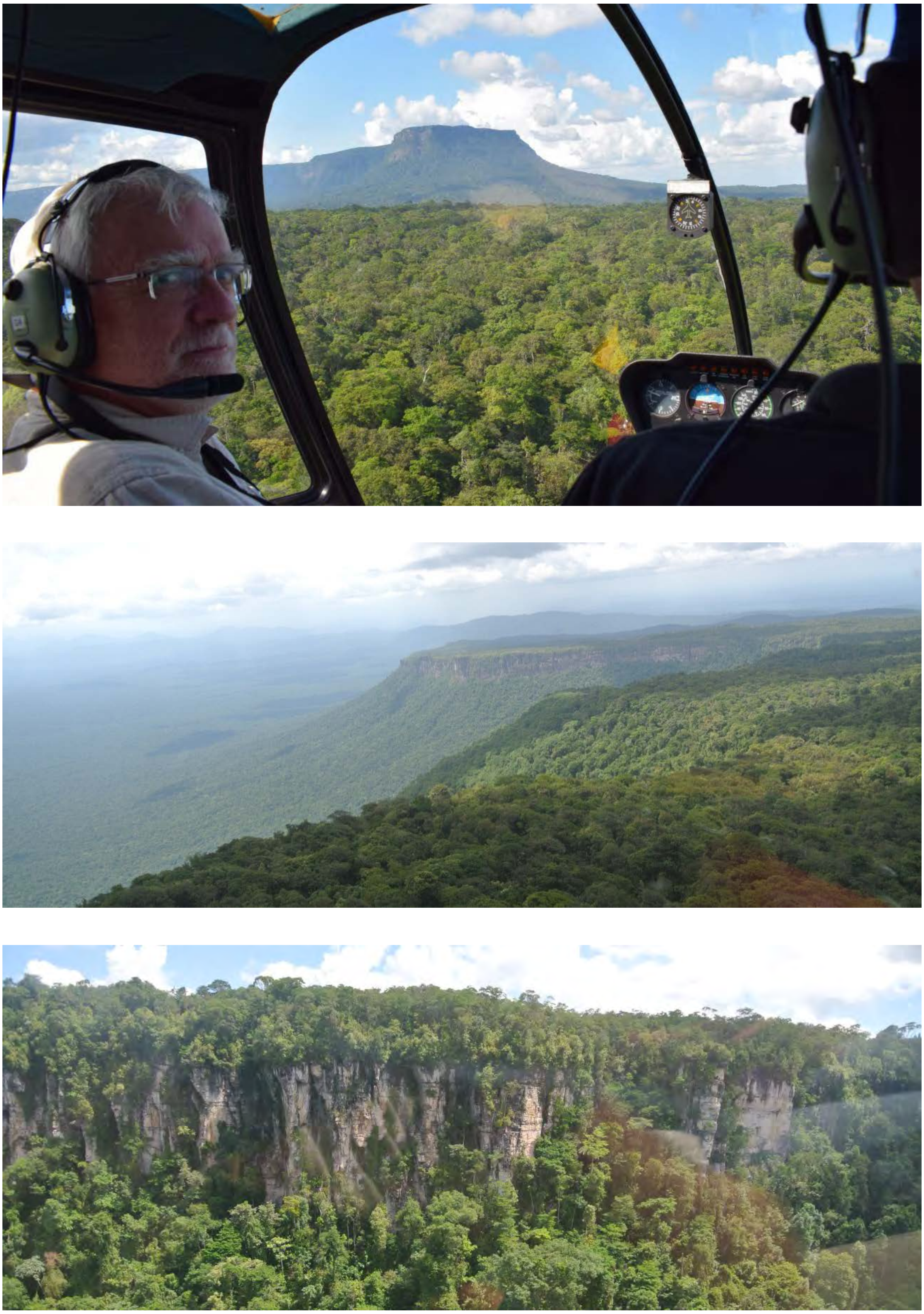


Figure 4-9. Tafelberg with Tafelberg Sandstone (Roraima Supergroup).

Figure 4-10. Different degrees of weathered basement in Suriname: Rosebel goldmine (upper), illegal goldmine near Brownsberg (middle) and the quarry at Saras Lust near the Suriname River (lower).

Figure 4-11. Bauxite deposits in Palaeogene sediments in Mungo (above) and east of Mungo (below).

5. Brazil

5.1 Aspects of the geology of the Amazon Basin

5.1.1 Palaeozoic strata and their erosional truncation

At the localities that we visited, Palaeozoic strata of the Amazon Basin are well exposed along the southern and northern margins of the basin as well as the underlying basement rocks and the overlying Cretaceous Alter do Chão Formation (Figures 5-1 to 5-4). Figures 5-5 to 5-6 from the guide book of Matsuda et al. (2010) highlight that the Paleozoic exposures along Rio Tapajós represent the tilted and truncated strata that are more deeply buried in the central part of the basin.

A major hiatus of Triassic to earliest Cretaceous age separate the Permian strata (only preserved in the central part of the basin) and the deposits of the Alter do Chão Formation. However, intrusive rocks belonging to the ~200 Ma Central Atlantic Magmatic Province (CAMP, De Min *et al.* 2003) cut across the Palaeozoic strata in the entire basin, often as NNE-SSW trending dikes; e.g. red lines in Figure 5-5 and green lines in Figure 5-9. The Brazilian term for this magmatic event is Penatecaua (Figure 5-4). In Suriname and French Guiana intrusions of this age are known as Apatoe dolerites.

Figure 5-1 shows that the sub-Palaeozoic basement surface dips 1 km over a distance of about 28 and 54 km, north and south of the Amazon, respectively. This corresponds to a dip of 1 to 2 degrees. The seismic line in Figure 5-2 illustrates the erosional truncation of the upper Paleozoic strata below the Cretaceous Alter do Chão Formation (Mosmann et al. 1986; Caputo 1991). The profile shows a reverse fault which part of the Solimões megashear which is characterized by the en-echelon arrangement of folds and faults interpreted as the result of right-slip displacements in a transpressive regime. According to Caputo (1991) the deformation took place during Late Jurassic time after emplacement of the latest Triassic (CAMP) dikes and the Late Jurassic sills (Apoteri Formation; 149.5 Ma according to Vaz et al. 2007) (and tholeitic flows in the Tucano rift; Berrangé & Dearnley 1975). The deformation was followed by widespread erosion before deposition of the Alter do Chão Formation; e.g. in the interval between 150 and 125 Ma. Note that Reis (2006) suggested that the term 'Apoteri' should be restricted to designate the basalt flows in the Tacutu Rift whereas the term 'Taiano dolerite should be used to designate the dyke swarm there.

That a major deformation of the Palaeozoic sequence took place prior to the deposition of the Alter do Chão Formation is further supported by this statement from Peter Szatmari who used to tell his students that "there are no Paleozoic basins in Brazil, only Mesozoic-Tertiary basins in which the Paleozoic strata are preserved, separated by Mesozoic-Tertiary highs from which they have been removed. There are, for example, nice Devonian strata outcropping over the rim of the Recôncavo–Tucano rift and Permian strata within the same rift. The same must have happened with the inception of the Equatorial rifted margin" (Peter Szatmari, pers.comm. 2017).

This view is further supported by Edison Milani: “There is a major difference between the early and the late Paleozoic sequence. From the Ordovician to the Devonian, there was wide depositional continuity, although buried arches and emergent areas modify thicknesses and facies. During this time, little of what is known of the southern paleocontinent was above the water. Depositional environments were rather uniform, as especially evident in the geochemical correlation of Devonian black shales from Bolivia through the Solimões, Amazonas, and Parnaiba basins to the Paraná Basin. During the late Paleozoic, in the Carboniferous and the Permian, the basins as we know them today became increasingly individualized. There was a clear paleoclimatic gradation from periglacial environments in the south to the evaporitic ones in the north. Differences in sedimentary facies permit in some places (everything is sandier) to identify "basin margins". But no doubt the events that formed the basins as we see them today took place subsequently, during the Meso-Cenozoic.” (Edison Milani, pers.comm. 2017)

5.1.2 Cretaceous and younger strata

The Alter do Chão Formation is of Aptian to Maastrichtian age (Figure 5-3; Cunha et al. 2007), but these continental deposits are difficult to date. According to Hoorn *et al.* (2010), the characteristics of the Alter do Chão Formation are typical for alluvial plain and fan environments, and the sedimentary sequences suggest a braided fluvial system, but fluvial-lacustrine depositional conditions may also have existed. However, Rossetti and Netto (2006) who documented a marine influence on the deposits of the Alter do Chão Formation at a locality east of Manaus.

Further, according to Hoorn et al. (2010), palaeocurrent directions, detrital zircon ages, isotopic signature, sedimentological characteristics and geographic distribution together suggest that the Alter do Chão Formation was formed by alluvial fans to braided fluvial systems fed from a cratonic source (Guiana Shield to the north and Brazilian Shield to the south) throughout the margins of the pre-existing Amazonas and Solimões basins. These braided fluvial systems, which were coming from opposite directions, merged in the central depression of the Amazonas and Solimões Basins forming an E-W-oriented trunk river. In the middle Late Cretaceous (Santonian or Campanian), the river split into two separate systems. One river continued to flow to the west, as a continuation of the Alter do Chão system, whereas the other flowed east, into the Foz do Amazonas Basin (Upper Cretaceous Limoeiro Formation). Still, according to Hoorn et al. (2010), the Alter do Chão River system was discontinued during the Paleogene.

According to Cunha *et al.* (2007), Cenozoic strata in the Amazon Basin is represented by the Solimões and the Marajó Formations that attain a total thickness of 200 m. We did, however, not encounter outcrops of these formations. Rossetti (2001) studied facies and sedimentary sequences in northern Pará (east of Belem) and identified three late Cenozoic depositional sequences; in particular three significant sea level falls: in the Paleogene, at the end of the early Miocene, and in the late Miocene. During these periods, the study area was subaerially exposed and underwent remarkable paleosol development. The sea level falls were successively followed by major sea level rises and transgressions, one in the late

Oligocene to early Miocene and the other in the mid-Miocene. Rossetti found this history of sea level fluctuations to be consistent with data documented from other areas in South America and worldwide, reflecting eustacy, ‘perhaps combined with regional tectonic events’.

5.1.3 Reversal of the Amazon River

There has been debate about when the Amazon River reached its present shape during the late Neogene. Figueiredo *et al.* (2009) analyzed new data from exploration wells on the outer continental shelf and uppermost Amazon deep-sea fan and concluded that the Amazon River was initiated as a transcontinental river between 11.8 and 11.3 Ma ago (middle to late Miocene), and that it reached its present shape and size during the late Pliocene.

Latrubesse *et al.* (2010) studied the uppermost levels of the Solimões Formation in western Amazonia, and concluded that it is of late Miocene age (9–6.5 Ma). They found that it was during the Pliocene that the southwestern Brazilian Amazonia ceased to be an effective sedimentary basin, and became instead an erosional area that contributed sediments to the Amazon fluvial system. They concluded that it was during the early Pliocene that the Amazon fluvial system integrated regionally and acquired its present appearance, and also when it started to drain water and sediments on a large scale to the Atlantic Ocean.

However, Gorini *et al.* (2013) found that the margin of the Foz do Amazonas Basin shifted from predominantly carbonate to siliciclastic sedimentation in the early late Miocene. They argued that by that time, the Amazon shelf had also been incised by a canyon that allowed direct influx of sediment to the basin floor, and they thus concluded that the palaeo-Amazon fan had already initiated by that time (9.5–8.3 Ma).

Gorini et al. (2013) noted that Latrubesse et al. (2010) used inland data to propose an early Pliocene age for the beginning of the Amazonian transcontinental drainage. Instead, Gorini et al. (2013) suggested that the event described by Latrubesse et al. (2010) represented an important evolutionary stage of both the onshore and offshore Amazon basins. They argued that the first change in sedimentation rate (5.6 Ma) observed along the margin of Foz do Amazonas, points to a more efficient transcontinental river, and that this change may be equivalent to the event considered by Latrubesse et al. (2010).

Whereas Hoorn et al. (1995) found that Andean tectonics provided a strong control on the changing drainage patterns in Miocene northern South America (including the reversal of the Amazon), Costa et al. (2001) suggested that the main features of ancient and modern landscape largely result from Tertiary intraplate tectonics (not from uplift of the Andes) and that inherited basement structures play an important role.

5.1.4 Maturity of sediments in the Amazon and Solimões Basins

Lima and De Ros (2002) studied the Devonian sandstones of the Uerê Formation at a depth of 2–3 km (São Mateus oil field, eastern Solimões Basin). They found that both vitrinite reflectance (average 1% Ro) and illite transformation reaction suggested that the sandstones had been subject to maximum temperatures of about 120˚C (however, Ro of 1% corresponds to a palaeotemperature of 150˚C according to Burnham & Sweeney 1989). Palaeotemperatures in this range correspond to burial below a cover of 3–4 km for a palaeogeothermal gradient of 30˚C and a surface temperature of 30˚C. Lima and De Ros (2002) interpreted the high maturity of these sandstones as partly beeing due erosional removal of ~800 m of Permian–Triassic sediments after the the CAMP intrusive event and prior to deposition of the Alter do Chão Formation (Figure 5-7).

Gonzaga *et al.* (2000) studied the petroleum geology of the Amazon Basin and found that along the northern and southern flanks of the Basin and on the western platforms (near the Purus Arch), where the lower Barreirinha Formation is shallow (1500 m depth), the maturation is low (<0.65% Ro). In the central trough, source rock maturity reaches 1.0% Ro at about 4000 m depth. Gradients extrapolated from the wells suggest that the source rock may reach 1.3–1.4% Ro in the depocenter as a result of the overburden effect. A higher degree of maturation (Ro > 1.4 %) is only reached due to heating from the diabase dikes and sills. Maturity data indicate that the thermal evolution of the source rock was controlled mainly by subsidence history and that heat from igneous intrusions played an important role only in those areas where dikes and sills were intruded into the Devonian sequence. Thus, in the eastern part of the basin, where most dikes and sills intruded the Devonian sequence, the source rock is overmature, while in the western part, where the intrusions are far from the source rock, the maturation was controlled by subsidence (wells A and B in Figure 5-8).

Gonzaga *et al.* (2000) concluded that the extent of the Amazon Basin has been larger than the present configuration and that 1800 m of section were eroded along the basin margins based on palinspastic reconstructions supported by stratigraphic correlations and thermal maturity data. They reported that apatite fission-track data supported this interpretation and that these data indicated that the exhumation began in the mid-Cretaceous, ~110 Ma.

5.1.5 The Monte Alegre Dome

The Monte Alegre Dome (Figures 5-9 to 5-12) is a very fascinating geological structure that may prove to provide us with observations that can support our understanding of the bigger picture of the region. We were very fortunate to have access to the wealth of information in the PhD thesis of Isabella Figueira (2011) and her publication (Figueira *et al.* 2012) – both in Portuguese (to our surprised we learned that Isabella Figueira is married with our Brazilian guide, Ernesto Goldfarb Figueira). To my knowledge, there are no publications in English that describe the Monte Alegre Dome, so here I copy the English abstract from Figueira *et al.* (2012):

> **Abstract** *Ruptile deformation in Penatecaua magmatic rocks at the dome of Monte Alegre (PA)*. Monte Alegre dome, which stands out amid the plains of the Amazon

River, is a topographic high on the left bank of the river, about 10 km northwest of the city of the same name, in Para. From its discovery, many hypotheses have been for the genesis of the dome, however only in 1975 Montalvão and Oliveira associated geometry with tholeitic intrusion that have shaped as braquianticlinal structure, with ellipsoid-shaped 30 km long and 20 km wide. Through morphostructural researchers of the dome, of the rock layers tilted and, in particular, systems of fractures in intrusive rocks generated by magmatism Penatecaua was possible to verify that the current braquianticlinal structure of the dome, originated as a result of deformation at least two phases of deformation (Fl and F2) Juro-Cretaceous, which generated at least two systems of locally ductile and brittle shearing, when the rheology is ripe. Correlated these stages of deformation, by analyzing the paleostress with regional tectonic regimes, such as diastrophic Jurua, confirming that it had a decisive influence on the finite deformation of the dome.

As the Dome is shaped by Palaeozoic strata (Figure 5-10), it is obviously post-Palaeozoic, and according to the interpretation referred to above, it was generated by Penatecaua magmatism; i.e. a CAMP intrusion (~200 Ma). Furthermore, the analysis by Figueira (2011) and Figueira et al. (2012) showed the influence of two deformation phases during Jurassic–Cretaceous time. Figueira (2011) speculated that if the F1 deformation phase corresponds to the Late Jurassic, Juruá compressive tectonics (Szatmari 1983; Caputo 1991), then the F2 may correspond to a Cenozoic reactivation. Further important insights about the Monte Alegre Dome can definitely be learned from the work of Isabella Figueira.

One aspect of the geology of the Dome that seems particularly relevant for our work is that a fault separates the inclined Palaeozoic strata of the southern and eastern part of the Dome from the flat-lying Cretaceous sediments of the Alter do Chão Formation (Figure 5-9). The fault must therefore have been active after the deposition of the Alter do Chão Formation and thus most likely in Cenozoic times. During our fieldwork, Jean-Yves noted the coincidence between the south-western portion of the fault and the pronounced mountain range of the Serra do Ereré (~200 above the surrounding terrain; Figure 5-12) which are characterized by very hard and well-cemented sandstone, possibly made up of the sediments of the Alter do Chão Formation. This led Jean-Yves to speculate that fluids migrating through the fault might have led to the extraordinary cementation of the sandstone. Should those fluids also have been hot, it is possible that any fission tracks in apatites become totally annealed in this event. AFTA data from these rocks may reveal if this was the case and thus possibly provide us with an age for the movement of the fluids. AFTA data from samples within the Dome may also reveal if the thermal doming around 200 Ma is detectable relative to AFTA data from samples outside the Dome.

5.2 Localities visited

5.2.1 The southern margin of the Amazon Basin along the Transamazonian Highway and Rio Tapajós

We sailed along Rio Tapajós and had thus great opportunities to visit and sample the excellent exposures along the river (Figures 5-5, 5-13); see the detailed description presented by Matsuda *et al.* (2010). At many localities, rocks near the water table were affected by considerable weathering (Figure 5-14), however, where the cliffs along the river had a considerable height, boulders from the top of the cliff were much less affected by weathering.

The outcrops included

- Precambrian rocks; Palaeoproterozoic granite (GC1196-83, 84) and Mesoproterozoic sandstone (Figure 5-13; GC1196-85). As Devonian and Silurian sediments, respectively, rest on these rocks they were exhumed to the surface prior to the deposition of these sediments.

- Palaeozoic rocks ranging from the Devonian Maecuru Fm to the Pennsylvanian Nova Olinda Fm (Figure 5-14; GC1196-80 – 82.1, 86–90). We did not visit outcrops of the Silurian Pitinga Fm (Trombetas Group) that rest on basement along Rio Tapajós (Figure 5-5) nor outcrops of the Permian Andirá Fm which is not exposed in this part of the Amazon Basin.

- The Aptian–Maastrichtian Alter do Chão Fm (Figure 5-15; GC1196-91 – 93). Figure 5-15 illustrates the range between very coarse-grained conglomerates in the basal part of the formation to the finer-grained red-beds of the high cliffs further north.

- Dikes, most likely of CAMP age (Figure 5-16).

5.2.2 The northern margin of the Amazon Basin, north of Monte Alegre and across Serra Azul

For two days we drove from Monte Alegre along a 110 km long N-S transect to north of Serra Azul beyond the extent of the Palaeozoic strata. The highest part of the mountains (<650 m a.s.l.) was clearly defined by extent of the hard sandstones of the late Ordovician – early Silurian Manacapuru Formation (Trombetas Group). Our two samples of the Precambrian basement north of Serra Azul were at ~350 m a.s.l. and the samples of the early Devonian Jatapu Formation and of the younger formations further south were at elevations below 400 m a.s.l. We discussed the possibility that intrusives could be important for the resistance of the highest parts of Serra Azul, but as these mountains are oriented E-W and the dikes typically follow a N-S direction (Figure 5-9), this explanation does not seem likely.

The outcrops included

- Precambrian rocks (GC1196-101, 102); two samples of which one was penetrated by a pegmatite vain whereas the origin of the other sample was not easy to establish in the field.

- Palaeozoic rocks (Figure 5-17; GC1196-103 – 111, 113.1, 114); from the late Ordovician – early Silurian Manacapuru Formation (exposed in the highest part of Serra Azul) to the Pennsylvanian Nova Olinda Formation (exposed in a big quarry, Pedreira Calpará).

- Alter do Chão Formation (Figure 5-18; GC1196-112, 115); sampled at two exposures well outside the Monte Alegre Dome itself (in both cases, the sediment was rather unconsolidated). GC1196-115 was sampled ~1 km east of the quarry with the Nova Olinda Formation (Figure 5-18); according to the CPRM map (Figure 6-4), the extent of the Alter do Chão Formation here reaches across the area occupied by the quarry which means that the Cretaceous sediments there rest on Palaeozoic rocks. According to the map of Figueira (Figure 5-9 right-hand map; Figueira locality 20), a N-S fault separates the Cretaceous sediments from the Palaeozoic rocks. Further north, the Alter do Chão sediments seem to rest directly on the Palaeozoic rocks (GC1196-112).

5.2.3 Monte Alegre

The outcrops visited within the Monte Alegre Dome included:

- Paleozoic rocks (Figure 5-19; GC1196-94 – 99); ranging from the Early-Middle Devonian Ereré Fm to the Pennsylvanian Monte Alegre Fm.

- Alter do Chão Fm (Figure 5-19; GC1196-100, 116, 117); all heavily cemented samples from Serra do Ereré. This locality is considered by Figueira (2011) to Alter do Chão Fm (her locality MA-42).

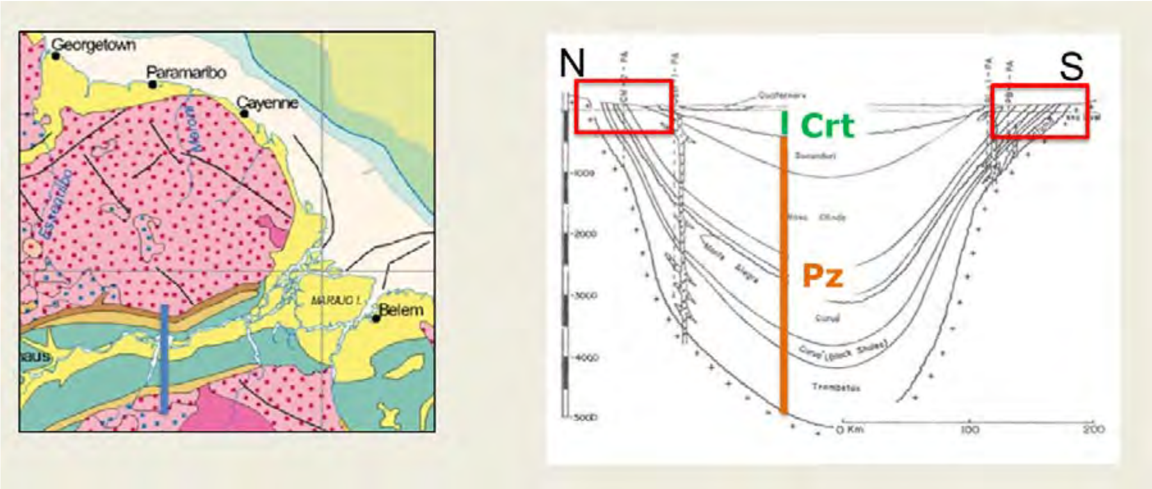


Figure 5-1. Erosional truncation of the Paleozoic (Pz) strata north and south of the Amazon along a profile that roughly corresponds to the transect visited during the fieldwork. The Cretaceous Alter do Chão Formation (Crt) overlie the Paleozoic strata. In the case shown, the basement surface dips 1 km over a distance of about 28 and 54 km, north and south, respectively. Corresponding to a dip of 1 to 2 degrees.

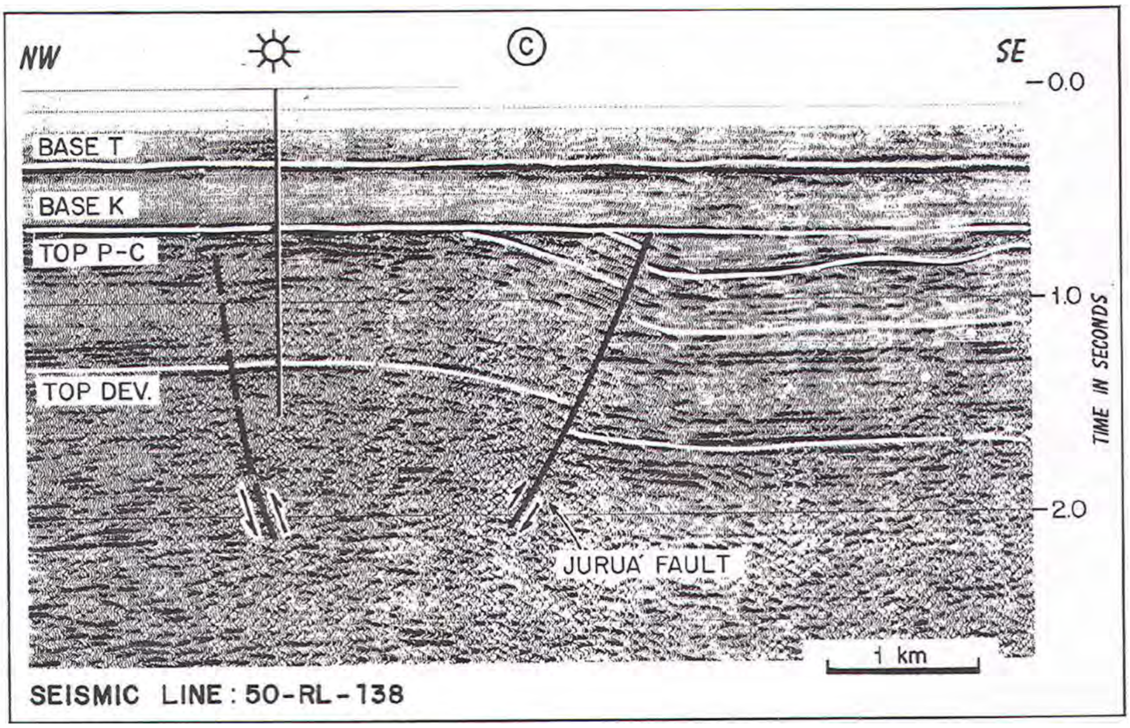


Figure 5-2. Seismic line from the Upper Amazon Basin / Solimões Basin, Juruá area, illustrating the erosional truncation of the upper Paleozoic strata below the Cretaceous Alter do Chão Formation (Mosmann *et al.* 1986; Caputo 1991). The profile shows a reverse fault which part of the Solimões megashear which is characterized by the en-echelon arrangement of folds and faults interpreted as the result of right-slip displacements in a transpressive regime. According to Caputo (1991) the deformation took place during Late Jurassic time after emplacement of Triassic–Jurassic sills and dikes and was followed by widespread erosion before deposition of the Alter do Chão Formation.

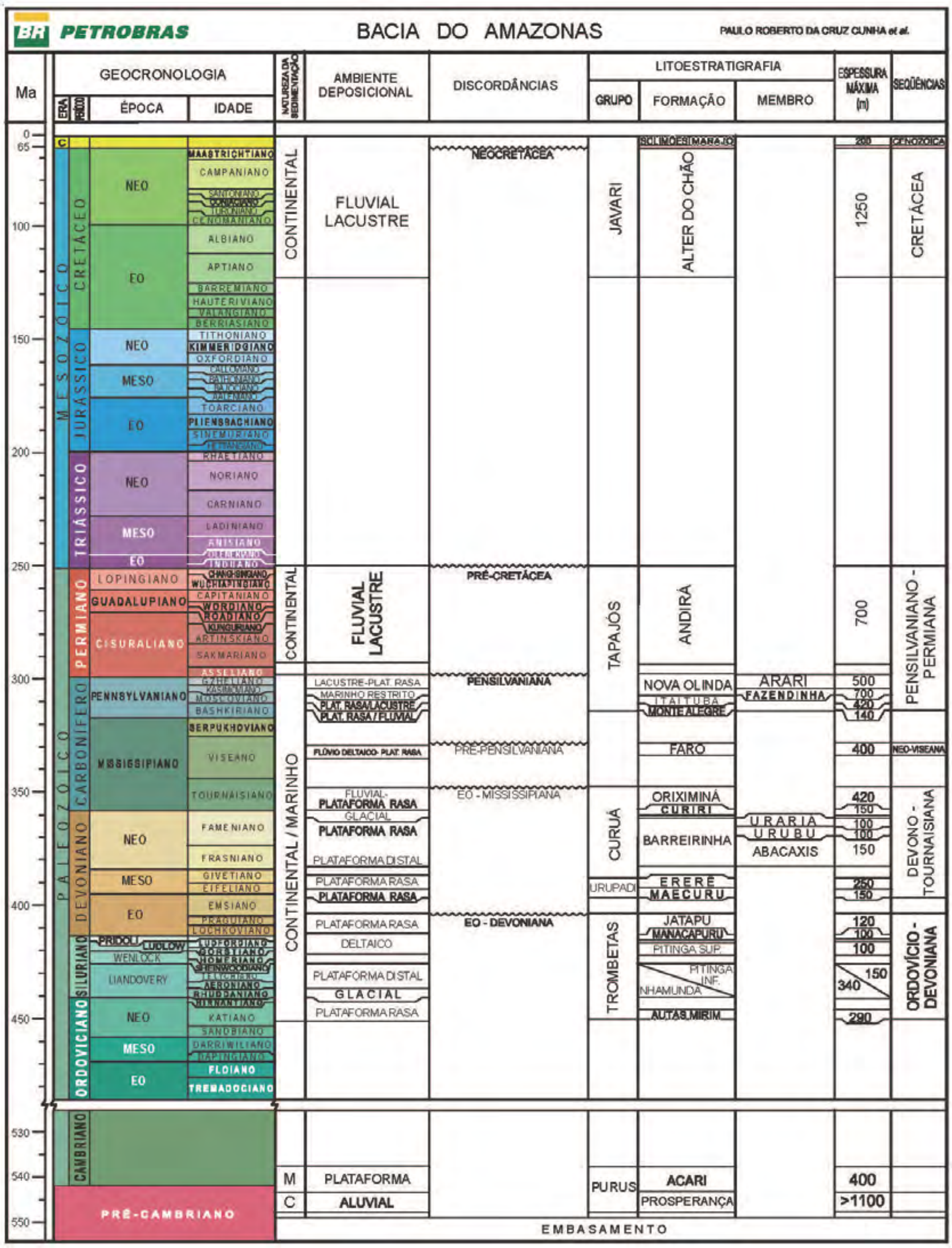


Figure 5-3. Lithostratigraphic table for the Amazon Basin (Cunha *et al.* 2007).

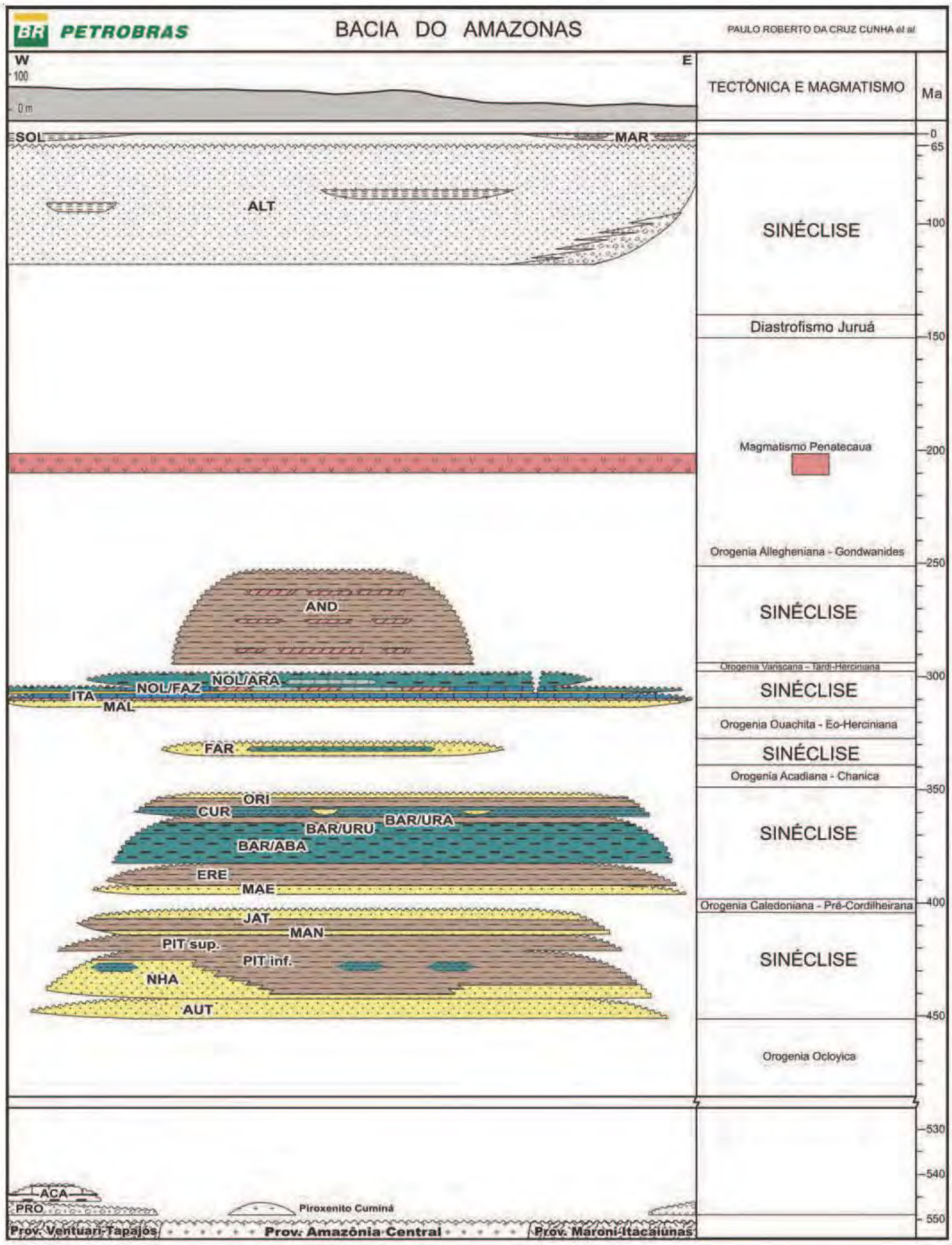


Figure 5-4. Tectono-stratigraphic table for the Amazon Basin (Cunha *et al.* 2007).

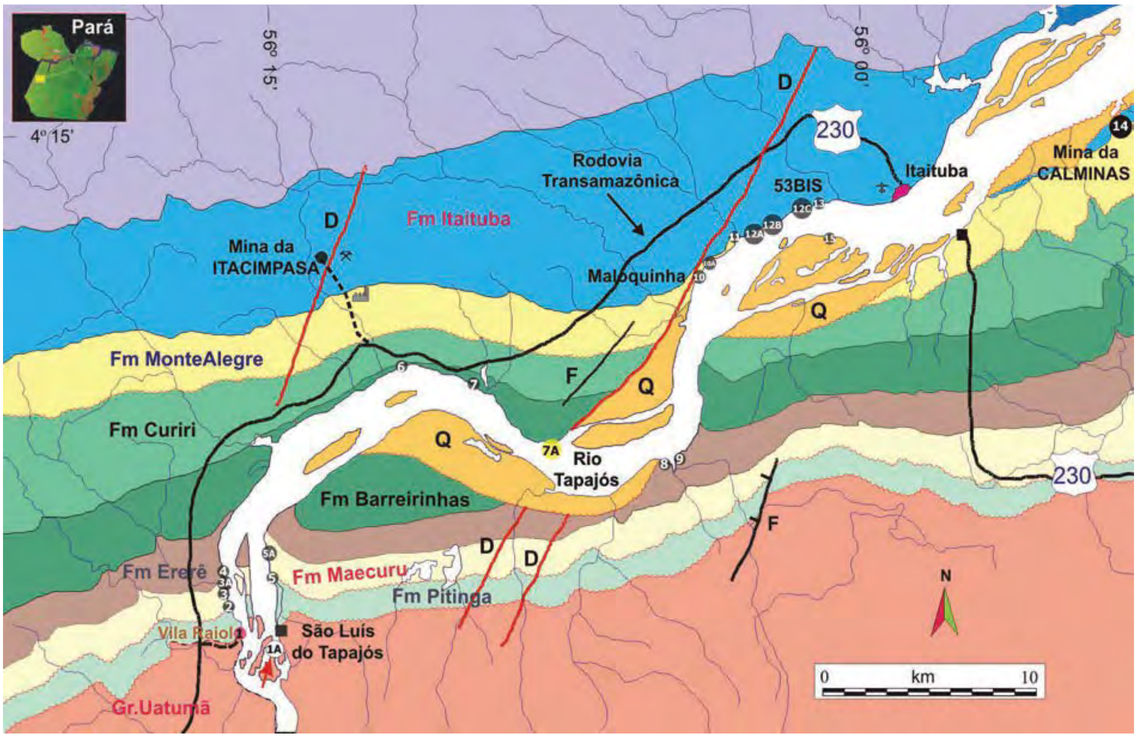


Figure 5-5. Geological map of southern border of the Amazonas Basin with the numbers indicating the localities in the geological field guide of Matsuda *et al.* (2010).

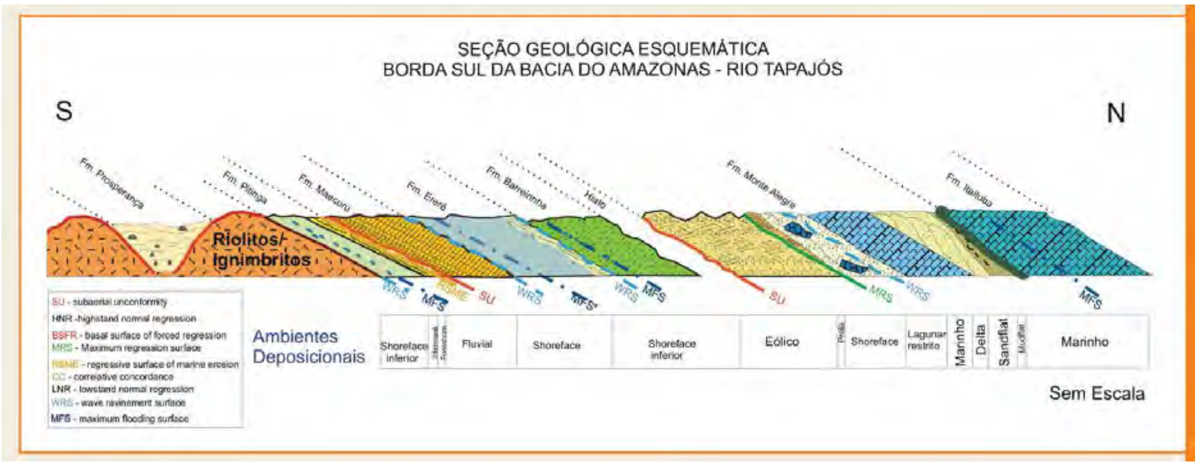


Figure 5-6. Schematic geological section along the southern border of the Amazonas Basin. From Matsuda *et al.* (2010).

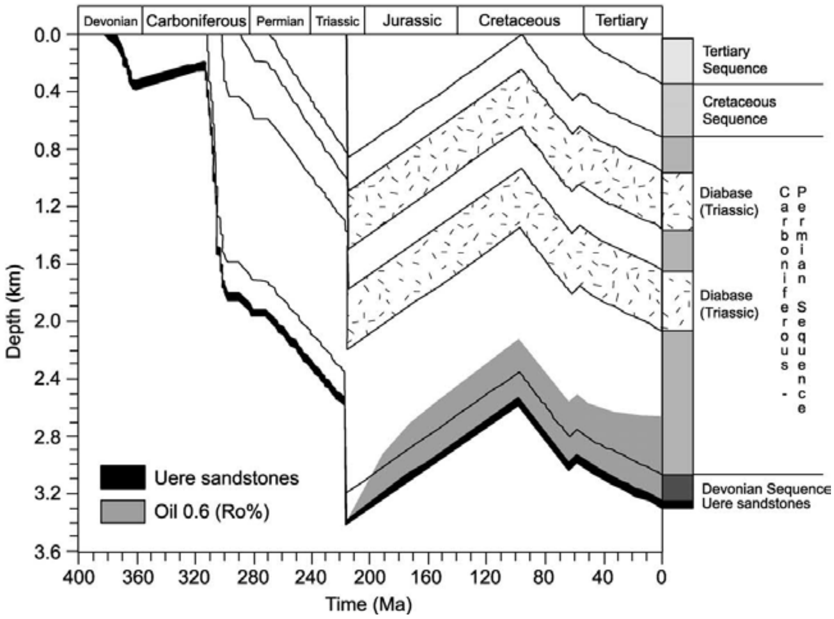


Figure 5-7. Burial history of the Devonian Uerê sandstones in the São Mateus oil field, eastern Solimões Basin (Lima & De Ros 2002). Lima and De Ros (2002) interpreted the high maturity of these sandstones as partly beeing due burial below (and late exhumation) of ~800 m of Permian–Triassic sediments after the the CAMP intrusive event and prior to deposition of the Alter do Chão Formation (Figure 5-7)

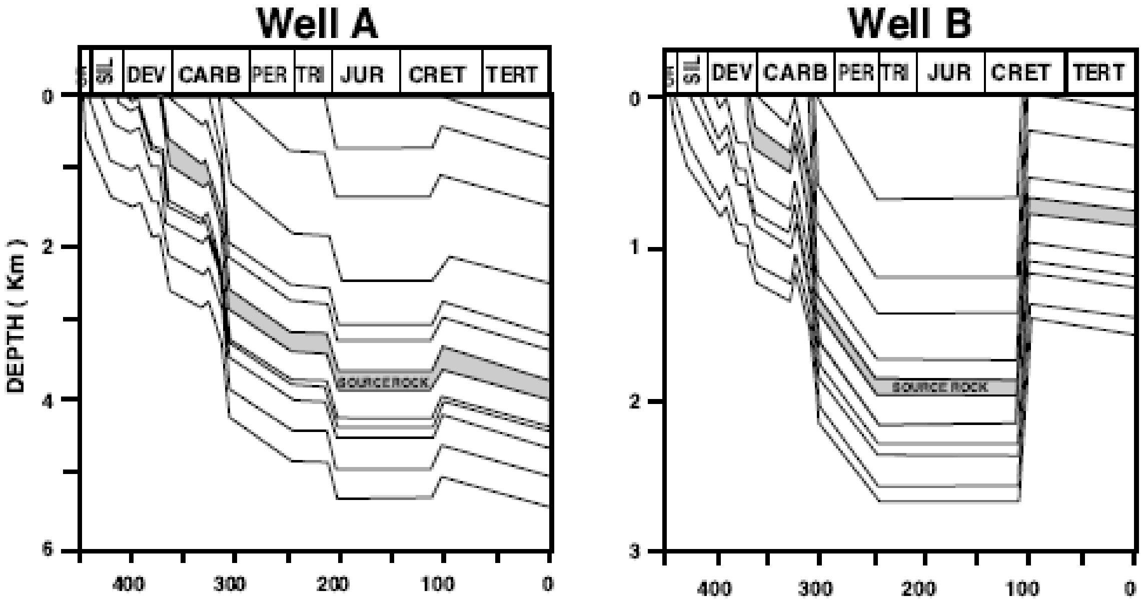


Figure 5-8. Geologic history for two wells from the Amazonas Basin based on basin modelling; both wells at about 58˚W (Gonzaga et al. 2000). According to this interpretation, mid-Cretaceous erosion removed less than 500 m of Permo-Triassic sediments from the central part of the basin (well A) and more than 1000 m of mainly Permian sediments along the northern margin of the basin (well B). Notice that well A (basin center) and well B (northern basin margin) are at different scales.

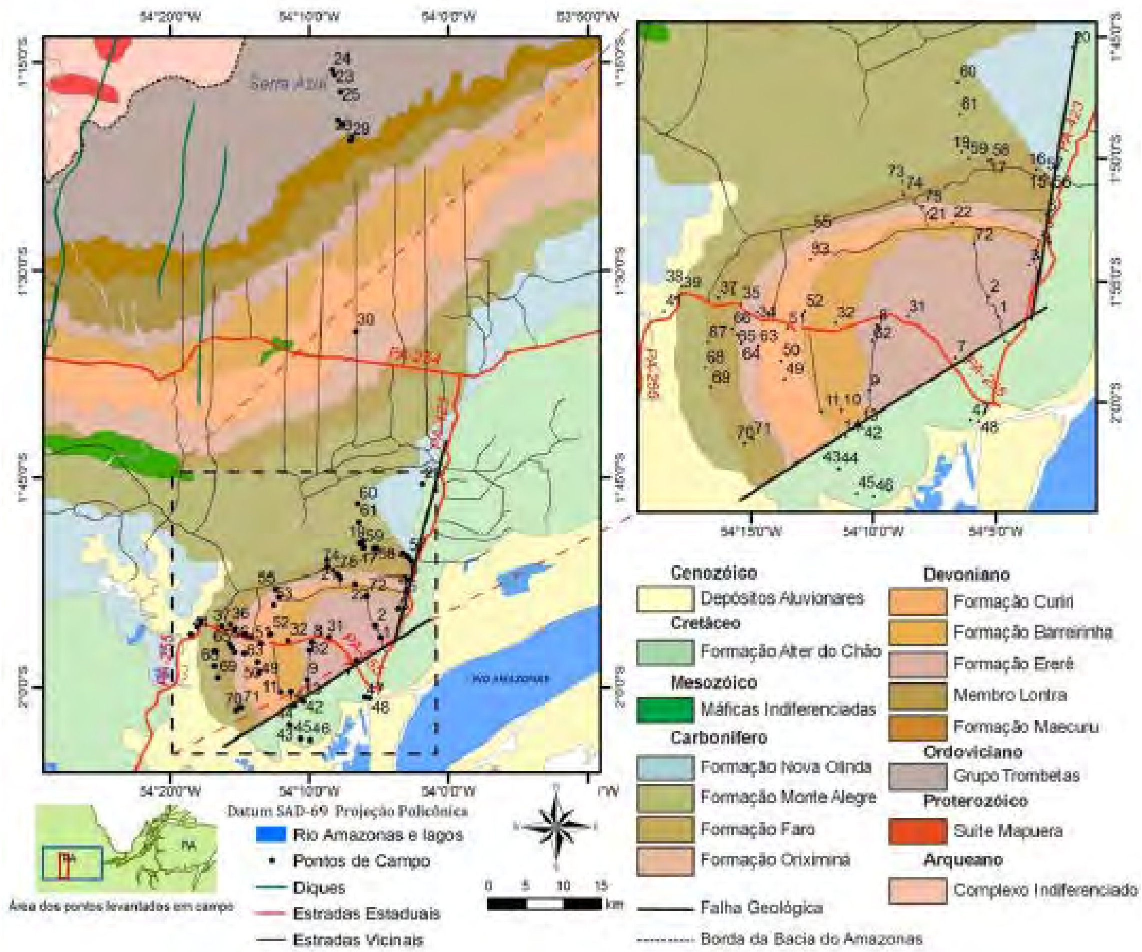


Figure 5-9. Geological map of the Monte Alegre Dome from (Figueira 2011). With observation points from Figueira (2011). Map modified after CPRM (2008). We also followed the roads indicated (PA-255, PA-423, PA-254) and the route indicated by the northernmost points in Serra Azul.

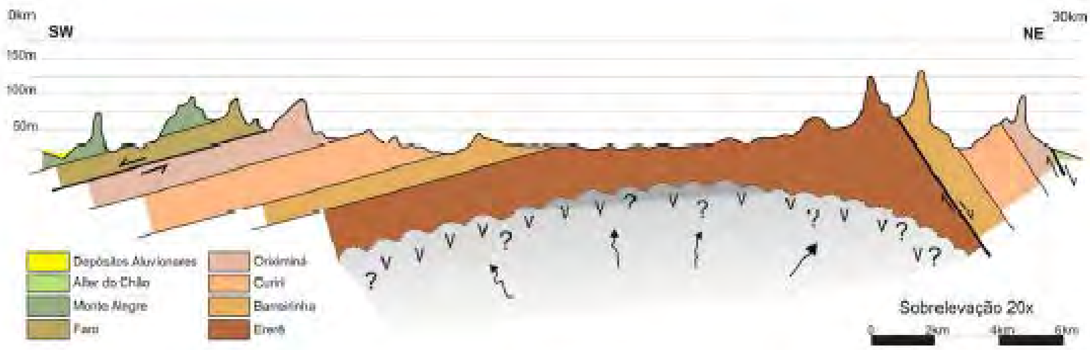


Figure 5-10. Schematic SW-NE profile across the Monte Alegre Dome (Figueira 2011). Note the offset of the Alter do Chão Formation indicated on the right-hand side of the profile.

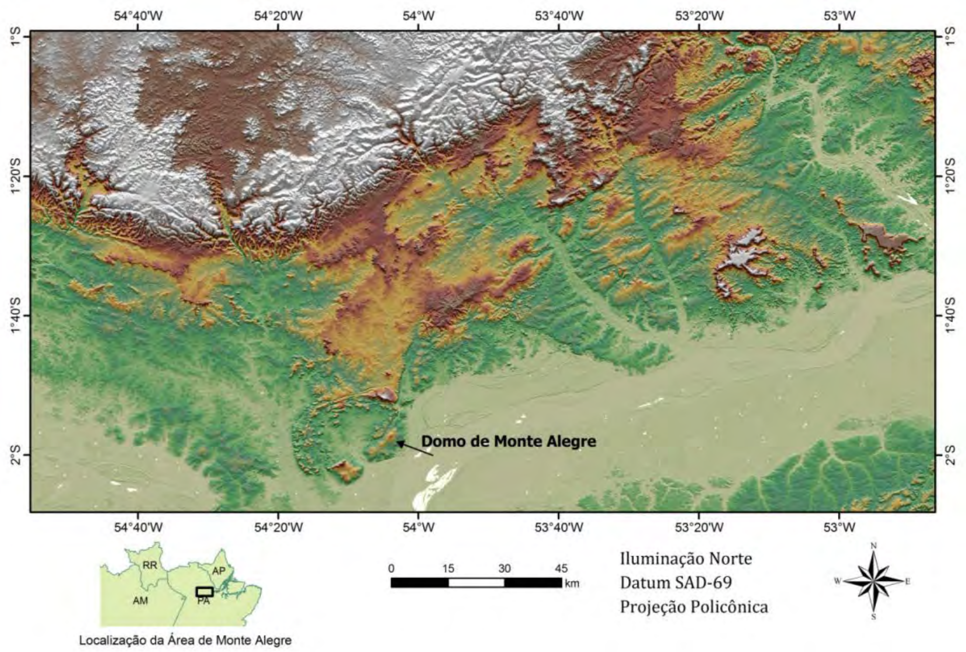


Figure 5-11. Elevation in the Monte Alegre region (Figueira 2011).

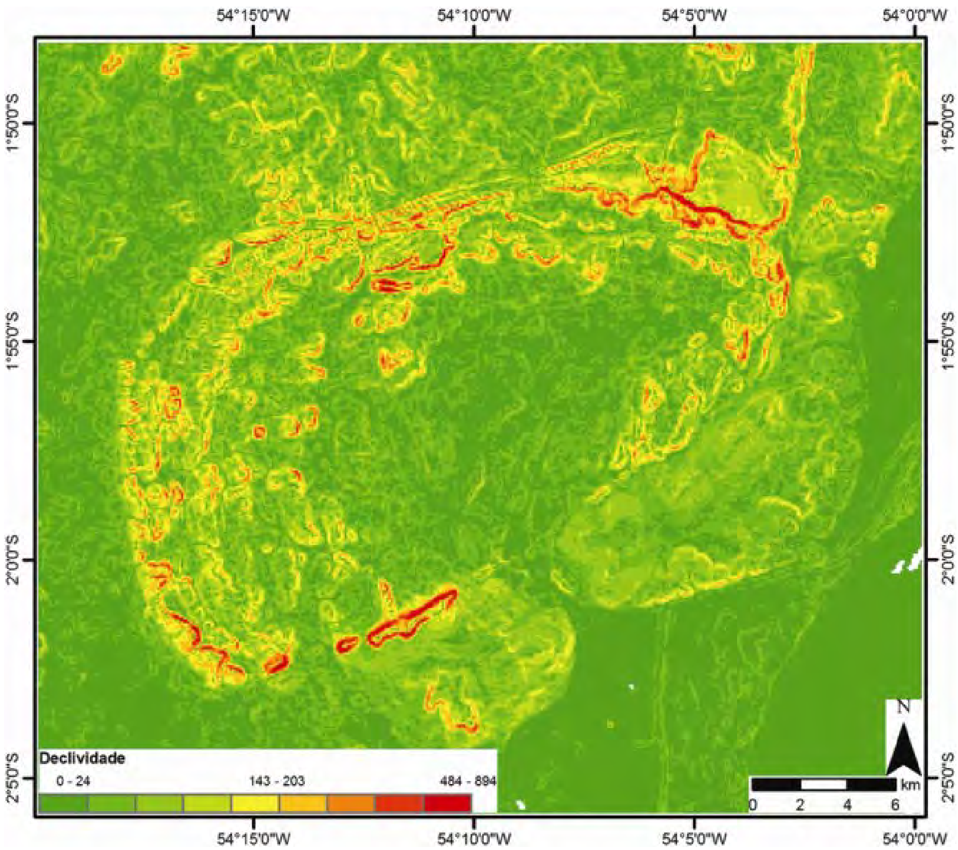


Figure 5-12. Slope of the Monte Alegre Dome (Figueira 2011). Note the well-defined SE border of the dome which coincides with the fault between the Paleozoic and the Cretaceous strata. The elongated structure along the SW portion of the fault defines Serra do Ereré where very hard and cemented sandstones were sampled (Figure 5-9).

Figure 5-13. The magnificent outcrops of the Mesoproterozoic Prosperança Formation; Cachoeira da São Luiz de Tapajós (GC1196-85). Note the mass-flow unit in the second photo.

Early – Middle Devonian Maecuru Fm (near GC1196-86).

Late Devonian Barrerinha Fm (GC1196-87.1).

Pensylvanian Itaituba Fm (GC1196-90)

Figure 5-14. Exposures of the Palaeozoic succession along Rio Tapajós. The rocks at these locations were affected by weathering to different degree.

Figure 5-15. Exposures of Alter do Chão Formation along Rio Tapajós. Two lower pictures: very coarse-grained conglomerate in the lowest (southernmost, GC1196-91) part of the formation. Two upper pictures: high cliffs with red sandstone (north of GC1196-92).

Figure 5-16. Road cut through a massive dike along the (N-S) Transamazonian Highway, most likely of CAMP age (not sampled).

Thick weathering mantle in the highest part of Serra Azul.

Late Ordovician - early Silurian sandstones of the Manacapuru Fm, 580 m a.s.l. (GC1196-103).

Pennsylvanian limestone and sandstone of the Pennsylvanian Nova Olinda Formation (GC1196-113.1, -114; Pedreira Calpará).

Figure 5-17. Rock exposures along a N-S transect across Serra Azul.

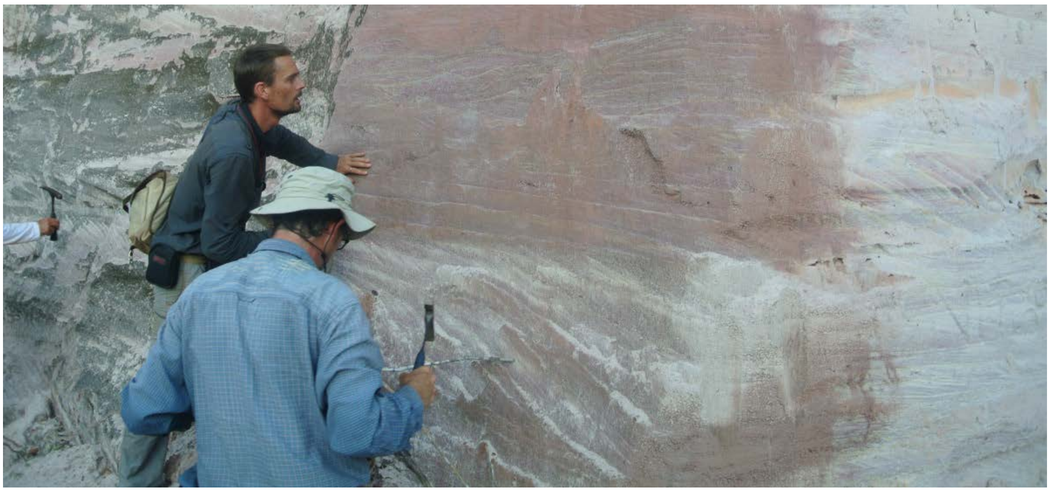


Figure 5-18. Uncemented Alter do Chão Formation near the quarry with Nova Olinda Formation, about 10 km NE of the Monte Alegre Dome (GC1196-115, 1 km from Pedreira Calpará).

Figure 5-19. Rocks at outcrop within the Monte Alegre Dome. **Upper**: Major fault through deposits of the Ereré Formation (GC1196-94). **Middle**: Anticlinal structure and fault through deposits of the Ereré Formation (GC1196-95). **Lower**: The summit of Serra do Ereré with very hard and well-cemented sandstone; 270 m a.s.l. (GC1196-100).

6. Samples collected

Samples were shipped to Geotrack International, Australia, for AFTA and VR from Paramaribo, Suriname and from Santarem via Curitiba. All samples are now in Geotrack's office. The details of these samples are listed in Table 6-1.

Salomon Kroonenberg has been so kind as to check the information regarding age and formation names for the samples collected in Suriname.

The samples collected in Brazil have been assigned with formation names and ages based on maps and field guides as indicated in Table 6-1. But there is of course some uncertainty in this assignment, even though it may not be important for the details of the interpretation of the AFTA data.

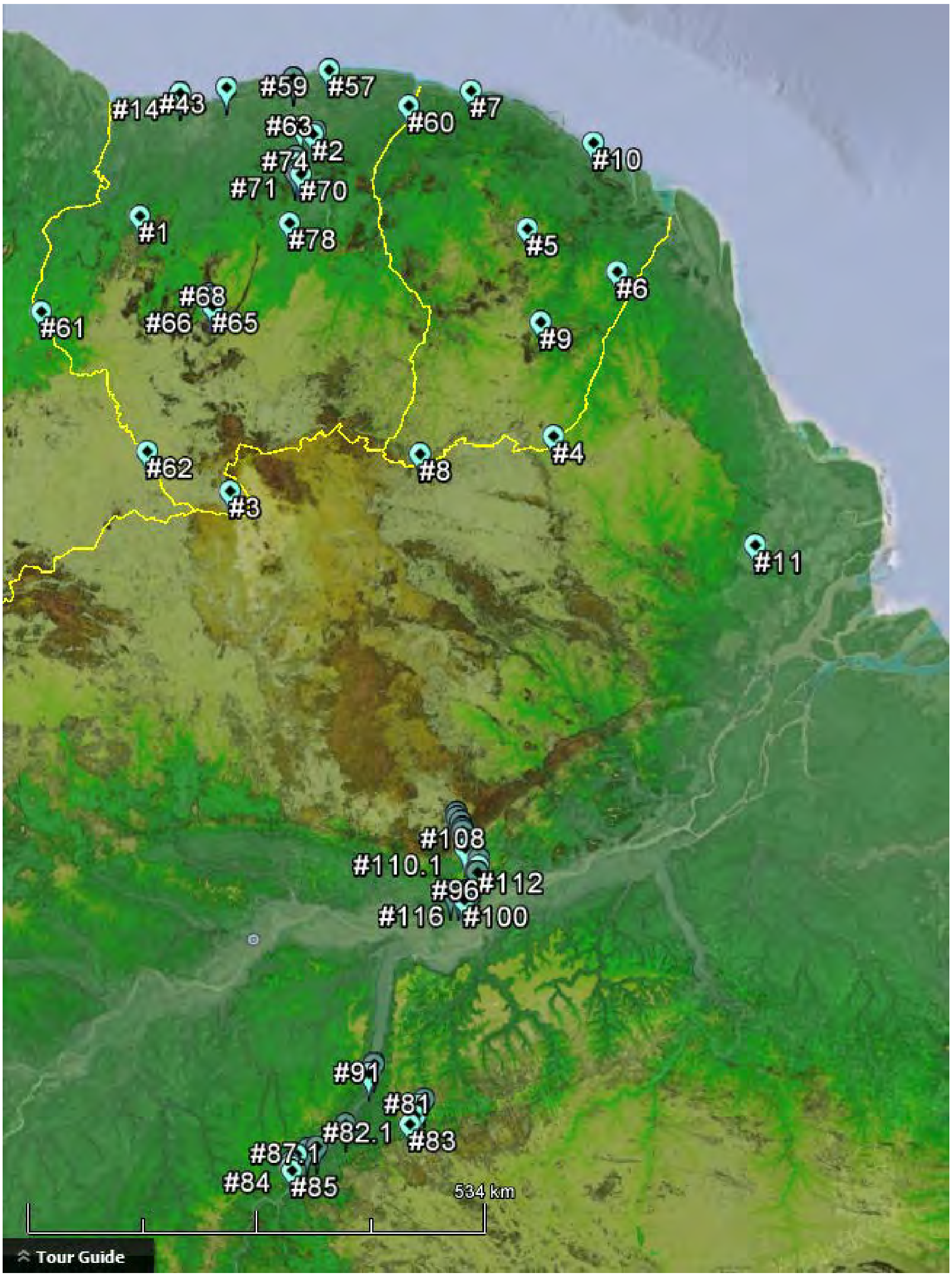


Figure 6-1. Overview of the onshore samples available for the project relative to the elevation model in Figure 3-1. We acquired samples 63–117 during the field campaign focussed along a 1200 km long N-S transect. Samples 1–11 are provided by the BRGM and 60–62 by the GMD. Samples 14–59 are from Cretaceous sediments from boreholes (AFTA data in 8 samples). Sample numbers refer to Geotrack prefix GC1196 (Table 6-1).

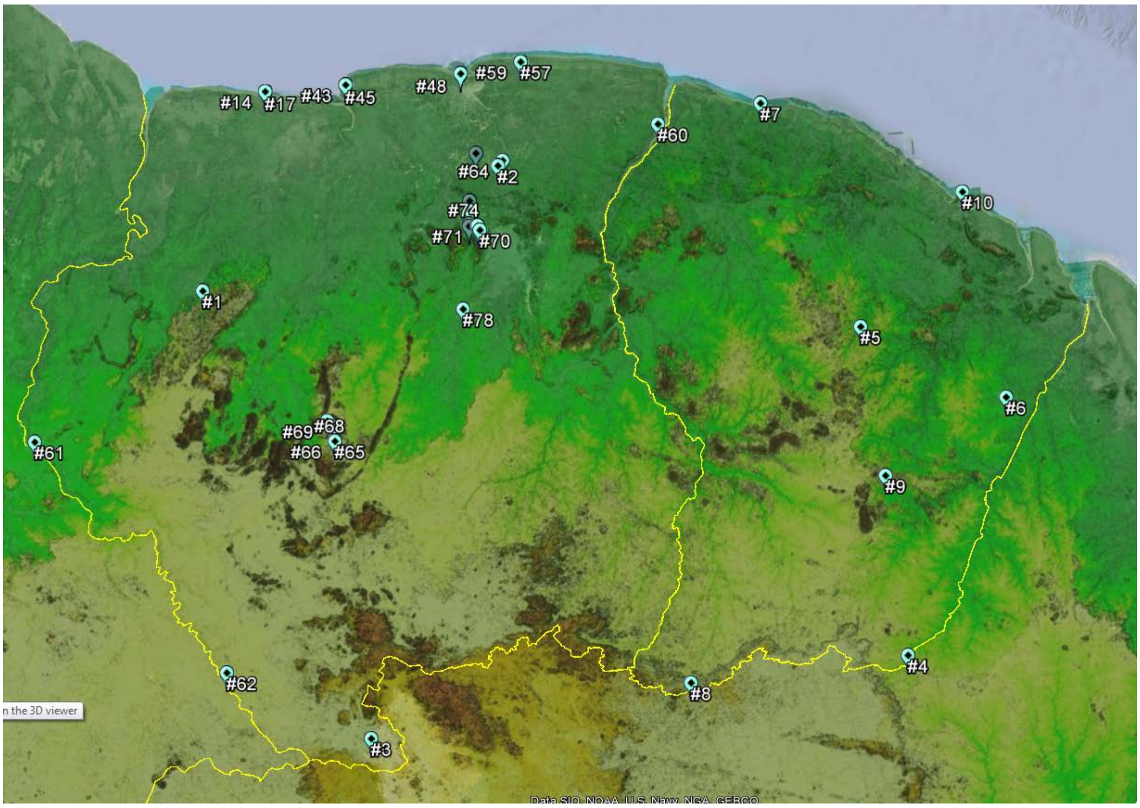


Figure 6-2. Onshore samples available from Suriname and French Guiana project relative to elevation.

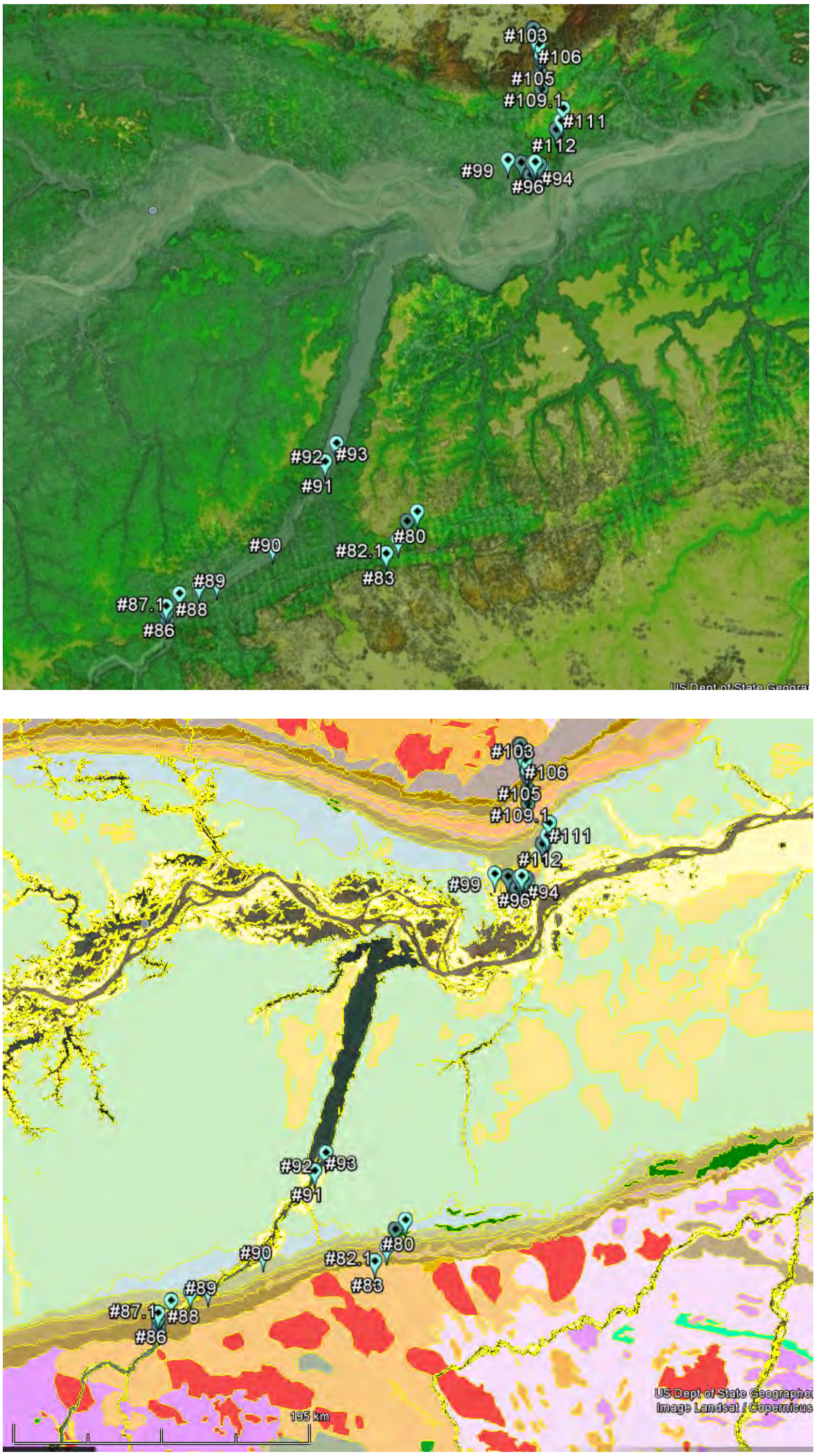
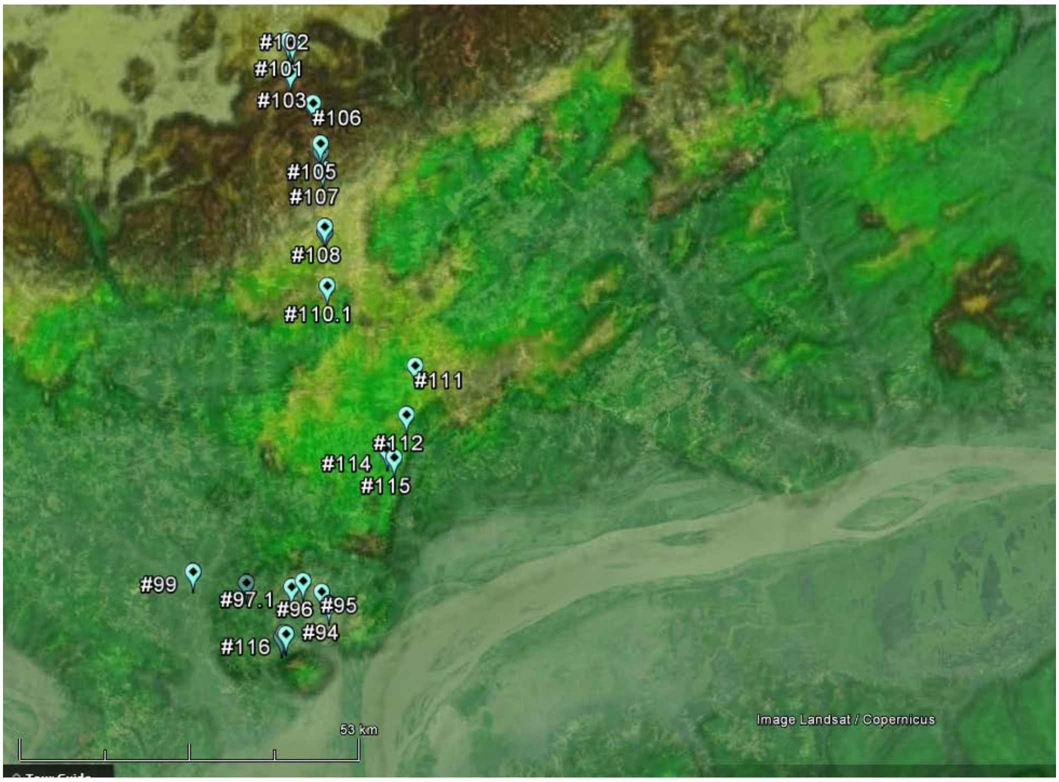


Figure 6-3. Samples collected along a 450 km long transect north and south of the Amazon relative to elevation (upper) and geology (upper; CPRM map). The Alter do Chão Fm (green) dominates the rocks at outcrop along the Amazon whereas Paleozoic strata (brown) crop out along the southern flank of the Guiana Shield and the northern Flank of the Brazilian Shield.



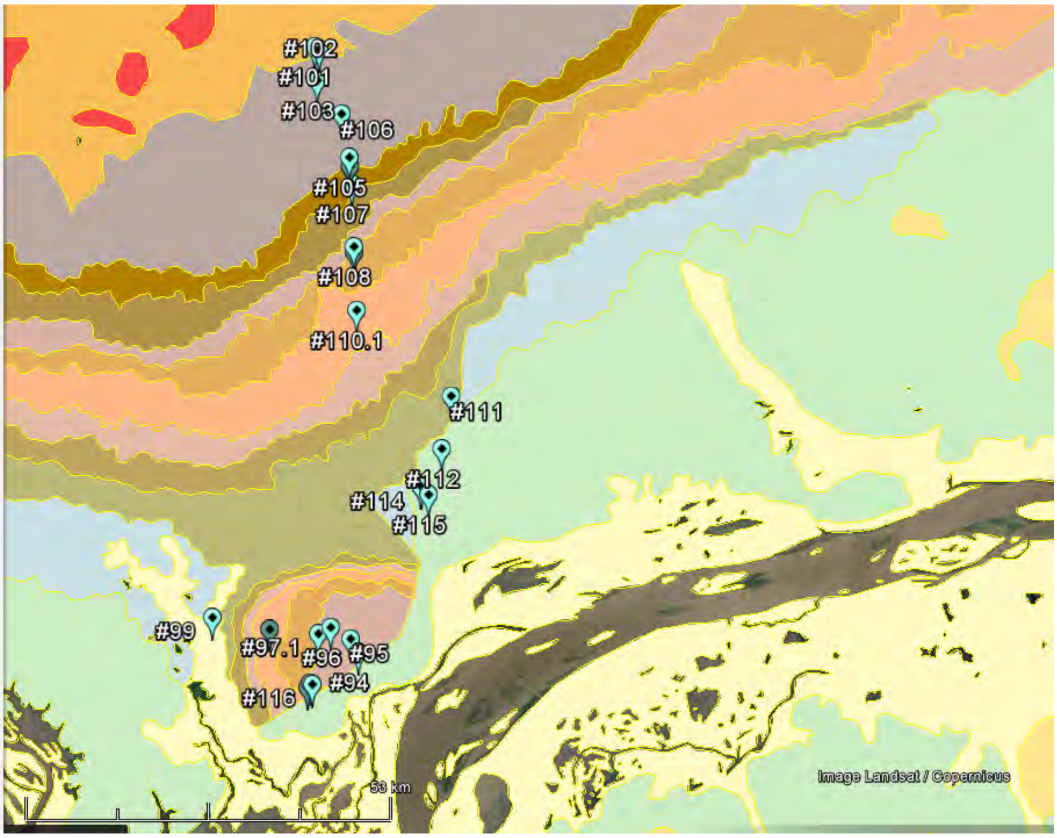
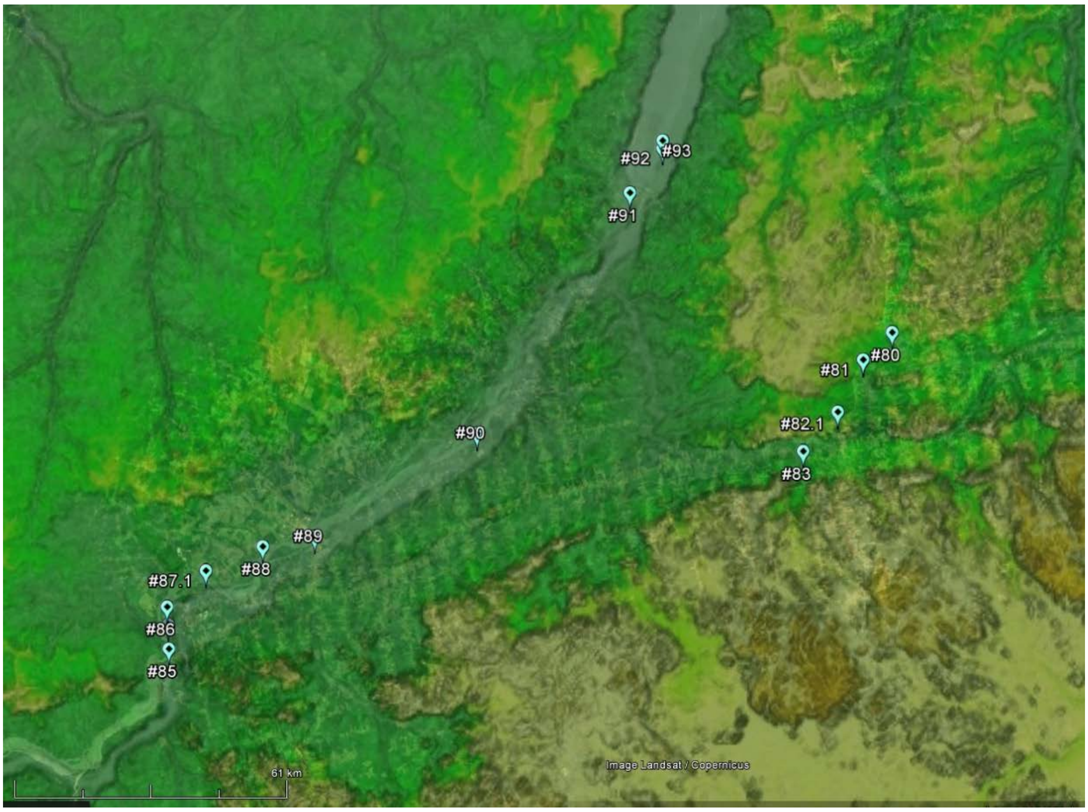


Figure 6-4. Samples collected along the southern flank of the Guiana Shield (across Serra Azul) relative to elevation (upper) and geology (lower). The outline of the Monte Alegre Dome is clearly visible on both maps.



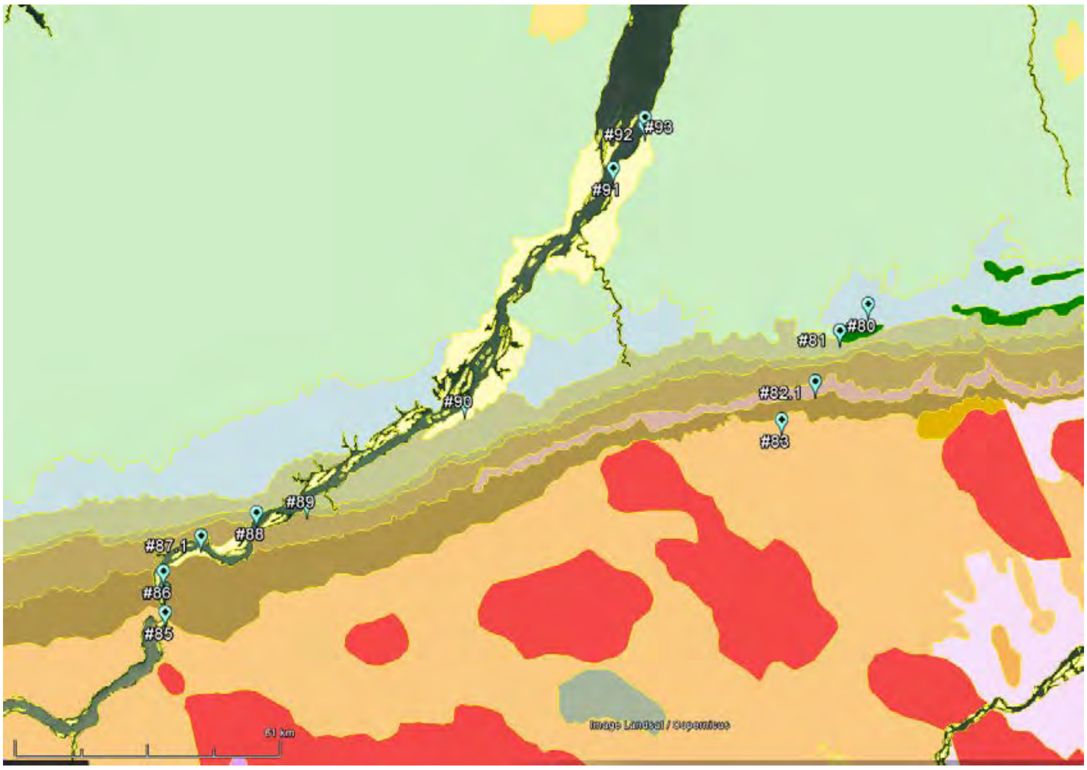


Figure 6-4. Samples collected along the northern flank of the Brazilian Shield (along the Transamazonian Highway and Rio Tapajós) relative to elevation (upper) and geology (lower).

Table 6-1. List of samples collected during fieldwork (next pages)

Comments to the table:

(*) Exact formation name difficult to determine, but all samples are likely to belong to Paleozoic sequence II.
Note the reference to outcrop localities presented by Matsuda et al. (2010) and by Figueira (2011).

Paleozoic sequences (Cunha *et al.* 2007):

I. Ordovician–Devonian
II. Devonian–Tournaisian
III. Early Visean (not sampled)
IV. Pensylvanian–Permian

Ages and formation names for Suriname samples (S. Kroonenberg, pers.comm. 2016).
(PRIEM *et al.* 1971; Kroonenberg 1978; Wong *et al.* 1998; Cunha *et al.* 2007; Matsuda *et al.* 2010; Daoust *et al.* 2011; Figueira 2011; Beyer *et al.* 2015; Daoust 2016; Kroonenberg *et al.* 2016; Naipal & Kroonenberg 2016).

Geotrack	GEUS	AFTA	VR	Apatite yield	Locality	Lat.	Long.	Elev. (m asl)
GC1196-60	548201	AFTA		Excellent	Albina, Papatamkondre	5.485	-54.080	15
GC1196-61	548202	AFTA		Excellent	Corantijn River,Tiger Falls	3.945	-57.979	100
GC1196-62	548203	AFTA		Excellent	Coeroeni River	2.476	-56.938	200
GC1196-63	548204	AFTA		not proc.	Airport S	5.412	-55.175	25
GC1196-64	548205	AFTA		Excellent	Saras Lust quarry	5.355	-55.020	20
GC1196-65	548206	AFTA		Excellent	Tafelberg, waterfall	3.790	-56.161	290
GC1196-66	548207	AFTA		not proc.	Tafelberg, waterfall	3.790	-56.161	290
GC1196-67	548208	AFTA		Excellent	Tafelberg, waterfall	3.790	-56.161	290
GC1196-68	548209	AFTA		Excellent	Tafelberg summit	3.873	-56.144	1010
GC1196-69	548210	AFTA		Excellent	Tafelberg intermediate	3.913	-56.197	600
GC1196-70	548211	AFTA		none	Brownsberg, Leo Val	4.954	-55.191	360
GC1196-71	548212	AFTA		none	Brownsberg, Irene Val	4.981	-55.202	100
GC1196-72	548213	AFTA		none	Brownsberg, Irene Val	4.981	-55.202	100
GC1196-73	548214	AFTA		Excellent	Brownsberg, Irene Val	4.981	-55.202	100
GC1196-74	548215	AFTA		Excellent	Rosebel gold mine	5.073	-55.235	-26
GC1196-75	548216	AFTA		Excellent	Rosebel gold mine	4.997	-55.250	-24
GC1196-76	548217	AFTA		Excellent	Rosebel gold mine	5.133	-55.237	-583
GC1196-77	548218	AFTA		Excellent	Rosebel gold mine	5.133	-55.237	-215
GC1196-78	548219	AFTA		Excellent	Atjoni, Kwai-Kwai Eiland	4.498	-55.332	25
GC1196-79	548220	AFTA		Excellent	Brownsweg SW	4.983	-55.252	50
GC1196-80	548221	AFTA			Transamazonia Highway	-3.884	-54.813	110
GC1196-81	548222	AFTA			Transamazonia Highway	-3.938	-54.871	125
GC1196-81.1	548222		VR		Transamazonia Highway	-3.938	-54.871	125
GC1196-82.1	548223		VR		Transamazonia Highway	-4.042	-54.921	75
GC1196-83	548224	AFTA			Transamazonia Highway	-4.119	-54.990	150
GC1196-84	548225	AFTA			Rio Tapajós S	-4.462	-56.255	5
GC1196-85	548226	AFTA			Cachoeira da São Luiz de Tapajós	-4.511	-56.253	5
GC1196-86	548228	AFTA			Rio Tapajós S	-4.427	-56.257	5
GC1196-87.1	548229		VR		Vila de Barrerinhas	-4.355	-56.179	5
GC1196-88	548231	AFTA			Rio Tapajós S	-4.307	-56.064	5
GC1196-89	548232	AFTA			Itaituba, east coast	-4.288	-55.960	5
GC1196-90	548233	AFTA			Cotovelo do Monte Christo	-4.083	-55.637	5
GC1196-91	548235	AFTA			Aveiro	-3.607	-55.333	5

Geotrack	Strat. age	Lithology
GC1196-60	Palaeoprot.	Gneiss
GC1196-61	Palaeoprot.	Metapelitic gneiss
GC1196-62	Palaeoprot.	Sillimanite- biotite-muscovite gneiss
GC1196-63	Pliocene	Loose, white sand. Pure? angular quartz
GC1196-64	Palaeoprot.	Gneiss
GC1196-65	Palaeoprot.	Granite, fine grained
GC1196-66	Palaeoprot.	Paleosol
GC1196-67	Palaeoprot.	sandstone
GC1196-68	Palaeoprot.	sandstone
GC1196-69	Palaeoprot.	sandstone
GC1196-70	Palaeoprot.	Sedimentary rock with chert
GC1196-71	Palaeoprot.	Meta-clastic
GC1196-72	Palaeoprot.	Meta-gabbro (mix with #71?)
GC1196-73	Palaeoprot.	Meta-quartzite (maybe mix)
GC1196-74	Palaeoprot.	granite
GC1196-75	Palaeoprot.	granodiorite
GC1196-76	Palaeoprot.	Arenite, turbidite
GC1196-77	Palaeoprot.	Arenite, turbidite
GC1196-78	Palaeoprot.	Migmatite
GC1196-79	Palaeoprot.	Conglomerate
GC1196-80	Pensylvanian (IV)	Sandstone
GC1196-81	Pensylvanian (IV)	sandstone + organic material
GC1196-81.1	Pensylvanian (IV)	sandstone + organic material
GC1196-82.1	Late Devonian (II)	Organic rich shale, source rock
GC1196-83	Palaeoprot. (Devonian cover)	Granite
GC1196-84	Palaeoprot. (Devonian cover)	Granite
GC1196-85	Mesoprot. (Silurian cover)	Sandstone, fine grained
GC1196-86	Early-Middle Devonian (II)	Coarse grained sandstone
GC1196-87.1	Late Devonian (II)	Organic rich shale, source rock
GC1196-88	Pensylvanian (IV)	Hard, coarse-grained sandstone
GC1196-89	Pensylvanian (IV)	Fairly fresh sandstone
GC1196-90	Pensylvanian (IV)	Hard sandstone, coarse grained
GC1196-91	Cretaceous (Aptian - Maastr.)	Conglomerate

Geotrack	Formation	Comment
GC1196-60	Sara's Lust Gneiss	GMD Papatam quarry
GC1196-61	Bakhuis Granulite Belt	GMD core store. KG572
GC1196-62	Amotopo Gneiss	GMD core store. SBR-26
GC1196-63	Zanderij Fm	Derived from weathered basement
GC1196-64	Sara's Lust Gneiss	
GC1196-65	Sipaliwini Leucogranite	Samples within 5 m vertical
GC1196-66	-	Boundary basement and sandstone
GC1196-67	Tafelberg Fm, Roraima Supergroup	1555 Ma according to Priem 1971; see also Beyer 2015 (Roraima ages)
GC1196-68	Tafelberg Fm, Roraima Supergroup	See Kroonenberg 2016
GC1196-69	Tafelberg Fm, Roraima Supergroup	Collapse of cavity may be the cause for the low elevation (Kroonenberg)
GC1196-70	Paramaka Fm (Greenstone Belt)	Near illegal goldmine
GC1196-71	Paramaka Fm (Greenstone Belt)	Samples 12.13.14 are from the same location, different lithologies
GC1196-72	Paramaka Fm (Greenstone Belt)	
GC1196-73	Paramaka Fm (Greenstone Belt)	
GC1196-74	Patamacca Granite?	Borehole, south of intrusion. Deviated borehole. RHD-722, 82 m
GC1196-75	Kabel Tonalite?	Borehole, south of intrusion. Deviated borehole. KO12-36, 81 m
GC1196-76	Armina Fm (Greenstone Belt)	Late Amazonian. Devaiated borehole. PCD-556, 697 m
GC1196-77	Armina Fm (Greenstone Belt)	Late Amazonian. Devaiated borehole. PCD-556, 280 m
GC1196-78	Sara's Lust Gneiss	Late Amazonian
GC1196-79	Rosebel Fm (Greenstone Belt)	Late Amazonian
GC1196-80	Nova Olinda Fm	Recent road cut
GC1196-81	Monte Alegre Fm	Also VR sample
GC1196-81.1	Monte Alegre Fm	Also VR sample
GC1196-82.1	Barrerinha Fm (Erere Fm?)	
GC1196-83	Uatumã Granite	Covered by Maecuru Fm
GC1196-84	Uatumã Granite	Covered by Maecuru Fm; Early-mid Devonian (Matsuda et al. 2010)
GC1196-85	Prosperanca Fm	South of granite. Matsuda et al. (2010): Locality 1A. Cover: Silurian Pitinga Fm
GC1196-86	Maecuru Fm	Too weathered?. Matsuda et al. (2010): 5A
GC1196-87.1	Barrerinha Fm	Matsuda et al. (2010): Locality 7
GC1196-88	Monte Alegre Fm	Fresh rock, fallen from higher elevation. Matsuda et al. (2010): Locality 10
GC1196-89	Monte Alegre Fm	
GC1196-90	Itaituba Fm	
GC1196-91	Alter do Chão Fm	Deeply weathered matrix, cm-size pebbles (AFTA provenance?)

Geotrack	GEUS	AFTA	VR	Apatite yield	Locality	Lat.	Long.	Elev. (m asl)
GC1196-92	548236	AFTA			Aveiro N	-3.518	-55.268	5
GC1196-93	548237	AFTA			Further north of Aveiro	-3.503	-55.267	5
GC1196-94	548238	AFTA			PA255, Quarry, Airi	-1.970	-54.113	50
GC1196-95	548239	AFTA			PA255	-1.953	-54.123	50
GC1196-96	548240	AFTA			PA255; Campo do Esterro	-1.939	-54.149	50
GC1196-97.1	548241		VR		Igarape do Urubu	-1.947	-54.165	50
GC1196-98.1	548242		VR		PA255	-1.941	-54.227	50
GC1196-99	548243	AFTA			PA255, Caucu	-1.926	-54.302	50
GC1196-100	548245	AFTA			Pico do Erere, Pedra do Mirante	-2.016	-54.178	270
GC1196-101	548246	AFTA			Northernmost locality	-1.195	-54.165	340
GC1196-102	548247	AFTA			Small farm (Setor 06)	-1.199	-54.159	380
GC1196-103	548248	AFTA			Serra Azul, big valley (Setor 06)	-1.239	-54.159	580
GC1196-104	548249	AFTA			Serra Azul (Setor 06)	-1.348	-54.120	400
GC1196-105	548251	AFTA			(Pa 254 Setor 06)	-1.337	-54.120	320
GC1196-106	548252	AFTA			Small quarry	-1.282	-54.129	375
GC1196-107	548253	AFTA			(Pa 254 Setor 06)	-1.370	-54.118	260
GC1196-108	548254	AFTA			(Pa 254 Setor 06)	-1.450	-54.116	190
GC1196-109.1	548255		VR		(Pa 254 Setor 06)	-1.458	-54.116	200
GC1196-110.1	548256		VR		(Pa 254 Setor 06)	-1.532	-54.113	150
GC1196-111	548257	AFTA			PA423	-1.641	-53.992	210
GC1196-112	548258	AFTA			PA423	-1.709	-54.004	130
GC1196-113.1	548259		VR		Pedreira Calpará; MA-20	-1.757	-54.031	130
GC1196-114	548260	AFTA			Pedreira Calpará; MA-20	-1.757	-54.031	130
GC1196-115	548261	AFTA			Just 1 km from the quarry	-1.768	-54.021	130
GC1196-116	548262	AFTA			Serra do Erere, East	-2.012	-54.172	80
GC1196-117	548263	AFTA			Serra do Erere, East	-2.010	-54.175	80

Geotrack	Strat. age	Formation
GC1196-92	Cretaceous (Aptian - Maastr.)	Alter do Chão Fm
GC1196-93	Cretaceous (Aptian - Maastr.)	Alter do Chão Fm
GC1196-94	Early-Middle Devonian (II)	Ereré Fm
GC1196-95	Early-Middle Devonian (II)	Ereré Fm
GC1196-96	Early-Middle Devonian (II)	Ereré Fm
GC1196-97.1	Late Devonian (II)	Ereré Fm
GC1196-98.1	Early Mississipian (II)	Curiri Fm
GC1196-99	Pensylvanian (IV)	Monte Alegre Fm
GC1196-100	Cretaceous? thermal effect?	Alter do Chão Fm, probably
GC1196-101	Paleoprot. (near Ord-Sil cover)	
GC1196-102	Paleoprot. (near Ord-Sil cover)	
GC1196-103	Late Ord. - early Silurian (I)	Manacapuru Fm, Trombetas Group
GC1196-104	Early Devonian (I)	Jatapu Fm; Trombetas Group
GC1196-105	Early Devonian (I)	Jatapu Fm; Trombetas Group
GC1196-106	Late Ord. - early Silurian (I)	Manacapuru Fm, Trombetas Group
GC1196-107	Early-Middle Devonian (II)	Maecuru Fm*
GC1196-108	Early-Middle Devonian (II)	Ereré Fm*
GC1196-109.1	Late Devonian (II)	Barerinhas Fm*
GC1196-110.1	Early Mississipian (II)	Curiri Fm*
GC1196-111	Pensylvanian (IV) (Cret. cover)	Monte Alegre Fm
GC1196-112	Cretaceous (Aptian - Maastr.)	Alter do Chão Fm
GC1196-113.1	Pensylvanian (IV)	Nova Olinda Fm
GC1196-114	Pensylvanian (IV) (Cret. cover?)	Nova Olinda Fm
GC1196-115	Cretaceous (Aptian - Maastr.)	Alter do Chão Fm
GC1196-116	Cretaceous? thermal effect?	Alter do Chão Fm, probably
GC1196-117	Cretaceous? thermal effect?	Alter do Chão Fm, probably

Geotrack	Lithology	Comment
GC1196-92	Sandstone, medium to fine grained	Felspar preserved. 25 m high cliff; alluvial plain
GC1196-93	Sandstone, coarse grained; heavy mineral zones	Fluvio-deltaic system
GC1196-94	Sandstone	Center of MTA Dome, Large-scale fault. Maybe 20 m high outcrop, Topographic expression. Figueira MA-7
GC1196-95	Sand-shale	Within dome, clear fault (drag fault), Outcrop only 1 m high
GC1196-96	Coarse grained sandstone	Figueira MA-31
GC1196-97.1	Black shale	within dome, Figueira MA-8
GC1196-98.1	Shale, sandy	Figueira MA-51
GC1196-99	Fine-grained sandstone	Figueira MA-40
GC1196-100	Coarse grained sandstone, hard and cemented	Elongated mountain range located right on top of fault separating Paleozoic and
GC1196-101	Basement, metasediment cut by pegmatite	Small river
GC1196-102	Gneiss?, metasediment	(JY: age of metam. unknown)
GC1196-103	Coarse-grained sandstone, cemented, fresh	
GC1196-104	Fine-grained sandstone, weathered	Mountains coinsides with Trompetas sandstone
GC1196-105	Weathered sandstone	
GC1196-106	Hard and fresh sandstone	
GC1196-107	Fresh, fine-grained sandstone	
GC1196-108	Fine-grained sandstone	
GC1196-109.1	Siltstone	(sent by mail from Copenhagen)
GC1196-110.1	Black, organic rich siltstone	
GC1196-111	Weathered sandstone, ok?	Alter do Chão resting on Paleozoic
GC1196-112	Fairly fresh sandstone, very coarse grained	A good AFTA candidate
GC1196-113.1	Black shale	
GC1196-114	Sandstone, fine to medium grains.	Alter do Chão on top of quarry (map) or
GC1196-115	Coarse-grained sandstone, not cemented	fairly fresh outcrop, a good AFTA candidate. 1 km from limestone quarry (GC1196-114)
GC1196-116	Very coarse-grained sandstone, totally cemented	Car-size boulder below summit. Same as GC1196-100
GC1196-117	Very coarse-grained sandstone, totally cemented	Car-size boulder below summit. Same as GC1196-100

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