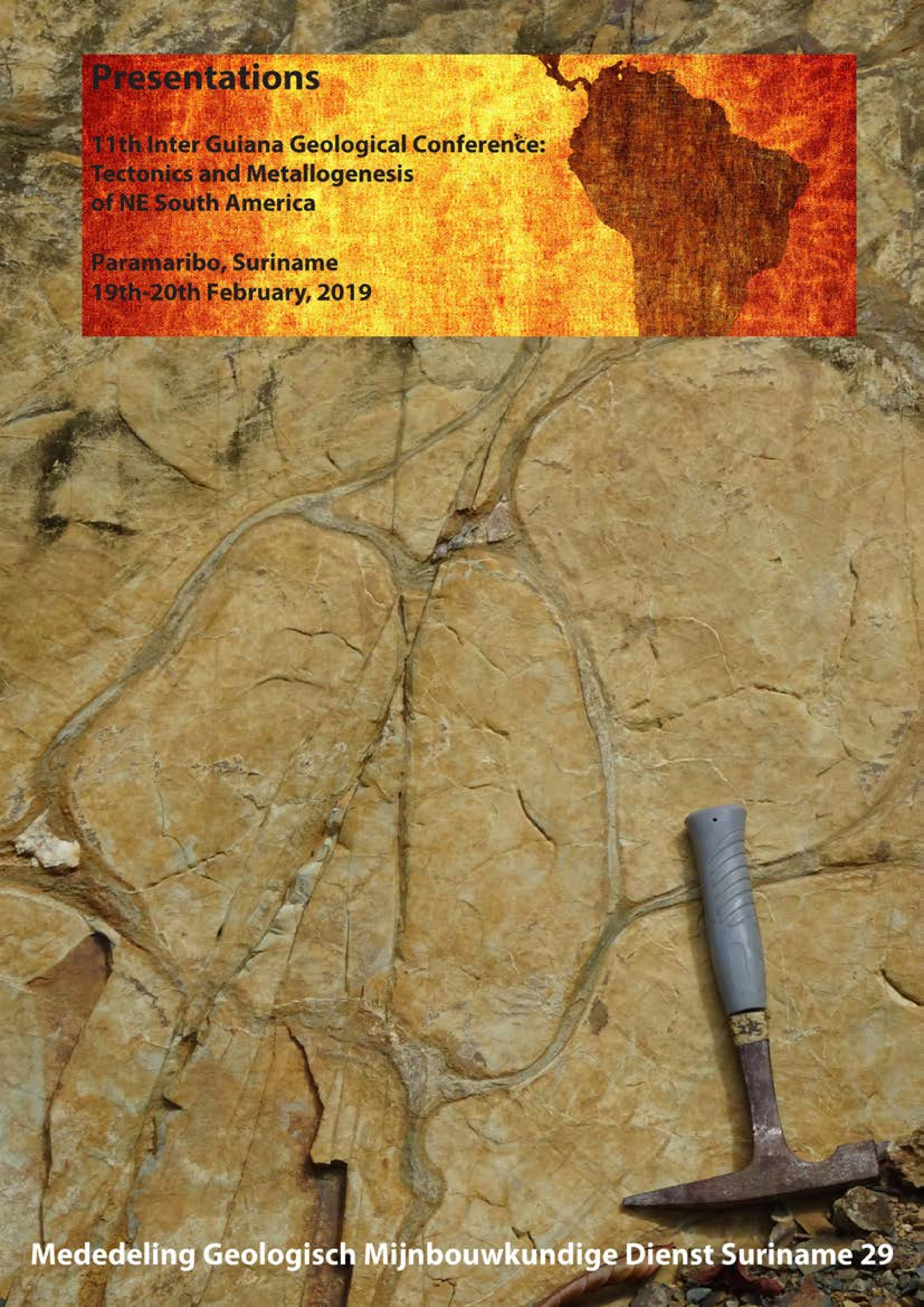


# Presentations

## 11th Inter Guiana Geological Conference: Tectonics and Metallogenesis of NE South America

Paramaribo, Suriname
19th-20th February, 2019

Mededeling Geologisch Mijnbouwkundige Dienst Suriname 29

# Geochemical Exploration in Regolith Dominated Terrains

**Ravi Anand, Rob Thorne, Walid Salama, Vasek Metelka**

MINERAL RESOURCES
www.csiro.au

# Characterization of physical and chemical parameters of Guiana shield surfaces Application to geological & regolith mapping

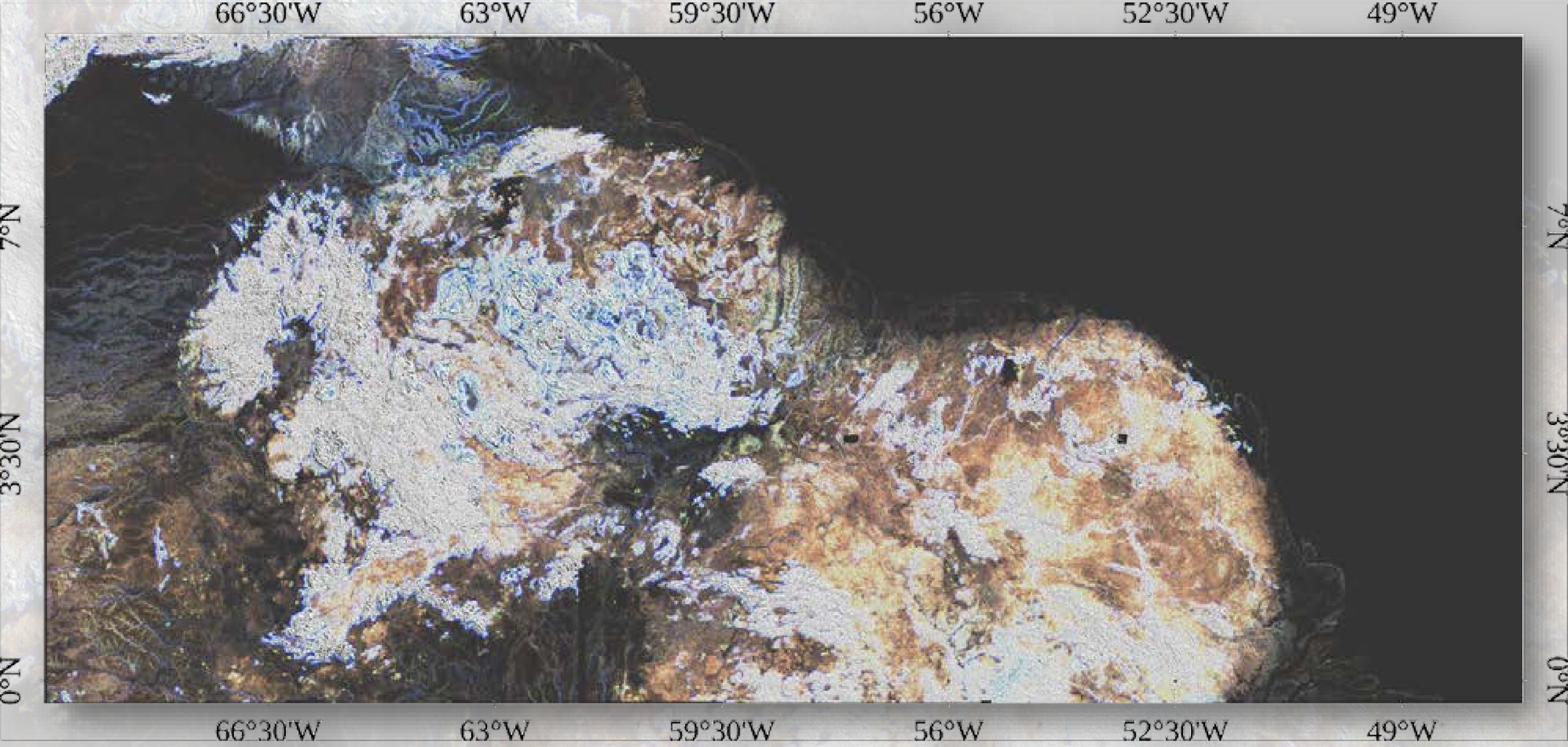
David BARATOUX

French National Research Institute for Sustainable Development
Géosciences Environnement Toulouse

The Tectonics and Metallogenesis of NE South America
Paramaribo, Surniname, 19th - 20th February 2019

# Motivations

- In the context of limited outcrops, new approaches may be developed to identify the nature of the bedrock from recent remote sensing data
- Geomorphology – Preliminary results in West Africa and previous works in the Guiana shields (Kroonenberg and Melitz 1983, Bugnicourt et al. 2018) indicate the potential of quantitative geomorphological approaches (=> multi-scale roughness mapping).

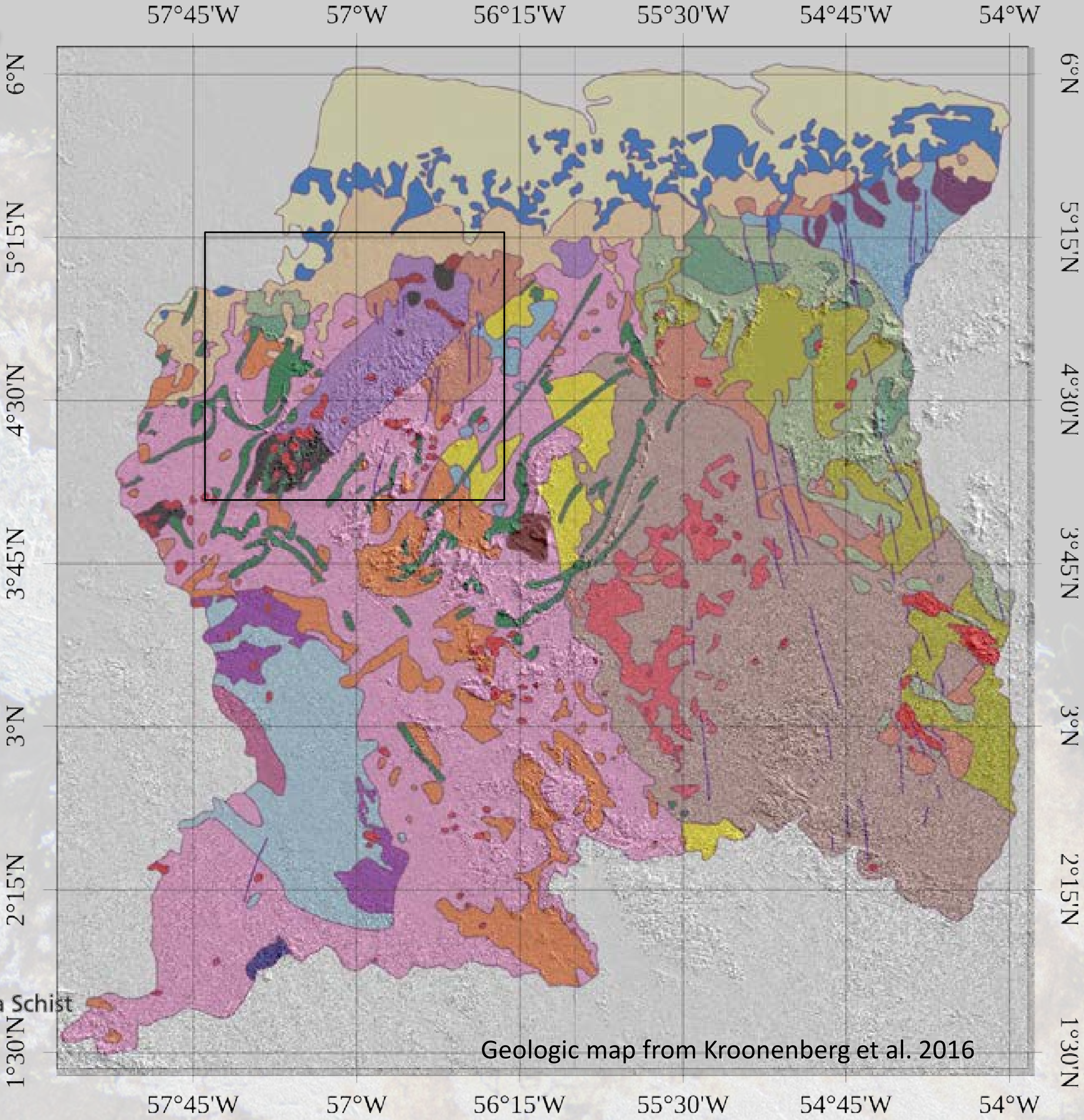


# Suriname geology & roughness

## Bakhuis Granulite Gneiss

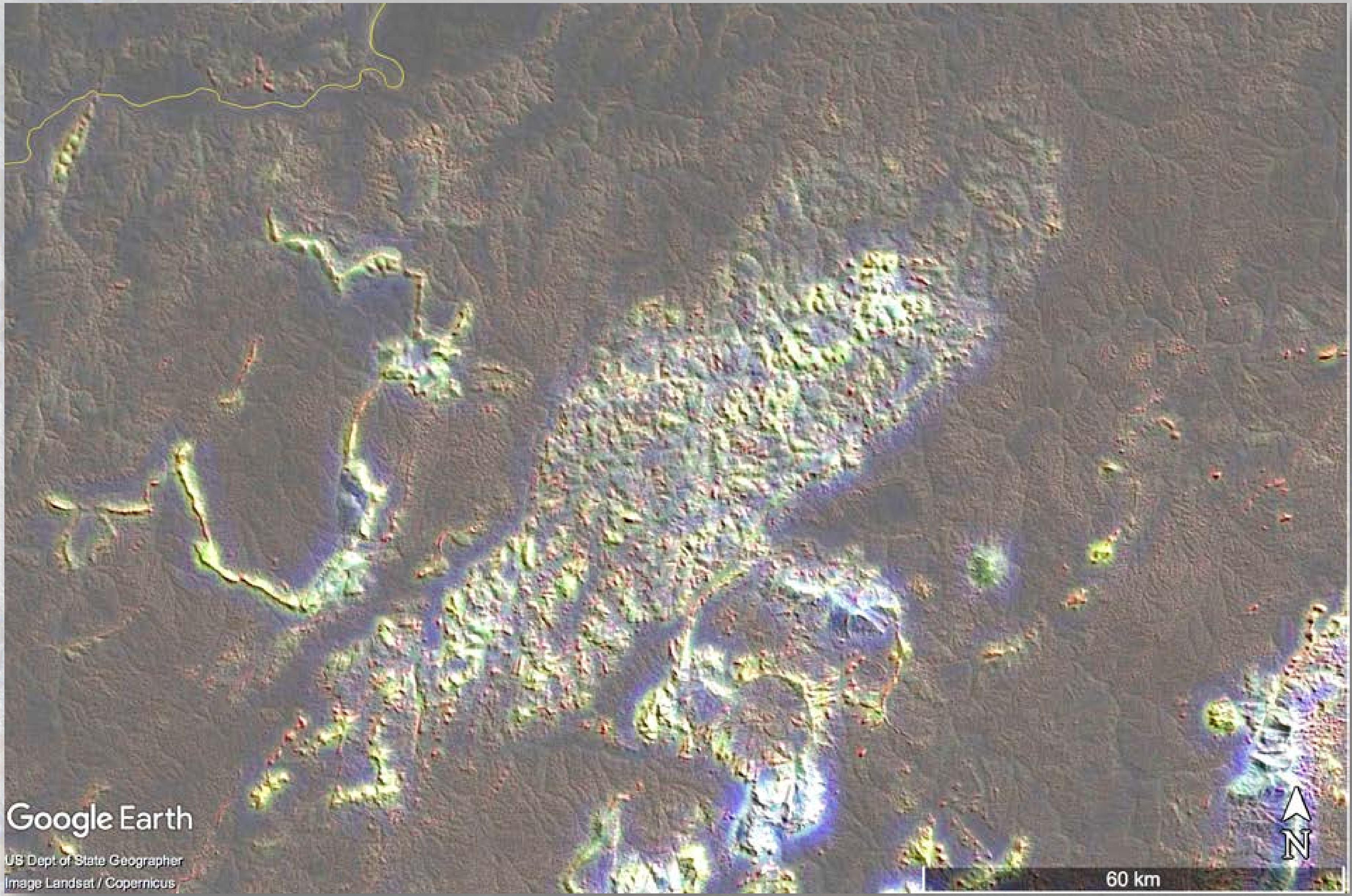
**Proterozoic**

- Muri Alkaline Complex
- Avanavero and Käyser Dolerite
- Tafelberg Formation
- Kabalebo Charnockite
- Lucie Gabbro and Bemau Ultramafitite
- Coppename Muscovite Granite
- Wonotobo Granite and Sipaliwini Leucogranite
- Dalbana Formation
- Coeroeni Gneiss Belt: Dome Hill Gneiss
- Coeroeni Gneiss Belt: Amotopo Gneiss
- Coeroeni Gneiss Belt: Werekitto Gneiss
- Bakhuis Granulite Belt: Stondansi Gneiss
- Bakhuis Granulite Belt: Bakhuis Granulite
- Gran Rio Granite
- Pikien Rio Pyroxene Granite
- Sara's Lust Gneiss
- Greenstone belt, Rosebel Formation
- Greenstone belt, Patamacca Granite
- Greenstone belt, Armina Formation and Taffra Schist
- Greenstone belt, TTG, Kabel Tonalite
- Greenstone Belt, Paramaka Formation



Geologic map from Kroonenberg et al. 2016

# Suriname geology & roughness



# Suriname geology & roughness

Geologic map from Kroonenberg et al. 2016

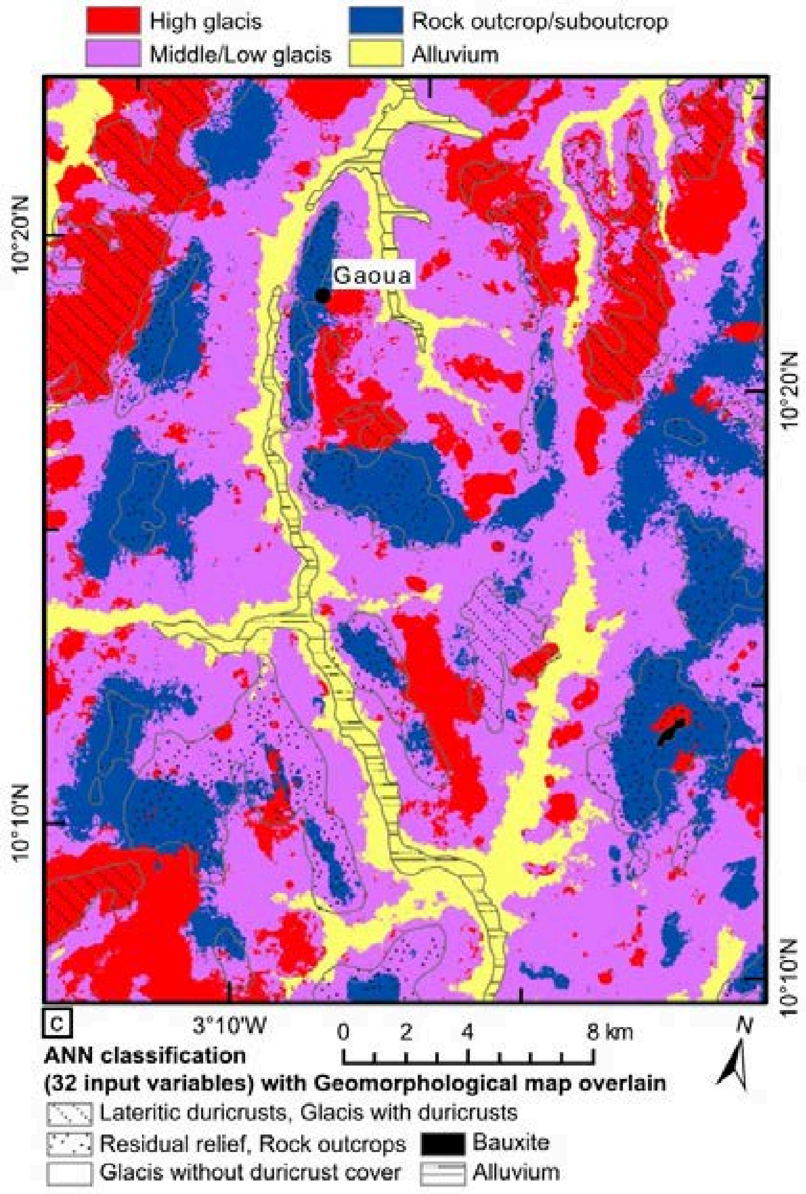
# Motivations

- Geostatistical analyses of radiometric data – WAXI experience in the WAC
  Variograms modified by superfical processes
  Potential to distinguish in-situ from transported regolith

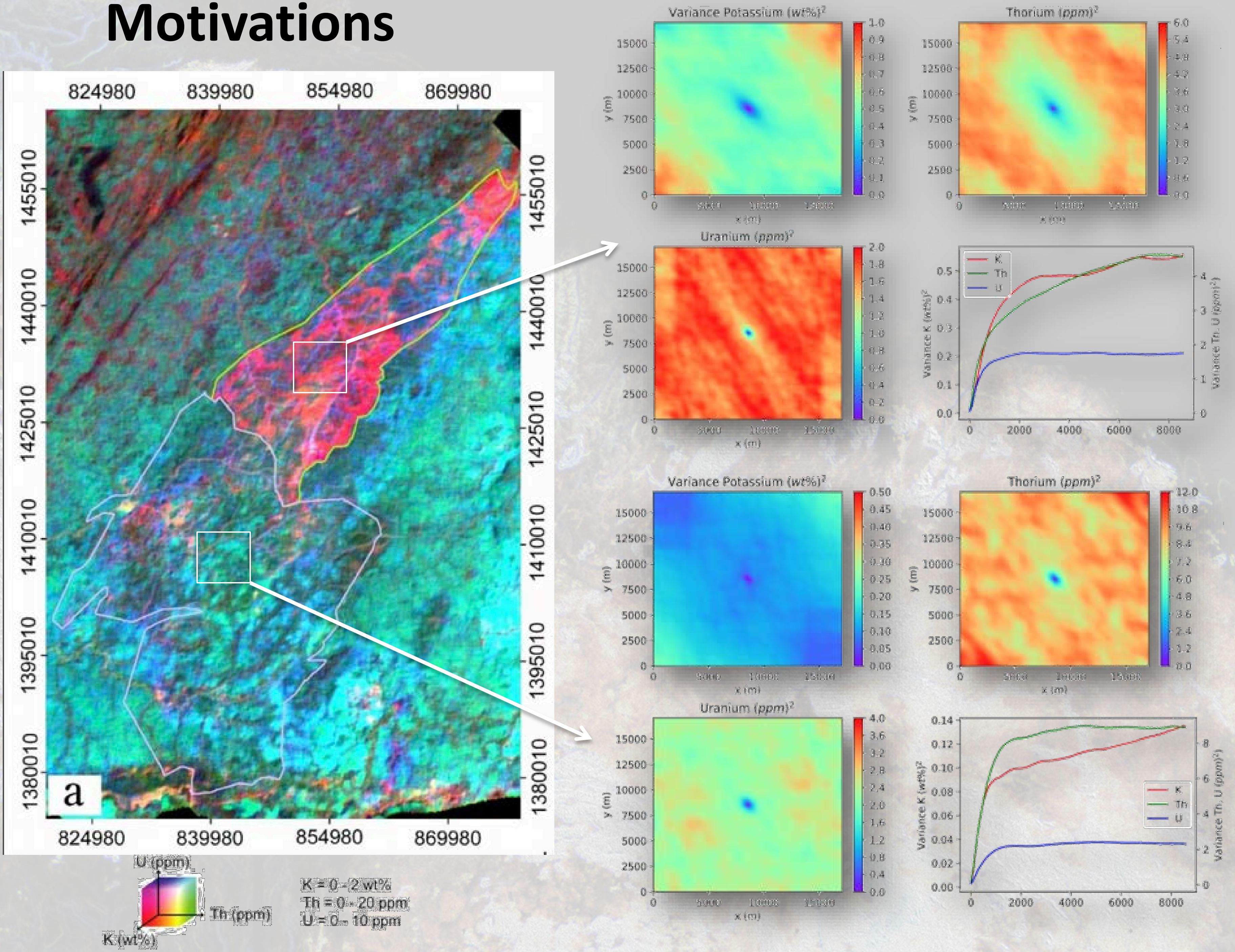
**Metelka et al. (2018)** Automated regolith landform mapping using airborne geophysics and remote sensing data, Burkina Faso, West Africa. Remote sensing of Environnement.

Slope
Roughness
K, Th, U  maps
Radar data
Imagery
Geophysics

**Machine learning**



# Motivations



# Module objectives - methodological developpements

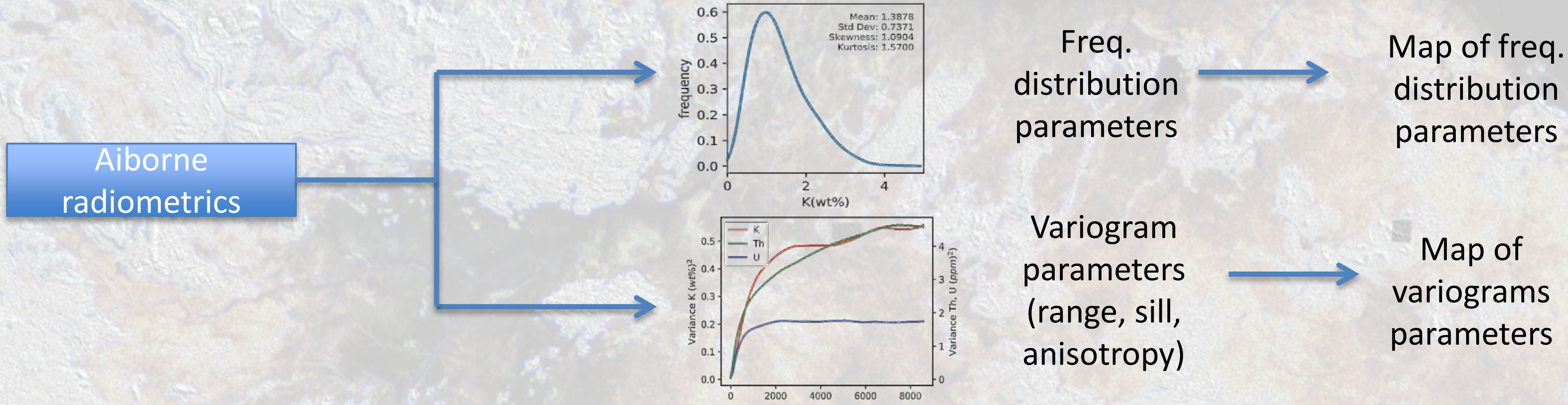
- Regional quantitative morphology (multi-scale roughness maps)
  Based on SRTM data 1”/pixel and 3”/pixel denoised

- Regional geostatiscal analyses of radiometric data

**Chemical dispersion indices**
**Geostatistical analyses from airborne radiometrics**

**Multi-scale automatic extraction of geostat. parameters**

**Maps + interpretation**



Aiborne radiometrics

Freq. distribution parameters

Map of freq. distribution parameters

Variogram parameters (range, sill, anisotropy)

Map of variograms parameters

- Multi-scale regional roughness maps + geostatistical analyses of airborne radiometrics & comparison with other geophysical data > support for geological & regolith mapping

- Application of similar approaches for high-resolution mapping using high-resolution geophysical data + high-resolution topographic data (Lidar)

# Module Deliverables

- Multi-scale roughness map of the Guiana shield (up to 10 different baselines)
- Mapping products based on geostatistical analyses of airborne radiometrics
- Regional Interpretations and lessons for the use of similar approaches at the local scale
- Multi-scale roughness maps and mapping products based on geostatistical analyses of airborne radiometrics on key localities base on high-resolution data, and interpretation

This module may be an independent module or part of a module on structural geophysics.

# Budget

- High-performance computer: 3000 €

- Software licence (ENVI): ~1000 €/y

- Field work
  Validation of remote sensing interpretations: 4000 €/y

- Participation to annual meeting and other traveling costs
  5000 €/y

- Ph.D. student from South America: ~ 40 k€

Total: ~ 73 k€

REUNION GOLD CORPORATION

# The Nivré Gold Deposit

## Dorlin Project

### French Guiana

South American Exploration Initiative

Paramaribo, February 19, 2019

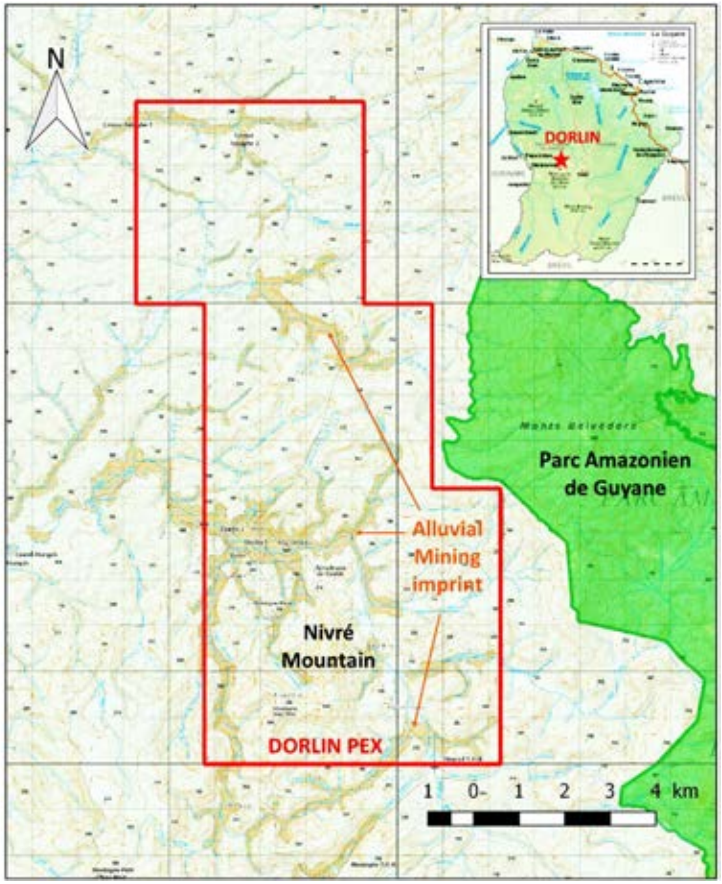
Carlos H. Bertoni

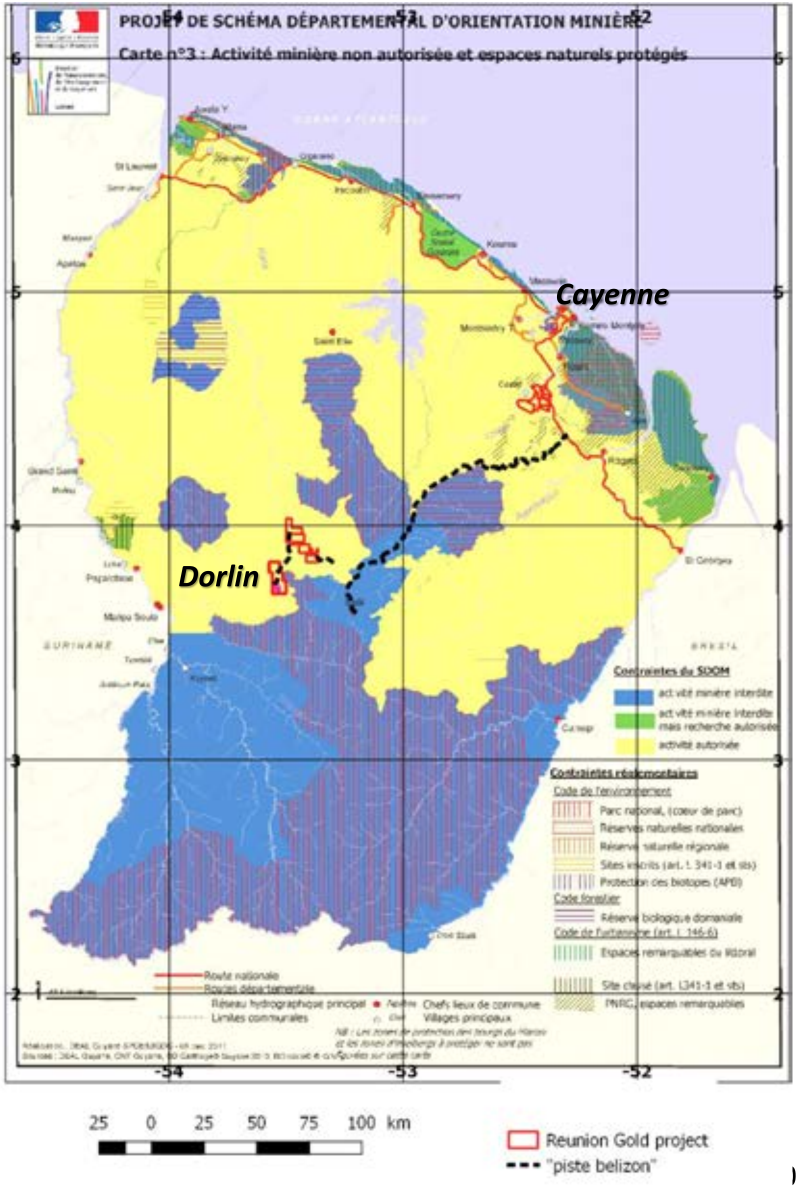
and

Dorlin Project team

# Introduction

- Dorlin Project is located 190 km SW of Cayenne, accessible by air, bush trail and boat.
- In 2018, Reunion Gold entered option to acquire up to 80% interest of the *PEX* (85 km²).

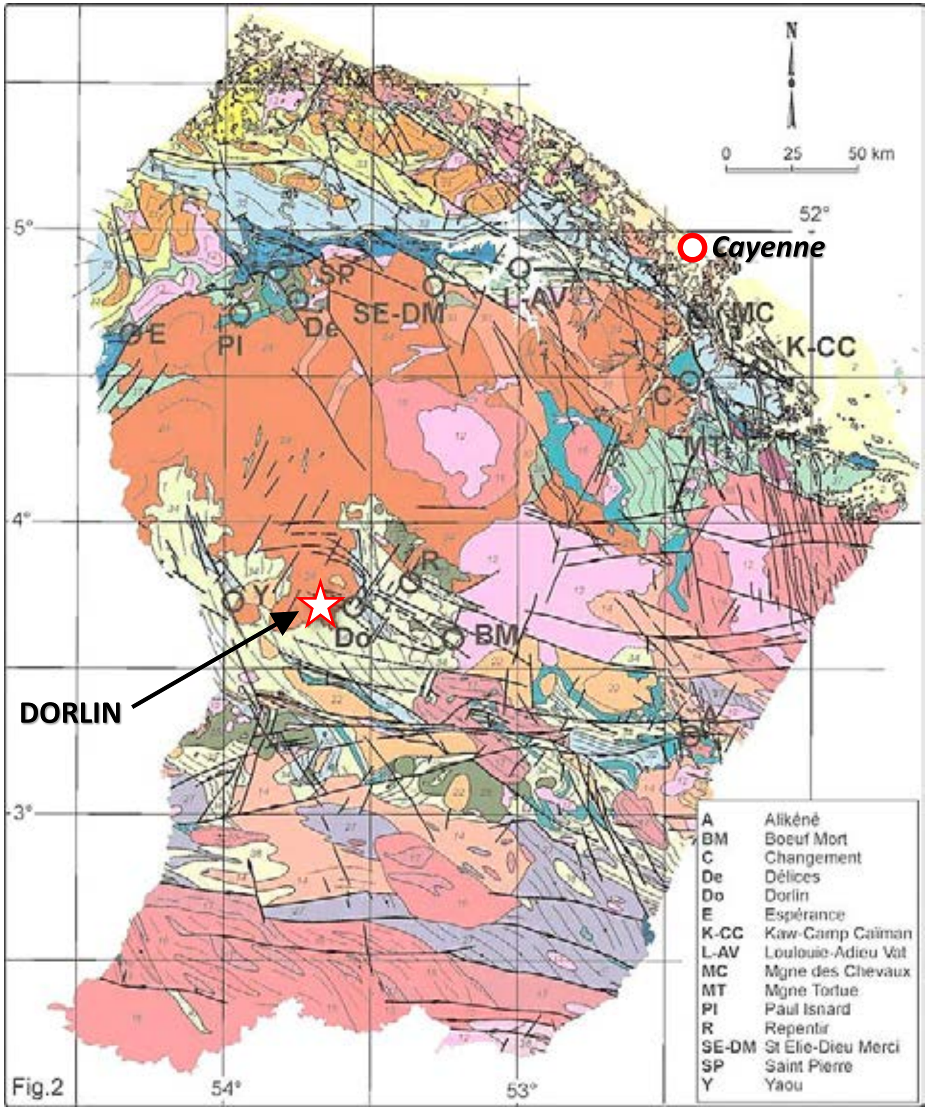




# History

- Active artisanal mining from 1st half of 20th century and nineties.
- Project previously explored from seventies until 1998 by BRGM + BHP, Guyanor Resources + Cambior.

Artisanal adit

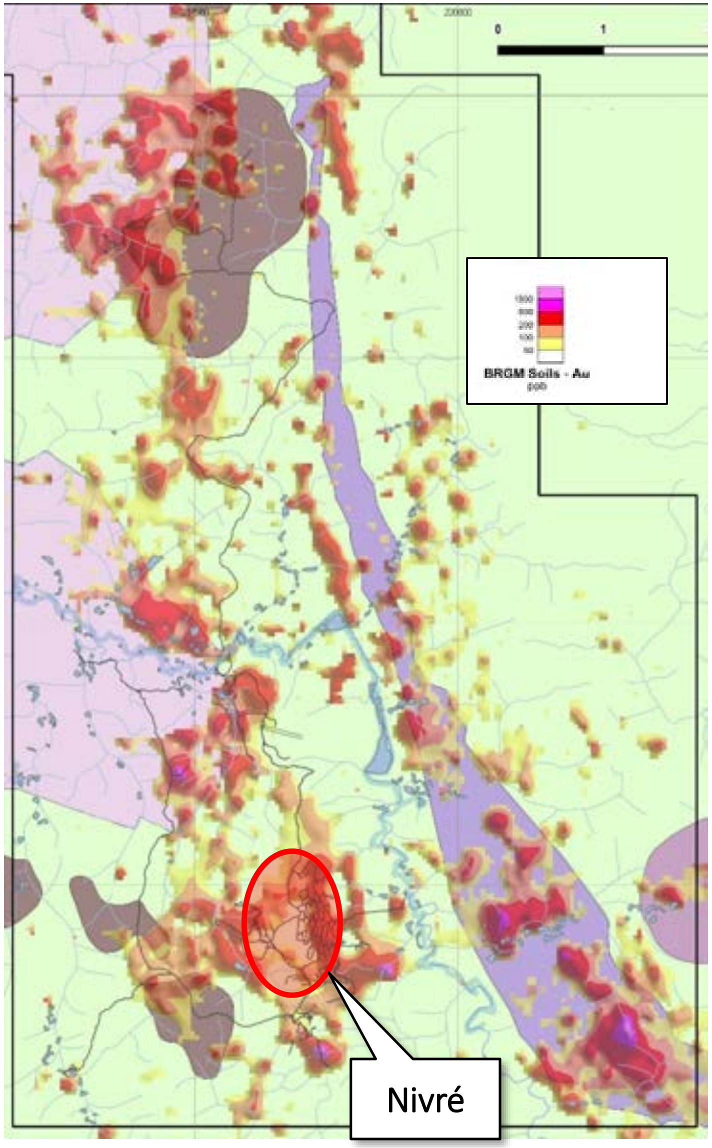


after Delor et al., 2001, 2003

# Exploration work

- BRGM discovered sources of alluvial gold and did extensive soil geochem, mapping and preliminary drilling of Nivré deposit.
- Pre-Reunion Gold drilling: 18,427 m
- Reunion Gold 2018 drilling: 6,585 m (validation & resource expansion)
- Total drilling: 31,211 m (91% Nivré)
- Historical resources (non NI 43-101 compliant) by Guyanor-Cambior in 1998 for Nivré deposit (at US$ 400/oz.):
  - ✓ M&I = 21.9 Mt @ 1.1 g/t = 779 k oz.
  - ✓ Inferred = 22 Mt @ 1.1 g/t = 793 k oz.

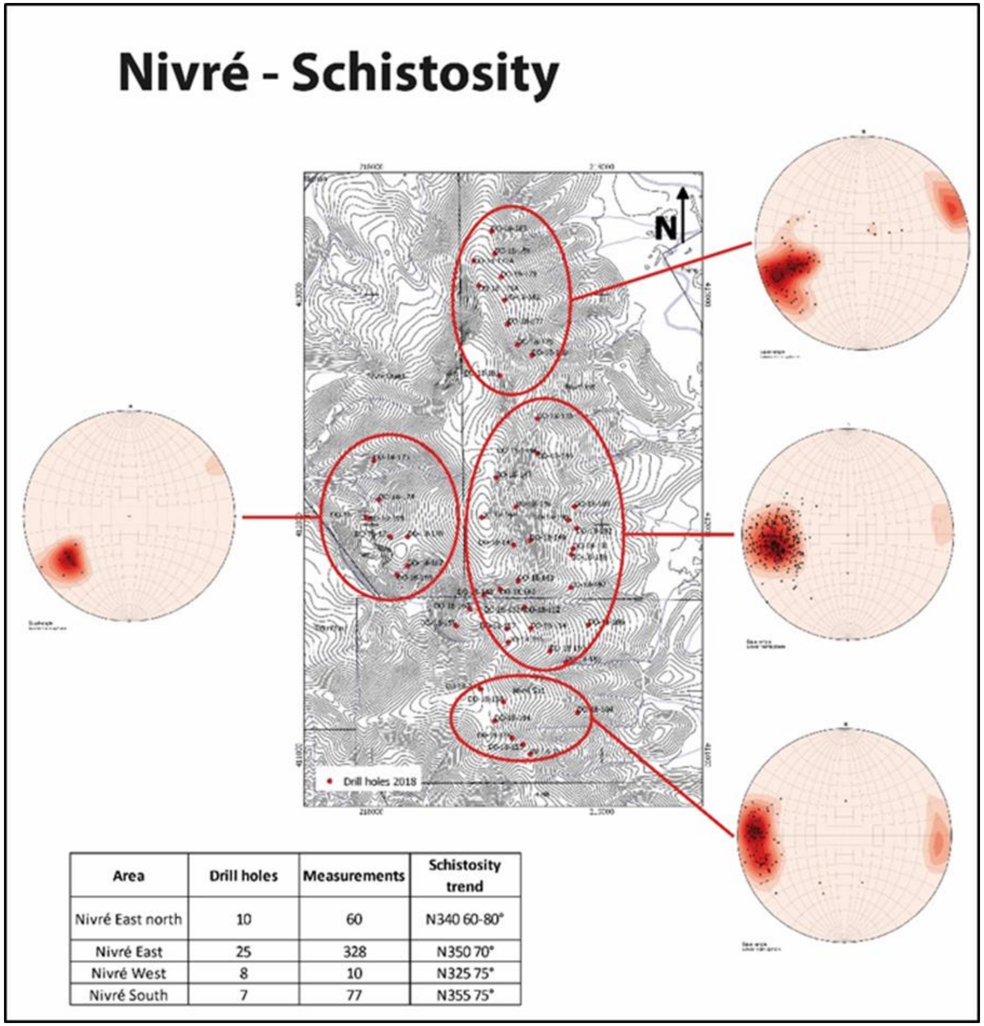
# Geology and gold soil geochem



- Proterozoic volcanic sequence (Paramaca Group) of dacitic to basaltic composition: mostly volcaniclastics
- Ultramafic “lineament” from Cr+Co+Ni anomaly on BRGM soil data
- Granitic / granodioritic plutons on the western edge of the *PEX*
- Diorite & gabbro intrusives.
- Gold soil anomalies associated with more than one geological environment.

# Alteration & Structure

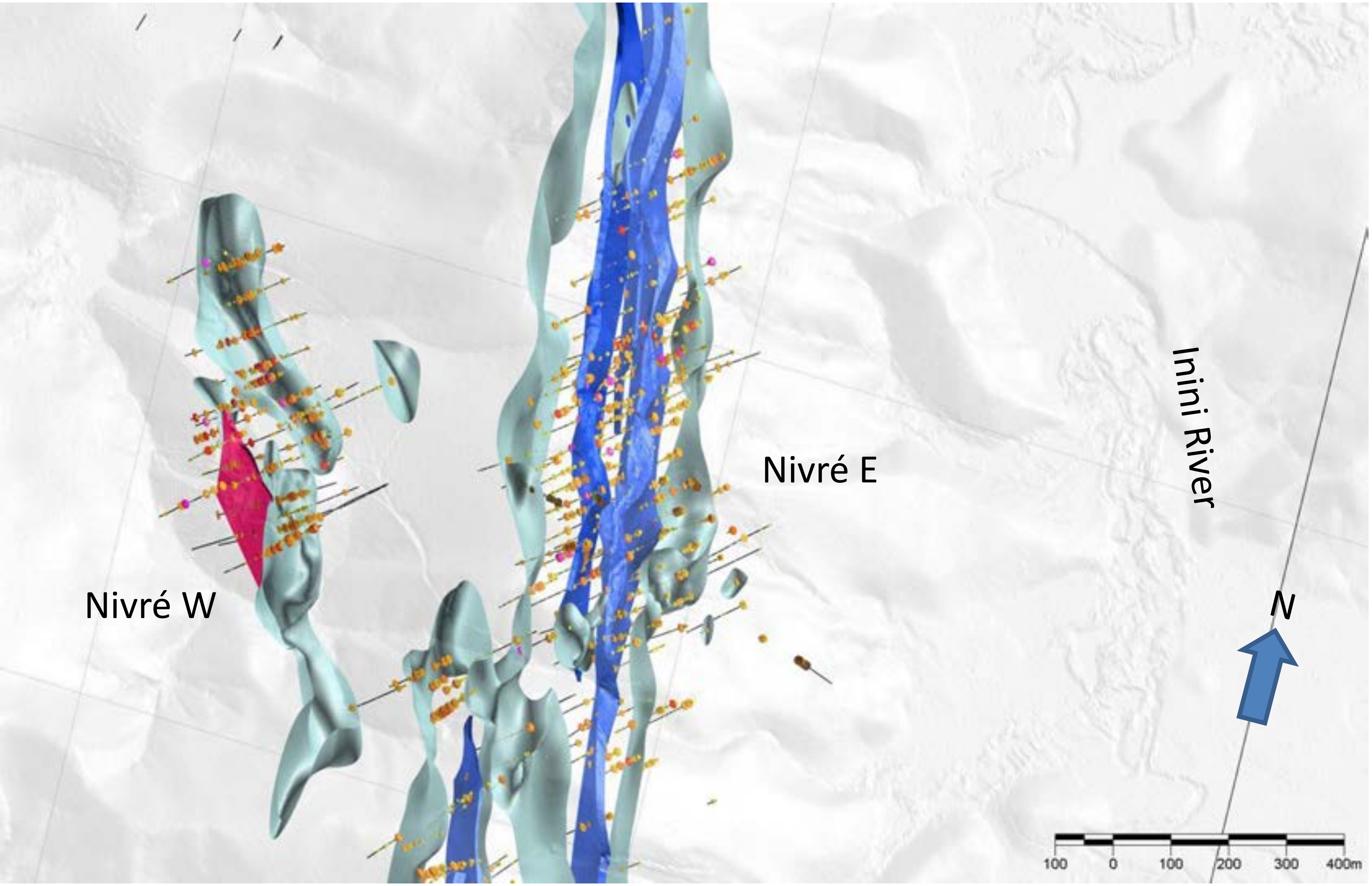
- Early and intense pervasive boron-silica alteration along NS "corridor" in volcanic sequence, forming tourmaline-silica bodies within a regional N-NW shear zone, locally deflected to a NS orientation due to the western granitic plutons.
- Wider halo of chlorite-clay alteration enveloping the massive silica-tourmaline.
- Numerous veining events, including a late quartz-ankerite phase that crosscuts mineralization.
- Strong pervasive S1 fabric, generally subvertical and striking NS, parallel to mineralization.



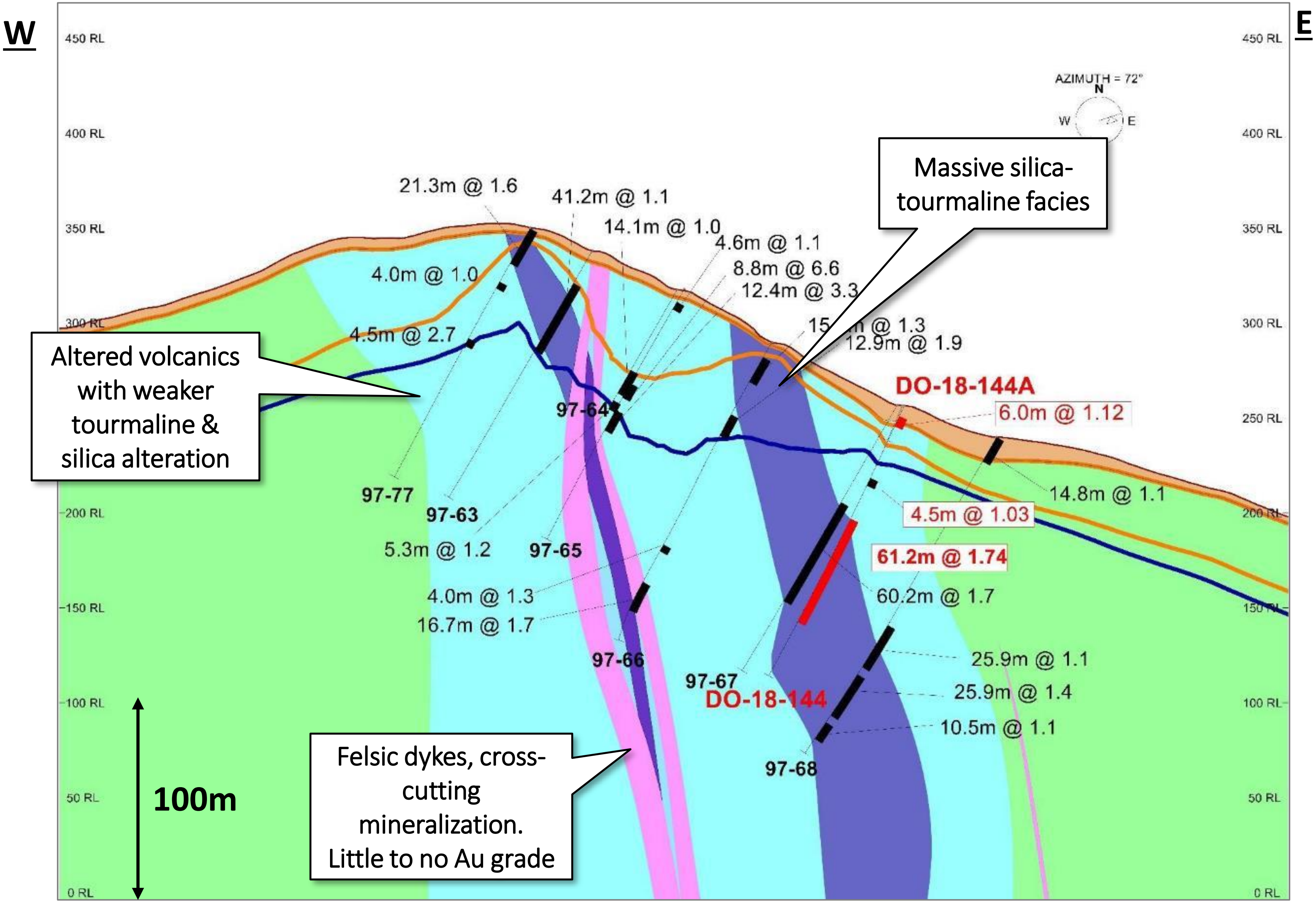
**Nivré - Schistosity**

| Area | Drill holes | Measurements | Schistosity trend |
|---|---|---|---|
| Nivré East north | 10 | 60 | N340 60-80° |
| Nivré East | 25 | 328 | N350 70° |
| Nivré West | 8 | 10 | N325 75° |
| Nivré South | 7 | 77 | N355 75° |

# Nivré deposit E and W zones (looking N-NW)



# Section across Nivré East



Massive silica-tourmaline facies

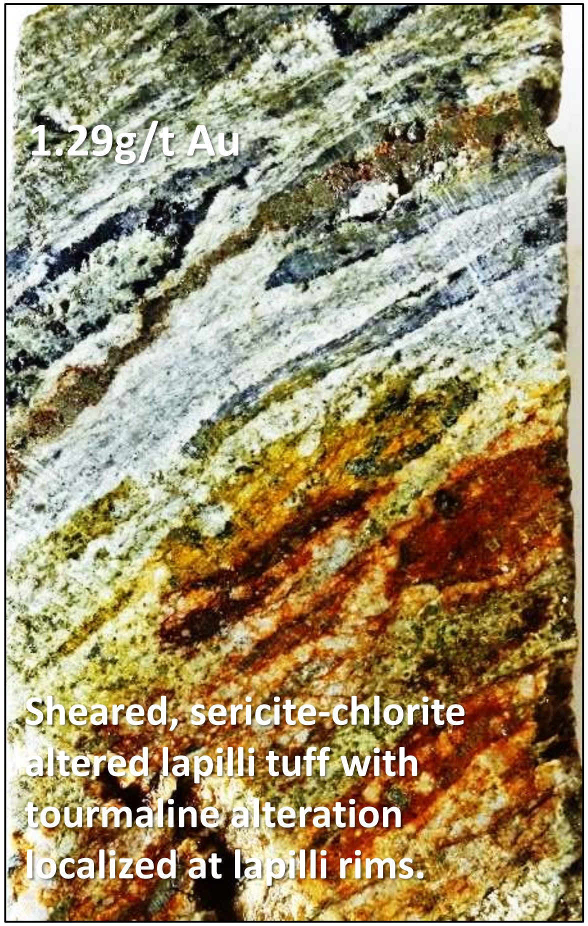
Altered volcanics with weaker tourmaline & silica alteration

Felsic dykes, cross-cutting mineralization. Little to no Au grade

# Mineralization (1)

- Gold mineralization best known at Nivré mountain and prospects.
- Spatial association with tourmaline-silica-pyrite facies (both syn- and post-tourmalinisation)

- Tourmaline alteration a function of protolith:
  - Gradual clast replacement within lapilli tuff
  - Crystalline tourmaline growth within tuff units



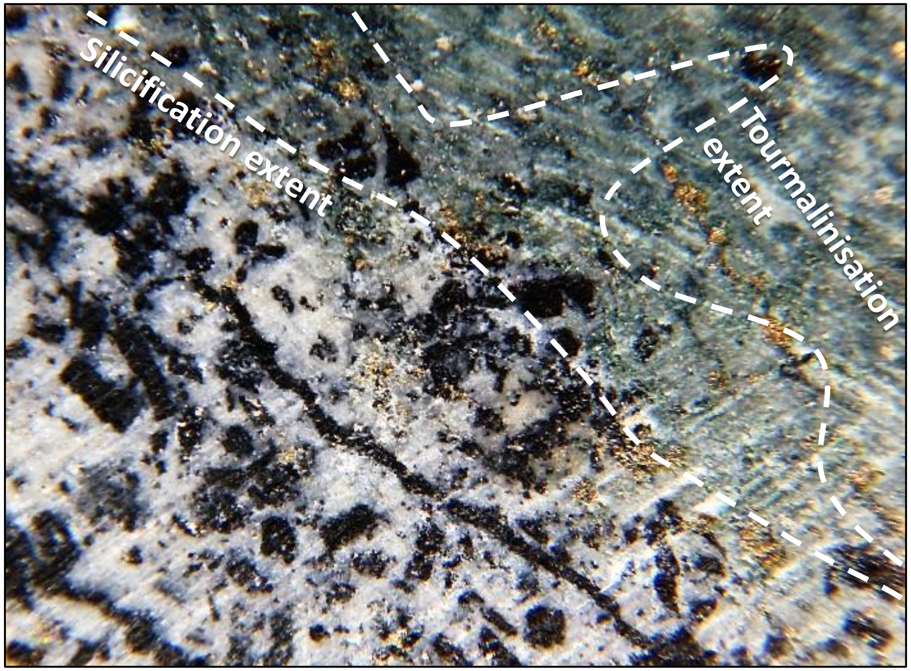
Sheared, sericite-chlorite altered lapilli tuff with tourmaline alteration localized at lapilli rims.

Intense tourmaline-silica replacement of lapilli tuff unit "globular tourmaline"

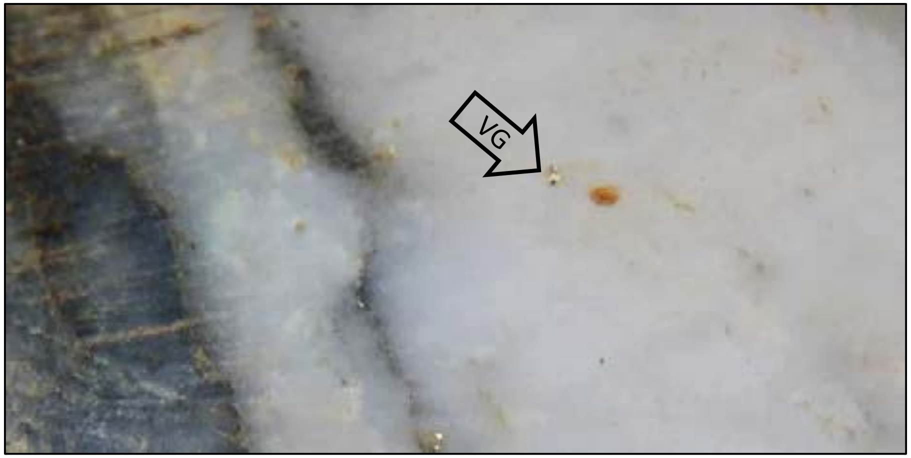
Intense tourmaline-silica replacement within tuff unit "crystalline tourmaline"

# Mineralization (2)

- At least two stages of gold mineralization.
    - Early hyrothermal/metasomatic tourmaline-silica alteration with syn-sulphides (py)
    - Later pyrite veining crosscutting S1 and cross-cutting tensional quartz veins define a second stage.

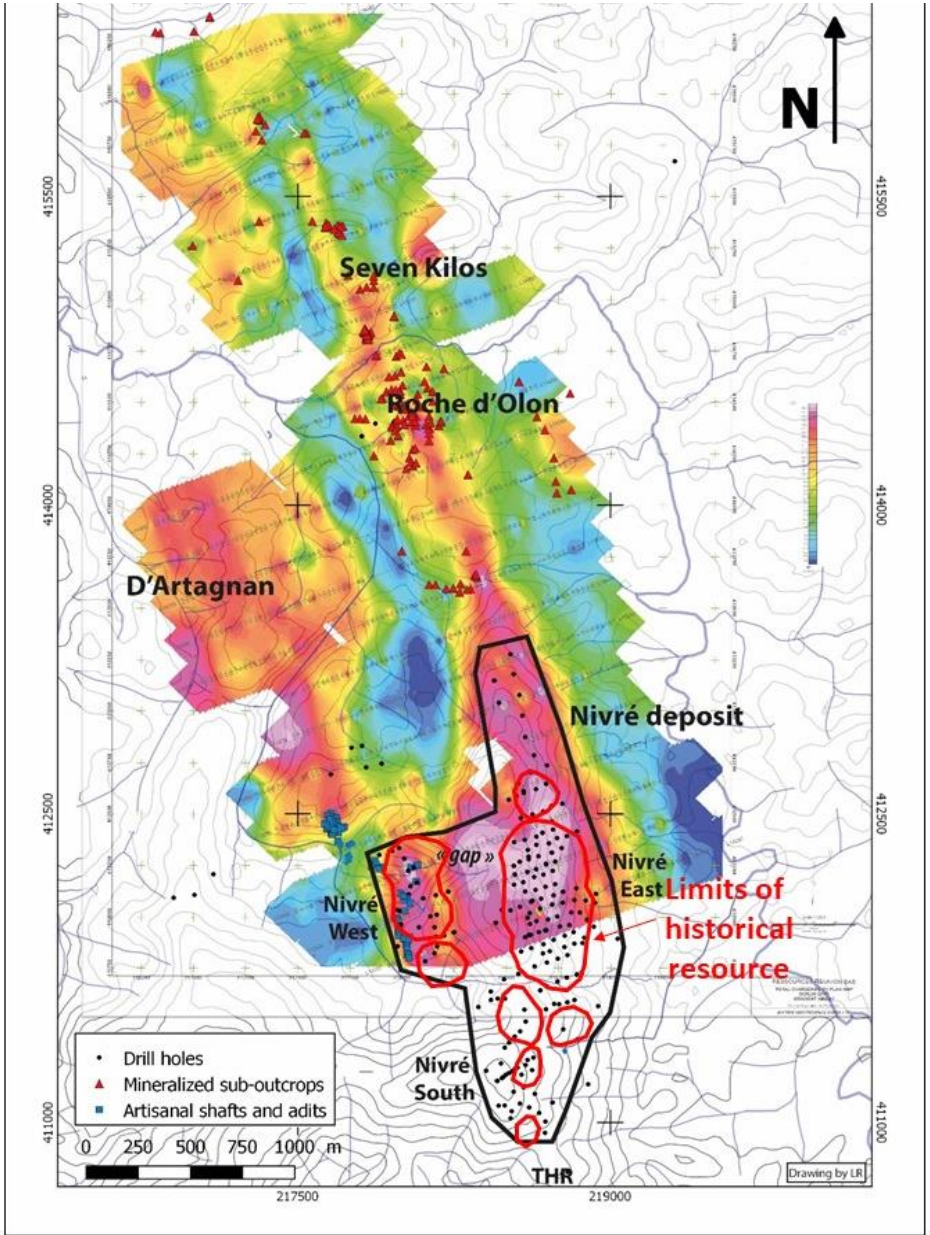


- In 2018 drilling, visible gold noted on shear vein, at the contact of sub-volcanic intrusion with massive andesitic-dacitic units in Nivré West.



# Gold mineralization and sulphide

- Extension along newly mapped silica-tourmaline zones, north of Nivré. Drilling planned at Roche D’Olon, 7 kilos and D´Artagnan prospects.
  - IP chargeability has shown an excellent response to sulphides present at Nivré.
  - Resistivity also maps out zones of silica-tourmaline alteration.



# Metalogenic indicators

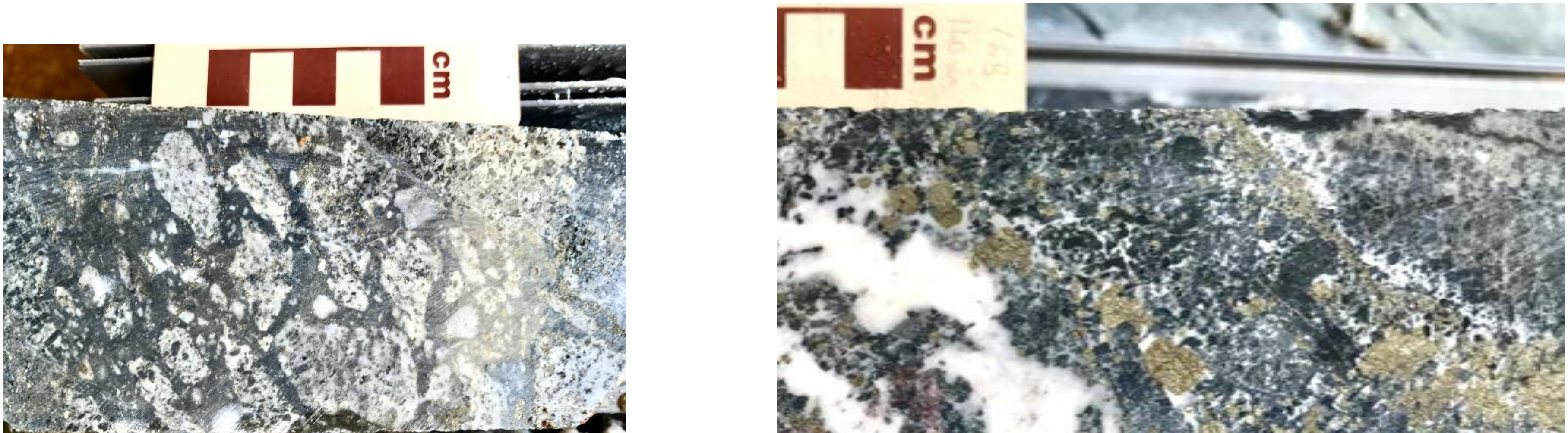
- Nivré deposit is hosted by Proterozoic volcanic rocks of the Paramaca Group, metamorphosed to greenshist facies - no known clastic sedimentar rocks in local stratigraphy

- Volcanogenic component of mineralization evidenced by small VMS occurrence south of Dorlin permit and chert beds

- Gold mineralization consists of envelope with inner tourmaline-suphide core surrounded by chlorite-sulphide zone, in rocks with high content of K2O, As, B and MgO

- Available data suggests a zoned hydrothermal system controlled by a network of paleofractures reworked by a late muscovite-sulphide-quartz stockwork

- Isotope studies (Lerouge et al., 1998) indicate large input of seawater in the Dorlin hydrothermal fluids and evidence of a magmatic component.



# Thank you

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Tectonics and
Metallogenesis of
NE South America
2 Day Conference

Paramaribo, Suriname
19th and 20th February 2019

# Regolith geology of the Saramacca project

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Keywords: Geochemistry, Regolith, Greenstone, Suriname, Gold

## Introduction

Exploration in a tropical environment as the rainforest in Suriname has many challenges. Deep weathering and a regolith ranging from two to two hundred meters is the norm. The Marowijne greenstone belt in Suriname hosts the gold deposits explored and exploited in the recent decades in Suriname. It is therefore of great importance to understand the landscape and the regolith developed onto this geological setting. The Saramacca gold project of IAMGOLD provides the unique opportunity to "peek" into the regolith over mineralized greenstone rocks in Suriname. The objectives of this study were:

- Mapping of the regolith/surface expression of the mineralization over the Saramacca project area
- To conduct sampling of the regolith units, do trace element geochemistry and SWIR for identifying exploration tools for future exploration within the greenstone belt of Suriname

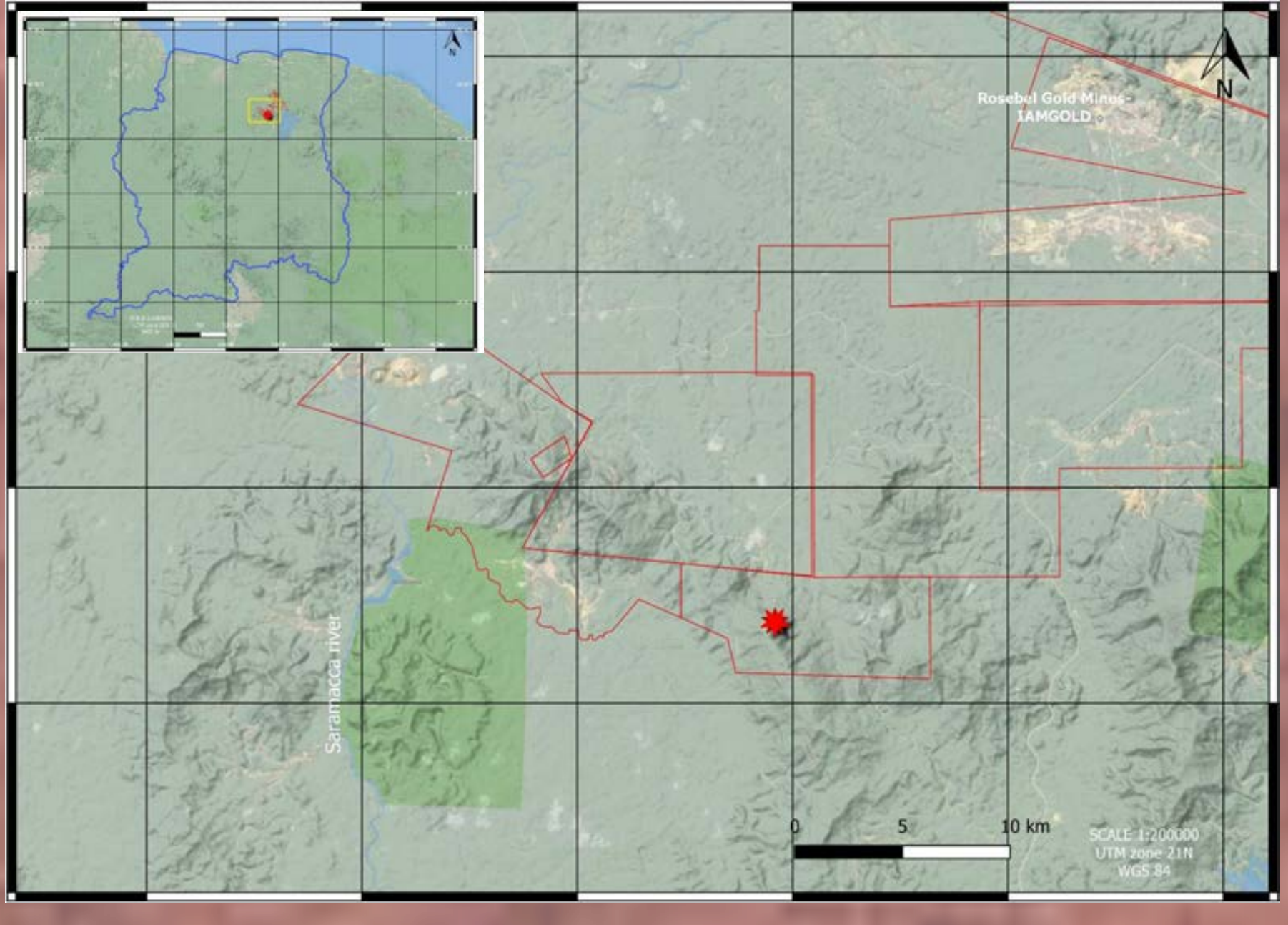


*Figure 1.* Location map of Saramacca project (red star) within IAMGOLD concessions and within Suriname.

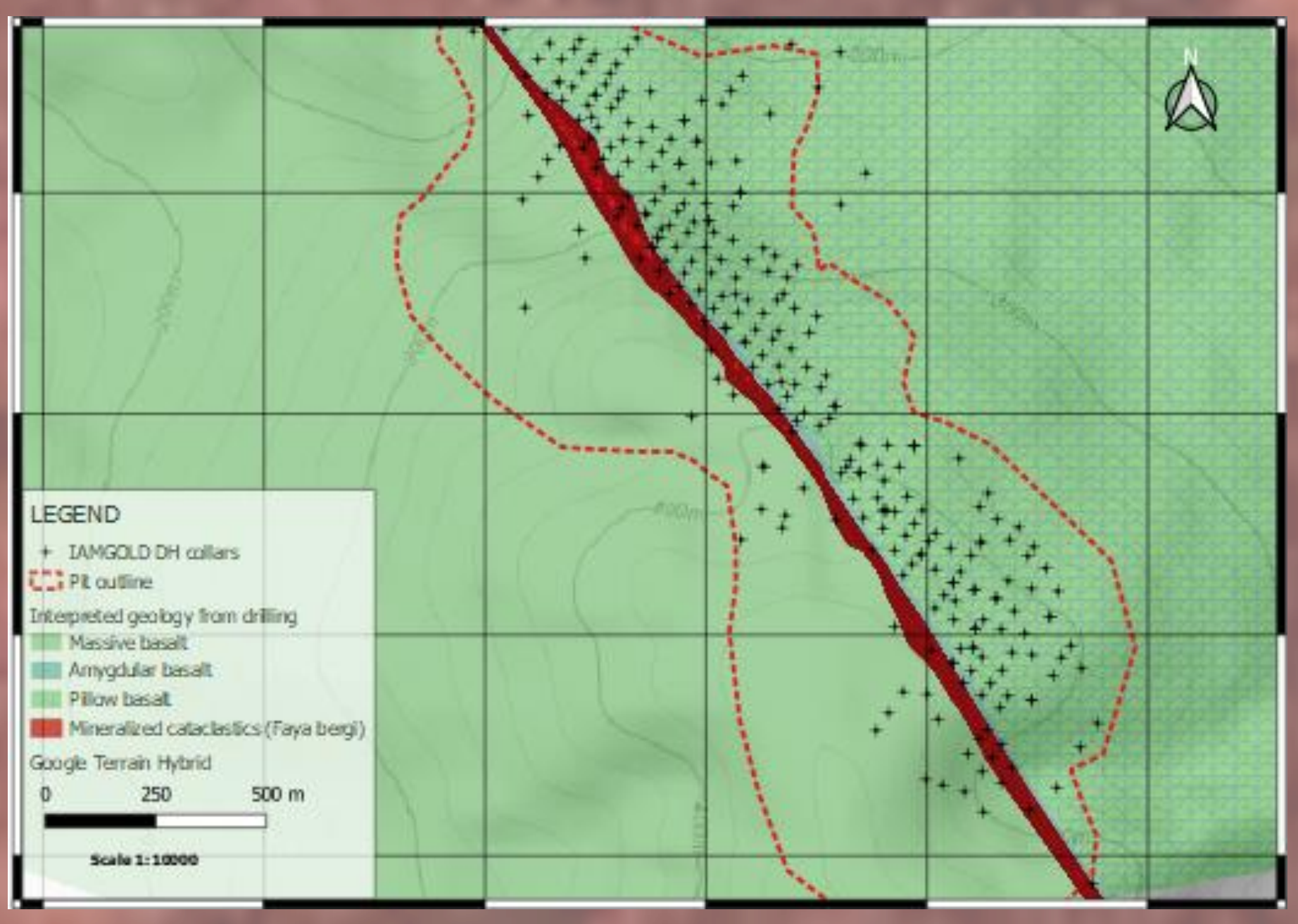


*Figure 2.* Interpreted geology, boreholes and pit outline (modified after SRK, 2017)

## Geology and exploration of the Saramacca project

Saramacca gold project lies within the Saramacca concession of IAMGOLD in the district of Brokopondo, Suriname. Situated 25 km south west (straight line) of the Rosebel Gold Mines N.V. and 104 km south (straight line) of Paramaribo, the capital of Suriname (Figure 1). Geologically the project lies in the Paramacca formation which is dominated by pillow lavas, andesites and tuffs (Kroonenberg, et al., 2016).

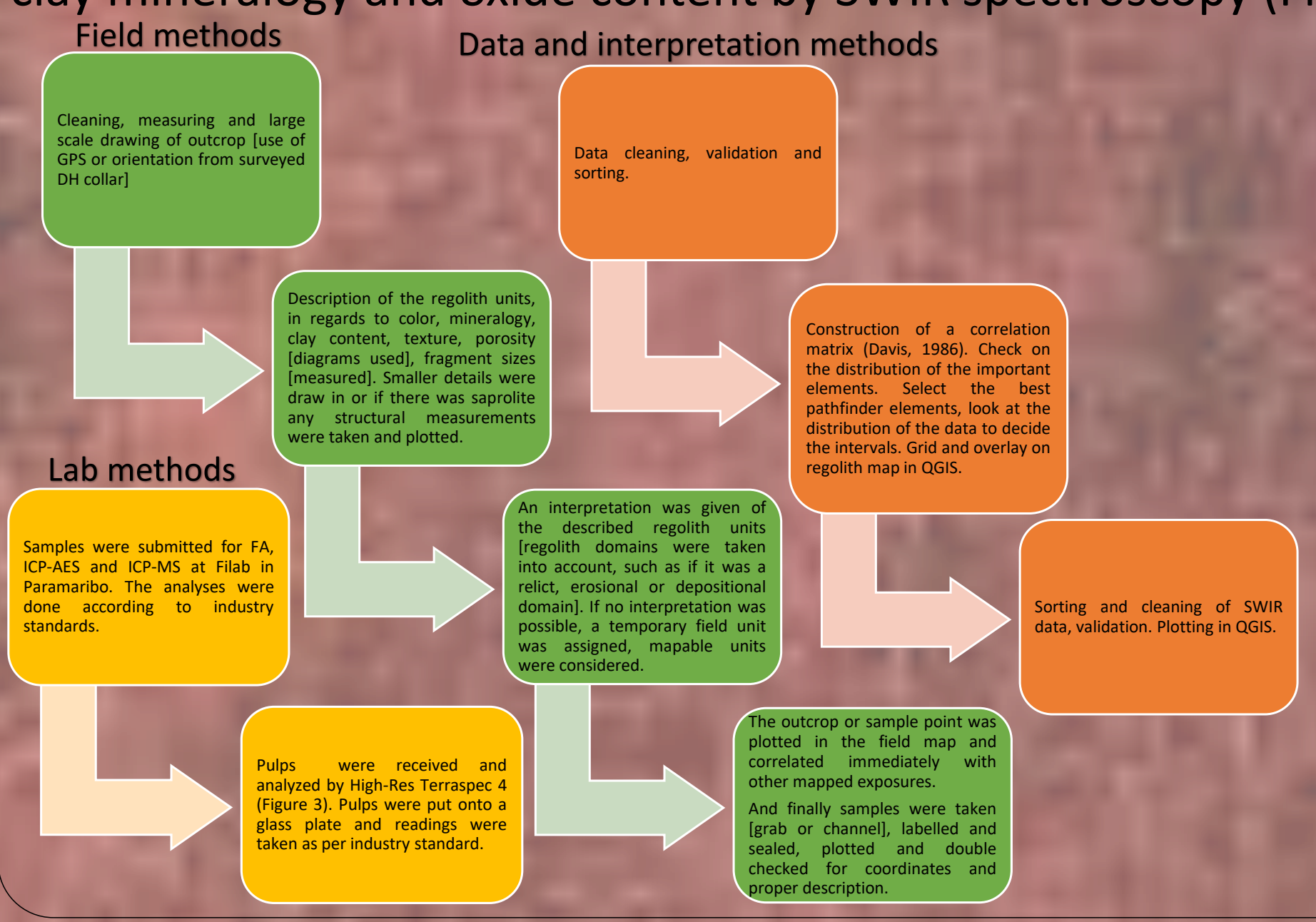
Exploration work done in Saramacca were (SRK consulting, 2017):

- Pre 2016: airborne magnetics, radio metrics, stream sediment, augering, IP and 90 boreholes for 9293.5 meters (Goldenstar and Newmont)
- Since 2016: IAMGOLD drilled 217 boreholes (DD&RC) for 38,731 meters and were able to define indicated resources of 1.022 MOz grading 2.2 g/T Au and inferred resources of 0.518 Moz grading 1.18 g/T Au

The property geology (Figure 2) consists of subvertical units (striking NW) of massive basalt with a thin unit of amygdule basalt (1m to 2m) and a pillow basalt unit to the NE at least 75 m thick. It is between the amygdule and pillow basalt that the main mineralized, Faya bergi, fault (dip-slip) is located. The Faya bergi fault is a cataclastic zone with brittle to ductile features and strong silica alteration, sulfide mineralization and Fe/Mg carbonate alteration.

## Methods and techniques

450 channel and grab samples were taken and sent for FA, ICP-AES and ICP-MS at Filab in Paramaribo. 150 selected pulps were analyzed for clay mineralogy and oxide content by SWIR spectroscopy (Figure 3).



Field methods

Cleaning, measuring and large scale drawing of outcrop [use of GPS or orientation from surveyed DH collar]

Description of the regolith units, in regards to color, mineralogy, clay content, texture, porosity [diagrams used], fragment sizes [measured]. Smaller details were draw in or if there was saprolite any structural measurements were taken and plotted.

An interpretation was given of the described regolith units [regolith domains were taken into account, such as if it was a relict, erosional or depositional domain]. If no interpretation was possible, a temporary field unit was assigned, mapable units were considered.

The outcrop or sample point was plotted in the field map and correlated immediately with other mapped exposures.
And finally samples were taken [grab or channel], labelled and sealed, plotted and double checked for coordinates and proper description.

Lab methods

Samples were submitted for FA, ICP-AES and ICP-MS at Filab in Paramaribo. The analyses were done according to industry standards.

Pulps were received and analyzed by High-Res Terraspec 4 (Figure 3). Pulps were put onto a glass plate and readings were taken as per industry standard.

Data and interpretation methods

Data cleaning, validation and sorting.

Construction of a correlation matrix (Davis, 1986). Check on the distribution of the important elements. Select the best pathfinder elements, look at the distribution of the data to decide the intervals. Grid and overlay on regolith map in QGIS.

Sorting and cleaning of SWIR data, validation. Plotting in QGIS.

*Table 1.* Summary best correlating trace elements with Au

| Pearson's r | ICP-AES | Pearson's r | ICP-MS |
|---|---|---|---|
| As ppm | 0.571 | As ppm | 0.678 |
| Be ppm | ~~0.373~~ | Sb ppm | 0.634 |
| Bi ppm | ~~0.353~~ | Cd ppm | 0.412 |
| Zn ppm | 0.245 | W ppm | 0.302 |
| Ta ppm | 0.222 | Be ppm | 0.269 |

*Table 2.* Summary of the dominant mineralogy obtained from SWIR analysis

| Regolith unit | Dominant SWIR mineral | Dominant SWIR oxide |
|---|---|---|
| Ferricrete | | Hematite |
| Colluvium | Gibbsite | Hematite |
| Duricrust | Gibbsite | Hematite |
| Mottled clay | Mix (Gbs, Kln, Pg) | Goehtite |
| Saprolite | Kaolinite/Paragonite | Hematite |

## Conclusions

- Occurrences of colluvium are the result of material moving downslope, evidence is clearly seen in Figure 4-F1. This unit is hosts fragments of duricrust and ferricrete, massive clay, soft and indurated saprolite fragments and mottled clays.
- The ferricrete in Saramacca shows macroscopic evidence of transported material and may have formed during dryer climates. It would seem there is inversion of topography. We would argue that the lack of Gibbsite dominating in this unit indicates a dryer climate. As Gibbsite is formed in the duricrust below. In wet tropical climate Kaolinite weathers to Gibbsite (Beauvais and Colin, 1992), Gibbsite may be key in differentiating between ferricrete and duricrust (Table 2 and Figure 8).
- Paragonite which has been related to mineralization(Ojeda, 2018) is observed from mottled clay to saprolite in close proximity to the Faya bergi zone (Figure 8). Purple basalt saprolite is mostly (>70%) Kaolinite and Hematite.
- Au correlates strongly with As and Sb (Figure 5, Figure 6 and Figure 7), these are the pathfinders to look for in the Saramacca trend and the greenstone belt. ICP-AES does not have the detection limits needed to measure Sb, Be and Bi (50% n <DL)in the regolith (Table 2).
- Ti vs Zr ratios for duricrust all the way to saprolite indicate a basaltic/minor andesitic protolith. As seen by plots in Figure 9.
- Sr vs V which work in Mali (Benn et al., 2012) can also be used for lithogeochemical discrimination when mapping the regolith in Suriname (Figure 10). Only the ICP-MS data was used here as ICP-AES does not have the detection limits needed for Sr.

## Geochemistry and SWIR results

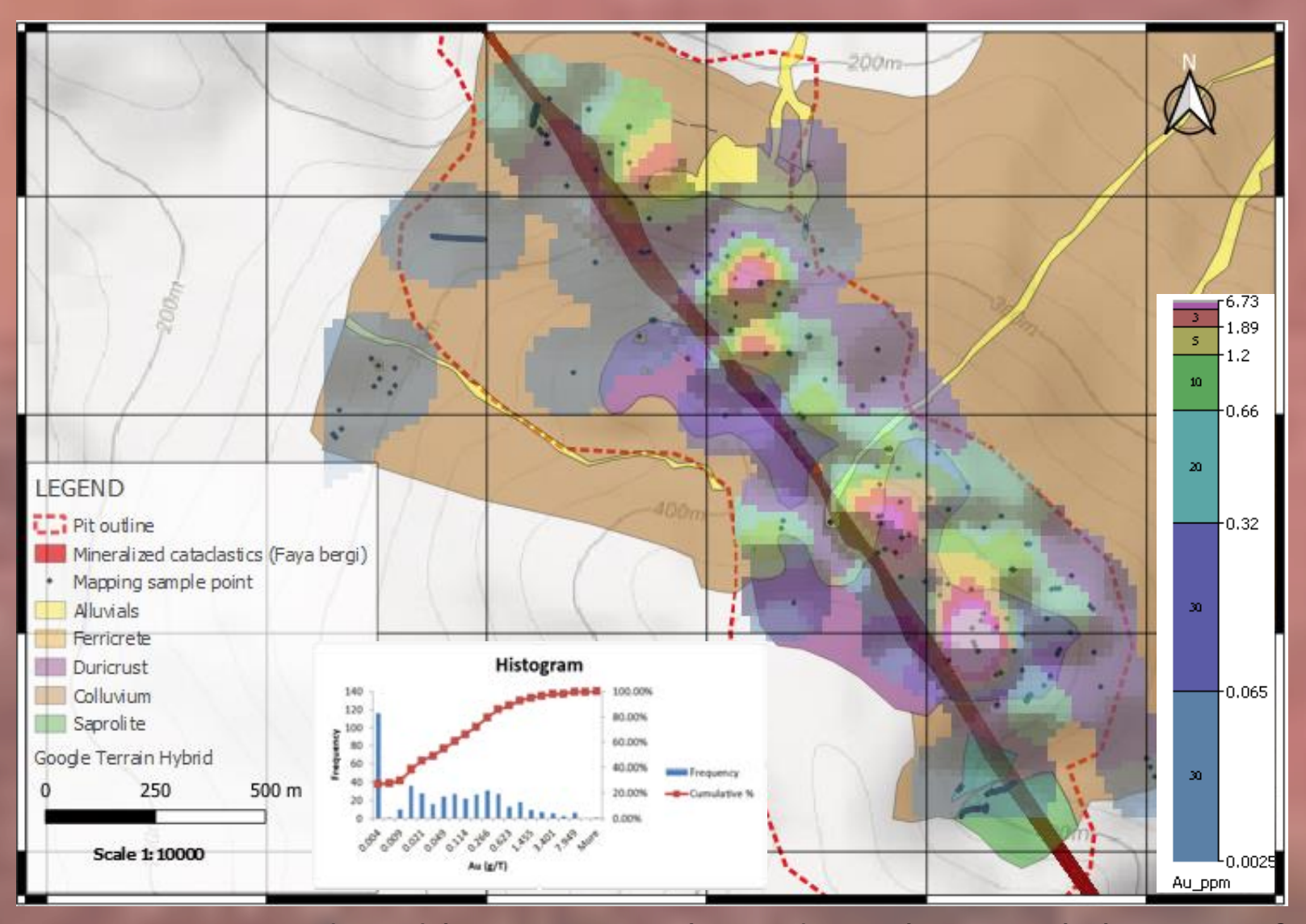


*Figure 5.* Au grid and histogram plotted on the regolith map of Saramacca

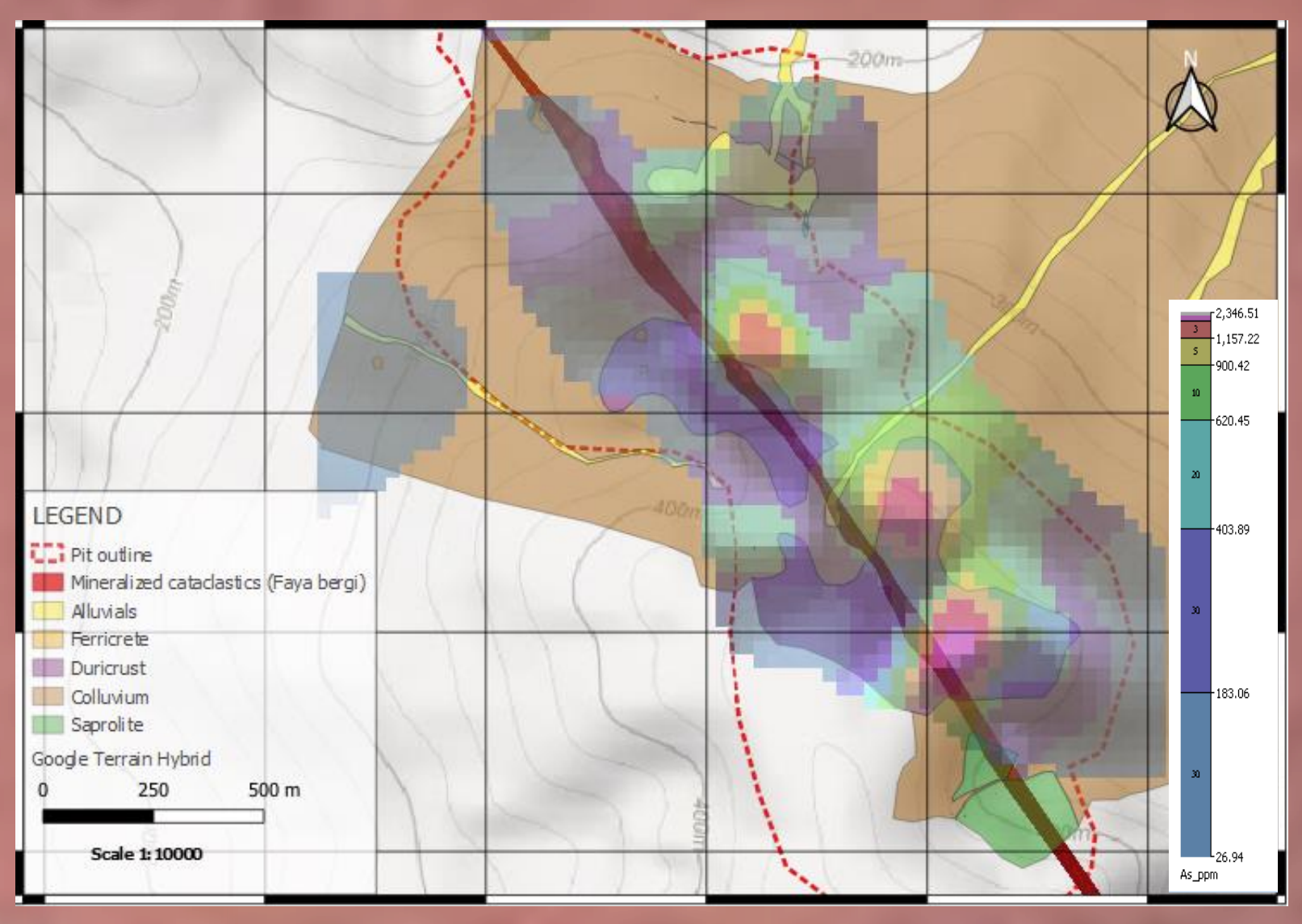


*Figure 6.* As grid plotted on the regolith map of Saramacca

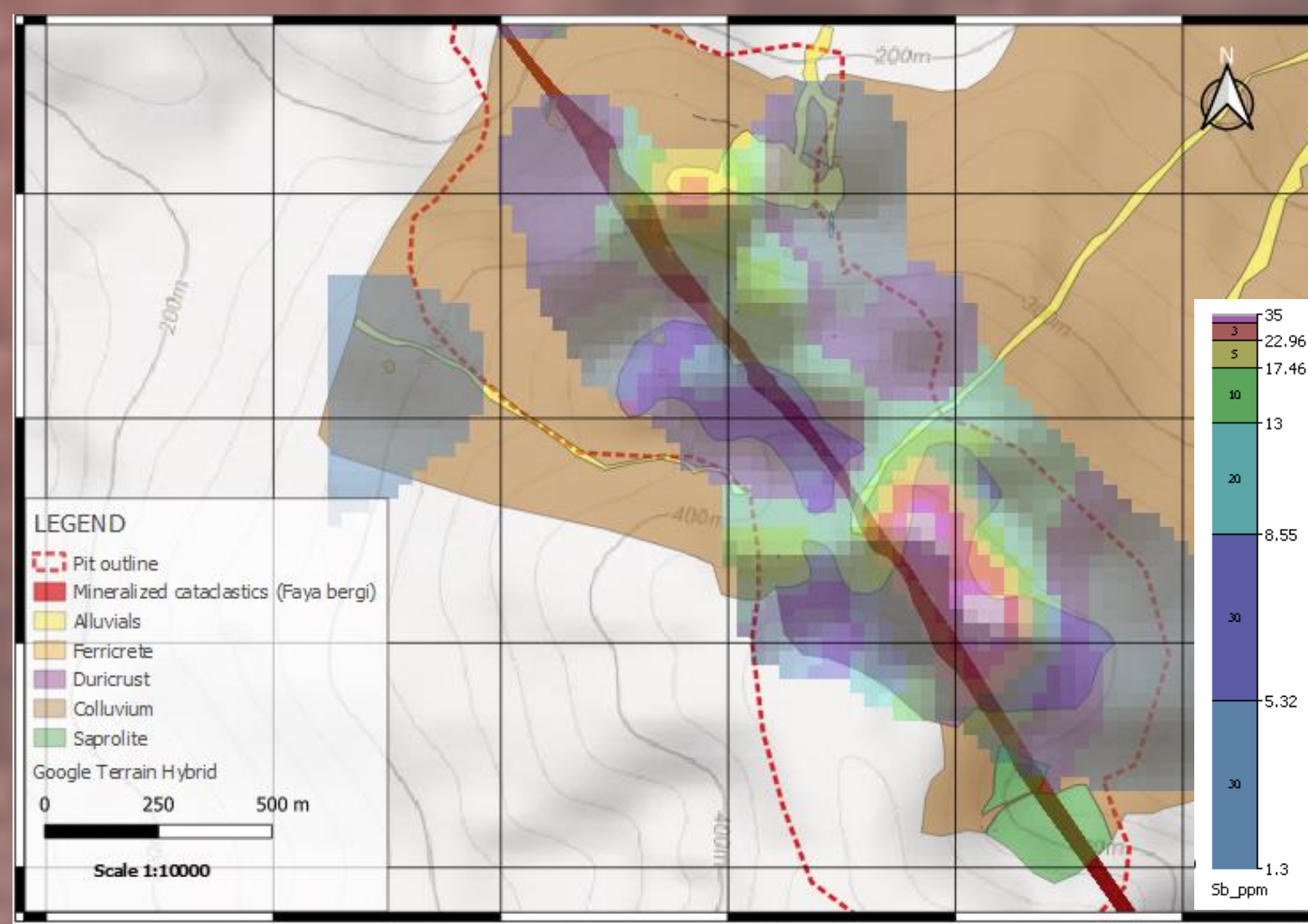


*Figure 7.* Sb grid plotted on the regolith map of Saramacca

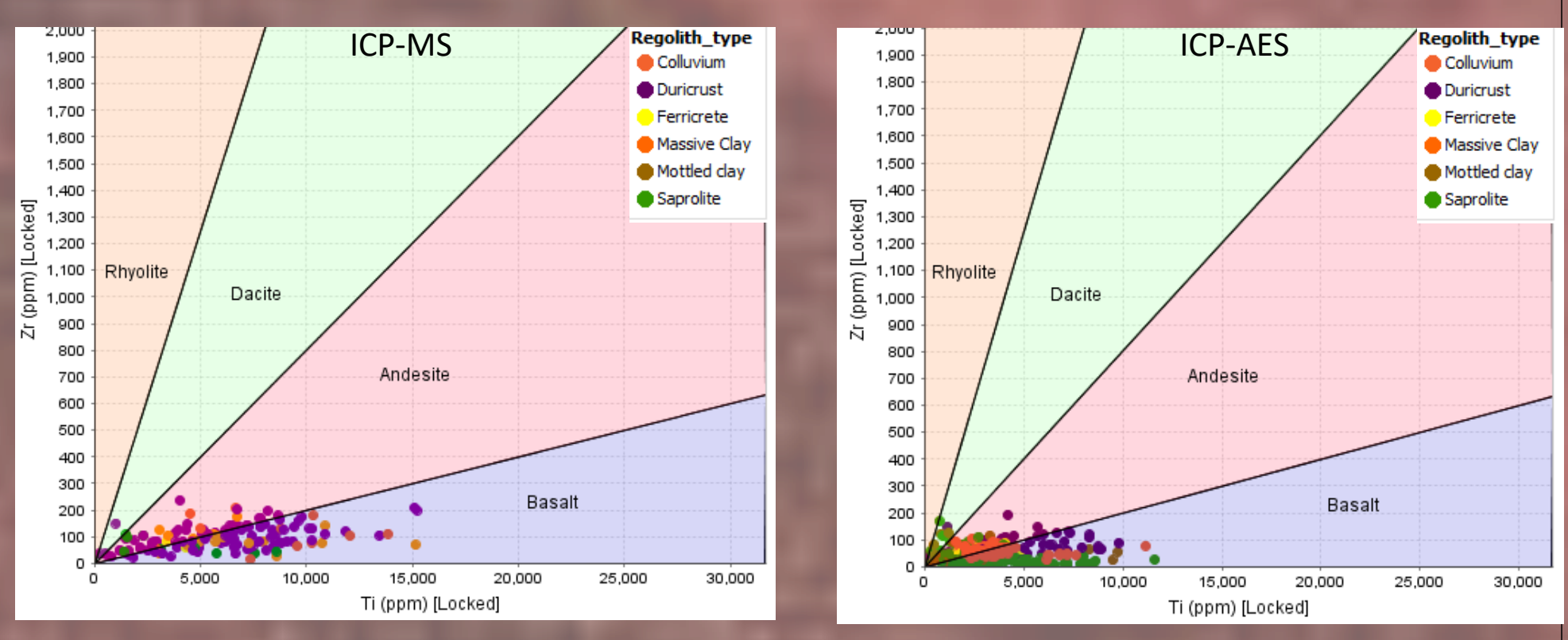


*Figure 9.* Zr vs Ti (Hallberg, 1984)

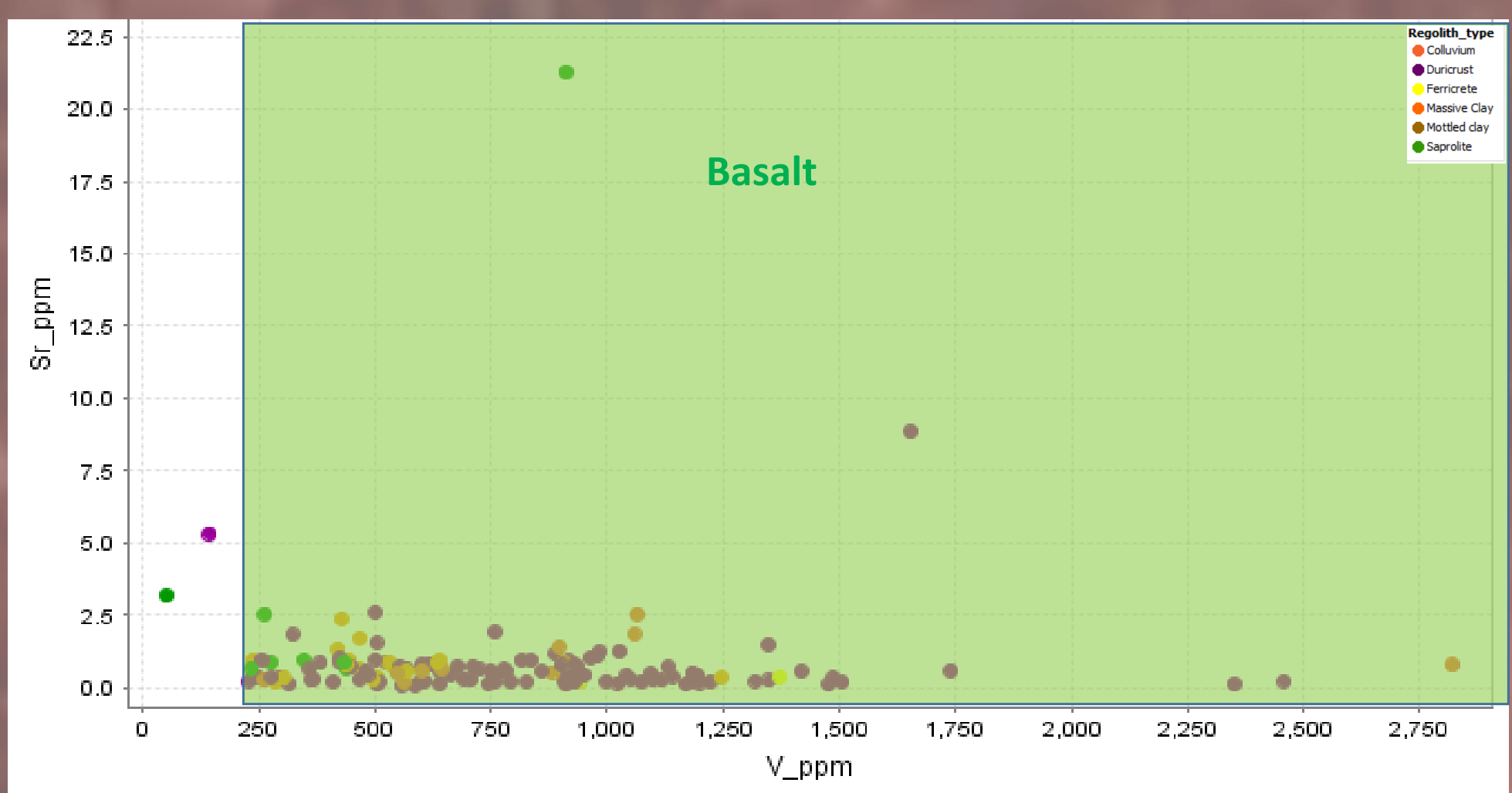
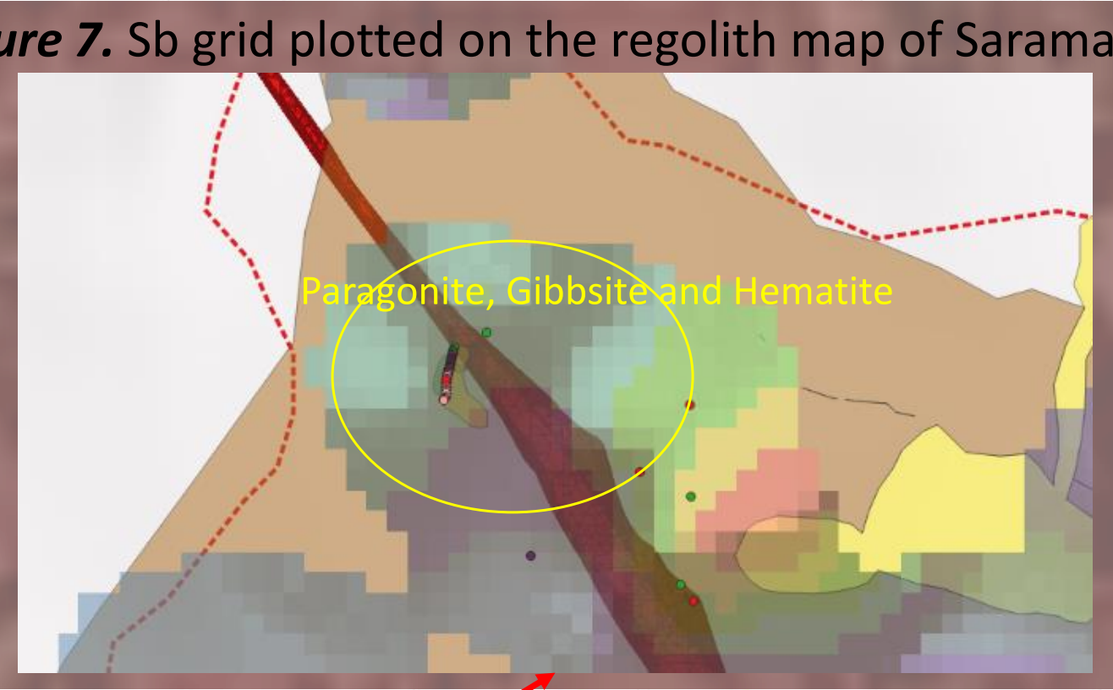


*Figure 10.* Sr vs V for ICP-MS data set (Benn et.al., 2012)



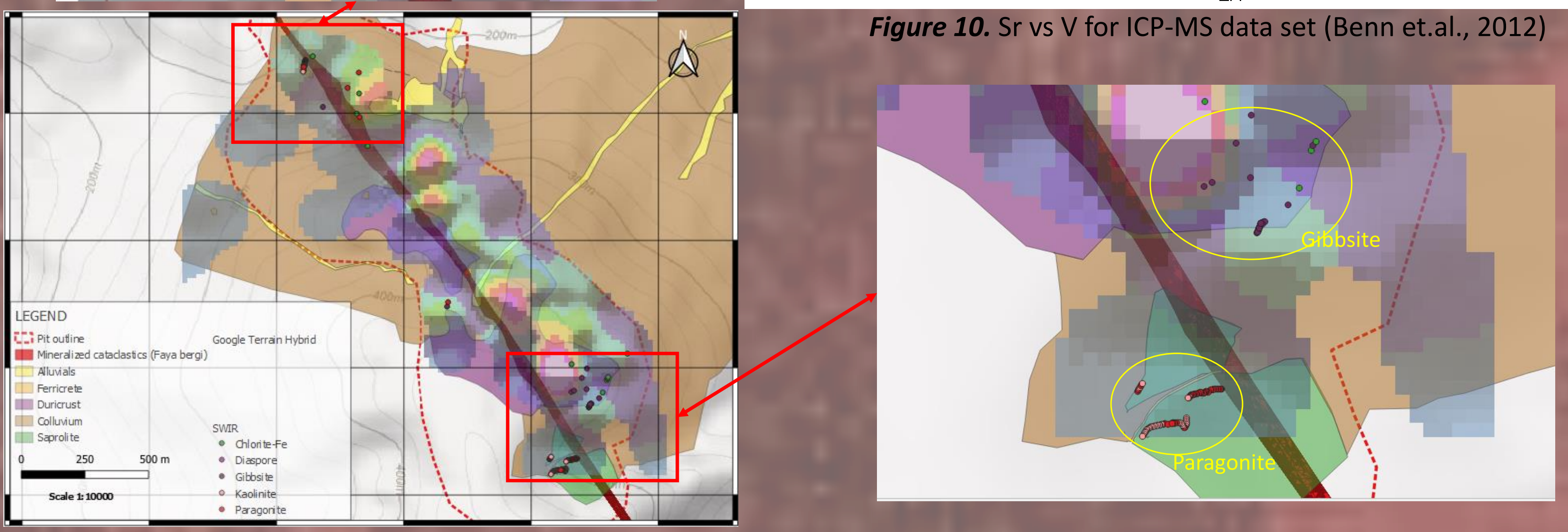


*Figure 8.* Selected SWIR plots on top of Au gridded regolith map

*Figure 3.* Terraspec 4 High-Res mineral analyzer

## Regolith mapping results

The regolith map is presented in Figure 4. 7 regolith units were encountered in the area. The recent alluvials in Figure 4 were mapped but not sampled/considered.

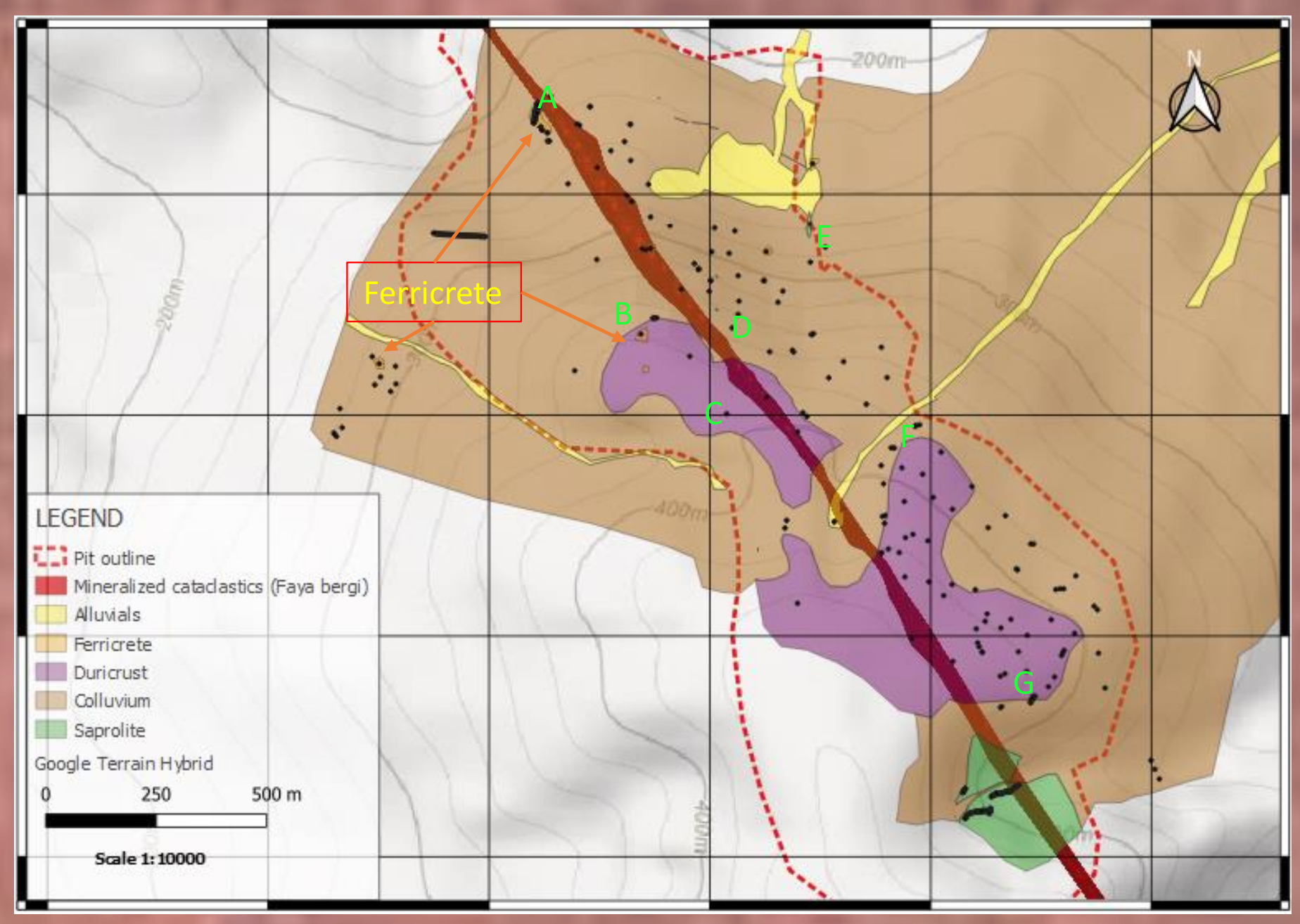
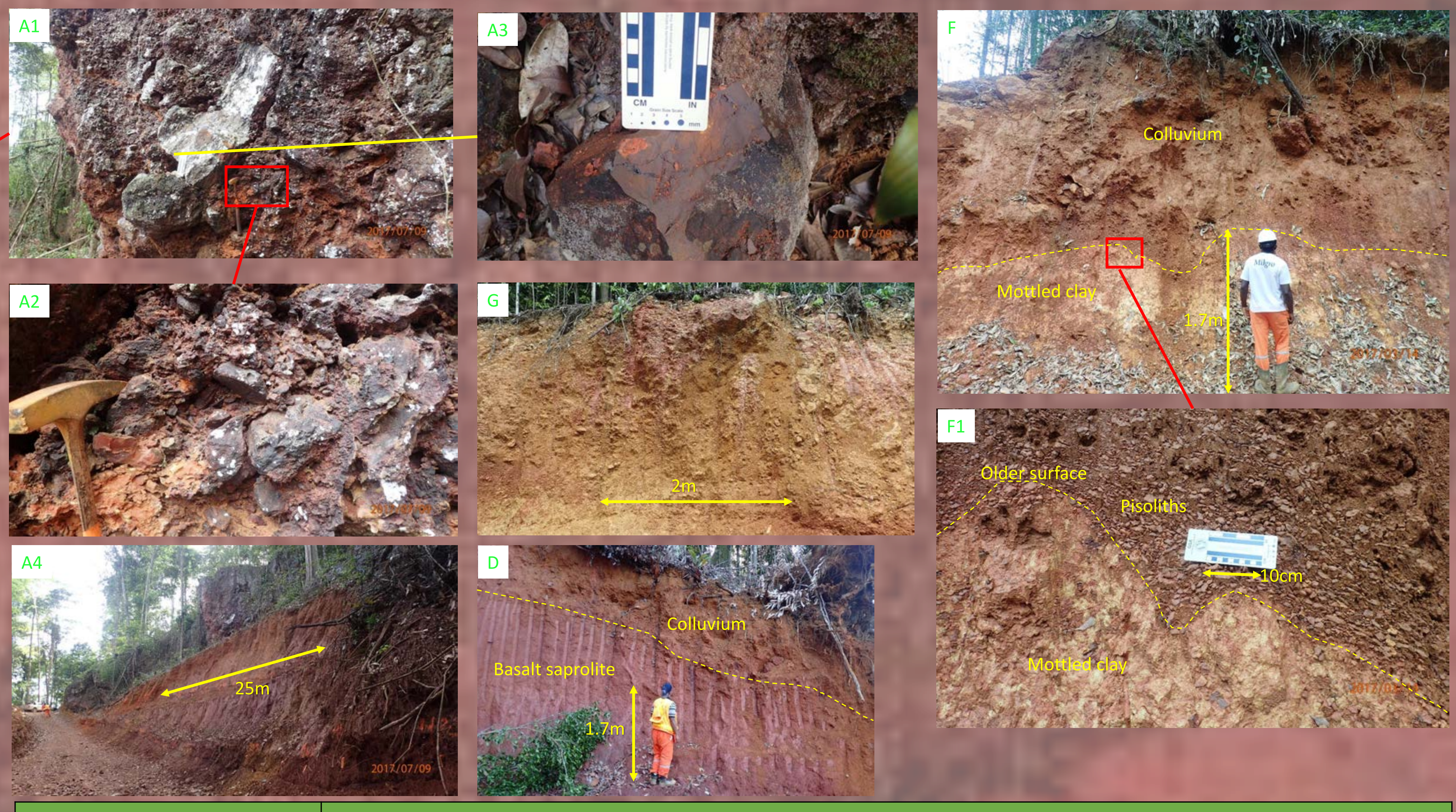
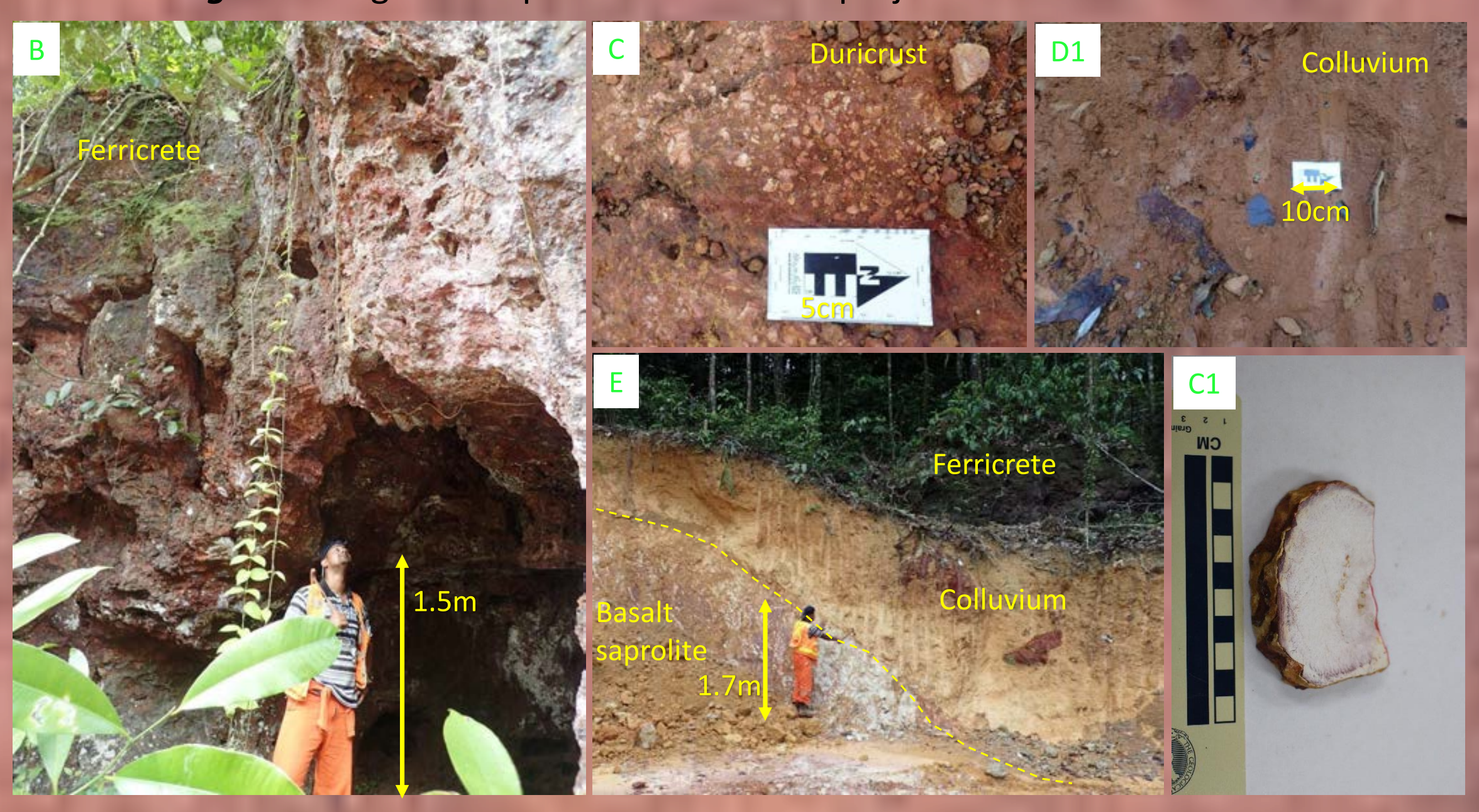


*Figure 4.* Regolith map of the Saramacca project





| Unit | Description |
|---|---|
| Alluvials | Recent clays, sand and gravel in gullies, active creeks. |
| Colluvium | Consists of poorly sorted Fe –oxide rich clay material with duricrust fragments, indurated saprolite fragments, ferricrete fragments and pisoliths. Sizes of the fragments vary from 1cm to 3m in size and are angular to sub-rounded in nature. |
| Ferricrete | Highly weathered unit, with conglomerate like texture of many Hematite rich (>90%) fragments [1m to 1m]. Erratic. |
| Duricrust | Porous to massive unit, with >70% Hematite, massive to botryoidal in texture, often has Limonite and Gibbsite. |
| Massive clay | Red to yellow massive clay with some minor Fe-Ox fragments or occasional pisoliths. Original texture completely gone. |
| Mottled clay | Stained yellow to white clay with remnants of saprolite in Fe occurrences. Kaolinite and Limonite rich. |
| Basalt saprolite | Fine grained purple to red colored clay rich saprolite, very little to no very fine Quartz. 60% -70% Fe/Mn-oxide rich clays and fractures. Interpreted as basalt saprolite |

A lot of gratitude is expressed towards the mapping/sampling crew: Armand Awetie, Rudewald Main, Rinaldo Antomoi and Avinash Bhagwat. The Suriname exploration department of IAMGOLD is also thanked for the support and finance of this study

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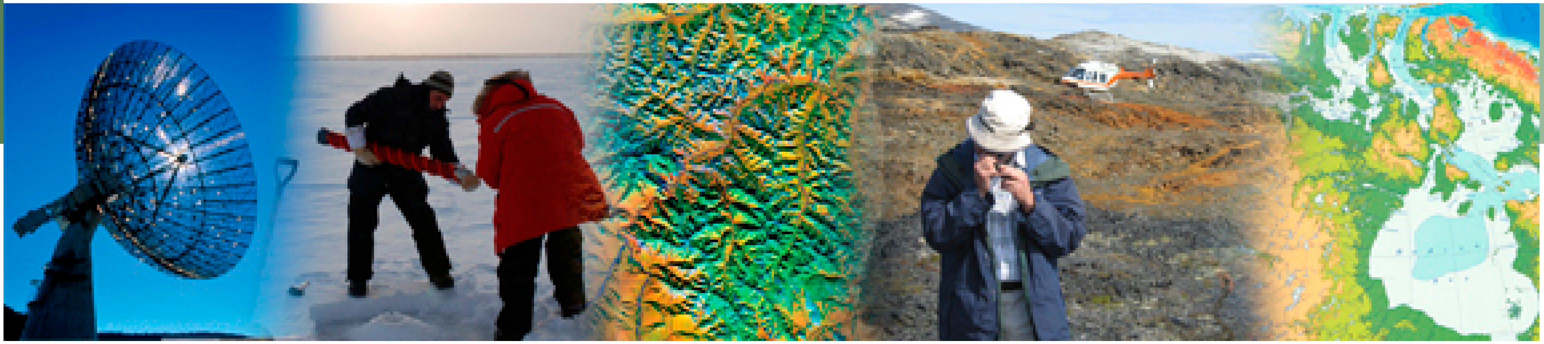
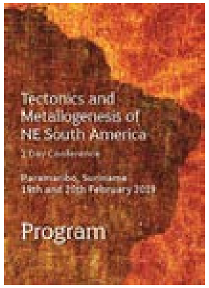


# Complex 3D Integration for Mineral Exploration

Eric de Kemp
Geological Survey of Canada



Tectonics and
Metallogenesis of
NE South America
2 Day Conference

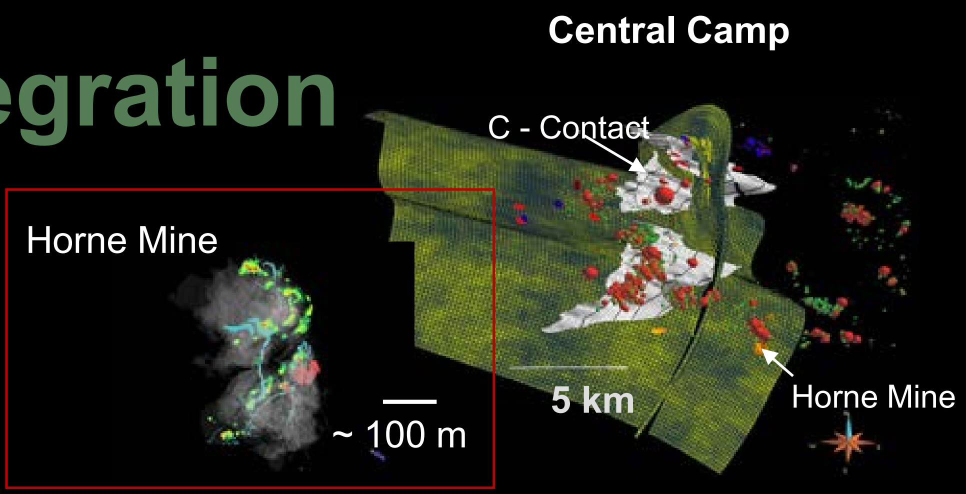
Paramaribo, Suriname
19th and 20th February 2019

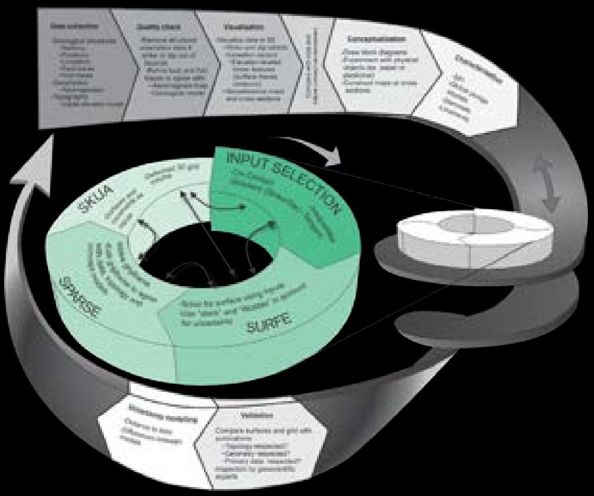
Program

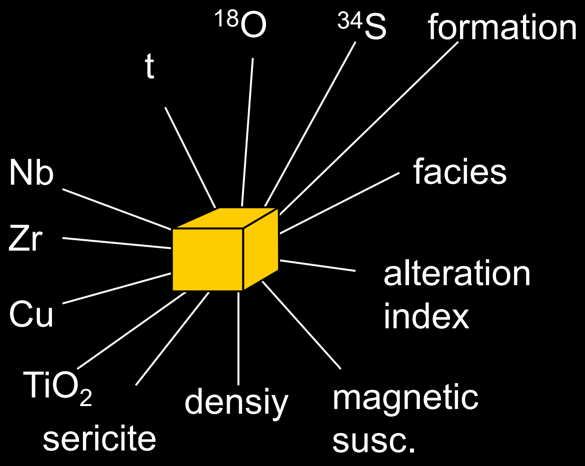
# Complex Data Integration

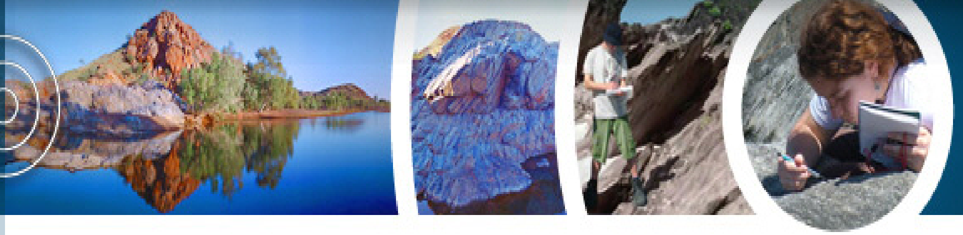
CDI = MMI

- Multi-scalar
- Multi-parameter
- Iterative









# Greenfields Exploration

“ Greenfields Exploration is the process whereby broad target areas are selected on the basis of favorable geology and/or geophysics with little or no evidence of the target mineralization”.

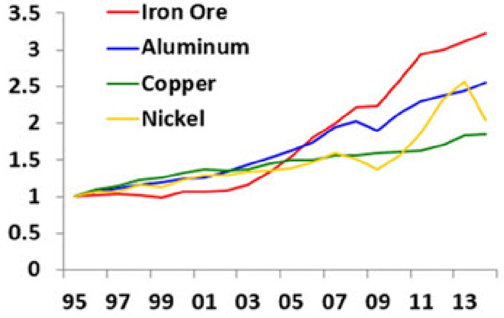
*CET ~ 2006*

Beyond the headframe …

# Greenfields

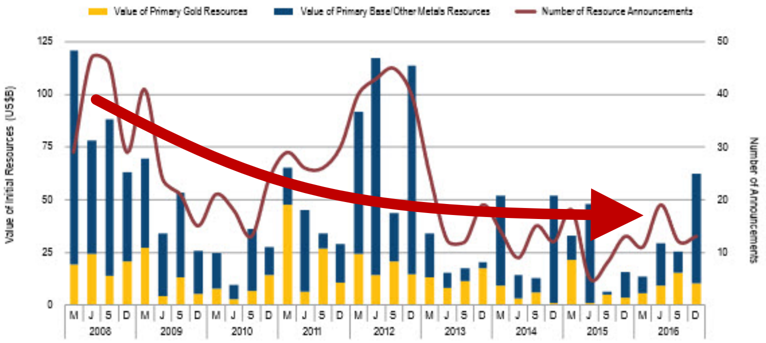
- Increasing consumption and production
- Depletion of finite resource

**Chart 3. World Metal Production**
(1995=1)



Sources: IMF, Primary Commodity Price System; and IMF staff calculations.

**Figure 4: Initial Resource Values**



Note: As defined in S&P Global Market Intelligence's Monthly Industry Monitor, initial resources include initial estimates for both new deposits and new zones at mines and projects with previously defined reserves and/or resources.

S&P GLOBAL MARKET INTELLIGENCE

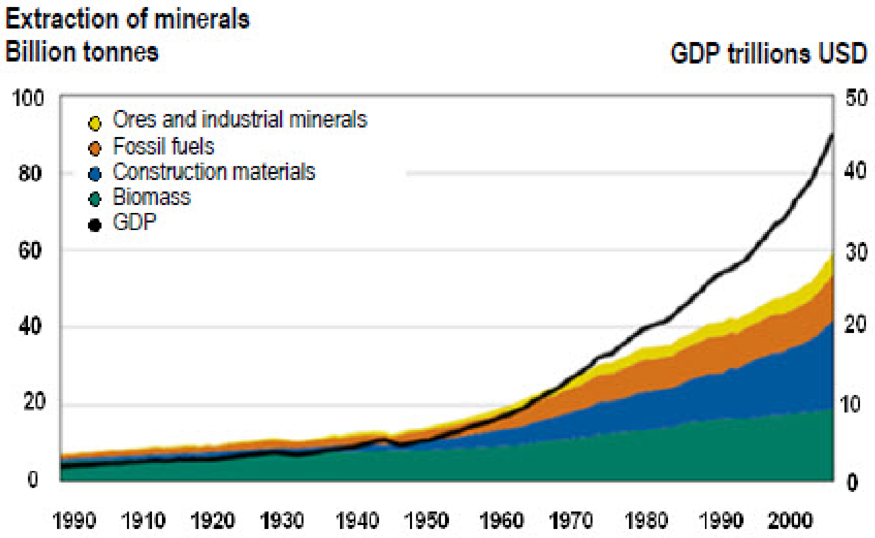


**Fig. 2.** Growth in demand for mineral resources in the world economy (SERI 2011)

SERI (2011): Global resource extraction by material category 1980–2008. http://www.materialflows.net

# Metals for the Low Carbon Economy

- Increased demand;
- Copper
- Aluminum
- Nickel

Au – $H_2$ Fuel Cells
Electronics

**Electric Vehicles:**

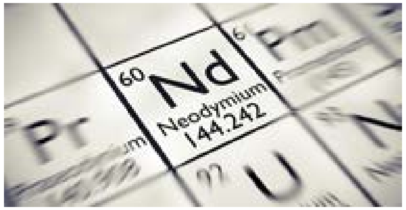
Cobalt **x30**
Lithium
Copper
Aluminum
Nickel **x2**

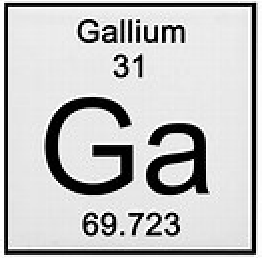
**Energy Storage:**
**(1000%)**
Aluminum
Cobalt
Iron
Lead
Lithium
Manganese
Nickel

**Solar Photovoltaics:**
**(300%)**
Aluminum
Copper
Indium
Iron
Lead
Molybdenum
Nickel
Silver
Zinc

**Wind:**
**(250%)**
Aluminum
Chromium
Copper
Iron
Lead
Manganese
Molybdenum
Neodymium
Nickel
Zinc

Information from summary article by Carrie Carlson – *FEECO International* on; ***The Growing Role of Minerals and Metals for a Low Carbon Future***. Report, Washington, DC: The World Bank Group, 2017.





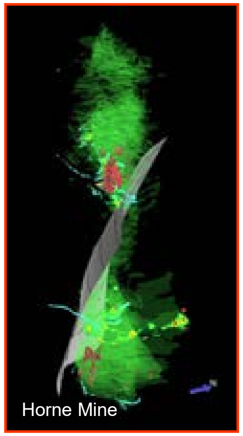
# Greenfields

- Many major giant class ore deposits were once in a Greenfields setting.

Discovery site of nickel-copper ore
1883, Copper Cliff – Sudbury Camp.

Courtesy Mines Branch
Government of Newfoundland and Labrador

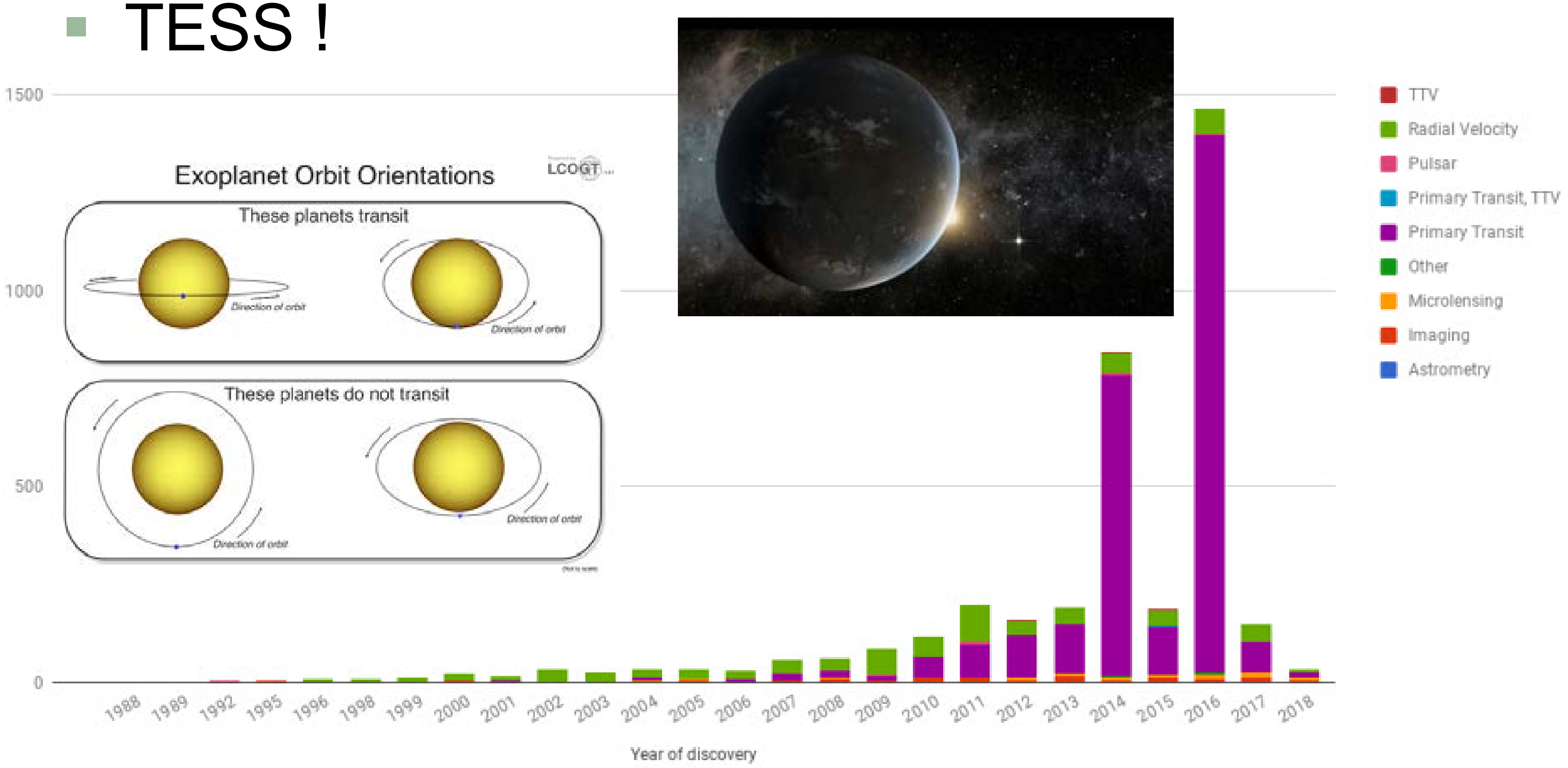
*Exploration camp – Michelin property –*
*Central Mineral Belt, Labrador.*



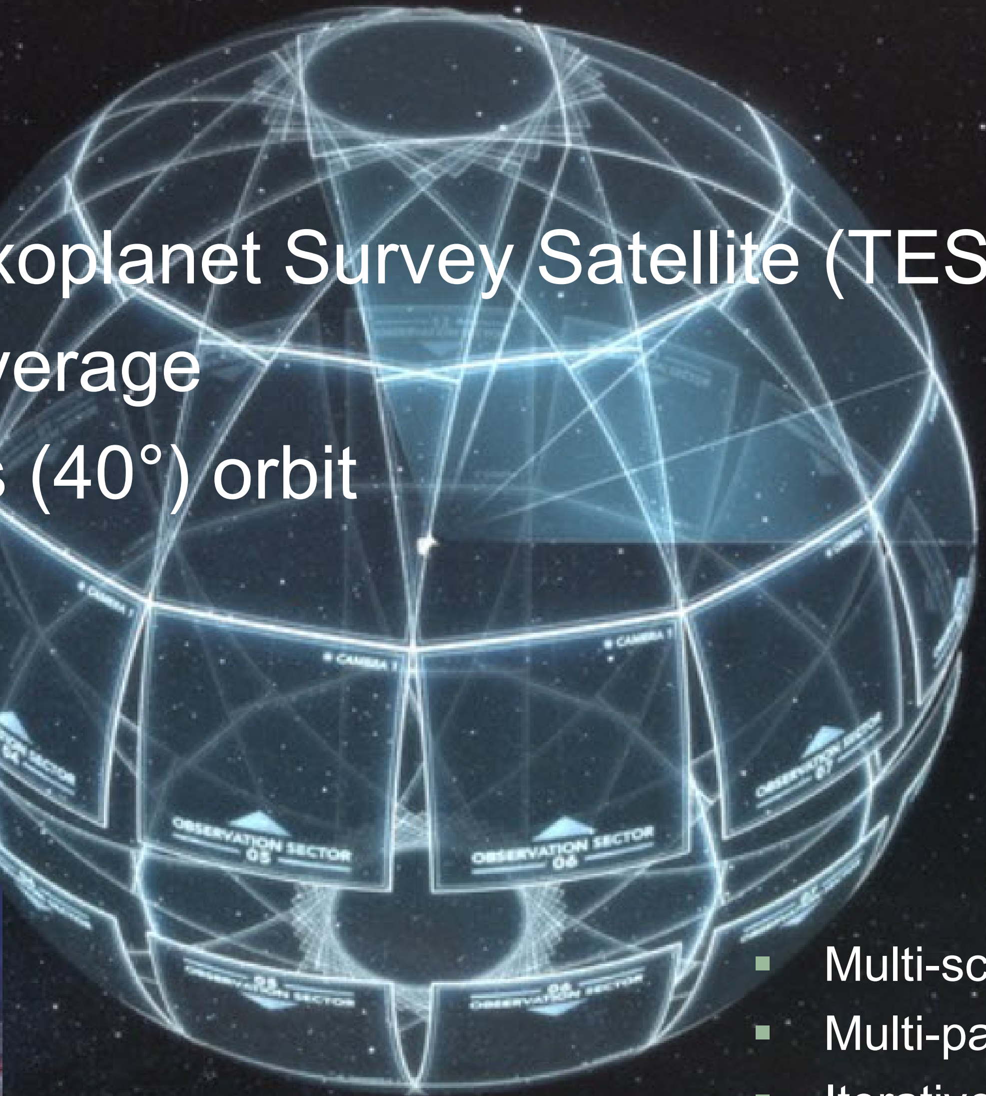
Edmund Henry Horne 1864-1953
Discovered ore ~1920, that led to development
of the Giant Horne Mine, Rouyn-Noranda, Québec

# Greenfields – Galactic Scale

- Not necessarily linear function of investment
- Technology and practice impact critical
- Discoveries in < 25 years… from 0 to ~ 4000
- TESS !



# Greenfields – Search for Exoplanets

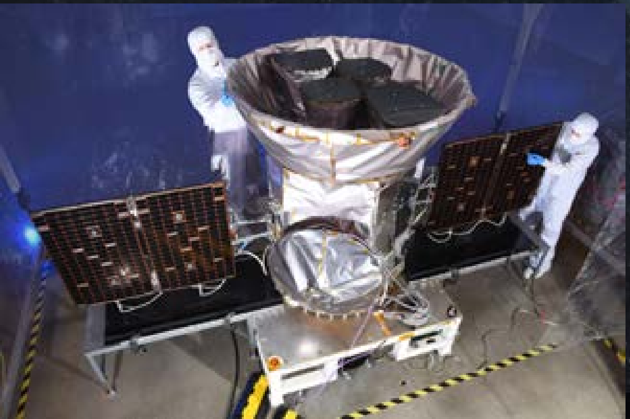


- Transiting Exoplanet Survey Satellite (TESS)
- 85% Sky coverage
- Wide off axis (40°) orbit

Launch April 18, 2018

200,000 stars – 2 years

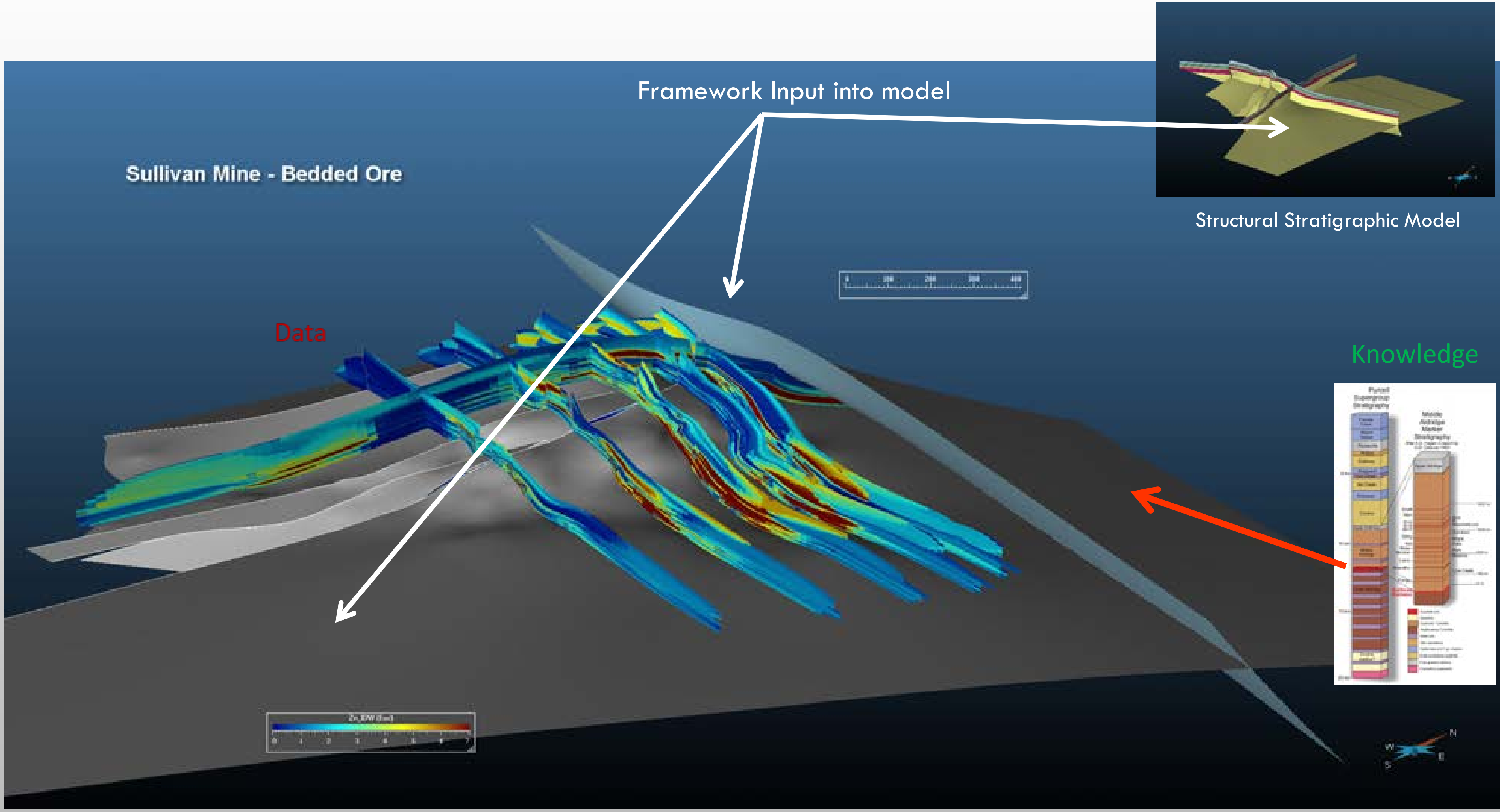
**Data**



- Multi-scalar
- Multi-parameter
- Iterative

**Knowledge of star and planetary genesis**

# 3D Mine Modelling



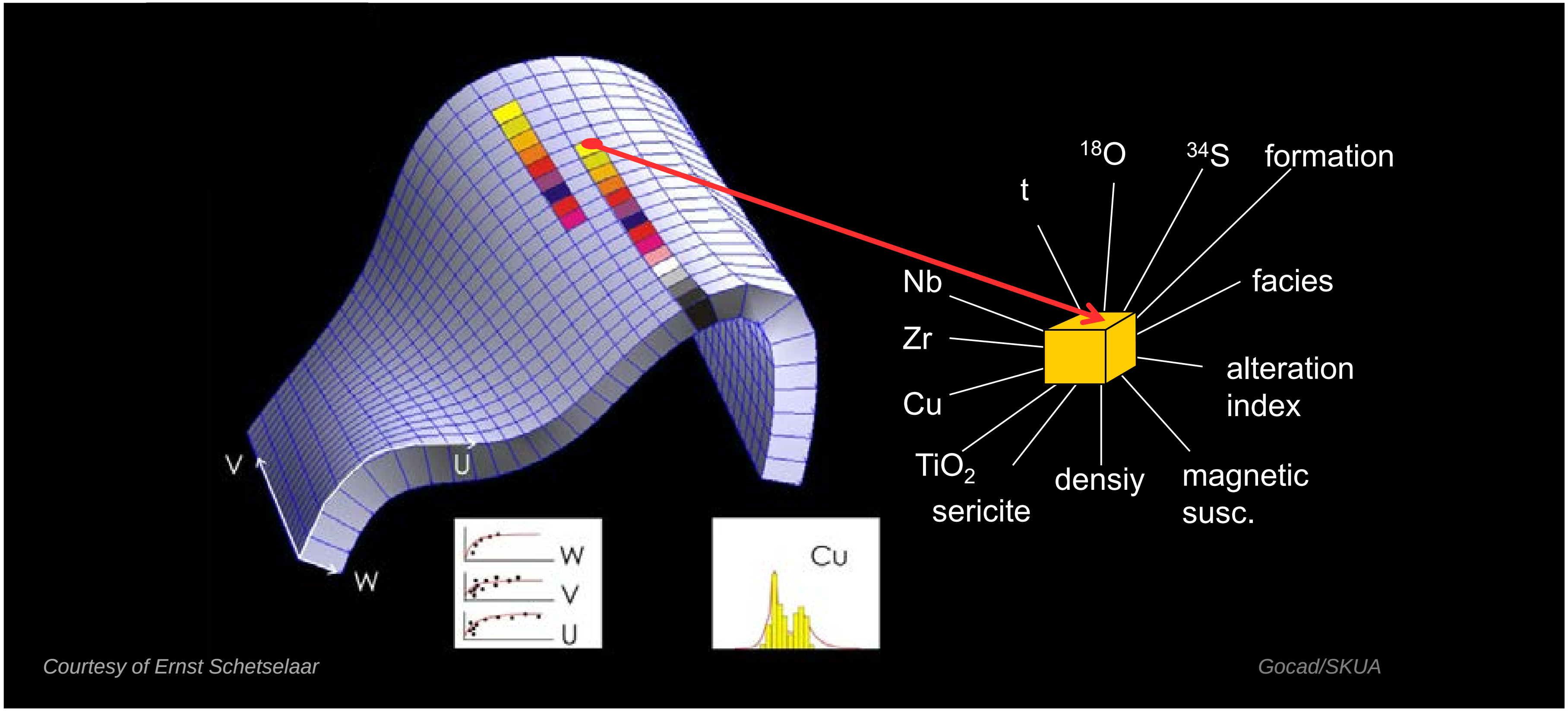
Framework Input into model

Structural Stratigraphic Model

Data

Knowledge

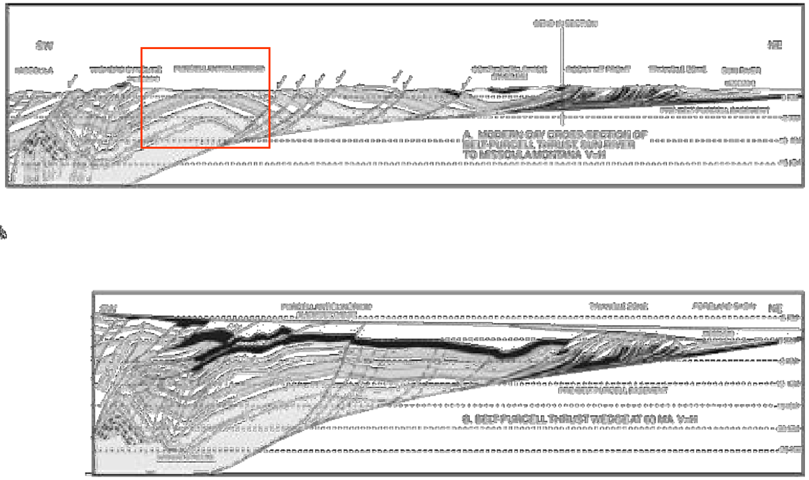
# 3D Multi-Parameter Container



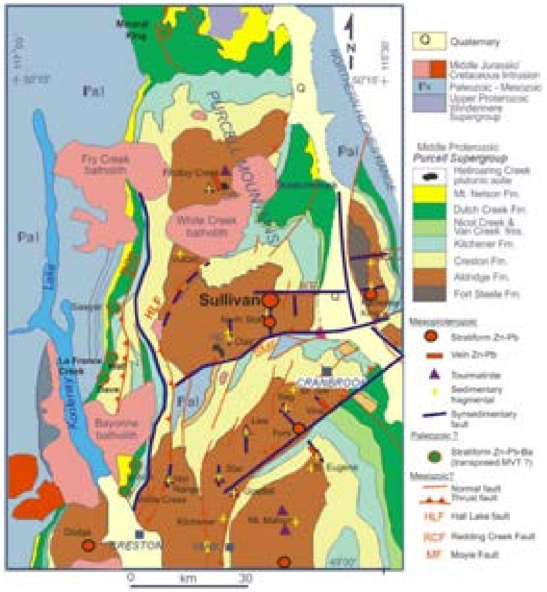
Courtesy of Ernst Schetselaar

Gocad/SKUA

# 3D Modelling of the Purcell Basin

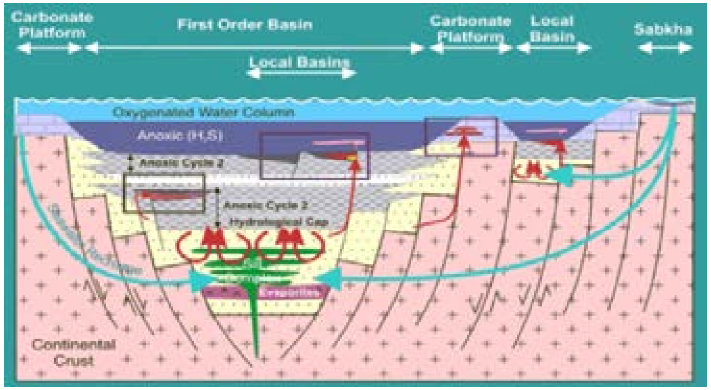


Sears J Geological Society of America Special Papers 2007;433:147-166



## “A project to make a 3D regional model – beyond the head frame…”

SEDEX System



Goodfellow and Lydon 2007

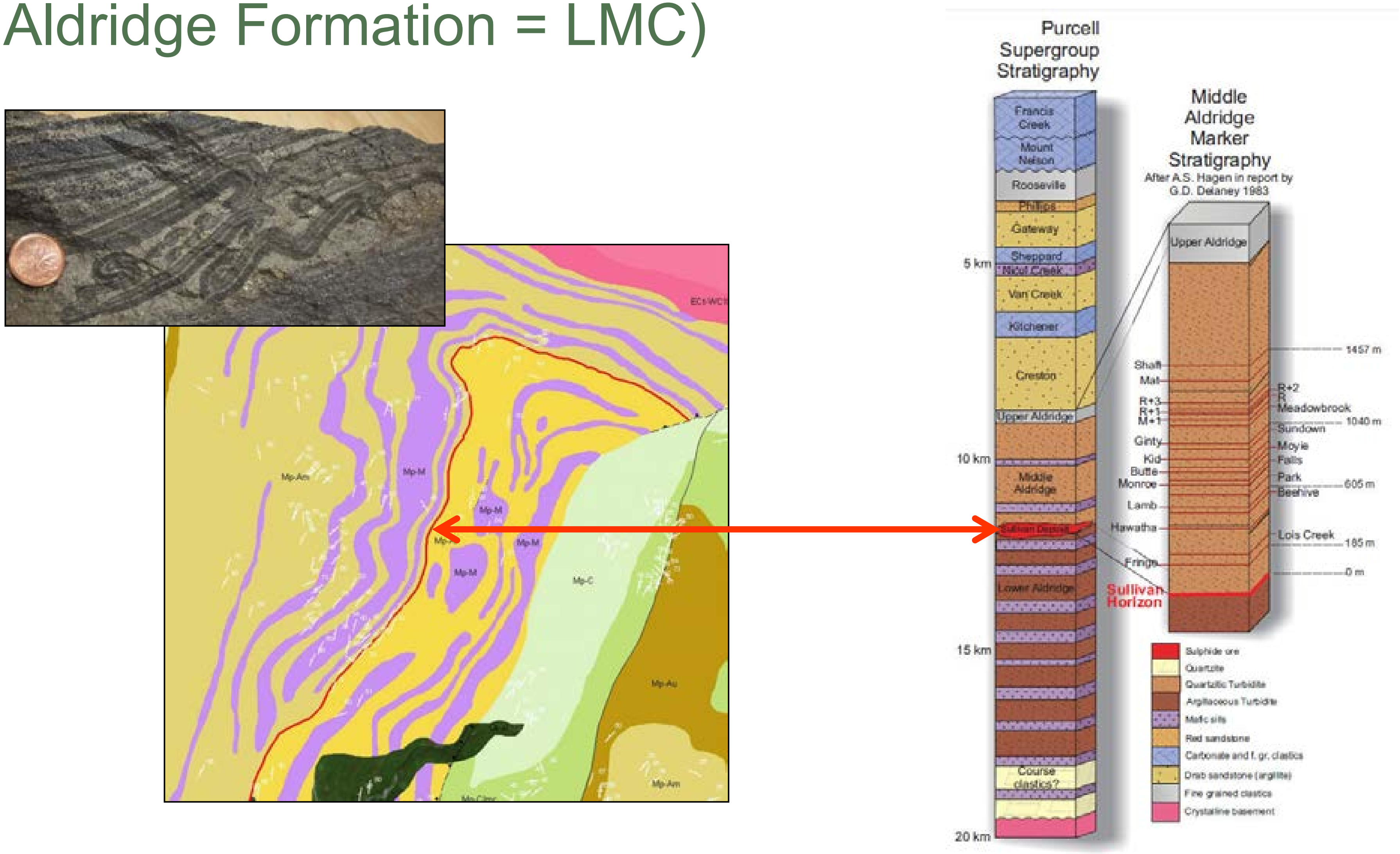
Wikipedia

# Modern Red Sea and Dune Fields

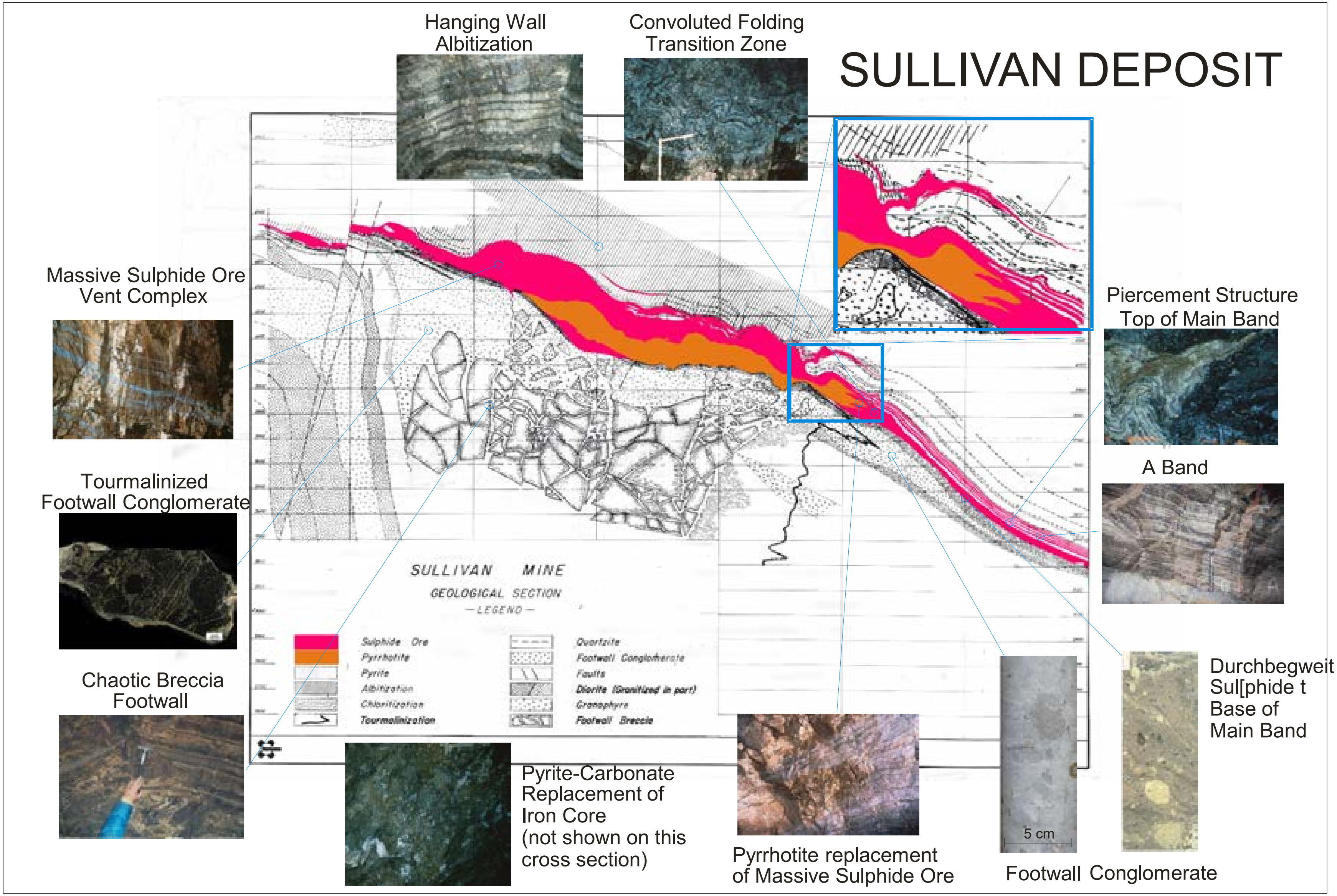
World Atlas

# ‘Barcode’ siltite markers provide unique 3D modelling constraints in hanging wall of the Sullivan horizon

# Sullivan horizon (contact between Middle – Lower Aldridge Formation = LMC)



# SULLIVAN DEPOSIT



Hanging Wall
Albitization

Convoluted Folding
Transition Zone

Massive Sulphide Ore
Vent Complex

Tourmalinized
Footwall Conglomerate

Chaotic Breccia
Footwall

Piercement Structure
Top of Main Band

A Band

Durchbegweit
Sul[phide t
Base of
Main Band

Pyrite-Carbonate
Replacement of
Iron Core
(not shown on this
cross section)

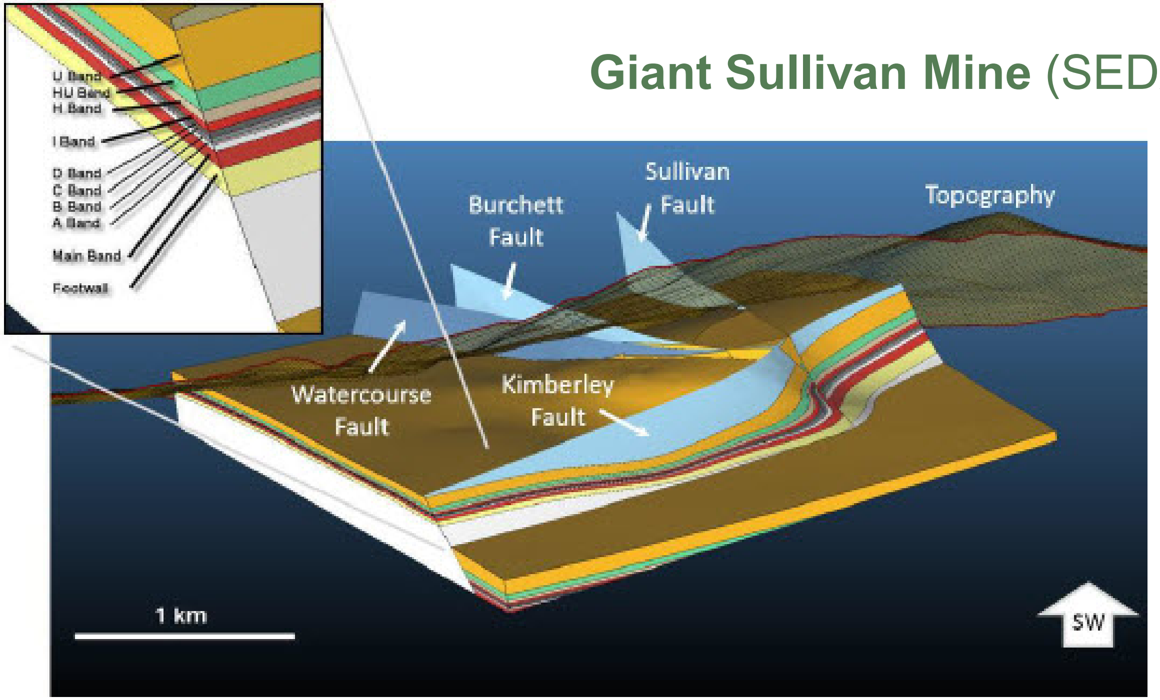
Pyrrhotite replacement
of Massive Sulphide Ore

Footwall Conglomerate

John Lydon 2015

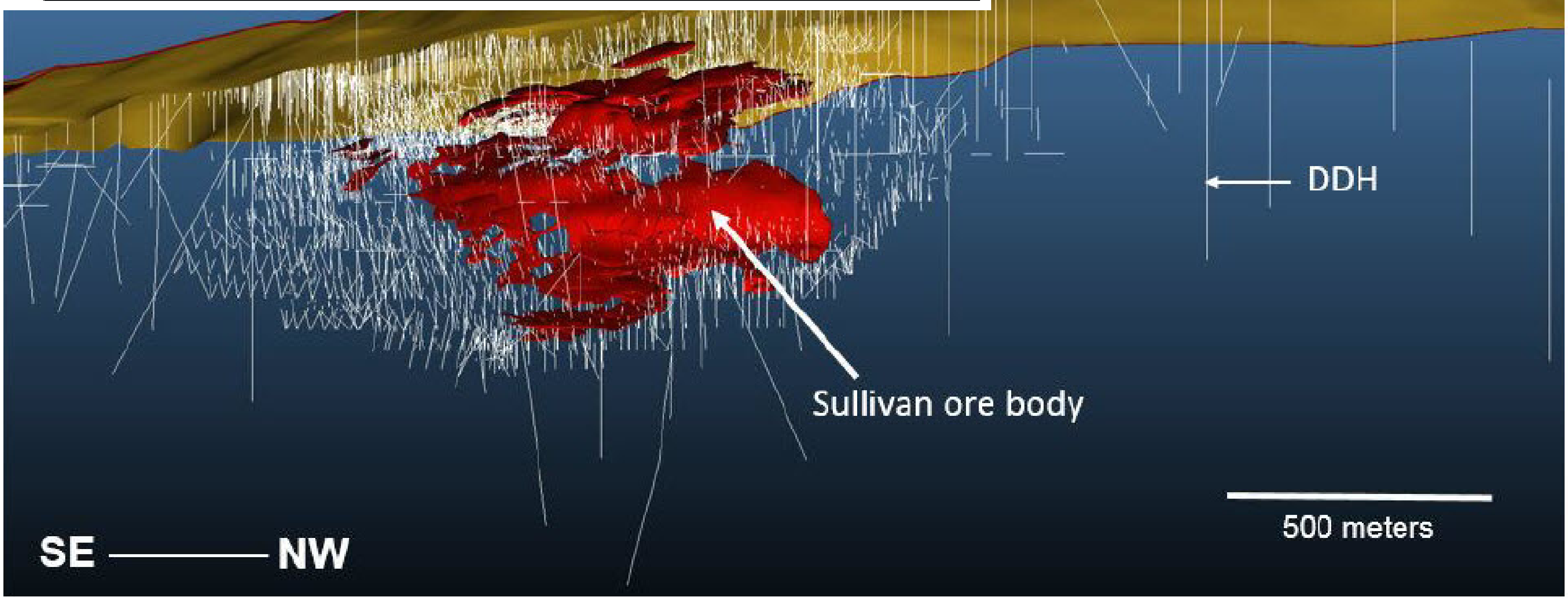
SEDX - Sedimentary Exhalative mineral system

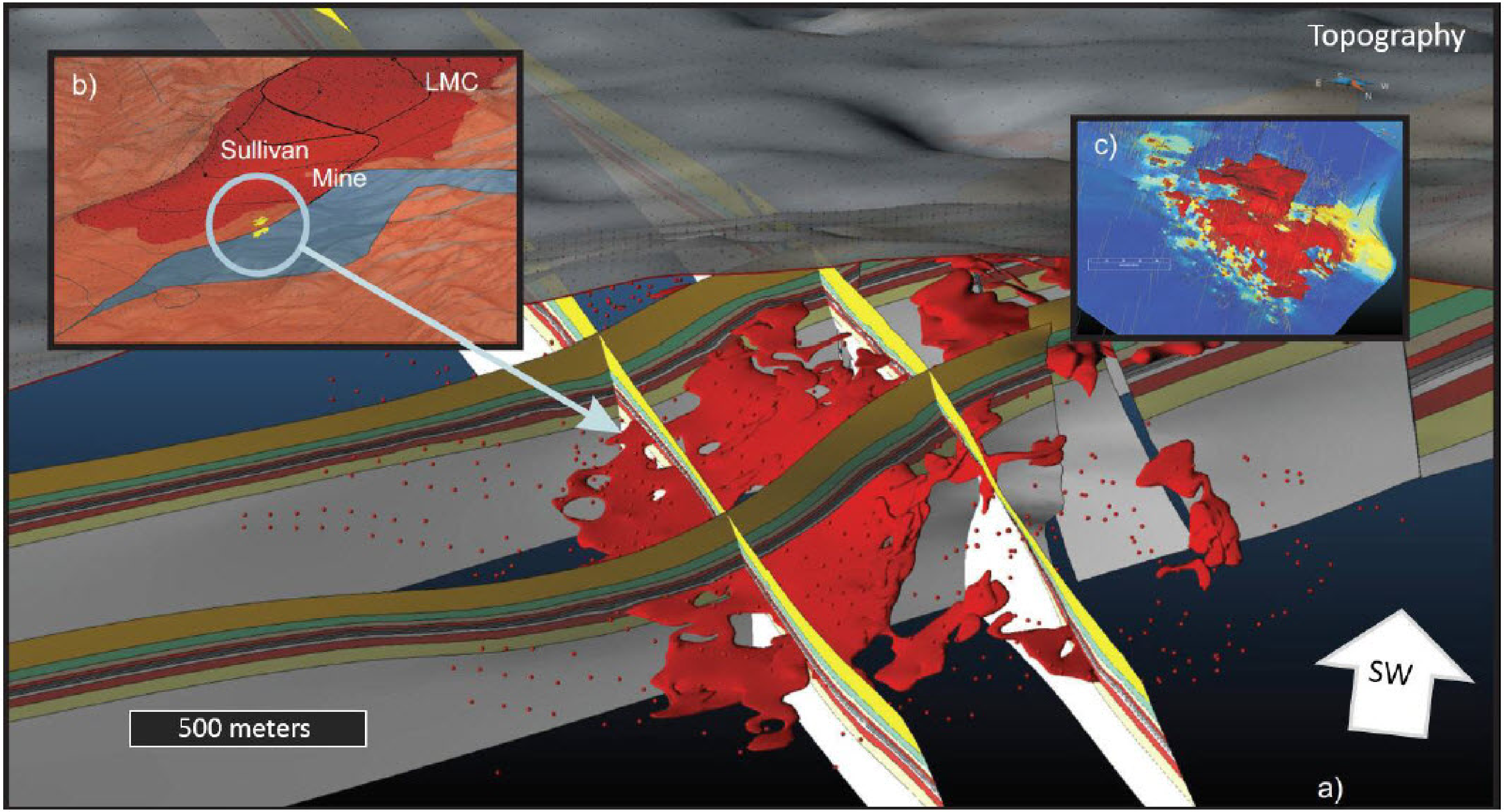
# **Giant Sullivan Mine** (SEDX) – $50 Billion US NPV



160 Mt Ore

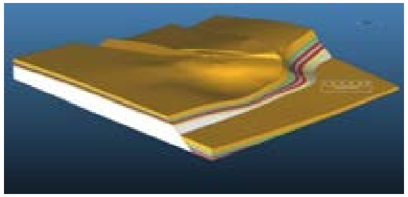
(8 Mt Pb, 7 Mt Zn,
285 Ounces (8.9 x $10^9$ g) Ag

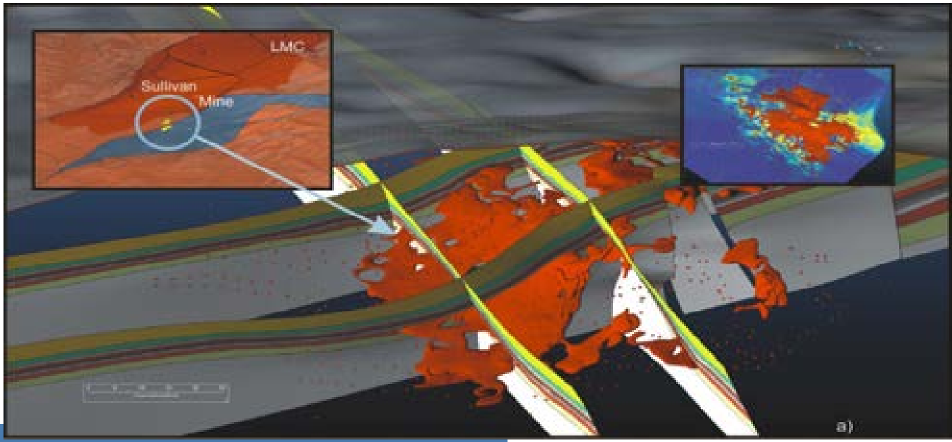


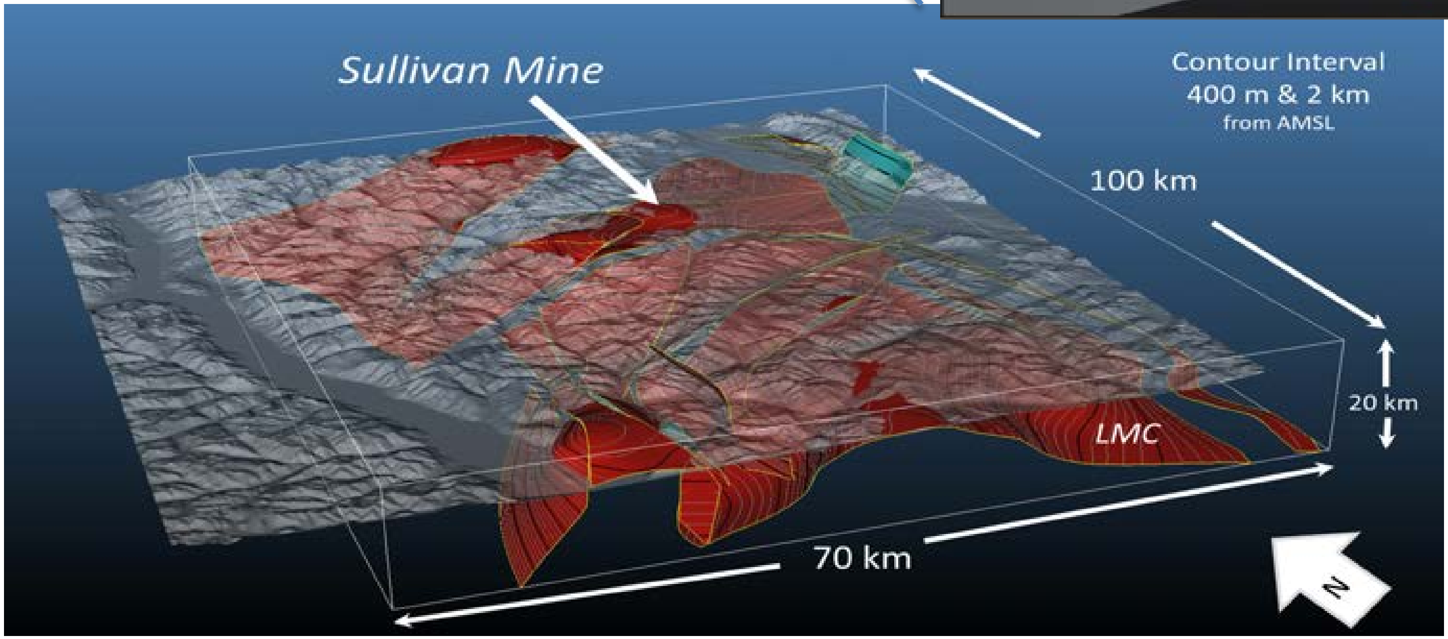

Topography
b)
LMC
Sullivan
Mine
c)
500 meters
SW
a)

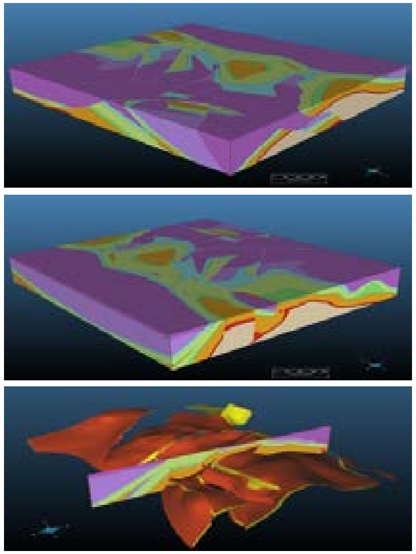
# Multi-Scalar

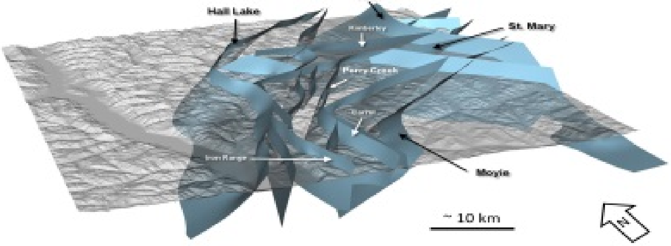
# Purcell 3D





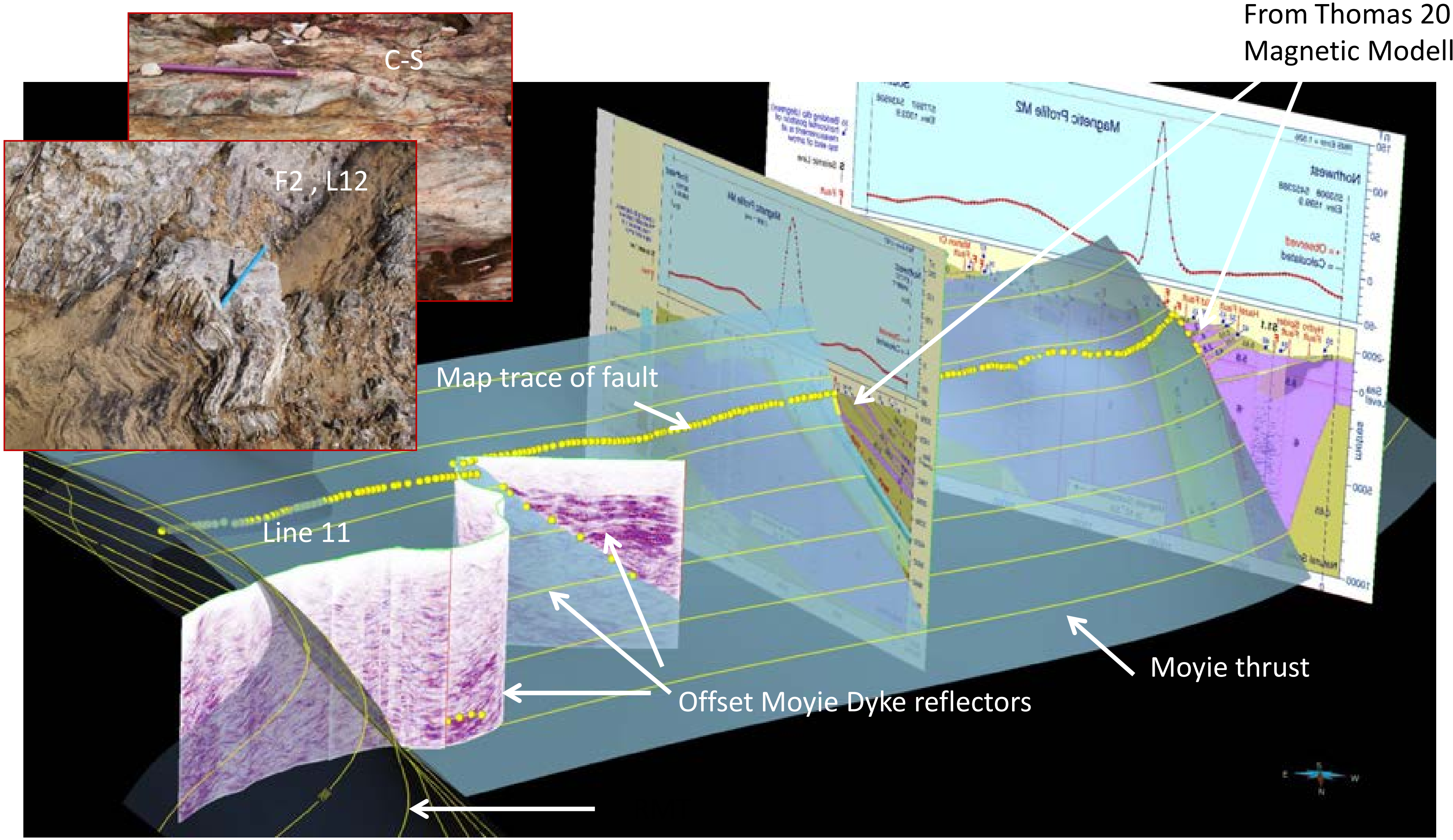






# Multi-Parameter

# Purcell 3D Faults



From Thomas 2013
Magnetic Modelling

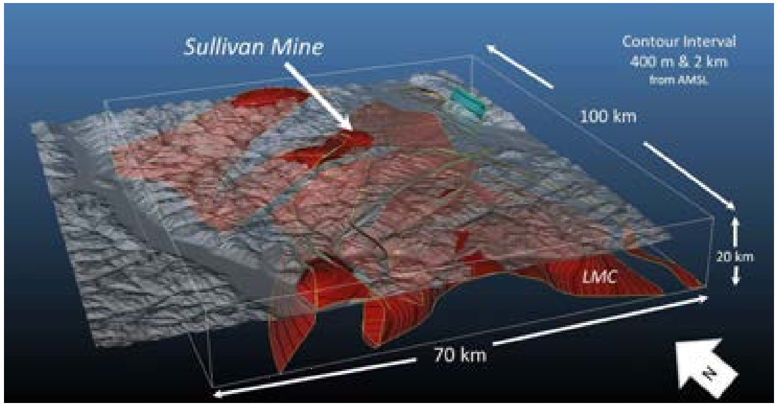
Map trace of fault

Line 11

Offset Moyie Dyke reflectors

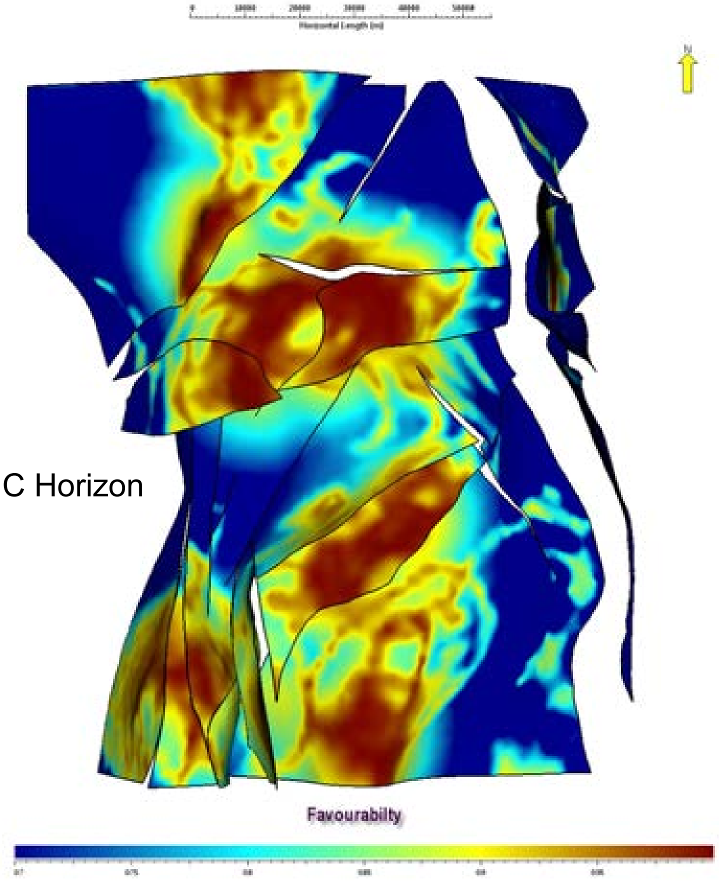
Moyie thrust

# Iterative

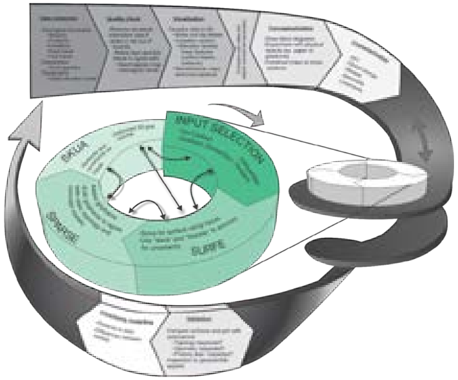


- Regional Uncertainty

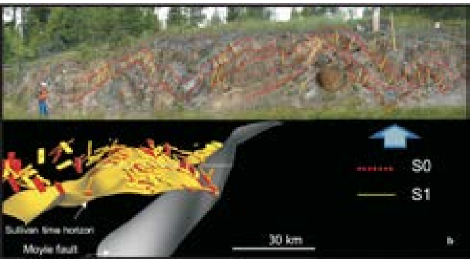
LMC Horizon



Montsion 2017

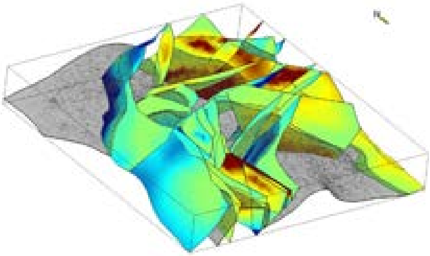


Structures

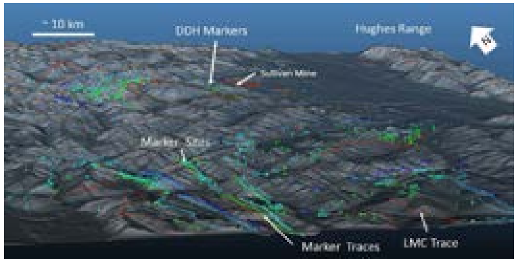


Stratigraphic Markers

Discontinuities



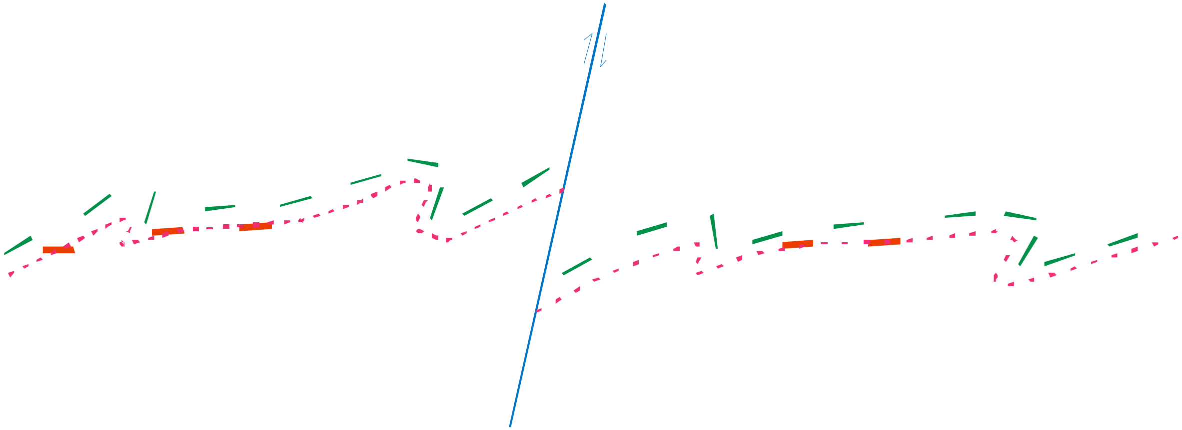
Spatial Integration

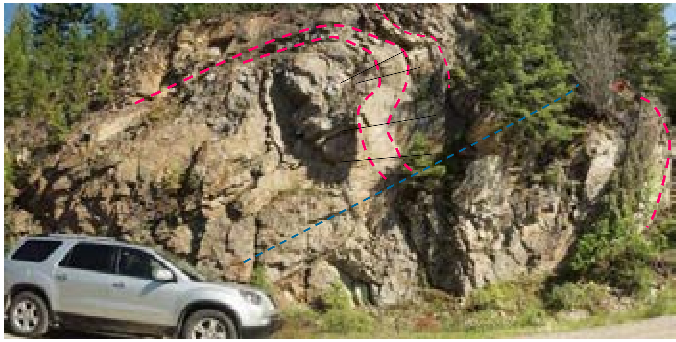


# Regional 3D Modelling Challenge, Purcell anticlinorium

A) primary drill hole constraints

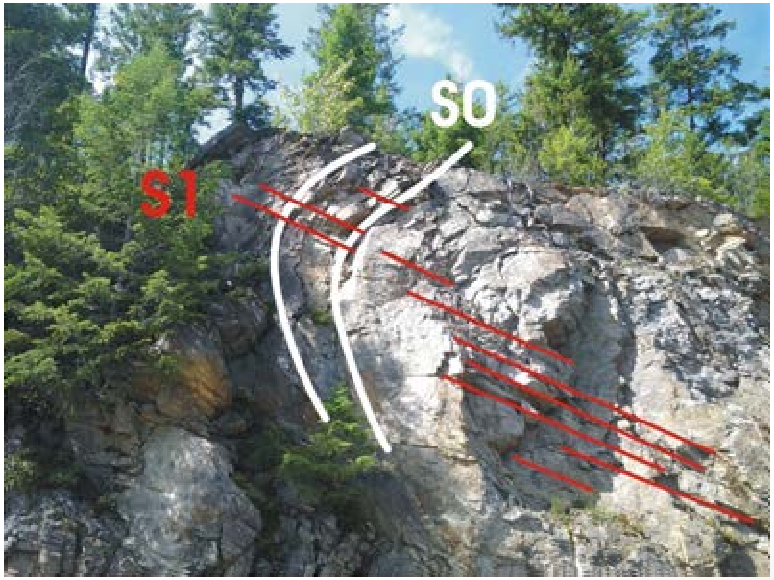
B) primary drill hole + secondary strike/dip constraints





# Spatial Continuity - Estimation

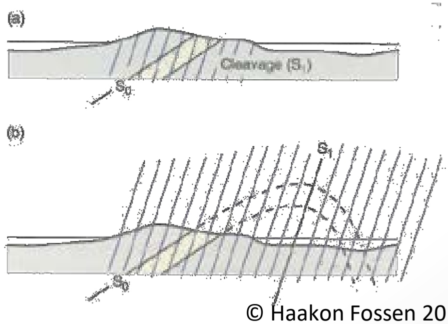
## Orientation and Direction Data



Structural Observations

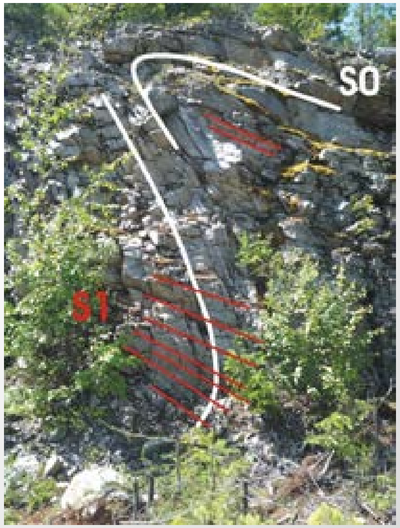
**Knowledge**

Structural style, fold parameters, etc.



© Haakon Fossen 2010

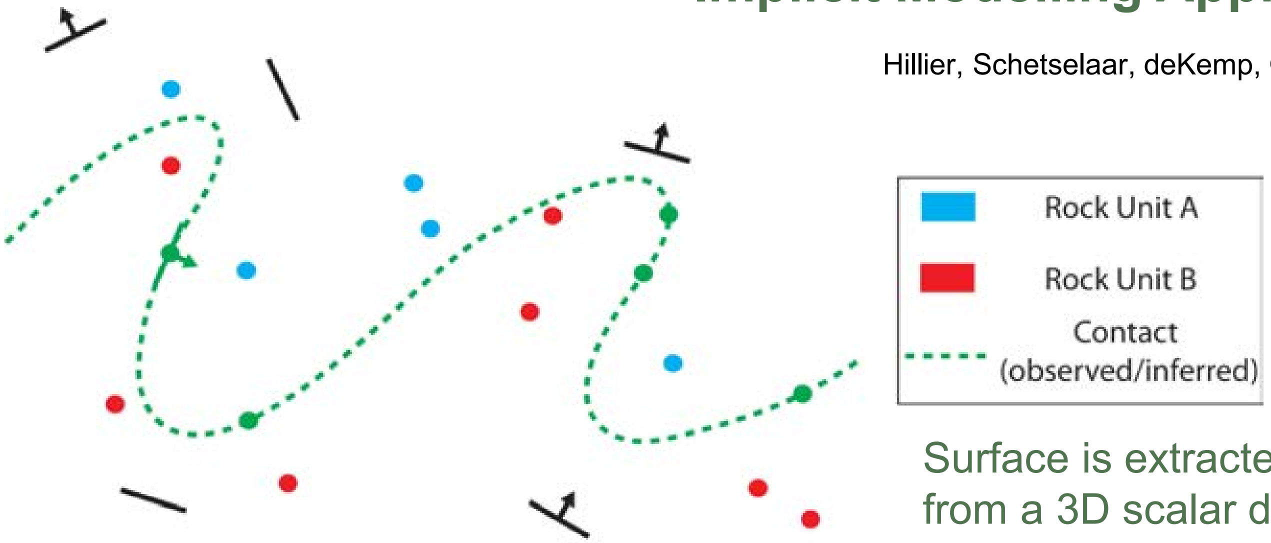
**Data**



# Geologic constraints: types and abundance

## Implicit Modelling Approach ( SURFE )

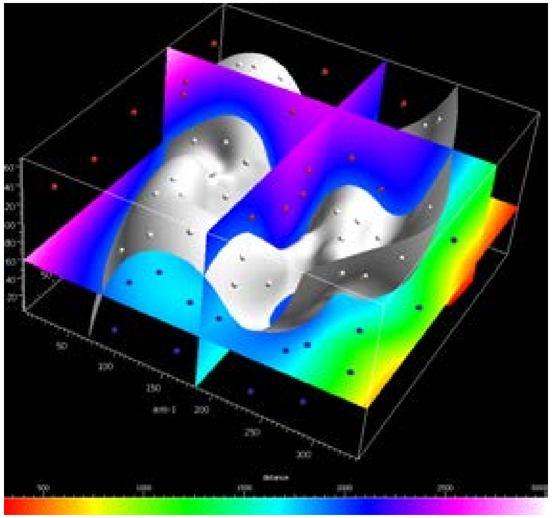
Hillier, Schetselaar, deKemp, GSC, Mathematical Geosciences 2015



Surface is extracted by tracing equipotentials from a 3D scalar distance function

### Constraint Types

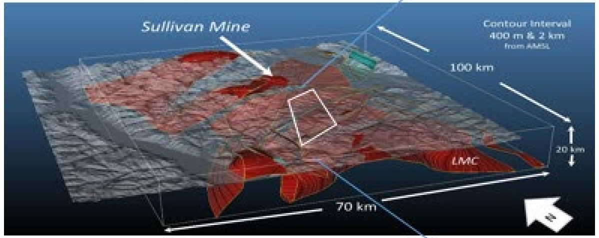
| | | |
|---|---|---|
| ● , ● | lithologic markers (inequality) → | $f(\mathbf{x})>0, f(\mathbf{x})<0$ |
| ⊥ | off-contact structural (gradient) → | $\nabla f(\mathbf{x})=\mathbf{n}$ |
| — | lineations (tangent) → | $\langle \nabla f(\mathbf{x}),\mathbf{t}\rangle=0$ |
| ● | on-contact (equality) → | $f(\mathbf{x})=0$ |
| ⊥ | on-contact structural → | $f(\mathbf{x})=0,\nabla f(\mathbf{x})=\mathbf{n}$ |



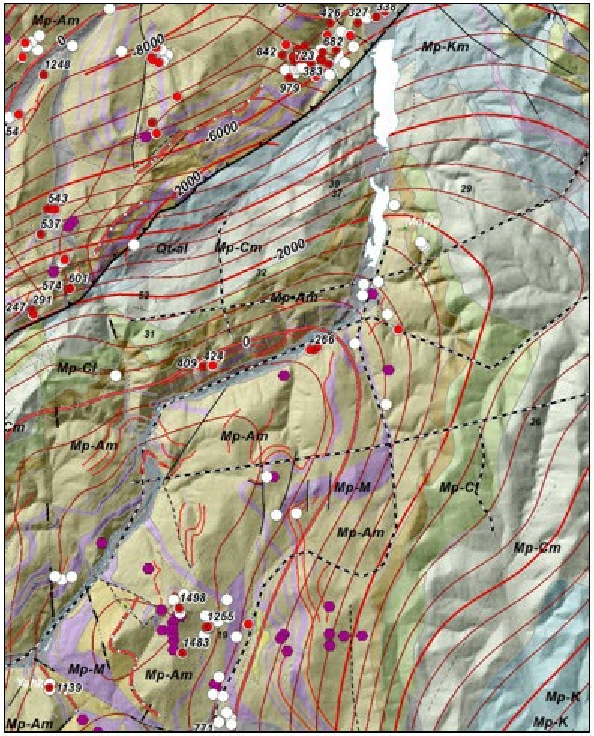
# Predictive Region Model

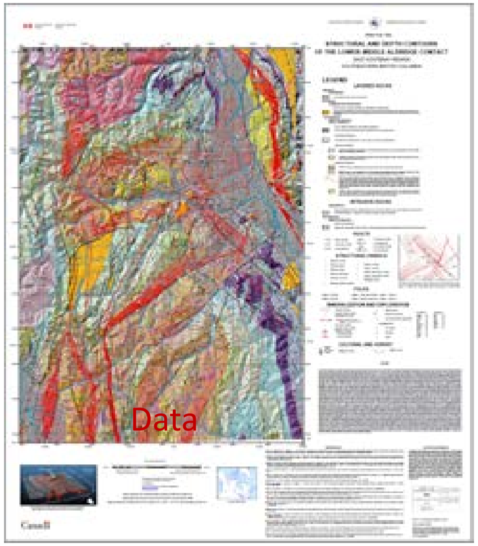
Purcell 3D

Model



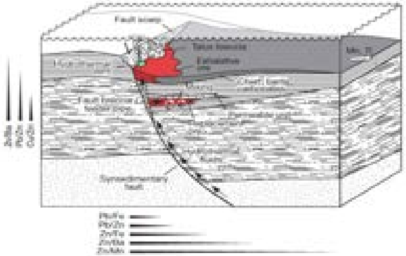
Map





de Kemp, E.A. and Schetselaar, E.M., 2015. Structural and Depth Contours of the Lower-Middle Aldridge Contact, East Kootenay Region, Southeastern British Columbia, Geological Survey of Canada, Open File 7903 3 - 1:100 000 maps with 3D model.

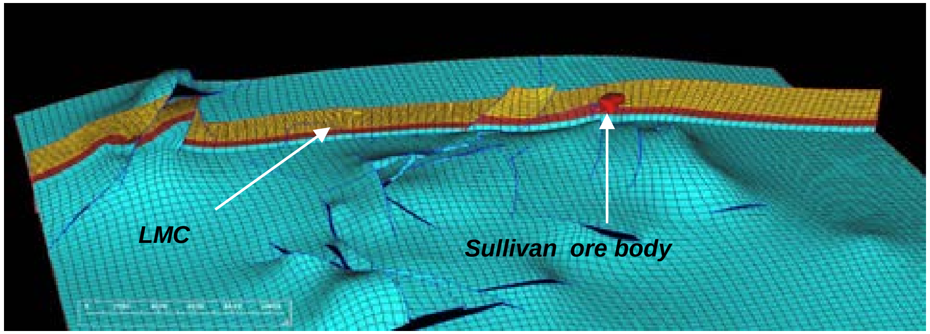
Knowledge



From J.J. Wilkinson 2014

Data

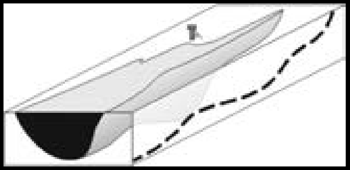
Data + Knowledge = Model



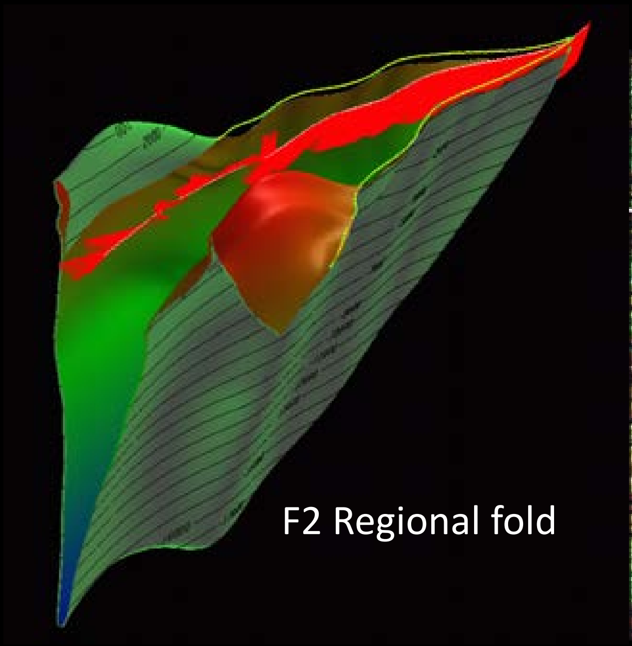
de Kemp et al. , 2016,Interpretation, Vol. 4, No. 3, p. SM33–SM50 http://dx.doi.org/10.1190/INT-2015-0191.1.

# Propagation techniques

Regional (camp) Scale

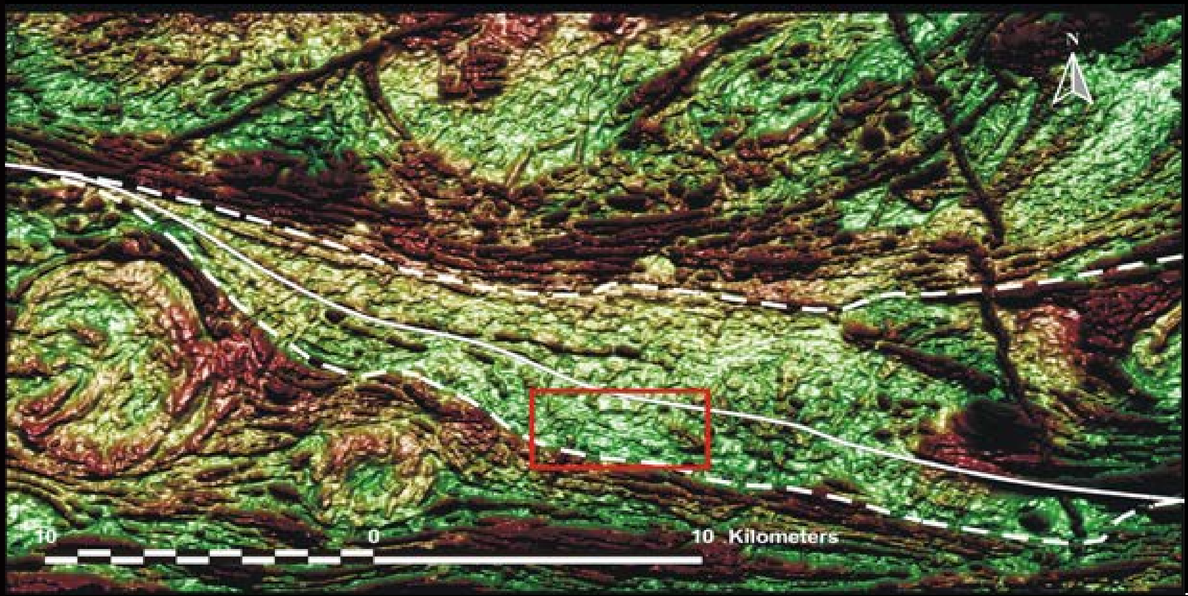


Vector field integration – field observations
Cross-section form lines for tie-lining
F2 Fold prediction ….



F2 Regional fold

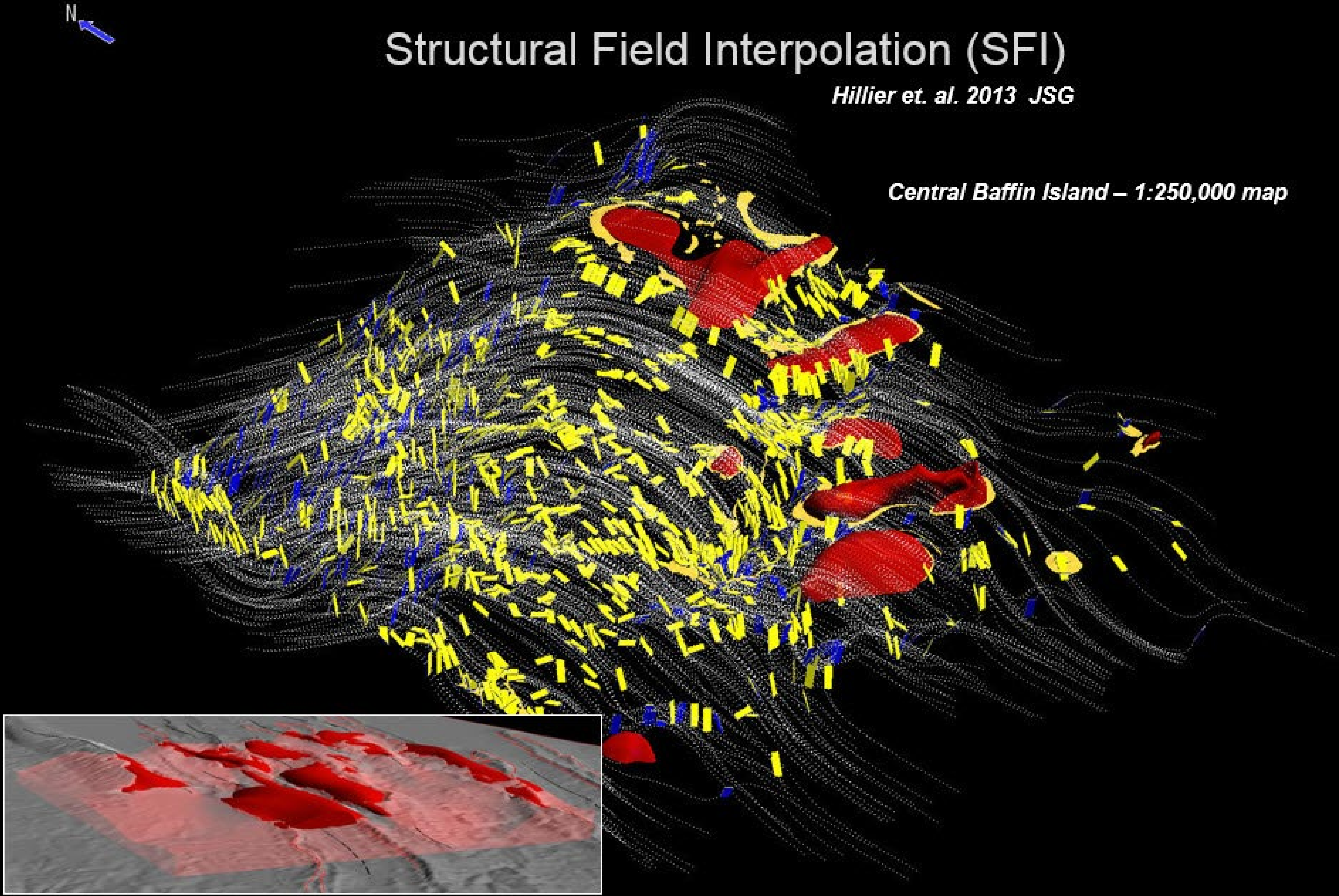
Caopatina Formation – Abitibi Greenstone
de Kemp, 2000 (Enhanced Magnetics 100 m flight lines, 25 m grid)



# Structural Field Interpolation (SFI)

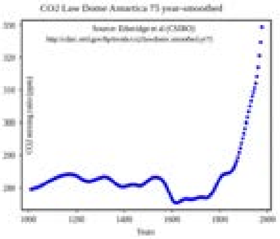
***Hillier et. al. 2013 JSG***

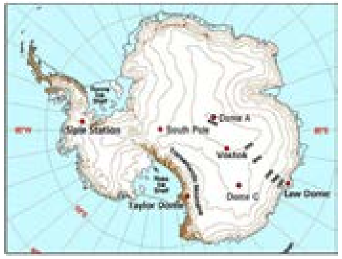
***Central Baffin Island – 1:250,000 map***

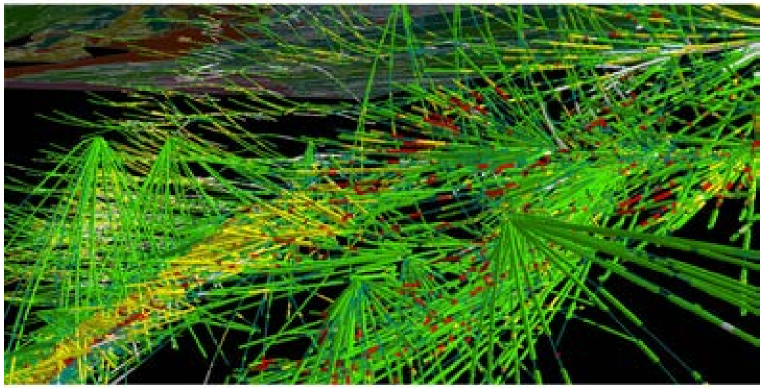


# Greenfields

Data is precious… Knowledge is essential





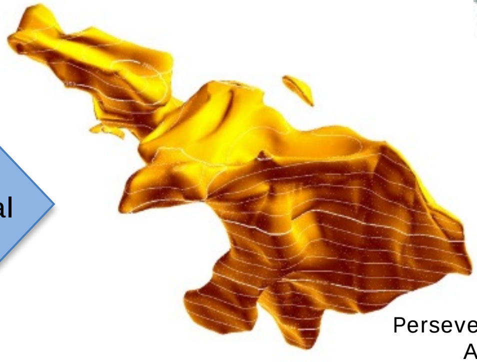


Dense Flin Flon lithostratigraphic drill core logs. Courtesy Ernst Schetselaar (GSC)

Dr. Kendrick Taylor (Desert Research Institute - Reno) examining Antarctic ice core. www.dri.edu

Global

Local



Courtesy CBGcorp

Perseverance VMS ore body
Abitibi, Quebec

# Earth Model Space

Knowledge

Data

# Reasonable Models ?

# Geologic relationships

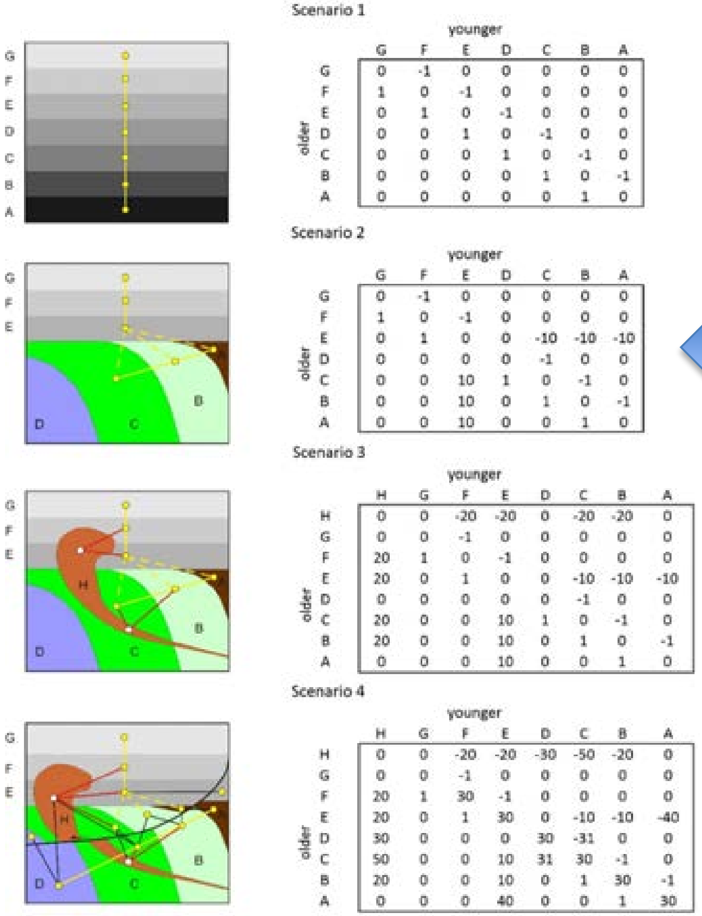
Folded gneiss. Teton Range, Wyoming. Courtesy of Marli Bryant Miller, Eugene, Oregon, marlimiller@earthlink.net Downloaded from http://marlimillerphoto.com/contact.html

# Geologic relationships and complexity

“Need to quantify complexity of the 3D geologic Model”

Pellerin et al. 2014

Geologic Topology Diagrams



Scenario 1

younger

| | | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|
| | G | 0 | -1 | 0 | 0 | 0 | 0 | 0 |
| | F | 1 | 0 | -1 | 0 | 0 | 0 | 0 |
| | E | 0 | 1 | 0 | -1 | 0 | 0 | 0 |
| older | D | 0 | 0 | 1 | 0 | -1 | 0 | 0 |
| | C | 0 | 0 | 0 | 1 | 0 | -1 | 0 |
| | B | 0 | 0 | 0 | 0 | 1 | 0 | -1 |
| | A | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

Scenario 2

younger

| | | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|
| | G | 0 | -1 | 0 | 0 | 0 | 0 | 0 |
| | F | 1 | 0 | -1 | 0 | 0 | 0 | 0 |
| | E | 0 | 1 | 0 | 0 | -10 | -10 | -10 |
| older | D | 0 | 0 | 0 | 0 | -1 | 0 | 0 |
| | C | 0 | 0 | 10 | 1 | 0 | -1 | 0 |
| | B | 0 | 0 | 10 | 0 | 1 | 0 | -1 |
| | A | 0 | 0 | 10 | 0 | 0 | 1 | 0 |

Scenario 3

younger

| | | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|---|
| | H | 0 | 0 | -20 | -20 | 0 | -20 | -20 | 0 |
| | G | 0 | 0 | -1 | 0 | 0 | 0 | 0 | 0 |
| | F | 20 | 1 | 0 | -1 | 0 | 0 | 0 | 0 |
| | E | 20 | 0 | 1 | 0 | 0 | -10 | -10 | -10 |
| older | D | 0 | 0 | 0 | 0 | 0 | -1 | 0 | 0 |
| | C | 20 | 0 | 0 | 10 | 1 | 0 | -1 | 0 |
| | B | 20 | 0 | 0 | 10 | 0 | 1 | 0 | -1 |
| | A | 0 | 0 | 0 | 10 | 0 | 0 | 1 | 0 |

Scenario 4

younger

| | | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|---|
| | H | 0 | 0 | -20 | -20 | -30 | -50 | -20 | 0 |
| | G | 0 | 0 | -1 | 0 | 0 | 0 | 0 | 0 |
| | F | 20 | 1 | 30 | -1 | 0 | 0 | 0 | 0 |
| | E | 20 | 0 | 1 | 30 | 0 | -10 | -10 | -40 |
| older | D | 30 | 0 | 0 | 0 | 30 | -31 | 0 | 0 |
| | C | 50 | 0 | 0 | 10 | 31 | 30 | -1 | 0 |
| | B | 20 | 0 | 0 | 10 | 0 | 1 | 30 | -1 |
| | A | 0 | 0 | 0 | 40 | 0 | 0 | 1 | 30 |

Feature Adjacency Matrices

Diagram Modified from Burns 1976, Theille 2016

# Complex Data Integration

## Benefits to companies

- Reduces risk in mineral exploration.
- Enables synthesizing of multi-disciplinary knowledge.
- Maximizes return on expensive exploration data, (Legacy data).
- Offers a context for deeper geologic targeting.
- Provides more opportunities for predictive 3D mapping and targeting.
- Provides a more rigorous basis for exploration decision-making.
- Promotes and focuses teamwork and expertise.
- Consolidates corporate knowledge as an asset in a dynamic repository (evergreen strategy).
- Highlights data and interpretive uncertainties.
- Streamlines analysis of large data volumes (Big Data).

# 3D Workflow of the future…

- Multi-scaler (outcrop to global, mine – regional integration)
- Multi-Parameter (geophysics – geology – geochemistry)
- Circular workflow (many updateable models)
- Challenging terrains (Sparse-Regional)
- Uncertainty Modelling
- Geological Reasonableness (All the **Data** + **Knowledge**; GeoEvent History)
- Simulation – Process Coupled – Implicit+
- Collaboration Practice **M** = f(Geophysics:Geology)

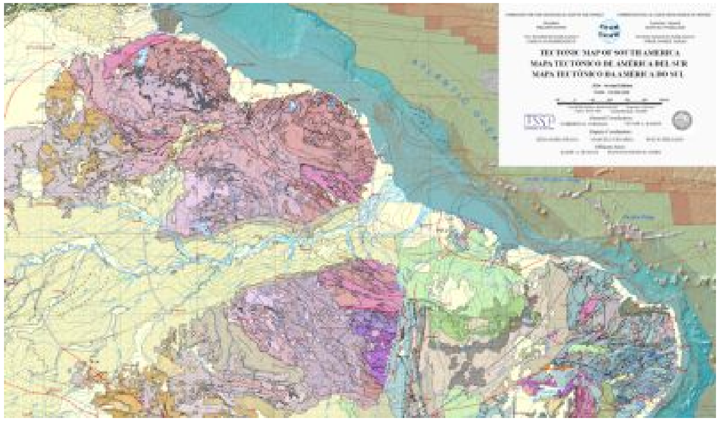
# Summary

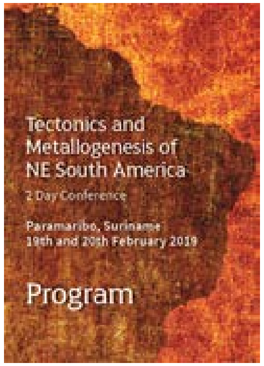
Onne Van Der Wall 2013
Courtesy of CNN

- Greenfields is where we need to go.
- Crew that stays in the harbor discovers nothing. The farther we sail the greater the reward!

*“It’s not that I’m so smart, it’s just that I stay with problems longer.”*

*Albert Einstein*





Tectonics and Metallogenesis of NE South America

2 Day Conference

Paramaribo, Suriname
19th and 20th February 2019

Program

# Summary

- Greenfields is where we need to go.
- There are abundant benefits with data integration.
- Complex geology and sparse data should not stop us.
  - Tools and active research going on **(ie. loop3d.org).**
- Invest in the infrastructure, staffing and technologies
  - Enhance your organization
- Needs collaboration – competition…**(ie. SAXI)**

# Greenfields

- New approaches and technology is needed to reduce risk
- Key technologies:
  - Deep imaging – Seismic, MT, Gravity
  - Near surface – Magnetics, Gravity (FTG)
  - Structural Integration – Vector field visualization
  - GIS integration and reconciliation – (2D & 3D)
    - Geophysics – Geology
    - Geochemical – Geophysics
  - 3D Modelling –Geophysical Inversion, Implicit modelling
  - Uncertainty assessment and modelling
  - Knowledge and Data driven 3D simulation

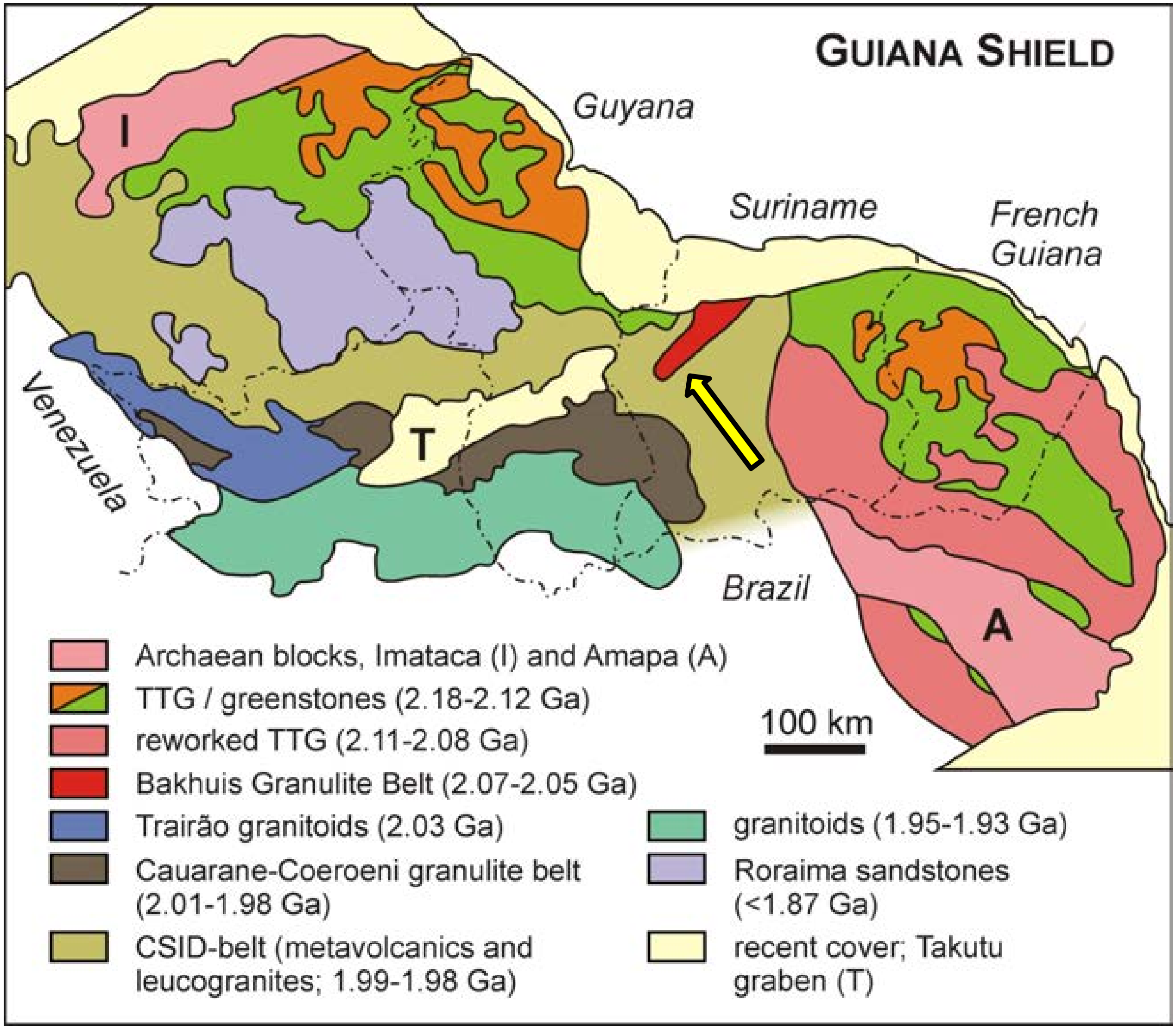
# The Bakhuis Granulite Belt in W Surinam, its development and exhumation

**E.W.F. de Roever, F.F. Beunk, K. Yi, K. de Groot, M. Klaver, J.A.M. Nanne, W. van de Steeg, A.C.D. Thijssen, B. Uunk, H. Vos, G.R. Davies, F.M. Brouwer**

Free University Amsterdam

# Bakhuis Granulite Belt

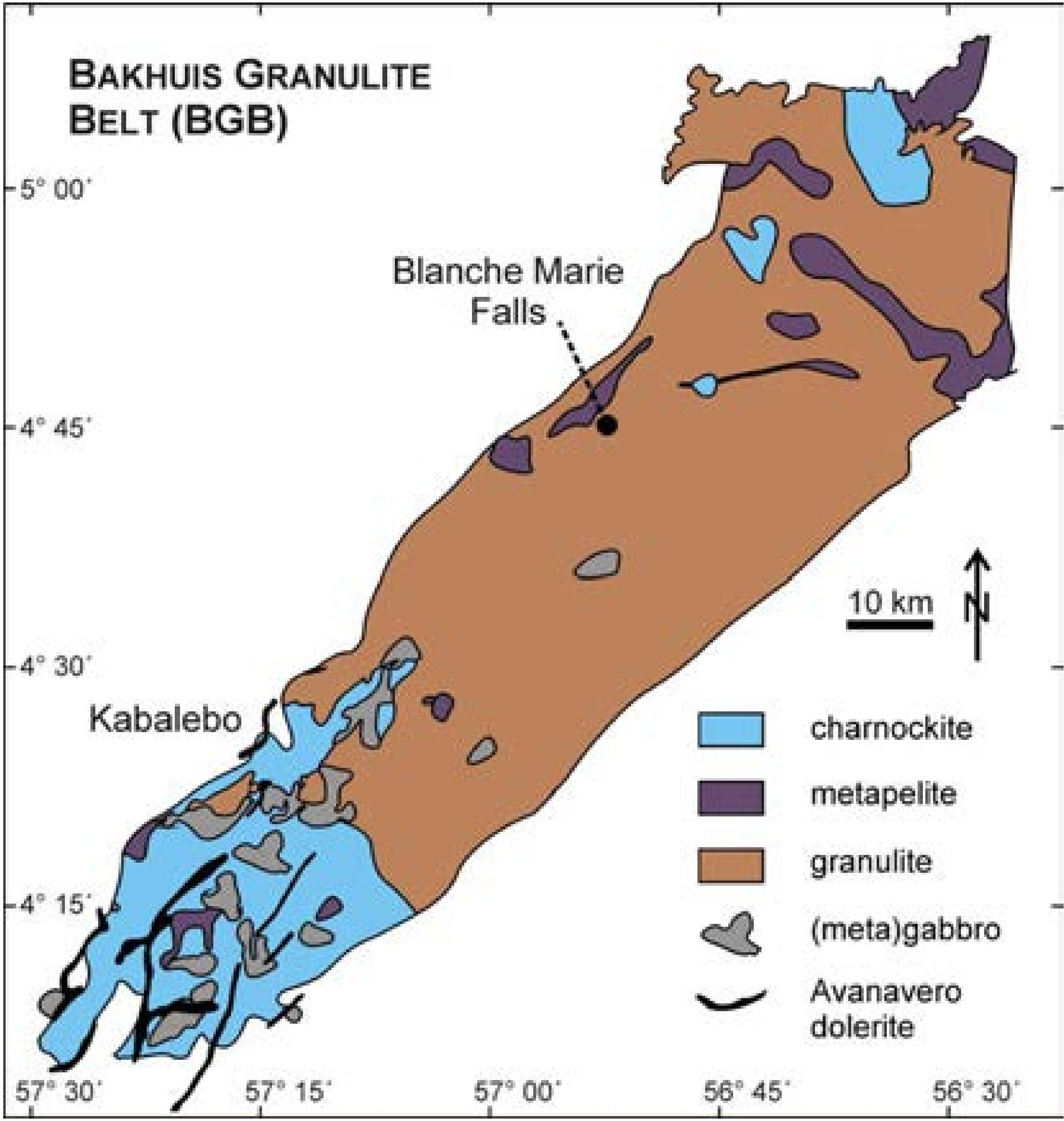
- BGB 30-40 x 100 km
- Between two arms of 1500 km long greenstone belt in the Guiana Shield, along NE coast of S. America
- Greenstone belt age 2.26 - 2.08 Ga



# Bakhuis Granulite Belt

- intermediate and mafic granulites
- with metapelite intercalations
- younger felsic and mafic intrusions

- NW and SE faults separate belt from younger granites and metavolcanics and some green-stones and schists
- in the north sands of the coastal plain



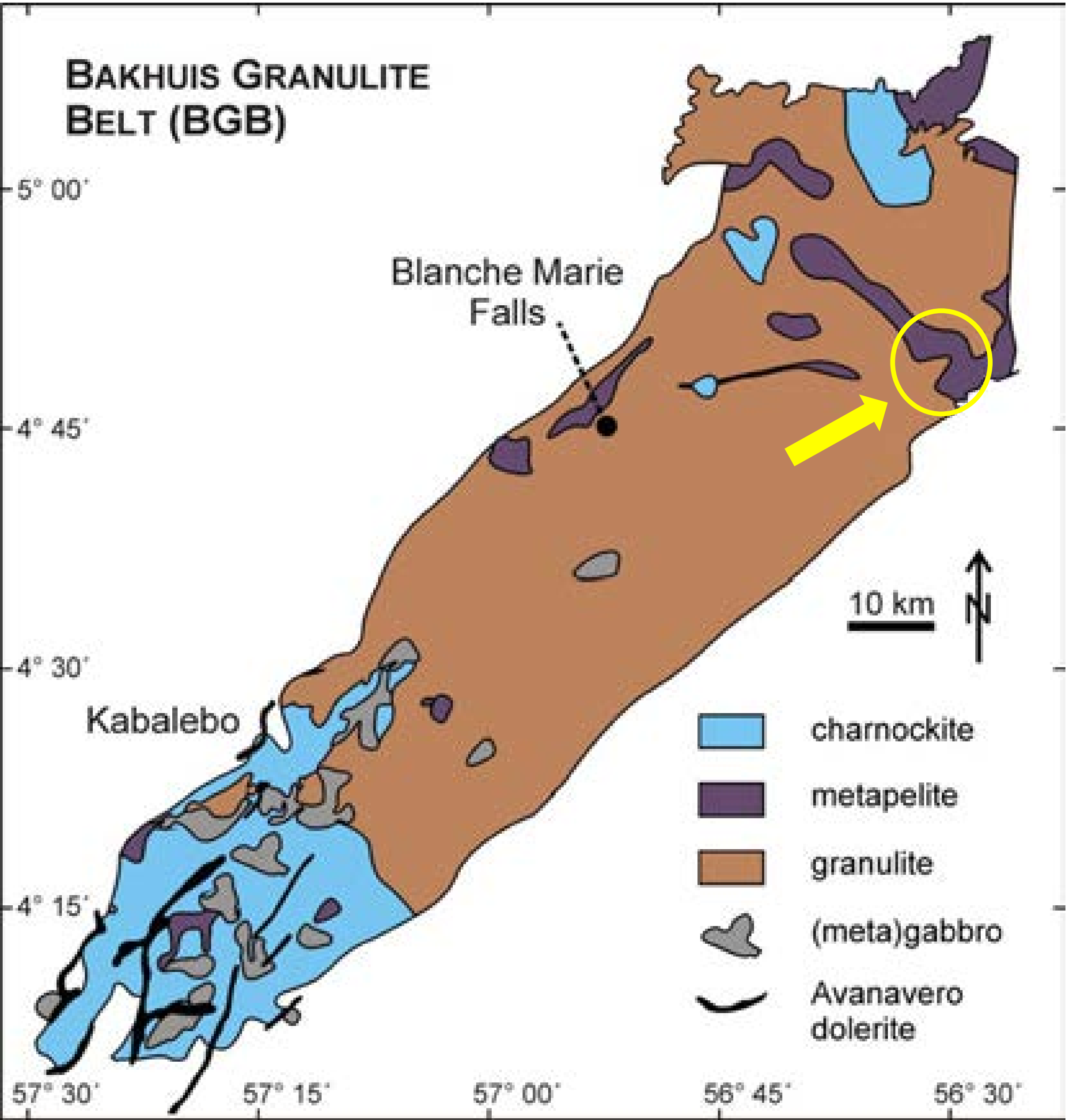
# Granulites : Supracrustals

- Granulites show conspicuous banding at dm (cm-m) scale (coin for scale)
- Intercalations of clear metasediments such as metapelites, quartzites and calcsilicate rocks

# Granulites : Supracrustals

- Mafic granulites have major and trace element chemistry of mafic volcanics
- Intermediate granulites in part derived from intermediate volcanics, with euhedral zircons of one age.
  Zircon age 2156 ± 6 Ma, similar to age of volcanism in the greenstone belt in French Guiana, 2135 – 2160 Ma
- Intermediate granulites in part derived from metasediments with varying zircon habit and age, and wacke-like chemistry
- Granulites represent volcanic-sedimentary supracrustals, not much different from greenstone belt lithology

# UHT Metamorphism in NE part of belt



Ultrahigh-temperature metamorphism defined as > 900°C (and regional)

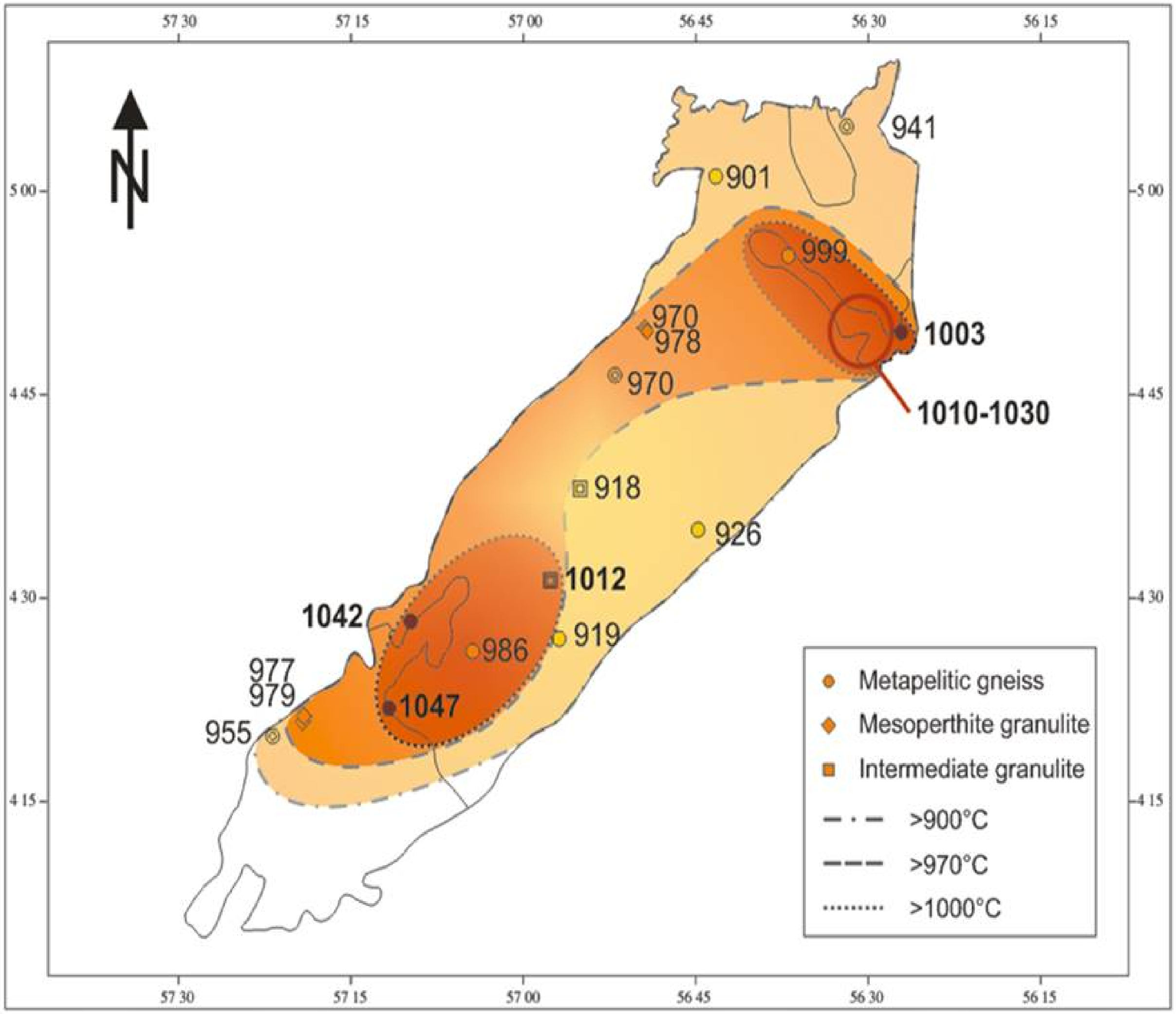
Characteristic assemblage Al-rich Orthopyroxene + Sillimanite ± Sapphirine in metapelite

Opx 8 – 10½ $Al_2O_3$

Feldspar thermometry $T_{peak}$ 1000-1030 °C

Opx - garnet P 9-10 kbar (depth $30^+$ km)

# UHTM peak temperature from feldspar thermometry

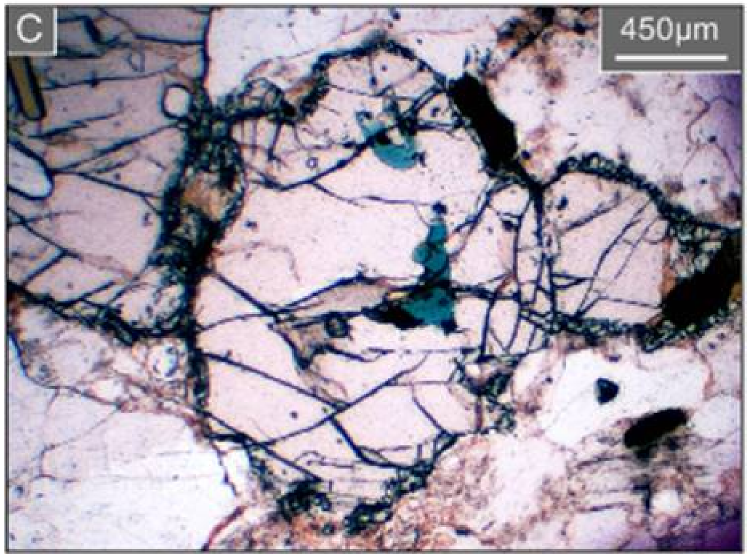


- T 900 - 1050°C : UHT metamorphism (>900°) in entire BGB
- Other metapelites show cordierite + sillimanite ± Al-rich orthopx. : not characteristic, but also formed by UHT metamorphism

NE part of belt

Opx + sill

Sapph in Garnet

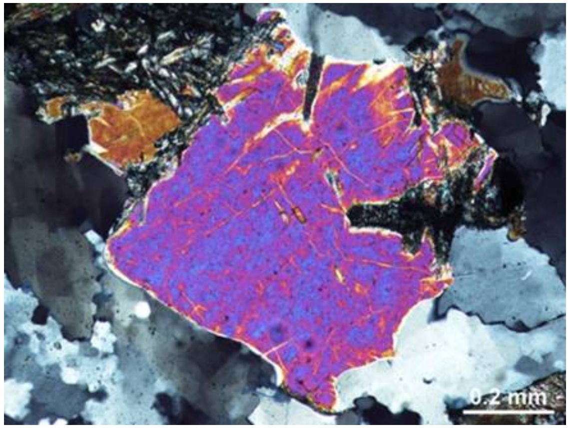


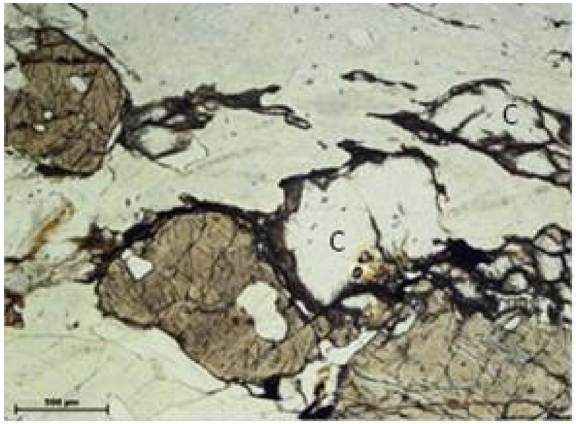
SW part of belt

PPL

$CO_2$-bearing cordierite, ~ 2% $CO_2$

XPL





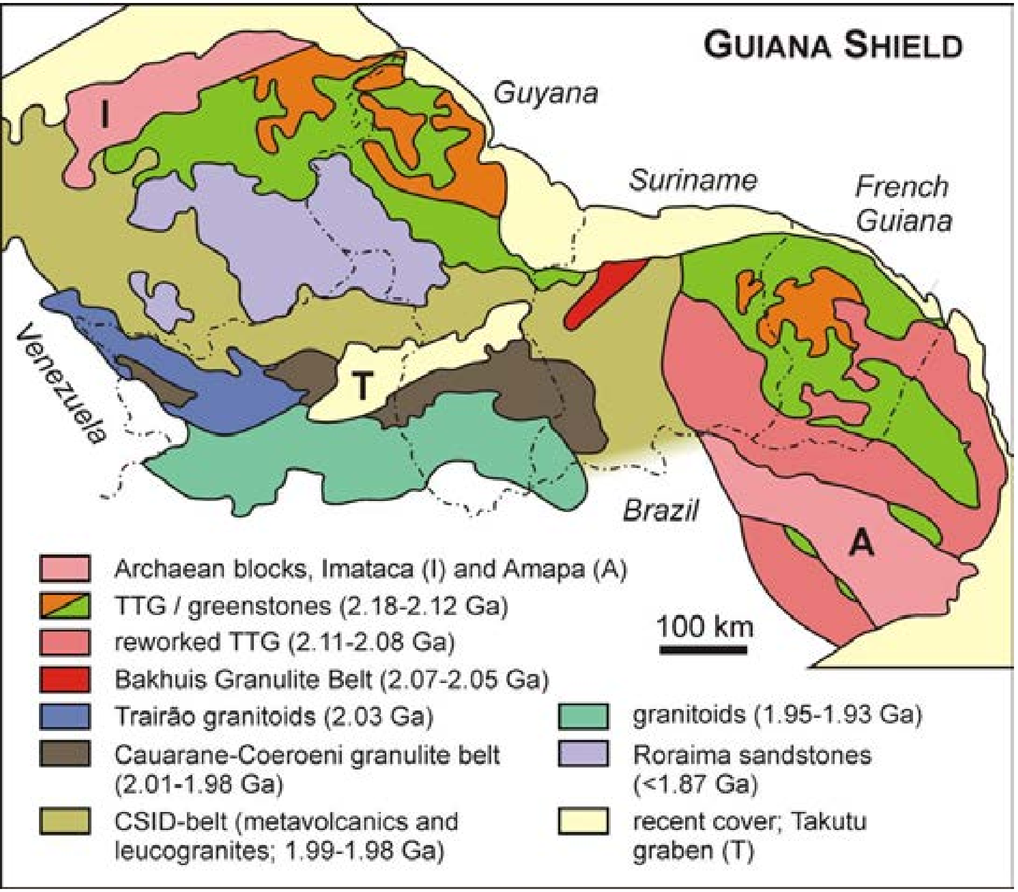
Opx + Crd (C)

# AGE of UHT Metamorphism

- Earlier work (2003): Pb-Pb evaporation dating of zircon, confirmed by SHRIMP, gave 2072 – 2055 Ma age
- Oldest age found for quartz-feldspar vein, 2088 ± 4 Ma for zircon (SHRIMP). Monazite from vein younger, 2056 ± 15 Ma. Therefore, probably peak of UHT metamorphism.
- Younger ages at 2075-2070 Ma and 2060-2050 Ma,
with simultaneous zircon and monazite crystallization
- Youngest age for narrow rims 2031 ± 4 Ma (zircon, SHRIMP)
- Age range 2088 ± 4 to 2031 ± 4 Ma gives duration of 50 – 65 Ma, rather long for UHTM, slow cooling

# Bakhuis Belt transects one greenstone belt or lies between two greenstone belts ??

- Picture obscured by younger granites and volcanics, 1.99 – 1.98 Ga



- W and E belt differ :
  - upper detrital unit only East
  - younger ages in West for metavolcanics, 2120-2145 Ma and undeformed TTG, 2090 - 2120 Ma
  - E : Archean to the south
- Map shows present time, after exhumation of BGB
- Bakhuis supracrustals metamorphosed at $30^+$ km depth, BELOW greenstone belt

- Probably one continuous greenstone belt above granulite protolith

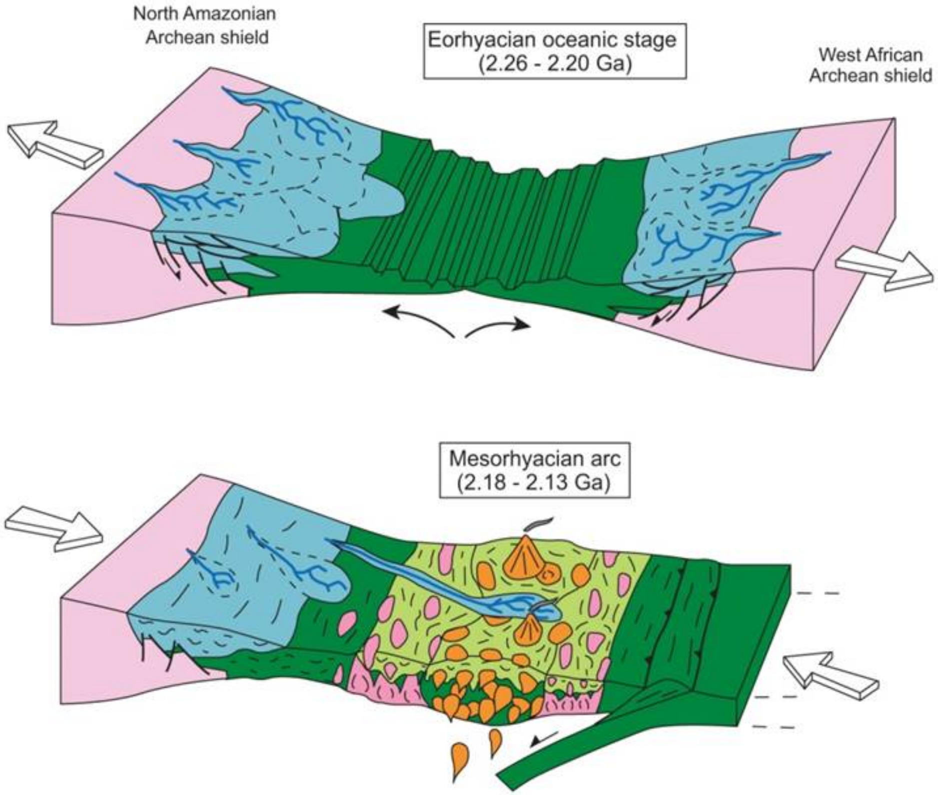
# Bakhuis Supracrustals

- How did they arrive at 30+ km??

- Intermediate granulite with 4 out of 10 zircon cores 2200 Ma or older, up to 2263 ± 72 Ma
- Coarser, non- pelitic greenstone belt metasediments mainly juvenile material, younger than 2.18 Ga (in French Guiana)

- Bakhuis metasediments may have origin outside the greenstone belt, near a craton with older material, West-African margin, where such material was available

# Bakhuis Supracrustals



Delor et al., 2003

- If the Bakhuis metasediments indeed originated from the margin of the West African Shield (blue on profile), they may have been subducted in a late stage below the greenstone belt

- At 30+ km depth, they may have been subjected to UHT metamorphism. Cold instead of very hot : what is heat source ??

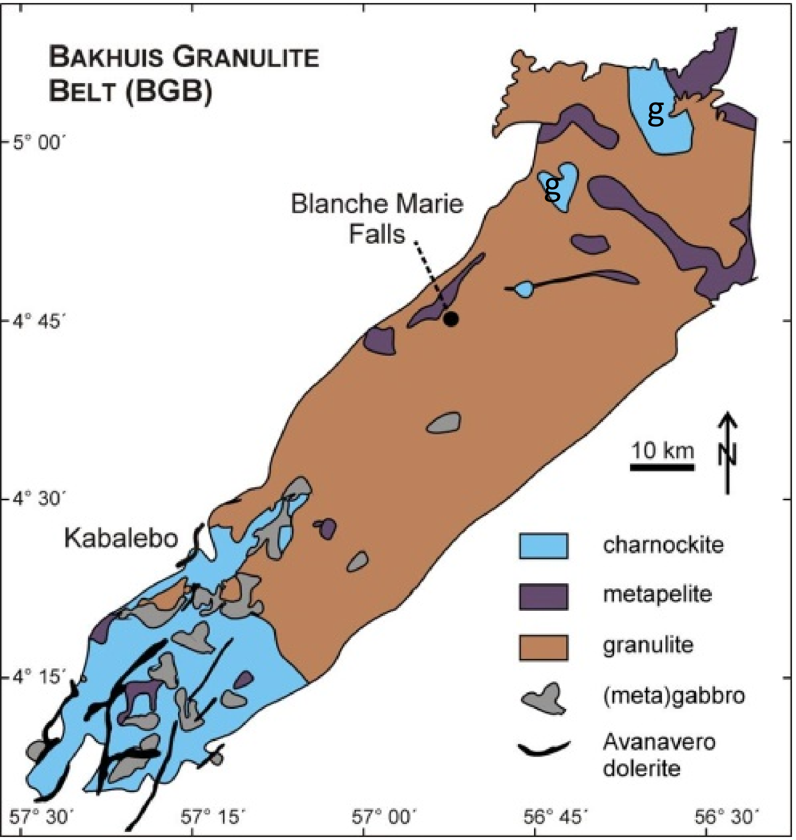
- Delor et al (2003) : mantle-derived thermal perturbation, situated probably in a zone of maximum crustal stretching, between the two greenstone arms ("slab tear??")

# Heat source for UHT metamorphism?

- Metadolerite dykes occur in BGB and not outside
- High-grade
- Contain zircons from granulites > false age
- Too narrow for dating
- In part folded, but much less than granulites
- Slight folding implies age at late stage of folding and (probably) of UHTM

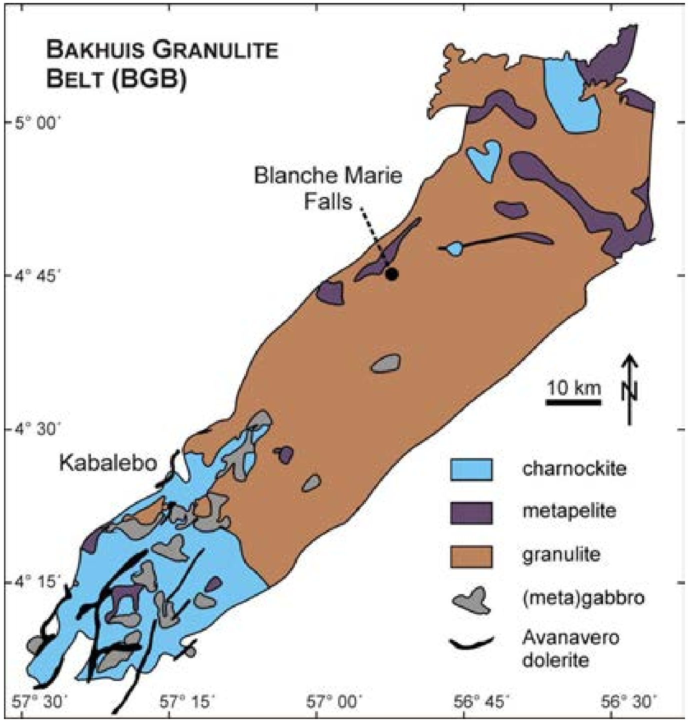
- Metadolerites are insignificant as heat source in terms of volume, but are a clear indication of contemporaneous mantle magmatism. More voluminous at deeper level (mafic underplating, upwelling) ?

# Younger charnockites dominate SW of BGB



- Charnockite (opx granite) age 1993 – 1984 Ma, 70-80 Ma younger than UHT metamorphism, at 2090-2030 Ma
- Crystallization at 960-990°C, a new (U)HT event > 900°C
- 70-80 Ma younger than UHTM, so probably not related
- Charnockites associated with abundant mafic intrusions

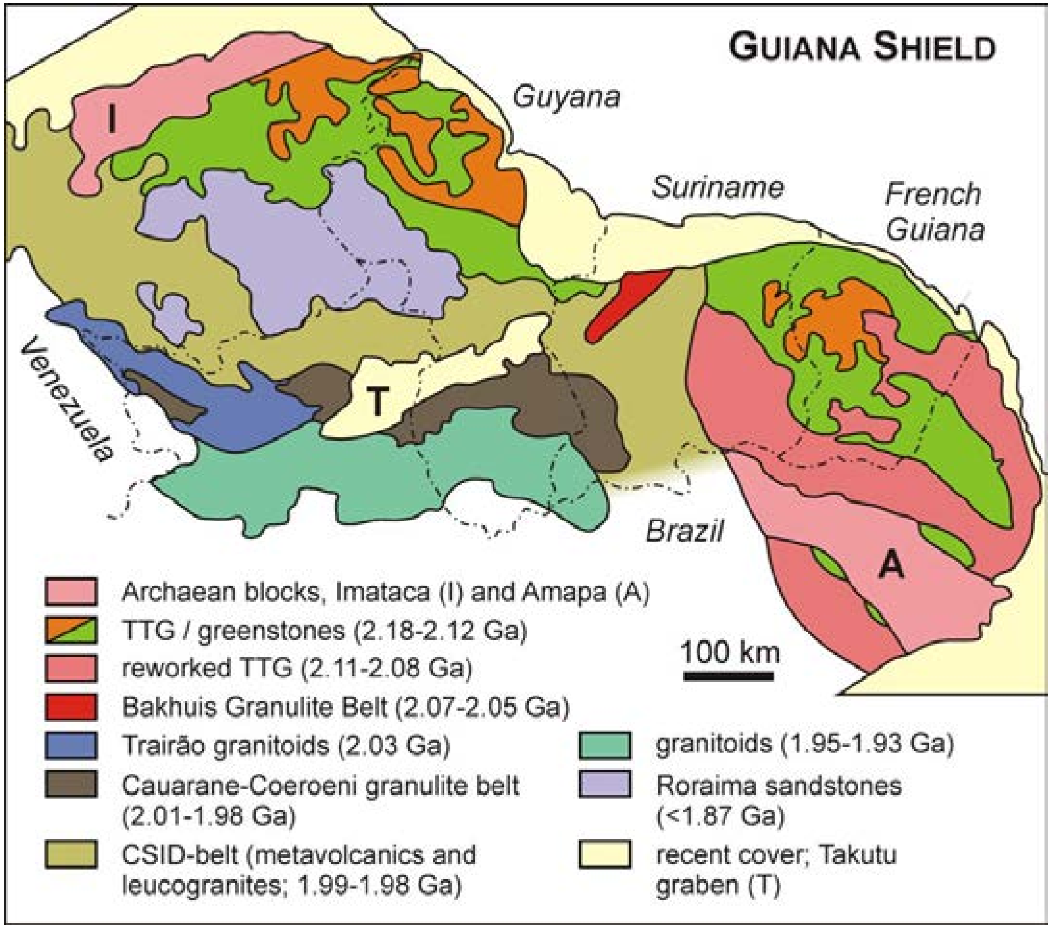
# Charnockites and mafic bodies in SW of BGB



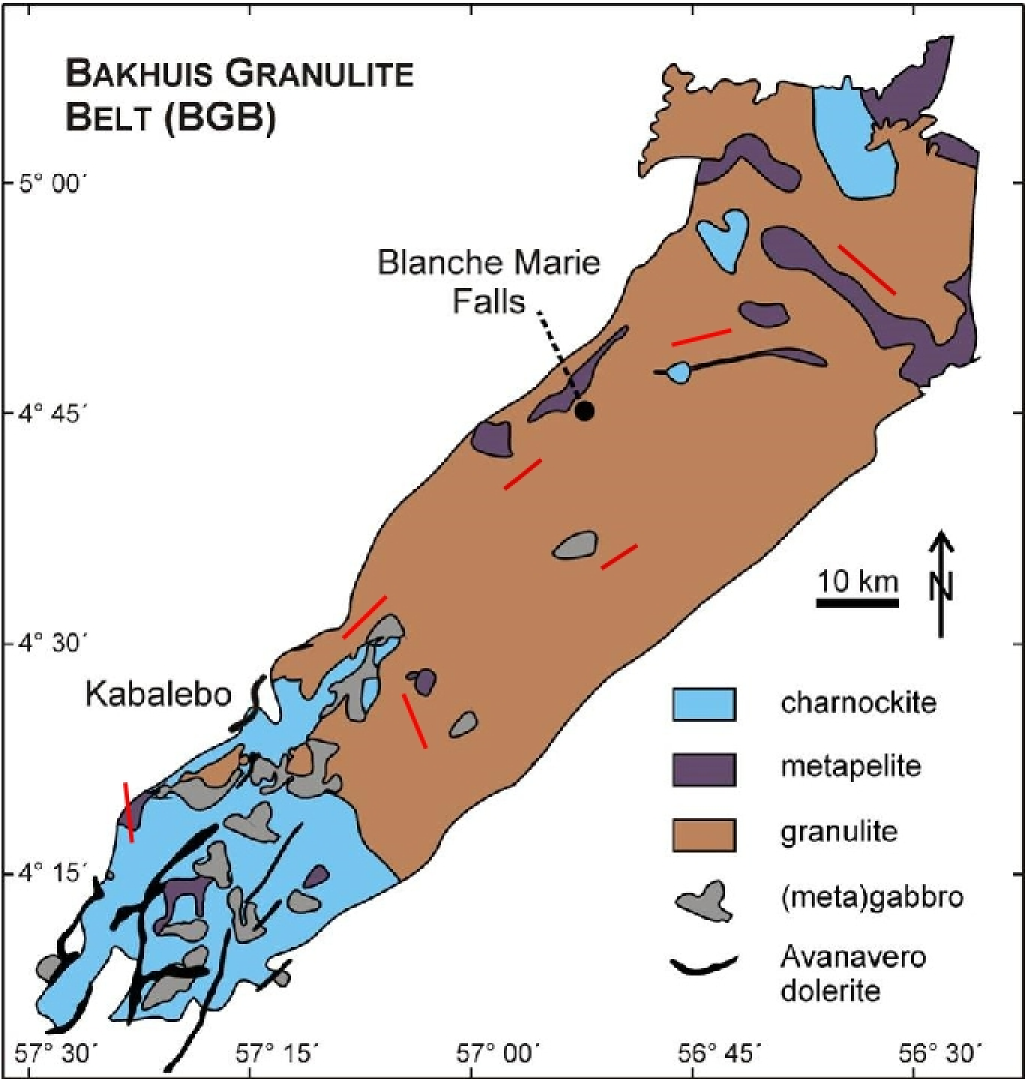
- Mafic bodies dated at ~1984 Ma, similar to charnockite age
- Charnockites formed by melting of intermediate granulites during intrusion of mafic magma
- Mafic bodies strongly resemble Alaskan-type mafic-ultramafic complexes, generally interpreted as the root zones of volcanic arcs

# Charnockites and mafic bodies in SW of BGB

- Volcanic arc-like belt around BGB : felsic metavolcanics and leucogranites of 1400 km long Caicara-Dalbana belt, of 1990 – 1980 Ma age
- Caicara - Dalbana magmatism influenced SW of BGB
- The mafic bodies are not restricted to BGB, but also rather common in C - D belt in W Surinam

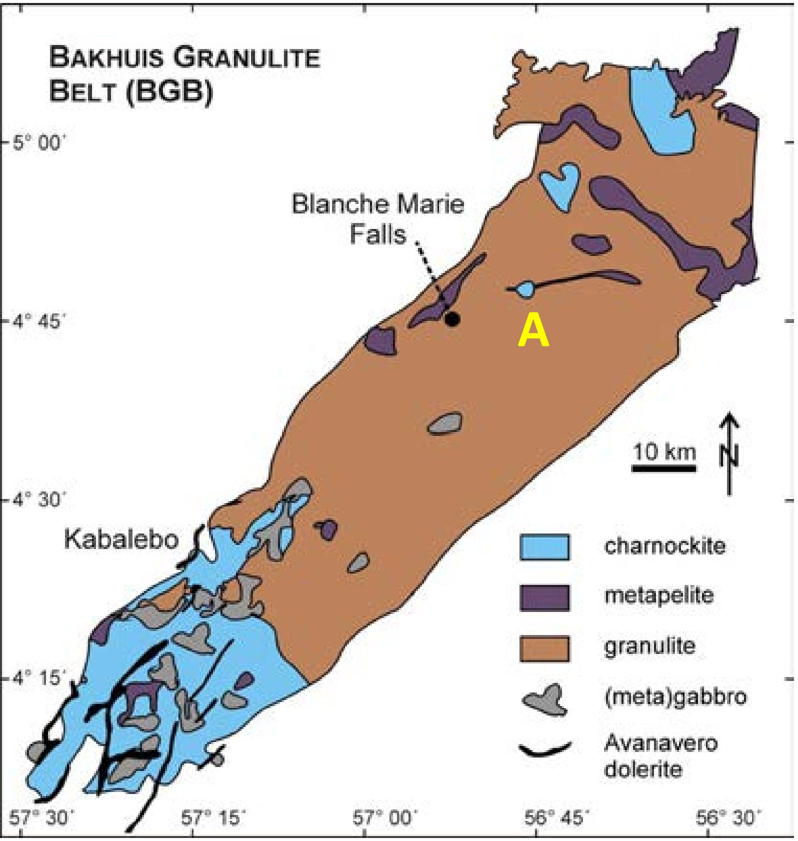


# Structure and exhumation of BGB



- Banding largely subvertical
- Banding strike bends round from NE to SE in NE corner
- Bending of strike indicates dome-like structure
- Dahlberg (1971) :
  also bending at SW side
- SE side : younger fault zone cuts off dome-like structure

# Anorthosite body with igneous layering

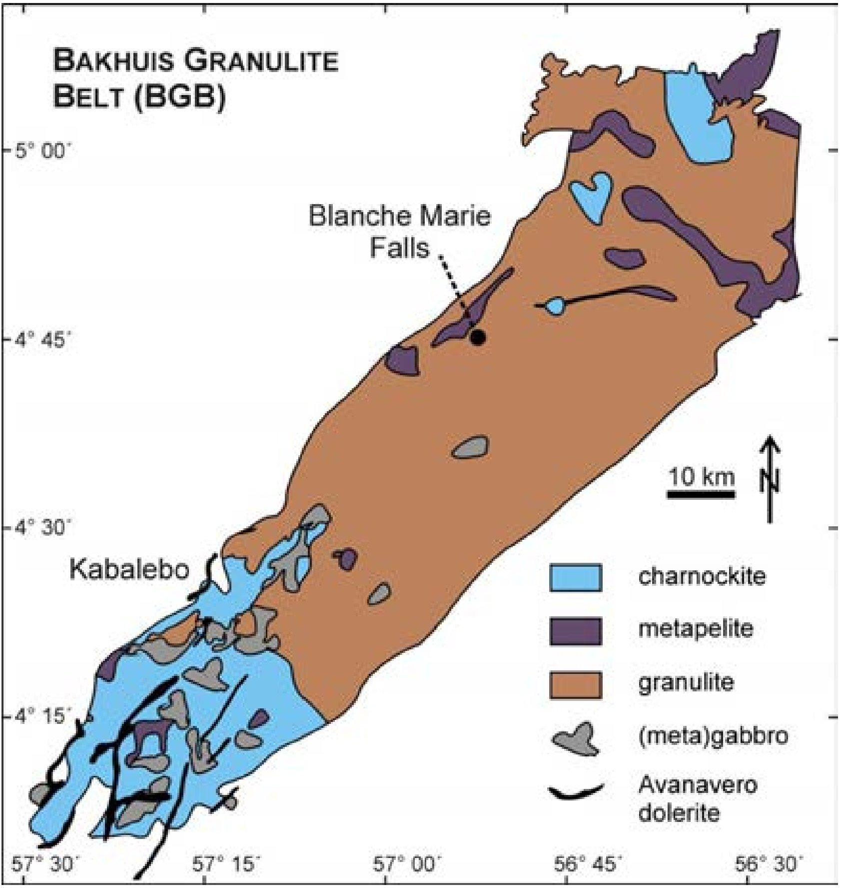


- Anorthosite body of 3 x 4 km covered by high quality bauxite
- Anorthosite age 1980 ± 5 Ma
- Body shows igneous layering,

  but layering is now subvertical
- Steepening of layering and banding, and probably doming : after 1.98 Ga, but before end of Trans-Amazonian orogeny (probably around 1.95 Ga)

- Considerable exhumation before end of T-A orogeny, in part during steepening/doming and in part before : hornblende in SW charnockite suggests 4-5 kbar (15 km)

# Bakhuis Host and Nickerie Mylonite zones



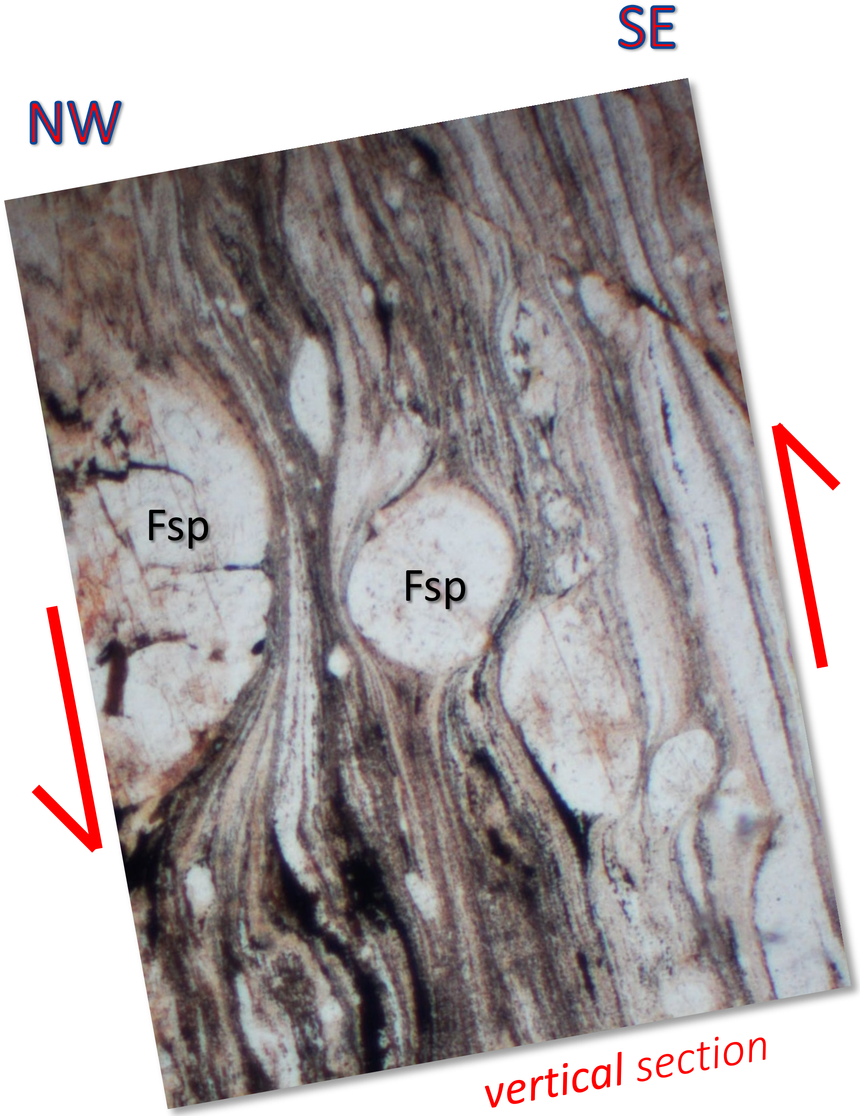
- BGB bordered by $1^+$ km wide mylonite zones, Bakhuis Horst
- Nickerie Tectonothermal Event (or Kmud´ku) around 1200 Ma, from K-Ar and Rb-Sr ages of biotite
- Ar-Ar age of mylonites: 1214±5 Ma

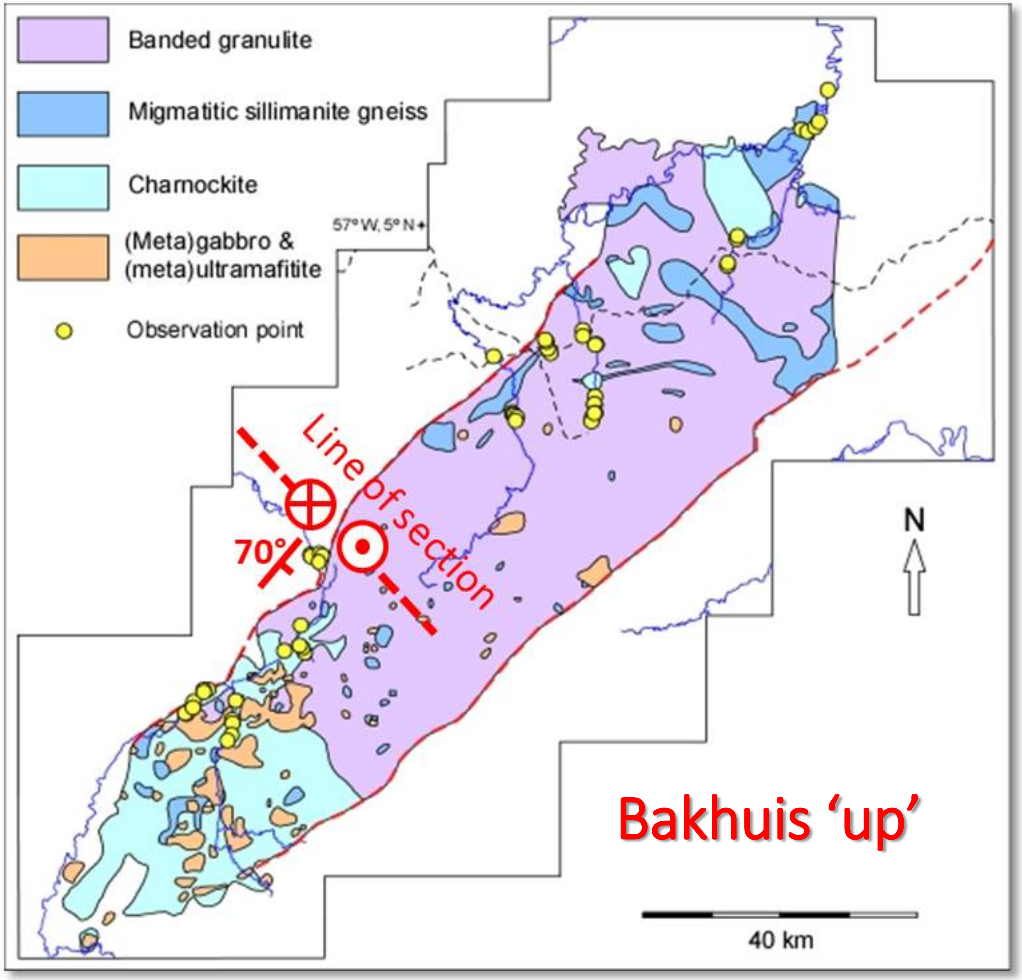
- Low-grade metamorphism, with muscovite, biotite, garnet
- SE zone cuts off dome structure, NW zone parallel to TA direction??

- Nickerie : Continued BGB exhumation

# Bakhuis Horst or Bakhuis Pop-up ??

- Not an extensional Bakhuis Horst, with normal faults, but compressional Bakhuis Pop-up, with reverse dip. Also some strike-slip.





# Continued, limited exhumation after Nickerie Event

- Along pseudotachylyte zones in/ near main Nickerie mylonite zones
- Ar-Ar dating of ps. (one location) : ~ 950 Ma, younger than Nickerie

- Tertiary : at least two bauxite levels in BGB, slight exhumation
- Horst-like topography, exhumation probably going on (extension or compression?)

# THANK YOU !!

# QUEST IONS ??

- Thanks to the Geological and Mining Service (GMD) of Surinam and its managing director, Dr. G. Gemerts, and in the past, Mrs. P. Simons MSc, Mr. M. Autar and Mrs. R. Mahabier MSc
- Thanks to the staff of Kabalebo Nature Resort and in particular Karel and Joyce Dawson, for providing facilities and help with fieldwork
- Thanks to Norman Mac-Intosh (Discover Suriname) for preparing and facilitating our 4-WD journeys, cooking and camp-building

VU VRIJE UNIVERSITEIT AMSTERDAM

Dr. Schürmannfonds

# Timing of the origin and uplift of the Bakhuis-Tambaredjo Horst, Suriname

**Rohini Girjasing[1], Salomon Kroonenberg[1], Rakesh Ramdajal[2], Theo Wong[1].**

[1]Anton de Kom Universiteit van Suriname. [2] Staatsolie Maatschappij Suriname N.V.

## Introduction

Seismic studies carried out by Staatsolie around the Tambaredjo oil field revealed an uplifted structure near the main producing fields which is in line with the Bakhuis structure and was therefore considered to form the continuation of the Bakhuis horst (**Fig.1&2** )

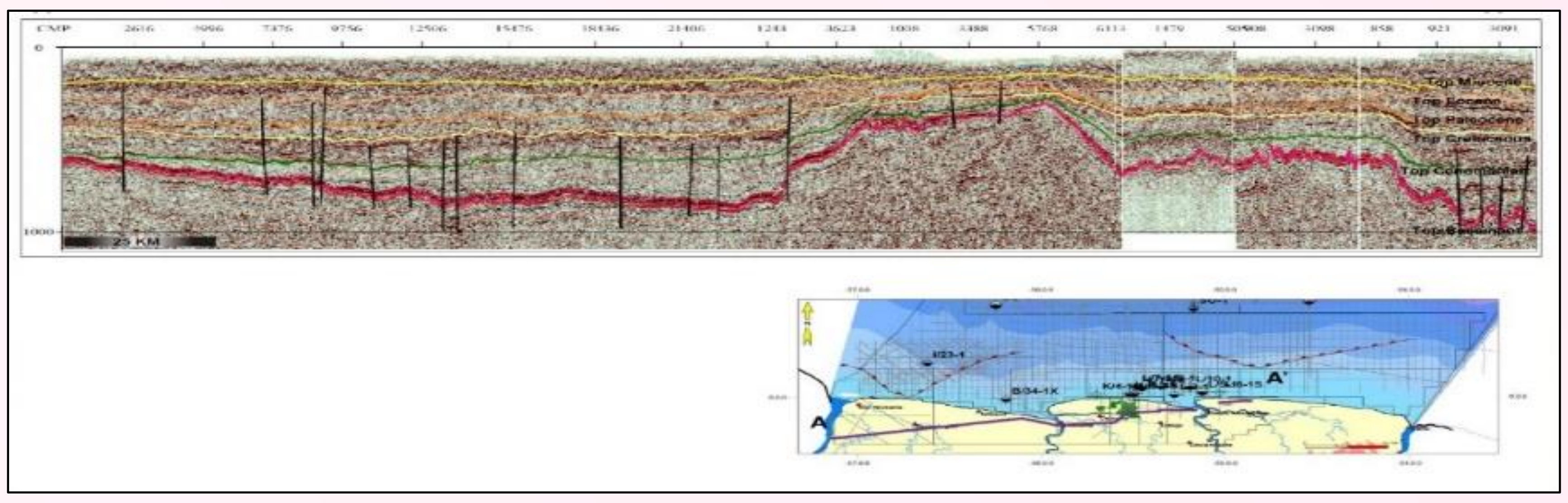


**Fig.1. Seismic profile W-E through coastal plain: Bakhuis Horst trap for oil Tambaredjo (Staatsolie database)**

- Bakhuis Montains is dated between 2.07-2.05 Ga within the Trans Amazonian Orogeny (De Roever et al., 2003)
- The border faults are dated ±1.2 Ga. (Nickerie metamorphic episode) and are recognized by the extensive mylonitization (Bosma et al., 1983)
- Morphological freshness of the eastern fault scarp suggests that the Bakhuis Horst has been active relatively recently (**Fig.3**).

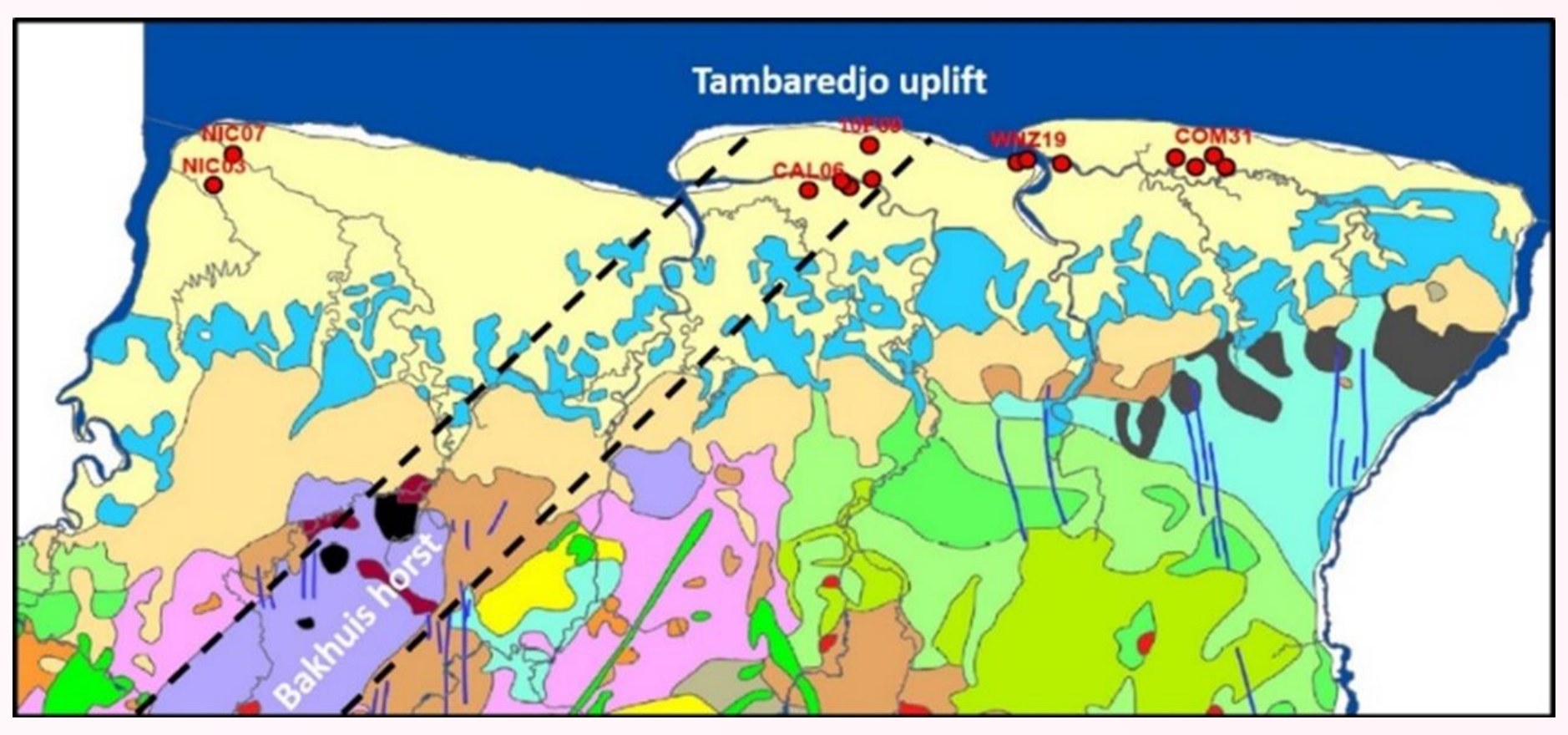


**Fig.2. Conjectural continuation of the Bakhuis horst into the Tambaredjo uplift, on a simplified geological map of northern Suriname. Red dots represent studied wells.**

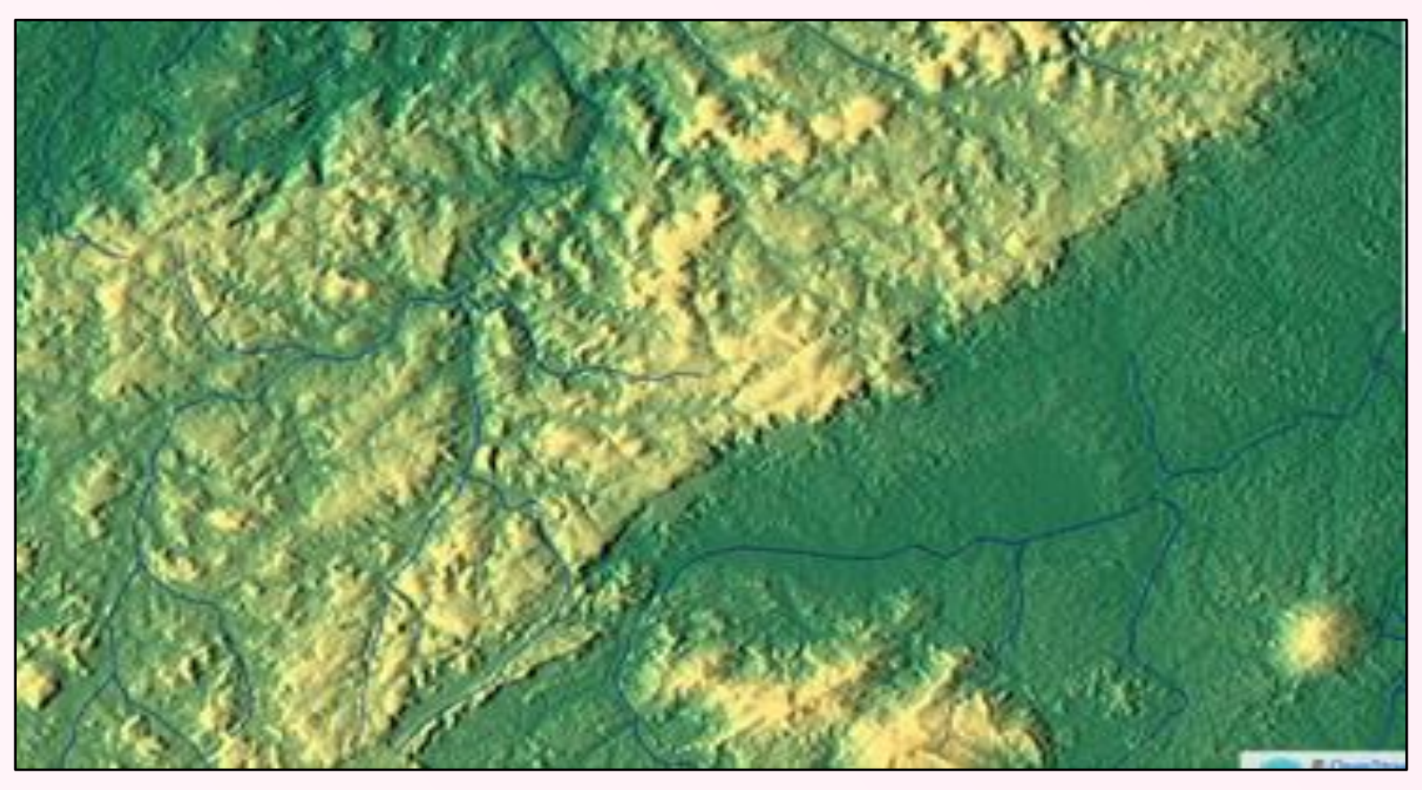


**Fig.3. The Bakhuis Horst and its eastern border fault.**

- Recent aeromagnetic data cast doubt on the continuation of the Bakhuis horst into the Tambaredjo uplift, as it seems that the Bakhuis structure is cut off by the 2.18-2.09 Ga Marowijne Greenstone Belt, in spite of its older age (**Fig. 4a** ).

- Also the aeromagnetic border faults of the Bakhuis Belt don't continue into the Greenstone belt even though the border faults are both younger than the Bakhuis Granulite Belt and the Greenstone Belt.

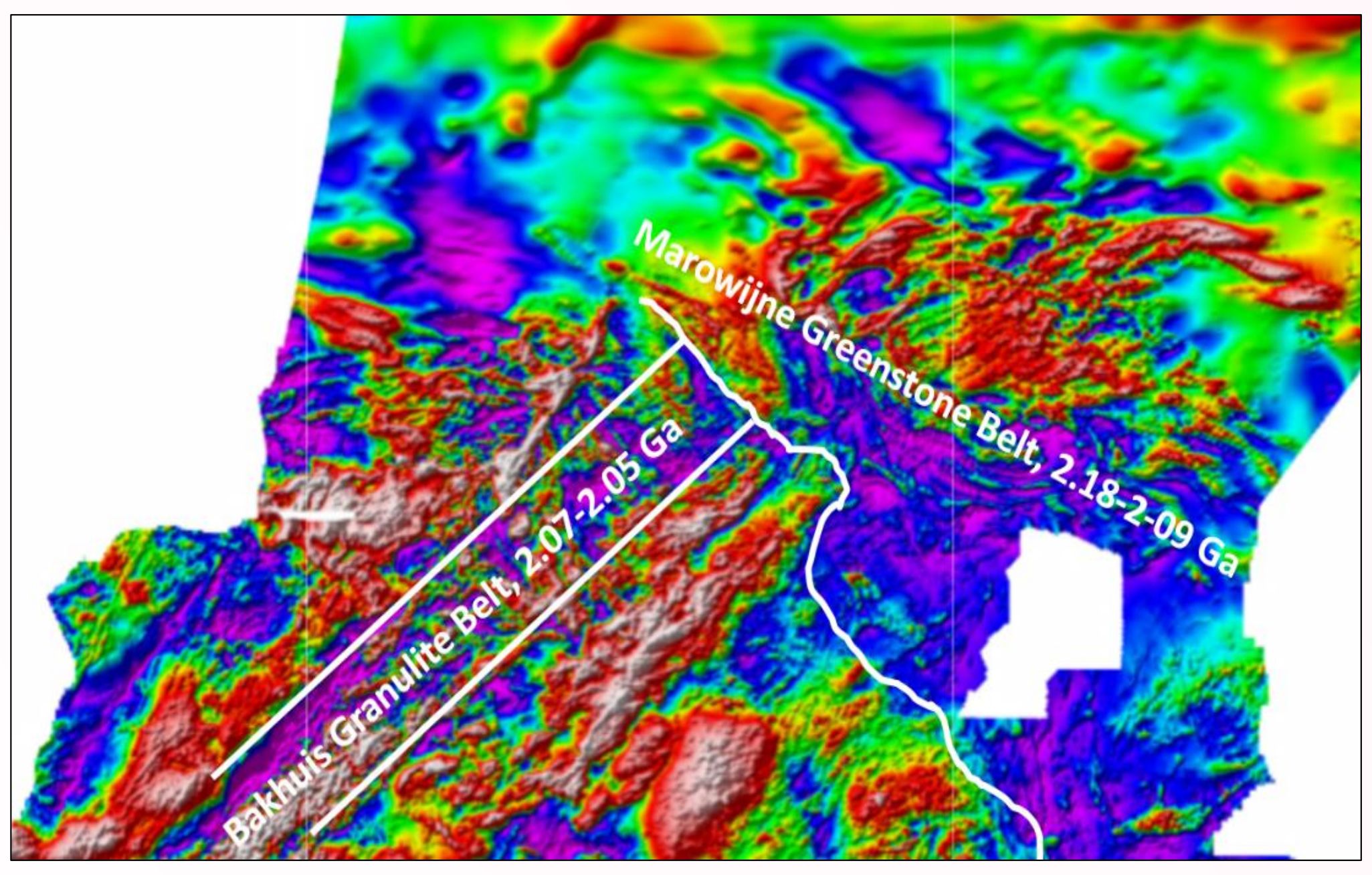


**Fig.4a. Aeromagnetics suggest that the Bakhuis Granulite Belt is cut off by the Marowijne Greenstone Belt.**

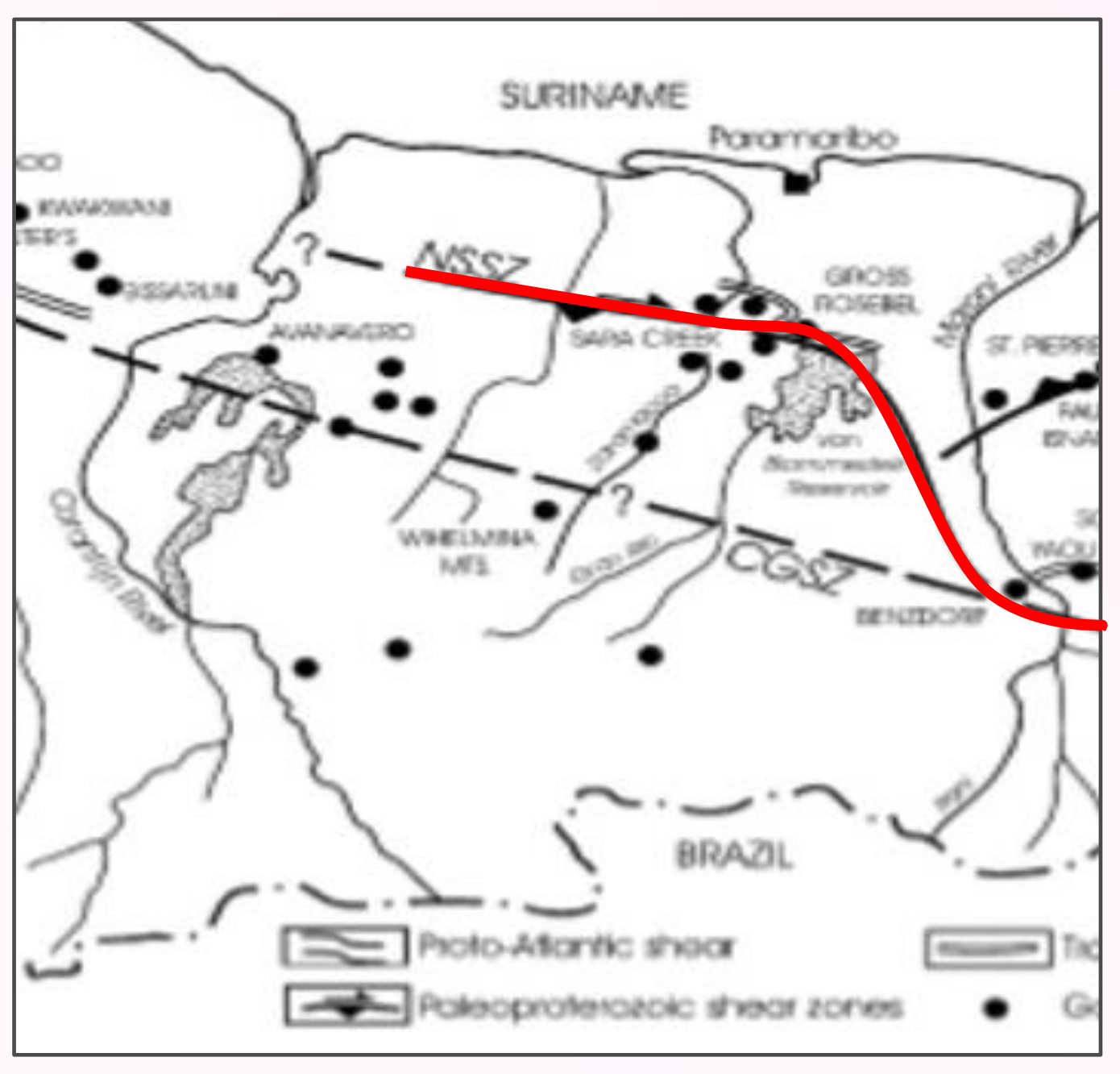


**Fig. 4b. Northern Suriname Shear Zone (NSSZ) elaborated by Voicu et al, 2001**

- To solve these problems the nature of the Precambrian rocks from oil wells are studied to know if they show more similarities to the Bakhuis Granulites or Marowijne Greenstones.

## Methodology

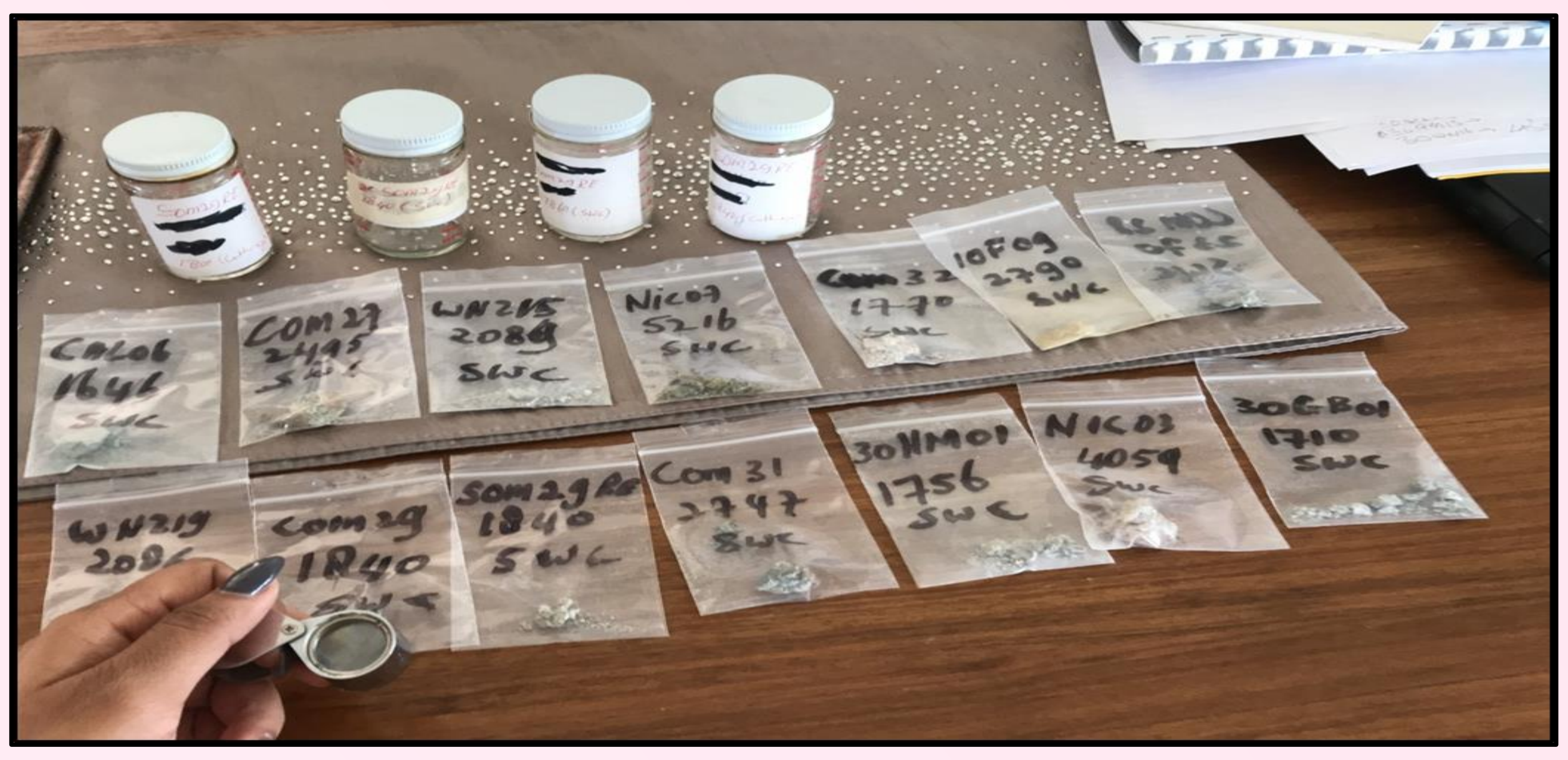


**Fig.5. Provided samples by Staatsolie used for microscopic research**

Using Petrel, out of 154 oil wells drilled by Staatsolie in the coastal plain, 15 were selected which penetrated the Precambrian basement. Well-bore cuttings and SWC (Side Wall Cores) (**Fig.5**) from the basement were investigated in the stereomicroscope and in thin sections of impregnated material to establish the rock type below the oil fields.

## Results

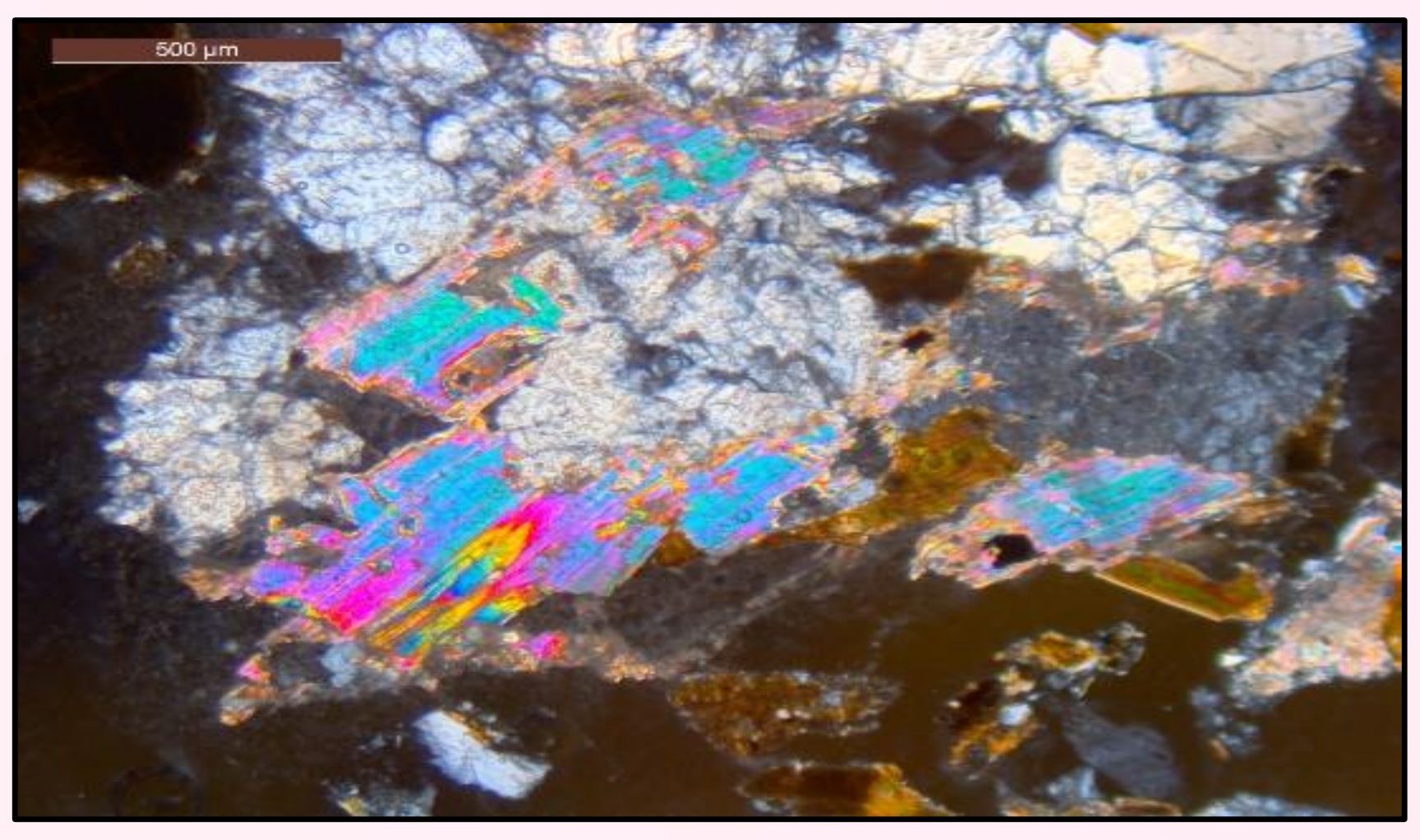


**Fig. 6a. Patamacca bimica granite, Tambaredjo**

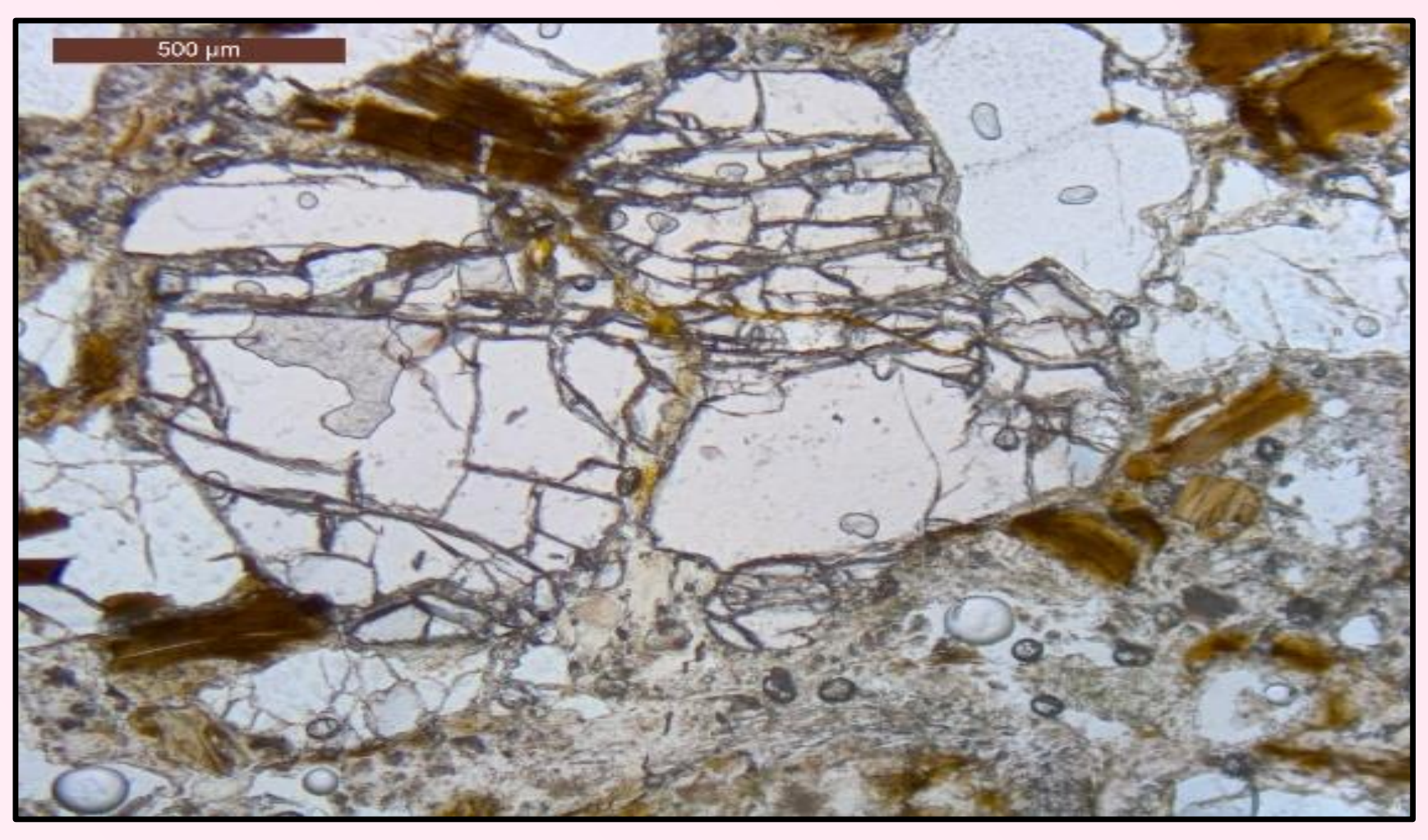


**Fig. 6b. Sara's Lust biotite-garnet gneiss, Commewijne**

The rocks below the oil wells consist mainly of biotite-garnet-(sillimanite-) gneisses and biotite-muscovite granites, resembling the Sara's Lust Gneiss and Patamacca Bi-Mica Granite, respectively, typical components of the greenstone belt, and differ from the rocks in the Bakhuis GranuliteBelt.

## Discussion

The fact that the 2.07-2.05 Ga Bakhuis Granulite Belt is cut-off by the older 2.18-2.09 Ga Marowijne Greenstone Belt requires a tectonic event younger than both. The most probable candidate is the Northern Suriname Shear Zone around 2.0 Ga (Voicu et al., 2001) (**Fig.4b**). It also requires that the mylonitic border faults of the Bakhuis horst are older than the Nickerie Metamorphic Episode of 1.2Ma. Nevertheless, the morphological freshness of the Bakhuis border fault in line with the Tambaredjo border fault supports their common origin. This Mesozoic-Cenozoic uplift event is only not visible in the aeromagnetics because it is an extensional event unlike to give magnetic responses.

## Conclusion

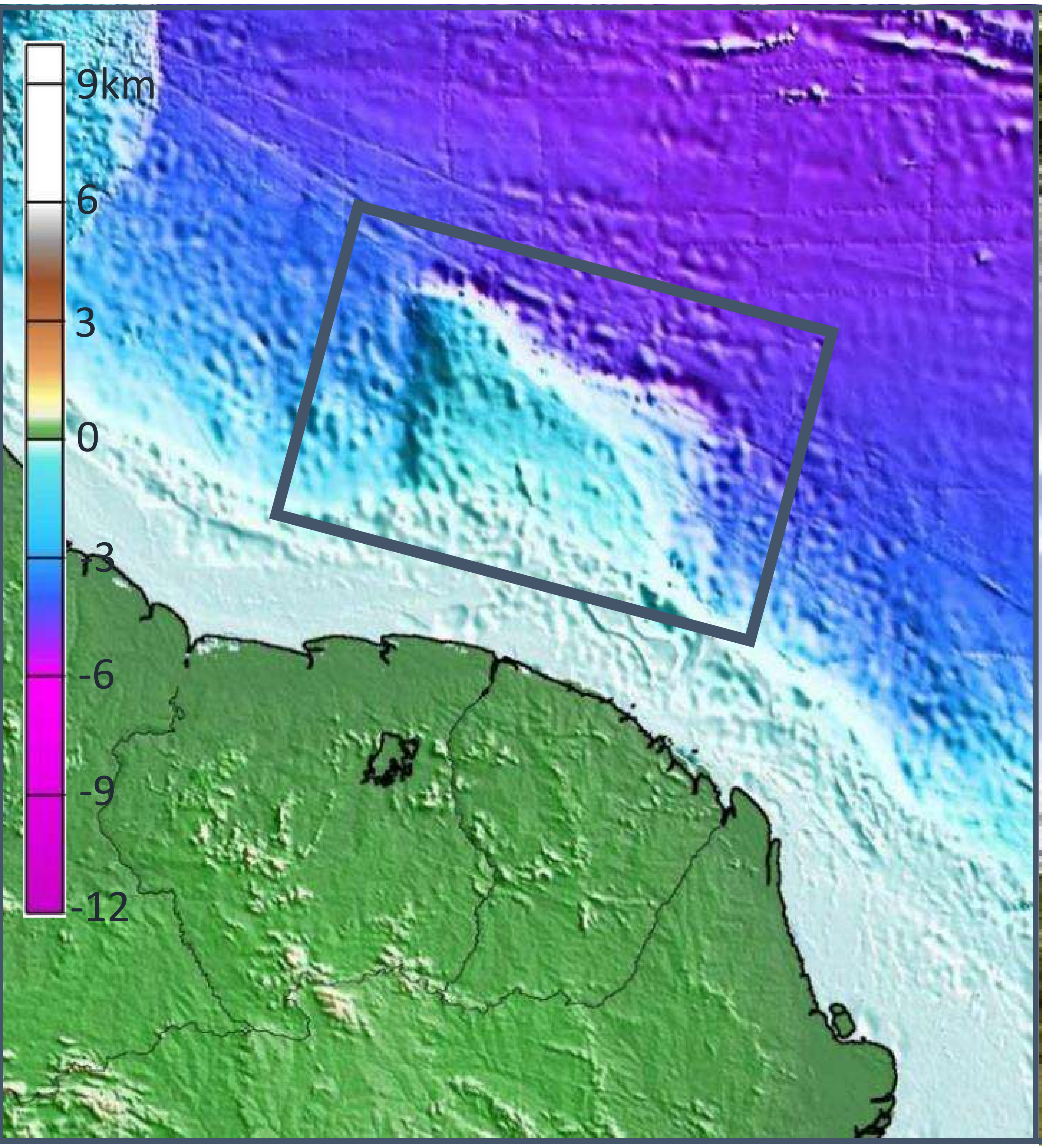
In spite of the aeromagnetic discontinuity, the Bakhuis-Tambaredjo Horst is a coherent tectonic entity uplifted during the Mesozoic-Cenozoic, probably related to the breakup of Gondwana.

## References

- *Bosma, W., S.B. Kroonenberg, K. Maas & E.W.F. De Roever 1983 Igneous and metamorphic complexes of the Guiana Shield in Suriname. Geologie & Mijnbouw, 62:241*
- *De Roever, E.W.F., Lafon, J.-M., Delor, C., Rossi, P., Cocherie, A., Guerrot, C. & Potrel, A., 2003a. The Bakhuis ultra-high temperature granulite belt : I Petrological and geochronological evidence for a counterclockwise P-T path at 2.07–-2.05 Ga. Géologie de la France 2003, 2-,3,-4: 175–205.*
- *Voicu, G., Bardoux, M. & Stevenson, R., 2001. Lithostratigraphy, geochronology and gold metallogeny in the northern Guiana Shield, South America: a review. Ore Geology Reviews 18: 211–236.*

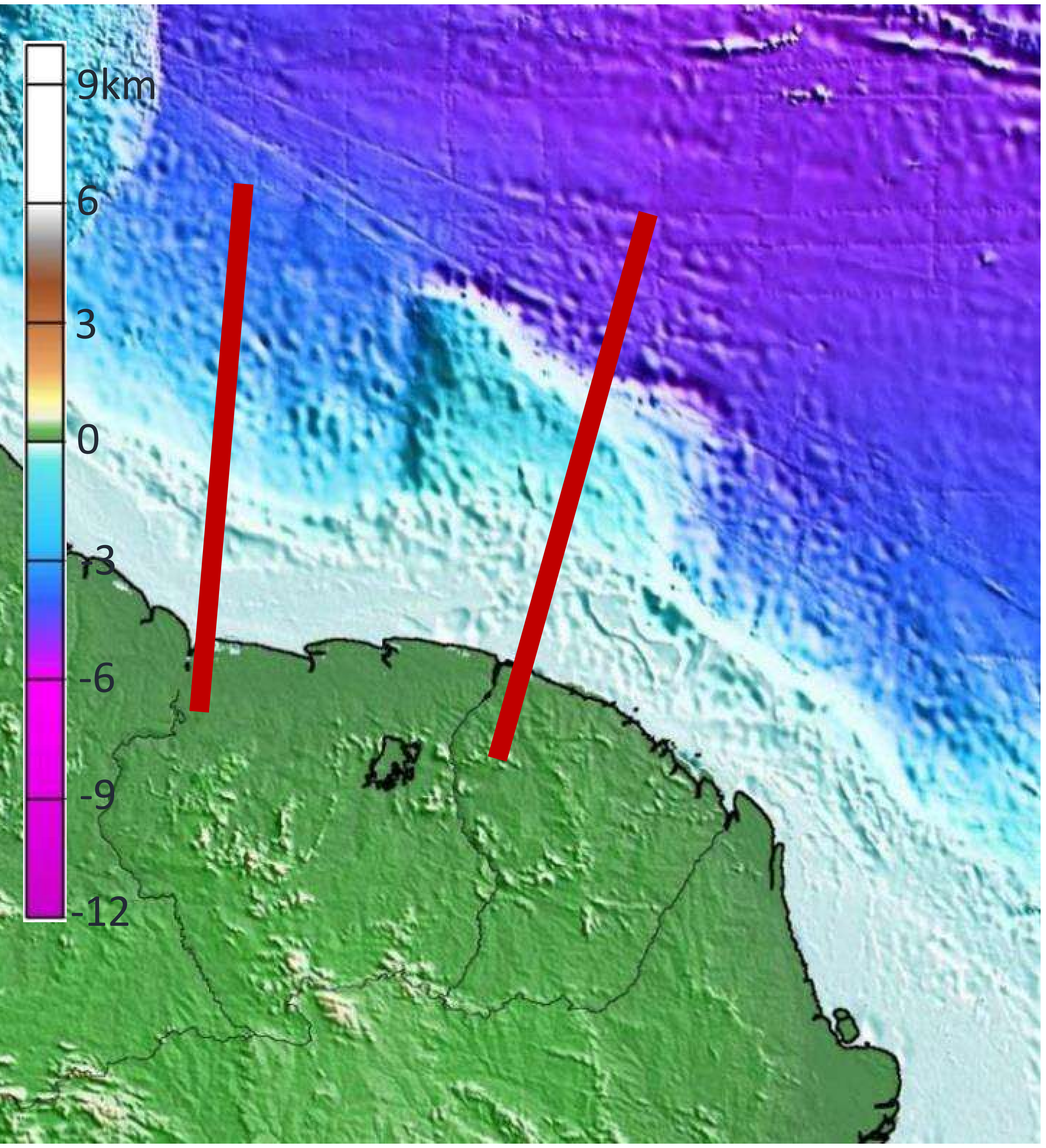
# Structure, evolution and magmatic origin of the Demerara marginal plateau

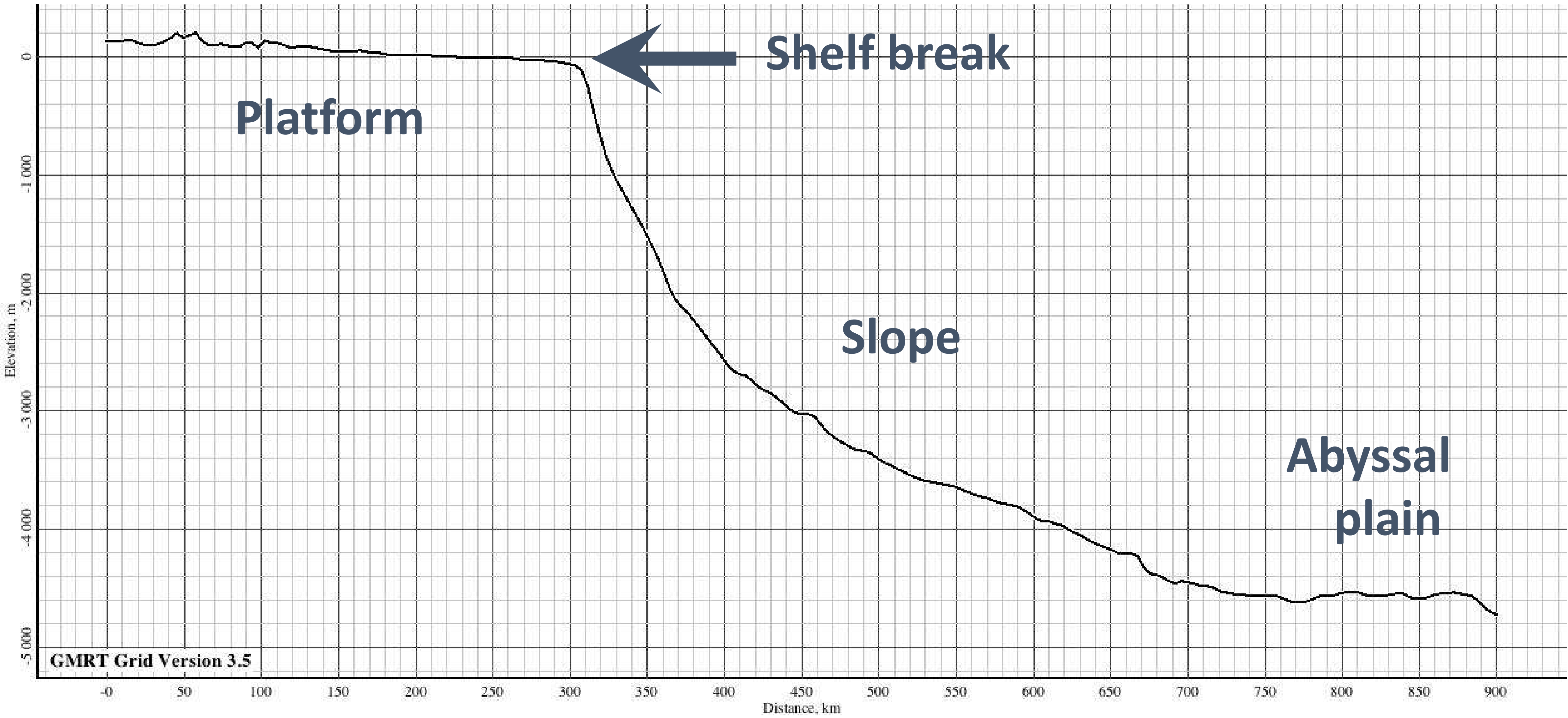
## as revealed by multidisciplinary oceanographic exploration

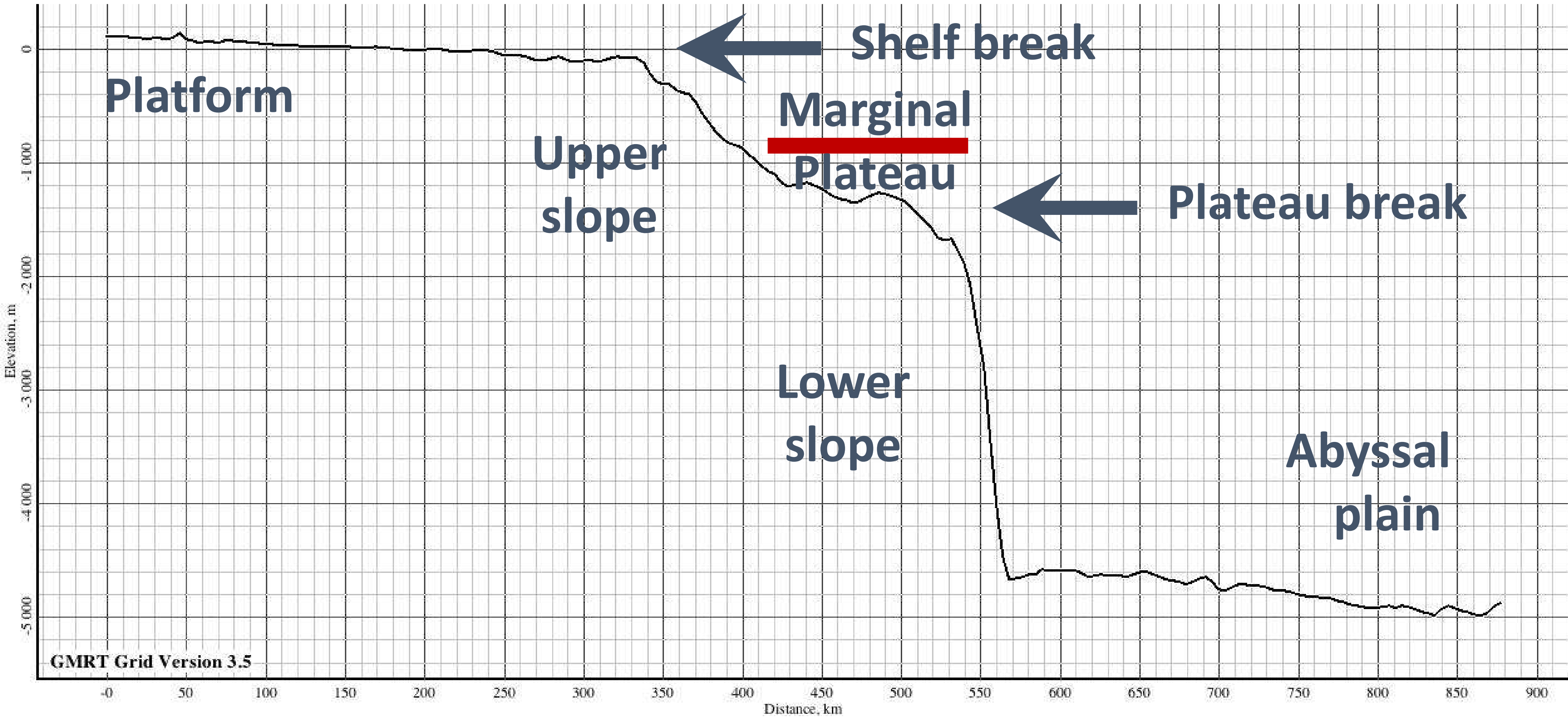


**A. HEURET**, L. LONCKE, W. ROEST, C. BASILE, D. GRAINDORGE, E. POETISI

# Characteristics of the Demerara Plateau







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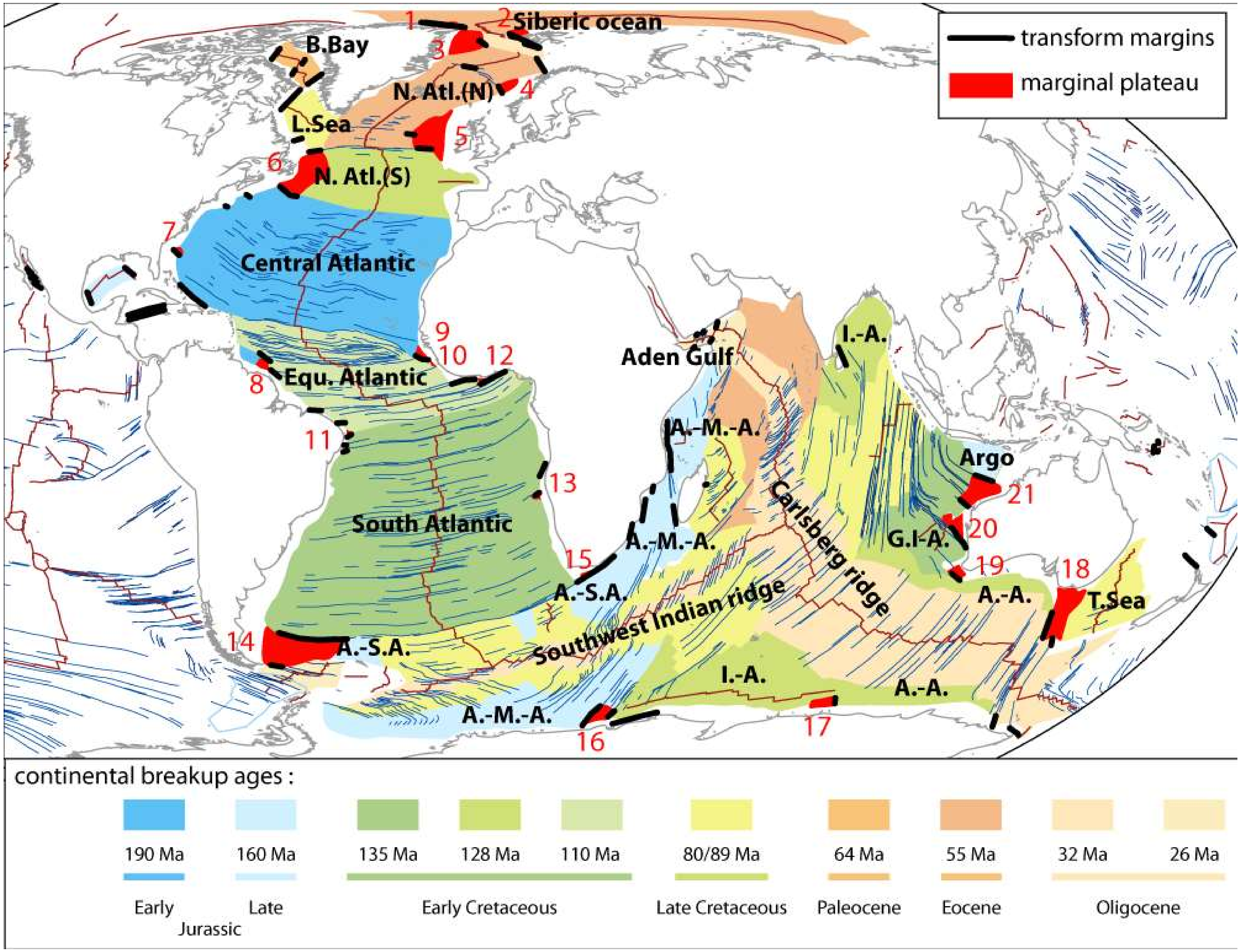
# Marginal plateaus : worldwide distribution



Mercier (2016)

- ± 20 marginal plateaus around the world
- Located at the intersection of oceanic domains of different ages
- All limited by or related to transform margins

# Oceanographic exploration of the Demerara Plateau

- May, 2003 – GUYAPLAC (N/O Atalante) : W. Roest (Ifremer)
  Bathymetry, seismic imaging (shallow structure)

- April-may, 2013 – IGUANES (N/O Atalante) : L. Loncke (Perp.)
  Bathymetry, seismic imaging (shallow structure)

- July, 2016– DRADEM (N/O Pourquoi pas ?) : C. Basile (Grenoble)
  Dredging

- Oct.-nov., 2016 - MARGATS (N/O Atalante) : D. Graindorge (UBO)
  Seismic imaging (deep structure)

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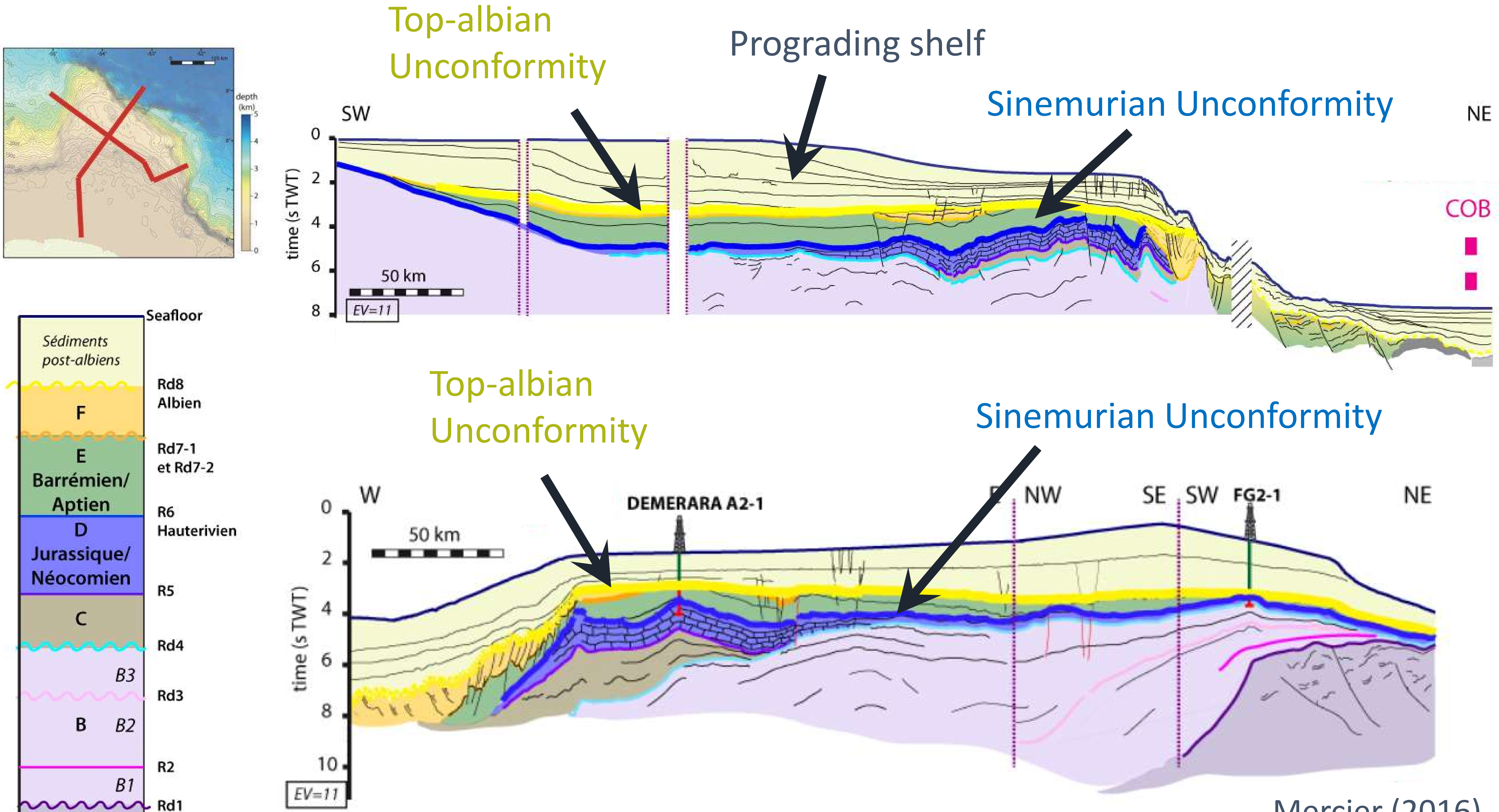
# Shallow structure of the Demerara Plateau



Top-albian Unconformity

Prograding shelf

Sinemurian Unconformity

Top-albian Unconformity

Sinemurian Unconformity

Mercier (2016)

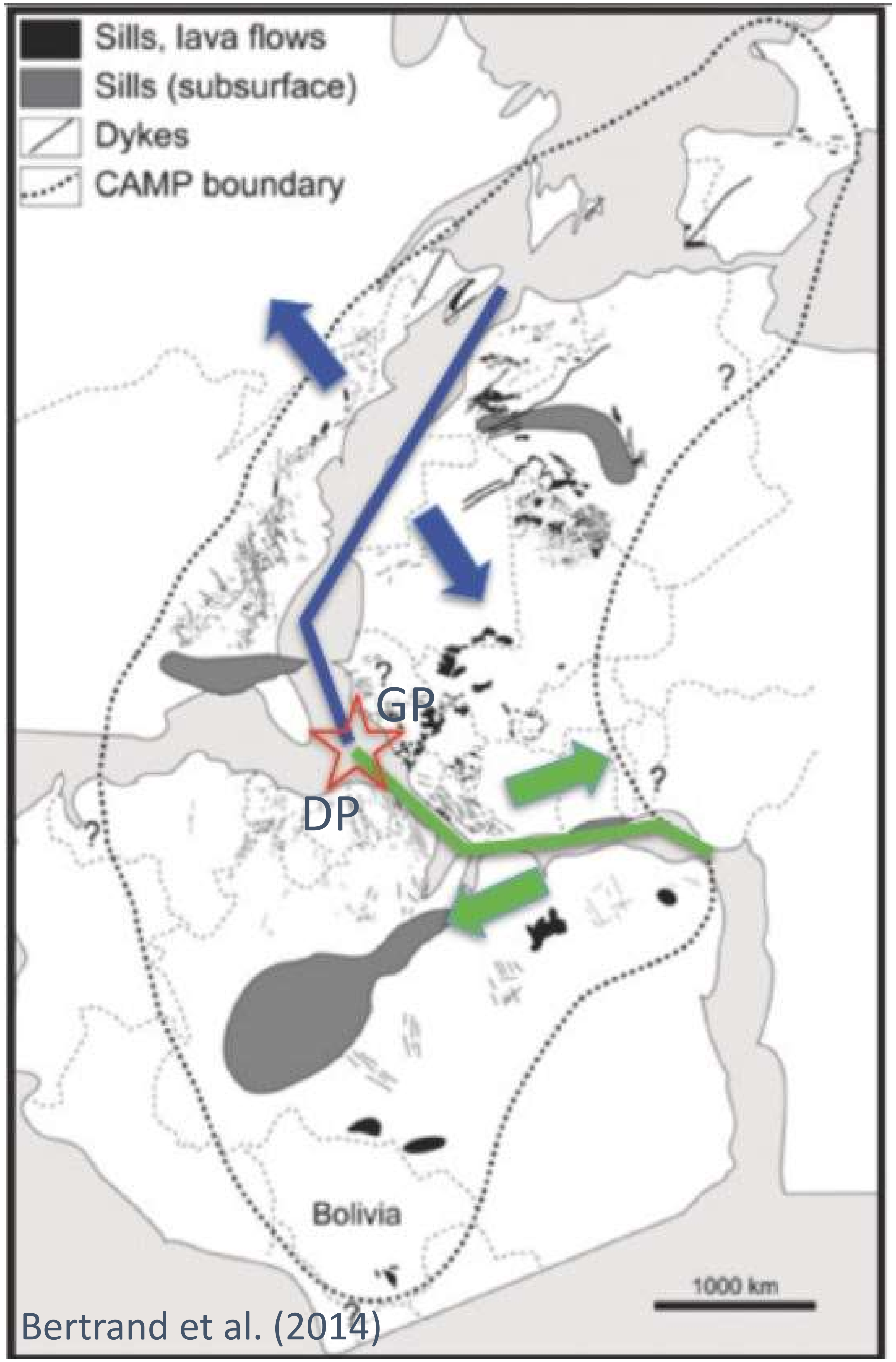
- A deep horizontal surface 200 x 200 km at 2000 m depth
- Partly covered by the prograding shelf
- Two regional unconformities

# Geodynamical background of the Demerara Plateau

- The Central Atlantic Magmatic Province (CAMP) : 201 Ma

- Jurassic opening of the Central Atlantic
  - 190 Ma in the northern part
  - 170 Ma in the southern part

- Cretaceous opening of the Equatorial Atlantic : ~ 120 Ma

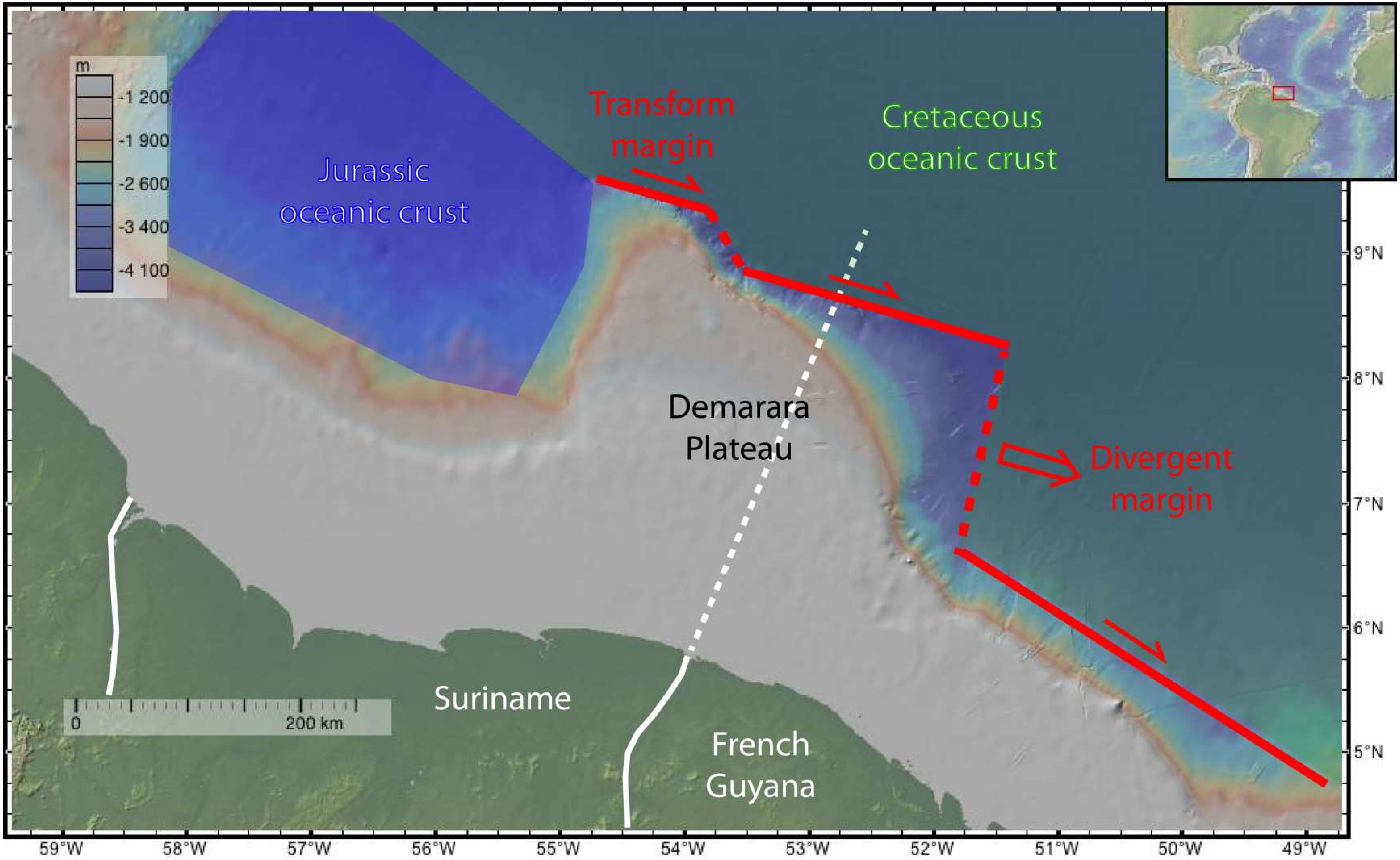


Bertrand et al. (2014)

DP = Demerara Plateau
GP = Guinean Plateau

Two regional unconformities = two stages of oceanic formation

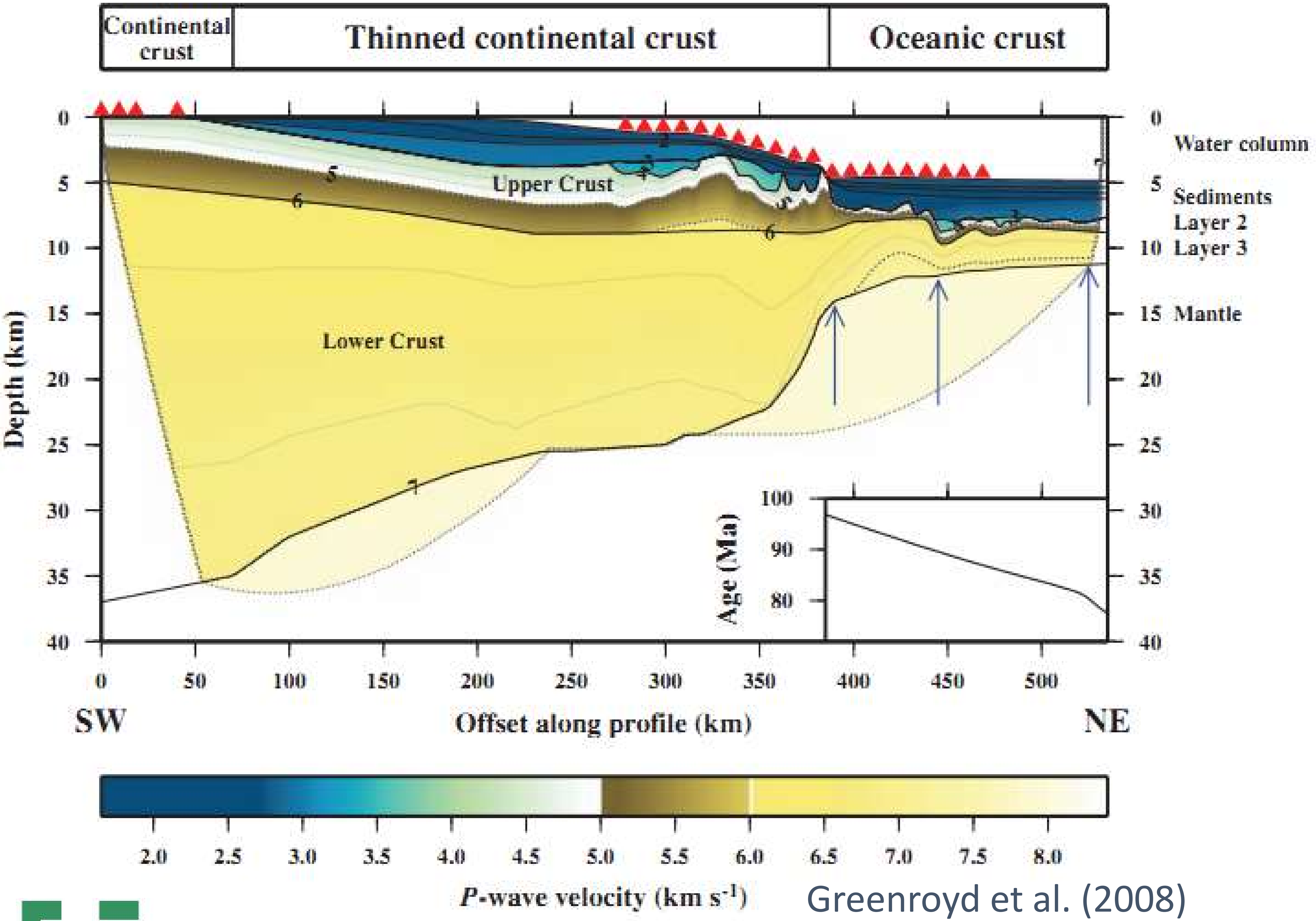
# Geodynamical background of the Demerara Plateau



Two types of continental margins

# The deep structure of the Demerara Plateau

## The starting point



Greenroyd et al. (2008)

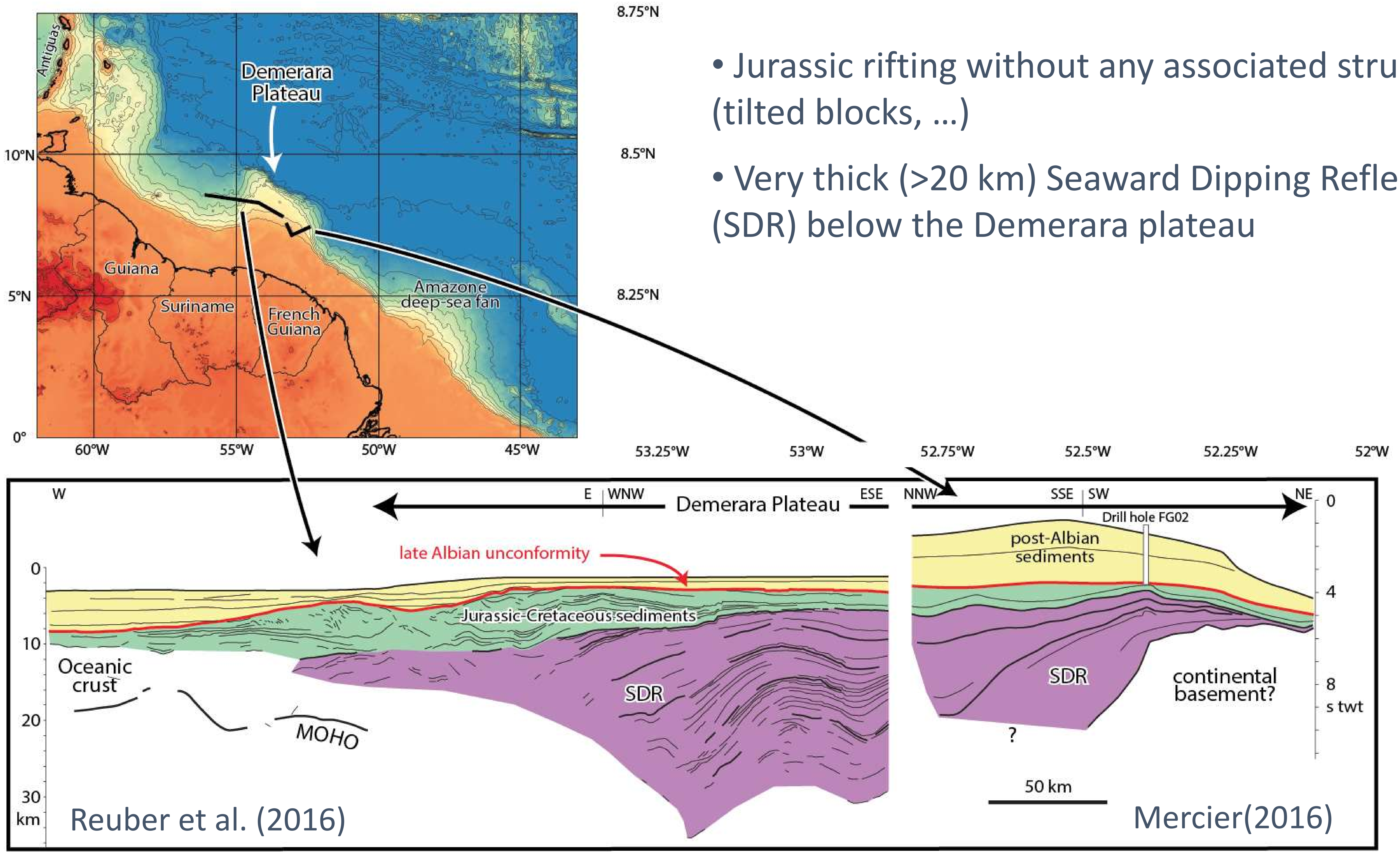
'The Demerara Plateau is, therefore, interpreted as a margin segment comprising **thinned continental crust**'

i.e. deep plateau at isostatic equilibrium implying jurassic stretching

# The deep structure of the Demerara Plateau

## The starting problems

- Jurassic rifting without any associated structures (tilted blocks, …)
- Very thick (>20 km) Seaward Dipping Reflectors (SDR) below the Demerara plateau

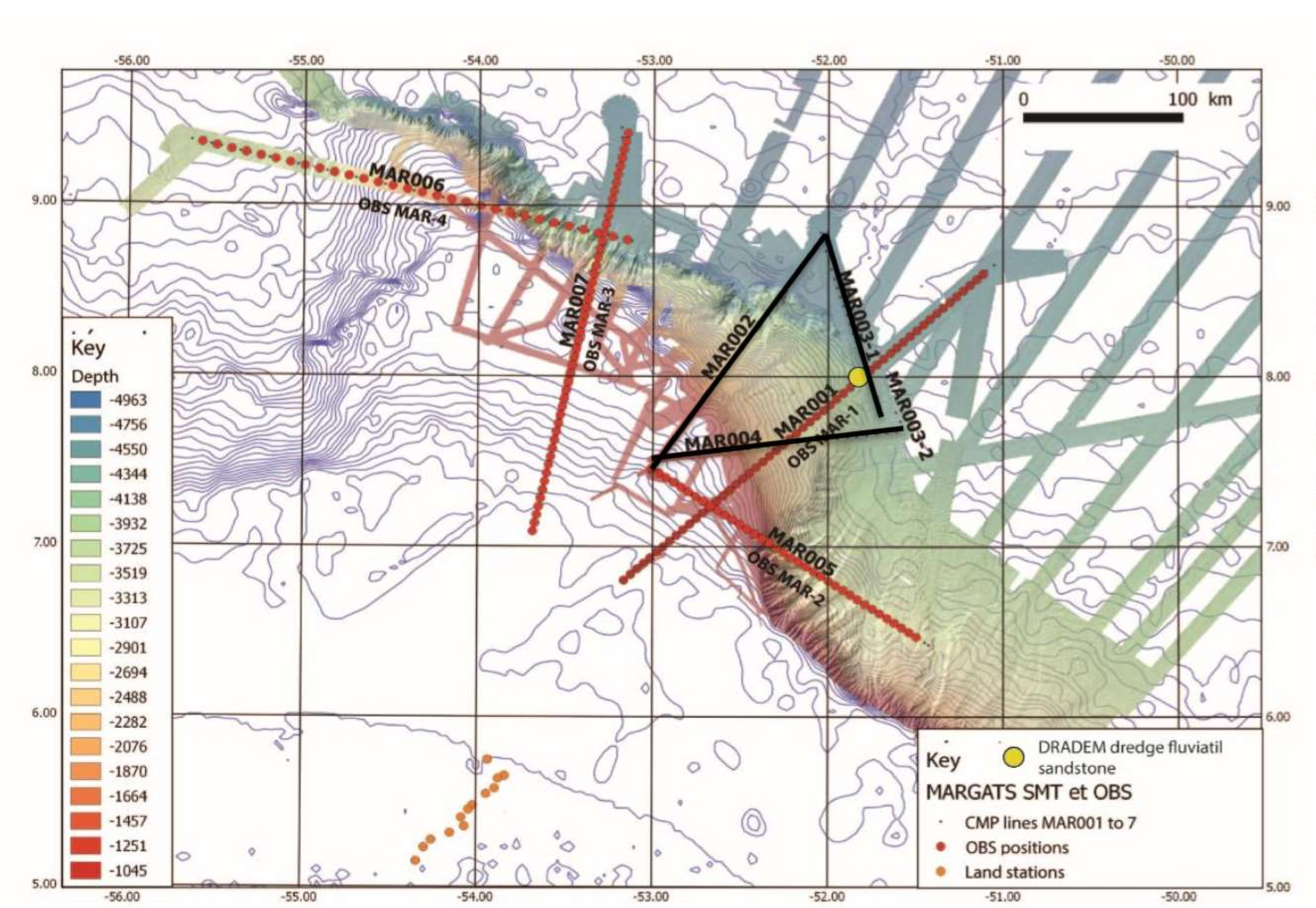


Reuber et al. (2016)

Mercier(2016)

# The deep structure of the Demerara Plateau

## MARGATS cruise



From October 20th to November 16th 2016 on the R/V L'Atalante.

171 OBS deployments along 4 combined wide-angle and reflection seismic profiles as well as 3 additional MCS profiles.

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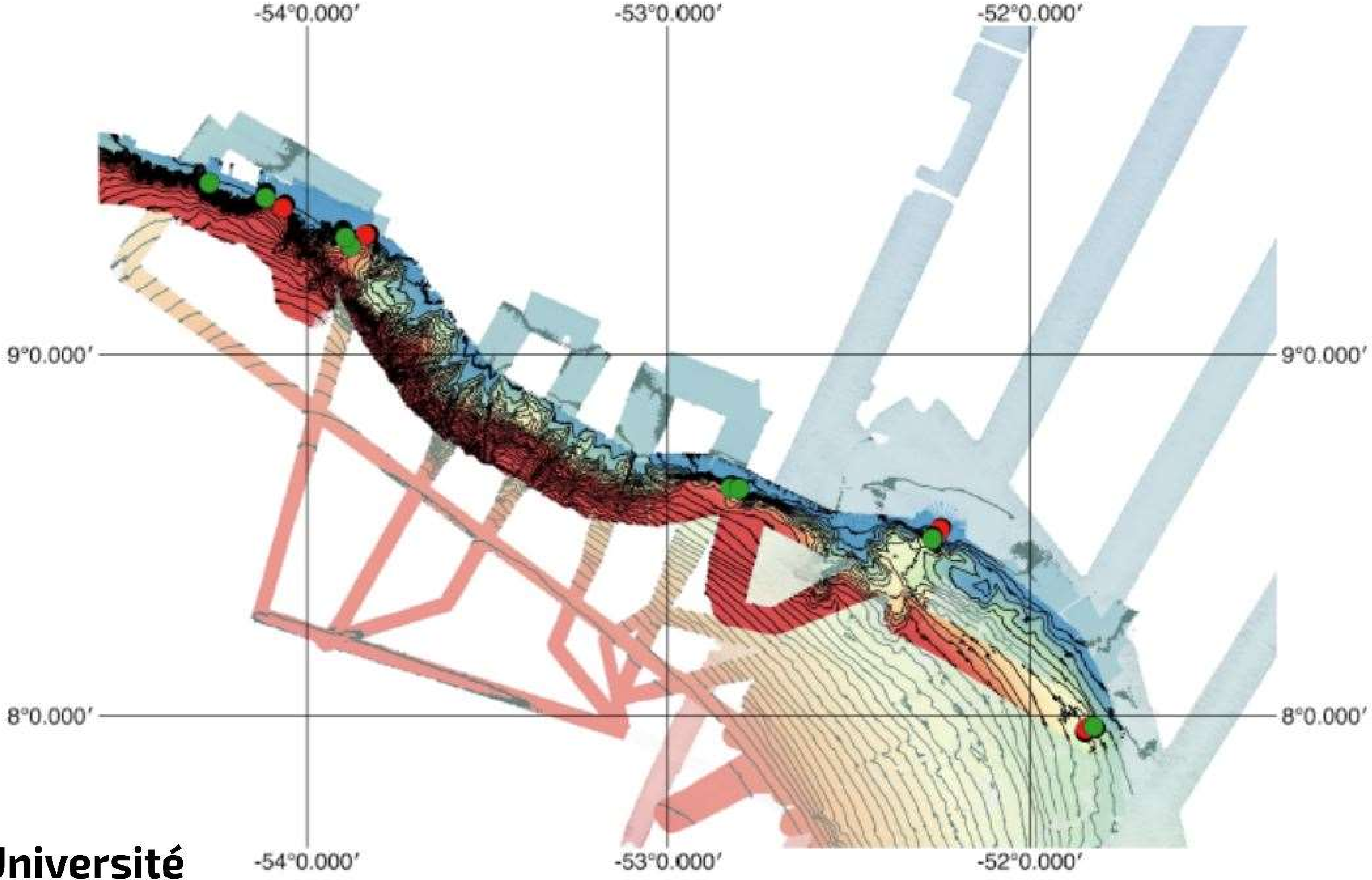
# The deep structure of the Demerara Plateau

## DRADEM cruise



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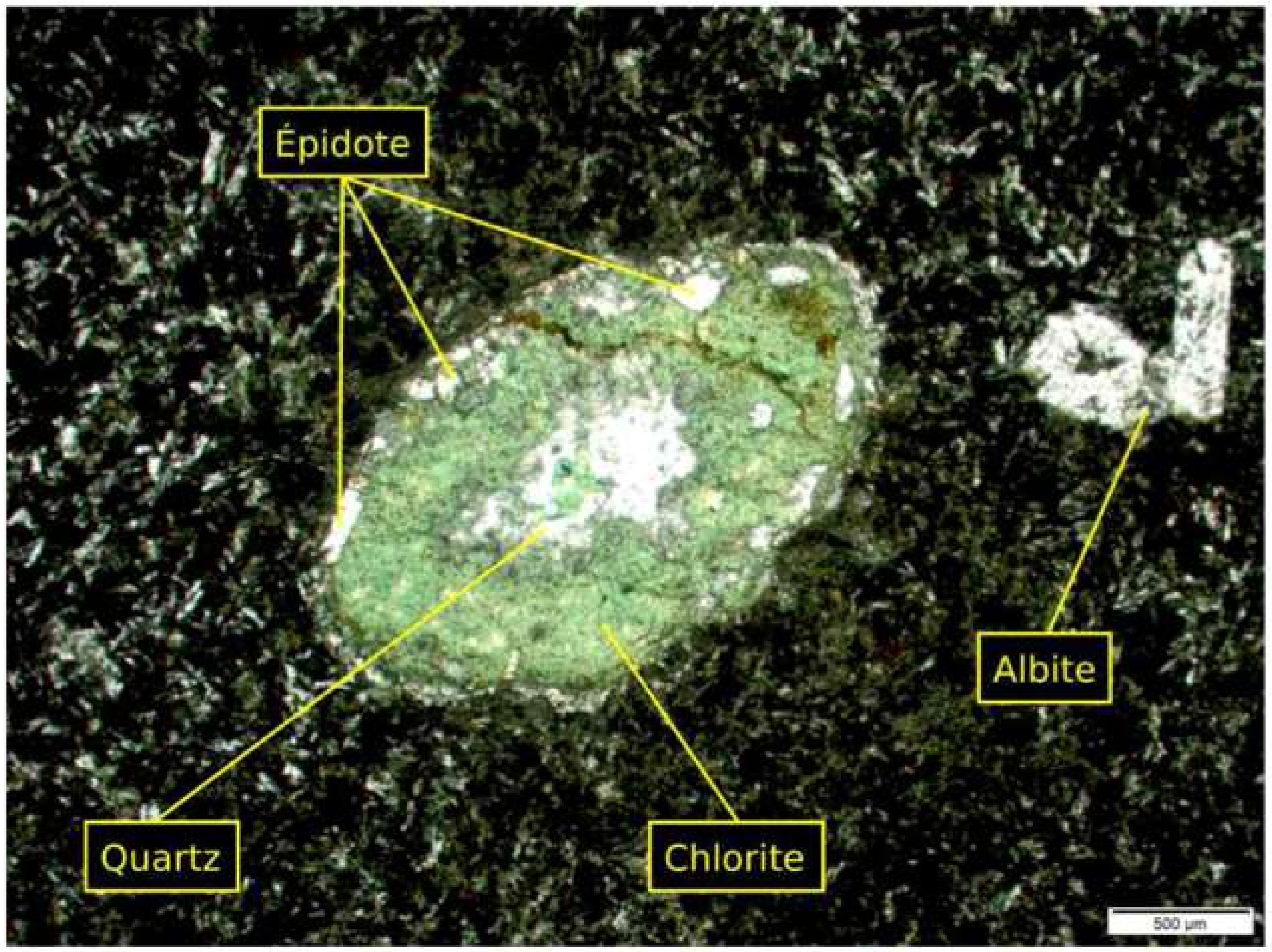
# The deep structure of the Demerara Plateau

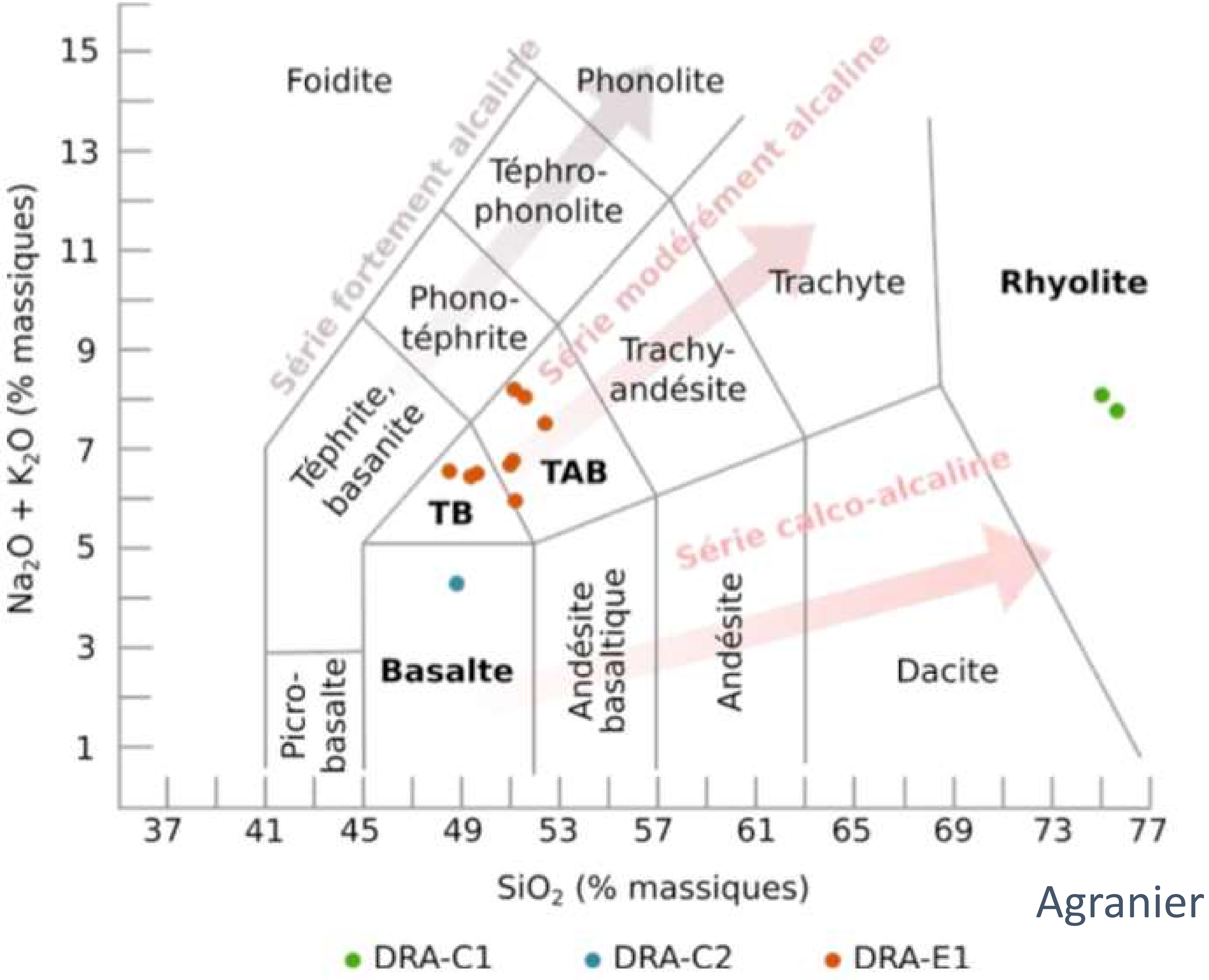
## DRADEM cruise

3 dredges at 2 sites recovered magmatic rocks:

- Basalts
- Trachy-basalts (altered)
- Rhyolites

Girault



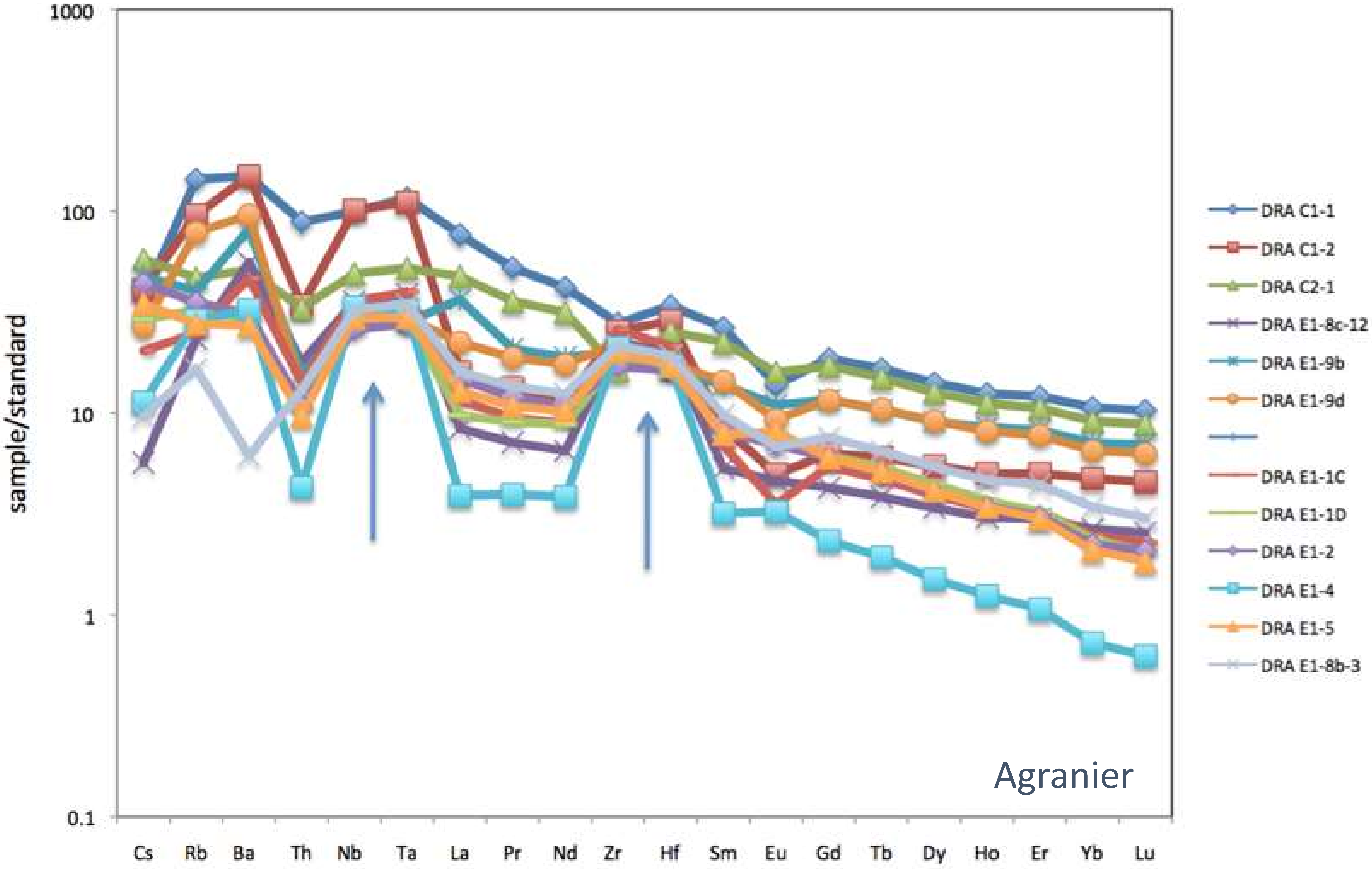


Agranier

Rare Earth Elements spectra characteristic for hotspot lava

# The deep structure of the Demerara Plateau

## DRADEM cruise



Same Rare Earth Elements spectra : positive anomalies in Nb, Ta, Zr, Hf
Characteristic for hotspot lava (Ocean Island Basalts = OIB type)

# The deep structure of the Demerara Plateau

## DRADEM & MARGATS cruises

The basement of the Demerara plateau includes

- Very thick SDR units
- Remnants of hotspot magmatism
- Magmatic rocks 28 Ma younger than the CAMP

We test the hypothesis of a hotspot below the Demerara plateau at 173 Ma :

- Hot spot fixed by reference to the terrestrial rotation axis
- Use the GPlates model (Seton et al. 2012) that describes the absolute displacements of lithospheric plates during the last 200 Ma

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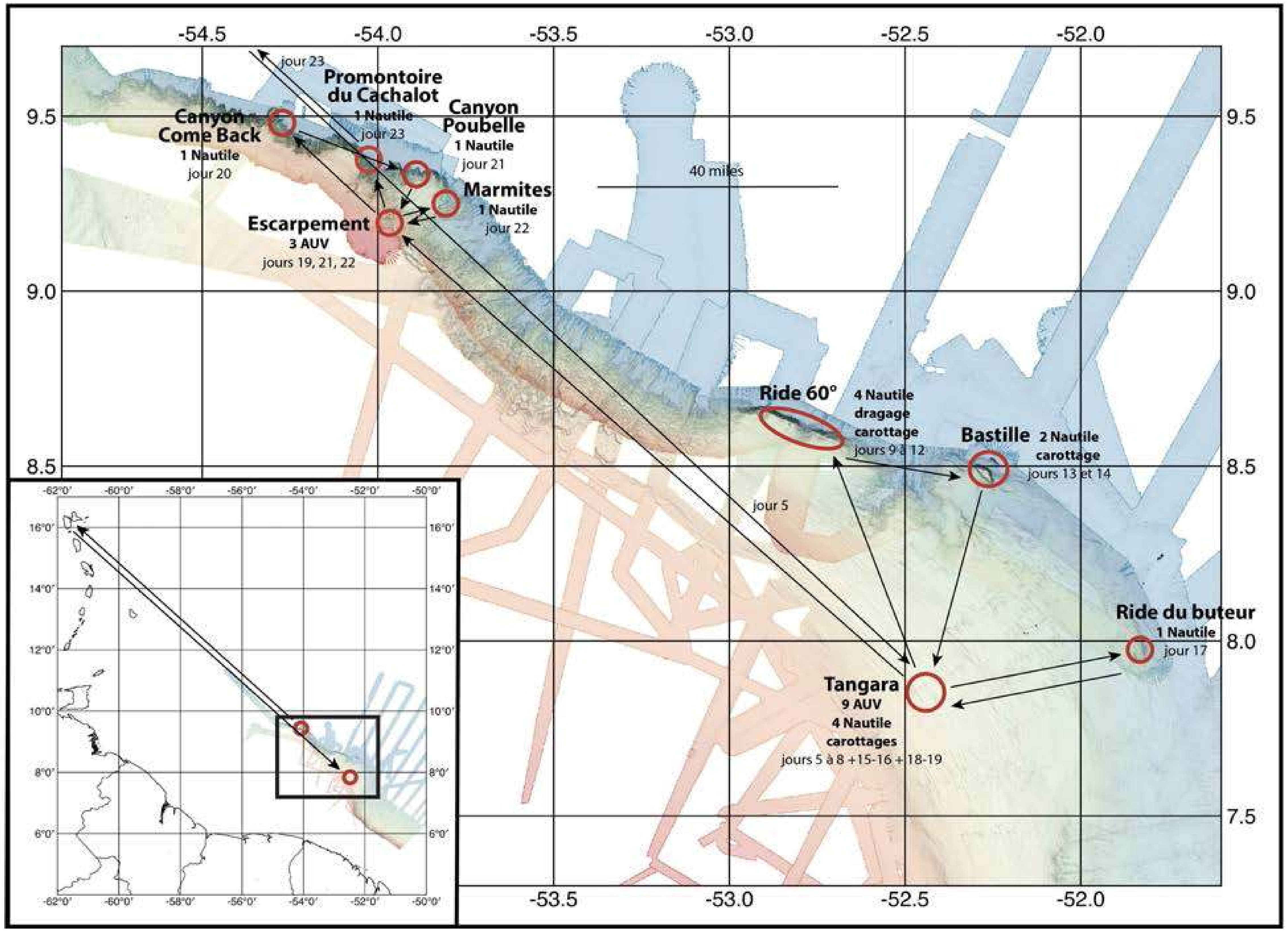
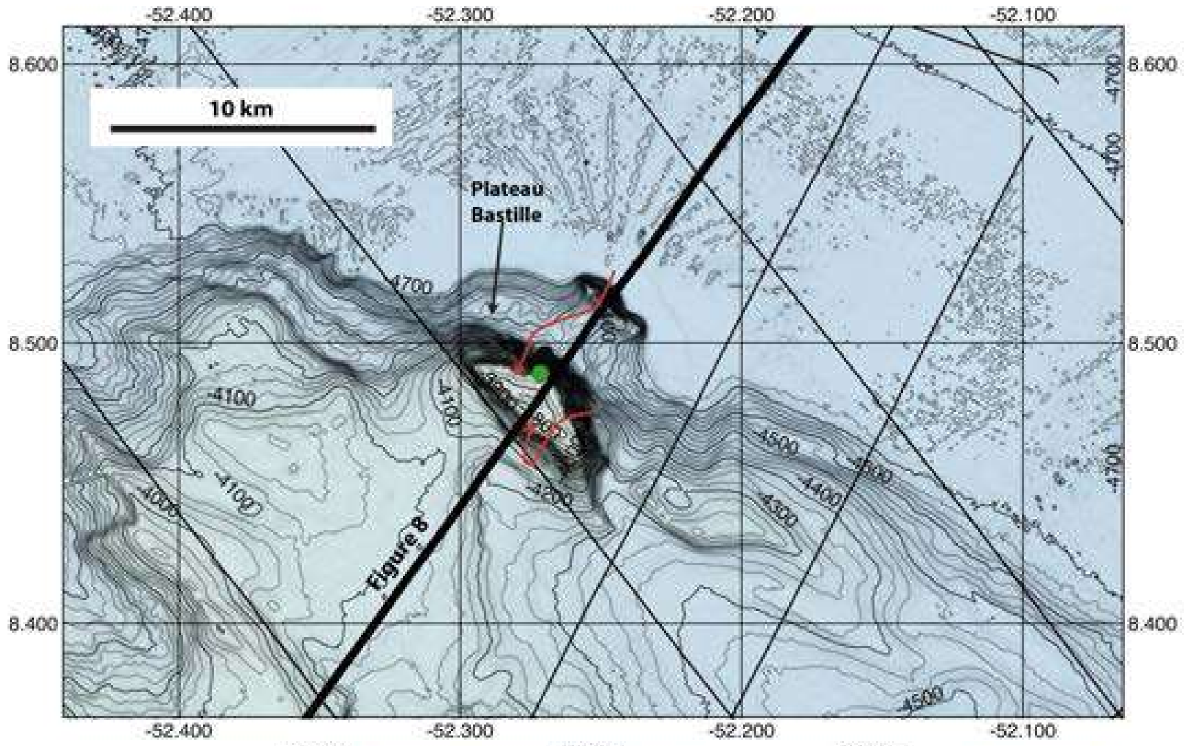
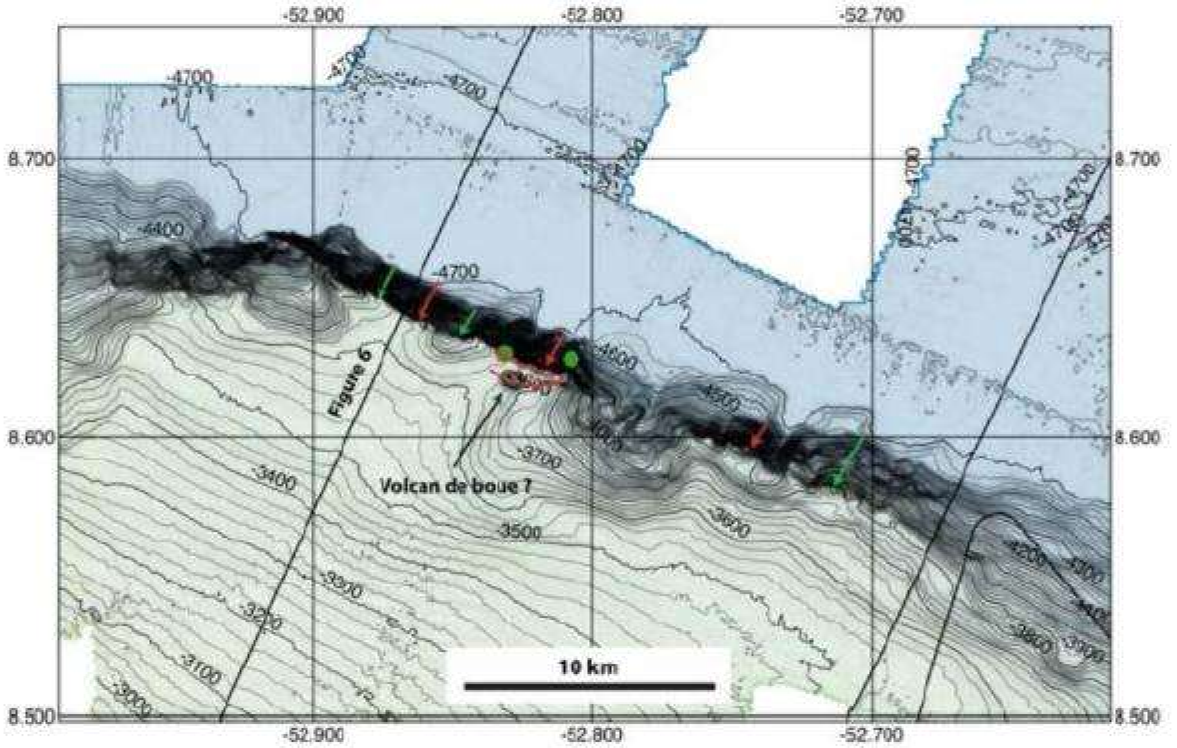
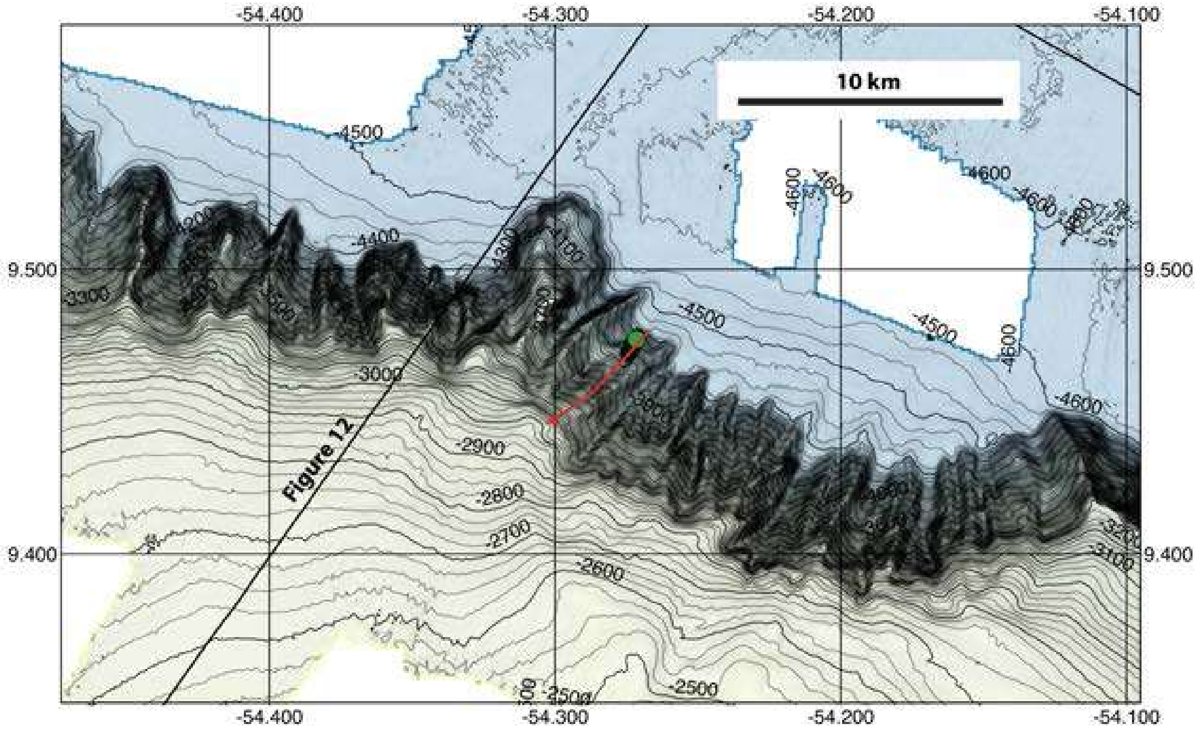
# Next step : DIves At DEMerara (DIADEM, 2020)









# SAXI:
# The South American Exploration Initiative

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Mark Jessell, SAXI Team

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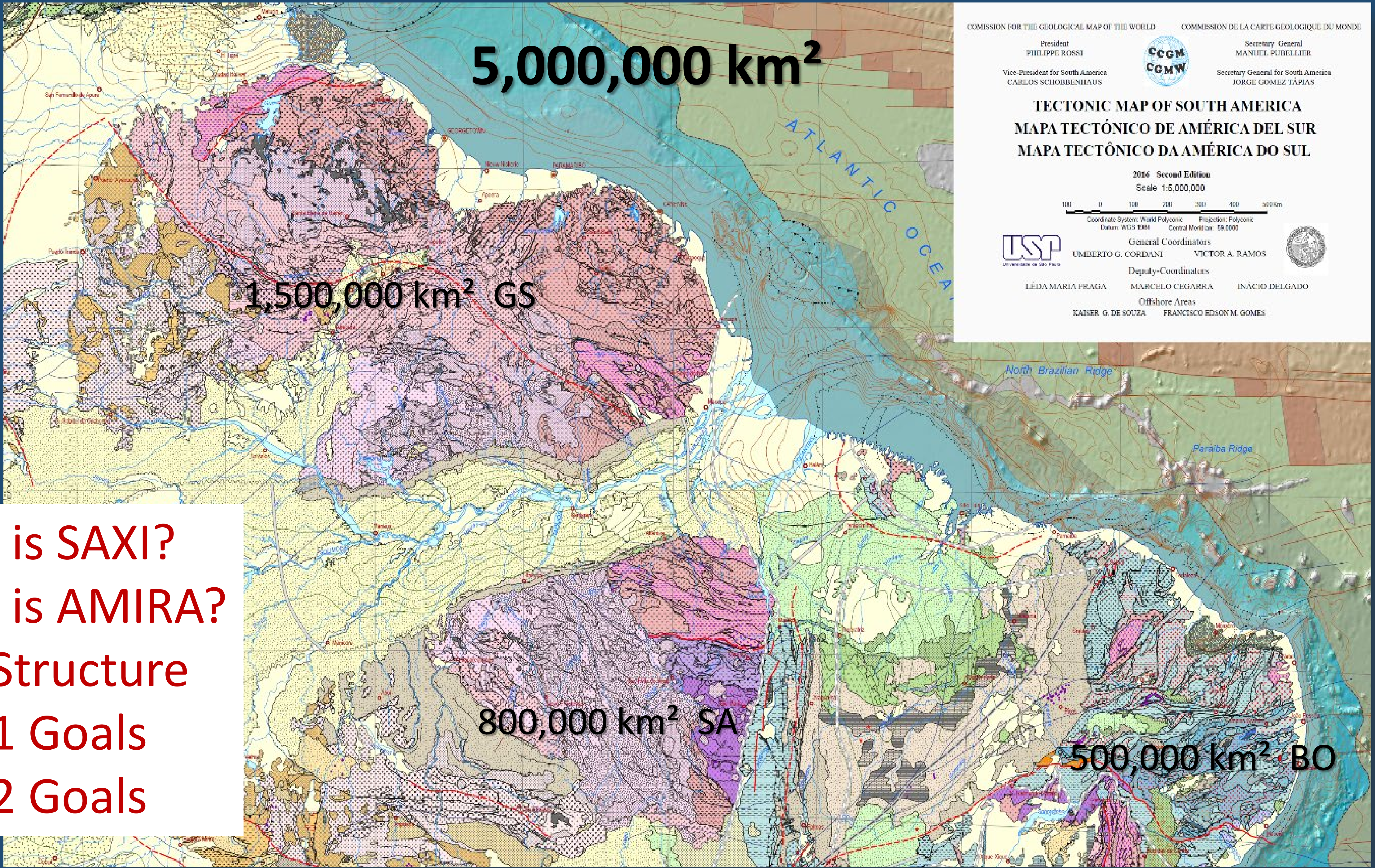


1. What is SAXI?
2. What is AMIRA?
3. SAXI Structure
4. SAXI 1 Goals
5. SAXI 2 Goals

# SAXI AIMS

*The overall aim of South Ameircan Exploration Initiative is to enhance the exploration potential of North Eastern South America through an integrated program of research and data gathering into its “anatomy’.*

*Key motivations for undertaking this initiative are to assist exploration companies in focusing their activities in areas of maximum prospectivity and to help local Geological Surveys and Universities in their role of collecting and providing pre-competitive data and information.*

# AMIRA International Core purpose –

## Creating a better future through collaboration

By developing and managing collaborative projects and other activities, to enable:

- ➢ The sustainable development of the minerals and associated industries that is acceptable to society;
- ➢ Enhanced standing of the minerals and associated industries amongst stakeholders locally and globally; and
- ➢ Deliver new data, knowledge, technologies, products and services in order to help members, or other organisations as approved by the Board, to improve all aspects of their businesses including providing opportunities to educate the next generation of industry leaders, operators and researchers.

# Operational focus

Operations

Exploration / Discovery

Development Design/Construction

Mining

Minera Processing & Metallurgy

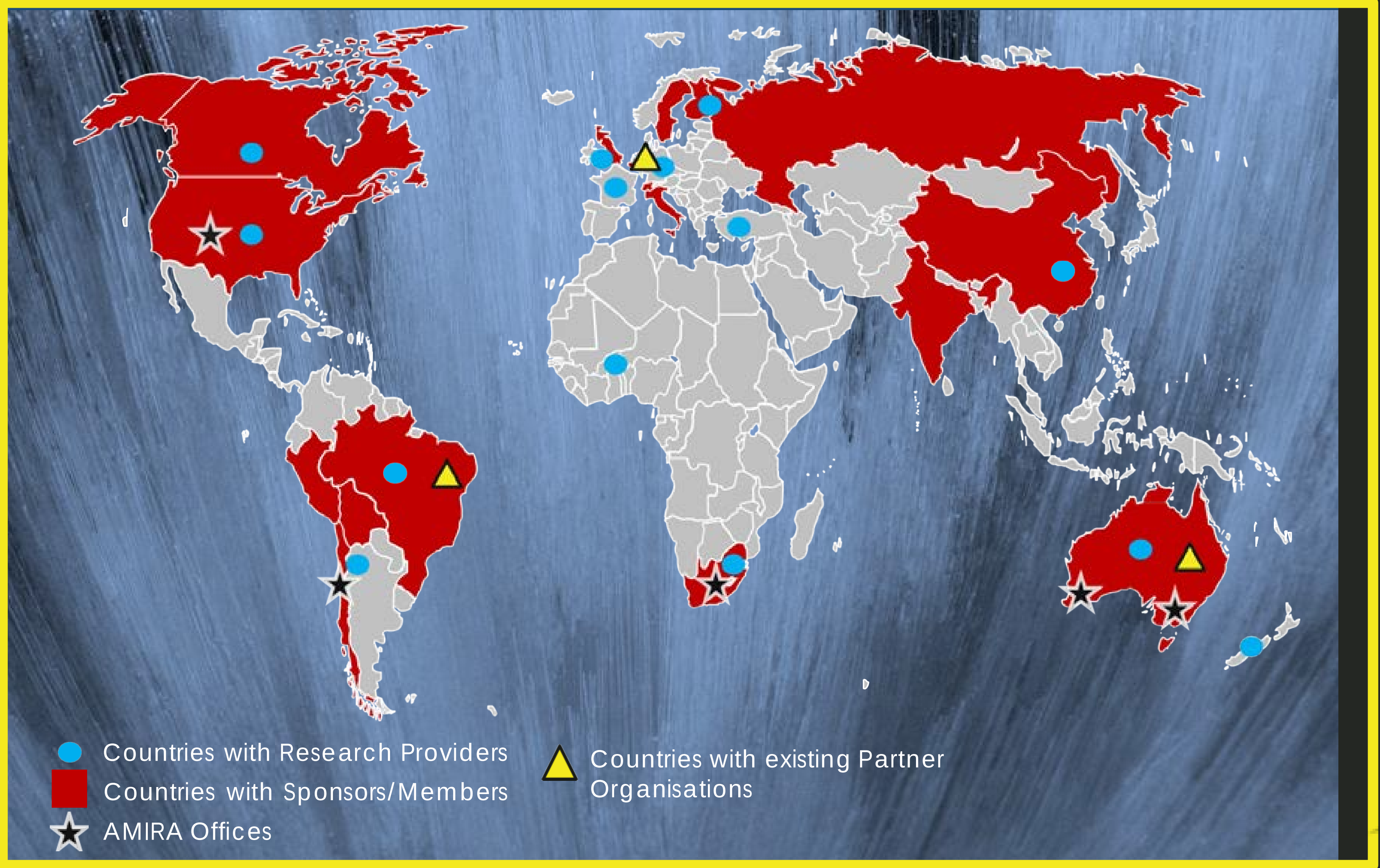
Closure / Reclamation

**Sustainability: Licence to Operate; New management practices**

**Industry Roadmaps:**

**Alumina, Copper, Drilling, Exploration undercover, In-situ extraction, Heap-leach**

# Global network which our Members access



● Countries with Research Providers

🟥 Countries with Sponsors/Members

★ AMIRA Offices

▲ Countries with existing Partner Organisations

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## Industry Sponsors

AMIRA INTERNATIONAL Delivering solutions through collaboration

## Project Broker & Coordinator

ADIMB Agência para o Desenvolvimento Tecnológico da Indústria Mineral Brasileira

## Research Organisations

Universidad de Chile

LaurentianUniversity UniversitéLaurentienne

Centre for EXPLORATION TARGETING

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## Sponsors in Kind

GUYANA GEOLOGY & MINES COMMISSION

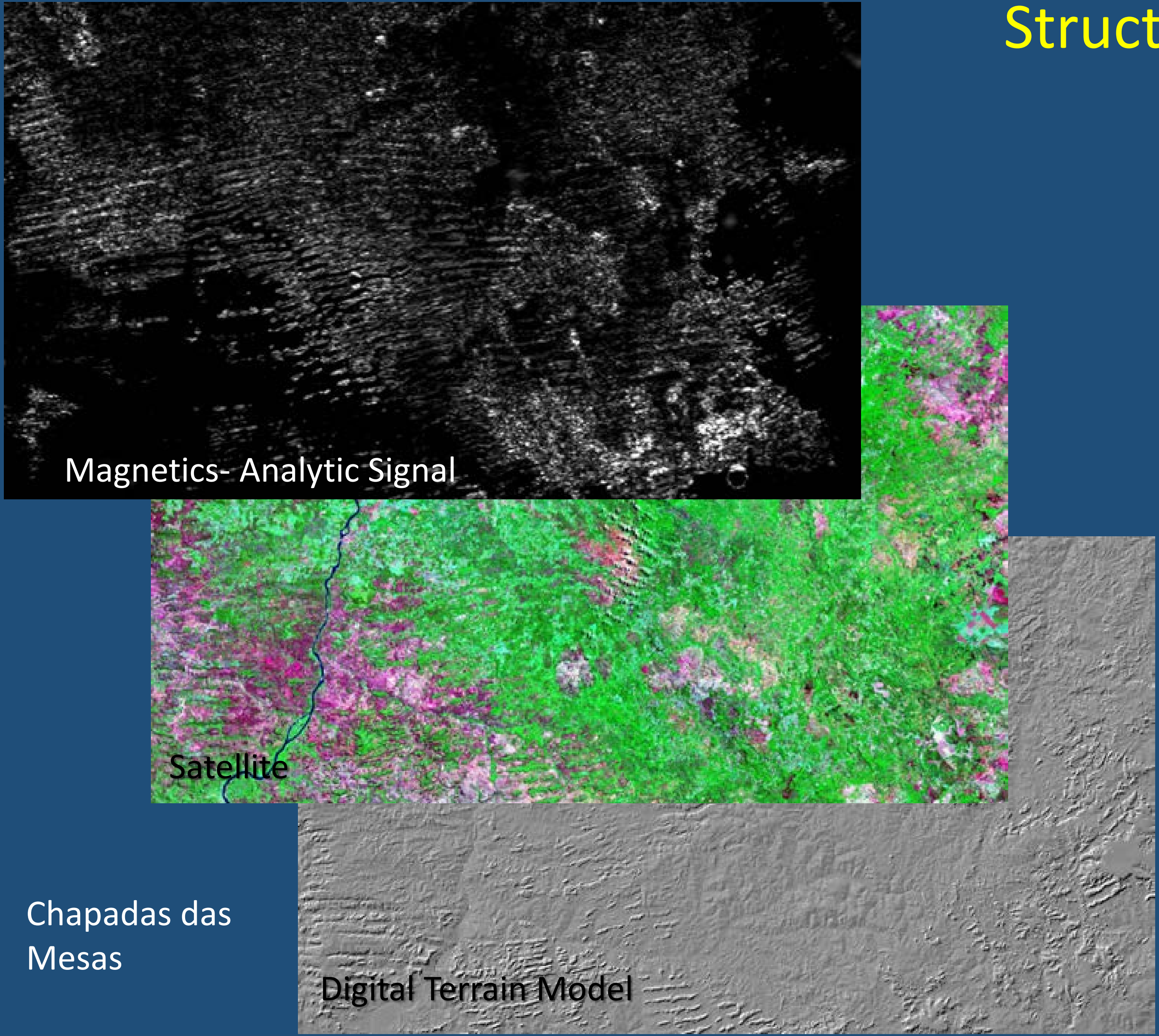
CPRM Serviço Geológico do Brasil

GMD GEOLOGISCH MIJNBOUWKUNDIGE DIENST

# Stage 1 Work program

1. Exploration geoscience gap analysis leading to Exploration GIS, integrating with WAXI 2 West African data
2. Targeted geochronological studies
3. Craton-scale structural interpretation of geophysical data
4. Seminar and workshop for potential stakeholders with training course leading to draft Stage 2 project proposal

# Structural Geophysics Training



Chapadas das
Mesas

SAXI Structural Geophysics Course
11th – 15th February 2019
Paramaribo, Suriname

Practical Exercises

rganised by The University of Western Australia and the Anton de Kom Universiteit van Suriname

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# Exploration GIS

**Scope:**

- Country
- (West Africa)
- North East South America
- South America
- (Africa)
- Global
- Marine

**Themes:**

- Geography
- Geology
- Geophysics
- Mineralisation
- (Tectonics)

**Format:**

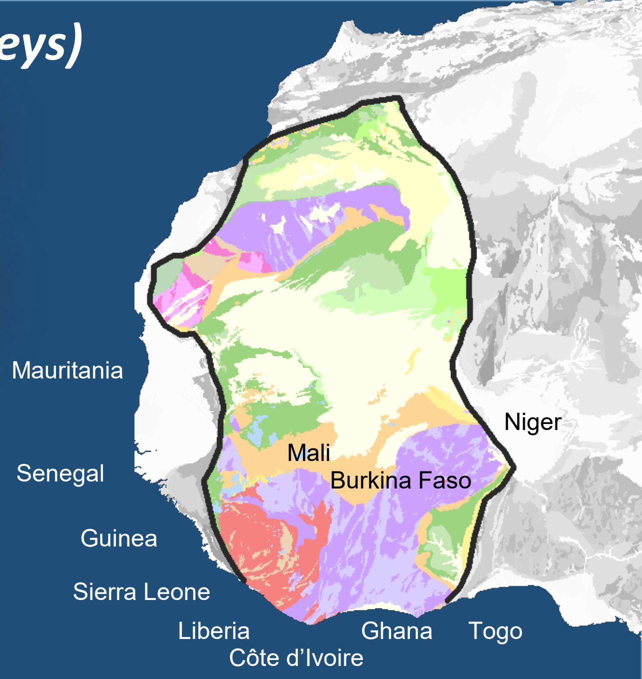
- 60 layers plus 200 WAXI 2 layers
- 370 Gb plus 350 Gb WAXI data
- ArcMap and MapInfo

WAXI - West African Exploration Initiative

IXOA - L'Initiative d'Exploration Ouest Africaine

## 12 Sponsors in kind (Geological Surveys)

Liberia
Mali
Guinea
Niger
Burkina Faso
Ghana
Senegal
Togo
Sierra Leone
Mauritania
Minerals Commission
Côte d'Ivoire



## Project Broker & Coordinator

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Delivering solutions through collaboration

## 36 Industry & Government Sponsors

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Pelican
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Resolute Mining Limited
SEMAFO
Azumah Resources Limited
Newgenco Group
Newcrest Mining Limited
Northern Territory Government
Volta Resources Inc
First Quantum
IAMGOLD
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bhpbilliton
Kinross
Votorantim Metais
drake resources
Toro Gold
Acacia
Avocet Mining
Teranga Gold Corporation
Barrick
Orezone
Sarama
ampella
castlepeak

WAXI 1

WAXI 2

WAXI 3

2006-2018

## 24 Research and Capacity Building Partners

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Université de Lorraine
QUT
Ong-D Le Soleil dans la Main
James Cook University Australia
Macquarie University
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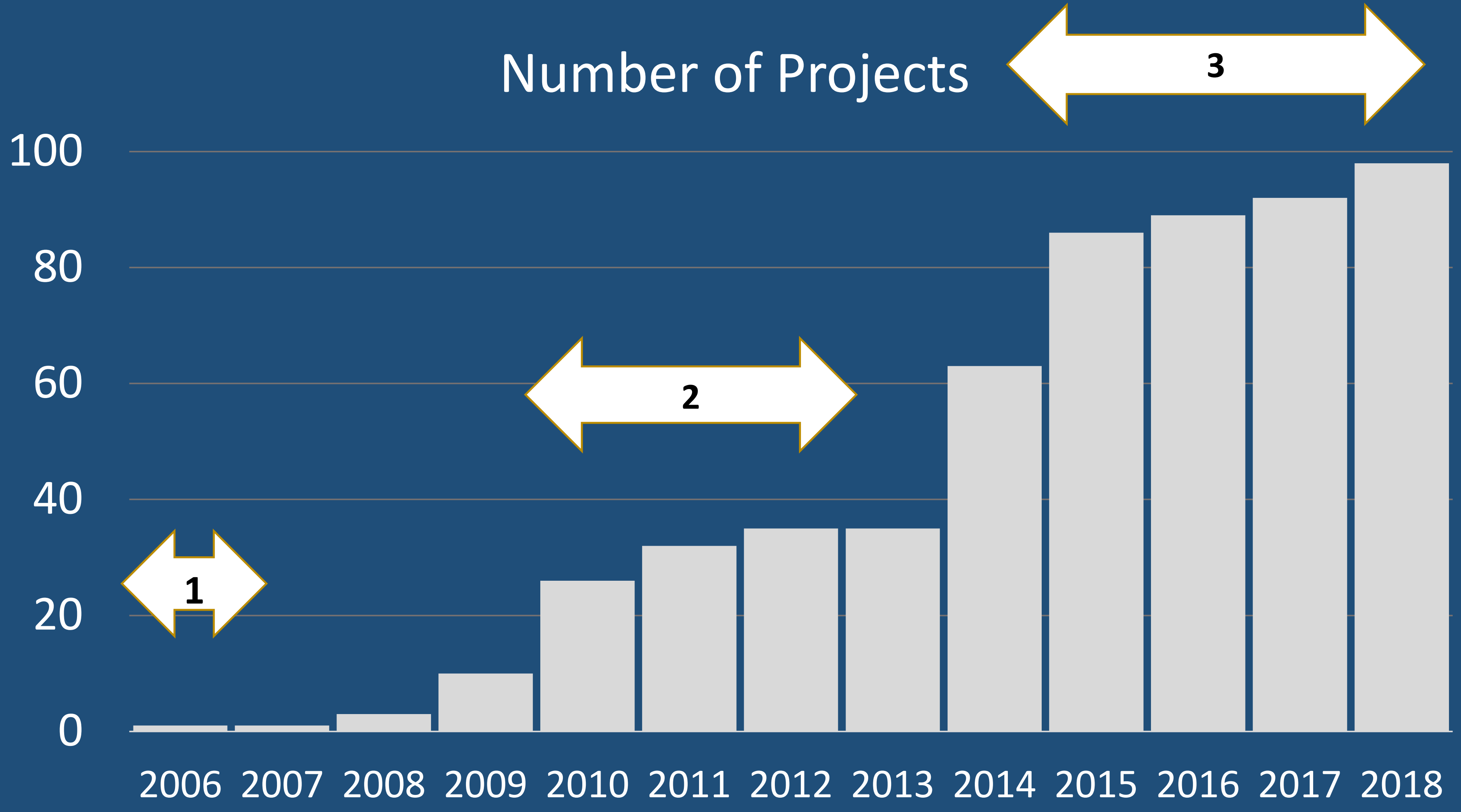
U.S.T.T-B
Monash University
Kalabash
Université Paul Sabatier Toulouse III
IRD Institut de recherche pour le développement
Tshwane University of Technology
The University of Western Australia

## 73 partners over 10 years

# Hons, MSc, PhD & Postdoctoral Projects over life of WAXI 1-3

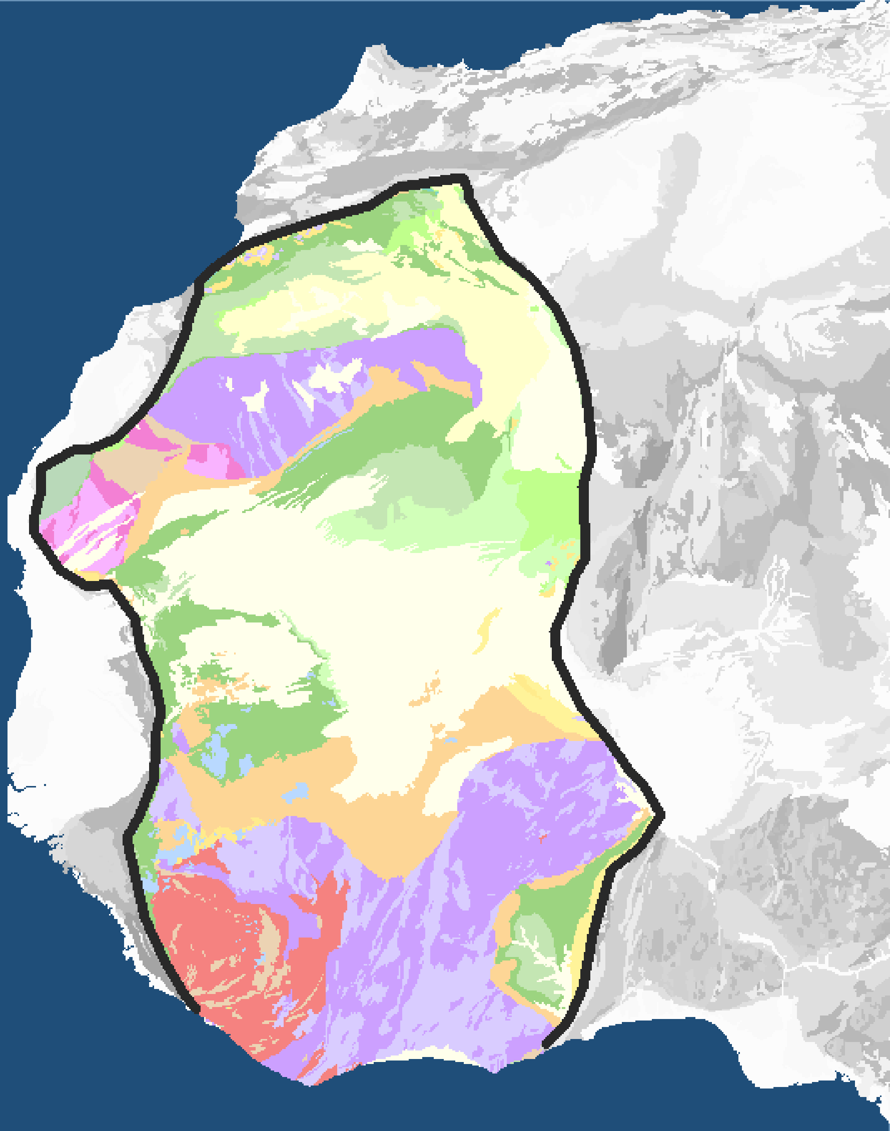


# Integration of Research and Capacity Building

- **Multi-dimensional:** 1D (Geochron), 2D (Map), 3D (3D Models)
- **Multi-scale:** Grain, Deposit, Belt, Craton
- **Multi-data & Technique:** grav, mag, em, mt, field, geochron, geochem
- **Multiple hypotheses:** tectonics, 3D
- **Multiple organisations:** Research, Geosurvey, Exploration, NGO

The success of the WAXI project has come from the recognition of the **different drivers** of the partner organisations**,** but **common interests** in improving the research capacity and knowledge base for West Africa

# The WAXI project in numbers



**12** countries

**73** partner organisations over 11 years

**81** International Publications

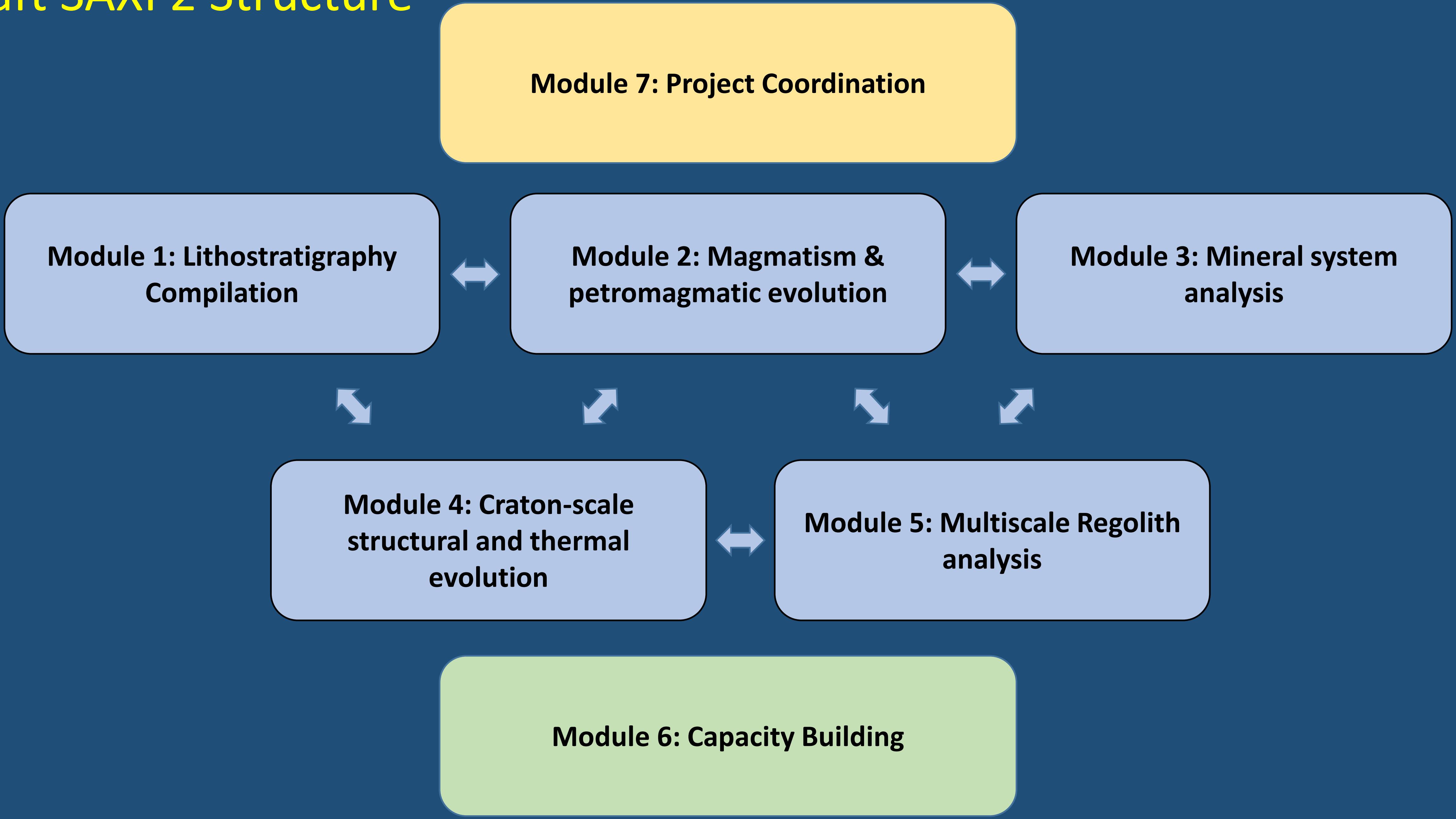
**90** Postdoc, PhD, MSc & Hons projects

**650** GB exploration geoscience database

**1800** person-days of technical training in West Africa

**650,000** km$^2$ of geophysically constrained geological mapping

# Draft SAXI 2 Structure



Module 7: Project Coordination

Module 1: Lithostratigraphy Compilation

Module 2: Magmatism & petromagmatic evolution

Module 3: Mineral system analysis

Module 4: Craton-scale structural and thermal evolution

Module 5: Multiscale Regolith analysis

Module 6: Capacity Building

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# SAXI:
# The South American Exploration Initiative

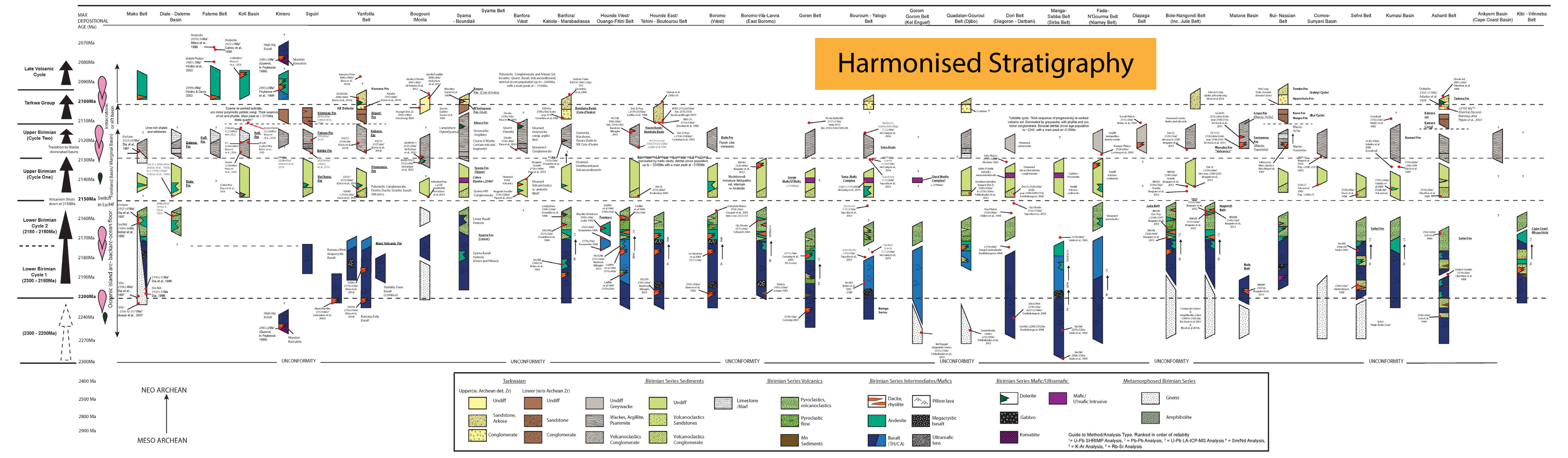
www.saxiproject.org

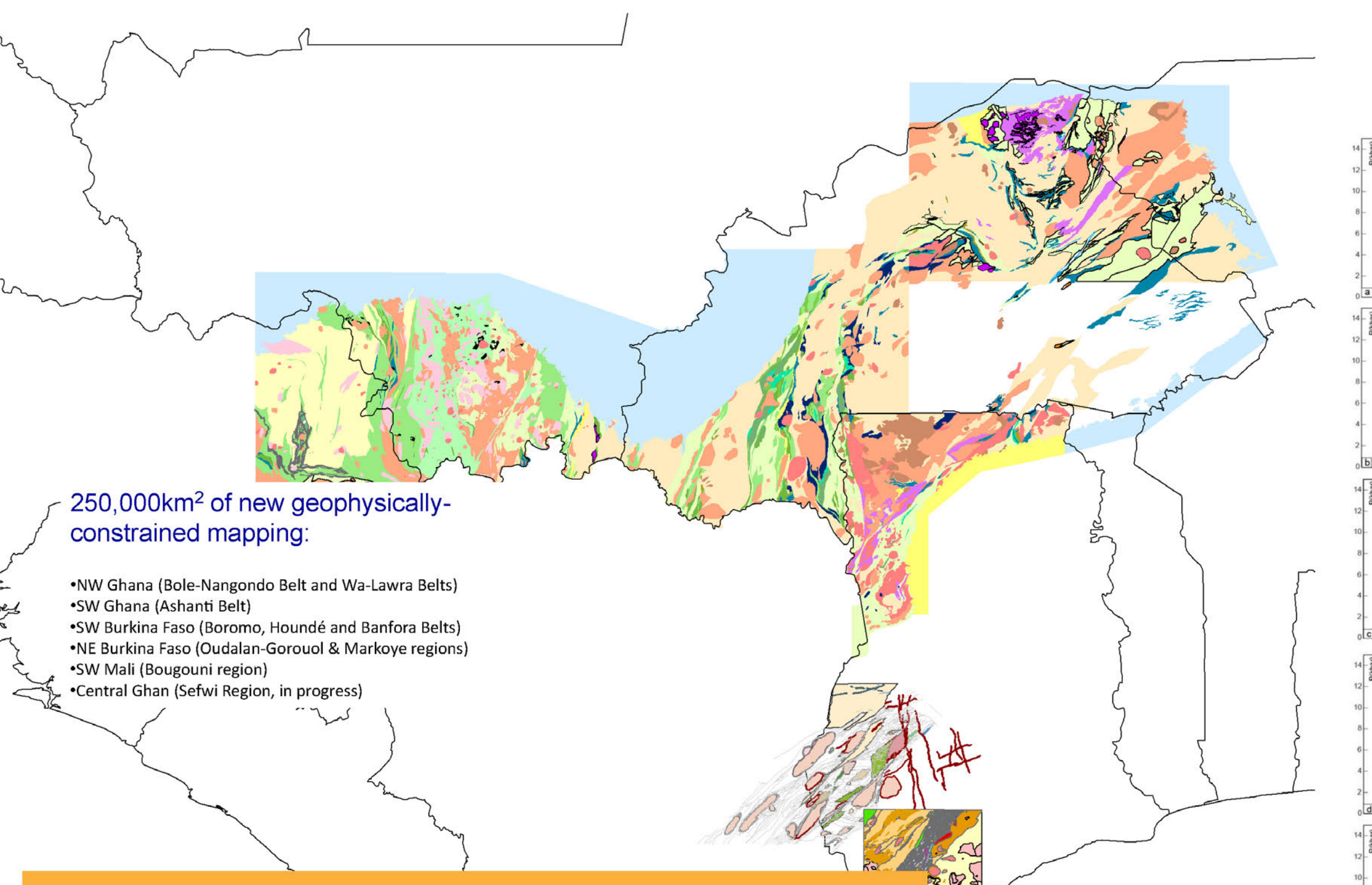
# WAXI - West African Exploration Initiative

Stage 2

# IXOA - L'Initiative d'Exploration Ouest Africaine

## Harmonised Stratigraphy



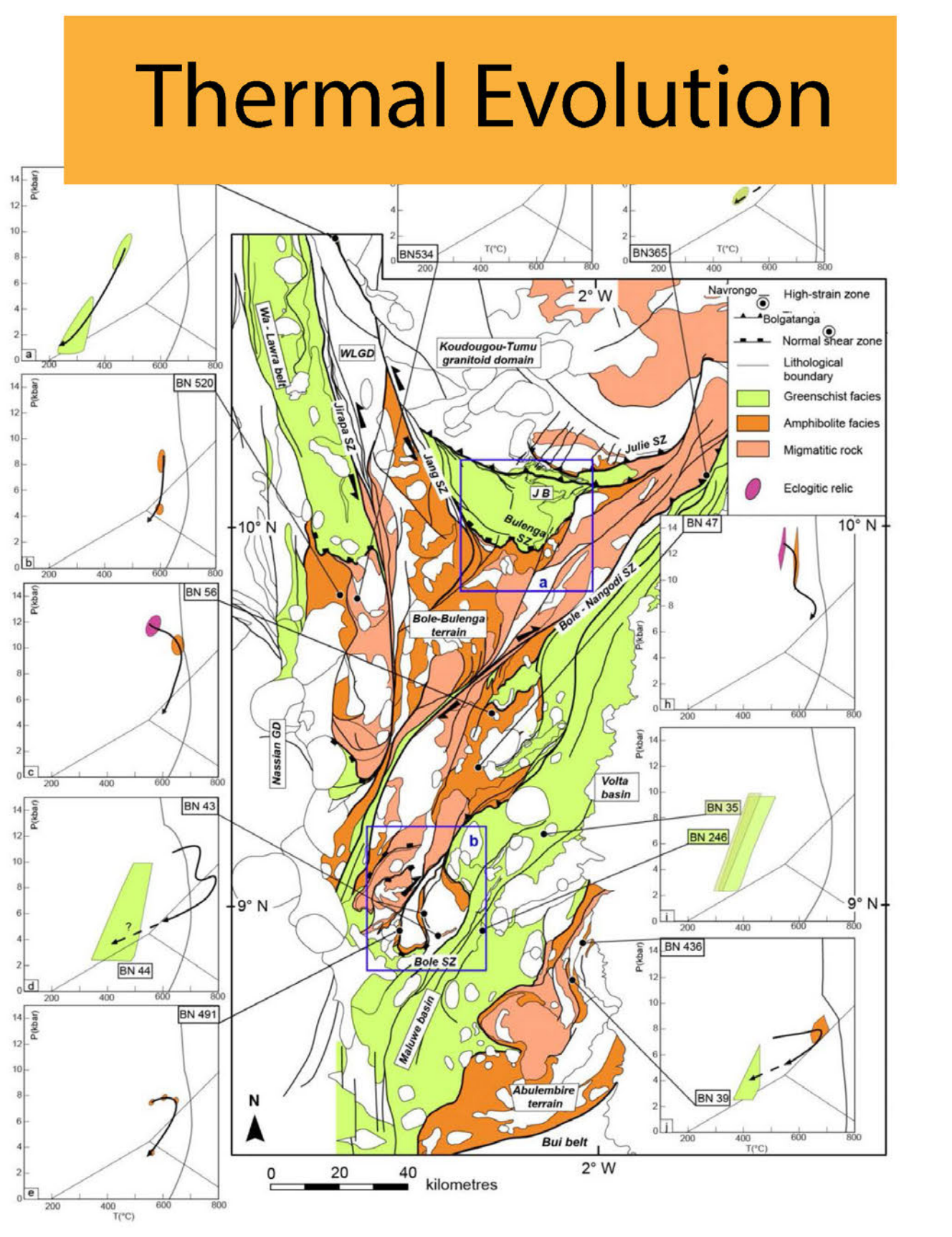


250,000km² of new geophysically-constrained mapping:

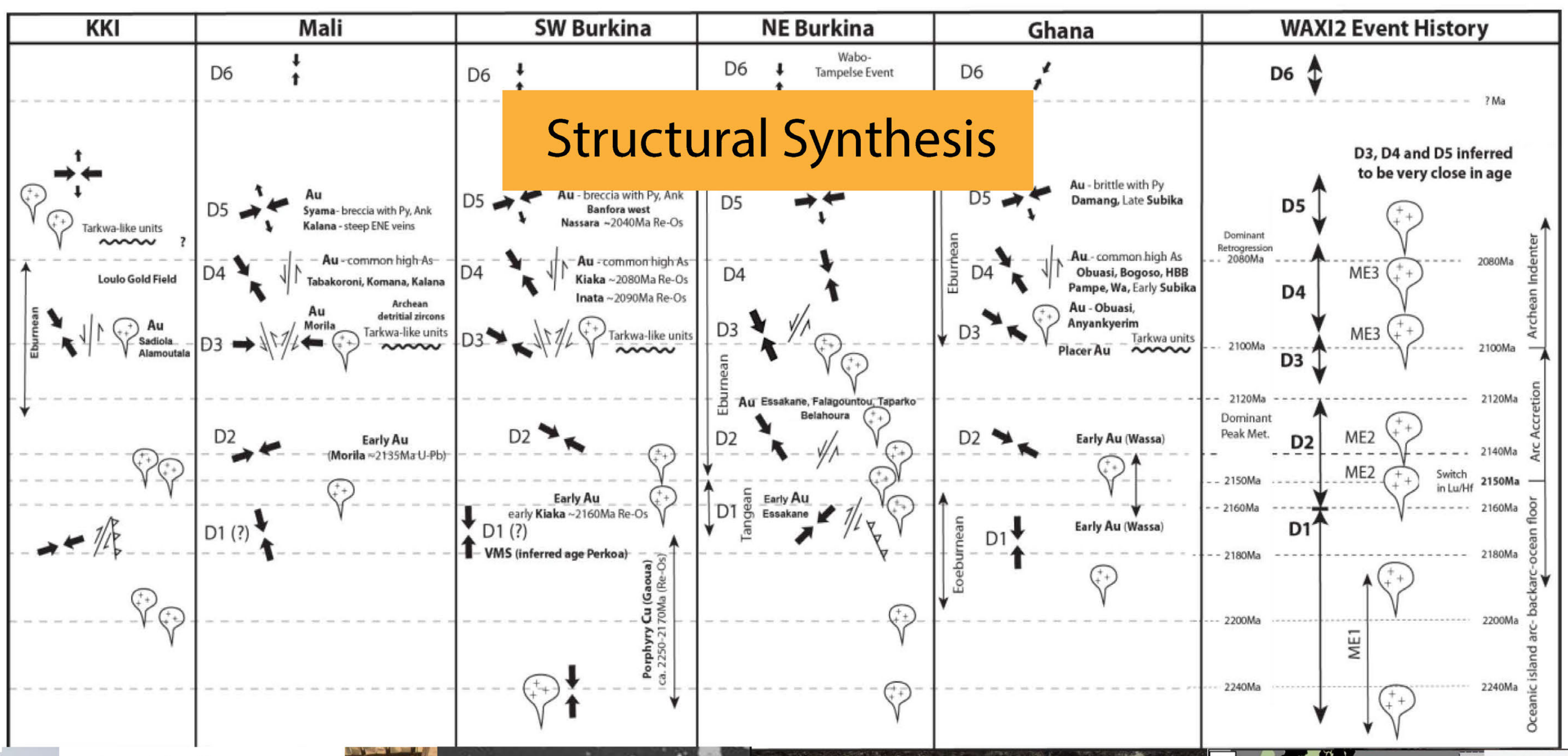
- NW Ghana (Bole-Nangondo Belt and Wa-Lawra Belts)
- SW Ghana (Ashanti Belt)
- SW Burkina Faso (Boromo, Houndé and Banforas Belts)
- NE Burkina Faso (Oudalan-Gorouol & Markoye regions)
- SW Mali (Bougouni region)
- Central Ghan (Sefwi Region, in progress)

## Harmonised Mapping

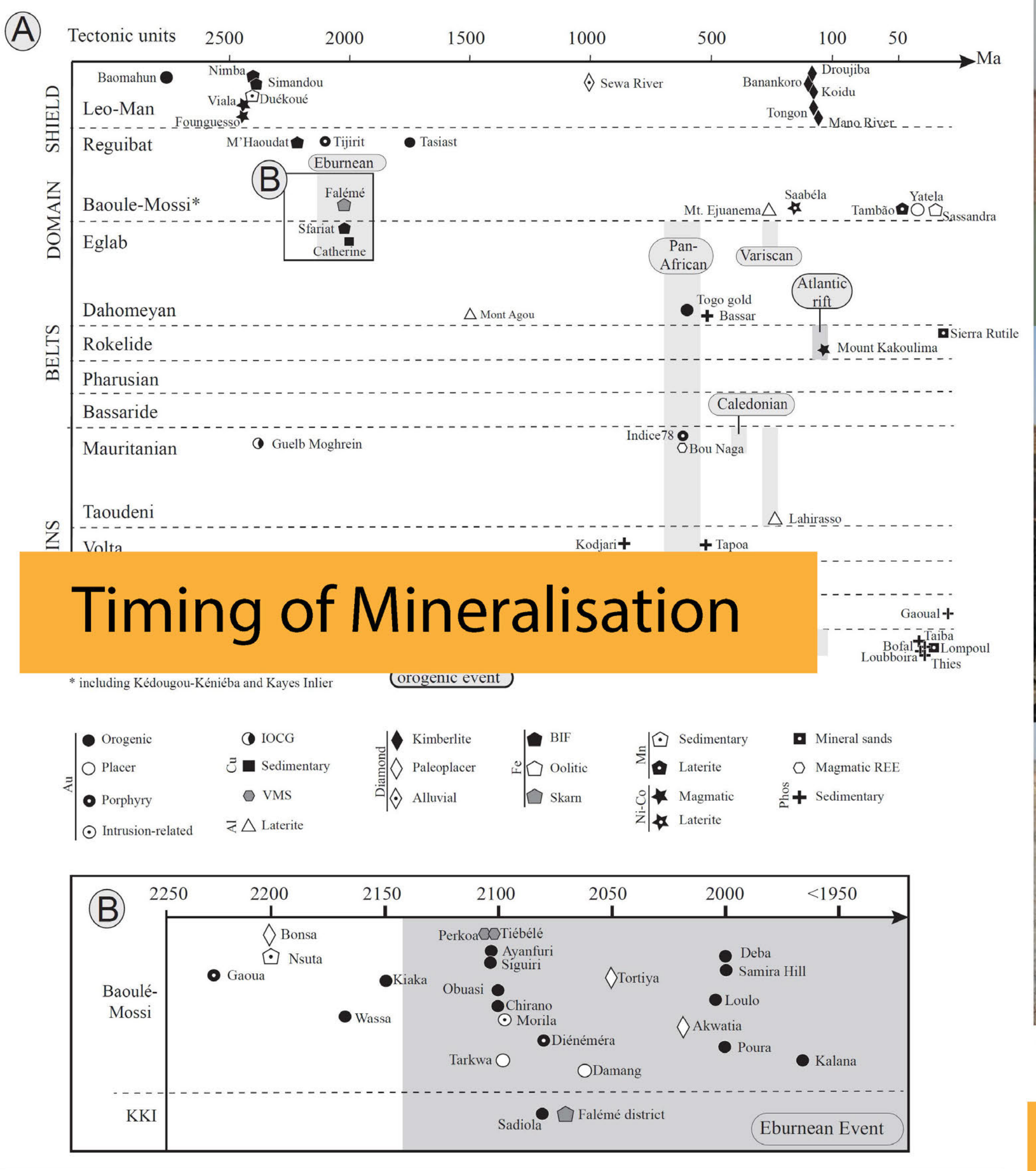
## Thermal Evolution



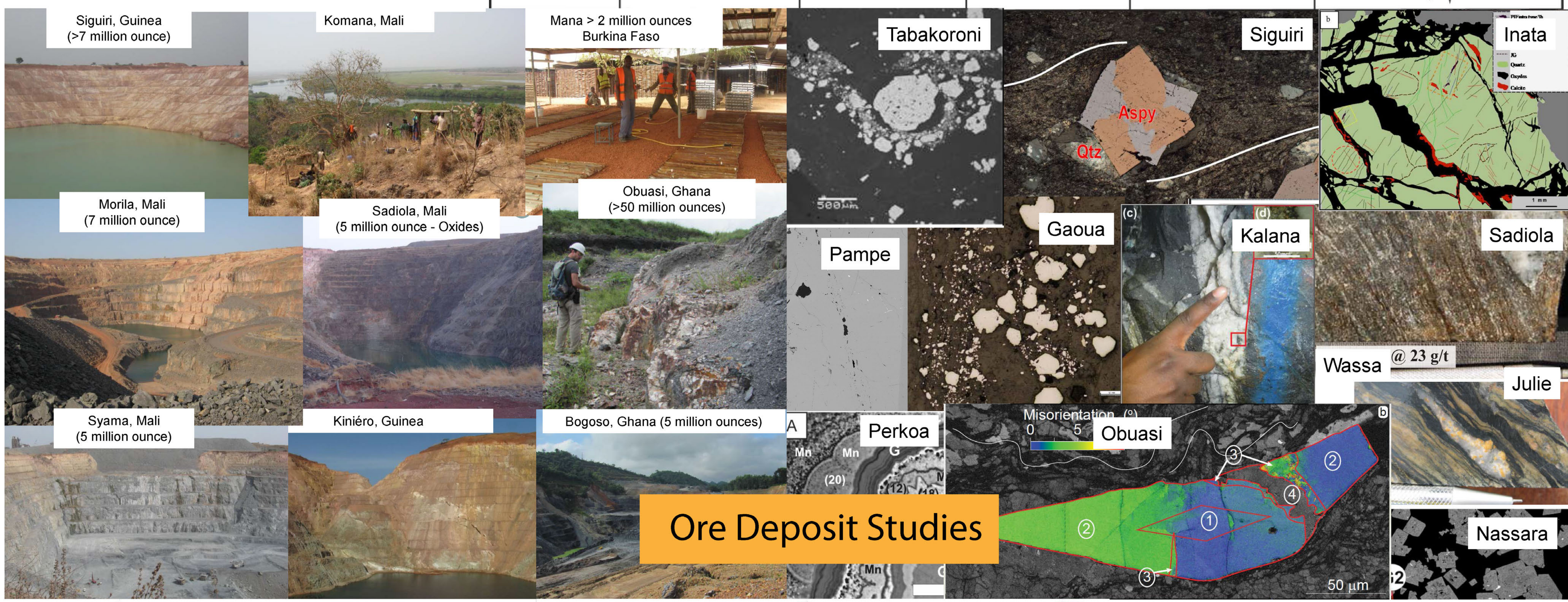
## Structural Synthesis



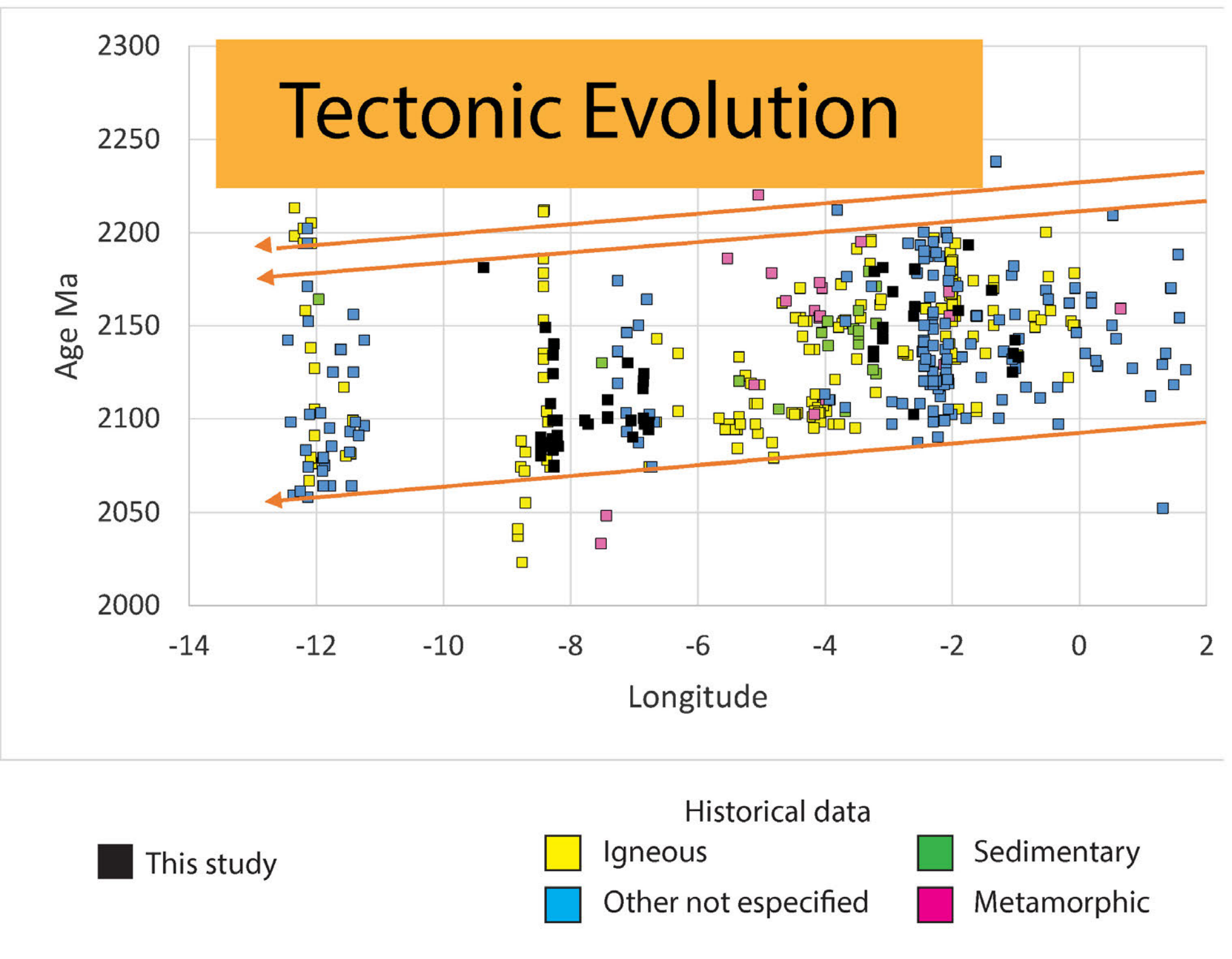
## Timing of Mineralisation



## Ore Deposit Studies

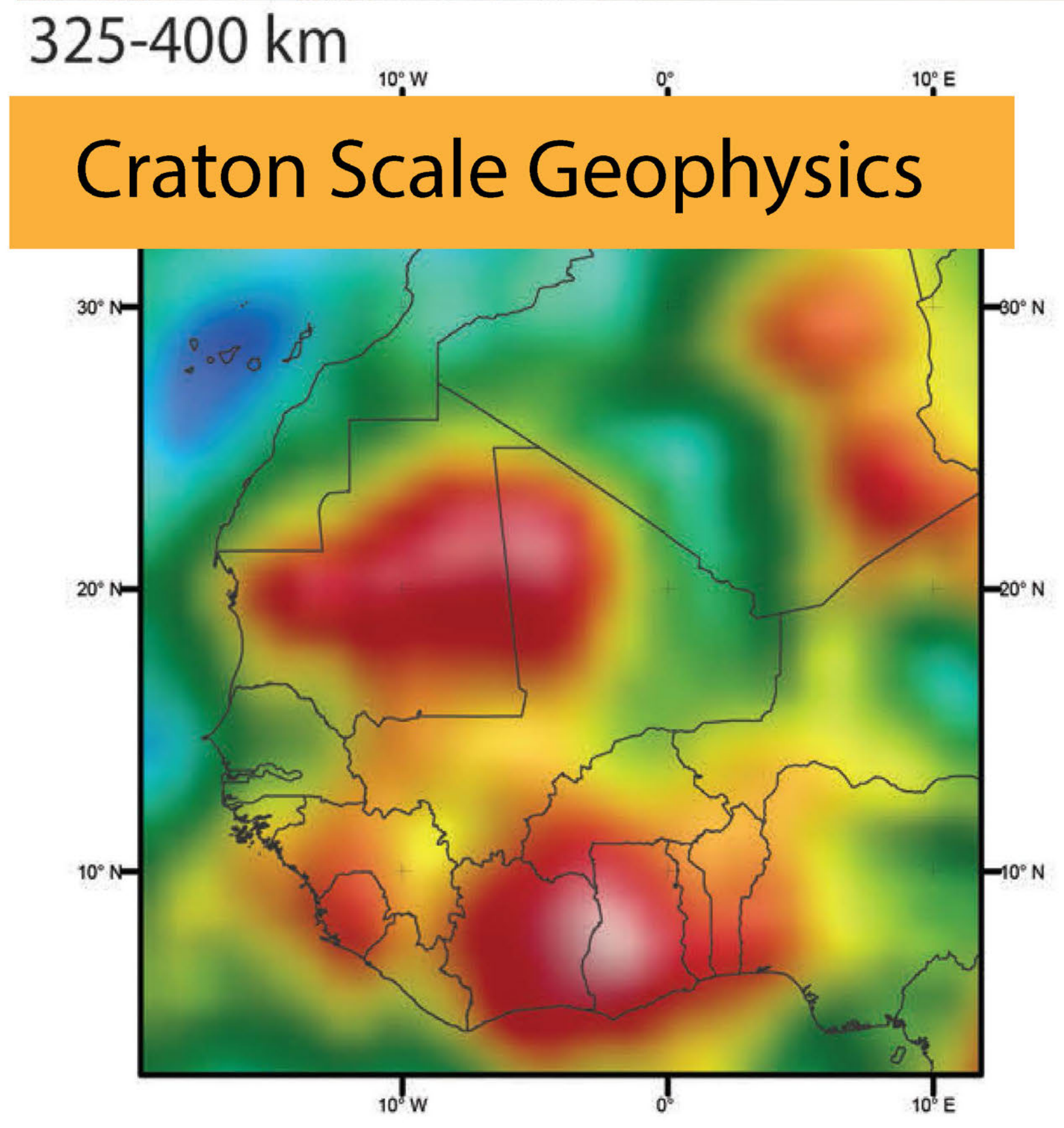


## Tectonic Evolution

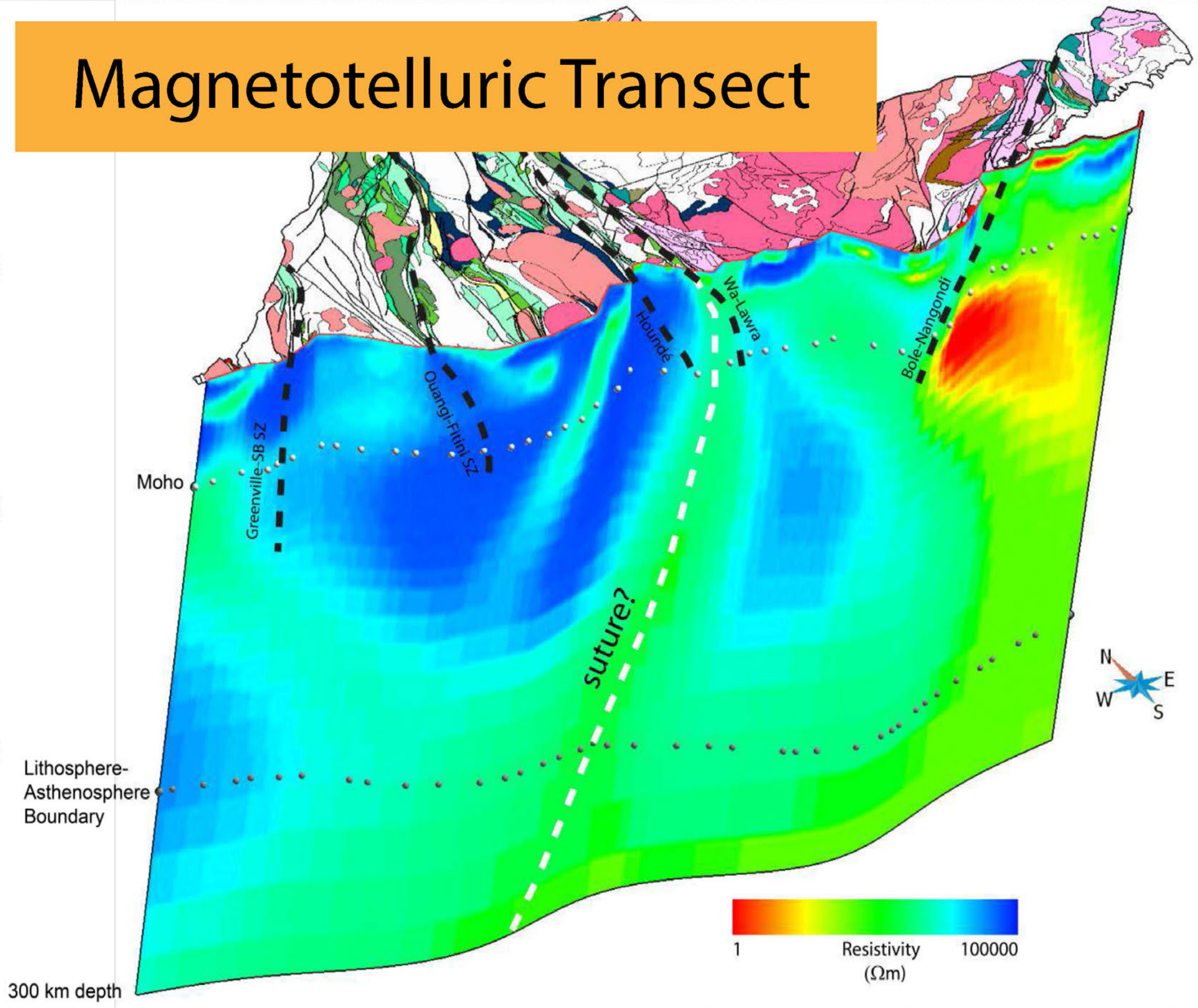


## Craton Scale Geophysics

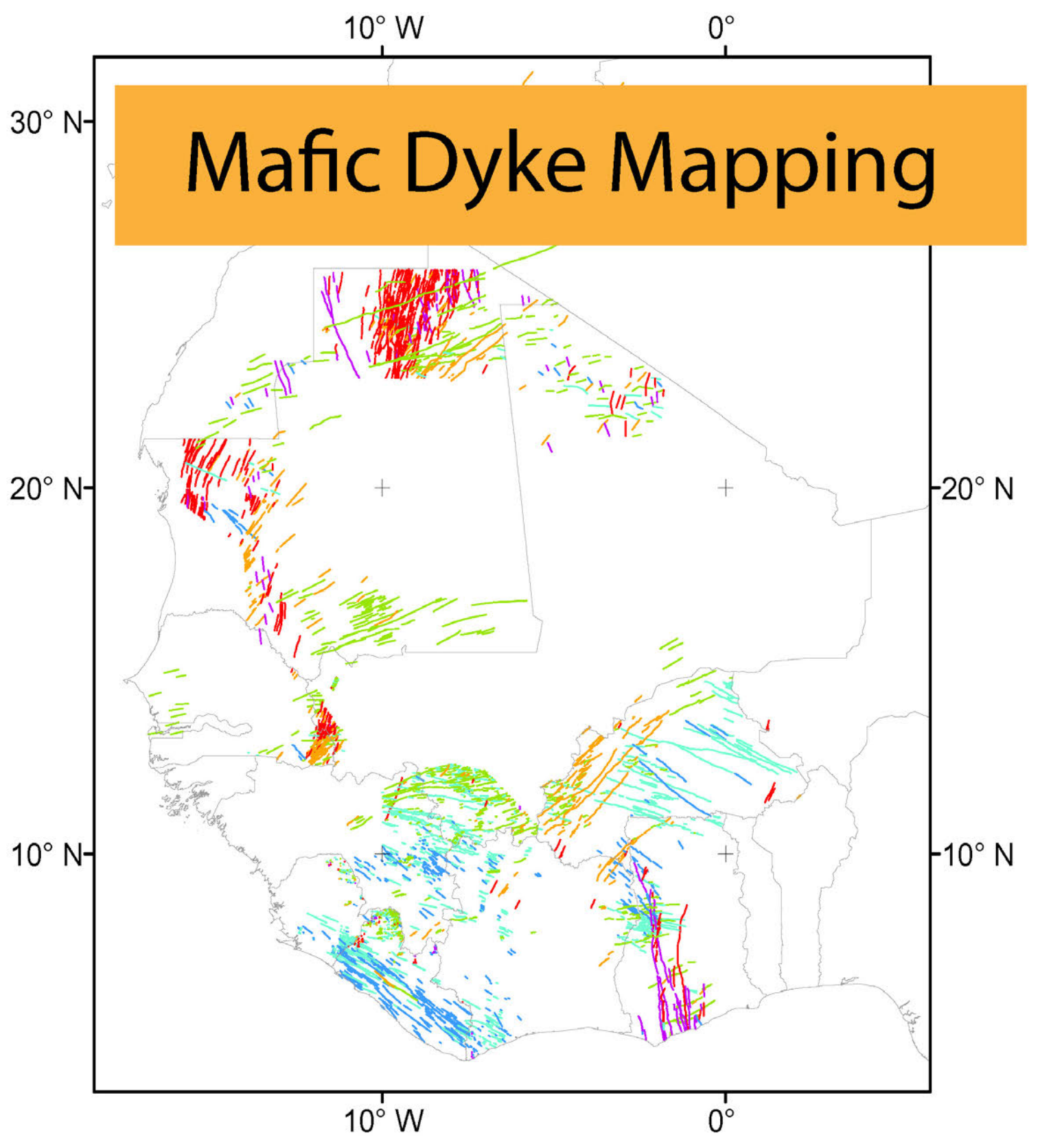
325-400 km



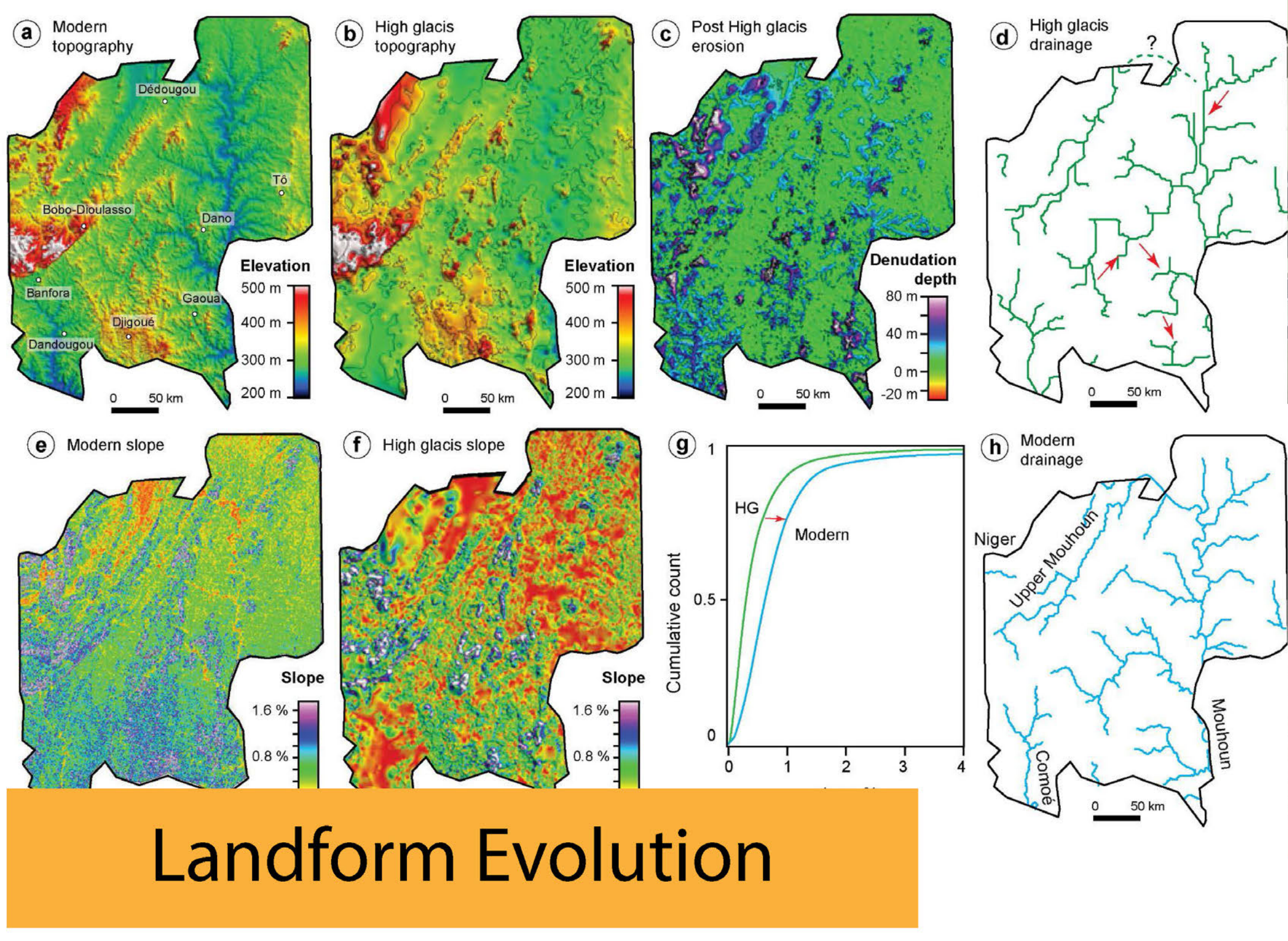
## Magnetotelluric Transect



## Mafic Dyke Mapping



## Landform Evolution



## Professional Training

**Exploration Geochemistry**, Jan 2012, Ouagadougou, Presented by Yann ITARD, Consultant 20 participants. 3 days

**Applied Structural Geology in Mineral Exploration and Mining** (SW Ghana), 4th Quarter, 2012, Presented by John Miller. 25 participants. 4 days

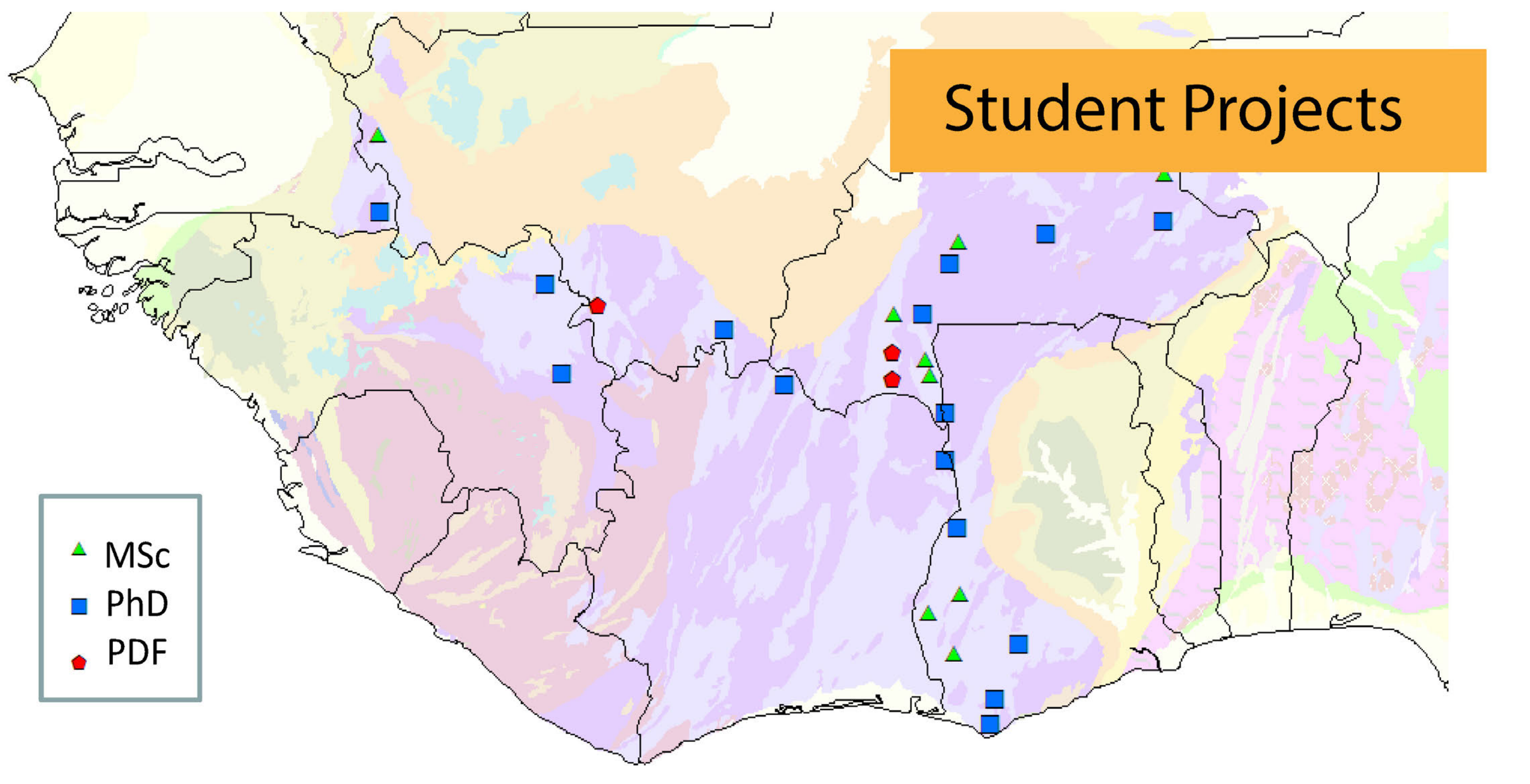
Annually
5 WAXI Courses
20 total days training
100 total participants

Plus 1-2 IM4DC Courses

**Field Structural Mapping**, Jan 2012, Kaya. Presented by Kim Hein, 27 participants. 6 days.

**Structural Geophysics**, April, 2012, Dakar, Presented by Mark Jessell, Laurent Ailleres, 25 participants. 5 days

## Student Projects



Niger
Senegal
Togo
Liberia
Mali
Mauritania
Burkina Faso
Ghana
Guinea

# Overman – an exceptional gold deposit in the Rosebel mining area, Suriname

N.M.E. Kioe-A-Sen[1,2], M.J. van Bergen[2], R. Schreefel[3] and P.Z. Vroon[3]

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*[2]Utrecht University, Faculty of Geosciences, Budapestlaan 4, Utrecht, The Netherlands*
*[3]Vrije Universiteit, De Boelelaan 1085, Amsterdam, The Netherlands*
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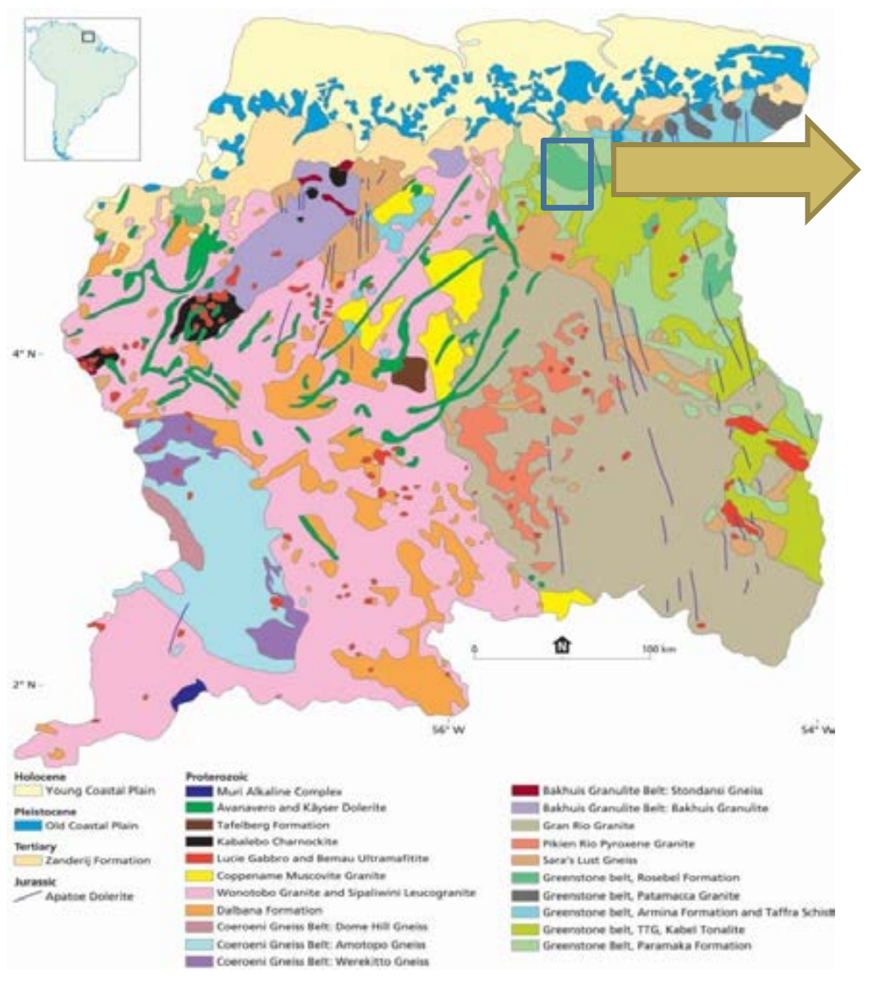
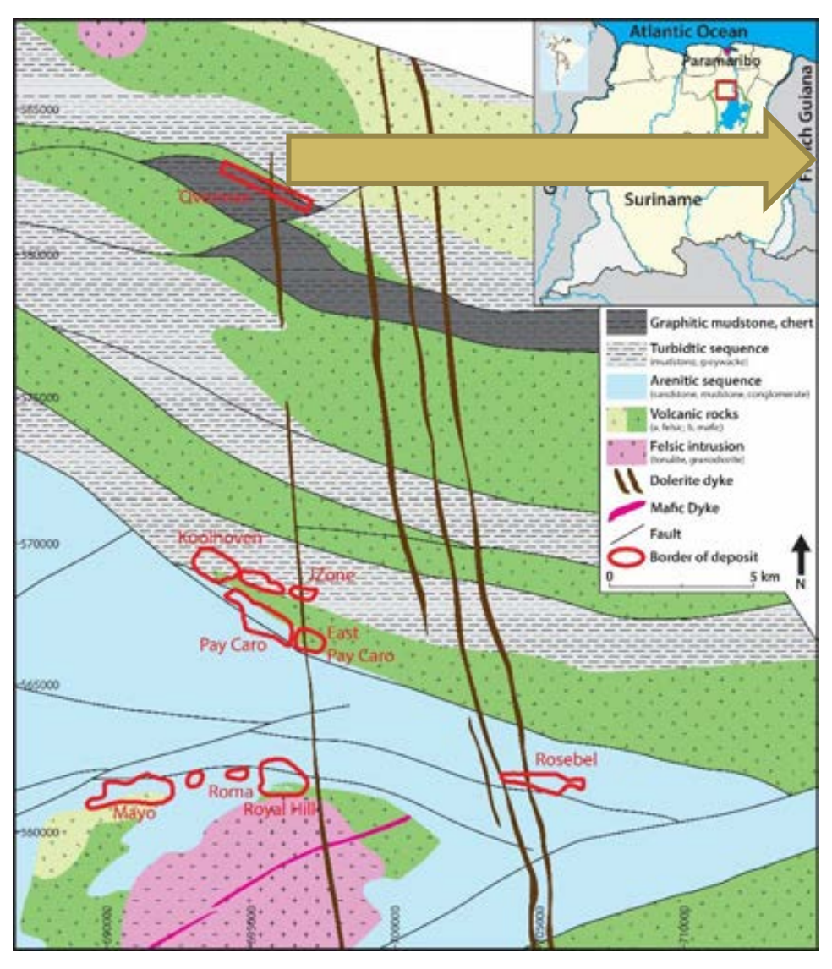
## Geological Setting

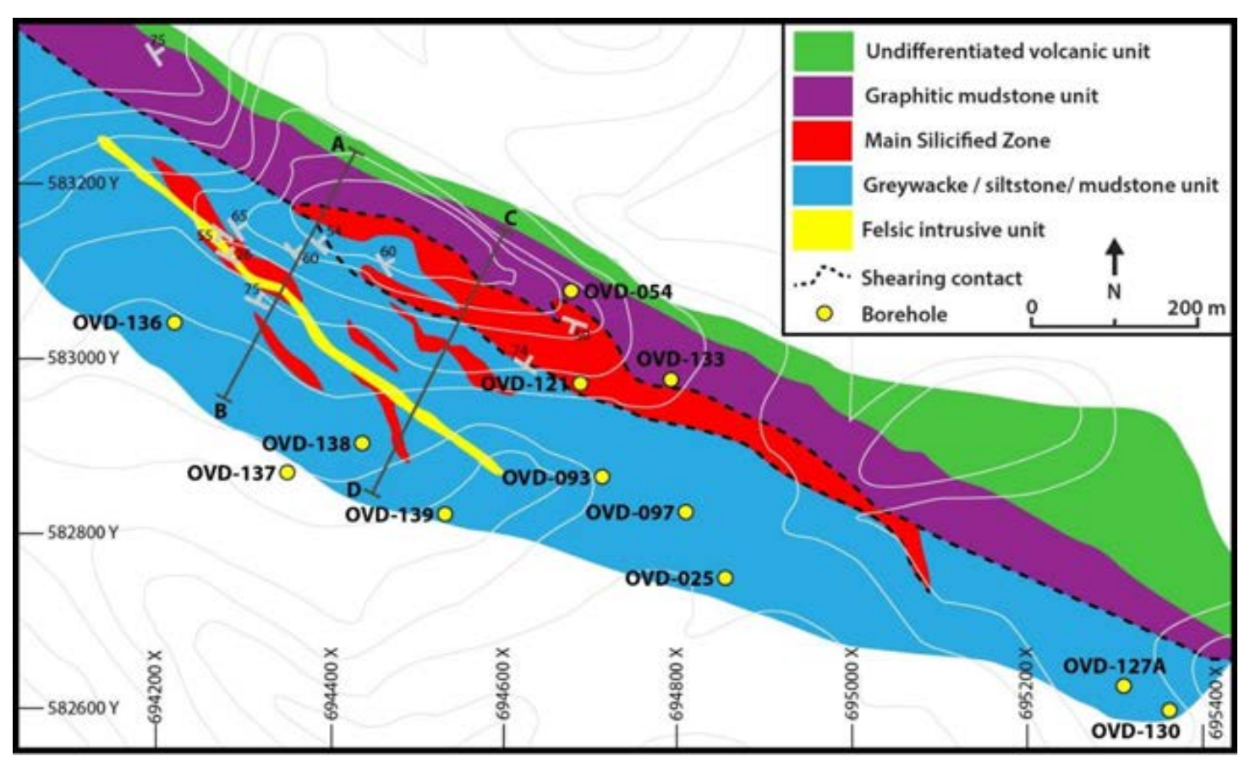
- The Overman Gold Deposit, a prospective area in the Paleoproterozoic Marowijne Greenstone Belt, is located 16 km north of the currently operating Rosebel mines
- The Rosebel Gold District currently comprises eight identified deposits and several prospective areas
- Gold mineralization in the Rosebel Gold District is hosted in low-medium grade metamorphic rocks, including turbiditic sediments, conglomerates, lavas and intrusions



Geological map of Suriname after Kroonenberg et al. (2016)



Geological map of the Rosebel Gold District illustrating the eight identified gold deposits and the Overman Gold Deposit after Daoust et al. (2011).



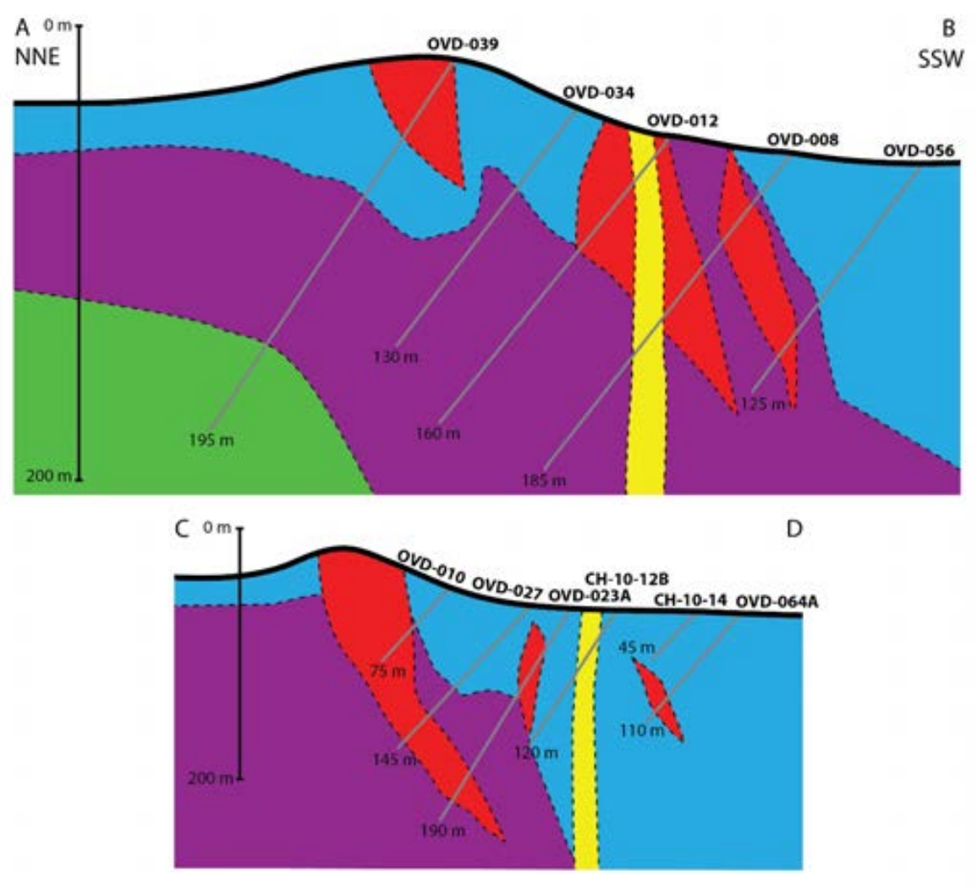
Geological interpretation map of the Overman Gold deposit after Alimoenadi (2013), Daoust (2013) and Schreefel (in prep.)

### Lithology

- Main south-dipping silica body
- Graphitic mudstone
- Greywacke-siltstone
- Felsic intrusive

All rocks show low-grade metamorphism

Sharp stratigraphic contact between silica body and graphitic mudstone



Interpretation profiles indicating the lateral and vertical discontinuity of the silica lenses after Alimoenadi (2013), Daoust (2013) and Schreefel (in prep.).

## Geochemistry

### Pre-silicification precursors from bulk-rock data

- 24 drill core samples from main lithological units were analyzed for major and trace elements by XRF, ICP-AES and ICP-MS.
- Geochemical and petrographic results identify 5 distinct rock types.
- Original rocks, prior to silicification were probably heterogeneous and mainly of (meta-)sedimentary origin.
- Trace-element signatures of lithological groups, least affected by silicification, show strong resemblance to meta-sediments of the northern deposits of the Rosebel district (J-Zone and Koolhoven) and the Rosebel deposit in the Central trend.

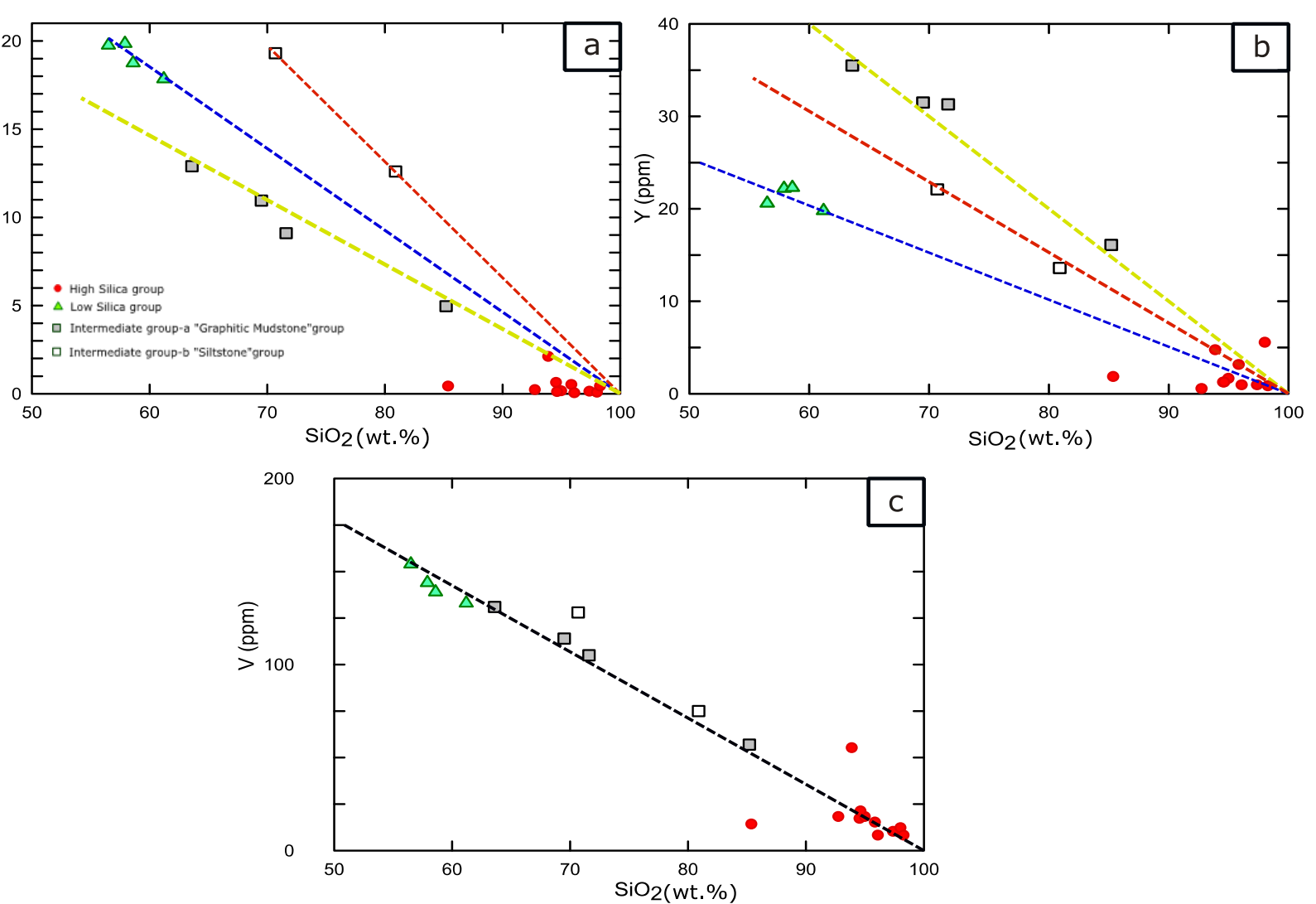
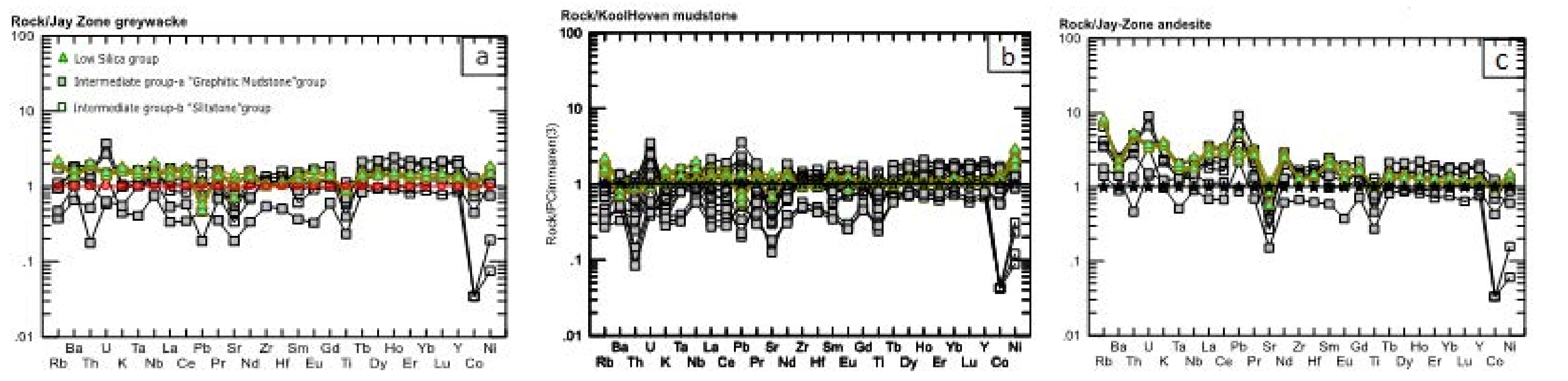
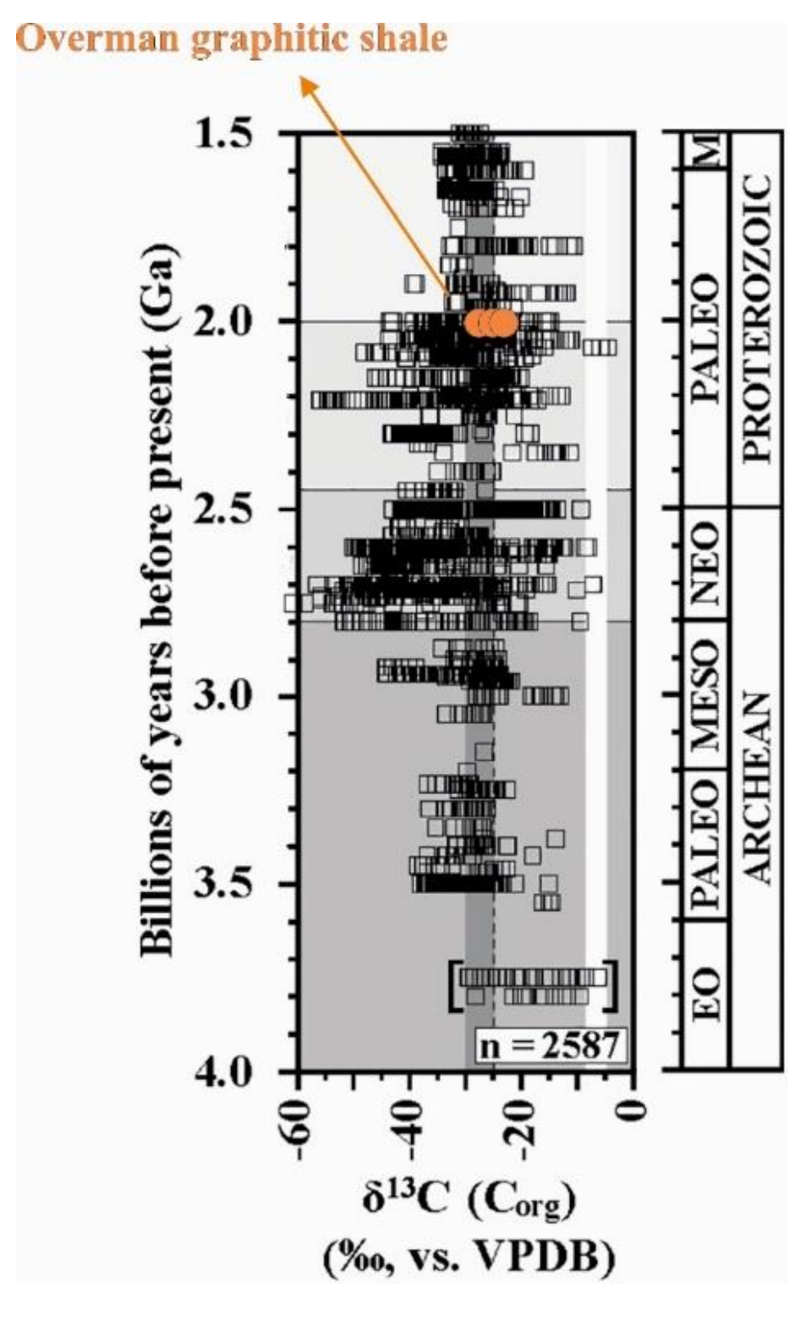


Fig. 3 a-b-c: Diagrams illustrating near-linear decreases of $Al_2O_3$, Y and V concentrations with increasing $SiO_2$. The three separate trends shown in the (a) and (b) panels are controlled by silicification and point to original lithological heterogeneity of precursor rocks.



Multi-element diagrams normalized to average concentrations in a) Jay Zone Greywacke b) Koolhoven mudstone and c) Jay-Zone andesite, according to data from Daoust (2016). Flat trends in a) and b), relative to the spiky pattern in c} favour (meta-)sedimentary over (meta-)volcanic rock types as precursors prior to silicifiation



Carbon isotope signature of the Graphitic mudstone in a stratigraphic compilation of available data on organic C (Havig et al., 2017)

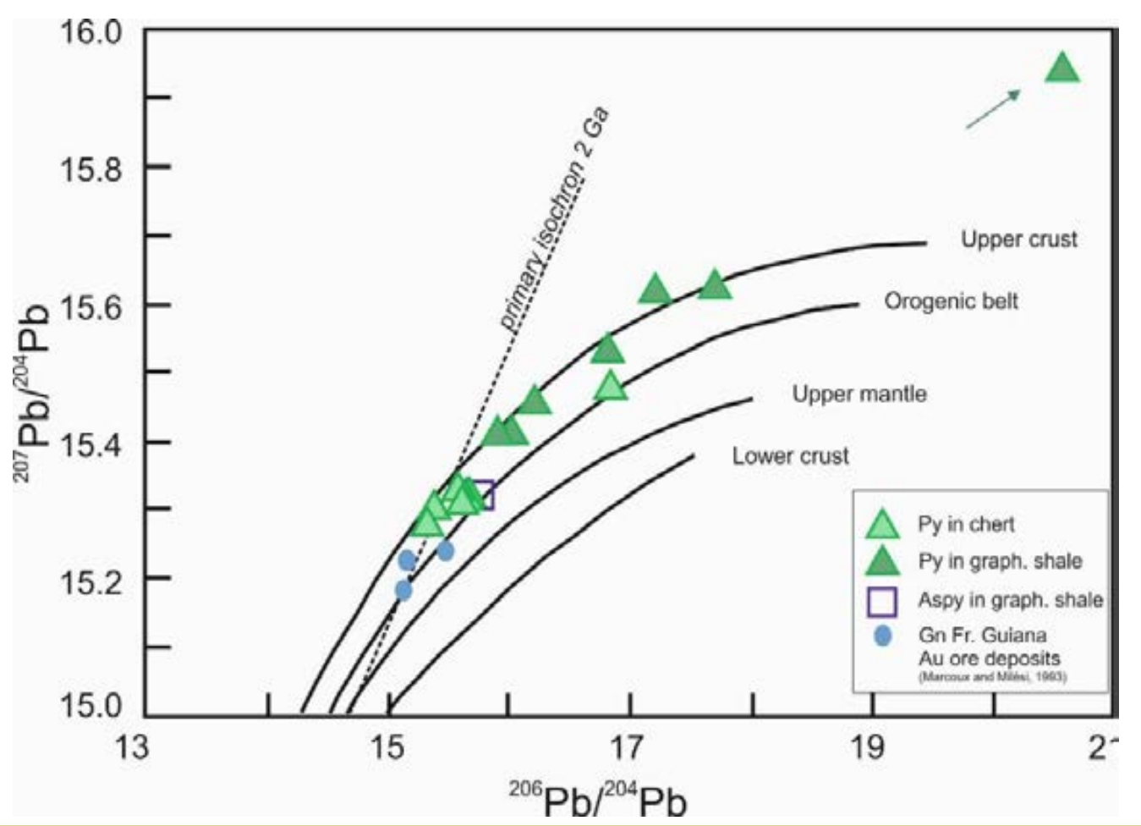
### C-isotopes and the depositional environment of the graphitic mudstone

- $\delta^{13}$C values between -25 and -30‰ for graphite in the mudstone/shale unit point to organic carbon
- Falls in the range of compiled Paleoproterozoic organic carbon
- Graphitic mudstone likely deposited in reducing marine environment

### Pb-isotope compositions of (arseno)pyrites and the source of gold

- Pb-ratios of pyrites in the graphitic mudstone more radiogenic than those in the silica body; probably due to local availability of U.
- Pb ratios in most unradiogenic population close to galenas from Au deposits in French Guiana; consistent with a Paleoproterozoic age around 2 Ga.
- Pb in sulphides (and probably also Au) largely derived from a source with a large Upper Crust component.

Pb Isotopes compositions of sulphides in the Overman deposit and comparison with data from French Guiana



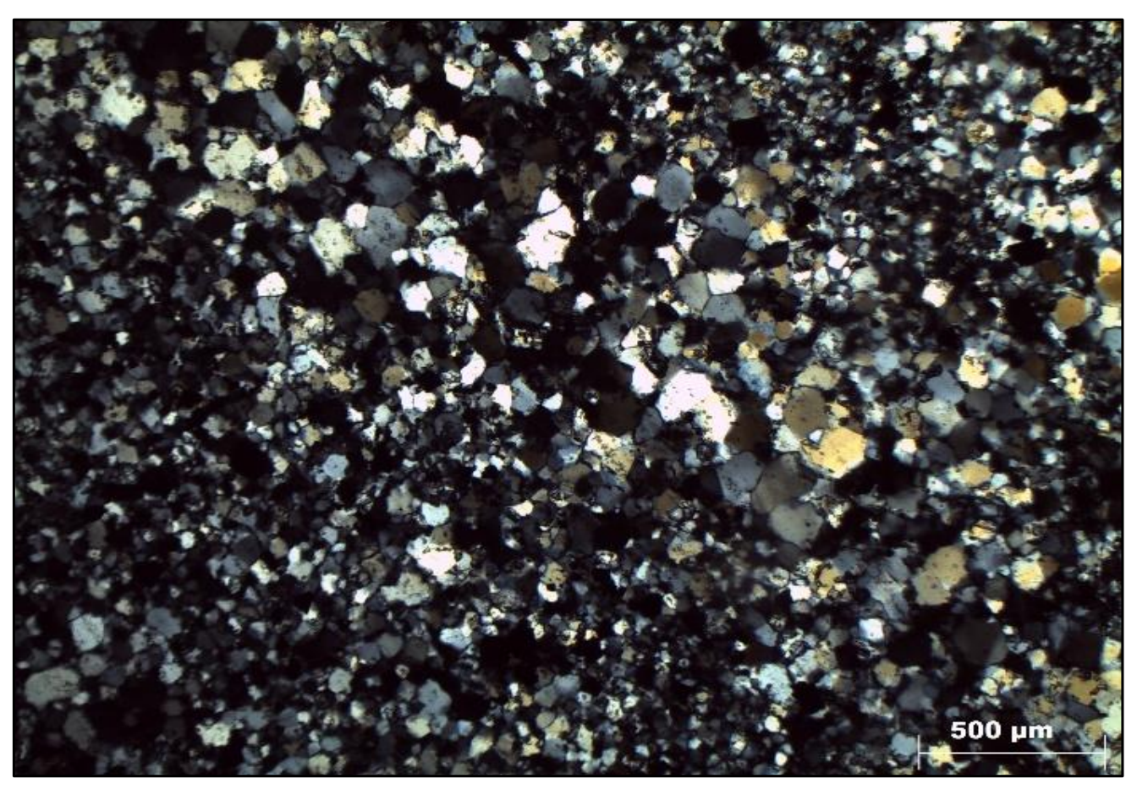
## References

- Alimoenadi, G.A. (2013). Geology of the Overman Deposit: Preliminary structural and lithological characterization of the mineralized ore body and the surrounding rocks. BSc thesis, Anton de Kom University of Suriname
- Daoust, C., Voicu, G., Brisson, H. and Gauthier, M., (2011), Geological setting of the Paleoproterozoic Rosebel gold district, Guiana Shield, Suriname, Journal of South American Earth Sciences 32: 222-245.
- Kioe-A-Sen, N.M.E., van Bergen, M.J., Wong, T.E. and Kroonenberg, S.B., (2016), Gold deposits of Suriname: geological context, production and economic significance, Netherlands Journal of Geosciences - Geologie en Mijnbouw (95-4): 429-445.
- Kroonenberg, S.B., De Roever, E.W.F., Fraga, L.M., Reis, N.J., Faraco, T., Lafon, J.M., Cordani, U. and Wong, T.E., (2016), Paleoproterozoic evolution of the Guiana shield in Suriname: A revised model, Netherlands Journal of Geosciences - Geologie en Mijnbouw (95-4): 491-522.
- Schreefel, R. (in prep.), Sulphides in the Overman Gold Deposit, Suriname: constraints on the provenance of Sulphur-bearing fluids. MSc-thesis, VU University Amsterdam

## Gold mineralization

### Prominent features

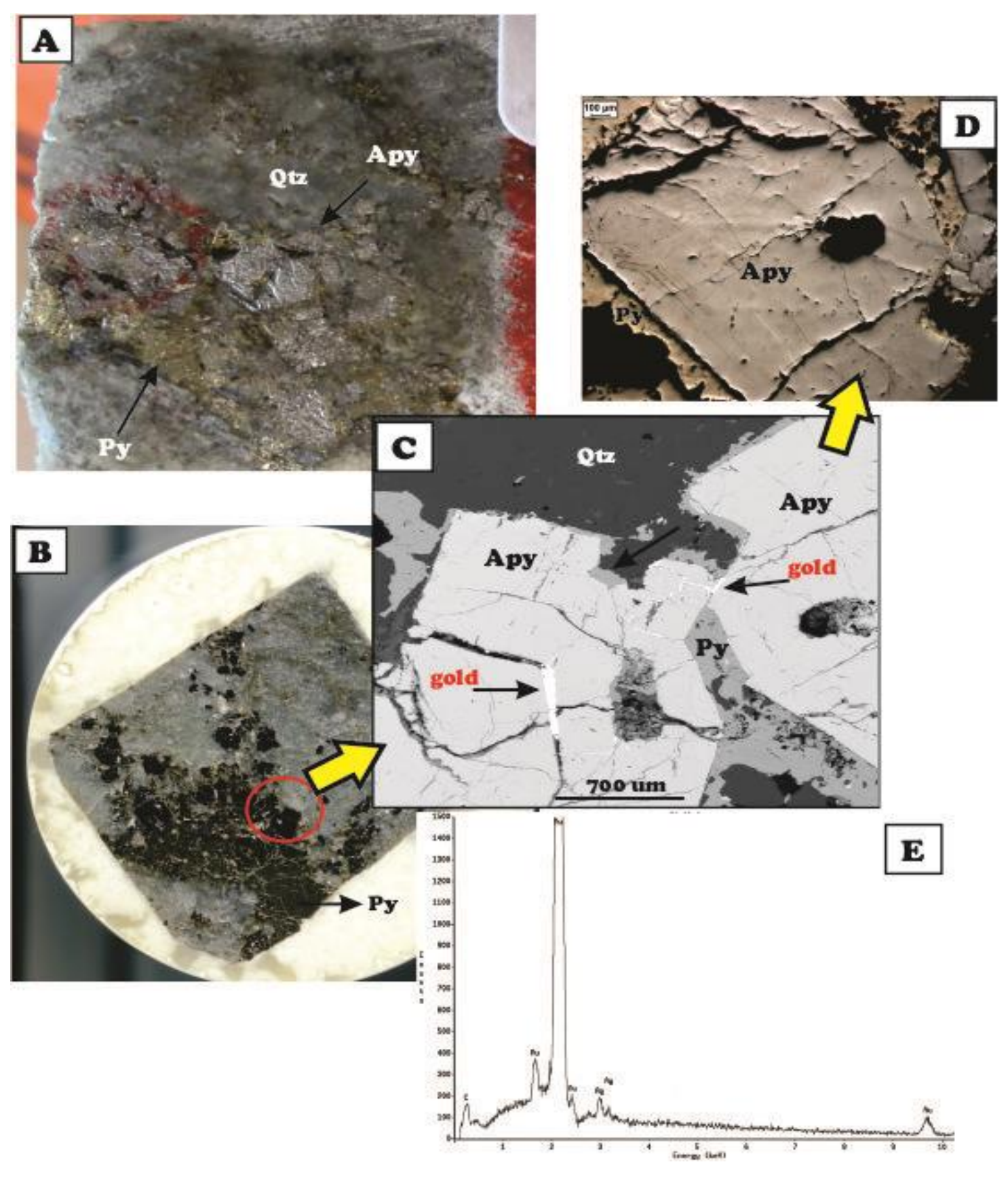
- Unusual gold mineralization within rigid silica body (90-95% quartz)
- Field association with sheared graphitic mudstone (with lower maximum Au content)
- Visible gold associated with arsenopyrite, and invisible gold in As-bearing sulphides
- Style of mineralization uncommon for the Marowijne Greenstone Belt



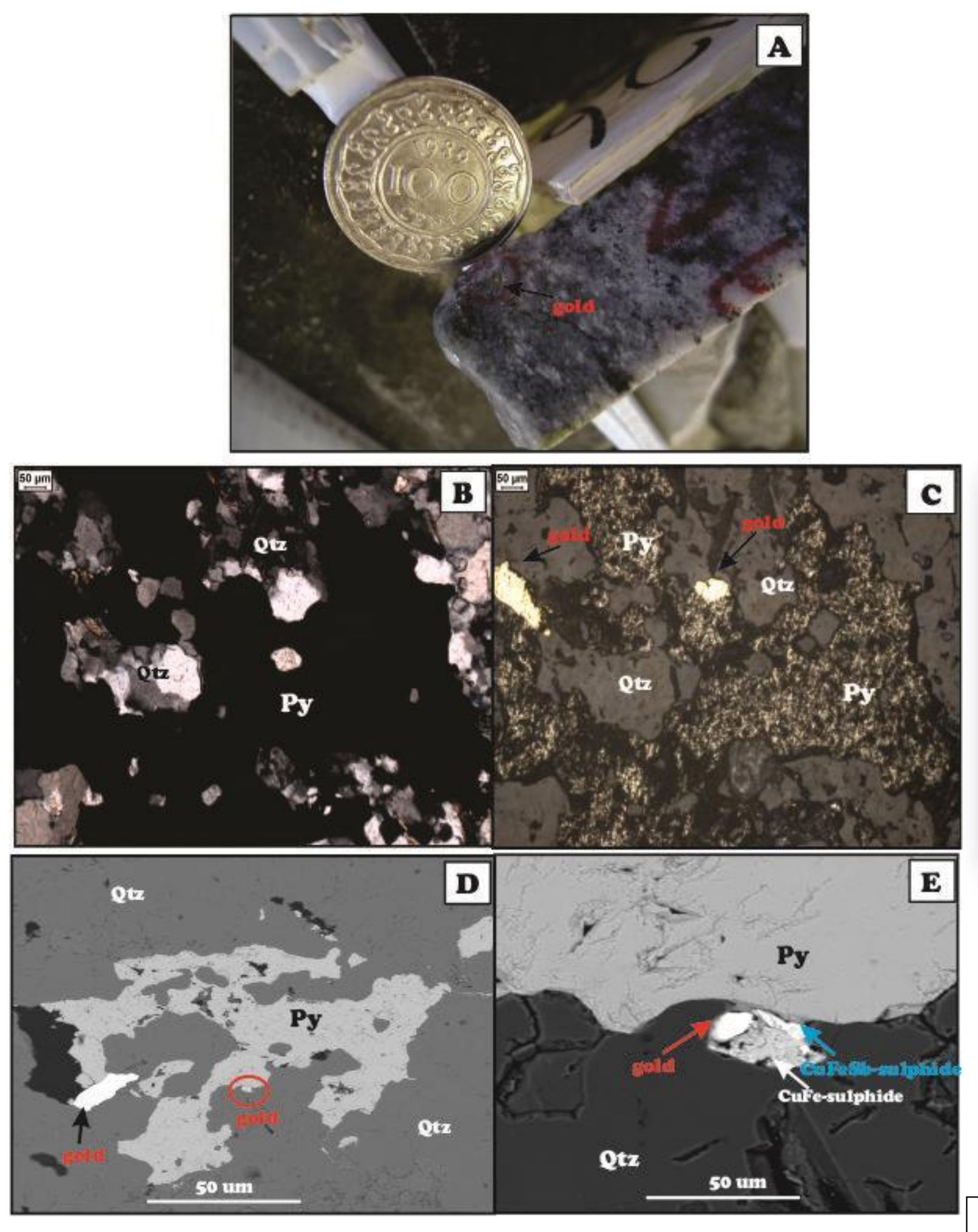
Microphotograph of a sample from the silica body

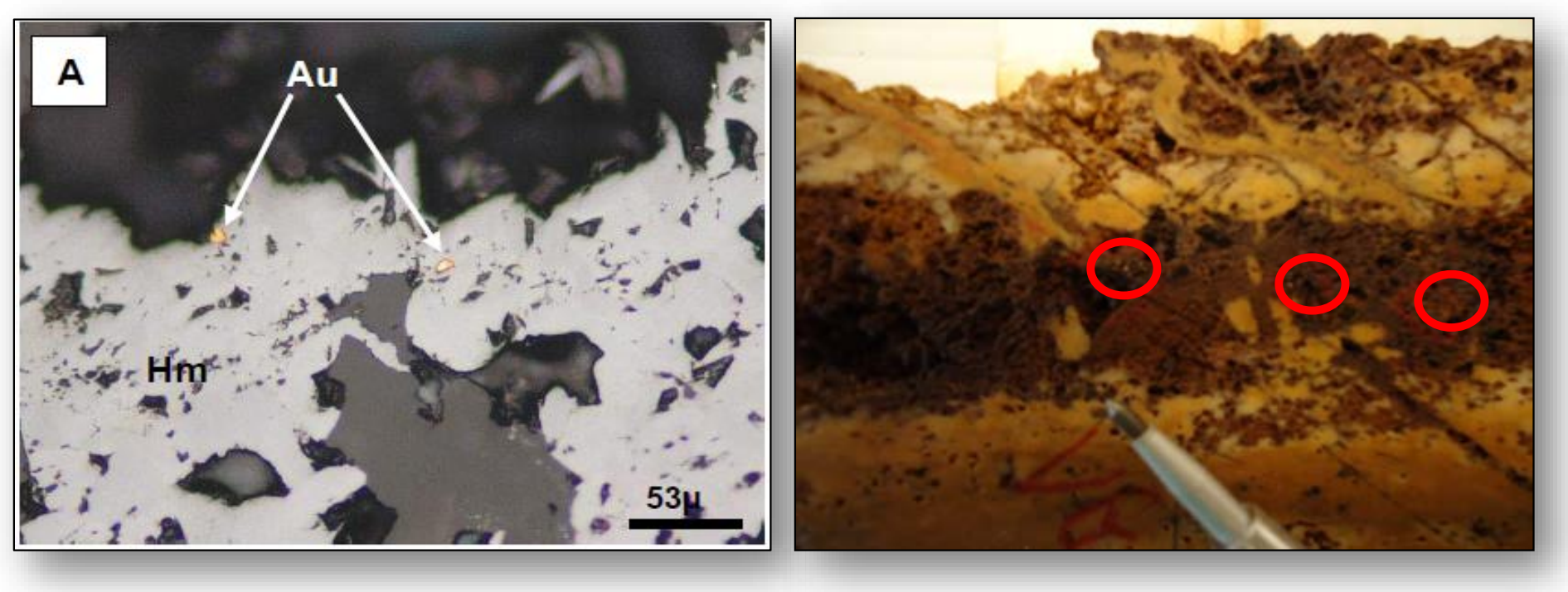
### Sulphides

- Disseminated or fracture-associated in silica body
- Disseminated or vein-associated in graphitic mudstone
- Pyrite, arsenian pyrite and arsenopyrite most abundant; pyrrhotite, chalcocite, chalcopyrite, galena and other sulphides present as well
- Textural and mineral chemical evidence for multiple generations and a complex mineralization history



Gold in fractures in arsenopyrite





Gold associated with arsenopyrite, pyrite and iron-rich "veins" in silica rock

*Micro-textures in the silica body* indicate that
- Arsenopyrite is associated with native gold
- The secondary mineral assemblage includes hematite and carbonates

*Preliminary LA-ICPMS* **data point to**:
- Invisible gold in sulphides.
- Different gold concentrations in pyrite, arsenian pyrite and arsenopyrite.
- More gold in As-bearing sulphides than in pyrite.

## Overman vs other primary gold deposits in Suriname

**Overman**
- Gold in brecciated and strongly silicified (ore)body with vuggy texture
- Invisible gold in sulphides.
- Abundance of arsenopyrite and presence of various other sulphides
- Relationship between arsenopyrite and gold
- Association with graphitic meta-sediment.

**Widespread in Suriname**
- Gold in greenstone lithologies, spatially associated with major fault zones.
- Carbonate and sericite alteration.
- Gold in/near quartz+carbonate veins in/near brittle-ductile shear zones.
- Gold mostly in association with pyrite.

## Work in progress

- Complementary geochemical analysis
- Chemical mapping of sulphides
- Sulphur isotope analysis of sulphides
- Re-Os dating on sulphides

## Acknowledgement

This research project is funded by Rosebel Goldmines N.V., subsidiary of IAMGOLD Corporation.

11th Inter Guiana Geological Conference

# Sr-Nd-Hf ISOTOPIC TRACING OF THE ARCHEAN CONTINENTAL CRUST IN THE BRAZILIAN PART OF THE SOUTHEASTERN GUIANA SHIELD: A REVIEW

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**Lucia Travassos da Rosa-Costa**[2]
**João Marinho Milhomem Neto**[1]

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# The Amazonian Craton

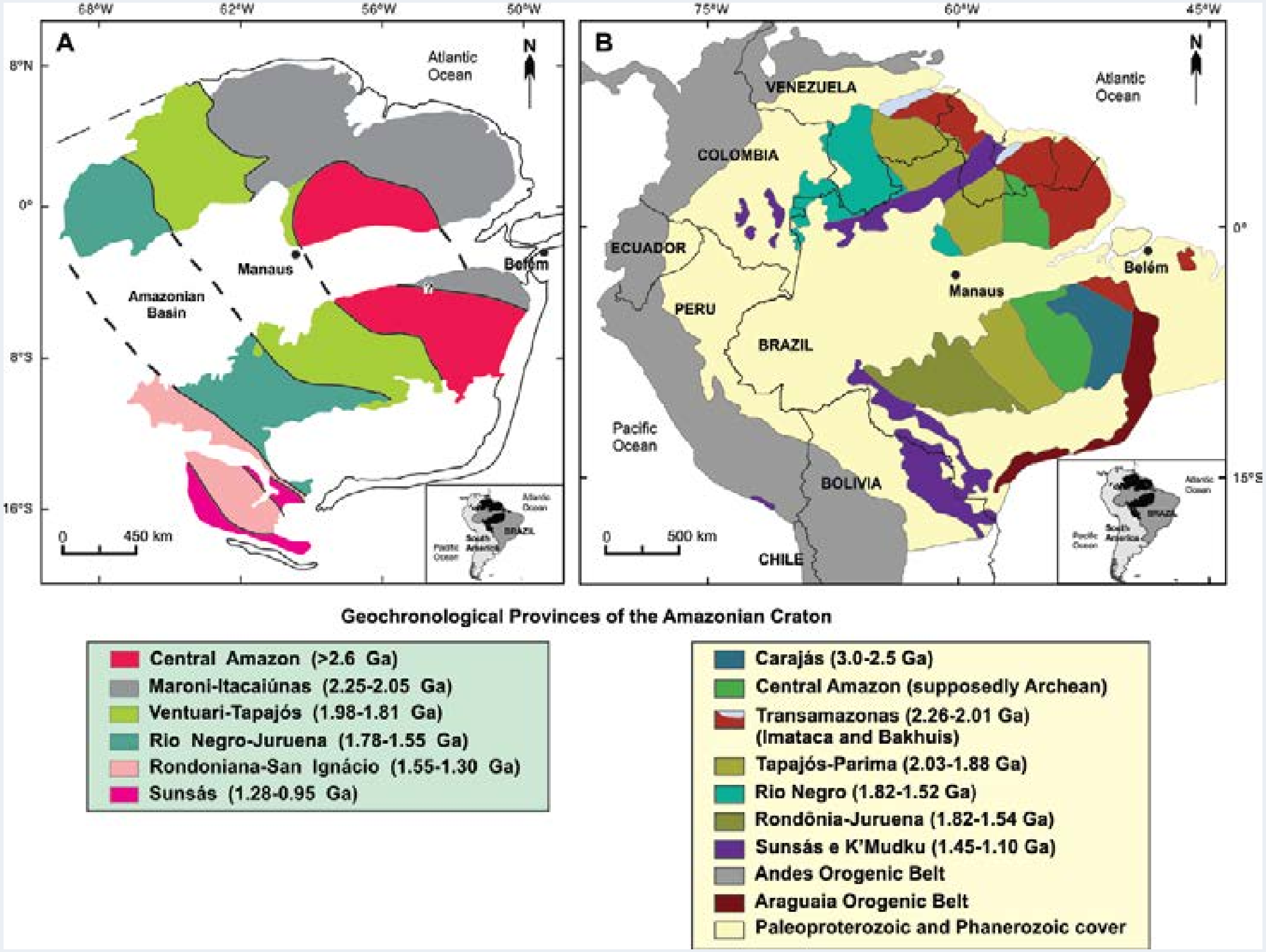
Archean rocks in the Amazonian craton: ⇨ Limited areas

| | |
|---|---|
| **Guaporé Shield**: | **Carajás Province** (Brazil)<br>**Rio Apa Terrane** (??? some relics ; Brazil) |
| **Guiana Shield**: | **Imataca Terrane** (Venezuela)<br>**Amapá Block** (Brazil) |

- In the Brazilian part of the Amazonian Craton, the age, nature and extension of the Archean provinces/domains is still a key issue , specially in the Guiana shield (difficult access, weathering, rain florest, reserves, National parks etc.)

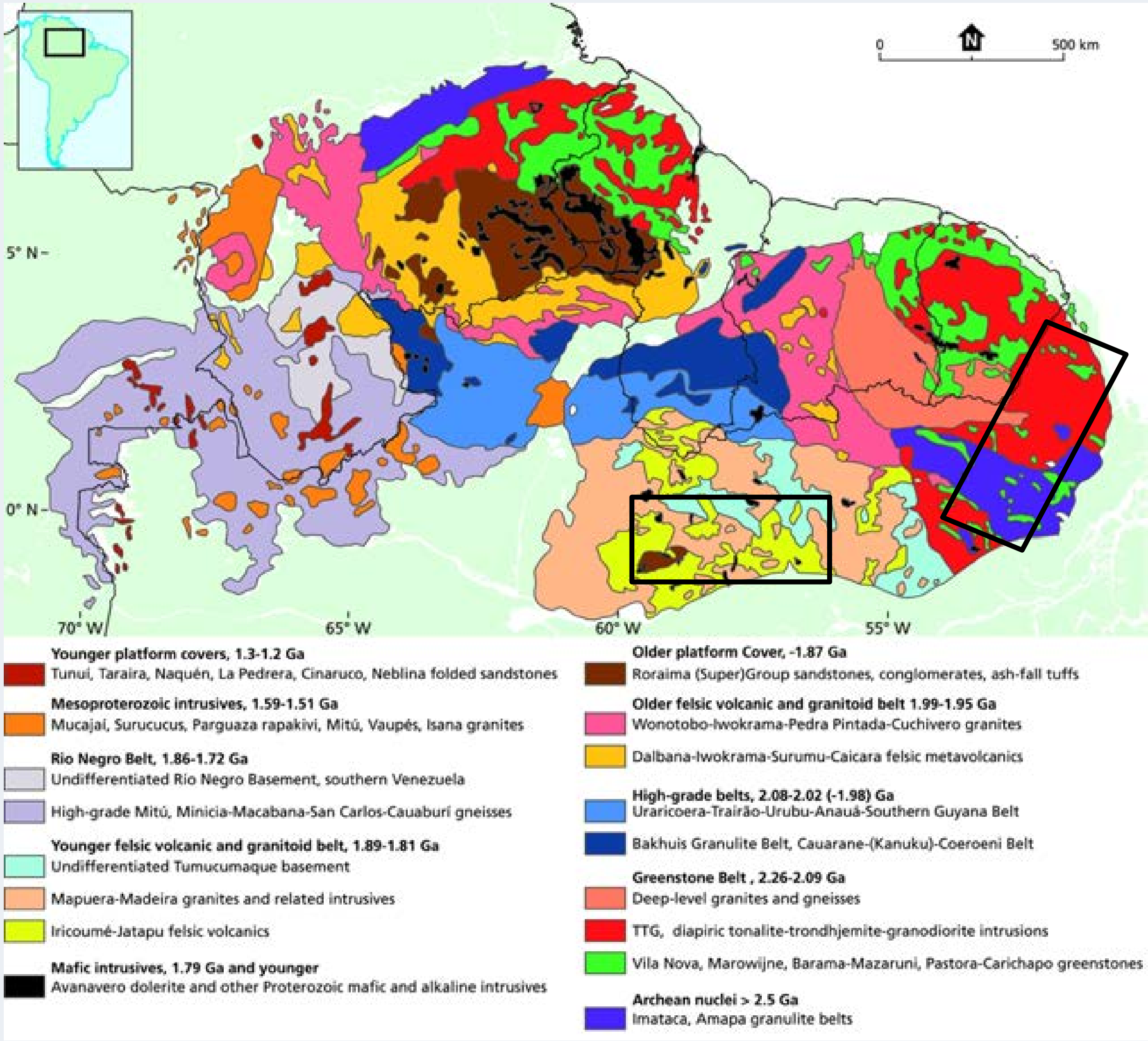
⇨⇨ **low density of geochronological data**

# Geochronological/Geotectonic partitioning of the Amazonian Craton - Current models



Geochronological provinces of the Amazonian Craton according to the models of (A) Tassinari and Macambira (2004) , with age ranges updated by Cordani et al. (2009) and (B) Santos et al. (2006, 2008) .

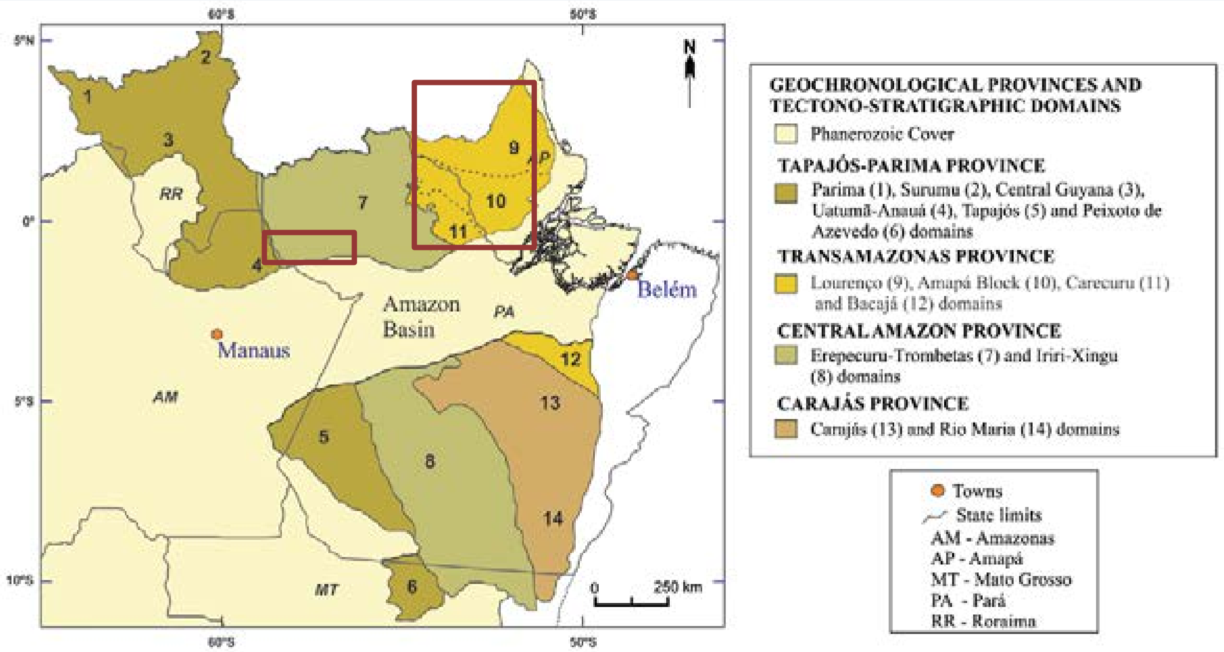
# Simplified geological map of the Guiana Shield



Kroonenberg et al. (2016) and references herein

# Geotectonic configuration of the Brazilian part of the Southeastern Guiana Shield

- **Amapá Block**: Transamazonas/Maroni-Itacaiunas Province
- **Lourenço Domain**: Transamazonas/Maroni-Itacaiunas Province (linked with French Guiana).
- **Carecuru Domain**: Transamazonas/Maroni-Itacaiunas Province.
- **Erepecuru-Trombetas Domain**: Central Amazon Province.



**Tectono-stratigraphic domains from Eastern Amazonia in Brazil, modified from Reis et al. 2006 and Rosa-Costa et al. 2006**

# Main purpose of the lecture

Present an up-to-date compilation of the Sr-Nd-Hf isotopic records of Archean continental crust in the Brazilian part of the Southeastern Guiana Shield, with emphasis to recent Hf isotopic data on zircon

- Estimate the extension of the influence of this Archean continental crust in the adjacent Paleoproterozoic domains.
- In addition, the geotectonic partitioning of the Brazilian part of the Southeastern Guiana Shield is discussed at the light of the Sr-Nd-Hf isotopic signatures.

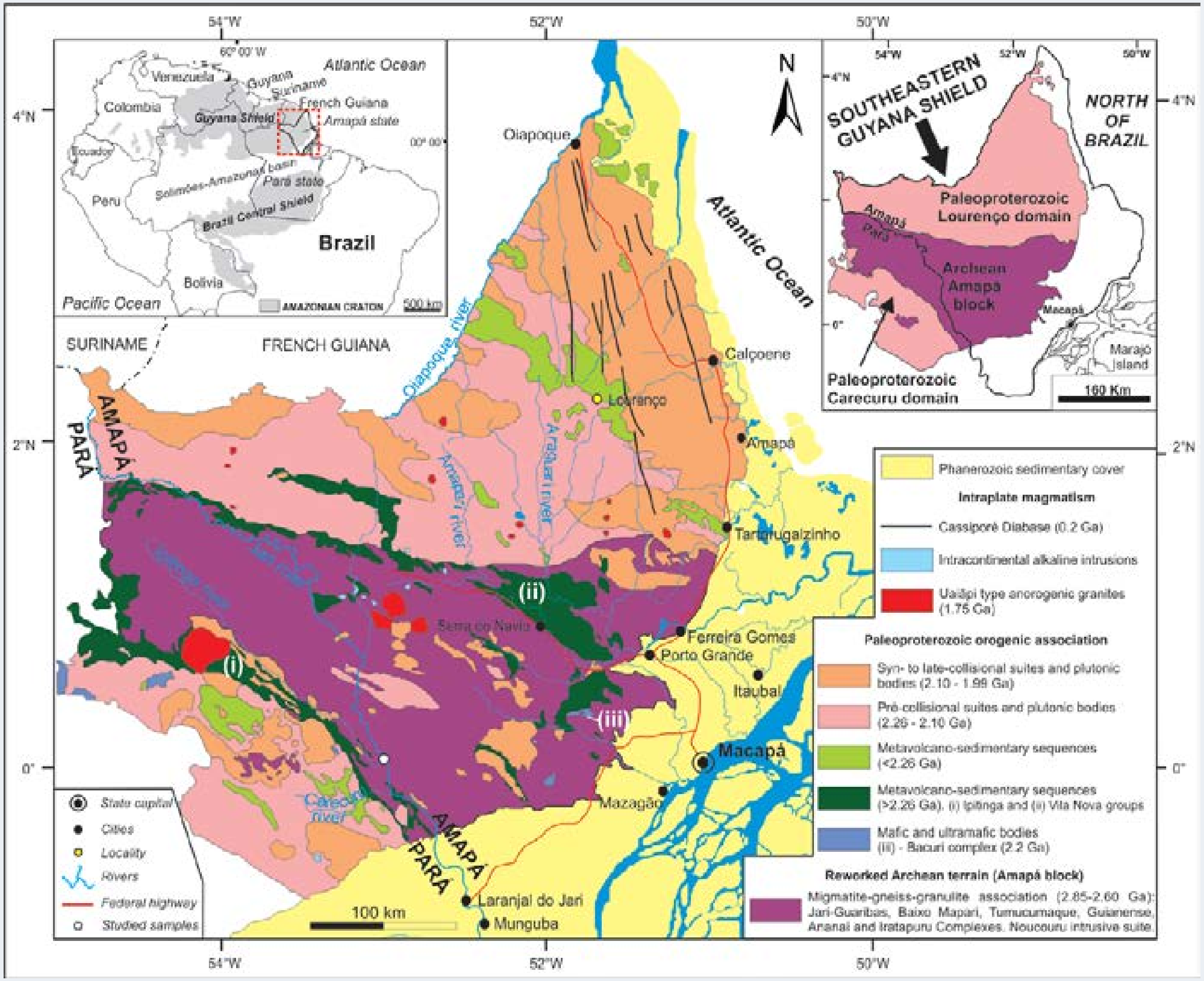
## -Where the isotopic and geochronological data come from ?

- Maps and reports from the Geological Mapping projects of **CPRM**
- Publications
- Master thesis and PhD dissertations
- Congress (regional, national and international)
- Papers in progress and unpublished data

- Some areas still **without geochronological/isotopic data** (northern and eastern Erepecuru – Trombetas Domain).

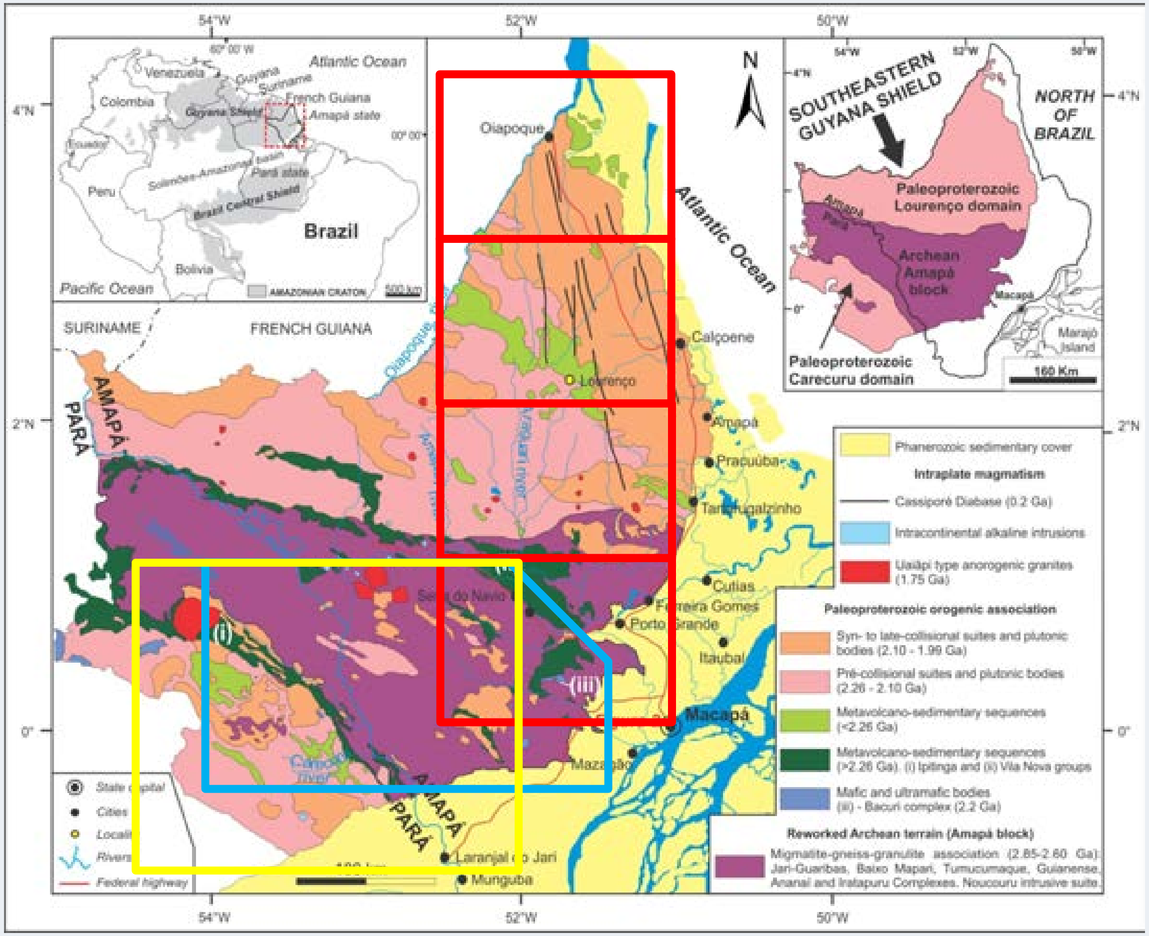
# THE ARCHEAN AMAPÁ BLOCK

# Archean Amapá Block



Rosa-Costa et al. (2017) and references herein

# GEOLOGICAL MAPS AND MAPPING PROJECTS – AMAPÁ –NW PARÁ



**SCALE 1:1.000.000**

**MACAPÁ SHEET- NA.22**
**(Faraco *et al.*, 2004);**

**SCALE 1:250.000**

**MACAPÁ SHEET - NA.22-Y-D**
**(Barbosa *et al.*, 2013);**

**RIO ARAGUARI SHEET - NA.22-Y-B**
**(Rosa-Costa *et al*. 2012);**

**LOURENÇO SHEET- NA.22-V-D**
**(Sousa & Costa Neto, 2014);**

**OIAPOQUE SHEET - NA.22-V-B**
**(Faraco & Théveniaut, 2011);**

**Promin-RENCA PROJECT**
**(Ricci *et al*. 2001; Rosa-Costa, 2006);**

**ARIM RENCA PROJECT**
**(Rosa-Costa *et al*. 2017);**

CPRM
Serviço Geológico do Brasil

**GEOLOGICAL SURVEY OF BRAZIL**

# Archean Amapá Block: main features

**(Rosa-Costa et al. 2017; Borghetti et al. 2018 and references therein)**

Based on field data, aerogeophysics, U-Pb and Pb-Pb zircon, U-Th-Pb monazite, Ar-Ar amphibole and biotite dating.

**Large Archean continental landmass** - roughly oriented in a WNW- ESE direction, approximately 200 km wide (N-S axis) and at least 400 km long (E-W axis)

Dominant Structural trend: **NW-SE regional trend**

**Mesoarchean** and **Neoarchean** basement rocks affected by large shear zones and associated high-grade metamorphism ⇨ Major **Transamazonian collisional event** at **2.10–2.08 Ga** and a late-collisional event at **2.06-2.03 Ga**, including HT-granulite *(Rosa-Costa et al. 2006, 2008, 2009)*

Main magmatic events at **3.19 Ga**, **2.85-2.79 Ga** and **2.65-2.60 Ga** *(Avelar et al., 2003; Rosa-Costa et al., 2006, Borghetti et al. 2018, Milhomem Neto & Lafon, 2018)*, with some Paleoarchean inherited Pb-Pb zircon ages at **~3.32 Ga** and ~ **3.49 Ga** *(Klein et al., 2003; Rosa-Costa et al., 2014).*

# Archean Amapá Block: main features

**Basement litho-stratigraphic units**

TTG-like orthogneisses (Porfírio Gneiss, Tumucumaque and Guianense complexes),
Ortho and paraderived granulite gneisses (Tartarugal Grande, Jari-Guaribas and Iratapuru complexes),
Charnockitic plutons (Noucouru Intrusive Suite),
Granitic orthogneisses (Baixo Mapari Complex)
Neoarchean granites (Pedra do Meio Metagranitoid, Riozinho and Anauerapucu granites)

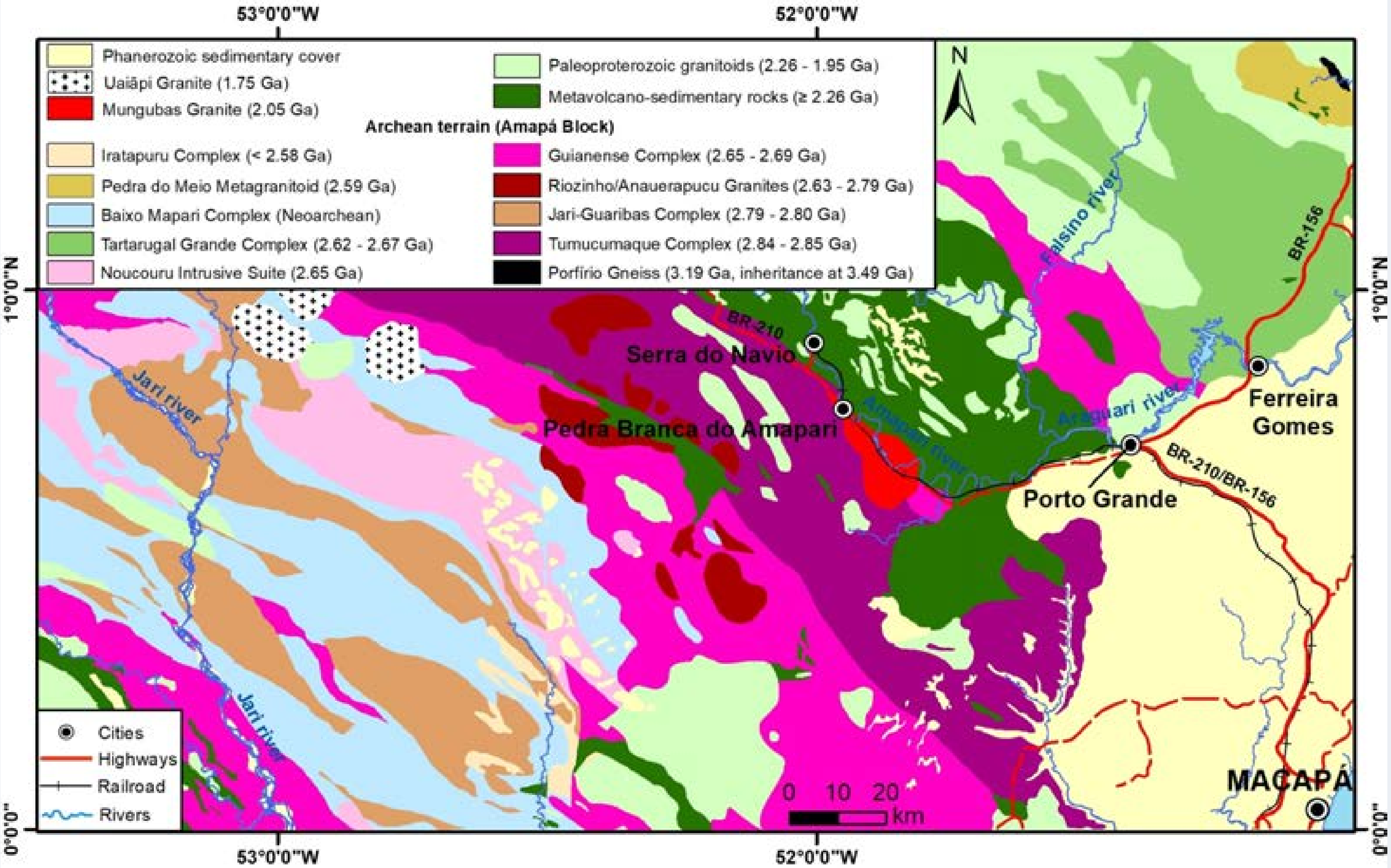
**Transamazonian litho-stratigraphic units**

- Mafic-ultramafic complex (Bacuri complex)
- Metavolcano-sedimentary sequences (Ipitinga and Vila Nova group ≥ 2.26 Ga ??)
- Granitoids (Pré-collisional, collisional and late orogenic granites 2.23-2.03 Ga)

**Available geochronological/isotopic dataset**

Pb-Pb (TIMS) and U-Pb (LA-ICP-MS and SIMS) on zircon; U-Th-Pb (EPMA) on monazite; Ar-Ar on Amphibole and biotite; Sm-Nd on WR and garnet; Some Rb-Sr on WR; Lu-Hf (LA-ICP-MS) on zircon

# Archean Amapá Block



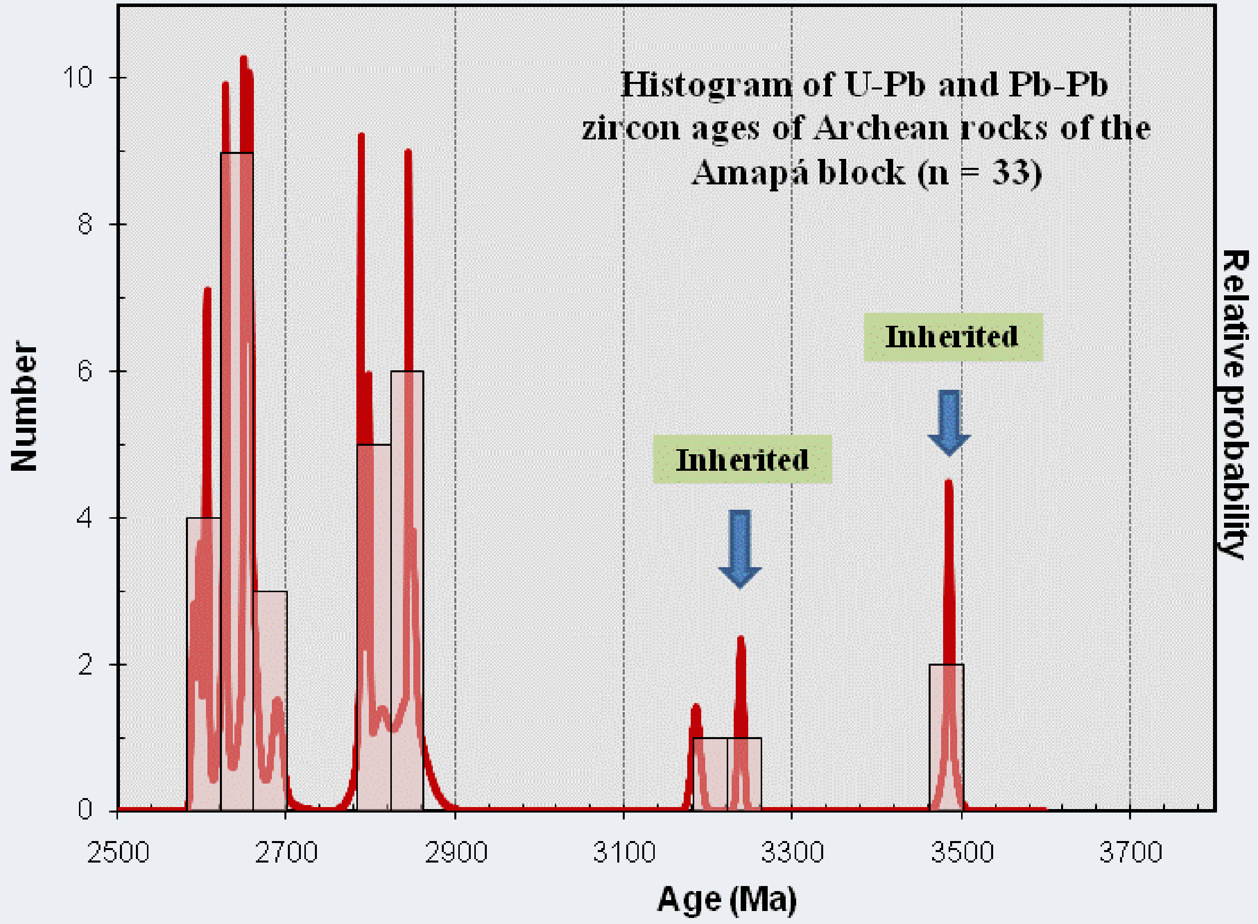
Tectono-stratigraphic associations of the Amapá Block (Compiled and modified from Barbosa et al., 2013; Rosa-Costa et al., 2014; Rosa-Costa & Abrantes, 2017).

# Three major magmatic episodes in the Archean

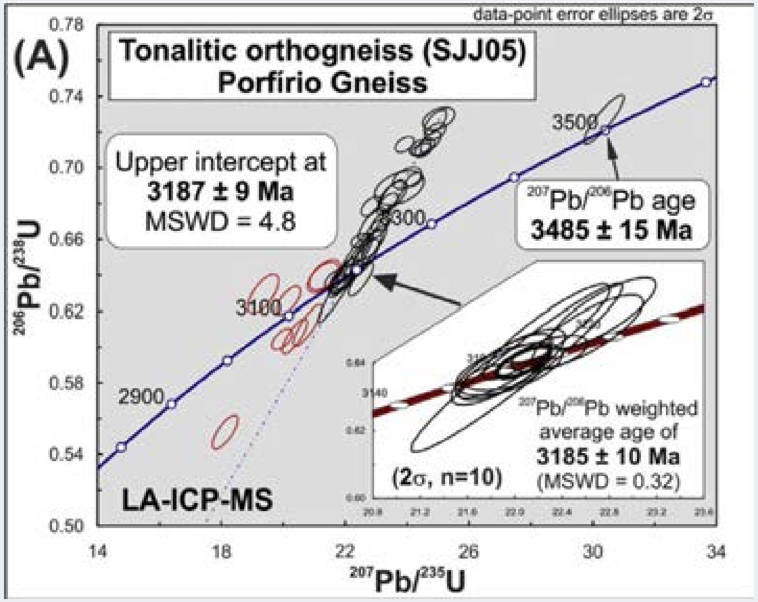
Neoarchean: **2.59-2.69 Ga**

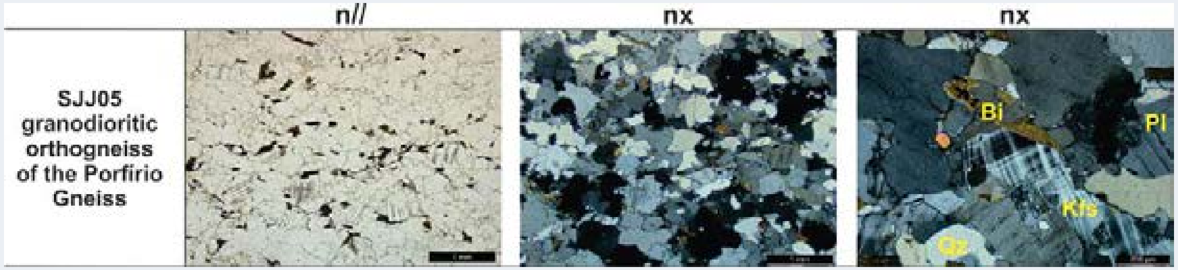
Mesoarchean: **2.78-2.85 Ga** and **3187 ± 9 Ma**

(Some Paleoarchean inherited zircons at **3.24-3.32 Ga** and **3.49 Ga**)



# The Porfírio gneiss: the oldest rock in the Amapá block 3185 ± 10 Ma (3.49 Ga)

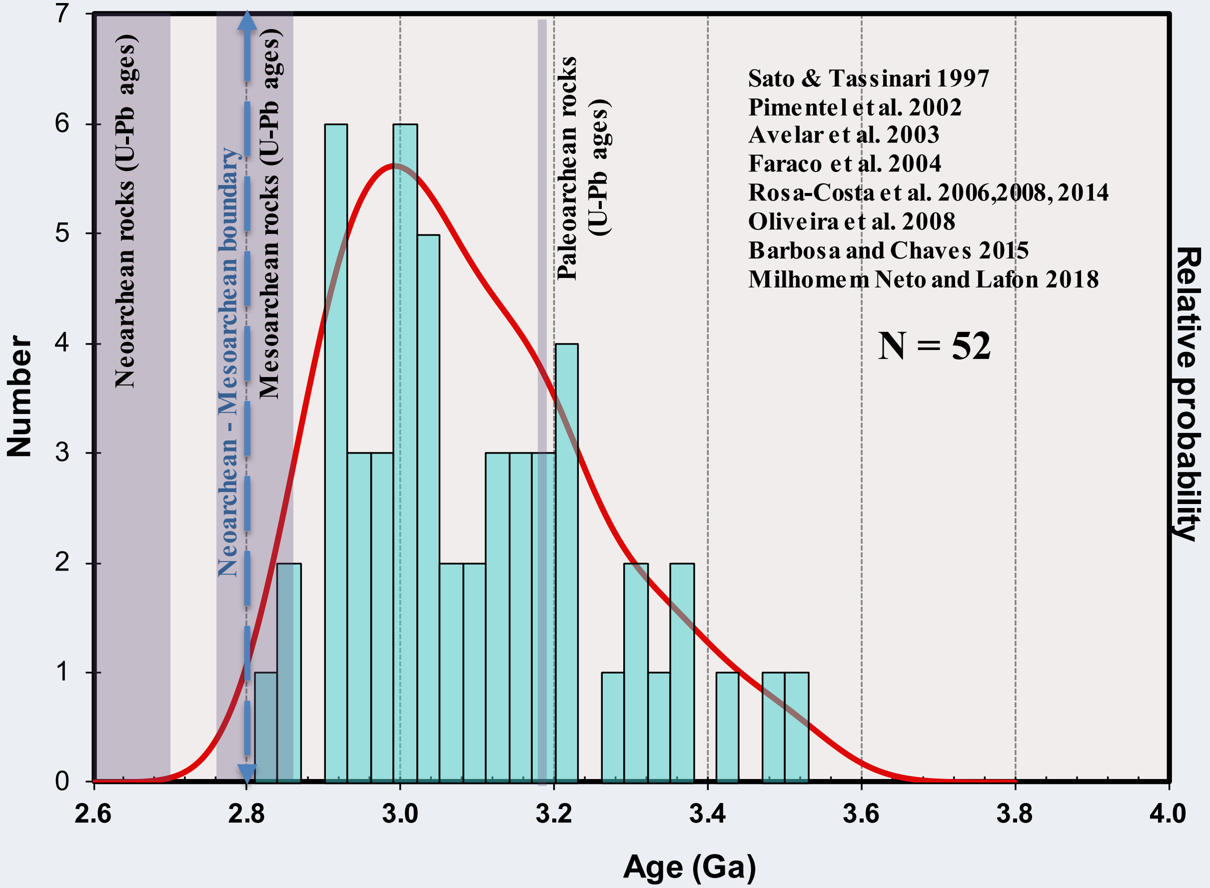




# Nd isotopic signature for the Archean units of the Amapá block

All Nd-$T_{DM}$ ages > **2.80 Ga** **No Neoarchean ages !**

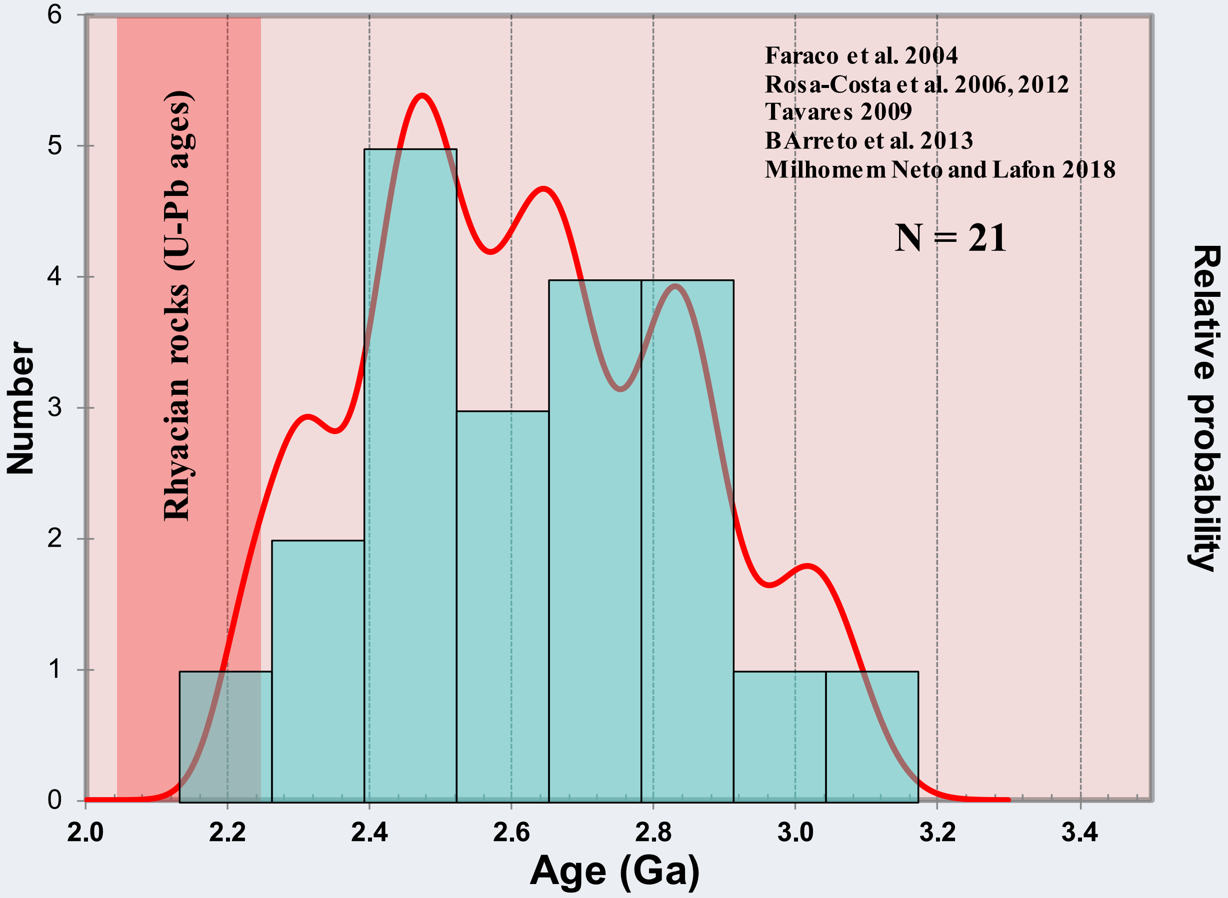
Main event of crust formation: **2.95-3.20 Ga (Mesoarchean)**



# Nd isotopic signature for the Rhyacian units of the Amapá block

All Nd-$T_{DM}$ ages from **2.23 Ga to 3.05 Ga**

⇨ Siderian and Neoarchean ages reveal mixing between Mesoarchean continental crust and “Transamazonian” juvenile magmas



| **Location/sample** | $^{87}$Rb/$^{86}$Sr | $^{87}$Sr/$^{86}$Sr | $T_{Sr}$UR (Ga) | **Ref.** |
|---|---|---|---|---|
| ***Central Amapá (Brazil)*** | | | | |
| **Granite** | **16.72** | **1.2190** | **2.15** | **3** |
| **Granulite** | **13.04** | **1.1478** | **2.37** | **1** |
| **Granite** | **11.42** | **1.0928** | **2.37** | **3** |
| **Gneiss** | **0.34** | **0.7136** | **2.44** | **3** |
| **Granite** | **12.60** | **1.1497** | **2.46** | **3** |
| **Charnockite** | **39.41** | **2.1078** | **2.47** | **1** |
| **Granulite** | **1.16** | **0.7439** | **2.53** | **1** |
| **Enderbite** | **19.60** | **1.4246** | **2.55** | **1** |
| **Granite** | **6.33** | **0.9450** | **2.66** | **3** |
| **Granitic leucossome** | **2.73** | **0.8108** | **2.77** | **2** |
| **Granite** | **4.88** | **0.9017** | **2.84** | **3** |
| **Migmatite** | **1.58** | **0.7676** | **2.91** | **3** |
| **Granitic leucossome** | **7.89** | **1.0375** | **2.94** | **2** |
| **Metatonalite** | **1.71** | **0.7753** | **2.99** | **2** |
| **Gneiss** | **0.36** | **0.7167** | **2.99** | **3** |
| **Granite** | **7.06** | **1.0090** | **3.01** | **3** |
| **Enderbite** | **0.43** | **0.7198** | **3.04** | **1** |
| **Granulite** | **0.86** | **0.7393** | **3.08** | **1** |
| **Charnockite** | **4.89** | **0.9426** | **3.40** | **1** |
| **Charnockite** | **1.29** | **0.7669** | **3.55** | **2** |
| **Tonalite** | **0.89** | **0.7536** | **4.16** | **3** |
| 1. João & Marinho 1982; 2. Unpublished; 3. Tassinari 1996 | | | | |

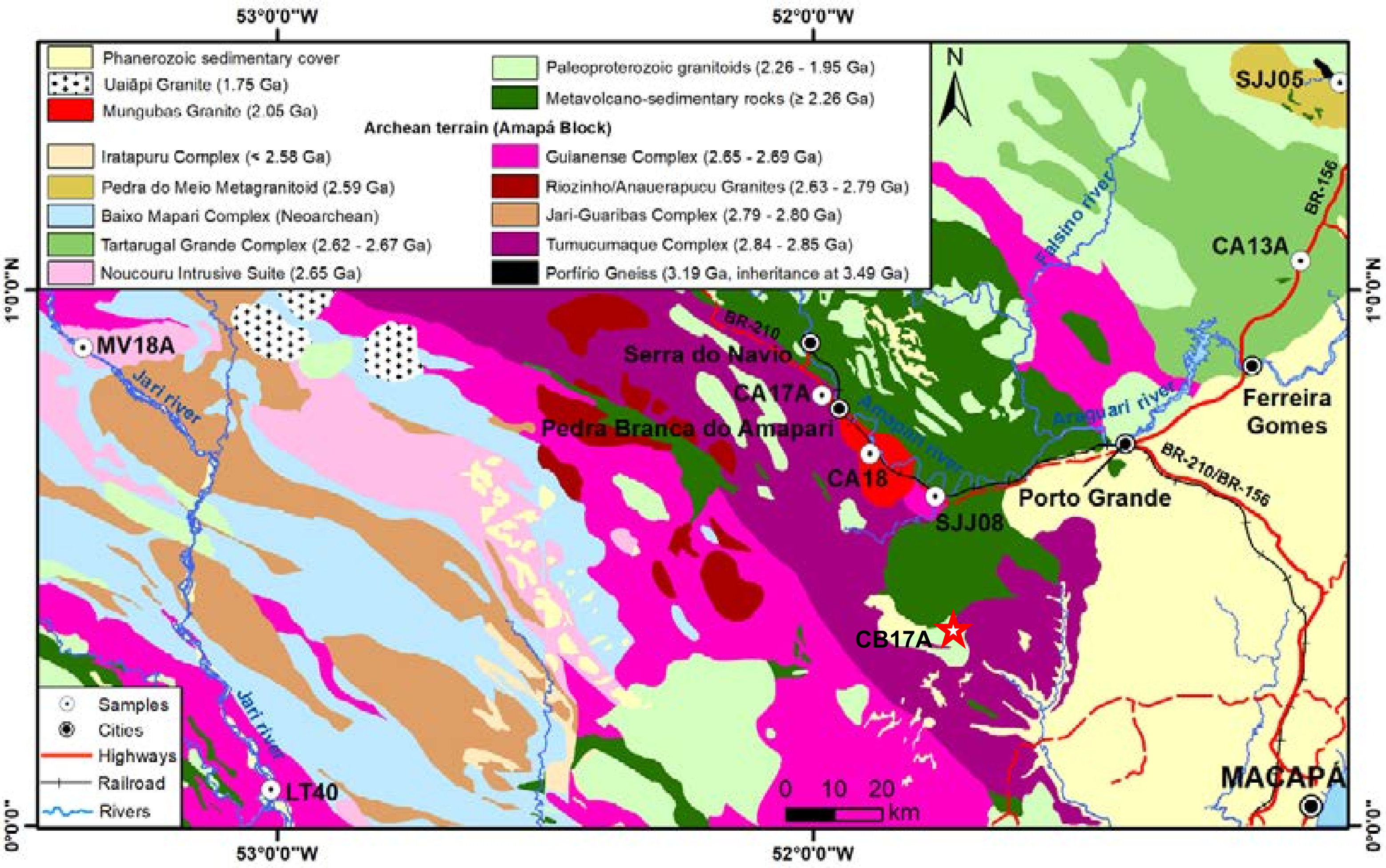
# Sr isotopic signature (Sr-$T_{UR}$ ages) of basement units of the Amapá block:

# No Transamazonian resetting of the Rb-Sr system

**Sr-$T_{UR}$ calculated using DePaolo, D.J., Wasserburg, G.J. (1977).**

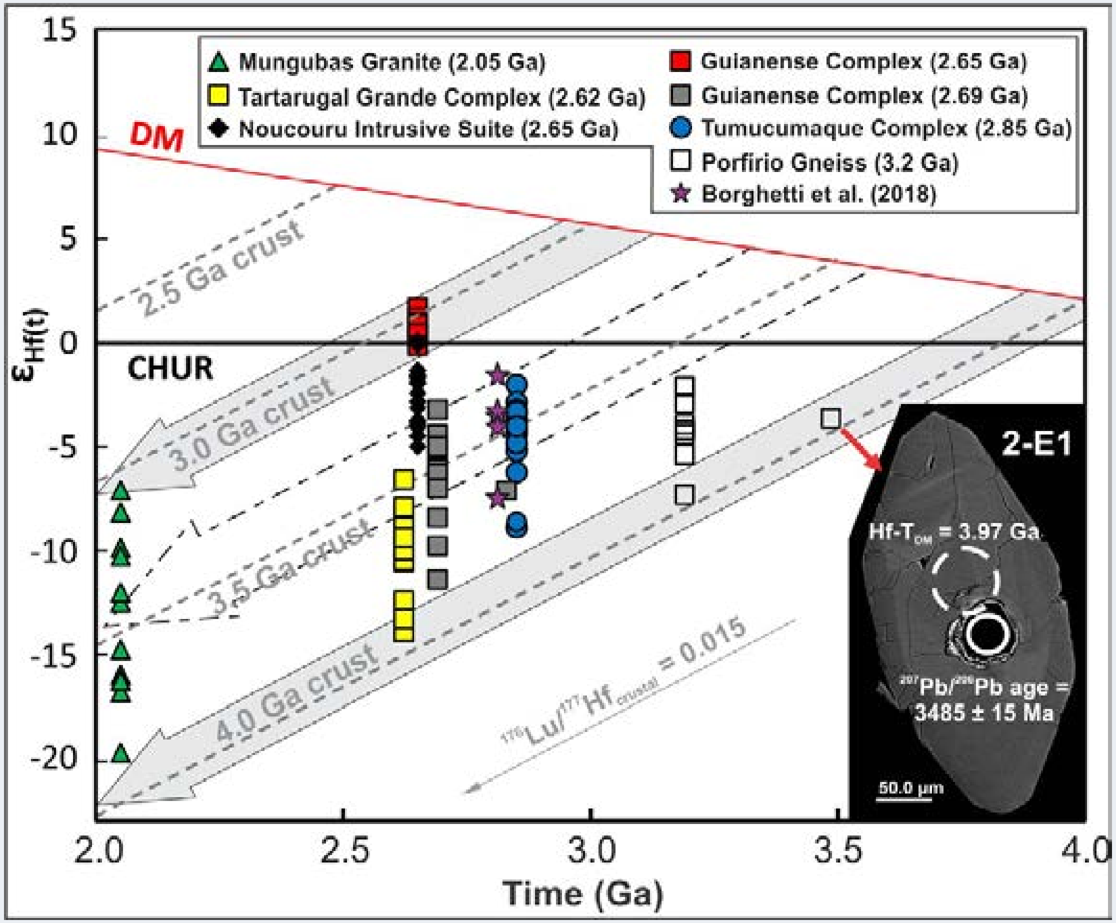
# Hf isotopic signature on zircon

## (Milhomem Neto & Lafon 2018, Borghetti et al. 2018)

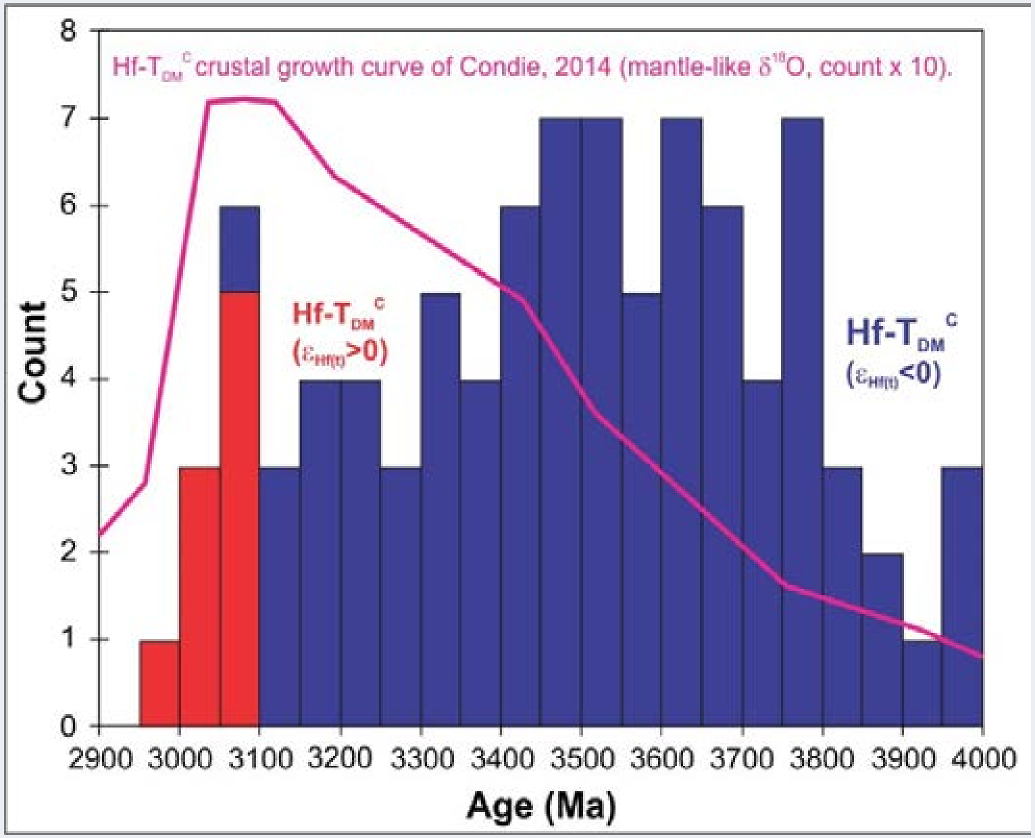


Geological map with Sample location

# $\varepsilon_{Hf}$ vs. time diagram for Archean units and a Rhyacian granite from the Amapá block



$\lambda = 1.867 \times 10^{-11}$ $years^{-1}$ (Söderlund et al., 2004); $^{176}Lu/^{177}Hf = 0.0336$ and $^{176}Hf/^{177}Hf = 0.282785$ for present day value of CHUR (Bouvier et al., 2008); $^{176}Lu/^{177}Hf = 0.0388$ and $^{176}Hf/^{177}Hf = 0.28325$ for the depleted mantle (DM) (Andersen et al., 2009). Two-stage crustal model age ($T_{DM}^{C}$) using the respective U-Pb age and a $^{176}Lu/^{177}Hf = 0.015$ for the average continental crust (Griffin et al., 2002, 2004).



**Hf-$T_{DM}^{C}$ model ages of the Amapá Block compared with the growth rate of continental crust through time (with $\delta^{18}O$ data filtered to include only mantle sources) of Condie (2014)**

The Sr-Hf-Nd isotopic signatures of Archean and Paleoproterozoic rocks betray the Archean history of the Amapá block. They are not significantly affected by the Transamazonian overprint.

**Nd isotopic signatures**:
Main **Mesoarchean event** of **crust formation** (**2.95-3.20 Ga**),
Dominant **crustal reworking** processes during **Neoarchean**.
Transamazonian magmatic rocks are mostly product of **mixing** between Mesoarchean continental crust and Rhyacian juvenile magmas.

**Hf-$T_{DM}^{C}$ model ages and εHf values**:
At least two episodes of mantle extraction and continental crust generation during the Archean in SGS:

⇨ an older one in the Eoarchean **(~ 4.0 Ga)**

⇨ a younger one in the Mesoarchean (**between ~ 3.0 and 3.1 Ga**)

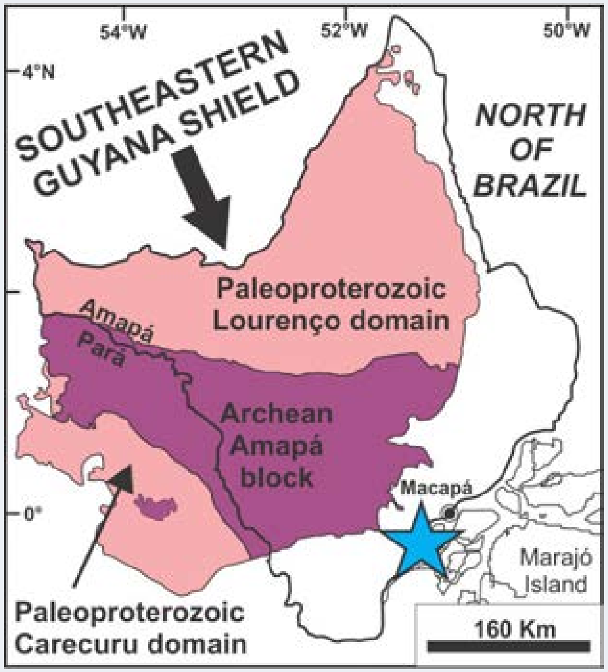
Possibly, a third Paleoarchean episode (**between 3.2 and 3.5 Ga**)

Hf signatures suggest the existence of two Archean crustal segments geographically distinct, respectively in the southwest and northeast of the Amapá Block, formed in different episodes and which were aggregated at some time in the Archean to form the current Amapá Block configuration **(TO BE VERIFIED !!!)**

The recognition of an Eoarchean episode **(~4.0 Ga**) and of a Hadean zircon xenocryst in magmatic rocks from southern Guyana (Nadeau et al. 2013) point to the existence of an Hadean-Eoarchean crustal remnant in Guiana Shield.

**⇨ The geological and tectonic evolution of the Amazonian Craton started more than 500 Ma earlier than previously observed.**

# U-Pb and Lu-Hf on detrital zircons from the Amazon River mouth (Iizuka et al. 2010)

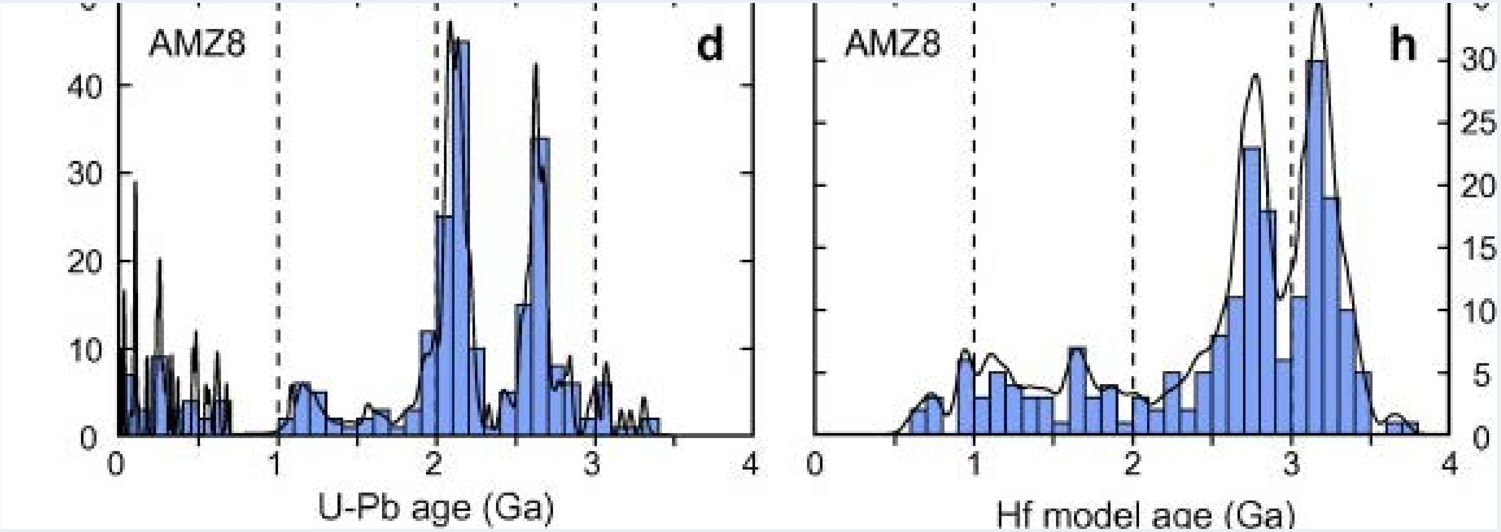


230 detrital zircon grains of modern sandy sediment collected at the mouth of the Amazon River, near the Amapá coast.

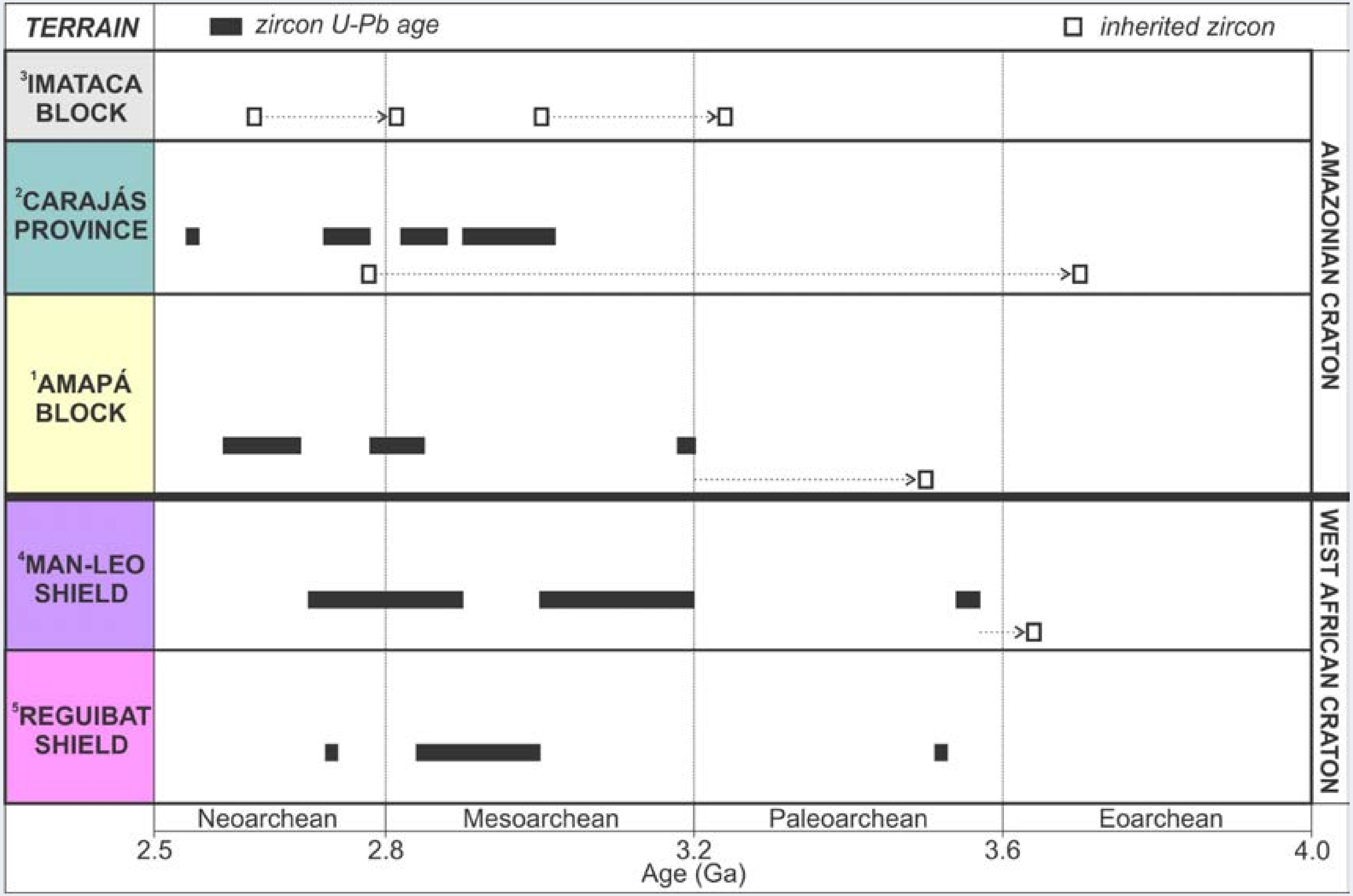
U-Pb ages: Two main groups at 2.5–2.7 and 1.9-2.3 Ga. Other grains with ages up to about 3.3 Ga.

$\varepsilon_{Hf(t)}$ mainly subchondritic. Hf-$T_{DM}^{C}$ ($^{176}Lu/^{177}Hf$ ratio of 0.0093) from 0.6 to 3.7 Ga (sharp peaks at 3.0-3.3 and 2.6-2.9 Ga) ⇨ some crust generation had taken place by 3.7 Ga (Eoarchean), and that it was subsequently reworked into <3.3 Ga granitoid crust.

Considering a $^{176}Lu/^{177}Hf$ ratio of 0.015 instead of 0.0093, the results are in agreement with those of he Amapá Block and probably betray the Southeasternmost Guiana Shield.



# Available zircon U-Pb-Hf and WR Sm-Nd data for the Archean domains from the Amazonian and West African cratons



1- Milhomem Neto & Lafon 2018; 2- Macambira et al. (1998); Teixeira et al. (2001), Feio et al. (2013), Martins et al. (2017); 3- Tassinari et al. (2004); 4- Kouamelan et al. (1997), Barth et al. (2002), Thiéblemont et al. (2004), Parra-Avila et al. (2016); 5- Potrel et al. (1996, 1998);

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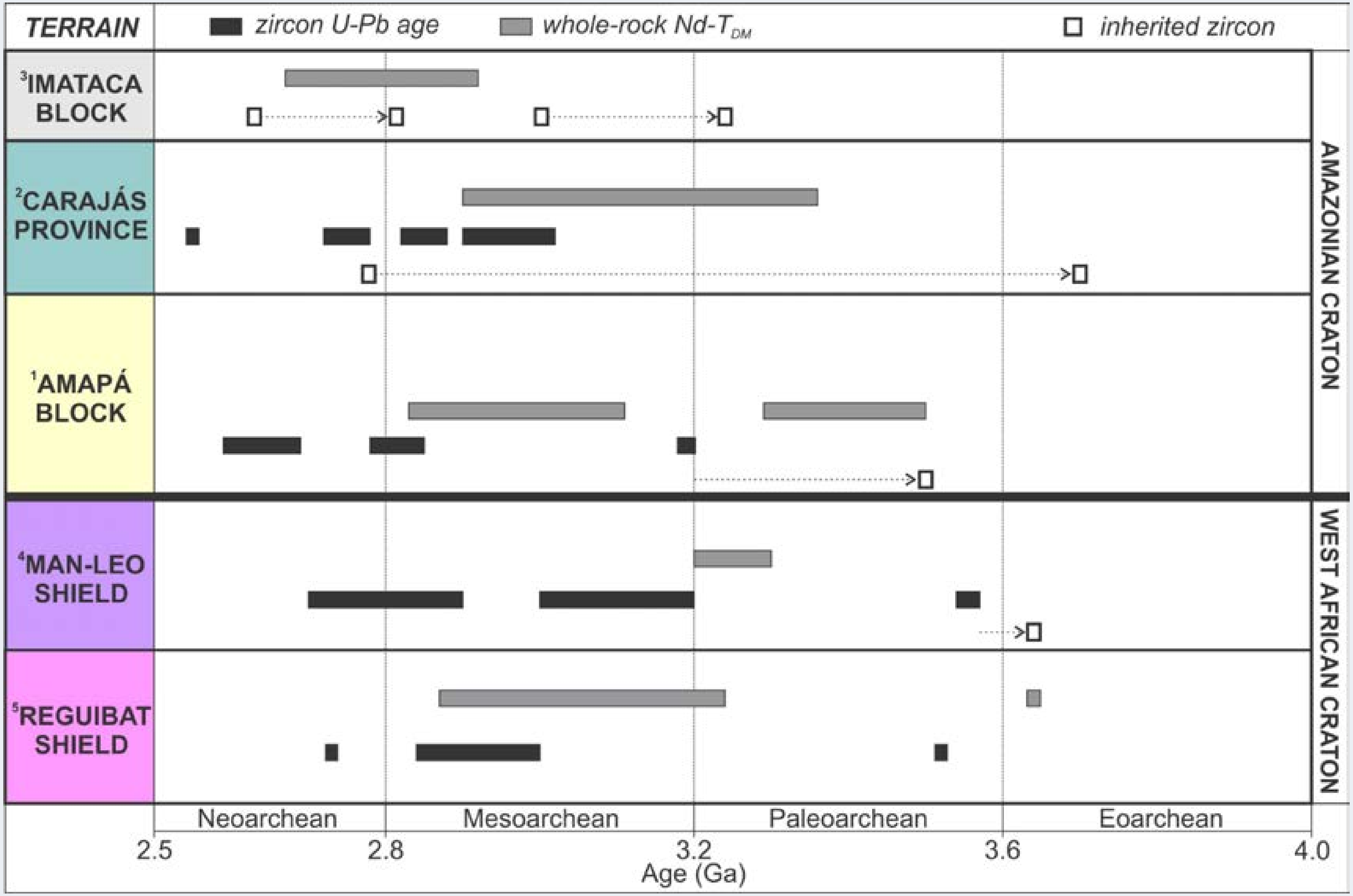

1- Milhomem Neto & Lafon 2018; 2- Macambira et al. (1998); Teixeira et al. (2001), Feio et al. (2013), Martins et al. (2017); 3- Tassinari et al. (2004); 4- Kouamelan et al. (1997), Barth et al. (2002), Thiéblemont et al. (2004), Parra-Avila et al. (2016); 5- Potrel et al. (1996, 1998);

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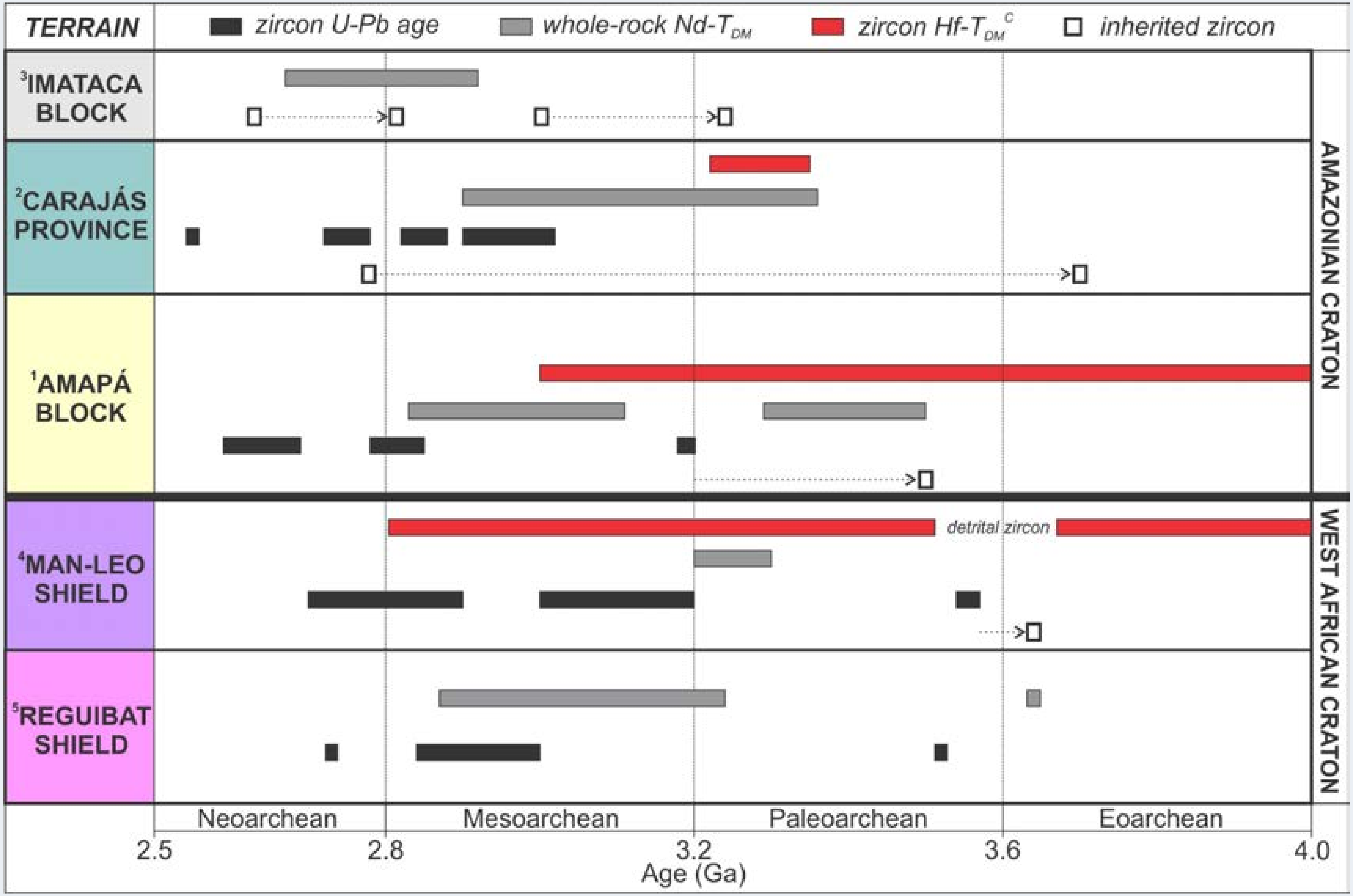
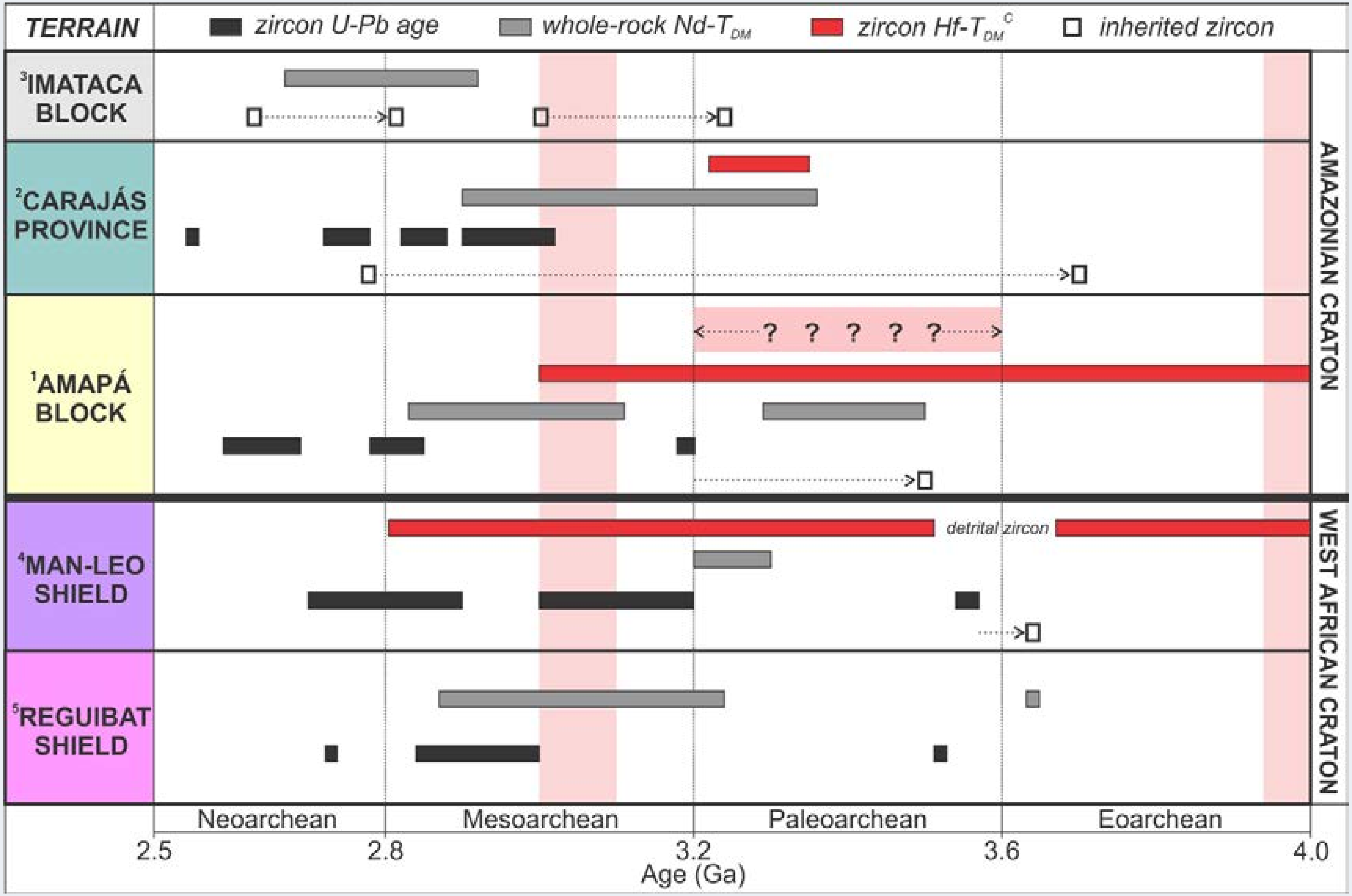


1- Milhomem Neto & Lafon 2018; 2- Macambira et al. (1998); Teixeira et al. (2001), Feio et al. (2013), Martins et al. (2017); 3- Tassinari et al. (2004); 4- Kouamelan et al. (1997), Barth et al. (2002), Thiéblemont et al. (2004), Parra-Avila et al. (2016); 5- Potrel et al. (1996, 1998);

# Available zircon U-Pb-Hf and WR Sm-Nd data for the Archean domains from the Amazonian and West African cratons



1- Milhomem Neto & Lafon 2018; 2- Macambira et al. (1998); Teixeira et al. (2001), Feio et al. (2013), Martins et al. (2017); 3- Tassinari et al. (2004); 4- Kouamelan et al. (1997), Barth et al. (2002), Thiéblemont et al. (2004), Parra-Avila et al. (2016); 5- Potrel et al. (1996, 1998);

U-Pb and Lu-Hf on zircon and Sm-Nd on whole rock radiometric data in the Archean domains from the Amazonian and West African cratons revealed **that Eoarchean crust existed in both cratons with crust generation starting at 4.0 Ga** and that all these Archean domains **share a Paleo-Mesoarchean history.**

# Archean signature in the Paleoproterozoic domains

**Lourenço Domain**

⇨ (Rhyacian – Transamazonian Orogeny)

**Carecuru Domain**

⇨ (Rhyacian – Transamazonian Orogeny)

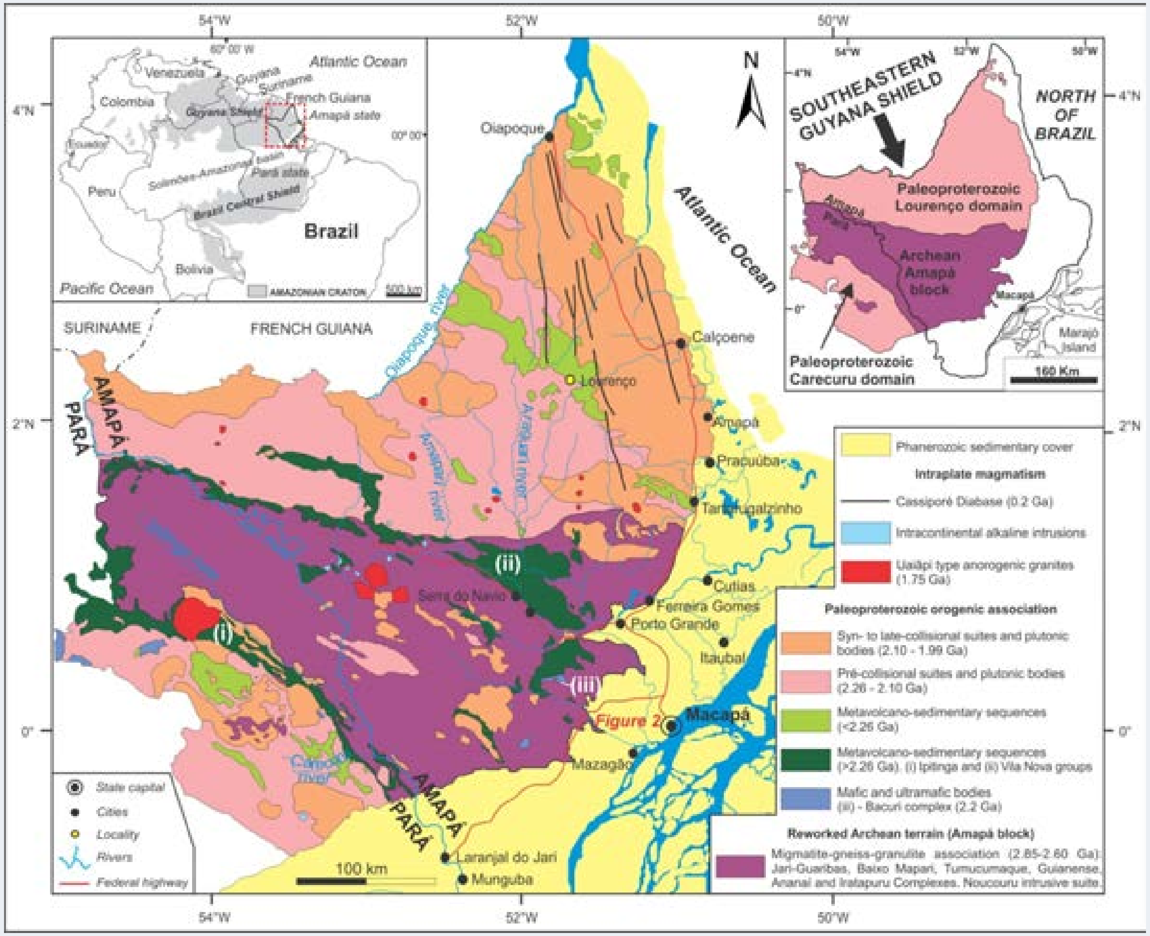
**Erepecuru-Trombetas Domain**

⇨ (Orosirian – Post-Tranzamazonian orogeny)

# THE PALEOPROTEROZOIC LOURENÇO AND CARECURU DOMAINS

# Lourenço and Carecuru Domains

**U-Pb and Pb-Pb zircon ages for the magmatic rocks in the Lourenço and Carecuru domains are all between 2.26 Ga and 2.03 Ga**



Rosa-Costa et al. (2017) and references herein

# Lourenço Domain: Main features

Dominant lithostratigraphic units:

**Paleoproterozoic granite-greenstone association**:

⇨ Orthogneisses and metagranitoids with dioritic, tonalitic and granodioritic composition. U-Pb and Pb-Pb zircon ages ~ 2.26–2.12 Ga

⇨ ⇨ Metamafic, metaultramafic rocks and metasedimentary units (Serra da Lombarda and Tartarugalzinho groups) (≤ 2.26 Ga)

*(Nogueira et al. 2000, Avelar 2002, Barreto et al. 2013, Rosa-Costa et al. 2012, Milhomem Neto 2018, Viana 2019)*

**Syn- to late collisional granitic suites** – U-Pb and Pb-Pb zircon ages between 2.10–2.08 Ga *(Faraco and Theveniaut 2011; Barreto et al. 2013; Milhomem Neto, 2018; Silva 2018, Viana 2019)*

**Late Transamazonian granulites and charnockitic rocks**: Pb-Pb and U-Pb zircon ages around 2.06-2.04 Ga *(Lafon et al., 2001; Avelar, 2002; Faraco et al. 2009; Faraco and Theveniaut 2011, Rosa-Costa et al. 2012)*

# Carecuru Domain: Main features

Dominant lithostratigraphic units :

**Granite-greenstone association** formed between 2.19-2.14 Ga *(Rosa-Costa et al. 2006; Milhomem Neto & Lafon, 2018).*

⇨ Granitoids and calc-alkaline gneisses (Carecuru Intrusive Suite)

⇨ Bands of metavulcano-sedimentary rocks (Fazendinha, Treze de Maio and Serra Cuiapocu sequences).

**Granitic plutons** (Paru granite and Parintins Intrusive Suite) with ages between 2.10-2.03 Ga and evolution related to orogenic stages syn- to post-collisional *(Rosa-Costa et al. 2006; 2017)*

**Oval-shaped Archean granulitic nucleus** (Paru Domain) with Neoarchean magmatism (≈2.60 Ga), calc-alkaline magmatism (≈2.32 Ga and ≈ 2.15 Ga) and charnockitic magmatism (≈2.07 Ga). *(Rosa-Costa et al. 2006; 2017)*

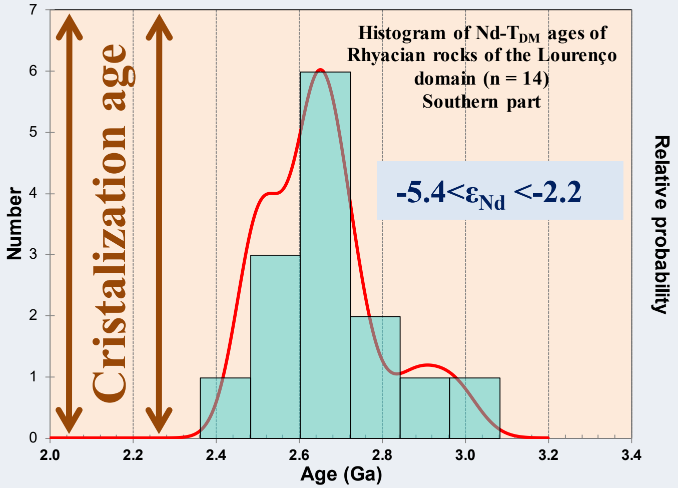
# Lourenço and Carecuru domains: Main features

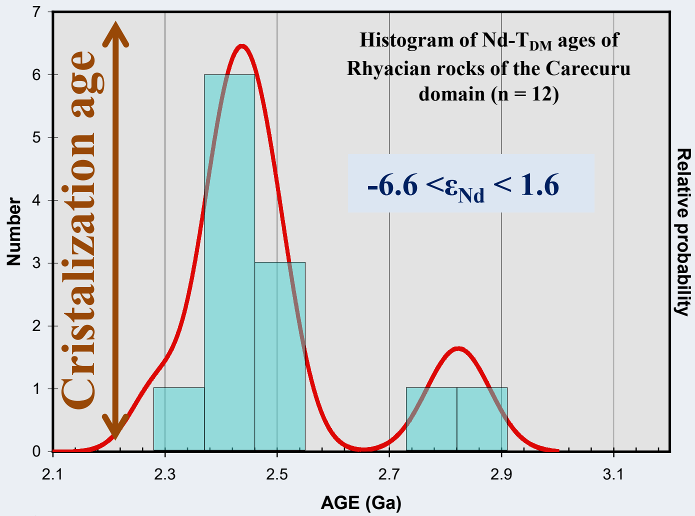
Dominant Structural trend: Transpressional and transtensional tectonic and transcurrent shear zones. NW-SE (NNW-SSE) regional trend.

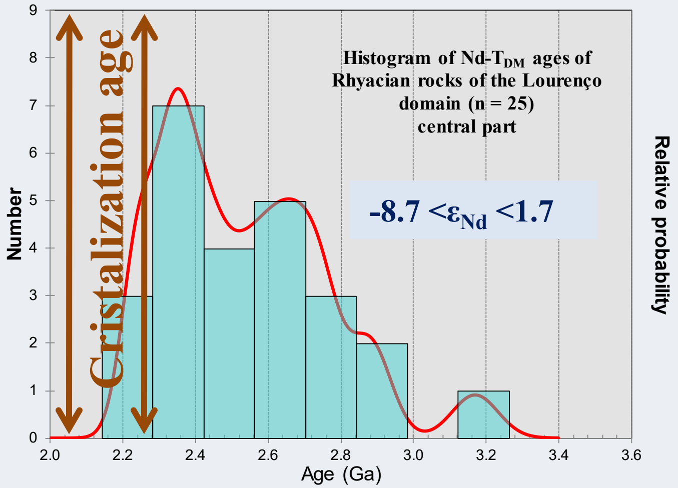
Transamazonian evolution: similar stages of oceanic crust subduction followed by tectonic crustal accretion like in French Guiana (Vanderhaeghe et al. 1998, Delor et al. 2003)

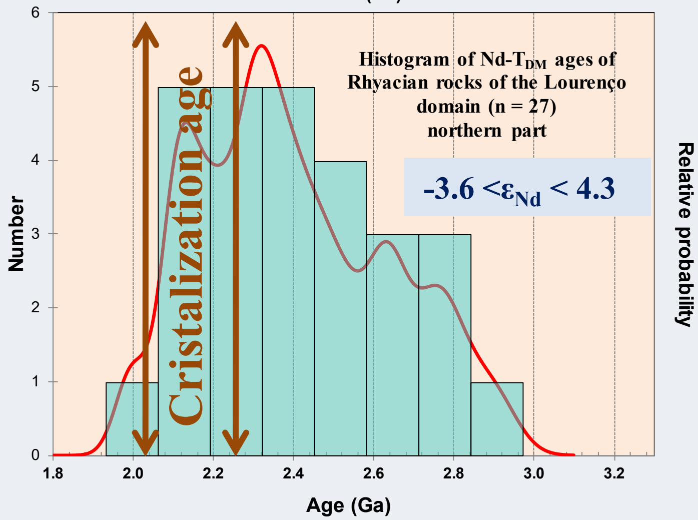
Late Rhyacian arc-continent collision or continental magmatic arc have also been suggested at the northern (Barreto et al. 2013) and southern (Rosa-Costa et al. 2017) margins of the Archean block.

# Lourenço and Carecuru domains: The Sm-Nd record



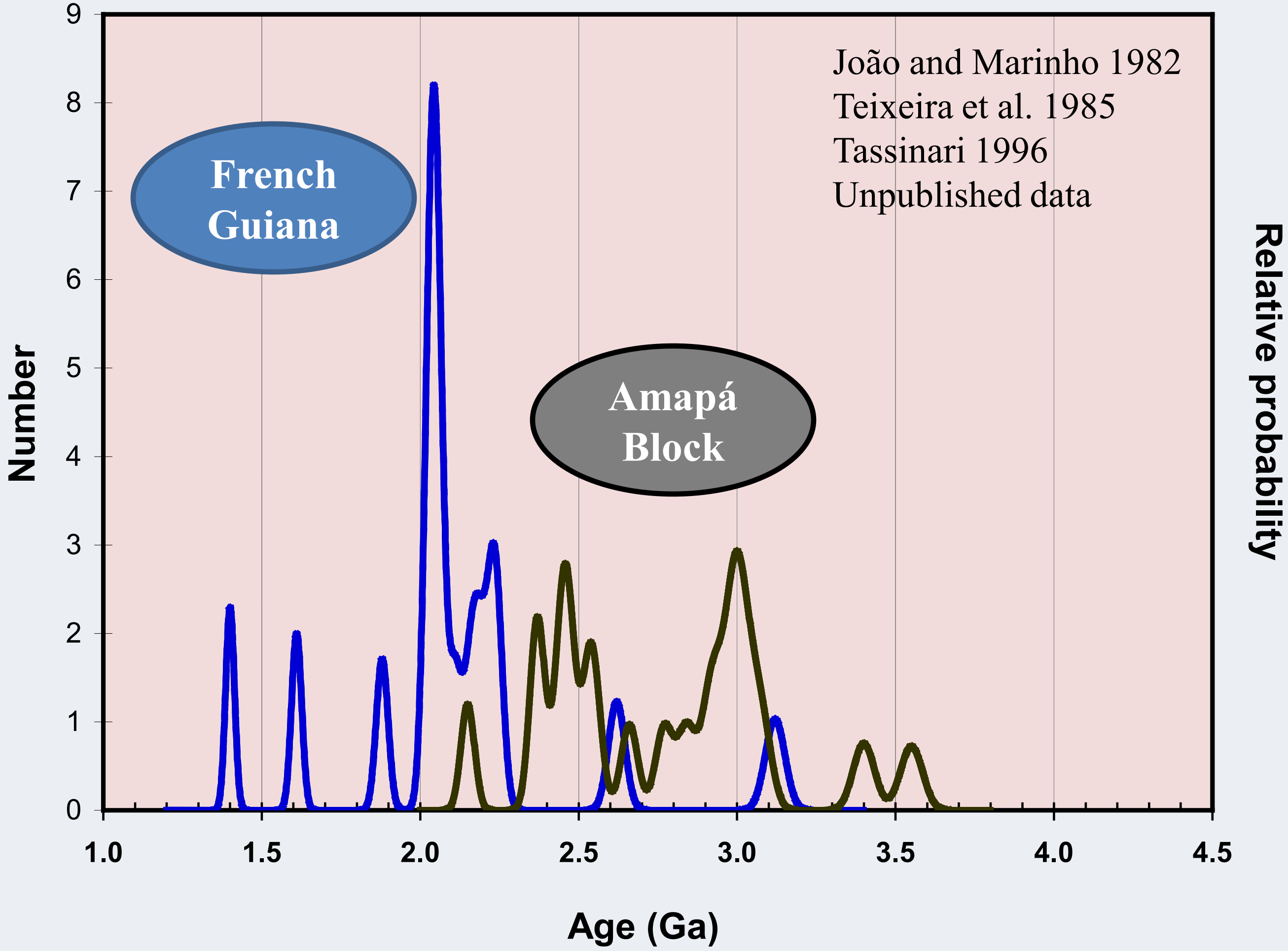






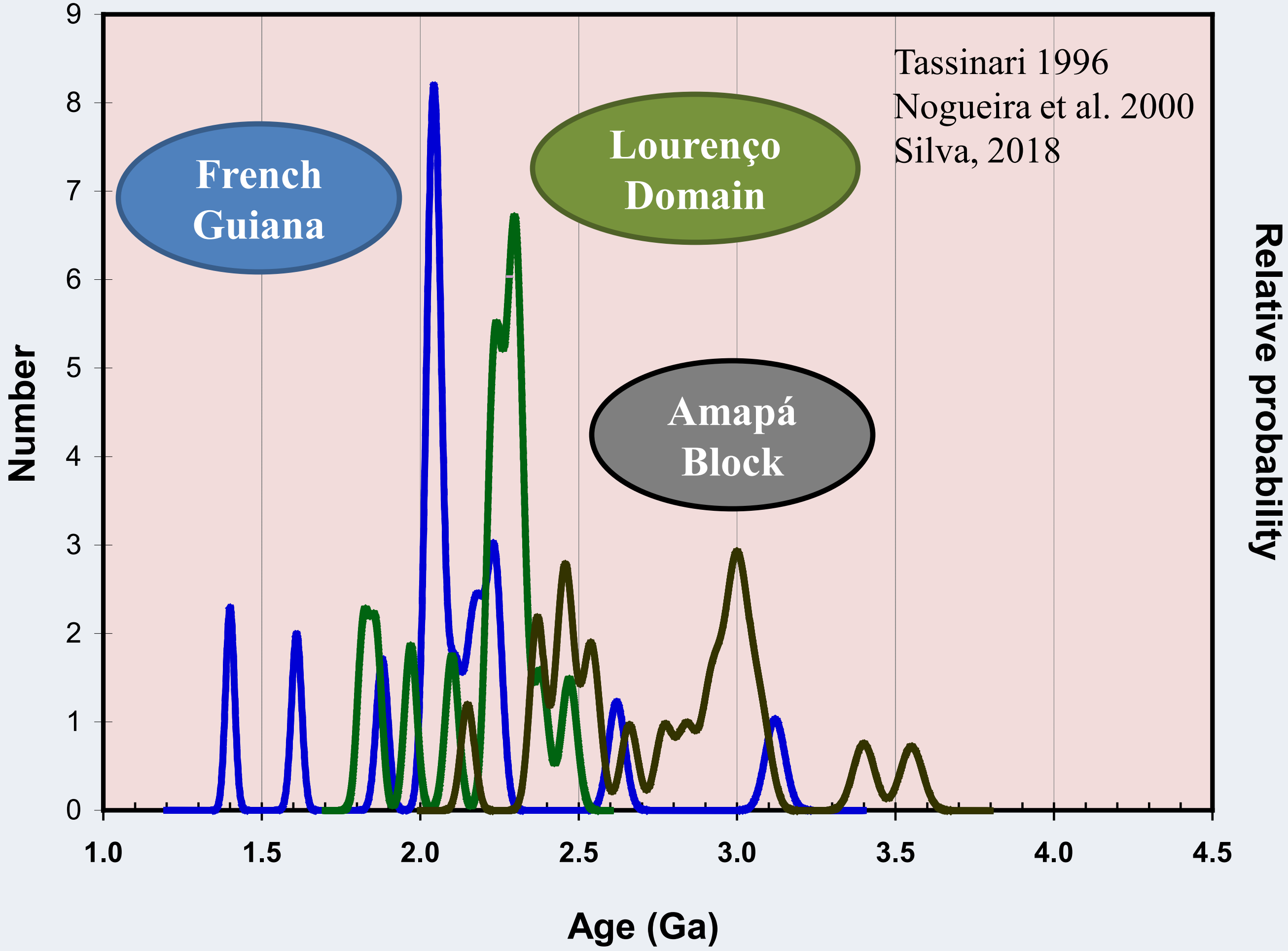
*Data from Nogueira et al.2000; Avelar 2002; Avelar et al.2003;Tavares 2004; Faraco et al. 2009;Faraco and Théveniaut 2011; Rosa-Costa et al.2012; Barreto et al.2013; Milhomem Neto,2018; Silva 2018; Viana 2019;*

# Lourenço Domain: The Rb-Sr record



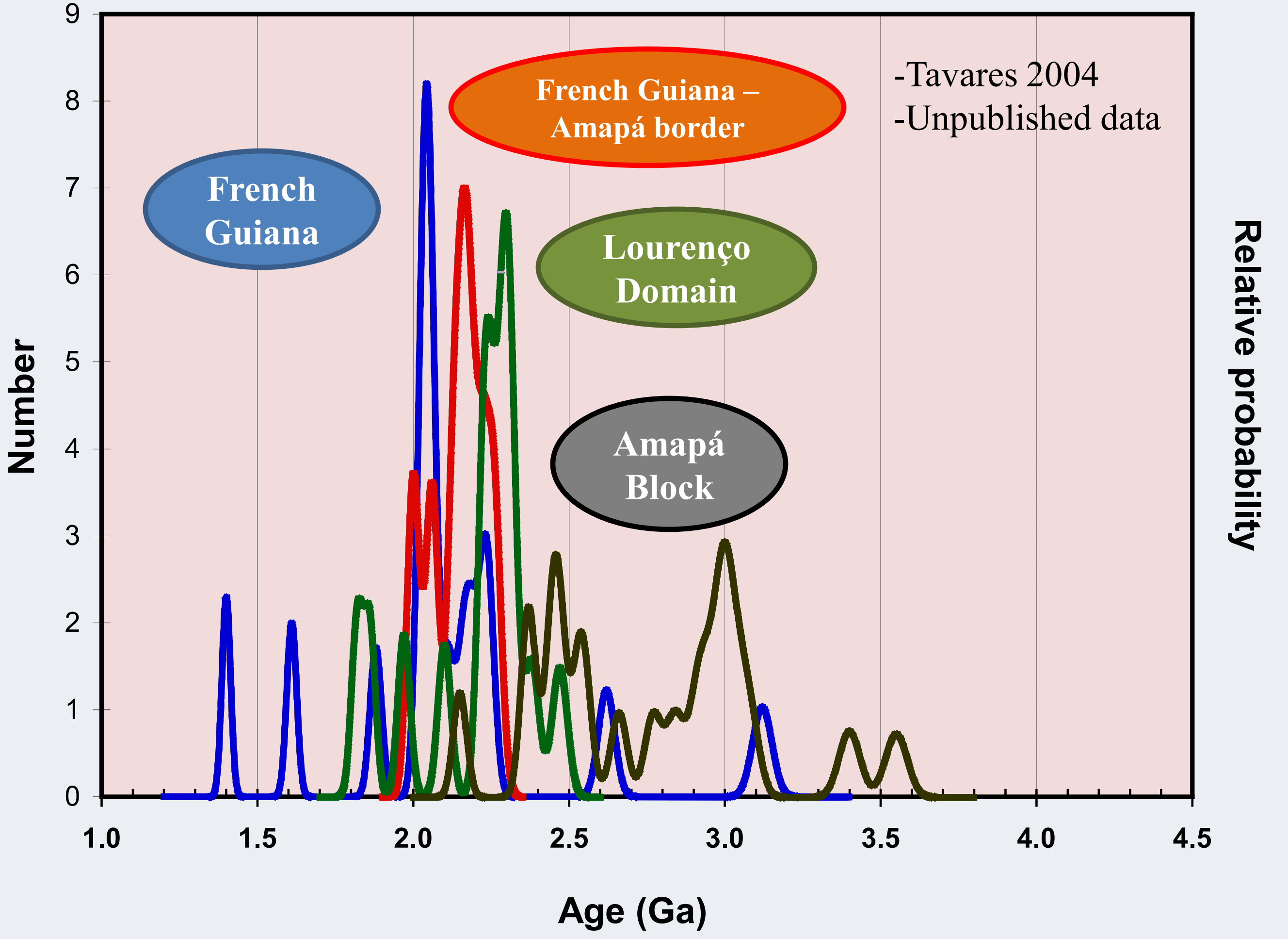
**Histogram of Sr-$T_{UR}$ ages for the Rhyacian rocks of the Lourenço domain (comparing with the Amapá Block and the French Guiana )**

# Lourenço Domain: The Rb-Sr record



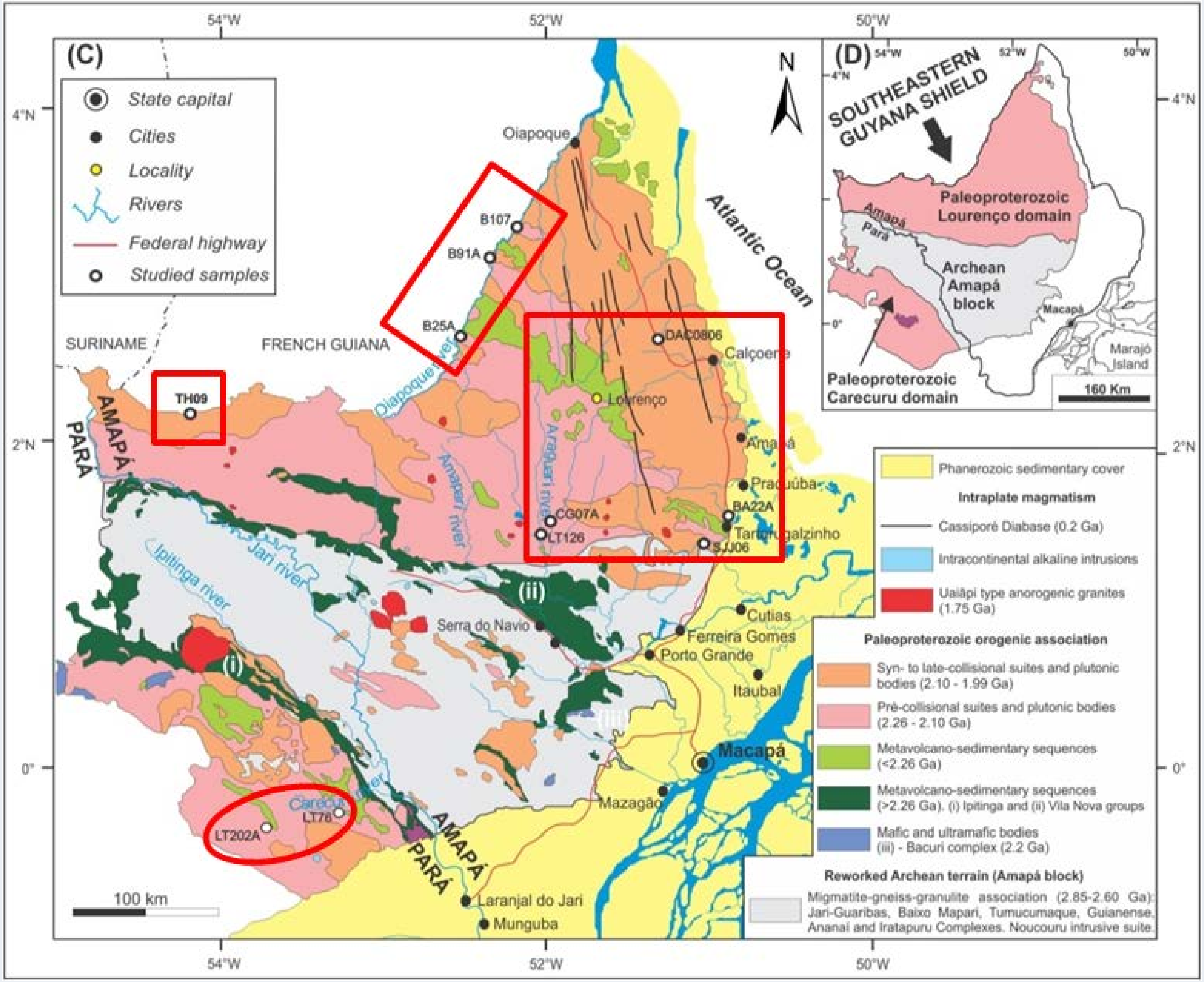
**Histogram of Sr-$T_{UR}$ ages for the Rhyacian rocks of the Lourenço domain (comparing with the Amapá Block and the French Guiana )**

# Lourenço Domain: The Rb-Sr record

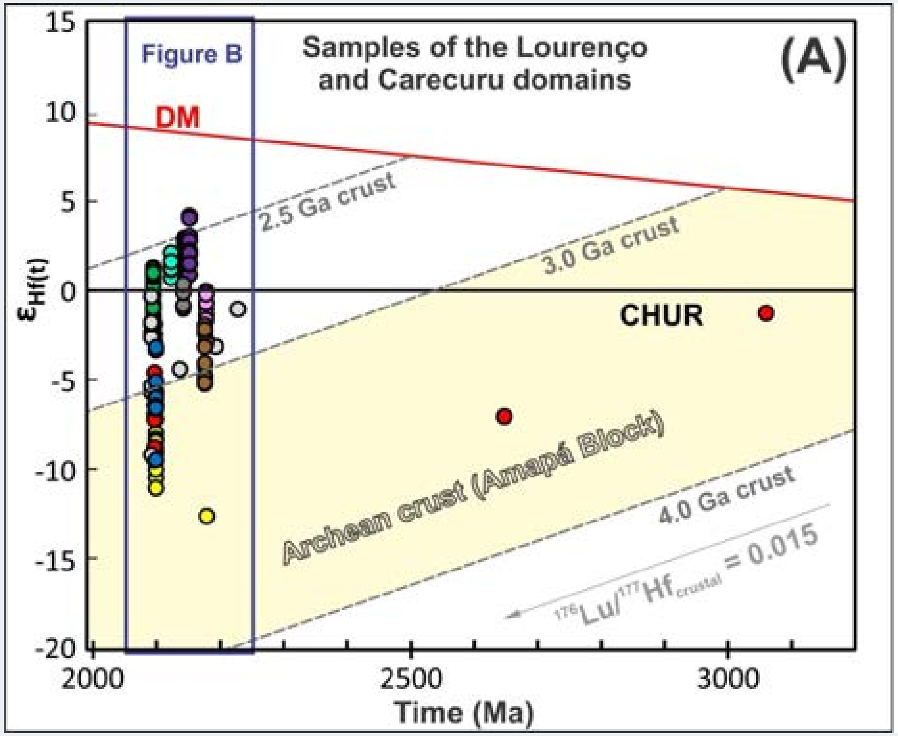


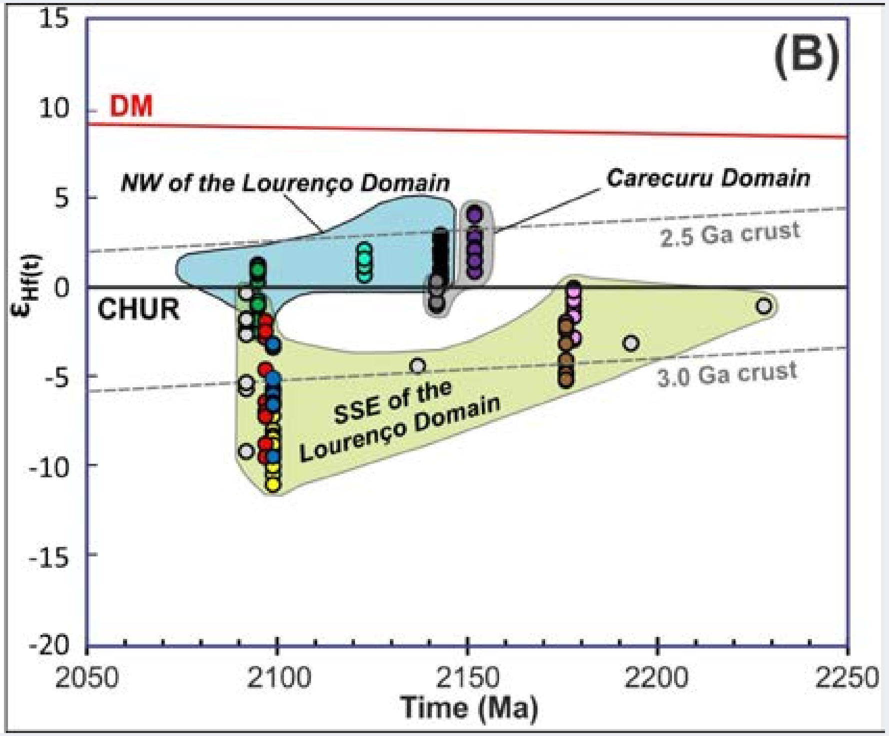
**Histogram of Sr-$T_{UR}$ ages for the Rhyacian rocks of the Lourenço domain (comparing with the Amapá Block and the French Guiana )**

# Lourenço and Carecuru domains: The Lu-Hf zircon record (unpublished data)

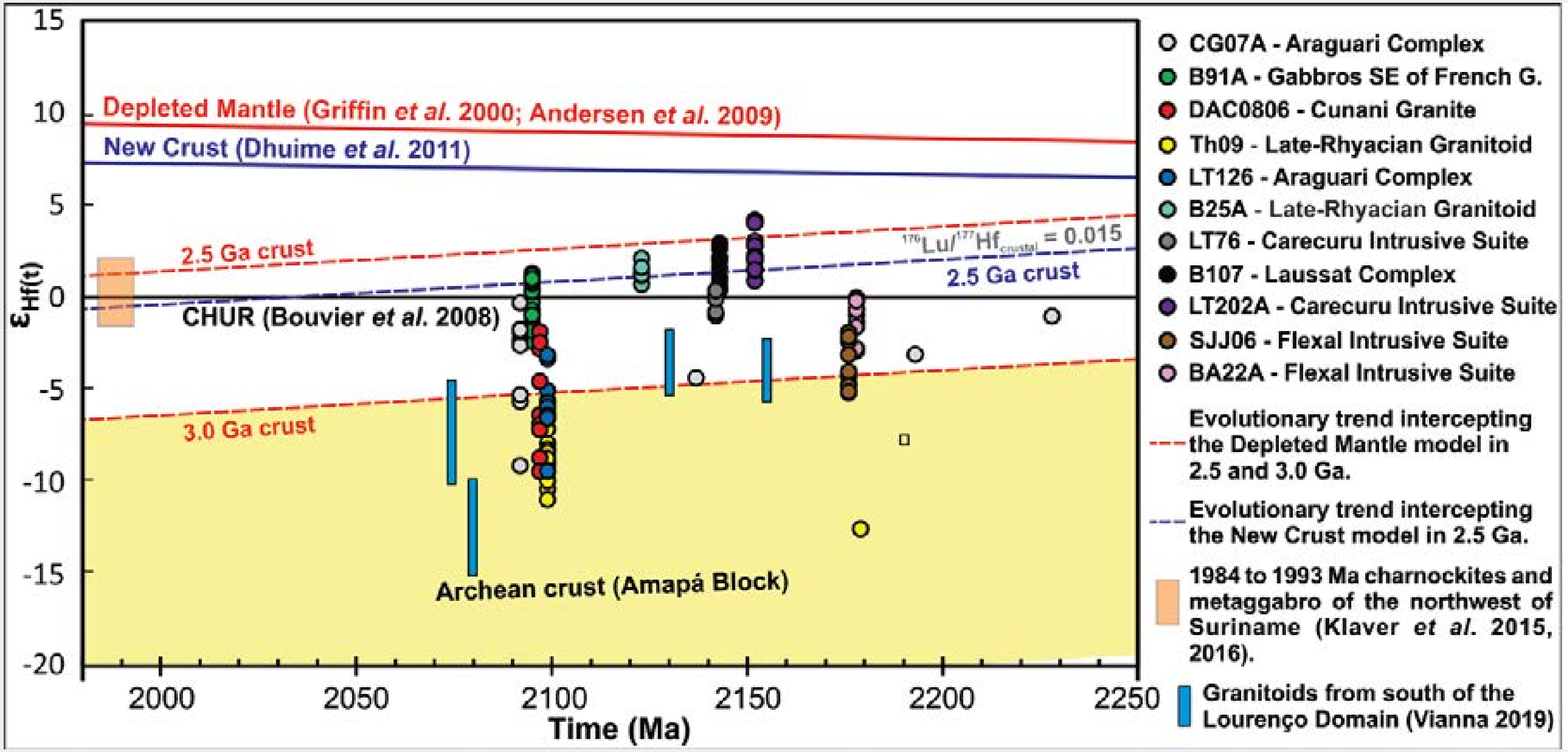


# Lourenço and Carecuru domains:
# The Lu-Hf zircon record **(unpublished data)**





# Lourenço and Carecuru domains:
# The Lu-Hf zircon record



# Interpretation of the Sr-Hf-Nd isotopic signatures

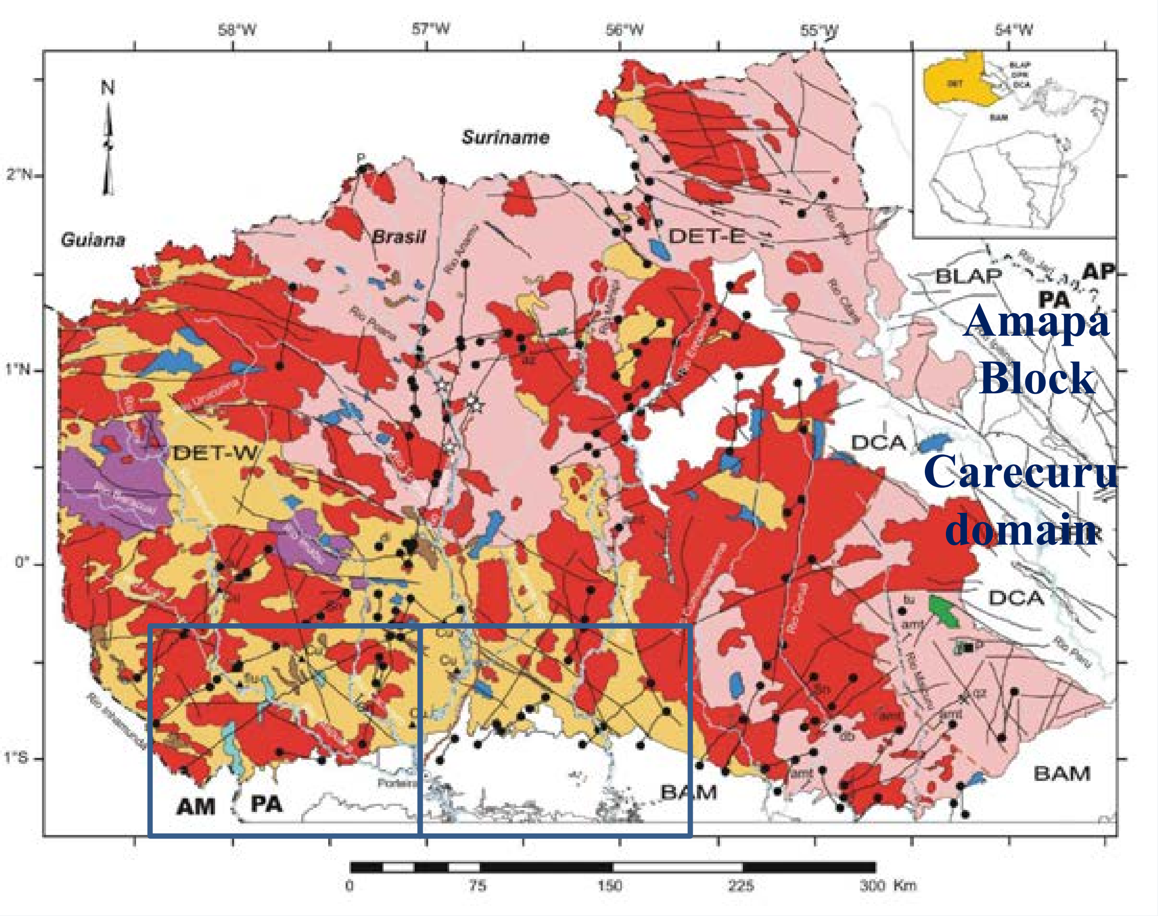
***Carecuru Domain***: Subchondritic $\varepsilon_{Hf}$ values, Hf-$T_{DM}$ dominantly Neoarchean; Archean and Siderian Nd-$T_{DM}$
⇨ assimilation of Archean continental crust (younger than the northern part of the Amapá block), probably in a continental margin environment (continental arc);

***South/Southeastern sector of the Lourenço Domain***: Subchondritic $\varepsilon_{Hf}$ values, Hf-$T_{DM}$ dominantly Paleo- to Mesoarchean and Archean Nd-$T_{DM}$ together with inherited zircons
⇨ assimilation of Archean continental crust, probably in a continental margin environment (continental arc);

***Northwestern sector of the Lourenço Domain /Southeast of the French Guiana***: Suprachondritic $\varepsilon_{Hf}$ values, Neoarchean or Neo-Mesoarchean Hf-$T_{DM}$ and Rhyacian and Neoarchean Nd-$T_{DM}$
⇨ Rhyacian island arc environment with minor contribution of Archean crust, probably by incorporation of Archean continental sediments durante subduction (similar processes than those invoked by Petersson et al. (2018) in Gana.)

# THE PALEOPROTEROZOIC EREPECURU-TROMBETAS DOMAIN

# The Erepecuru-Trombetas domain



| | |
|---|---|
| NPμλ | Neoproterozoic ultramafic and alkaline rocks |
| MPλ | Intracontinental syenitic magmatism (Stenian) |
| PP3brc | Paleoproterozoic sedimentary basin |
| PP4δ<br>PP34δ | Continental mafic magmatism (Statherian ?) |

**Orosirian Intracontinental felsic magmatism:**

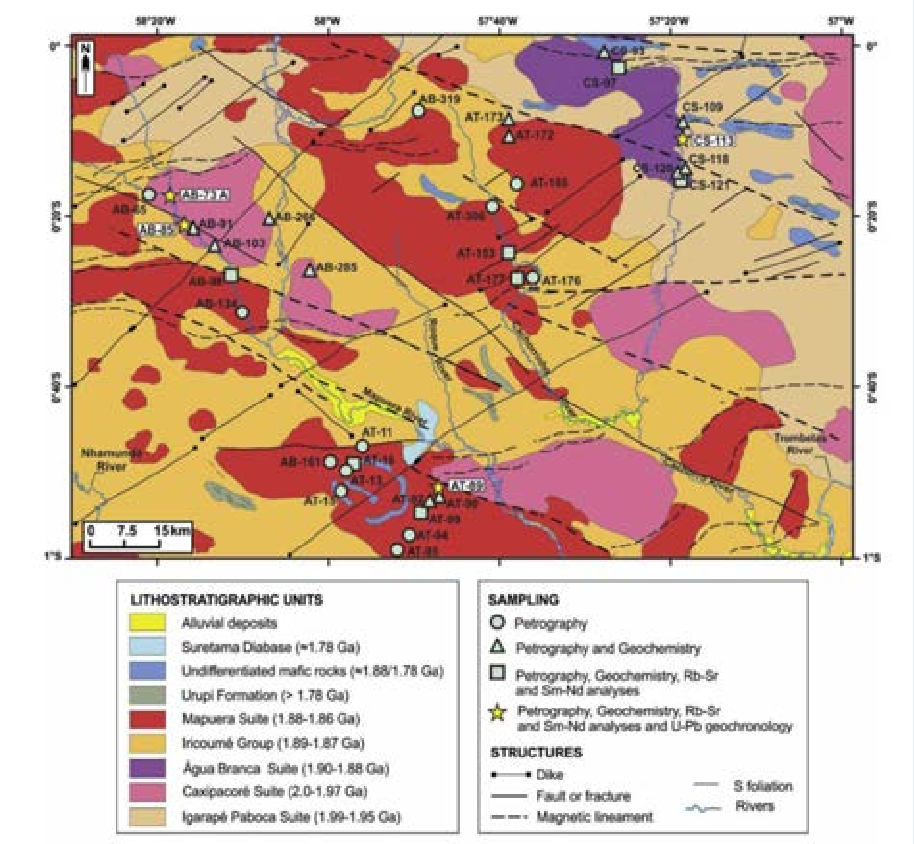
| | |
|---|---|
| PP34γa | Mapuera intrusive suite |
| PP3α | Iricoumé volcanics |
| PP3γi | Agua Branca intrusive suite |

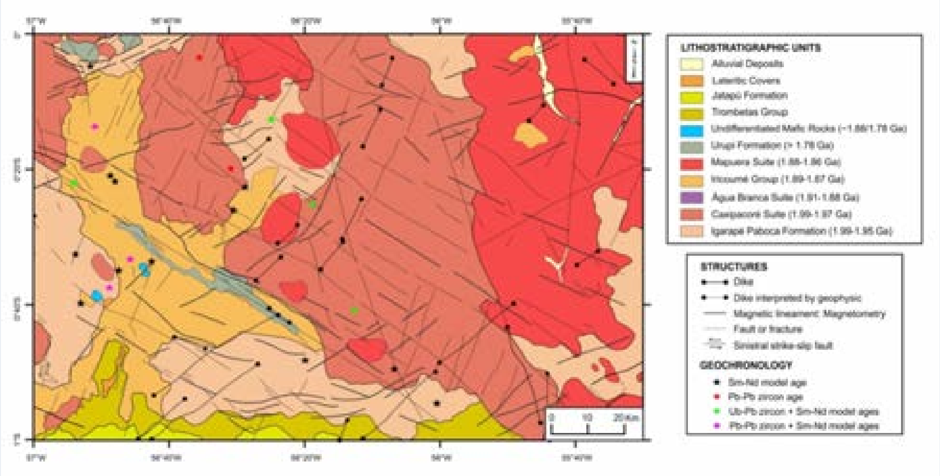
**Basement units (Archean ?)**

| | |
|---|---|
| APPgn | Granite-gneiss-migmatites complex |
| APPgb | Greenstone belt |

**Geological map of NW Pará (Vasquez and Rosa-Costa 2008), including location of the Mapuera and Trombetas sheets (1: 250,000)**

# The Erepecuru-Trombetas domain



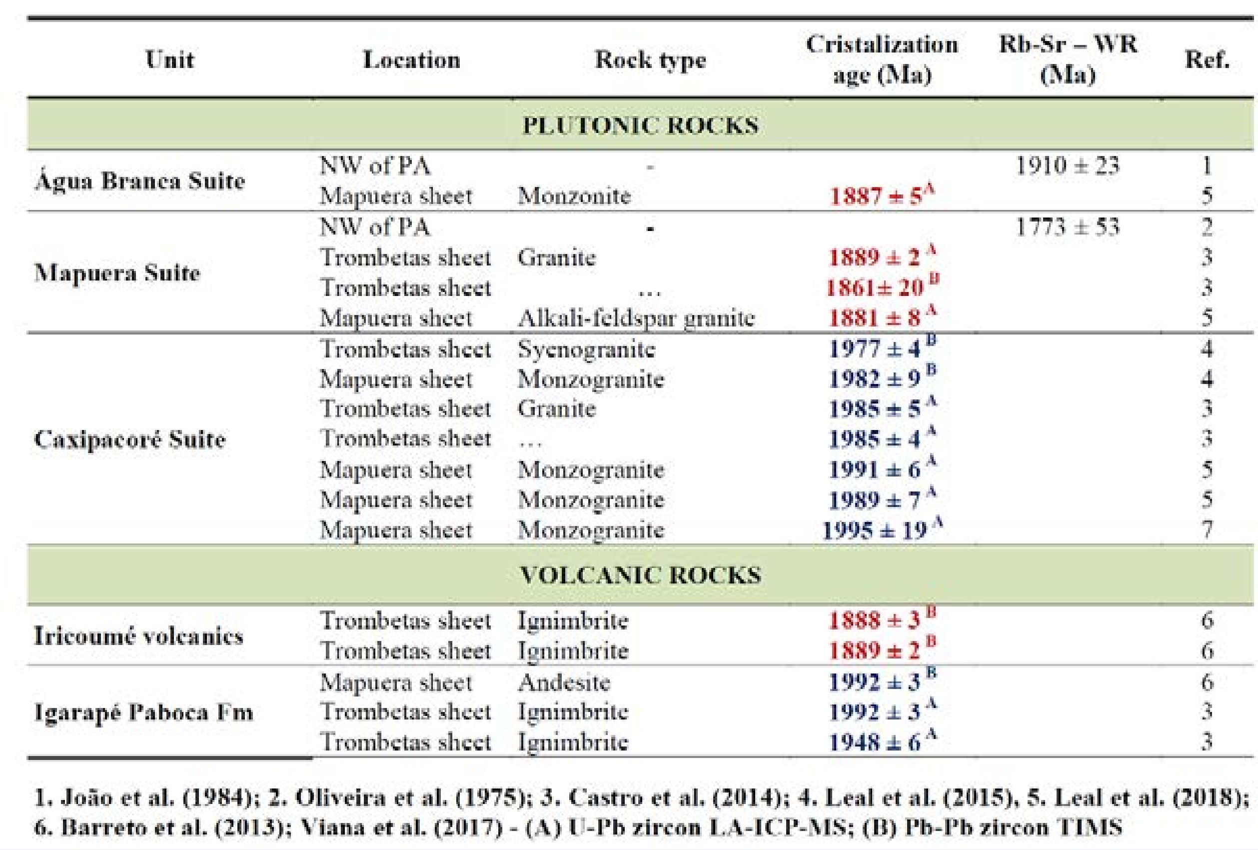


**Mapuera and Trombetas sheets (1: 250,000), with sample location (Castro et al. 2014; Rosa-Costa and Andrade, in press)**

# Two Orosirian plutonic-volcanic events:

⇨ **Older Orosirian event: 1.98-2.0 Ga**

⇨ **Younger Orosirian event: 1.86-1.89 Ga (Uatumã magmatism *s.s.* – SLIP)**



| Unit | Location | Rock type | Cristalization age (Ma) | Rb-Sr – WR (Ma) | Ref. |
|---|---|---|---|---|---|
| | | **PLUTONIC ROCKS** | | | |
| **Água Branca Suite** | NW of PA | - | | 1910 ± 23 | 1 |
| | Mapuera sheet | Monzonite | $1887 \pm 5^{A}$ | | 5 |
| **Mapuera Suite** | NW of PA | - | | 1773 ± 53 | 2 |
| | Trombetas sheet | Granite | $1889 \pm 2^{A}$ | | 3 |
| | Trombetas sheet | ... | $1861 \pm 20^{B}$ | | 3 |
| | Mapuera sheet | Alkali-feldspar granite | $1881 \pm 8^{A}$ | | 5 |
| **Caxipacoré Suite** | Trombetas sheet | Syenogranite | $1977 \pm 4^{B}$ | | 4 |
| | Mapuera sheet | Monzogranite | $1982 \pm 9^{B}$ | | 4 |
| | Trombetas sheet | Granite | $1985 \pm 5^{A}$ | | 3 |
| | Trombetas sheet | ... | $1985 \pm 4^{A}$ | | 3 |
| | Mapuera sheet | Monzogranite | $1991 \pm 6^{A}$ | | 5 |
| | Mapuera sheet | Monzogranite | $1989 \pm 7^{A}$ | | 5 |
| | Mapuera sheet | Monzogranite | $1995 \pm 19^{A}$ | | 7 |
| | | **VOLCANIC ROCKS** | | | |
| **Iricoumé volcanics** | Trombetas sheet | Ignimbrite | $1888 \pm 3^{B}$ | | 6 |
| | Trombetas sheet | Ignimbrite | $1889 \pm 2^{B}$ | | 6 |
| **Igarapé Paboca Fm** | Mapuera sheet | Andesite | $1992 \pm 3^{B}$ | | 6 |
| | Trombetas sheet | Ignimbrite | $1992 \pm 3^{A}$ | | 3 |
| | Trombetas sheet | Ignimbrite | $1948 \pm 6^{A}$ | | 3 |

**1. João et al. (1984); 2. Oliveira et al. (1975); 3. Castro et al. (2014); 4. Leal et al. (2015), 5. Leal et al. (2018); 6. Barreto et al. (2013); Viana et al. (2017) - (A) U-Pb zircon LA-ICP-MS; (B) Pb-Pb zircon TIMS**

# The Erepecuru-Trombetas domain

**Older Orosirian event:**

***Caxipacoré Intrusive Suite***: alkali-feldspar granites, syenogranites, monzogranites and granodiorites

***Igarapé Paboca Formation***: (effusive/pyroclastic volcanics) andesites, dacites to subordinate trachyandesites, trachytes, ignimbrites, tuffs and breccias.

⇨ High-K to shoshonitic, calc-alkaline signature of arc related setting

**Younger Orosirian event**

***Agua Branca Intrusive suite***:

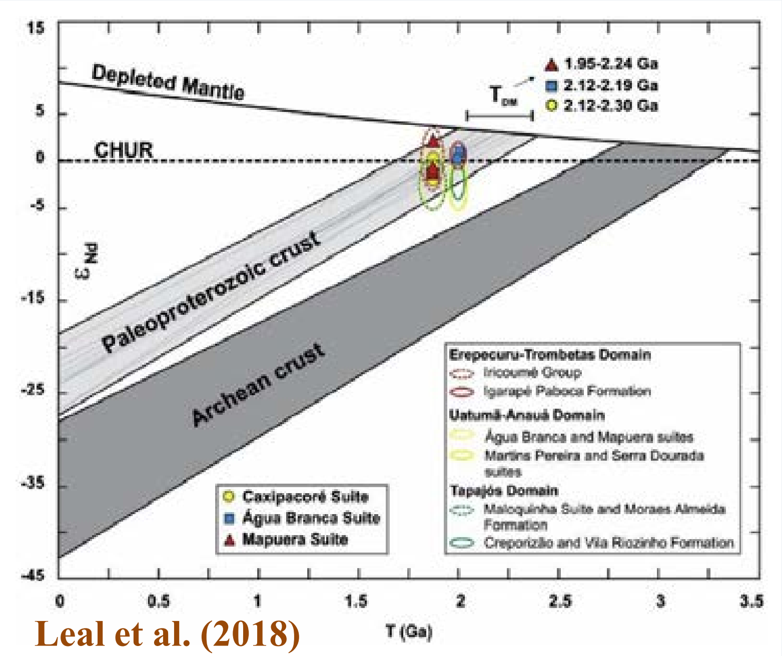
⇨ High-K and I-type calc-alkaline signature

***Mapuera Intrusive suite and Iricoumé Group*** (pyroclastic volcanics):

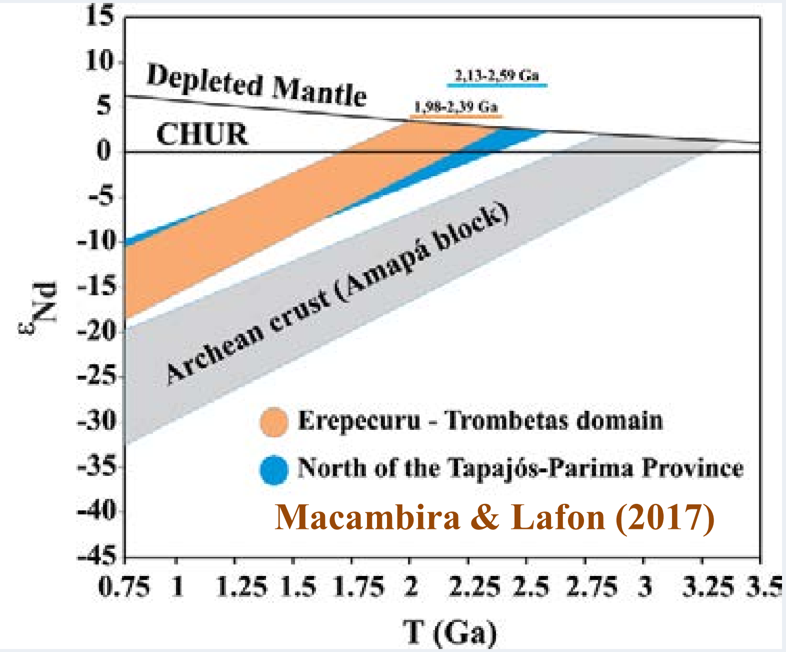
⇨ High-K and A-type affinity

**Vasquez and Rosa-Costa 2008; Barreto et al., 2013; 2014; Castro et al., 2014. Leal et al. 2018; Rosa-Costa and Andrade in press)**

# The Erepecuru-Trombetas domain: Nd-Sr isotopic results



Leal et al. (2018)

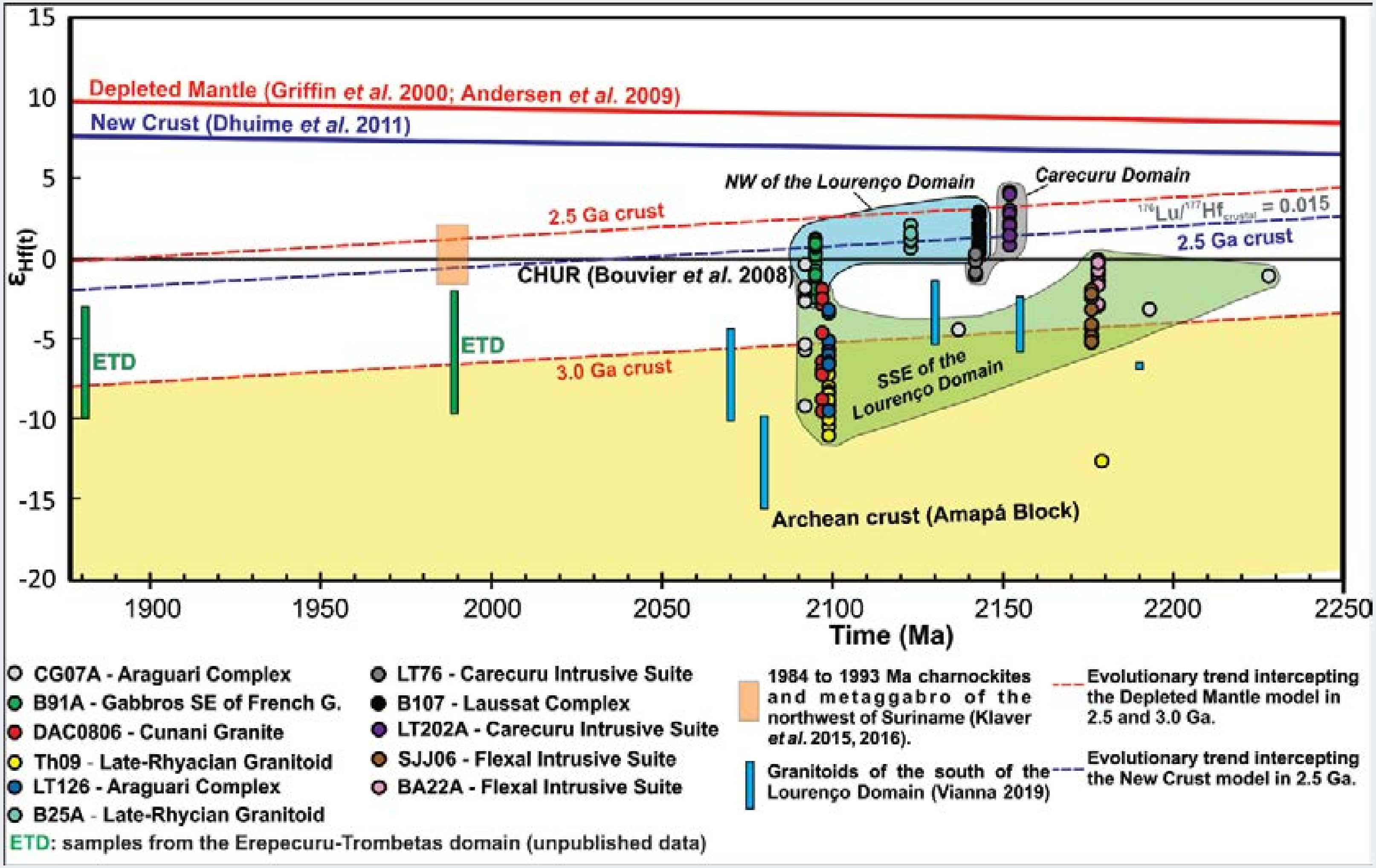


Macambira & Lafon (2017)

| Unit | $Rb^{87}/^{86}Sr$ | $Sr^{87}/^{86}Sr$ | $Sr\text{-}T_{UR}$ (Ga) | Ref. |
|---|---|---|---|---|
| Caxipacoré Suite | 1.78 | 0.7525 | **1.96** | 1 |
| | 1.47 | 0.7436 | **1.95** | 1 |
| Água Branca Suite | 1.56 | 0.7476 | **2.02** | 1 |
| | 0.60 | 0.7196 | **2.02** | 1 |
| | 0.33 | 0.7118 | **2.02** | 1 |
| Mapuera Suite | 78.20 | 22.89 | **1.41** | 1 |
| | 14.70 | 10.98 | **1.86** | 1 |
| | 4.08 | 0.8103 | **1.84** | 1 |
| | 16.60 | 11.69 | **1.96** | 1 |
| | 5.10 | 0.8494 | **2.01** | 1 |
| | 25.61 | 12.26 | **1.43** | 2 |
| | 107.53 | 29.83 | **1.48** | 2 |
| Iricoumé volcanics | 1.84 | 0.7566 | **2.05** | 2 |
| | 0.48 | 0.7186 | **2.44** | 2 |
| | 0.41 | 0.7140 | **2.01** | 2 |
| Basement rocks | 2.49 | 0.7739 | **2.00** | 2 |
| | 0.79 | 0.7268 | **2.18** | 2 |
| | 1.28 | 0.7431 | **2.24** | 2 |

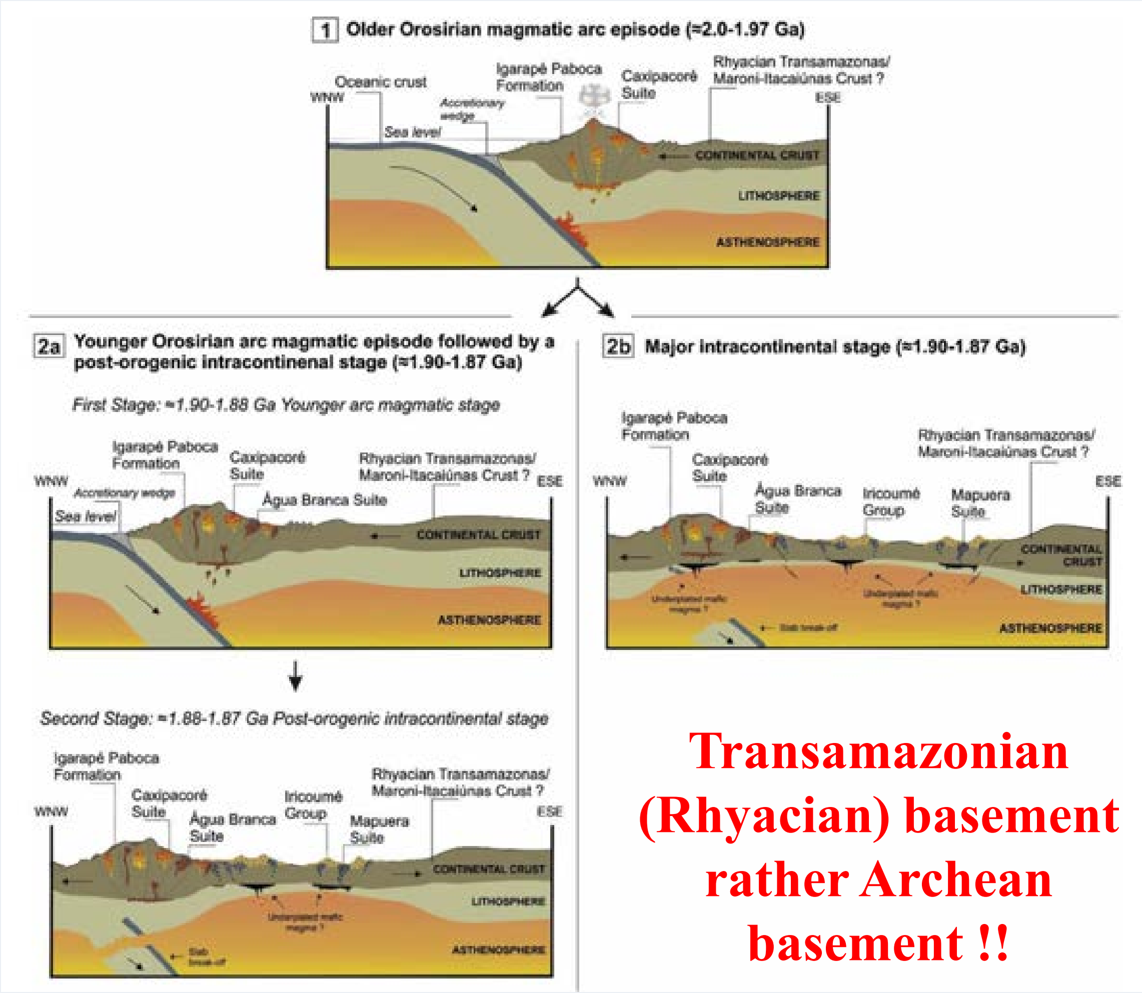
(1) Leal et al. 2018; (2) Radambrasil Project 1975

# The Erepecuru-Trombetas domain



# Schematic tectonic model for the Erepecuru-Trombetas Domain.

## (Leal et al. 2018)



**Transamazonian (Rhyacian) basement rather Archean basement !!**

**Subduction environment at 2.0-1.97 Ga** that produced the magmas of Caxipacoré Suite and Igarapé Paboca Formation by dehydratation of subducted oceanic crust and subsequent hydratation of overlying mantle wedge and lower crust.

Two models are proposed for the 1.90-1.87 Ga magmatic stage:

(2a) **a younger period of subduction setting**, related to a more mature magmatic arc (1.90-1.88 Ga), originating the Água Branca granitoids, **followed by post-orogenic intracontinental magmatism** at 1.88-1.87 Ga, producing the Iricoumé-Mapuera rocks or alternatively

(2b) **a major extensional event in an intracontinental environment**, generating the Água Branca, Mapuera and Iricoumé rocks. The heat could have been produced by asthenospheric upwelling, slab-break-off,underplated mafic magmas or mantle plumes.

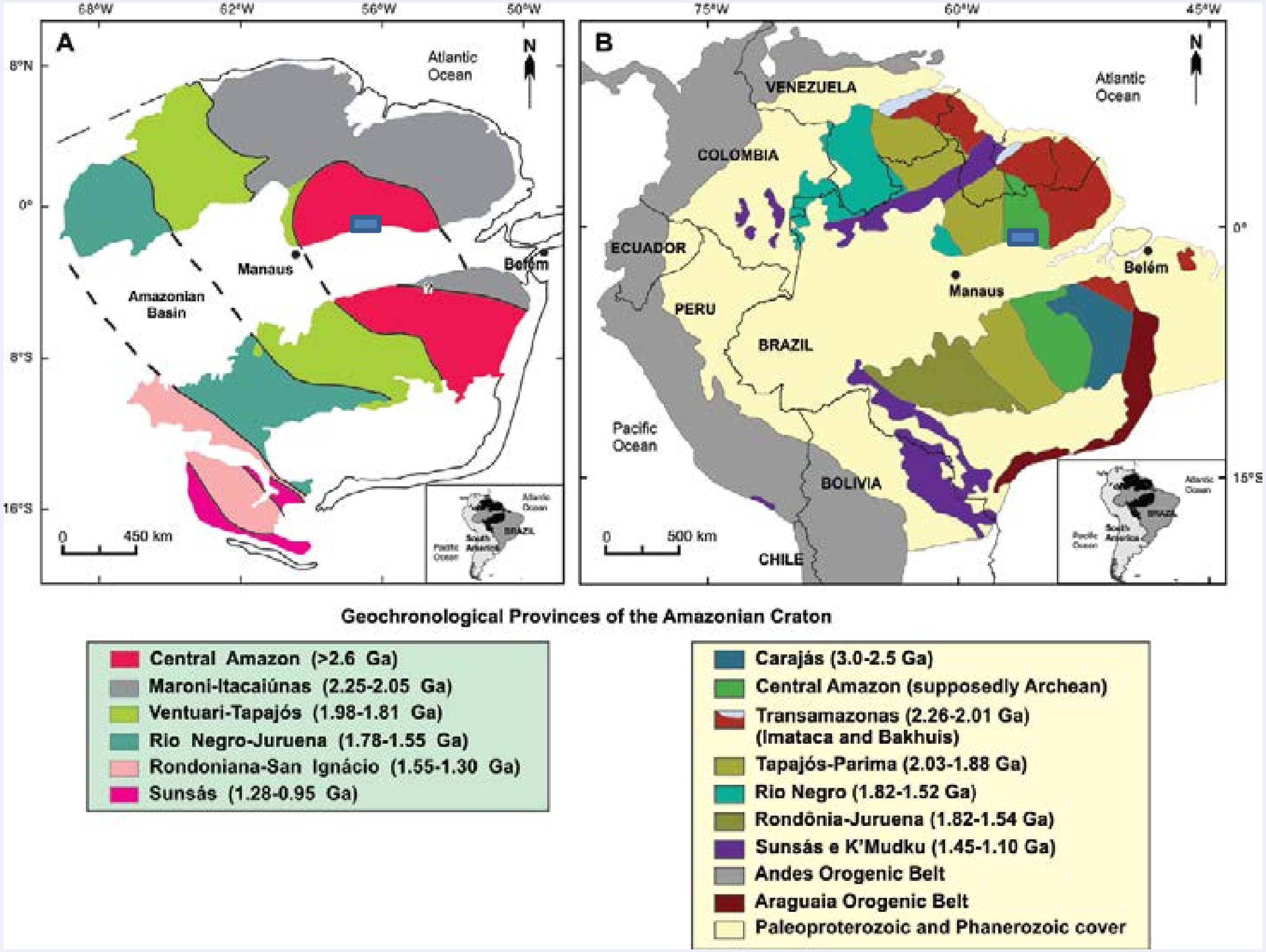
# Interpretation of the Sr-Hf-Nd isotopic signatures

**Older Orosirian magmatism**: Nd-$T_{DM}$ (**2.13–2.22 Ga**) and Sr-$T_{UR}$ (1.95–1.96 Ga) model ages and positive $\varepsilon_{Nd}$ (**+0.26 to +1.57**): origin from melting of mantle-derived magmas with participation of Rhyacian sialic crust.

**Younger Orosirian magmatism**: Nd-$T_{DM}$ (**1.95–2.39 Ga**) and Sr-$T_{UR}$ (1.84–2.02 Ga) model ages and positive to negative $\varepsilon_{Nd}$ (**+2.92 to −3.04**): that indicate parental magmas derived from melting of dominantly Rhyacian crustal sources with minor mantle contribution.

The subchondritic $\varepsilon_{Hf}$ values and Hf-$T_{DM}$ (**2.7-3.2 Ga**) suggest the participation of Transamazonian (Rhyacian) crust or contribution of sediments from the Archean block

# Implications for the the geotectonic partitioning of the Brazilian part of the Southeastern Guiana SHield



Position of the Trombetas and Mapuera geological maps (Erepecuru- Trombetas domain) in the Geochronological provinces of the Amazonian Craton according to the models of (A) Tassinari and Macambira (2004) , with age ranges updated by Cordani et al. (2009) and (B) Santos et al. (2006, 2008) .

# Implications for the the geotectonic partitioning of the Brazilian part of the Southeastern Guiana Shield

The geochemical, isotopic and temporal similarity of the Erepecuru-Trombetas with the adjacent Tapajós-Parima Province (Santos et al, 2000, 2006, 2008) indicates that the limit does not exist and both regions likely belong to the same geotectonic domain.

For all granitoids and volcanics rocks, the Nd-Sr isotopic data preclude the involvement of Archean sources. Therefore, the Archean Central Amazon Province (Tassinari and Macambira 2004) should not be extended to the southern Guyana Shield.

# CONCLUDING REMARKS

**The Sr-Nd-Hf isotopic signatures reveal:**

**Existence of an Eo- Paleoarchean crust in the Southeastern Guiana shield**
**⇨ The geological and tectonic evolution of the Amazonian Craton started more than 500 Ma earlier than previously accepted**

**Main period of crustal growth during Mesoarchean (3.0-3.2 Ga)**

**Neoarchean is dominated by crustal reworking**

**The influence of the Archean continental landmass extends far away in the adjacent Paleoproterozoic domains (crustal assimilation, sediment contribution)**

**The current models of geotectonic partitioning of the Amazonian craton must be revised/adapted for the Southeastern Guiana Shied**

Thank You !

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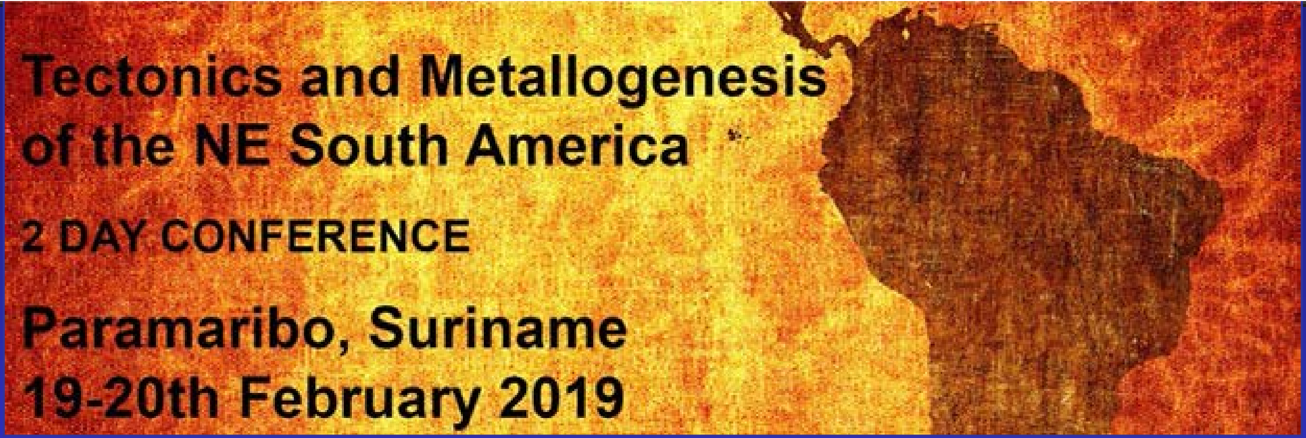


Tectonics and Metallogenesis of the NE South America

2 DAY CONFERENCE

Paramaribo, Suriname
19-20th February 2019

# GOLD IN BRAZIL

CPMTC
Centro de Pesquisa
Professor Manoel Teixeira da Costa
Universidade Federal de Minas Gerais

THE UNIVERSITY OF WESTERN AUSTRALIA

Centre for EXPLORATION TARGETING

UFVJM

UNIVERSIDADE FEDERAL DO CEARÁ

# Brazil

Gold producer for many centuries, leading in 18th and 19th.

**1982-1999** → 10 gold mines >20 t Au and seven smaller (3-8 t Au).

**1983-1990** → eight active mines (1st boom).

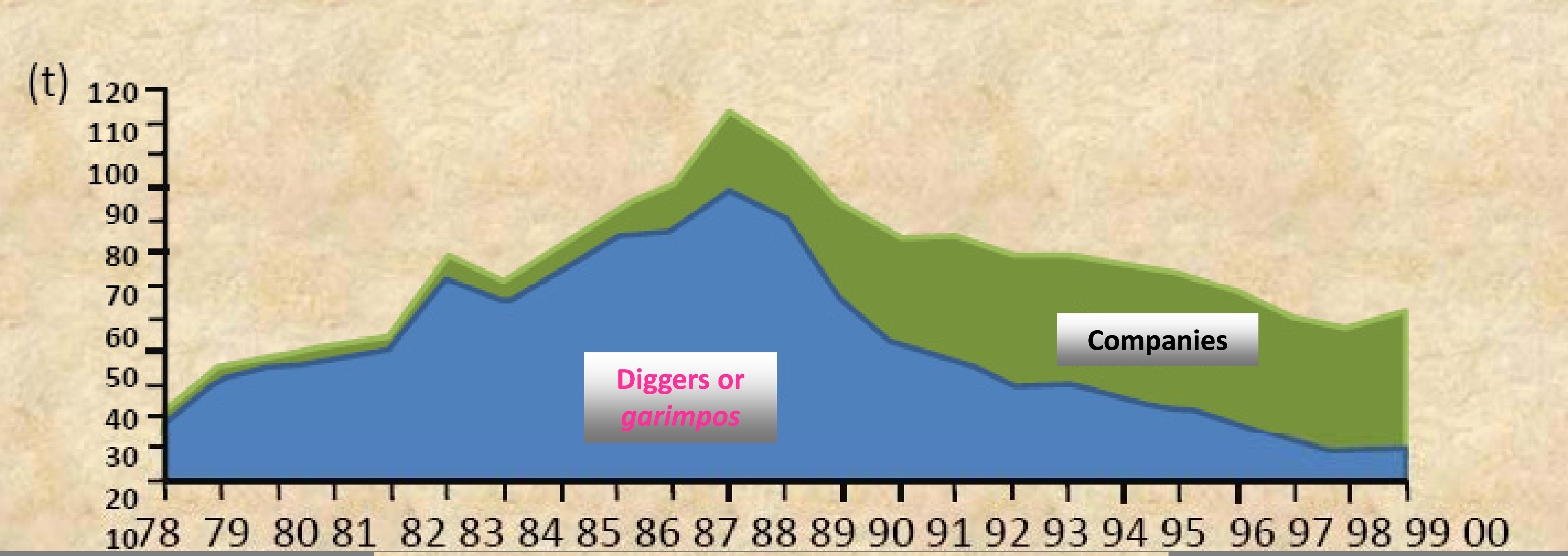
**1992** → mining companies produced ~ 40 t Au. Thorman et al., 2001

**Mid-2000s** 2nd boom. Production mainly due to new mines: Chapada (Goiás-GO), Cuiabá, Turmalina (Minas Gerais-MG) and Mamão (Pará-PA).

**2001-2007** → annual prodution 38 to 47 t Au (DNPM, Brasil). Since then new deposits in production as Caeté (MG; 2010); Aurizona (Maranhão) and Tucano (Amapá-AP), both 2011; C1 (Santa Luz BA, 2013).

**Lobato et al. (2019) – *Gold in Brazil***

# Gold historical Brazilian production



**Gold production between 1978 and 2000**

DNPM, F.Crocco (2009)

***Garimpeiro* (diggers) production surpassed by industry only in 1991.**
**Mineral Exploration fundamentally guided by existing Mineral Occurrences.**

*Brazilian production, 2015 → ~ 79,6 t Au – 68 t primary – 11% worldwide (DNPM).*

*Garimpos (diggers) → ~ 11,6 t Au – Mato Grosso (47,1%) & Pará (40,19%).*

**Lobato et al. (2019) – *Gold in Brazil***

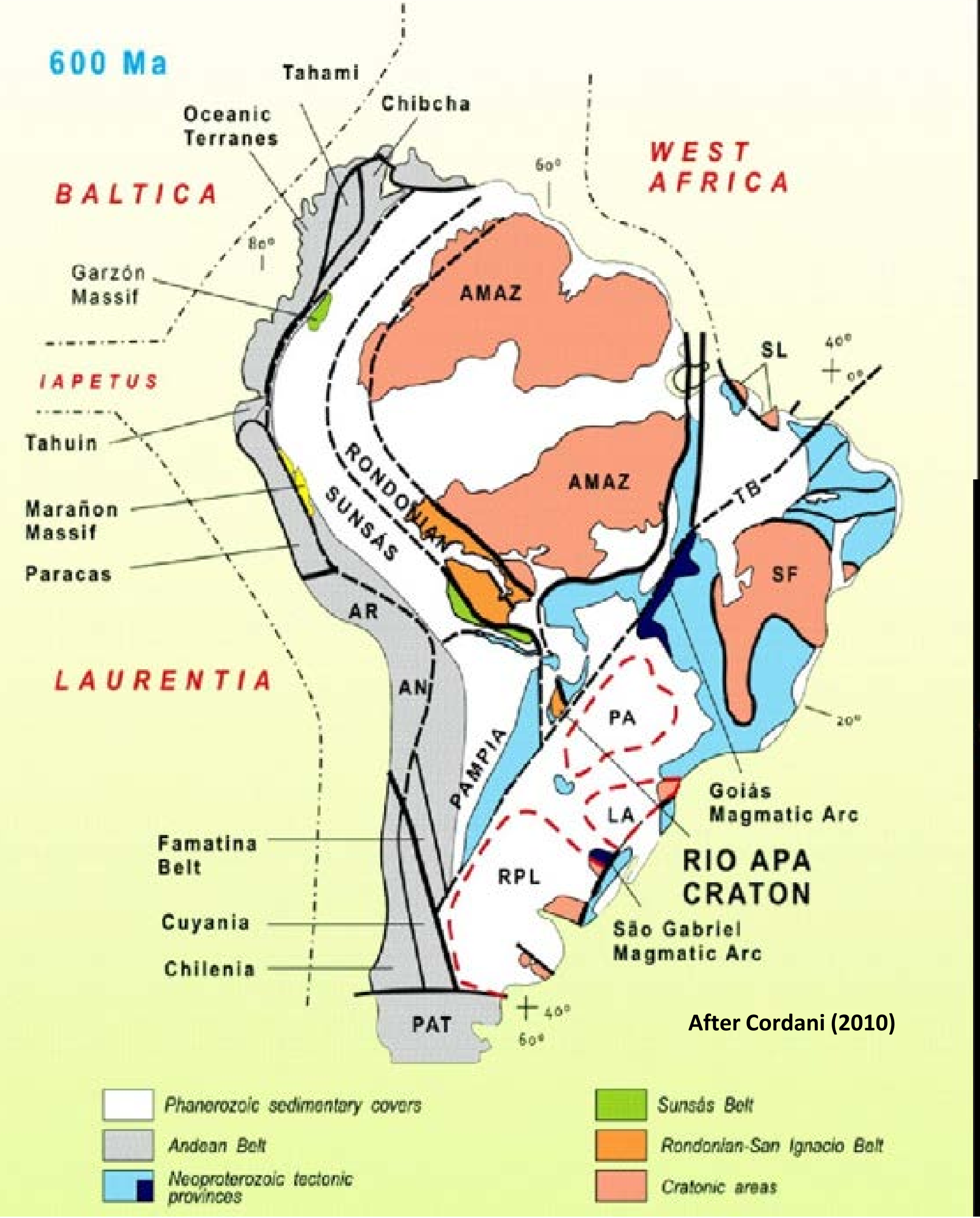
# Tectonic Setting
## Cratons

AMAZ = Amazonas

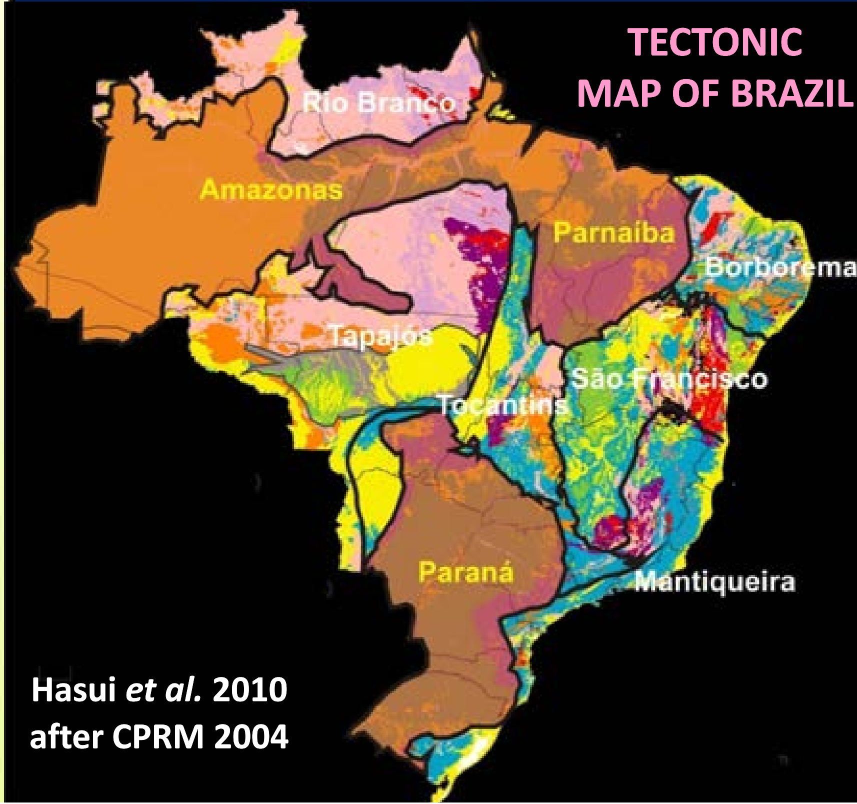
SF = São Francisco

SL = São Luis

RPL = Rio de la Plata



After Cordani (2010)

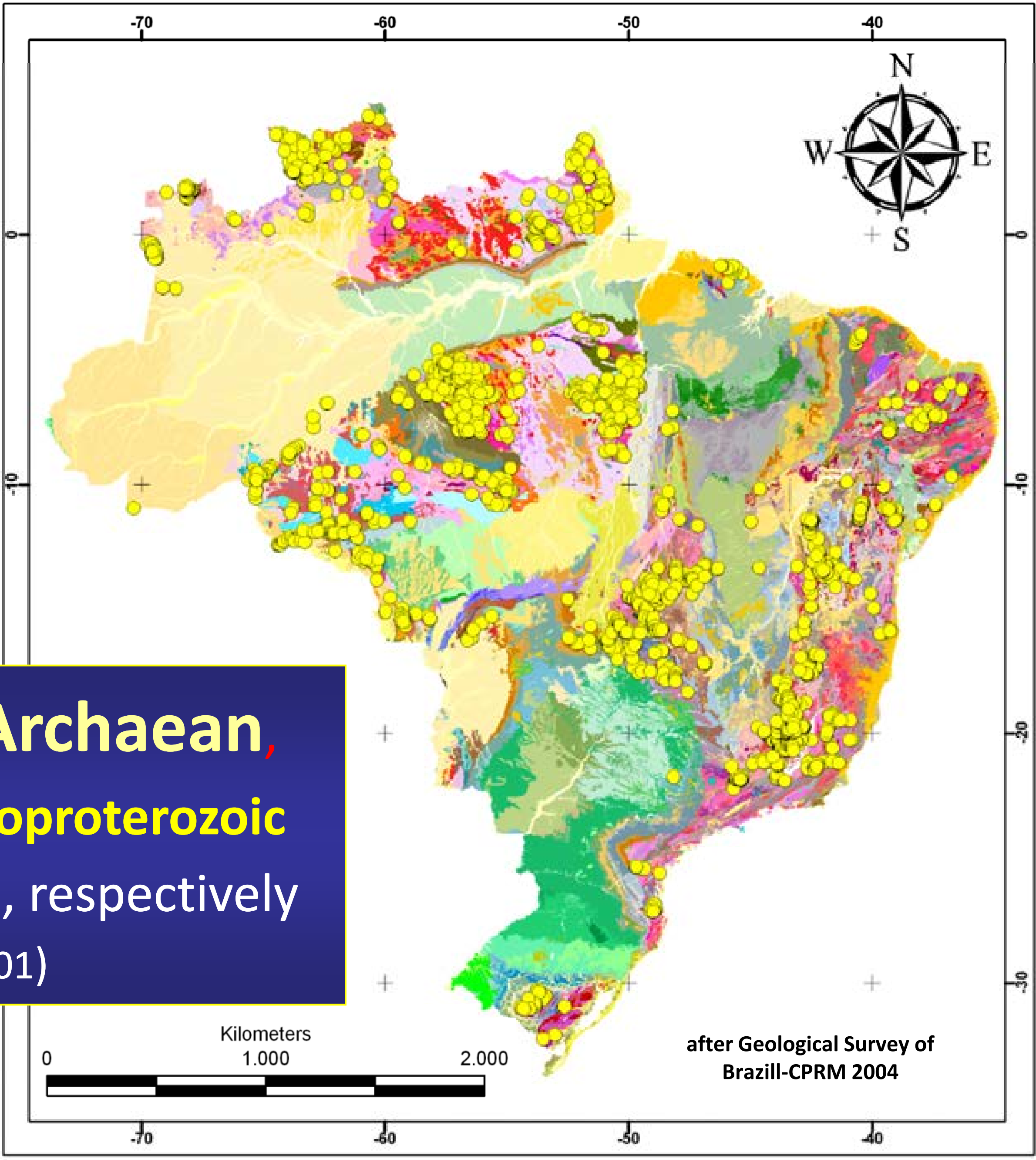

TECTONIC MAP OF BRAZIL

Hasui *et al.* 2010 after CPRM 2004

**Known gold occurences & mines of Brazil (~3,300)**

**Majority in Amazonas & São Francisco cratons.**

## Geological Map of Brazil and Au Occurrences



after Geological Survey of Brazill-CPRM 2004

***66%*** of **gold** from **Archaean**,

***19%*** and ***15%*** from **Palaeoproterozoic**

and **Neoproterozoic** rocks, respectively

(Thorman et al., 2001)

# Archaean nuclei and fragments

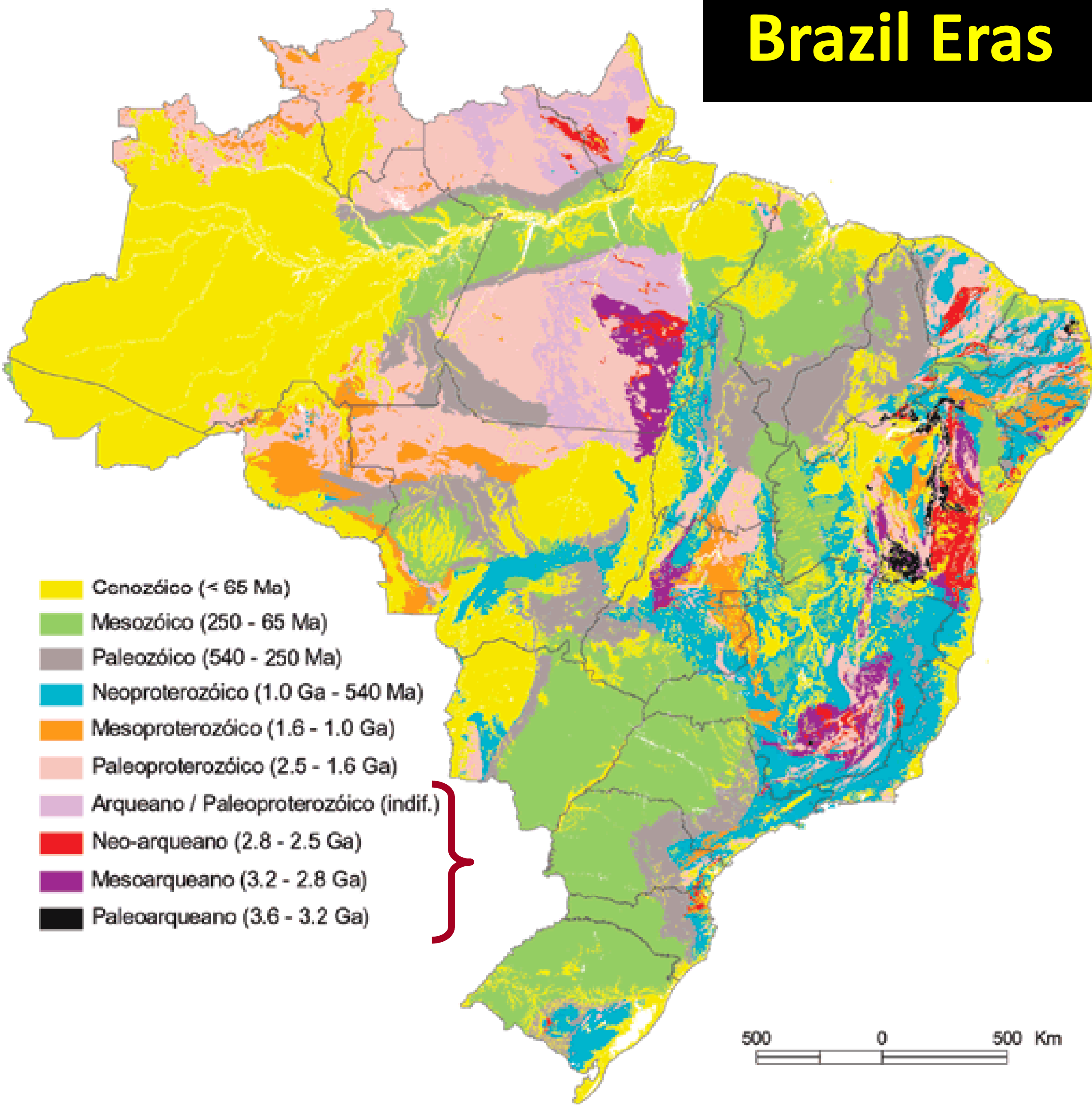
**Preserved in cratonic & denuded orogenic terranes, covering <170 000 km$^2$, 5.4% of Brazil's Precambrian surface.**

27 differentiated discrete & neighbouring terranes

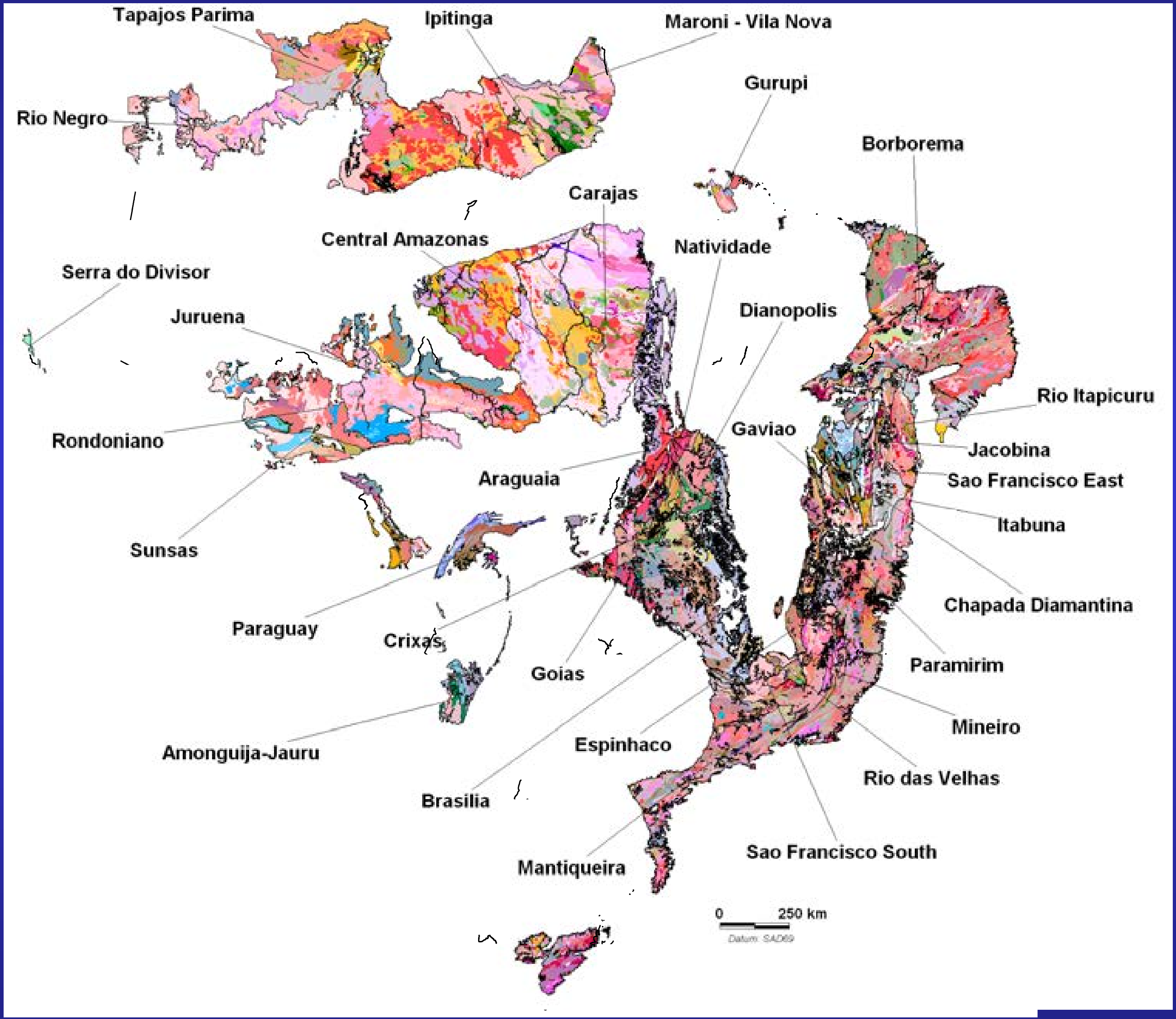
**4 undifferentiated complexes**

**3.5% of Brazil's surface is undifferentiated Archaean-Palaeoproterozoic terrane**

## Brazil Eras



**Schobbenhaus and Neves (2003)**



Lobato et al. (2019) – *Gold in Brazil*

019) – *Gold in Brazil*

# Gold in Brazil

**Brazil, tons of Au → production/reserves/resources**
**62 deposits (mines) and districts**
Lobato et al. (2016)

## Main deposit types

- Orogenic
- Iron-oxide copper gold (IOCG)
- Hydrothermal magmatic
  (epithermal, porphyry, intrusion related)
- Paleoplacers

**Lobato et al. (2019) – *Gold in Brazil***

## Main **gold** districts and deposits, with ≥0.1 Moz contained **Au** (under revision)

| Deposit Name | Province or Region | Commodity | Tons (gold) | Moz (gold) |
|---|---|---|---|---|
| Salobo | Carajás province - PA | Cu-Au | 426.38 | 18.06 |
| Sossego | Carajás province - PA | Cu-Au | 99.40 | 3.20 |
| Cristalino | Carajás province - PA | Cu-Au | 150.00 | 4.82 |
| Igarapé Bahia | Carajás province - PA | Au-Cu | 97.00 | 3.10 |
| Breves | Carajás province - PA | Cu-Au | 37.48 | 1.21 |
| Alemão | Carajás province - PA | Cu-Au | 133.73 | 4.30 |
| Serra Pelada | Carajás province - PA | Au-Pd | 56.24 | 1.81 |
| 118 | Carajás province - PA | Cu-Au | 51.00 | 1.64 |
| Águas Claras | Carajás province - PA | Au-Cu | 23.09 | 0.74 |
| Antas North | Carajás province - PA | Cu-Au | 3.74 | 0.12 |
| Pedra Branca | Carajás province - PA | Cu-Au | 15.48 | 0,50 |
| Andorinhas | Rio Maria (GBs), south of Carajás – PA | Au | 4.91 | 0,16 |
| Volta Grande | Três Palmeiras greenstone belt - PA | Au | 214.36 | 6.89 |
| Tocantinzinho | Tapajós province - PA | Au | 79.04 | 2.49 |
| Palito | Tapajós province - PA | Au | 18.64 | 0.56 |
| São Chico | Tapajós province - PA | Au | 30.21 | 0.97 |
| Cuiú-Cuiú | Tapajós province - PA | Au | 40.60 | 1.30 |
| Coringa | Tapajós province - PA | Au | 28.30 | 0.91 |
| São Domingos | Tapajós province - PA | Au | 4.20 | 0.14 |
| São Jorge | Tapajós province - PA | Au | 54.34 | 1.71 |
| Castelo dos Sonhos | Tapajós province - PA | Au | 8.71 | 0.28 |
| São Francisco | Aguapeí mobile belt- MT | Au | 10.42 | 0.34 |
| São Vicente | Aguapeí mobile belt- MT | Au | 5.57 | 0.18 |
| Ernesto/Pau a Pique | Aguapeí mobile belt- MT | Au | 9.99 | 0.32 |
| Araés | Nova Xavantina - MT | Au | 13.40 | 0.43 |
| Cabaçal | Alto Jauru - MT | Au-Cu | 4.34 | 0.14 |
| Cajueiro | Juruena-Teles Pires - MT | Au | 14.94 | 0.47 |
| União-Ouro Paz | Juruena-Teles Pires - MT | Au | 21.26 | 0.68 |
| X1 | Juruena-Teles Pires - MT | Au | 11.44 | 0.37 |
| Morro do Ouro | Brasília mobile belt - GO | Au | 321.46 | 10.34 |
| Mina Nova & Mina III (Crixás) | Crixás greenstone belt - GO | Au | 92.98 | 2.99 |

Modified fromLobato et al. (2016)

Academia Brasileira de Ciências; book chapter: ***“Recursos Minerais no Brasil - problemas e desafios”***

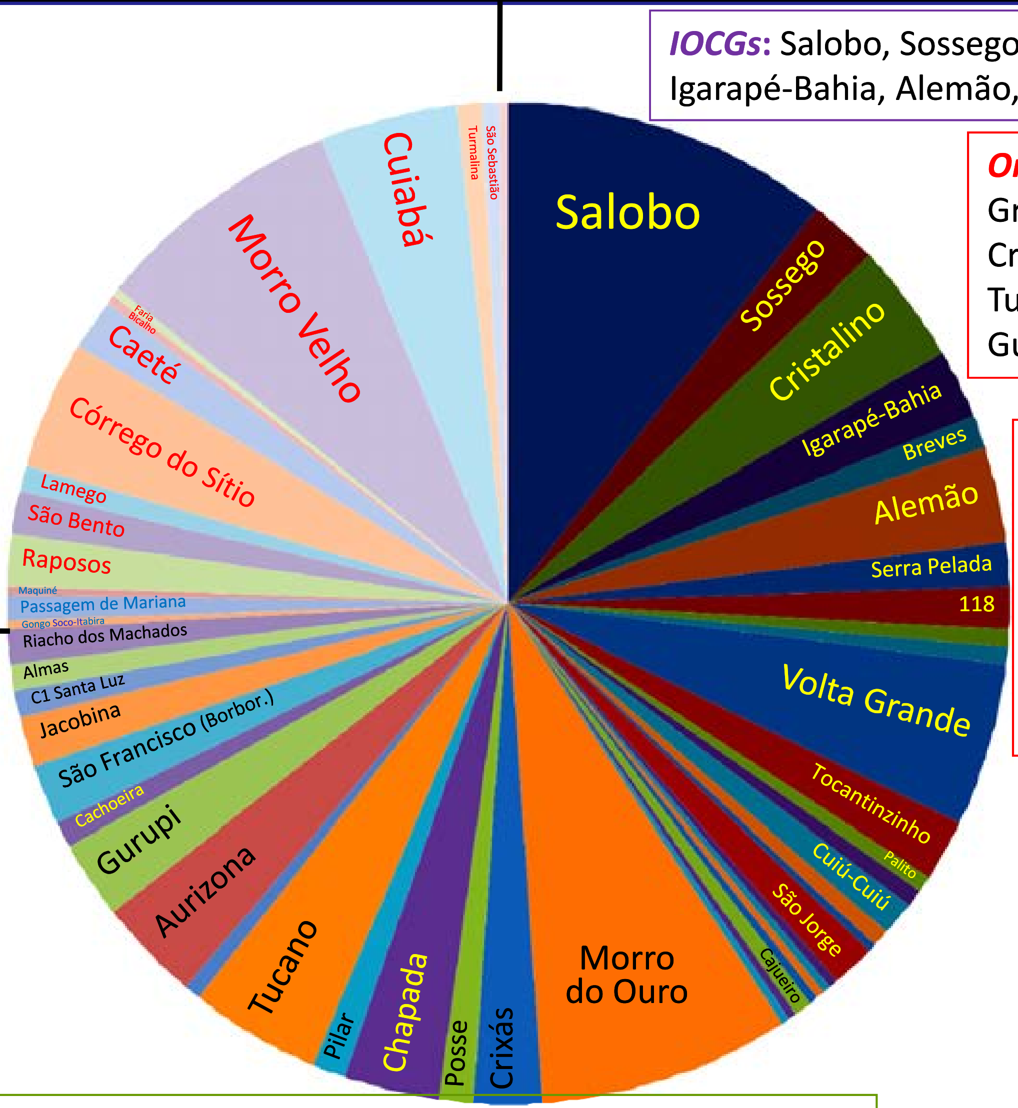
Main **gold** districts and deposits, with ≥0.1 Moz contained **Au** (under revision)

Modified fromLobato et al. (2016)

Academia Brasileira de Ciências; book chapter: ***“Recursos Minerais no Brasil - problemas e desafios”***

| Deposit name | Province or region | Commodity | Tons (gold) | Moz (gold) |
|---|---|---|---|---|
| Premier | *Greenstone belt* Crixás - GO | Au | 3.56 | 0.11 |
| Posse | Chapada-Mara Rosa district - GO | Cu-Au | 41.33 | 1.33 |
| Chapada | Chapada-Mara Rosa distric - GO | Cu-Au | 127.29 | 4.08 |
| Pilar | Pilar de Goiás greenstone belt - GO | Au | 42.10 | 1.36 |
| Amapari-Tucano | Vila Nova greenstone belt - AP | Au | 167.12 | 5.37 |
| Lourenço | Distrito Aurífero Lourenço - AP | Au | 19.96 | 0.64 |
| Aurizona | Gurupi province - MA | Au | 145.41 | 4.67 |
| Gurupi | Gurupi province - MA | Au | 96.41 | 3.21 |
| Cachoeira | Gurupi province- PA | Au | 38.24 | 1.23 |
| São Francisco | Borborema province - RN | Au | 75.46 | 2.43 |
| Jacobina | Serra de Jacobina - BA | Au | 64.51 | 2.07 |
| C-Santa Luz | Rio Itapicuru greenstone belt - BA | Au | 37.25 | 1.19 |
| Fazenda Brasileiro | Itapicuru - BA | Au | 4.49 | 3.15 |
| Almas | SE Tocantins - TO | Au | 27.31 | 0.88 |
| Riacho dos Machados | Ouro Fino. Paramirim - MG | Au | 47.38 | 1.52 |
| Itabira | Quadrilátero Ferrífero province – MG | Au | 0.71 | 0.02 |
| Gongo Soco | Quadrilátero Ferrífero province - MG | Au | 13.26 | 0.41 |
| Passagem de Mariana | Quadrilátero Ferrífero province - MG | Au | 35.08 | 1.09 |
| Maquiné | Quadrilátero Ferrífero province - MG | Au | 5.28 | 0.16 |
| Raposos | Quadrilátero Ferrífero province - MG | Au | 67.11 | 2.16 |
| São Bento | Quadrilátero Ferrífero province - MG | Au | 56.80 | 1.77 |
| Lamego | Quadrilátero Ferrífero province - MG | Au | 38.53 | 1.24 |
| Córrego do Sitio | Quadrilátero Ferrífero province - MG | Au | 168.62 | 5.42 |
| Caeté (Pilar e Roça Grande) | Quadrilátero Ferrífero province - MG | Au | 70.58 | 2.31 |
| Bicalho | Quadrilátero Ferrífero province - MG | Au | 8.78 | 0.29 |
| Faria | Quadrilátero Ferrífero province- MG | Au | 8.97 | 0.28 |
| Morro Velho | Quadrilátero Ferrífero province - MG | Au | 332.02 | 10.71 |
| Cuiabá | Quadrilátero Ferrífero province - MG | Au | 174.80 | 5.62 |
| Turmalina | Onça Pitangui region (NW QF) - MG | Au | 35.41 | 1.14 |
| São Sebastião | Onça Pitangui region (NW QF) - MG | Au | 19.86 | 0.64 |
| Butiá (Lavras do Sul) | Lavras do Sul - RS | Au | 15.99 | 0.52 |

# Brazil, tons of Au → production/reserves/resources
# 62 deposits (mines) and districts



***IOCGs*:** Salobo, Sossego, Cristalino, Igarapé-Bahia, Alemão, 118

***Orogenic gold:*** Volta Grande, Morro do Ouro, Crixás, Posse, Pilar, Tucano, Aurizona, Gurupi, São Francisco (?)

***Orogenic gold*:** C1, Almas, Riacho dos Machados, Passagem, Raposos, São Bento, Lamego, Córrego do Sítio, Caeté, Morro Velho, Cuiabá

***Others*:** Serra Pelada (replacement in sedimentary rocks); Tocantinzinho, Palito, Cuiu-Cuiu (porphyry); Chapada (metamorphosed porphyry); São Jorge (epithermal type); Jacobina (metaconglomerate hosted).

**Pie chart**

62 gold districts and deposits

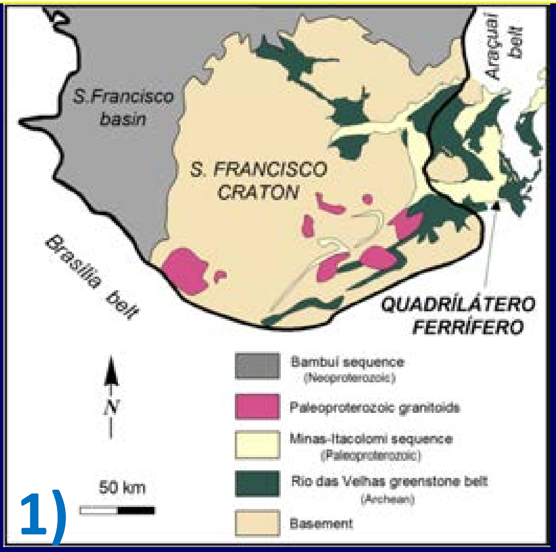
≥ 0.1 Moz contained Au

Lobato et al. (2016)

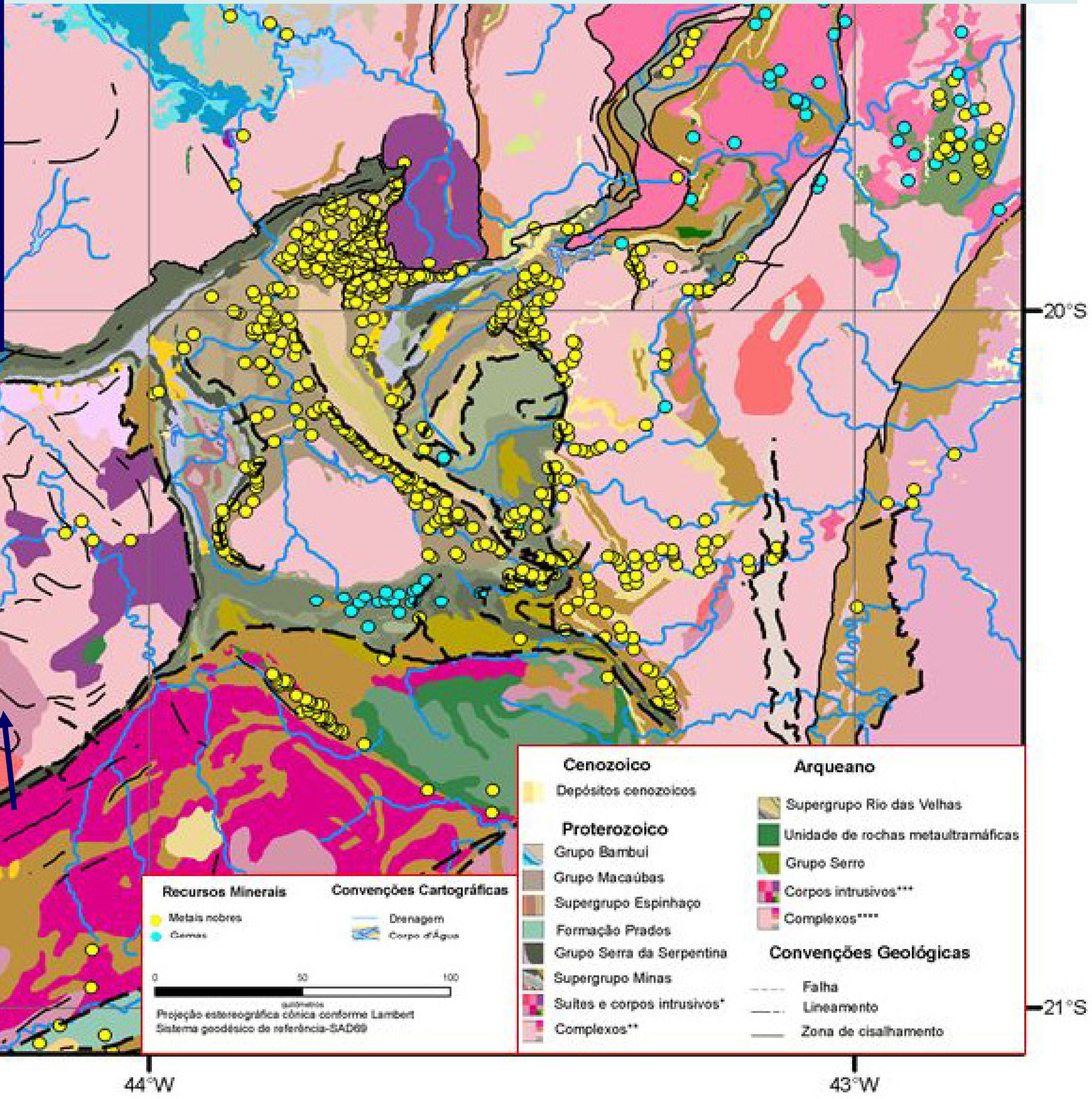
# SOUTHERN SÃO FRANCISCO CRATON

**Simplified geological maps where the Quadrilátero Ferrífero mining district:**

**1)** is located in the context of the southern São Francisco craton (from Alkmim & Martins-Neto 2012); and **2)** shows location of main Palaeoproteroizoic BIF-hosted **iron deposits**, and different types of **gold deposits** in Archaean and Palaeoproteroizoic sequences (from Lobato et al. 2014).

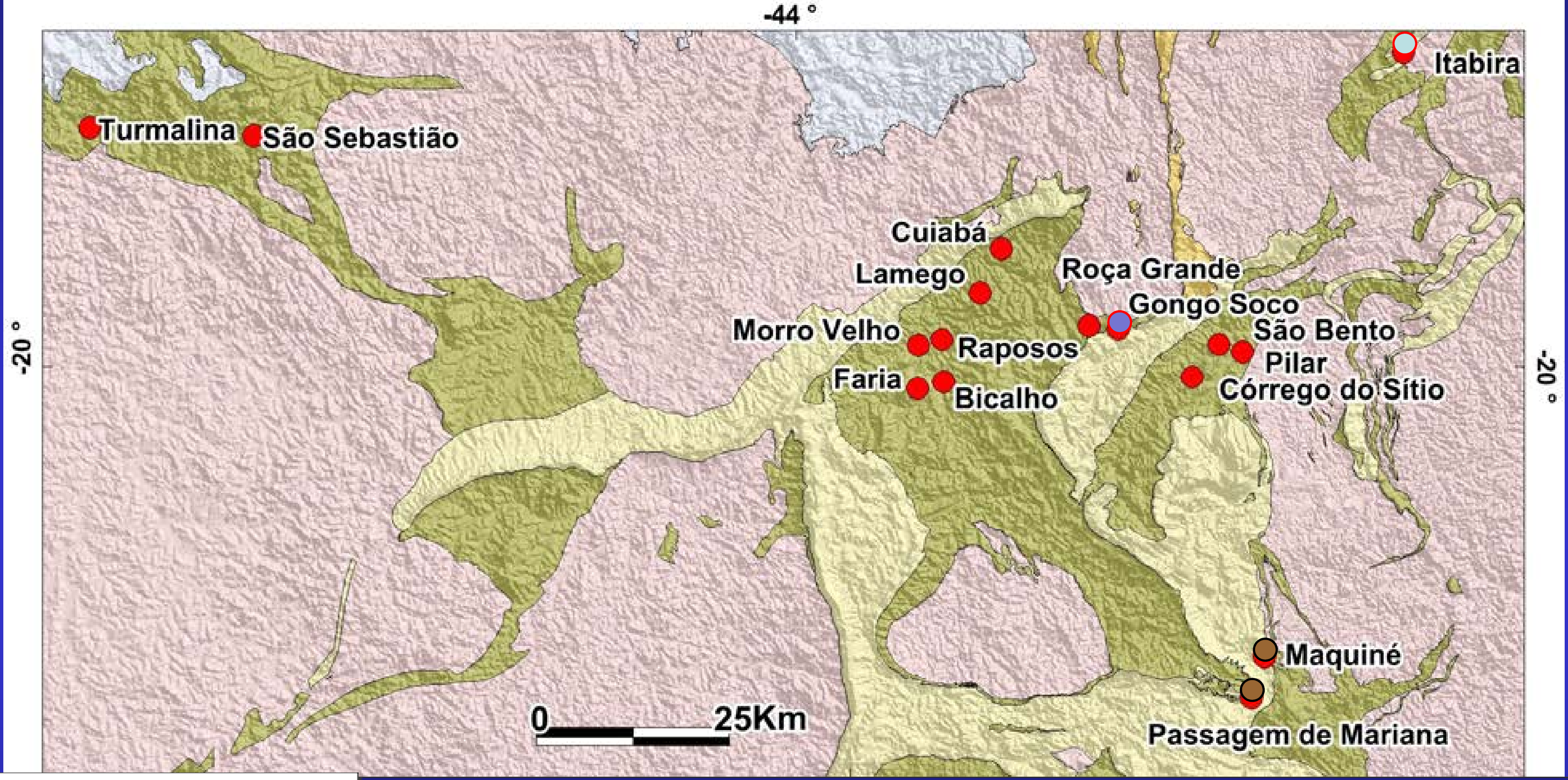


1)



2)

# Quadrilátero Ferrífero Archaean orogenic deposits



**Simplified Legend**

| | |
|---|---|
| 🟧 | Espinhaço Supergroup |
| ⬜ | São Francisco Supergroup |
| 🟨 | Minas Supergroup |
| 🟩 | Rio das Velhas Supergroup |

**(I) Archaean Rio das Velhas Supergroup, greenstone belt ●**
**(orogenic gold deposits)**

**(II) Metasedimentary Palaeproterozoic Minas Supergroup**

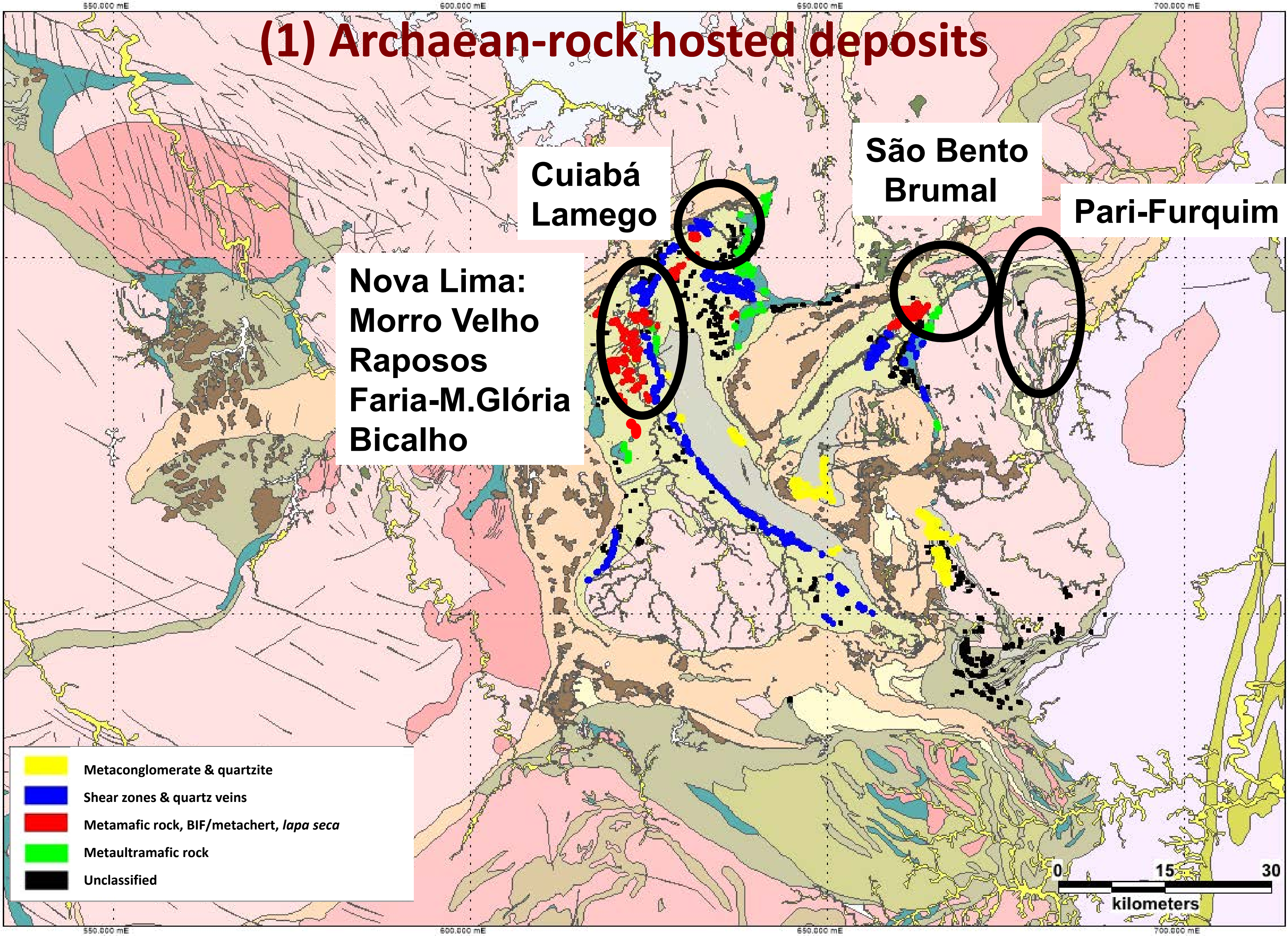
**1- orogenic gold in the contact with Nova Lima schists ●**

*2- basal Py-rich conglomerates*

**3- lodes of Pd-rich Au in friable iron ore (*jacutinga*) ●**

Lobato et al. (2015) – Gold in Brazil

# (1) Archaean-rock hosted deposits



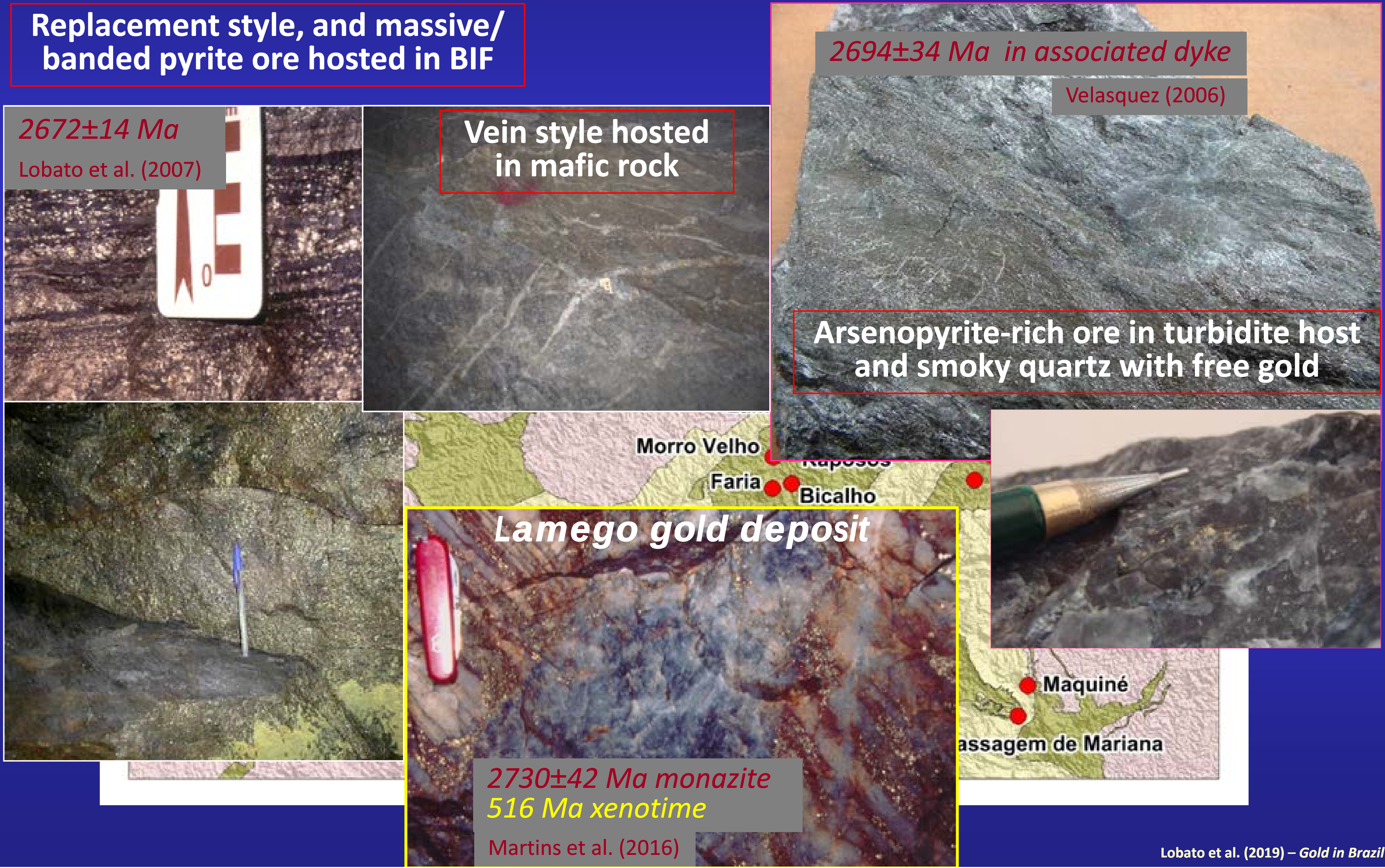
Marco Aurelio da Costa, Semin. Qualificação, MSc UFMG

Lobato et al. (2019) – *Gold in Brazil*

# Quadrilátero Ferrífero Archaean orogenic deposits

## *World-class Cuiabá deposit*

## *Córrego do Sítio lineament*



**Replacement style, and massive/ banded pyrite ore hosted in BIF**

*2672±14 Ma*

Lobato et al. (2007)

**Vein style hosted in mafic rock**

*2694±34 Ma in associated dyke*

Velasquez (2006)

**Arsenopyrite-rich ore in turbidite host and smoky quartz with free gold**

***Lamego gold deposit***

*2730±42 Ma monazite*
*516 Ma xenotime*

Martins et al. (2016)

Lobato et al. (2019) – *Gold in Brazil*

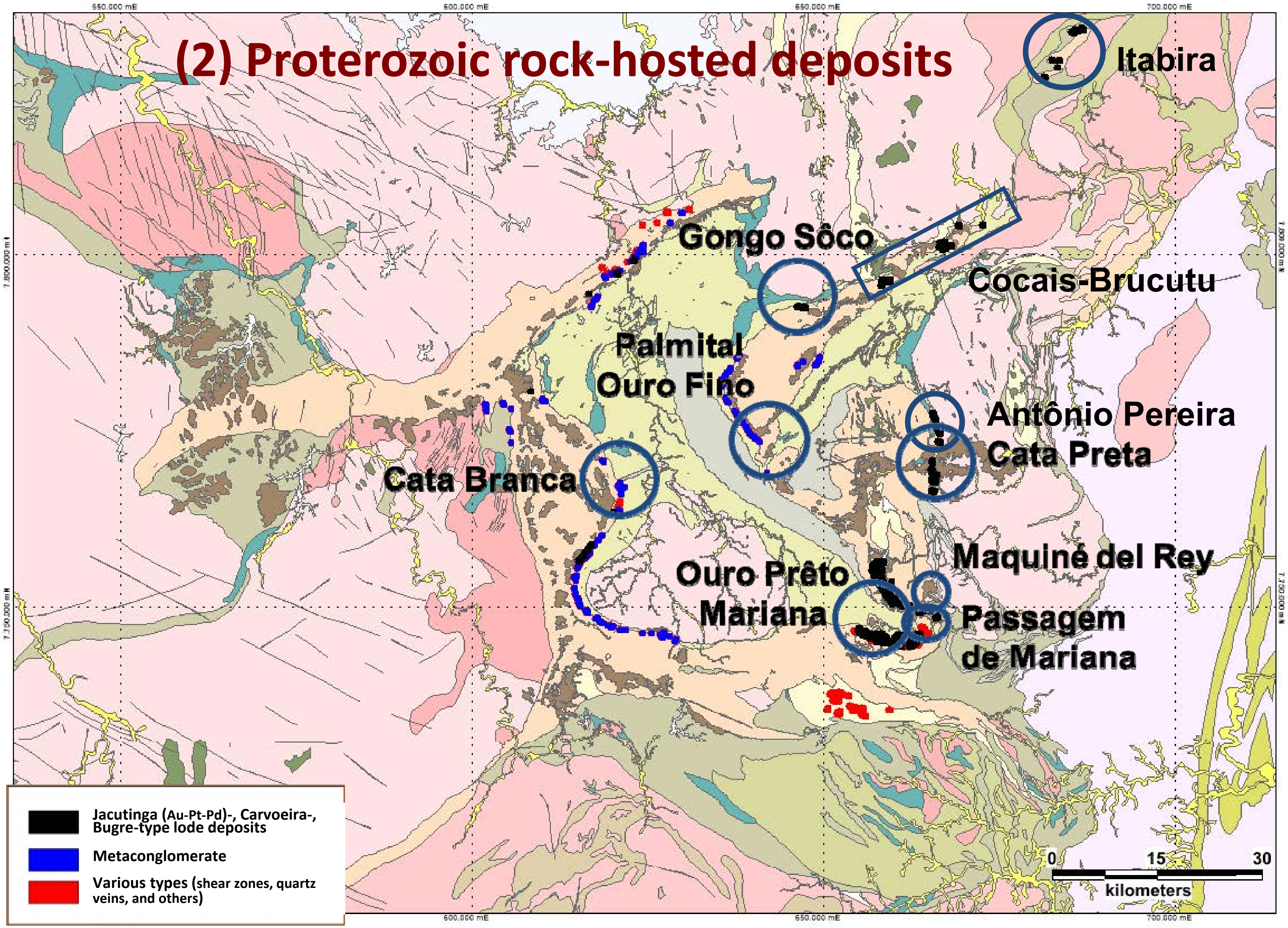
# Quadrilátero Ferrífero Archaean orogenic deposits

(1) Cuiabá

(1) Lamego

(1) Lamego

# (2) Proterozoic rock-hosted deposits



- ■ Jacutinga (Au-Pt-Pd)-, Carvoeira-, Bugre-type lode deposits
- 🟦 Metaconglomerate
- 🟥 Various types (shear zones, quartz veins, and others)

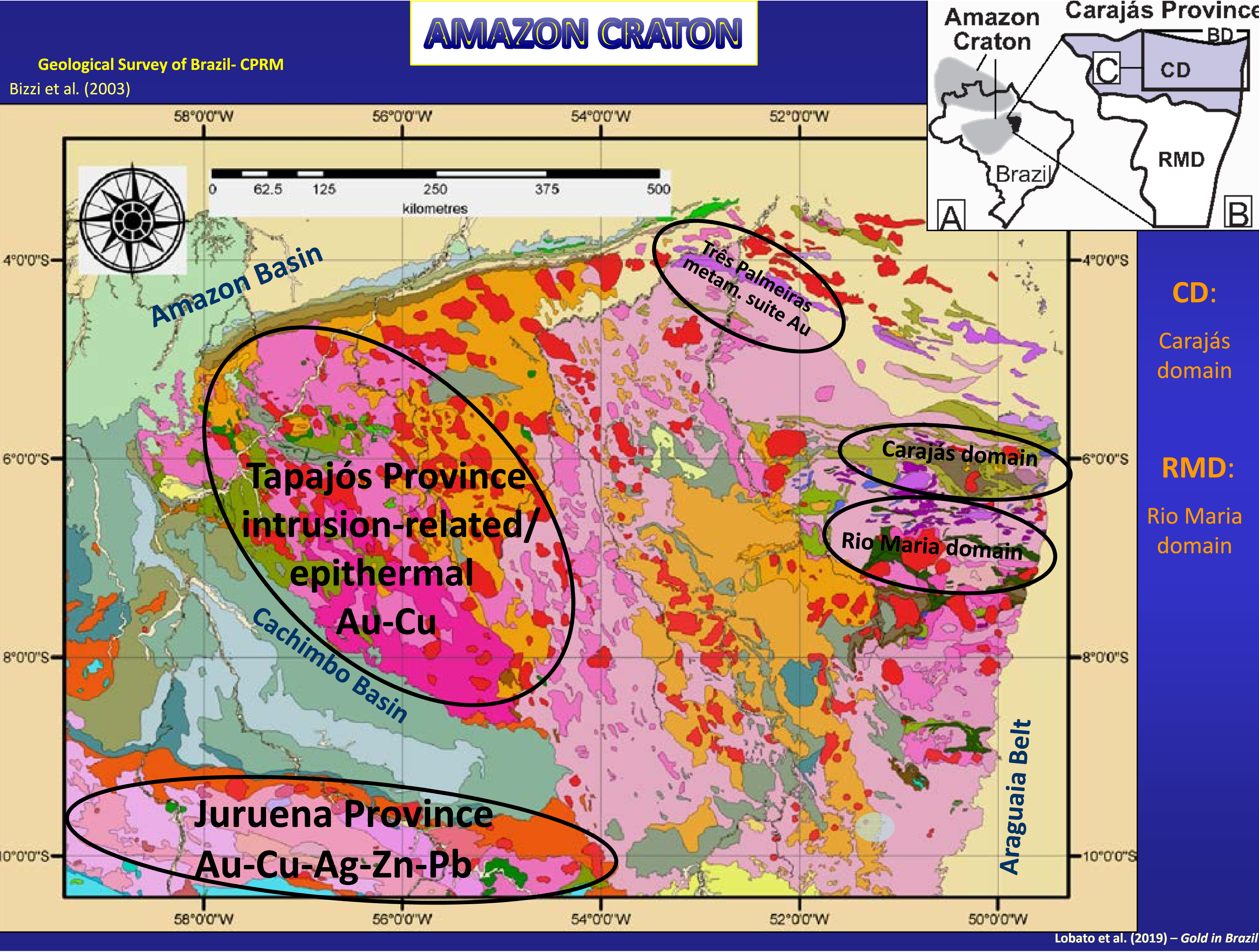
Marco Aurelio da Costa, Semin. Qualificação MSc UFMG

Lobato et al. (2019) – *Gold in Brazil*

# AMAZON CRATON

Geological Survey of Brazil- CPRM

Bizzi et al. (2003)



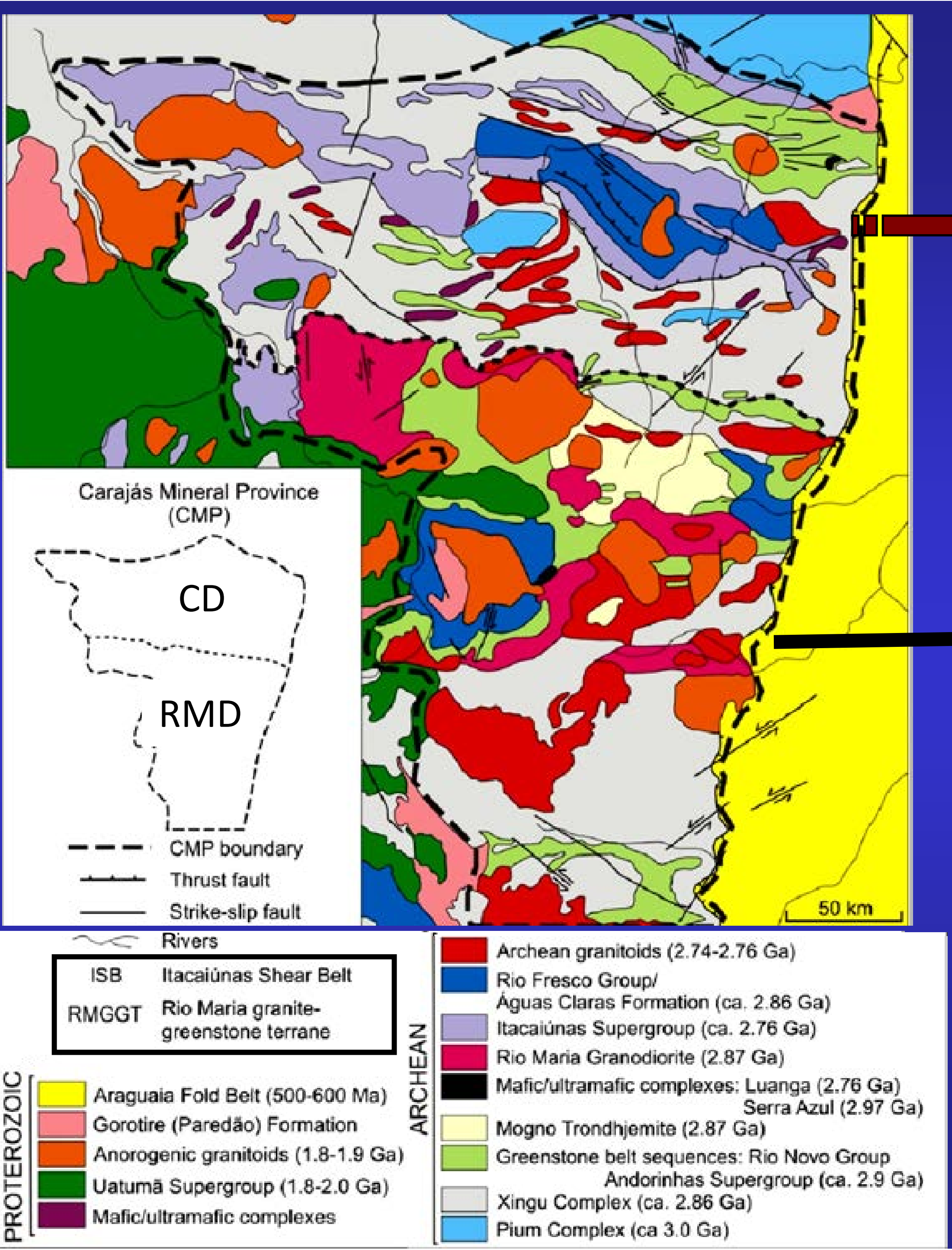
**CD:**

Carajás domain

**RMD:**

Rio Maria domain

Lobato et al. (2019) – *Gold in Brazil*



- **Northern** **Carajás (Neo-Archaean) domain**

➡ **2.76 to 2.68 Ga granitoids, metavolcano-sedimentary rocks & the Meso-Archaean igneous and metamorphic Pium & Xingu complexes**

- **Southern** **Rio Maria (Meso-Archaean) domain**

➡ **3.05 to 2.85 Ga granite-greenstone rocks**

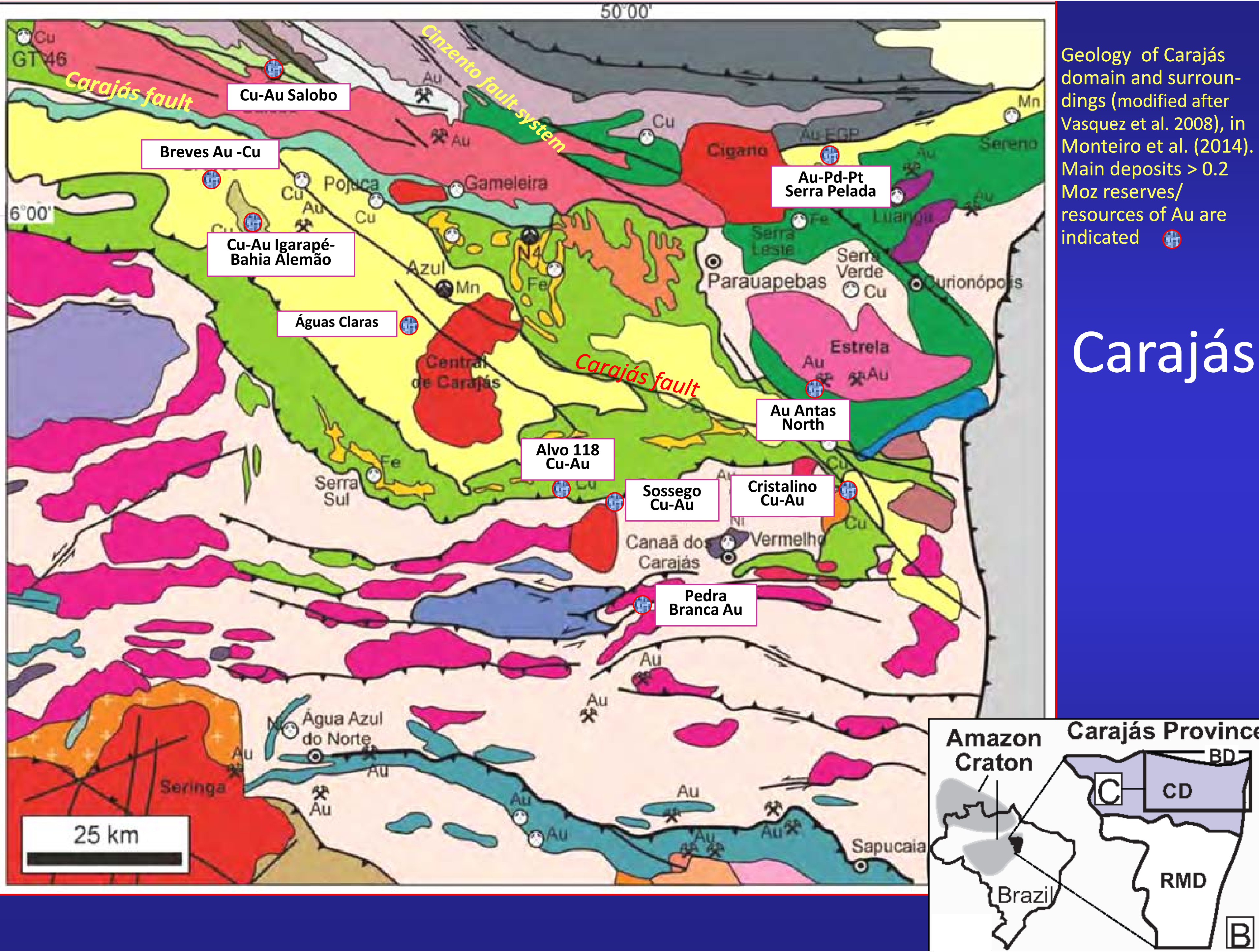
# Carajás mineral province

(Villas & Santos 2001)

Lobato et al. (2019) – *Gold in Brazil*

# Carajás

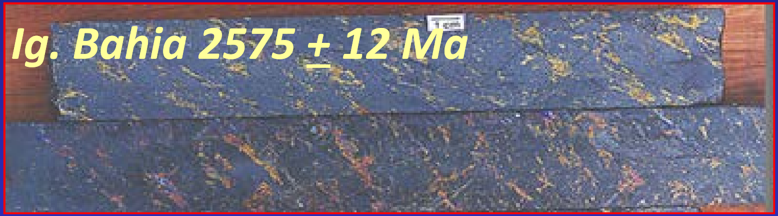
Geology of Carajás domain and surroundings (modified after Vasquez et al. 2008), in Monteiro et al. (2014). Main deposits > 0.2 Moz reserves/ resources of Au are indicated ●



# Carajás - Archaean & Palaeoproterozoic IOCGs

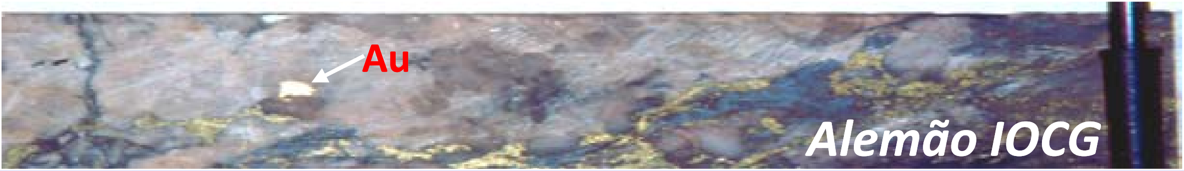
## *Alemão IOCG*

Chalcopyrite ore in magnetitite



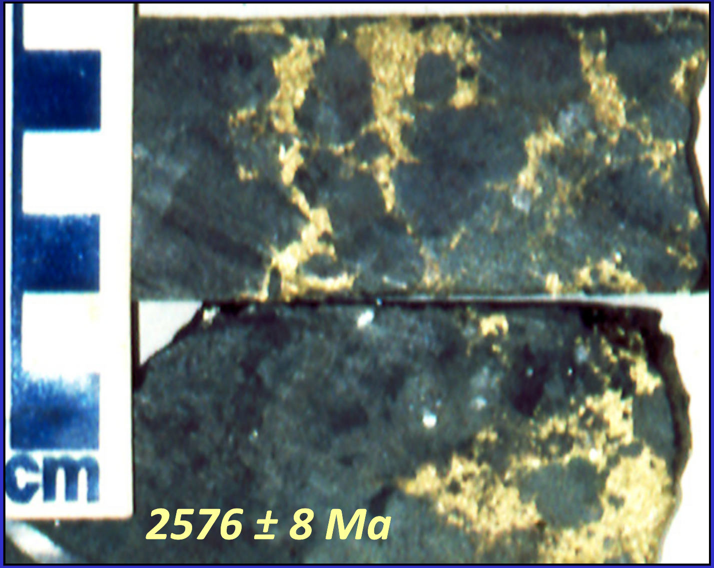
*Ig. Bahia 2575 ± 12 Ma*

Feldspar-rich breccia. Chalcopyrite at the expense of magnetite. Free gold grain.



***Alemão IOCG***

## *Salobo IOCG*



*2576 ± 8 Ma*

***Sequeirinho IOCG***

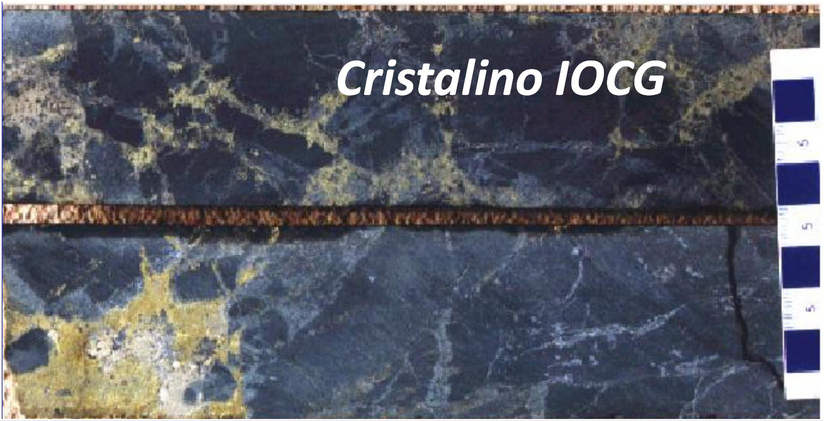
*2.71–2.68 Ga*

Sulphide breccias

***Sossego IOCG***

*1.90–1.88 Ga*

Brecciated mafic rock. Hornbl, Cpy, Magnet, Py, & Apatite.



***Cristalino IOCG***

see review in Moreto et al. (2015)

# Carajás - Palaeoproterozoic Au-bearing polymettalic systems

Gold nugget, 60 kg

## *Serra Pelada Au-Pd-Pt*

1997

*Garimpeiros* gold rush

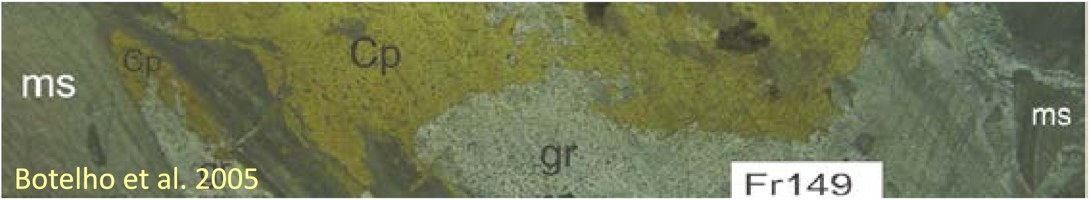
## *Águas Claras Cu(Au)*

Carbon gold-rich ore

Berni et al. (2014)

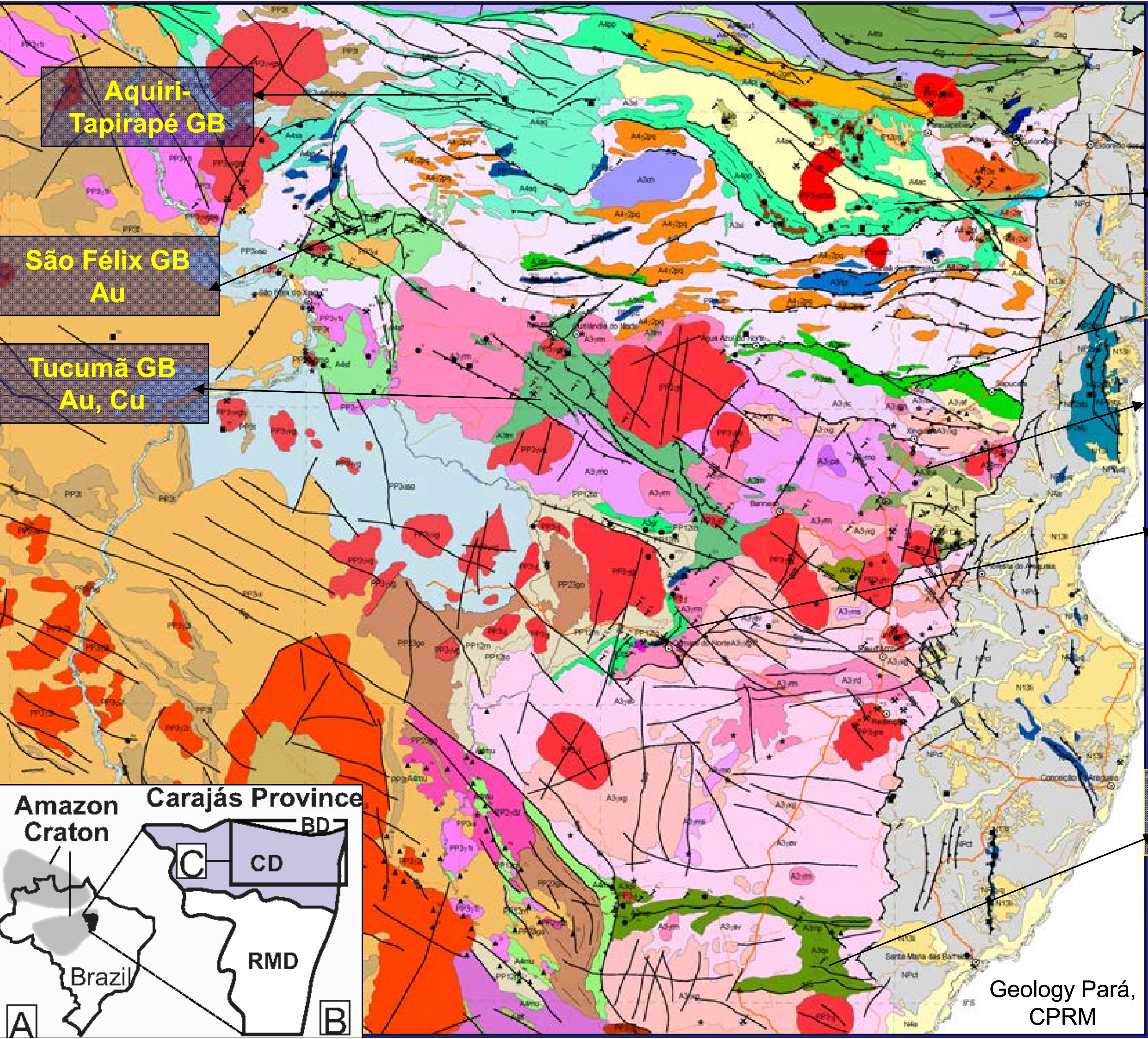
## *Breves Cu-Au-(W–Bi–Mo–Sn)*

Chalcopyrite breccia in hydrothermally altered granite



Botelho et al. 2005

Lobato et al. (2019) – *Gold in Brazil*



**Aquiri-Tapirapé GB**

**São Félix GB Au**

**Tucumã GB Au, Cu**

Buritirama Sq. Mn, Fe

Grão Pará GB Fe, BM, Au, U, Ni, PGE

**Sapucaia GB Au**

Rio Maria GB Au, Fe

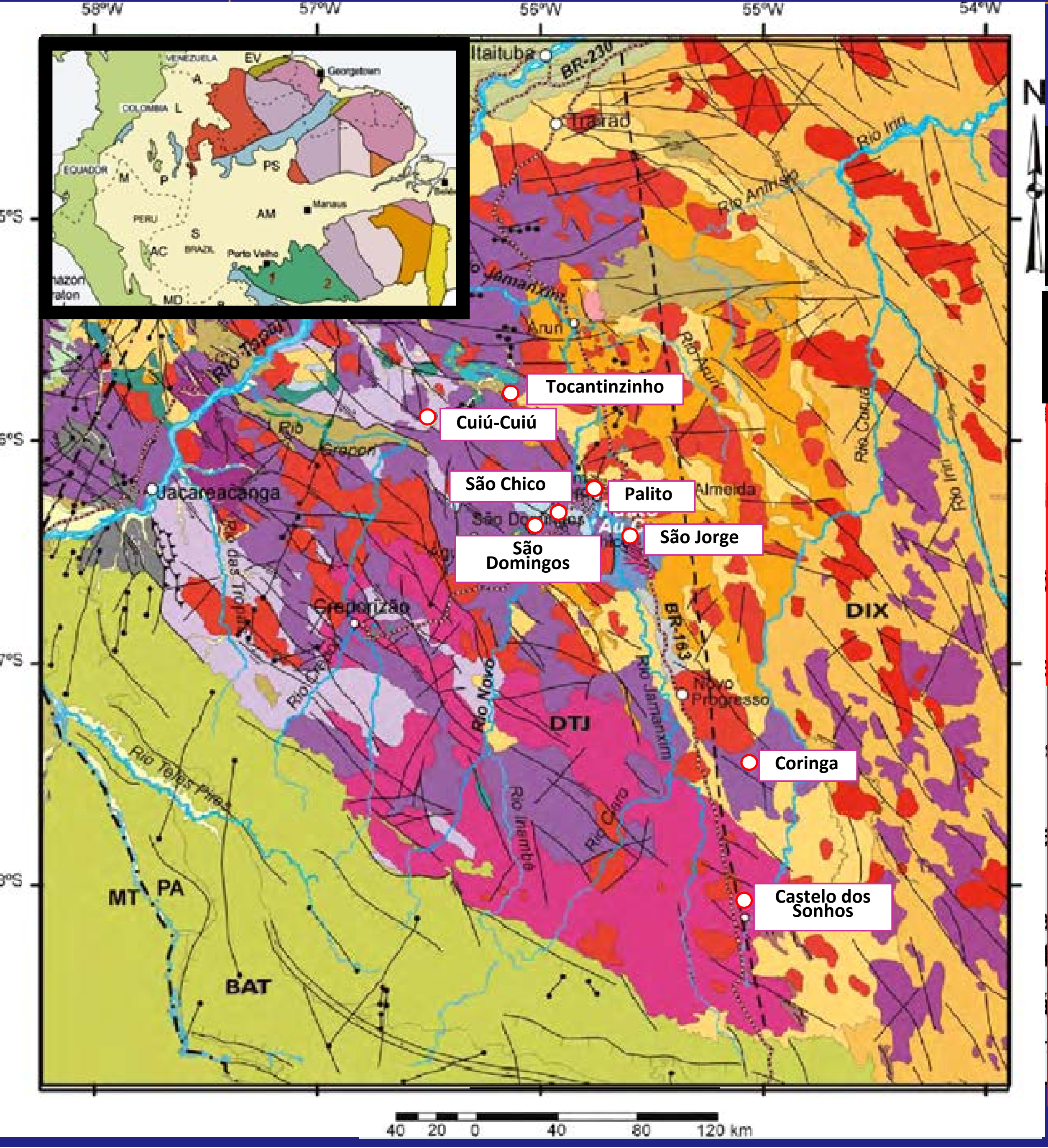
**Gradaús GB Au, BM**

**Inajá GB Au, Fe**

Geology Pará, CPRM

Lobato et al. (2019) – *Gold in Brazil*

# Tapajós – Palaeoproterozoic magmatic-hydrothermal systems

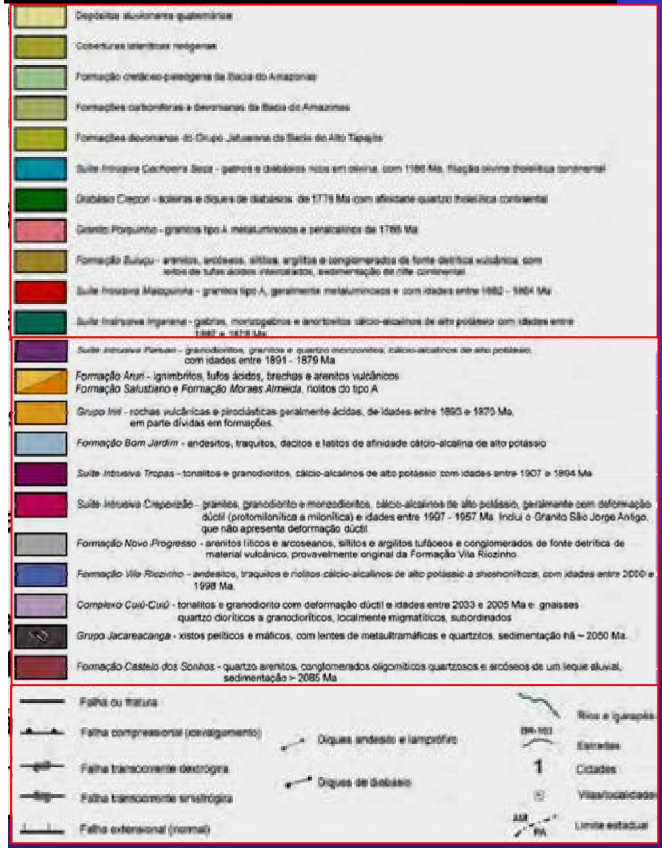


# Tapajós

Geology Tapajós domain (modified from Vasquez et al. 2008), in Juliani et al. (2014).

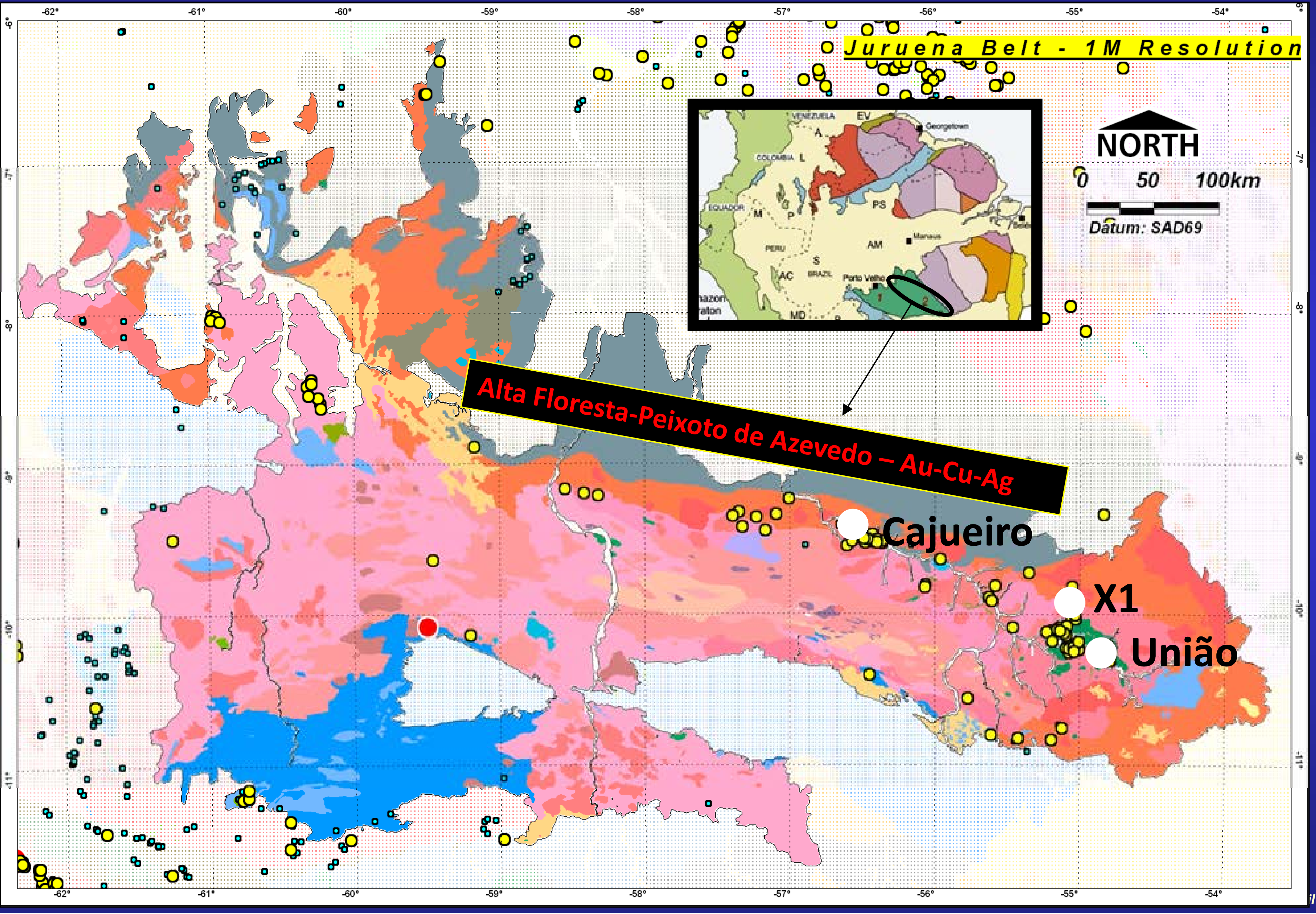
Main deposits > 0.2 Moz reserves/resources of **Au** are indicated ○

## Two main mineralisation epochs: 2.0 & 1.88 Ga



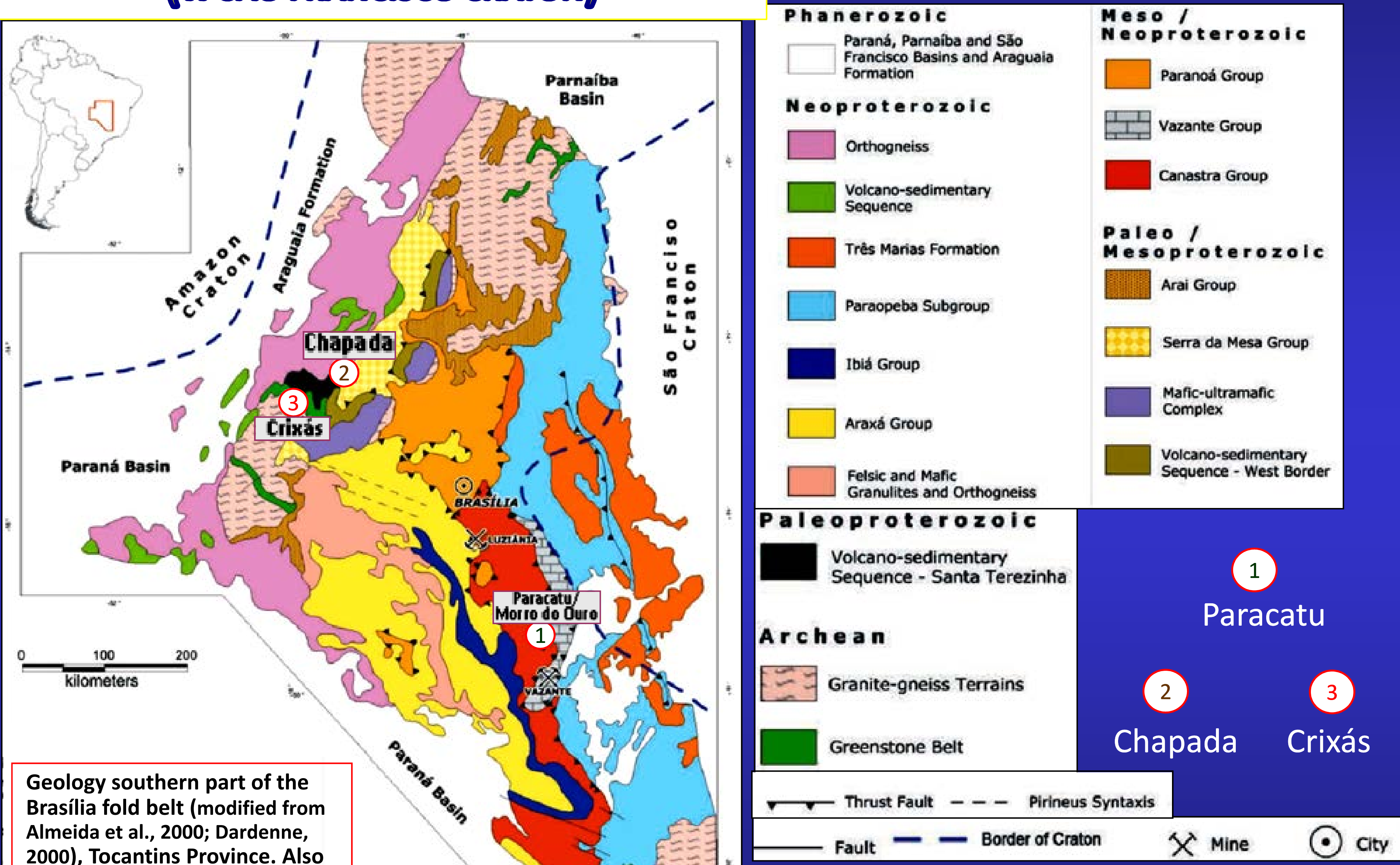
Lobato et al. (2019) – *Gold in Brazil*

# Juruena – magmatic-hydrothermal systems



# BRASÍLIA BELT, TOCANTINS PROVINCE (W SÃO FRANCISCO CRATON)

# Mara Rosa-Crixás gold province & Paracatu orogenic gold deposit



Geology southern part of the Brasília fold belt (modified from Almeida et al., 2000; Dardenne, 2000), Tocantins Province. Also shown are Crixás and Chapada. From Oliver et al. (2015).

① Paracatu

② Chapada

③ Crixás

Lobato et al. (2019) – *Gold in Brazil*

# Morro do Ouro (orogenic) gold deposit – Neoproterozoic metasedimentary rocks

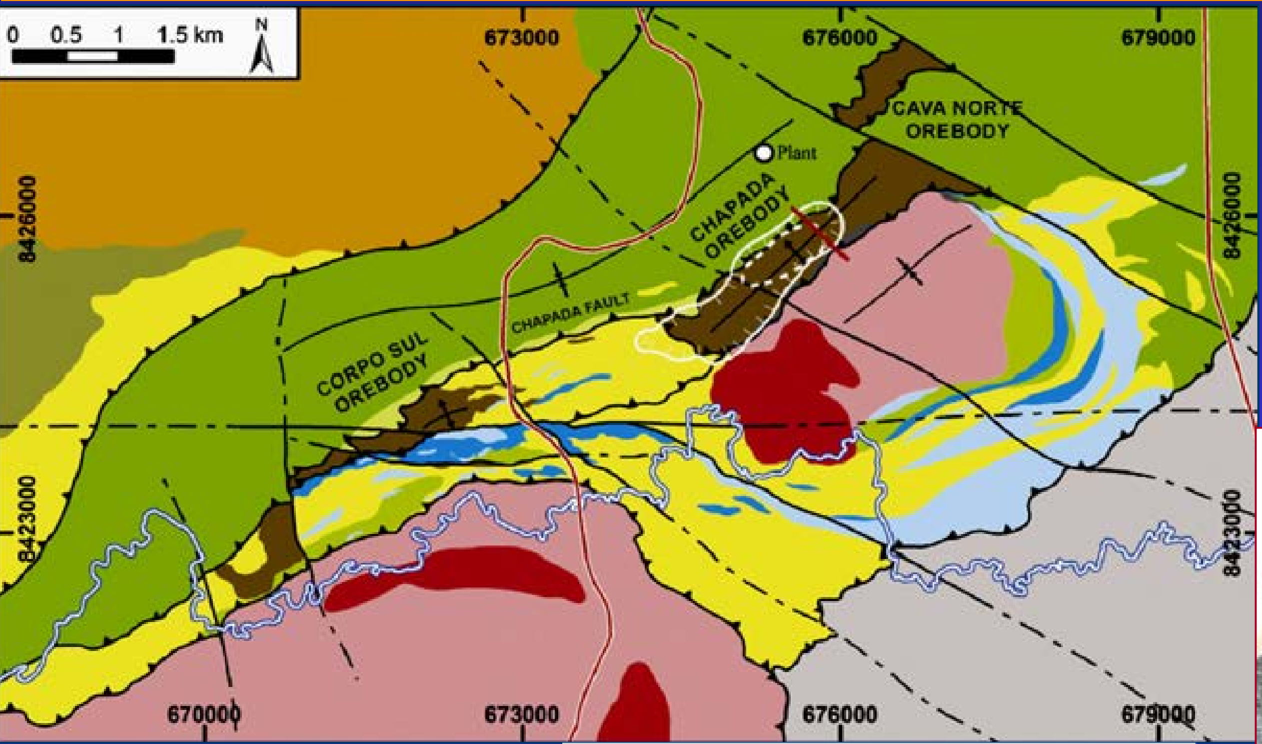

Brazil’s largest operating gold mine !!!


*Gold-rich boudins*


*Carbonaceous phyllite*

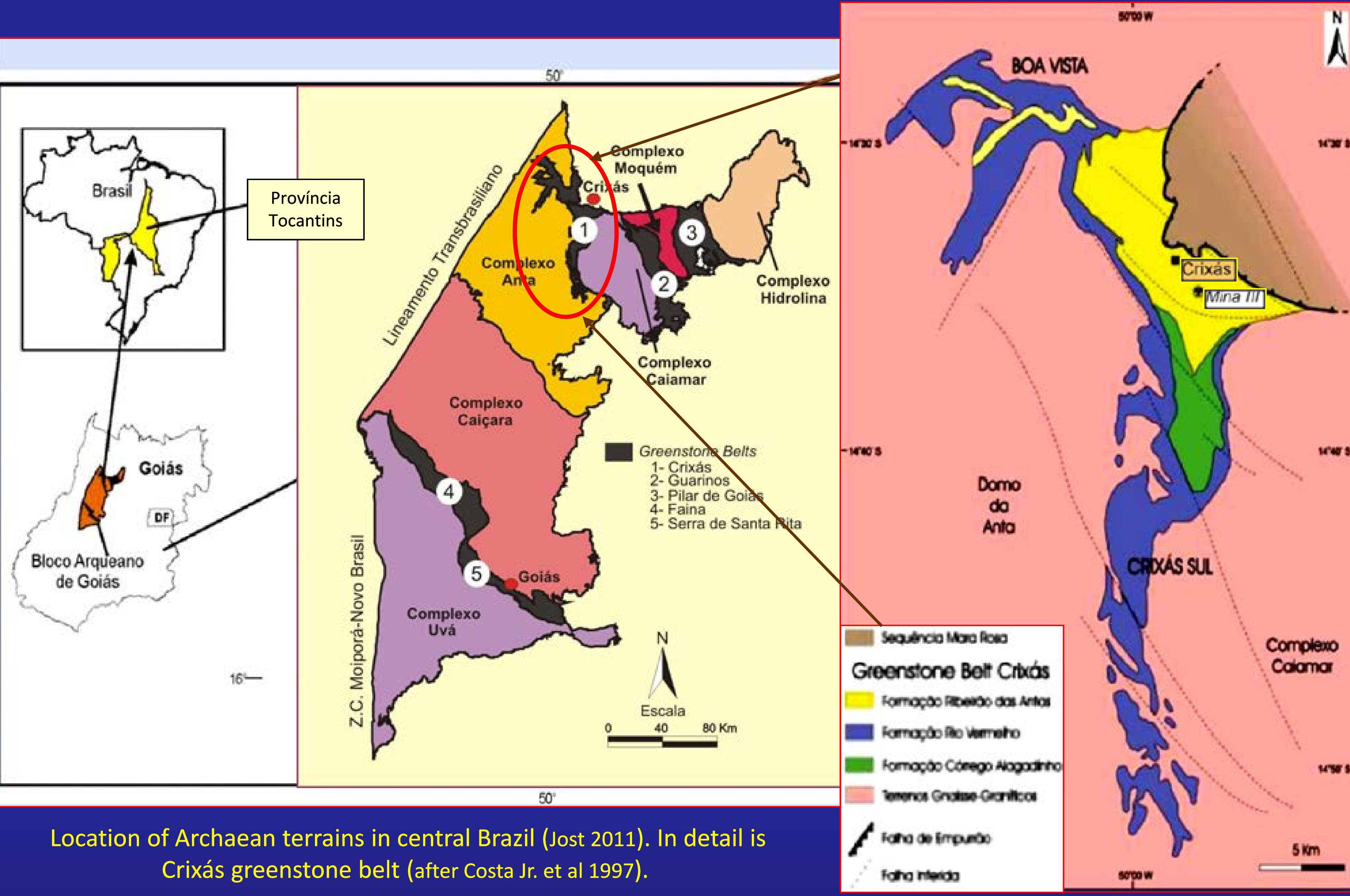
Lobato et al. (2019) – *Gold in Brazil*

# Chapada Cu-Au porphyry type deposit - Neoproterozoic



Geology of the Chapada Cu-Au deposit, with lithologic units, orebodies, major structures, and final contour area of open pit mine of ore body (from Oliveira et al. 2016).

# Crixás Archaean-Palaeoproterozoic greenstone belts & surroundings (orogenic gold)

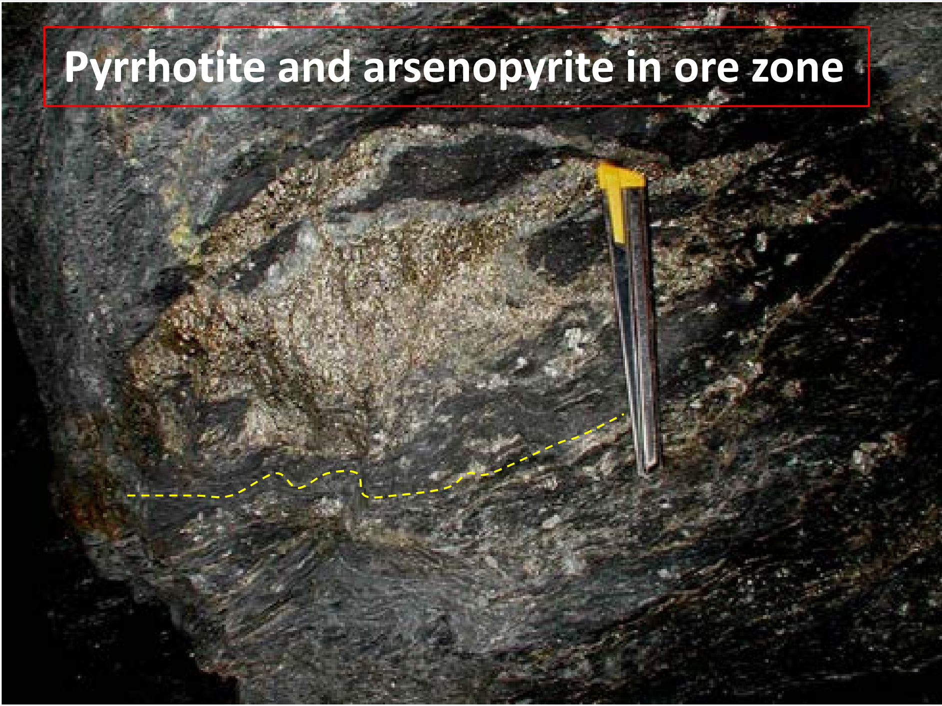


Location of Archaean terrains in central Brazil (Jost 2011). In detail is Crixás greenstone belt (after Costa Jr. et al 1997).

Lobato et al. (2019) – *Gold in Brazil*

# Crixás Archaean-Palaeoproterozoic greenstone belts & surroundings (orogenic gold)

Low-grade ore above qtz vein

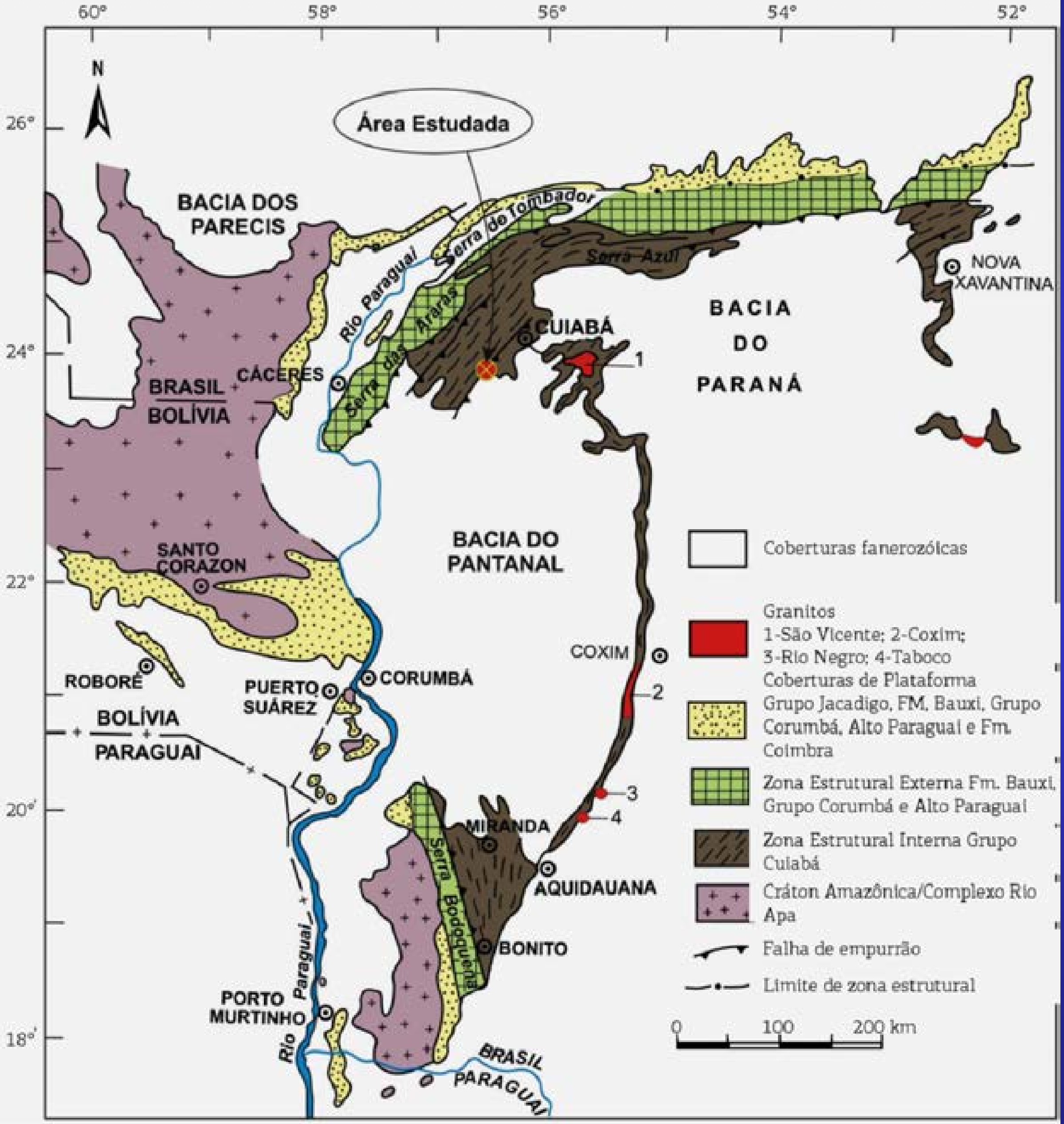


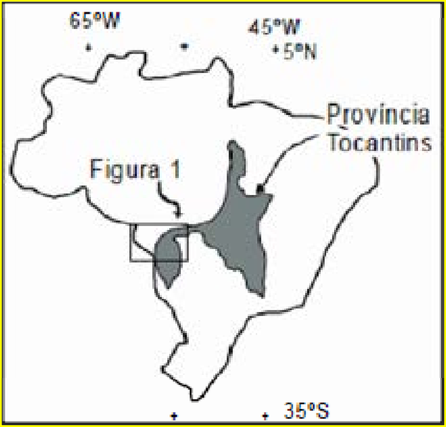
Pyrrhotite and arsenopyrite in ore zone

# PARAGUAY BELT, TOCANTINS PROVINCE
## (SW SÃO FRANCISCO CRATON)

**Orogenic gold, Baixada Cuiabana, MT**

**Neoproterozoic metasedimentary rocks**



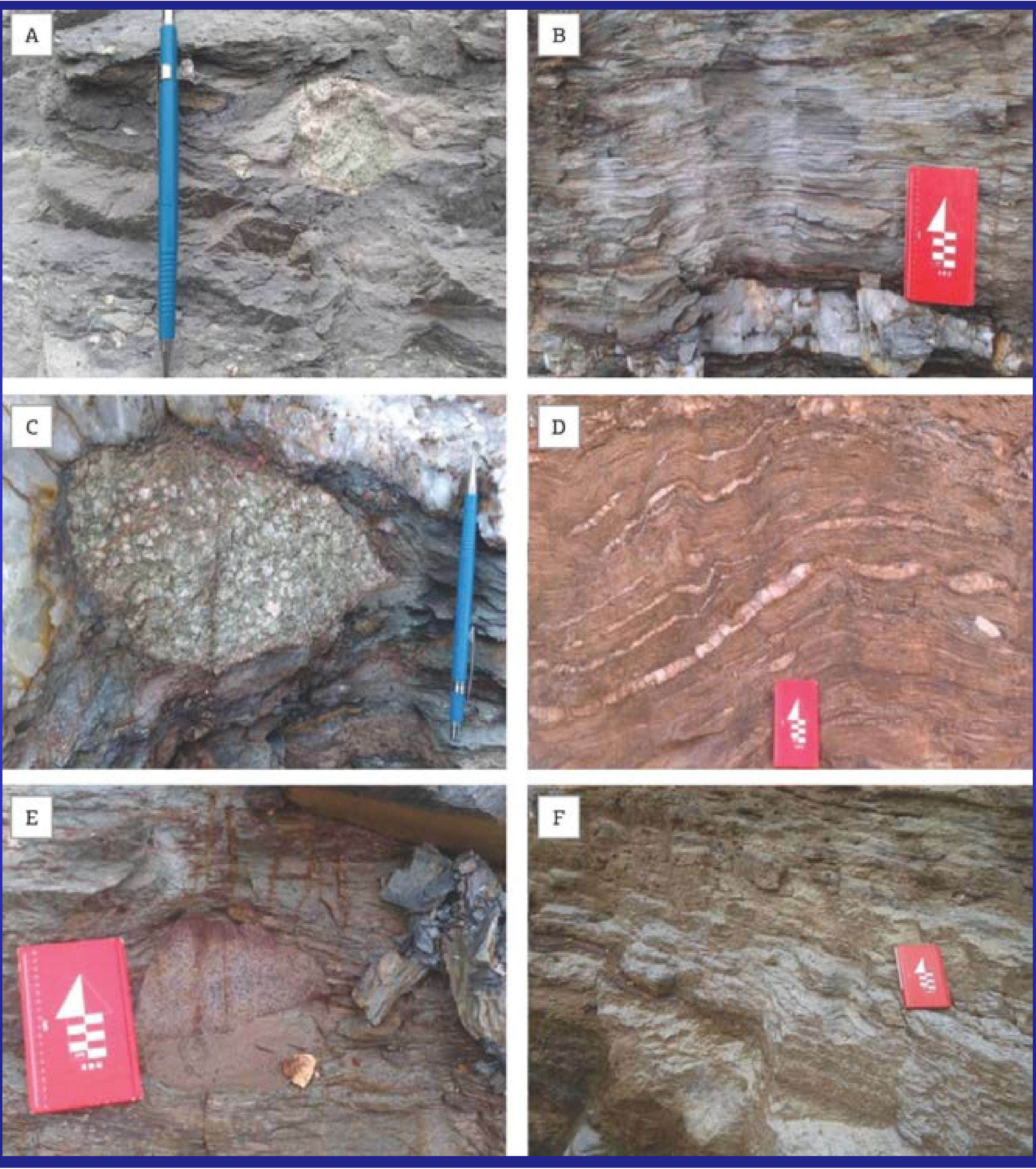


Regional geological map, showing the Cangas-Poconé lineament. Modified after Alvarenga & Trompette (1993). Reproduced from Costa et al. (2015)

Lobato et al. (2019) – *Gold in Brazil*

# Orogenic gold, Baixada Cuiabana, MT

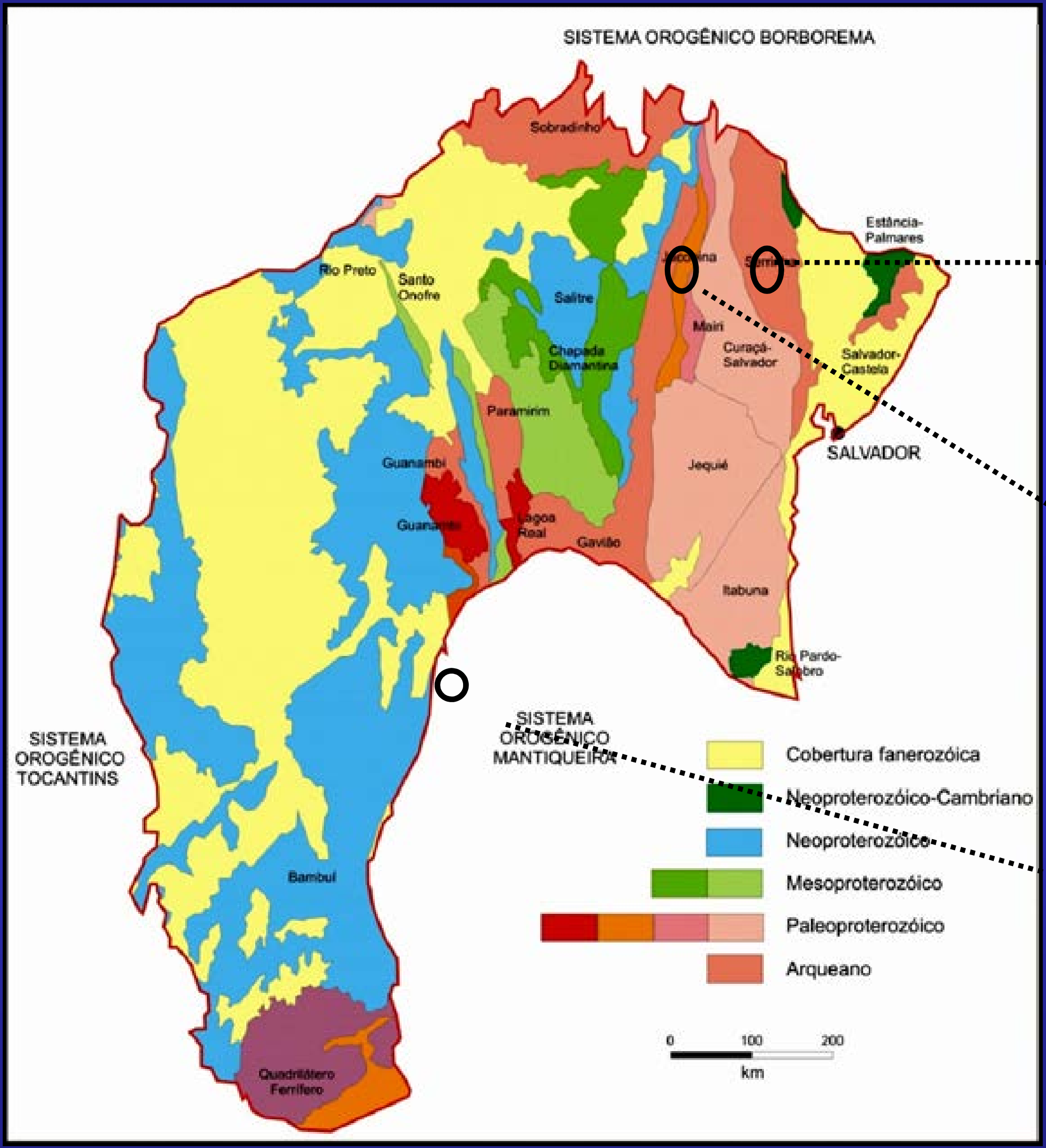
## Neoproterozoic



**(A)** Grey phyllite; **(B)** Same showing slaty cleavage (Sn); **(C)** Phyllite with granite pebbles ; **(D)** Metarhythimite defined by altenating cm-thick bands of grey sericite phyllite and meta-sandstone; **(E)** Metarenite pebbles in grey phyllite; **(F)** Fine- to medium-grained, brownish metarenite (from Costa et al., 2015)

Lobato et al. (2019) – *Gold in Brazil*

# EASTERN SÃO FRANCISCO CRATON & ARAÇUAÍ BELT



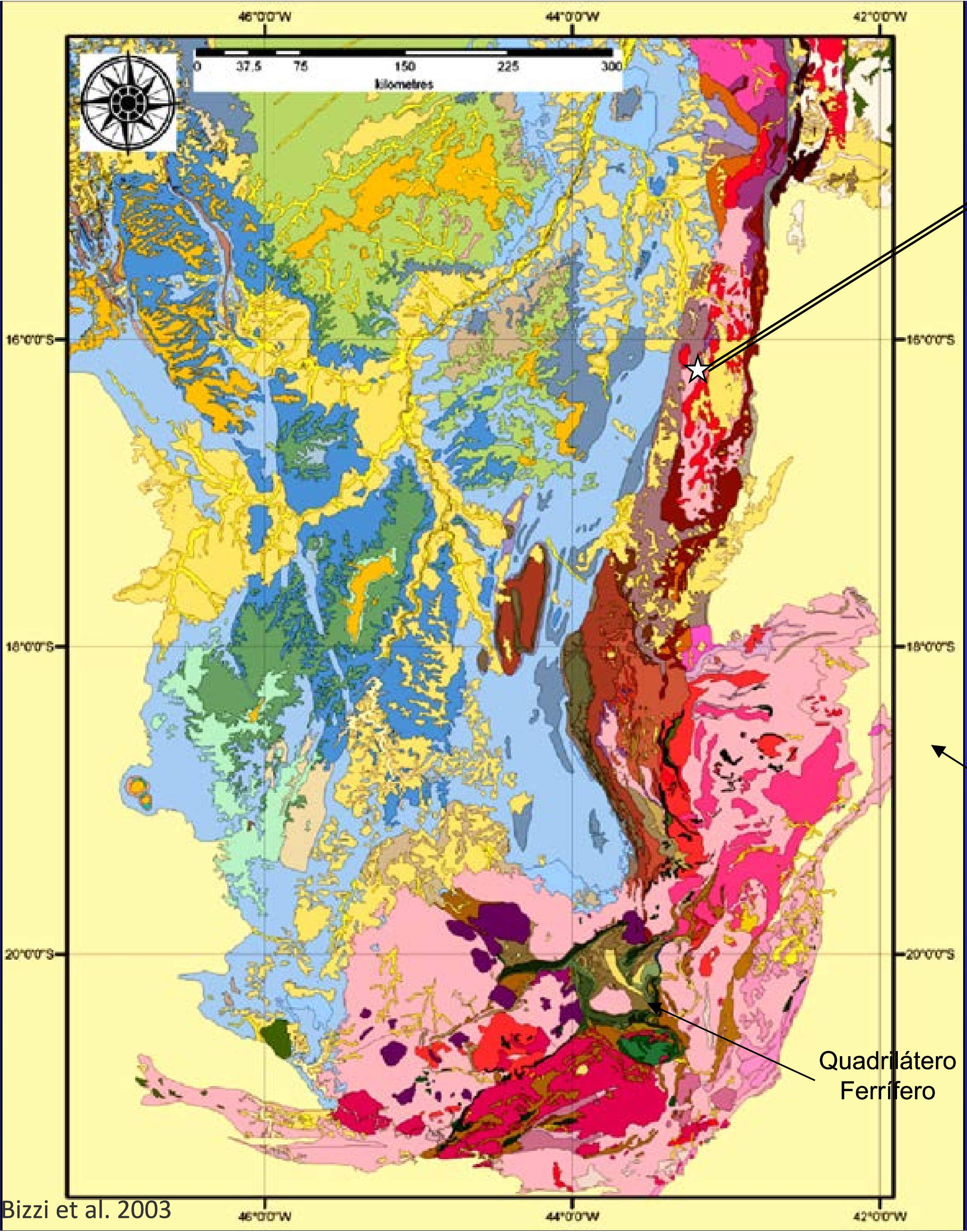
Fazenda Brasileiro

Jacobina

Riacho dos Machados

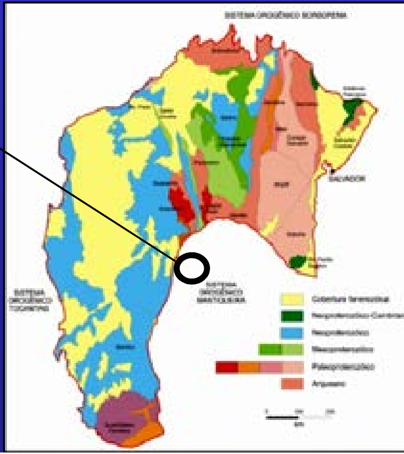
Lobato et al. (2019) – *Gold in Brazil*

Riacho dos Machados



Bizzi et al. 2003

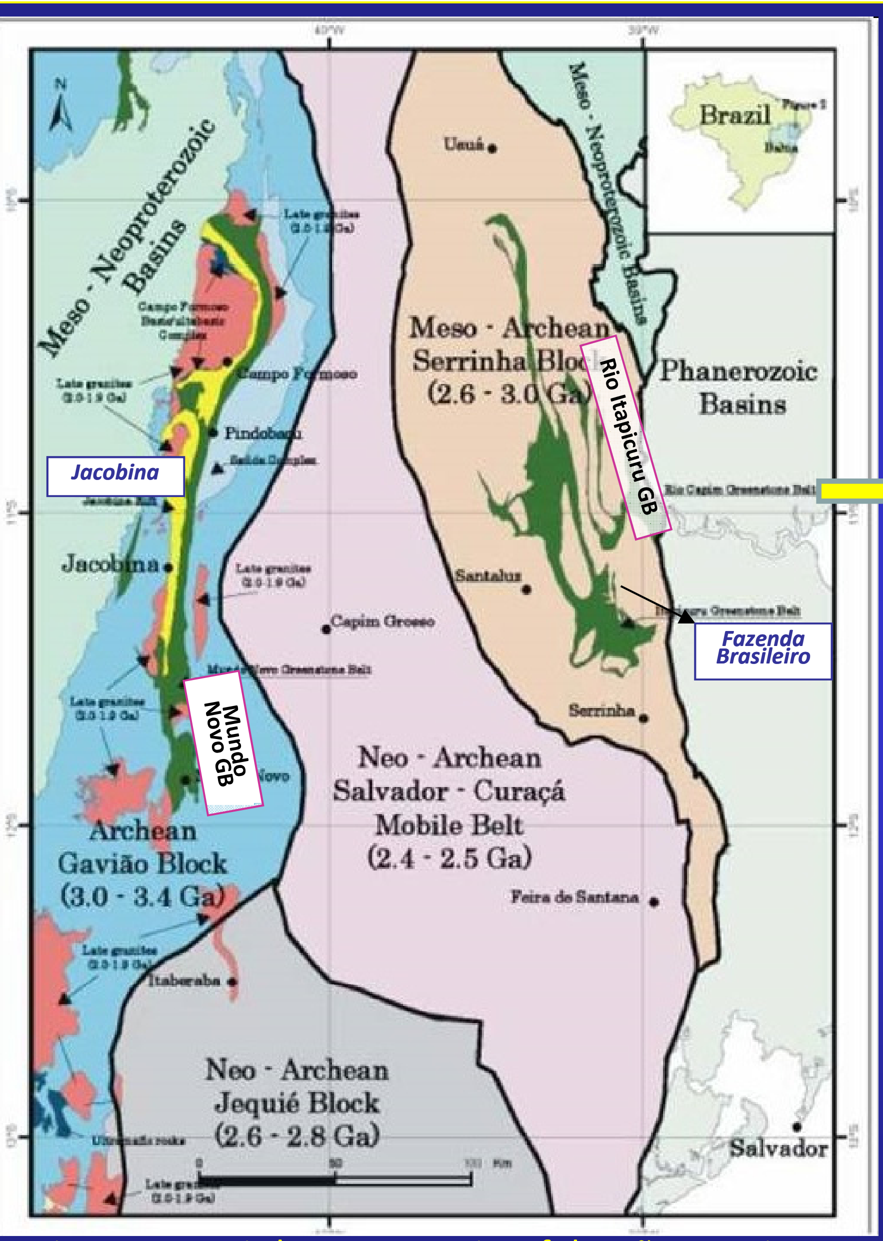
Palaeoproterozoic (??) volcano-sedimentary belt in São Francisco Craton basement window (through thin-skinned Araçuaí belt)

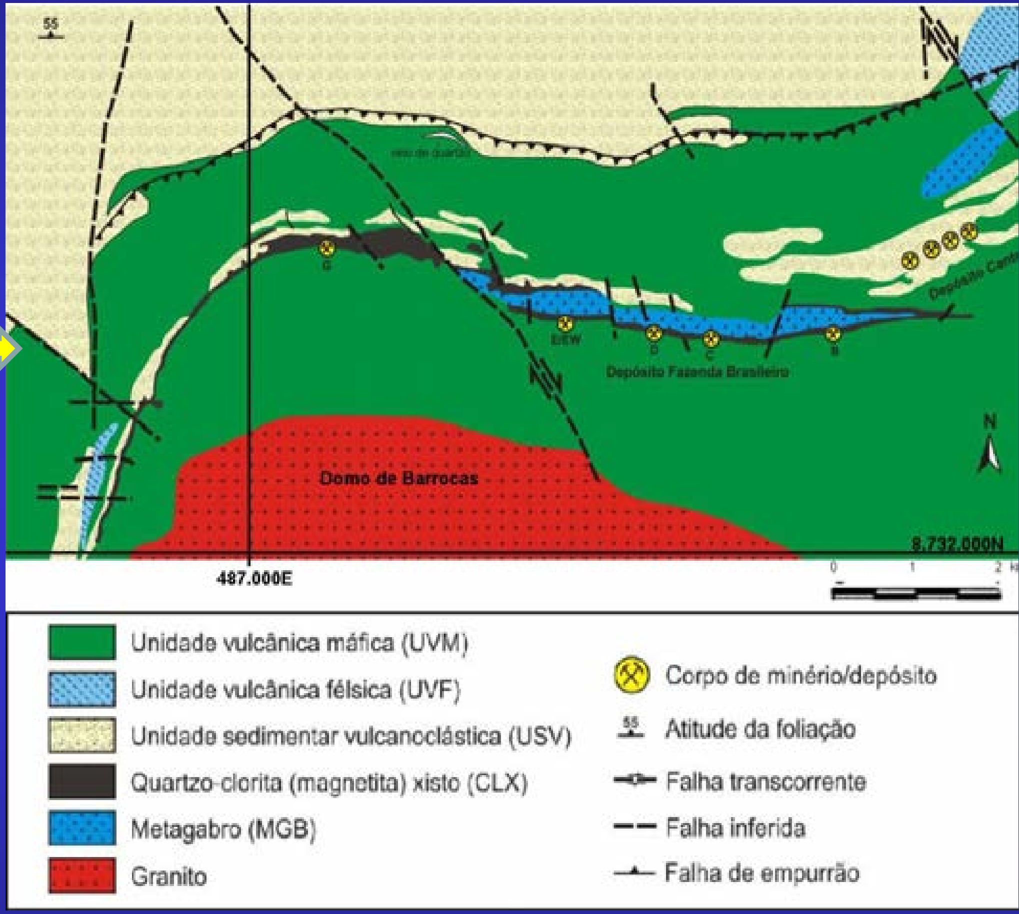


# EASTERN SÃO FRANCISCO CRATON

## Palaeproterozoic Rio Itapicuru GB orogenic gold & Palaeproterozoic Jacobina (Archaean?*) pyrite metaconglomerates

*Teles (2013)

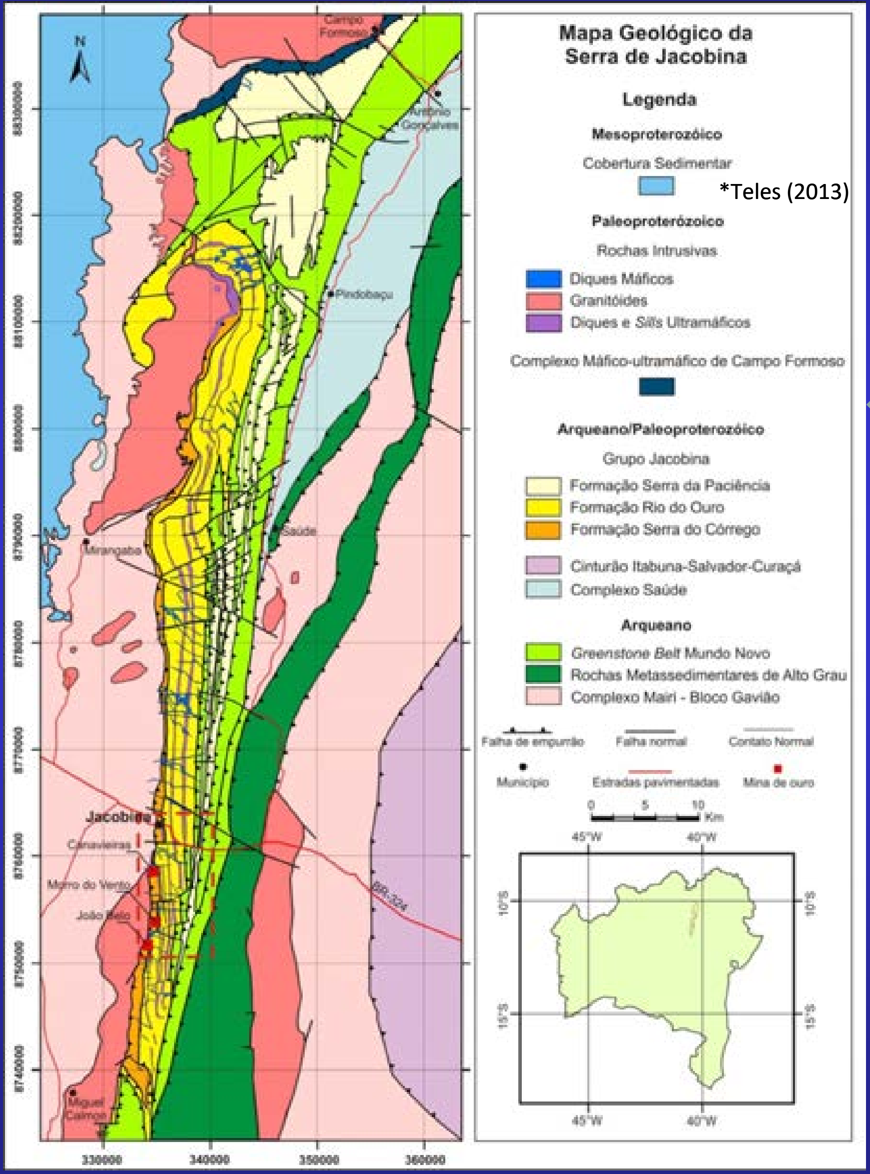




Main geotectonic basement units of the São Francisco craton in Bahia state. The Jacobina and Fazenda Brasileiro gold deposits are indicated (modified after Sampaio et al., 2001; Sabaté et al., 1990).

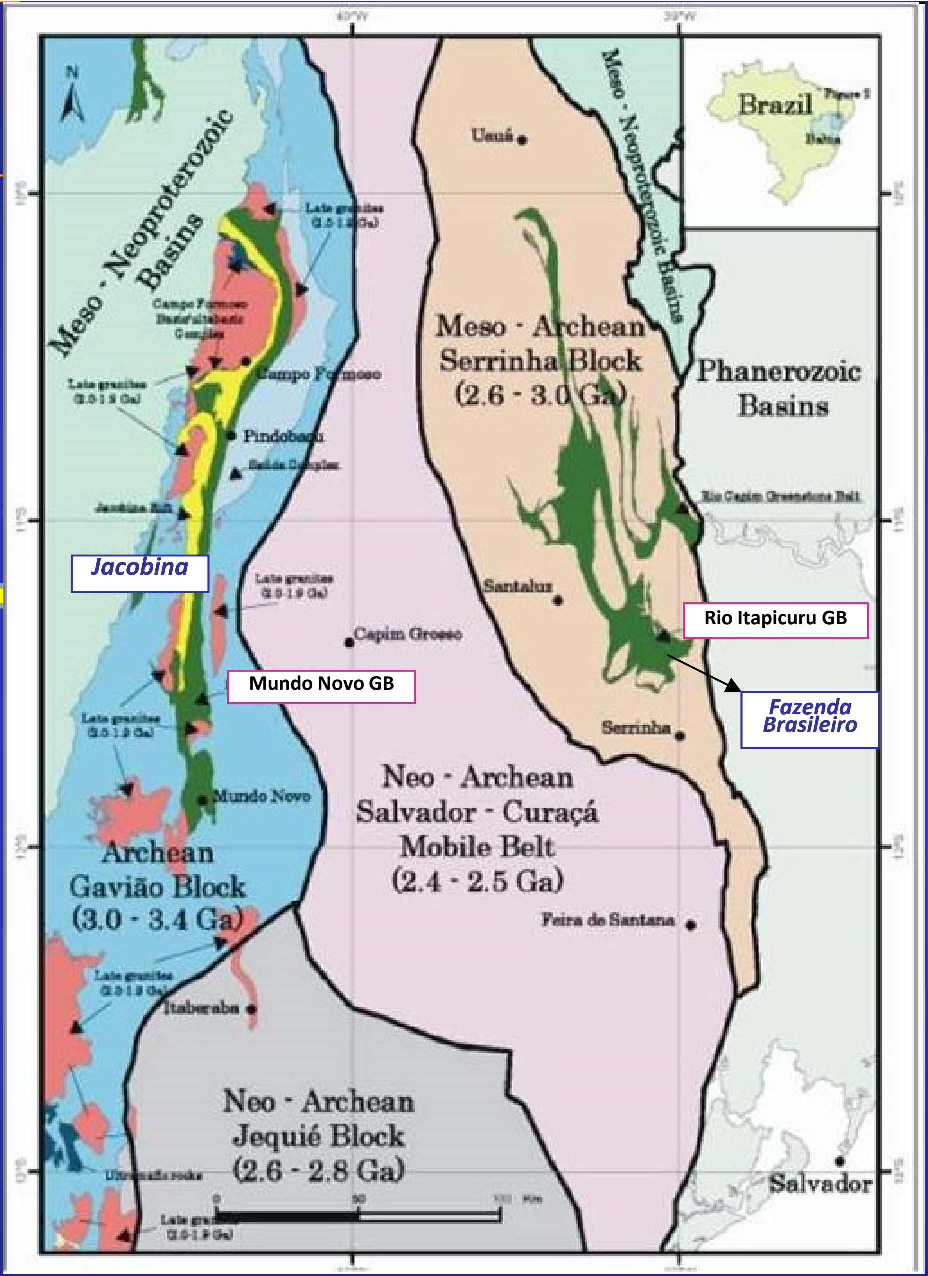
Lobato et al. (2019) – *Gold in Brazil*

# Palaeoproterozoic Rio Itapicuru GB orogenic gold & Palaeoproterozoic Jacobina (Archaean?*) pyrite metaconglomerates



*Teles (2013)

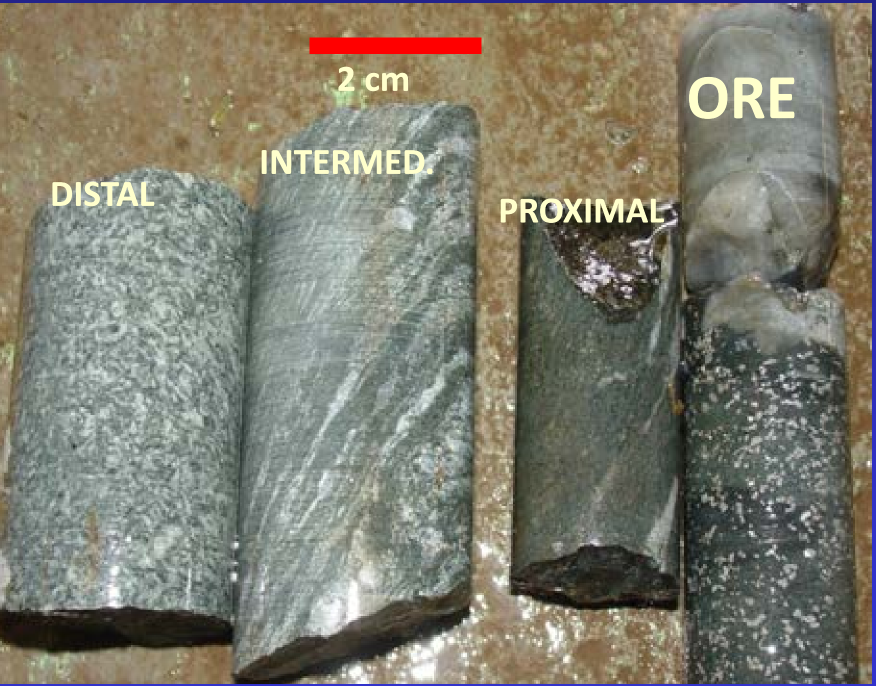
Geological map of the Serra de Jacobina (modified after Pearson et al., 2005), showing the main units (from Teles, 2013)



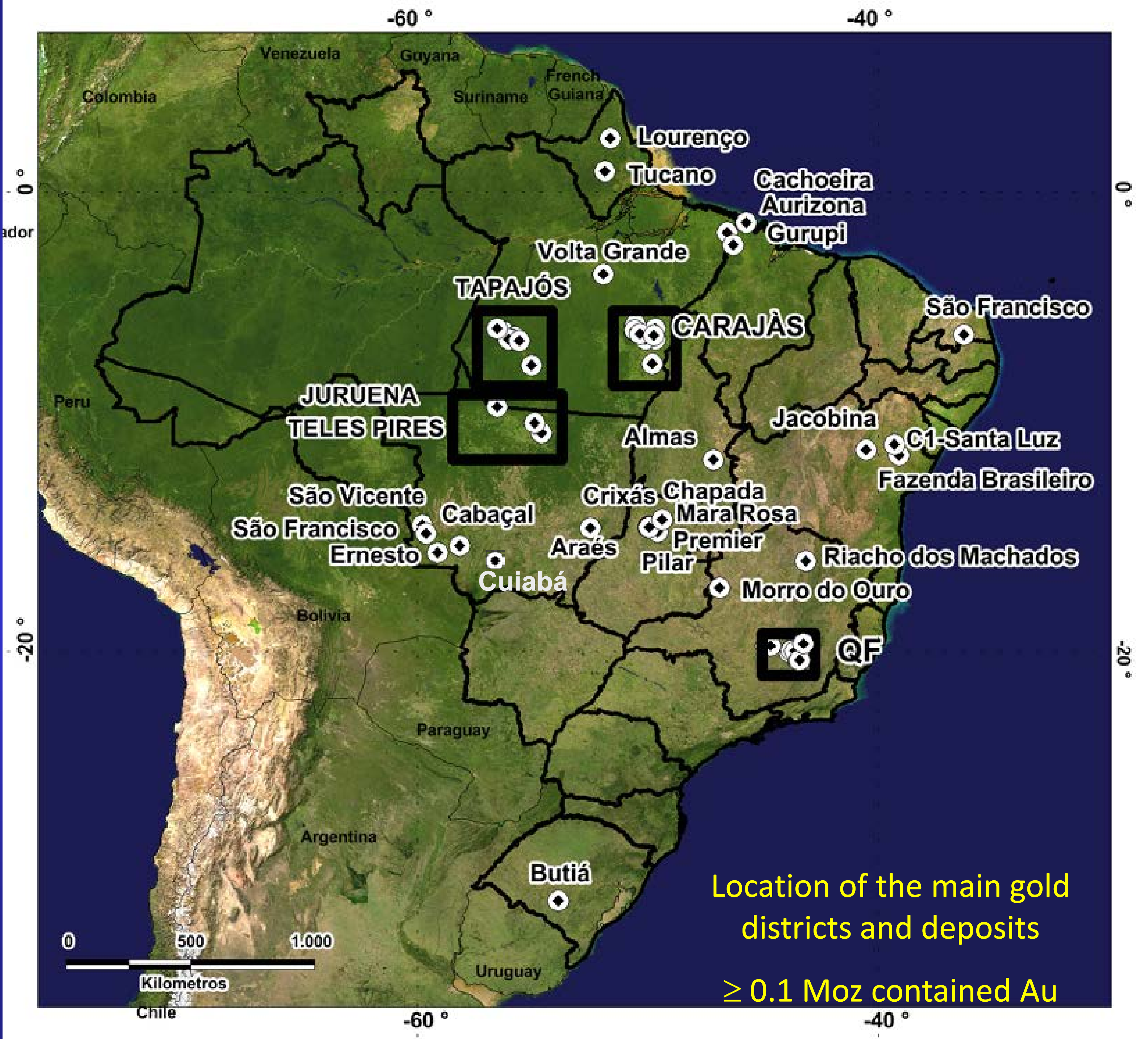
Main geotectonic basement units of the São Francisco craton in Bahia state. The Jacobina and Fazenda Brasileiro gold deposits are indicated (modified after Sampaio et al., 2001; Sabaté et al., 1990).

Lobato et al. (2019) – *Gold in Brazil*

## Fazenda Brasileiro orogenic gold deposit



## Metaconglomerate-hosted Jacobina deposit



Location of the main gold districts and deposits

≥ 0.1 Moz contained Au

019) – *Gold in Brazil*

# Types of Known Deposits

- ➔ Majority of significant deposits → orogenic gold systems mainly in mid-crustal levels
  Very large (> 15 Moz) sediment-hosted deposit; e.g., Morro do Ouro

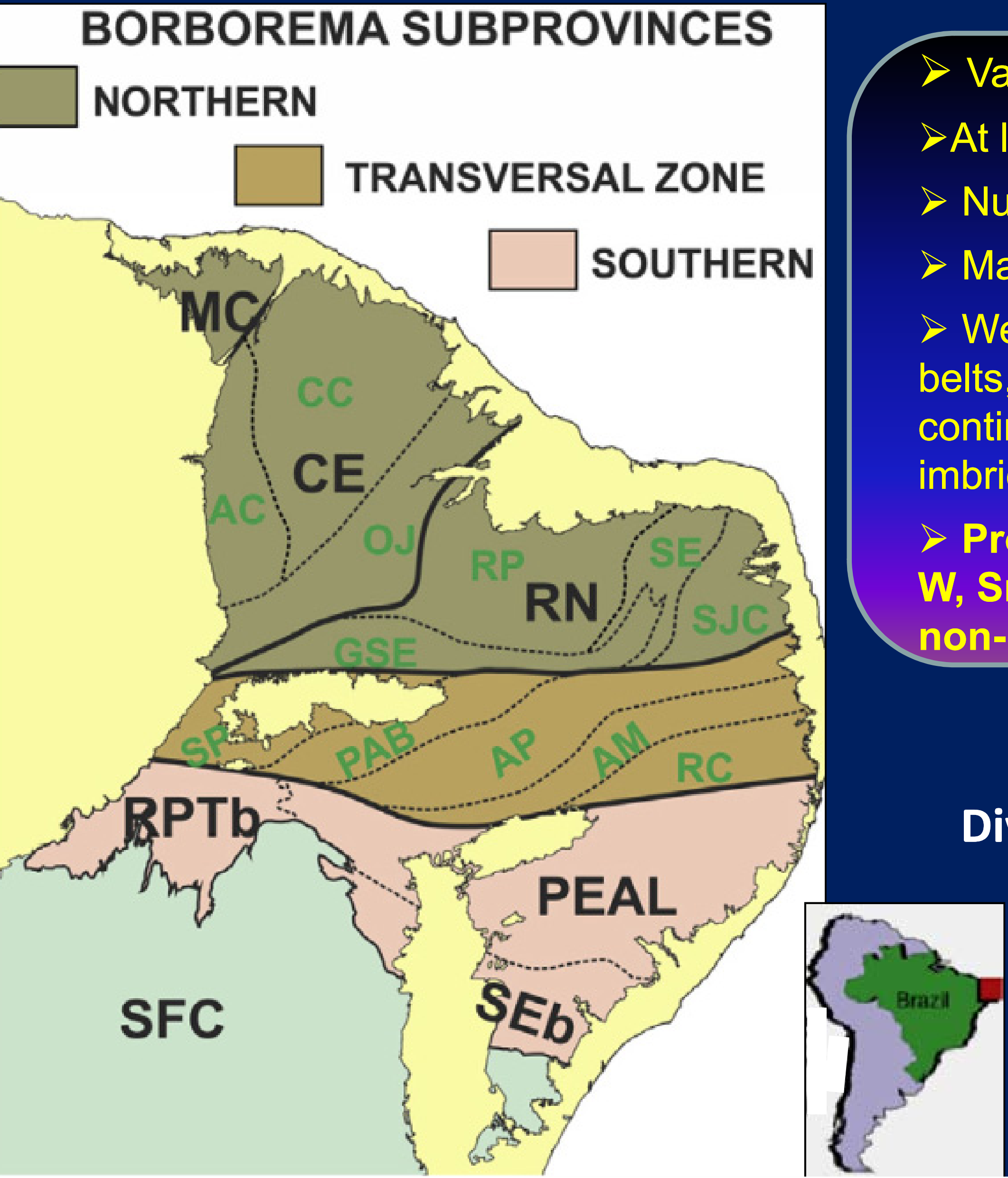
- ➔ Several significant gold-rich IOCG deposits
  All in the Carajás Mineral Province

- ➔ Magmatic-hydrothermal (porphyry, epithermal, intrusion-related?) deposits in Carajás, Tapajós, Lavras do Sul (RS)
  Many small; only one large deposit - Breves Carajás

- ➔ Metamorphosed porphyry Cu-Au systems in Goiás: Chapada

# Perspectives - Underexplored Au systems

## ➢ Borborema Province

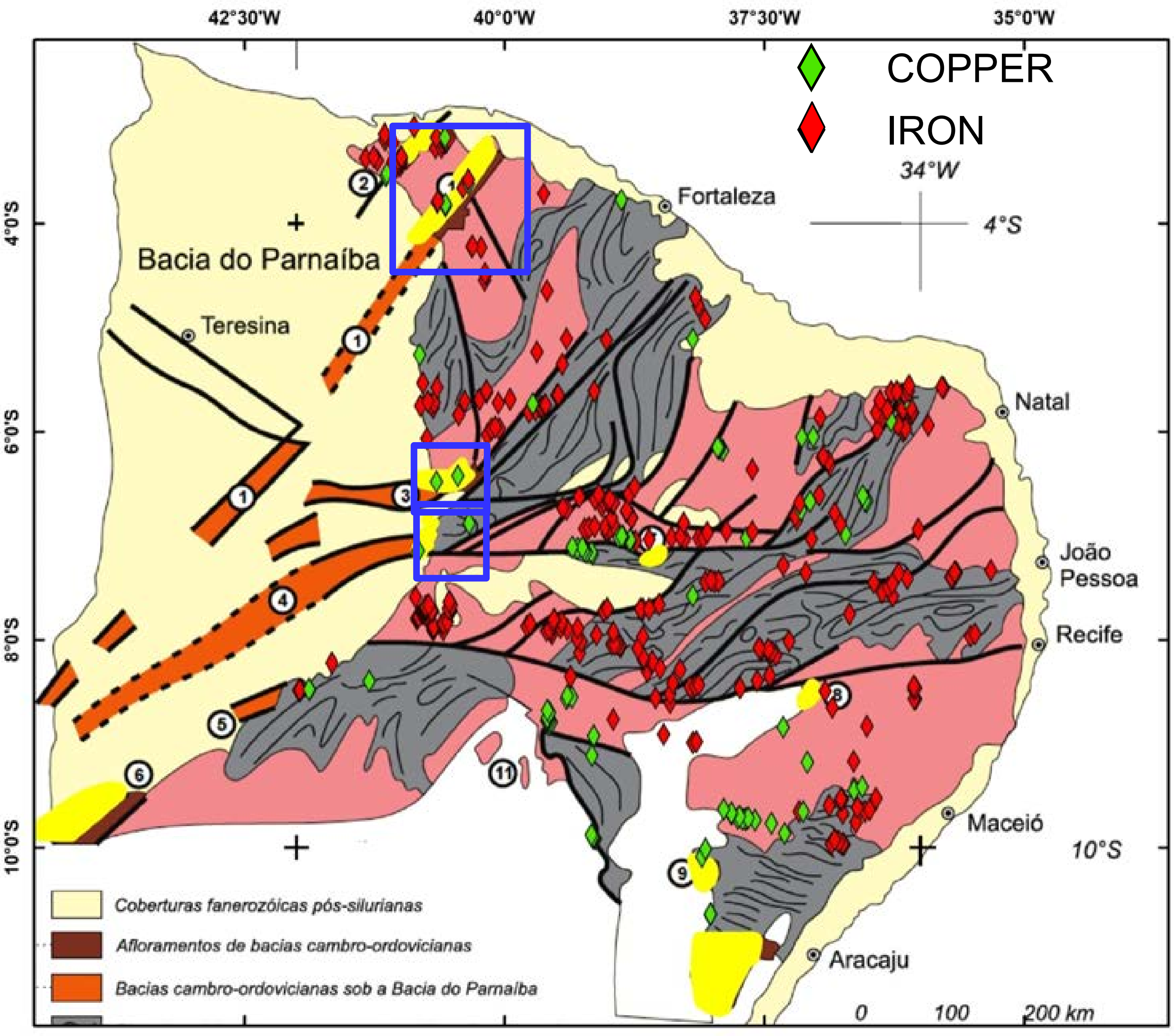


- ➢ Vast terrane covering 900 x 900 km
- ➢At least 5 Archaean nuclei
- ➢ Numerous Palaeoproterozoic tectonic blocks
- ➢ Major Mesoproterozoic metamophic belt
- ➢ Welded together by Neoproterozoic mobile belts, shear zones, fossil arcs, magmatic arcs, continental arc and a quintuple, ESE-vergent, imbricated thrust system
- ➢ **Prolific occurrence record of Au, Cu, Fe, Ni, W, Sn, Mo and Ta, amongst other metallic and non-metallic minerals**

**Divided into: Northern, Transversal (or Central), and Southern sectors.**

Major & secondary domains

# ➢ Borborema Province (Cambro-Ordovician basins & some IOCG-like..)



① *Jaibaras*
② *Sairi / Jaguarapi*
③ *Cococi / Rio Jucá*

④ *Catolé / São Julião*
⑤ *São Raimundo Nonato*
⑥ *Carnaúbas*

⑦ *Iara*
⑧ *Barra dos Domingos*
⑨ *Juá*

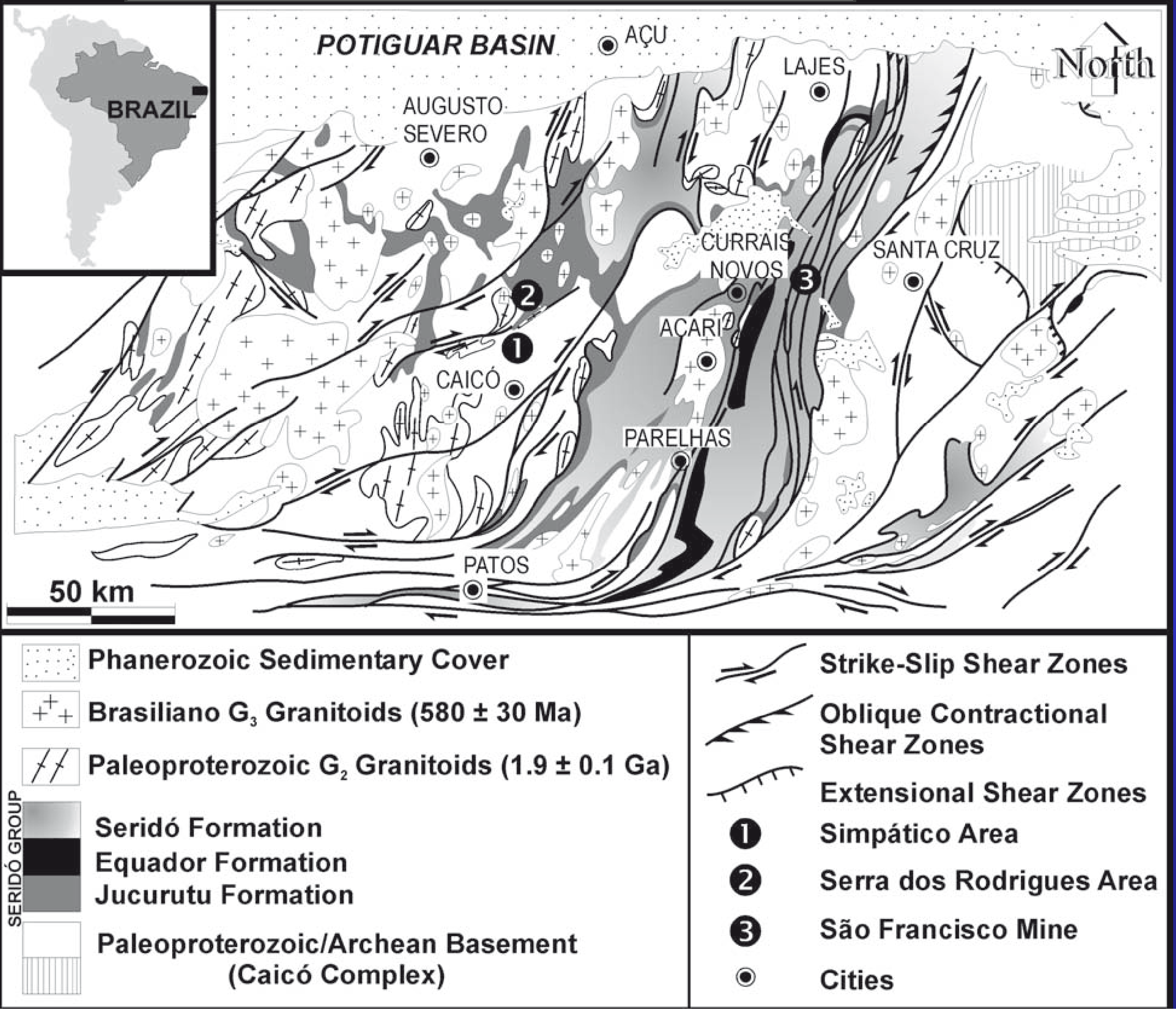
⑩ *Palmares*
⑪ *Serra do Cágado*

**Parente et al. (2011) –**
**In Berni et al. (2019)**

Lobato et al. (2019) – *Gold in Brazil*

# ➢ Borborema Province (RN)

Journal of South American Earth Sciences 15 (2002) 337–348



**Crusader Borborema gold deposit**

**Araújo et al. (2002)**

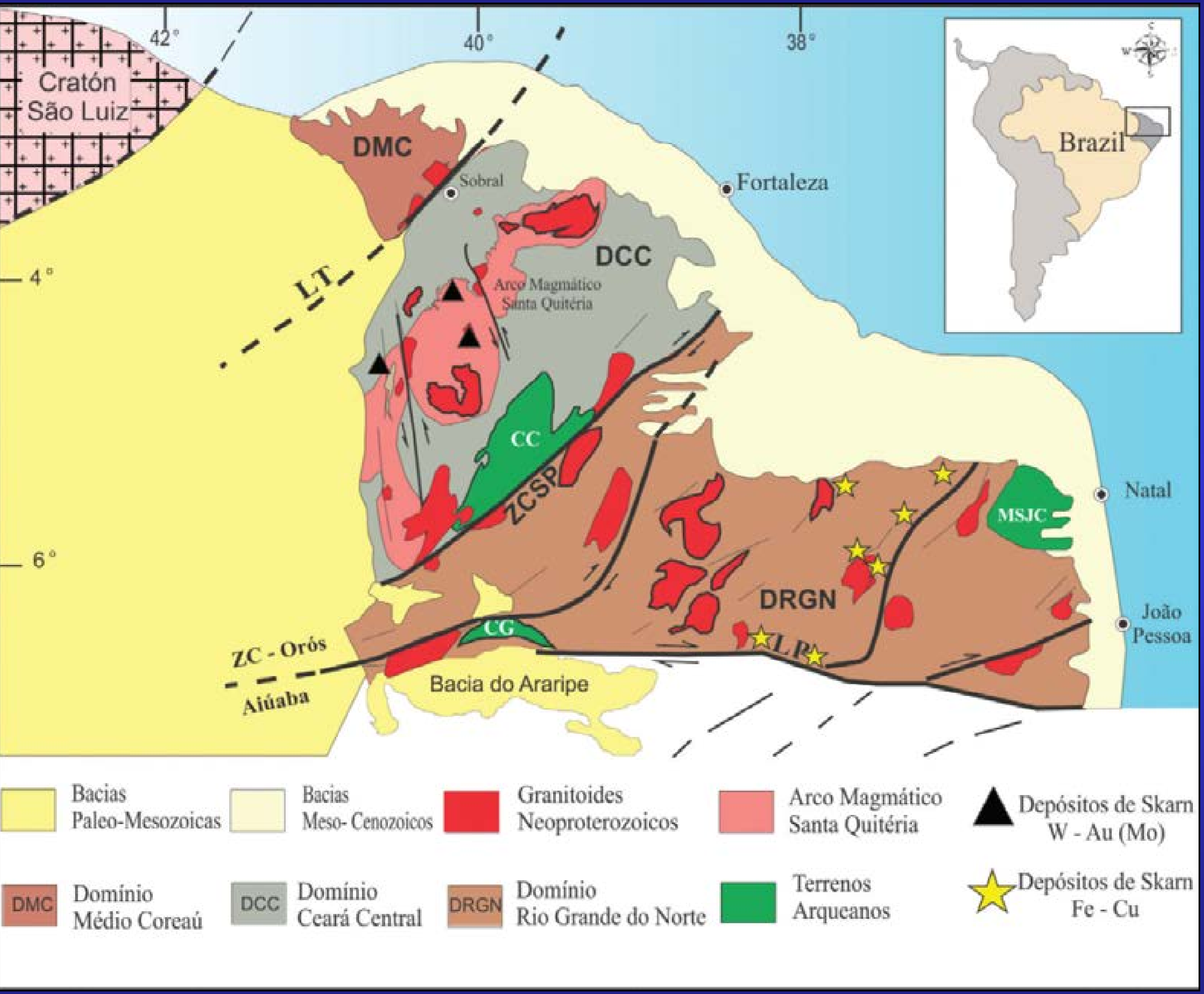
③

Shear-zone related, Neo-proterozoic high-meta-morphic grade orogenic gold?

(Crusader Resources Borborema Gold Project ) Faixa Seridó

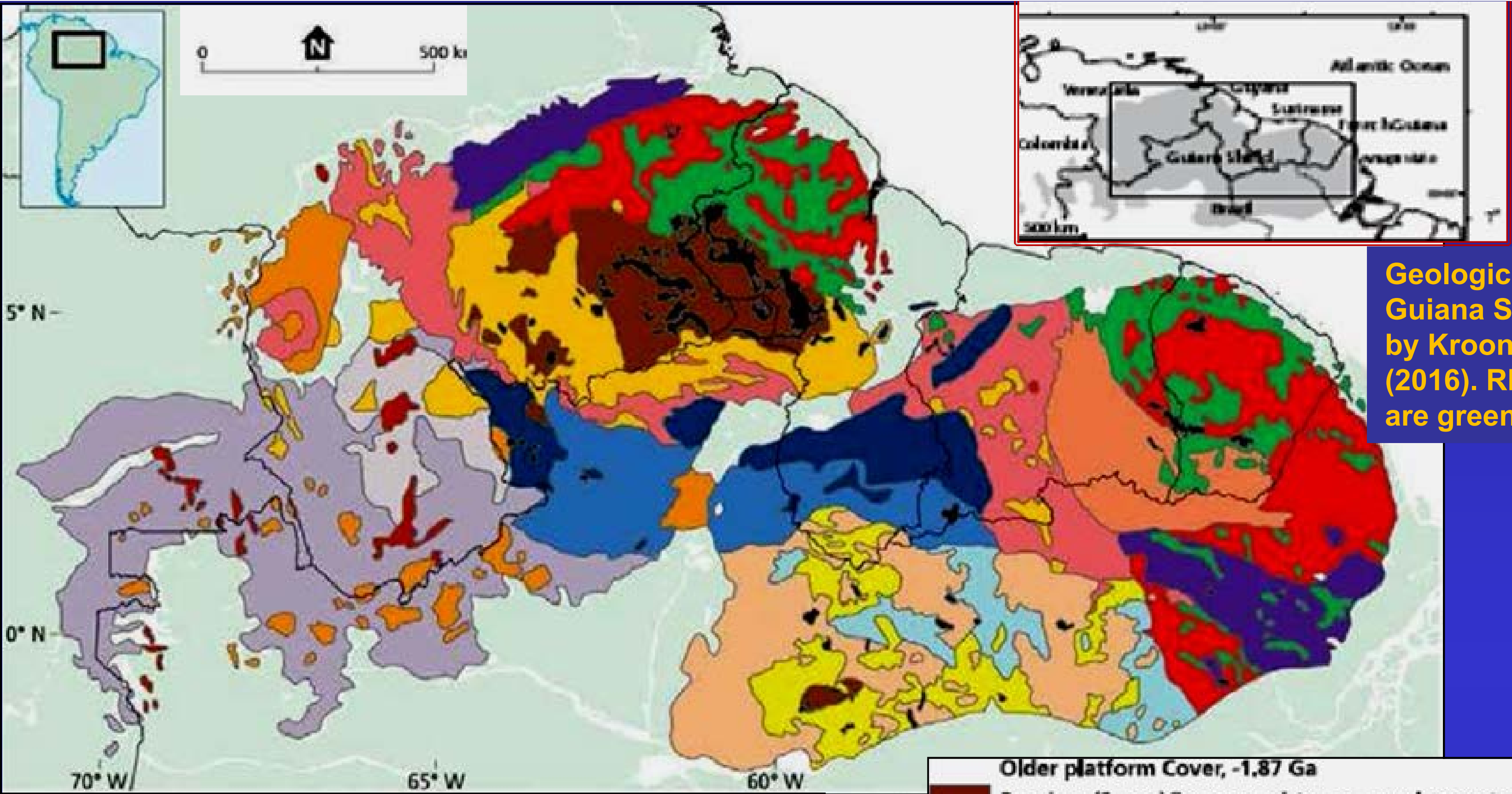
Lobato et al. (2019) – *Gold in Brazil*

# ➢ Borborema Province



Geological sketch of the Northern portion, Borborema province , with main regional shear zones.
Fetter et al. (2003); de Parente et al. (2015).

Lobato et al. (2019) – *Gold in Brazil*



**Geological framework, Guiana Shield, compiled by Kroonenberg et al. (2016). Rhyacian rocks are green and red.**

**Younger platform covers, 1.3-1.2 Ga**
🟥 Tunuí, Taraira, Naquén, La Pedrera, Cinaruco, Neblina folded sandstones

**Mesoproterozoic intrusives, 1.59-1.51 Ga**
🟧 Mucajaí, Surucucus, Parguaza rapakivi, Mitú, Vaupés, Isana granites

**Rio Negro Belt, 1.86-1.72 Ga**
⬜ Undifferentiated Río Negro Basement, southern Venezuela
🟪 High-grade Mitú, Minicia-Macabana-San Carlos-Cauaburí gneisses

**Younger felsic volcanic and granitoid belt, 1.89-1.81 Ga**
🟦 Undifferentiated Tumucumaque basement
🟧 Mapuera-Madeira granites and related intrusives
🟨 Iricoumé-Jatapu felsic volcanics

**Mafic intrusives, 1.79 Ga and younger**
⬛ Avanavero dolerite and other Proterozoic mafic and alkaline intrusives

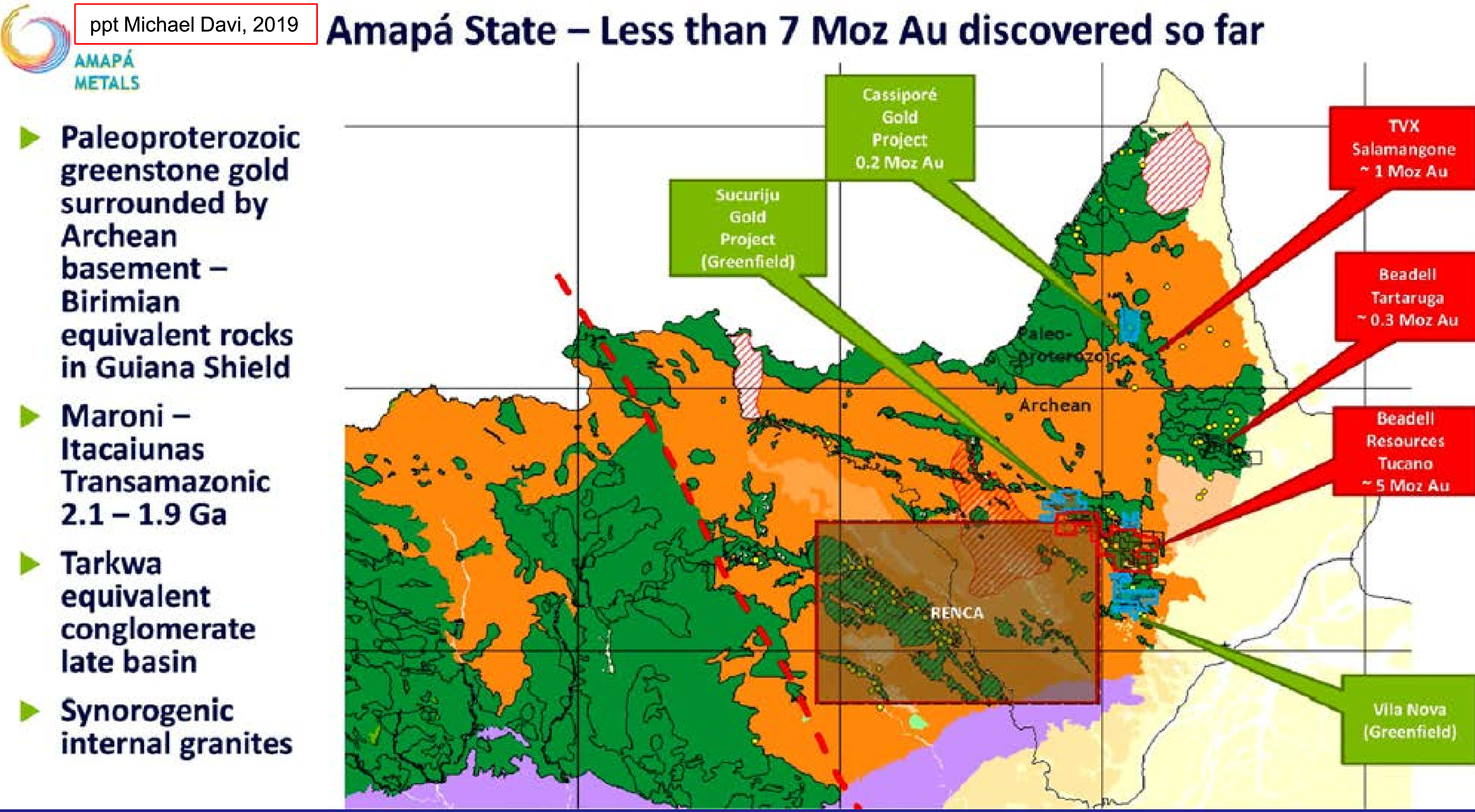
**Older platform Cover, -1.87 Ga**
🟫 Roraima (Super)Group sandstones, conglomerates, ash-fall tuffs

**Older felsic volcanic and granitoid belt 1.99-1.95 Ga**
🟥 Wonotobo-Iwokrama-Pedra Pintada-Cuchivero granites
🟨 Dalbana-Iwokrama-Surumu-Caicara felsic metavolcanics

**High-grade belts, 2.08-2.02 (-1.98) Ga**
🟦 Uraricoera-Trairão-Urubu-Anauá-Southern Guyana Belt
🟦 Bakhuis Granulite Belt, Cauarane-(Kanuku)-Coeroeni Belt

**Greenstone Belt , 2.26-2.09 Ga**
🟧 Deep-level granites and gneisses
🟥 TTG, diapiric tonalite-trondhjemite-granodiorite intrusions
🟩 Vila Nova, Marowijne, Barama-Mazaruni, Pastora-Carichapo greenstones

**Archean nuclei > 2.5 Ga**
🟪 Imataca, Amapa granulite belts



ppt Michael Davi, 2019

## Amapá State – Less than 7 Moz Au discovered so far

- Paleoproterozoic greenstone gold surrounded by Archean basement – Birimian equivalent rocks in Guiana Shield
- Maroni – Itacaiunas Transamazonic 2.1 – 1.9 Ga
- Tarkwa equivalent conglomerate late basin
- Synorogenic internal granites

Lobato et al. (2019) – *Gold in Brazil*

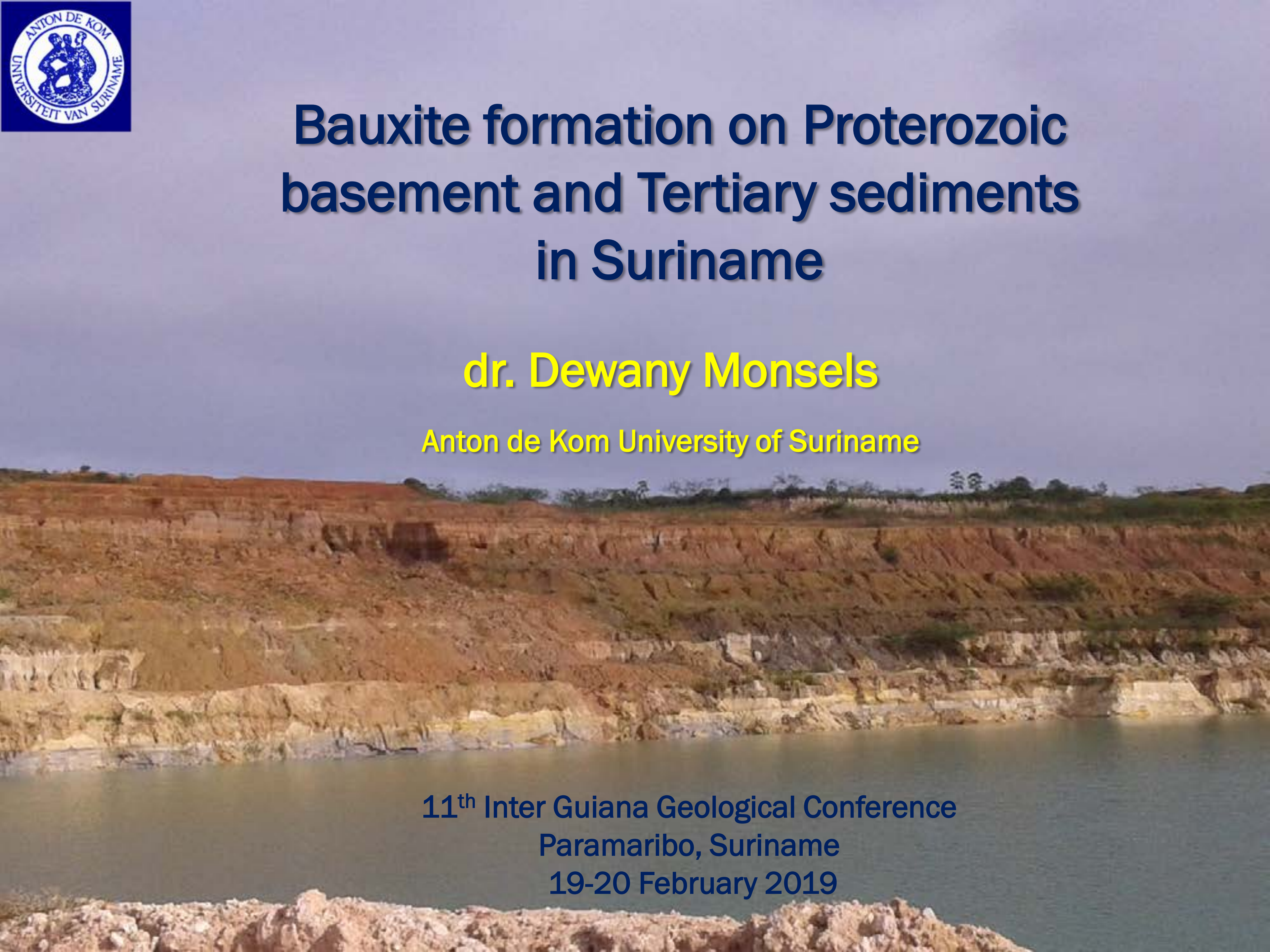
# Perspectives - Underexplored Au systems

- ***Modified? Paleoplacer Au system, e.g.,*** **in the Jacobina area, and Quadrilátero Ferrífero**
- ***Turbidite-hosted Au*** **in the Quadrilátero Ferrífero Archaean**
- ***Au-rich VHMS*** **in tracts of GB to the west of the Quadrilátero Ferrífero**
- ***Pd + Pt + Au (Jacutinga-type) system, e.g.,*** **in Carajás, Quadrilátero Ferrífero, and Goiás**
- ***Alkalic magmatic-hydrothermal Au systems***, **e.g., Lavras do Sul**

# Thank you

- *Students*
- *UFMG, CET, UFC*
- *CNPq*
- *Capes*
- *AngloGold*
- *Jaguar*

- *and so many other colleagues that support us!*



# Bauxite formation on Proterozoic basement and Tertiary sediments in Suriname

**dr. Dewany Monsels**

Anton de Kom University of Suriname

11th Inter Guiana Geological Conference
Paramaribo, Suriname
19-20 February 2019

# Overview

- ✓ Introduction
- ✓ Bauxite deposits in Suriname
- ✓ Timing of Bauxitization
- ✓ Main objective
- ✓ Research methods and techniques
- ✓ Sample material
- ✓ Results and discussion
- ✓ Conclusion

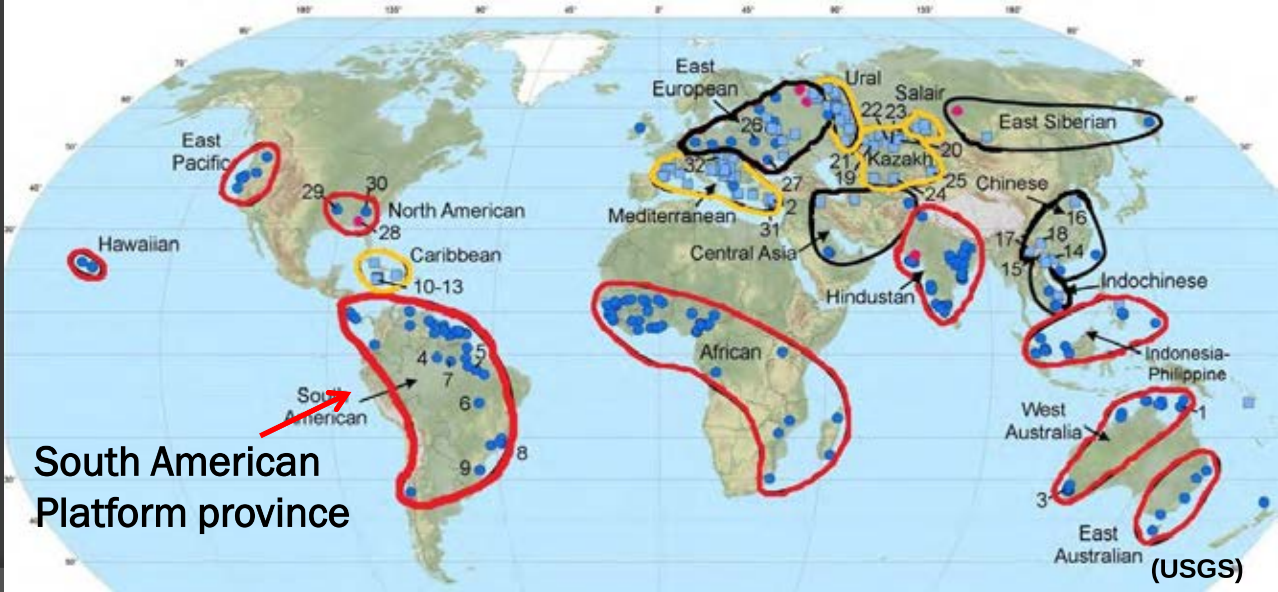
# Introduction: Bauxite

- ✓ Aluminum-rich rock of intense chemical weathering (e.g leaching $SiO_2$, alkali) in (sub-) tropical areas.

- ✓ Most important Aluminum ore + alternative (re-)source of REE.

- ✓ Classification of bauxite based on mode of formation and occurrence:

1. Lateritic (gibbsite)
2. Karst (boehmite+ diaspore)
3. Combination

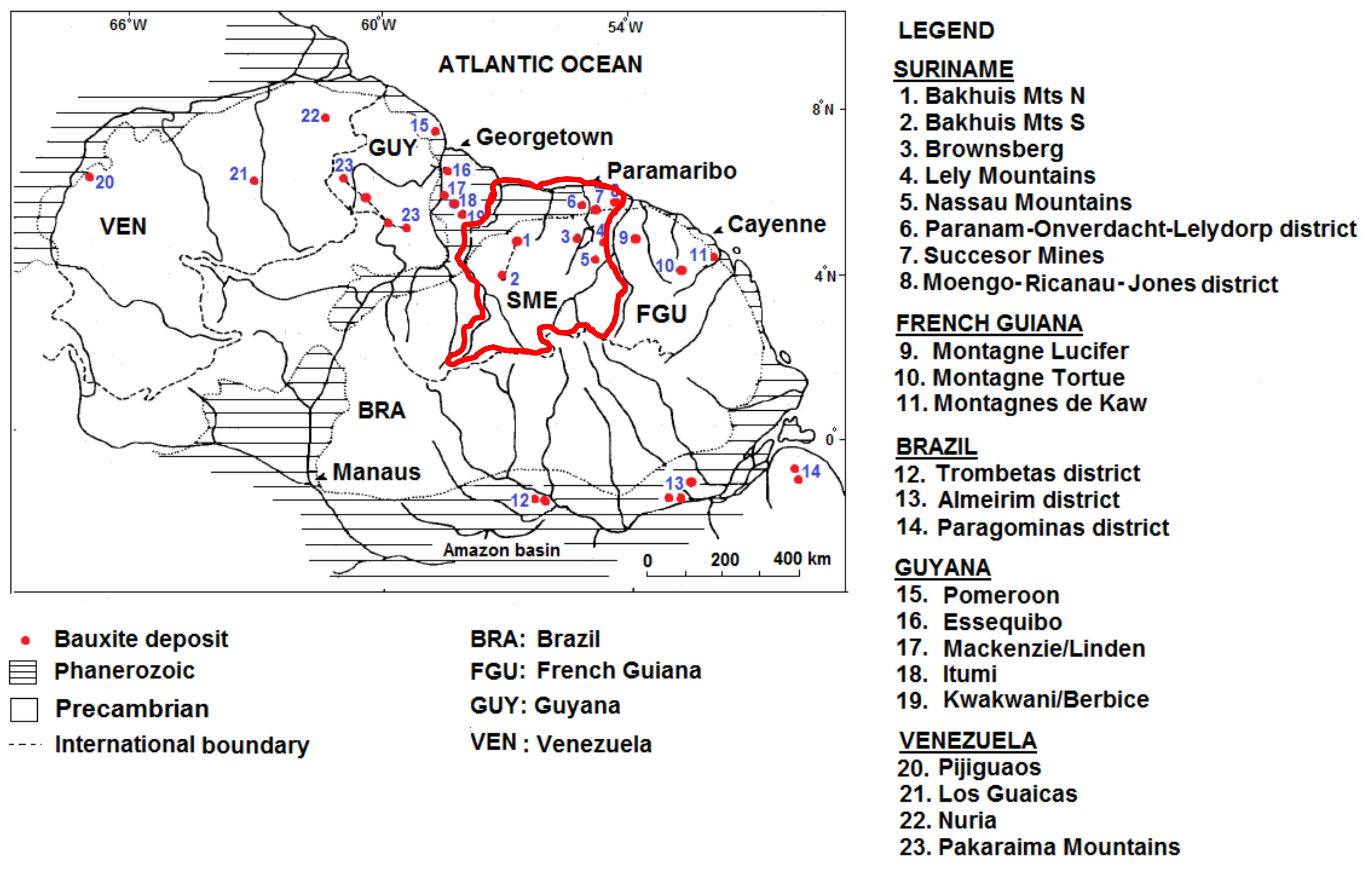


South American Platform province

(USGS)

Worldwide distribution of bauxite

# Bauxite on the Guiana Shield



**LEGEND**

**SURINAME**

1. Bakhuis Mts N
2. Bakhuis Mts S
3. Brownsberg
4. Lely Mountains
5. Nassau Mountains
6. Paranam-Onverdacht-Lelydorp district
7. Succesor Mines
8. Moengo-Ricanau-Jones district

**FRENCH GUIANA**

9. Montagne Lucifer
10. Montagne Tortue
11. Montagnes de Kaw

**BRAZIL**

12. Trombetas district
13. Almeirim district
14. Paragominas district

**GUYANA**

15. Pomeroon
16. Essequibo
17. Mackenzie/Linden
18. Itumi
19. Kwakwani/Berbice

**VENEZUELA**

20. Pijiguaos
21. Los Guaicas
22. Nuria
23. Pakaraima Mountains

● Bauxite deposit
▤ Phanerozoic
☐ Precambrian
- - - International boundary

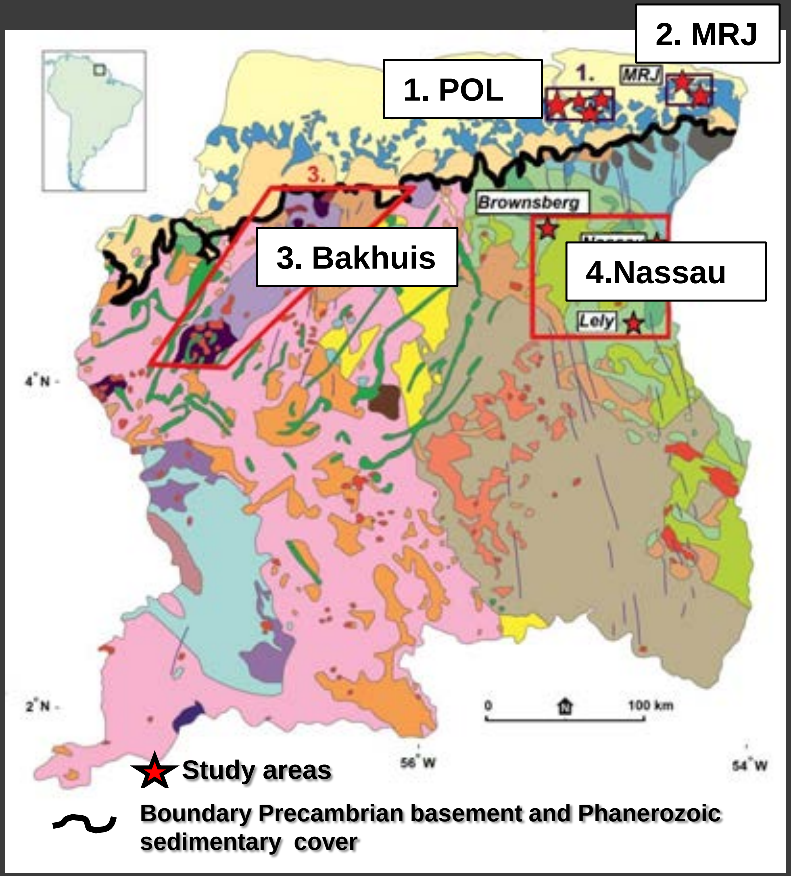
BRA: Brazil
FGU: French Guiana
GUY: Guyana
VEN : Venezuela

Bauxite subprovinces :

- ✓ Coastal plain subprovince
- ✓ Guiana Shield subprovince

modified after Bardossy & Aleva, 1990

# Geological framework: Bauxite in Suriname



Bauxite districts:

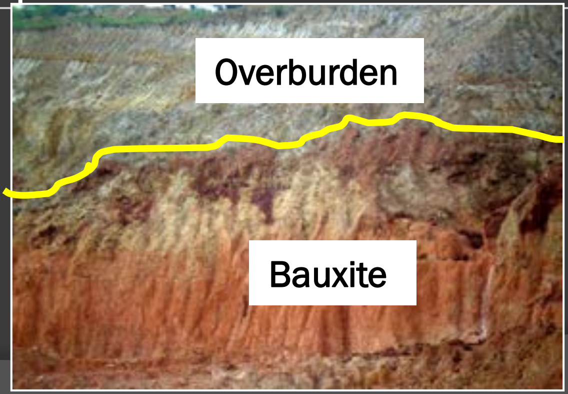
1. Paranam-Onverdacht-Lelydorp (POL)
2. Moengo-Ricanau-Jones (MRJ)
3. Bakhuis
4. Nassau

Groups of bauxite deposits:

a) Coastal plain bauxite deposits (1+2)
b) Plateau bauxite deposits (3+4)

# Characteristics of the bauxite types

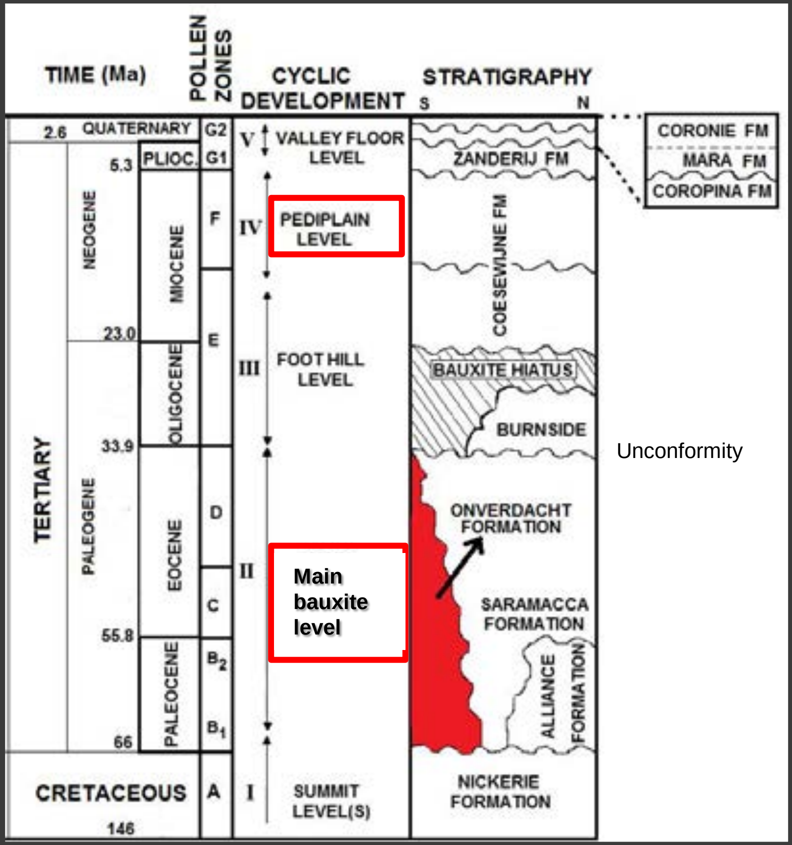
| | Coastal plain bauxites | Plateau bauxites |
|---|---|---|
| **Location** | Coastal zone | Hinterland |
| **Overburden** | a. Surface deposits (0-1 m)<br>b. Buried deposits (1-40 m) | None |
| **Precursor** | - Tertiary siliclastic sediments<br>- Onverdacht Fm.<br>- Kaolinitic clay and clayey sand | - Proterozoic metamorphic rocks<br>- Paramaka Fm.+ Falawatra Gr.<br>- Greenstone belt+ Granulite belt<br>➢***ad 1.****= Low grade metamorphic rocks (metabasalt, meta-andesite, amphibolite)*<br>➢***ad 2.****= High grade metamorphic rocks (charnokite, anorthosite, granulites,metapelite)* |



Klaverblad

Brownsberg

# Timing of bauxitization



Leonard, 1984; Wong et al., 1998, 2009

Five planation surfaces/levels

1. Summit level
2. Main Bauxite level
3. Foothill level
4. Pediplain level
5. Valley floor evel

**Palynology** (Van der Hammen & Wijmstra, 1964)

✓ Paleocene-Eocene (Main Bauxite Level)

**Paleomagnetic age** (Théveniaut et al., 2002)

* Bakhuis ≈ 60 ± 20 Ma
* Moengo ≈ 10 Ma

Two main bauxization cycles:

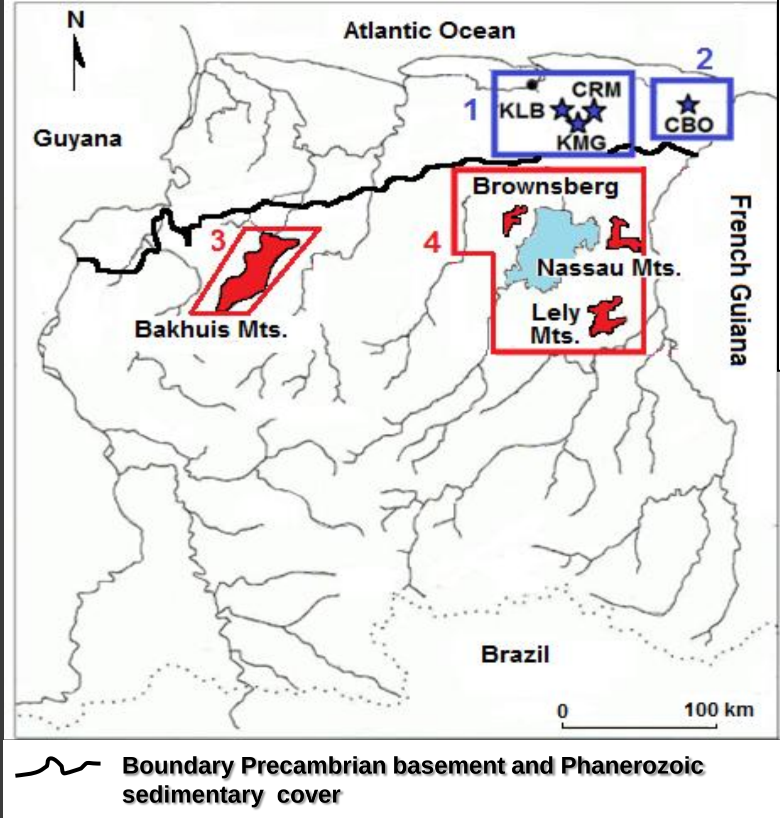
1. Paleocene - Eocene
2. Miocene

Théveniaut et al., 2002; Aleva, 1984

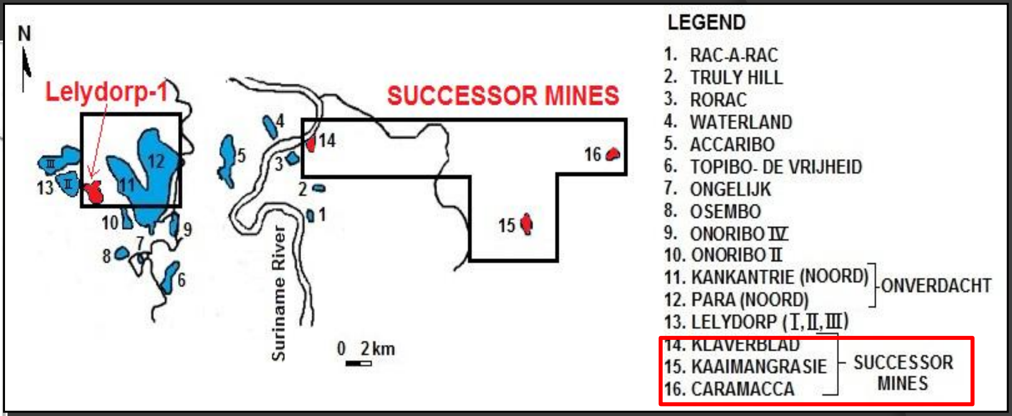
# Main objective

To study the influence of precursor on the resulting bauxites, while paying special attention to their compositional diversity and the distribution of REEs.

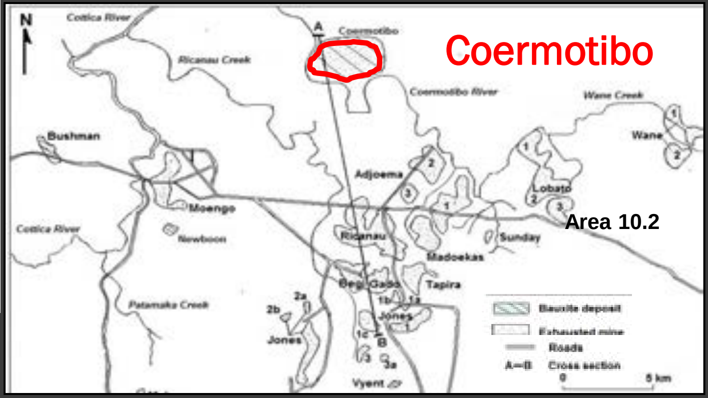
# Study locations

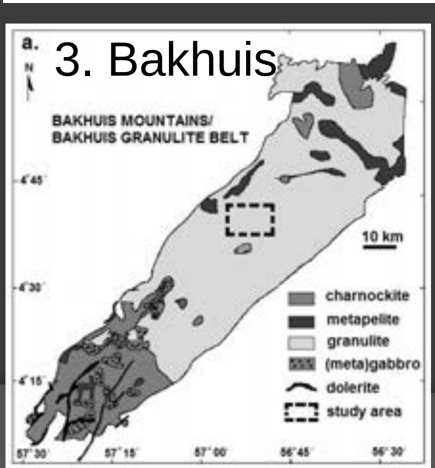


## 1. POL district

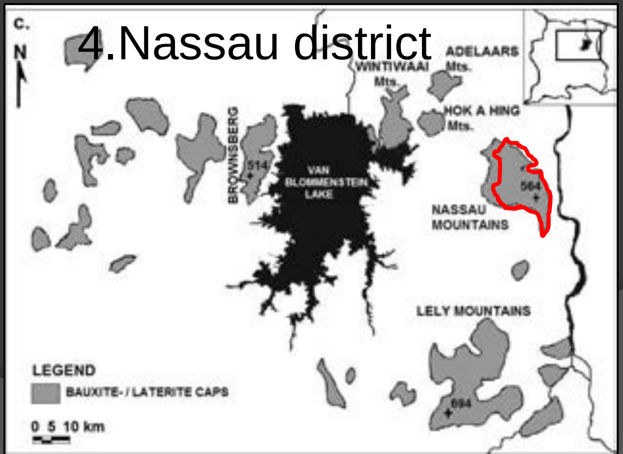


## 2. MRJ district





## 3. Bakhuis



## 4.Nassau district

(Janssen, 1979; SPS & OAS, 1988;
Bardossy & Aleva, 1990;
Klaver et al., 2015;
Monsels et al., 2017,2018,2019)

# Analytical methods

- Polarized light microscope
- Microprobe: - Energy dispersive analysis (EDS)
  - Wavelength-dispersive analysis (WDS)
  - Back-scatter electron imaging (BSE)
- X-ray diffraction (XRD)
- X-ray fluorescence (XRF)
- Laser-ablation inductively coupled mass spectrometry (LA- ICP-MS)
  - ✓ First effort to apply it to lithium borate glass beads
  - ✓ due to incomplete digestion of HF-resistant minerals e.g zircon (REE-host)*

* *Monsels, D., van Bergen, M. and Mason, P. (2017). Trace element analysis of bauxite using LA-ICPMS on lithium borate beads. Geostandards and Geoanalytical Research, 42 (2), 239-251.*

# Sample material

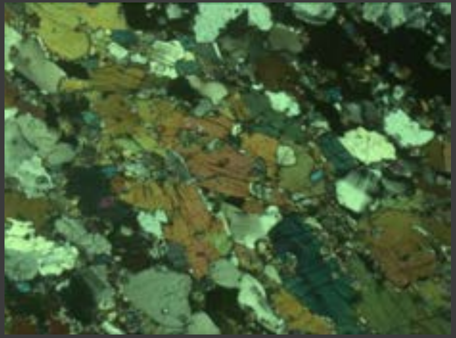
| | Successor Mines | Lelydorp-1 | CBO | SNE | MAC | BAK | NAS | Source |
|---|---|---|---|---|---|---|---|---|
| Chip + grab samples (hammer) | x | x | x | | | x | x | Monsels |
| Drill cuttings | | | x | x | x | | | Suralco |
| Drill cores | | x | x | | | | x | Suralco |
| XRF data | | x | x | x | | | x | Suralco, BIS |

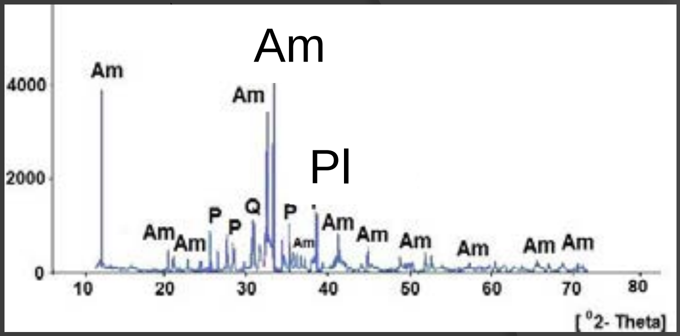
CBO= Coermotibo, SNE= Snesie, MAC= Macousi, BAK= Bakhuis Base Camp, NAS= Nassau

# Results

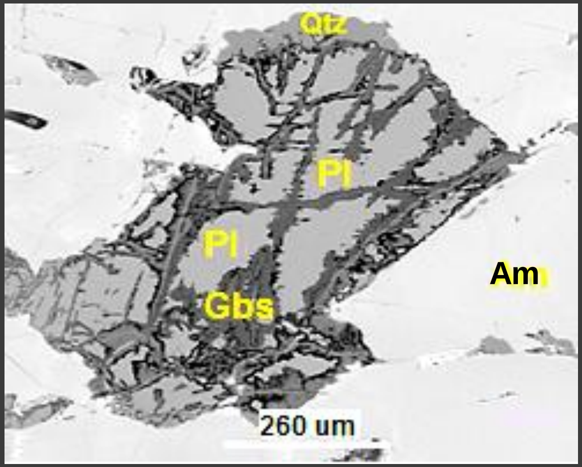
# Evidence for *in situ* bauxitization (plateau bxt)

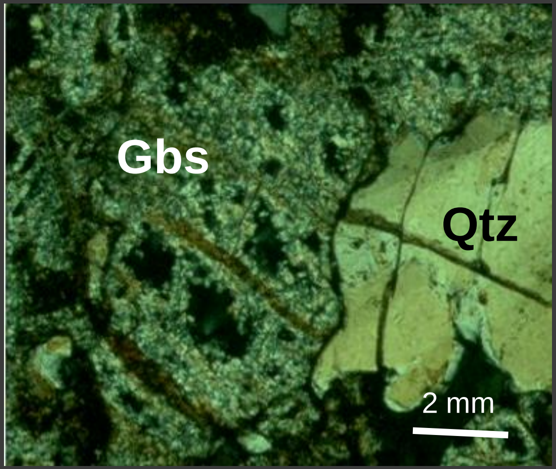
Amphibolite
(Bakhuis Base camp)





## 1. Direct bauxitization

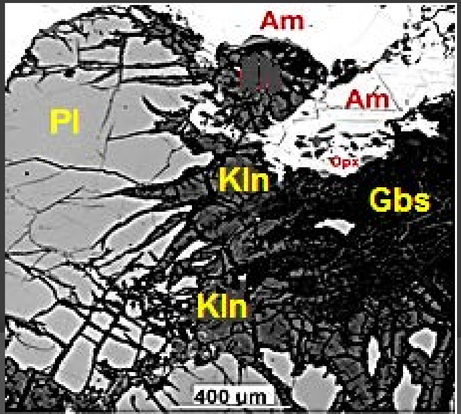




**Plagioclase ⟶ Gibbsite**

$NaAlSi_3O_8$ $Al(OH)_3$

## 2. Indirect bauxitization



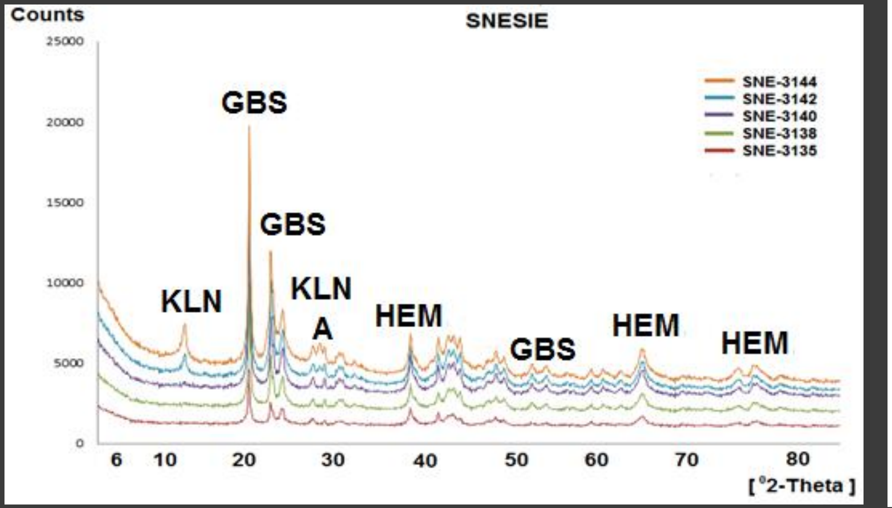
**Plagioclase ⟶ Kaolinite ⟶ Gibbsite**

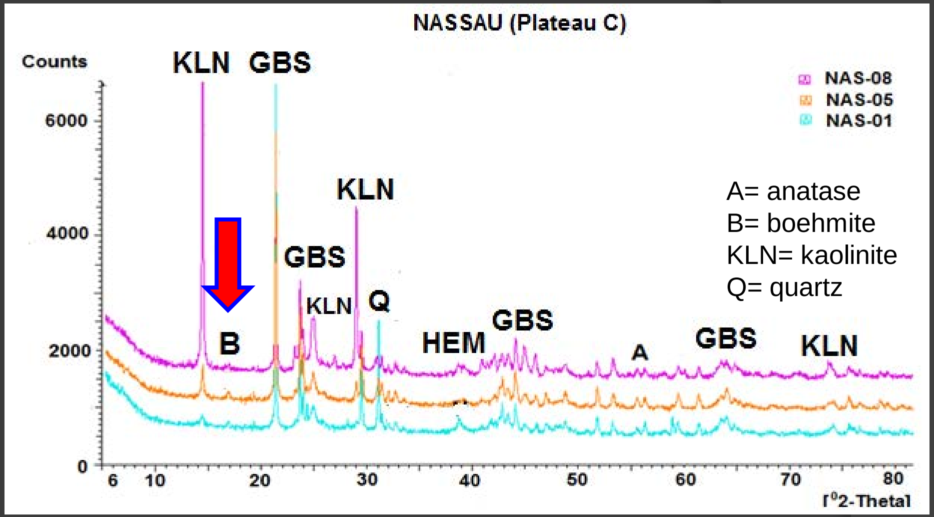
$NaAlSi_3O_8$ $Al_2Si_2O_5(OH)_4$ $Al(OH)_3$

Am = amphibole
Pl = plagioclase
Gbs = gibbsite
Qtz = quartz
Kln = kaolinite

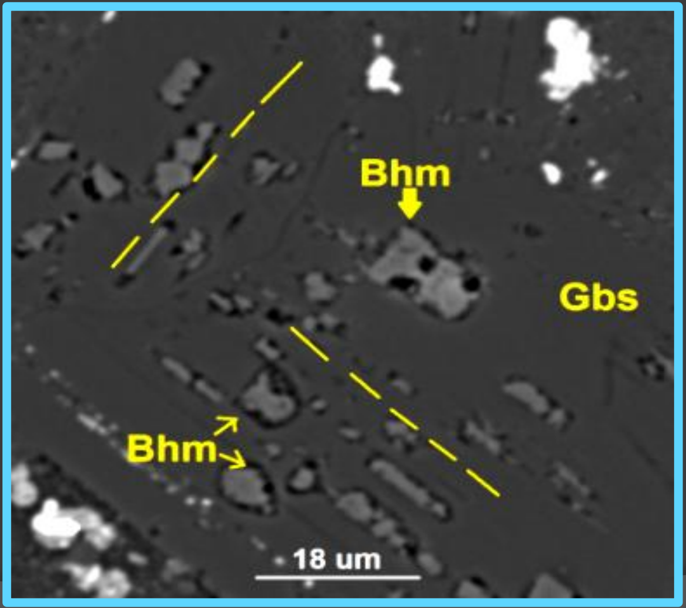
# Evidence for *in situ* bauxitization (Boehmite)

XRD





A= anatase
B= boehmite
KLN= kaolinite
Q= quartz



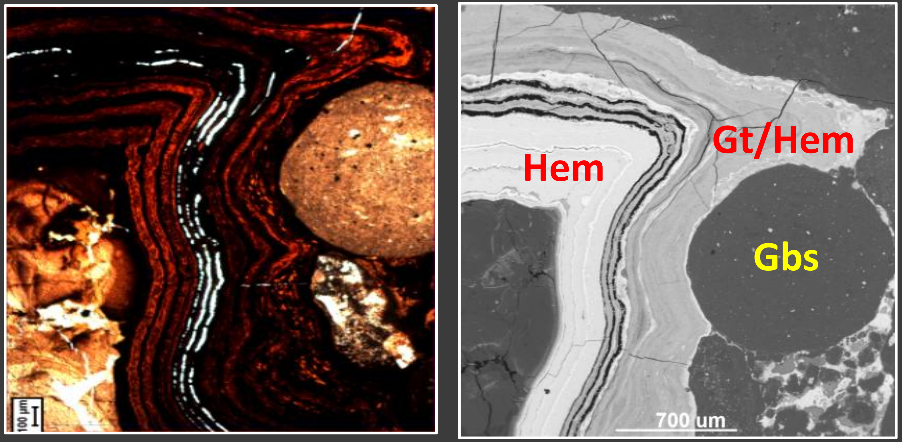
3. Dehydration of gibbsite → boehmite

$Al(OH)_3$ $AlO(OH)$

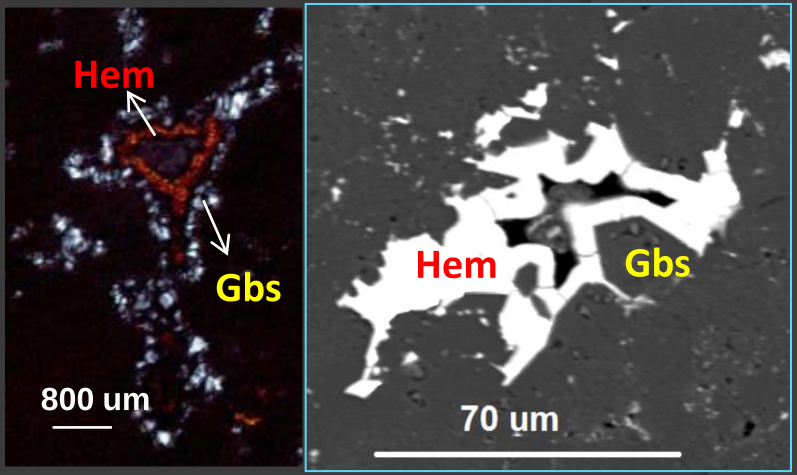
Also reports of boehmite in Cbo, Lelydorp3 but not detected in analysed samples

# Evidence for Al- Fe and Ti-migration, (re-)precipitation

## Plateau bauxites



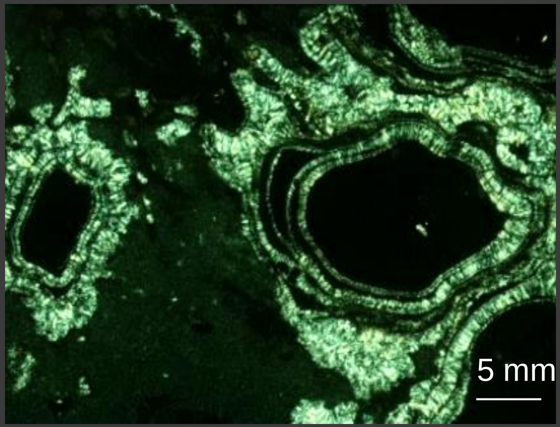
Recurring Fe-deposition



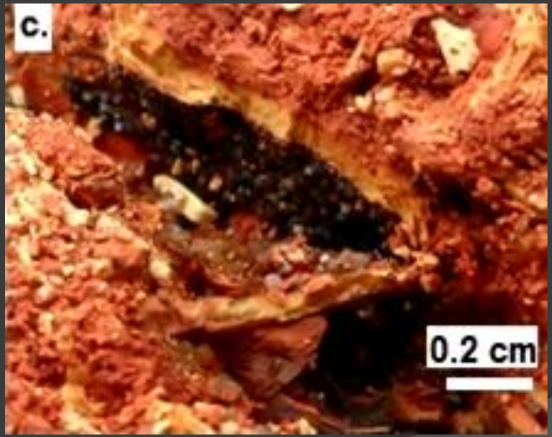
Al- followed by Fe-depositon

---

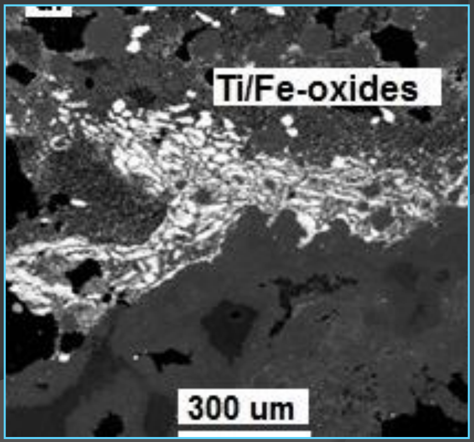
## Coastal bauxites



Multiple gibbsite linings

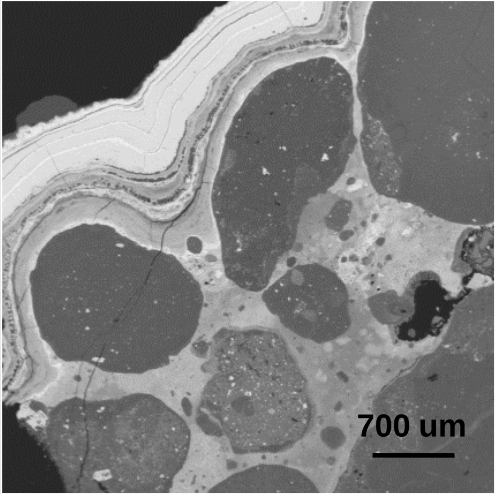


Crystalline hematite

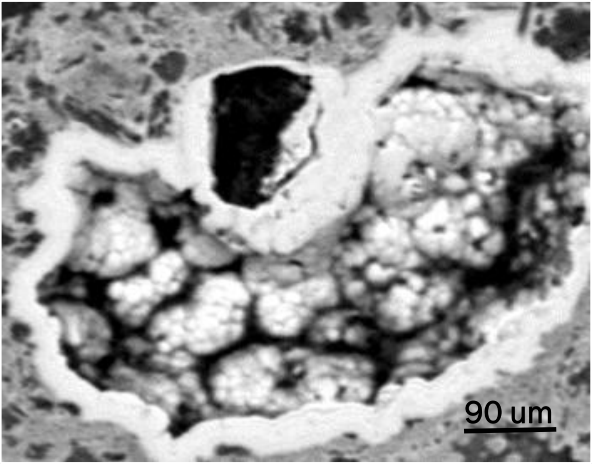


Cluster of Ti-Fe minerals

# Distinctive textures plateau bauxites

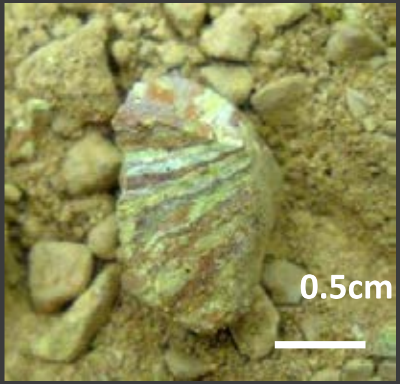


Pisolitic texture

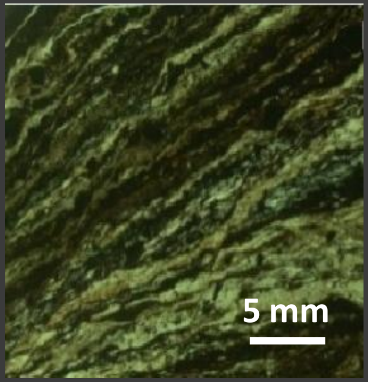


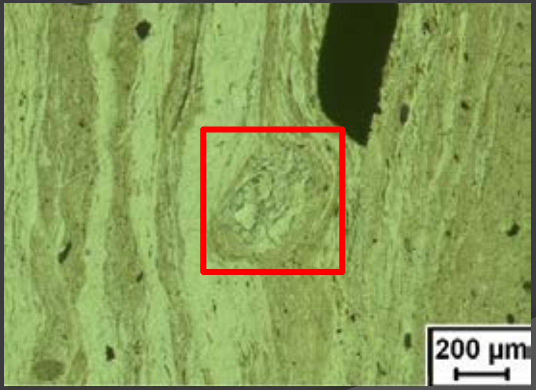
Botryoidal / Coloform texture

Hematite



Foliation





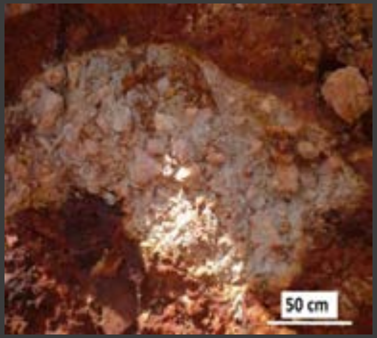
porfiroblast

# Distinctive textures in coastal bauxites

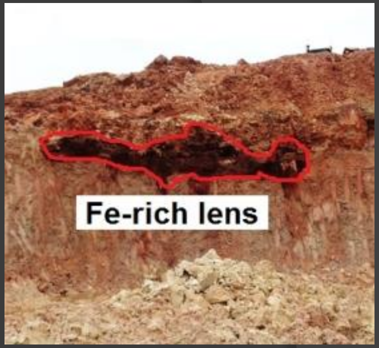
## Successor Mines

Red/white bauxite

'Spotted" bauxite



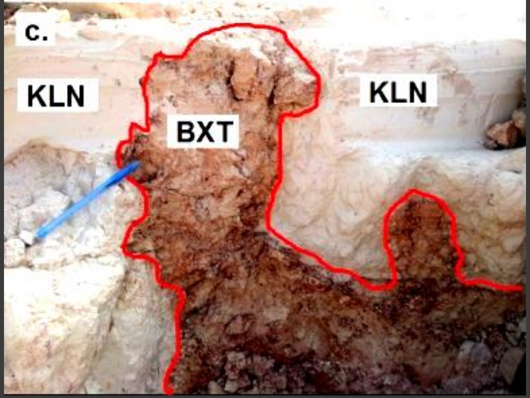
Grey $SiO_2$-rich lens



Fe-rich Lens

## Lelydorp-1

Banded kaolin



Bauxite 'diapir"+
Secondary Bxt Layer

## Coermotibo

Marcasite
(Av. $SO_3$= av.7%,
max.60%)

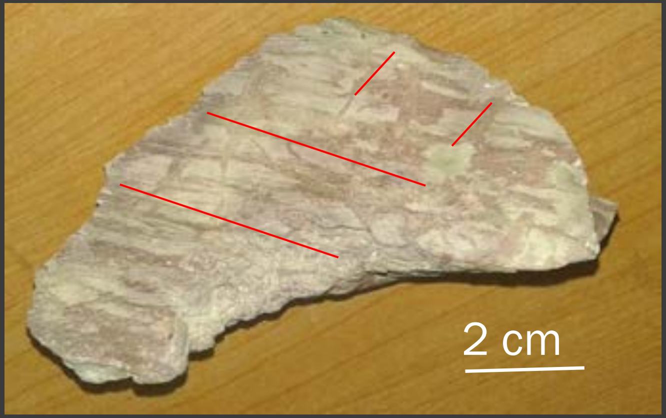
Grey slurry-like bauxite + red groundwater laterite

# Distinctive textures in coastal bauxites

## Bauxite spheroids ( Lelydorp-1)

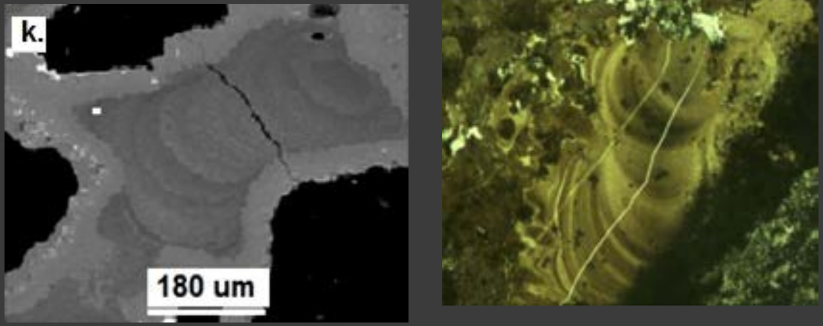
Both exclusively near the transition zone!

Exclusively in Lelydorp-1



## Evidence for bioturbation

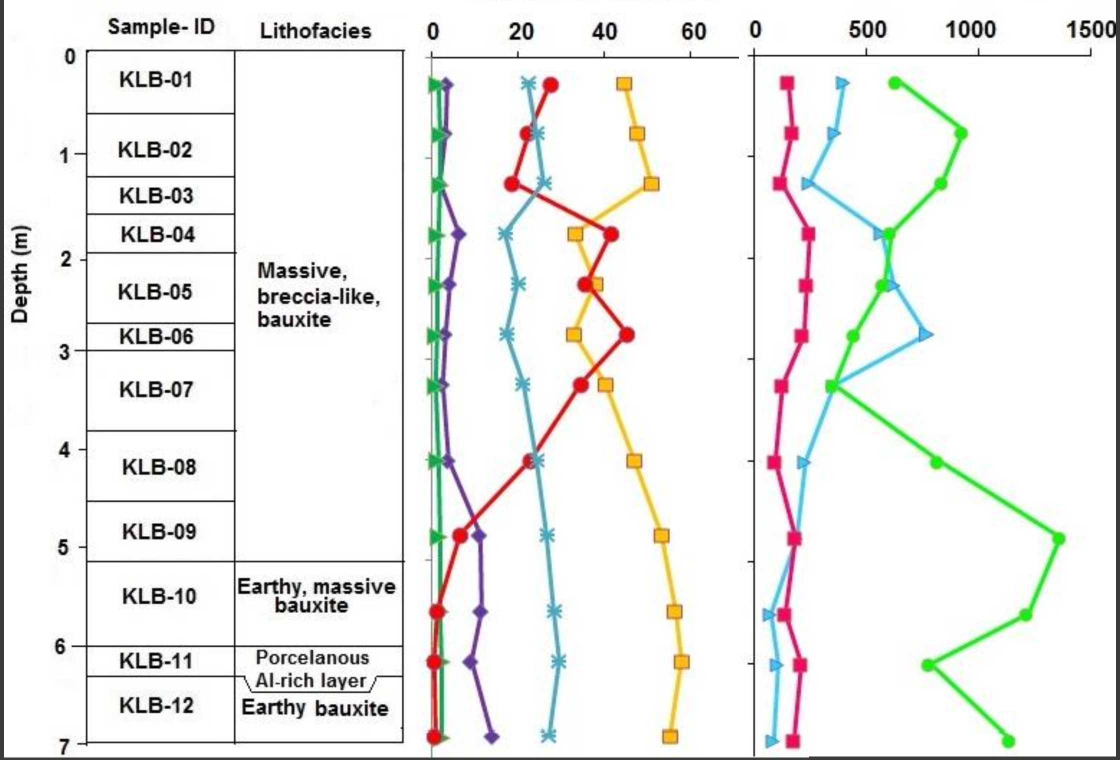
Filled burrow
(Al+ clay min.)

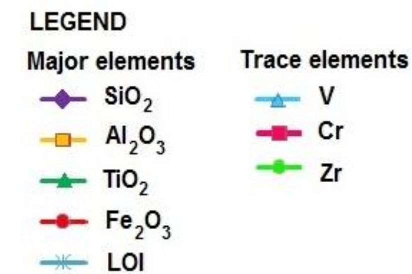


Illuviation/'Fill in" texture in burrows

Rootshaped concretions

# Lithofacies - chemical composition - mineralogy



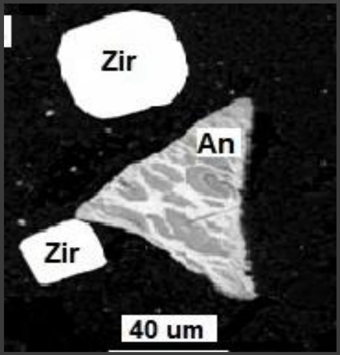


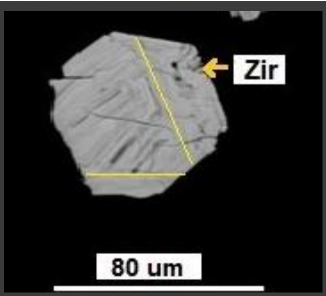
*Zircon= Zr, Nb, Hf, Ta , U*

*Ilmenite= Cr, V, Ti*

*Anatase/rutile= Ti, V, Zr*

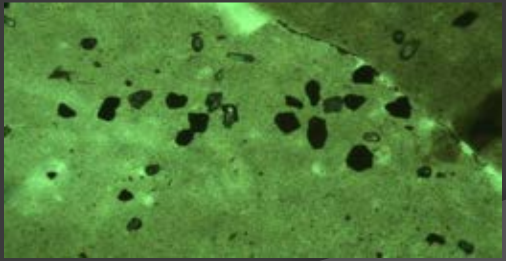
*Xenotime= LREE, MREE (Eu $^{3+}$)*





Zir= zircon

An= anatase

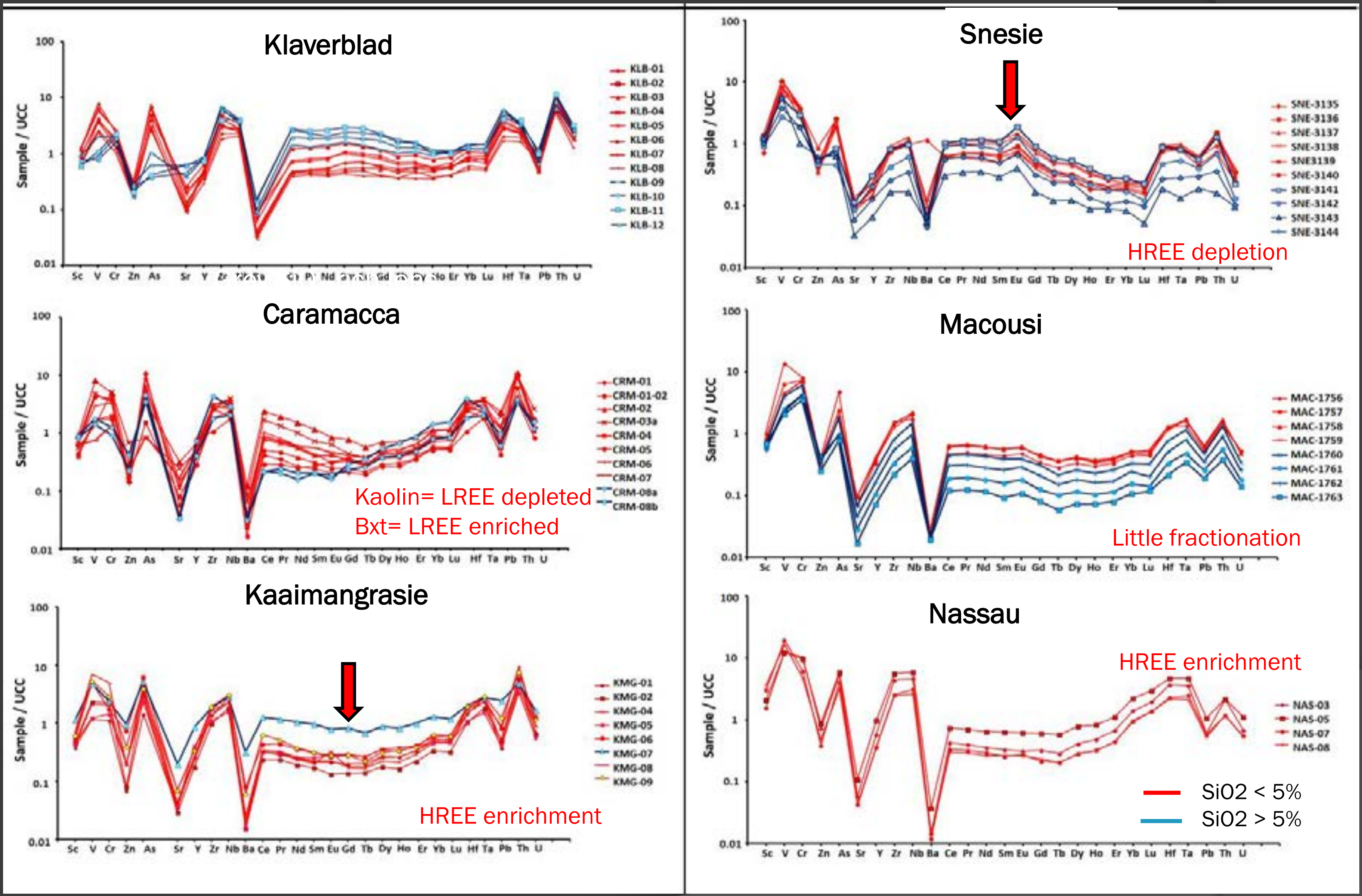


Pos. corr. Zr/Nb = 0.5 - 0.9 (zircon)

# Trace element trends

Coastal bauxites

Plateau bauxites



Kaolin= LREE depleted

Bxt= LREE enriched

HREE enrichment

HREE depletion

Little fractionation

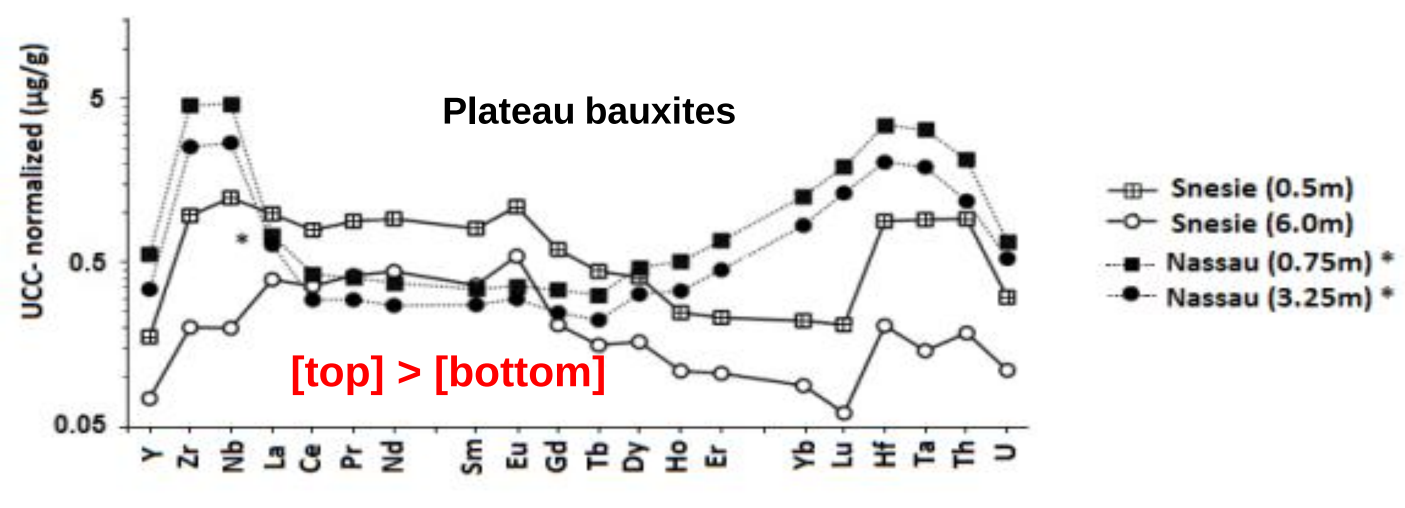
HREE enrichment

SiO2 < 5%

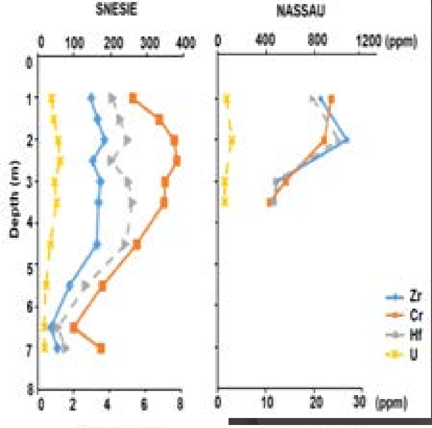
SiO2 > 5%

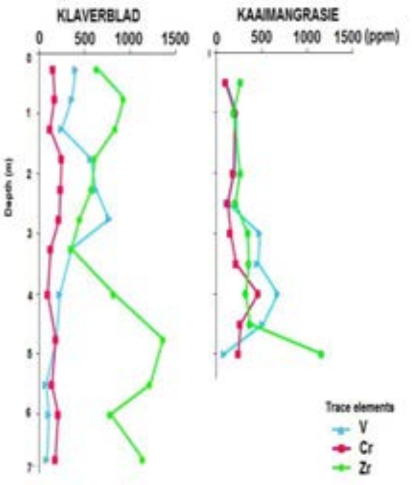
Monsels et al.,2016, 2017, 2018

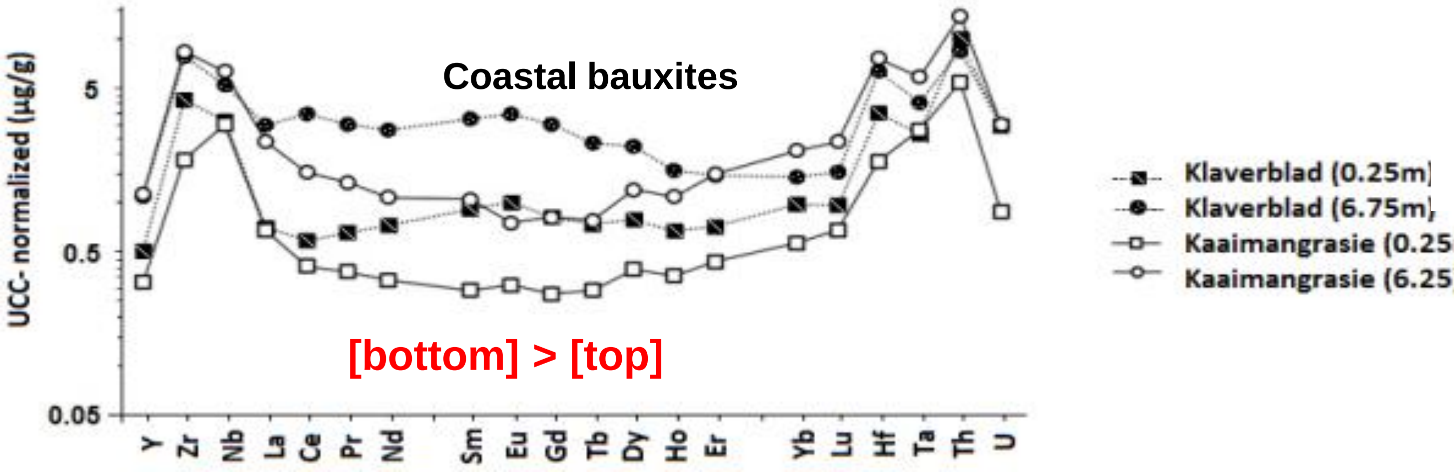
# HFSE and REE trends


Plateau bauxites

[top] > [bottom]






Coastal bauxites

[bottom] > [top]

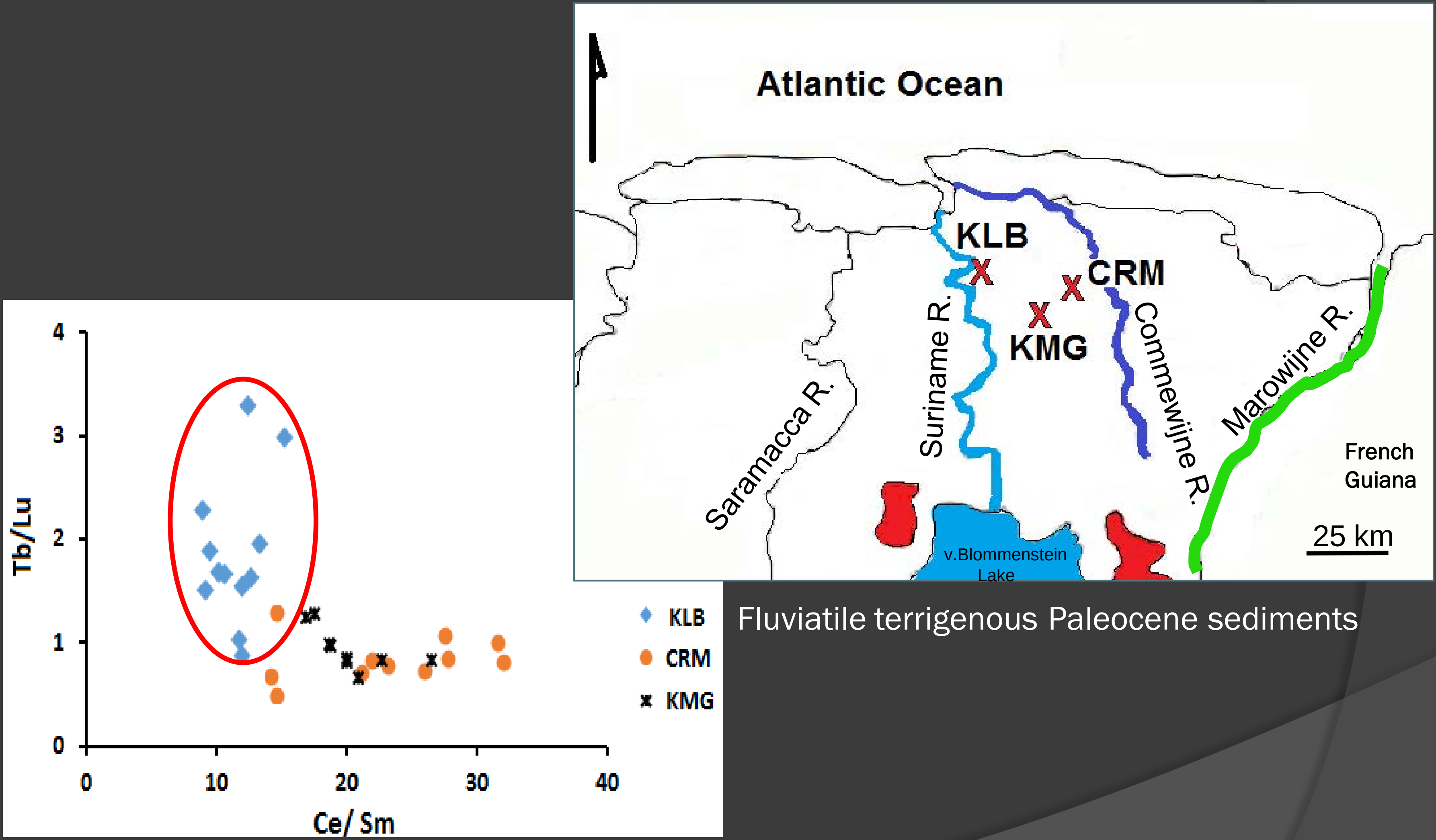
Mainly due to weathering-induced redistribution and stratigraphic heterogeneity or mobility.

*Zircon= Zr, Nb, Hf, Ta , U* *Ilmenite= Cr, V, Ti*

*Anatase/rutile= Ti, V, Zr* *Xenotime= LREE, MREE (esp. Eu $^{3+}$)*

(Monsels et al., 2017,2019)

# Provenance of sedimentary precursor



Fluviatile terrigenous Paleocene sediments

KLB was probably derived from another source than the sediments of KMG and CRM deposits, which may have had a separate, common source.

# Conclusion

The complex petrologic characteristics and compositional heterogeneity of the bauxite deposits can essentially be explained by element fractionation in combination with relative and absolute enrichment processes, erosion and reworking during two-stage, polycyclic bauxitization of heterogeneous precursors.

*Thank you for your attention*

# The West African Craton, Archean and Paleoproterozoic tectonic evolution, derived from in-situ zircon data

Luis A. Parra-Avila[1] and the WAXI team

[1]Centre for Exploration Targeting, School of Earth Sciences, The University of Western Australia

Curtin University

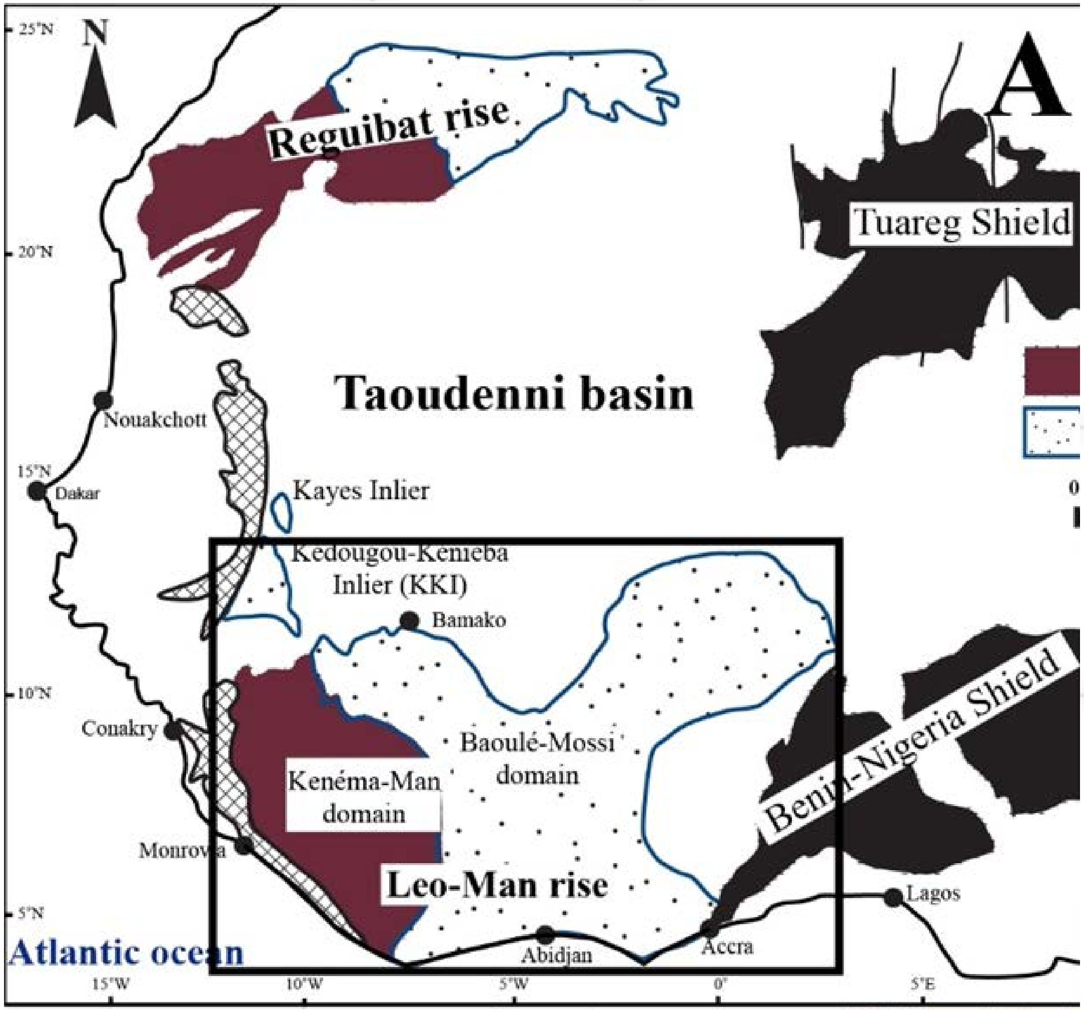
THE UNIVERSITY OF WESTERN AUSTRALIA

WAXI - West African Exploration Initiative

IXOA - L'Initiative d'Exploration Ouest Africaine

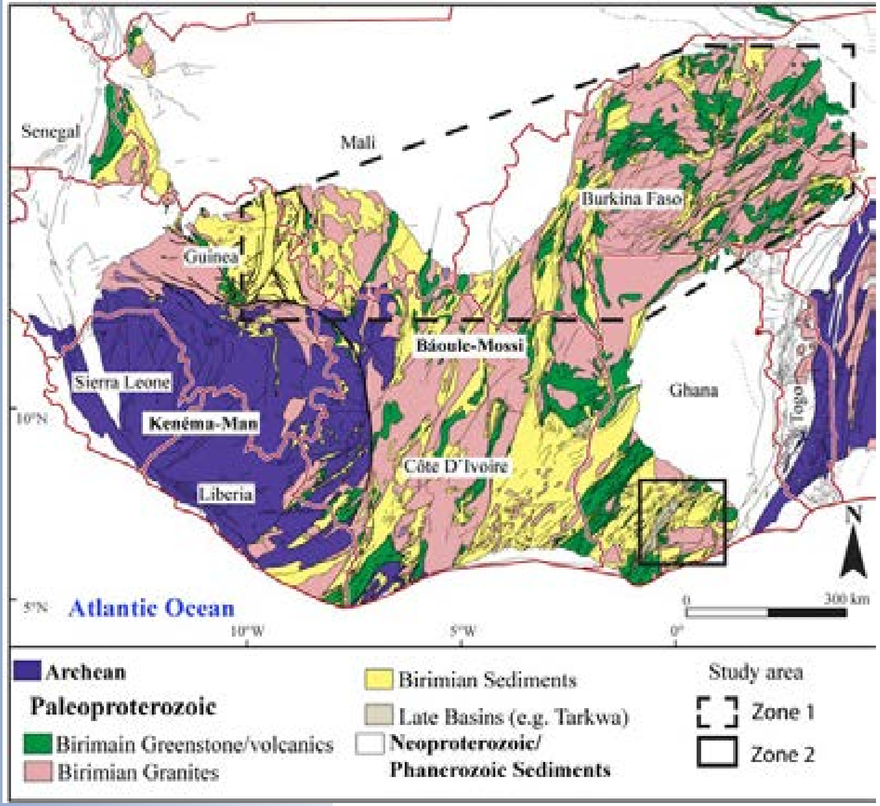
Centre for EXPLORATION TARGETING

# The West African Craton



*Simplified map of the West Africa Craton, Boher et al. (1992). Note the Paleoproterozoic domains in the eastern portions, while the western regions are dominated by Archean nuclei.*

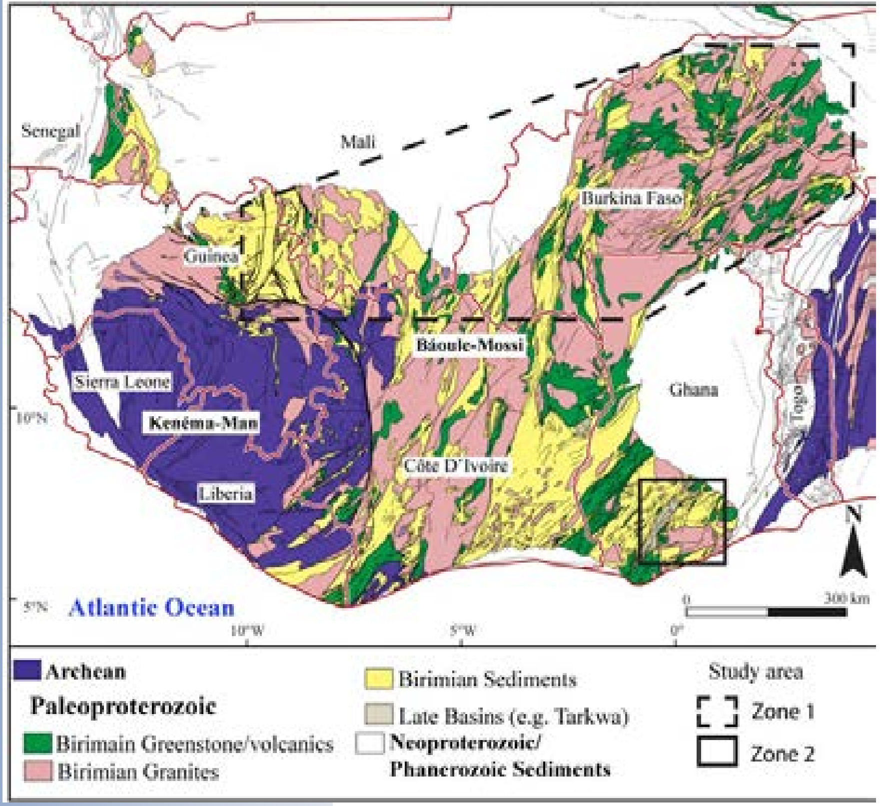
# SWAC Regional Geology



*Simplified geological map of the southern Leo-Man Rise of the West African Craton, after Lebrun et al., 2016; BRGM SIGAfrique map of Milési et al. (2004).*

- Kénéma-Man domain
  - Evidence of pre-Leonian
  - Leonian (ca. 3050–2950 Ma) and Liberian (ca. 2850–2700 Ma)
    - orthogneiss
    - granitoids
    - metavolcanics/ metasediments

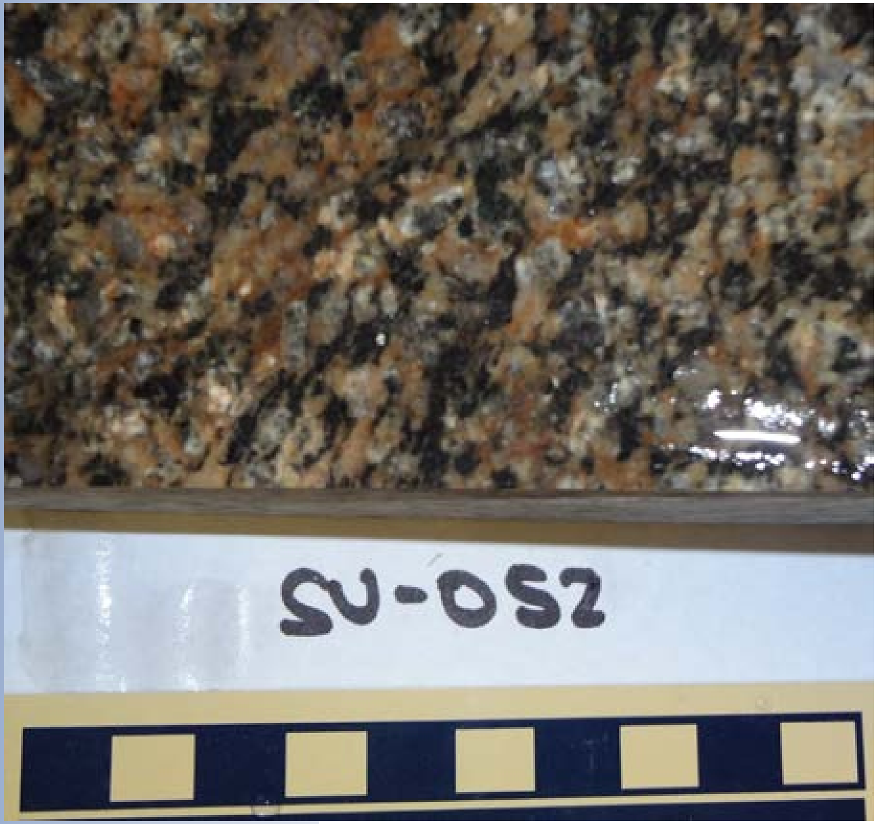
# SWAC Regional Geology



*Simplified geological map of the southern Leo-Man Rise of the West African Craton, after Lebrun et al., 2016; BRGM SIGAfrique map of Milési et al. (2004).*

- Baoulé-Mossi domain
  - Eoeburnean (ca. 2266-2150 Ma) and Eburnean periods (ca. 2130-1980 Ma)
    - linear/arcuate volcanic belts and associated sedimentary basins
    - **Felsic intrusions**

# SWAC Regional Geology



- Baoulé-Mossi domain
  - Felsic intrusions
    - commonly refer to as TTG
    - Foliated amphibole bearing rocks that are in some cases biotite rich, containing alkali feldspar, plagioclase, titanite, apatite and zircon
    - Potassic-alkaline intrusions (locally porphyritic)
    - Biotite rich rocks that lack amphibole, dominated by plagioclase, alkali feldspar quartz and in some cases muscovite

# Why the Southern West African Craton-SWAC

- Multiple-conflicting nomenclature
- **Diversity of tectonic models**
- Outdated data
- Relatively underexplore regions/scarcity of outcrops/access

# Diversity of tectonic models

- plume related-oceanic plateau, Abouchami et al., 1990
- subduction-related arcs then transcurrent shortening, Salah et al., 1996
- diapirs then transcurrent shortening, Vidal et al., 2009

# Diversity of tectonic models

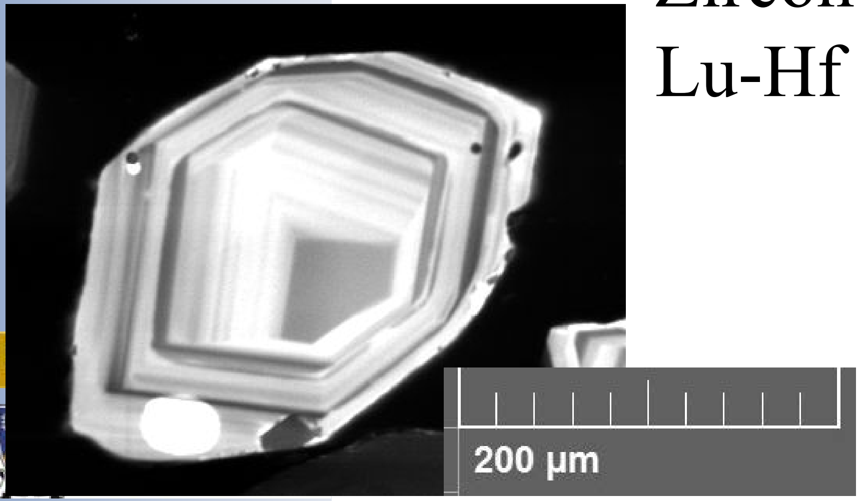
- collision zone between an Archean continental block (Sáo Luis Craton) and segments of newly formed paleoproterozoic crust, Feybesse et al., 2006
- arc-backarc basins complex in a Palaeoproterozoic intraoceanic environment, De Kock et al., 2012

# The aims…

- Evaluate the evolution of the Paleoproterozoic Baoulé-Mossi domain
  - – Study dispersal patters from eroded units
  - – Evaluate spatial and temporal changes of felsic intrusions
  - – Juvenile vs. Ancient

# Methods

- Streams/creeks:
  - Zircon U-Pb and Lu-Hf (LA-ICP-MS)
- Well constrain and chemically characterised felsic Intrusions:
  - Whole rock geochemistry
  - Zircon U-Pb (SHRIMP), O (SIMS), and Lu-Hf (LA-ICP-MS) isotopes



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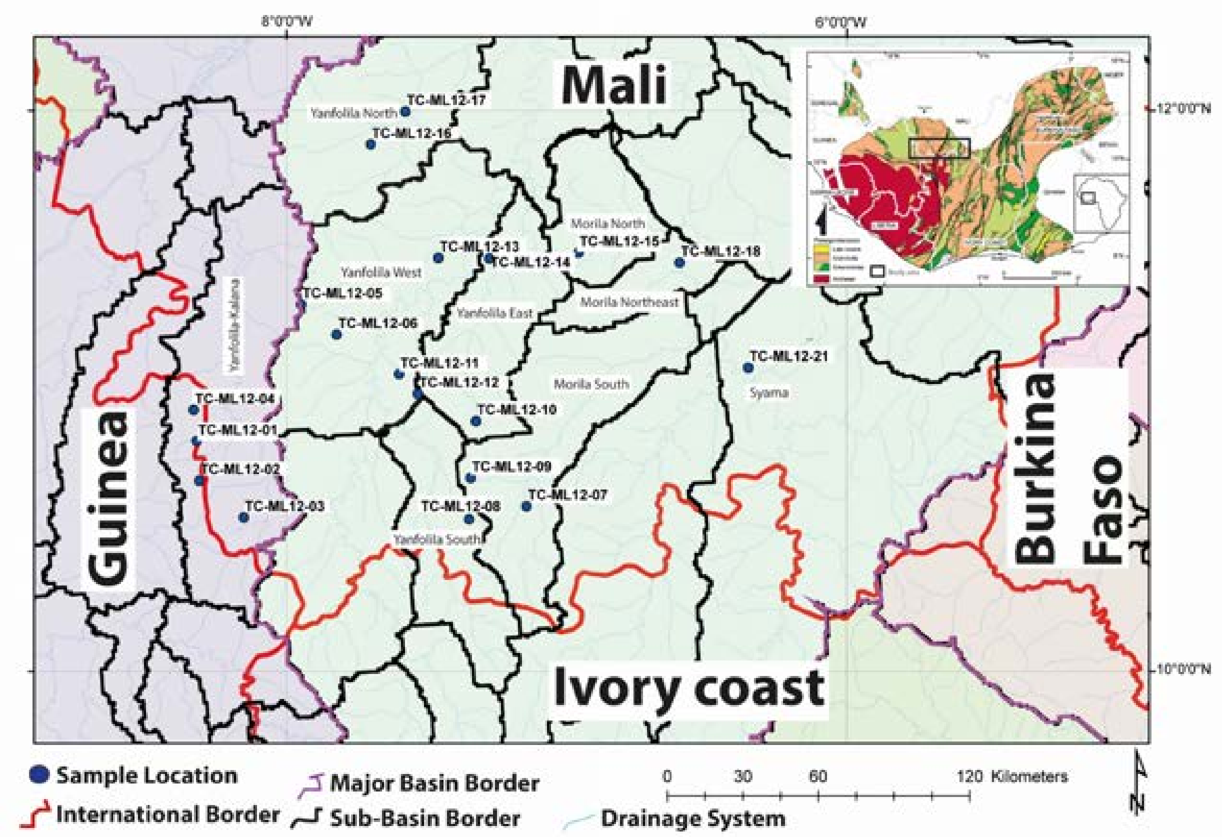
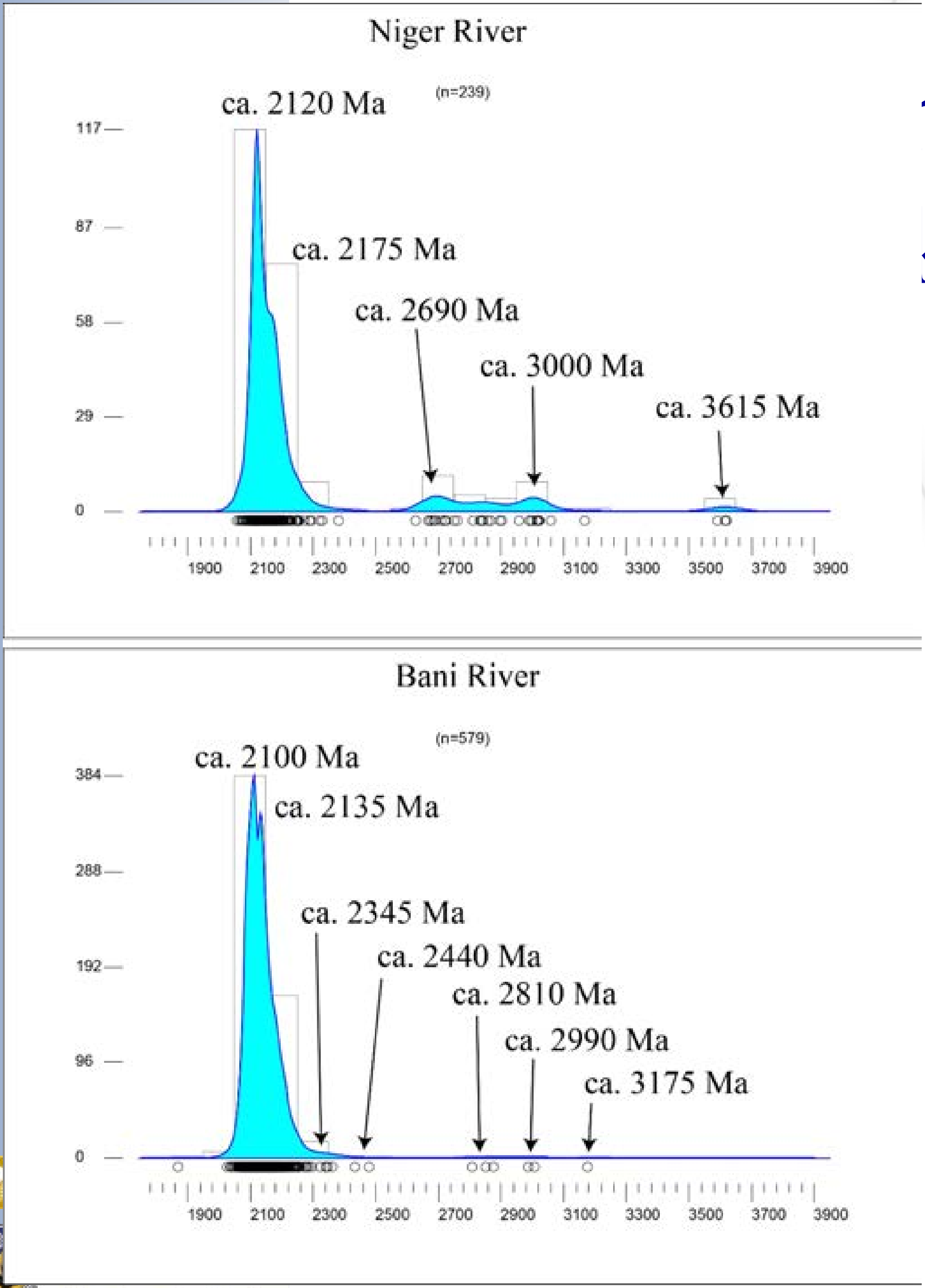
# Detrital zircons: Streams/creeks



- Two drainage systems 22 samples:
  - Bani River (light green)
  - Niger River (purple)

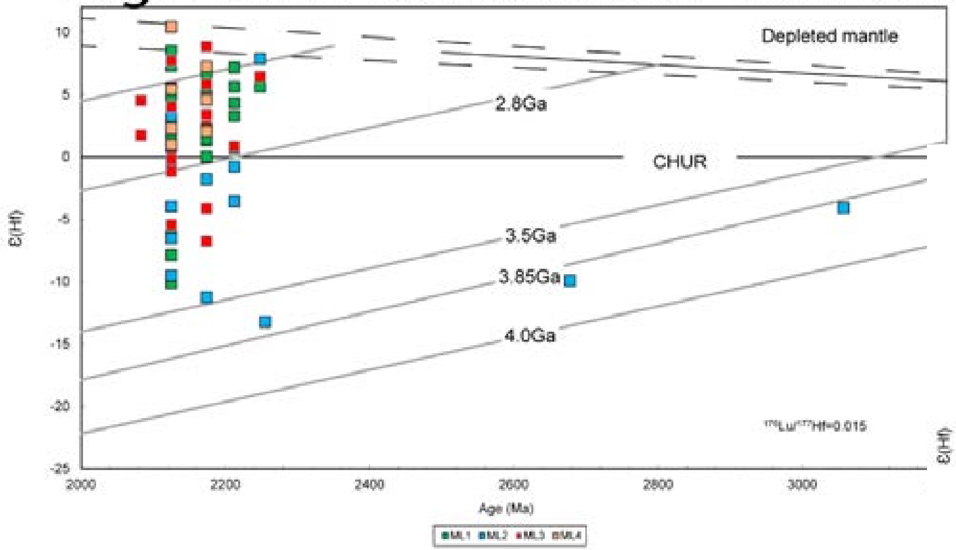
After Parra-Avila et al. (2016), Basins and sub-basins defined after USGS drainage system map, Lehner, 2006)

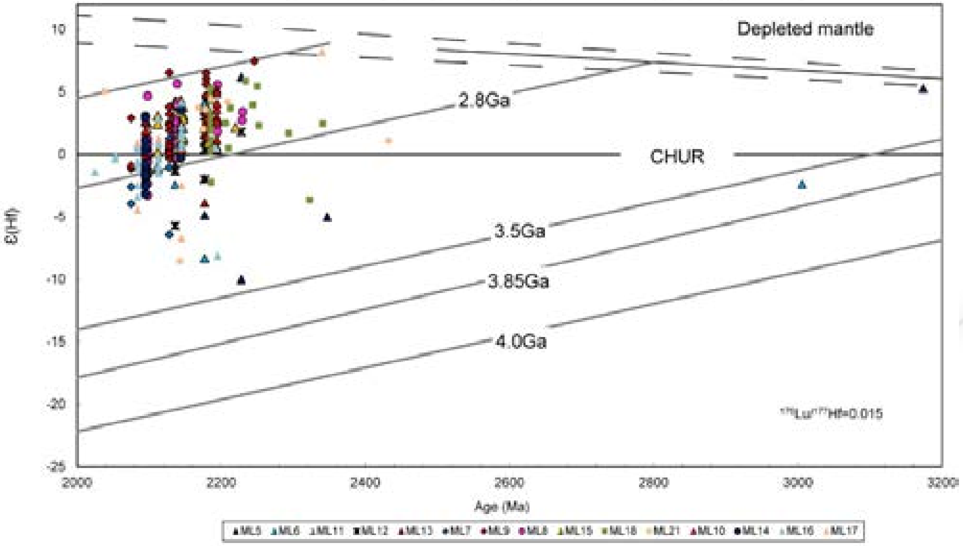


# ns:
# ks

- Highlights:
- Common evolution history for the period ca. 2200-2100 Ma
- Main peak of activity ca. 2130-2090 Ma
- Niger river basin:
  - Older grains between ca. 3600 and 2600 Ma
- Bani river basin:
  - Older grains between ca. 3175 and 2350 Ma
- So what…
  - Source of Archean grains?
    - Transported from the Kénéma-Man domain
    - A different source?

# l zircons:


Niger River Basin: Kalana-Yanfolila


Bani River Basin: All

After Parra-Avila et al. (2016)

## Lu-Hf highlights:

- 80% of samples display εHf > 0 and 20%, εHf < 0
- Mixing array that points to greater crustal re-working

# Detrital zircons: Streams/creeks

**Detrital zircons**

- Bulk of zircons yield Paleoproterozoic ages ca. 2400 - 2050 Ma
- A small group of zircons, yield U-Pb ages ca. 3600 – 2100 Ma
- Overall Hf-isotope signature yield model ages ranging between 3600 - 2800 Ma

# Felsic intrusions characterisation

Generally grouped as:

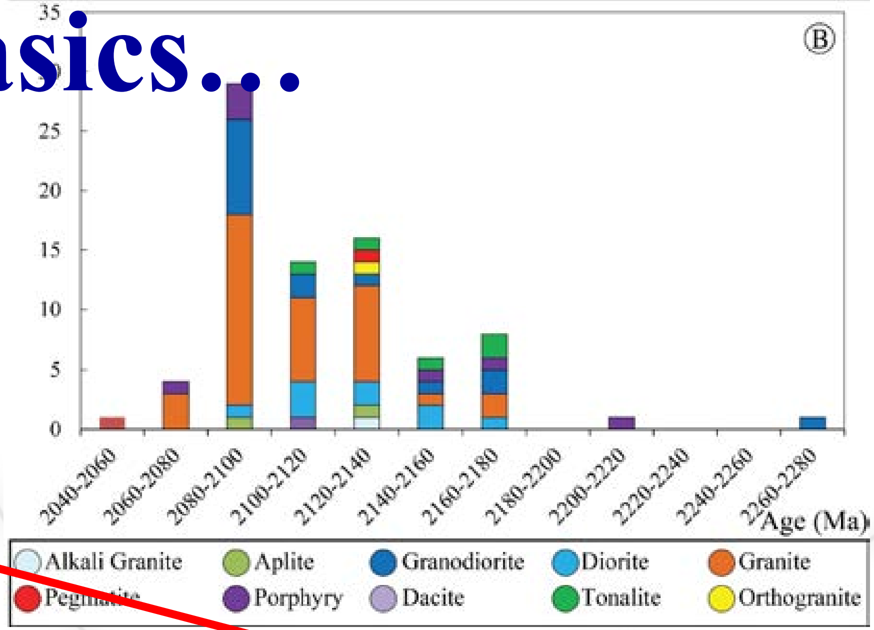
- amphibole bearing granitic rocks, with or without biotite, usually foliated
- biotite bearing granitic rocks without amphibole
- potassic alkaline plutons.

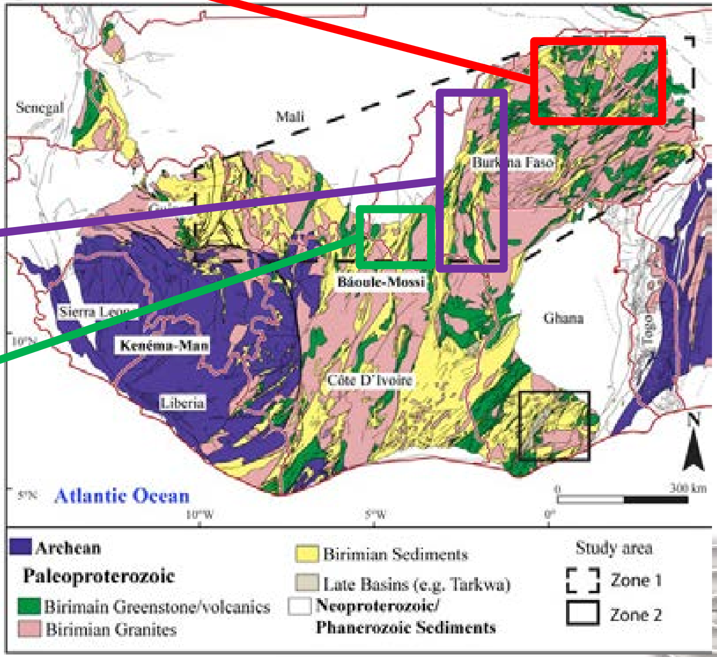
# Geochronology basics…

## Burkina Faso

- Goren Belt/Po-Tenkodogo-Yamba regions, ca. 2270 - 2120 Ma.
- Belahouro ca. 2180 - 2120 Ma
- Boromo-Hounde ca. 2180 - 2110 Ma
- Banfora ca. 2150 - 2110 Ma

After Parra-Avila et al. (2017)

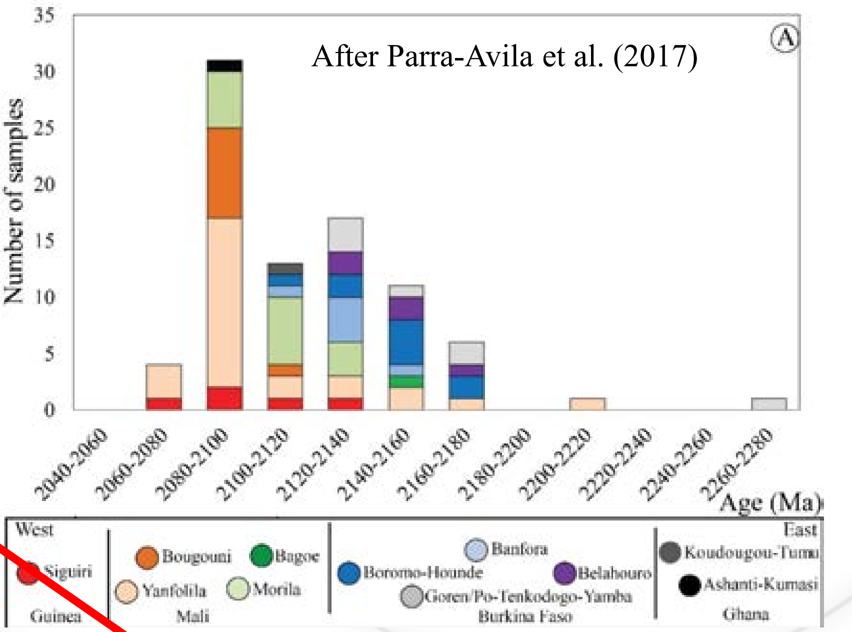


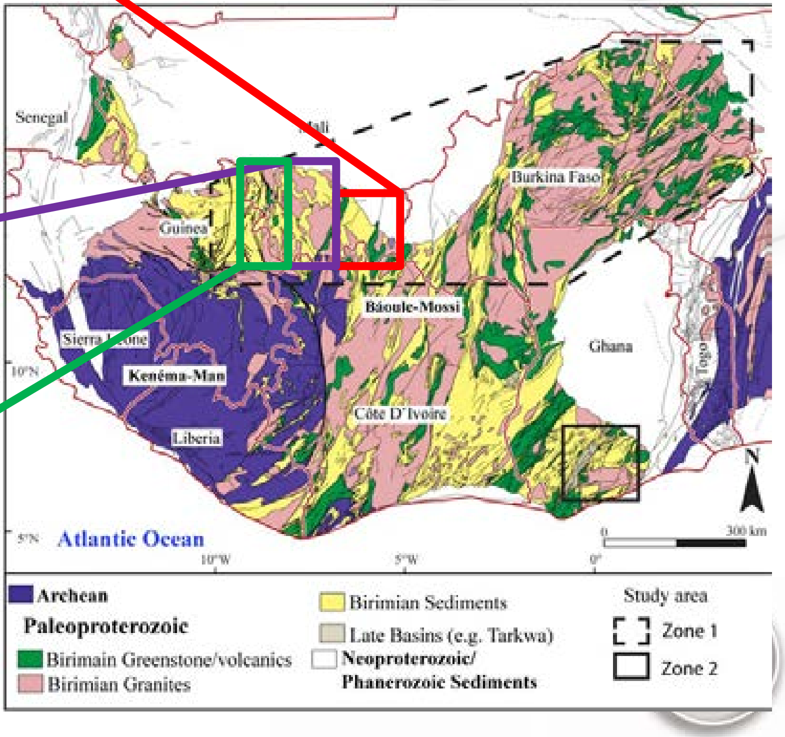


# Geochronology bas

## Southern Mali

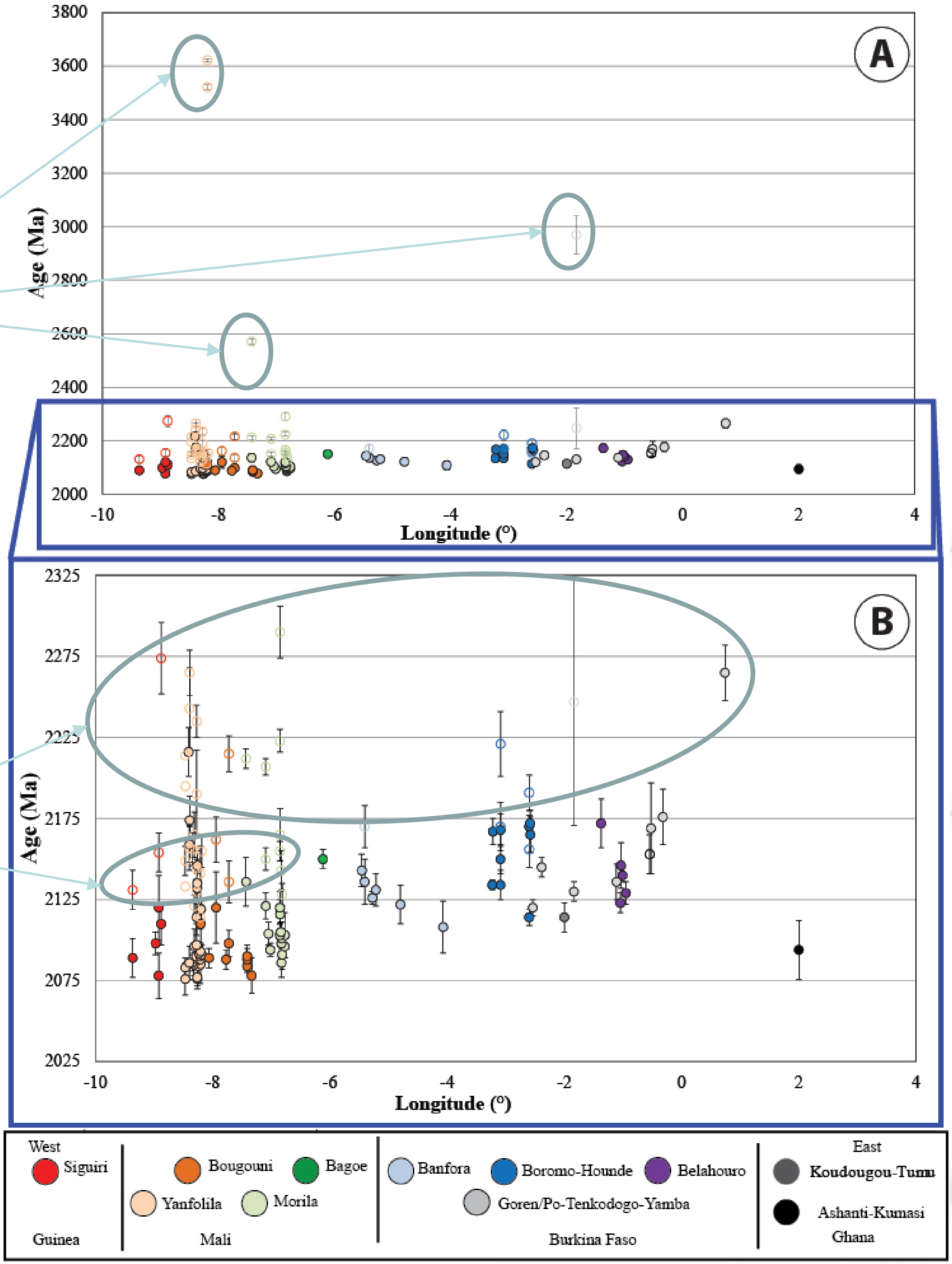
- Syama mine (Bagoe Belt) ages peak at ca. 2150 Ma
- Morila Belt inferred ages between ca. 2140 - 2080 Ma.
- Bougouni domain, ages between ca. 2100 - 2080 Ma.
- Yanfolila Belt, ca. 2220 - 2070 Ma.


After Parra-Avila et al. (2017)



# Geochronology

- Presence of Inherited grains/core (4 total>2500 Ma)
- Inheritance increases in the western portion, predominately in samples younger than ca. 2125 Ma
- Inheritance mainly between ca. 2275 and 2130 Ma.



After Parra-Avila et al. (2017)

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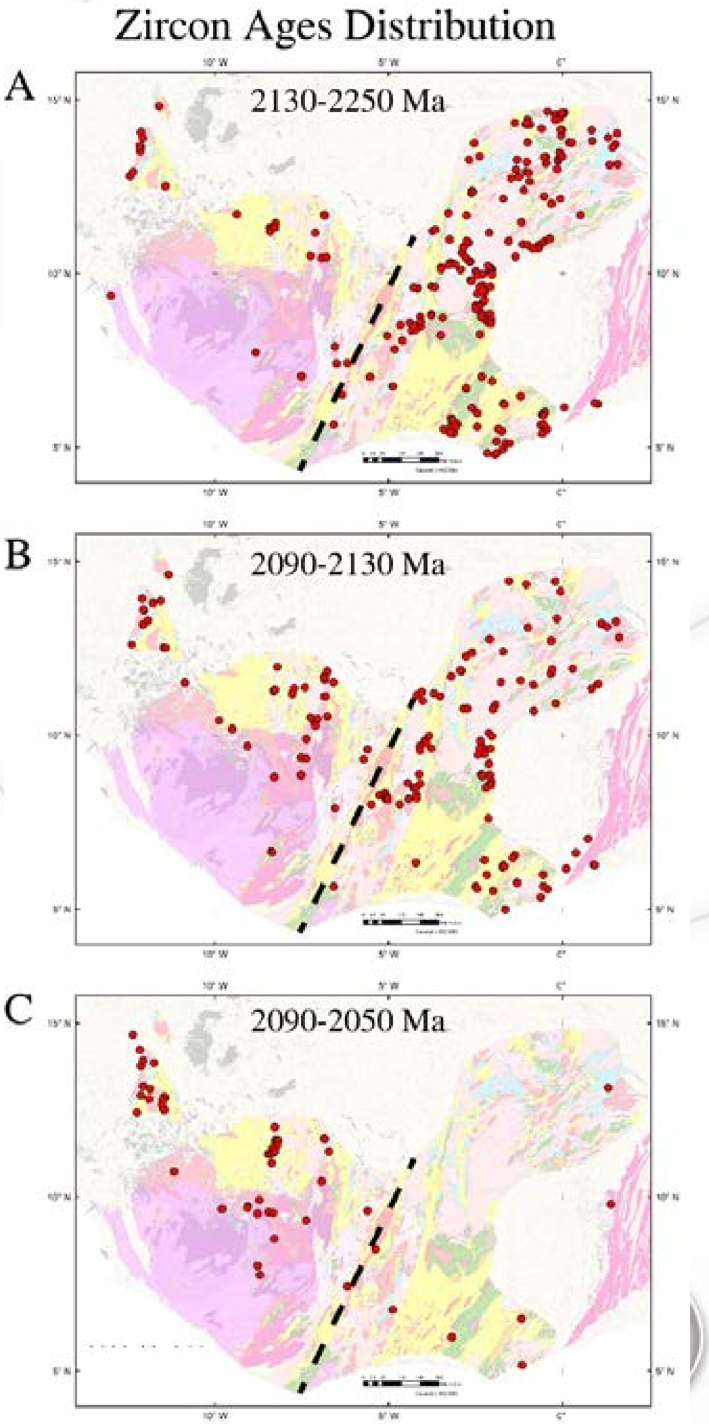
# Geochronology basics.

- all zircon ages (magmatic, metamorphic and detrital) supports diachronous evolution
- Cessation and retreat of magmatic activity
- Westward migration of the magmatic front of approximately 35 km/Myr.
- Offset of magmatism and distribution of inherited zircons points towards two crustal blocks
- An accretionary process might have started as early as ca. 2175 Ma. At this time a minor peak of magmatic activity is identified east of the Banfora Belt.
- Intrusions younger than ca. 2130 Ma generally contain inherited grains with ages up to 2250 Ma, mainly in the western portion of the Baoulé-Mossi domain.



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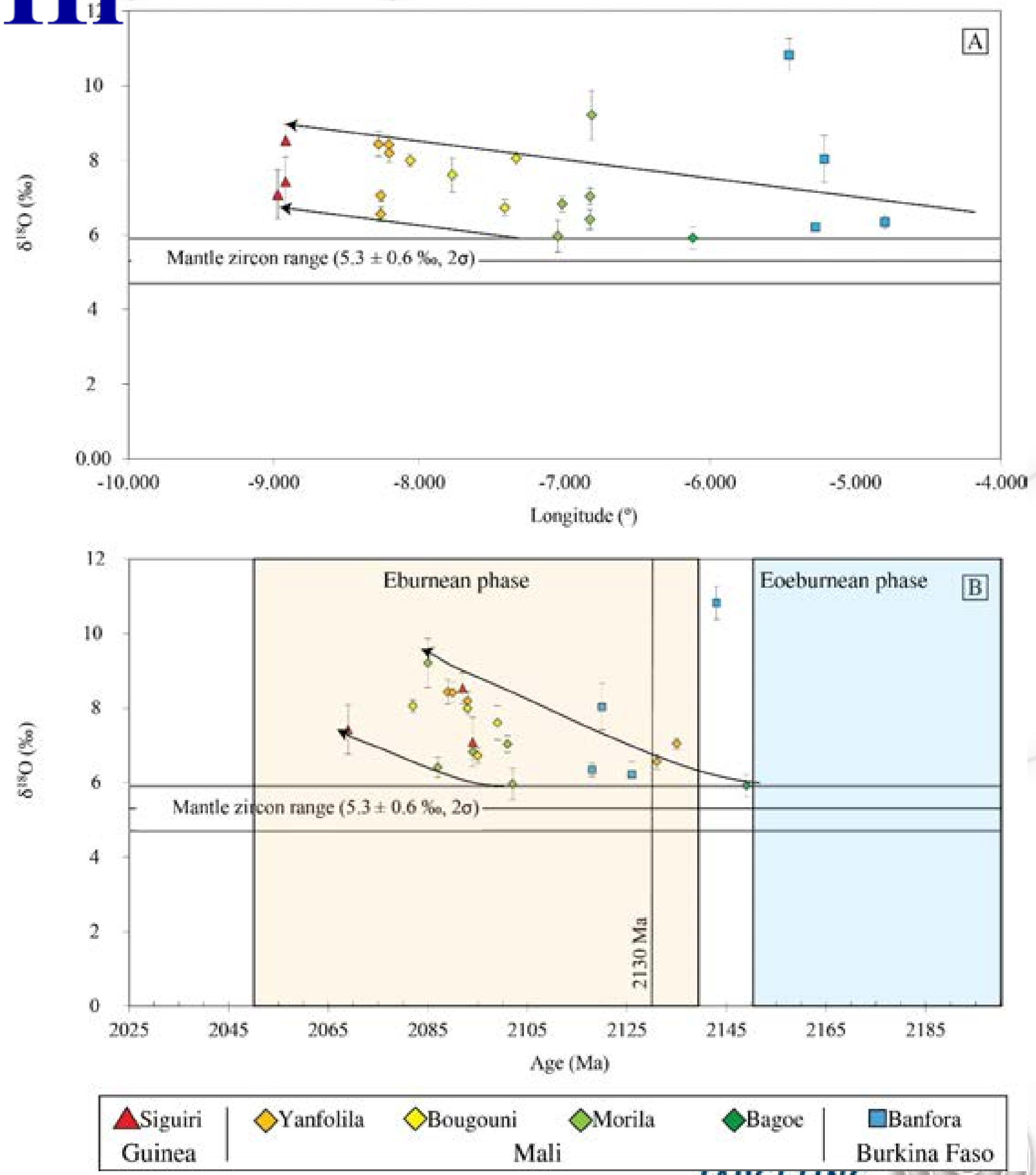
# The O and Lu-Hf signatures

After Parra-Avila et al. (2018)

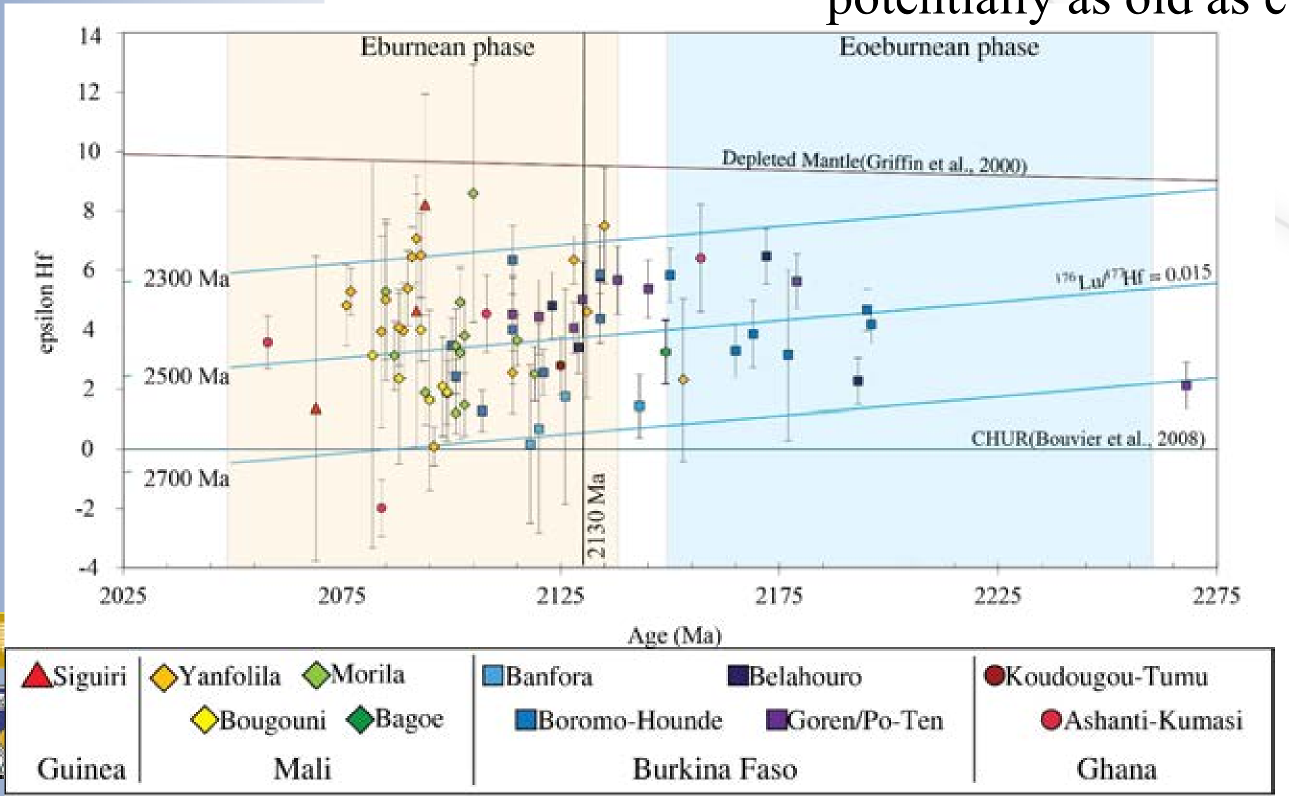
- Large $\delta^{18}O$ variability across Banfora Belt
- Increasing $\delta^{18}O$ from east to west
- Samples predominately show relatively high $\delta^{18}O$
- $\delta^{18}O$ values over 8 => Contamination with crustal material subject to near surface processes



# The O and Lu-Hf signatures

εHf from felsic intrusions mainly > 0

- Independent from belt sampling site
- Large variability among samples
- Predominately juvenile source
- Some mixing with a crustal component potentially as old as ca. 2700 Ma



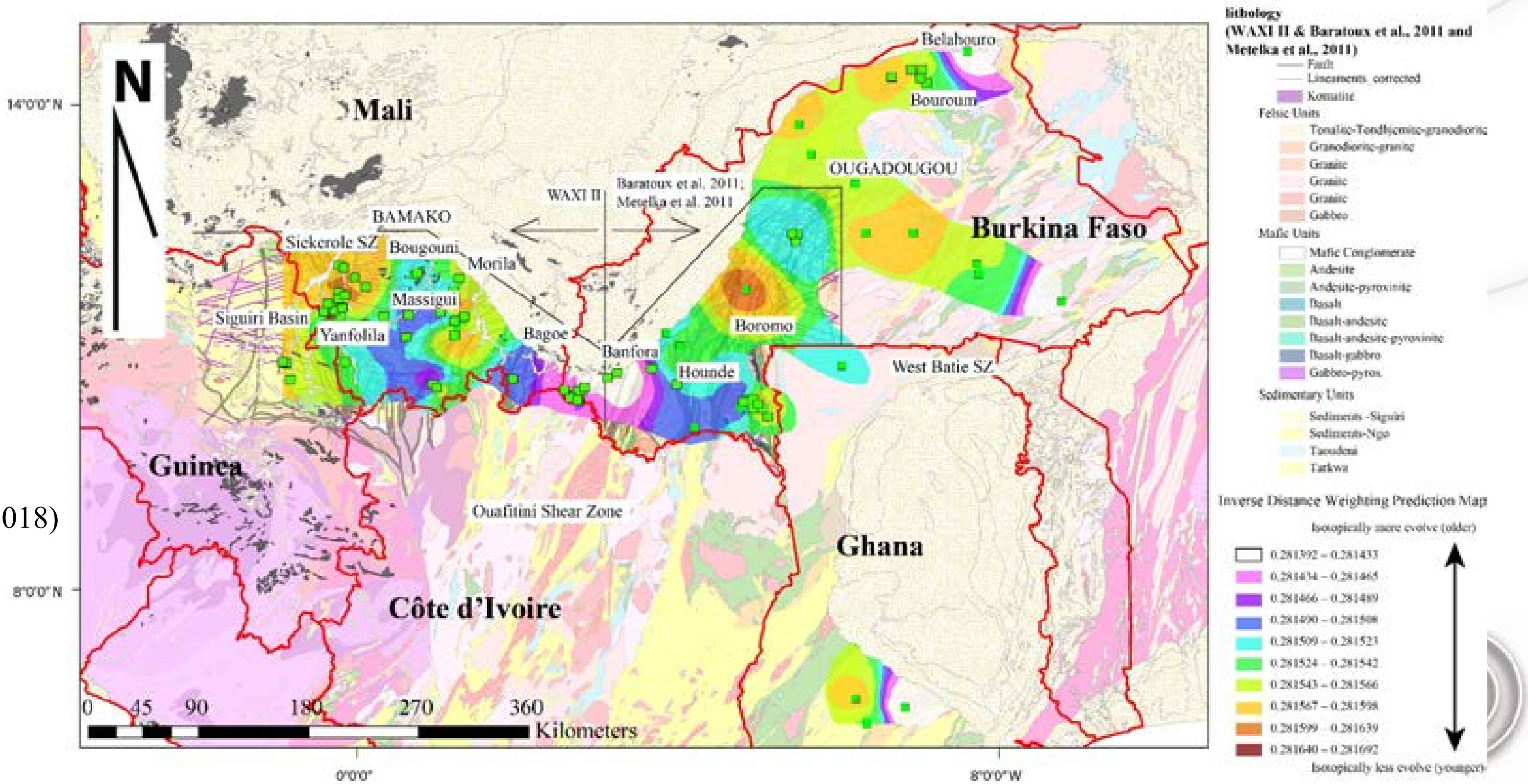
After Parra-Avila et al. (2018)

Centre for EXPLORATION TARGETING

# The O and Lu-Hf signatures

Potentially two crustal blocks

- Banfora – Bagoe belt a boundary?
  - Less radiogenic Hf signature
- South extension through the Greenville-Ferkessedougou-Bobo-Dioulasso fault



After Parra-Avila et al. (2018)

# The O and Lu-Hf signatures

**Felsic Intrusions, O and Lu-Hf isotopes**

- Two predominately juvenile regions
- One less radiogenic Hf signature between Banforal and Bagoe belts
- A crustal component potentially as old as ca. 2800 Ma
- Westernmost part has a higher proportion of older crustal material in the source when compared to the easternmost area
  - Greater interaction between Paleoproterozoic and Archean domains
- O-isotope data supports crustal contamination/interaction with supracrustal materials

# SUMMARY

- Detrital zircons match mean peaks of magmatic activity identified from the igneous record.
- Diachronous evolution
  - East magmatic activity ca. 2.26 - 2.13 Ga, peak at ca. 2.15-214 Ga.
  - West magmatic activity between ca. 2.10 and 2.07 Ga, peak at ca. 2.09 Ga.
- Inherited ages between ca. 3.6 and 2.13 Ga.
- O (magmatic zircons) and Hf data (detrital/magmatic zircons) suggest mixing and recycling of a crustal source as old as 2.8 Ga.

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IXOA - L'Initiative d'Exploration Ouest Africaine

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# The K3 Copper Deposit in the Bakhuis Granulite Belt, West Suriname

## *Restudy of the characteristics of the copper mineralization at Bakhuis Mountains after Dalhberg (1975- 1989)*

Raysree S. Patadien[1]; Dennis J. LaPoint[2]; Emond de Roever[3]

Keywords: Granulite Belt, Bakhuis, Copper

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[3] *Earth Sciences, VU Amsterdams, Netherland, ederoever@ziggo.nl*

## Introduction

The K3 deposit lies in the SW part of the Bakhuis Granulite Belt (BGB) (Figure 1), a metamorphic terrain located in the Bakhuis Mountains, West Suriname, in the center of the Paleoproterozoic Guiana Shield. Strong magnetic and electromagnetic anomalies were detected here during an airborne geophysical survey carried out for the Geological and Mining Service of Suriname (GMD) in the early sixties. In the 70"s the GMD carried out exploration at the site to determine the economic potential of the copper and phosphate occurrences. Diamond drilling was part of the program and 66 shallow holes were completed, with a maximum depth of 100m. Dalhberg (1987) summarized this research and concluded that the copper and phosphate mineralized syenitic and monzonitic rocks and lenses of clinopyroxene-apatite rocks represent metamorphosed cupriferous felsic to intermediate volcanics and phosphatic siliceous carbonate sediments of the supracrustal succession.

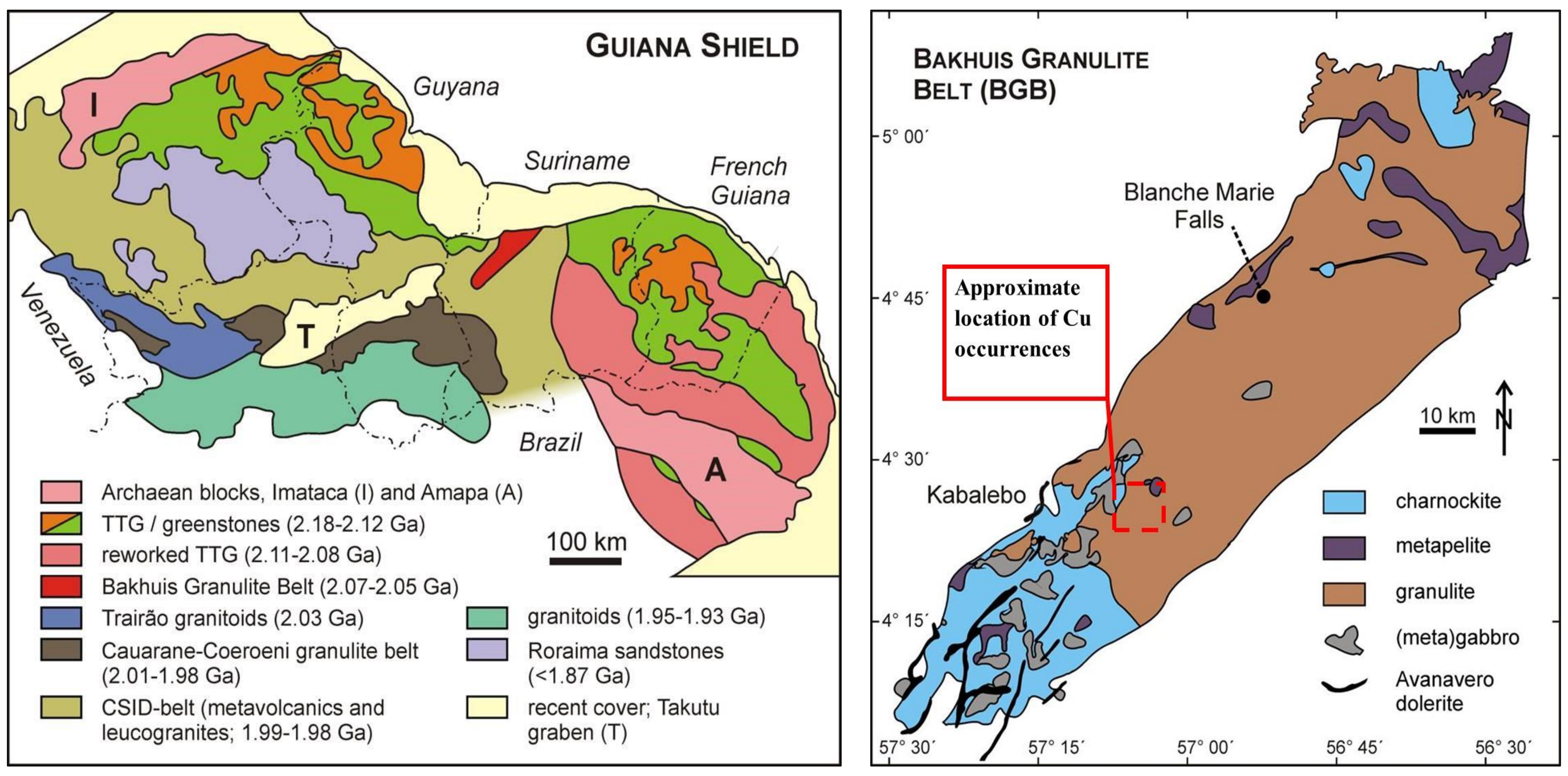

**Figure 1:** Simplified geology of the northern part of the Guiana Shield (left), Geology of the Bakhuis Granulite Belt (right) (Klaver et al, 2015)

## Aim of Research

The current research compiled and georeferenced the historic data and re-examined core and thin sections plus new ICP-MS analysis of pulps that are still retained. The intent of this research is to update and attempt to re-study the core and thin section, using new technology and mineralization models since the extensive investigation of Dalhberg and other geologists in the seventies and eighties of the previous century on this mineralization.

## Historic Study

In the 70's Dahlberg carried out an extensive program of exploration on the K3 Cu-phosphate anomaly in the SW part of the BGB, including a combined magnetic- induced polarization- resistivity survey, soil sampling, geological mapping and diamond drilling (Figure 2). The drill core with the strongest copper mineralization average 0.33% (Dahlberg, 1987). The drill-core did not go deeper than ~ 100m. The sulfidic copper mineralization consists mainly of chalcopyrite and bornite.
Phosphate mineralization in the form of apatite-rich lenses is associated to the Cu mineralization, but does not coincide exactly, the highest phosphate values were found outside the main copper mineralized zone (Dahlberg, 1987). Anomalous P, Ce, Th, Zr and Sr soils in an approximate north tending zone were thought to correspond to buried apatite-rich lenses. This zone is part of a larger northeast- trending Ce-Th anomaly found by stream sediment sampling (Dahlberg, 1987)

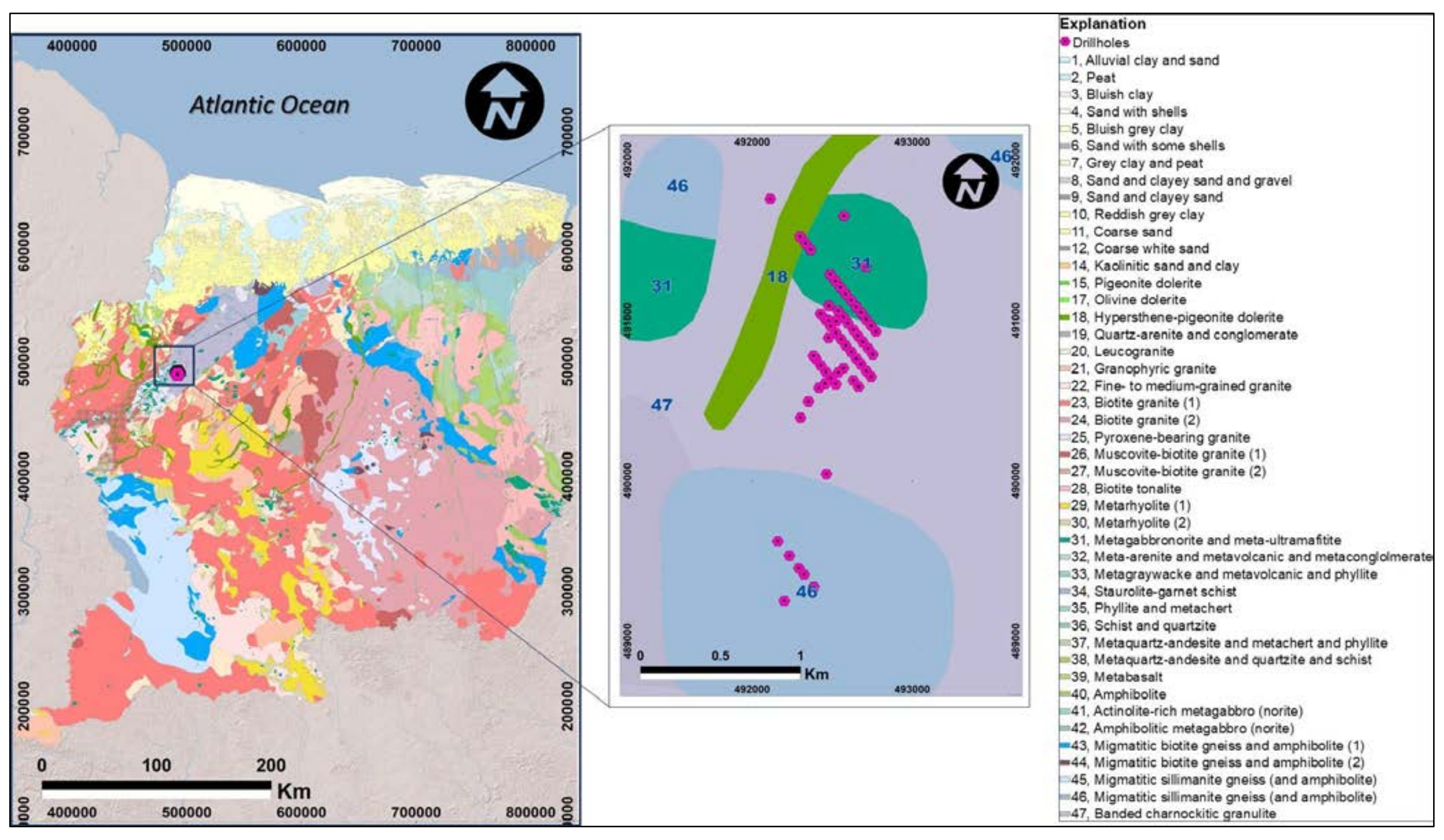

**Figure 2:** Location of the diamond drillholes drilled in K3 prospect relative to the geological map of Suriname (1977).

## Current Research

The current research involved macroscopic study of core from 22 drill holes, thin section study from 17 holes using an optical microscope and analyses of 220 pulp and sludge sample using ICP-OES.
Historic data including yearly and quaternary GMD reports, maps and publications were reviewed.
Interpretation of geochemical data is in progress and final conclusions are yet to be drawn. Copper models are being reviewed.

## Results- Rock Types

For main rock types were distinguished: migmatitic granulite, Ca-silicate granulite, metagabbros and ultramafics. These names are based on their mineralogy and texture and they are different from the names assignment by Dalhberg.
The granulites show a conspicuous banding and foliation and they occur parallel to subparallel relative to core-axis.

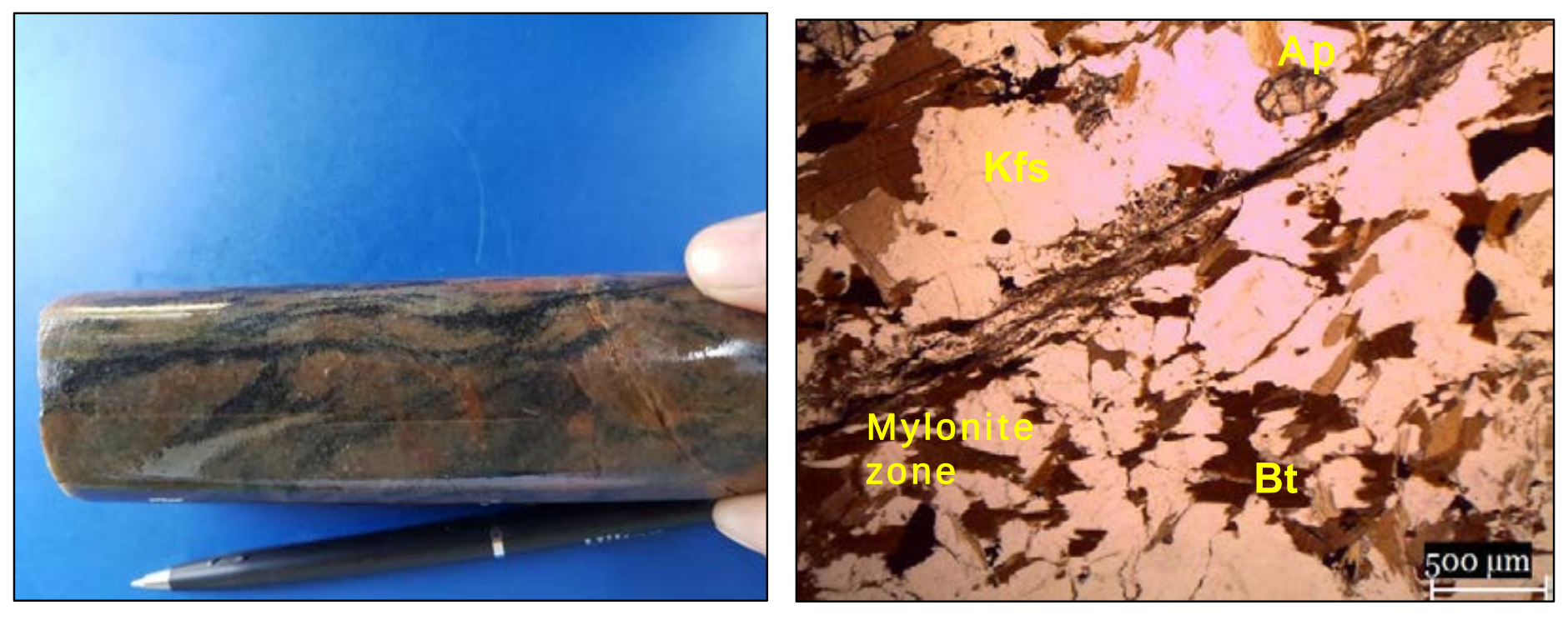

**Figure 3:**
Migmatitic granulite showing it's typical leuco- and melanosome (left);
Thin section in XPL of the leucosome with biotite and K-feldspar (right)

**Figure 4:**
Ca- silicate granulite with cpx and opx (left);
Thin section in PPL showing cpx, opx, K-feldspar and opaque minerals between contacts (right)

## Results- Copper and Phosphate mineralization

Geochemical analyses shows that the copper mineralization is distributed over various rock types, but higher values occur mainly in the migmatitic granulites and occasionally in the Ca-silicate granulites.
Macroscopic determination showed that the copper is mostly concentrated in the pink to cream bands of the migmatitic granulites, in the form of bornite, chalcopyrite and secondary minerals.
The bornite is frequently present in fractures, accompanied with the secondary minerals. The bornite may represent a supergene enrichment based on presence in fractures. These fractures are irregular in length and crosscutting the foliation/lineation of the rock. These fractures are also frequently filled with magnetite. Geochemical analyses shows that high Cu values are concentrated in shallow depth (5-50m) and decreasing with depth, suggesting a supergene enrichment.
Chalcopyrite appears as fine grain and disseminated usually found in the mafic layering and streaks and sometimes filled in minor fractures.
Phosphate as apatite occurs in the migmatitic granulites, but higher concentrations have been observed in the Ca-silicate granulites

**Figure 5:** Leucosome of migmatitic granulite containing copper minerals (left),
Ca-silicate granulite showing high concentration of apatite (right)

## Copper Models

| | Porphyry copper (Sillitoe 2010) | Skarns (Hammerstrom et al, 1995) | Volcanogenic massive sulfide (VMS) (Shanks et al, USGS, 2010) | Sedimentary hosted (Hayes et al, 2015) | IOCG (Pirajno, 2009) | | Bakhuis Cu (Dalhberg, 1987) | Bakhuis (Patadien et al, 2019) |
|---|---|---|---|---|---|---|---|---|
| **Host Rock Type** | Intermediate to felsic porphyry intrustions | Highly calcareous sedimentary rocks or metamorphosed carcareous sedimentary rocks; Carbonate rocks and clastic rocks as pelite, argillite, shale, graywacke etc | Volcanic and sedimentary rocks as tuffs, shales, siltstones, and (or) sandtsones, coarse volcanic breccias and fragmental pyroclastic rocks | Sedimentary rock sequences, deposited within 20- 30 degree of the paleo-equator | Variable | **Host Rock Type** | Metamorphosed felsic to intermediate volcanics and phosphatic siliceous carbonate sediments of the supracrustal succesion. | Migmatitic granulite, Ca-silicate granulite |
| **Depositional Environment** | Magmatic arc subjected to a spectrum of regional-scale stress regimes | Granitoid pluton intrusion in sedimentary strata of carbonate-rich rocks. | At or near seafloor where circulating hydrothermal fluids driven by magmatic heat are quenched through mixing with bottom waters or porewaters in near-seafloor lithologies | Proto-oceanic rifts/ post-collisional molasse | Forms in shallow crustal environments (4-6 Km) in Intrusion related magmatic-hydrothermal systems | **Deposition Environment** | Mafic rocks intrusion assimilate Cu, S and P from supracrustal sequence including copper-rich volcanices, phosphorites and sulphur-rich evaporites | |
| **Structural Controls** | Moderately extensional through oblique slip to contractional | No structural controls, related to magmatic- hydrothermal activity | Extensional oceanic seafloor spreading ridges, volcanic arcs (oceanic and continental margin), and related back-arc basin environments | Virtually undeformed to intense folded and thrust-faulted | Related to deep- seated megasturctures in intracontinental rifts | **Structural Controls** | Unknown; general trend of the rocks is northeast to north-northeast and dipping subvertical to steep to the north-west, cross cuts of strike -slip faulting | Not observed. Host rock oriented subparallel to core-axis and minor folds resulted from |
| **Ore minerals** | Quartz, tourmaline, specularite, chalcopyrite and pyrite | Chalcopyrite, pyrite, hematite, magnetite, sphalerite, galena, arsenopyrite | Pyrite, pyrrhotite, chalcopyrite, sphalerite and galena | Chalcocite, bornite, pyritic | Chalcopyrite, bornite, chalcocite, pyrite Magnetite, hematite | **Ore Minerals** | **Primary (Cu):** Bornite, chalcopyrite, accompanied by pyrite, pyrrothite, pentlandite, sphalerite, gold, magnetite, rutile and chromite<br>**(P2O5):** Fluor Apatite<br>**Secundary:** Covelite, Digenite, Chalcocyte | Primary (Cu): Bornite, chalcopyrite, pyrite. (P2O5): Apatite Secundary: Azurite? |
| **Alteration** | Potassic ± chlorite- sericite | Hornfels, narble, bleached limestone, skarn zones: potassic, sericite, argillic, propylitic alteration | Wide variety of hydrothermal alteration among individual deposits; Advanced argillic, argillic, sericitic, chloritic, carbonate propylitic | Albitization, hematitization | Allkali-rich alteration (Sodic-calcic-Na (Ca) and potassic-K, biotite, amphibole | **Alteration** | Montmorillonite, calcite, apatite, magnetite, microline, albite, biotite, muscovite, quarts, zircon, ilmenite, goethite, tremolite, epidote | Potassic and albitization? |
| **Element Enrichment** | Cu, Mo, Au, Pb, Zn, Ag | Cu, Au, Zn-Pb, Fe | Cu, Zn, Pb, Au, Ag | Cu, Ag, Co, Ba, Mg, B | Cu with/ without Au, Fe | **Element Enrichment** | Cu, Phosphate | Cu, Phosphate |
| | | | | | | **Metamorphic facies** | Granulite Facies | Granulite Facies |

## *Discussions and Conclusions*

Some preliminary conclusions can be drawn from the drill-core and thin sections study.
The copper mineralization is typically found in light pinkish-cream colored band rich in feldspar, intercalated between dark bands, associated with chalcopyrite, bornite and secondary Cu minerals that are macroscopically visible. The fresh appearance of the Cu mineralization and the lack of younger associated alteration suggests that the Cu enrichment occurred during UHT metamorphism, or even before, during the precursor stage of the granulites. Correlation matrix of ICP-OES data shows that copper is strongly correlated with sulphur, indicating presence of sulfide minerals. Ag, Na, B, Be, Li, Pb, Sb, Se and Sn show weak correlation with Cu. Similar weak correlation is found with phosphate. Supergene enrichment maybe a factor, due to Cu enrichment in shallow depth and reducing with depth.

## *Acknowledgement*

*We would like to acknowledge Professor Theo Wong, who is the faculty supervisor of the Mineral Geoscience course; all the personnel of the GMD who support us to have access to the data.*

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at the HARQUAIL SCHOOL OF EARTH SCIENCES

# Innovations for gold exploration in greenstone belts:

## *Highlights from the Footprint and Metal Earth programs and potential applications to the Guiana Shield*

**Stéphane Perrouty** *(sperrouty@laurentian.ca)*,
the NSERC-CMIC Footprint Team and the CFREF Metal Earth Team

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CANADA FIRST RESEARCH EXCELLENCE FUND | APOGÉE CANADA FONDS D'EXCELLENCE EN RECHERCHE
METAL EARTH

# Mineral Systems

- **Sources**

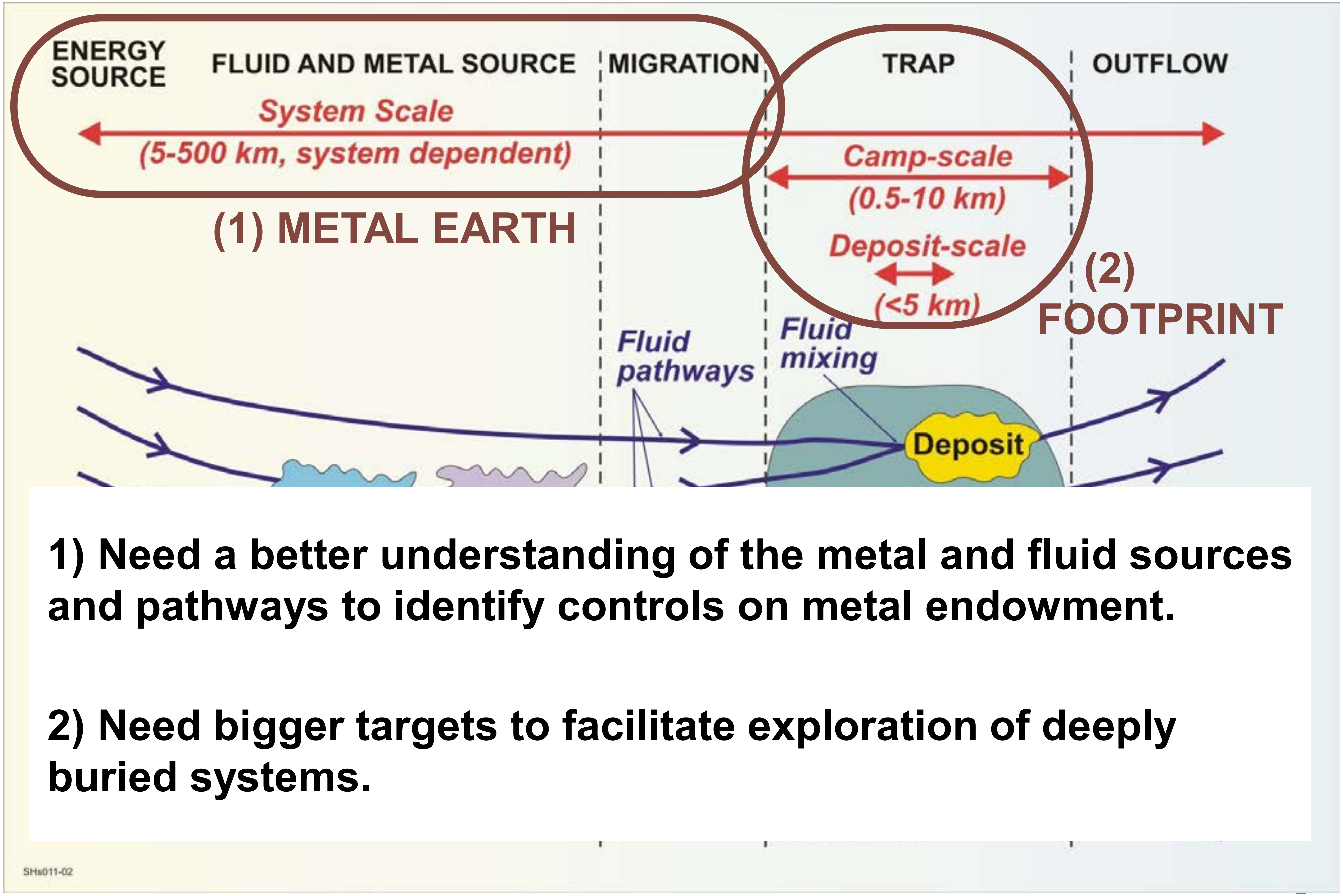
  (fluids + metals)

- **Pathways**

  (structures)

- **Traps**

  (chemical)



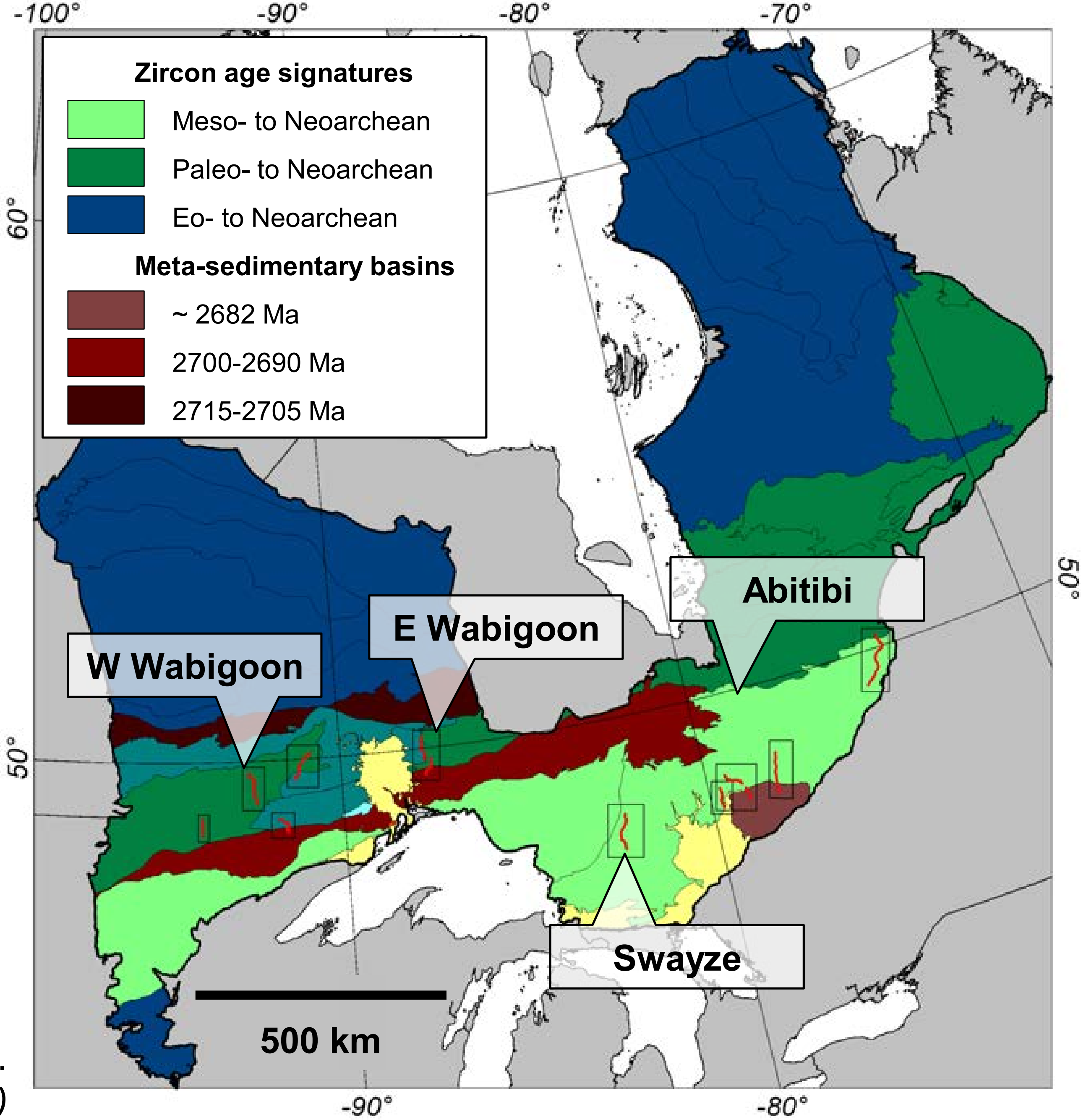
**1) Need a better understanding of the metal and fluid sources and pathways to identify controls on metal endowment.**

**2) Need bigger targets to facilitate exploration of deeply buried systems.**

McCuaig *(2013, CET-UWA)*

# Metal Earth Objectives

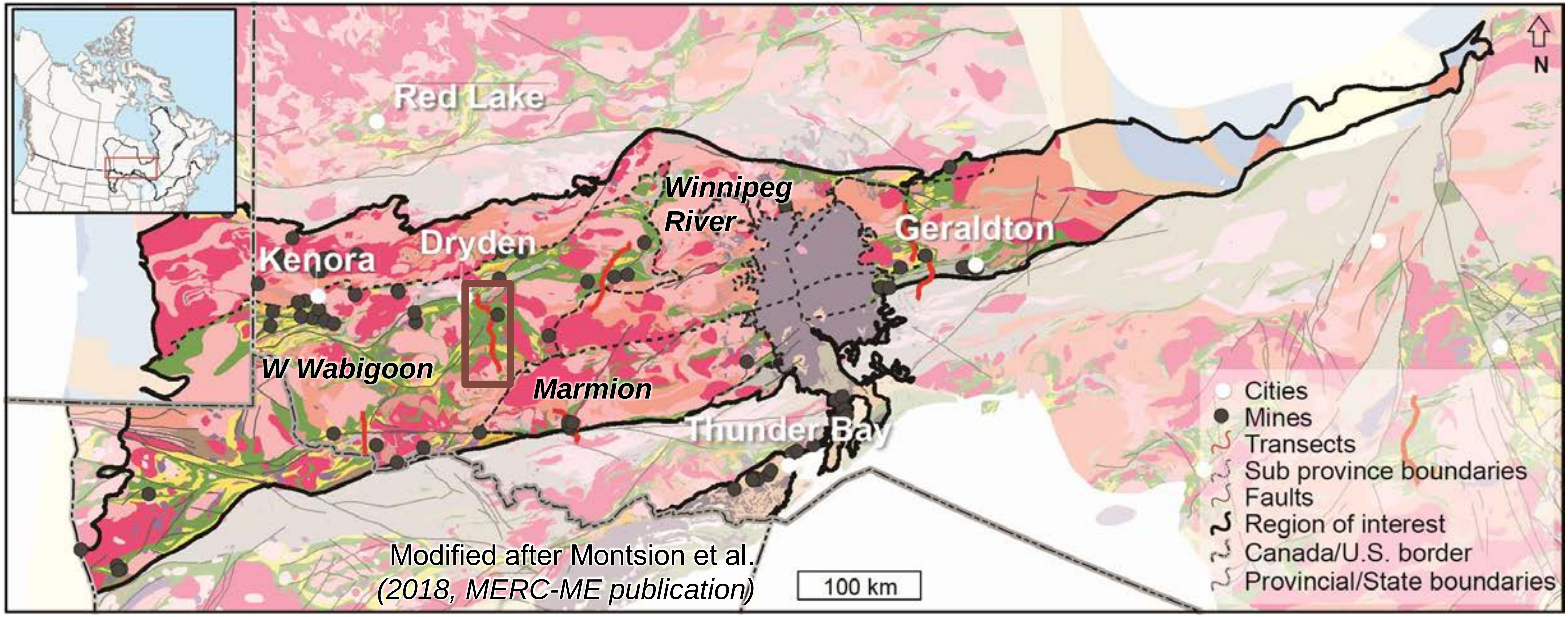
- **Define the key geological characteristics of well endowed versus less endowed crust**, to understand the processes responsible for Earth's differential base and precious metal endowment
- **Recognize differences in the mantle, the subcontinental lithospheric mantle, and in the deep crustal structures between well endowed and less endowed areas**, which may explain metal endowment localization



Modified after Frieman et al. *(2017, Precambrian Research)*

# **Abitibi** (>150 Moz) – **W Wabigoon** (~20,000 oz)

- **The Abitibi and the western Wabigoon subprovinces have similar scale, age, igneous and sedimentary stratigraphy, structural evolution and geodynamic setting … but very different historical gold production.**



Modified after Montsion et al. *(2018, MERC-ME publication)*

# Field Studies

(this slide is not provided)

# Crustal-Scale Investigations

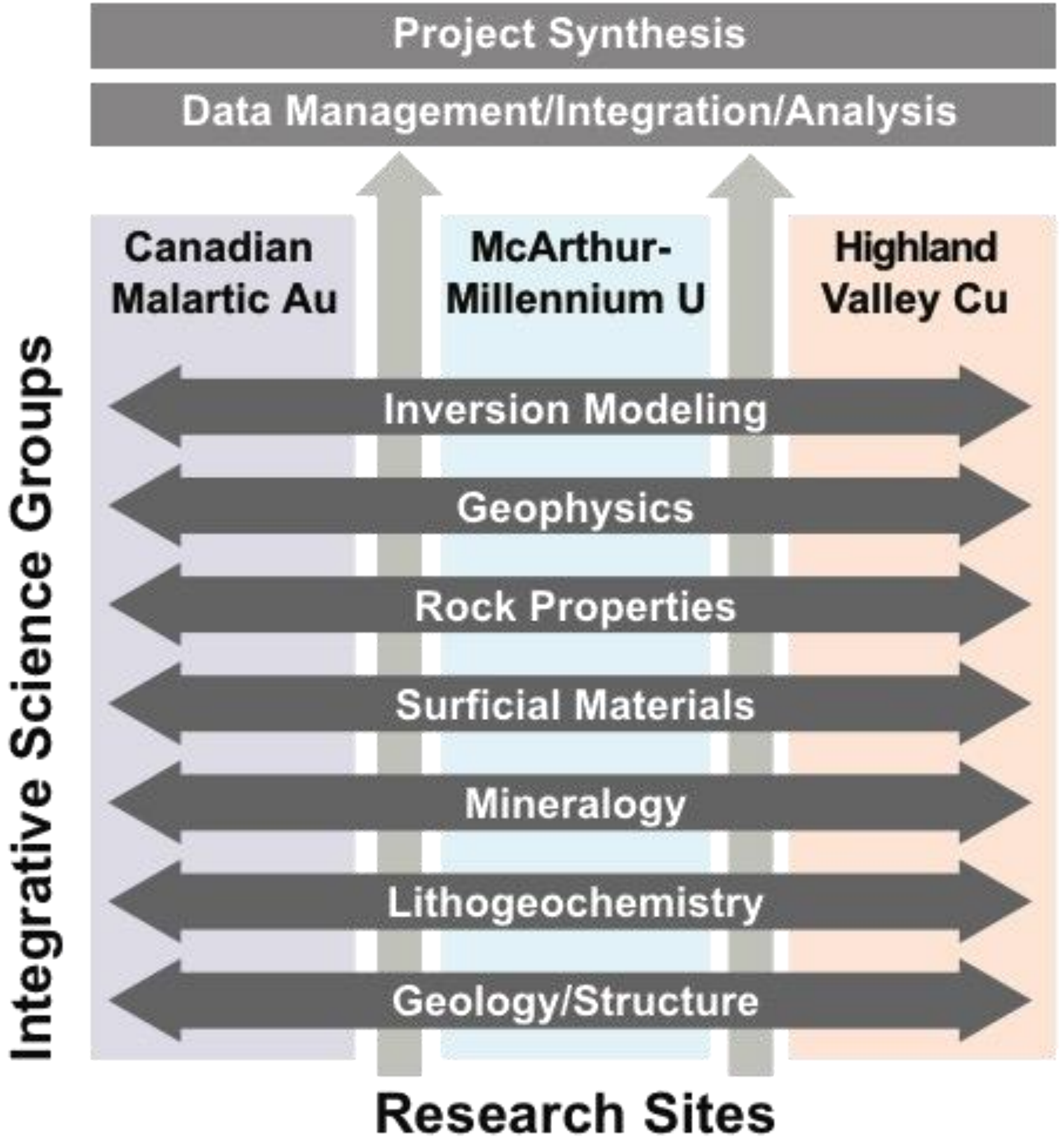
## *3D Implicit Modelling*

**(this slide is not provided)**

# Footprint (2013-2018) Objectives

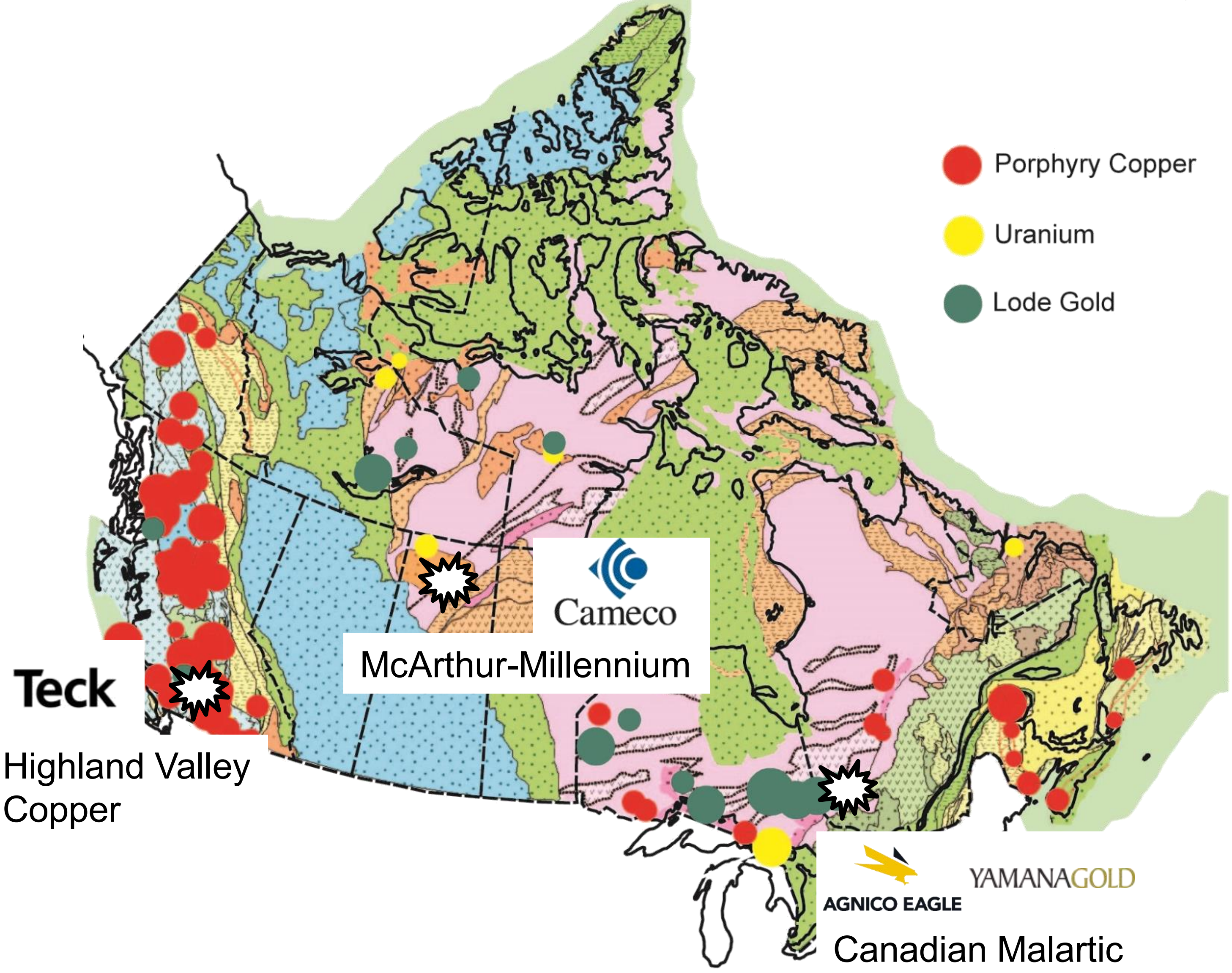
NSERC-CMIC FOOTPRINTS

- **Develop comprehensive and robust models of the footprints of large-scale ore-forming systems at three integrated study sites**, combining geological, mineralogical, geochemical, geophysical and physical rock properties from the local to the camp scale
- **Develop novel methods for integrating and interrogating multiple data sets that** will enhance the exploration process and, at the same time, answer fundamental questions about the origins of large-scale ore-forming systems



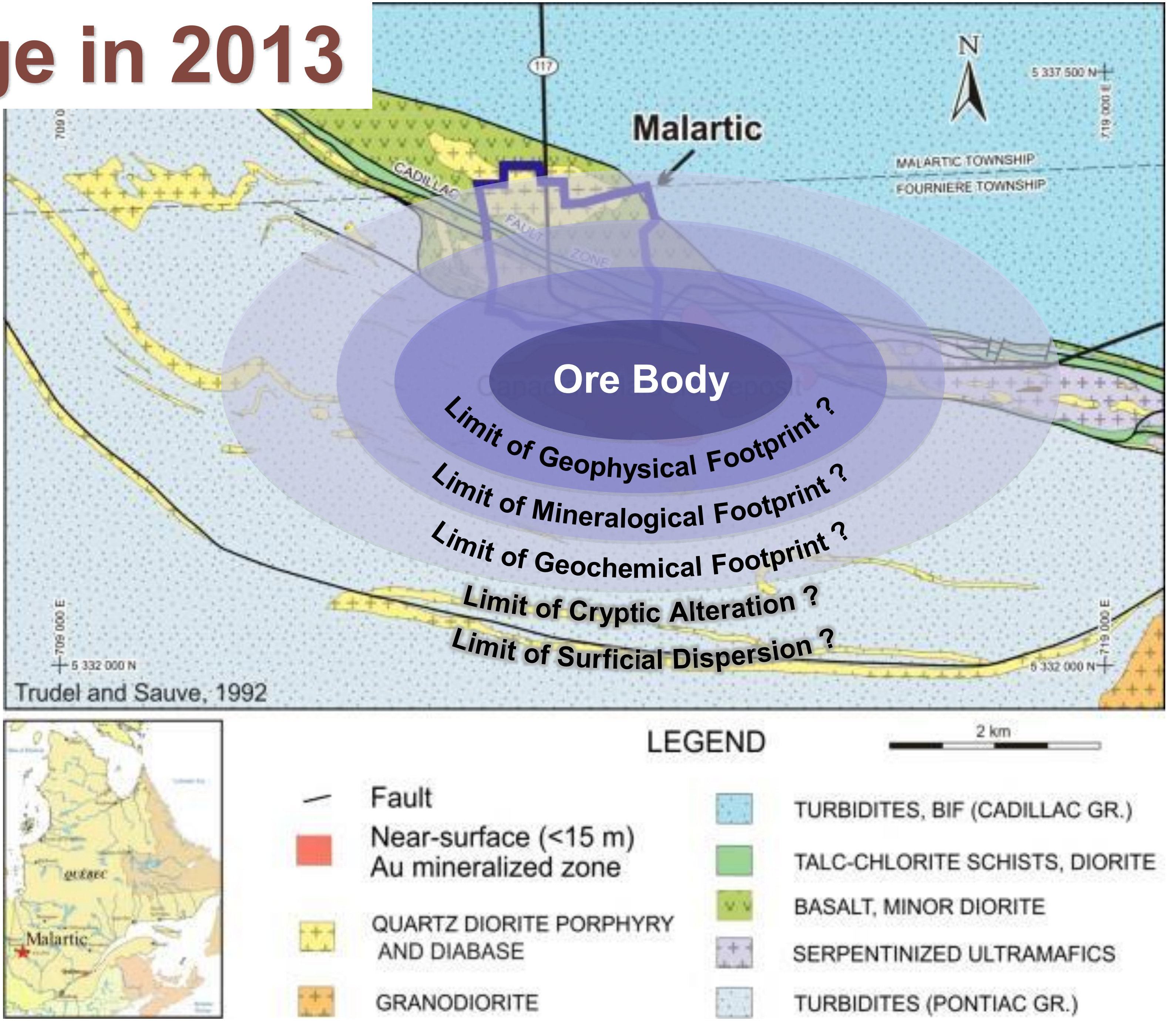
# Location of Footprint Sites

- **Canadian Malartic:**
  - **>18.6 Moz Au**
  - **South of the Cadillac - Larder Lake Deformation Zone, Québec**
  - **Oxidized intrusion-related deposit**
    (Helt et al., 2012, *Economic Geology*)
  - **Stockwork-disseminated system**
    (De Souza et al., 2016, *Economic Geology*)



# State of Knowledge in 2013

- **Structurally-controlled biotite, calcite and pyrite alteration** (Derry, 1939, *Econ. Geol.*)
- **This deposit should have a large footprint but its expression is unknown**
- **Geophysics does not work for direct ore targeting**
- **Long mining history makes current surficial exploration techniques (e.g., soil geochemistry) inefficient**

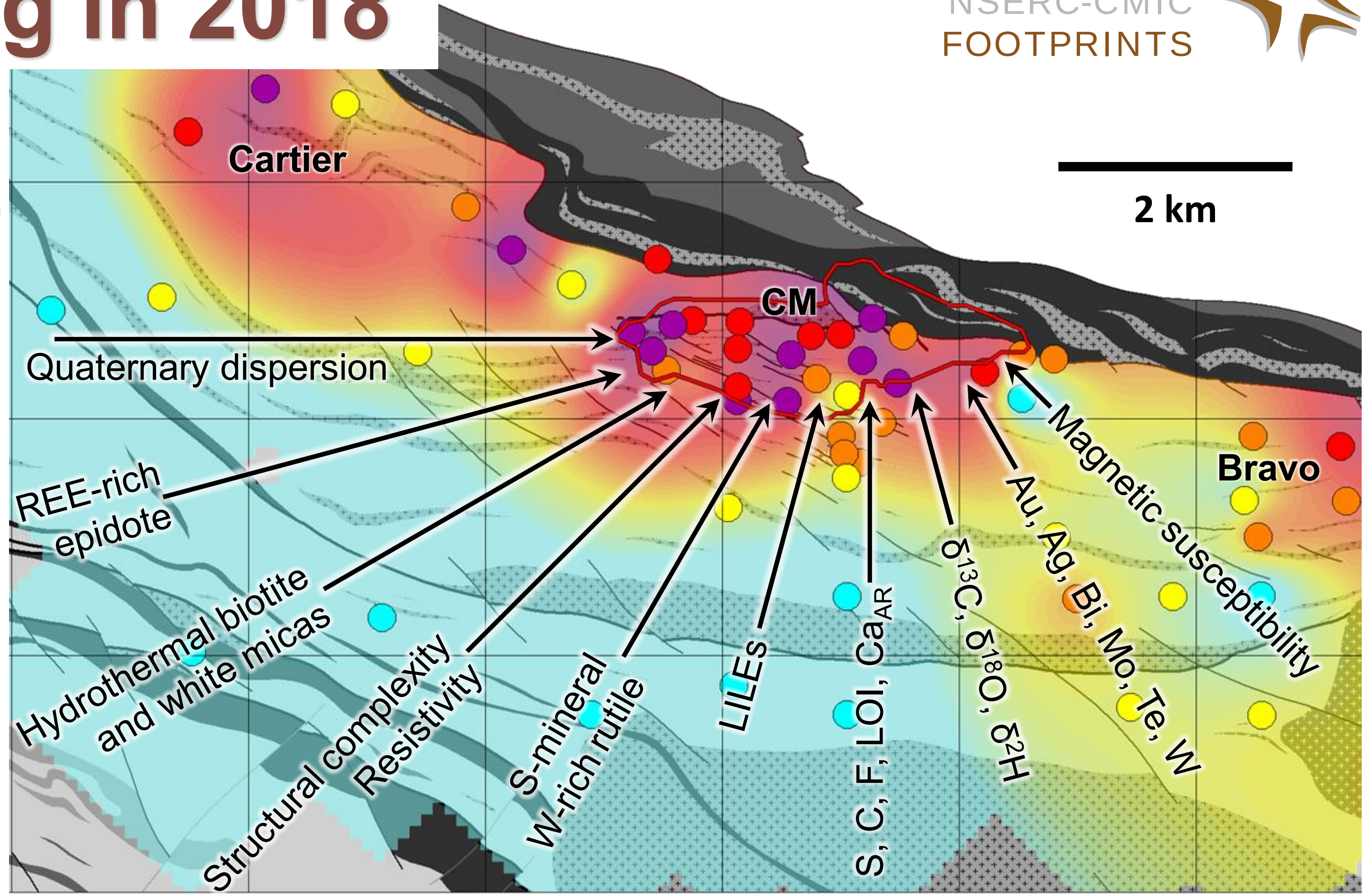


Trudel and Sauve, 1992

# Our Understanding in 2018

NSERC-CMIC FOOTPRINTS

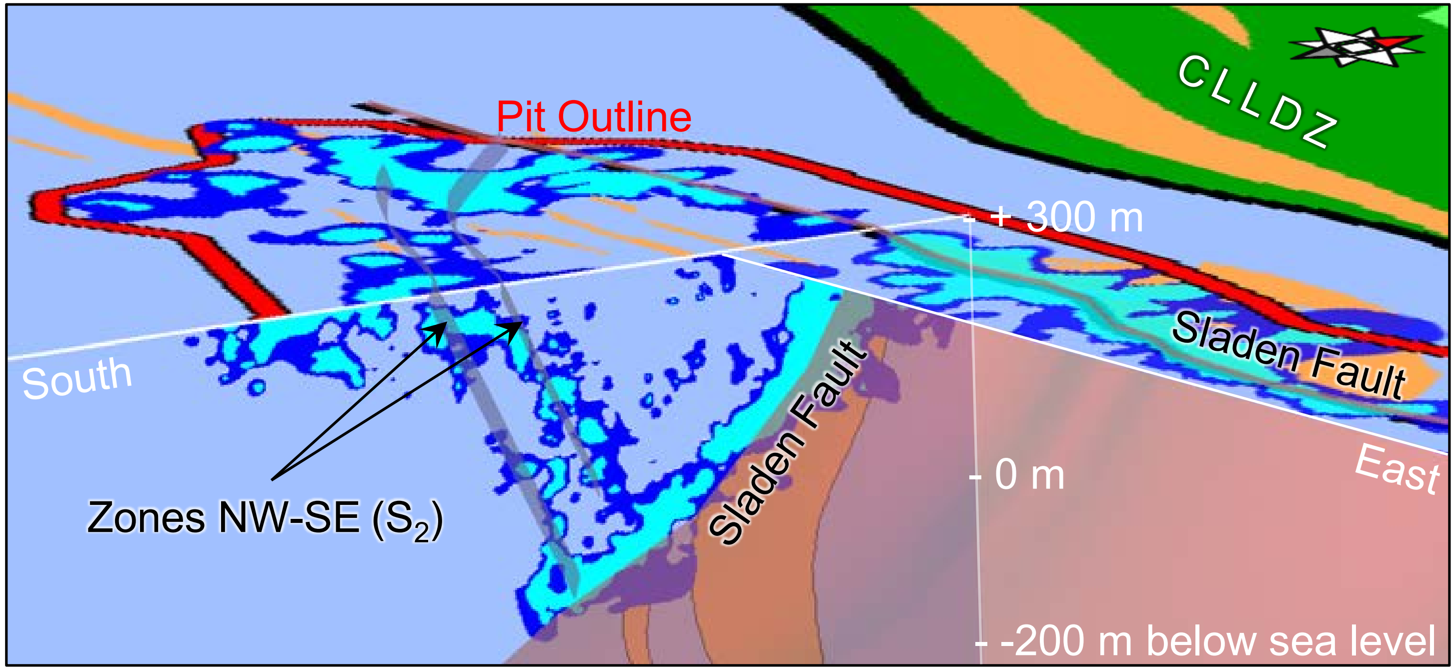
- **118 structural, geophysical, geochemical, mineralogical, and petrophysical halos**
- **Sizes range from 500 m to 6 km from the core of the system**
- **Multiple alteration centers** (CM, Cartier, Bravo/Odyssey)
- **New models: structural/ metamorphic/hydrothermal**
- **New techniques applicable to gold exploration**

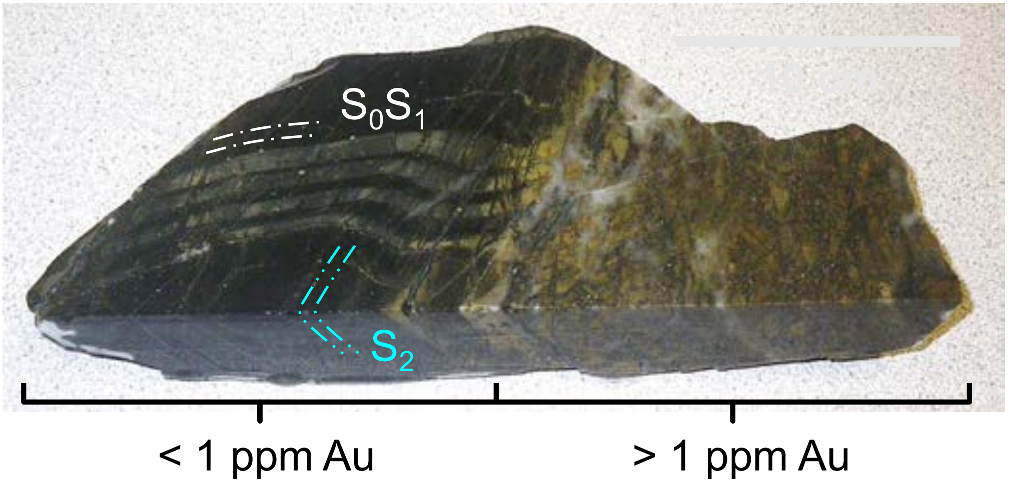


*Main vectoring tools in the Canadian Malartic footprint*

# Geological Setting

- **3 deformation events: $D_1$** - isoclinal $F_1$ folds, pressure-solution cleavage ($S_1$)
  **$D_2$** - close s-shaped $F_2$ folds, NW-SE biotite cleavage ($S_2$)
  **$D_3$** - subtle crenulation cleavage ($S_3$)
- **2 structural controls: E-W fault and NW-SE high-strain zones in $F_2$ fold hinges**



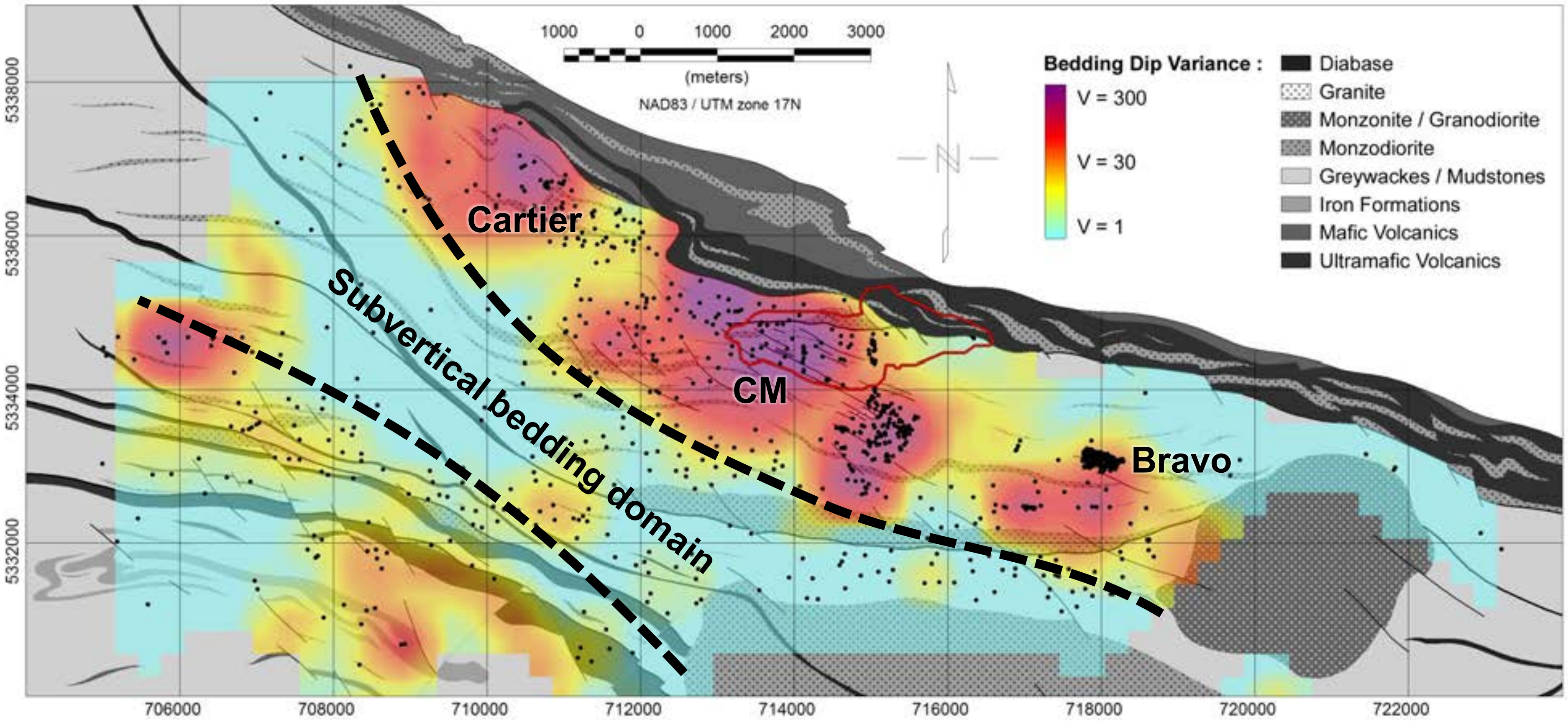


- **Main ore mineral association:**
  **Biotite, microcline, albite, calcite, ferroan-dolomite, pyrite, quartz**

Perrouty et al. *(2017, Ore Geology Reviews)*

# Structural Footprint

- Field mapping suggests that alteration zones are spatially associated with structurally complex zones ($F_1$ and $F_2$ fold hinges)
- The variance of the bedding dip highlights these fold interference zones

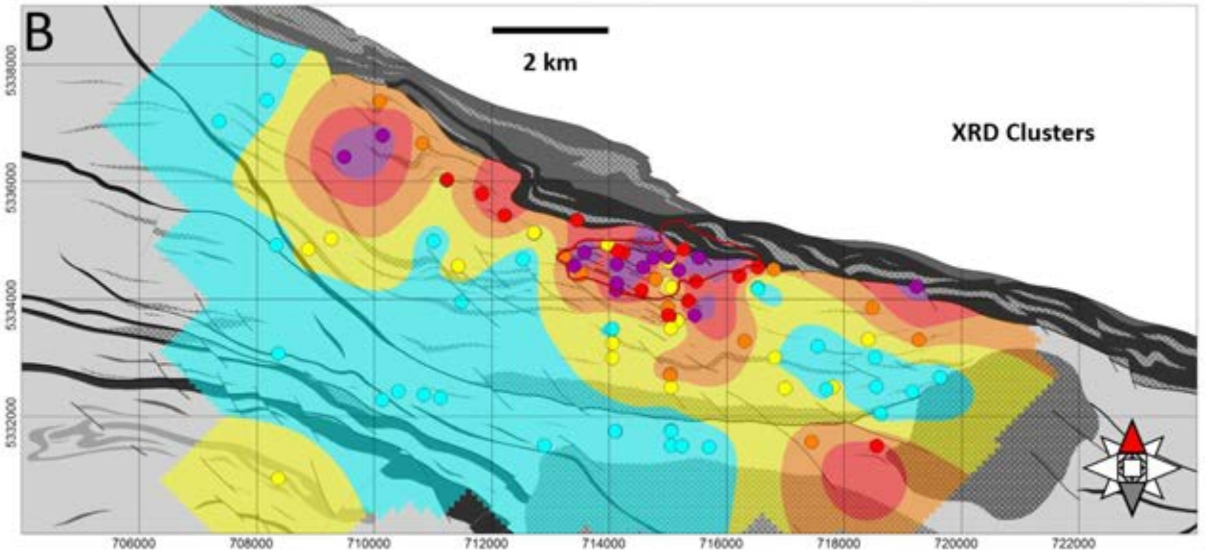


Perrouty et al. *(2017, Ore Geology Reviews)*

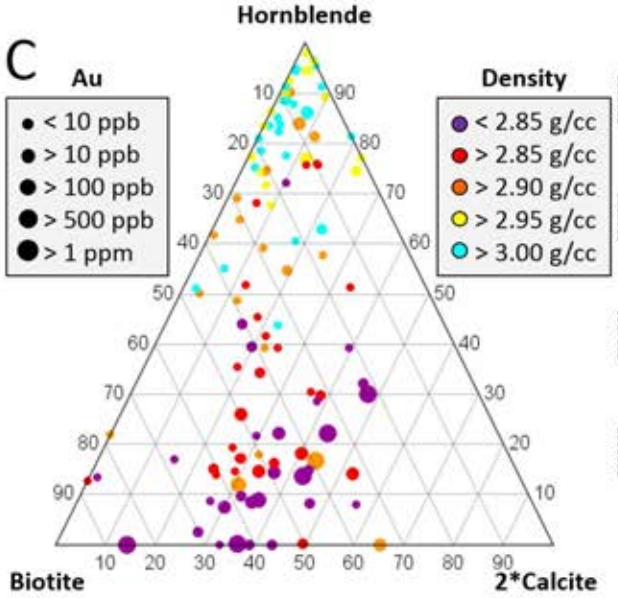
# Mineralogy *(mafic dykes)*

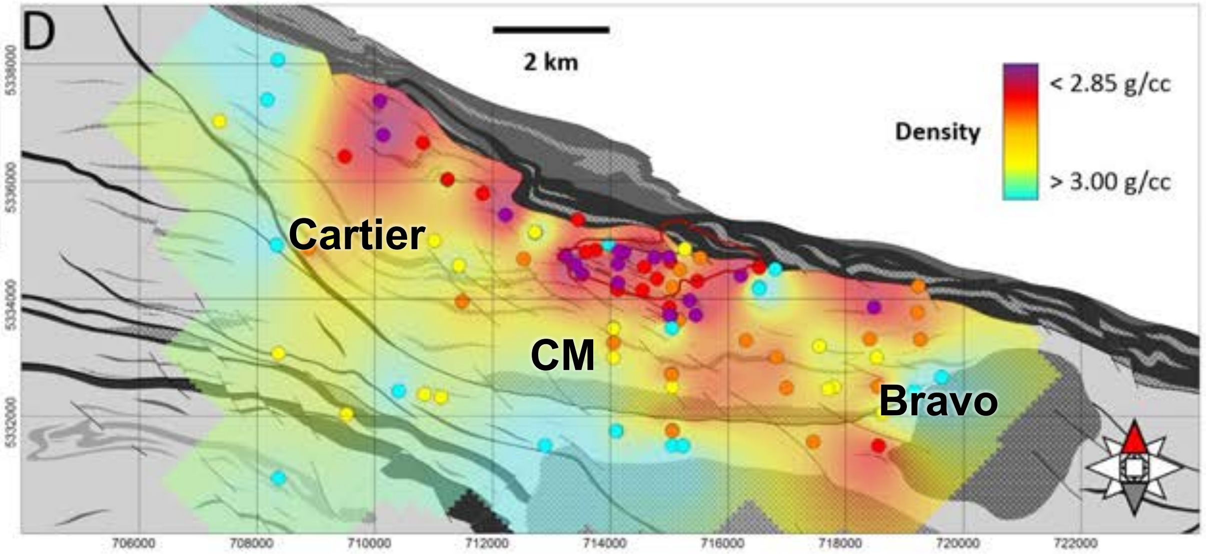
**A**

| Cluster | # | Amp (%) | Bt (%) | Chl (%) | Pl (%) | Qz (%) | Cal (%) |
|---|---|---|---|---|---|---|---|
| A | 6 | 84 | 1 | 2 | 13 | 2 | < 1 |
| B | 21 | 78 | 1 | 4 | 13 | 4 | < 1 |
| C | 9 | 77 | < 1 | 4 | 4 | 15 | < 1 |
| D | 11 | 53 | 3 | 5 | 28 | 11 | 1 |
| E | 12 | 39 | 16 | 2 | 31 | 12 | < 1 |
| F | 13 | 13 | 36 | < 1 | 24 | 24 | 3 |
| G | 18 | < 1 | 67 | 1 | 4 | 13 | 14 |
| H | 3 | < 1 | 48 | 3 | 4 | 31 | 14 |
| I | 17 | < 1 | 45 | 1 | 30 | 11 | 13 |



- **XRD cluster analysis was performed to quantify and outline mineralogical changes**
- **Mineralogical changes are integrated with WR lithogeochemistry and rock density.**

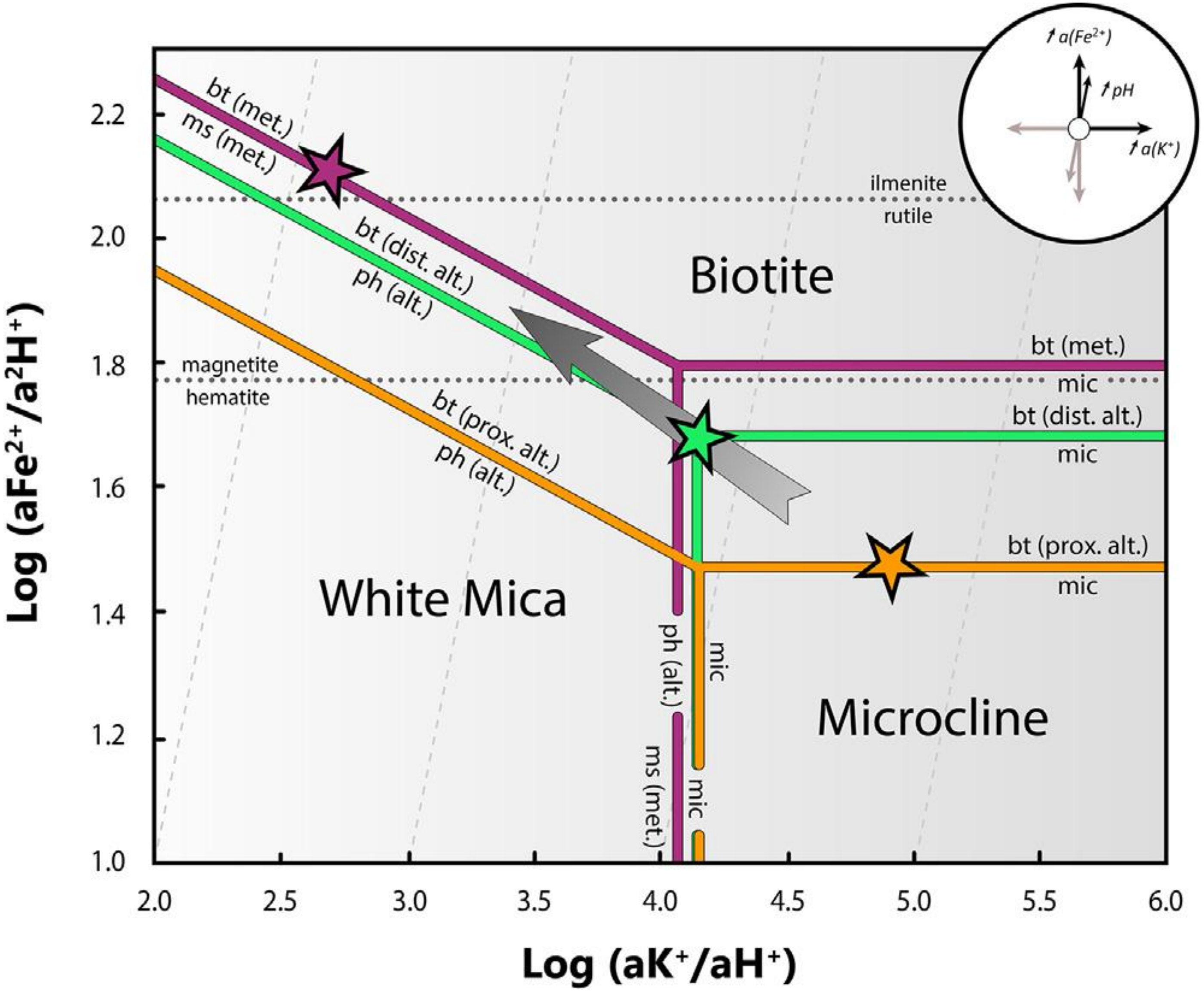




Perrouty et al. *(2018, Mineralium Deposita)*

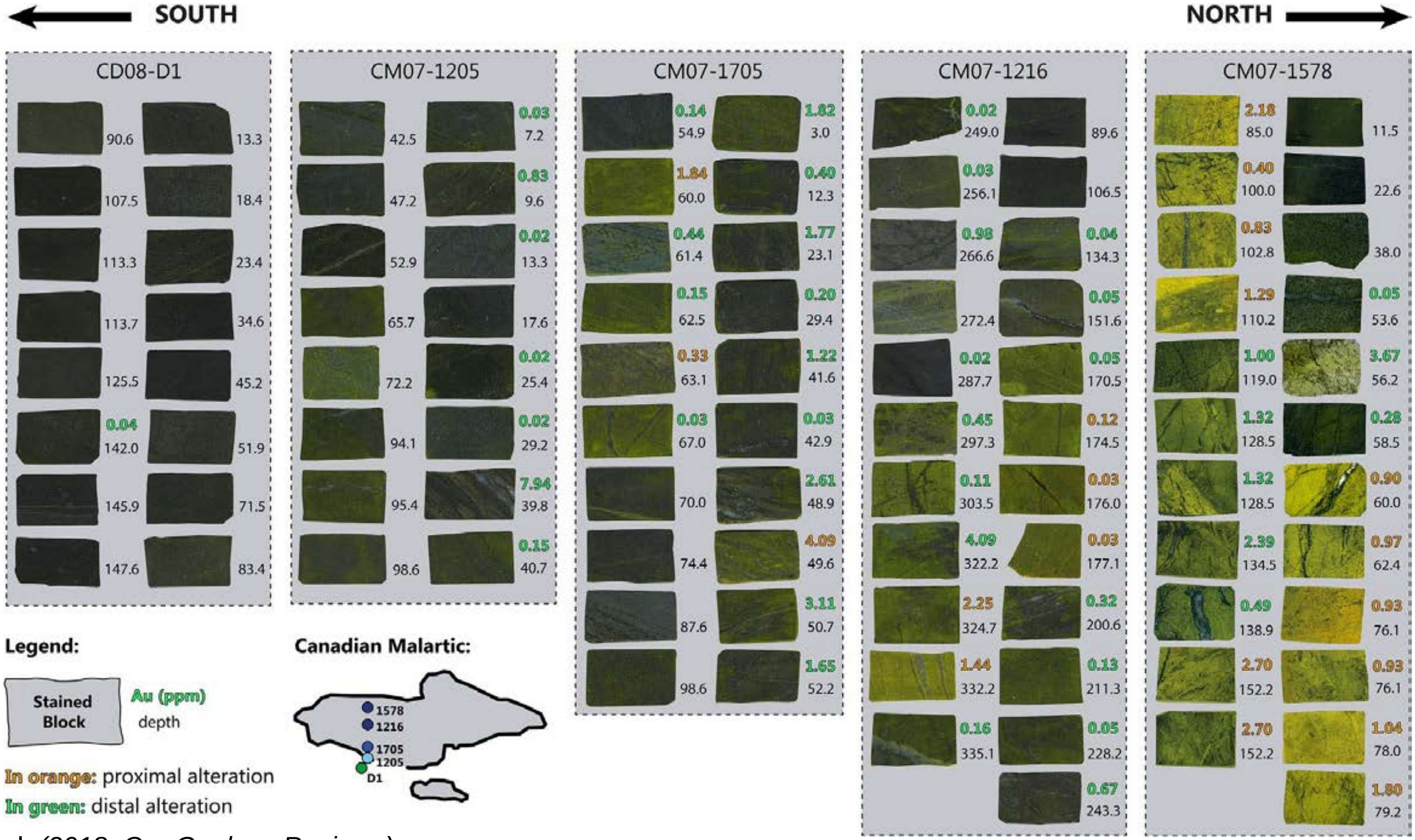
# Mineral Chemistry *(metasedimentary rocks)*

- **Diagram showing stability relationships among hydrothermal alteration K-silicates** (biotite, white mica and microcline) **in greywacke at the estimated conditions of ore formation** (475 °C and 3 kbar; Helt et al., *2014, Economic Geology*)
- The inferred physico-chemical conditions are represented by stars for the non-altered metamorphic assemblage (purple), and for the distal (green) and proximal (orange) alteration zones
- **The apparent increase in the $aFe^{2+}/a^2H^+$ ratio is interpreted to reflect decreasing sulfur content (less pyritization) with distance from the hydrothermal center**



Gaillard et al. *(2018, Ore Geology Reviews)*

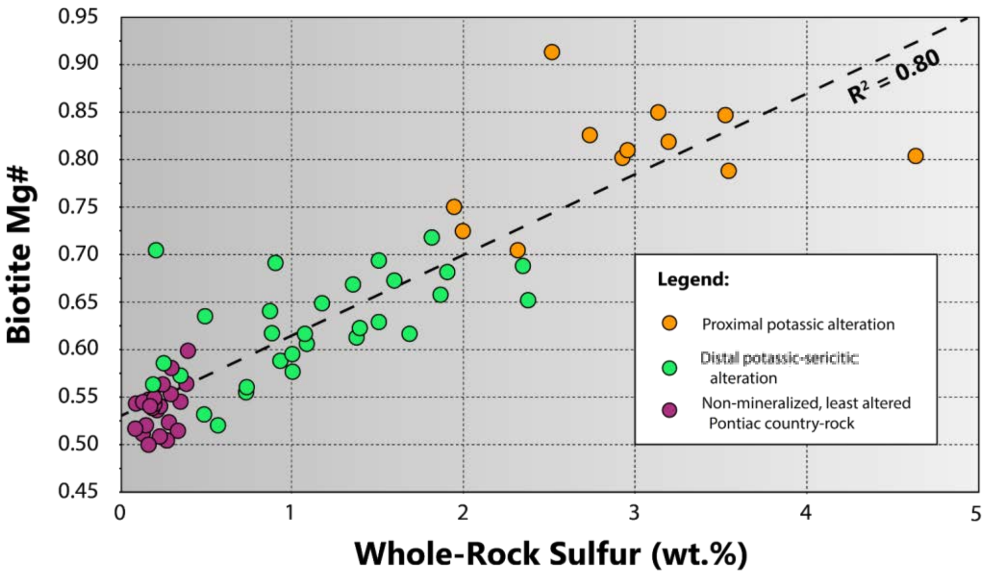
# Feldspar Staining



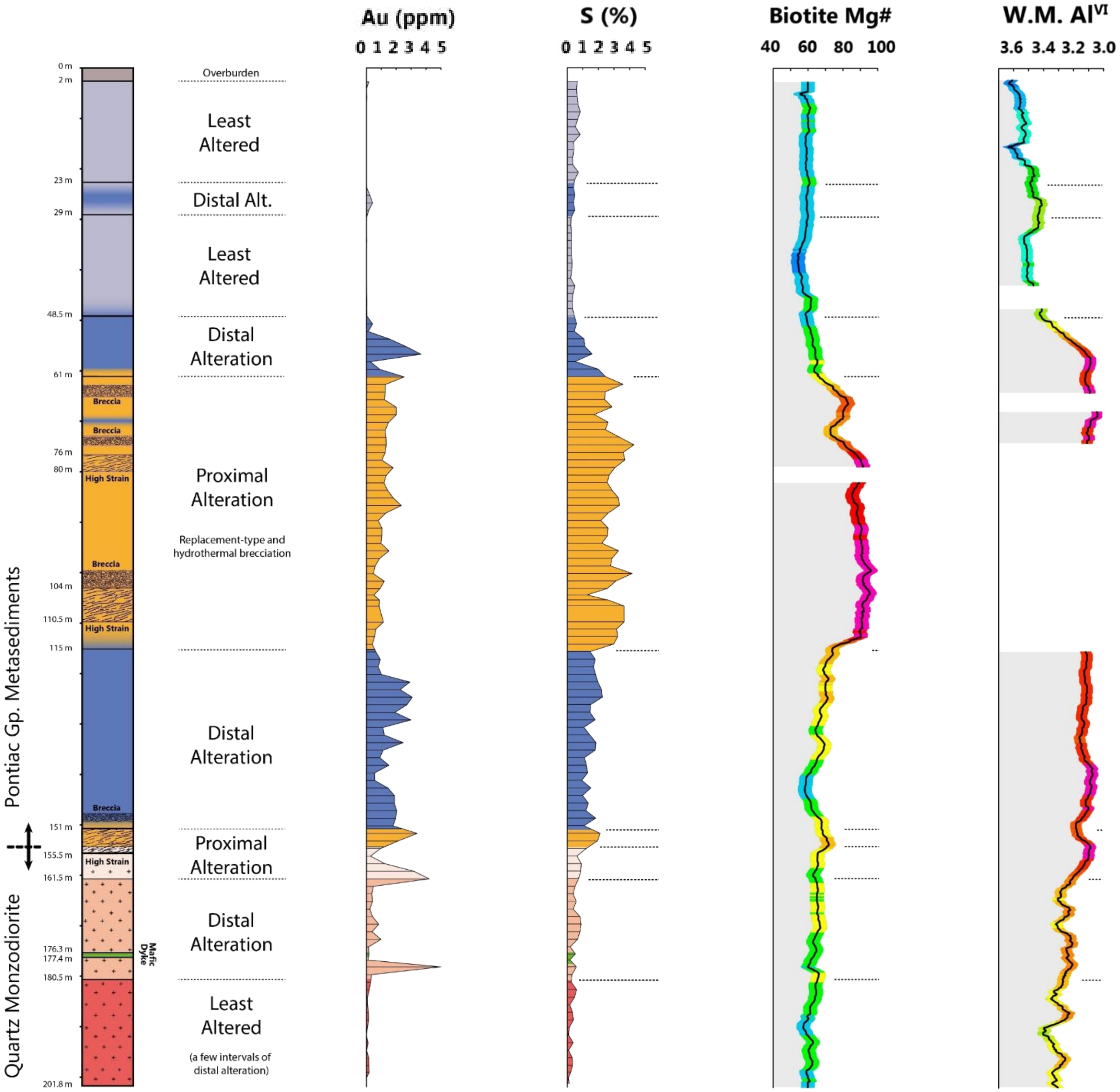
Gaillard et al. *(2018, Ore Geology Reviews)*

# Mica Chemistry

- **Biotite Mg# correlates positively with whole-rock sulfur content** *(i.e., a proxy for pyrite)*



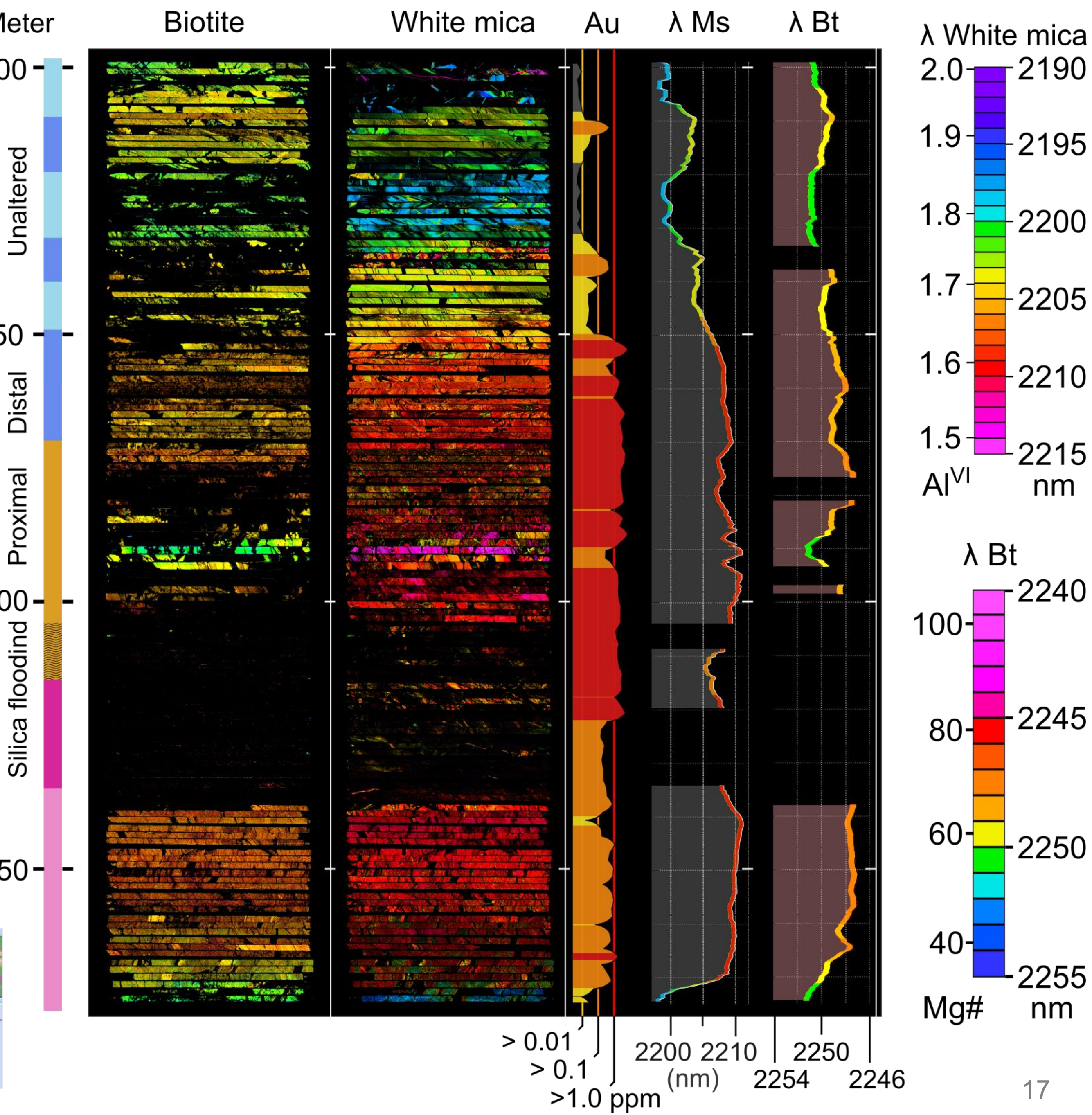
- Mg-enrichment of ore-zone biotite was caused by Fe-buffering by pyrite under increasing ∑aS-$fO_2$ conditions. Tschermak exchange in mica from proximal and distal alteration zones was controlled by variations in a($K^+$) and/or pH.



Gaillard et al. *(2018, Ore Geology Reviews)*

# Hyperspectral Imagery

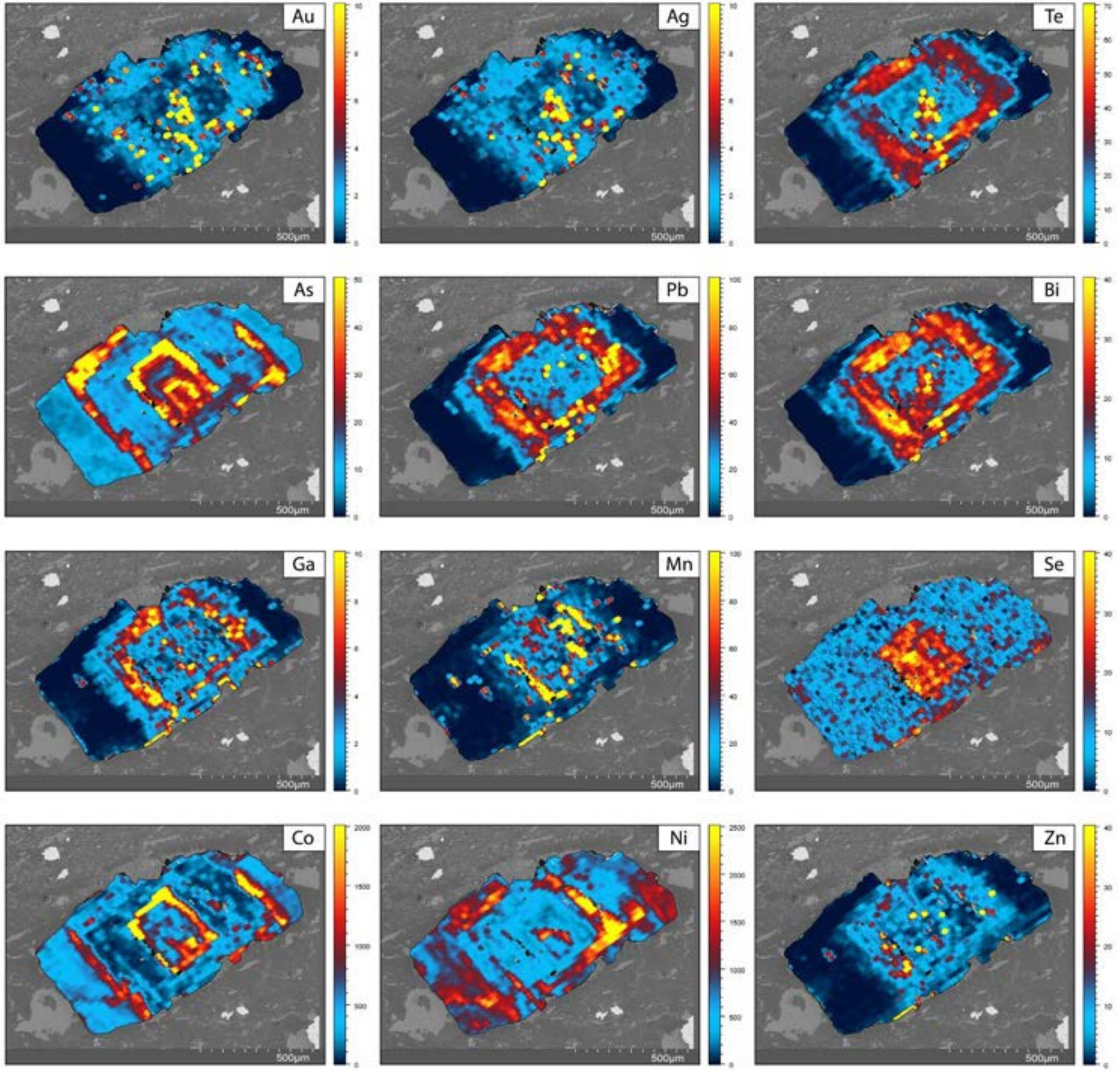
- Chemical analysis of biotite and white mica using hyperspectral imagery:
  - **Can be used as a proxy for alteration in metasedimentary and intrusive rocks.**
  - **Enables the rapid delineation of altered intervals.**
  - **Minimizes assaying barren intervals.**

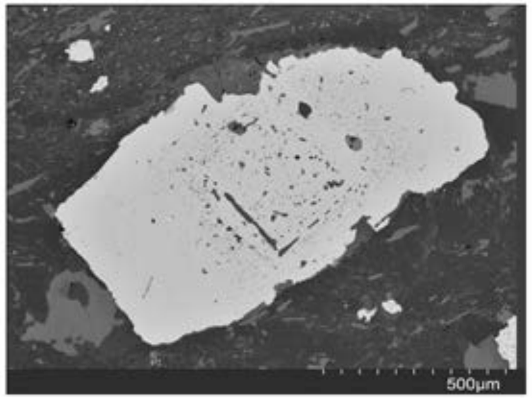


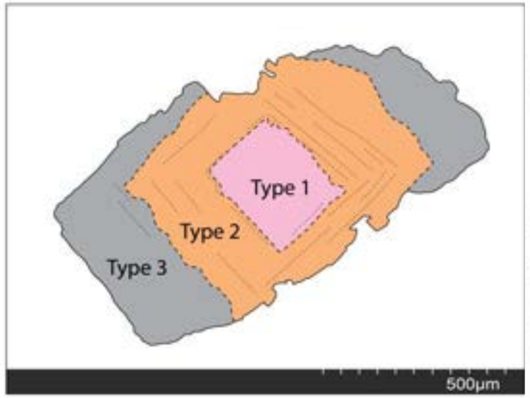
Lypaczewski et al. *(Submitted)*

# Pyrite Maps

- **Three hydrothermal pyrite types:** pyrite 1 and 2 contain numerous inclusions (gold, tellurides) and is overgrown by inclusion-free pyrite 3
- **ICP-MS trace element mapping shows that pyrite 2 is associated with the main ore-forming event and is enriched in Au-Ag-Te-Bi-Pb**

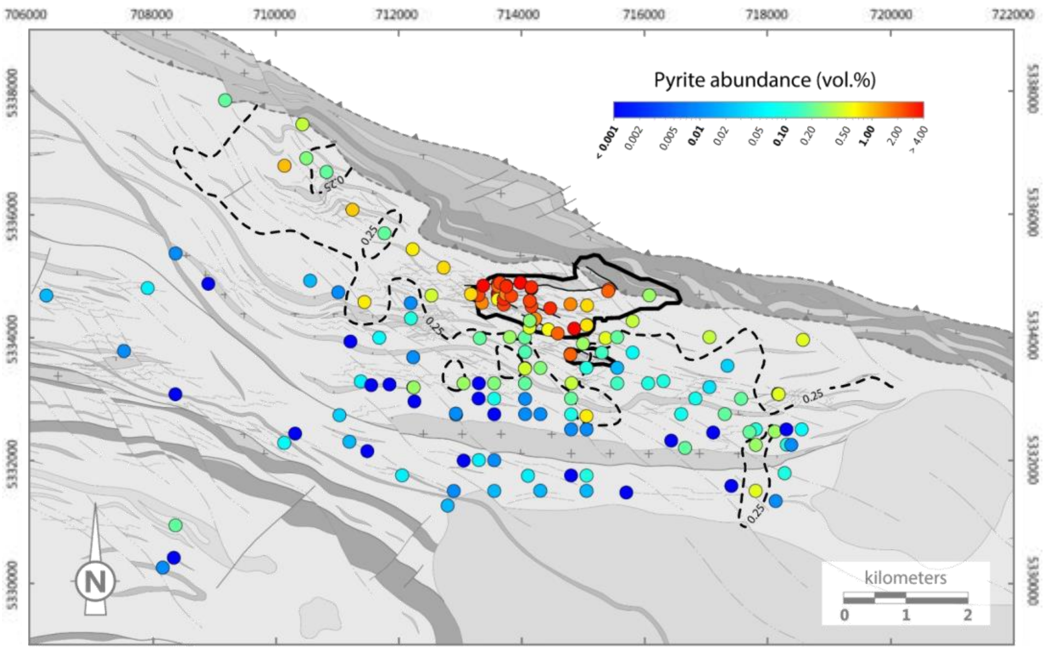




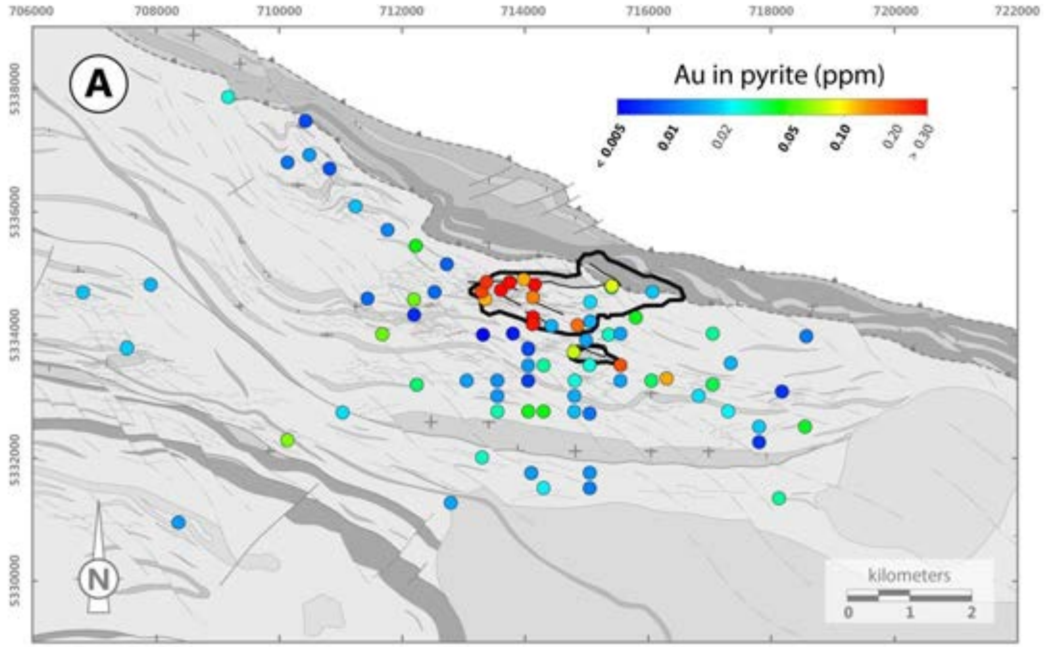


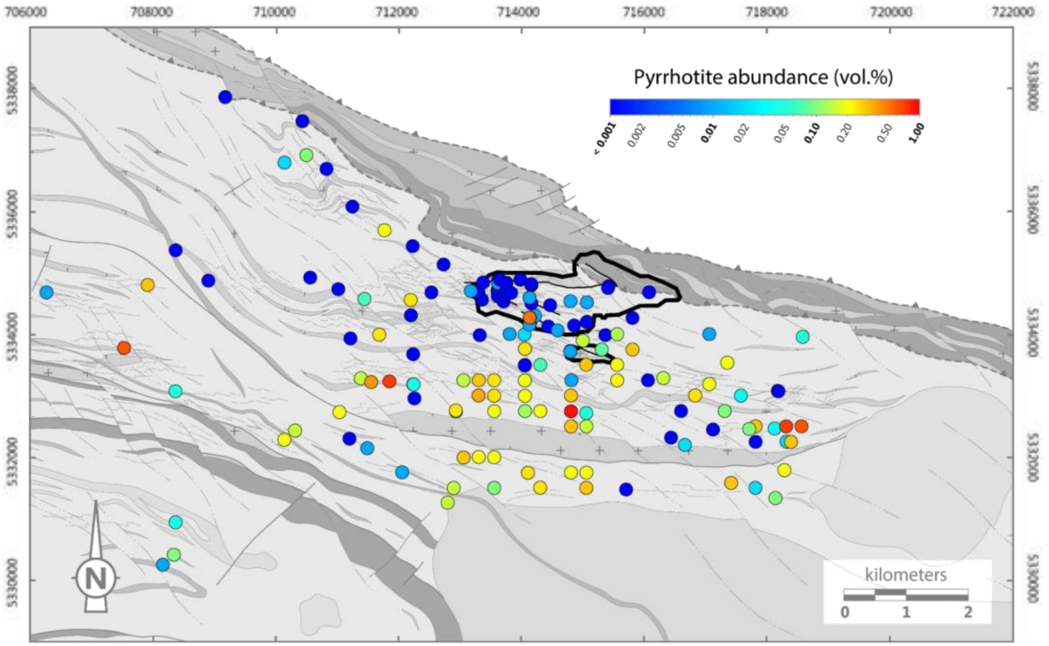
Gaillard et al.
*(submitted)*

# Sulfide Minerals



- Samples with elevated pyrite abundance (>0.25 vol%) delineate an hydrothermal halo parallel to the CLLDZ and to the E-W Sladen Fault.
- Pyrrhotite formed by gradual replacement of pyrite during prograde metamorphism.
- Hydrothermal pyrite in the deposit is enriched in Au (and Te) relative to pyrite beyond the ore-shell.

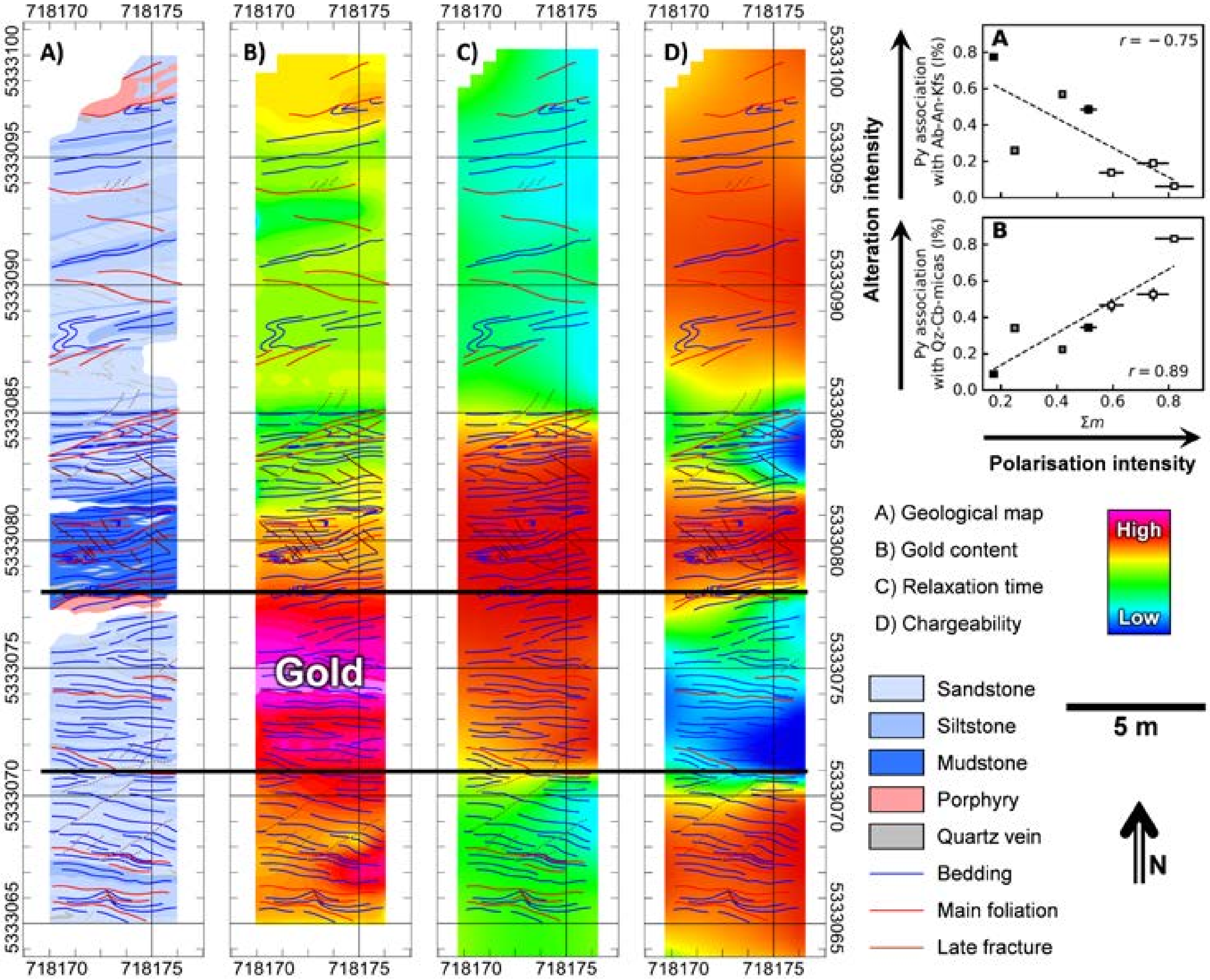




Gaillard et al. *(submitted)*

# Geophysical Implications

- ~~**More pyrite => more chargeability?**~~
- **Chargeability increases with increasing surface of contact between sulfide minerals and porosity:**
- Medial/distal alteration is marked by pyrite (or pyrrhotite) in contact with biotite and white mica.
- Proximal alteration is marked by pyrite encapsulated in microcline and/or albite.
- **At Canadian Malartic, zones of pervasive hydrothermal alteration are characterized by low chargeability.**



Bérubé et al. *(in preparation)*

# Summary

- **There are several structural, mineralogical, lithogeochemical and geophysical expressions of the footprint of the Canadian Malartic deposit:**
  - **Mineralogy analysis of mafic dykes** is a simple and field-based solution (just need a hand-lens) to detect hydrothermal alteration and gold mineralization.
  - **Carbonates or K-feldspar staining, hyperspectral imagery of mica and spectral IP survey** in metasedimentary rocks are simple tools to outline alteration and vector high-grade horizons.
  - **Pyrite abundance, texture and compositions** help to understand hydrothermal systems and can provide vectors toward mineralization.
  - **Zones of pervasive alteration are characterized by low chargeability** due to encapsulation of pyrite within feldspars.
  - **W-rich rutile and REE-bearing fluorocarbonates** are markers of the alteration.
  - **Whole-rock lithogeochemical analysis (total and partial digestion)** provides several vectoring information that can be easily integrated using PCA. Alternative field tools are pXRF.

# Footprint Sponsors/Collaborators

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# Multiphase TTG intrusions in the Paleoproterozoic greenstone belt of Suriname and their role in gold mineralization in the Rosebel gold district.

S. Ramlal[1] , S. B. Kroonenberg[2,3], P.R.D. Mason[4], L. M. Kriegsman[5], P. O'Sullivan[6]

## Abstract

Four new U-Pb ages indicate two phases of TTG magmatism, namely around 2.19 - 2.16 Ga and around 2.12 - 2.11 Ga. The two phases of TTG magmatism are separated by an erosional event.

## Introduction

The Rosebel gold district in the Paleoproterozoic greenstone belt of the Guiana Shield is a major orogenic gold district (Fig. 1), formed during the Trans-Amazonian Orogeny between 2.26 and 1.95 Ga (De Roever et al., 2015).

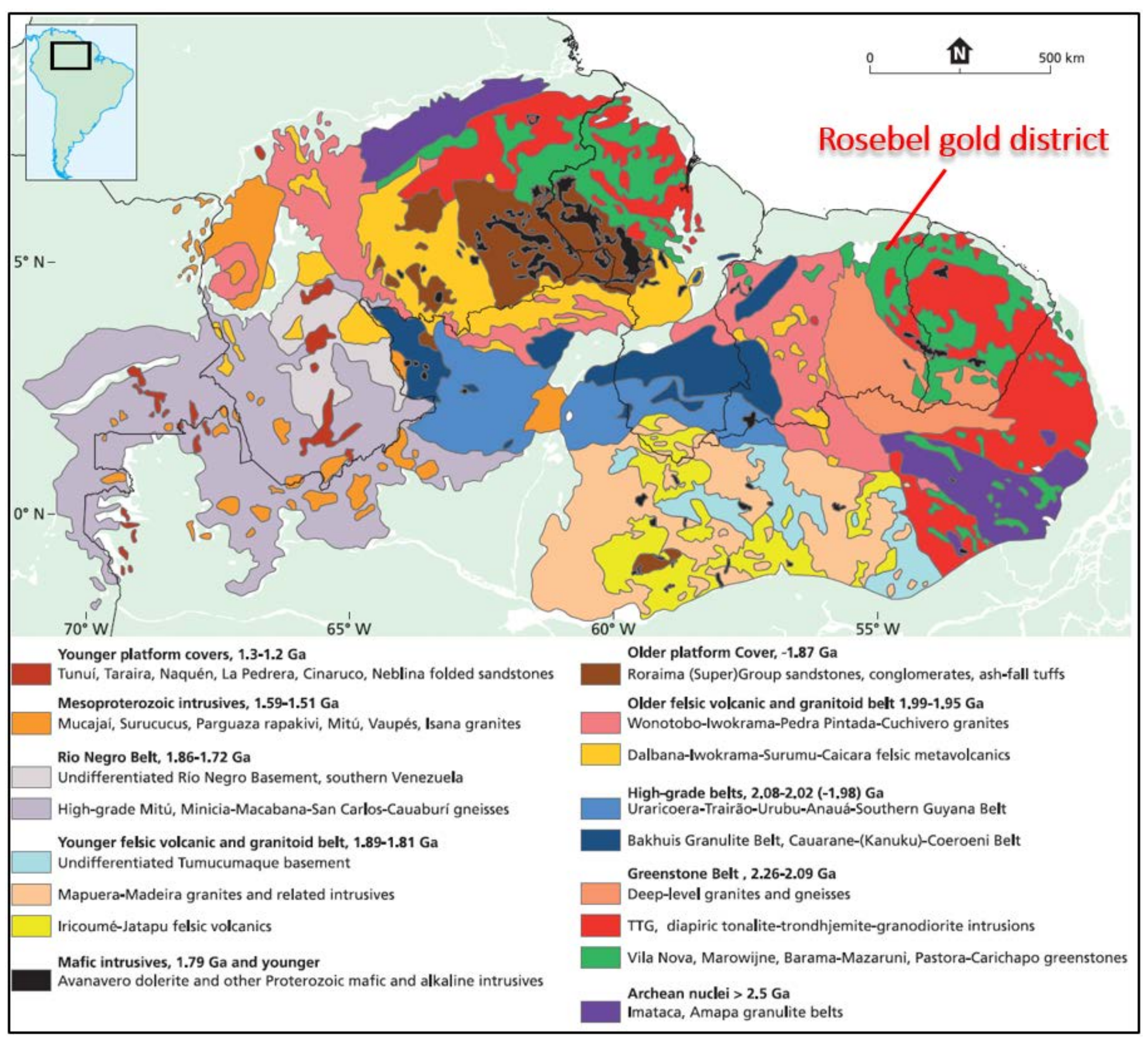

Fig. 1: Simplified geological map of the Guiana Shield (Kroonenberg et al., 2016).

## Problem Statement

A large granitic pluton known as the Brincks intrusion is present at the southern boundary of the Rosebel Mining Concession. Several gold deposits, and further prospects, are located around and proximal to the Brincks intrusion, although the emplacement and its relationship with the neighboring gold deposits is not fully understood.

## Purpose

This body of research investigates the role of the Brinck intrusion in the petrogeny of the Rosebel basin, whether it may have intruded as a single pulse (phase) or during multiple pulses (polyphase), and the genetic relationship between the intrusion and the neighboring gold deposits.

## Methods

Accurate data on the absolute timing of crystallization of rock types defined in the Rosebel area were crucial in order to reconstruct the stratigraphic and deformational relationships and to elucidate the evolutionary history of mineralization around the granites.
Zircon U-Pb ages of the rocks were obtained using the LA-ICP-MS technique. Detailed internal textures of zircons have been analysed using Cathodoluminesence (CL) imaging methods (Fig. 2).

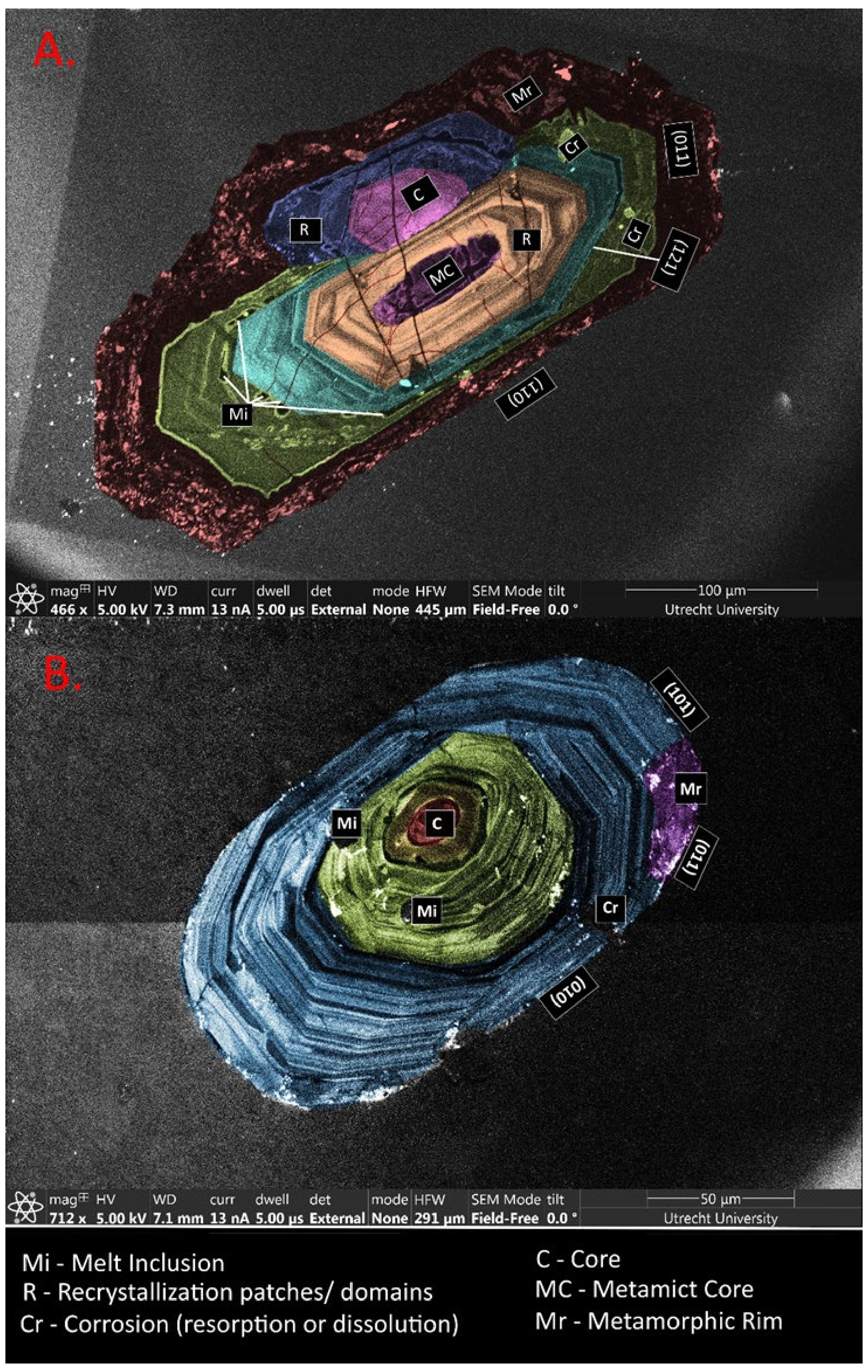

Fig. 2: Cathodoluminesence images of isolated zircon crystals showing detailed zircon patterns and different domains. (A) Zircon from the Atjoni Road granite with a pronounced outer-rim due to changing T-P conditions. (B) Zircon from the Royal Hill rhyolite with well-developed oscillatory zoning and in which metamorphic remnants are preserved (Hoogendoorn, 2017).

## Results of dating

1. Granite (Atjoni Road)

The calculated 207Pb/206Pb ages tend to cluster around 2,186 Ma (Fig. 3). The rock contain inherited older Hadean-Archean zircon ages, which demonstrates the existence of an underlying crustal block representing the oldest crustal component of the Guiana Shield. An age of 4.25 Ma records the signature of Early Earth.

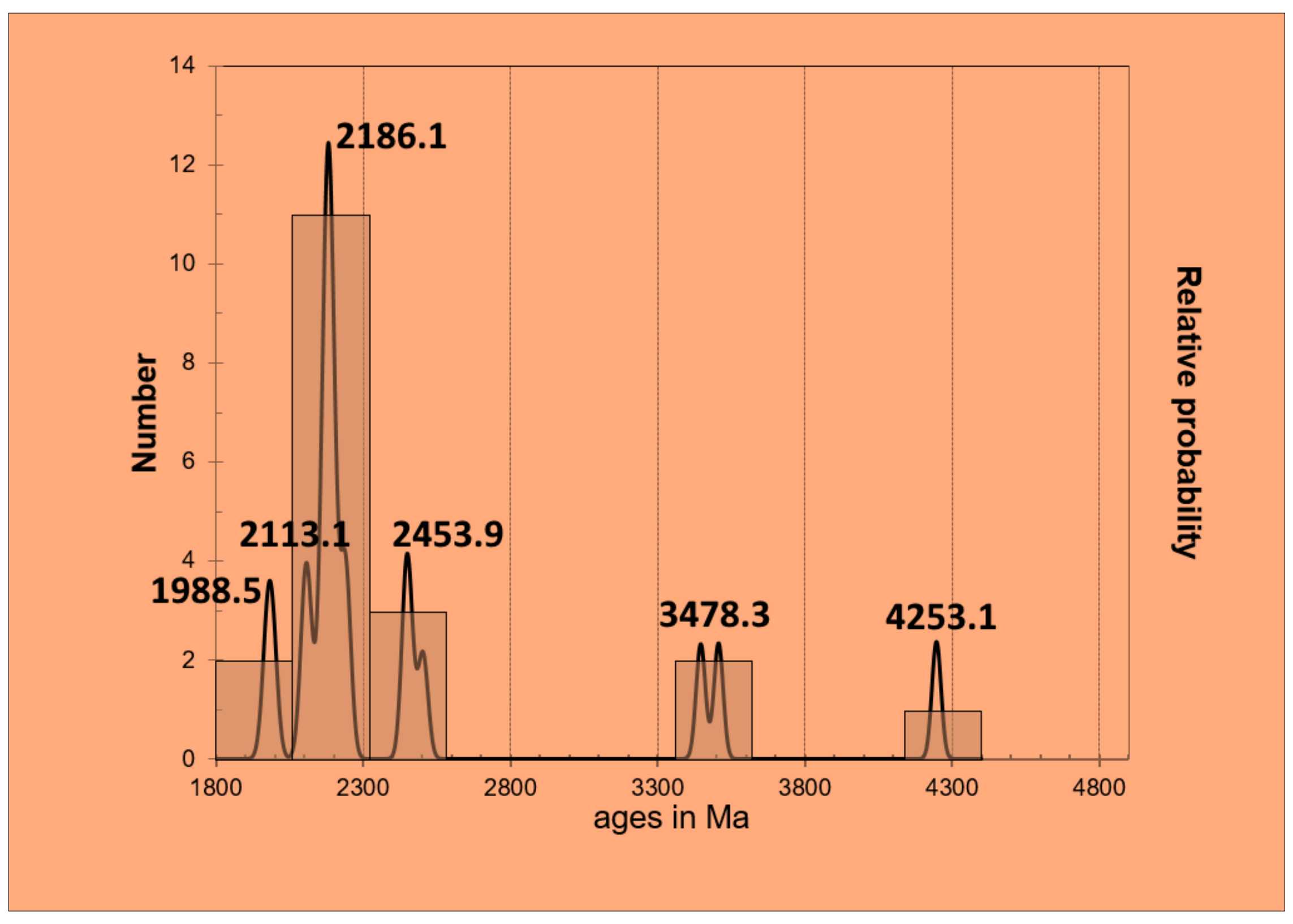

Figure 3: Probability frequency diagram of measured zircons of the granite sample from the Atjoni Road (Hoogendoorn, 2017).

2. Rhyolite (north of Royal Hill pit)

The 207Pb/206Pb values tend to cluster around 2,121 Ma. One of the zircons shows a significantly older age of 2,642 Ma which could be a recycled zircon from an Archean nucleus that has been reworked and mixed with a Paleoproterozoic source.

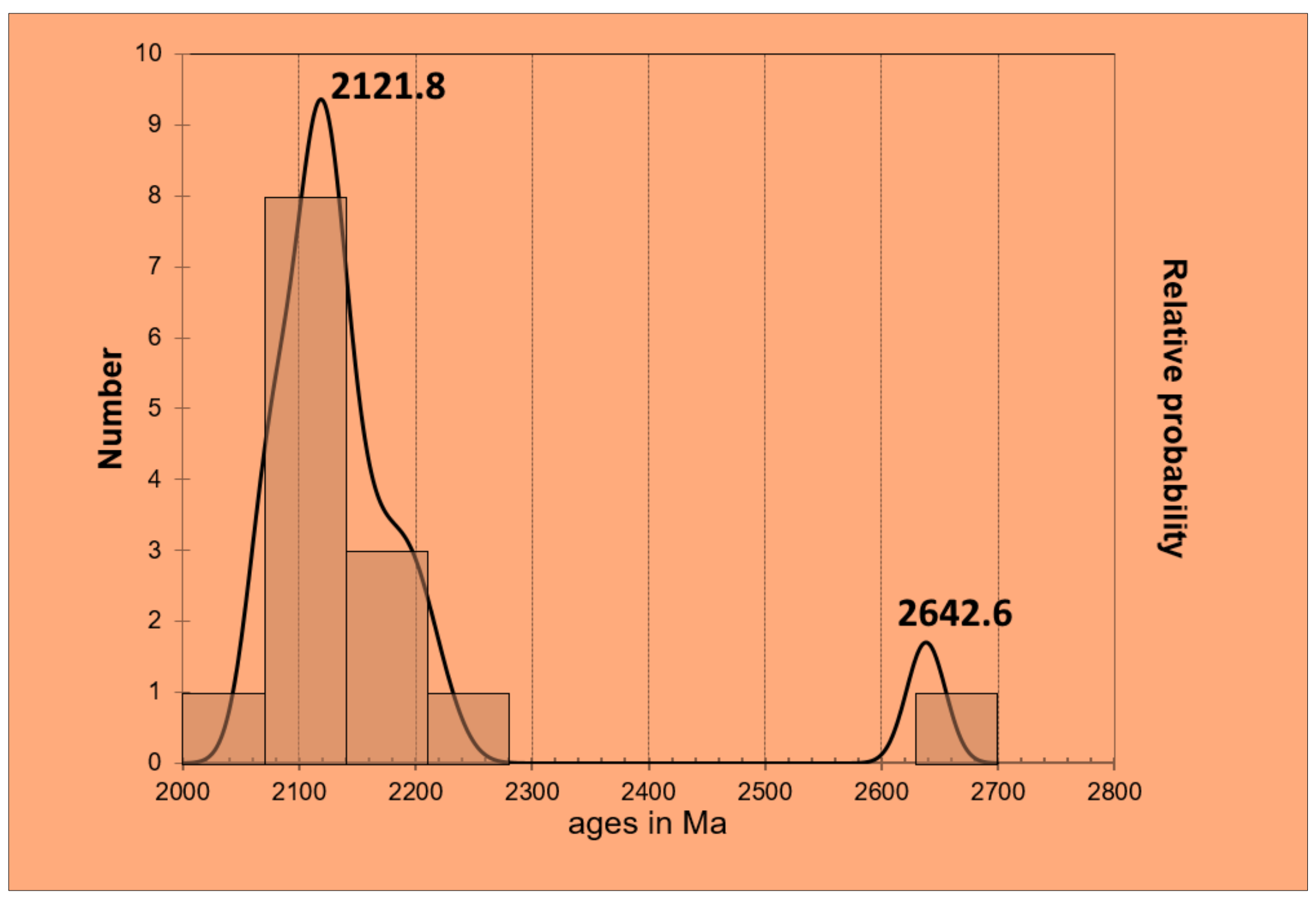

Figure 4: Probability frequency diagram of measured zircons of the rhyolite sample (Hoogendoorn, 2017).

3. Trondhjemite (north of Brinck intrusion)

The calculated 207Pb/206Pb ages tend to cluster around 2,113 Ma (Fig. 5). One of the zircons shows a significantly older age of 2,998 Ma which could be a recycled zircon from an older source rock.

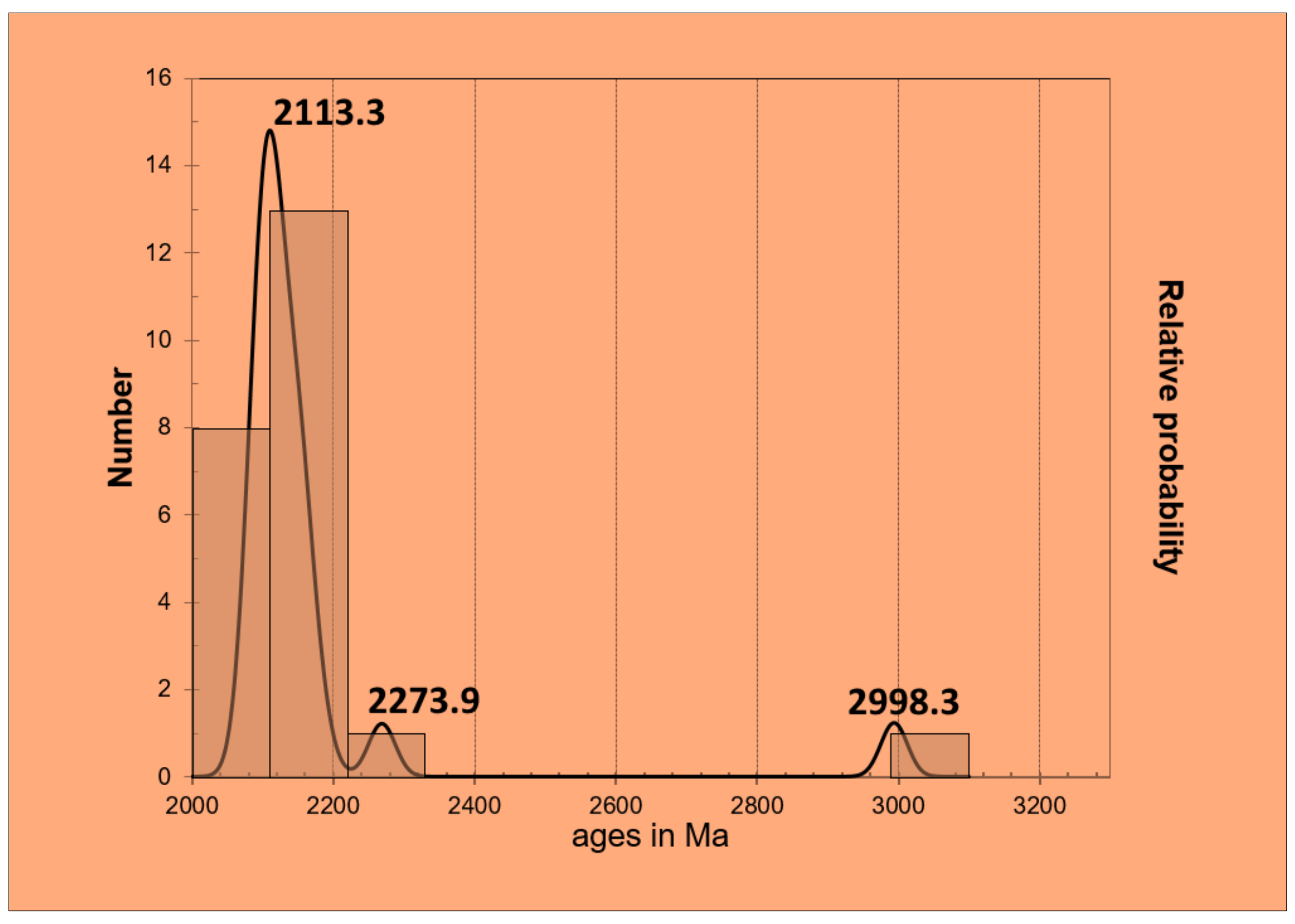

Figure 5: Probability frequency diagram of measured zircons of the trondhjemite sample (Hoogendoorn, 2017).

4. Granite (Koemboe area)

The 207Pb/206Pb values tend to cluster around 2,109 Ma (Fig. 6). Some older core exist which cluster around 2,221 Ma and in a specific case around 2,328 Ma.

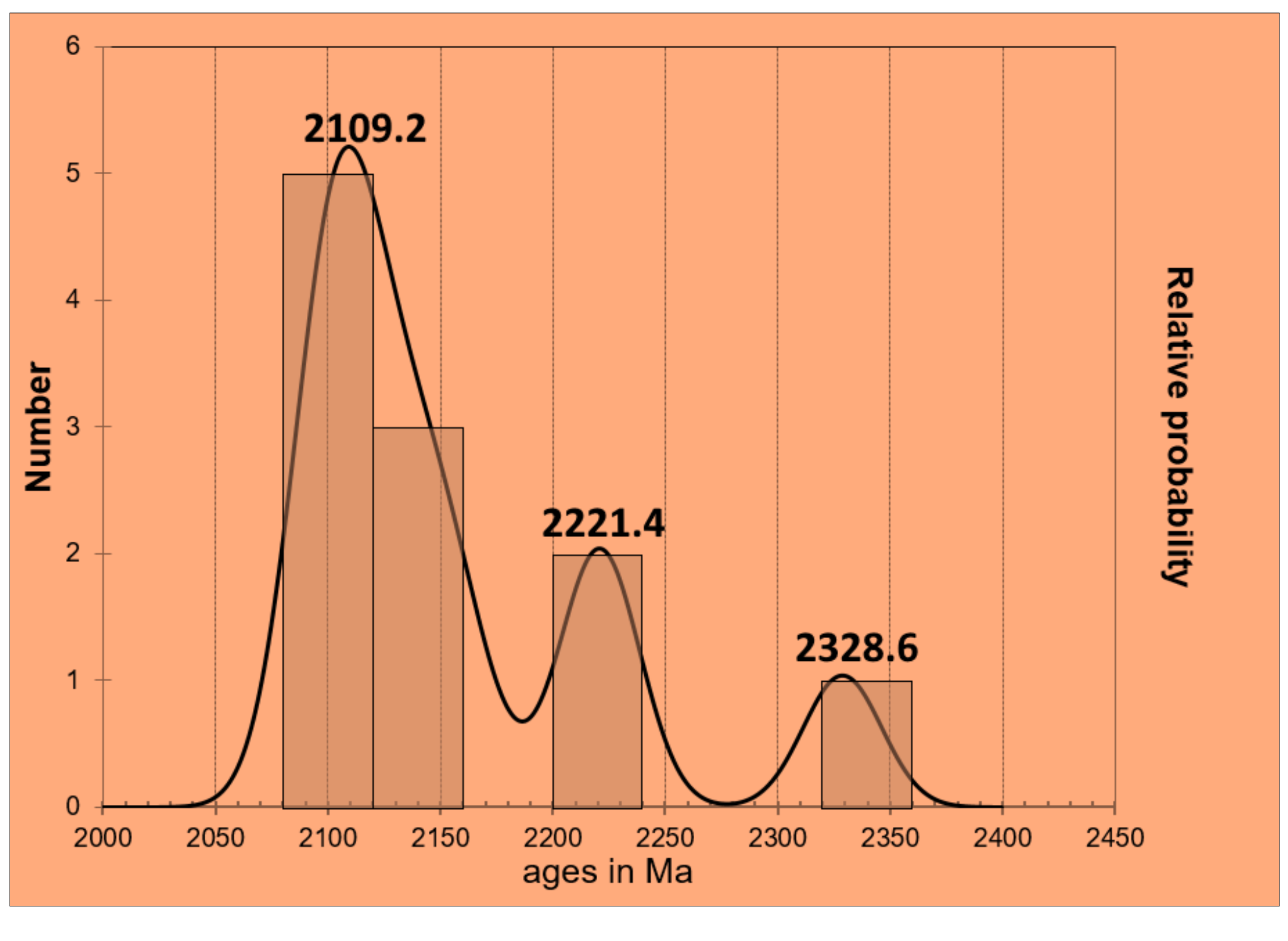

Figure 6: Probability frequency diagram of measured zircons of the granite sample from the Koemboe area (Hoogendoorn, 2017).

## Conclusions

- Based on the age dating results two phases of TTG magmatism at ca. 2.19 - 2.16 Ga and 2.12 - 2.11 Ga with a lack of geochronological values in the 2.16 - 2.12 Ga range can be distinguished (Fig. 7, 8).
- The two phases of TTG magmatism are separated by an erosional event as evidenced by a basal conglomerate containing granite clasts, which also contains the 2.12 Ga rhyolite layer from Royal Hill higher in the sequence.

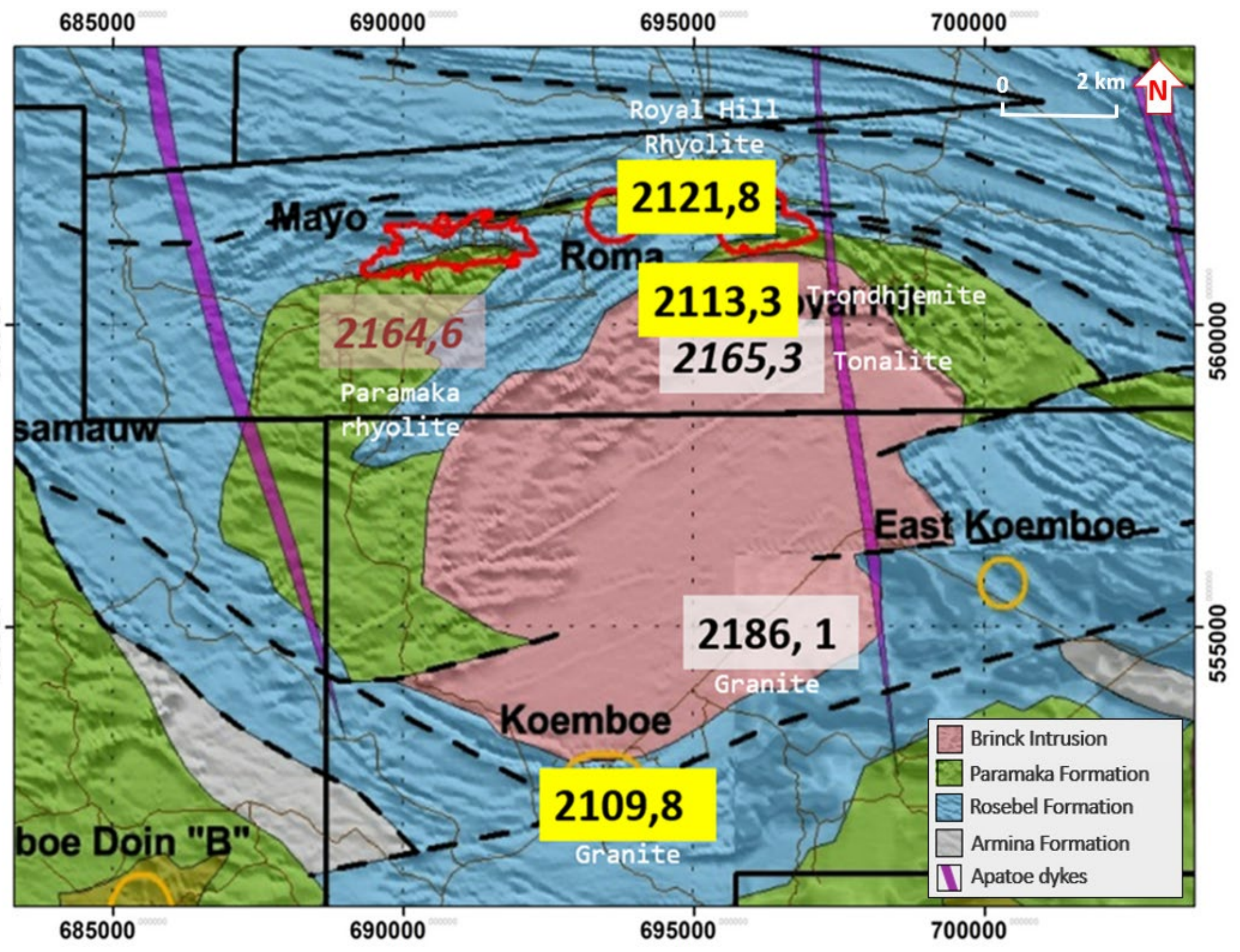

Figure 7: Age dating results of TTG intrusives in the Rosebel area. In grey dates which correlates with the first phase of TTG magmatism between 2.19 – 2.16 Ga and in yellow dates which correlates with the second stage of TTG magmatism between 2.12 – 2.11 Ga. In italic an age obtained by Daoust (2016) which correlates with the first phase of TTG magmatism.

- Limited published geochronology for the Guiana Shield orogenic gold deposits indicates mineralization during two distinct episodes between 2.08 - 2.02 Ga and 2.0 - 1.95 Ga which is broadly coëval with post-peak metamorphism at shallow levels and post-peak metamorphism at deeper crustal levels (Fig. 8).
- The two phases of TTG magmatism predate the two episodes of gold mineralization and a direct bearing on the gold mineralization is unlikely.

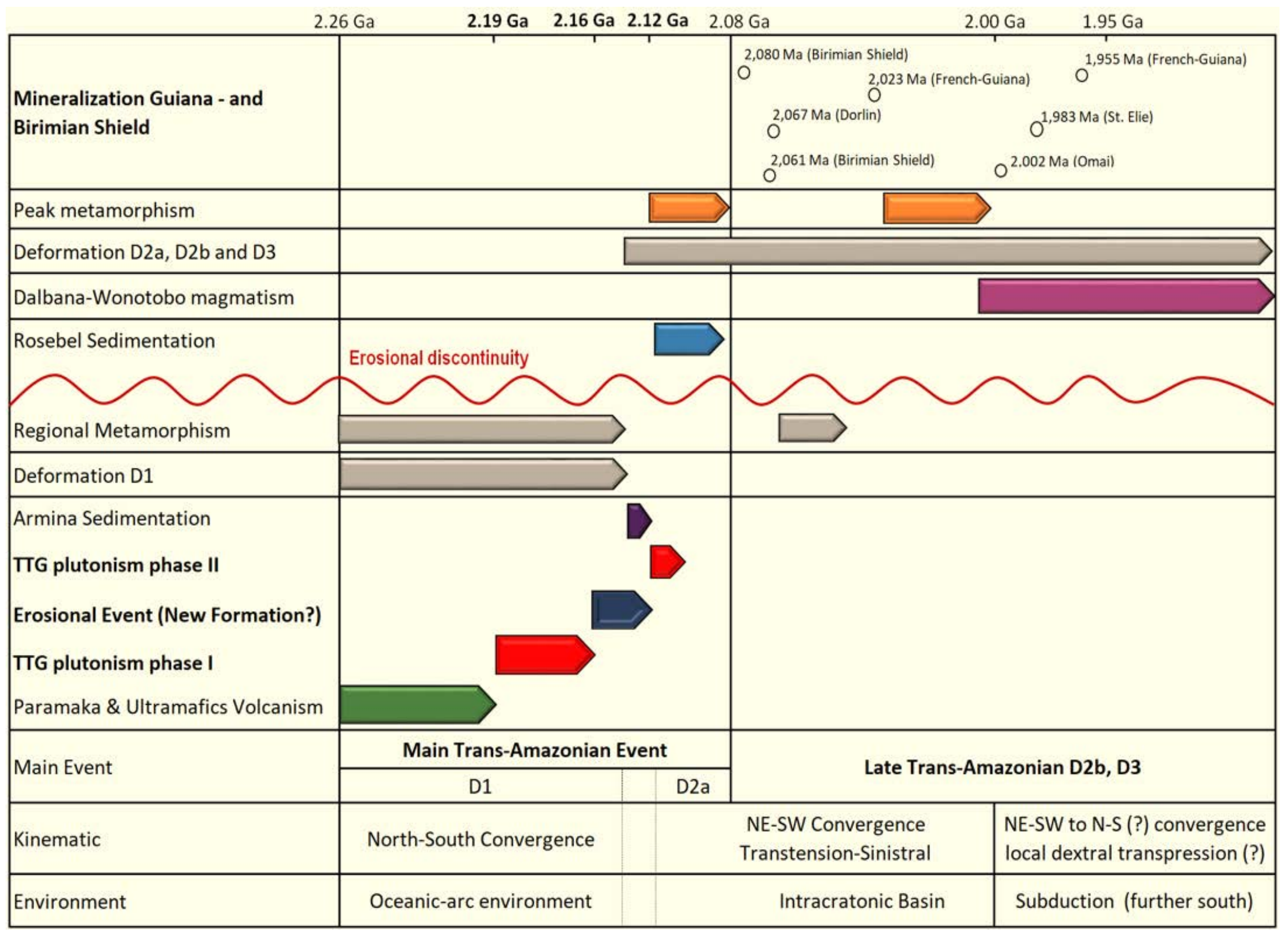

Figure 8: New dates for TTG magmatism at Rosebel with respect to the timing of major geotectonic events and gold mineralization in the Guiana Shield.

## Recommendations

- Further dating:
  - to better assess whether the two-step TTG accretion is valid or whether we are dealing with a relatively continuous TTG process from 2.19 – 2.08 Ga.
  - to better assess the implications of Archean material both on the source of gold and the development of the Guiana Shield in general.
- Dating of the gold mineralization:
  - further dating of the gold mineralization throughout the Guiana Shield including the Rosebel Gold district is recommended to constrain the two likely phases of gold deposition through time in relation to magmatic and deformation processes.

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# Geology of the Karouni Orogenic Gold Deposit: Guyana, South America

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2 Troy Resources Guyana
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# Today's Talk

- Guiana Shield
- Camp Scale
- Deposits
- Alteration
- Geochronology
- Implications for source

# Gold Mining in Guyana

- **Gold discovered in 1850s, mined continuously since**
- **Two current producing mines (Aurora, Karouni) and one major former producer, Omai**
- **Substantial artisanal gold mining community, "Pork Knockers"**

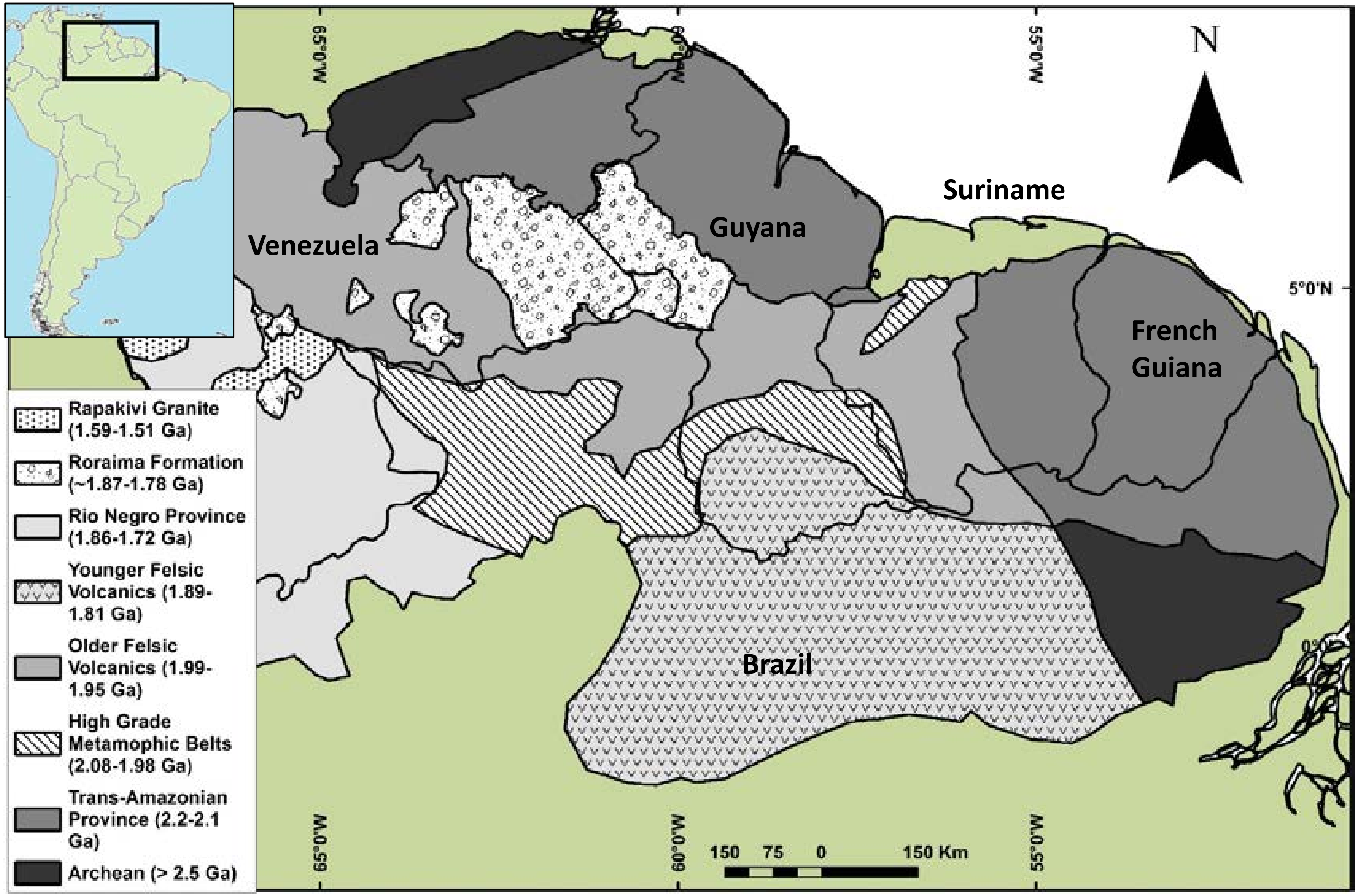
**Aurora Mine: Photo Guyana Gold Fields**

**Karouni Mine**

**Omai Mine: Photo Mahdiagold.com**

**Pork Knockers at work**

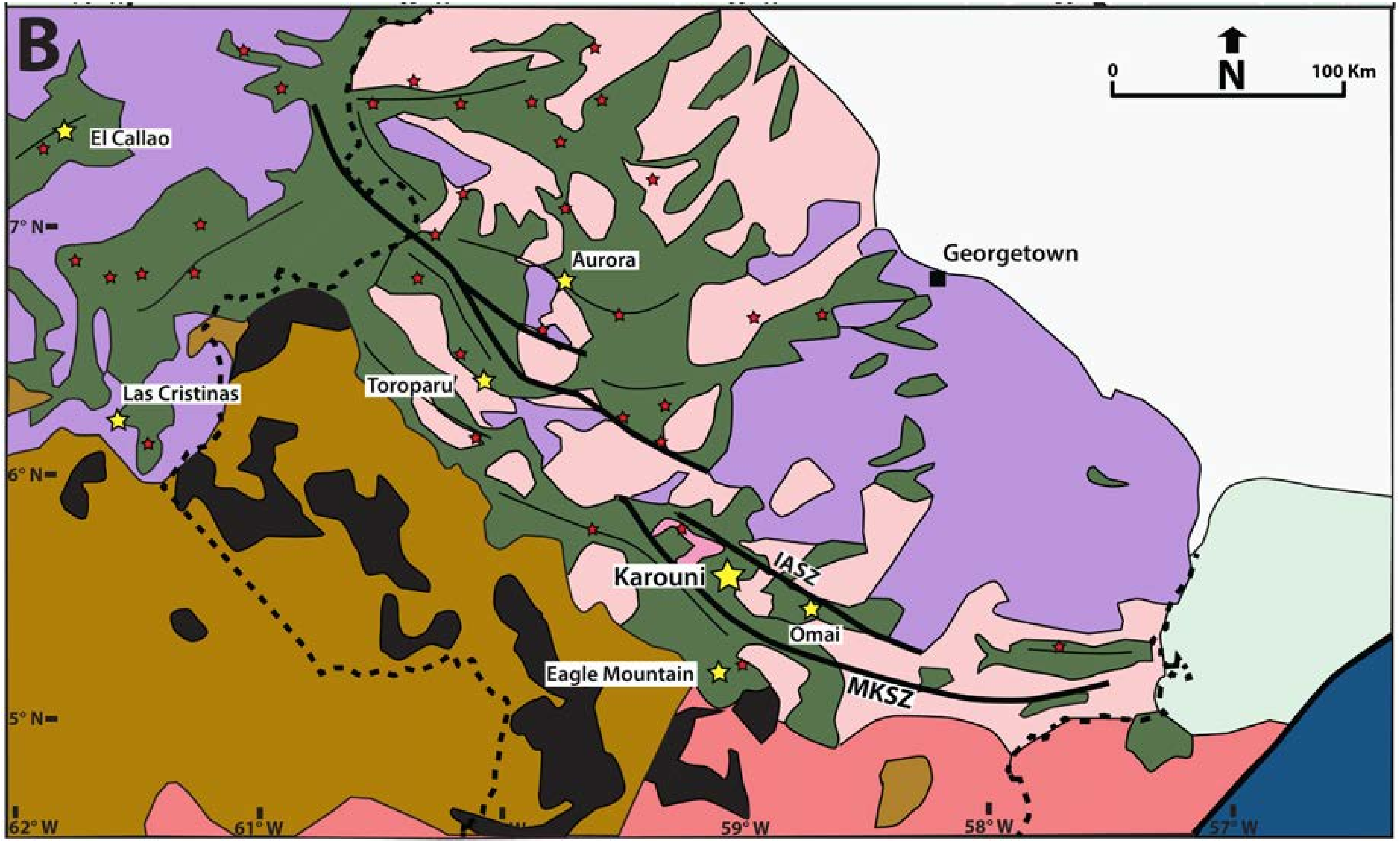
# Guiana Shield Geology



**Simplified geological province map of the Guiana Shield (modified from Kroonenberg et al., 2016)**

- **Northern portion of the Amazon Craton**
- **Trans-Amazonian Province (2.2-2.0 Ga)**
  - **granite-greenstone terrane**
  - **Host majority of Au deposits**
- **Younger belts to the SW (1.95-1.8 Ga)**

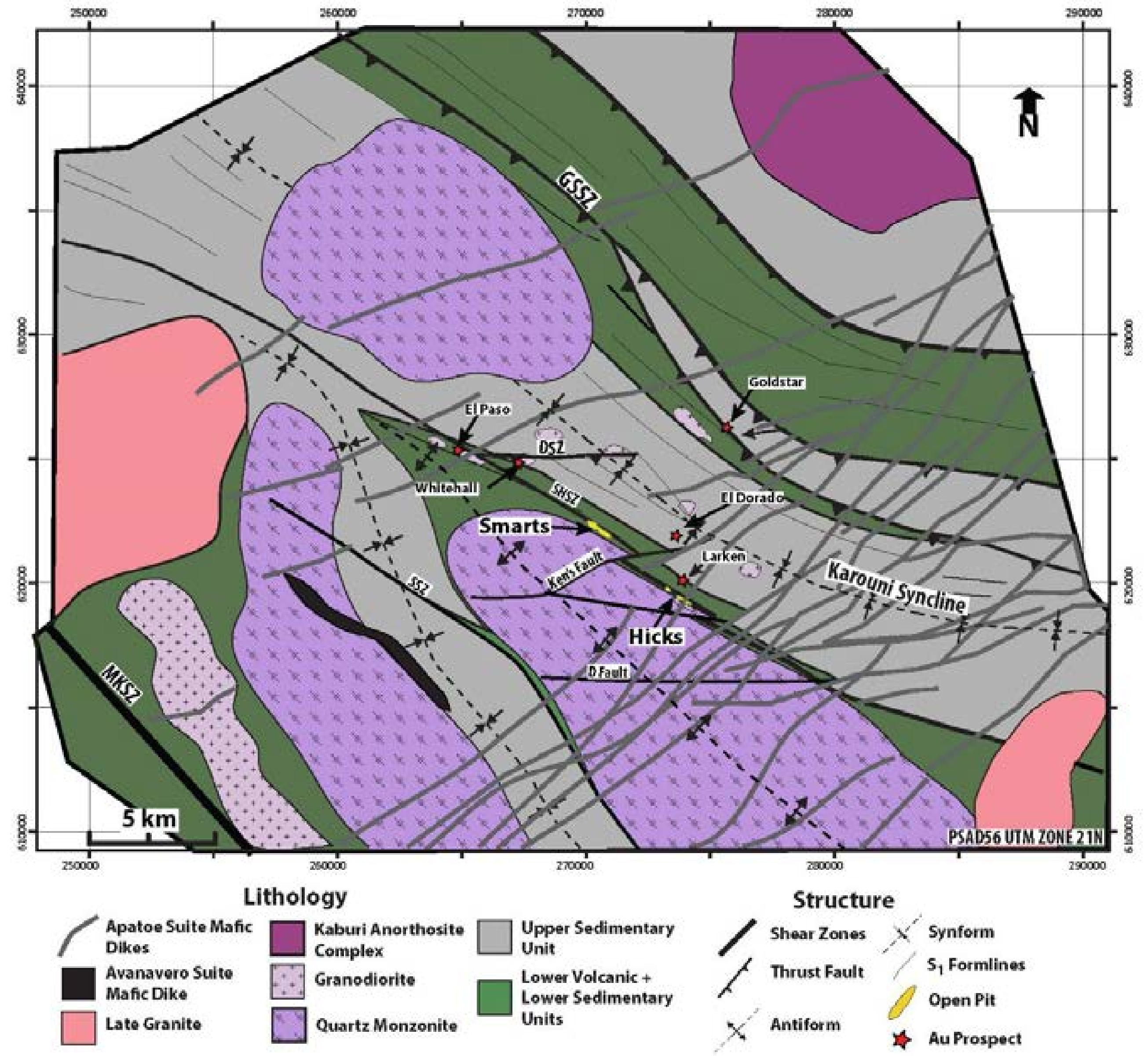
# Northern Guiana Shield Geology

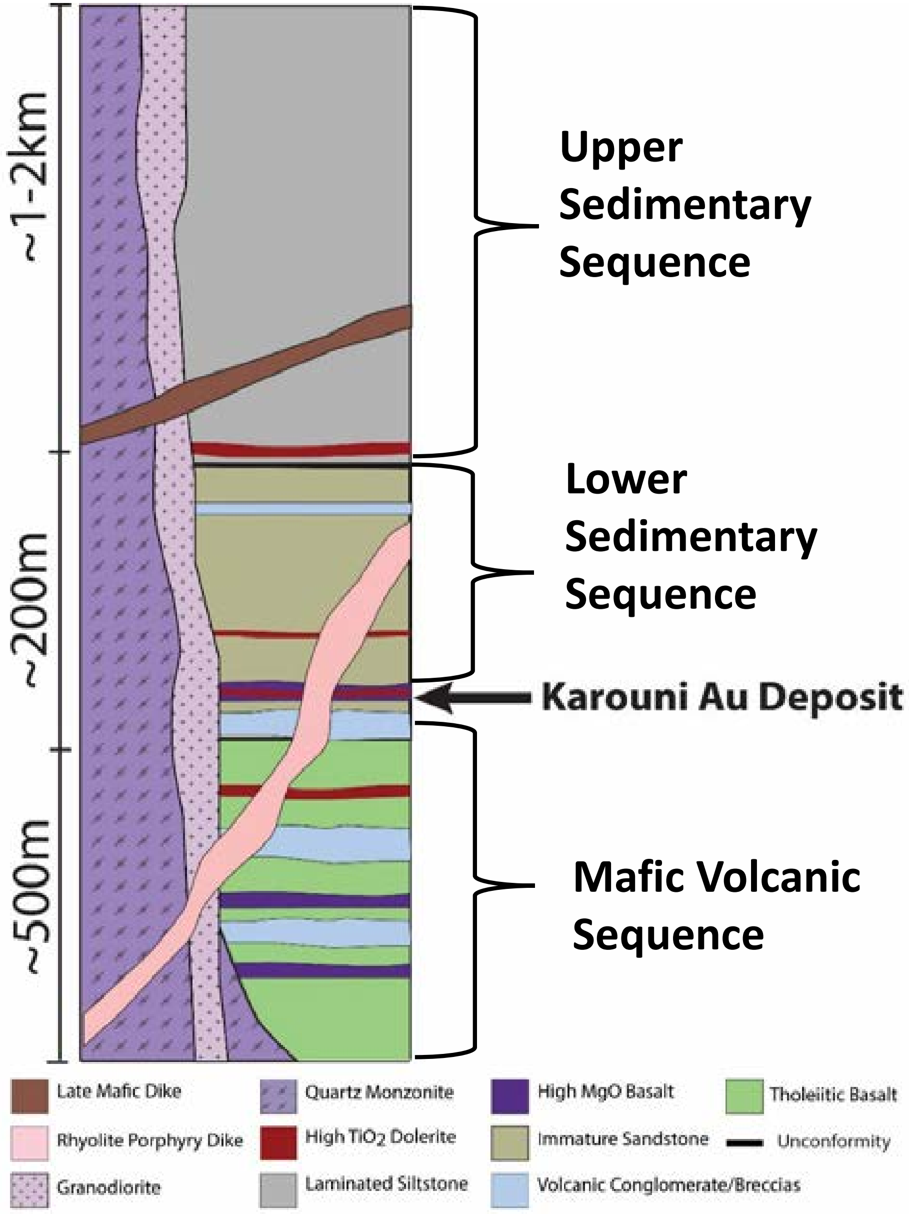


- **Multiple world-class deposits >10 Moz (Las Cristinas, El Callao, Aurora, Rosebel)**
- **Major Au deposits hosted the greenstone belts in proximity to regional shear zones**

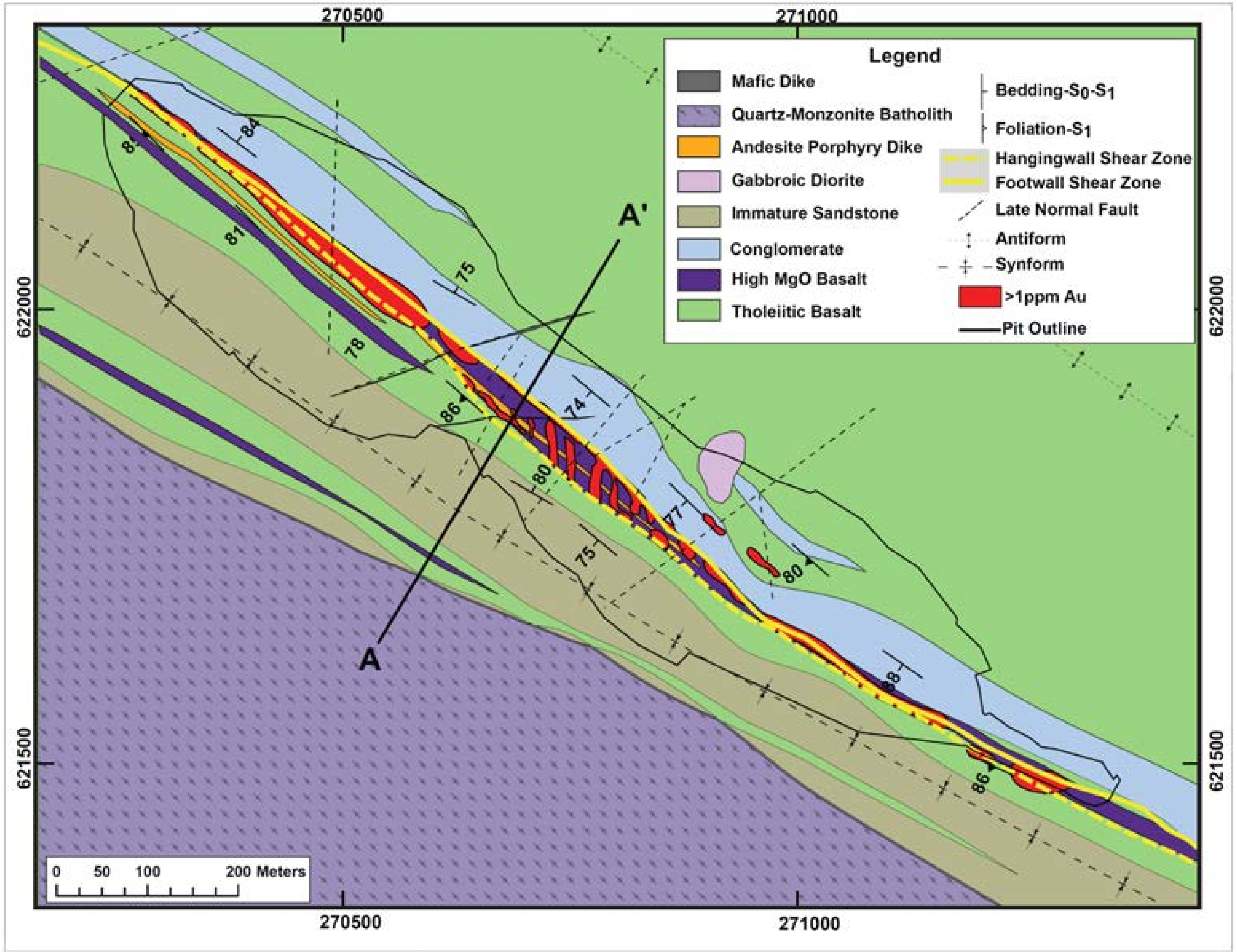
Simplified map of the north-western Guiana shield, complied from the national geological maps of Guyana, Venezuela and Suriname. MKSZ= Makapa-Kuribrong Shear Zone, IASZ = Issano-Aparu Shear zone

# Karouni Camp Scale

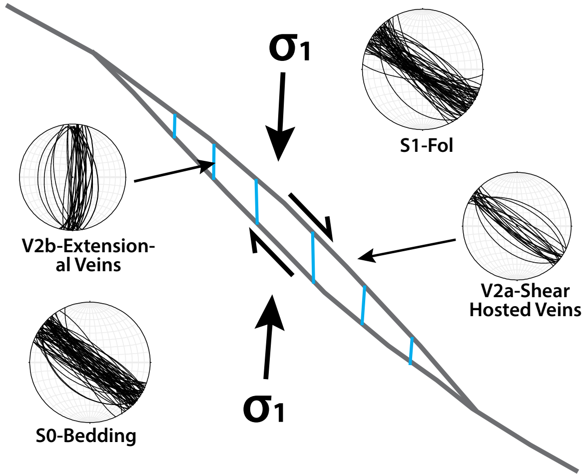




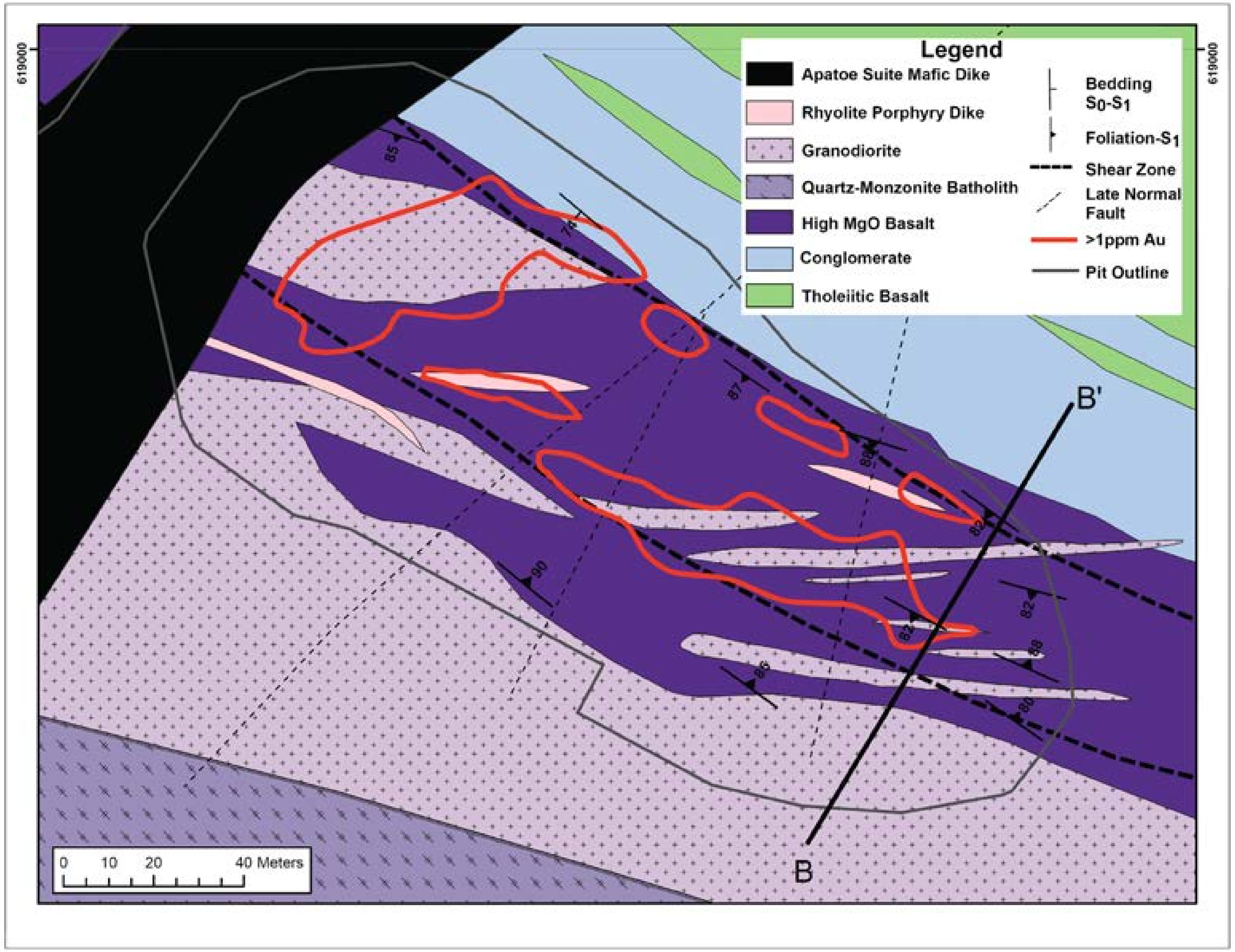
# Smarts Deposit



- **NW-SW trending Smarts-Hicks Shear zone hosted ductile High MgO basalt**
- **Single shear zone diverges into multiple shear zone segments at a 15° change in strike**
- **Mineralization:**
  - **$V_{2a}$ NW-SE shear zone hosted veins**
  - **$V_{2b}$ N-S extensional veins between the shear zones**

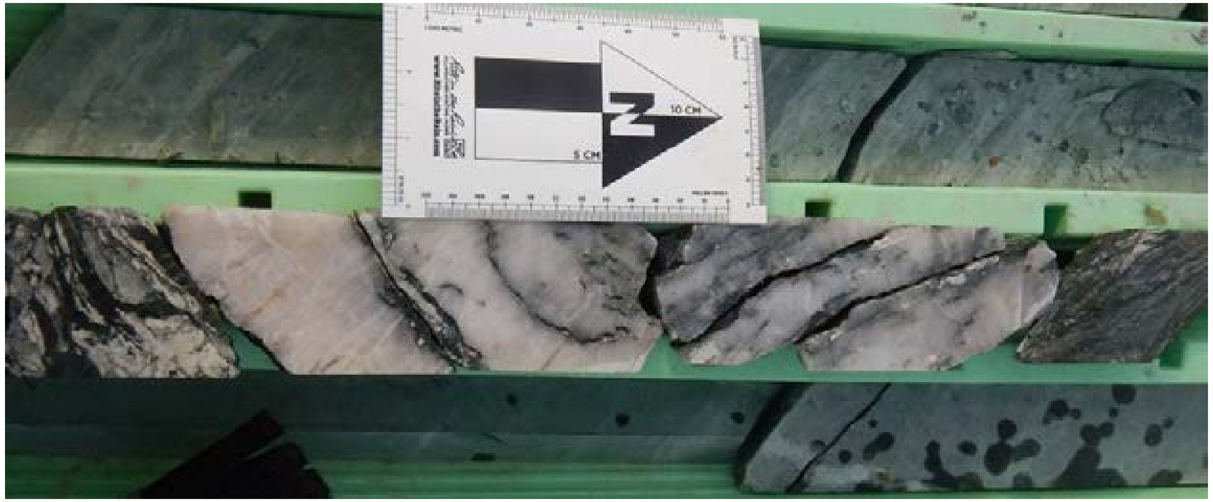


# Hicks Deposit

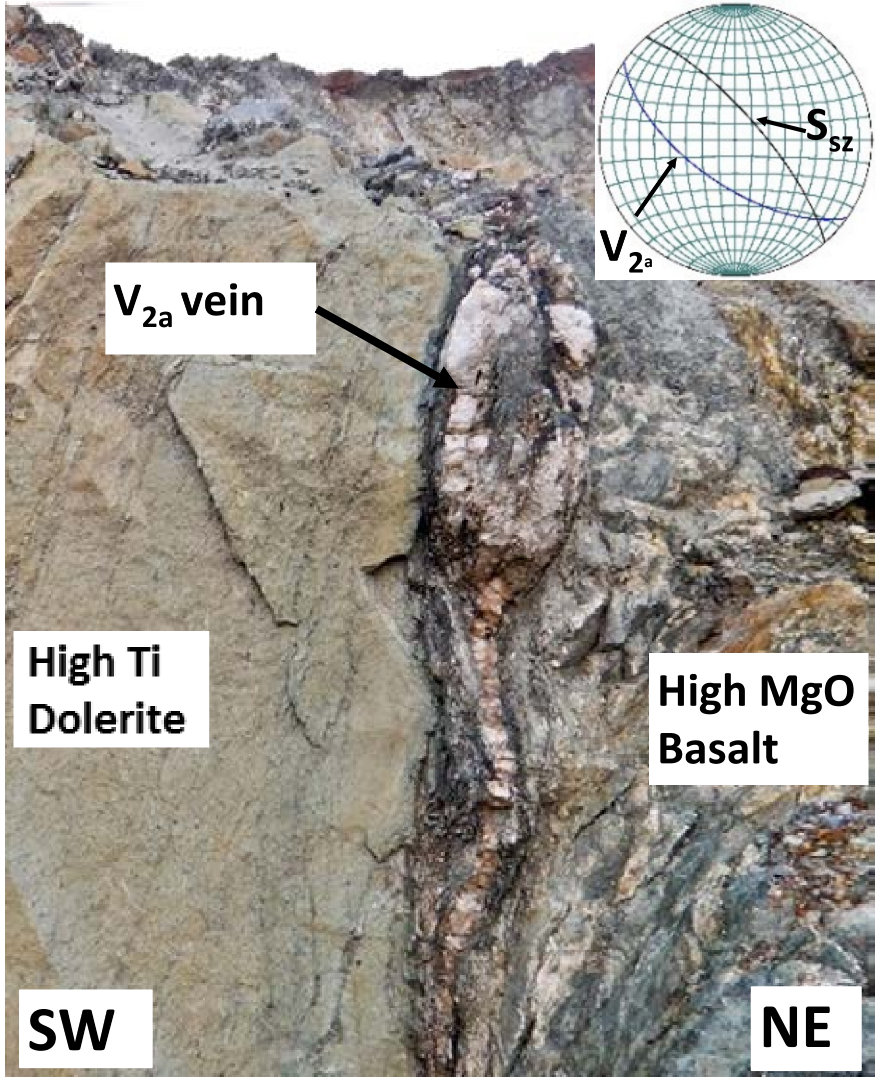


- Granodiorite/rhyolite porphyry and High MgO basalt host rocks
- Shear zones locally cut and offset dikes (1-2m)
- Same N-S and NW striking Qtz-Cal-Py veins
- Rheology is key for localizing veins

# Alteration and Mineralization: $V_{2a}$ Veins

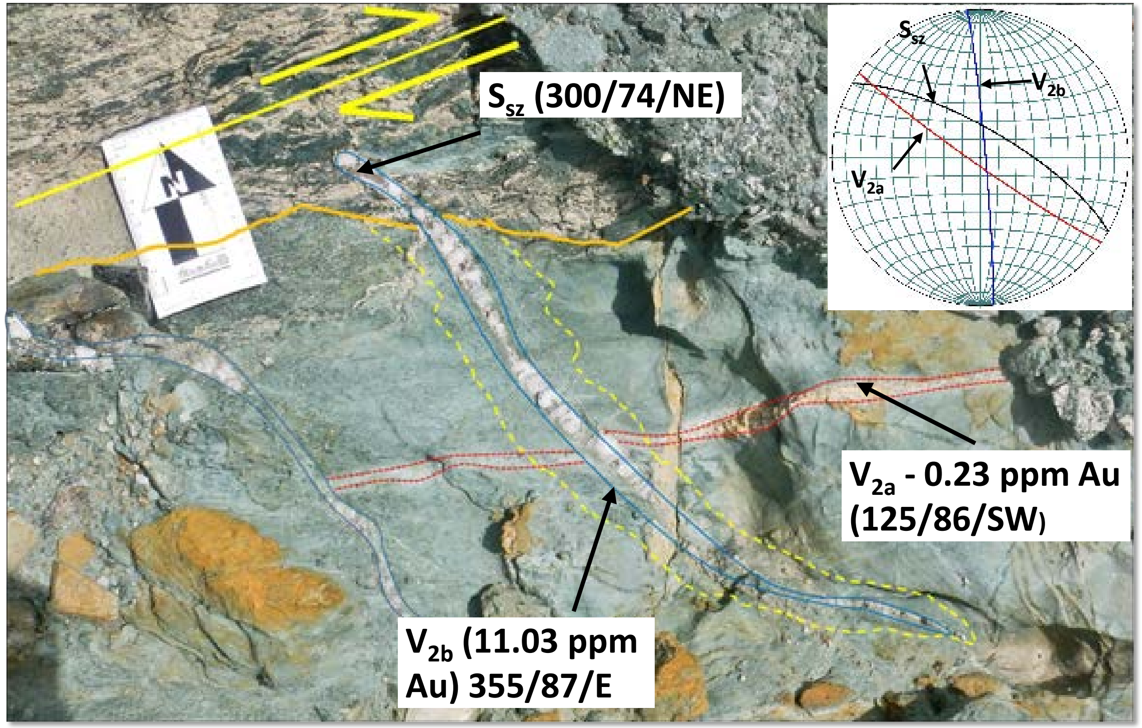


- Shear zone hosted, NW Strike, steep dip
- Hosted in high MgO Basalts
- qtz-cal-chl ±py, Au
- Laminated, crack-seal textures, folded, boudinaged
- Variable grades 0.2 to >20 g/t



# Alteration and Mineralization: $V_{2b}$ Veins

- N-S strike, steep dip
- Brittle lithologies, pinch out in ductile rocks
- Sigmoidal wings indicate dextral movement
- Qtz-cal-chl ± py-tourm-Au
- Sharp, brittle vein walls, cut foliation, perpendicular mineral fibers
- High Grade, up to 100 g/t, average 5-20 g/t, up to 20 g/t in the py halo



$S_{sz}$ (300/74/NE)

$V_{2a}$ - 0.23 ppm Au (125/86/SW)

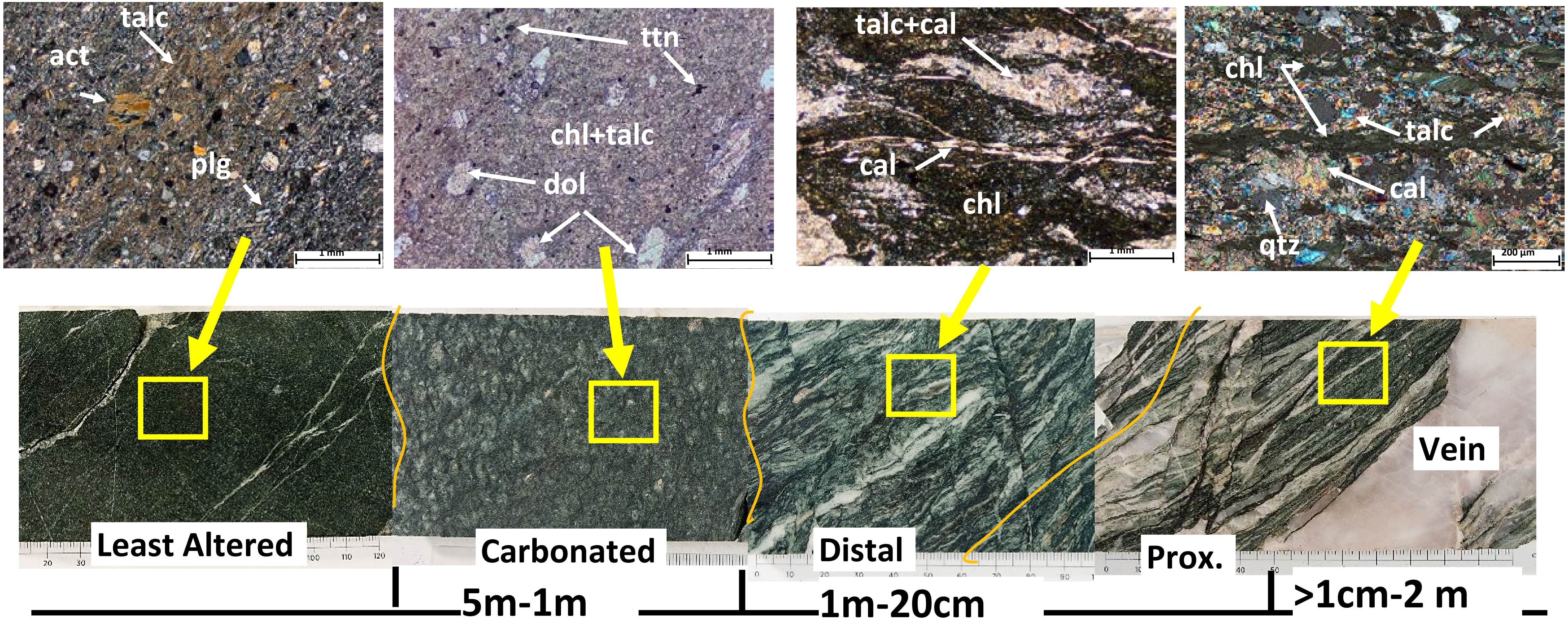
$V_{2b}$ (11.03 ppm Au) 355/87/E

# Hydrothermal Alteration: High MgO Basalt

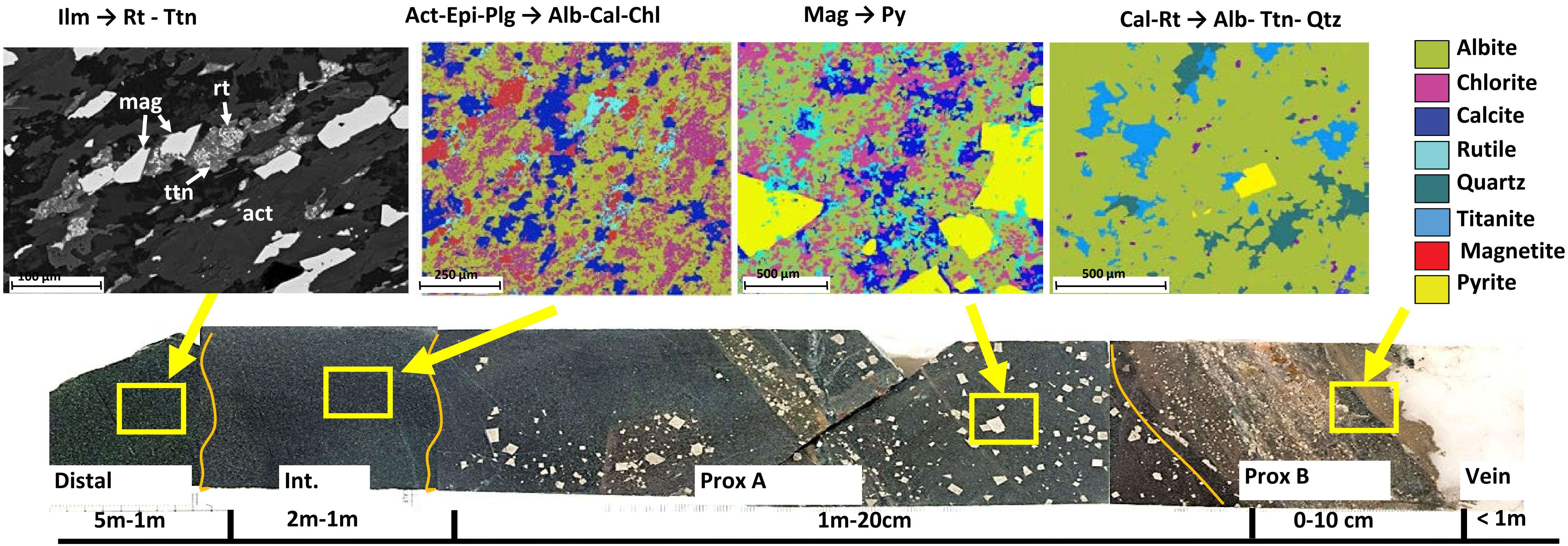
Cpx-Act-Plg → Talc-Chl-Dol-Ttn

Dol → Cal

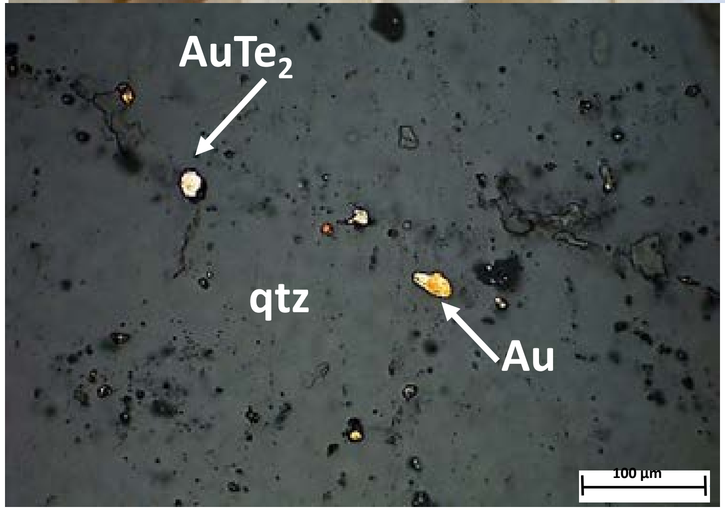
+ Qtz-Py



# Hydrothermal Alteration: High $TiO_2$ Dolerite

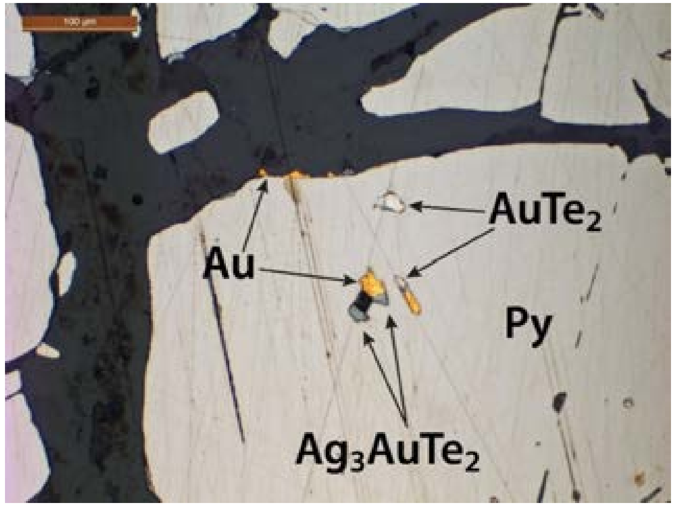


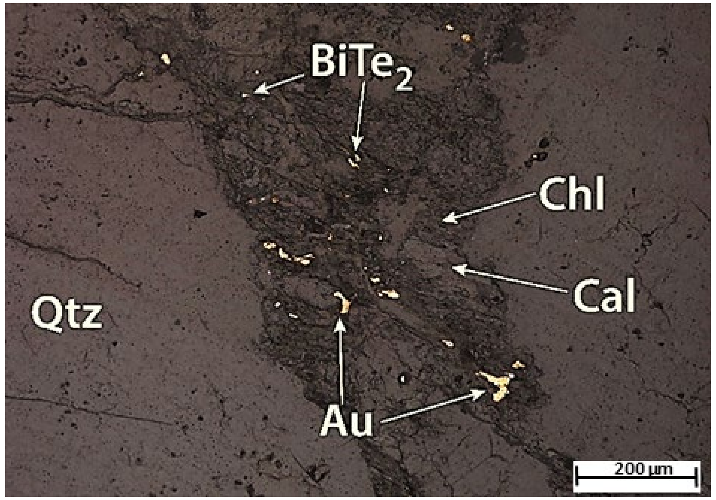
# Au Mineralization



- **Vein hosted: Coarse native gold in both $V_{2a}$ and $V_{2b}$ veins**
  - **Fracture fills and inclusions in quartz**

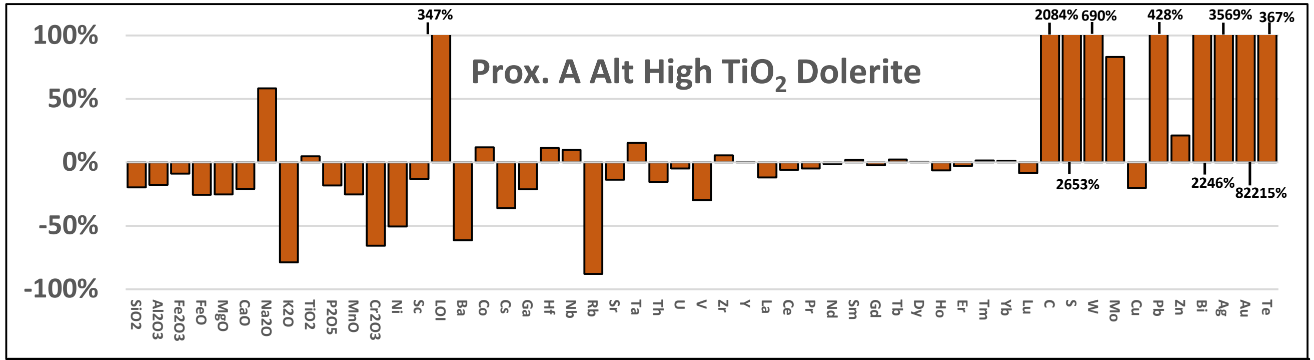
- **Wall rock hosted: native gold, Au bearing tellurides, calaverite ($AuTe_2$) and petzite ($Ag_3AuTe_2$) in pyrite**
  - **Inclusions and fracture fills**

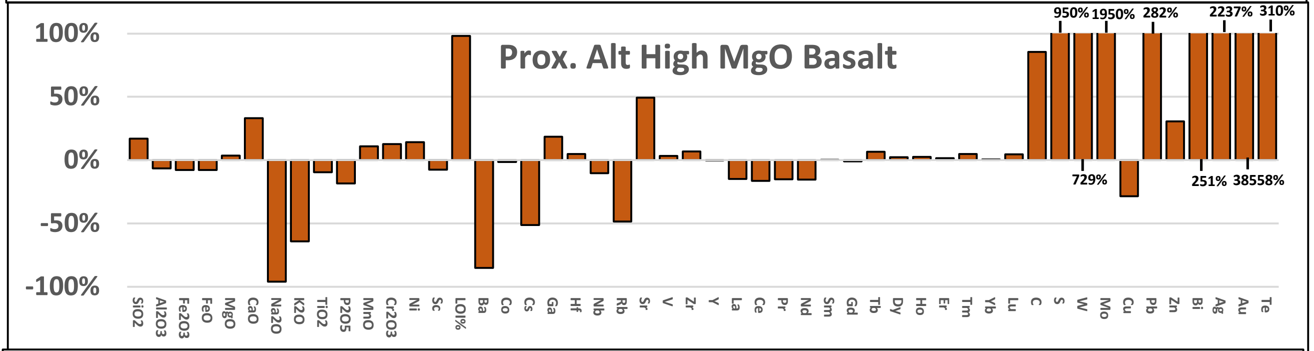


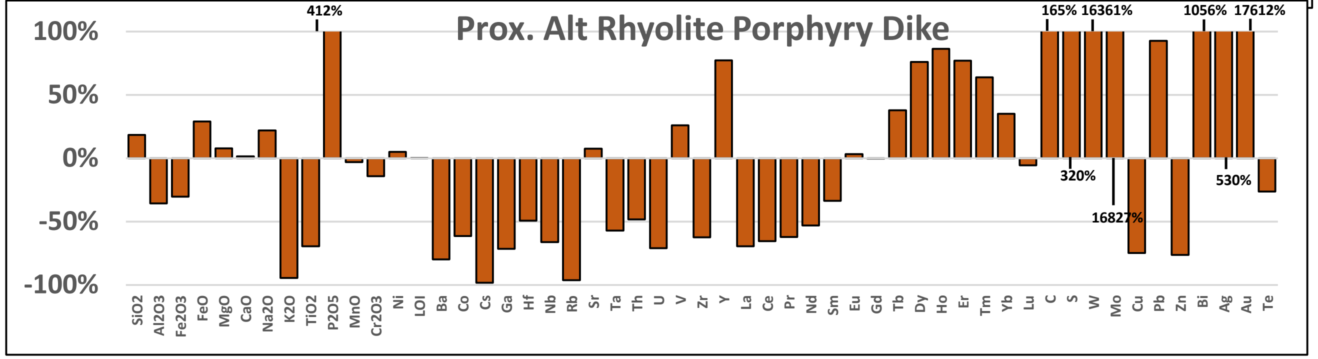


# Mass Balance Modeling of Alteration

- **Strong enrichment of Au, Ag, Bi, W, Pb, Te, Mo**
- **Enrichment of Na, C and S**
- **Depletion of alkalis, Ba, Rb, Cs**

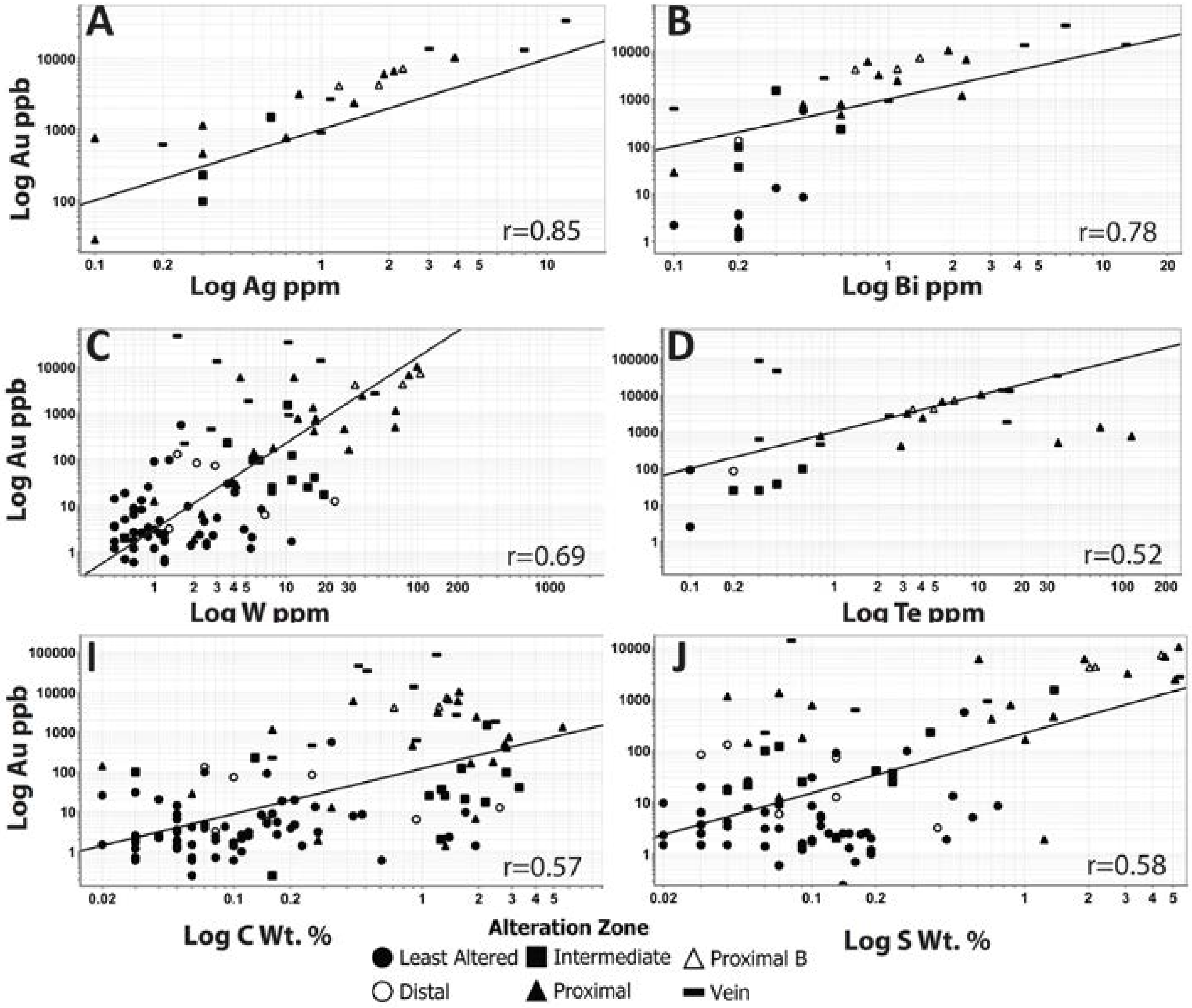




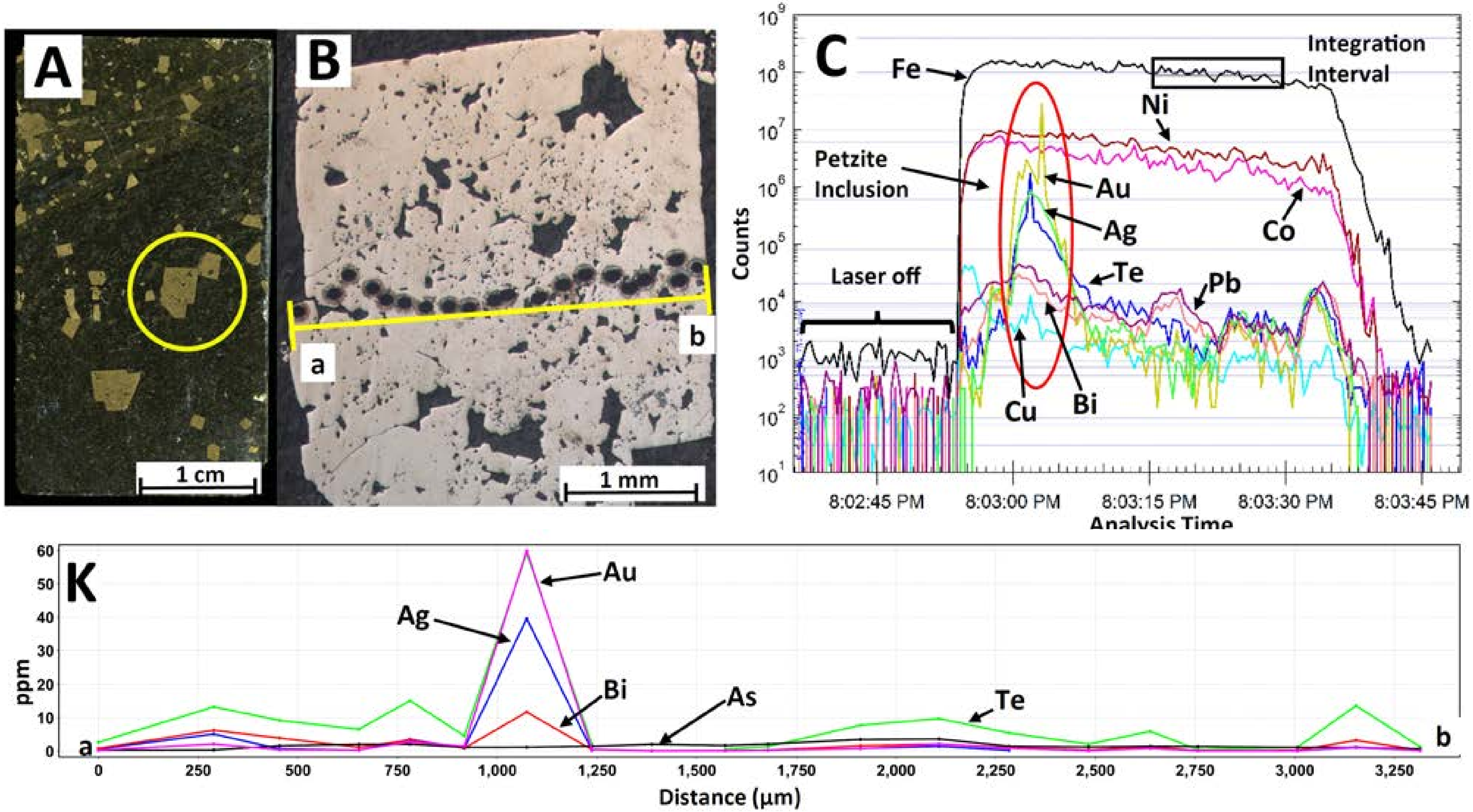


# Correlations to Au

- W, Ag, Te and Bi
- C and S
- Ag, Te and Bi have very low values compared to Au
- W is the only useful pathfinder

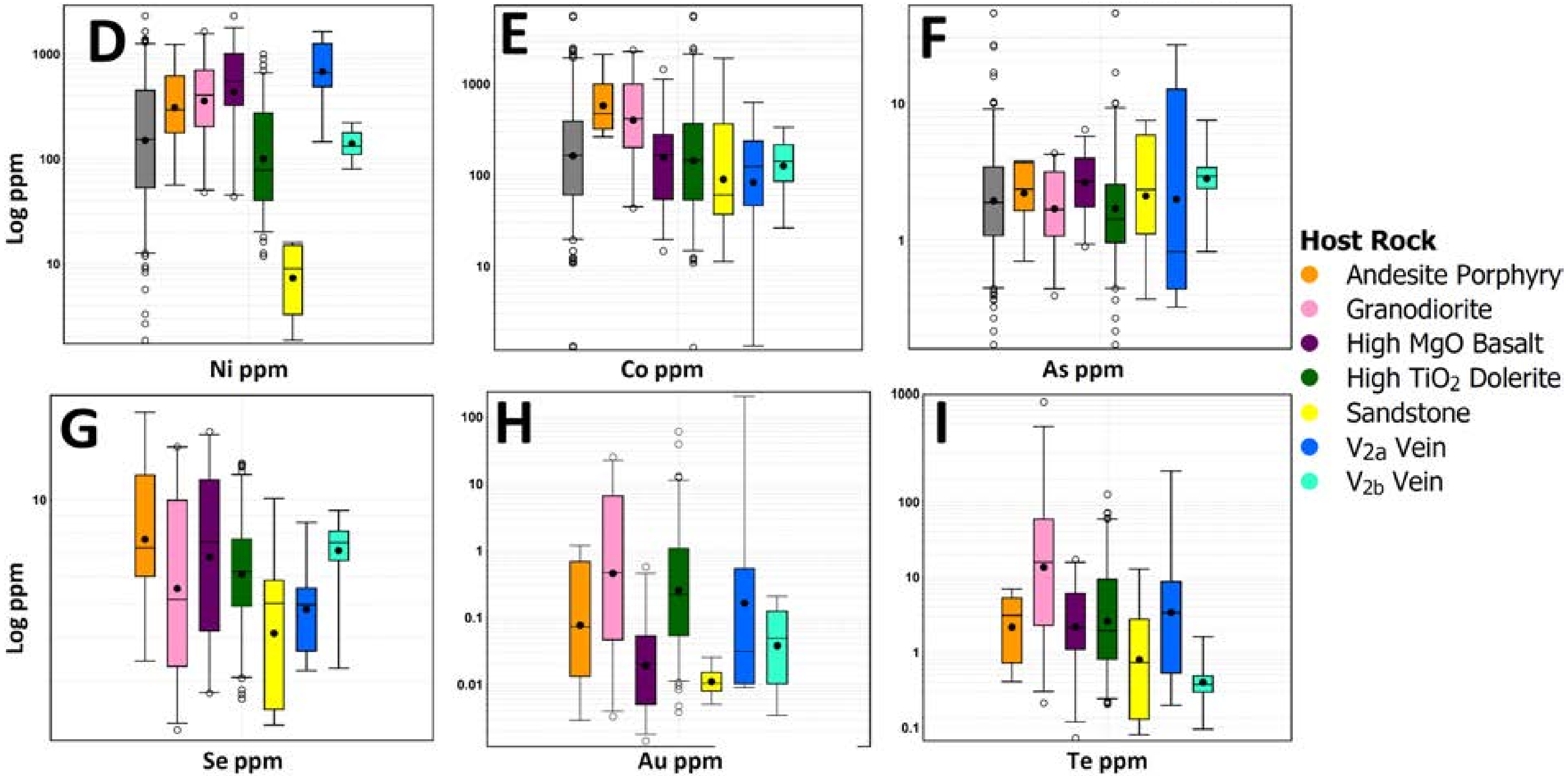


# LA-ICP-MS Geochemistry: Pyrite



Most trace elements are a function of inclusions

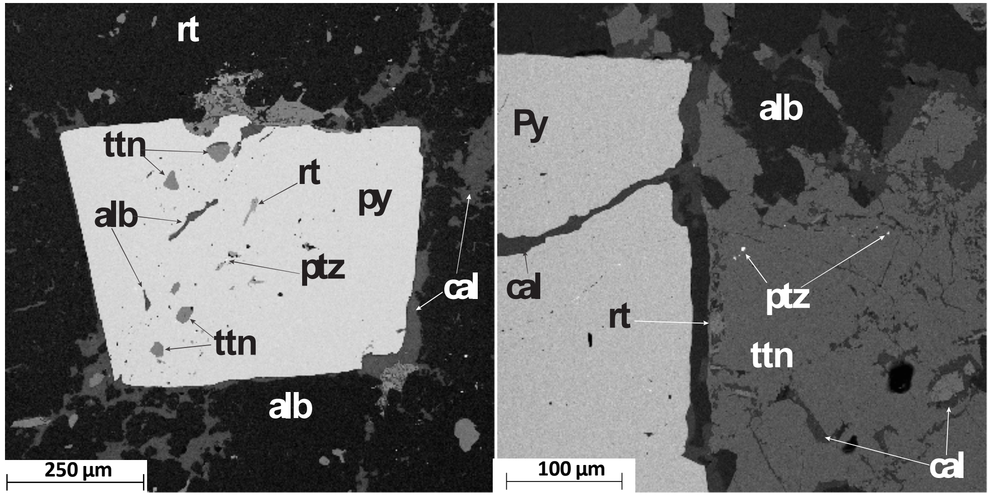
# LA-ICP-MS Geochemistry: Pyrite

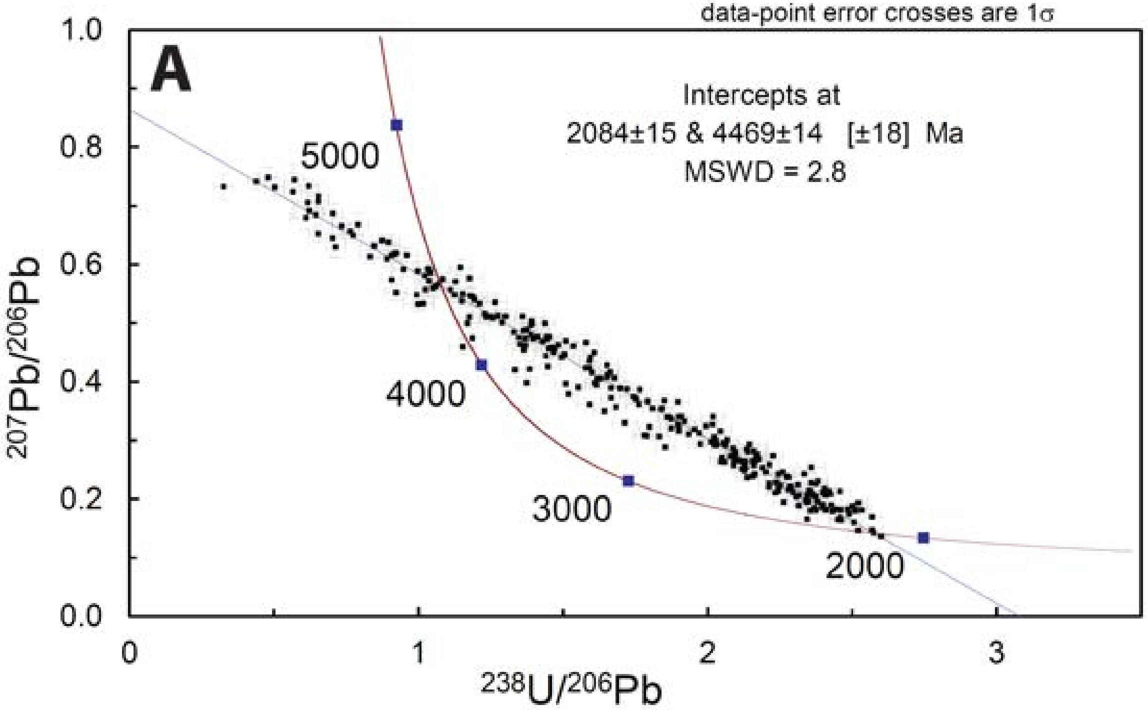


- No As, No Au
- Trace elements content (Ni, Co) a function of wall rock composition
- Consistent in both vein types (V2a and V2b), one pulse of fluid

# Age of Mineralization: Hydrothermal Titanite

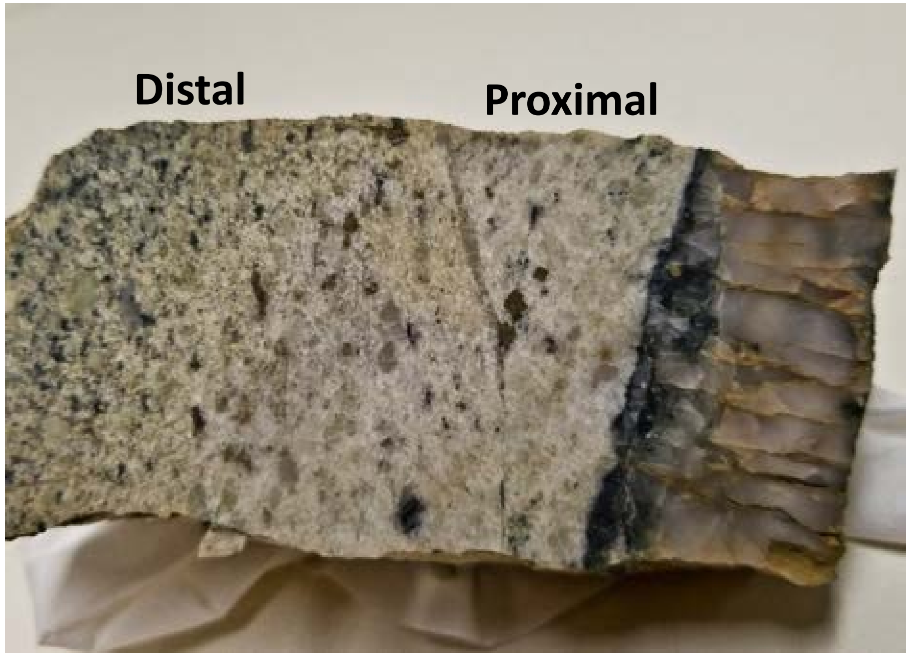
- **In-Situ U/Pb LA-ICP-MS of titanite in Prox. B alteration**
  - **>1mm grains**
- **Petrogenetic link between titanite and gold**
- **Common Pb mixing line, 350 spots**
- **Regression shows a mineralization age of 2084±15 Ma**

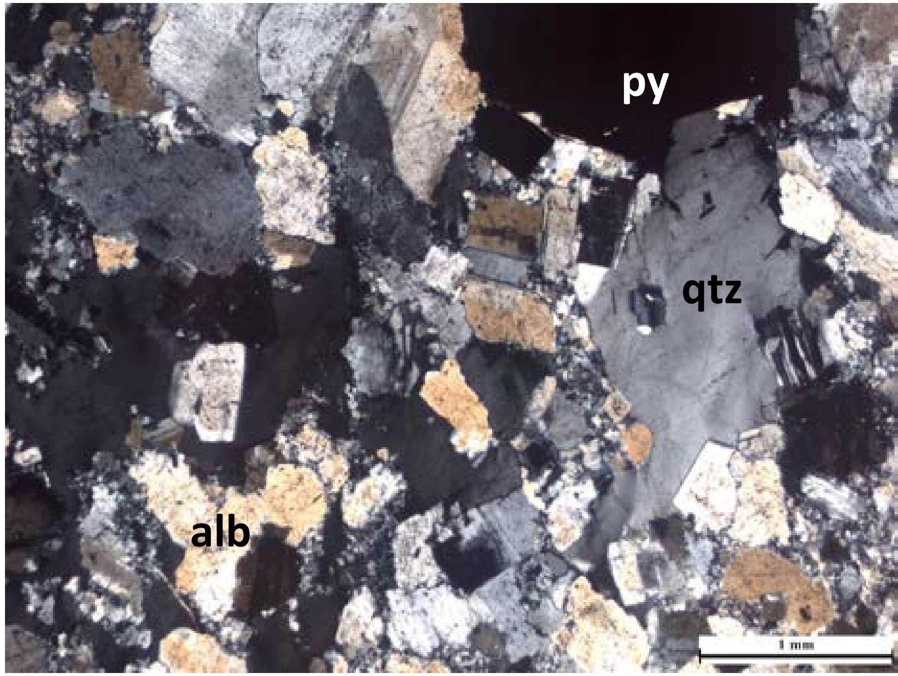




# Nature of ore fluids

- No potassic alteration, sodic dominant
  - No K in fluid? Depleted in altered zone
- Enrichment in W, Bi, Te, Ag, Mo, Pb
- No As, Sb; depletion in alkalis other than Na
- Neutral pH, moderately reducing (no hematite or pyrrhotite)
- Temp 270°-320° (chl geothermometry)
- Sulfidation reactions key for Au deposition





# Classic Orogenic gold deposit?

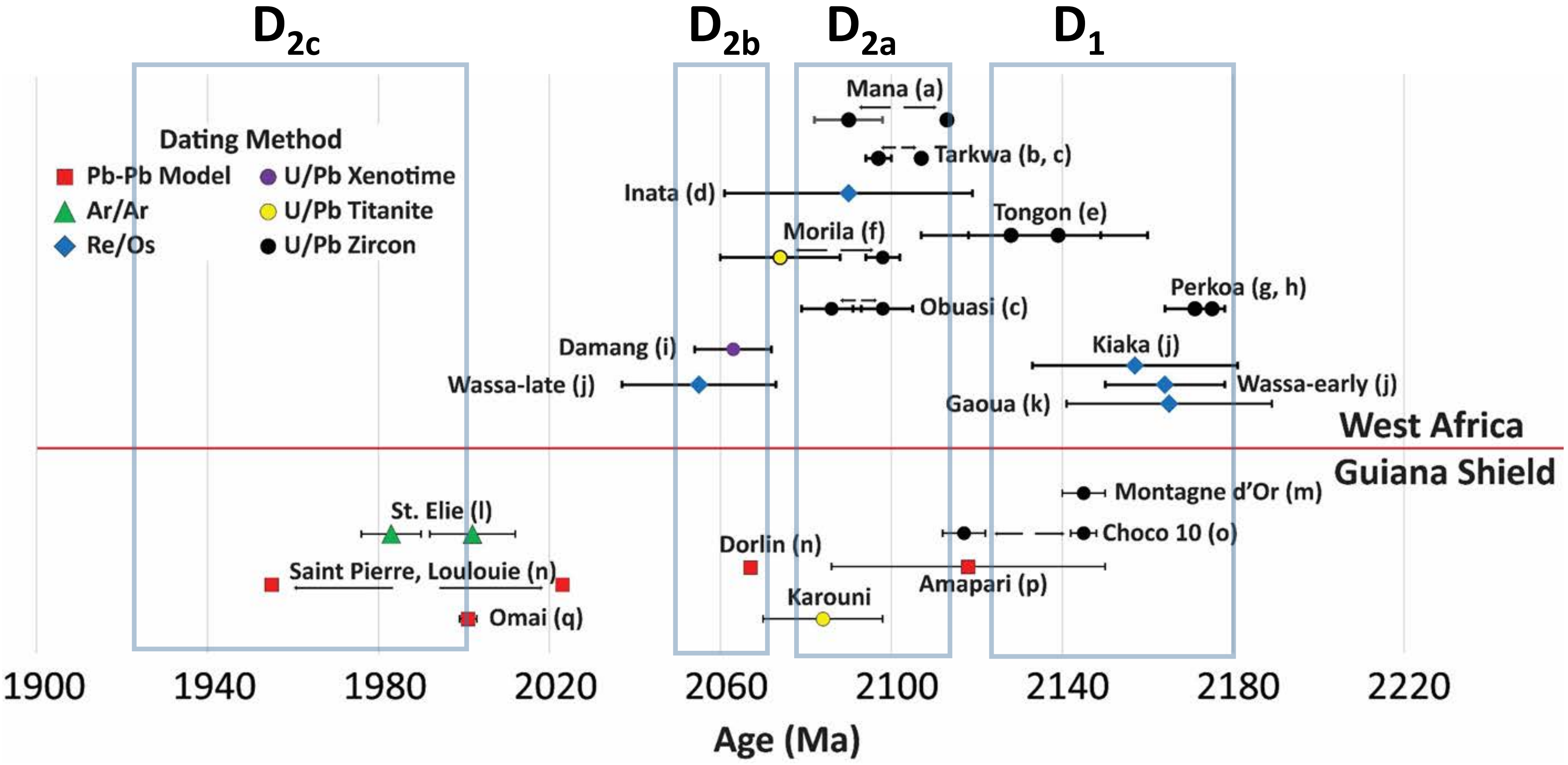
- Magmatic association?
  - Error margins overlap with rhyolite porphyry dikes (2088 ± 14 and 2089 ± 11 Ma)
  - Bi, W, Mo, Te element association
  - Dikes outside ore zone are un-mineralized, no element zoniation or fluid exsolution textures

- Classic Orogenic?
  - Greenschist facies host rocks, Strong structural control
  - Shear veins, quartz-carbonate vein arrays + albite alteration
  - late in deformation history

- But different
  - Lack of potassic alteration, As, Sb enrichment
  - Dominance of proximal calcite over ankerite/dolomite
  - Metamorphic fluids from a different source?

# Age Comparisons: Guiana Shield and West Africa

- Deposits dated with robust techniques are older, match deformation history
- Likely several gold events and more than just orogenic gold
- Similar to ages from West Africa



Sometimes there is a pot of gold at the end of the Rainbow…..

**Thank You!**

# Acknowledgments

- **Supervisors: Dr. Steffen Hagemann**

  **Dr. Tony Kemp**

- **Troy Resources Guyana: Analytical costs, flights, accommodation, on-site logistics, access to data, being all around good guys**
  - **Especially Neil Jones, James Davis, Peter Doyle, Jens Langhoff, Boaz Wade, Damion Lakna and Nigel Black and the rest of exploration department**

- **UWA: IRPS, APA and UWA "Safety Net" Scholarships**

# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral system*

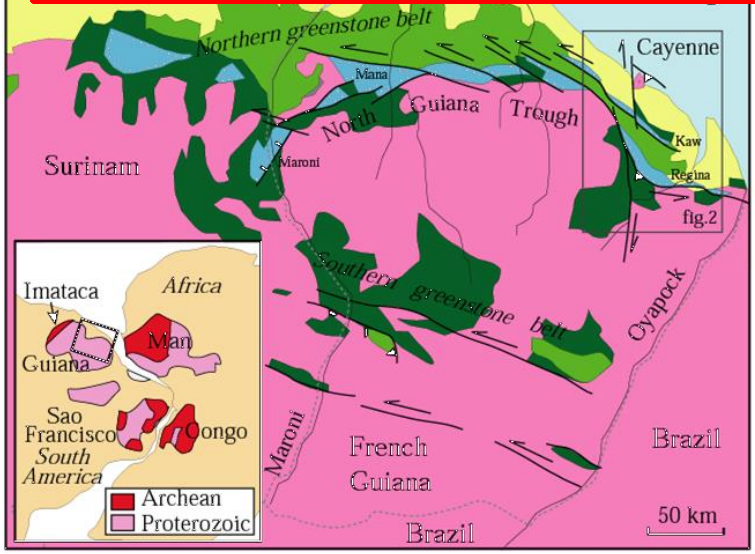
Vanderhaeghe O.
Ledru P.

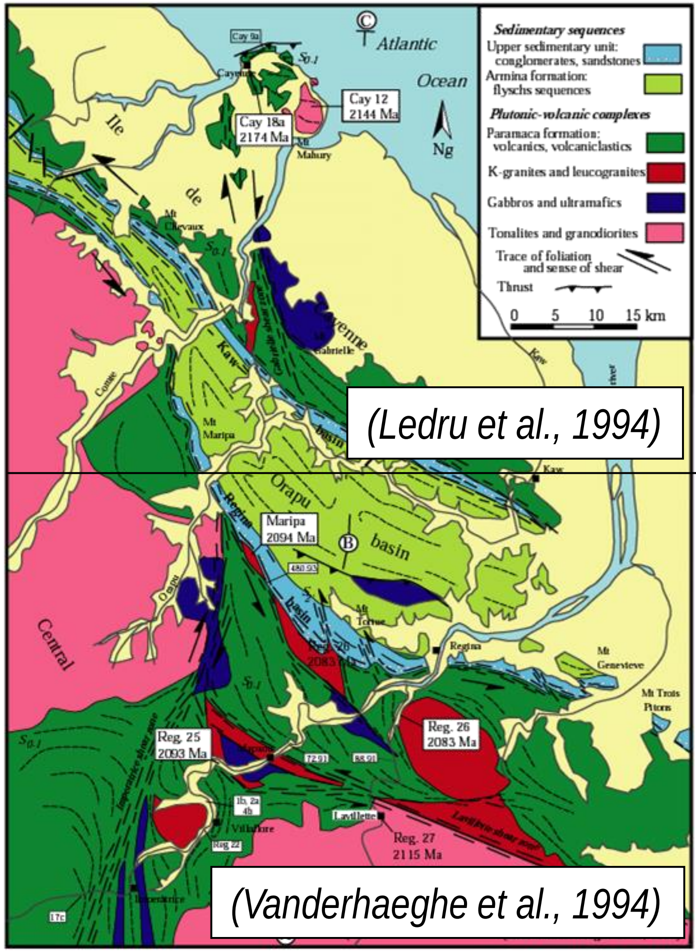
11th Inter Guiana Geological Conference:
The Tectonics & Resource Potential of NE South America

## Personnal context

*1991-1993* BRGM Guyane

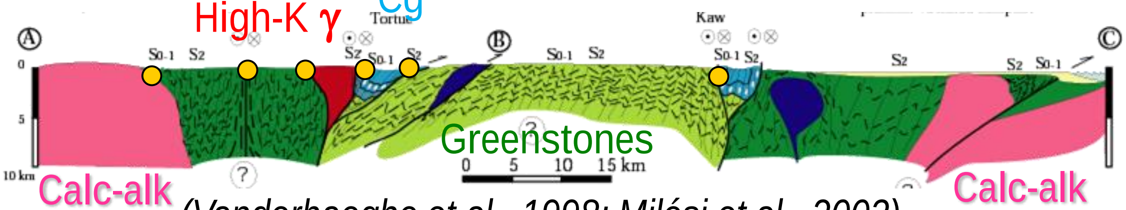
In memory of Gaston Brugnot
gone with the secrets of greenstone belts





(Ledru et al., 1994)

(Vanderhaeghe et al., 1994)



High-K γ

Cg

Greenstones

Calc-alk

Calc-alk

(Vanderhaeghe et al., 1998; Milési et al., 2003)

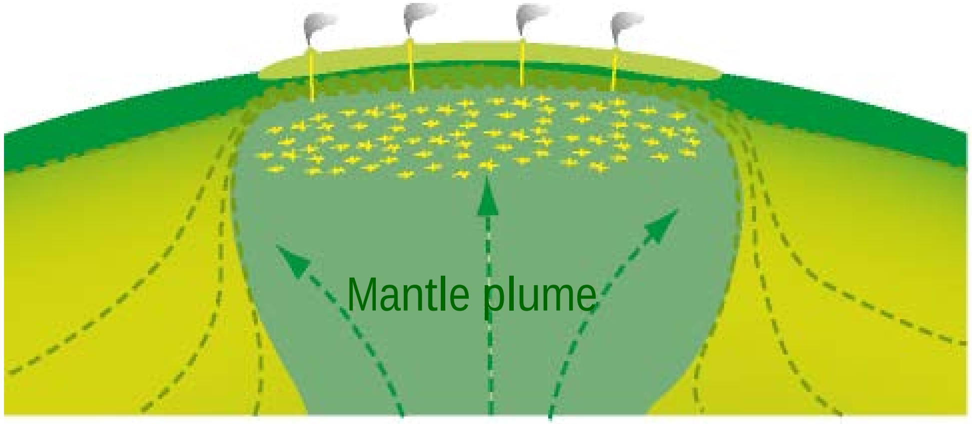
# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral system*

Vanderhaeghe O.
Ledru P.

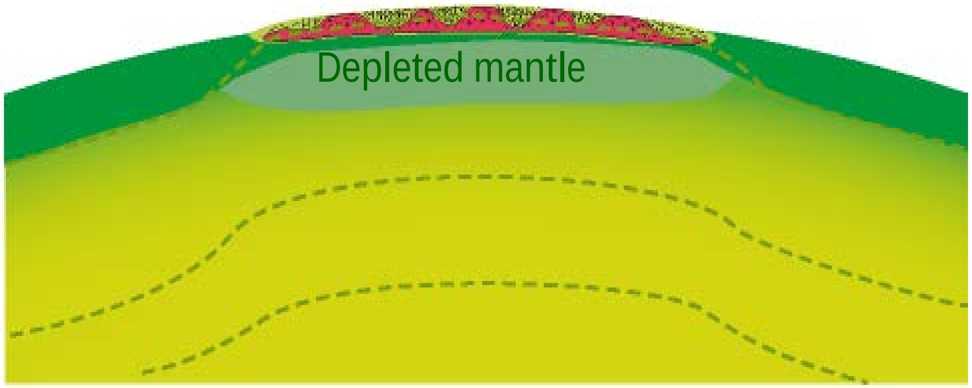
## Geodynamics of lithospheric construction and crustal-growth

### Mantle plume model

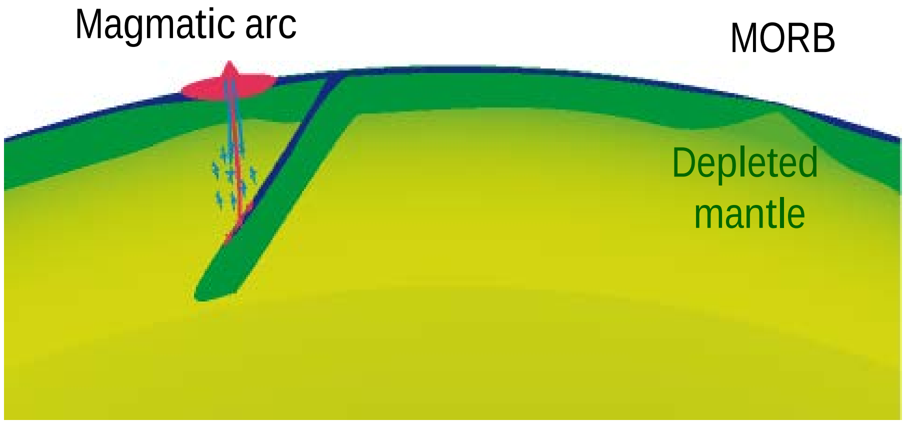
1. Oceanic plateau



2. Granite-Greenstone



### Subduction model



# Gold mineralization:
# *a guide for understanding crustal growth-differentiation*

Vanderhaeghe O.
Ledru P.

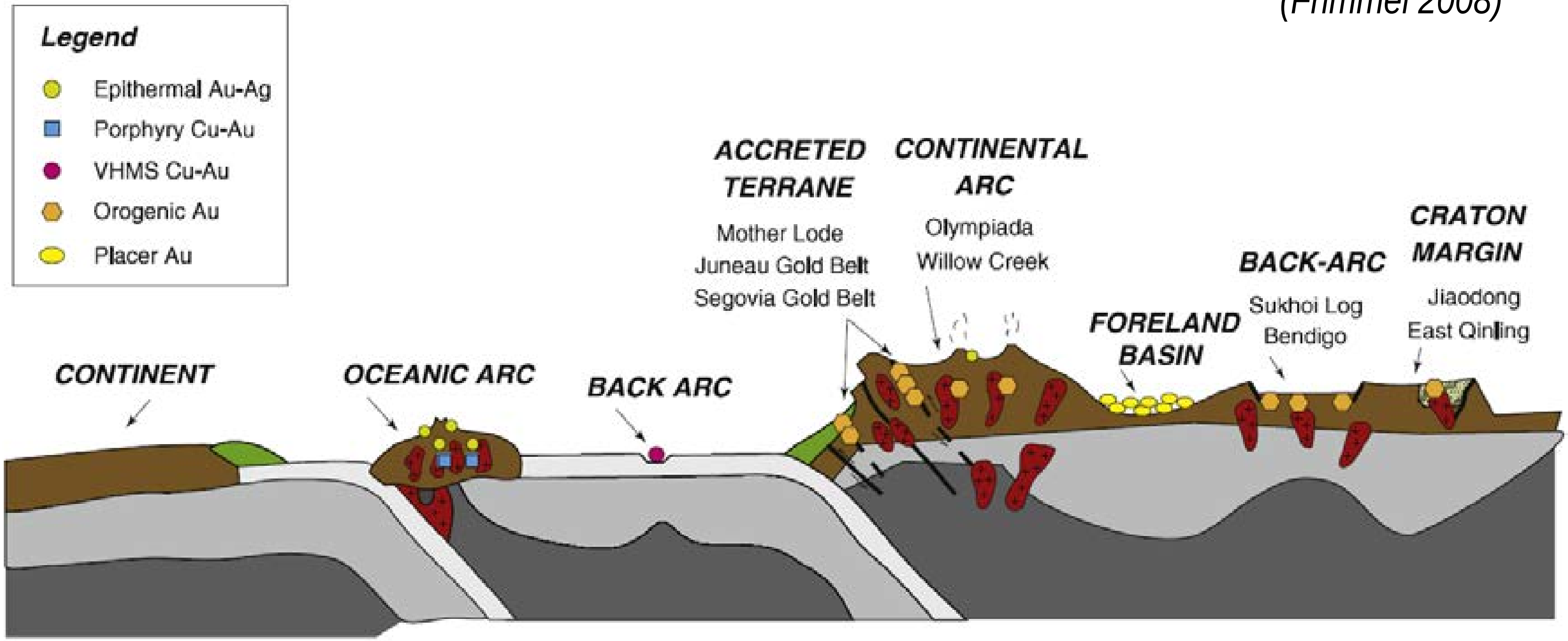
## Gold mineral system

Gold (Au):

- Siderophile element with little chemical affinity to oxygen
- Mobile in hydrothermal fluids enriched in sulfur and salt (Cl)
- Concentrates in ultramafic rocks or forms disseminated and/or vein-type ore-bodies
- Traces mantle/crust transfers and fluid generation-migration within the lithosphere

**“Gold was** added to the continental crust during a giant Mesoarchaean gold event at **3 Ga”**
**“Gold** was remobilized and concentrated during **subsequent crustal reworking”**

*(Frimmel 2008)*

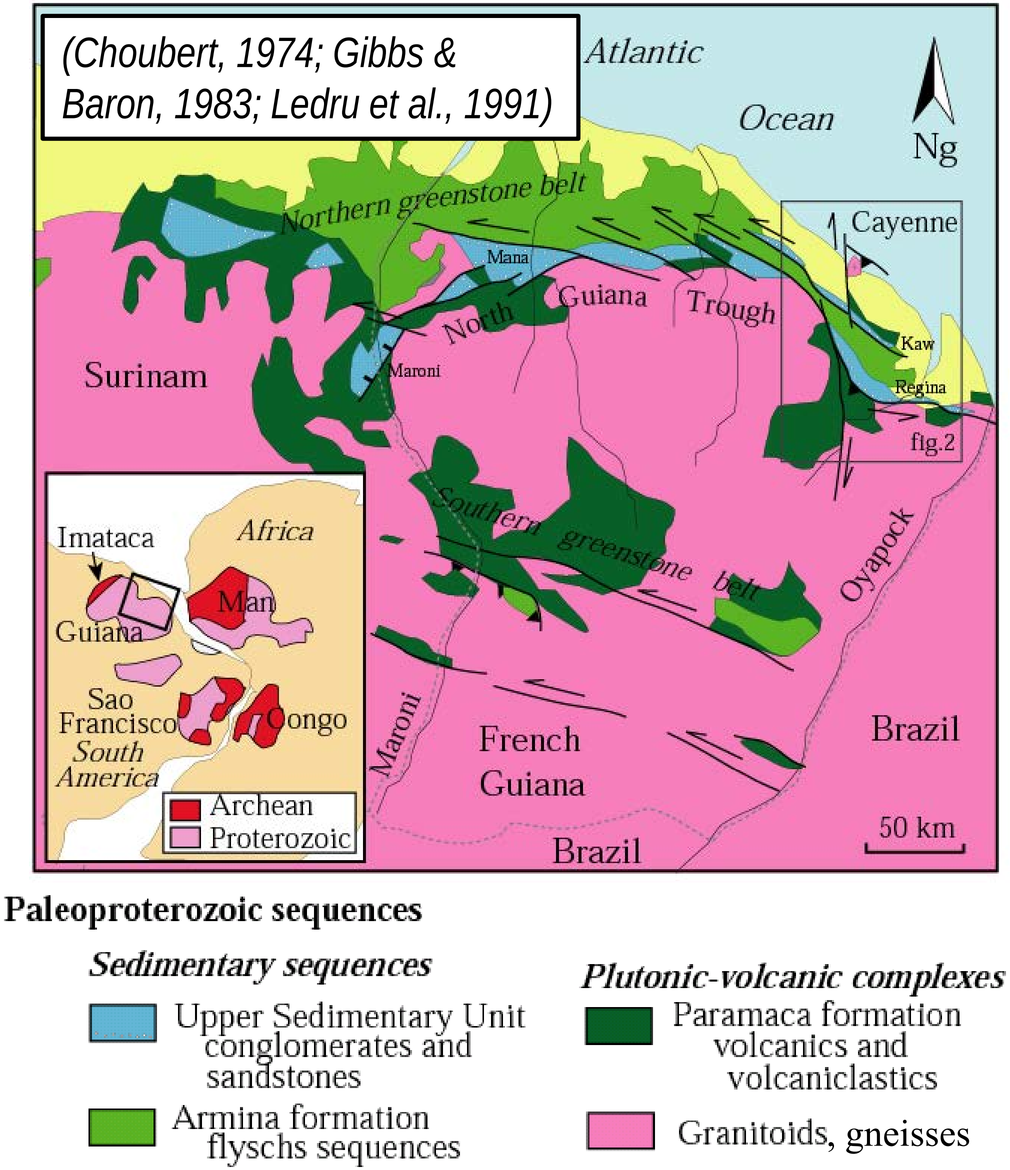


*(Goldfarb and Groves, 2015)*

# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral system*

Vanderhaeghe O.
Ledru P.

## Geological setting



*(Choubert, 1974; Gibbs & Baron, 1983; Ledru et al., 1991)*

## Strategy

Source of magmatic rocks?

- Mantle (depleted or enriched)
- Crust (mafics, felsic, sediments, …)

Context of melting?

- Plume (plateau)
- Subduction
- Orogenic belt

Significance of deformation?

- Plate kinematics
- Pluton emplacement
- Gravity-driven flow

Significance of metamorphism?

- Burial, exhumation
- Contact metamorphism

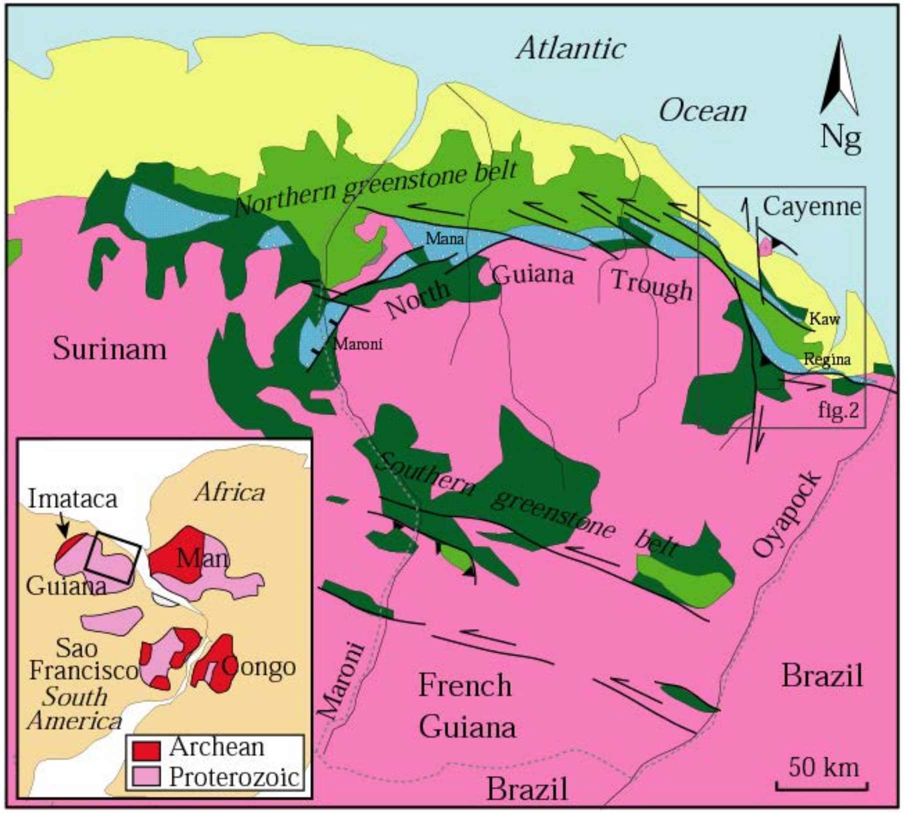
Sedimentation/erosion?

# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral system*

Vanderhaeghe O.
Ledru P.

## Geological setting

- Domes, plutons, belts, shear zones
- Gold mineralizations



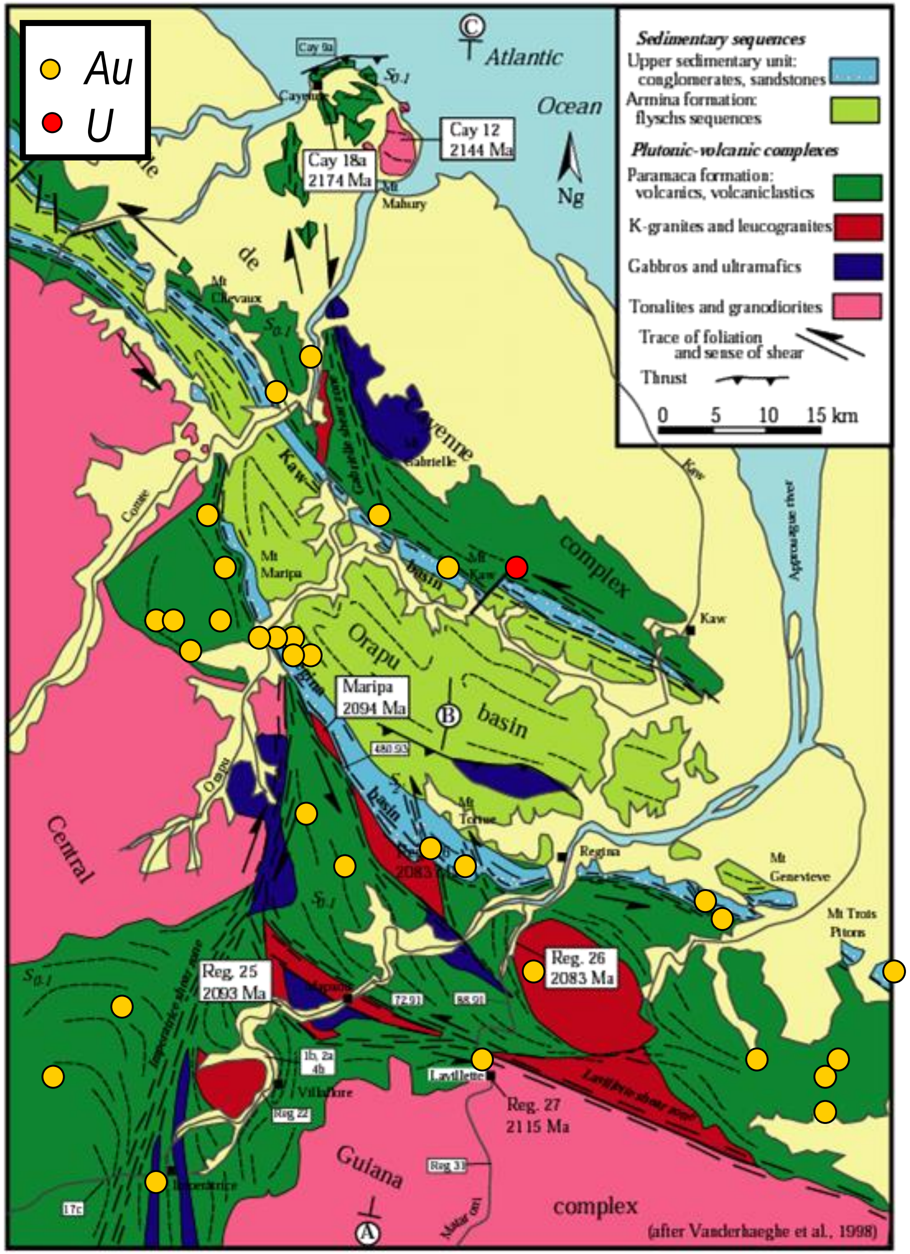
Neoproterozoic juvenile contribution

*(Gruau et al., 1985)*

$\varepsilon_{Nd}$ : +2.1±1.8

Sm–Nd isochron 2.11±0.09 Ga

*(Vanderhaeghe et al., 1998)*



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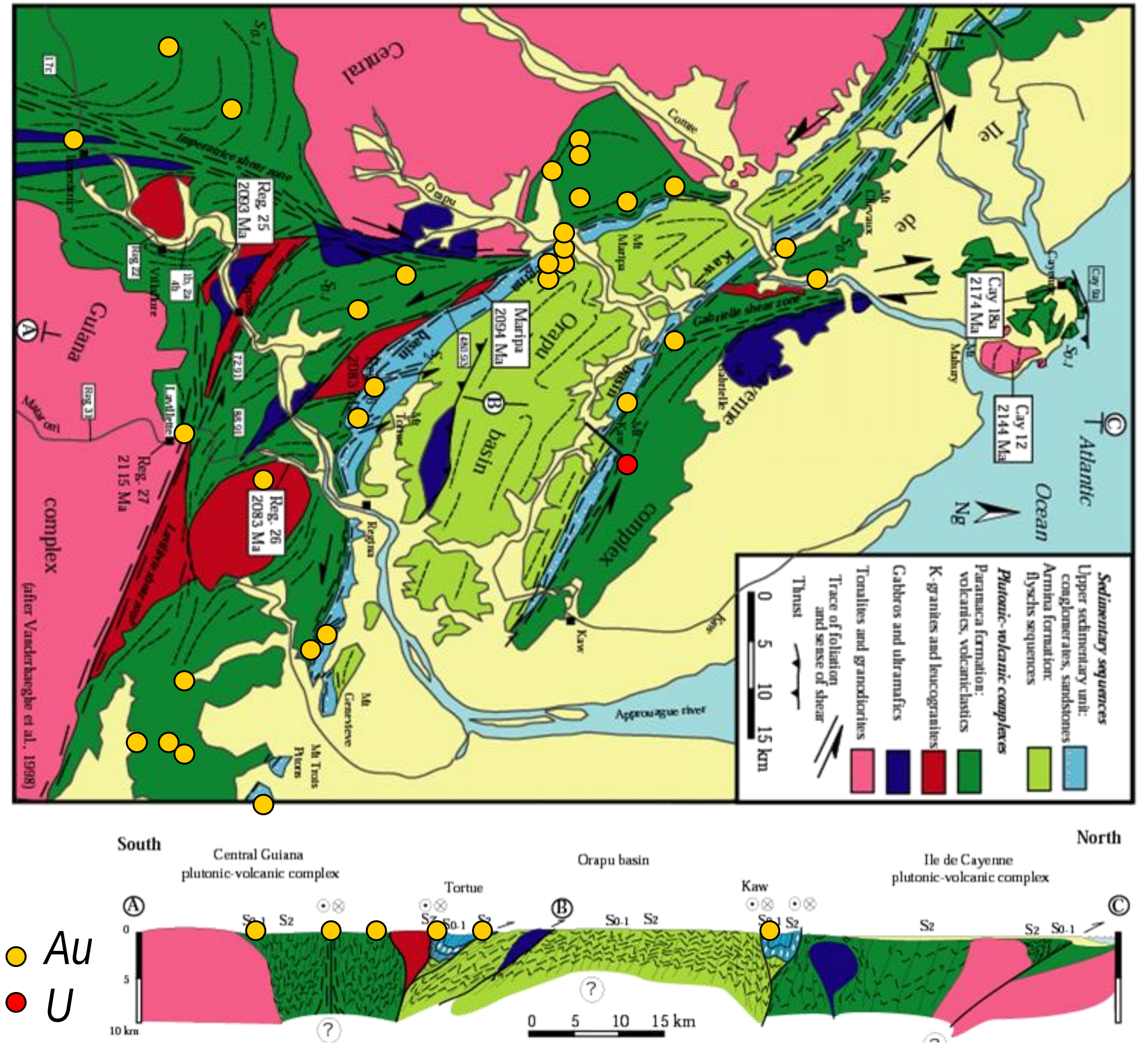
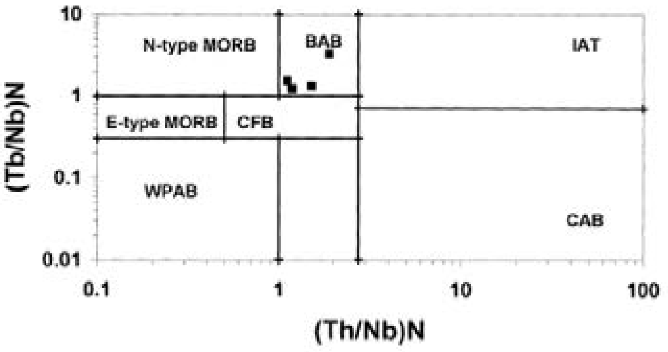
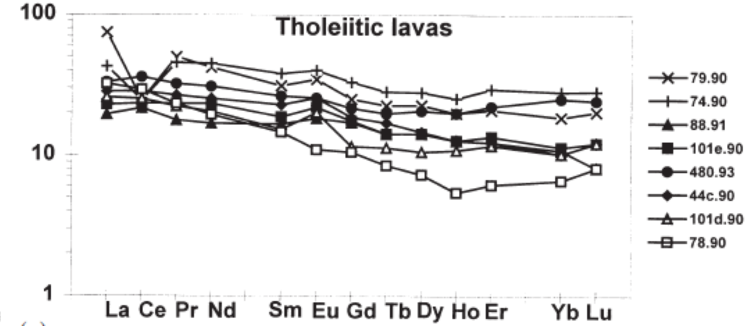
## Geological setting

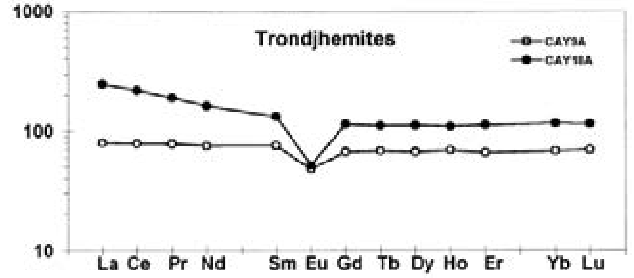


(Vanderhaeghe et al., 1998; Milési et al., 2003)

Metavolcanics (Paramaca)







- Tholeitic magmatism

# Paleoproterozoic crustal growth and differentiation :
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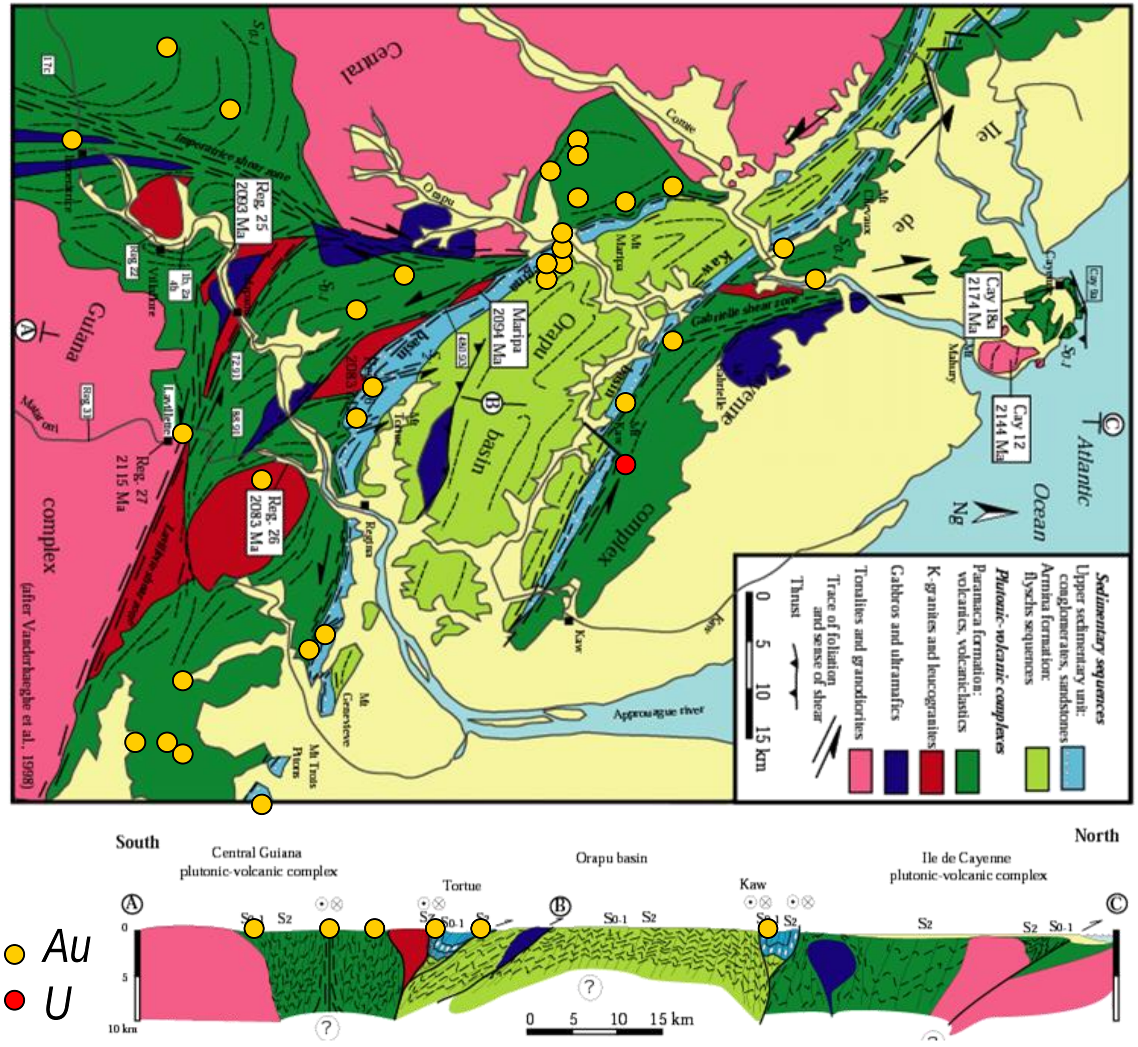
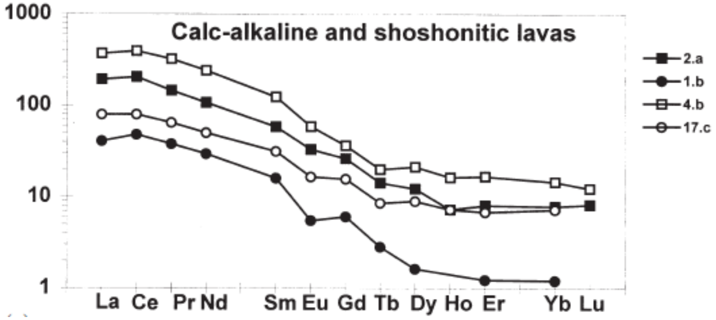
Ledru P.

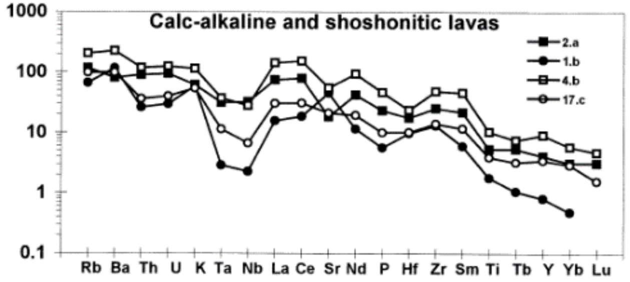
## Geological setting



*(Vanderhaeghe et al., 1998; Milési et al., 2003)*

Metavolcanics (Paramaca)





- Calc-alkaline magmatism

# Paleoproterozoic crustal growth and differentiation :
# *a guide for understanding Au mineral system*

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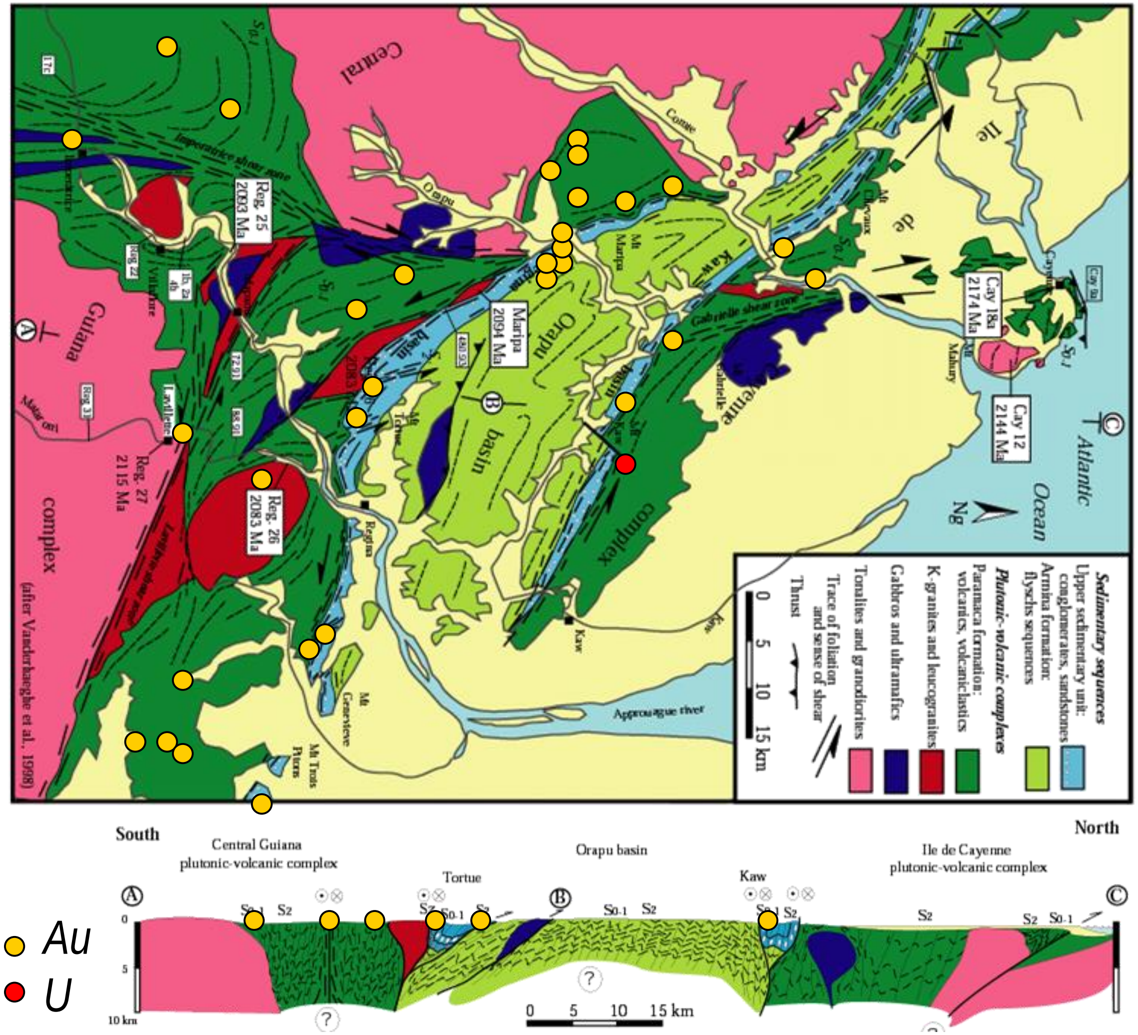
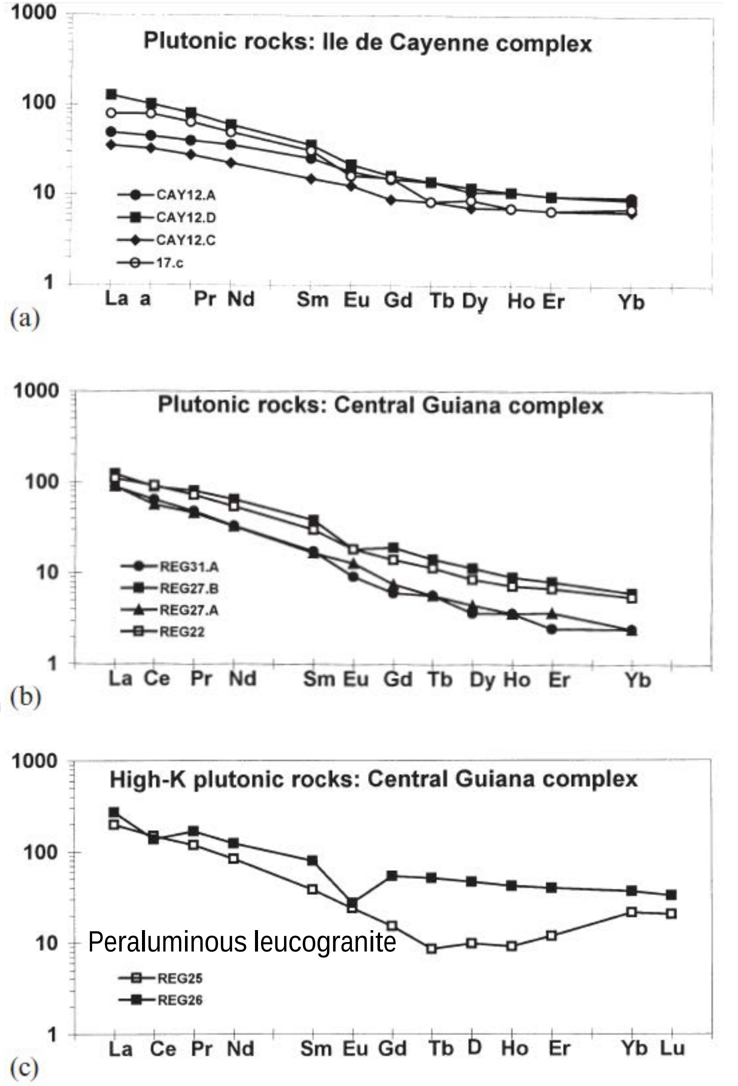
Ledru P.

## Geological setting



(Vanderhaeghe et al., 1998; Milési et al., 2003)

Plutonics (Ile de Cayenne, Central Guiana)

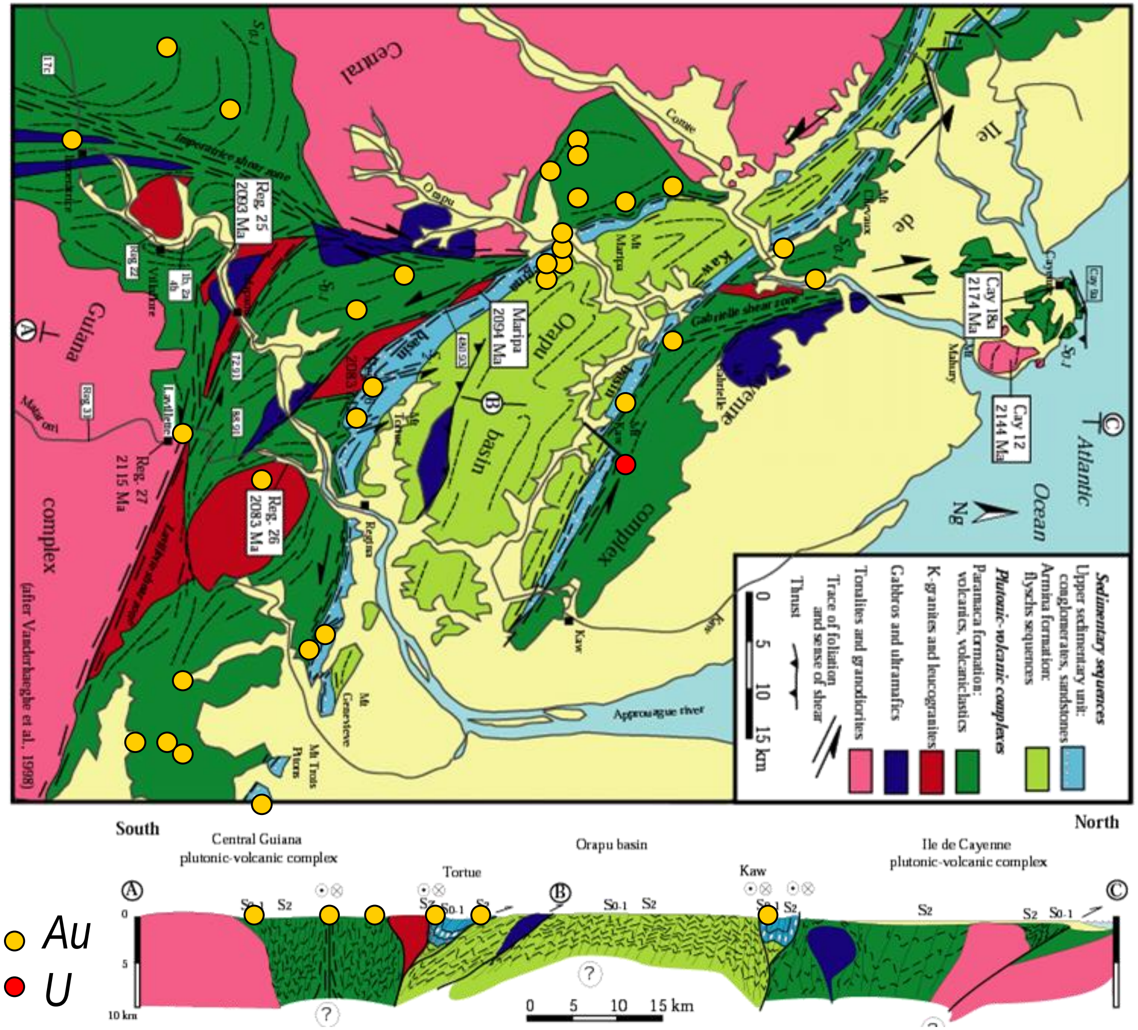


- Calc-alkaline, high-K and peraluminous magmatism

# Paleoproterozoic crustal growth and differentiation :
*a guide for understanding Au mineral system*

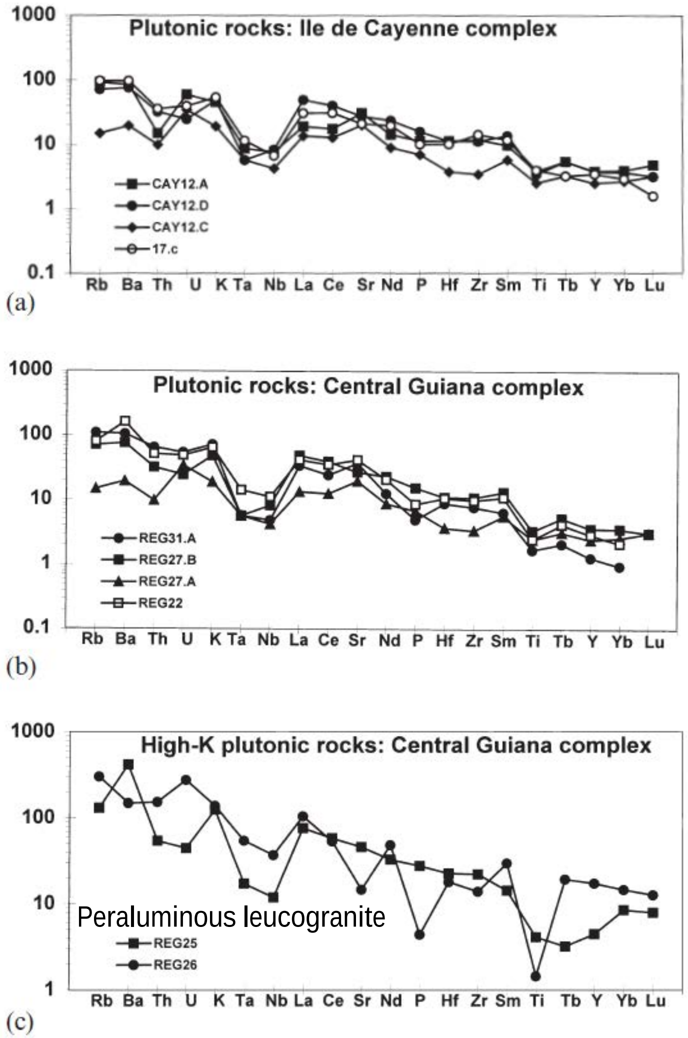
Vanderhaeghe O.
Ledru P.

## Geological setting



(Vanderhaeghe et al., 1998; Milési et al., 2003)

Plutonics (Ile de Cayenne, Central Guiana)



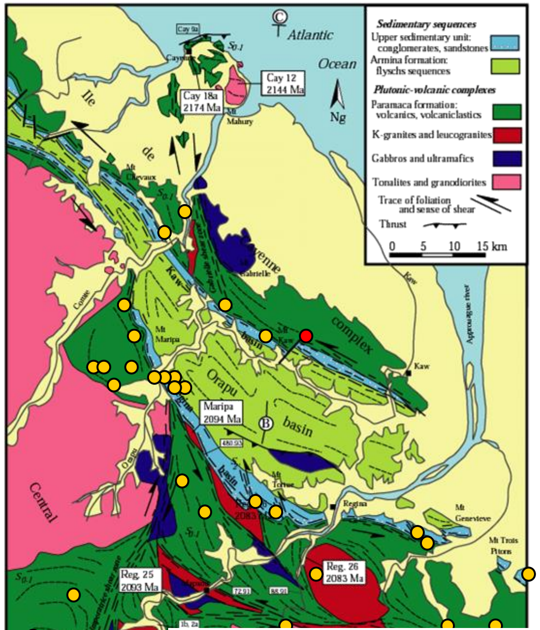
- Calc-alkaline, high-K and peraluminous magmatism

# Paleoproterozoic crustal growth and differentiation :
## *a guide for understanding Au mineral systems*

Vanderhaeghe O.
Ledru P.

*(Vanderhaeghe et al., 1998; Milési et al., 2003)*

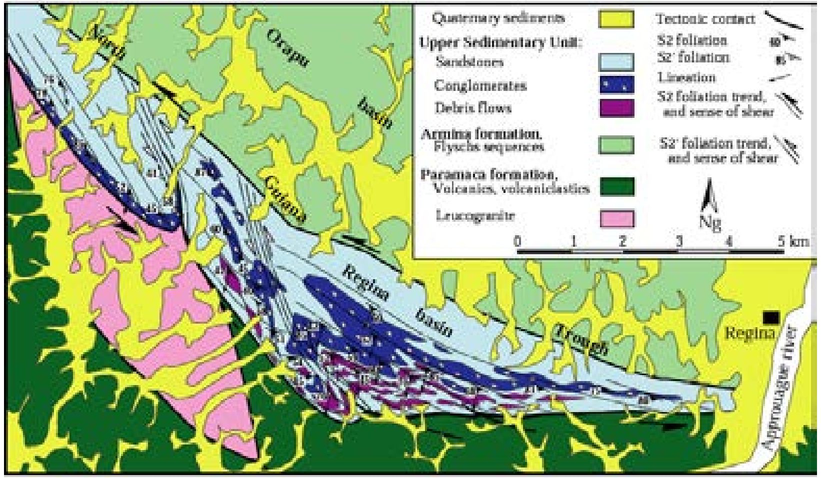
## Geological setting

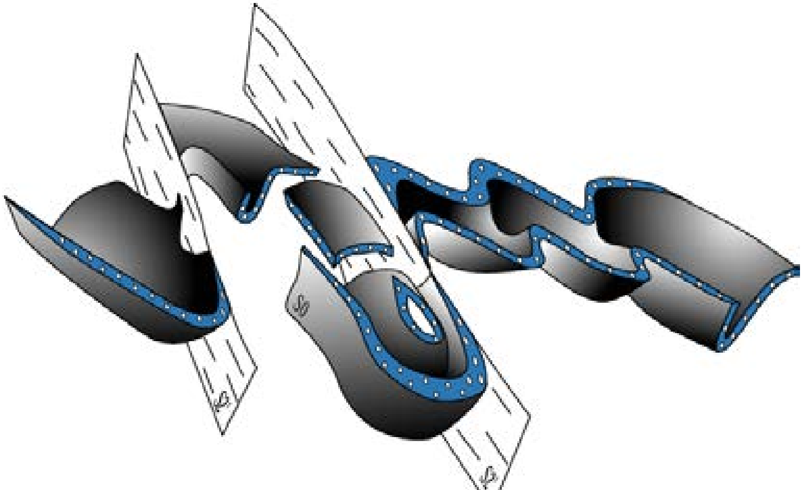


- Au
- U

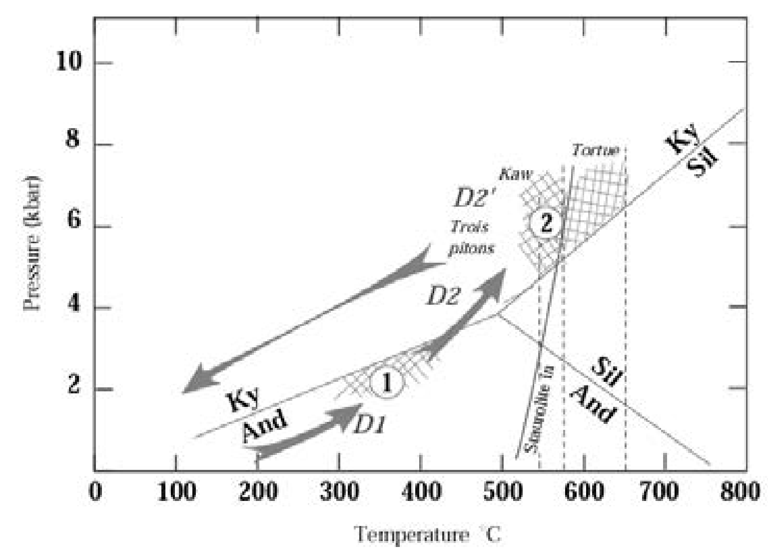
## D1:

- Domes cored by plutonic rocks
- Pervasive deformation of the greenstone belts
- HT/LP metamorphism





Style of folding of the bedding plane in the Tortue area.



## D2:

- Localized transcurrent deformation
- Pull-apart basins
- HT metamorphism

# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral systems*

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Ledru P.

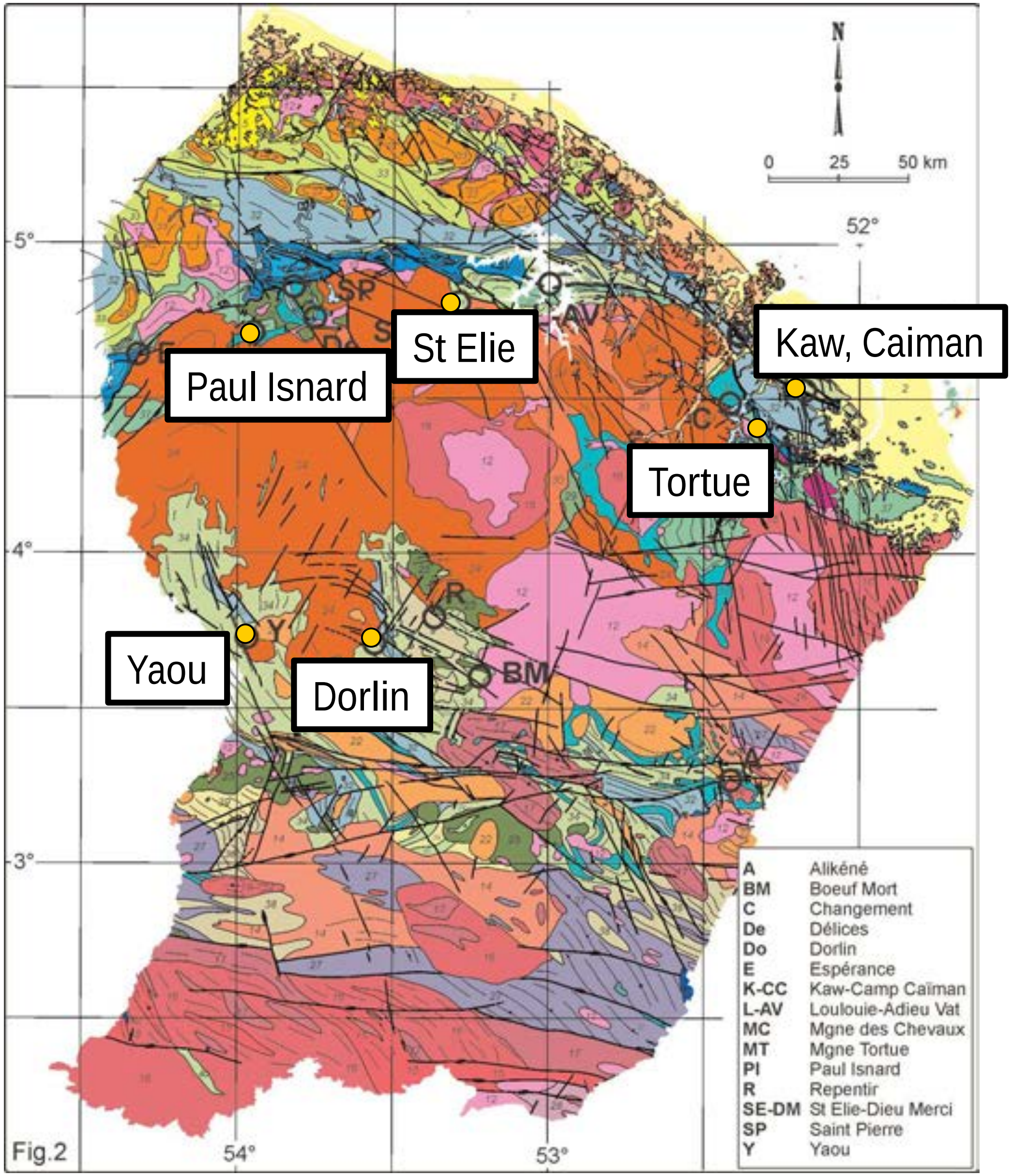


Fig.2

## Gold mineralizations

### Reworked paleoplacers

Montagne Tortue:
Paleoplacers, monogenic-polygenic conglomerates
Au mesothermal veins
Montagne de Kaw:
Syn-D2 mesothermal veins

### Hydrothermal shear zones

Saint Elie :
Au mesothermal veins
6t @ 4.2 g/t
Paul Isnard :
Au mesothermal veins
46t @ 2.5 g/t

### Reworked volcanic-hydrothermal Au

Dorlin :
Au stratiform, mesothermal veins
11t @ 1.3 g/t
Yaou :
Au stratabound, mesothermal veins, syn-$D_2$ $\gamma$
24t @ 2.2 g/t

# Paleoproterozoic crustal growth and differentiation :
*a guide for understanding Au mineral systems*

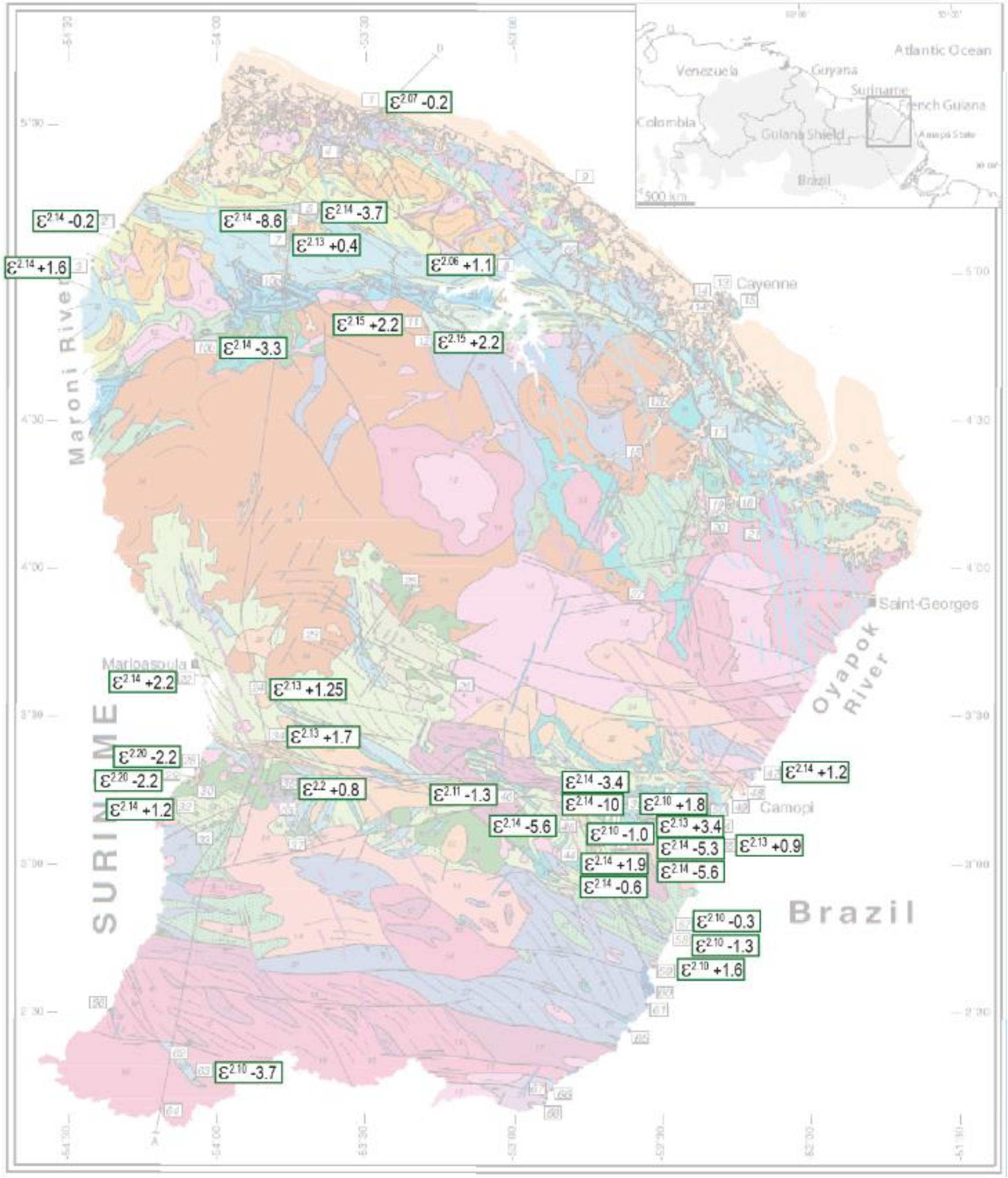
Vanderhaeghe O.
Ledru P.

## Geochronological data

$\varepsilon_{Nd}$:
- + for most rocks
- - for few detrital & inherited cores

⇨ Dominant input of juvenile rocks

Needs Lu-Hf datas on zircon!



# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral systems*

Vanderhaeghe O.
Ledru P.

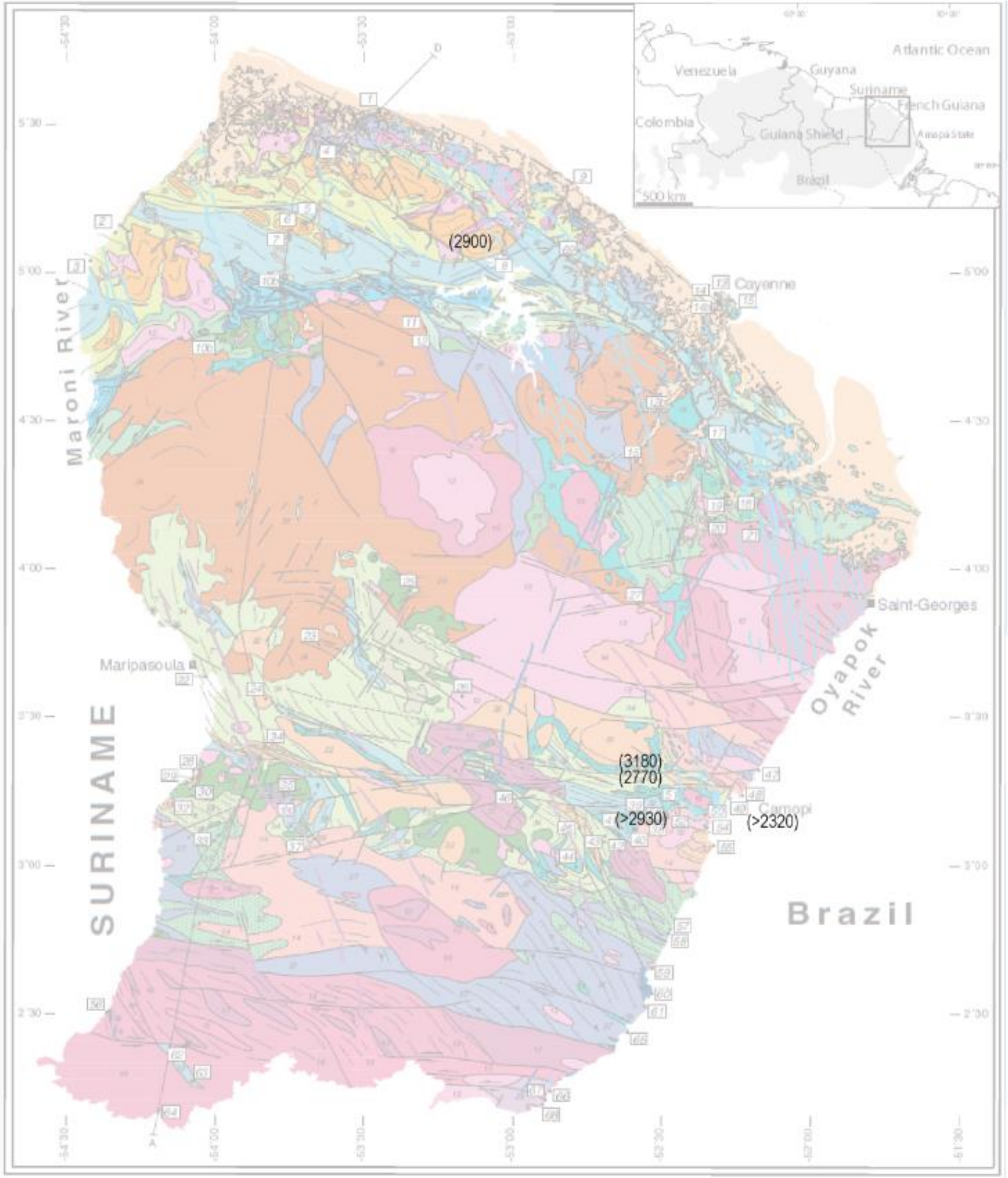
## Geochronological data

U-Pb > 2.6 Ga

- Inherited cores

⇨Little input of Archean rocks

Needs careful in situ dating!



# Paleoproterozoic crustal growth and differentiation :
## *a guide for understanding Au mineral systems*

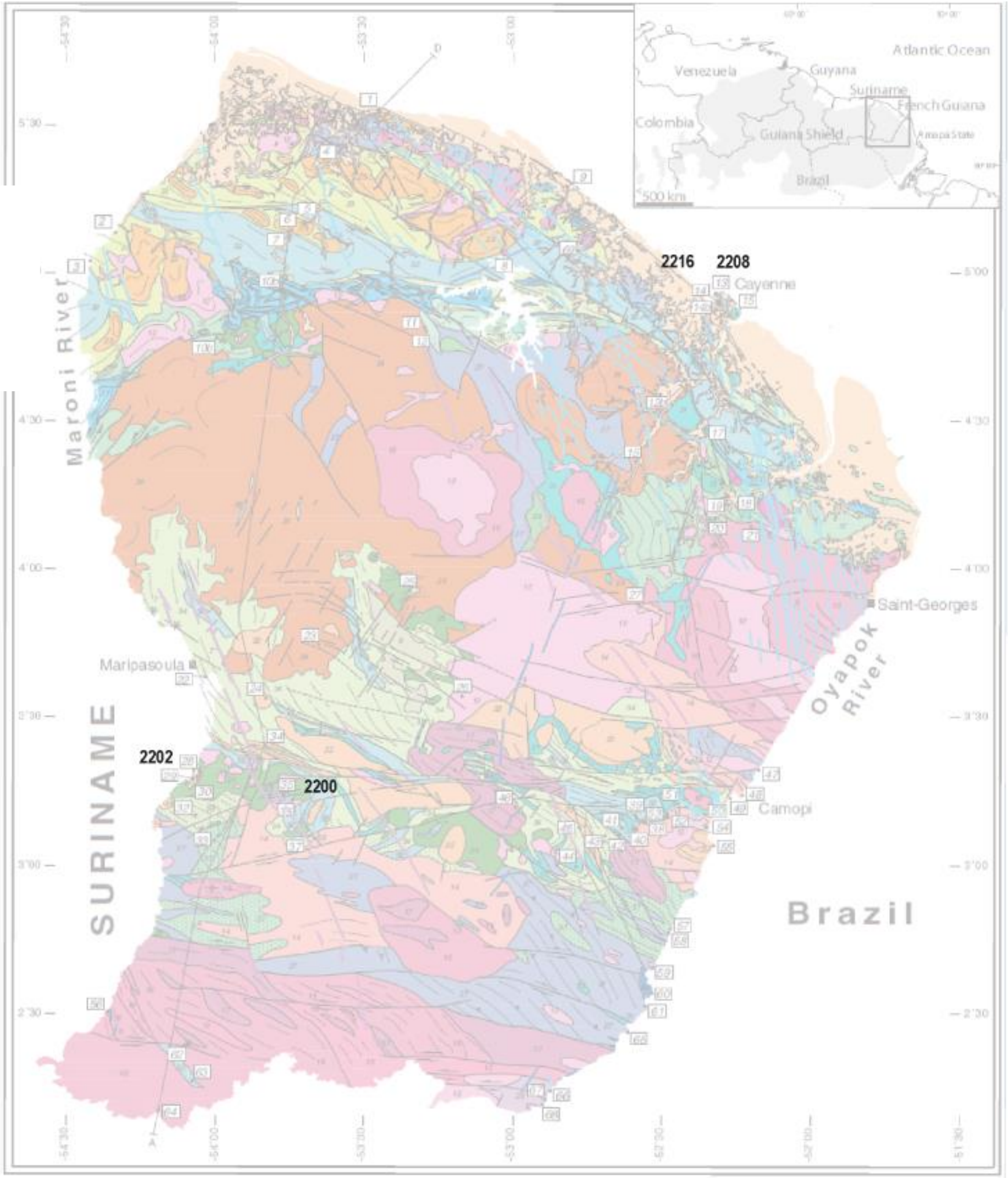
Vanderhaeghe O.
Ledru P.

Geochronological data

U-Pb 2.22-2.20 Ga
- Tholeitic trondjhemites

⇨ One or several oceans?

Needs more data!



# Paleoproterozoic crustal growth and differentiation :
## *a guide for understanding Au mineral systems*

Vanderhaeghe O.
Ledru P.

## Geochronological data

U-Pb 2.18-2.12 Ga

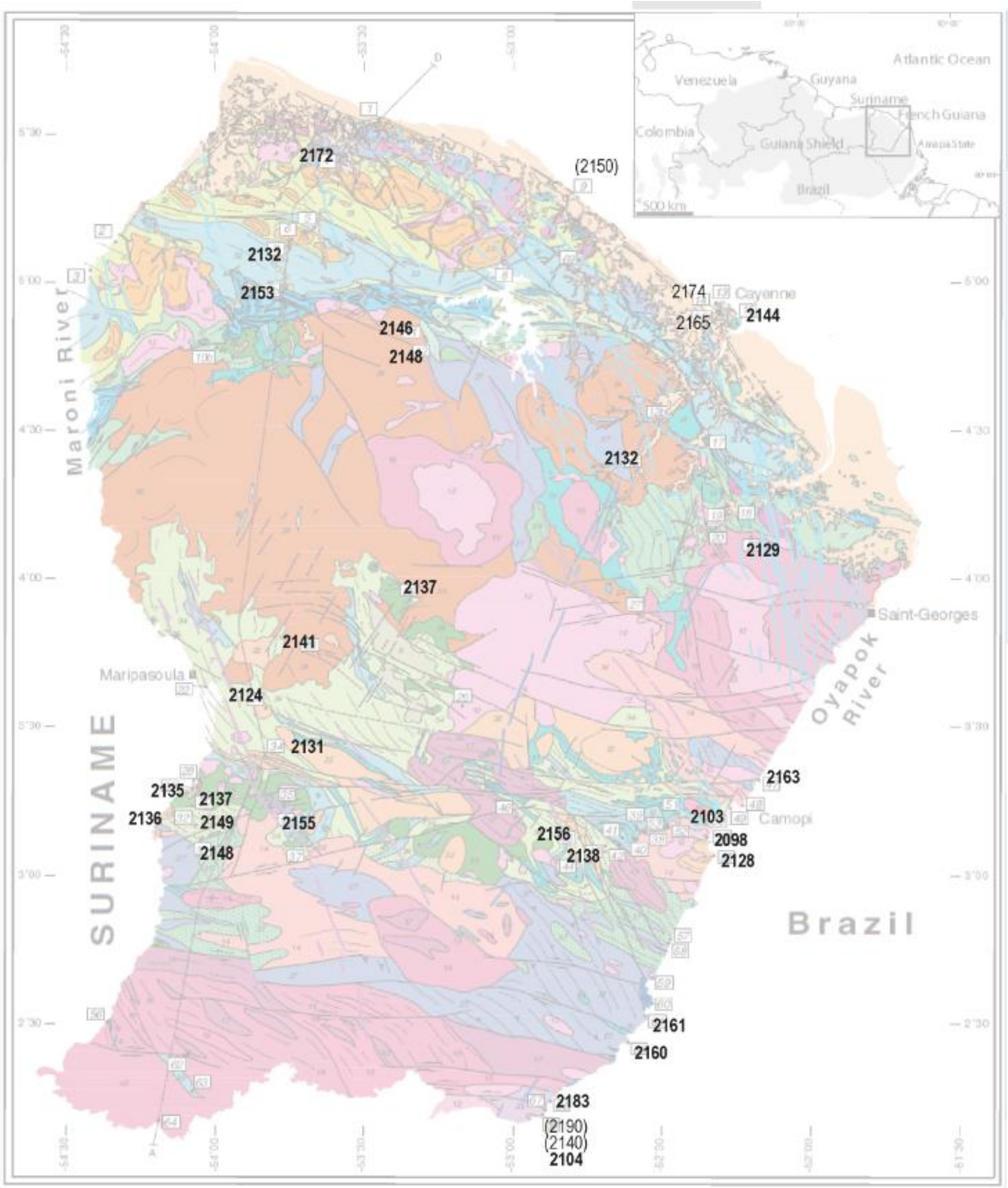
- Calc-alkaline plutonics-metavolc.

⇨ Widespread magmatism?

⇨ Partial melting of mafics?

⇨ Partial melting of enriched mantle?

Needs combined isotopic tracing and in situ geochronological dating!



# Paleoproterozoic crustal growth and differentiation :
## *a guide for understanding Au mineral systems*

Vanderhaeghe O.
Ledru P.

Geochronological data

U-Pb 2.11-2.08 Ga

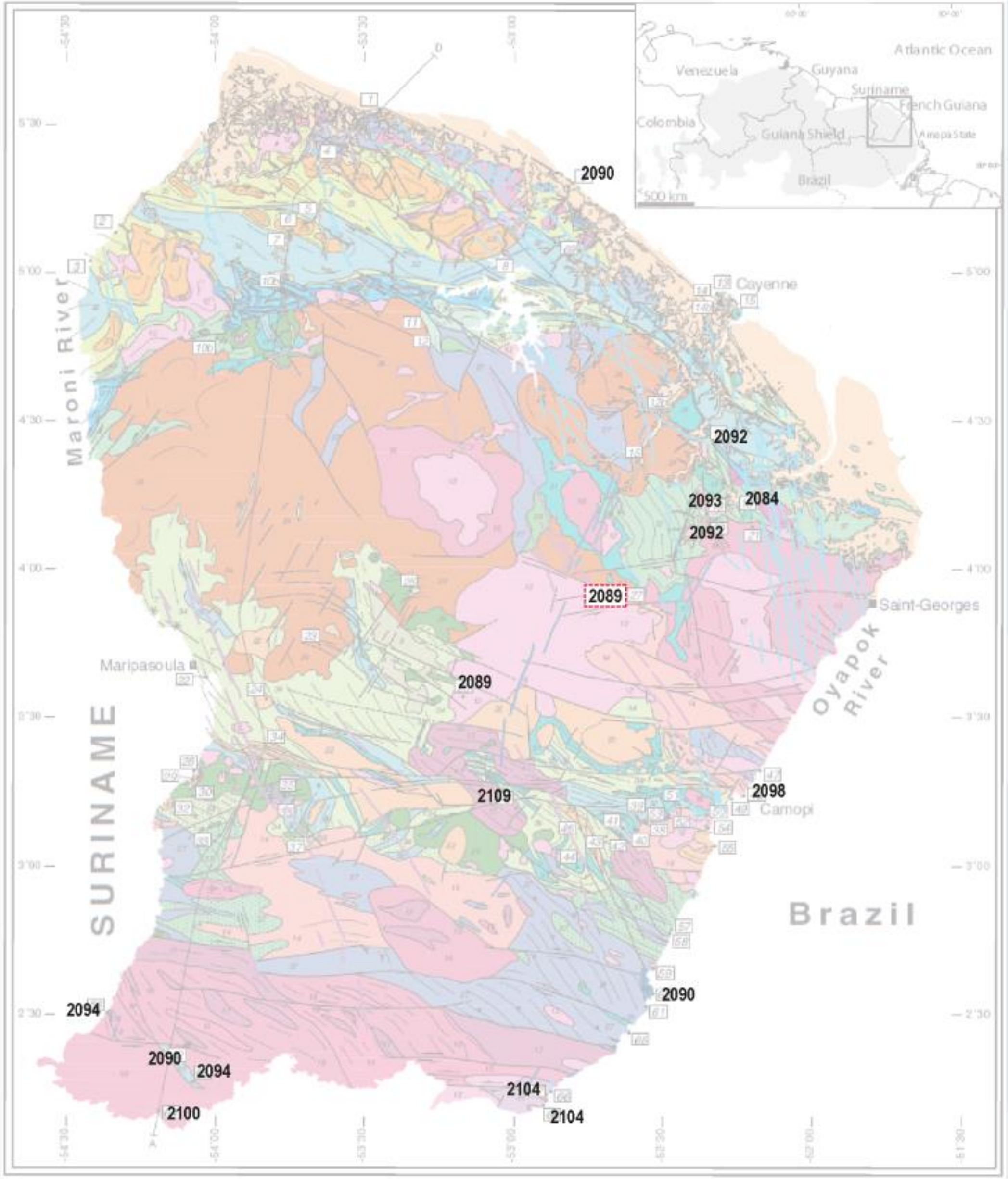
- High-K granites

⇨ Widespread magmatism

⇨ Partial melting of mafics?

⇨ Partial melting of enriched mantle?

Needs combined isotopic tracing and in situ geochronological dating!



# Paleoproterozoic crustal growth and differentiation :
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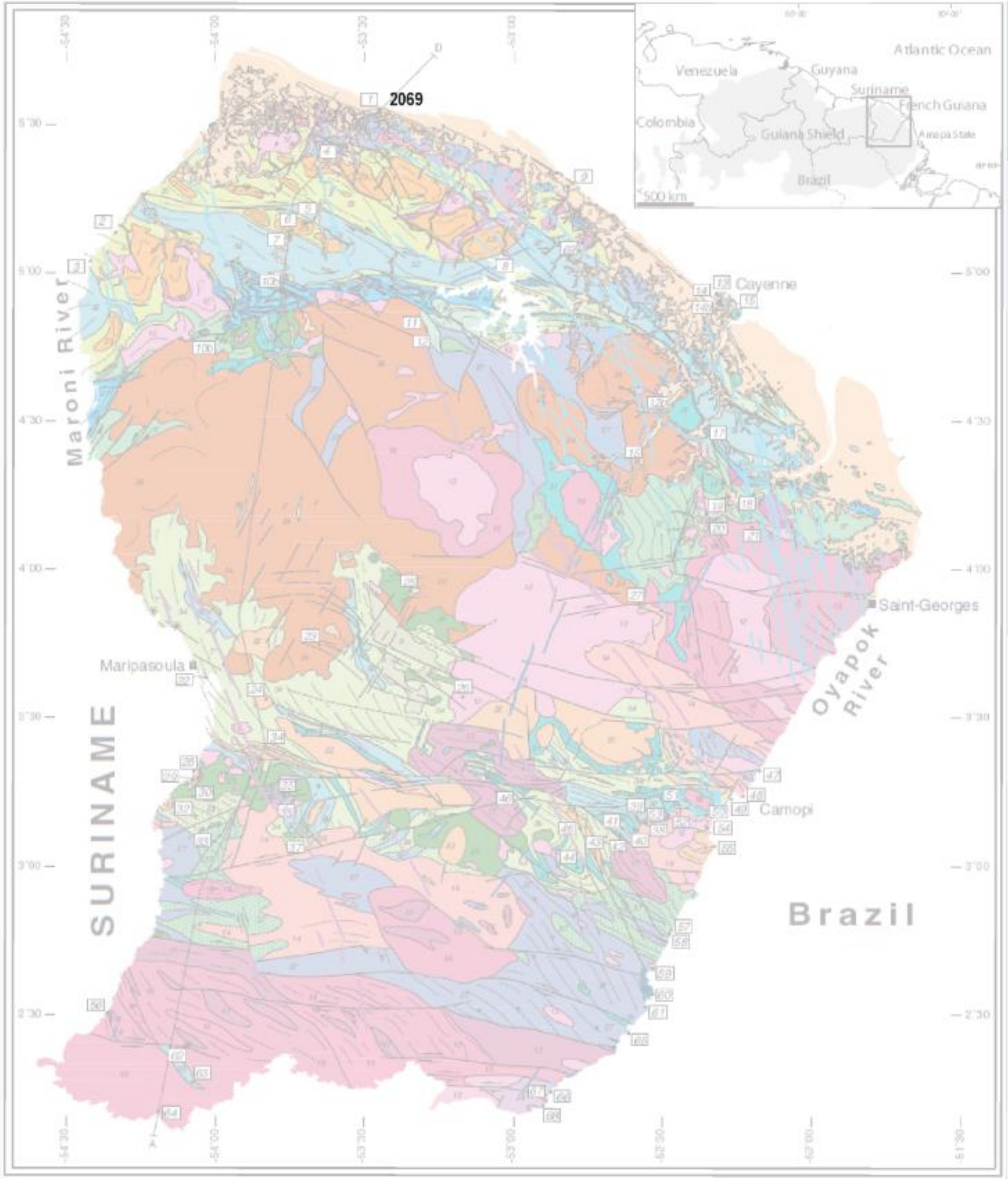
Ledru P.

## Geochronological data



U-Pb ~2.07 Ga

- Peraluminous granites

⇨ Partial melting of metasediments?

Needs more data!

# Paleoproterozoic crustal growth and differentiation :
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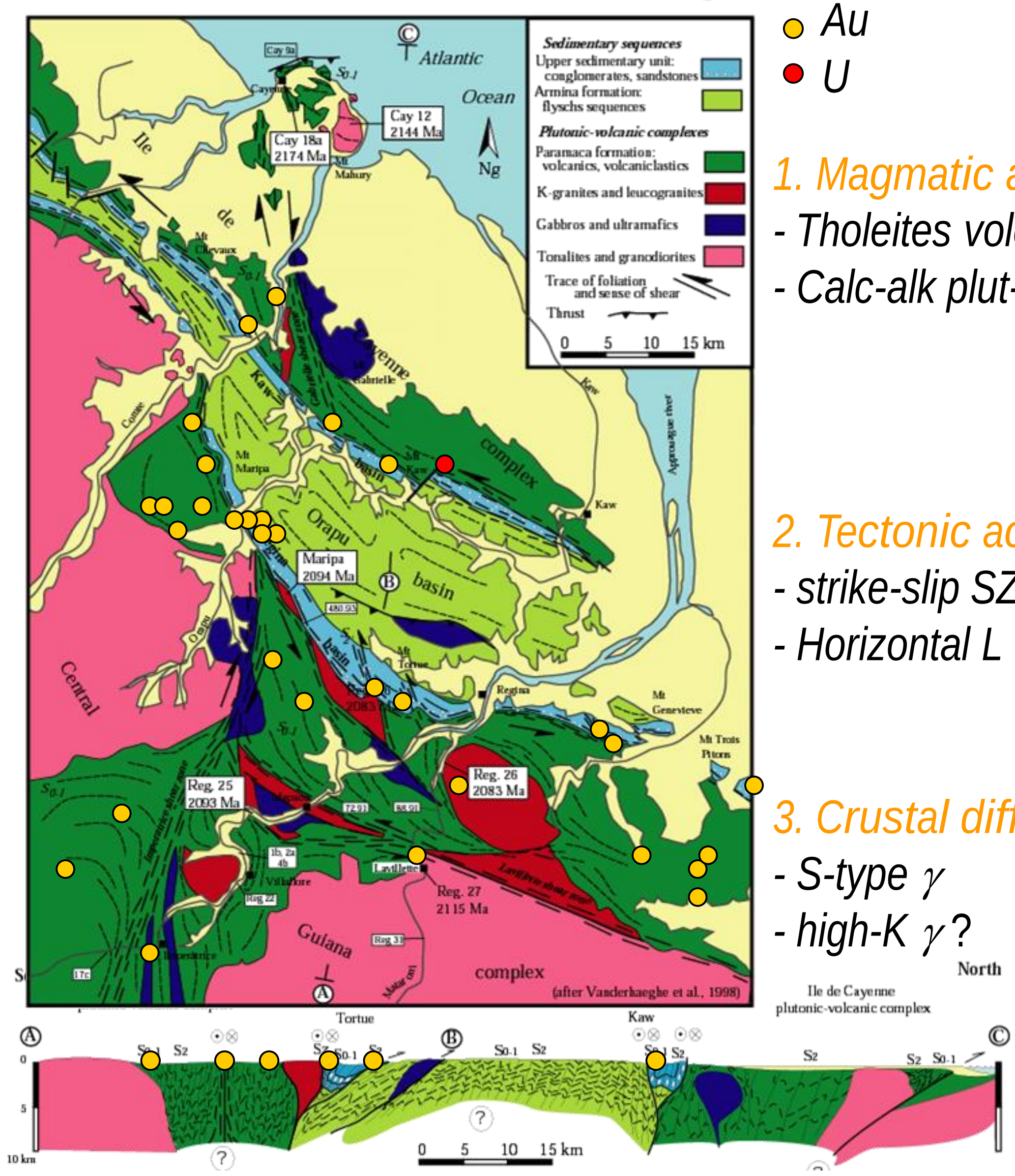
Ledru P.

**Tectonics-geodynamics**

*(Vanderhaeghe et al., 1998; Milési et al., 2003)*



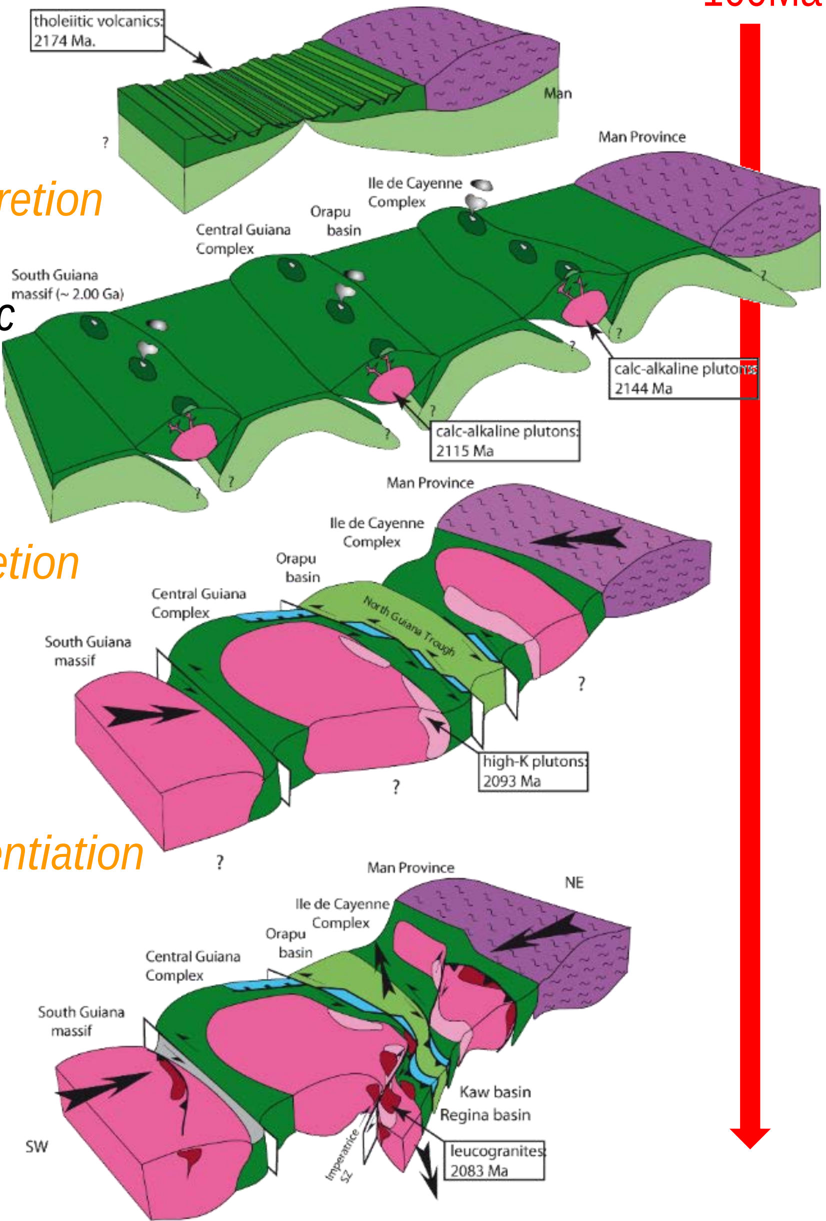
● *Au*
● *U*

*1. Magmatic accretion*
- *Tholeites volc.*
- *Calc-alk plut-volc*

*2. Tectonic accretion*
- *strike-slip SZ*
- *Horizontal L*

*3. Crustal differentiation*
- *S-type $\gamma$*
- *high-K $\gamma$ ?*

150km
~100Ma

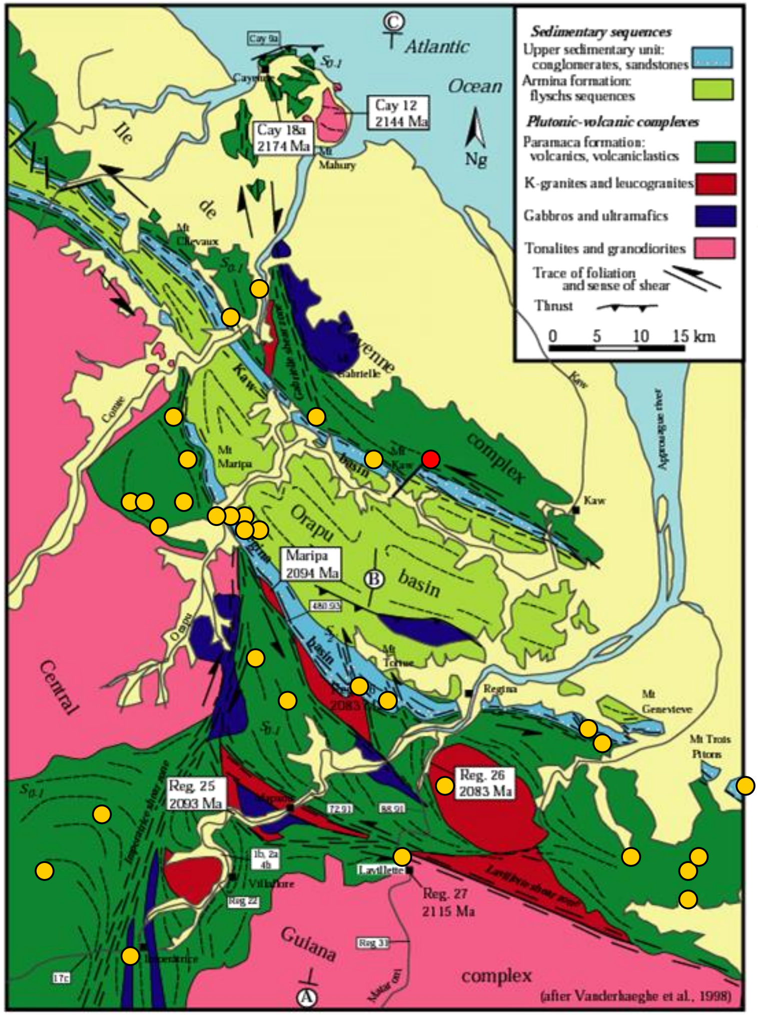


# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral systems*

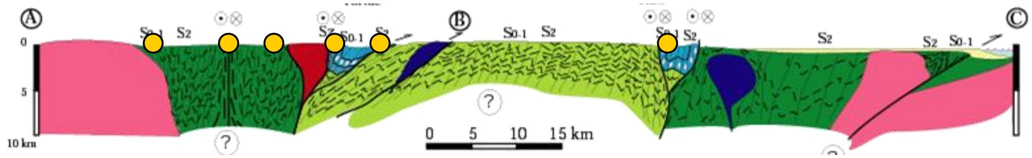
Vanderhaeghe O.
Ledru P.

## Tectonics-geodynamics

*(Vanderhaeghe et al., 1998; Milési et al., 2003)*



(after Vanderhaeghe et al., 1998)



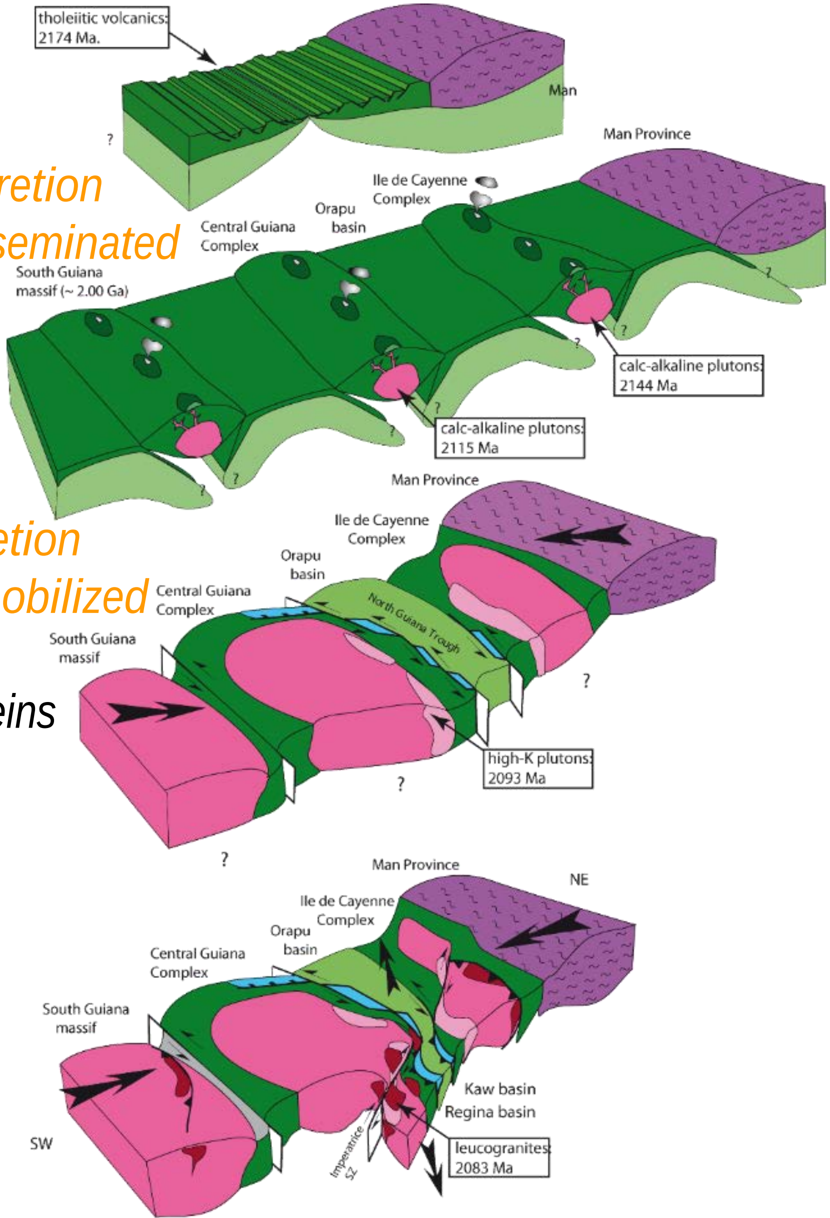
- ● Au
- ● U

### 1. Magmatic accretion
### Au deposits disseminated

- *Hydrothermal*

### 2. Tectonic accretion
### Au deposits remobilized

- *Paleoplacers*
- *Hydrothermal veins*
- *Shear zones*



# Paleoproterozoic crustal growth and differentiation :
# *a guide for understanding Au mineral system*

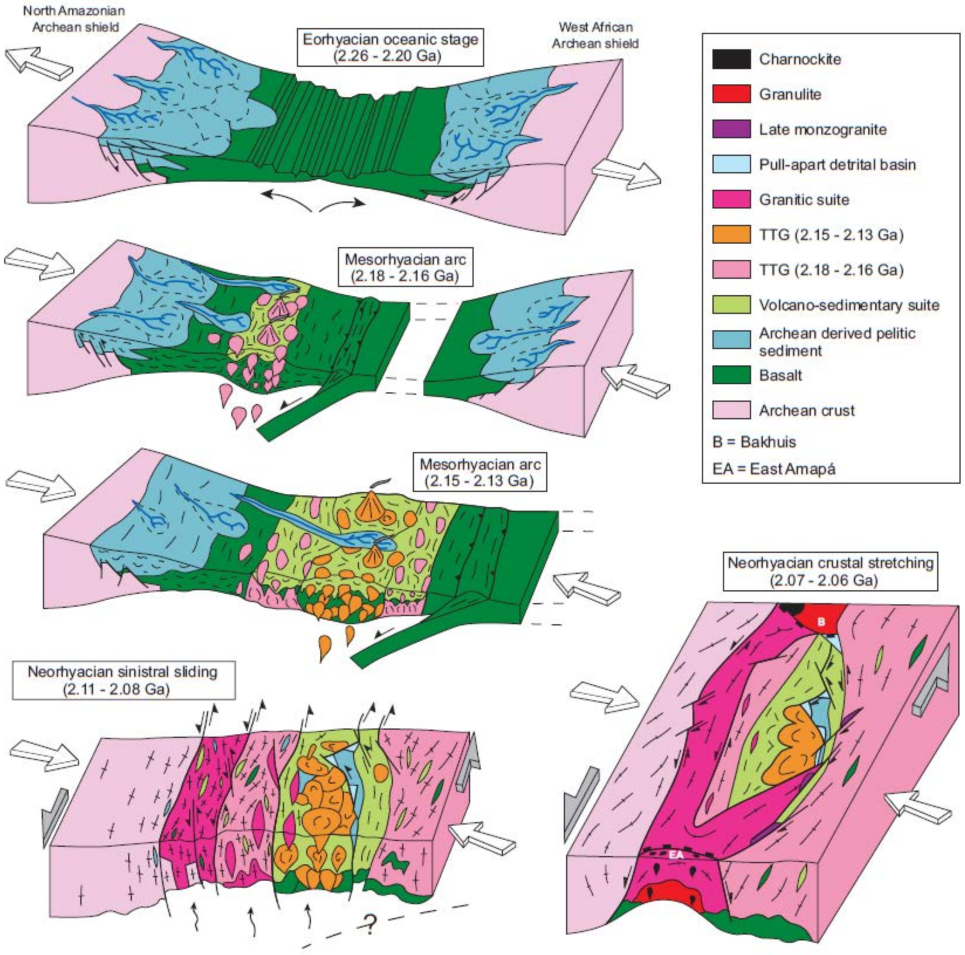
Vanderhaeghe O.
Ledru P.

## Tectonics-geodynamics

Generalization of the model to French Guiana

*(Delor et al., 2003)*

300km
~120Ma



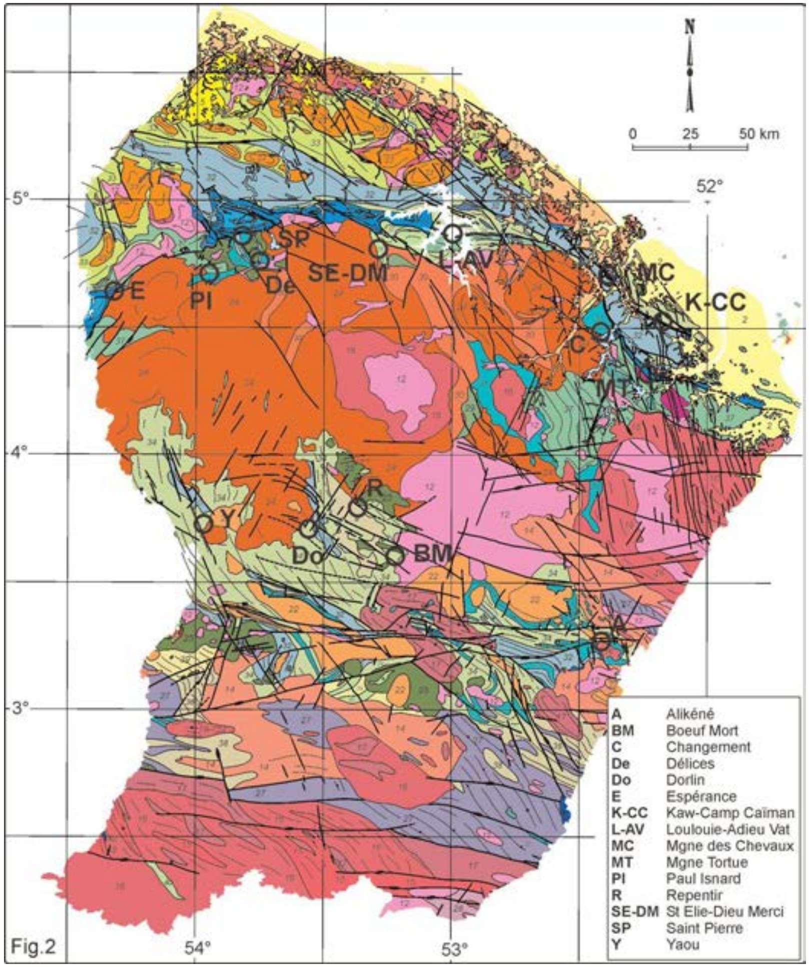
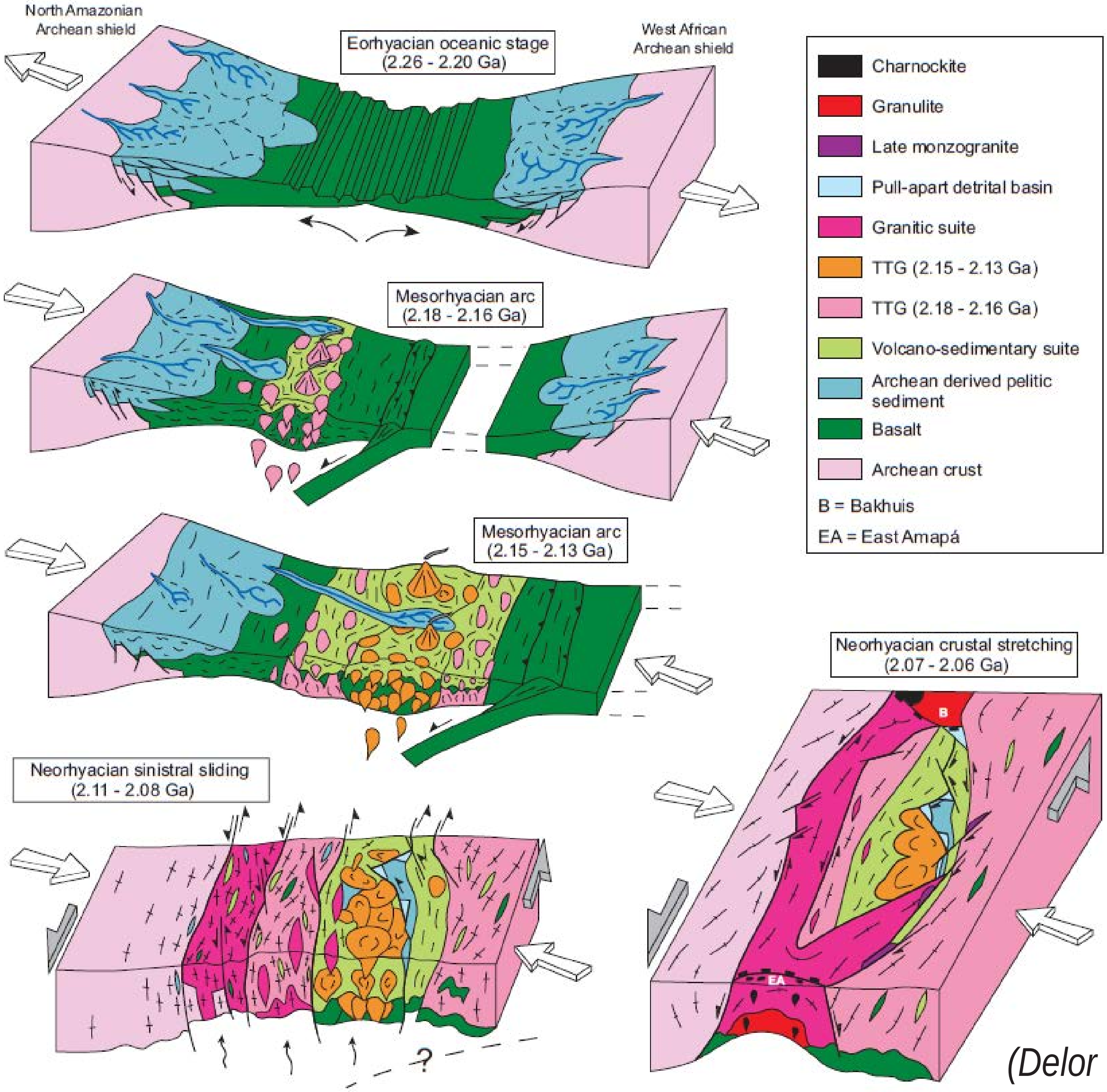


Fig.2

# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral systems*

Vanderhaeghe O.
Ledru P.

## Tectonics-geodynamics



*(Delor et al., 2003)*

~300km
~120 Ma

1. Tholeites : depleted mantle
2. Calc-alc: amphibolites pm
3. High-K : enriched mantle and/or mafic crust
4. Peraluminous: metasediments

► A single differentation trend!

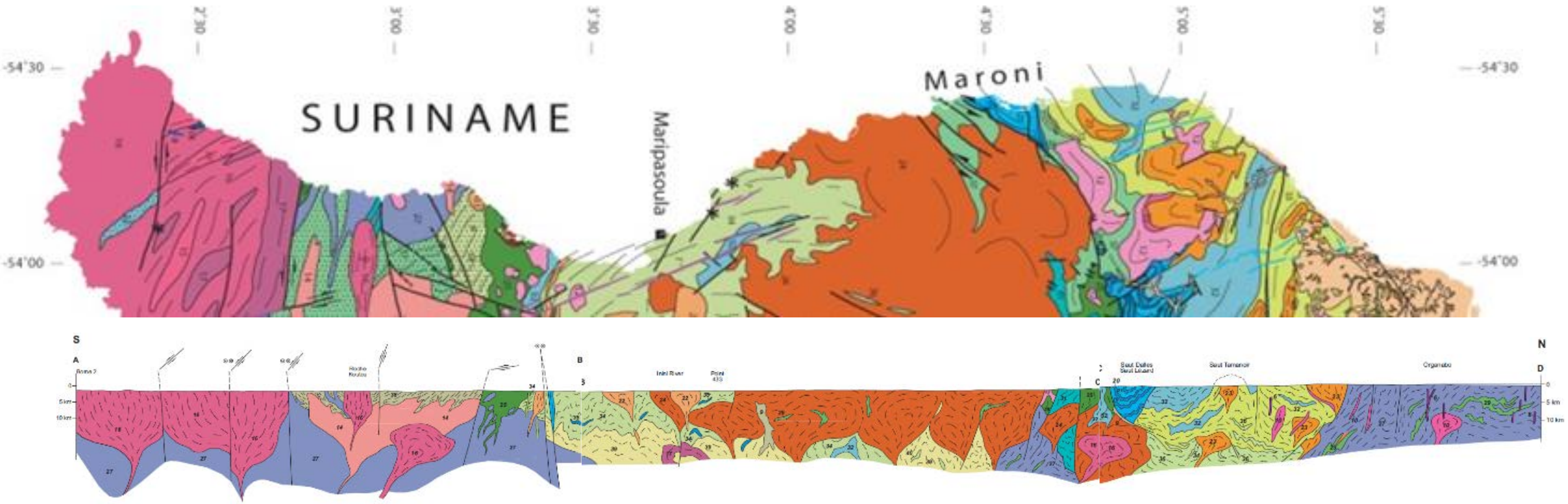
# Paleoproterozoic crustal growth and differentiation :
## *a guide for understanding Au mineral systems*

Vanderhaeghe O.
Ledru P.

Debated issues

- Greenstone belts : single ocean or mutiple sutures-arcs?
- Calc-alkaline, high-K, peraluminous magmatic complexes?
- HT/LP metamorphism (no HP/LT?): tectonic-thermal context?
- Relationships between greenstones, plutonics and migmatitic gneisses?
- Nature of the lower crust and of the subcontinental lithosphere?
- Mineral systems, source of metals and of mineralizing fluids?

*(Delor et al., 2003)*



# Paleoproterozoic crustal growth and differentiation : *a guide for understanding Au mineral systems*

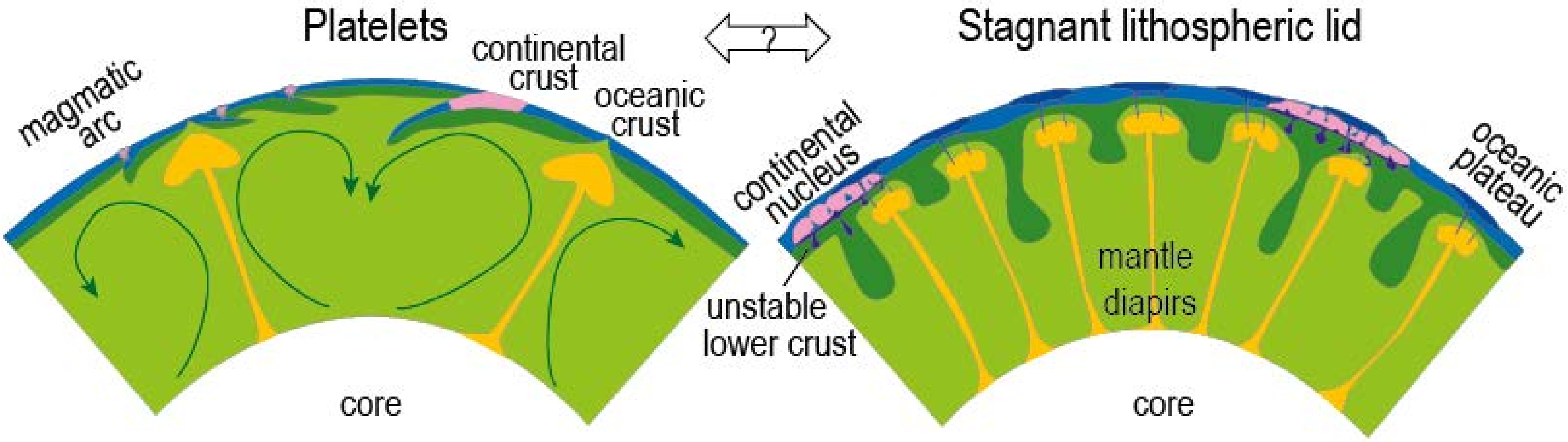
Vanderhaeghe O.
Ledru P.

## Conclusion

Major gold extraction associated with Paleoproterozoic crustal growth and reworking

“Gold was added to the continental crust during a giant Mesoarchaean gold event at 3 Ga”
*(Frimmel 2008)*

⇨ Inefficient Archean gold extraction or subsequent recycling of crust (and gold) into the mantle?
⇨ Geodynamic context of Paleoproterozoic crustal growth and reworking?



# Paleoproterozoic crustal growth and differentiation :
*a guide for understanding Au mineral systems*

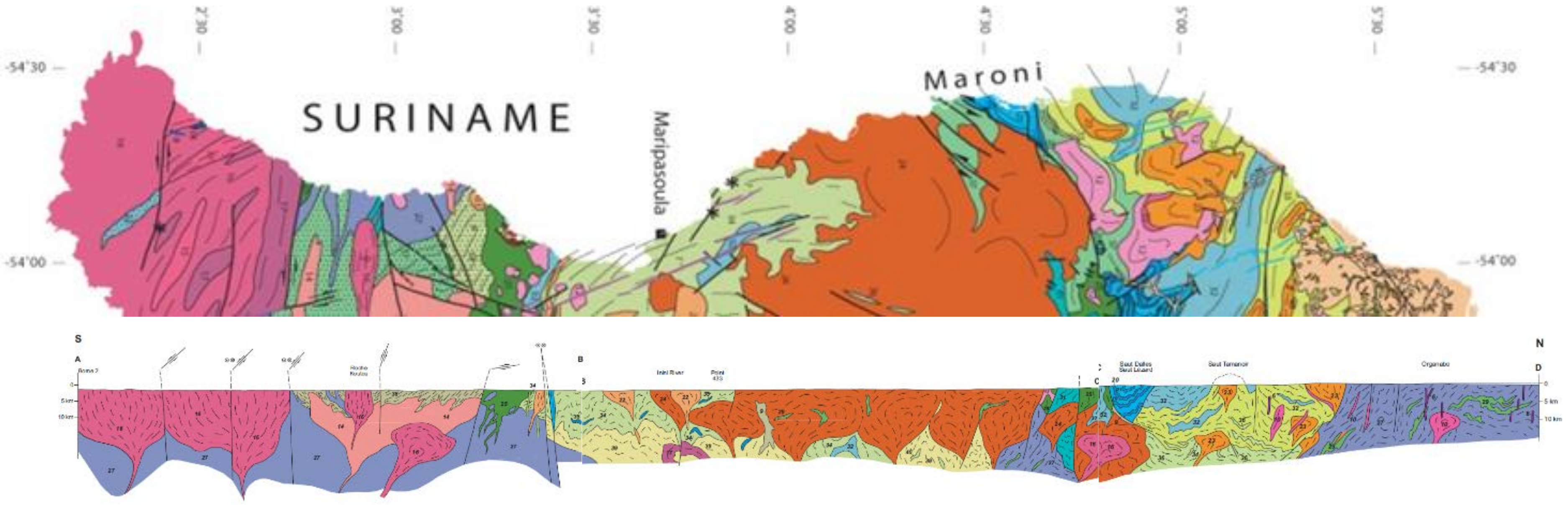
Vanderhaeghe O.
Ledru P.

## Perspectives

Linking crustal growth-differentiation and mineral systems:

- Lithostratigraphy of volcanic-sedimentary sequences
- Metamorphic-structural record
- Petrology-geochemistry-geochronology of magmatic complexes
- Petrology-geochemistry-geochronology of mineralizations and their host rocks

*(Delor et al., 2003)*



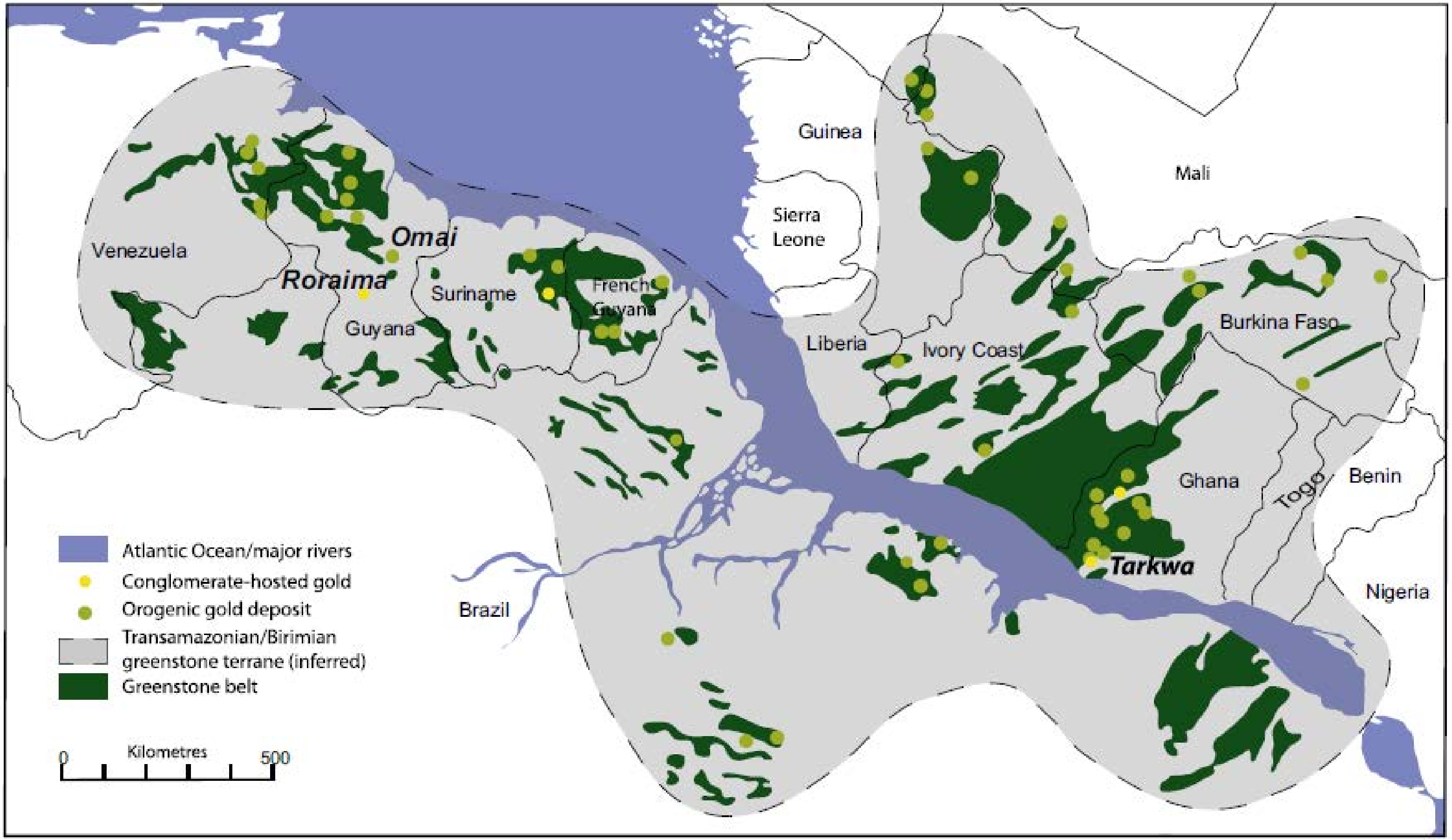
# Paleoproterozoic crustal growth and differentiation :
# *a guide for understanding mineral systems*

Vanderhaeghe O.
Ledru P.

## Perspectives

WAC-Guiana shield correlation**…**

*(Frimmel et al., 2014)*

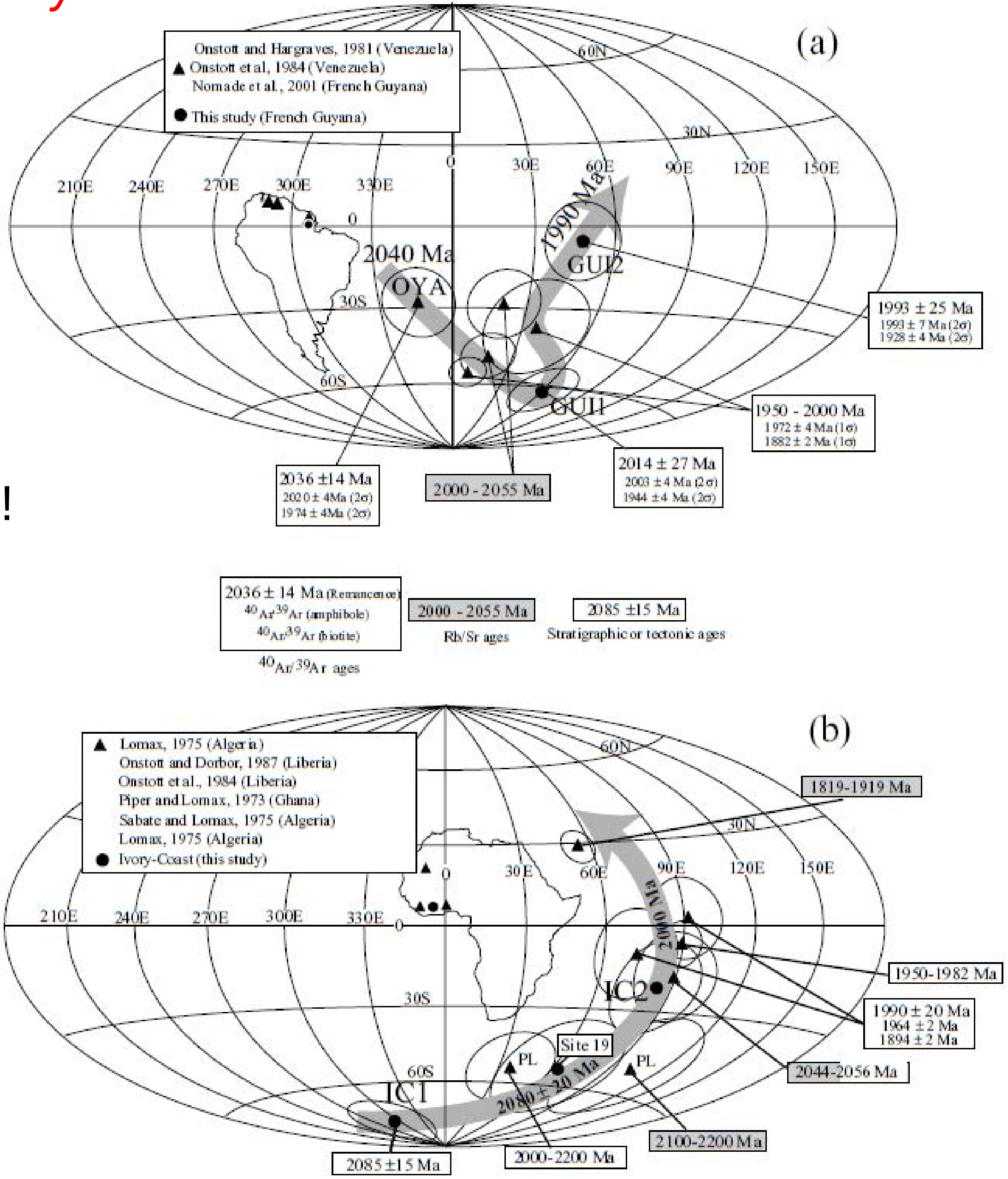


… **but not** with pre-Atlantic reconstruction!

# Paleoproterozoic crustal growth and differentiation :
*a guide for understanding mineral systems*

<u>Perspectives</u>

WAC-Guiana shield correlation



~2.1 Ga: 3000 km wide ocean between Guiana shield and the WAC!!

*(Nomade et al., 2003)*

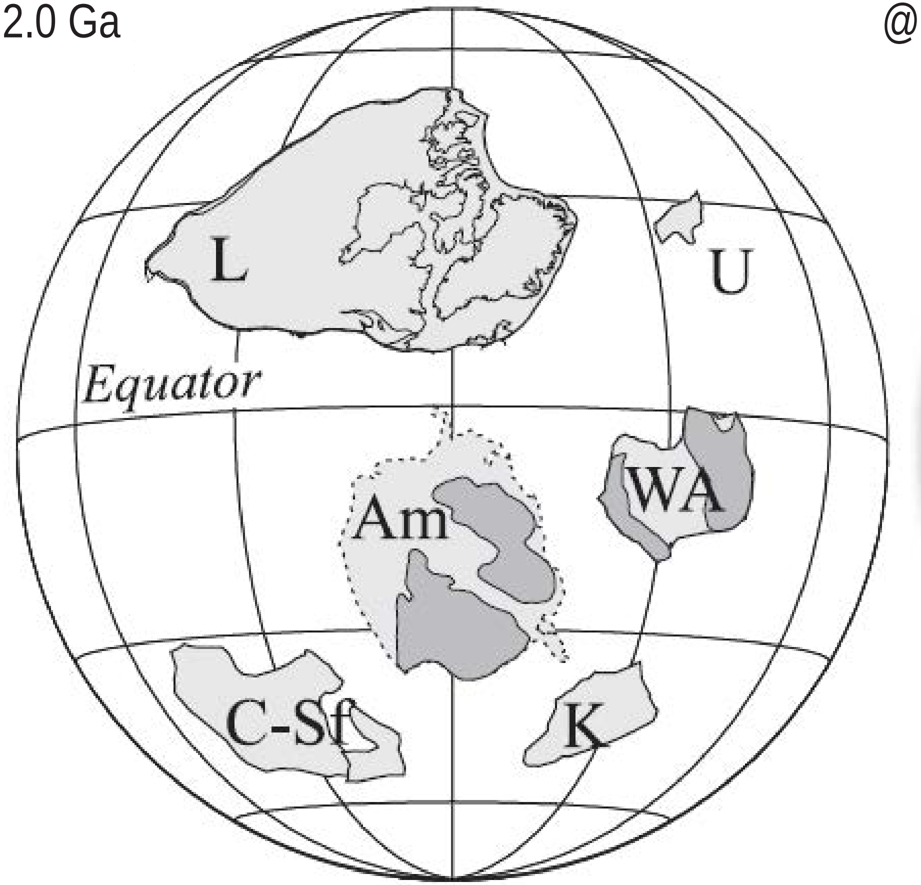
# Paleoproterozoic crustal growth and differentiation : *a guide for understanding mineral systems*

Vanderhaeghe O.
Ledru P.

## Perspectives

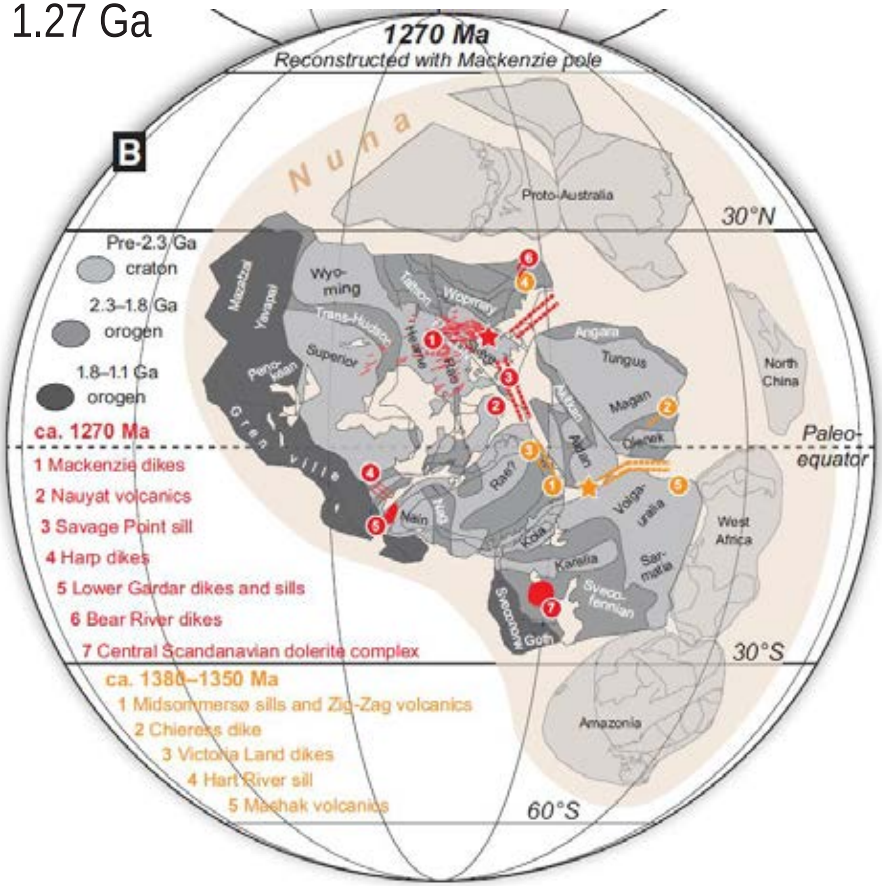
WAC-Guiana shield correlation

@ 2.0 Ga



(Pesonen et al., 2003)

@ 1.27 Ga



(Evans & Mitchell, 2011)

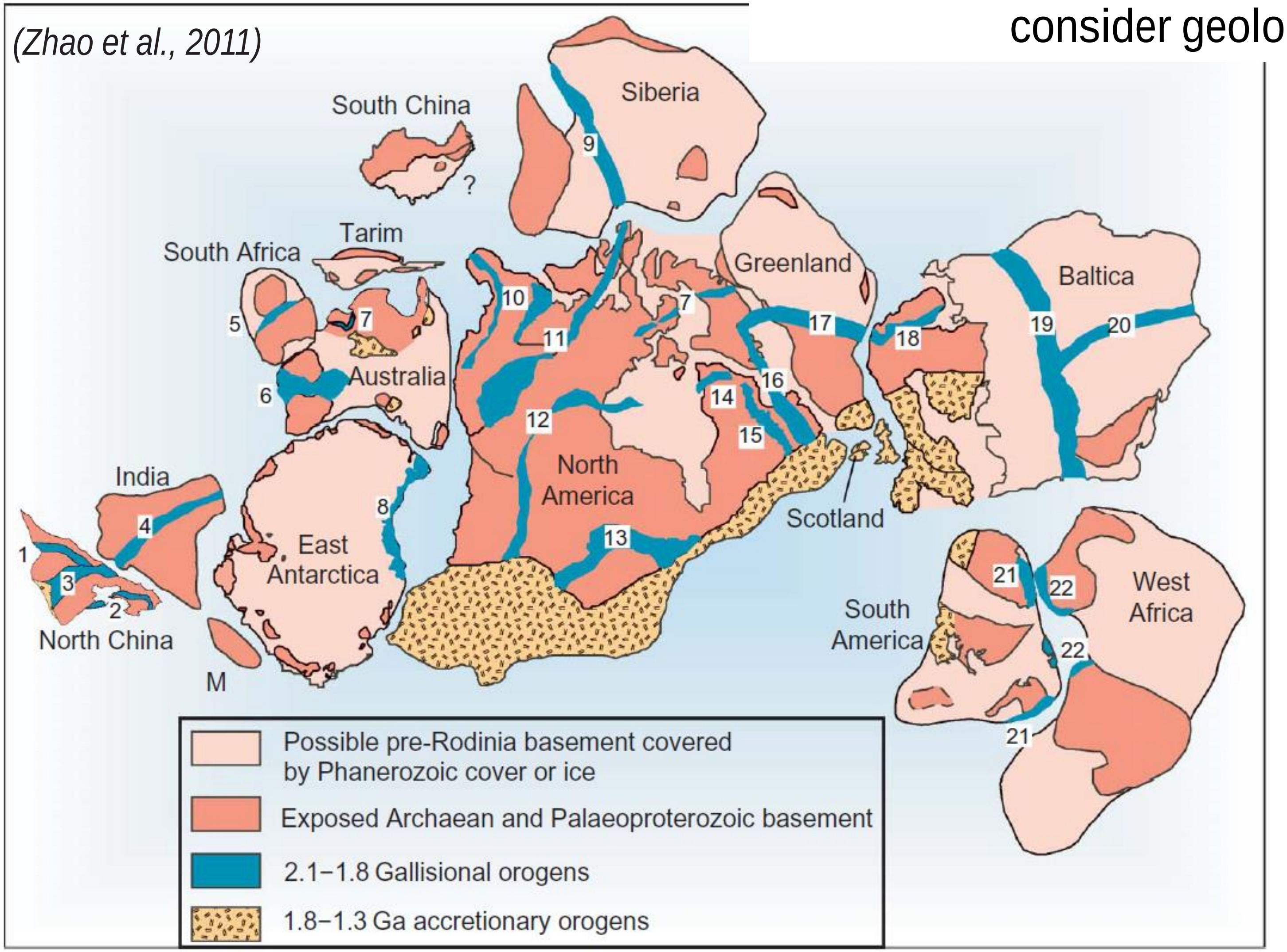
… **but** paleogeographic reconstructions are still a bit uncertain

# Paleoproterozoic crustal growth and differentiation :
## *a guide for understanding mineral systems*

Perspectives

WAC-Guiana shield correlations are uncertain

… **and** only approximately consider geology!


*(Zhao et al., 2011)*

Gold is a good tracer of mantle-crust and intracrustal transfers

Understanding these transfer provides guides for mineral exploration

# Questions?

**Tectonics and Metallogenesis of NE South America**

ANTON DE KOM UNIVERSITY OF SURINAME
Faculty of Technology
Department of Geosciences

Dr. Schürmannfonds

# *PETROGRAPHY, GEOCHEMISTRY AND AGE OF THE PALEOPROTEROZOIC ARMINA FORMATION METATURBIDITES OF THE COPPENAME RIVER IN SURINAME*

by

**Genevieve Wijngaarde**

Wednesday, February 20, 2019

# INTRODUCTION

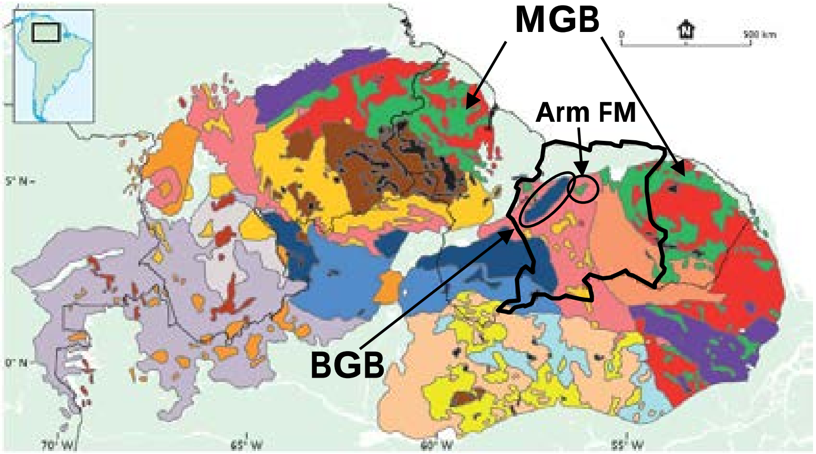
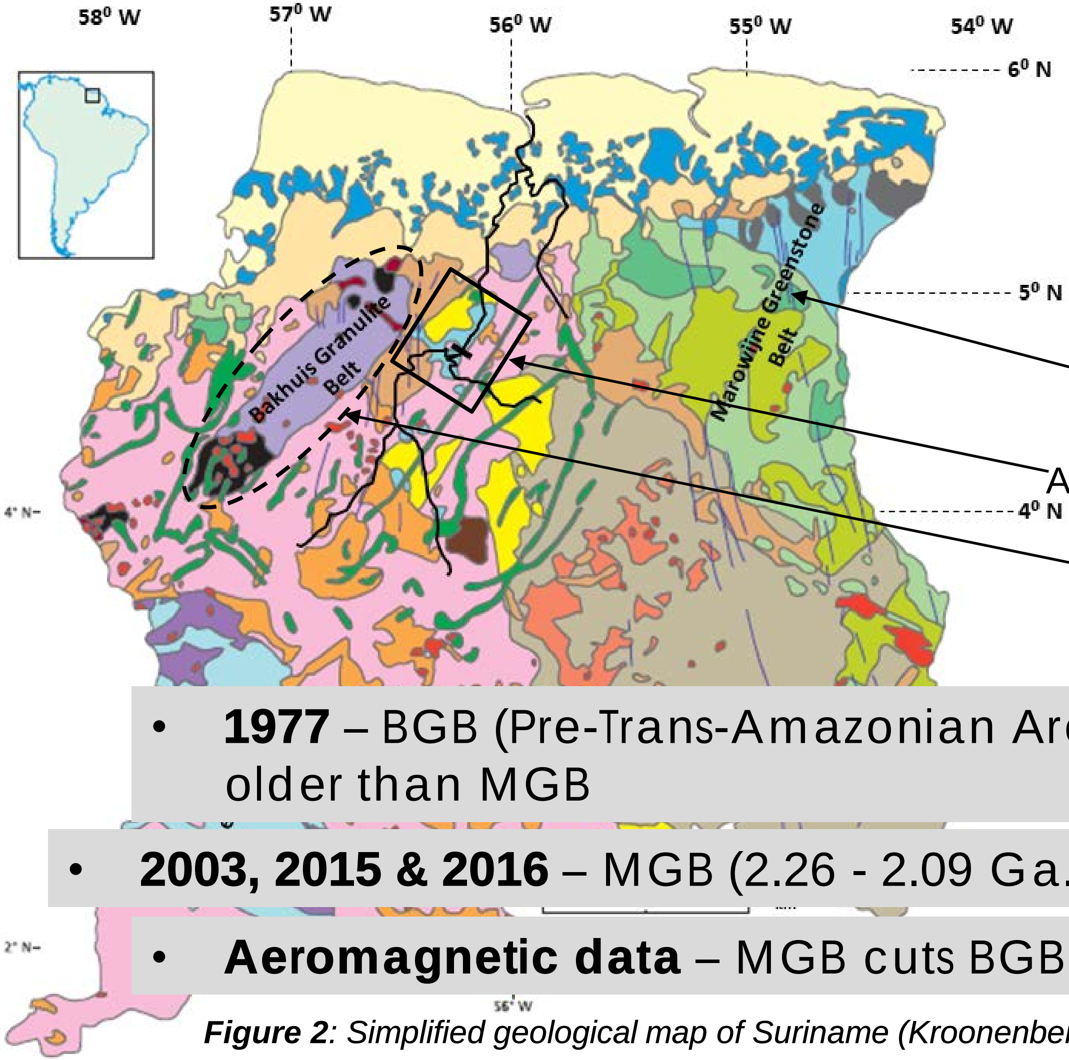


***Figure 1:** Simplified geological map of the Guiana Shield (Kroonenberg et al. (2016), compiled after various sources)*



Marowijne Greenstone Belt (MGB)
(2.26-2.10 Ga)

Armina Formation along the Coppename River

Bakhuis Granulite Belt (BGB)
granulites, gneisses, charnockites
(2.08-2.05 Ga)

- **1977** – BGB (Pre-Trans-Amazonian Archean age 4.03 - 2.42 Ga) older than MGB
- **2003, 2015 & 2016** – MGB (2.26 - 2.09 Ga.) older than BGB (2.08 - 2.05 Ga )
- **Aeromagnetic data** – MGB cuts BGB in the north – BGB older

***Figure 2**: Simplified geological map of Suriname (Kroonenberg et al. 2016)*

# PROBLEM STATEMENT

“Are the Coppename metaturbidites deposited in an outlier and/or tectonically displaced basin of the same greenstone belt,

**OR**

whether they could be a part of the same trans-tensional basin in which the Bakhuis protoliths have been deposited, and only escaped from being incorporated in the part of the basin that suffered granulite-facies metamorphism?”

- Sedimentological, Petrographical and Geochronological characteristics of Armina Formation
- Plate tectonic setting of the turbidite basin

# Facts about the Armina Formation

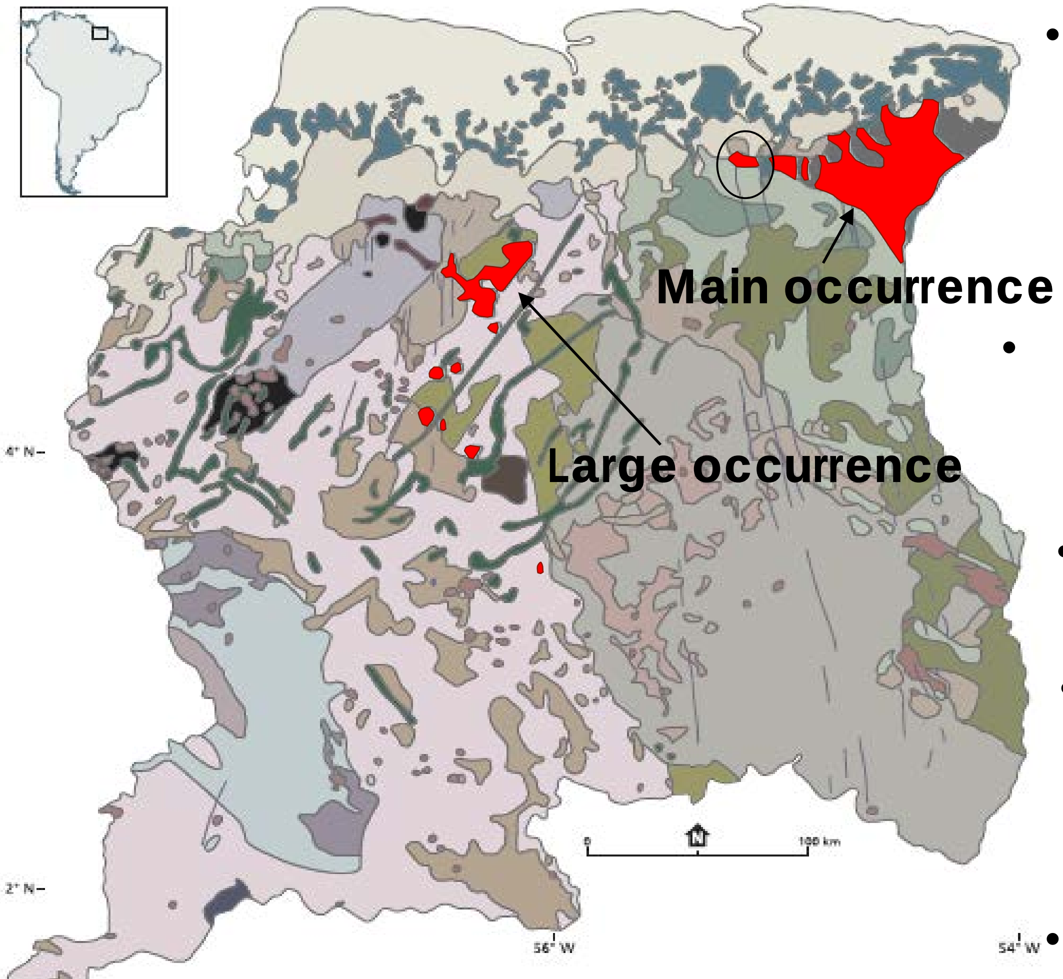


***Figure 3:*** *Simplified geological map of Suriname with the occurrences of the Armina Formation, modified after Kroonenberg et al. (2016)*

- A thick clastic marine sequence with turbidite characteristics consisting of regularly alternating sequences of low-grade metagreywacke and phyllite
- Meta-sediments predominantly derived from erosion of associated Paramaka Formation volcanics
- Intruded by bi-mica and biotite granite bodies (Wonotobo)
- Deposited in an arc-trench depositional environment (Naipal, 2015), marginal basins (Daoust et al., 2011)
- Detrital zircons indicate max. age of 2127 ± 7 Ma for turbidite sequences in eastern Suriname

# DATA ACQUISITION AND METHODOLOGY

**Preliminary Research**

- Literature
- Thin sections

**Fieldwork along the Coppename River**

- 52 samples collected
- Turbidite sequences measured

**Petrographical analysis**

- 25 samples
- 7 samples for point counting

**Geochemical analysis**

- 12 samples for major (XRF) and trace element (LA-ICPMS) analysis

**Geochronological analysis (Uranium-Lead zircon dating)**

- 6 samples (LA-ICPMS)

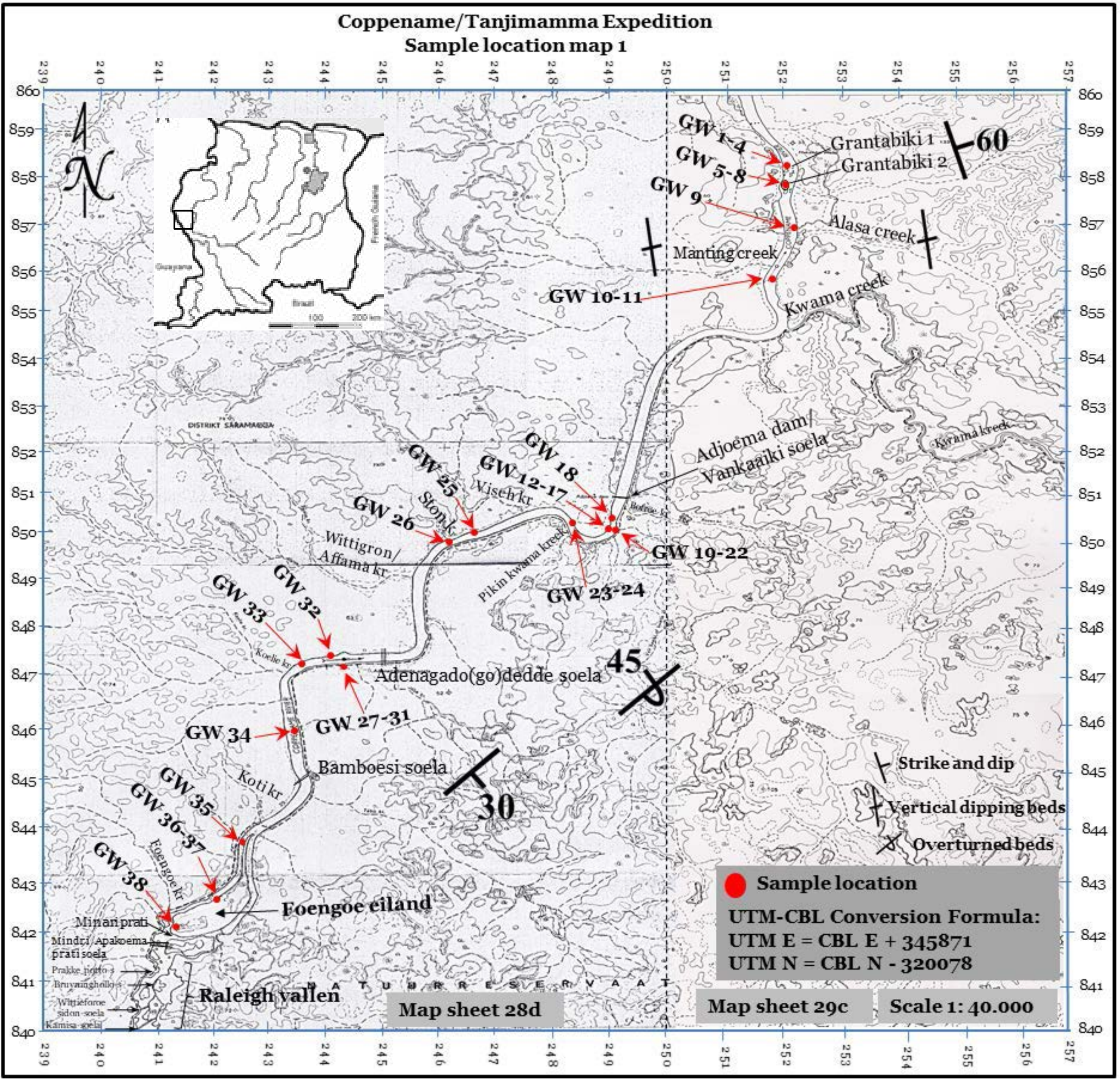


***Figure 4:*** *Field map 1*

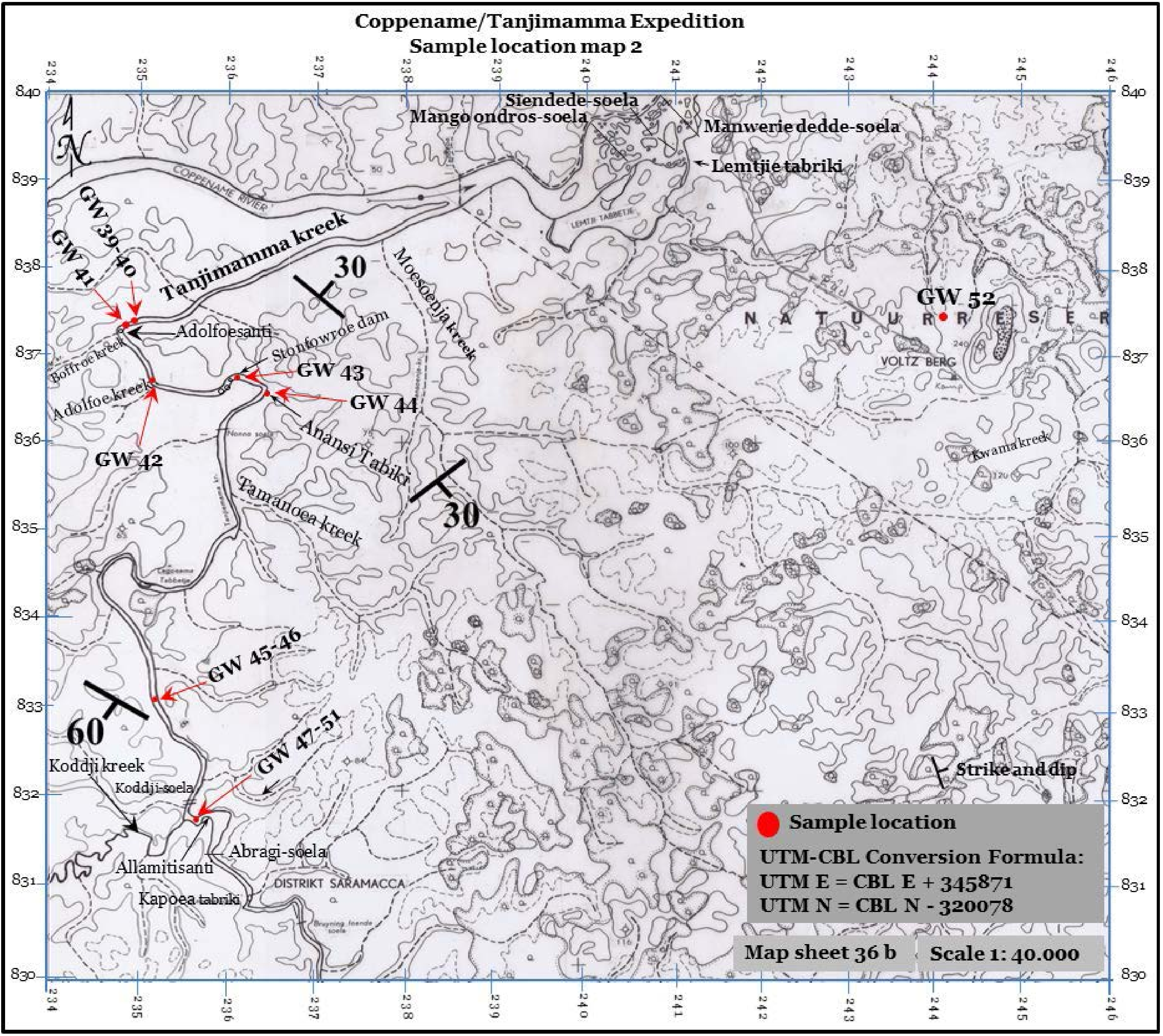


***Figure 5:*** *Field map 2*

# FIELD DATA

- The most extensive outcrops → Grantabiki in the north and along the Tanjimamma Creek in the south
- Turbidite sequences:

→ Thickness of continuous turbidite sequences → 1-5 m

→Alternation of 1) coarse grained greywacke beds with abundant quartz-veins (dm's) and

2) fine grained parallel laminated layers (cm's)

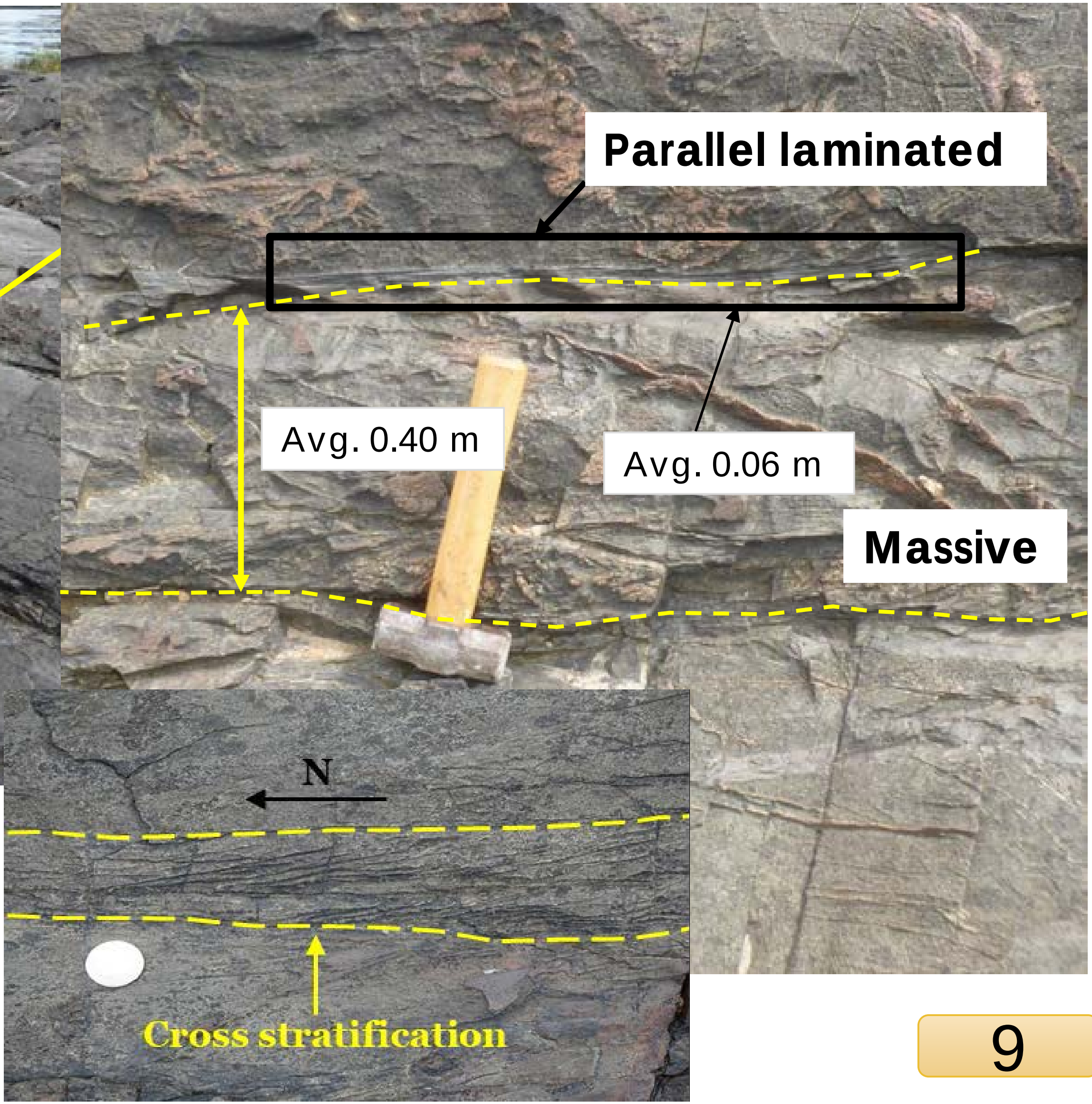
→ have undergone strong folding and jointing

**Important observed characteristics:**

- constant layer thickness,
- graded stratification in the coarser parts,
- small ripple-, wavy-, and convolute lamination and also cross stratification in the finer parts

# FIELD DATA - GRANTABIKI

***Figure 6:*** *7.4 m turbidite sequence of Grantabiki*



# FIELD DATA - GRANTABIKI

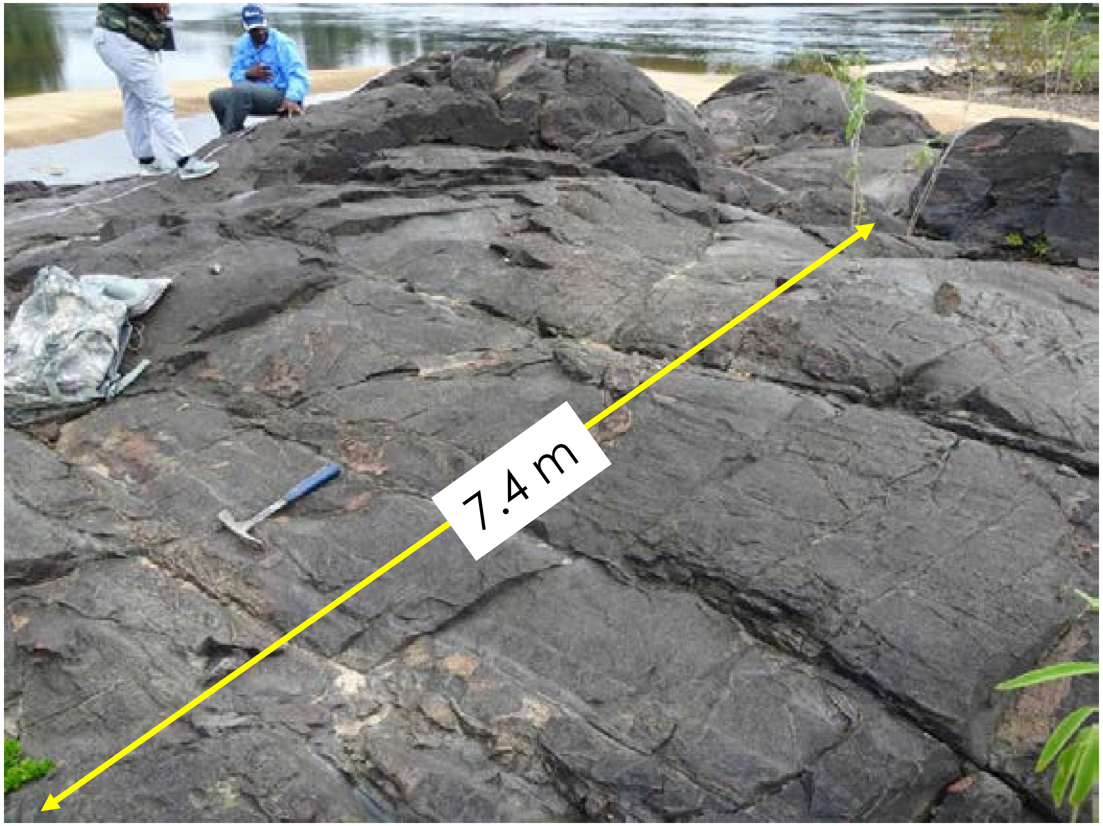


***Figure 6:*** *7.4 m turbidite sequence of Grantabiki*

Orientation → N20°W, dipping 60° to the east (340,60E)

Others → N20°W, dipping vertical

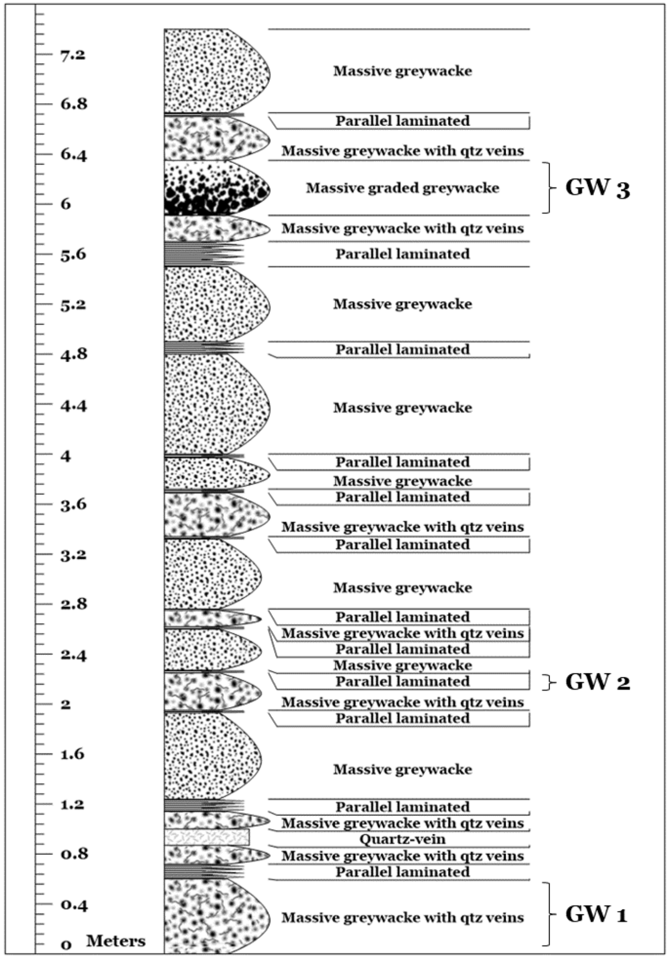


***Figure 7****: Schematic view of 7.4 m turbidite sequence of Grantabiki*

# 4. FIELD DATA – TANJIMAMMA CREEK

- Thickness → discontinuous 11.71 m → 4 separate sections
- Same alternating layers, but also wavy lamination in fine parts
- Convolute lamination → loose blocks

**Figure 9:** *Convolute lamination*

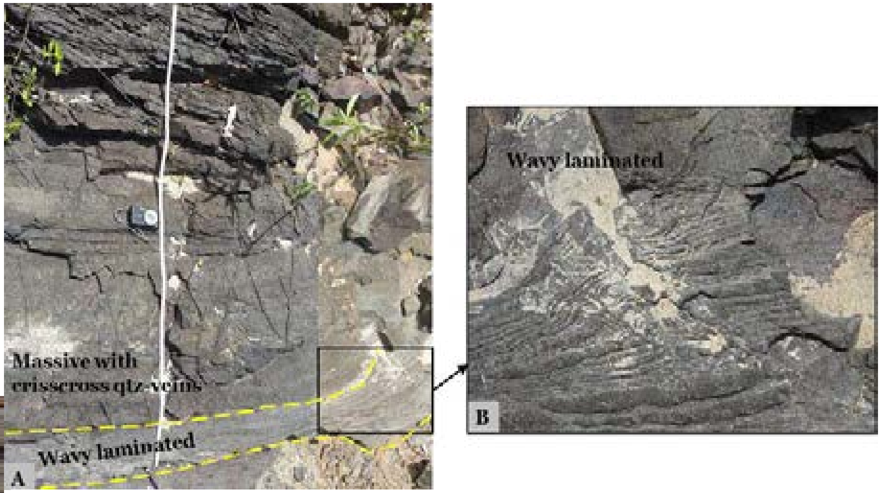


**Figure 8:** *Wavy laminated layer within the turbidite sequence along the Tanjimamma creek*

Orientation → N60°W, dipping 60° to the southwest (300,60SW)

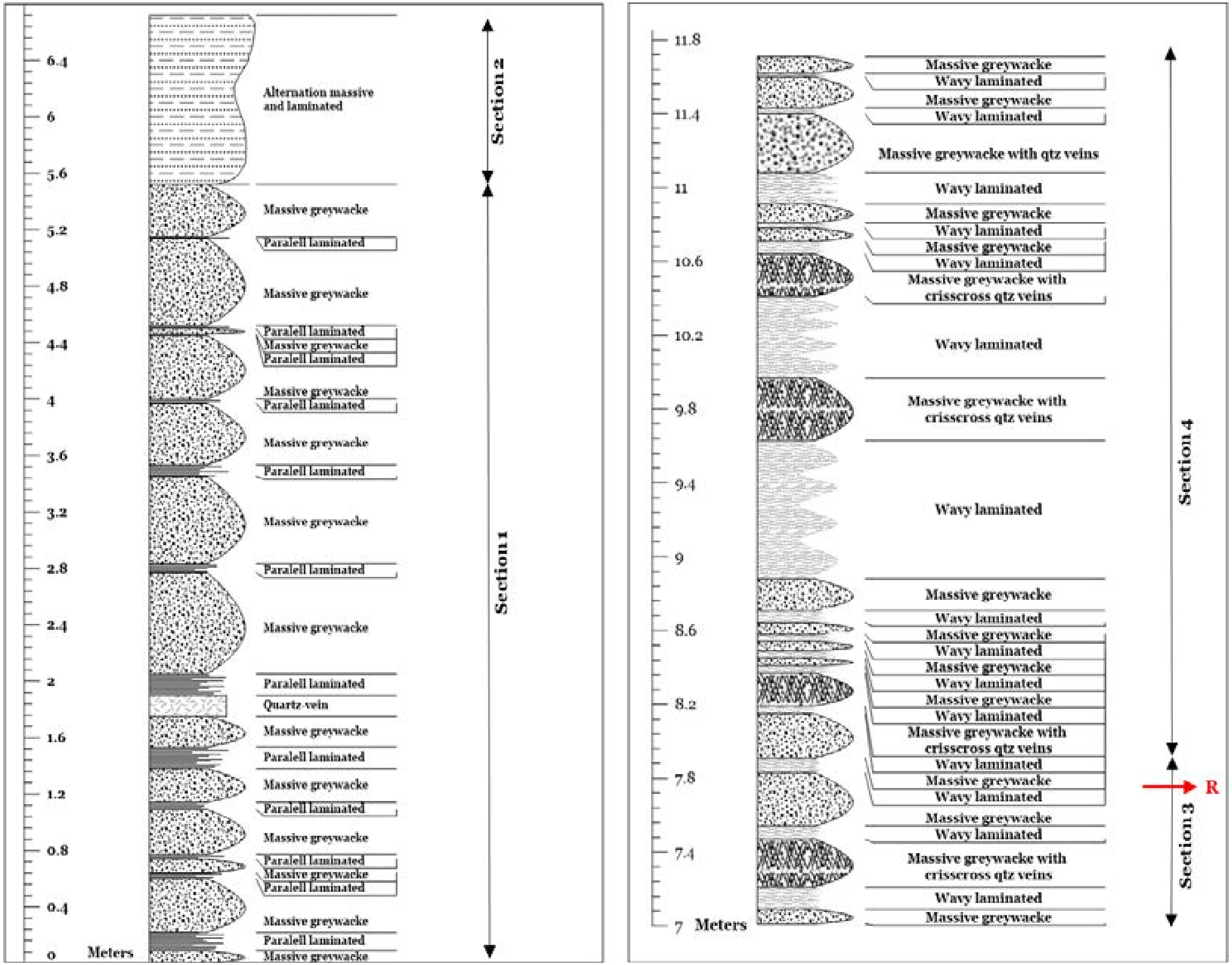


***Figure 10:*** *Schematic view of the turbidite sequence along the Tanjimamma creek*

# FIELD DATA:
## VANKAAKI DAM

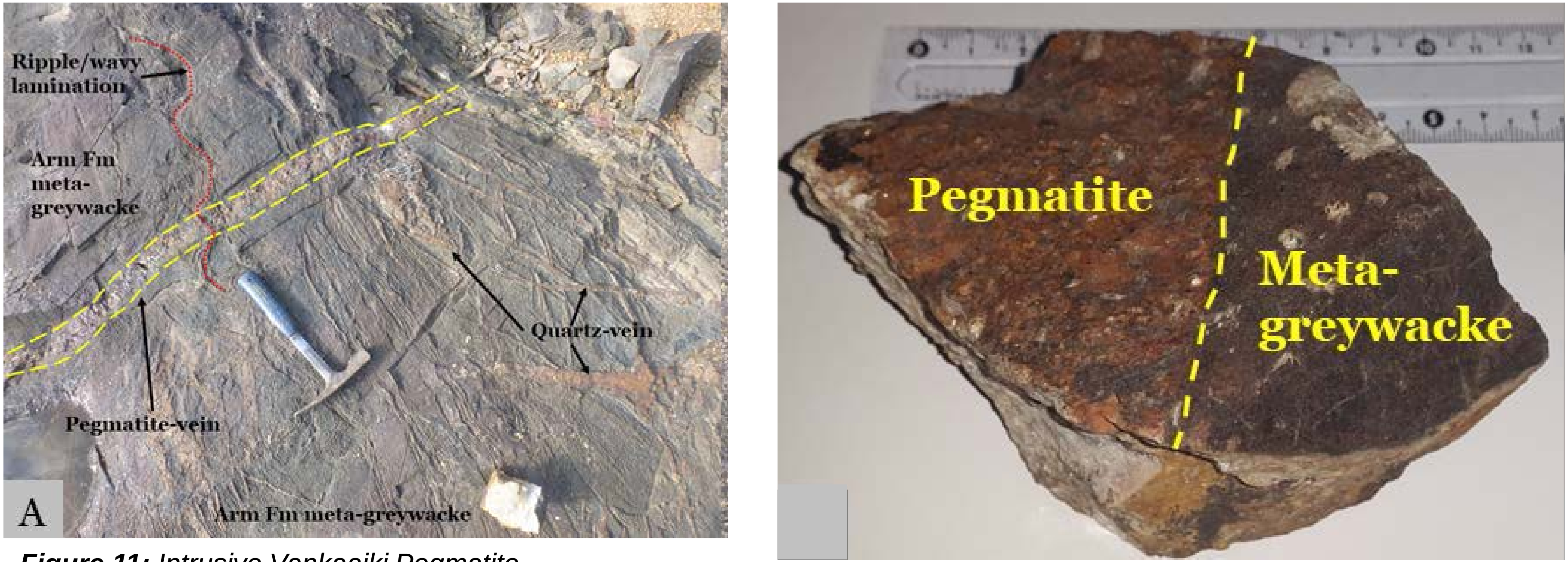


***Figure 11:*** *Intrusive Vankaaiki Pegmatite*

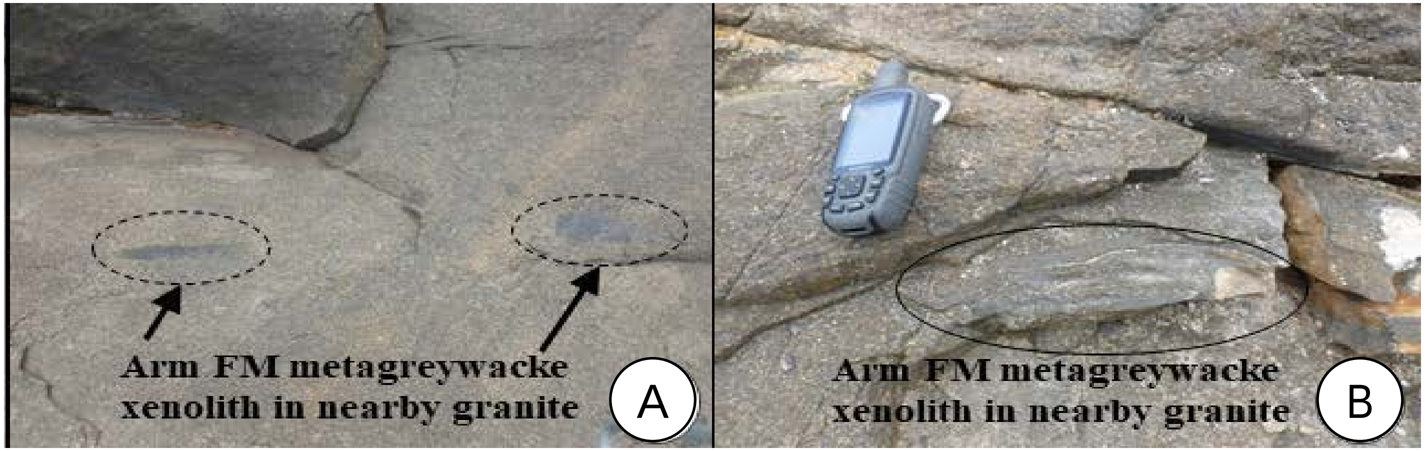


***Figure 12:*** *Metagreywacke xenoliths in the nearby granite*

# FIELD DATA:
## ADENAGADO SULA & RALEIGH FALLS

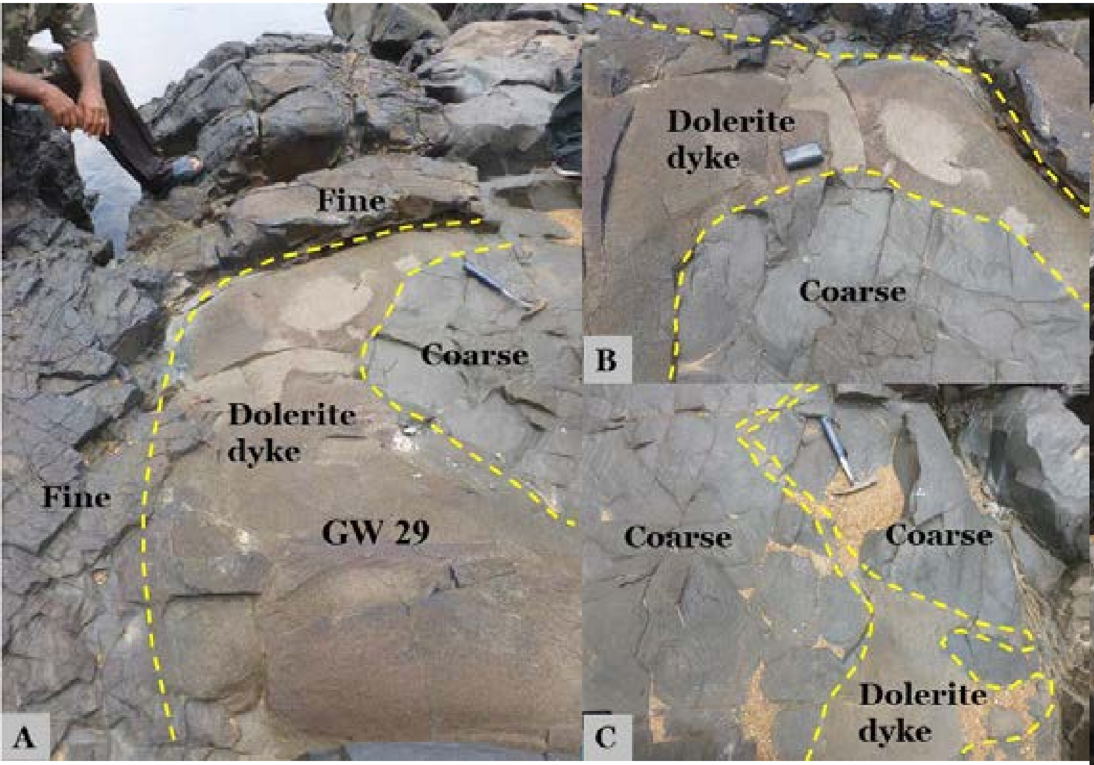


***Figure 13:*** *Intrusive Adenagado sula dolerite*

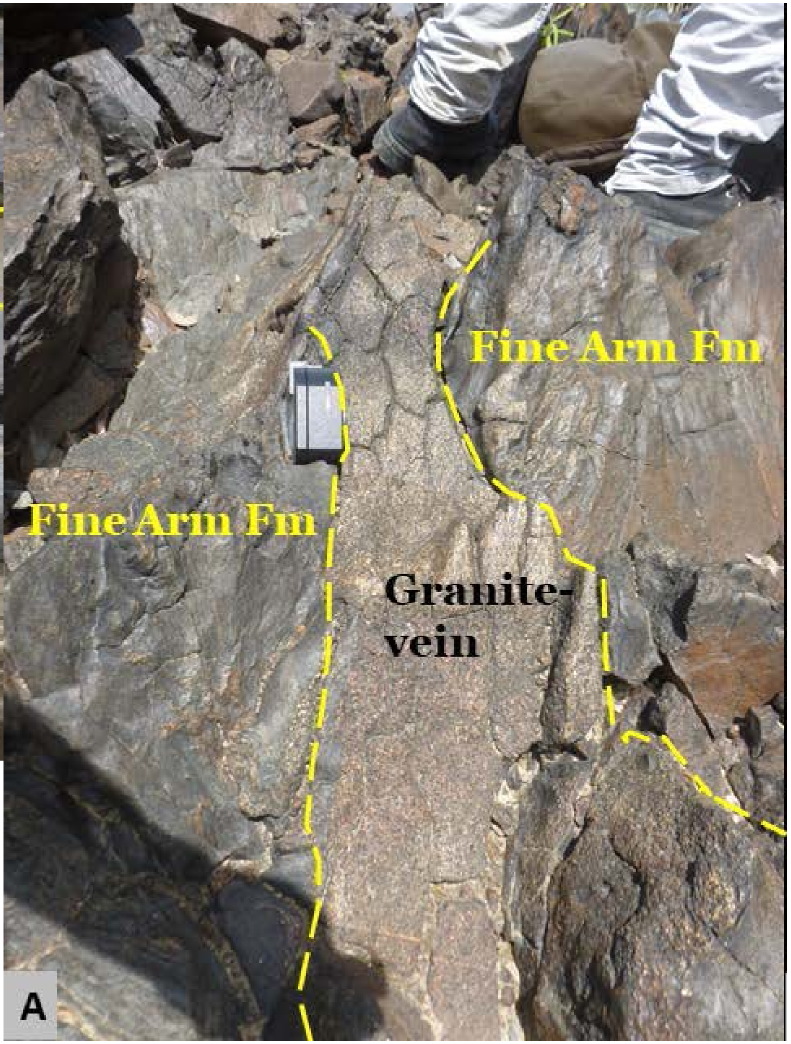


***Figure 14:*** *Intrusive Raleigh Falls granite*

# PETROGRAPHY

- The metagreywackes of this area:
  - Fine - very coarse-grained
  - consisting of
    - **quartz, plagioclase, K-feldspar (including microcline), biotite, muscovite**, chlorite, epidote, allanite, rutile, zircon, tourmaline, titanite, magnetite/ilmenite, pyrite/other sulfide mineral, and
    - igneous (both plutonic and volcanic), metamorphic and sedimentary lithic fragments → in coarse sections
  - The plutonic fragments → probably derived from TTG plutons due to the abundance of plagioclase relative to alkali feldspar.

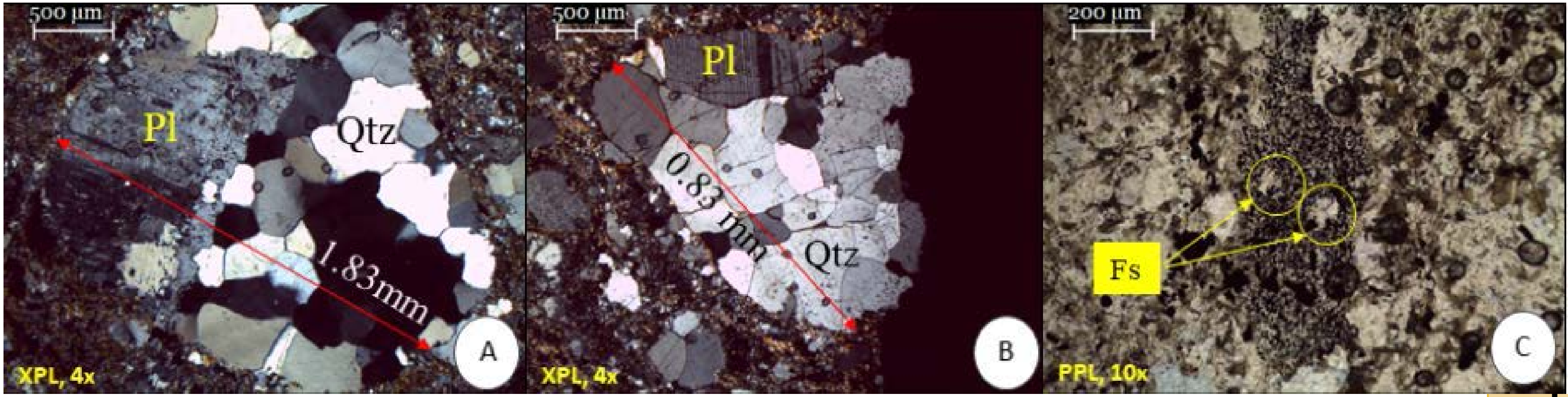


***Figure 15:*** *Plutonic and Volcanic lithic fragments*

# PETROGRAPHY

Modal analysis (point counting):

- GW 3 – lithic wacke, all others – feldspathitic wacke
- GW 46 pelitic rock
- From north to south - texturally and mineralogical immature to sub-mature

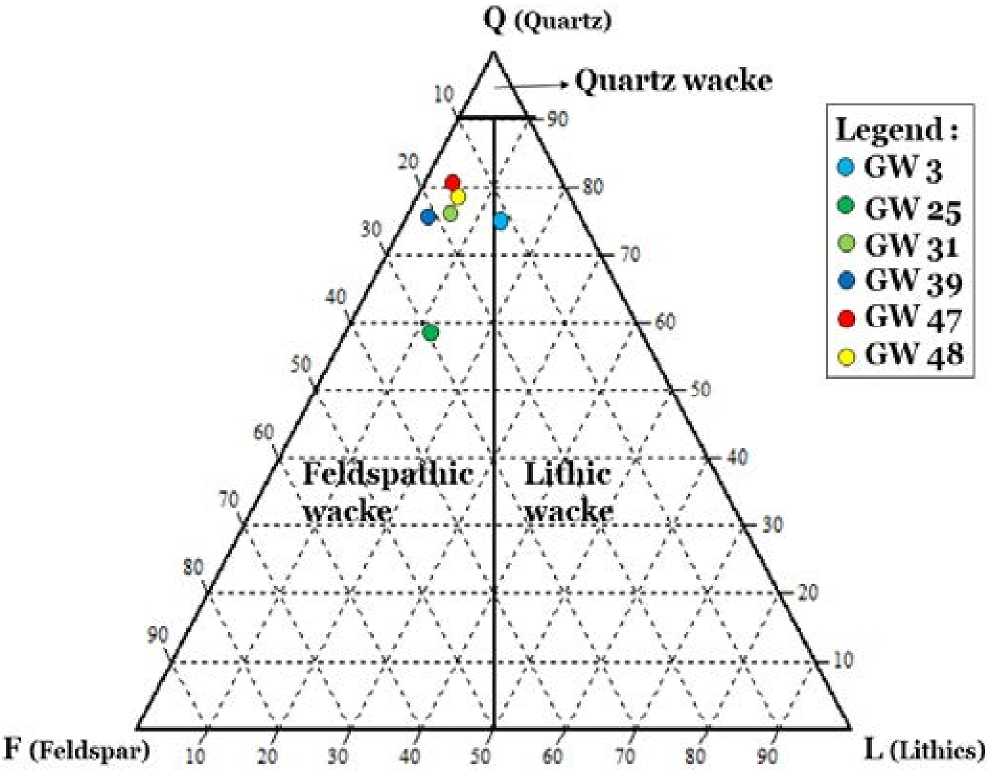


***Figure 16:*** *Modal analysis of 6 metagreywacke samples*

# PETROGRAPHY

- Provenance analysis (assess through point counting)
  - QFL & QmFLt provenance diagrams → greywackes with a volcanic provenance in the north at Grantabiki were deposited in an active island arc, whereas from Adenagado sula southwards the rocks become more arkosic with a more granitic provenance deposited in an active continental margin

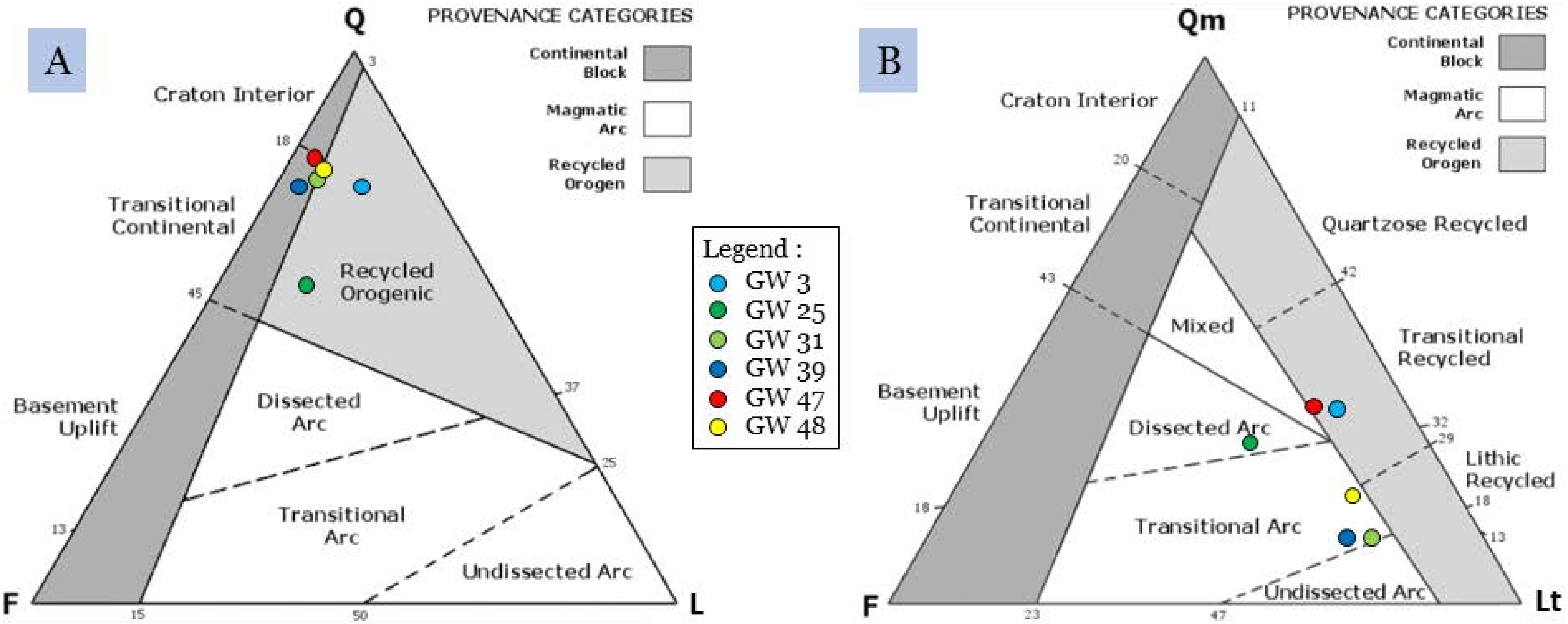


***Figure 17:*** *Provenance discrimination diagrams: QFL and QmFLt after Dickinson et al, 1983*

# METAMORPHISM

- The mineral assemblages indicate:
  - **regional metamorphism** from greenschist facies (chlorite and biotite zone) to lower amphibolite facies (garnet zone),
  - whereas in the vicinity of granitoid rocks **contact metamorphism** occurred.

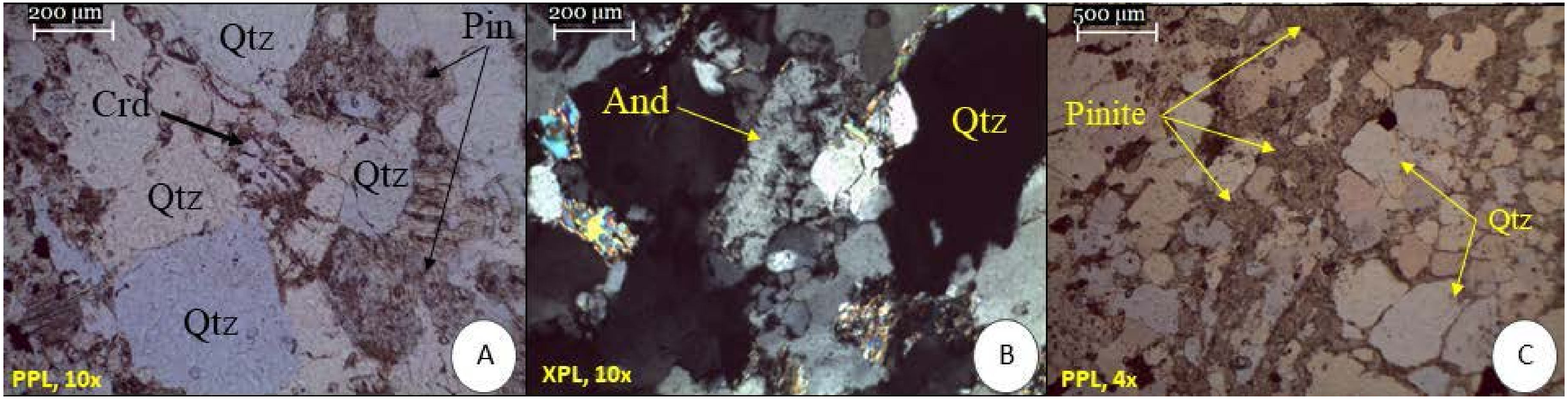


***Figure 18:*** *Contact metamorphic minerals and alteration products*
*Crd = CORDIERITE*

# GEOCHEMISTRY

- **Geochemical composition indicates:**

- Northern samples → greywackes

- Southern samples → arkos

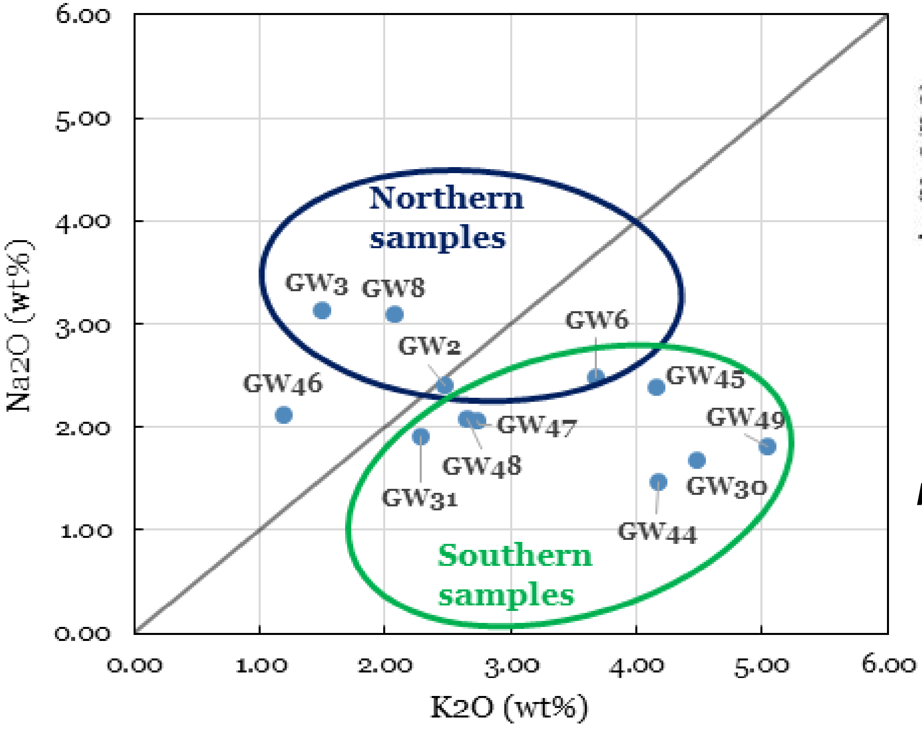


***Figure 19:** Correlation plot of K2O and Na2O*

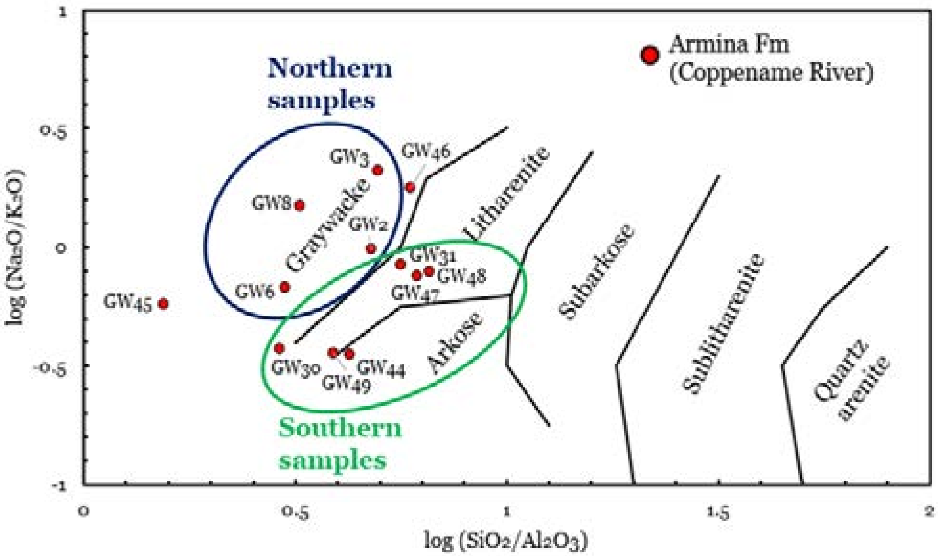


***Figure 20:** Classification plot after Pettijohn et al., 1972*

# GEOCHEMISTRY

- **Tectonic setting:**

- Northern rocks → deposited within an active island-arc (oceanic and continental),

- Southern rocks → deposited in an continental margin related to a felsic igneous provenance

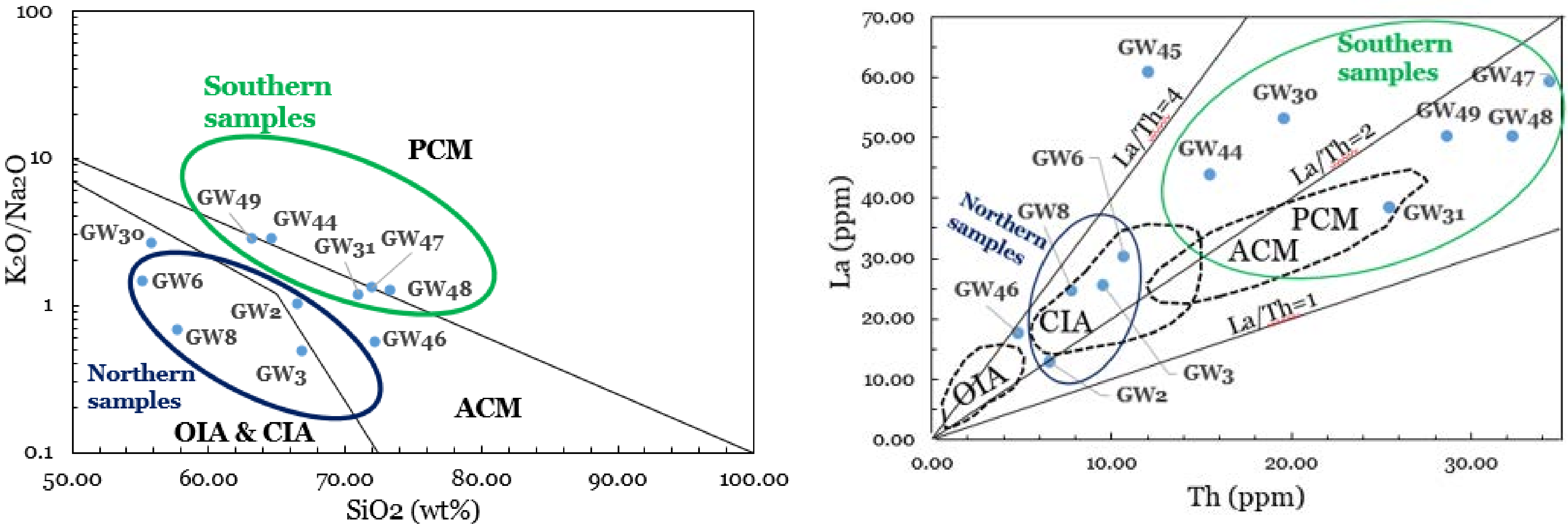


***Figure 21:*** *Tectonic setting discrimination diagram after Roser & Korsh, 1986 and Bhatia, 1986*
***OIA*** *= Oceanic Island Arc;* ***CIA*** *= Continental Island Arc;* ***ACM*** *= Active Continental Margin;*
***PCM*** *= Passive Continental Margin*

# GEOCHEMISTRY

- **Trace element concentration also point to different provenance:**

\- Higher Ni concentrations in the northern samples → a partly mafic igneous provenance (volcanic), while

\- Higher Th and U concentrations in the southern samples suggest a more felsic igneous provenance (granitic).

# GEOCHRONOLOGY

- Detrital zircons in the Armina Formation → **2162 ± 30 Ma** for the major sediment source of the metaturbidites sequence in the Coppename area

- Younger granites intruding the Armina metaturbidites:
  - → 2005 Ma (Voltzberg granite),
  - → 2004 Ma (Raleigh Falls granite),
  - → 1990 Ma (Vankaaikisula granite)

# INTERPRETATIONS

- The Armina Formation rocks along the Coppename River were deposited in 1-5 m thick fining-upwards (towards the north) turbiditic sequences → characterised by constant layer thickness, graded stratification in the coarser parts, small ripple-, wavy-, and convolute lamination and also cross stratification in the finer parts.
- Two generations of intrusives granitoid rocks in Armina Formation of the Coppename area.
  - Relatively older intrusion indicated by the plutonic fragments in the metagreywacke.
  - Younger granite intrusion evidenced by pegmatite veins, contact metamorphism in the metagreywackes, and metagreywacke xenoliths in the granite.
    - Ages of younger intruding granites are slightly higher than most Wonotobo granites in Western Suriname.

# INTERPRETATIONS

- Petrographical and geochemical analysis as well as individual trace elements → greywackes with a volcanic provenance in the north were deposited in an active island-arc, whereas from Adenagado soela southwards the rocks become more arkosic with a more granitic provenance deposited in an active continental margin.

- Detrital zircons indicate a similar age as that of the eastern Marowijne Armina Formation

- No zircons in Bakhuis age range (2.08-2.05 Ga) have been found in the Armina metagreywackes of the Coppename area, and no granulite clasts or other typical minerals such as orthopyroxene and meso-perthitic feldspar have been found either.

# CONCLUSIONS

**Explanation regarding the different provenances within the Armina Fm:**

- Probably due to the development of the arc over time, the bottom of the sequence is more volcanic while still an island arc (north), whereas higher in the sequence more granitic when it has already become an active continental margin due to the development of the subduction zone (south) OR
- The turbidites in the north and south were fed by different river systems and the two sequences lay next to each other on the same level

# CONCLUSIONS

- The turbidite deposits of the Armina formation show no affinity to the Bakhuis rocks and are a part of the same greenstone belt of northeastern Suriname deposited on the fore-arc side in an arc trench environment.
- There is no evidence that the Bakhuis Granulite Belt already existed when the Armina Formation was deposited HOWEVER,
- The presence of inherited zircons with ages between 2120 and 2150 Ma in the sillimanite gneisses of the Bakhuis Belt might indicate that the Bakhuis granulites could represent the high-grade equivalents of the Armina metaturbidites, and hence share the same provenance area.

**For more information, please contact me:**

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# Petrogenesis, Hydrothermal Alteration and Metamorphism of the Poederberg Pillow Basalts in the Paleoproterozoic Greenstone Belt of Suriname

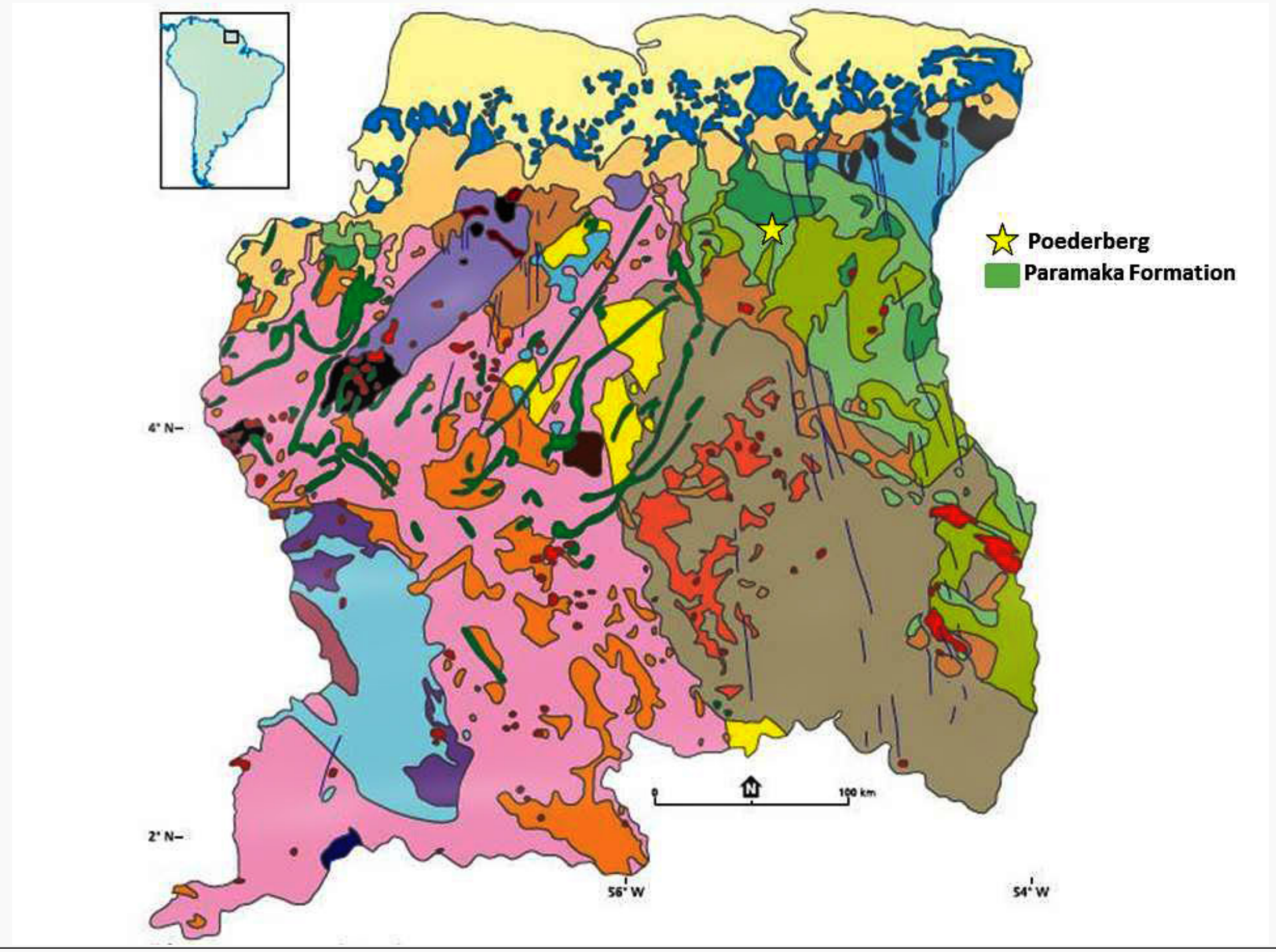
**Stacey Amattaram[1], Salomon Kroonenberg[1], Theo Wong[1], Paul Mason[2]**

[1] Anton de Kom University of Suriname, [2] University Utrecht

## INTRODUCTION

The Poederberg Pillow basalts of the Paleoproterozoic Greenstone Belt are part of the Paramaka Formation formed during the Trans Amazonian Orogeny (2.26 Ga) where new ocean crust is formed (Delor et al., 2003a; Kroonenberg et al., 2016).

**Objective**: To elaborate the chemical impact of sea-water alteration, hydrothermal alteration and metamorphism on the geochemistry of the pillow lavas.

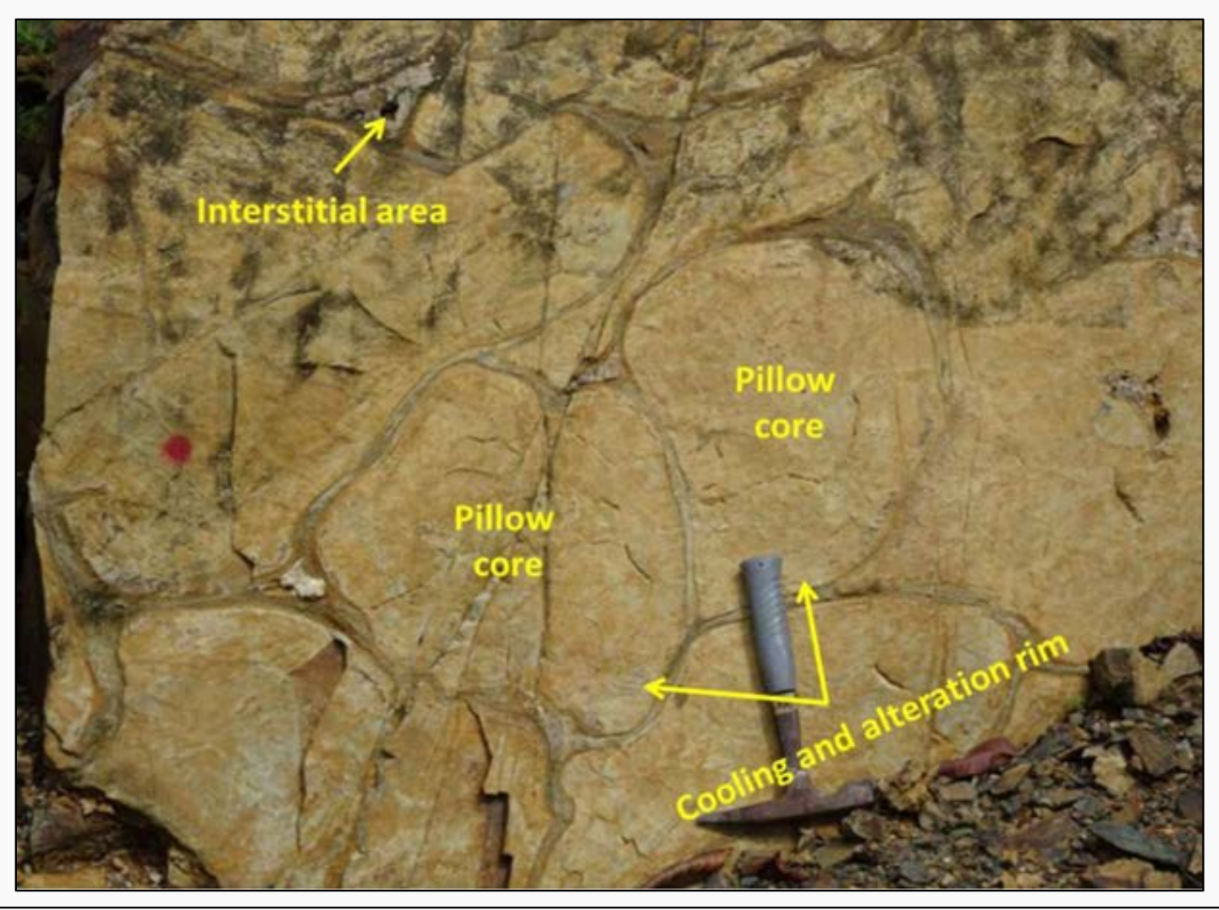


*Simplified geological map with Poederberg Location after Kroonenberg et al. (2016)*

## RESULTS AND DISCUSSION

### Morphology

- Dip of pillows is 38° with flow direction of N320°.
- The height varies from 0.2-1 m and the width varies from 0.2-1.2 m.
- Interstitial material is rarely present, radial cracks are absent and chilled margins are narrow.



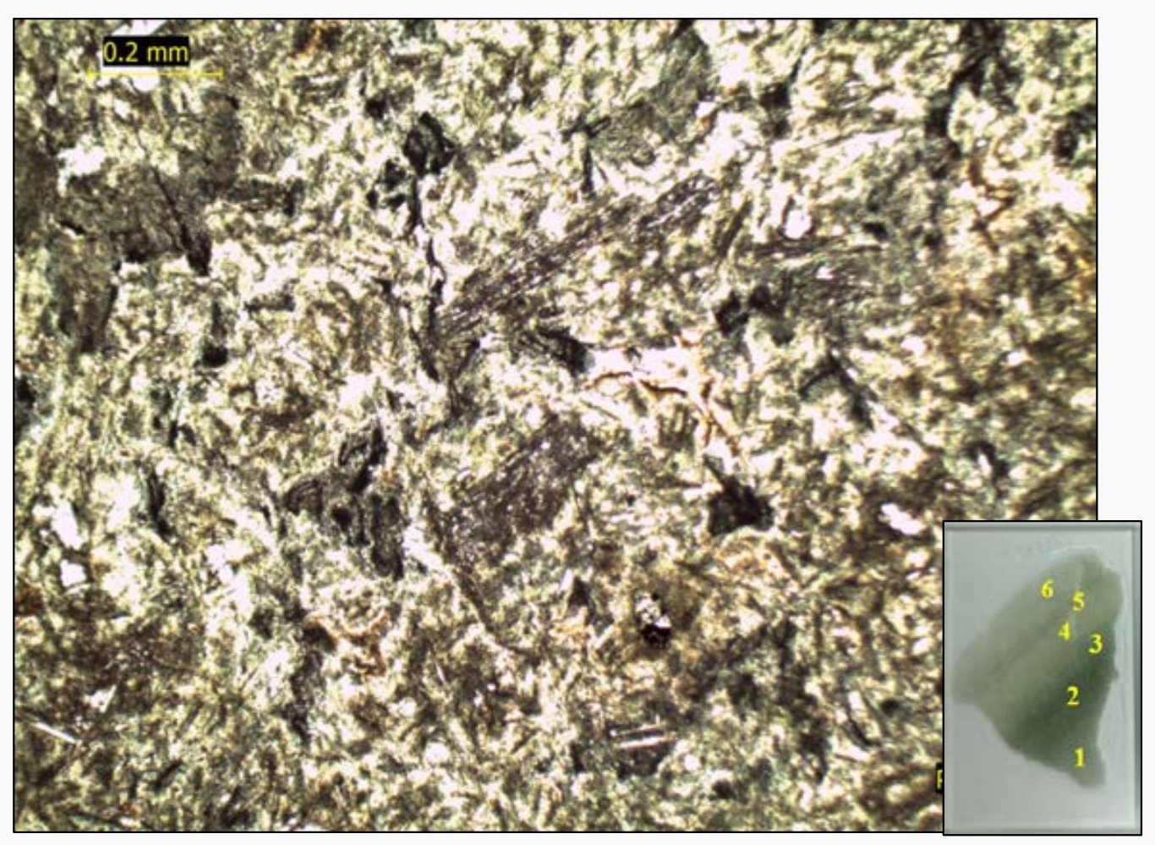
- No hyaloclastite nor vesicles are present suggesting deposition in a submarine environment at water depths of at least 2000 m (Lonsdale & Batiza, 1980).

These results are similar to studied pillows formed at ancient BAB.

*Sharp pointed pillows underside indicate that the pillows are in normal nearly horizontal position*

### Petrography

- ***Pillow core***: actinolite, chlorite, epidote, plagioclase phenocrysts and albite.
- ***Pillow rim***: in PB02 six textural zones, while in SA10 only 4 zones are present. Zone 2-6 are formed by metamorphism of palagonite.
- ***Interstitial material***: quartz and some amphibole.



*PB02 Zone 2 metabasalt and palagonite*

**Zone 1**: altered metabasalt (actinolite, chlorite, epidote).

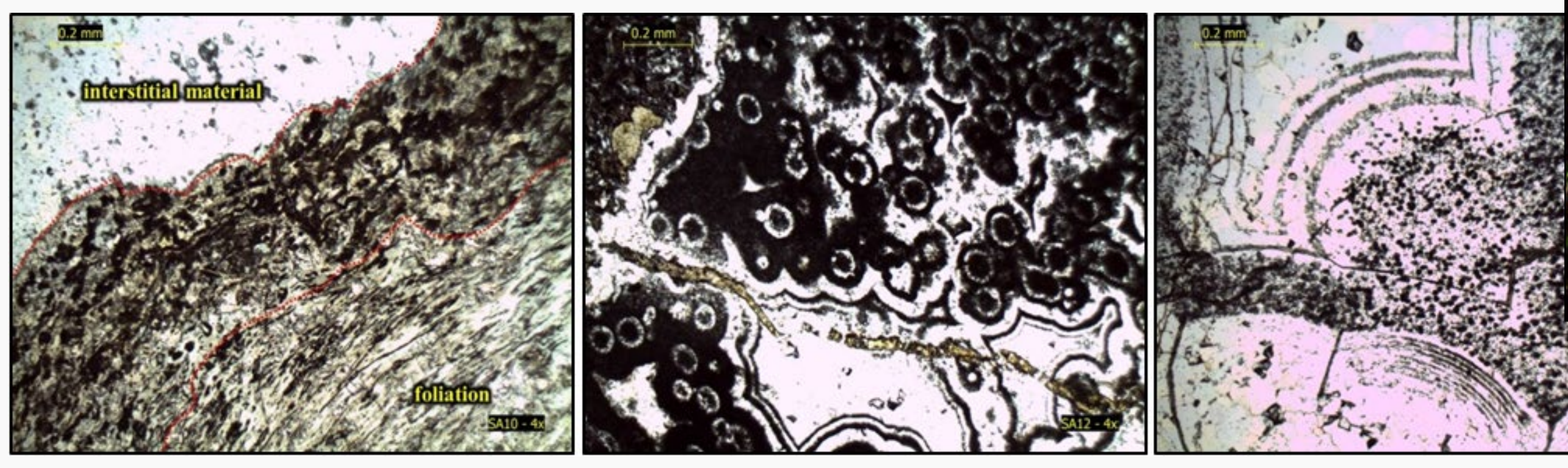
**Zone 2**: metabasalt + palagonite.

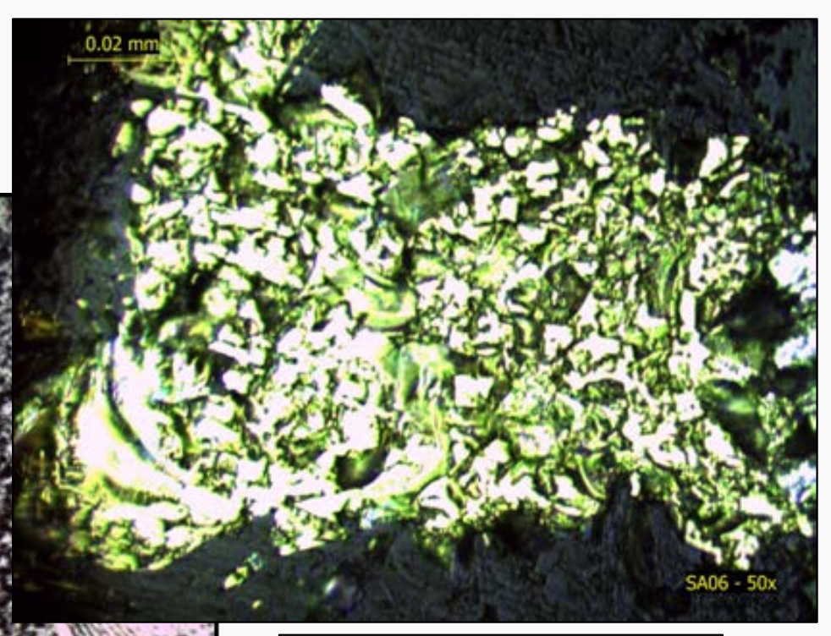
**Zone 3**: spherulites of tremolite, actinolite + epidote.

**Zone 4**: foliated zone of chlorite, epidote spherulites, calcite + albite.

**Zone 5**: micro-folds with epidote, titanite, quartz, epidote-calcite-quartz veins.

**Zone 6**: chlorite, epidote, muscovite + chlorite-epidote-quartz veins





*Gold in pyrite*

*Gel-like mass of epidote, quartz + actinolite on top of pillow rims Some show concentric bands.*

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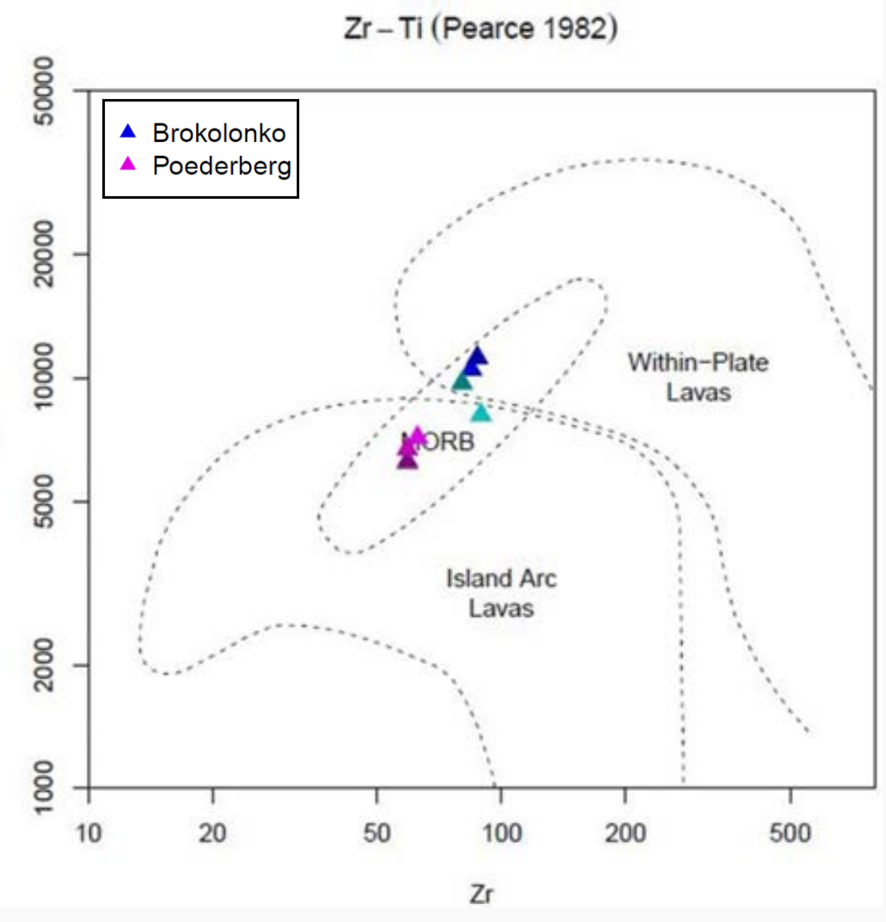
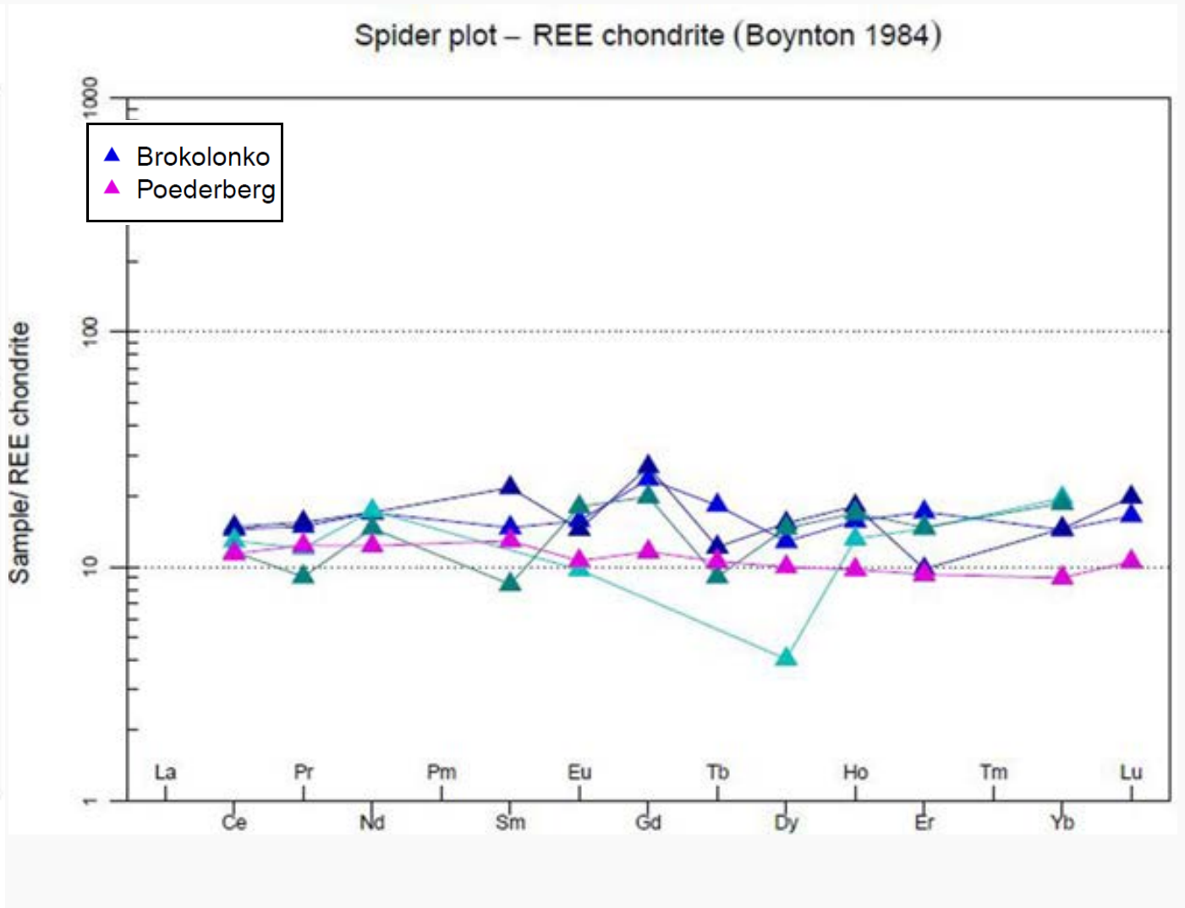
### Geochemistry



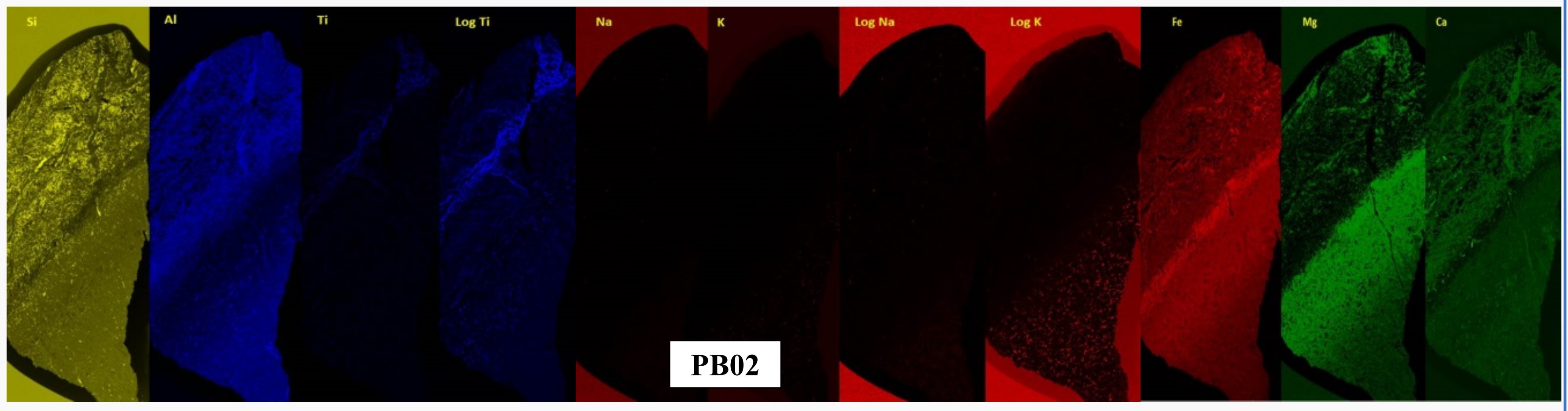


Poederberg pillows and Brokolonko basalts show MORB characteristics. A flat chondrite-normalized REE indicating deposition at spreading zones.

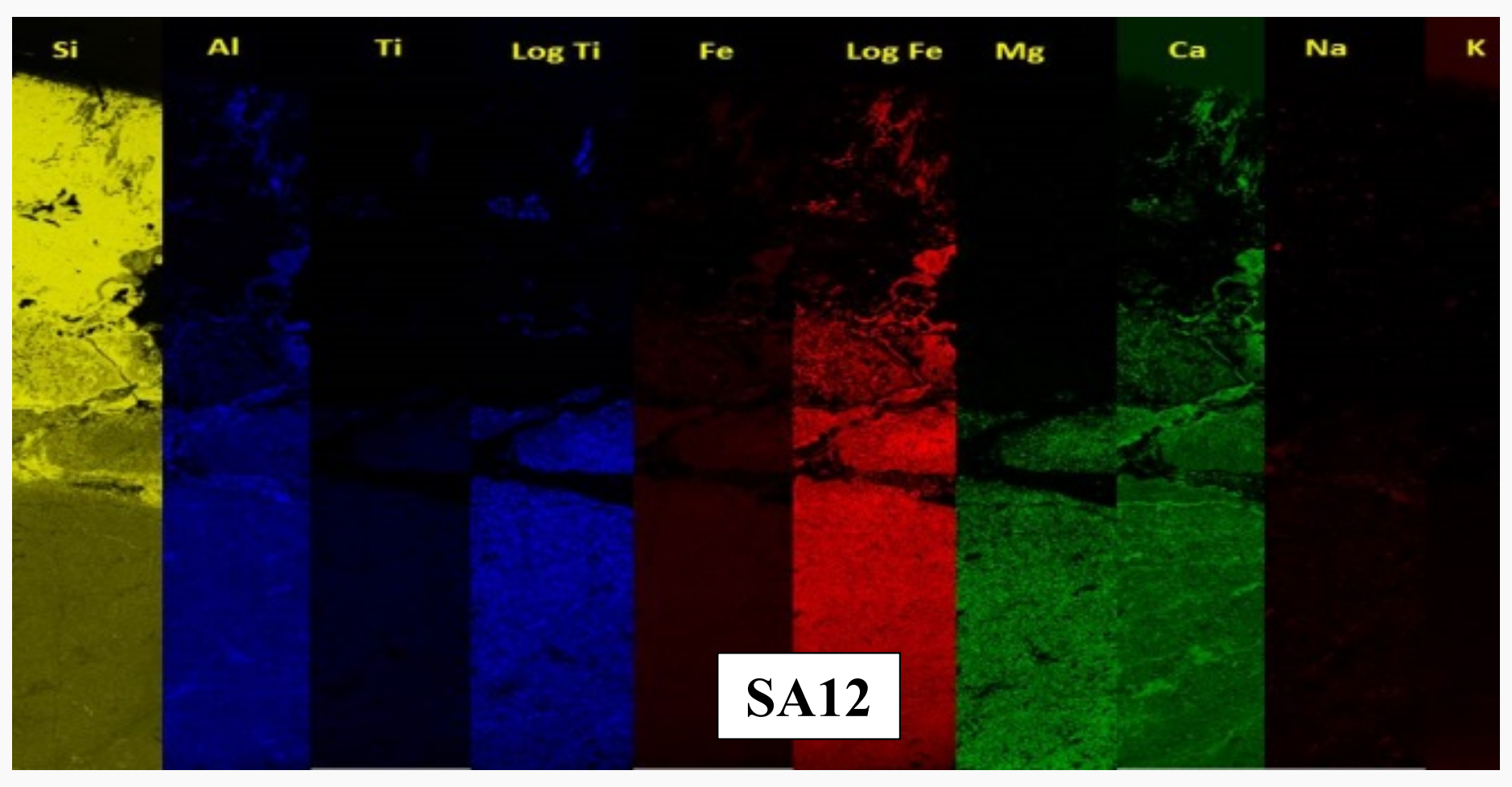
### Micro XRF

- Given results are relative amounts in terms of counts or intensities.

**++ : enriched**
**-- : depleted**



**PB02: Si** ++ outer zones → palagonite. **Al** ++ zone 4 and 5. **Ti** ++ → titanite. **Fe+Mg** ++ zone 1 and zone 2. **Ca** ++ outer zones → carbonate+calcite veins. **K** included in plagioclase in zone 1 → still a low concentration in this zone. **K+Na --** in other zones → no enrichment by seawater.



**SA12: Si** ++ in interstitial material → quartz and quartz veins.

**Al, Ti, Mg+Fe** ++ in zone 1 and transition to interstitial material.

PB02 and SA12 → 2 different types of pillows rims.

## CORRELATION MINERALOGY AND PETROLOGY

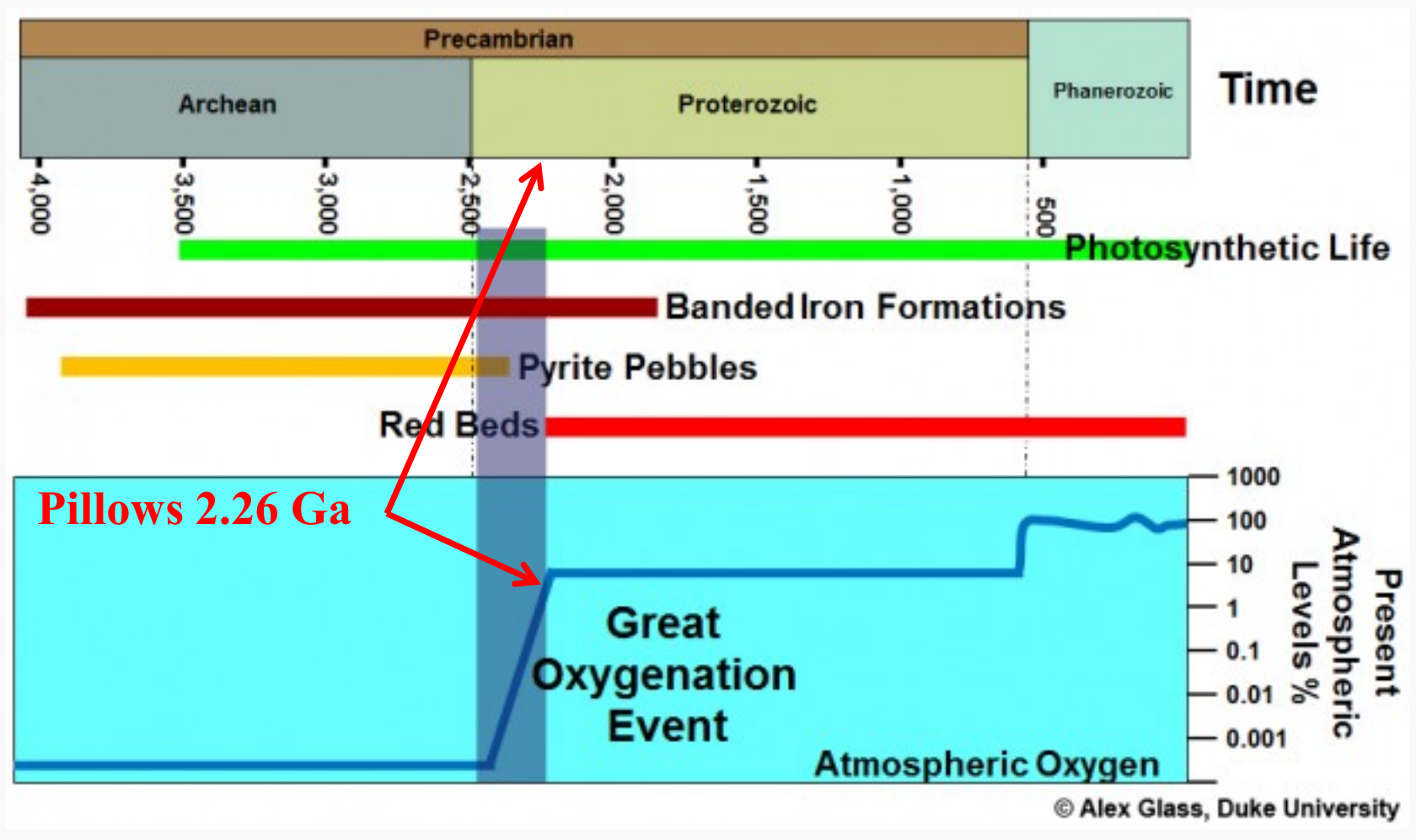
### PB02

- Altered palagonite
- Na and K dissolved in seawater during deposition.
- Epidote concentrated Fe, while chlorite have varying proportions of Mg and Fe (zone 1-4).
- **Fe in rims** less than zone1-4 but still enriched →epidote crystals

1. Beginning of GOE during pillow lava deposition (2.26 Ga). Deep ocean was still anoxic (Holland, 2006; Session et al., 2009) → Fe (reduced state, mobile) migrated inwards → formed actinolite, chlorite.
2. Epidotization → pseudomorphism after actinolite and plagioclase. But first, actinolite must have been metamorphosed after palagonite.

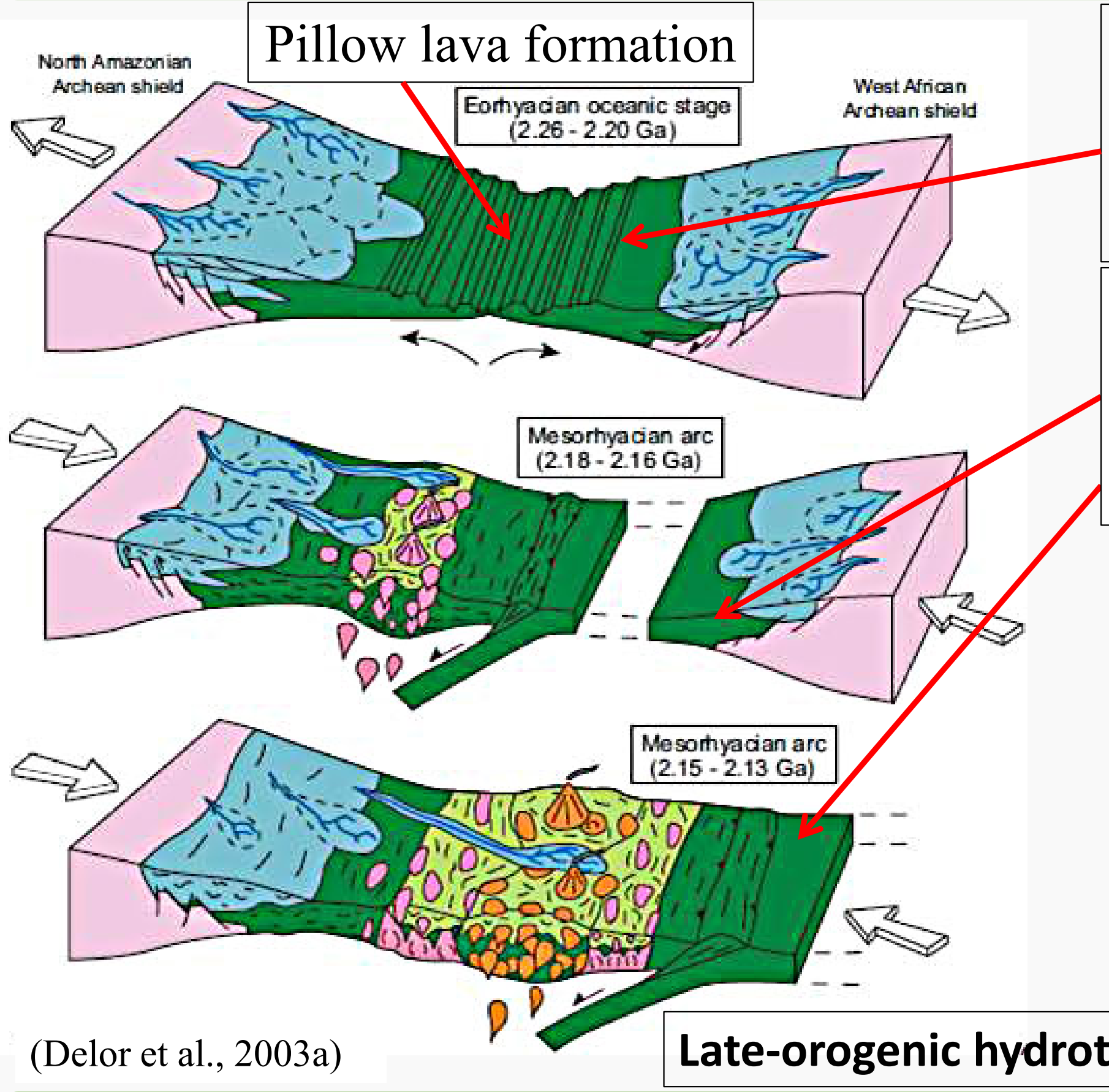
### SA12

- No altered palagonite. Gel on top of metabasalt
- Enrichment in rims →Gel with concentric bands altered to epidote, quartz + some amphibole.
- Fe depleted.



© Alex Glass, Duke University

## CONCLUSION

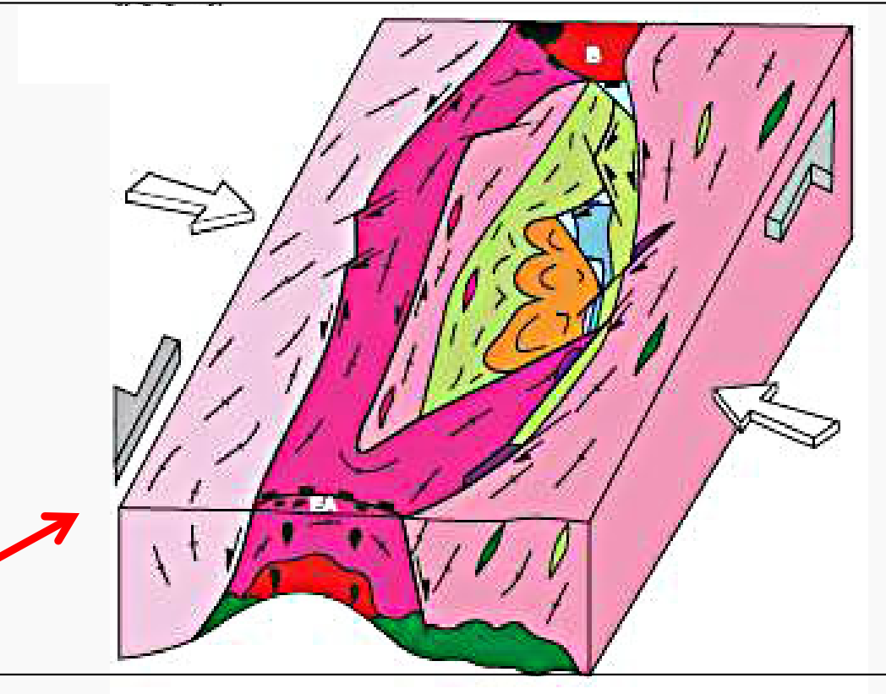


Pillow lava formation

(Delor et al., 2003a)

**Seawater (pre-metamorphic) alteration:** 1. Formation palagonite from glass. 2. interaction with sea water, Fe, Mg, Ca, Ti, Na+K mobility.
3. deposition interstitial Si-gel

**Regional metamorphism during Trans-Amazonian Orogeny**: 1. **Basalt** > amp, ep, chlor, alb. 2. **palagonite** > qtz, chlor, ep, act, gar.
3. **Si-gel** > qtz, ep, chl



**Late-orogenic hydrothermal alteration**: qtz-calc-ep veins, pyrite-gold(?)

## ACKNOWLEDGEMENT

The Master in Mineral Geosciences program is sponsored by Rosebel Goldmines N.V., subsidiary of IAMGOLD CORPORATION. Prof. Dr. Salomon Kroonenberg is genuinely thanked for his guidance and support. Sanne Braat is thanked for chemical analyses.

# Timing of the origin and uplift of the Bakhuis-Tambaredjo Horst, Suriname

**Rohini Girjasing[1], Salomon Kroonenberg[1], Rakesh Ramdajal[2], Theo Wong[1].**
[1]Anton de Kom Universiteit van Suriname. [2] Staatsolie Maatschappij Suriname N.V.

## Introduction

The Bakhuis Mountains with its NE-SW stretching horst structure is underlain mainly by high-grade metamorphic rocks which originated between 2.07-2.05 Ga within the Trans Amazonian Orogeny (De Roever et al., 2003; Klaver et al., 2015). Extensive mylonitization along the border faults of this Bakhuis Granulite Belt has been attributed to the Nickerie Metamorphic Episode around 1.2 Ga (Priem et al., 1971; Bosma et al., 1983). The morphological freshness of the eastern fault scarp suggests that the Bakhuis Horst has been active relatively recently (**Fig.1**).

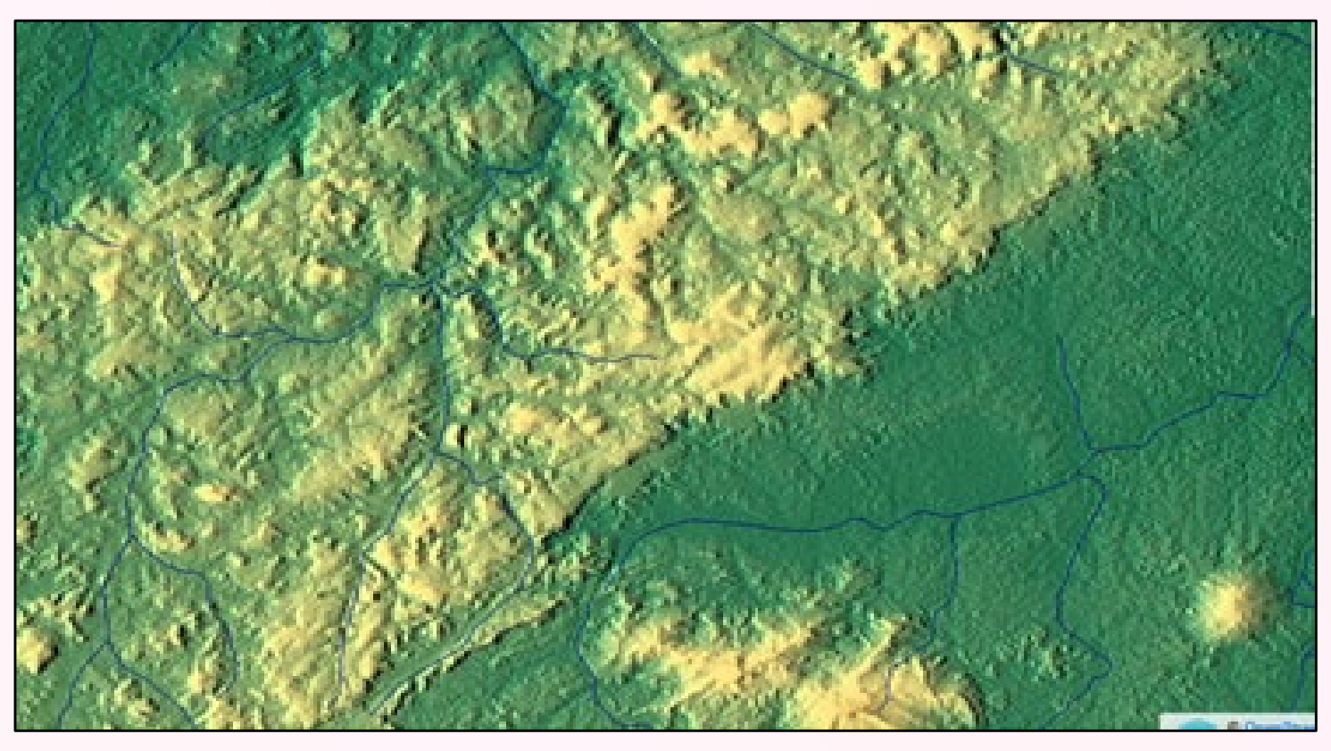


**Fig. 1.** The Bakhuis Horst and its eastern border fault.

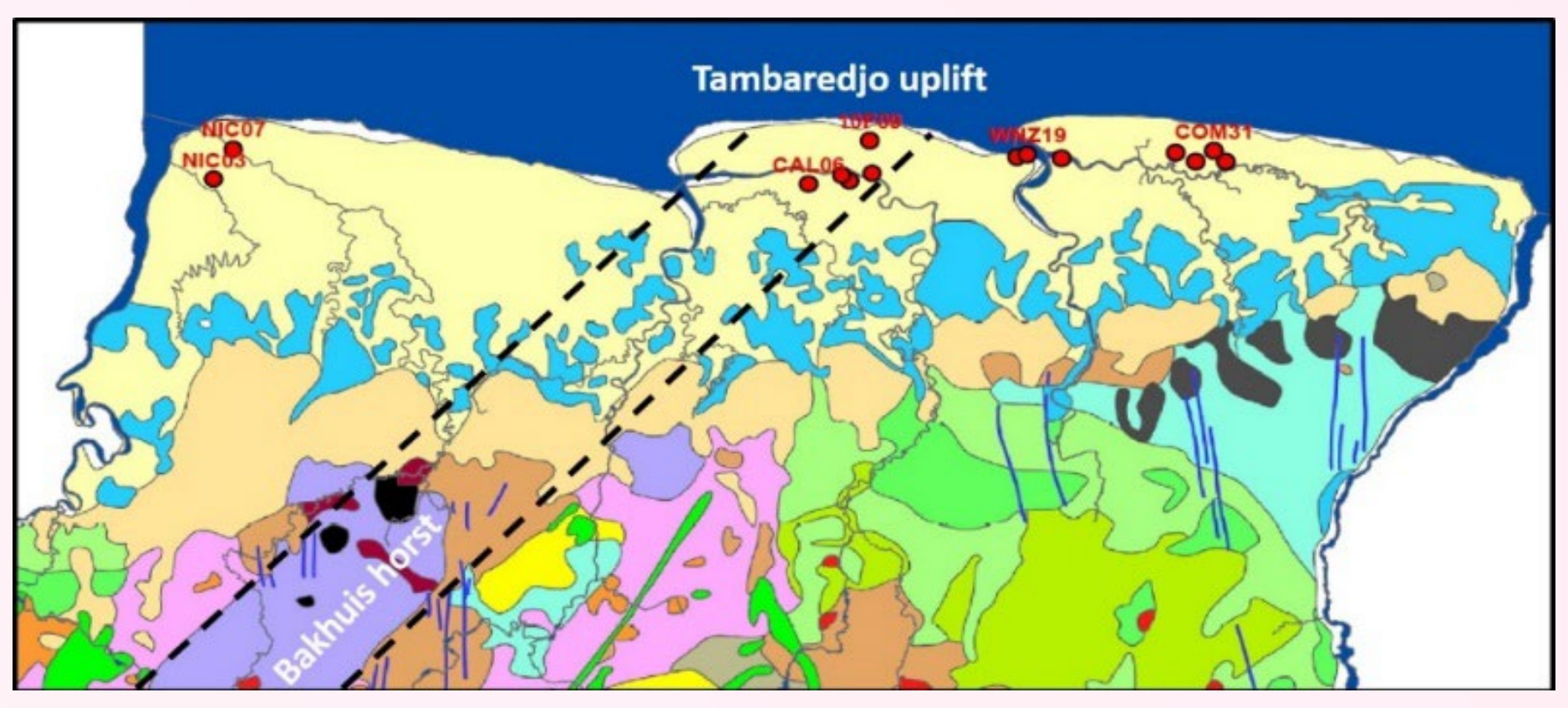


**Fig. 2.** Conjectural continuation of the Bakhuis horst into the Tambaredjo uplift, on a simplified geological map of northern Suriname. Red dots represent studied wells

Seismic studies carried out by Staatsolie revealed an uplifted structure below the main oil producing oil fields in Tambaredjo which is in line with the Bakhuis structure and was therefore considered to form the continuation of the Bakhuis horst. (Tambaredjo uplift) (**Fig. 2,3**).

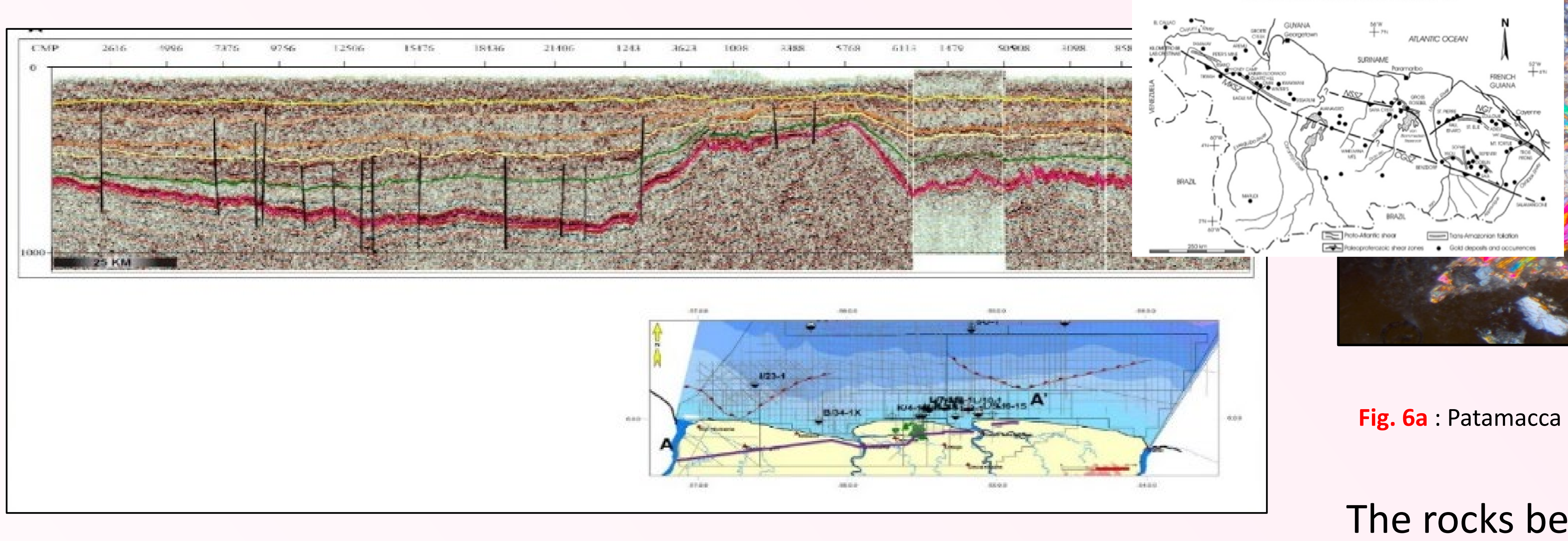


**Fig. 3.** The Tambaredjo uplift in a W-E seismic profile of the coastal plain. Nelson, 2016

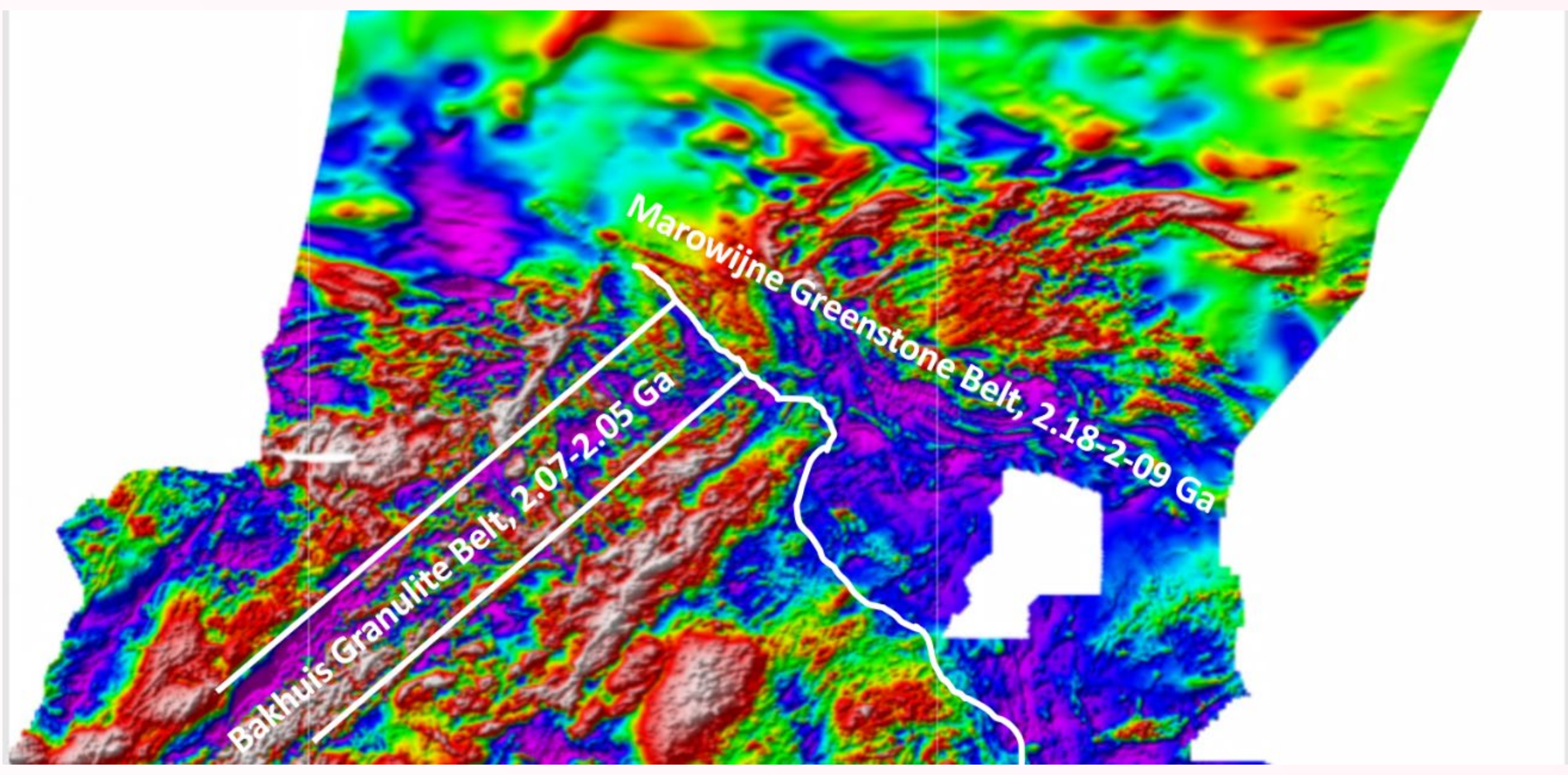


**Fig.4.** Aeromagnetics suggest that the Bakhuis Granulite Belt is cut off by the Marowijne Greenstone Belt.

However, recent aeromagnetic data cast doubt on the continuation of the Bakhuis horst into the`Tambaredjo uplift, as it seems that the Bakhuis structure is cut off by the 2.18-2.09 Ga Marowijne Greenstone Belt, in spite of its older age (**Fig. 4**). Also the aeromagnetic border faults of the Bakhuis Belt don't continue into the Greenstone belt even though the border faults are both younger than the Bakhuis Granulite Belt and the Greenstone Belt. To solve these problems the nature of the Precambrian rocks from oil wells are studied to know if they show more similarities to the Bakhuis Granulites or Marowijne Greenstones.

## Methodology

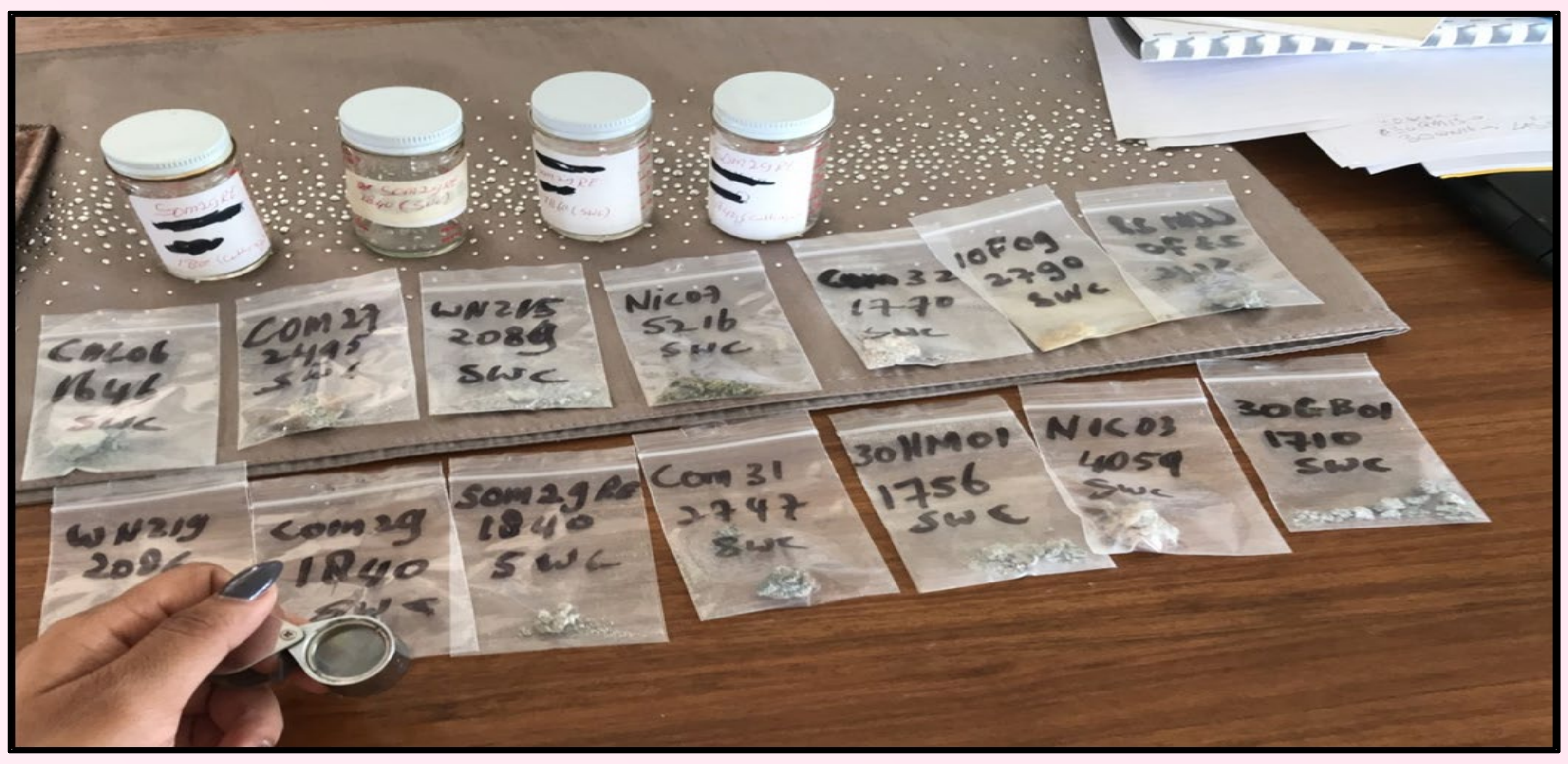


**Fig.5.** Provided samples by Staatsolie used for microscopic research

Using Petrel, out of 154 oil wells drilled by Staatsolie in the coastal plain, 15 were selected which penetrated the Precambrian basement. Well-bore cuttings and SWC (Side Wall Cores) (**Fig.5**) from the basement were investigated in the stereomicroscope and in thin sections of impregnated material to establish the rock type below the oil fields.

## Results

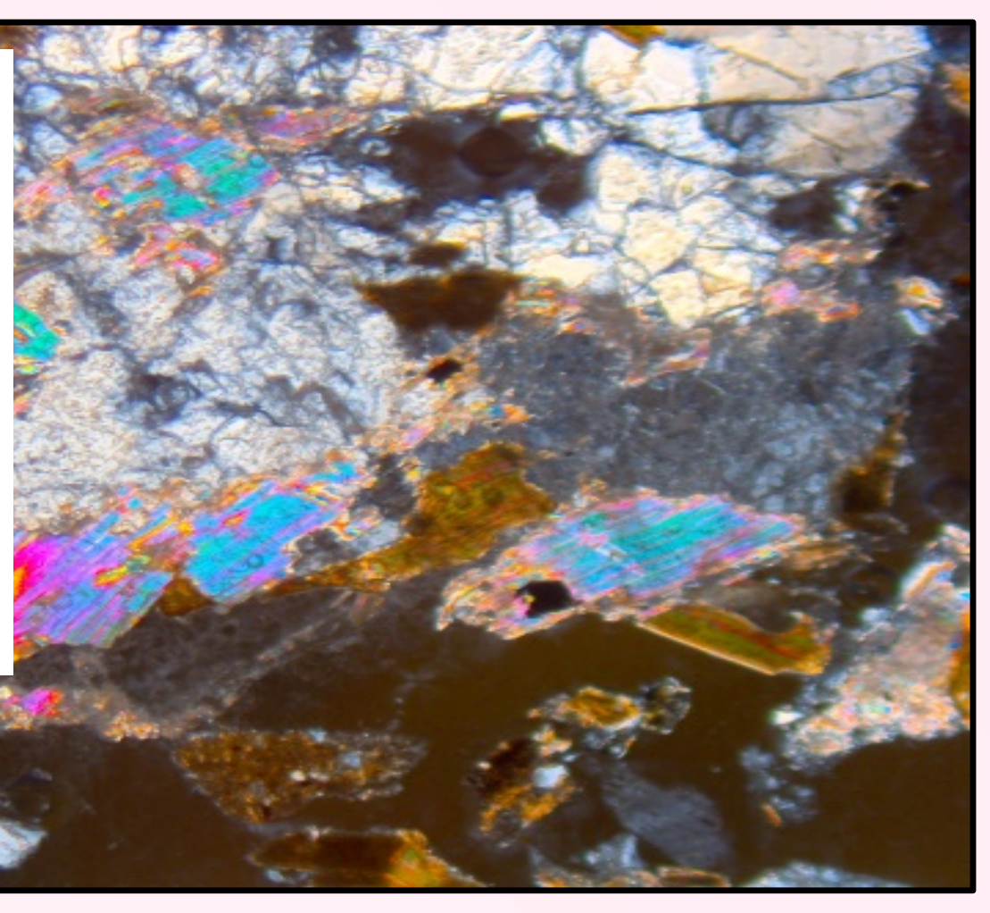


**Fig. 6a** : Patamacca bi-mica granite, Tambaredjo

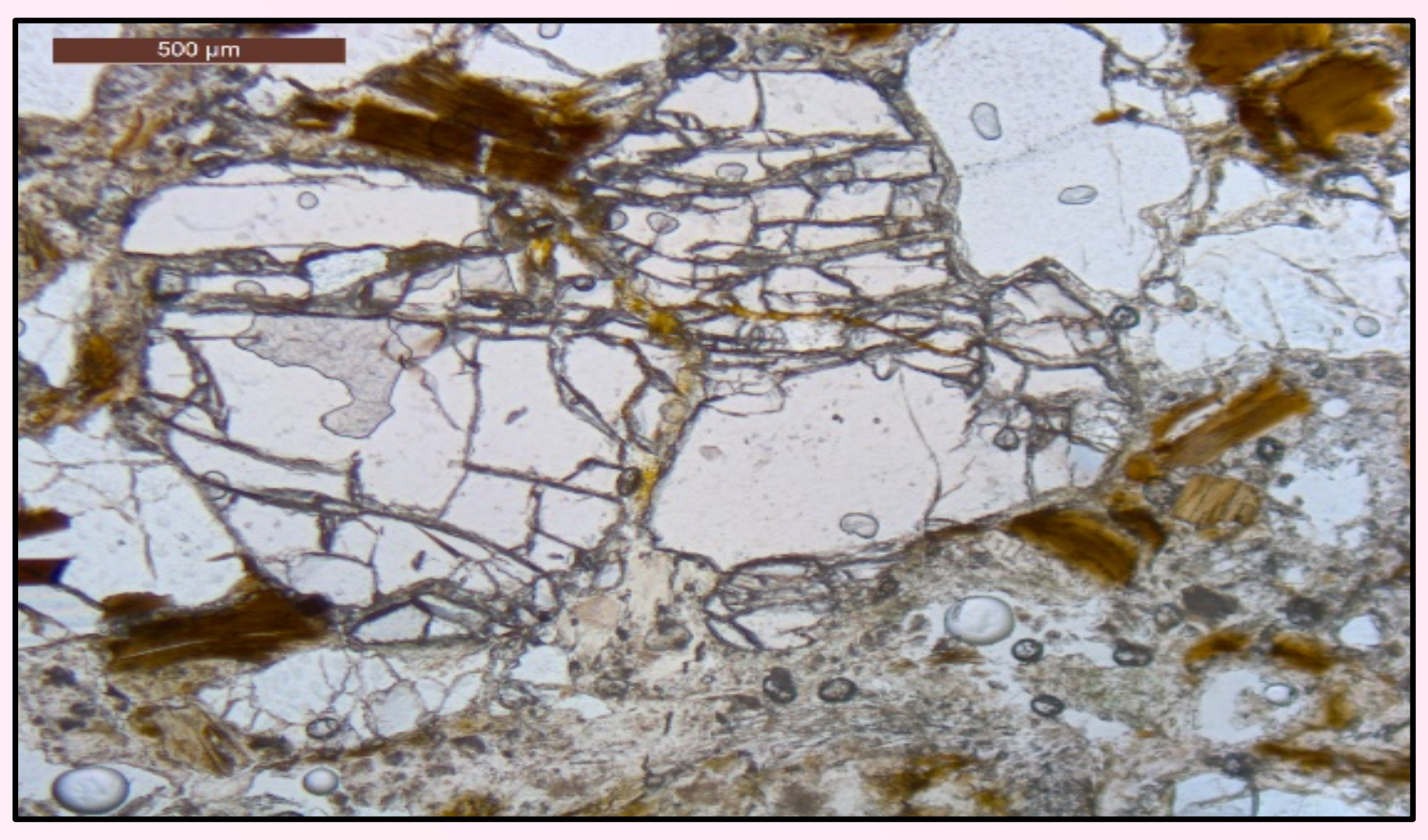


**Fig. 6b.**: Sara's Lust biotite-garnet gneiss, Commewijne

The rocks below the oil wells consist mainly of biotite-garnet-(sillimanite-) gneisses and biotite-muscovite granites, resembling the Sara's Lust Gneiss and Patamacca Bi-Mica Granite, respectively, typical components of the greenstone belt, and differ from the rocks in the Bakhuis Granulite Belt.

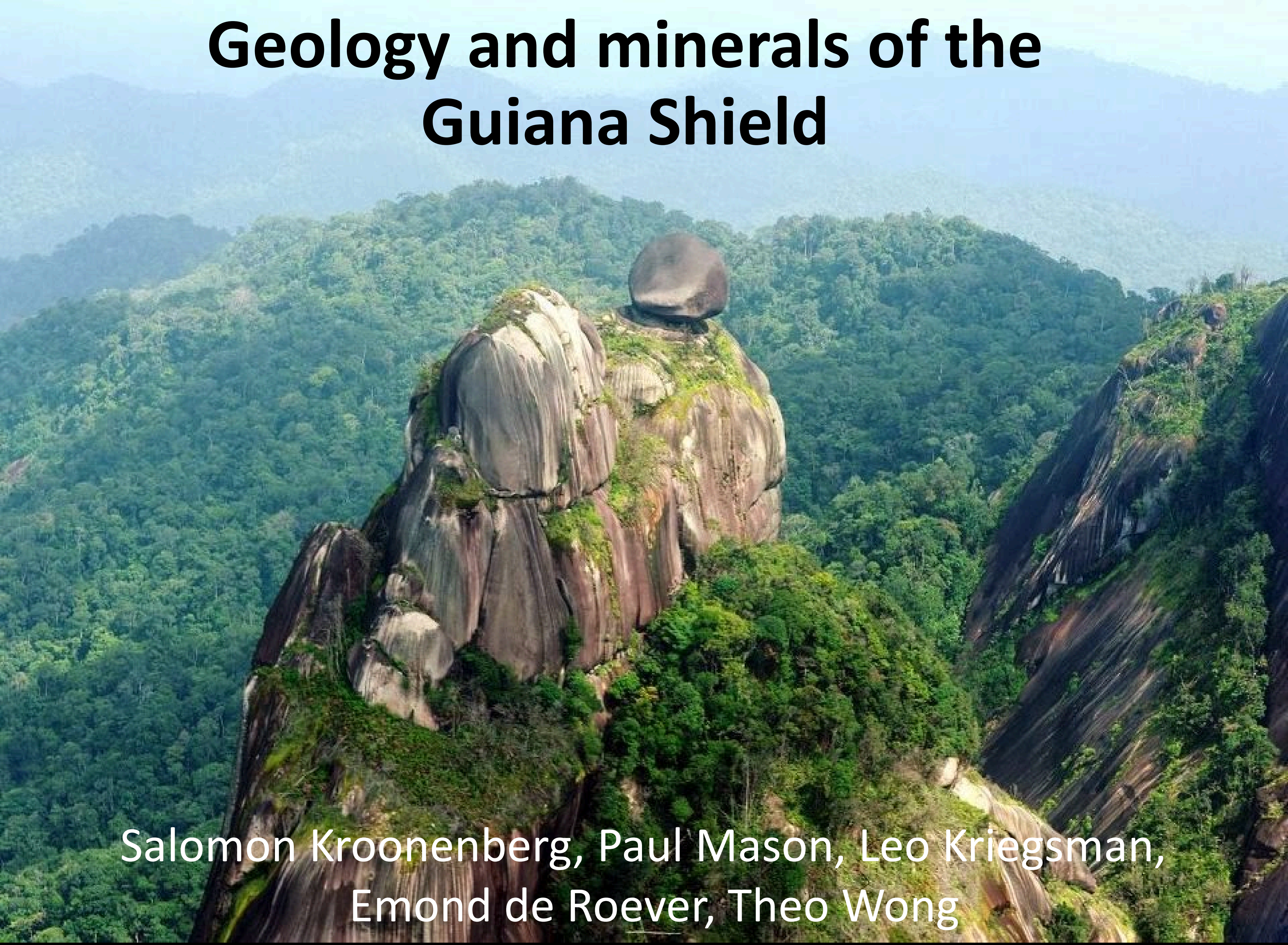
## Discussion

The fact that the 2.07-2.05 Ga Bakhuis Granulite Belt is cut-off by the older 2.18-2.09 Ga Marowijne Greenstone Belt requires a tectonic event younger than both. The most probable candidate is the North Suriname Shear Zone around 2.0 Ga (Voicu et al., 2001). It also requires that the mylonitic border faults of the Bakhuis horst are older than the Nickerie Metamorphic Episode of 1.2 Ma. Nevertheless, the morphological freshness of the Bakhuis border fault in line with the Tambaredjo border fault supports their common origin. This Mesozoic-Cenozoic uplift event is only not visible in the aeromagnetics because it is an extensional event unlike to give magnetic responses.

## Conclusion

In spite of the aeromagnetic discontinuity, the Bakhuis-Tambaredjo Horst is a coherent tectonic entity uplifted during the Mesozoic-Cenozoic, probably related to the breakup of Gondwana.

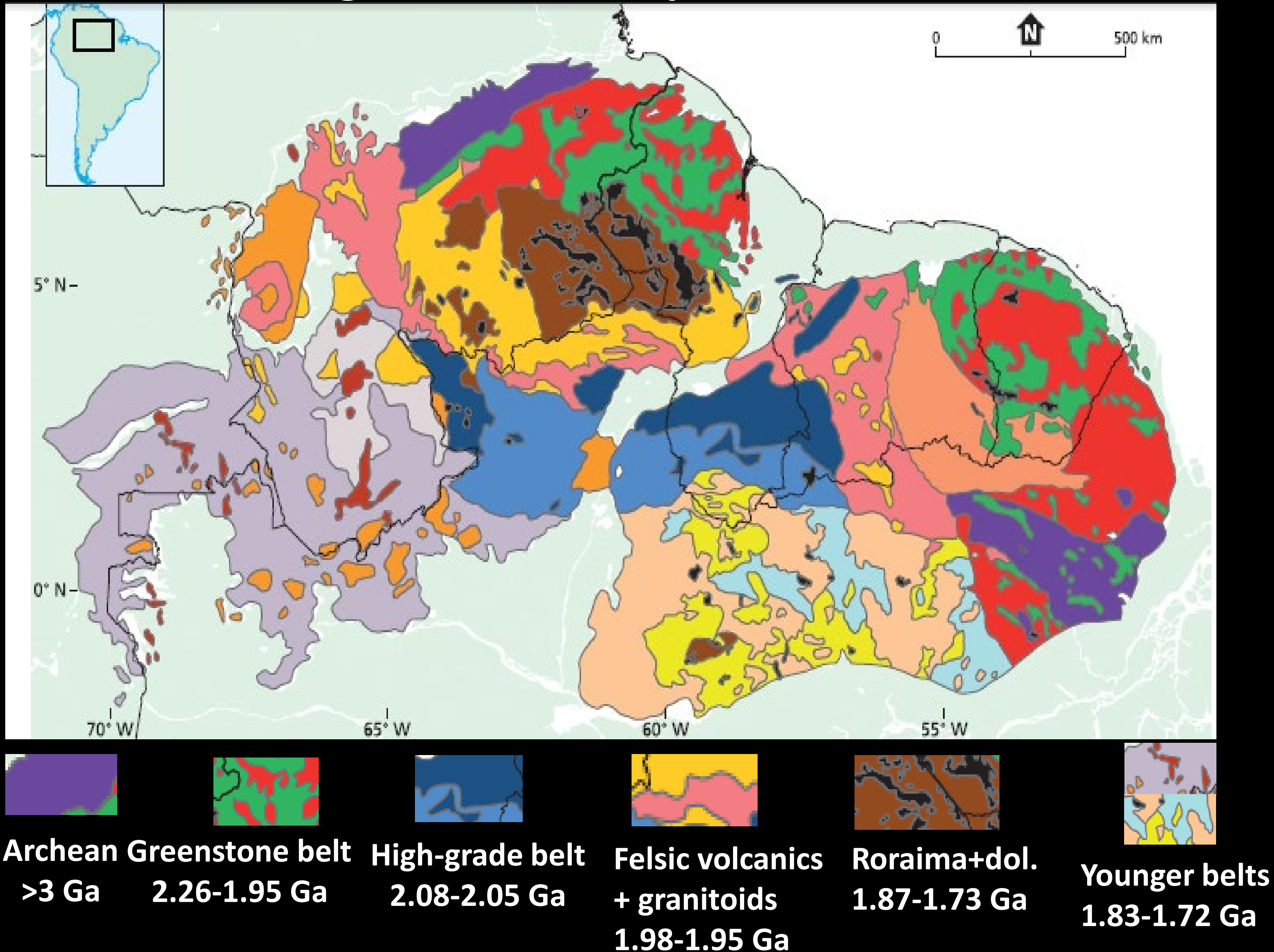
## Acknowledgements



# Geology and minerals of the Guiana Shield

Salomon Kroonenberg, Paul Mason, Leo Kriegsman,
Emond de Roever, Theo Wong

# Geological sketch map Guiana Shield



Archean
>3 Ga

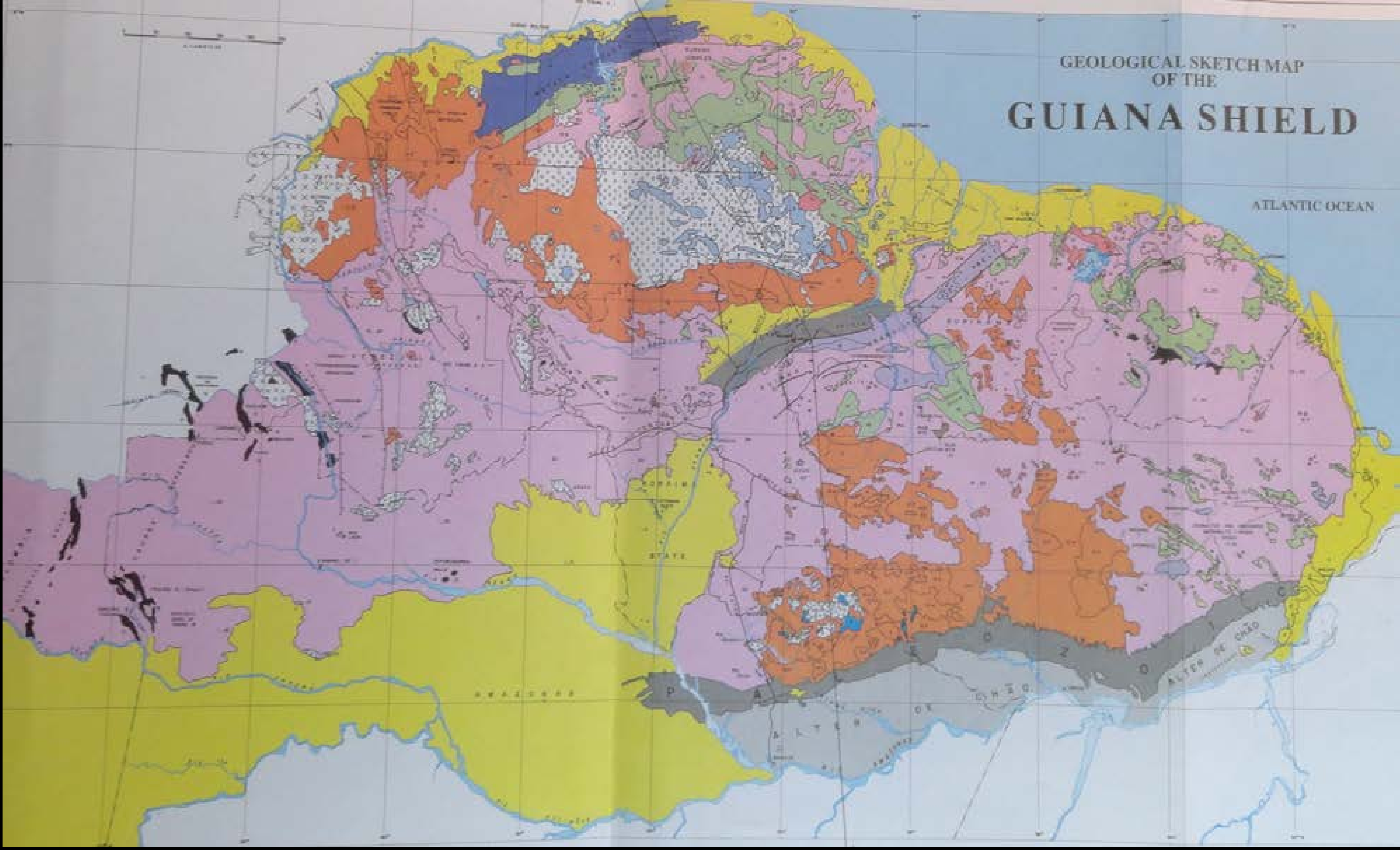
Greenstone belt
2.26-1.95 Ga

High-grade belt
2.08-2.05 Ga

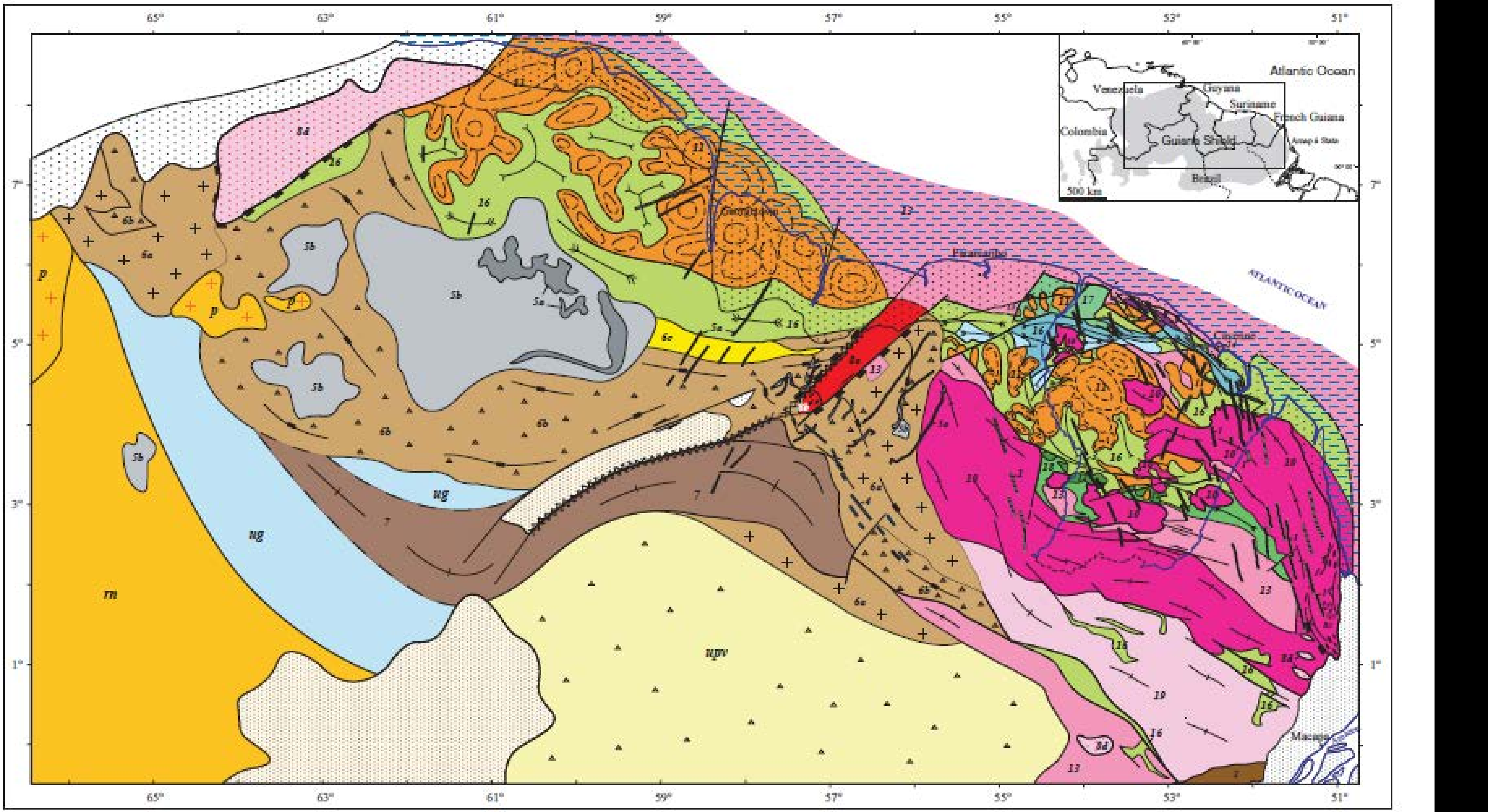
Felsic volcanics
+ granitoids
1.98-1.95 Ga

Roraima+dol.
1.87-1.73 Ga

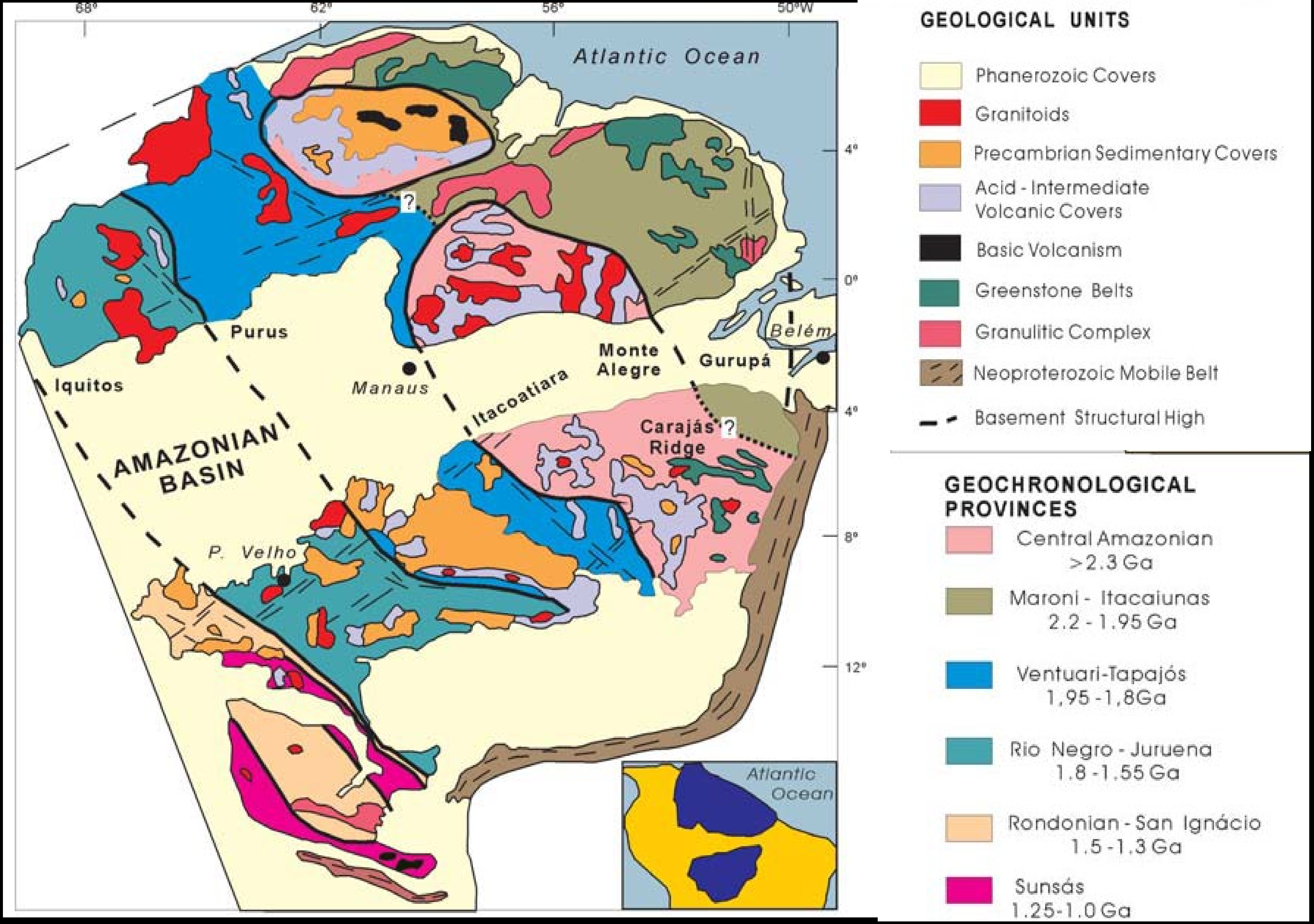
Younger belts
1.83-1.72 Ga



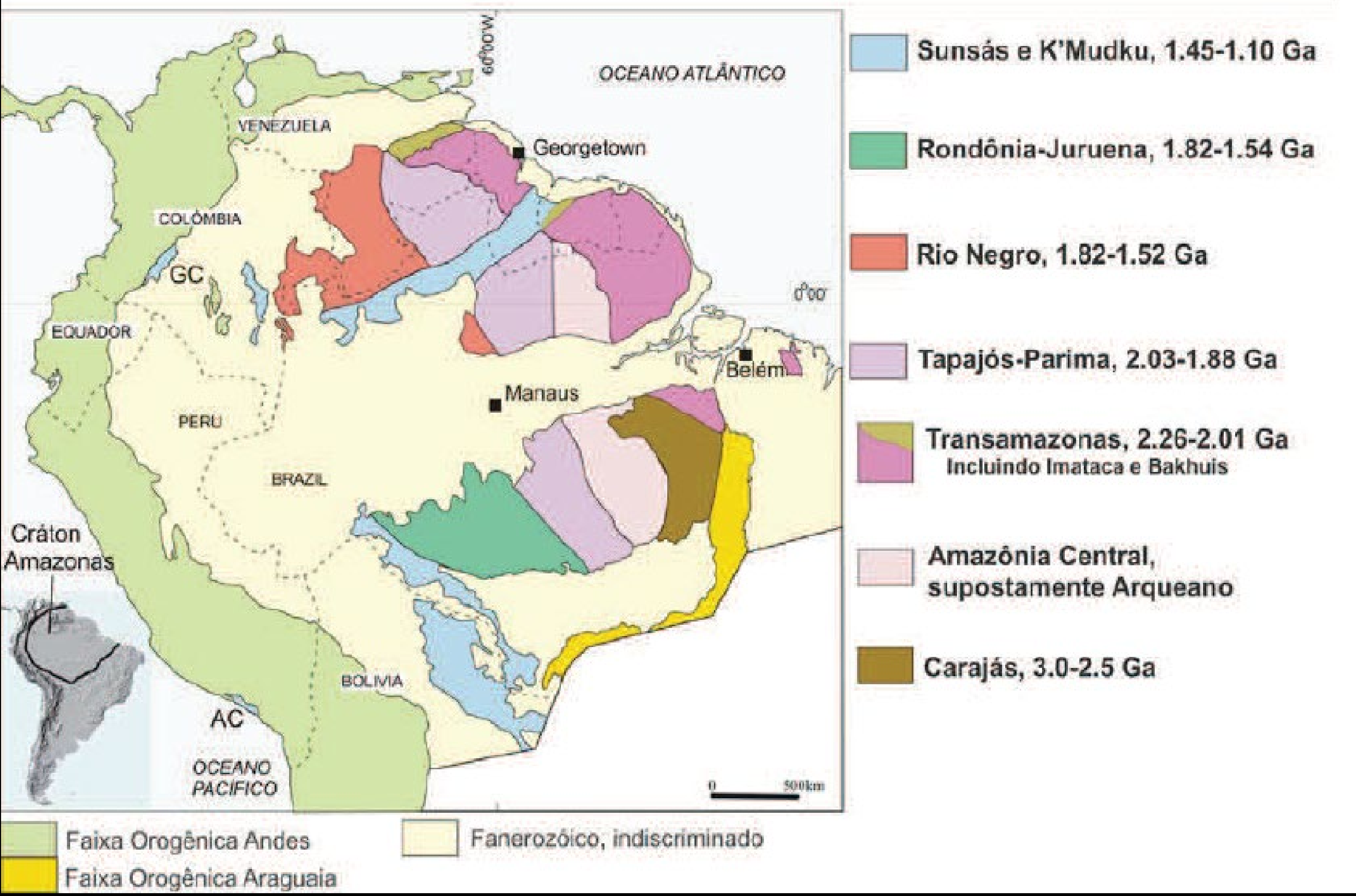
Gibbs and Barron, 1993, book: *Geology of the Guiana Shield*
Still much unknown



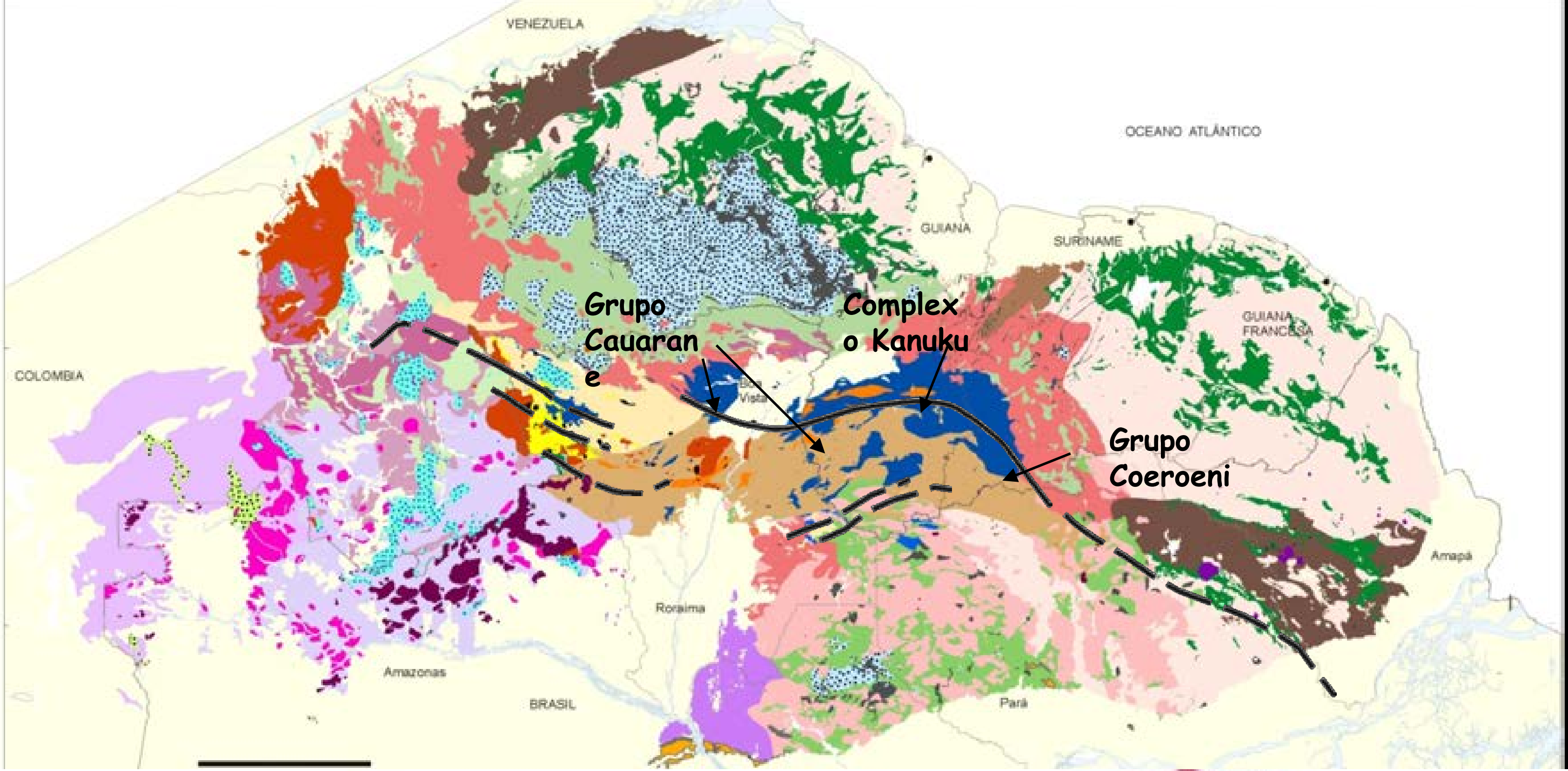
Delor et al., 2003: Trans-Amazonian Orogeny
Details in greenstone belt, good geodynamic analysis,
Little differentiation in Brazil

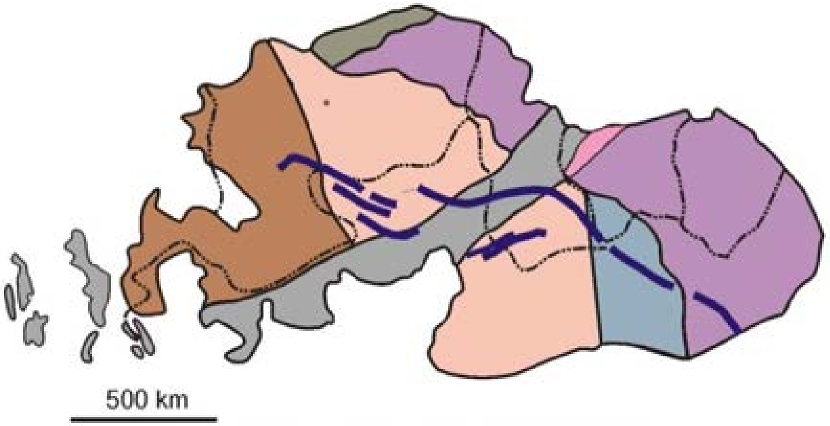


Tassinari&Macambira, 1999: westward continental accretion;
Influential map, but Guiana Shield mostly incorrect

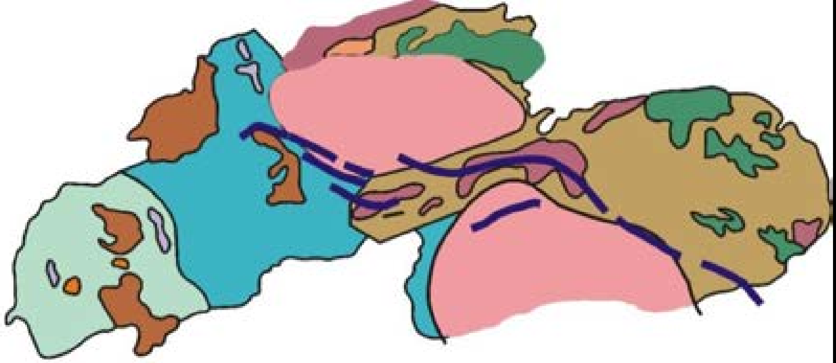


Last reconstruction by Santos, 2006; K'Mudku belt incorrect



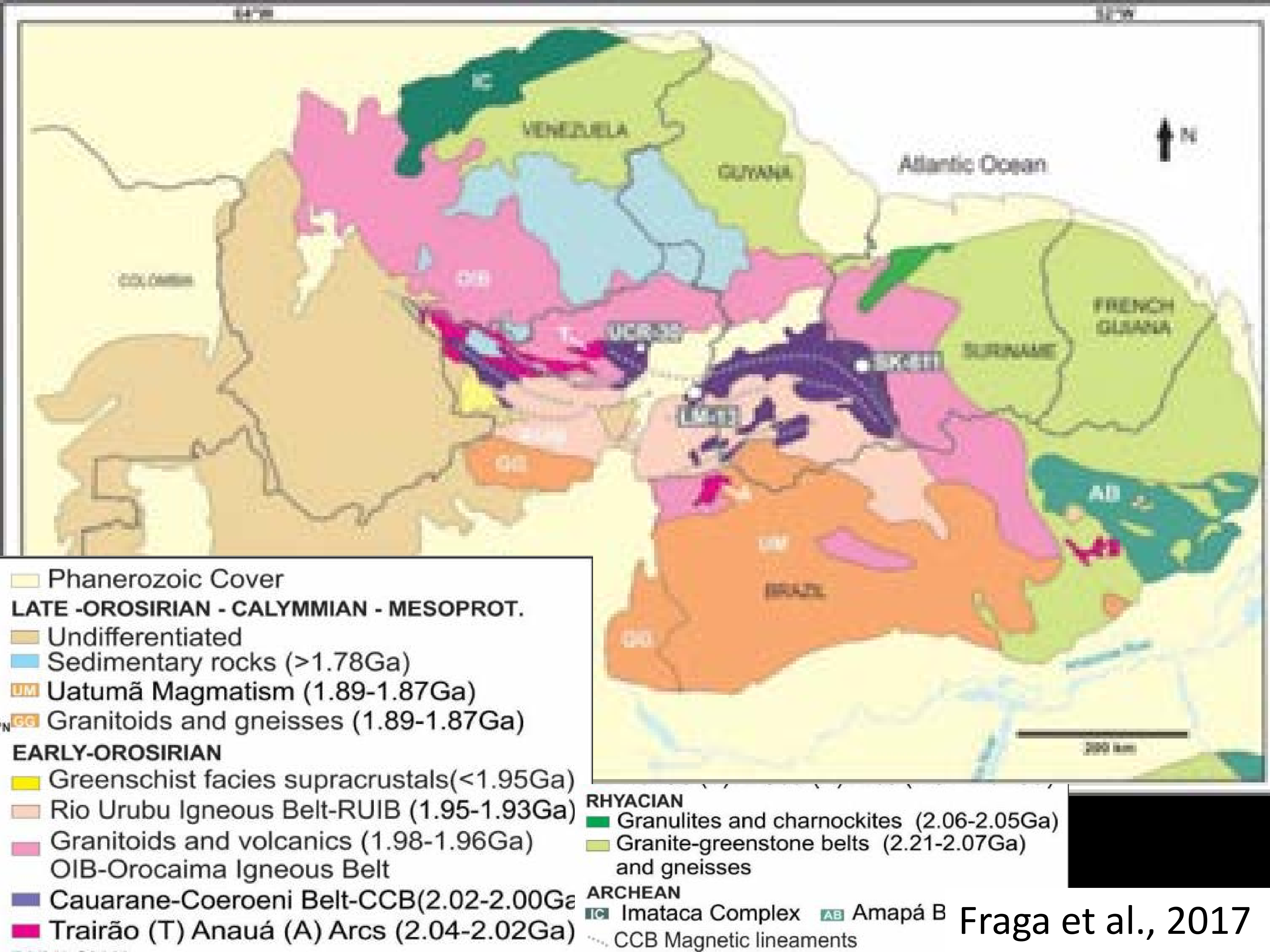


GEOTECTONIC PROVINCES
Santos et al. (2000, 2006)

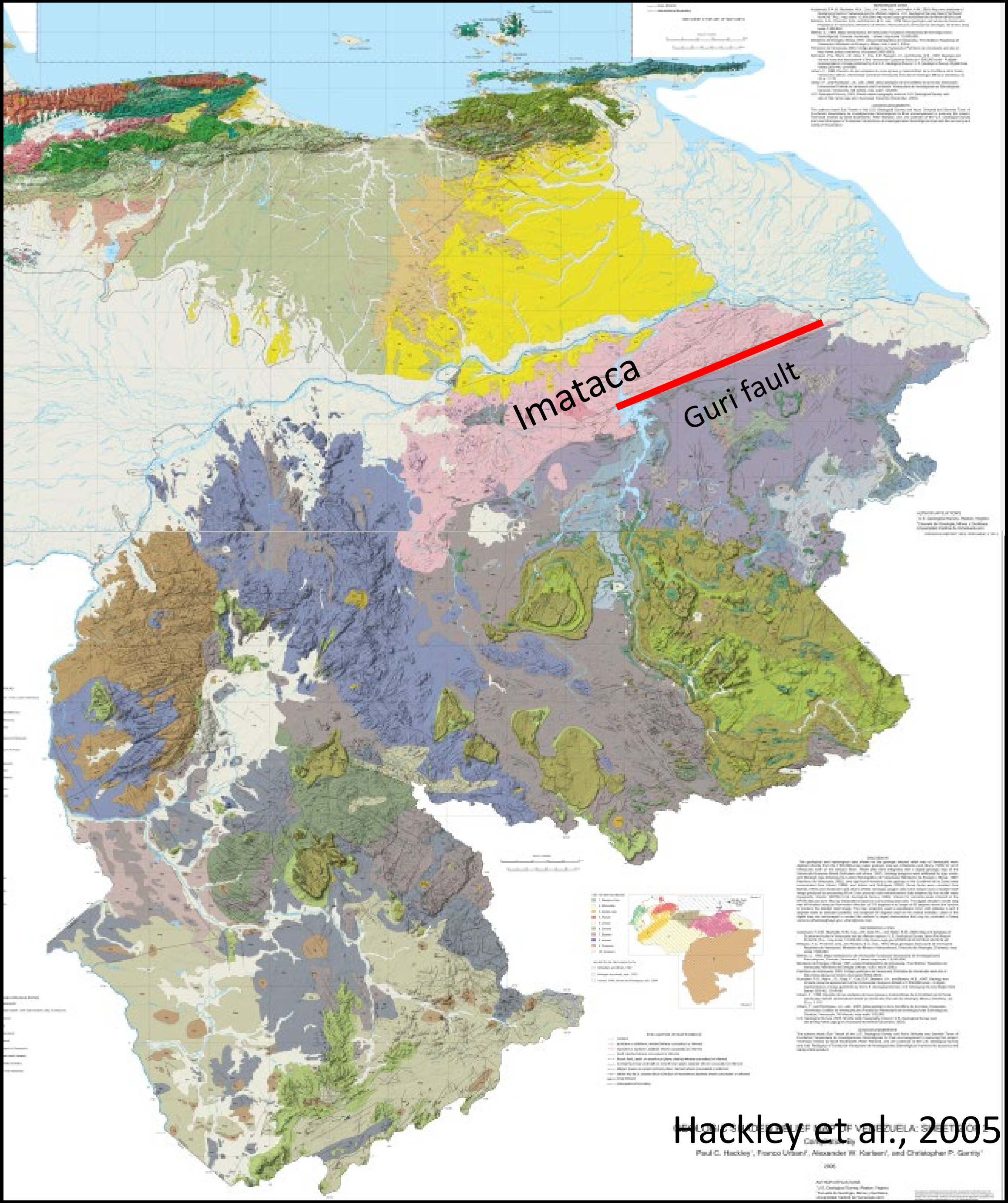


GEOCHRONOLOGICAL PROVINCES
Tassinari & Macambira (1999, 2004)

**Fraga et al., 2009: N>S younging, subduction and collision from south**



Fraga et al., 2017



Hackley et al., 2005

# Pre-Trans-Amazonian

**Imataca Archean belt, Venezuela**
(allochthonous?)

Granulite-facies paragneisses, amphibolites orthogneisses, granulites, dolomitic marbles, BIF

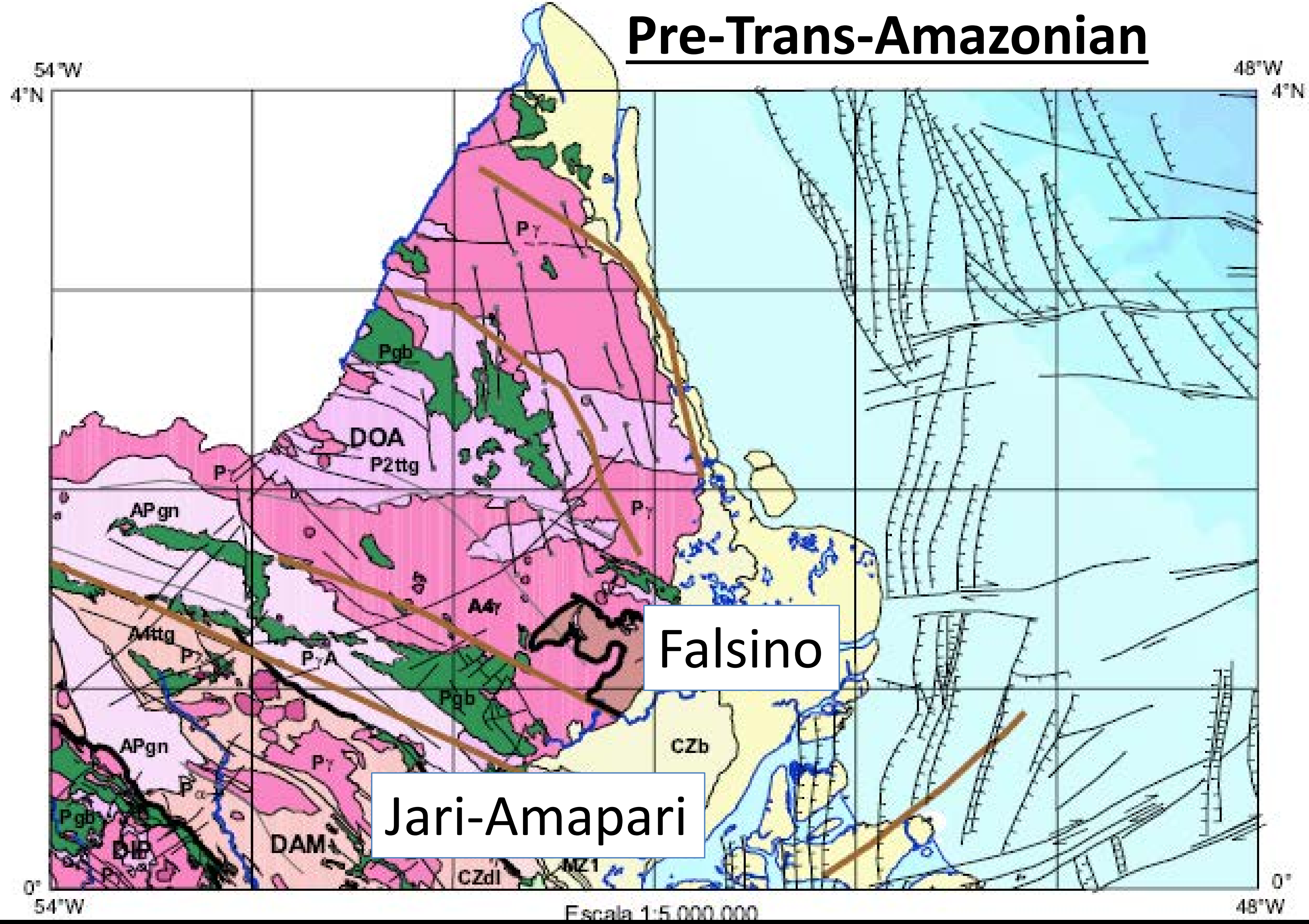
3.23 Ga (U-Pb SHRIMP) with metamorphic overprint down to 2.21-2.05 Ga (Trans-Amazonian)

©EDGAR CHACÍN, 2001

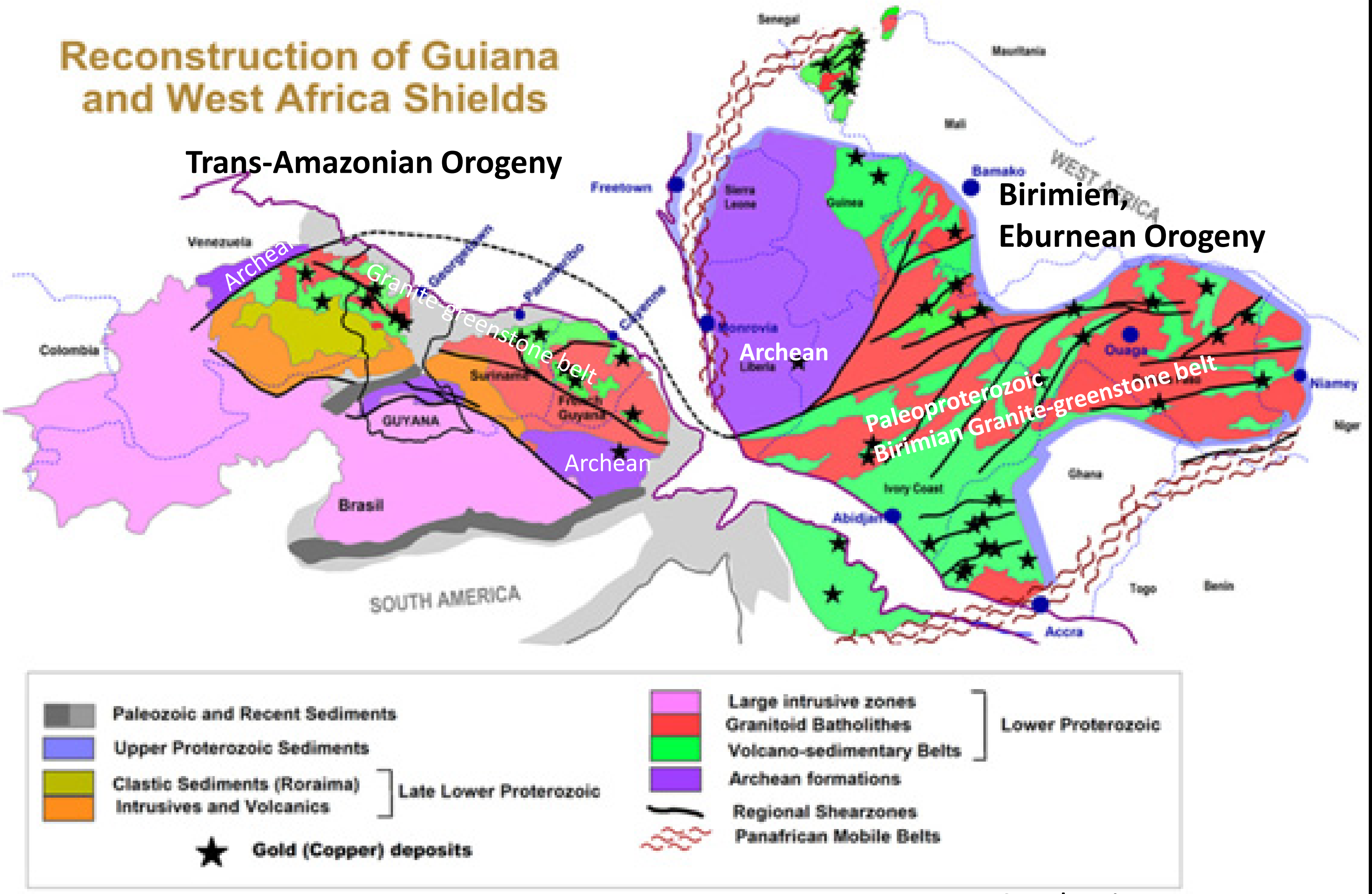
Estratos de formaciones de hierro del Complejo de Imataca

Archean Banded Iron Formation, Superior/Algoma type, El Pao, Venezuela

# Pre-Trans-Amazonian



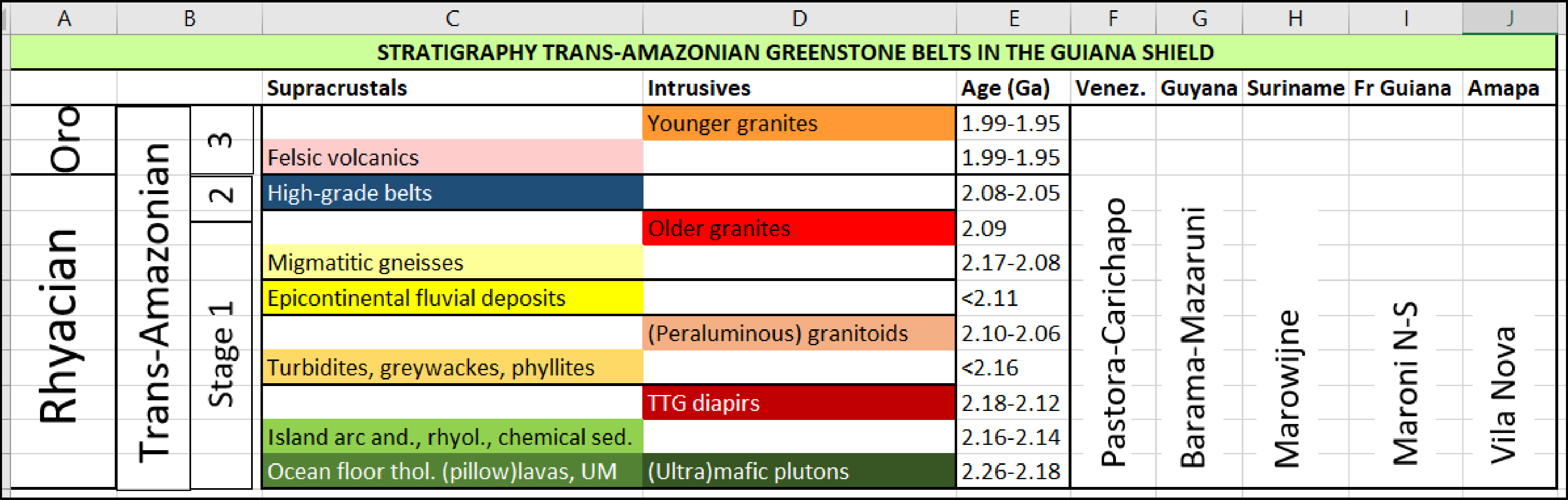
Archean domains in Amapa, Brazil (CPRM)



Sandspringresources.com

Trans-Amazonian greenstone belts, 2.26-2.08 Ga (=Birimien, West-Africa)

# Trans-Amazonian Orogeny Stage I: Greenstone belts, 2.26-2.08 Ga



| A | B | | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| **STRATIGRAPHY TRANS-AMAZONIAN GREENSTONE BELTS IN THE GUIANA SHIELD** | | | | | | | | | | |
| | | | **Supracrustals** | **Intrusives** | **Age (Ga)** | **Venez.** | **Guyana** | **Suriname** | **Fr Guiana** | **Amapa** |
| Oro | Trans-Amazonian | 3 | | Younger granites | 1.99-1.95 | Pastora-Carichapo | Barama-Mazaruni | Marowijne | Maroni N-S | Vila Nova |
| | | | Felsic volcanics | | 1.99-1.95 | | | | | |
| Rhyacian | | 2 | High-grade belts | | 2.08-2.05 | | | | | |
| | | Stage 1 | | Older granites | 2.09 | | | | | |
| | | | Migmatitic gneisses | | 2.17-2.08 | | | | | |
| | | | Epicontinental fluvial deposits | | <2.11 | | | | | |
| | | | | (Peraluminous) granitoids | 2.10-2.06 | | | | | |
| | | | Turbidites, greywackes, phyllites | | <2.16 | | | | | |
| | | | | TTG diapirs | 2.18-2.12 | | | | | |
| | | | Island arc and., rhyol., chemical sed. | | 2.16-2.14 | | | | | |
| | | | Ocean floor thol. (pillow)lavas, UM | (Ultra)mafic plutons | 2.26-2.18 | | | | | |

General consensus on major lithostratigraphic units but not on geodynamic interpretation

Tholeiitic pillow lavas, Poederberg, Suriname

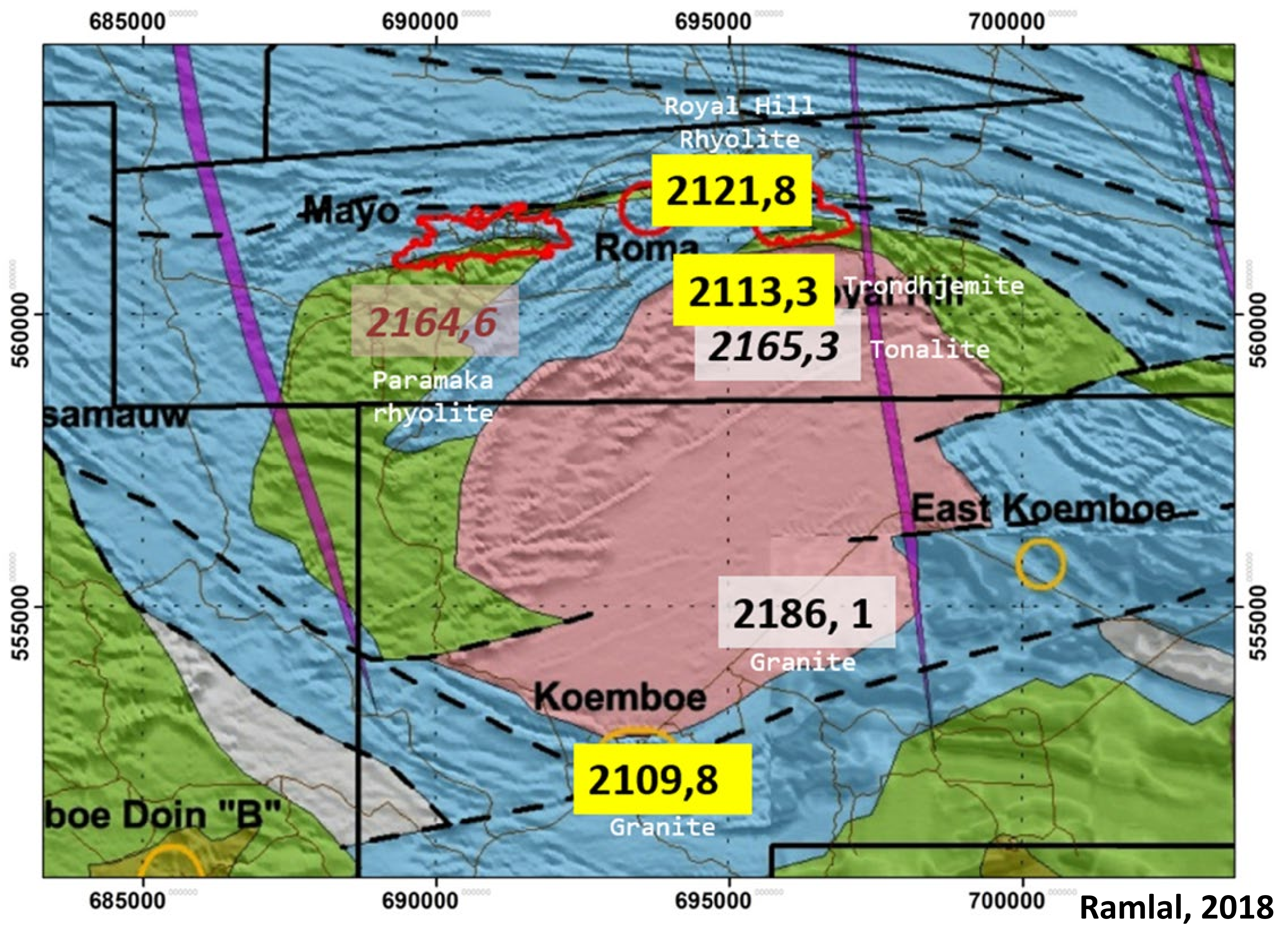
Gold nugget, 245 gram

Diamonds in volcaniclastic komatiite from French Guiana

Nickel-rich talcschist Saramacca

Chromite float, Upper Saramacca

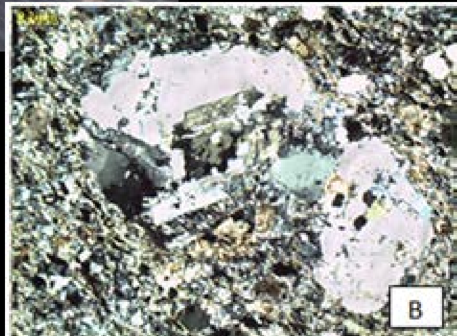
Serra do Navio manganese mine, Mn-laterite on Mn-carbonates
Vila Nova greenstone belt, Amapá, Brazil, 1975



Ramlal, 2018

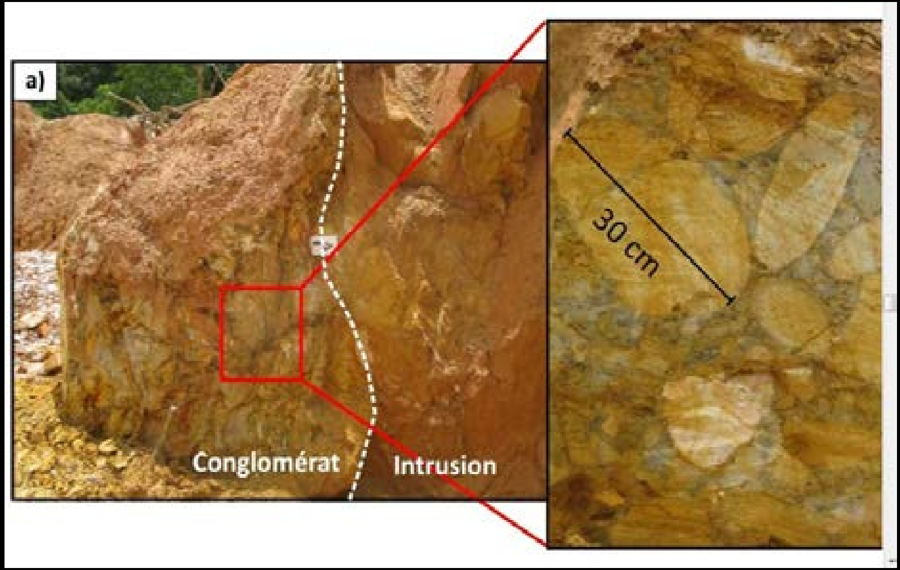
A typical multiphase TTG intrusion, IAMGOLD Rosebel Gold Mine

Meta-turbidites (Armina, Haimaraka Fmns)
Meta-greywackes, shales/ phyllites
Detrital zircons ~2.16 Ga



**Tonalite clast** Armina Formation
Naipal & Kroonenberg, 2016

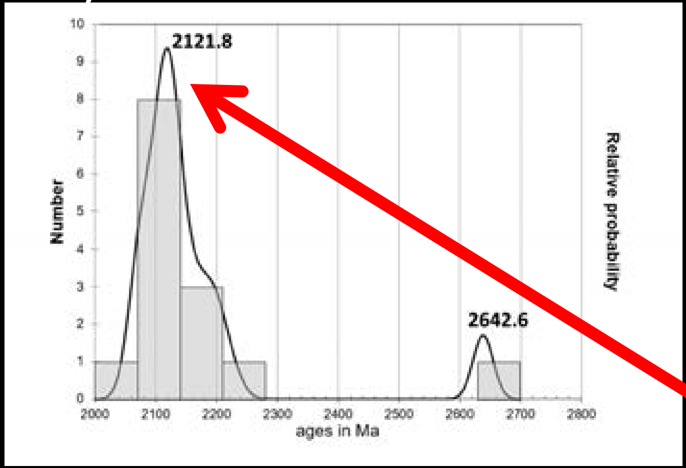
Gold-bearing pyrite in  metagreywackes and quartz vein
IAMGOLD Rosebel Gold Mines



Rosebel basal conglomerate with granitoid pebbles (Daoust, 2016)

Rosebel fluvial sandstone

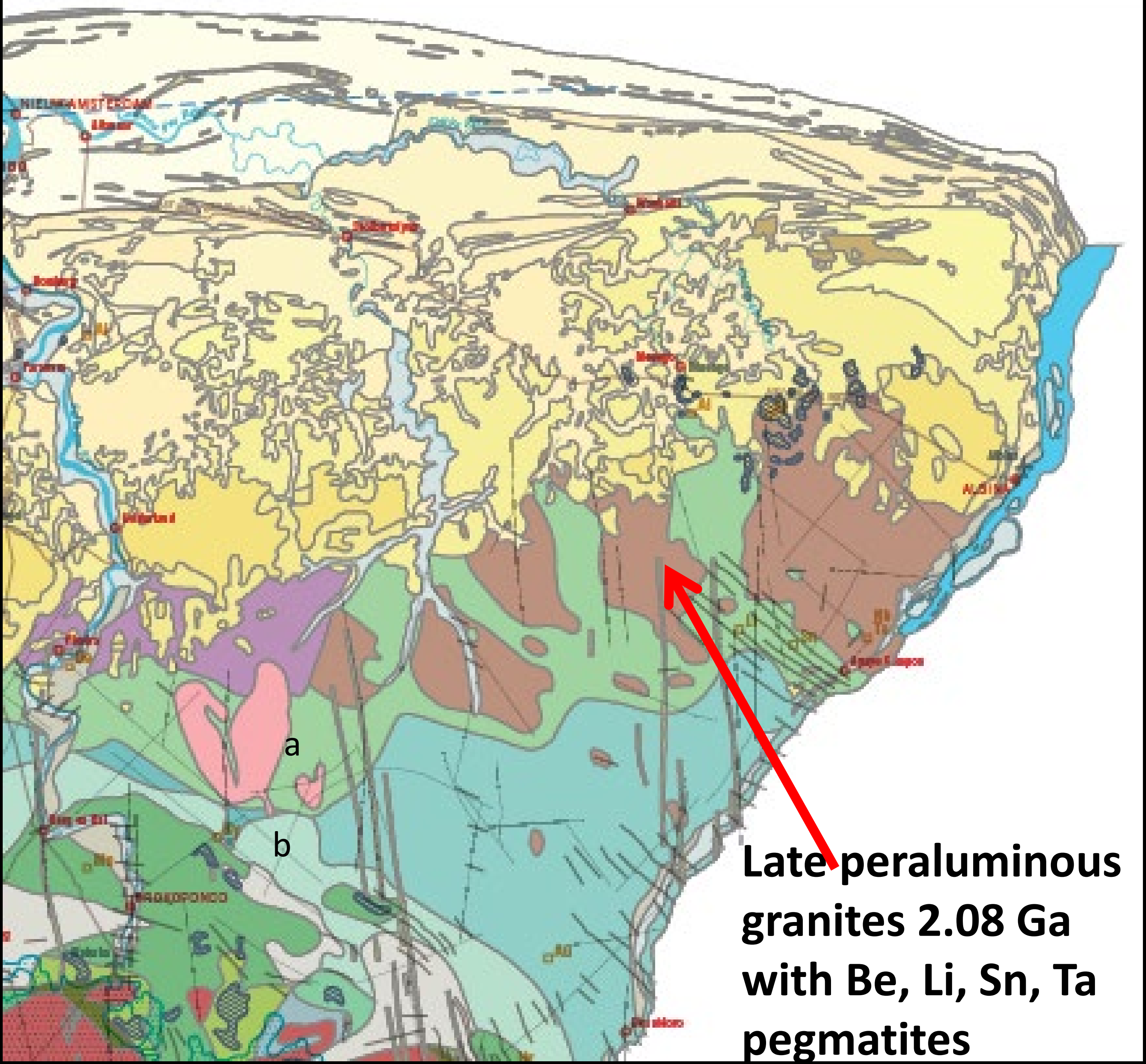
Daoust, 2016



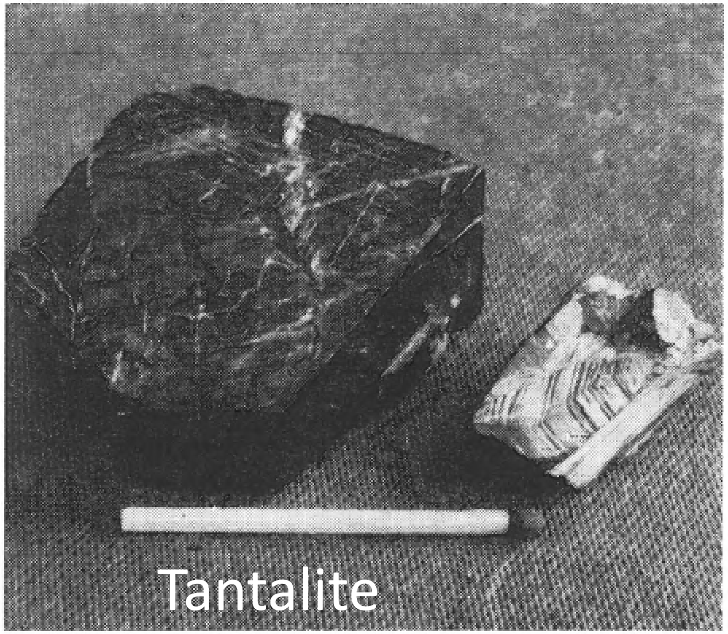
Intercalated rhyolitic ash bed: **2.12 Ga**

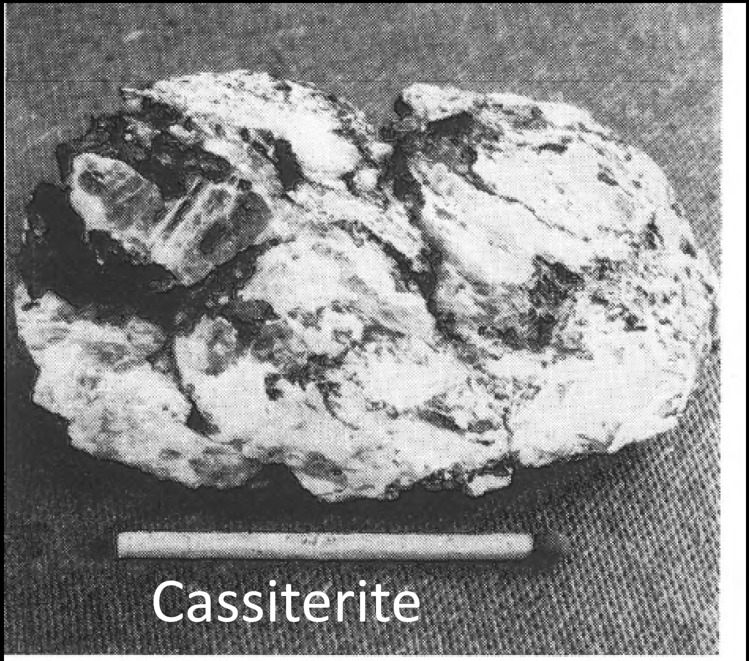
**Only Suriname and French Guiana**

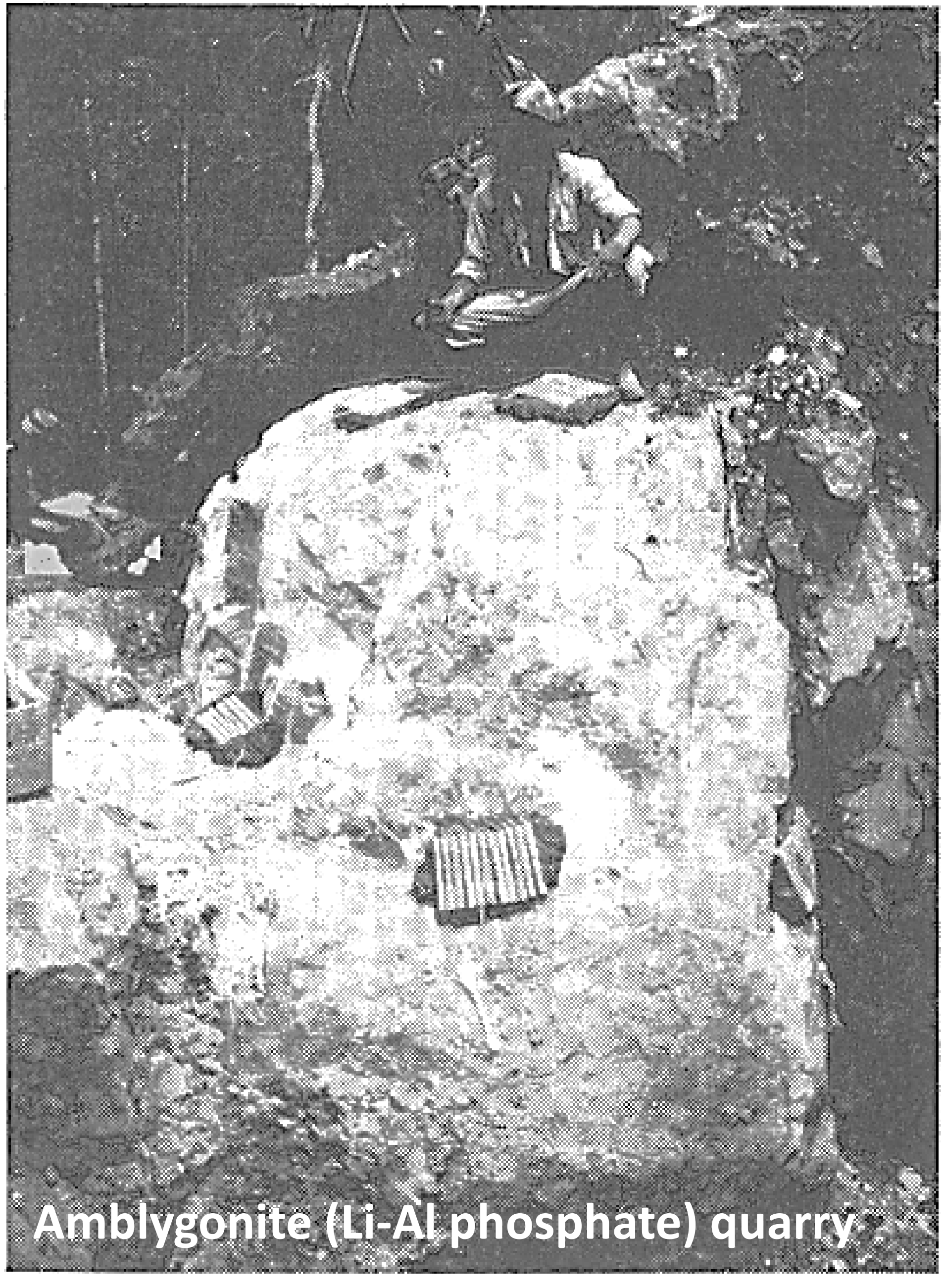
Dissected by late Au-qz veins



Late peraluminous granites 2.08 Ga with Be, Li, Sn, Ta pegmatites

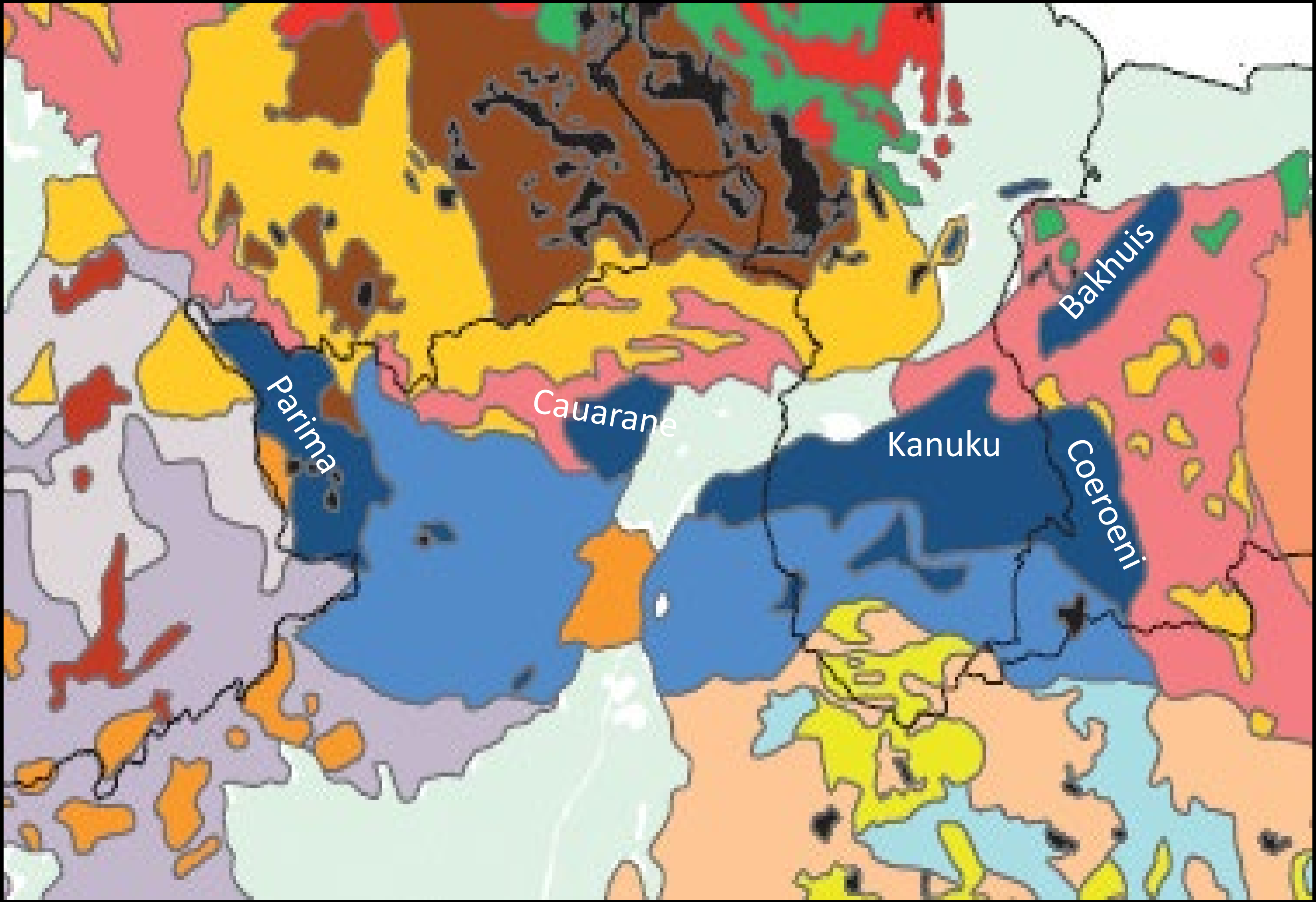

Tantalite


Cassiterite

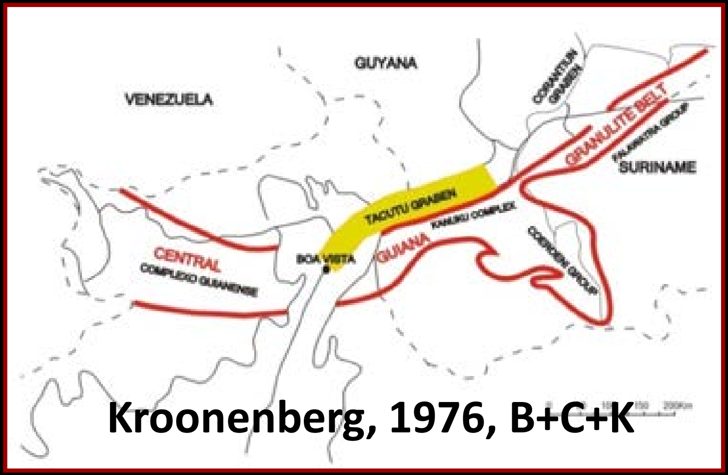

Amblygonite (Li-Al phosphate) quarry

# Late pegmatite minerals: Sn, Ta, Be, Li

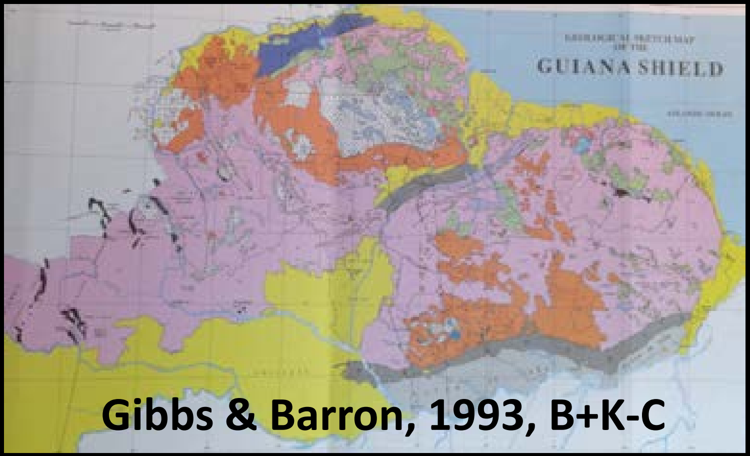
# Trans-Amazonian Orogeny Stage II: High-grade belts: 2.08-2.03, 1.98 Ga



Rifting, sedimentation, high-grade metamorphism?
Or orogenic belt due to northward subduction from S?

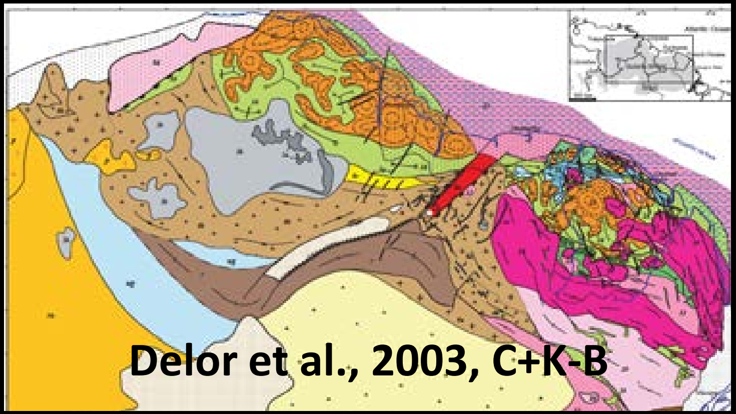


Kroonenberg, 1976, B+C+K

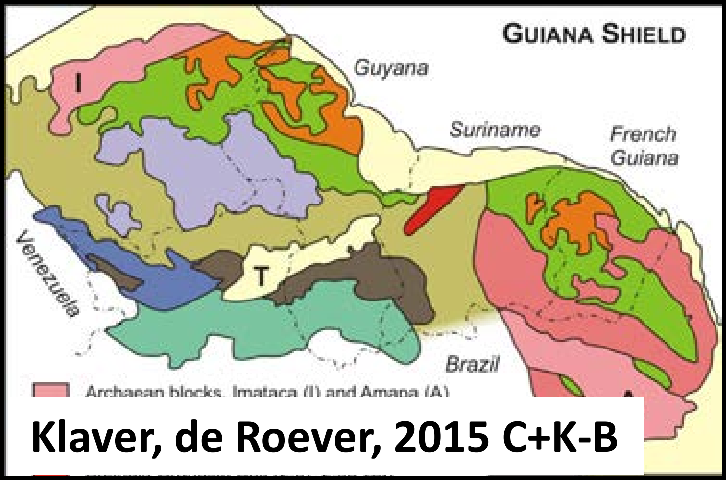


Gibbs & Barron, 1993, B+K-C

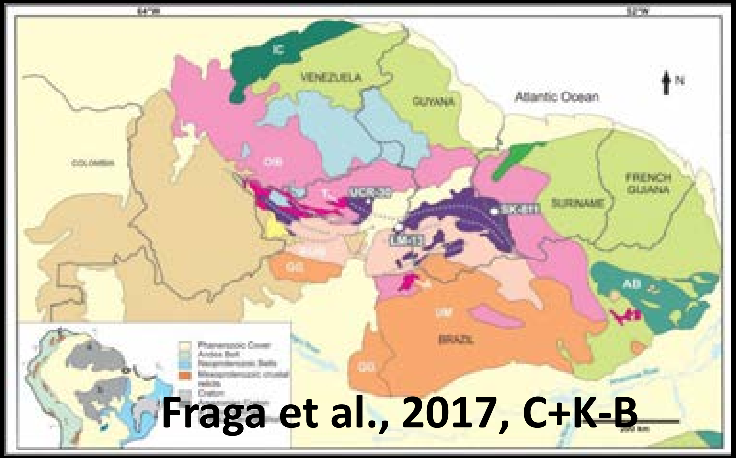
Tassinari,Macambira, 1999 B+C+K



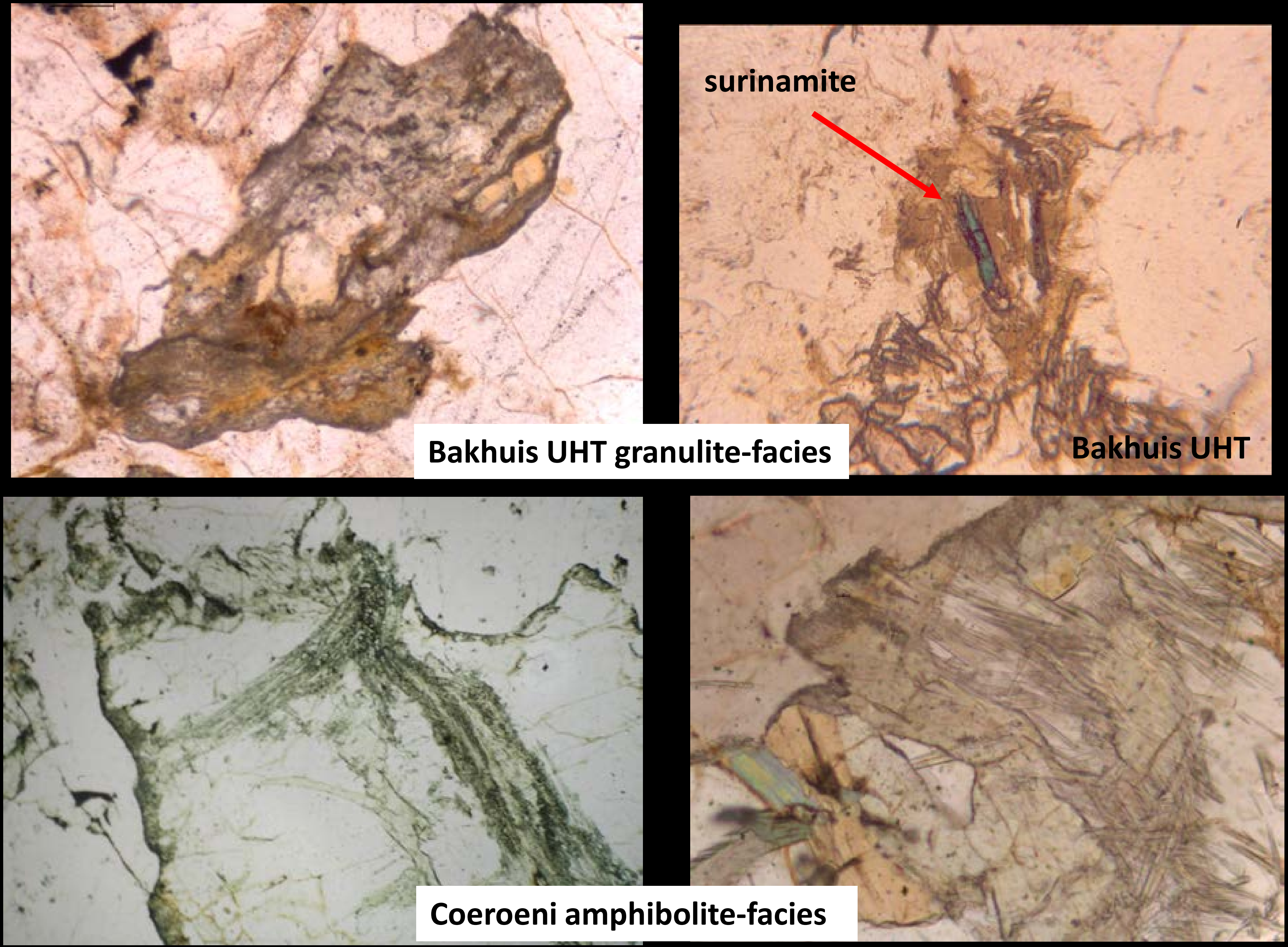
Delor et al., 2003, C+K-B



Klaver, de Roever, 2015 C+K-B

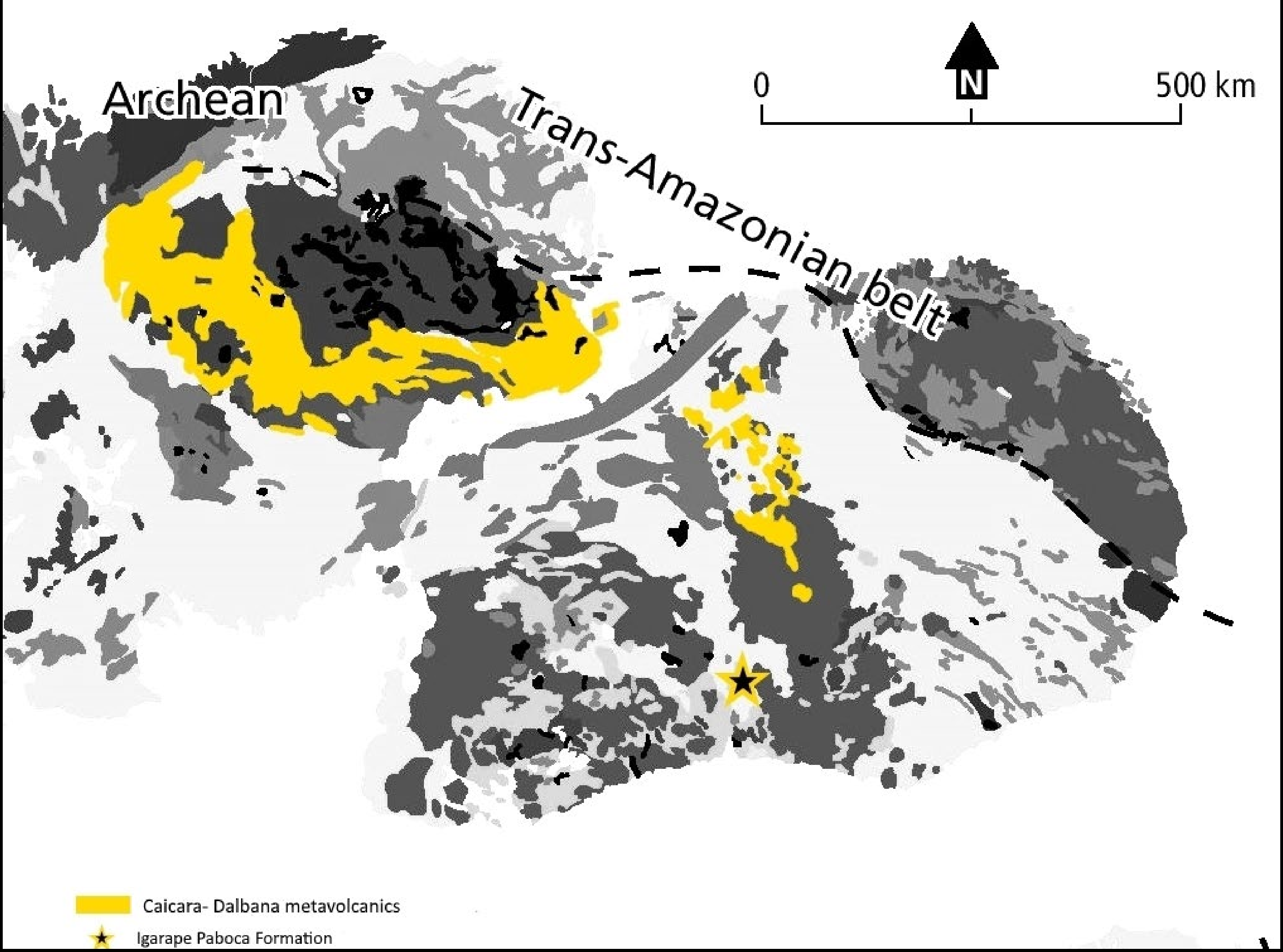


Fraga et al., 2017, C+K-B



Both belts have same age and anticlockwise metamorphic history, cordierite > HP assemblages

# Trans-Amazonian Orogeny Stage III: felsic magmatism

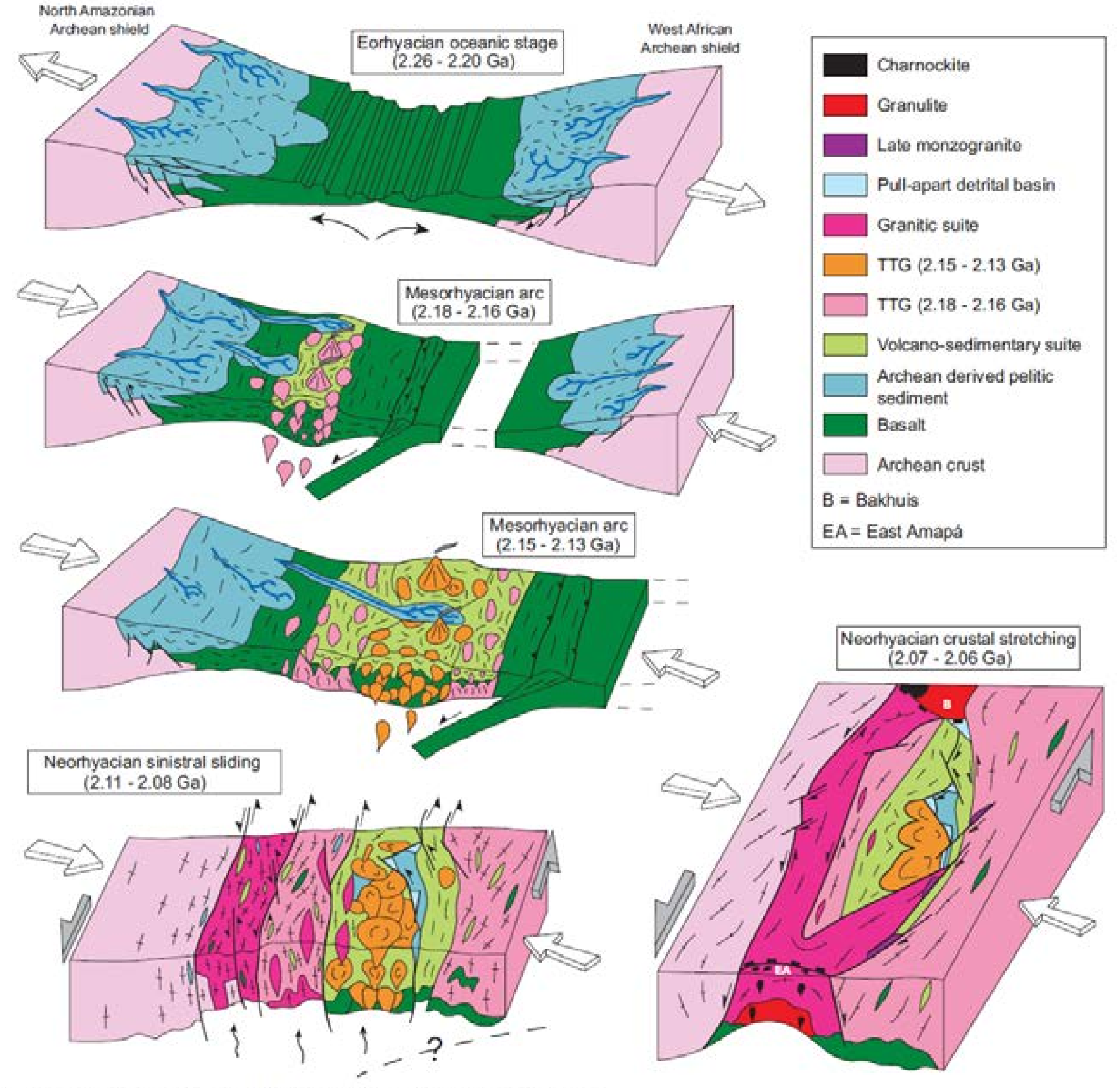


1.98 Ga Caicara-Dalbana felsic volcanic belt (Mahabier, 2017)

Ignimbritic felsic
(meta)volcanics:
1987±4 Ma

Suriname: Dalbana,
Guyana: Iwokrama
Brazil: Surumu
Venezuela: Caicara

Biotite granite, subvolc. leucogranite
gabbro, charnockite , 1.99-1.98 Ga
Suriname: Wonotobo
Guyana: Iwokrama
Brazil: Pedra Pintada
Venezuela: Cuchivero

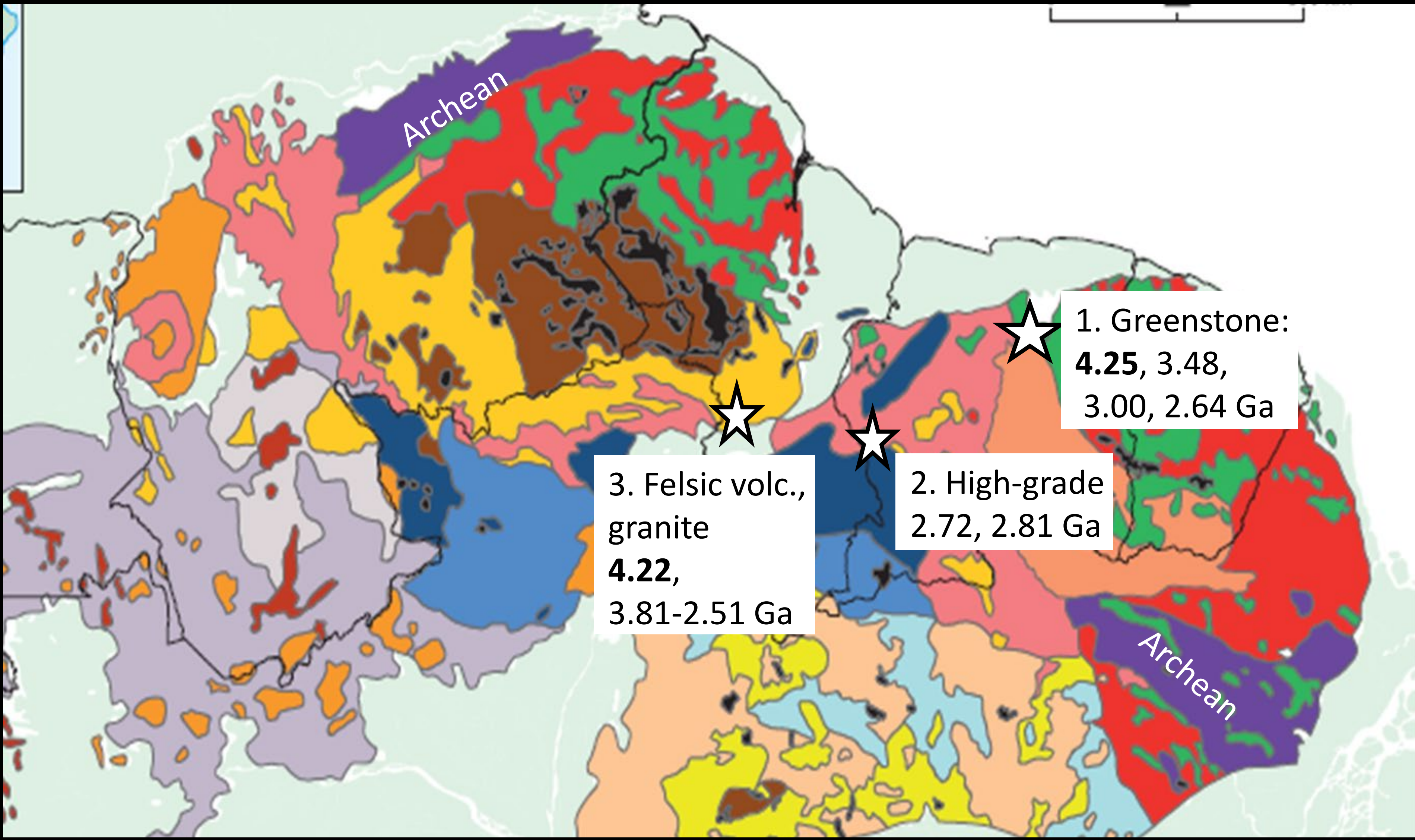


ig. 13.- A geodynamic evolution model for French Guiana Paleoproterozoic terrains.

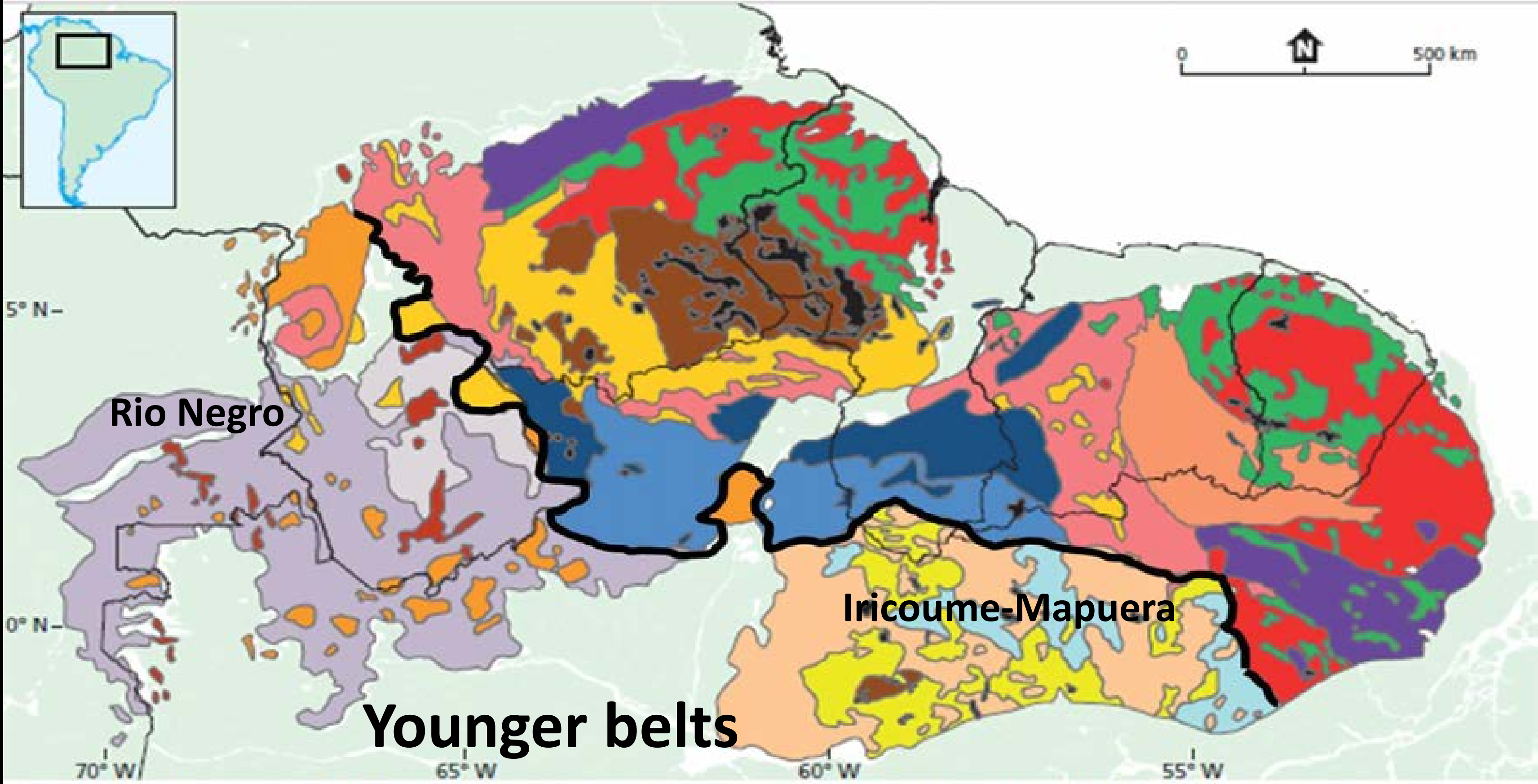
*ig. 13.- Evolution géodynamique des terrains paléoprotérozoïques de Guyane.*

**Delor et al., 2003**

So far the only geodynamic model of the Trans-Amazonian Orogeny



Scarce Sm-Nd data suggest largely juvenile origin. **BUT:** Hadean, Archean inherited zircon xenocrysts: older basement?



**Younger belts**

**Younger platform covers, 1.3-1.2 Ga**
🟥 Tunui, Tarairа, Naquén, La Pedrera, Cinaruco, Neblina folded sandstones

**Mesoproterozoic intrusives, 1.59-1.51 Ga**
🟧 Mucajai, Surucucus, Parguaza rapakivi, Mitú, Vaupés, Isana granites

**Rio Negro Belt, 1.86-1.72 Ga**
⬜ Undifferentiated Rio Negro Basement, southern Venezuela
🟪 High-grade Mitú, Minicia-Macabana-San Carlos-Cauaburi gneisses

**Younger felsic volcanic and granitoid belt, 1.89-1.81 Ga**
🟦 Undifferentiated Tumucumaque basement
🟧 Mapuera-Madeira granites and related intrusives
🟨 Iricoumé-Jatapu felsic volcanics

**Mafic intrusives, 1.79 Ga and younger**
⬛ Avanavero dolerite and other Proterozoic mafic and alkaline intrusives

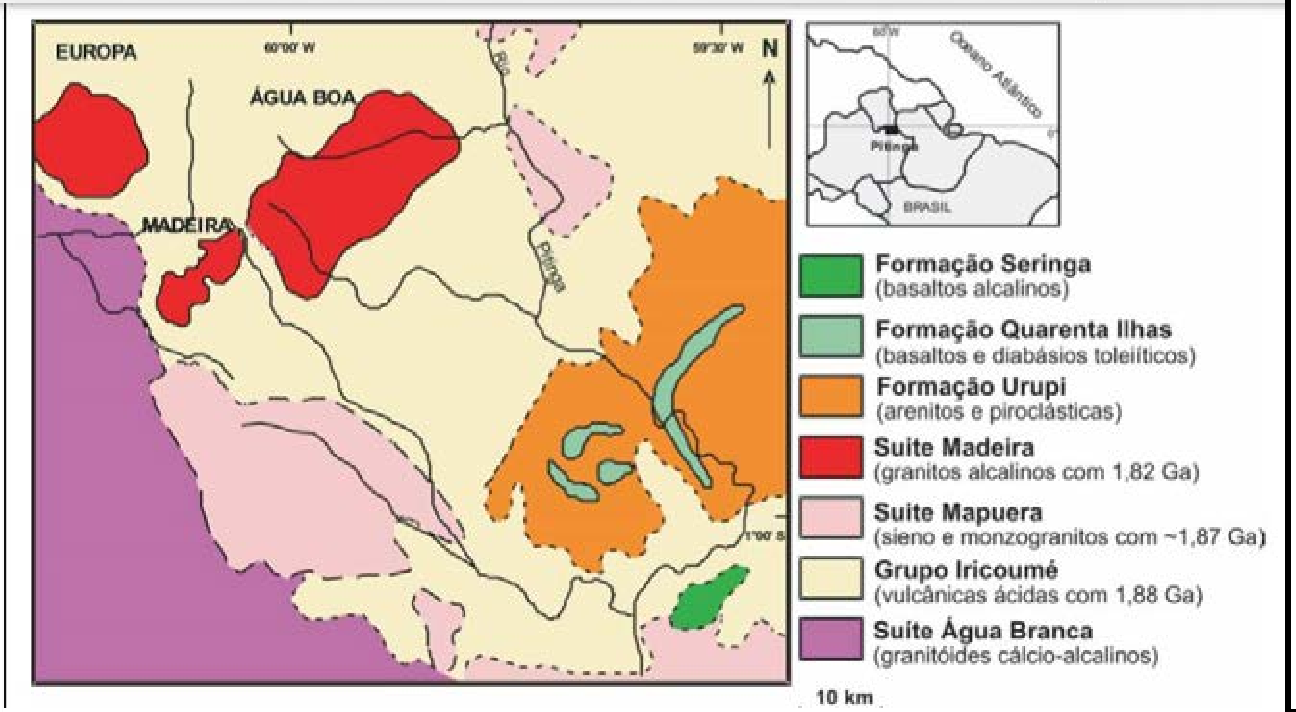
**Older platform Cover, -1.87 Ga**
🟫 Roraima (Super)Group sandstones, conglomerates, ash-fall tuffs

**Older felsic volcanic and granitoid belt 1.99-1.95 Ga**
🟥 Wonotobo-Iwokrama-Pedra Pintada-Cuchivero granites
🟨 Dalbana-Iwokrama-Surumu-Caicara felsic metavolcanics

**High-grade belts, 2.08-2.02 (-1.98) Ga**
🟦 Uraricoera-Trairão-Urubu-Anauá-Southern Guyana Belt
🟦 Bakhuis Granulite Belt, Cauarane-Coeroeni Gneiss Belt

**Greenstone Belt , 2.26-2.09 Ga**
🟧 Deep-level granites and gneisses
🟥 TTG, diapiric tonalite-trondhjemite-granodiorite intrusions
🟩 Vila Nova, Marowijne, Barama-Mazaruni, Pastora-Carichapo greenstones

**Archean nuclei > 2.5 Ga**
🟪 Imataca, Amapa granulite belts



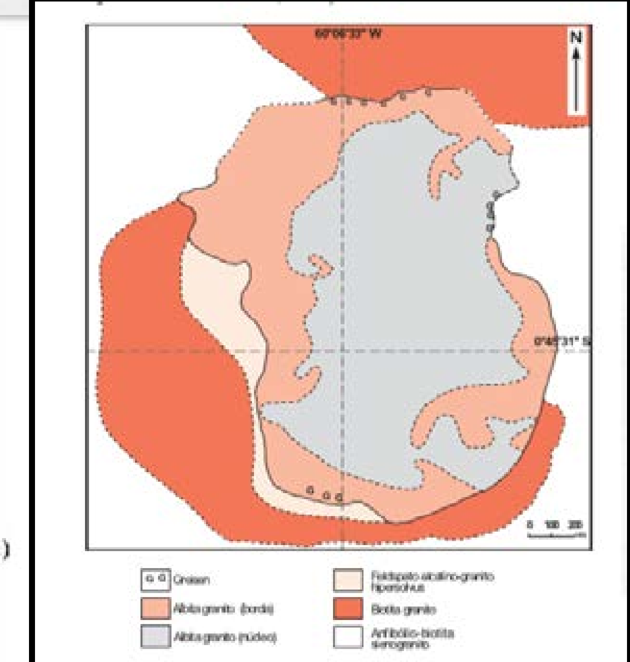


*Figura 7 – Mapa geológico da fácies albita-granito, Granito Madeira*

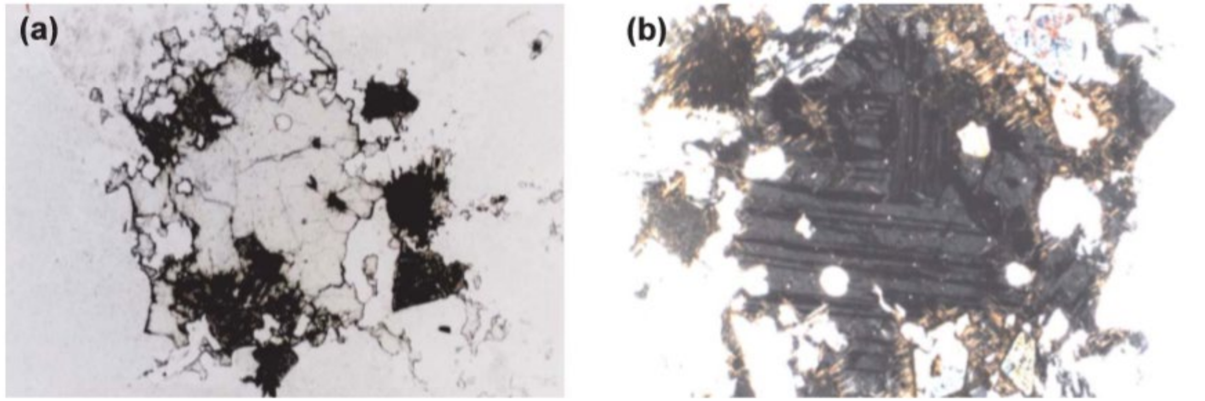
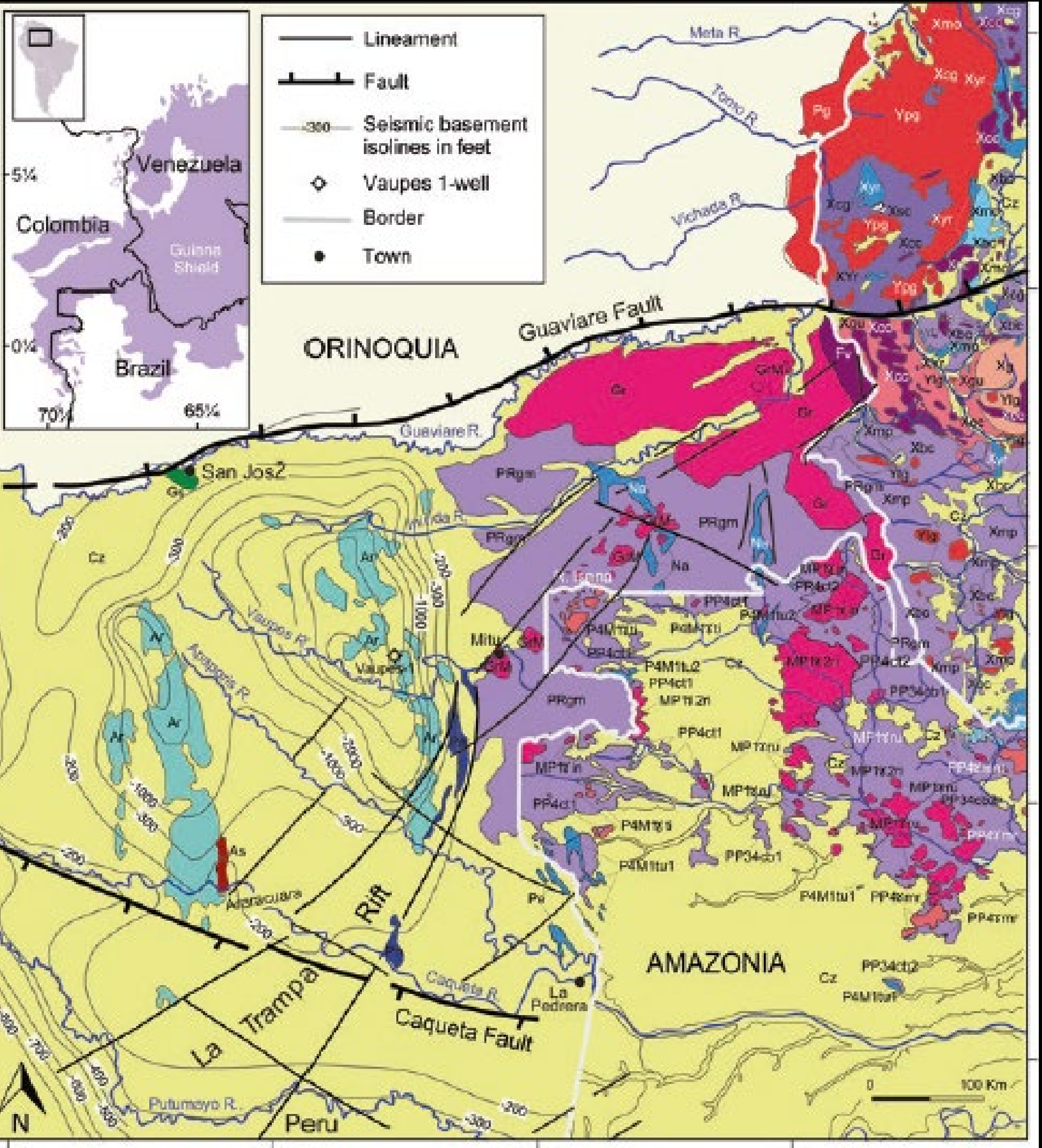


*Figura 12 – Aspecto microscópico de cristais de criolita em albita-granito de núcleo. (a) Nicóis paralelos. (b) Nicóis cruzados); largura da imagem - 4 mm*

**Costi et al, 2005**

Cryolite in albite granite, Pitinga tin mine, 1.88-1.82 Iricoume-Mapuera Belt, Brazil



# Western Guiana Shield:

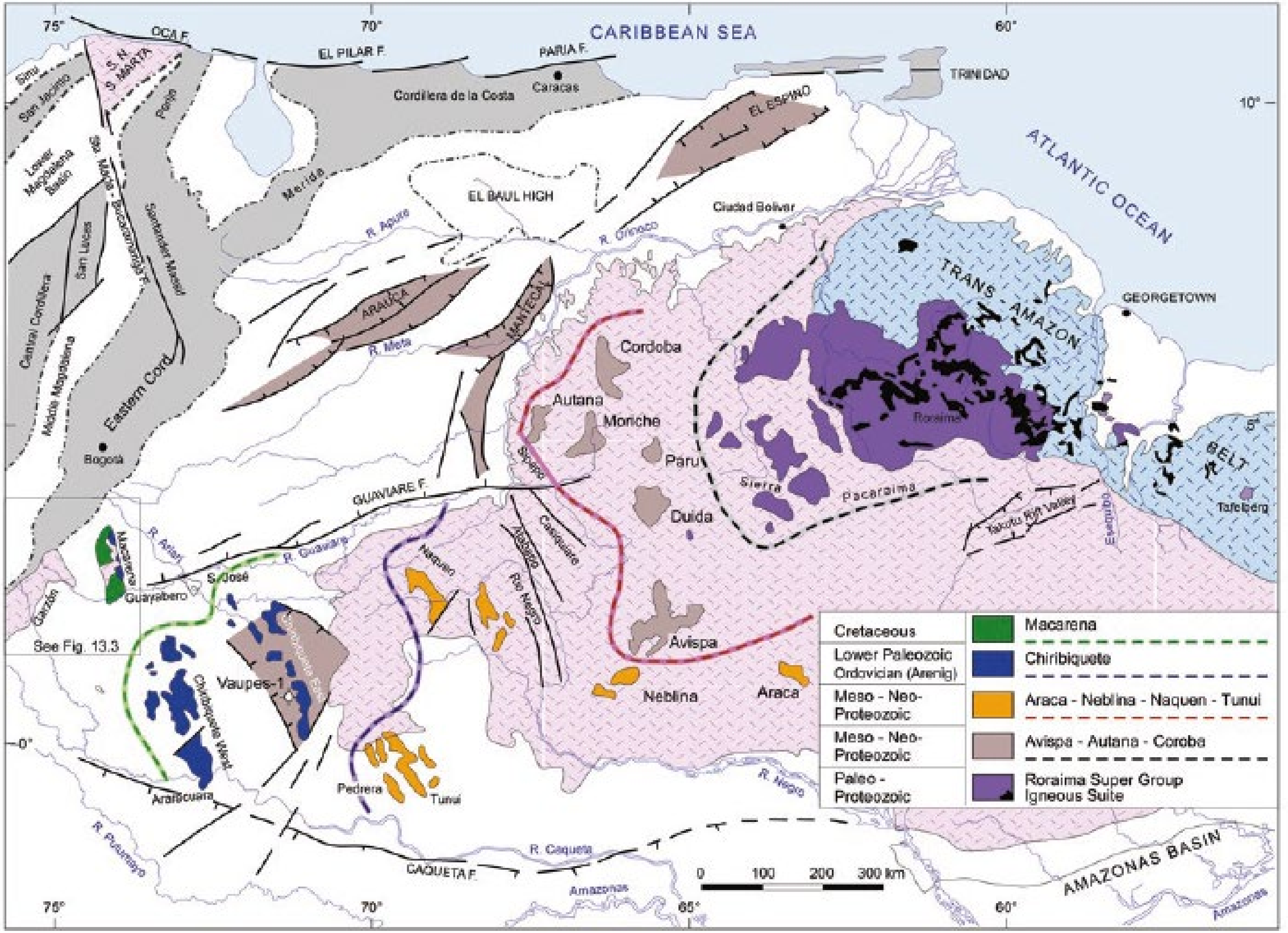
Querari orogeny, 1.86-1.72 Ga,

1.55-1.40 Ga anorogenic (rapakivi) magmatism

Tunui sandstones

Kroonenberg, 2018

Parguaza Rapakivi granite, Caño Cupaven, Venezuela; Sn, Ta; Al



# Sandstone covers of the Guiana Shield

Kroonenberg, 2018

Roraima tepui, diamondiferous, Venezuela, Guyana

**Tafelberg, Suriname**

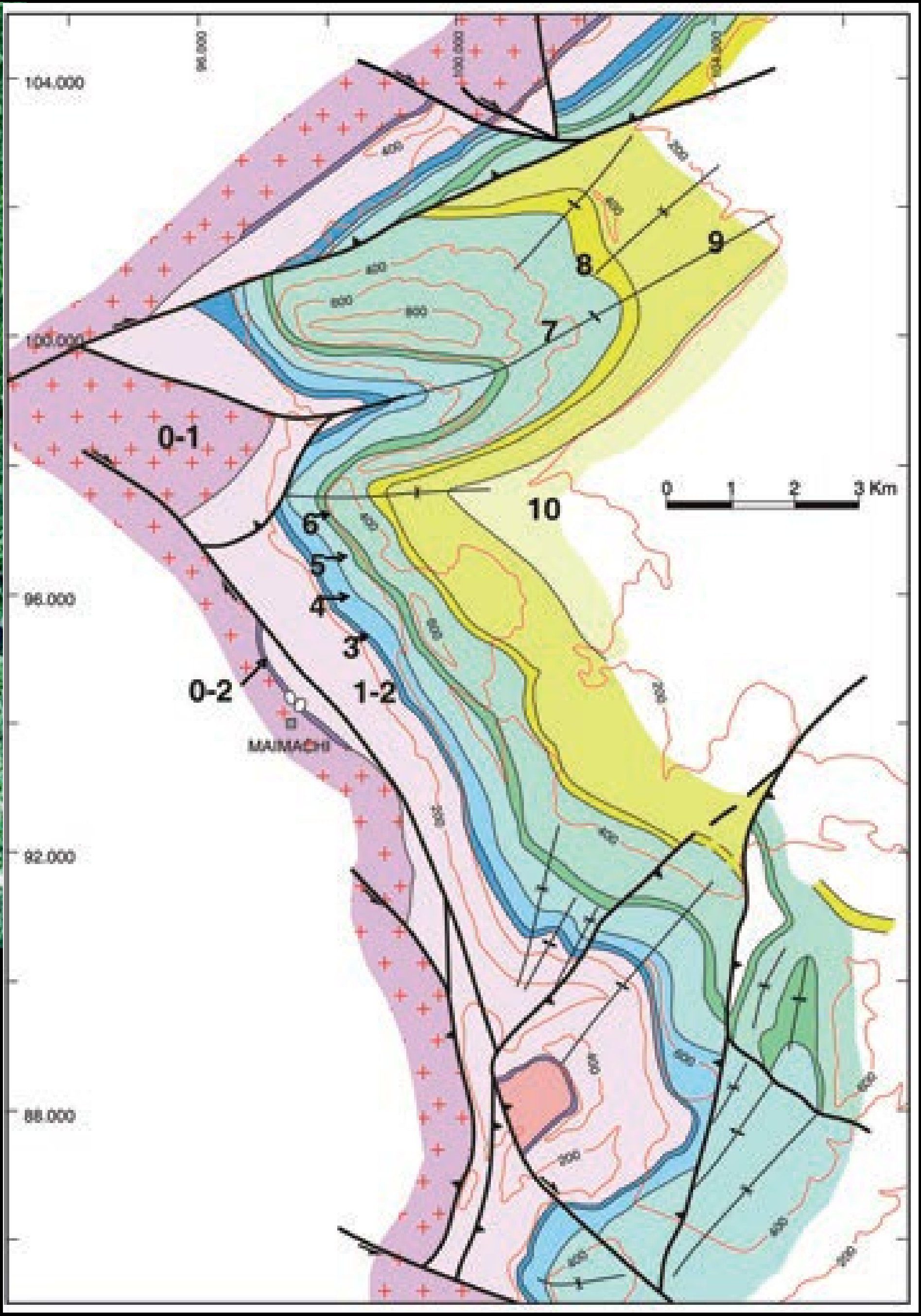
**Tafelberg, Suriname**

Basal paleosol

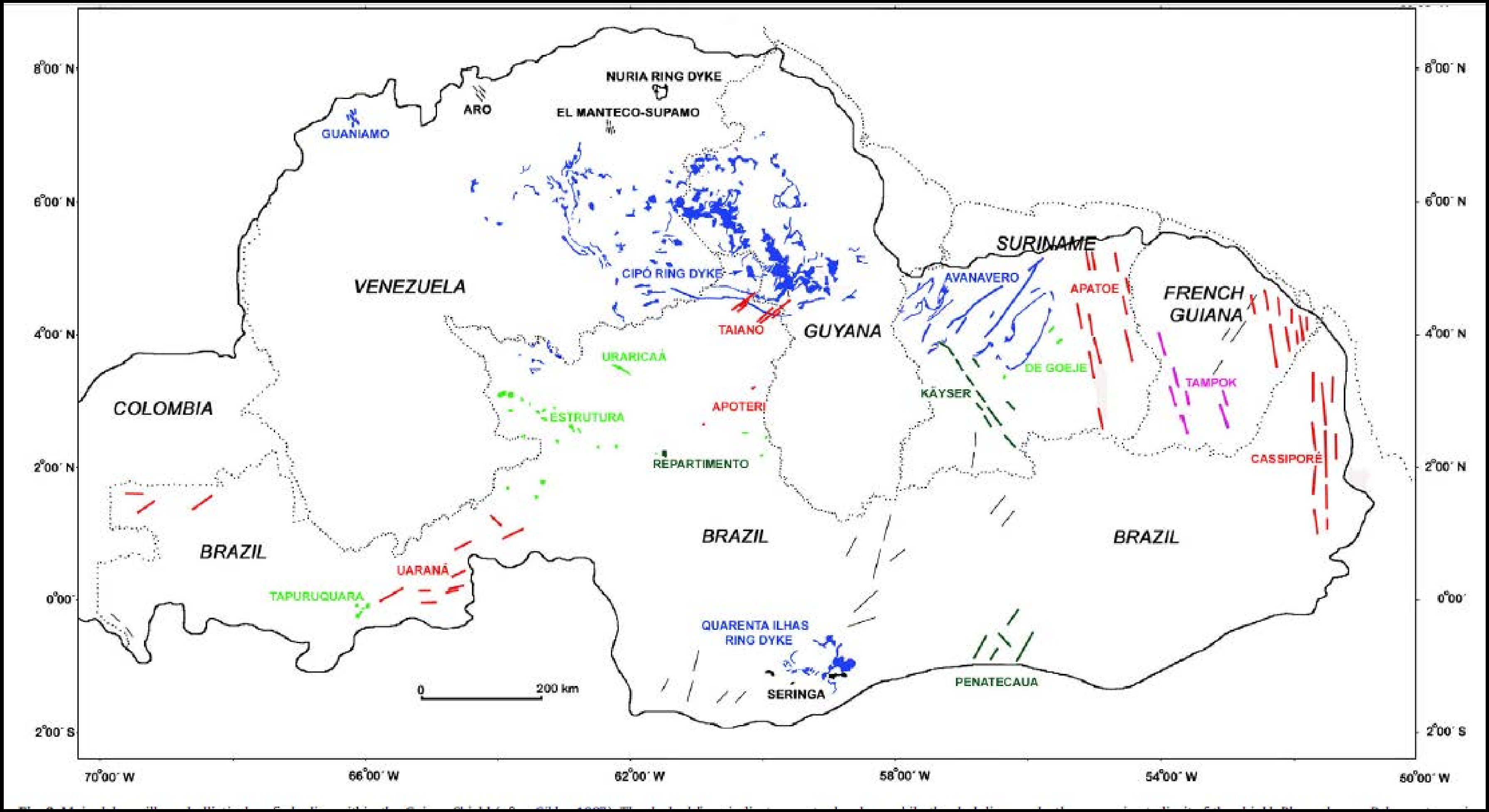
Dated ash bed

Roraima Supergroup,
1873 Ma,
Santos et al, 2003

**Moriche Conglomerate on Cuchivero granite, Ventuari river, Venezuela:**
Exploration for radioactive minerals, 1981



Gold-bearing Mesoproterozoic
Serranía de Naquén
sandstone ridge (800 m)
Colombia



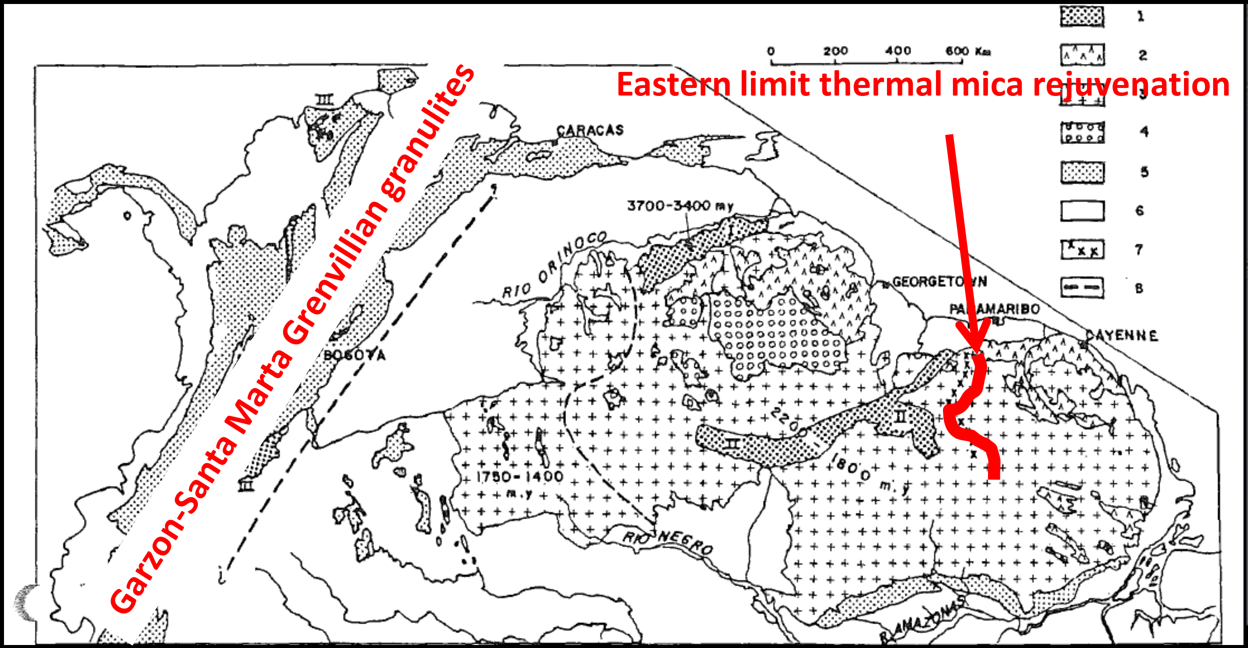
# Dyke swarms in the Guiana Shield (Reis et al., 2013)

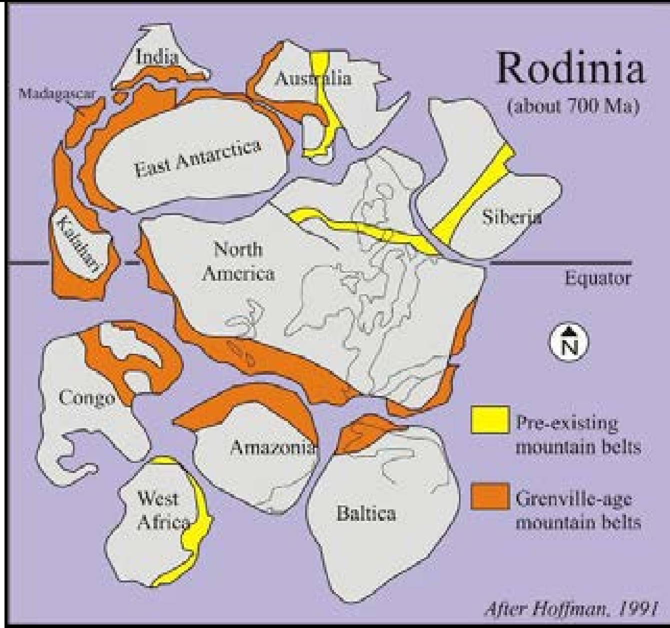
Avanavero 1783 Ma

Käyser, 1501 Ma

Tampok 809 Ma

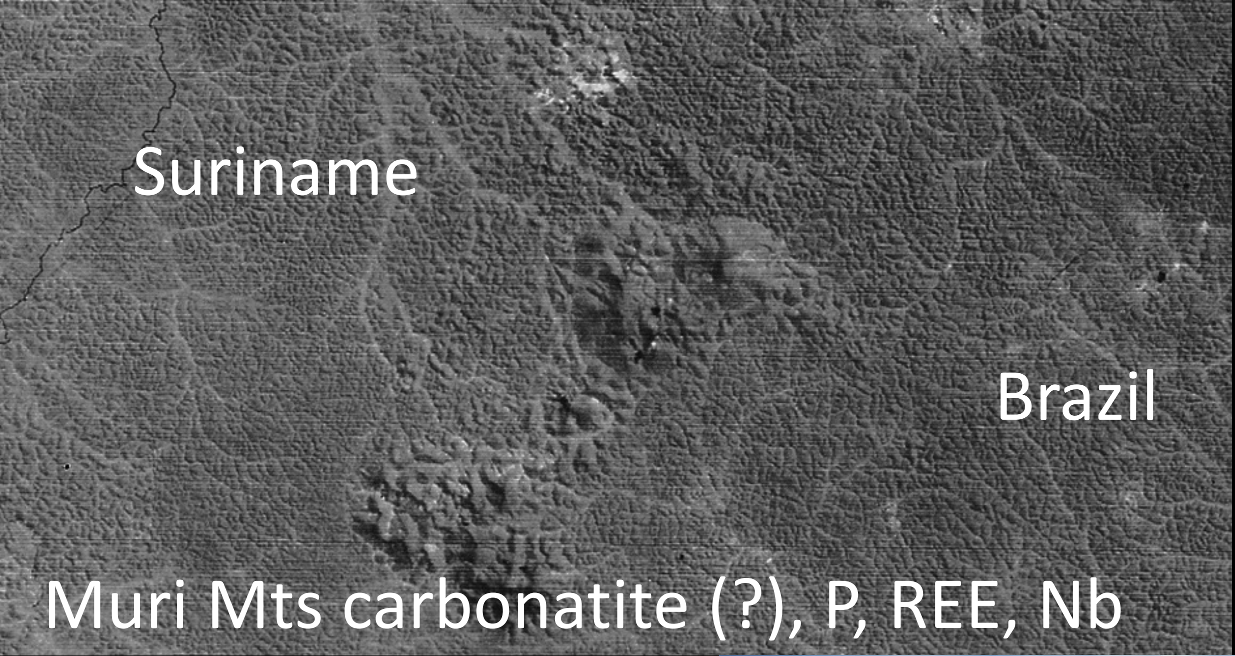
Apatoe-Penatecaua, 198 Ma





Grenvillian :~1200-1100 Ma:
Nickerie/K'Mudku/Orinoquense
Metamorphic Episode
Widespread shearing, mylonitization,
thermal resetting, alkaline magmatism

Amazonia-Laurentia
collision (1 Ga):
supercontinent Rodinia



Muri Mts carbonatite (?), P, REE, Nb

Alkaline magmatism
~1100-1000 Ma

Carbonatito Seis Lagos, Brazil (Nb)

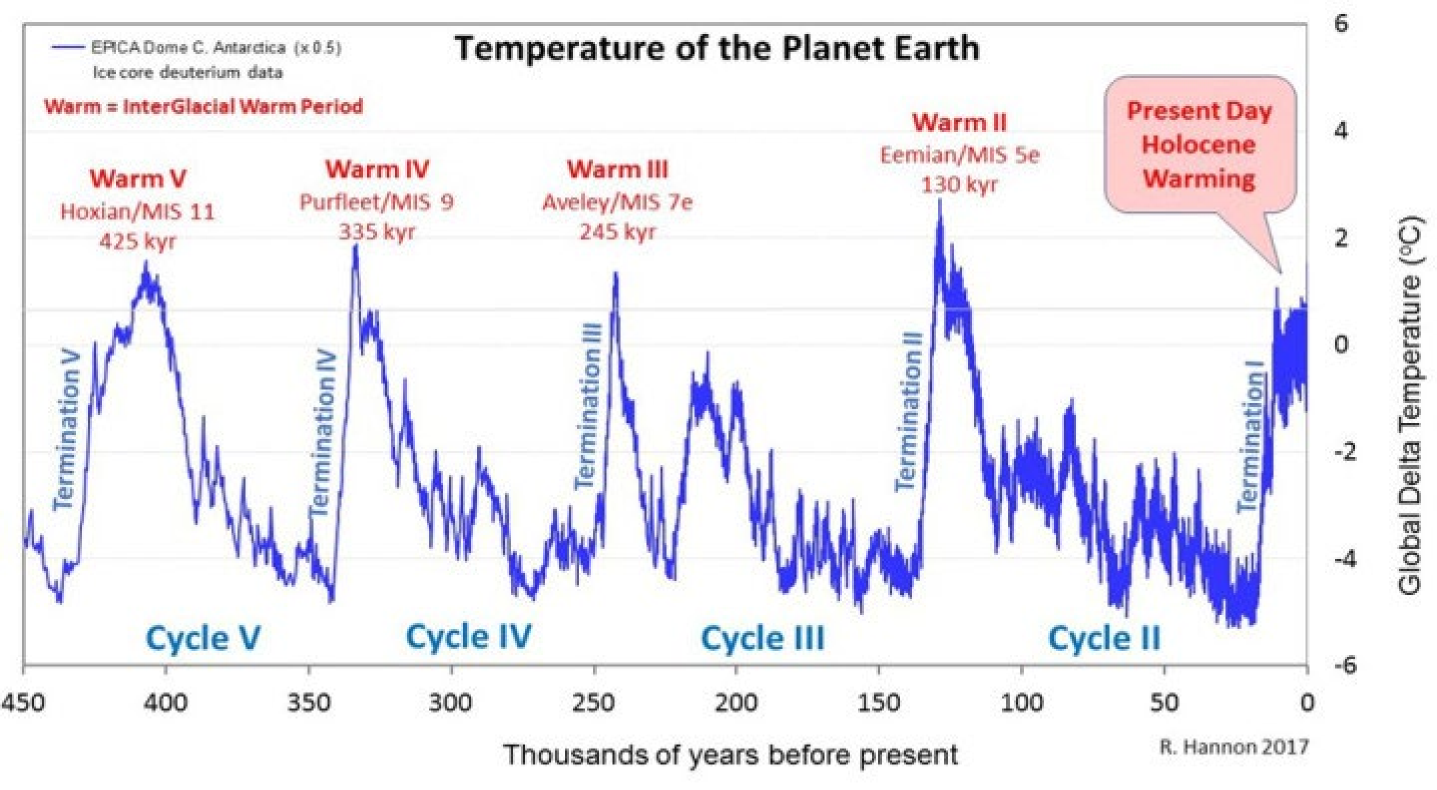
Guaniamo diamond kimberlite, Venezuela, 840-710 Ma

**Bauxite** on mafic metavolcanics, granulite/anorthosite, rapakivi granites

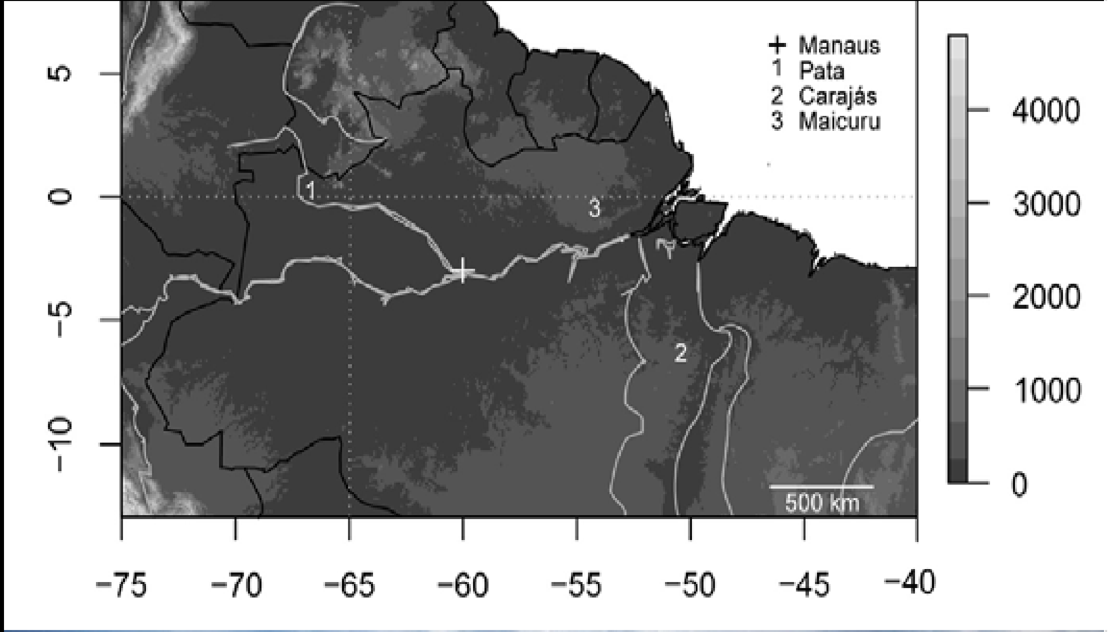
Let’s get to work!

# Quaternary climate change and its importance for gold exploration in the Guiana Shield

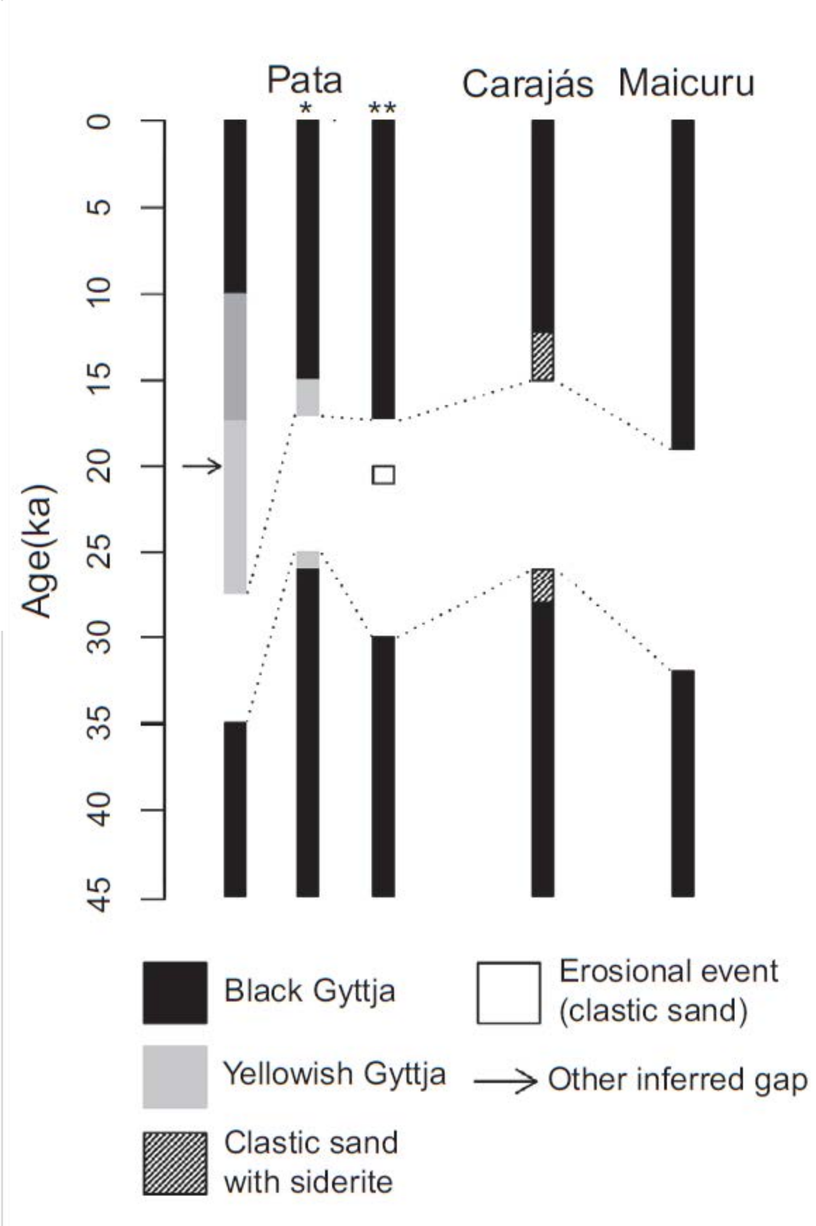
Salomon B. Kroonenberg, Kathleen Gersie



R. Hannon 2017



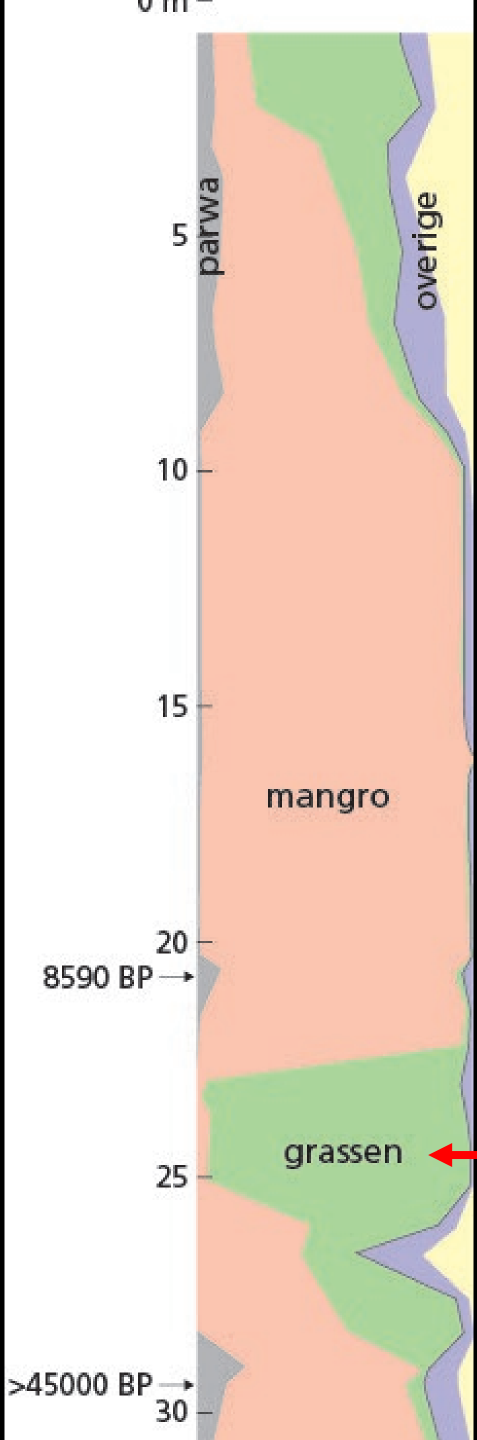
Carbonatito Seis Lagos



Ice age aridity according to pollen studies

D'Apolito et al., 2013

Ice-age hairpin dunes (médanos) SW Venezuela, E. Colombia



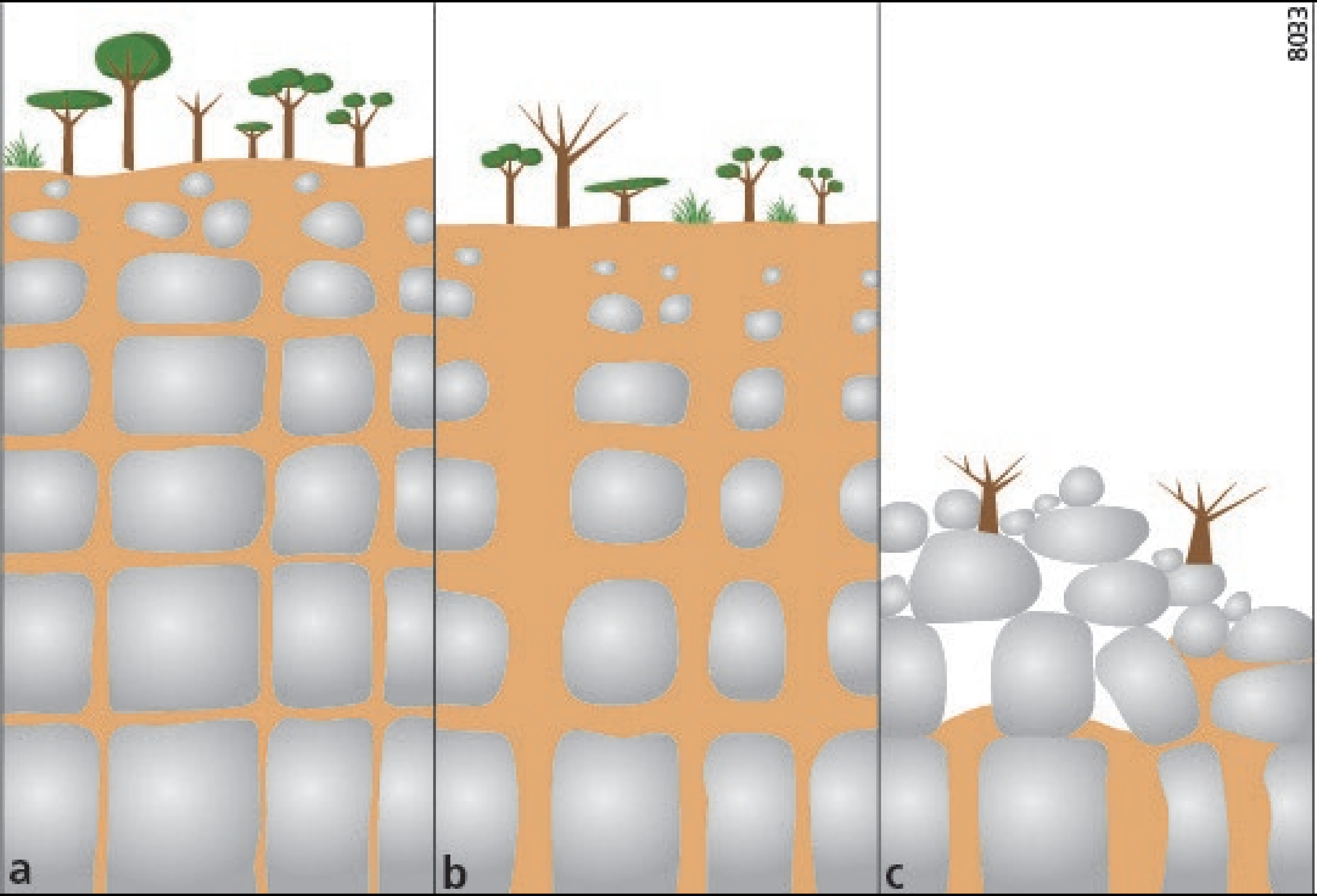
Pollen data from coastal Ogle Bridge site, Guyana indicate ice age aridity (Van der Hammen, 1963)

Ice age grass savannah vegetation

Hard rock and regolith, Bakhuis Mts

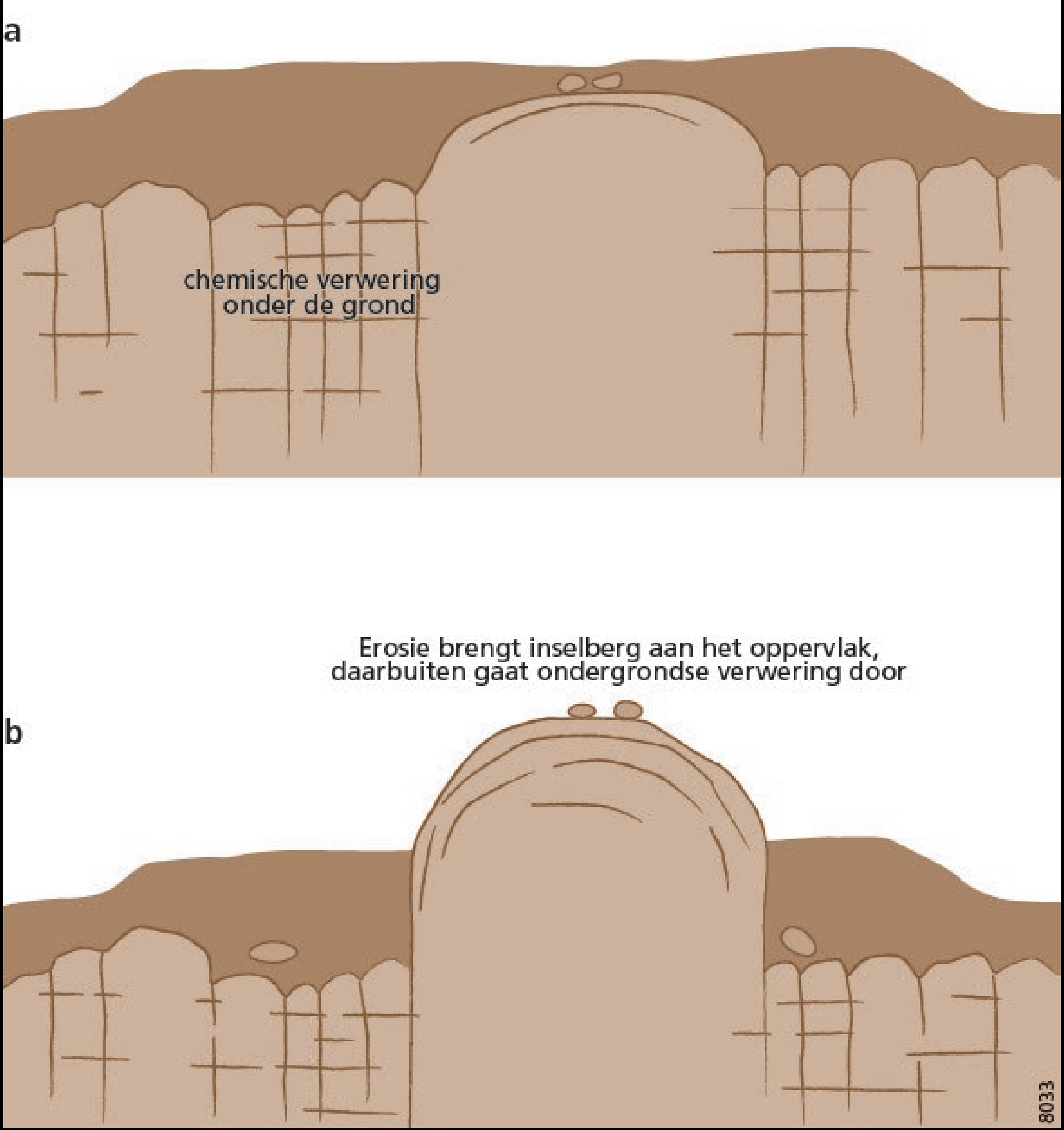
Saprolite: retains rock structure

Colluvial material, Peto Creek, Saramacca

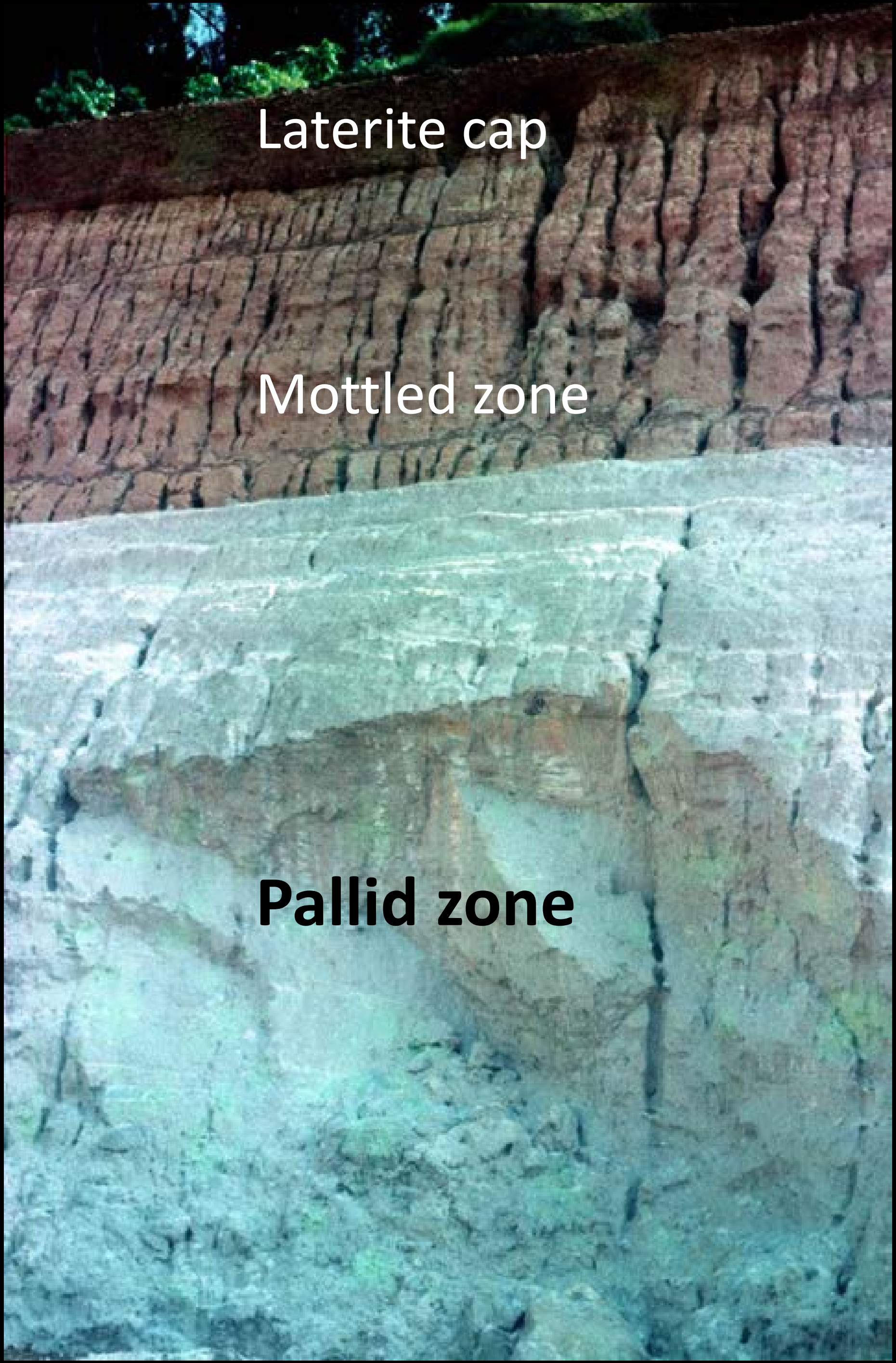


Tor formation by stripping regolith

Inselberg, Devil’s Egg, Wilhelmina Mountains

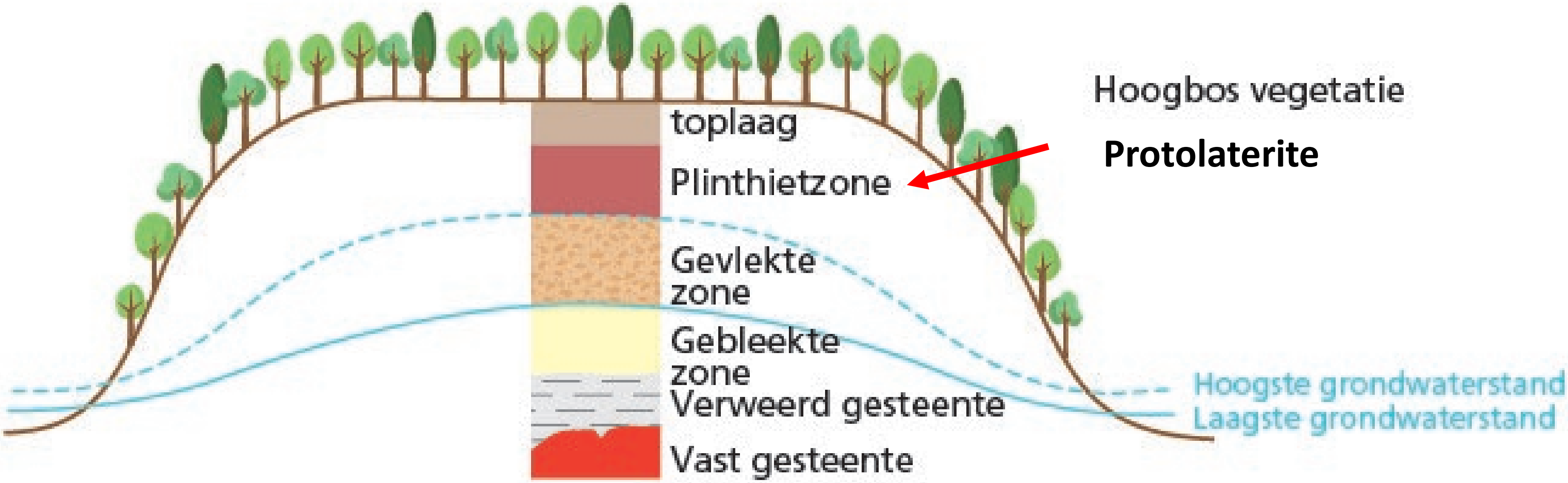

a
chemische verwering
onder de grond
Erosie brengt inselberg aan het oppervlak,
daarbuiten gaat ondergrondse verwering door
b
8033

Bauxite cap, Bakhuis Mountains

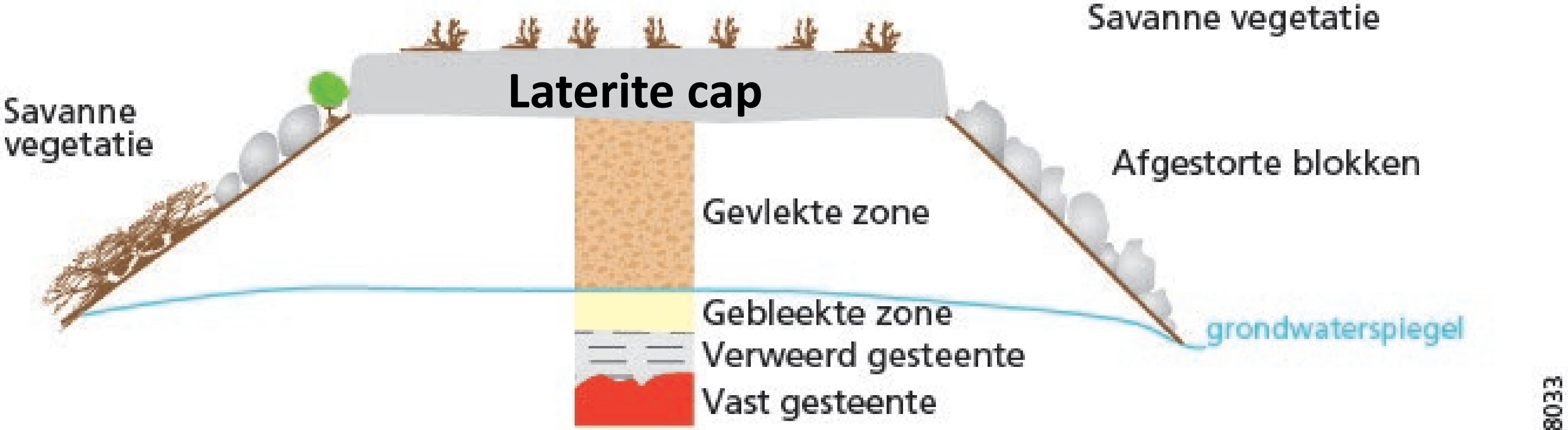


Classic laterite profile on Avanavero Dolerite, Avanavero, Suriname

### 1. Afwisselend droog-nat klimaat



### 2. Semi-aride klimaat



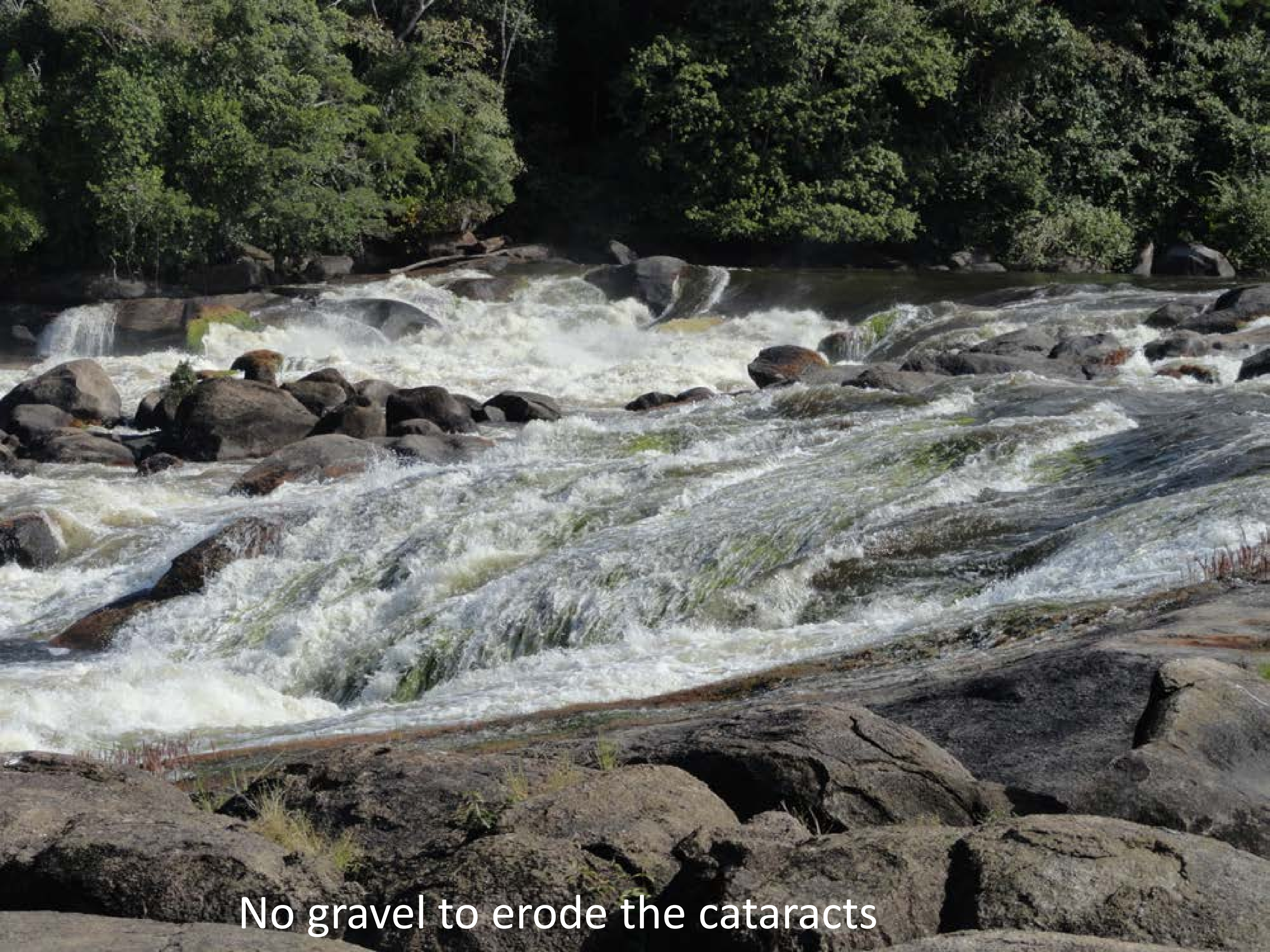
Normal
flat-bottomed creek

Former flat swampy creek bottom
downstream from laterite cap Nassau Mts
converted in boulder stream by gold miners
Points to more arid flow regime in ice age

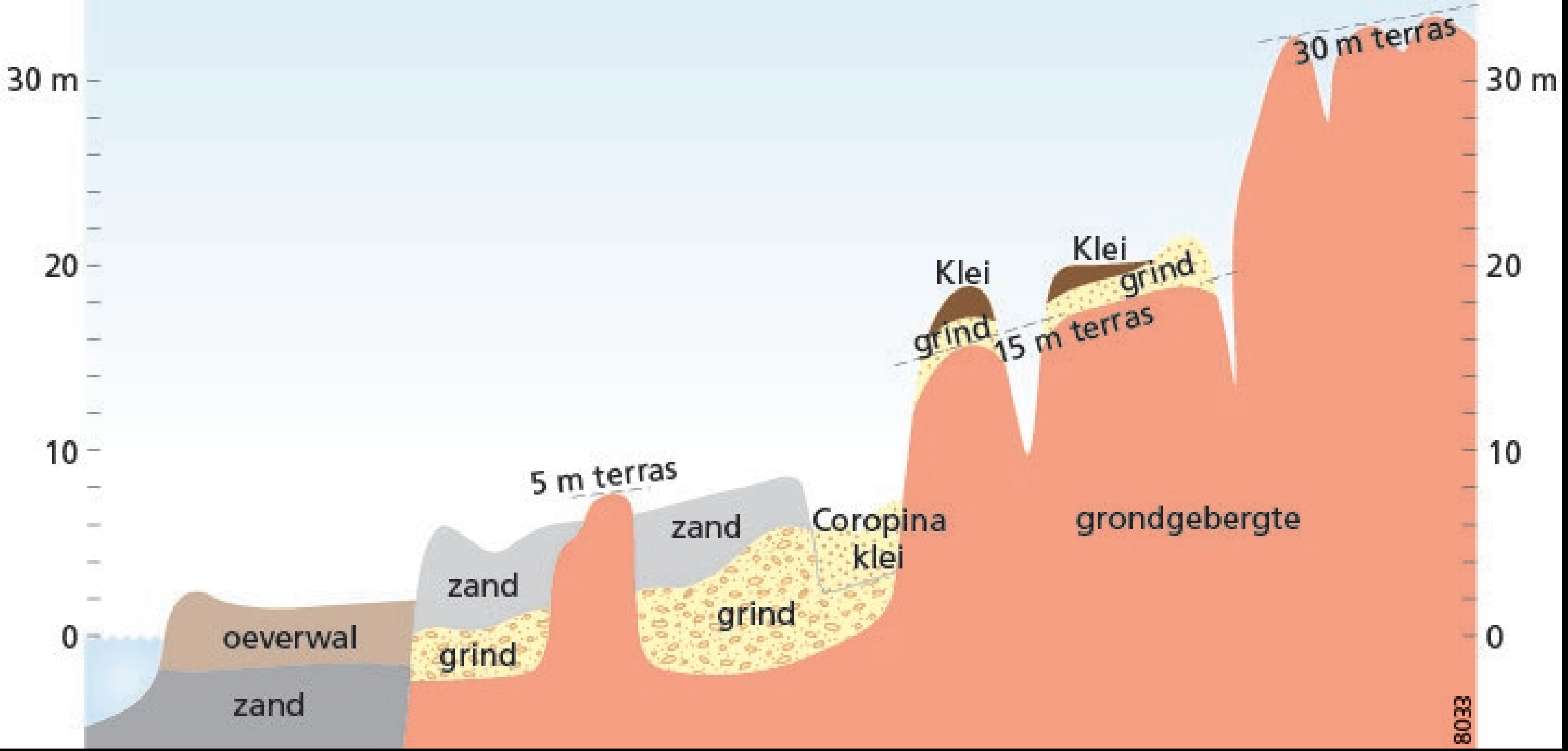
Diamant Nassaugebergte

Further downstream grain size diminishes

Gold-bearing river terrace quartz gravel, Marowijne River, Suriname,



No gravel to erode the cataracts

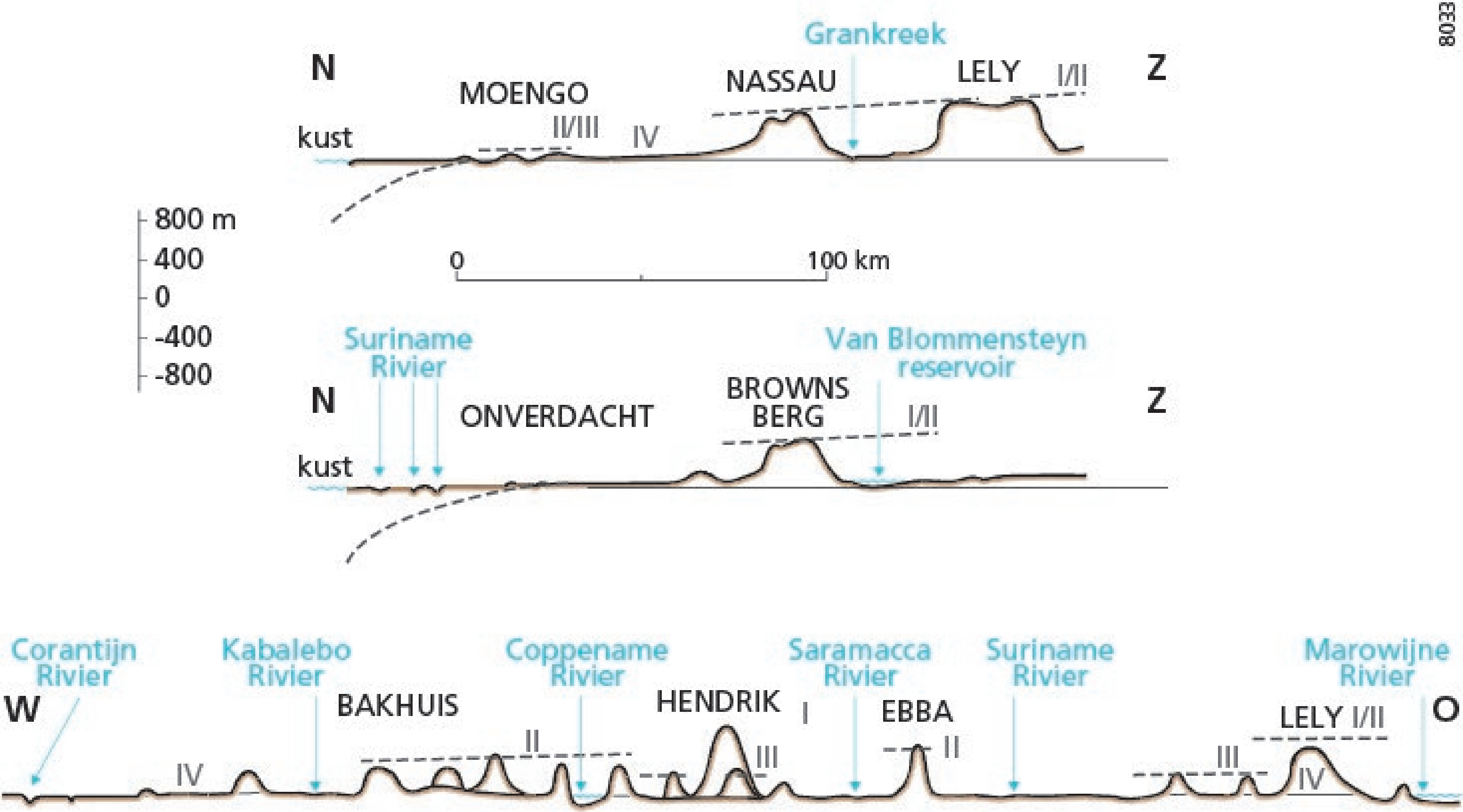


**Marowijne River terraces:**

(Semi-)arid climate, braided river systems, accumulation gravel terraces

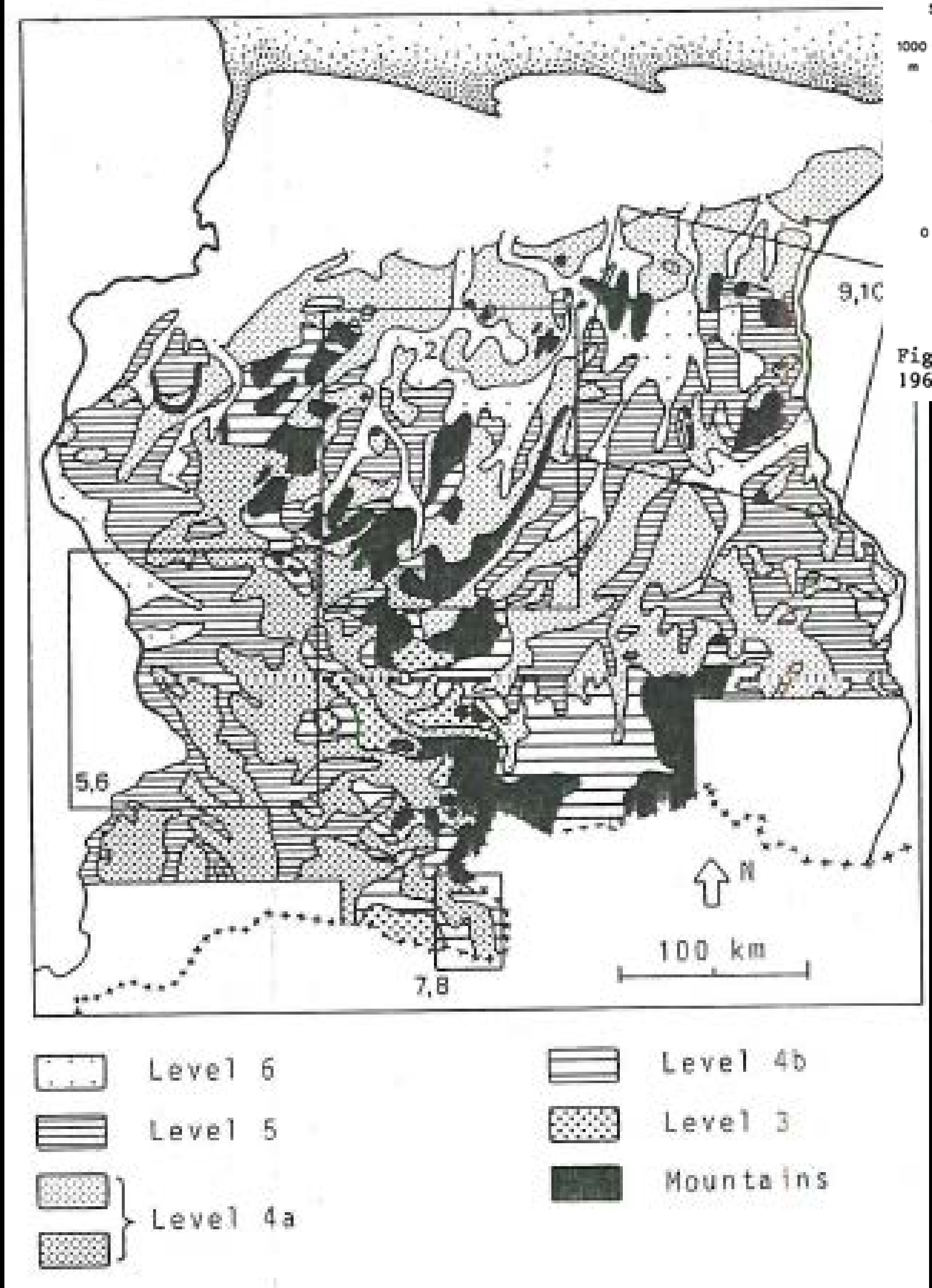
Present humid climate:, no gravel formation, dissection, cataracts

Gold dredge, Saramacca, reworks gravel from river bottom



Planation surfaces reconstructed by connecting  laterite caps

Aleva, 1979



Zonneveld, 1993

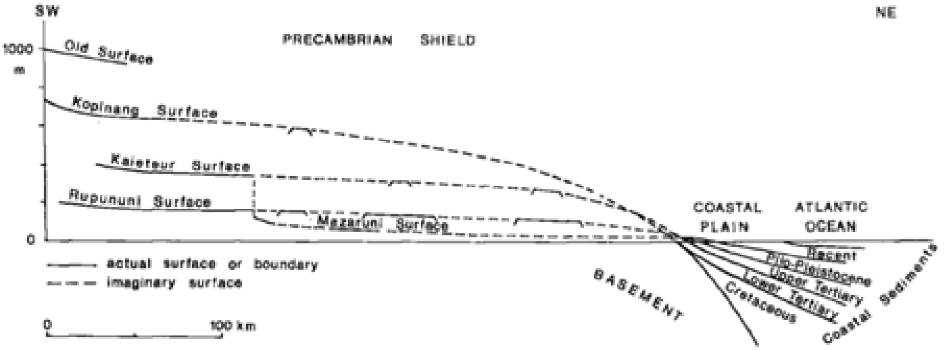
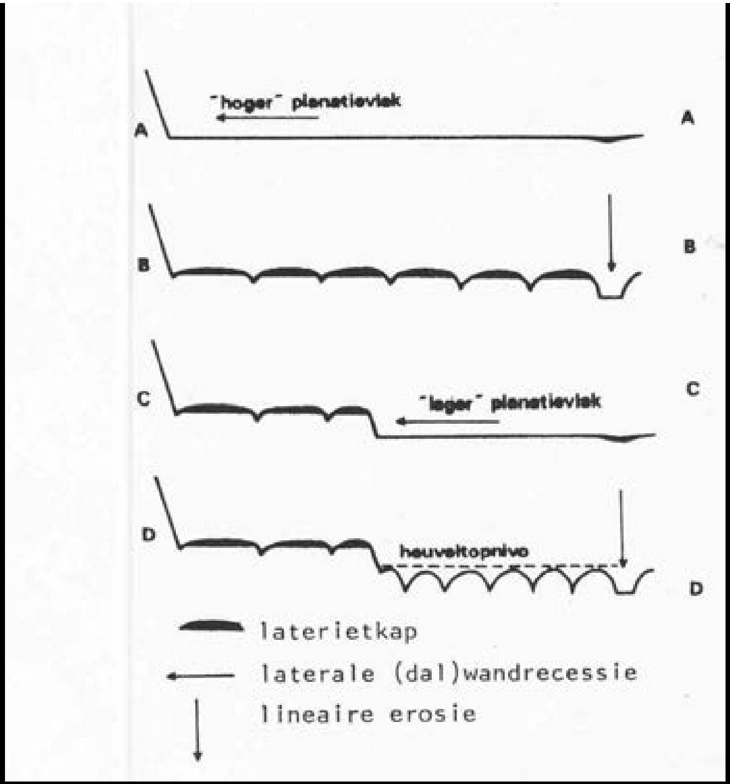
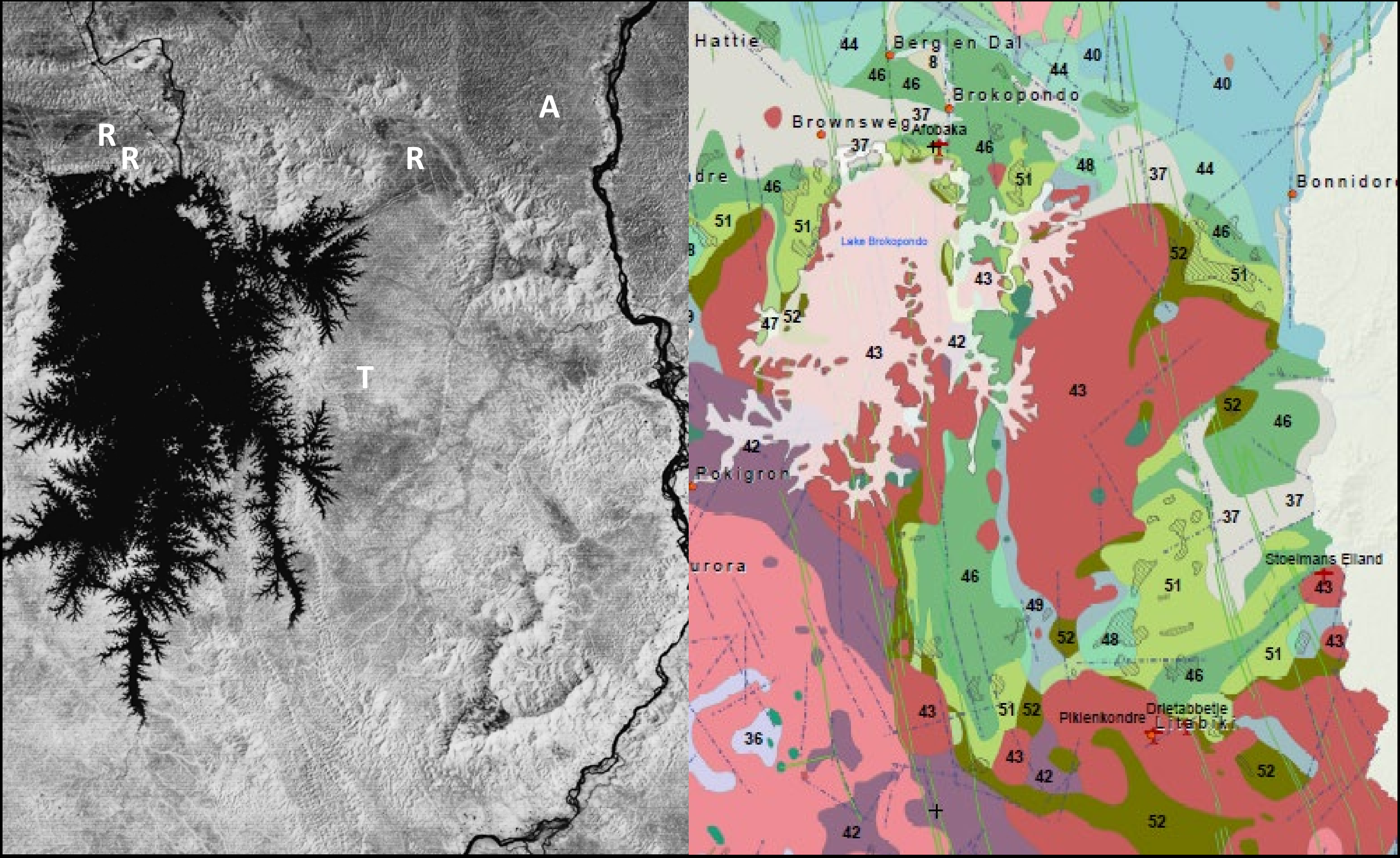


Fig. 11. Provisional diagram of planation surfaces in Guyana (from Mc Connell, 1966, slightly modified).



Planation levels by backwearing?
Doesn't work in crystalline basement rocks



Relief and elevation follow lithological boundaries

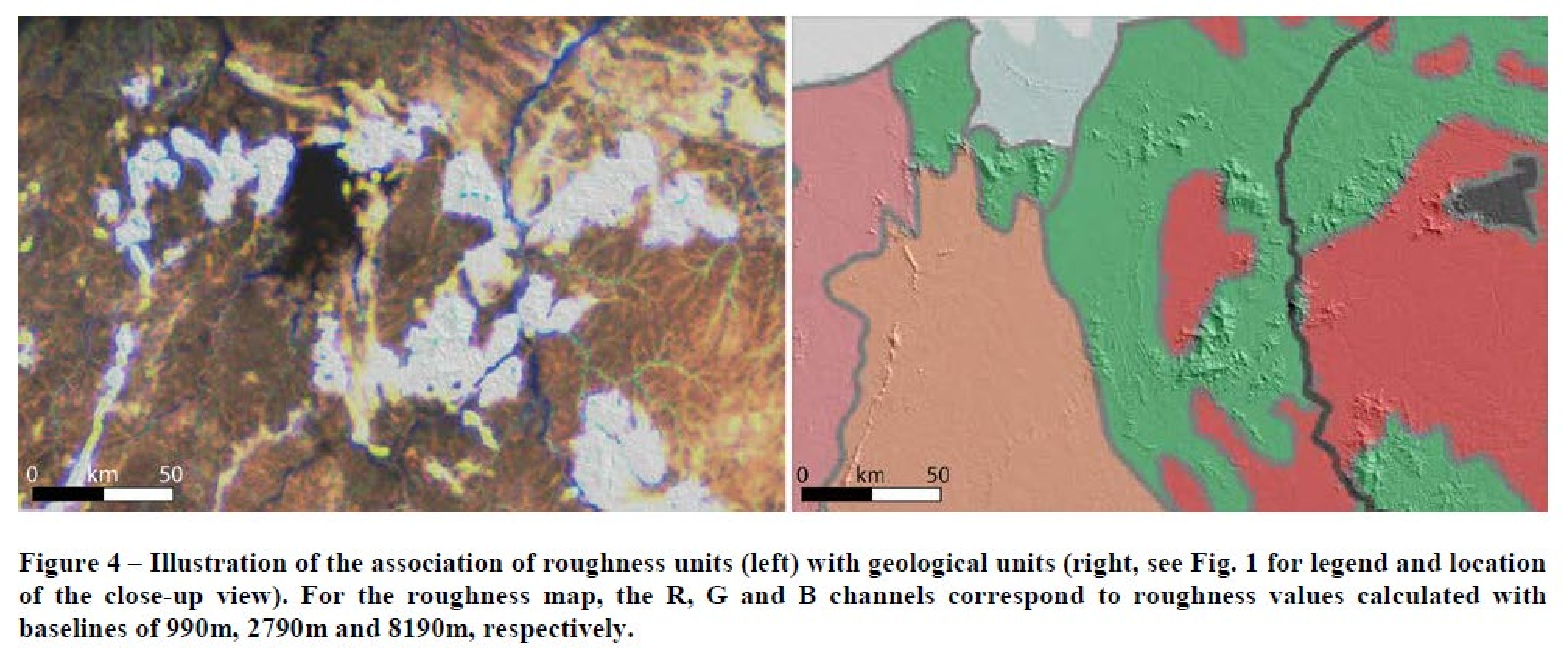
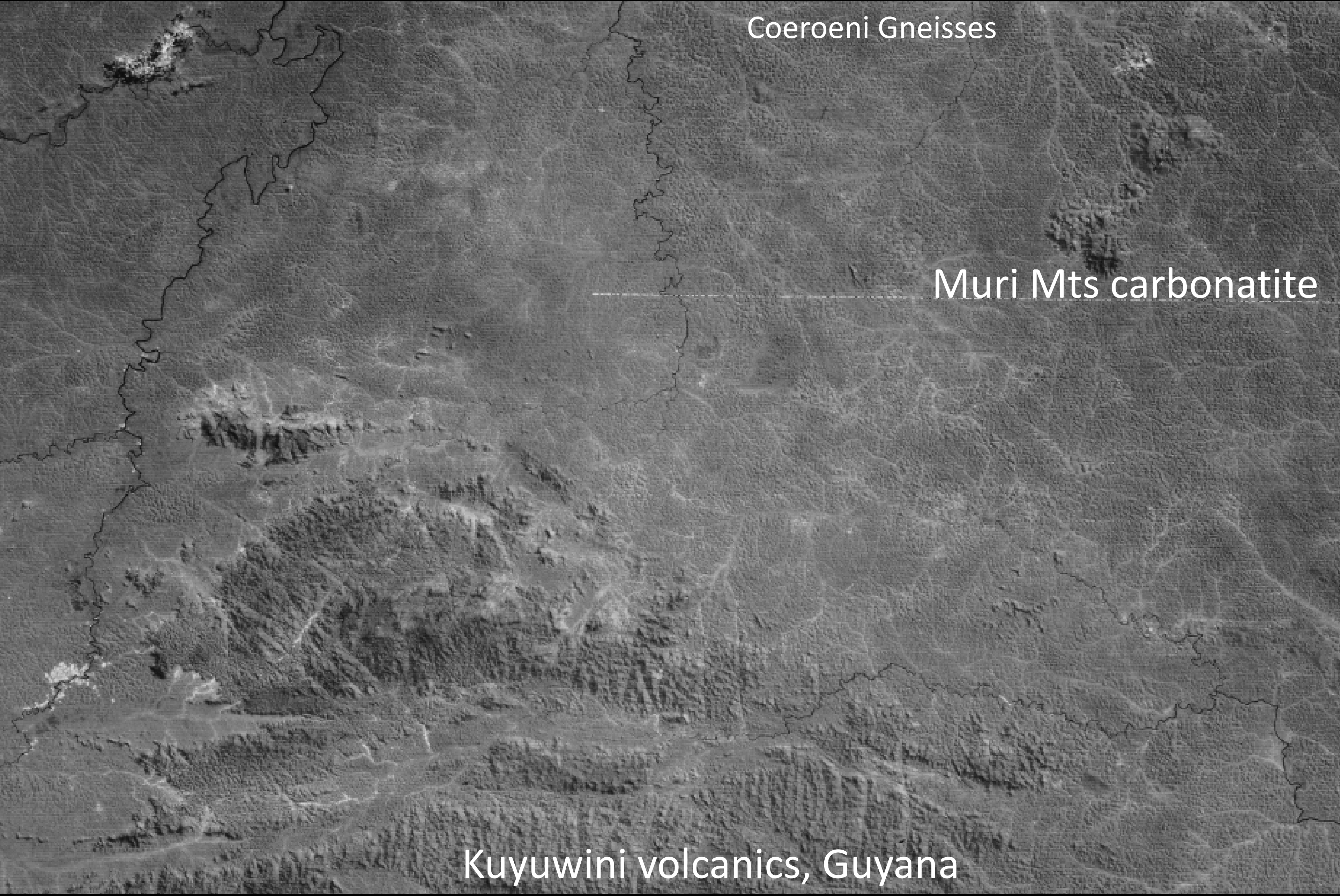
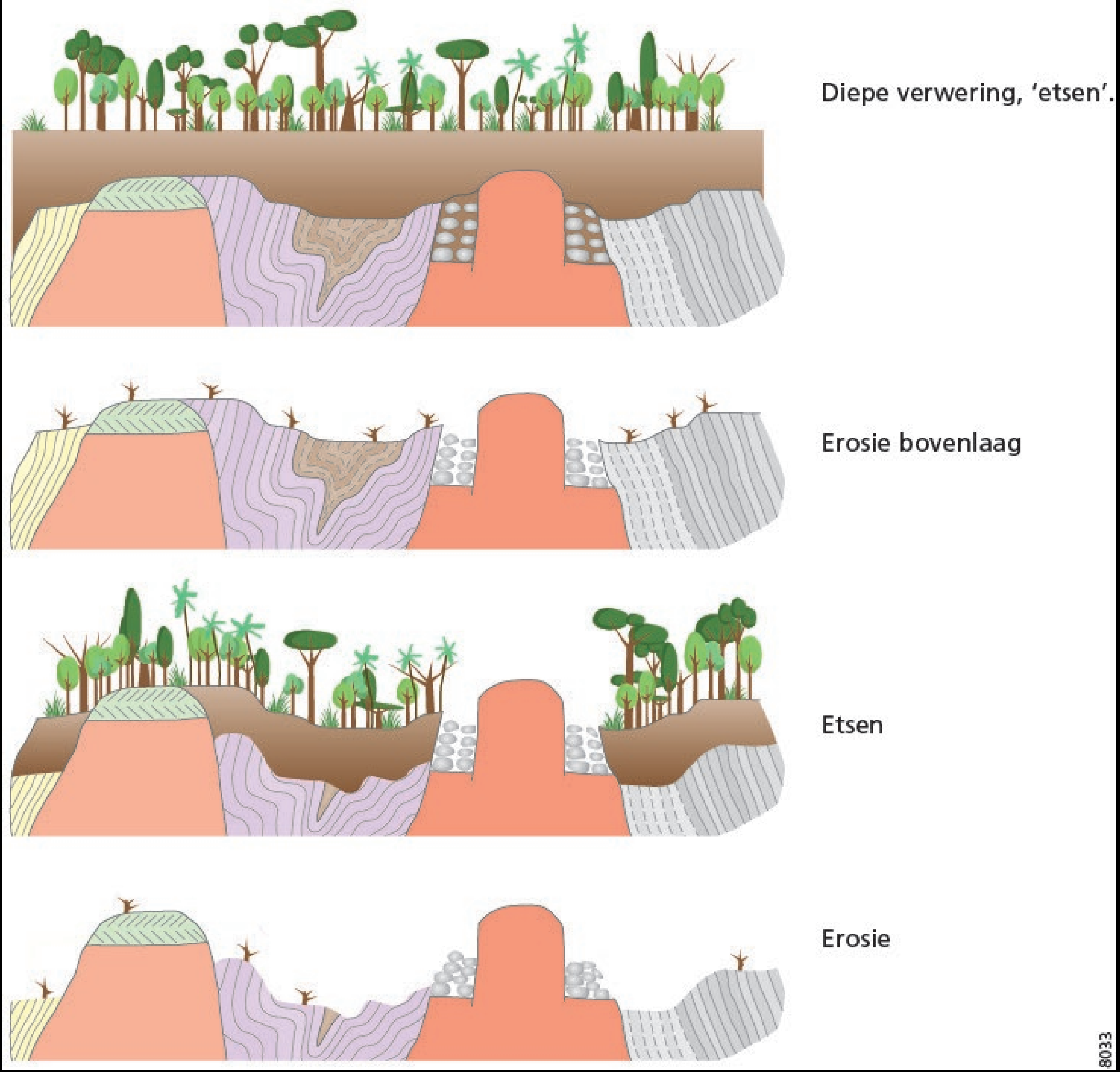


**Figure 4** – Illustration of the association of roughness units (left) with geological units (right, see Fig. 1 for legend and location of the close-up view). For the roughness map, the R, G and B channels correspond to roughness values calculated with baselines of 990m, 2790m and 8190m, respectively.

David Baratoux Roughness map of the same area (this conference)



Landforms follow lithology, not planation levels



The etchplain concept:
elevation is a function of lithology, not of age

Take home messages:

(1)Most gold concentrated in colluvial and alluvial deposits from former drier climates

(2) Planation surfaces can only be reonstructed from laterite plateaus

(3) Outside laterite caps elevation of terrain forms is determined by Lithology, not by age

Are the ultra-mural lavas and vulkani clastic rocks from the same magmatic pulse as the cumulates, or are the cumulates injected into older lava and vulcanic charges?

# Ultramafic rocks of the Paleoproterozoic greenstone belt in the Guiana Shield of Suriname, and their mineral potential

R. Naipal[1] , S. B. Kroonenberg[2,3],  P.R.D. Mason[4]

## Abstract

The ultramafic rocks of the Marowijne Greenstone Belt in Suriname comprise intrusive dunite-gabbroic bodies, ultramafic lavas and volcaniclastic rocks. They were emplaced in the early stages of the Trans-Amazonian Orogeny(2.26-2.09 Ga). They present several economically interesting mineralisations including chromium, nickel, platinum, gold and diamonds. In Suriname diamonds are found since the 19th century; possible source rocks show similarities with the diamondiferous komatiitic volcaniclastic rocks in Dachine, French Guiana and in Akwatia in the Birimian greenstone belt of Ghana. This might point to a regionally extensive diamond belt in the Guiana Shield and its pre-drift counterpart in the West-African Craton.

## Introduction

- The ultramafic rocks of Suriname are one of the least investigated, but economically most promising rocks in the Paleoproterozoic greenstone belt.
- It stretches over a distance of 1500 km along the whole northern coast of the Guiana Shield from Venezuela to the Amapá state in Brazil (Figure 1).

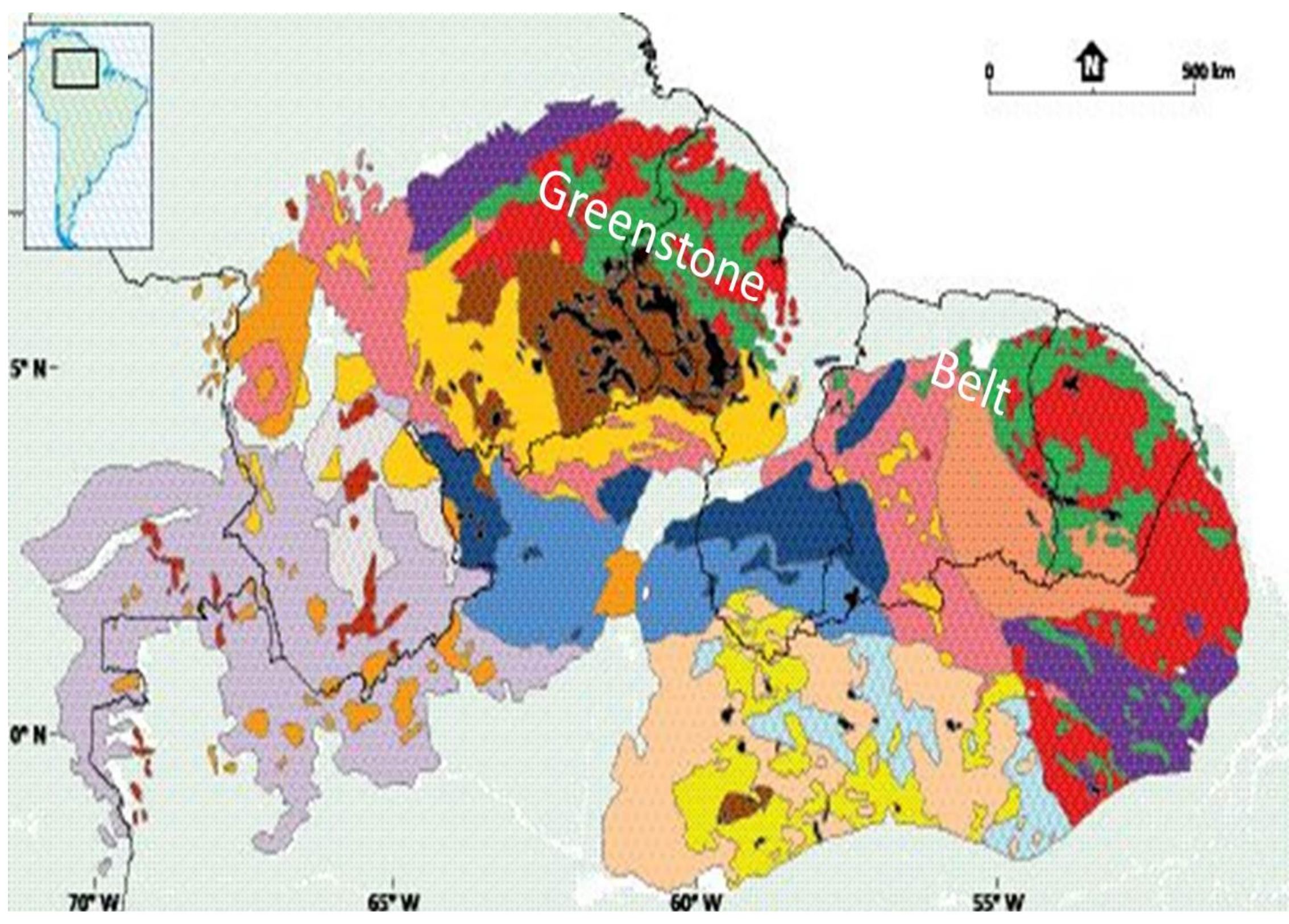


**Figure 1: The Trans-Amazonian Greenstone Belt of the northern Guiana Shield (Daoust et al., 2011).**

- Ultramafic rocks are the host rocks of nickel, chromium, platinum, gold and diamond mineralisations in the Guiana Shield.
- According to Bosma et al., 1984 all ultramafic and mafic bodies in Suriname were classified together as De Goeje Gabbro.
- These rocks were considered to belong to a single magmatic event around 1870 Ma (Priem et al., 1971).
- Recent zircon datings from French Guiana (± 2147 Ma; Tampok gabbro, Pb–zircon evaporation; Delor et al., 2003a), showed that the ultramafics in the greenstone belt are at least 100 million years older than those found in western and central Suriname (dated at 1985 Ma, Kroonenberg et al., 2016).
- The ultramafic bodies in the Surinamese part, the Marowijne greenstone belt, have been renamed as the Bemau Ultramafitite.
- Those in western and central Suriname Lucie Gabbro (Kroonenberg et al., 2016).
- The two sets ultramaic bodies also differ in lithologies, talc schists, chlorite schists, tremolite and serpentinites are common accompanying rock types in the greenstone belt, but absent in the Lucie Gabbro of western Suriname.

## Problem Statement

The nature of the emplacement of the lavas and volcaniclastics are still not understood, wheter they are extruded in a submarine environment, as suggested by the nature of the volcaniclastics. Whetrer the ultramafic lavas and vulkaniclastic rocks are from the same magmatic pulse as the cumulates, or else the cumulates injected into older ultramafic lavas.

## Purpose

- The purpose of this study is to investigate the petrogenesis, emplacement and tectonic setting of ultramafic rocks in the greenstone belt.
- To evaluate their importance for mineralisation, in order to elucidate whether the source rock of the Suriname diamonds is comparable to the diamond bearing rock units occurring in Dachine and Akwatia.

## Ultramafics in the Marowijne greenstone belt

The ultramafic rocks in the Marowijne Greenstone belt (Figure 2), can be grouped into three (3) main occurrences:

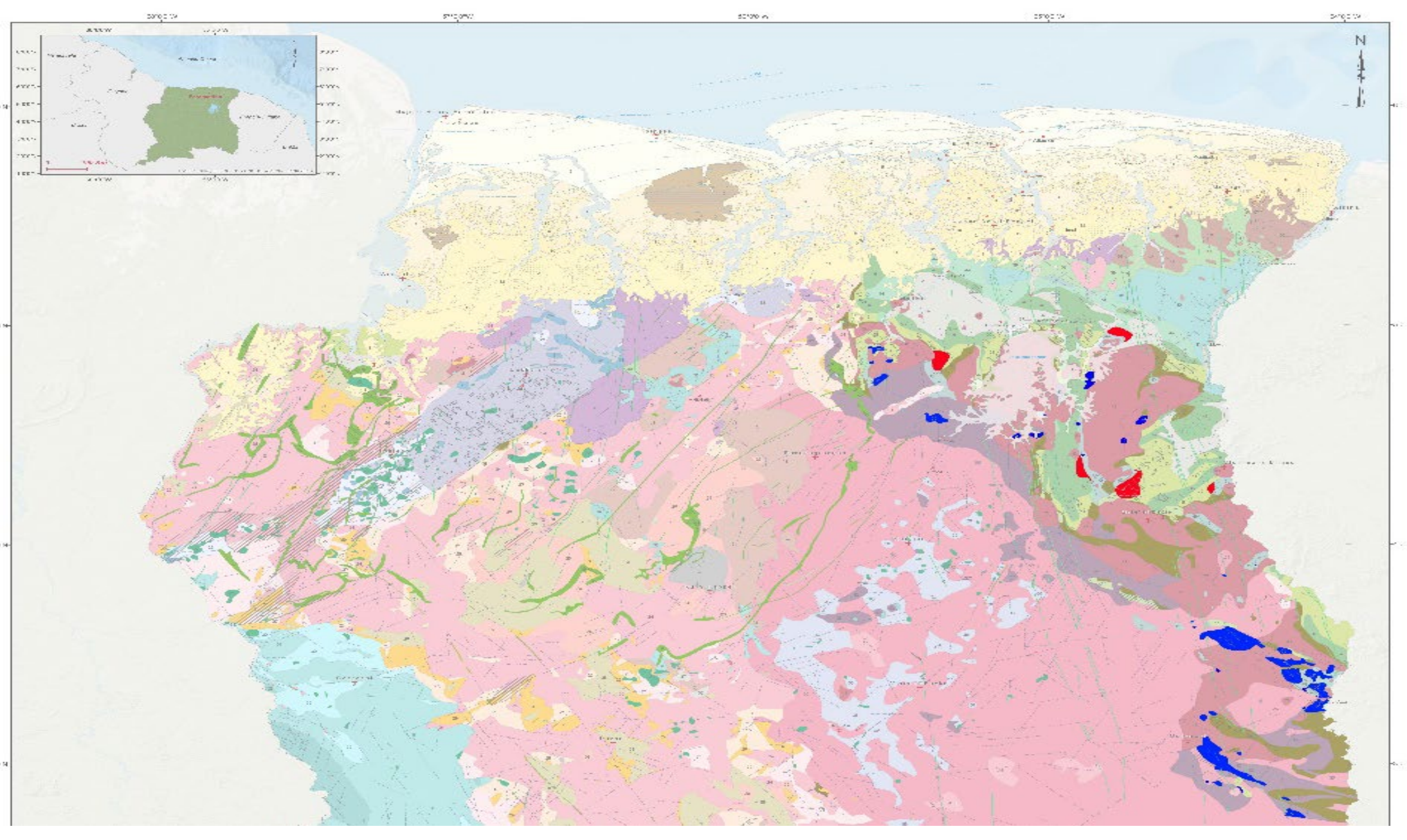


**Figure 2: Occurrences of ultramafic rocks in red and metagabbros in blue (modified form geological map of Suriname, the national geological survey GMD).**

1) **The Bemau ultramafic complex in the Saramacca area (Figure 3a).**

- consists of cumulate dunite-wehrlite-clinopyroxenites and gabbroic plutonic rocks, probably Alaskan-type intrusives (Veenstra, 1983; Teuling, 2018)
- as well as ultramafic talc-chlorite schists, which might represent ultramafic lavas and volcaniclastic rocks based on the presence of vesicular and sedimentary structures (Figure 3b & c).

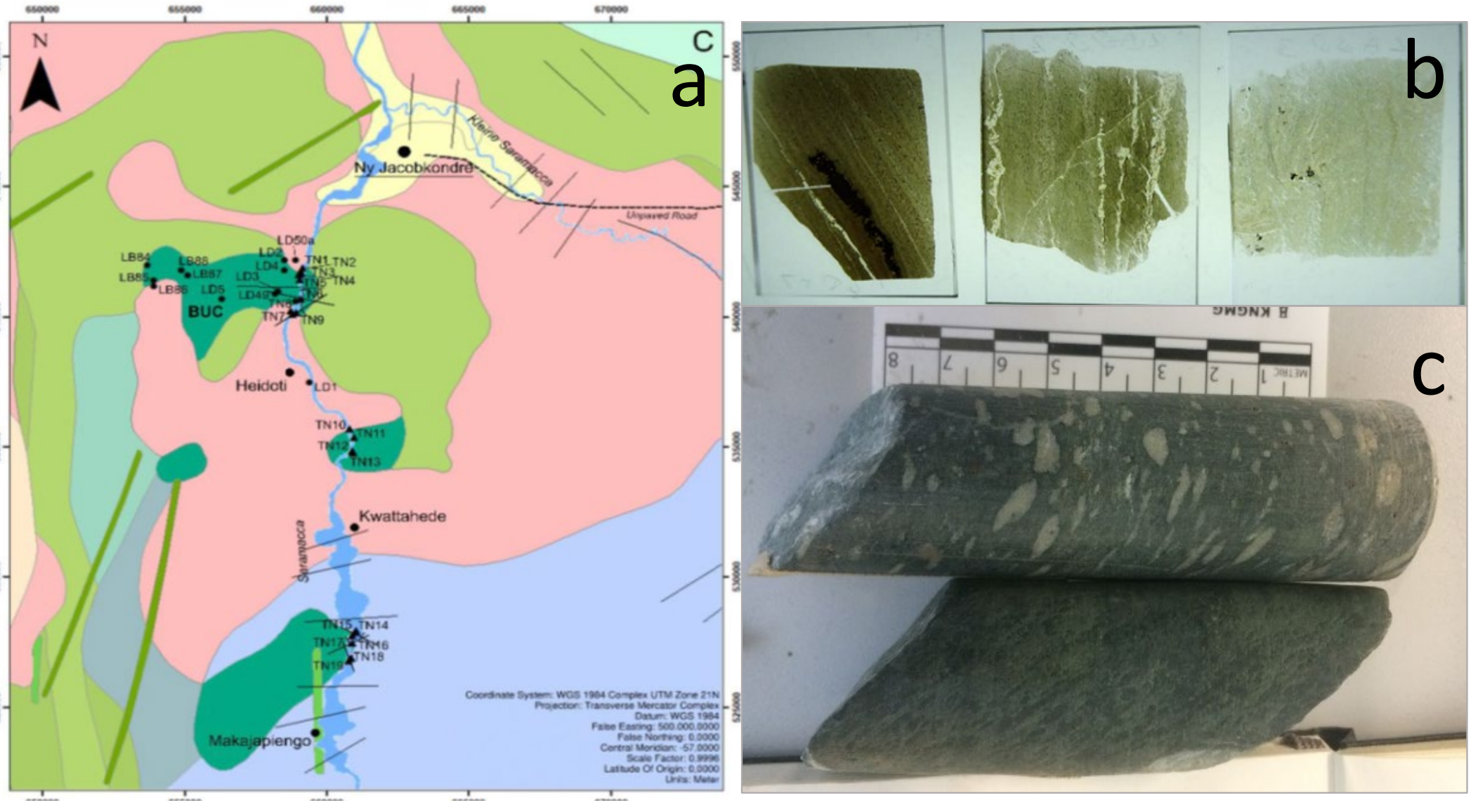


**Figure 3: (a) The Bemau ultramafic complex modified from the geological map of Suriname (the national geological survey GMD), (b) Ultramafic volcaniclastic chlorite schists with sedimentary structures in thin sections of RGM cores (c) and vesicular textures in GMD chromite-bearing -chlorite-talc schists.**

- An unusual corundum-chrome spinel rock is thought to represent a metasomatically desilicified cumulate (Teuling, 2018). The primary rocks in drill cores contain up to 0.5% Ni and 1,3% Cr, the overburden up to 0,25% Ni.
- The corundum-chrome spinel rocks contain up to 0,7% Ni and 6,5% Cr (Bosma et al., 1973; Veenstra, 1983).

**2) Residual chromite deposits associated with peridotites and talc schists**

- In a tributary of the Saramacca River (Upper Toekoemoetoe Creek): found in a weathering zone on top of a ± 2 km long ultramafic body, intercalated between biotite-hornblende gneisses (Bisschops, 1969).
- Similar small chromite bodies are found in an area west of the Upper Saramacca River (Den Hengst, 1975).
- Cr-bearing ultramafic intrusive rocks (≥ 1.0% Cr) have been recovered from the Piqué Hill, east of the Brokopondo storage lake (Bosma et al., 1973).

**3) The De Goeje mountains ultramafics (Figure 4)**

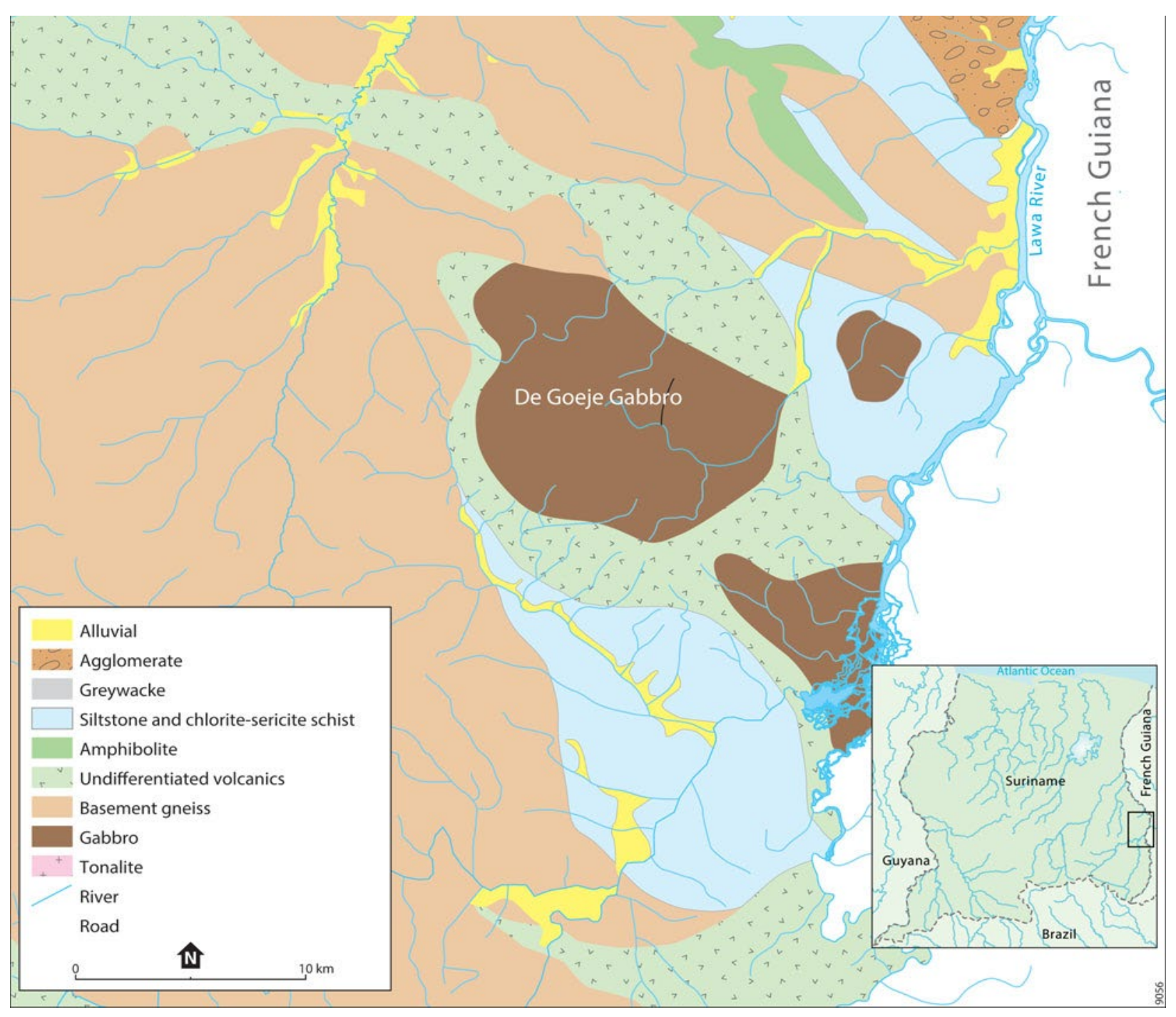


**Figure 4: De Goeje Mountains, (Ultra-) mafic intrusive in dark brown (Kioe-A-Sen et al., 2016).**

- consist of intrusive metagabbronorite and meta-ultramafitite (pyroxene-bearing granite-granodiorite to peridotite-dunite).
- Smaller amounts of serpentines and talc rocks, with hornblende, biotite or phlogopite and dusty plagioclase.
- Opaque minerals found are apatite and spinel, the latter especially in olivine bearing rocks (Bosma et al., 1983; Bosma et al., 1984; Kroonenberg et al., 2016).
- Apart from placer gold, alluvial platinum has been recovered, as small rounded grains (≥ 0.5 g/t), but still not encountered in the primary rock (Bosma and Groenweg, 1973).
- In French Guiana across the Marowijne River, alluvial platinum has been recovered as well in a similar setting (BRGM, 1980).

## Diamond-bearing ultramafic rocks

- **In Suriname** diamonds are found since 1880, mainly in the Rosebel- Sabanapasi area derived alluvium from the Rosebel conglomerates (Kooten, 1954).
- Schönberger, (1974) washed many samples of Rosebel conglomerates, and concluded the the source to be ultramafic rocks.
- Recent research resulted in the discovery of ultramafic volcaniclastic rocks in GMD drill cores (Figure 3c).
- Volcaniclastic-ultramafic rocks (Figure 3b) (chlorite-carbonate and phlogopite-talc–carbonate schists), are found in drill cores from Rosebel Gold Mines, (Ramlal, 2018).
- These rocks show high contents of chromium (>1000 ppm Cr) and nickel (>600 ppm Ni).
- RGM chemical database indicate these rocks are widespread in the whole area, suggesting a larger distribution.
- Findings of diamonds are also reported in the NE part of the Nassau Mountains area, near the Conglomerate and the Paramacca Creek (Headley, 1913).

**Diamond occurrence in the neighbouring countries**

- The main sources of gem-grade diamonds are ultrapotassic kimberlites or lamproites (Janse and Sheahan, 1995).
- In Venezuela, diamond bearing kimberlites have been found in the Guaniamo region (Kaminsky et al., 2004).
- Other important diamond occurrences in Venezuela are alluvial deposits, mainly associated with Roraima Formation.
- Similar diamond deposits are found in Guyana, Roraima.
- All rivers and streams that flow along or across Roraima group contain diamonds (Swiecki, 2011).
- However, in French Guiana recent research revealed an unusual diamond deposit in the Paleoproterozoic Inini Greenstone belt at Dachine (Figure 5).

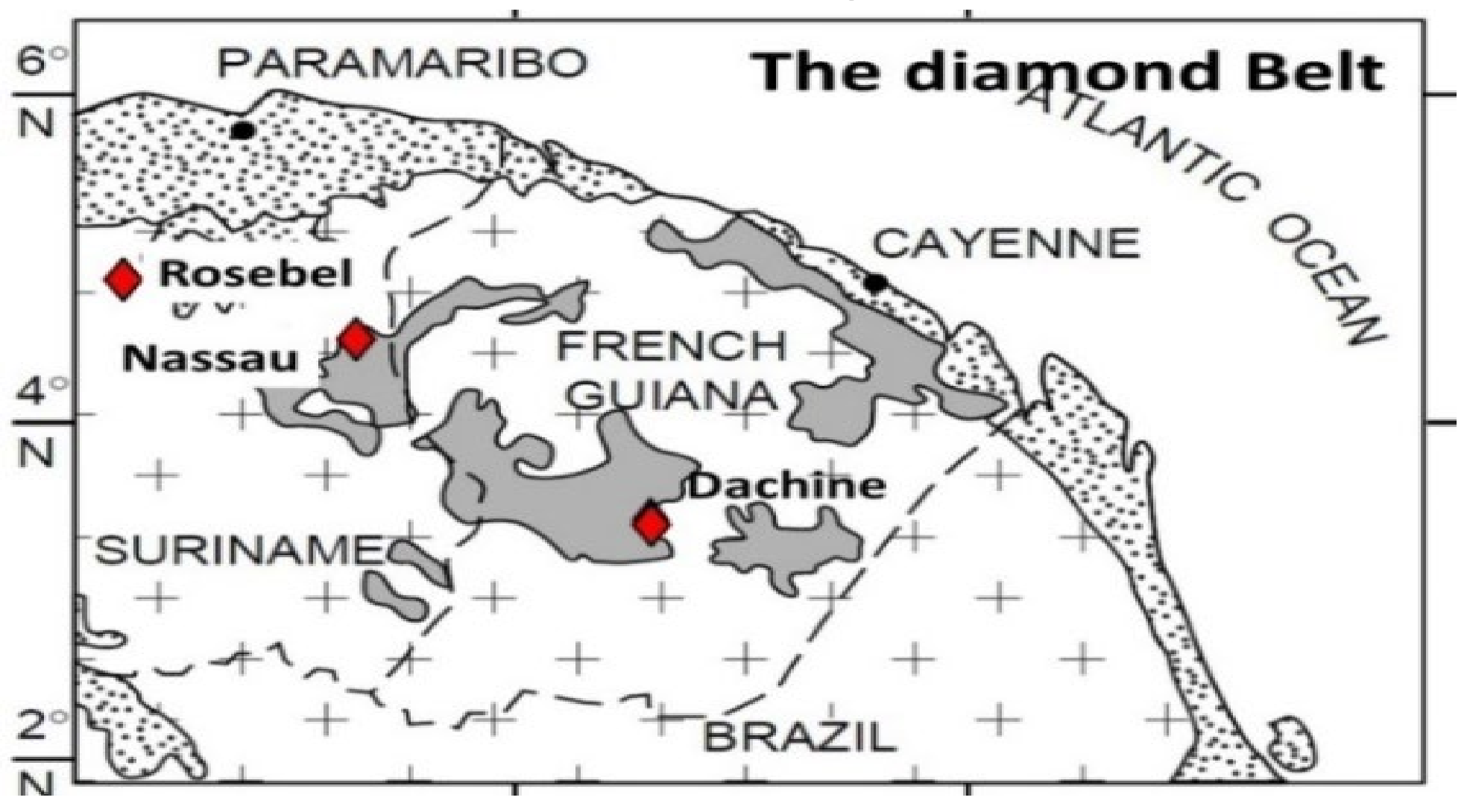


**Figure 5: possible regional diamond belt,mmodified from Capdivela et al., 1999.**

- The host rock is a ultramafic volcaniclastic body (chlorite-carbonate-talc schists and phlogopite-talc schist) with komatiitic geochemical affinities (Capdevila, et al., 1999).
- A similar type of diamond deposit is found in Akwatia, Ghana, within the Early Proterozoic Birimian Belt.
- The diamonds are associated with syn-eruptive volcaniclastic metaturbidites, with composition resembling komatiites (Canales, 2005), the host rock is actinolite-tremolite schist.

## Conclusions

- Ultramafic rocks in Suriname are an integral part of the Trans-Amazonian Orogen, their role in the magmatic history of this event still has to be elucidated.
- The age and stratigraphic relations of the ultramafic rocks should be investigated, age dating is required to elucidate the position of these rocks in the magmatic deformational and metamorphic events in the Greenstone belt.
- The processes that gave rise to the nickel, chromium, platinum and gold mineralisations have to be sorted out.
- The source rocks of the diamonds in Suriname have not yet been found, there is a possibility that the ultramafic rocks represent a regional event of diamondiferous komatiitic volcanism in the eastern Guiana Shield, further research is ongoing to test this hypothesis.

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# Petrography, geochemistry and age of the Armina Formation metaturbidites of the Coppename River, Suriname.

G.W. Wijngaarde[1] , S. B. Kroonenberg[2,3], P.R.D. Mason[4], L. M. Kriegsman[5]

## Abstract

The sedimentological, petrographic, geochemical and age characteristics of the Armina Formation along the Coppename River as well as its relation to the Bakhuis Granulite Belt based on field observations and laboratory analyses. The Armina Formation is deposited on the fore-arc side in an arc trench environment as turbidite sequences. The Bakhuis granulites and Armina metaturbidites protoliths might be coeval and share a common provenance area.

## Introduction

The turbiditic Armina Formation along the Coppename River is a part of the 2.26-2.10 Ga Paleoproterozoic Marowijne Greenstone Belt (MGB) of Suriname (**Fig. 1**). The belt is diapirically intruded by numerous TTG (tonalite-trondhjemite-granodiorite) bodies and the Armina Formation in turn by bi-mica and biotite granite bodies (Bosma et al., 1983; De Vletter, 1984).

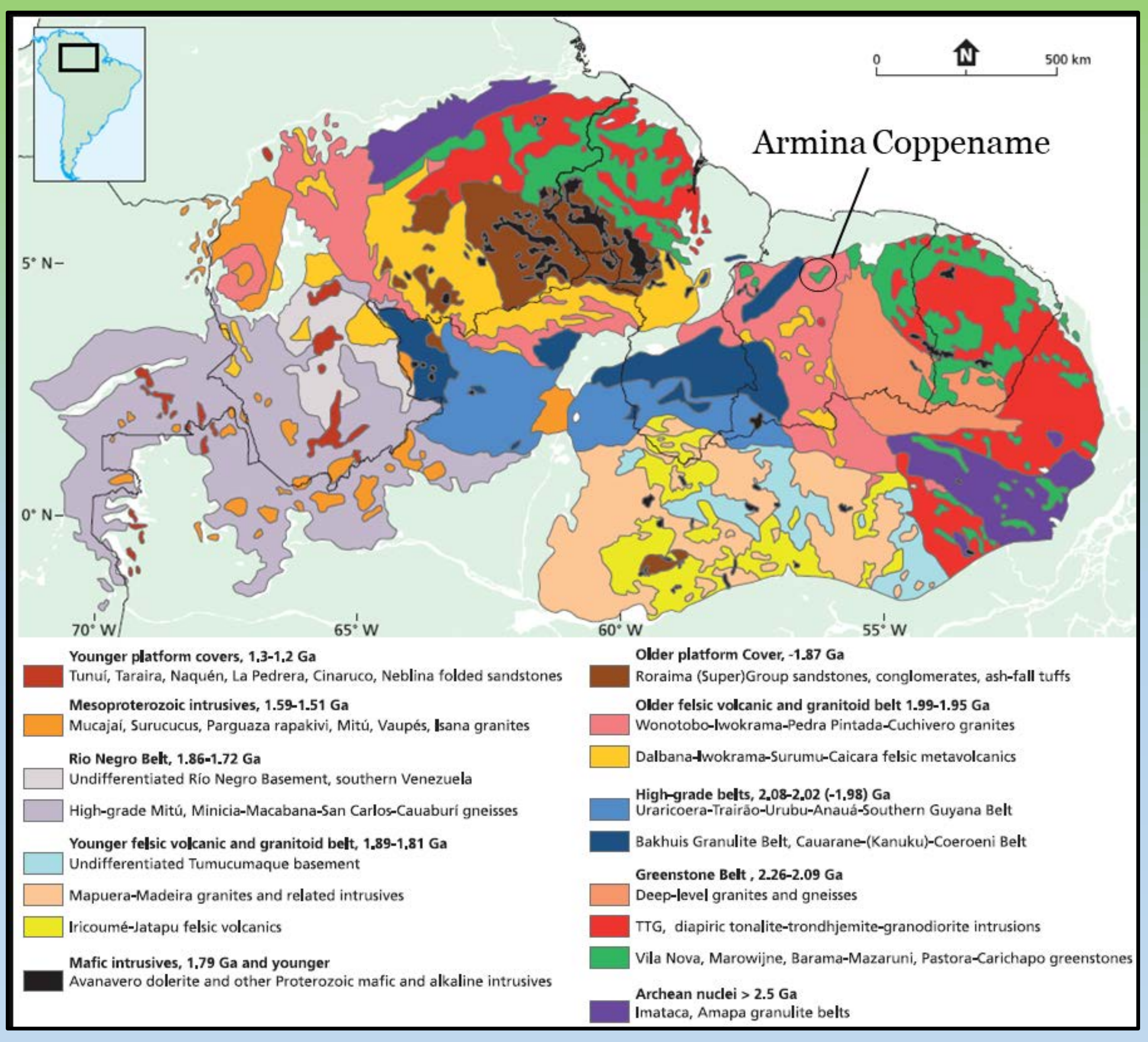

**Figure 1:** Simplified geological map of the Guiana Shield (Kroonenberg et al., 2016).

## Problem Statement

The Armina Formation in the Coppename area is situated outside the main trend of the Greenstone Belt, but is in faulted contact with the 2.08-2.05 Ga Bakhuis high-grade Granulite belt (BGB). Formerly the BGB was considered to be older (of Archean age) than the MGB (Bosma, et al. 1983), whereas recent research showed that it is just the reverse (De Roever et al., 2003; Klaver et al. 2015; Kroonenberg et al. 2016). On the other hand aeromagnetic surveys show that the MGB cuts the BGB in the north thus reopening the question of age relations. The position of the Armina Formation outcrop in contact with the Bakhuis belt offers an opportunity to confirm or reject the present ideas.

## Purpose

The research investigates whether the Coppename metaturbidites are deposited in an outlier and/or tectonically displaced basin of the same greenstone belt, or whether it could be a part of the same trans-tensional basin in which the Bakhuis protoliths have been deposited, and only escaped from being incorporated in the part of the basin that suffered granulite-facies metamorphism.

## Methods

Fieldwork was carried out along the Coppename River and the most extensive outcrops are encountered at Grantabiki in the north and along the Tanjimamma creek in the south. 25 samples were studied for petrography and geochemistry, and 6 for geochronology. Major elements were analysed using XRF, trace elements with LA –ICPMS on fragments of the XRF beads, and U-Pb zircon dating was performed using LA -ICPMS as well, all at Utrecht University, the Netherlands.

## Results – Field characteristics

The Armina Formation rocks along the Coppename River were deposited in 1-5 m thick fining-upwards turbiditic sequences characterised by constant layer thickness, graded stratification in the coarser parts, small ripple-, wavy-, and convolute lamination and cross stratification in the finer parts (**Fig. 2**).

**Figure 2:** Outcrop of Armina Formation metaturbidites at Grantabiki, Coppename River (Wijngaarde, 2019).

The Armina Formation metagreywackes are intruded by a younger granite evidenced by pegmatite veins, contact metamorphism in the metagreywackes, and metagreywacke xenoliths in the granite (**Fig. 3**).

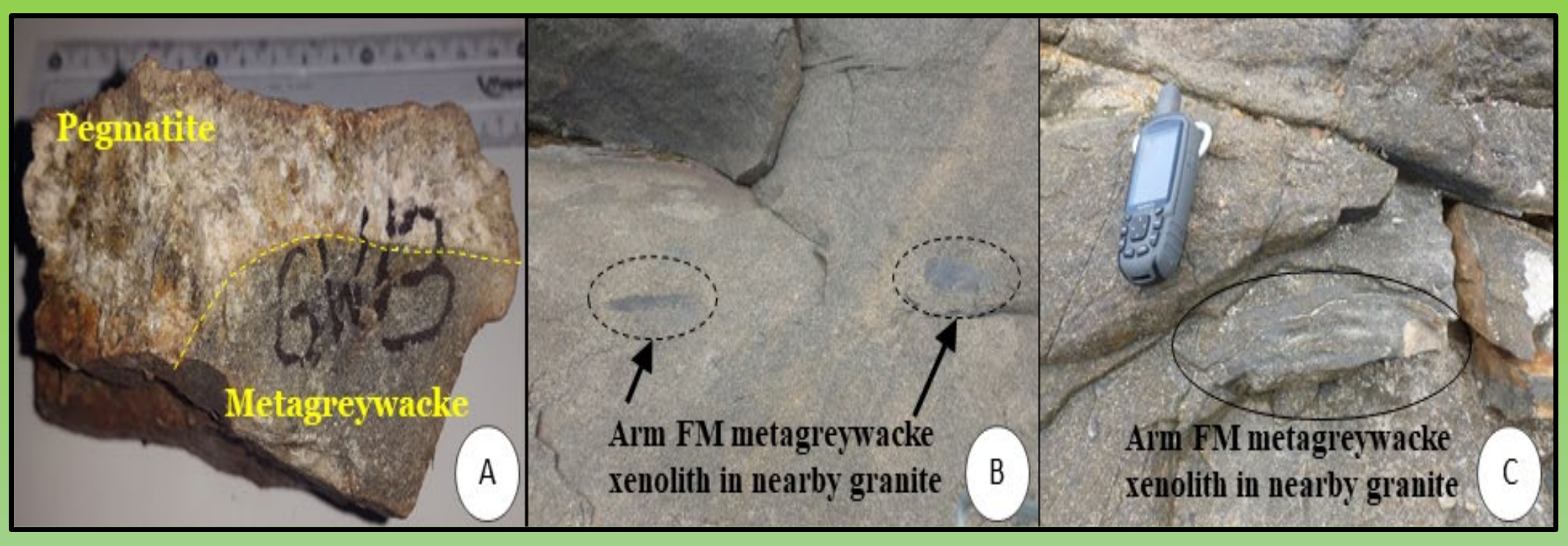

**Figure 3:** Vankaaiki sula (a) Contact of pegmatite vein and metagreywacke, (b & c) Armina Formation (Arm Fm) metagreywacke xenoliths in the nearby granite.

## Results - Petrography

The metagreywackes range from north to south from texturally and mineralogical immature to sub-mature, and consist of quartz, plagioclase, K-feldspar (including microcline), biotite, muscovite, chlorite, epidote, allanite, rutile, zircon, tourmaline, titanite, magnetite/ilmenite, pyrite/other sulfide mineral, and magmatic (both plutonic and volcanic; **Fig. 4**), metamorphic and sedimentary lithic fragments. In the north lithic wackes occur, while southwards they are more feldspathic.

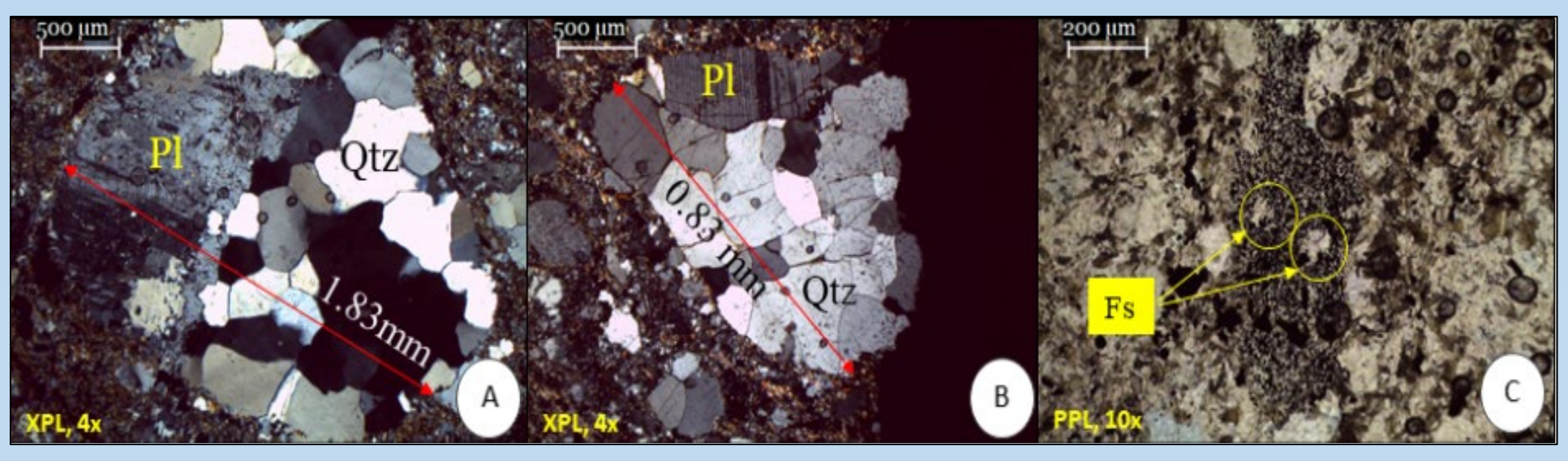

**Figure 4:** (a & b) Plutonic fragments, consisting of plagioclase (Pl) and quartz (Qtz) in sample GW 3 and GW 25, (c) Fine-grained mafic volcanic fragment with lots of small opaque minerals and feldspars (Fs) in sample GW 3.

The plutonic fragments are probably derived from TTG plutons due to the abundance of plagioclase relative to alkali feldspar. QFL & QmFLt provenance diagrams indicate that greywackes with a volcanic provenance in the north at Grantabiki were deposited in an active island-arc, whereas from Adenagado sula southwards the rocks become more arkosic with a more granitic provenance deposited in an active continental margin (**Fig. 5**).

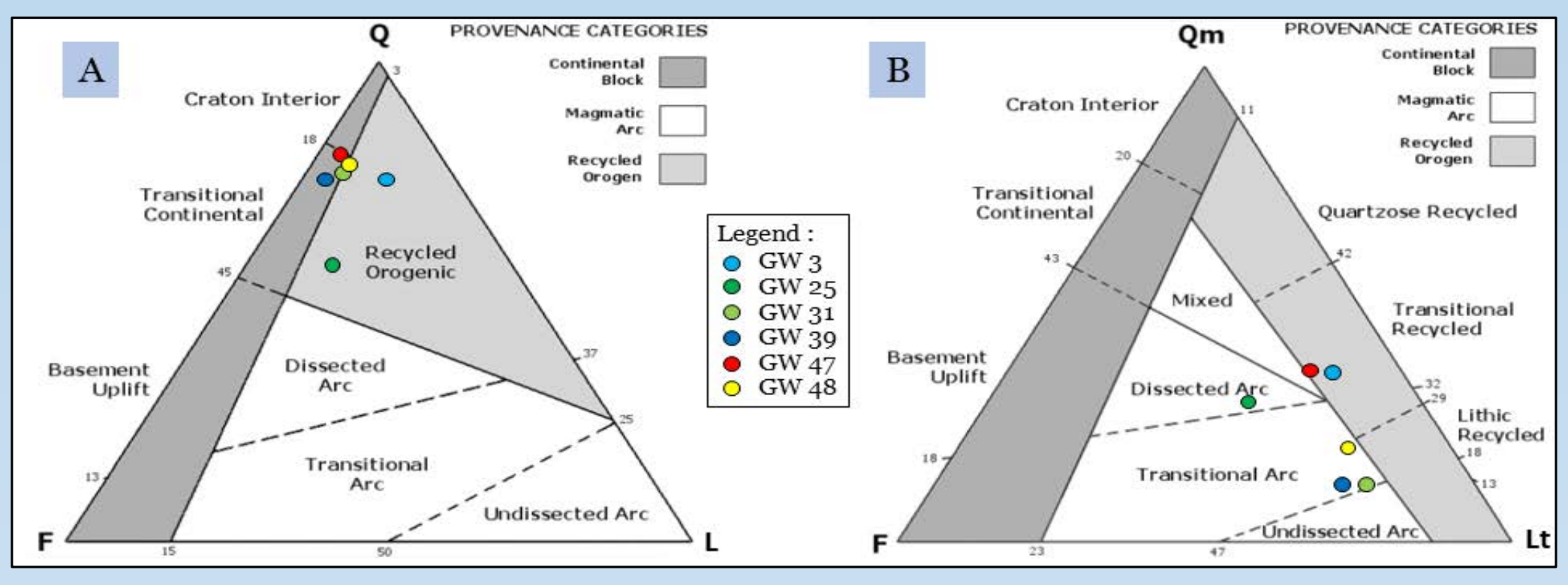

**Figure 5:** (a & b) QFL and Qm-F-Lt ternary provenance diagram after Dickinson et al. (1983).

The mineral assemblages indicate regional metamorphism from greenschist facies (chlorite and biotite zone) to lower amphibolite facies (garnet zone), whereas in the vicinity of granitoid rocks contact metamorphism occurred (**Fig. 6**).

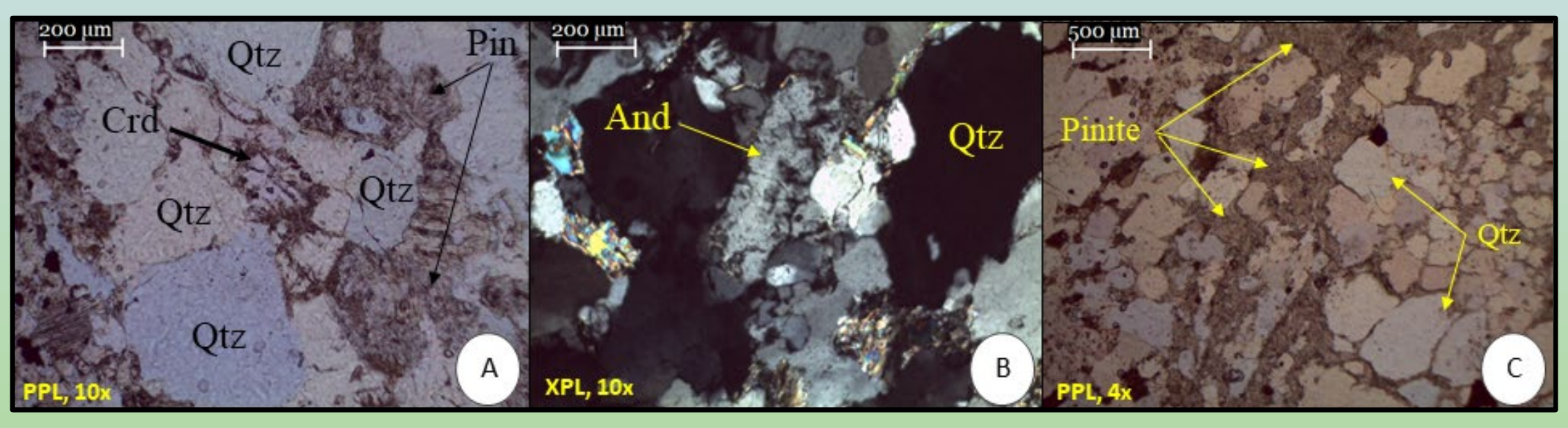

**Figure 6:** (a) Contact metamorphic variants with the typical metamorphic mineral cordierite (Crd) and (b) andalusite (And) in sample GW 15, (b) Pinite (Pin), alteration of cordierite to micas in sample GW 36.

## Results - Geochemistry

Geochemical analysis and higher Ni concentrations in the northern samples point to a partly mafic igneous provenance (volcanic), while higher Th and U concentrations in the southern samples suggest a more felsic igneous provenance (granitic). The geochemical data confirm the volcanic arc depositional environment for the northernmost samples and a continental margin type setting for the southernmost ones (**Fig. 7**).

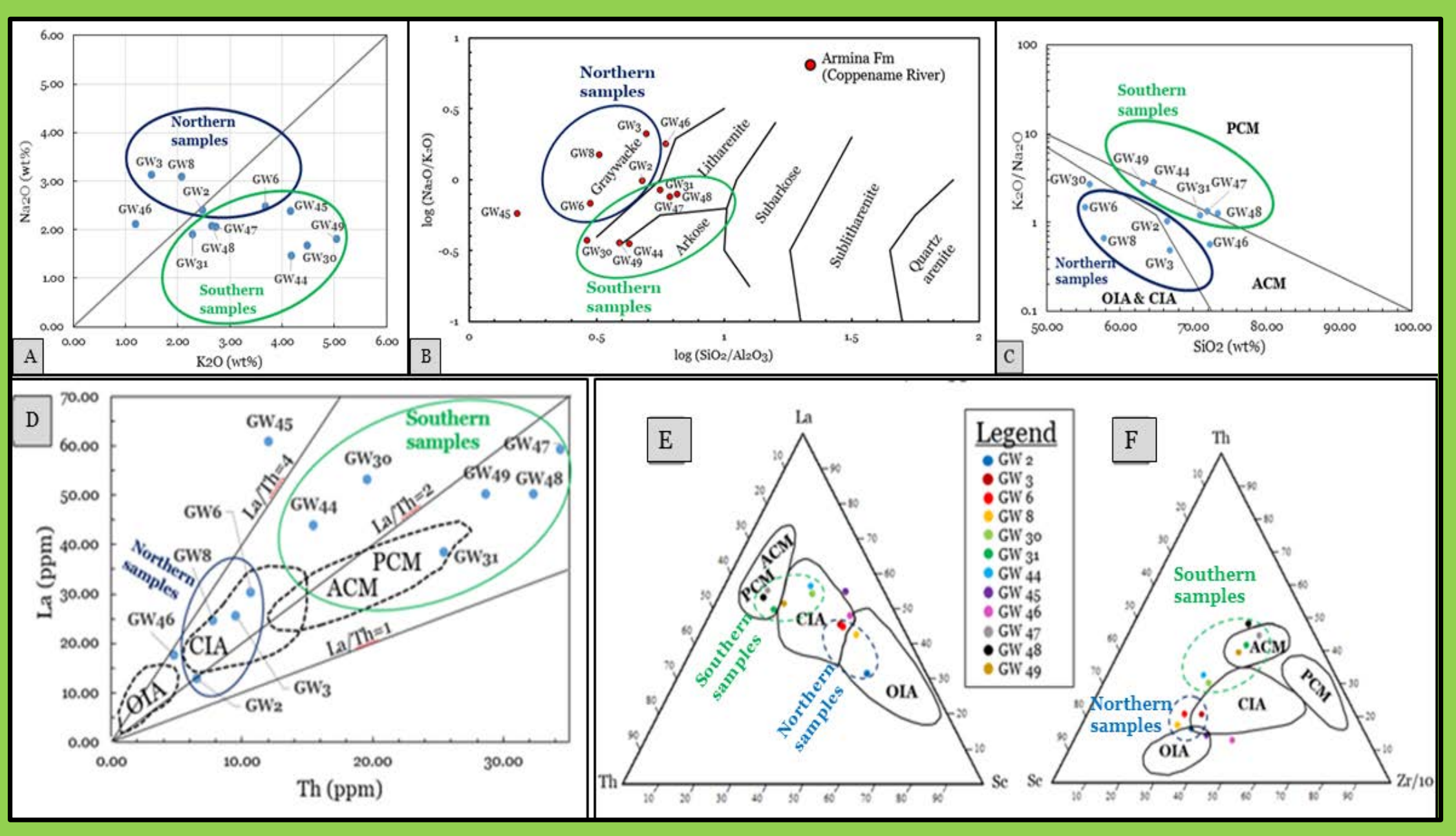

**Figure 7:** (a) Correlation and (b) Classification plots after Pettijohn et al (1972), (c) Tectonic discrimination diagram after Roser & Korsch (1986), (d) La versus Th, (e) La-Th-Sc and (f) Th-Sc-Zr/10 discrimination diagrams after Bhatia & Crook (1986). OIA=Oceanic Island-Arc; CIA=Continental Island-Arc; ACM=Active Continental Margin; PCM=Passive Continental Margin.

## Results - Age

Detrital zircons in the Armina Formation along the Coppename River indicate an age of about 2162 ± 30 Ma for the major sediment source of the metaturbidite sequence, which is similar to that of the eastern Marowijne Armina Formation. Younger granites intruding the Armina metaturbidites show ages of 2005 (Voltzberg), 2004 (Raleigh Falls) and 1990 Ma (Vankaaikisula), slightly higher than most Wonotobo granites in western Suriname.

## Conclusions

- The turbidite deposits of the Armina formation show no affinity to the Bakhuis rocks and are a part of the same greenstone belt of northeastern Suriname deposited on the fore-arc side in an arc trench environment.
- No zircons in the Bakhuis age range of 2.08-2.05 Ga and no granulite clasts have been found in the Armina metagreywackes.
- The presence of inherited zircons with ages between 2120 and 2150 Ma in the sillimanite gneisses of the Bakhuis Belt (Klaver et al., 2015) might indicate that the Bakhuis granulites could represent the high-grade equivalents of the Armina metaturbidites, and hence share the same provenance area.
- Probably due to the development of the arc over time, the bottom of the sequence is more volcanic while still an island arc (north), whereas higher in the sequence more granitic when it has already become an active continental margin due to the development of the subduction zone (south) OR the turbidites in the north and south were fed by different river systems and the two sequences lay on each other on the same level.

## Recommendations

- Further sampling and dating southwards along the Coppename River
- Investigation of the absence of gold within the Armina Formation of the Coppename Area.
- Bakhuis Granulite Belt Vs. Armina Formation based on geochemistry.
- Detailed aeromagnetic survey of the Bakhuis Granulite Belt.

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# 2.12 – 2.07 Ga Late- to post-collisional peraluminous granitoid magmatism in the Marowijne Greenstone Belt of Suriname

S. C. Kromopawiro[1], S. Kroonenberg[2], L. Kriegsman[3], P. Mason[4]

## SUMMARY

Magmatic evolution of the Marowijne Greenstone Belt occurred in several phases during the Trans-Amazonian Orogeny. The first episode initiated the emplacement of the TTG-suites in multiple phases between 2.19 – 2.16 Ga and 2.15 – 2.11 Ga, during convergence and collision of the Amazonian and African cratons. TTG plutons that arose include the Brinck pluton, the Kabel Tonalite and the Saramacca batholith. Convergence during the second phase of the TTG magmatism, led to crustal processes resulting in the formation of the Tibiti biotite-granite from melts emerging from lithospheric structural acirvities, unrelated to subduction. Between 2.10 – 2.07 Ga another magmatic event presented itself, marking continuing convergence and the emplacement of syn-tectonic peraluminous granites such as the Phedra and the Patamacca, and at a later - to post-collision stage, the formation of the Akinto Soela granite.

## GEOLOGY

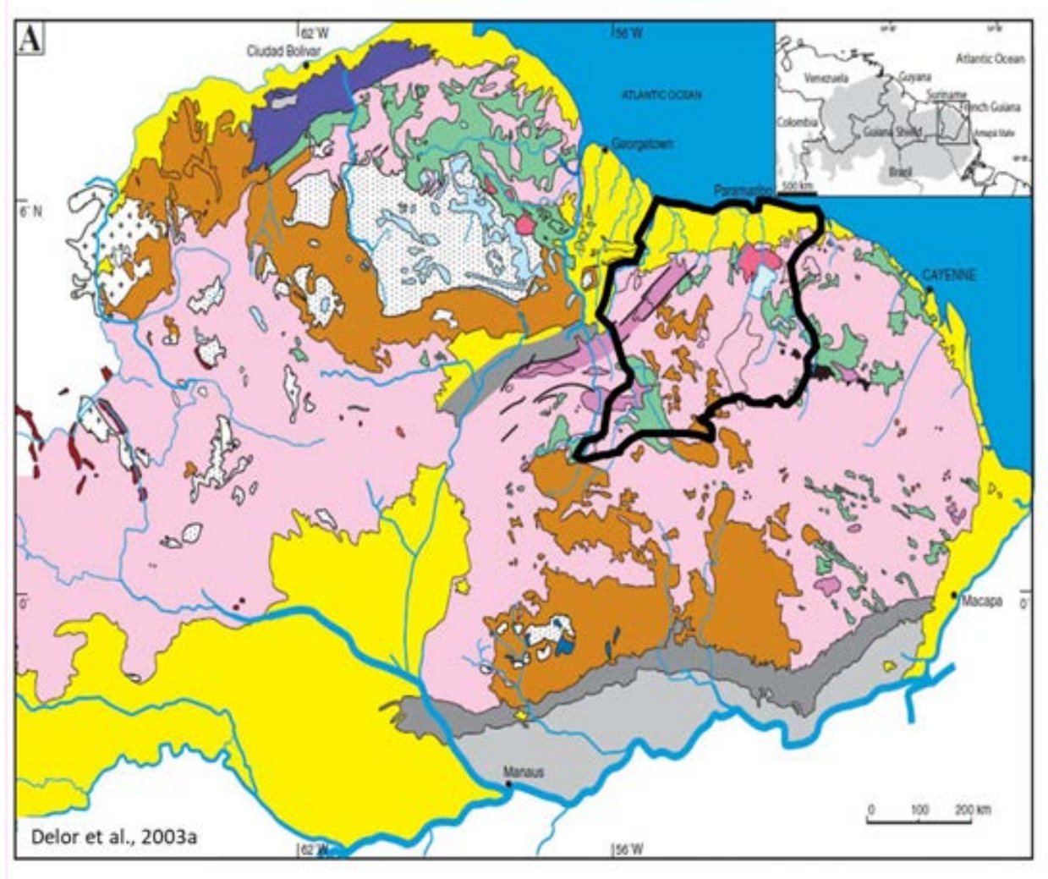


Figure 1: Simplified geological sketch map of the Guiana Shield (Delor et al., 2003a) with Suriname highlighted in black.

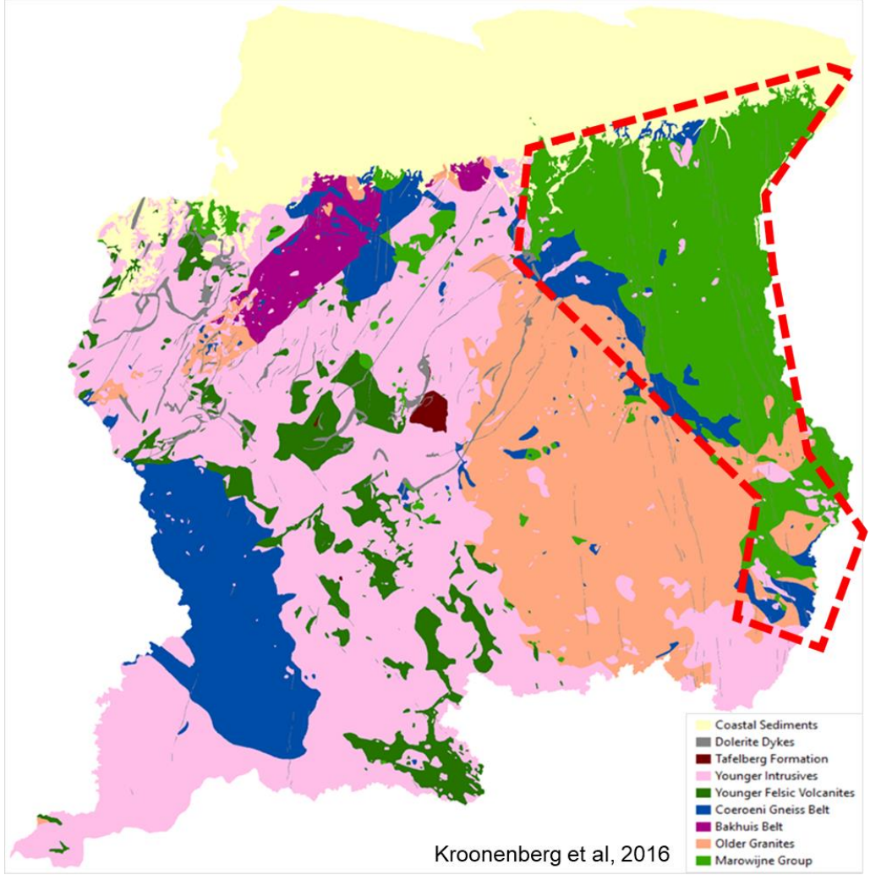


Figure 2: Simplified geological map of Suriname with the main units, after Bosma et al. (1977), modified by Kroonenberg et al. (2016).

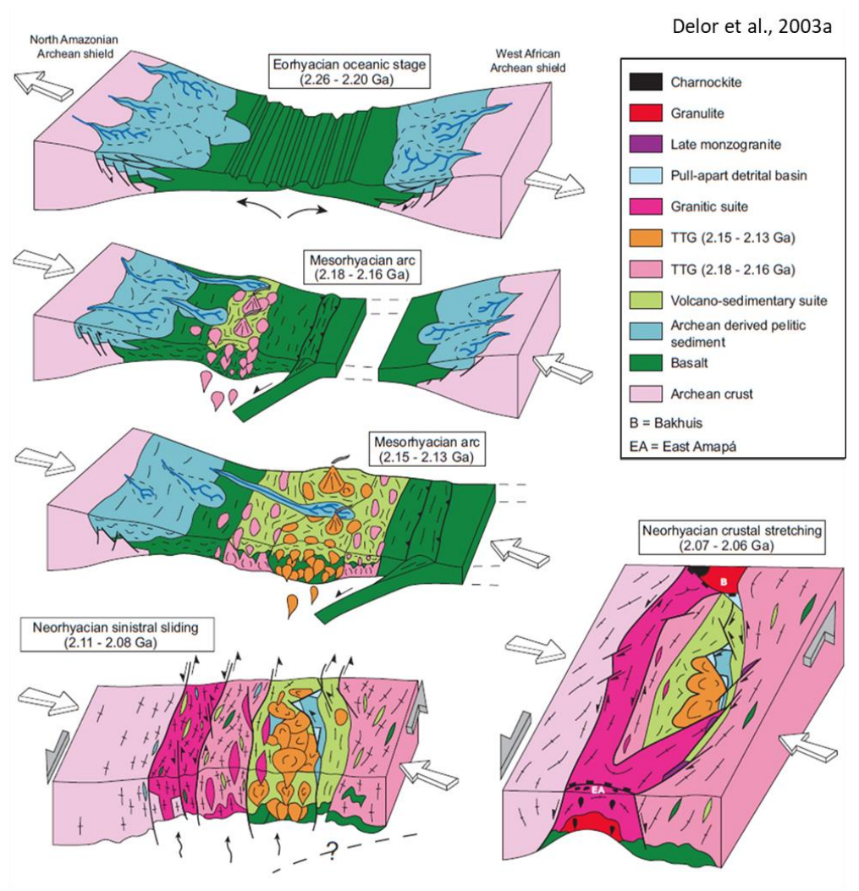


Figure 3: A geodynamic evolution model for the Guiana Shield (Delor et al., 2003a).

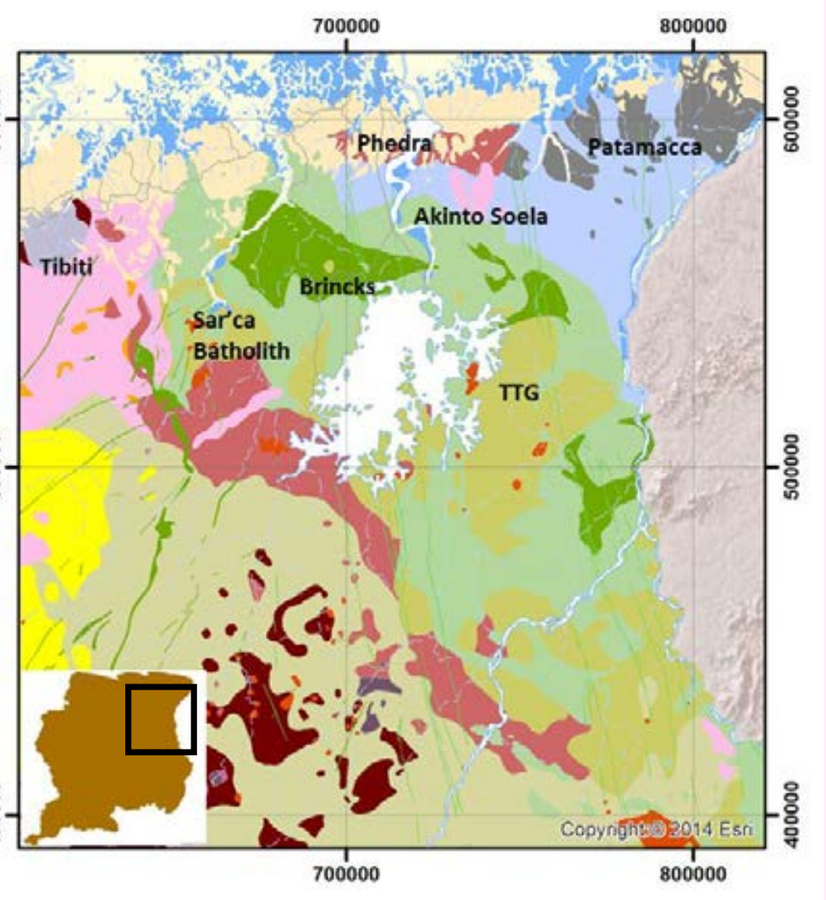


Figure 4: Geological map of the Suriname after Bosma et al. (1977) and Kroonenberg et al. (2016), with the locations of the granitoid of the Marowijne Greenstone Belt.

## GEOCHEMICAL CLASSIFICATION

### Magma Sources

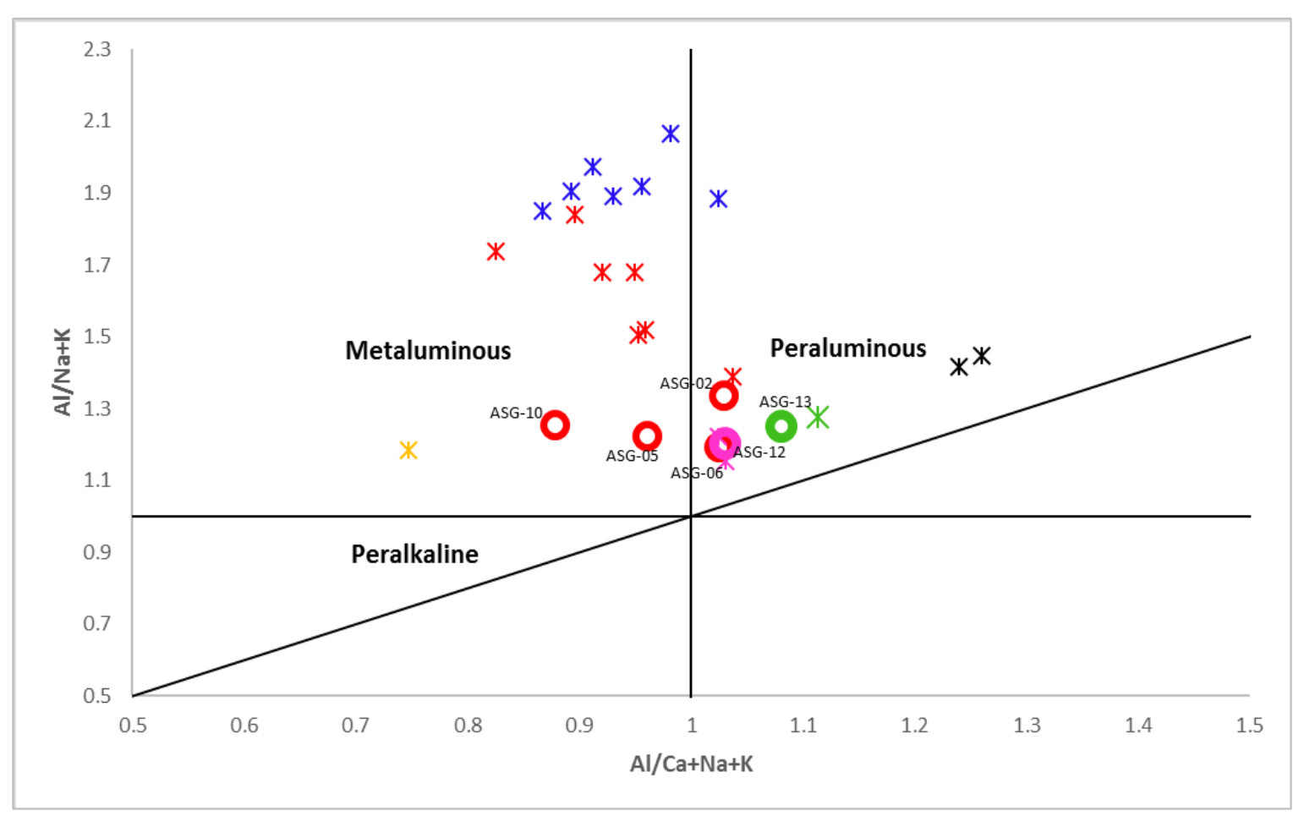


Figure 5: ASI-classification of the granitoid rocks after Shand (1947), with discrimination fields for different geochemical types of granitoids, after Maniar and Picolli (1989). The Akinto Soela granite plots in both the peraluminous and metaluminous fields. The Tibiti and Phedra granites both plot in the peraluminous fields.

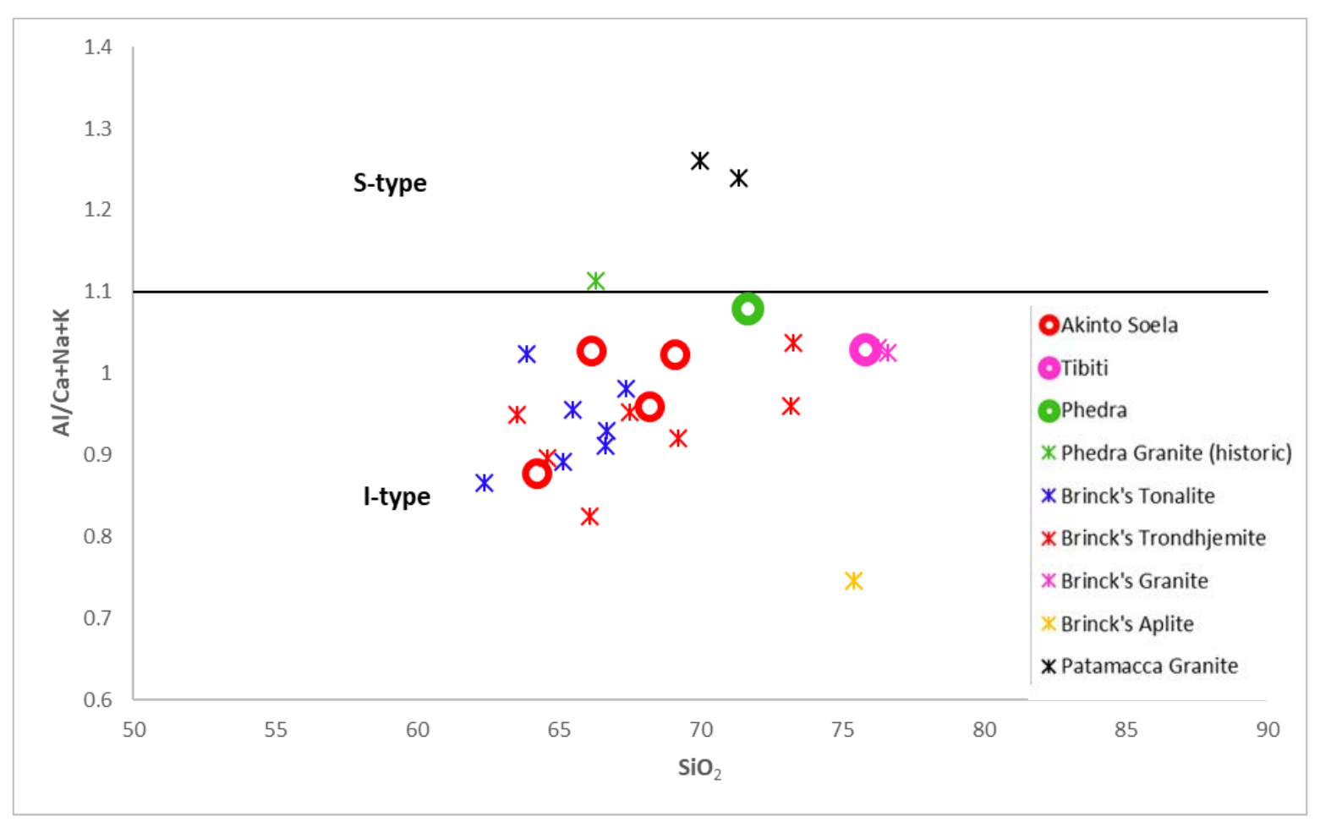


Figure 6: ASI-diagram (Al/Ca+Na+K vs SiO2) for the classification of the granitoids into I- and S-types, after Chappell and White (1974). The granitic samples studied in this report all plot as I-type with ASI values < 1.1.

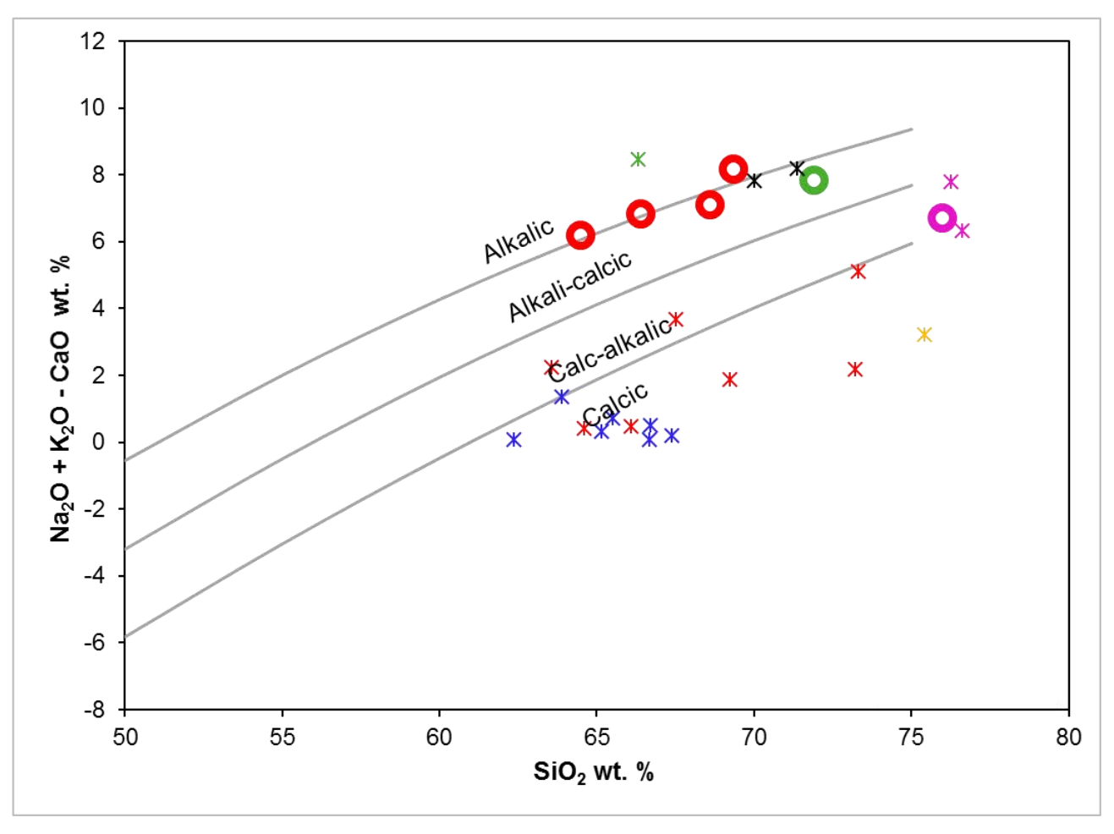


Figure 7: MALI index after Frost et al. (2001) illustrating the Akinto Soela and Phedra granites having an alkalic to alkali-calcic character, suggesting derivation from a sedimentary source, while the Tibiti granite has a calc-alkalic character similar to the Brink pluton, suggesting derivation from mafic to intermediate sources.

### Tectonic Setting

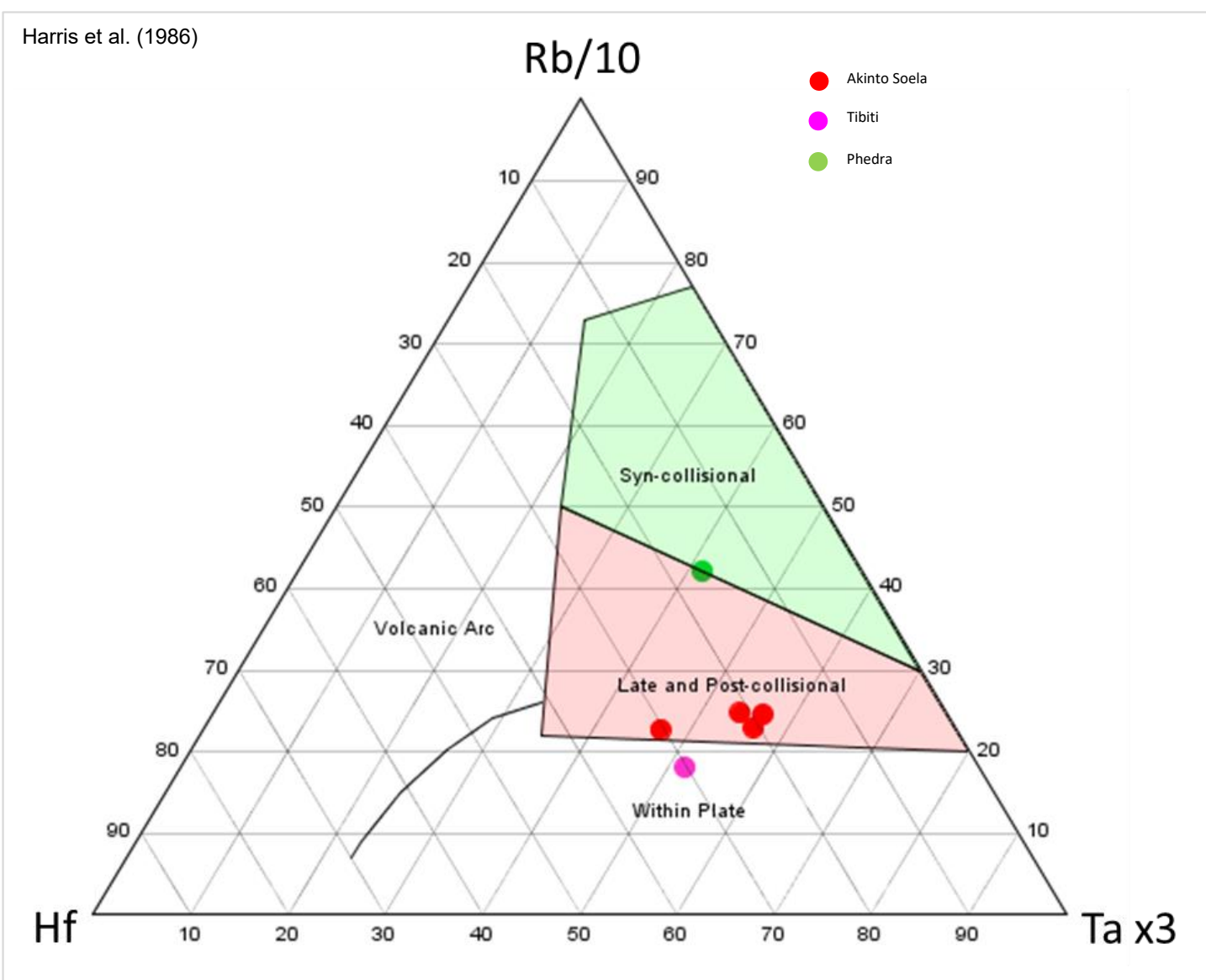


Figure 8: Rb-Hf-Ta triangular plot for acid-intermediate intrusive magmatism by Harris et al. (1986). The Akinto Soela granite (red) plotting as late and post collisional, the Tibiti granite as within plate and the Phedra granite on the border of the two collisional fields, but considered as syn-collisional,

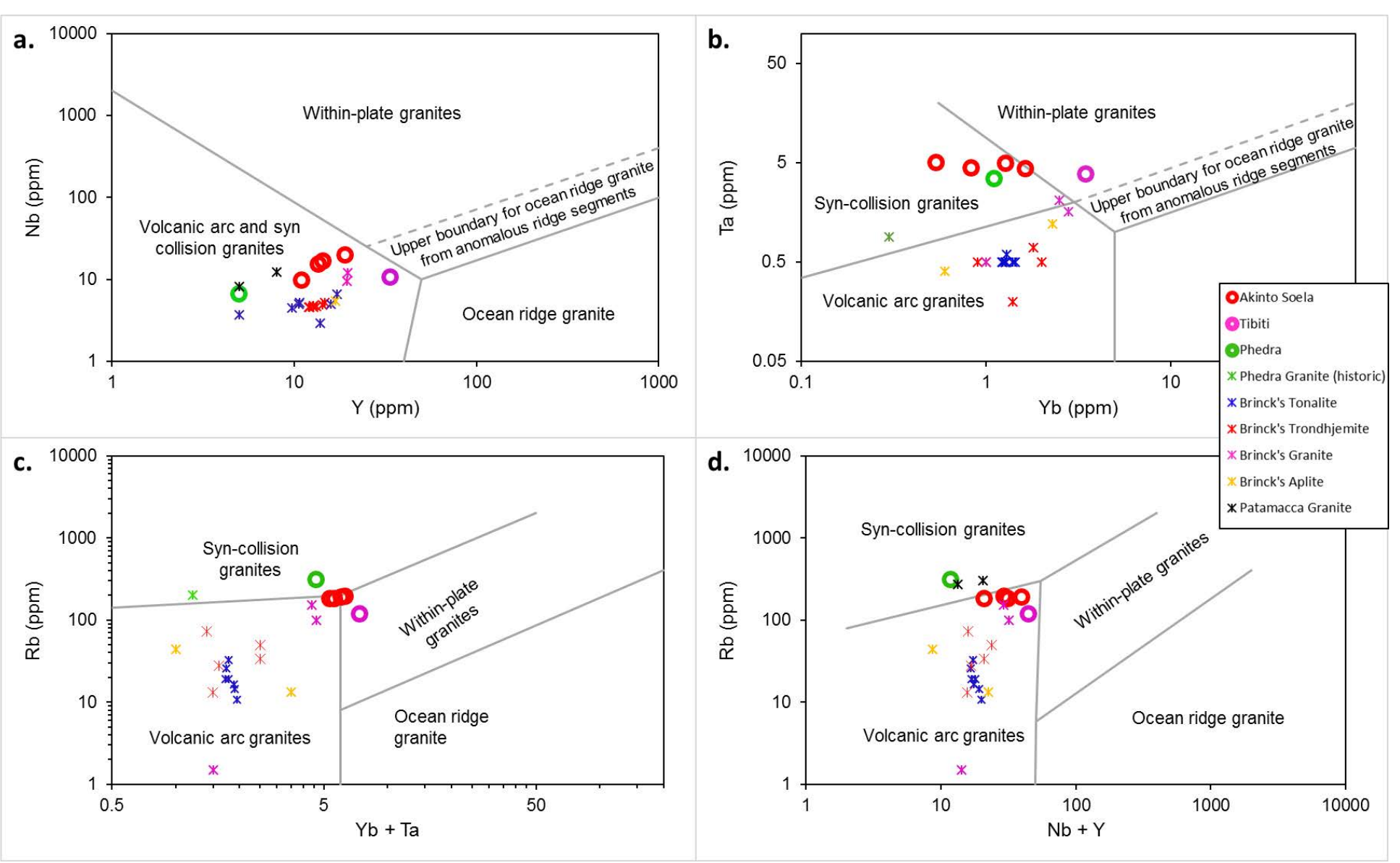


Figure 9: Tectonic discriminant diagrams after Pearce et al. (1984). a.) Nb-Y diagram in which all samples plot in the VAG and syn-COLG field. b.) Ta-Yb diagram showing the Akinto Soela and Phedra samples plotting as syn-COLG, and the Tibiti sample plotting as WPG. c.) Rb-(Yb+Ta) diagram illustrating the Tibiti sample plotting as a WPG, the Phedra sample as syn-COLG and the Akinto Soela samples occupying the triple corner of the WPG, the VAG and the syn-COLG fields. d.) Rb-(Nb+Y) diagram showing the Akinto Soela and Tibiti samples plotting as VAG and the Phedra sample plotting as syn-COLG.

### REE and Spider Diagram

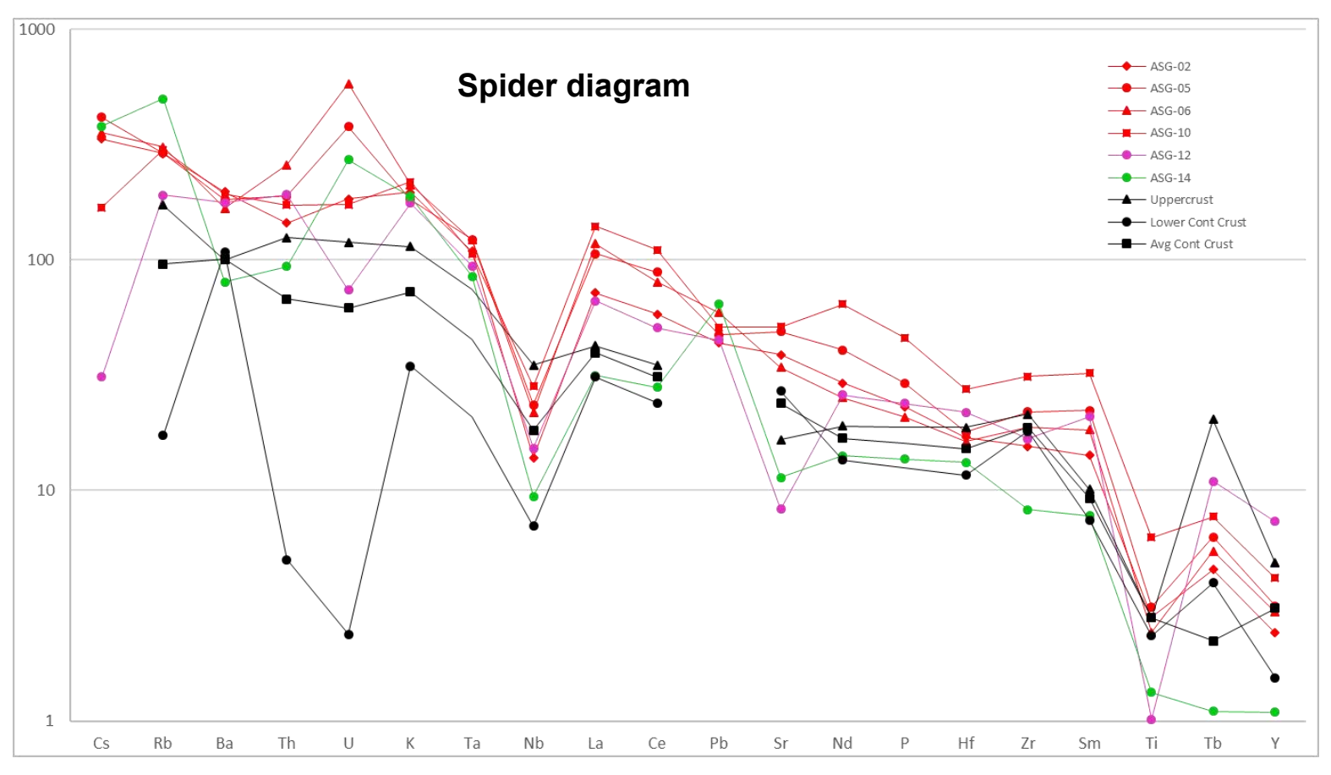
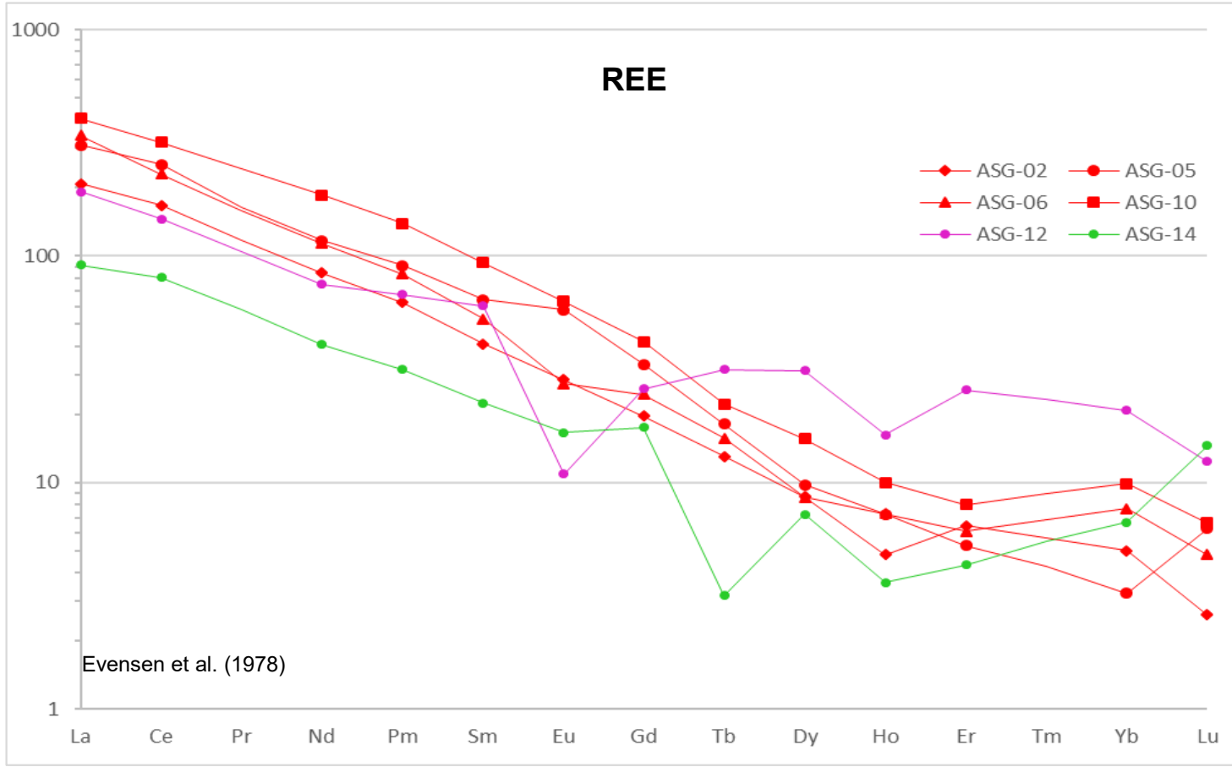


Figure 10: Spider diagram after Sun and McDonough (1992) normalized to a primordial mantle. The granitic samples mostly reflect influences from the uppercrust with minor element concentrations similar to the average continental crust.

Figure 11: REE patterns of the Akinto Soela (red), Phedra (green) and Tibiti (magenta) granites, normalized to an average CI chondrite, after Evensen et al. (1978).



## TIBITI GRANITE

This Tibiti granite is classified as a peraluminous, calc-alkalic, I-type biotite-granite, derived from mafic to intermediate sources by possible fractional crystallization. The age of unit (~2119 Ma), suggests emplacement during the second phase of TTG plutonism, within a continental plate setting, as the result of lithospheric structural activity, unrelated to subduction.

This unit is not considered part of the TTG-group as trace element concentrations show compositional variation.

Figure 12: Photographs of the pink Tibiti granite. The left photograph shows a weak banded texture in the rock and the right photograph, the medium to coarse grained texture is presented.

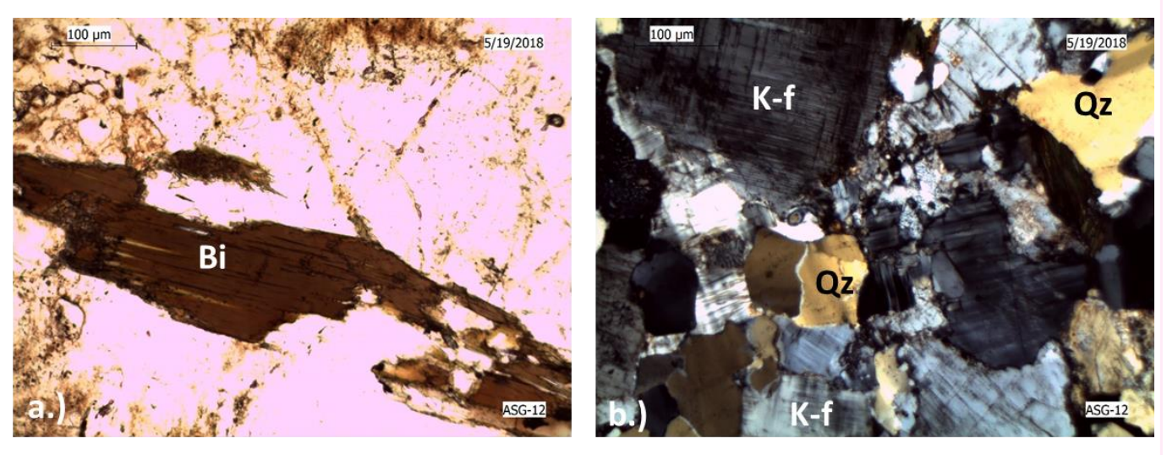
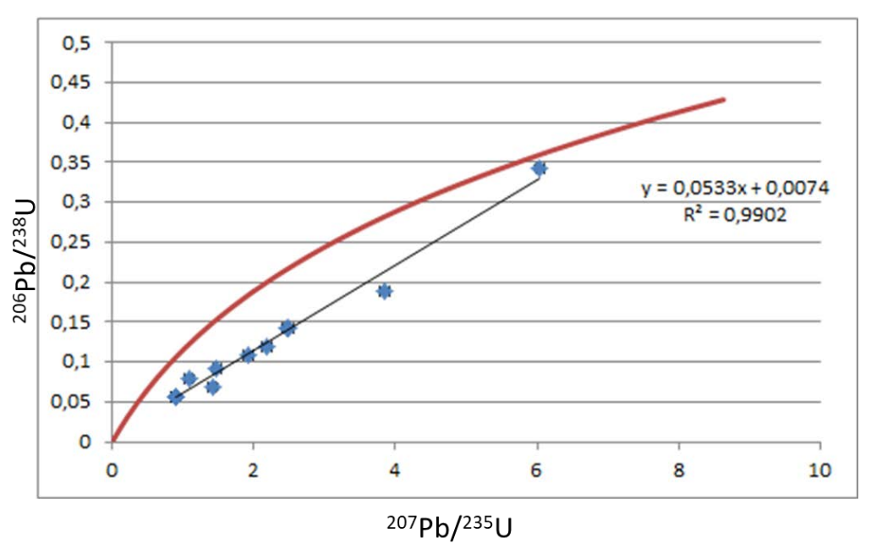


Figure 13: Microphotographs of thin sections from the Tibiti granite. a.) Reddish-brown biotite grain showing weak pleochroïc halos. b.) Rock forming minerals of the Tibiti Granite, including quartz and k-feldspars.

## PHEDRA GRANITE

Figure 14: Concordia diagram of the Phedra zircon measurements. Data processed by Dr. Kriegsman (report in progress).



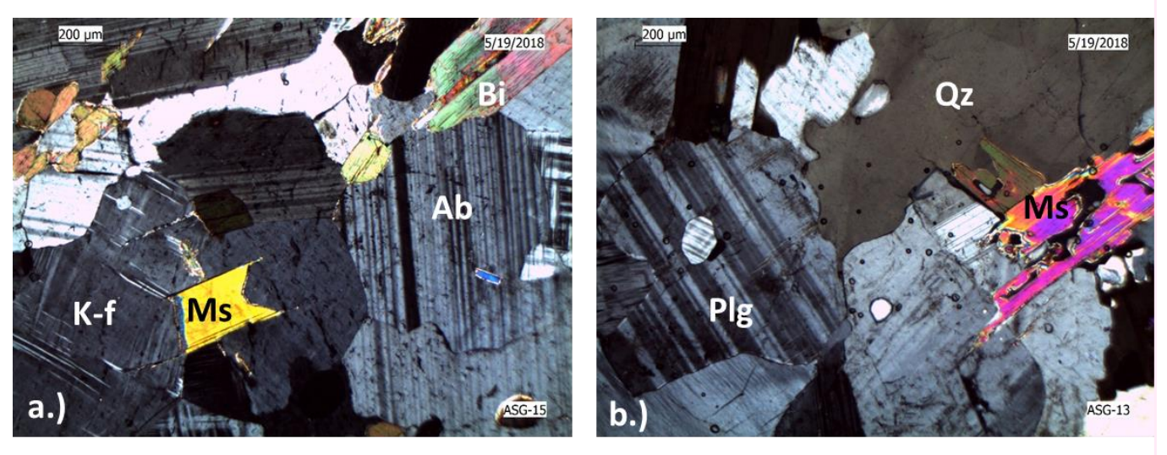


Figure 15: Microphotographs of thin sections from the Phedra granite. a.) Coarse grains of K-felspar with biotite and muscovite plates. b.) Large grains of the rock forming minerals quartz, plagioclase, muscovite and biotite.

The Phedra granite is classified as a peraluminous, alkali-calcic S-type two- mica granite, derived from melting sedimentary sources and emplaced within a syn-collisional tectonic environment. This unit has the most in common with the Patamacca granite.

Figure 16: Sample of the Phedra granite collected along an abandoned quarry.

## AKINTO SOELA GRANITE

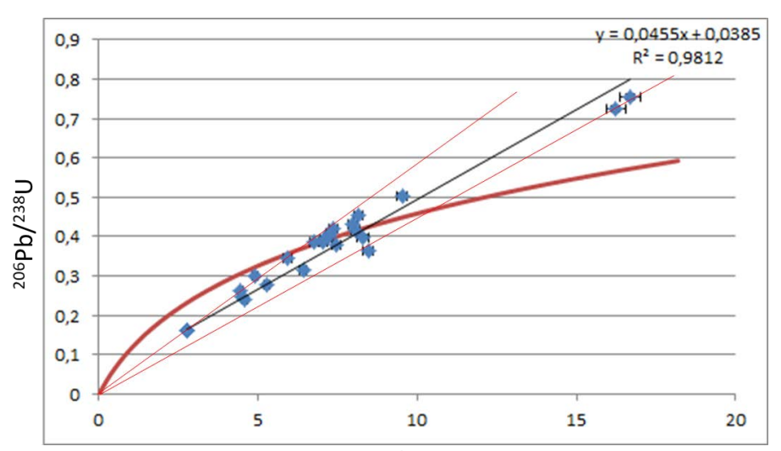


Figure 17: Concordia diagram of the Akinto Soela zircon measurements. Data processed by Dr. Kriegsman (report in progress).

Figure 18: Left photograph shows a boulder of the granite with geologist for scale and the photograph on the right shows drill core samples of the Akinto Soela granite, clearly showing the well-defined K-megacrysts in a coarse-grained texture

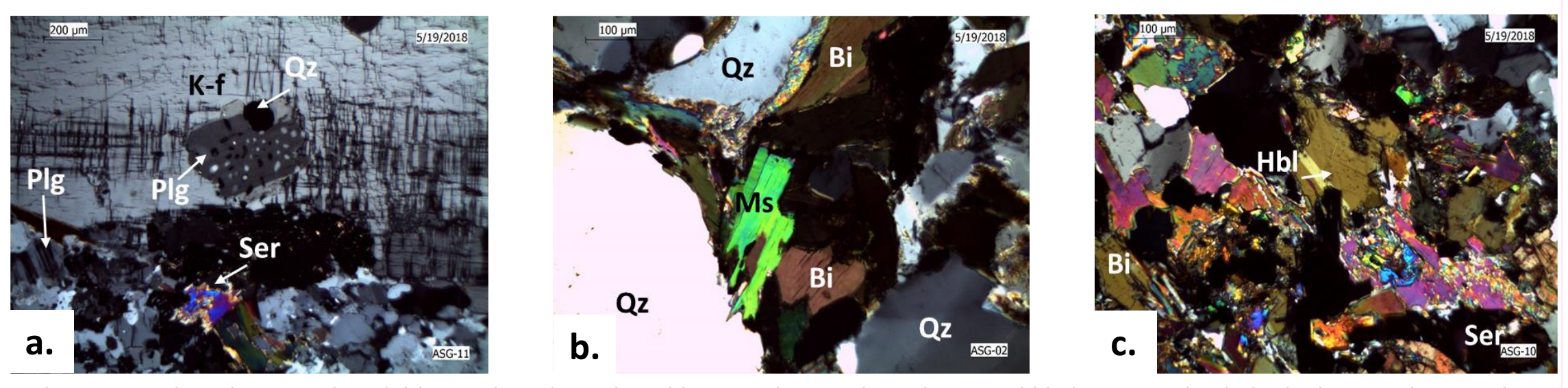


Figure 19: Microphotographs of thin sections from the Akinto Soela Granite. a.) Myrmekitic intergrowth of plagioclase and quartz in a K-feldspar megacryst. b.) Muscovite and biotite minerals. c.) Hornblende mineral.

The Akinto Soela granite is classified as an alkalic to alkali-calcic granite derived sedimentary sources with contamination of mafic rock material, hence the per- and metaluminous nature. This unit is the youngest magmatic occurrence yet, in the MGB, emplaced during late- to post collision events.

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## RECOMMENDATION

Additional analyses of the granitoids, especially the Tibiti and Phedra units, for more reliable interpretations

Reprocessing of zircon age dating results with the correction of "common" non-radiogenic Pb (204Pb) to eliminate uncertainties

Evaluation of other isolated granitoid occurrences in the Marowijne Greenstone Belt to find possible deposits of Sn, Li, Be and REEs

Isotopic studies, of both radiogenic and oxygen isotopes, on granitoids and nearby gold occurrences to understand fluid pathways and sources

## THE MAGMATIC EVOLUTION OF THE MAROWIJNE GREENSTONE BELT

a. Pre- to early collision magmatism of the TTG suites in multiple phases (2.19 – 2.11 Ga), as the result of oceanic lithospher subduction, including the Brinck pluton, Saramacca batholith, Kabel tonalite, etc.

b. Second phase of the TTG magmatism (2.15 – 2.11 Ga) and emplacement of within-plate granites (Tibiti granite) as the result of possible lithospheric structural activities, unrelated to subduction

c. Syn-collision magmatism resulting from crustal thickening and the emplacement of the peraluminous two-mica granites (2.10 – 2.08 Ga), such as the Patamacca and Phedra granites

d. Late- to post collision magmatism (Akinto Soela granite) resulting from possible crustal relaxation and subsidiary subduction (2.08 – 2.06 Ga)

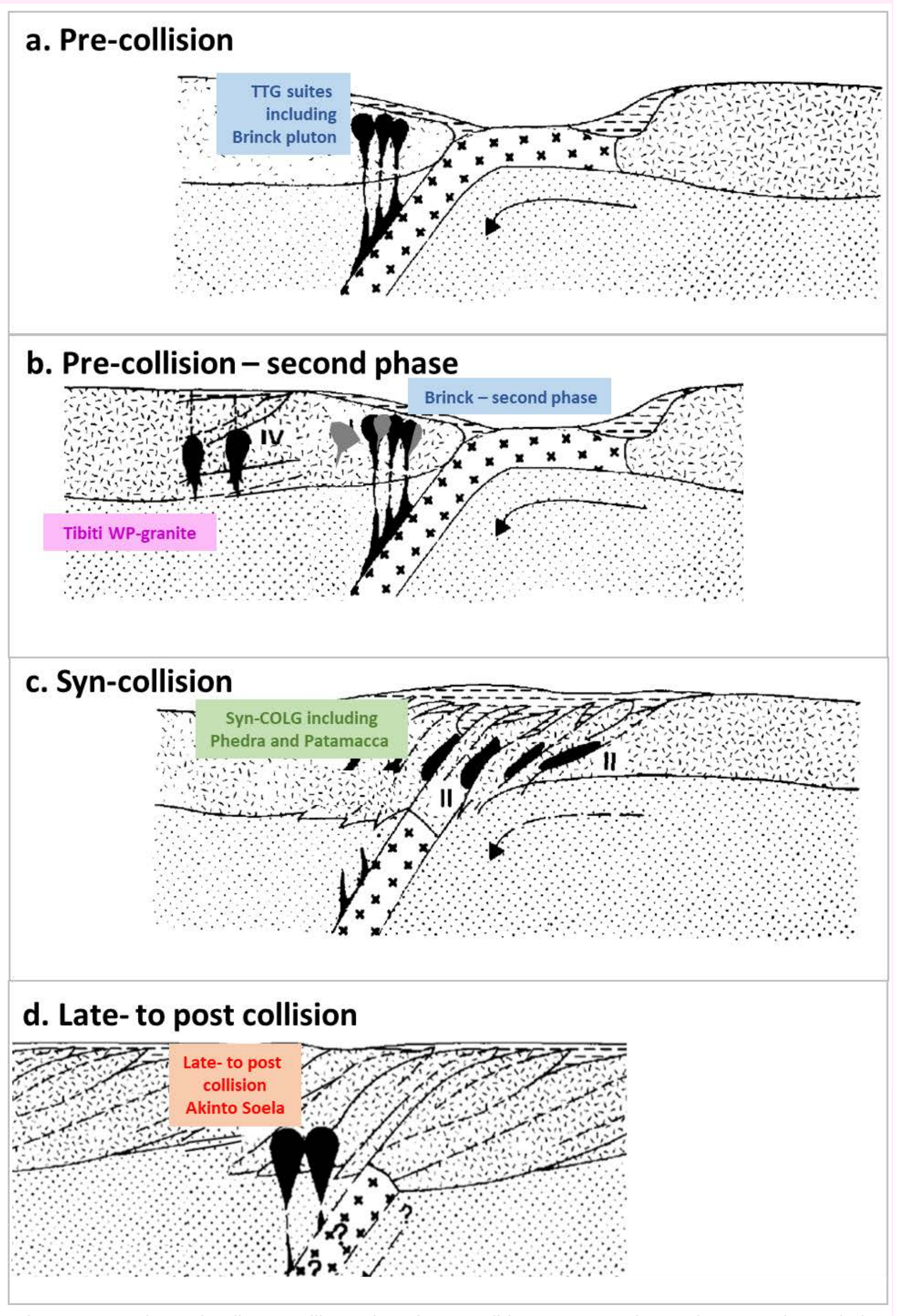

Figure 20: Schematic diagram illustrating the possible source regions of magmatism of the northeastern Marowijne Greenstone Belt, modified after Harris et al. (1998).

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# The La Trampa wedge (SE Colombia) revisited

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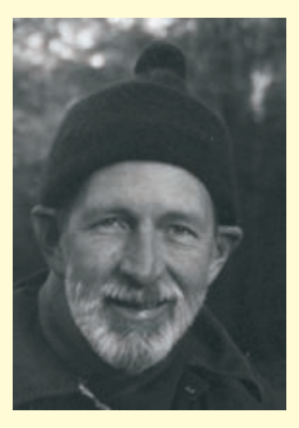

**11th Inter Guiana Geological Conference, Paramaribo, 19-20 February 2019**

**THE PROBLEM** - a SLAR-derived NE-SW striking set of lineaments (Fig. 1), ca. 500 km long, in a surface pattern defining a wedge-like outcrop between the Rio Vaupes and the Rio Putumayo (Fig. 1) in a region still largely covered by dense rainforest.

The pattern extends northeastward to the Rio Negro and Rio Atabapo as a belt of multiple, parallel lineaments (Fig. 1). Total length is ca. 1300 km. **What does this pattern mean?** A **r**ift (graben) structure [1] or a figment of the imagination?

**A/b magnetometry suggests that the causative structure is not a graben because an infilling sediment body would, at this latitude, produce a dominantly positive anomaly [2].**

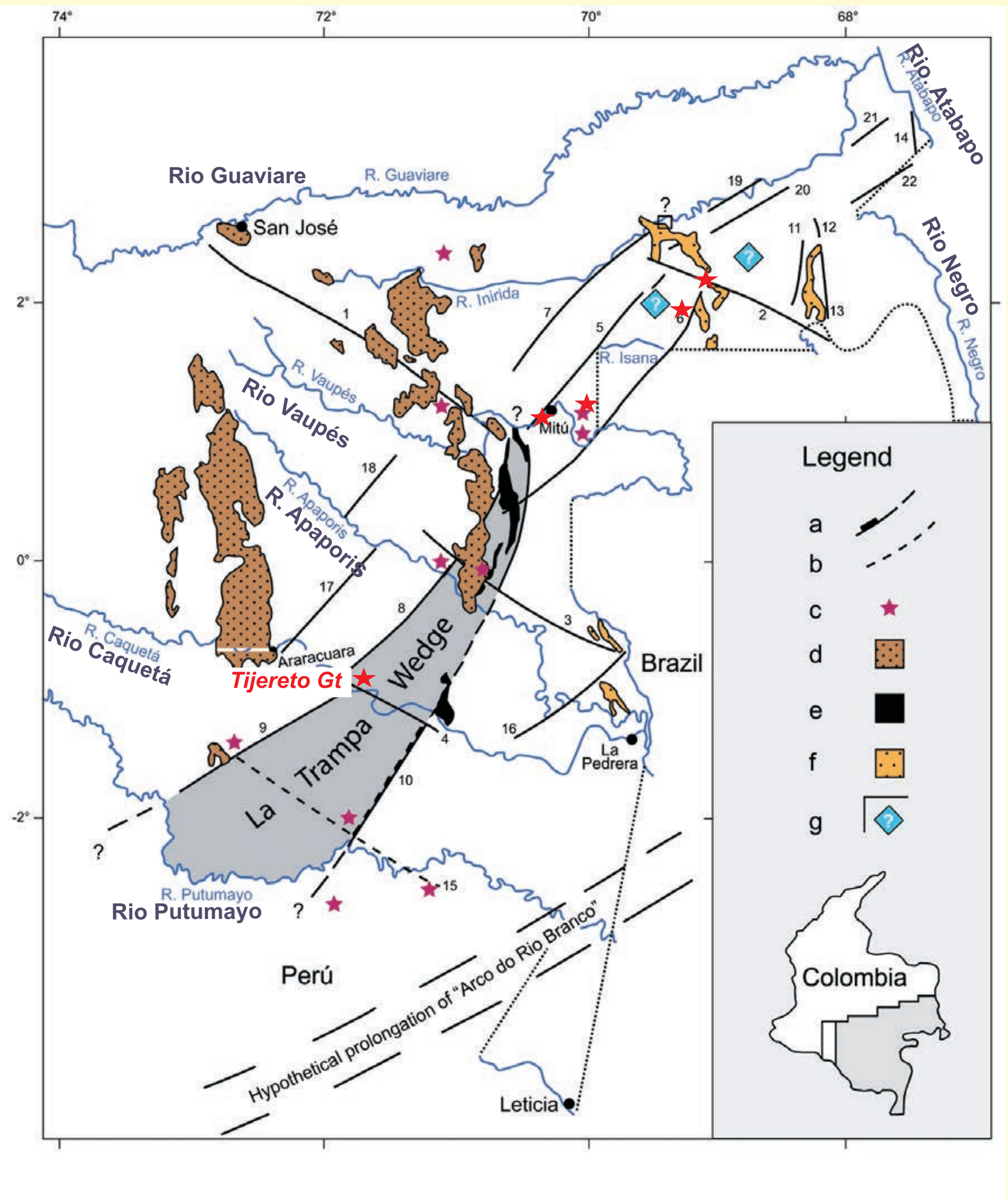

*Fig. 1 SLAR-derived lineaments of the La Trampa structure between the Atabapo and Putumayo rivers. Modified after [1]and [4].*
*★ - Epicentres of 200-600 km deep earthquakes[3].*
*★ - Anorogenic, 1495 Ma, Tijereto granite and correlates.*

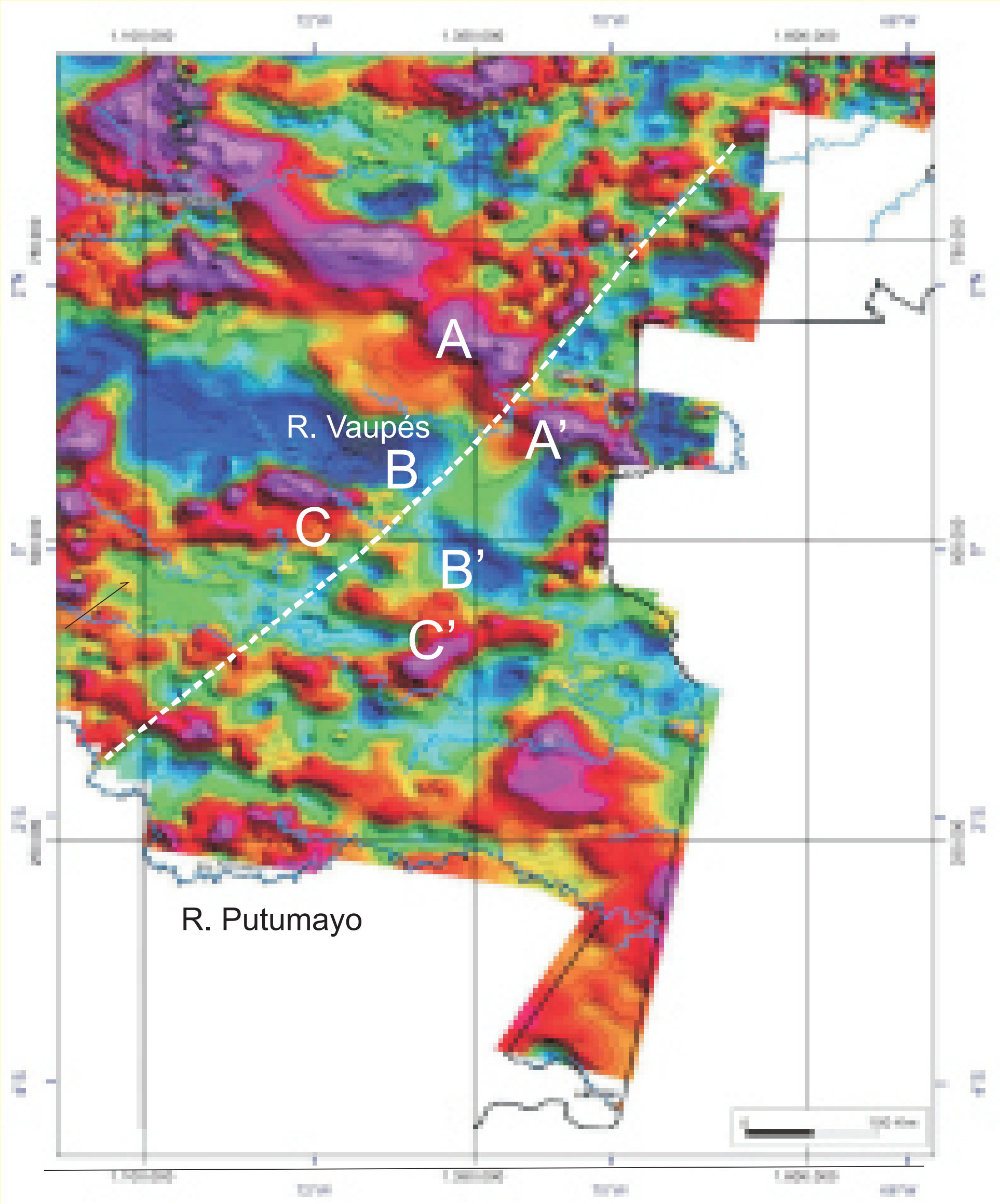

*Fig. 2 Low-resolution magnetometry of SE Colombia. Modified after [2]. The dashed, white line marks a discontinuity in the anomaly pattern between the Rio Putumayo in the SW and the Rio Atabapo in the NE. A NE-striking discontinuity (dashed white line) is expressed along which prominent NW-SE anomalies A, B and C appear dextrally displaced.*

**The length of the discontinuity (ca. 650 km) and the dextral displacement seen in Fig. 2 suggest that the underlying structure includes a major strike-slip fault. The proximity of the SLAR - derived La Trampa domain suggests they are one and the same.**

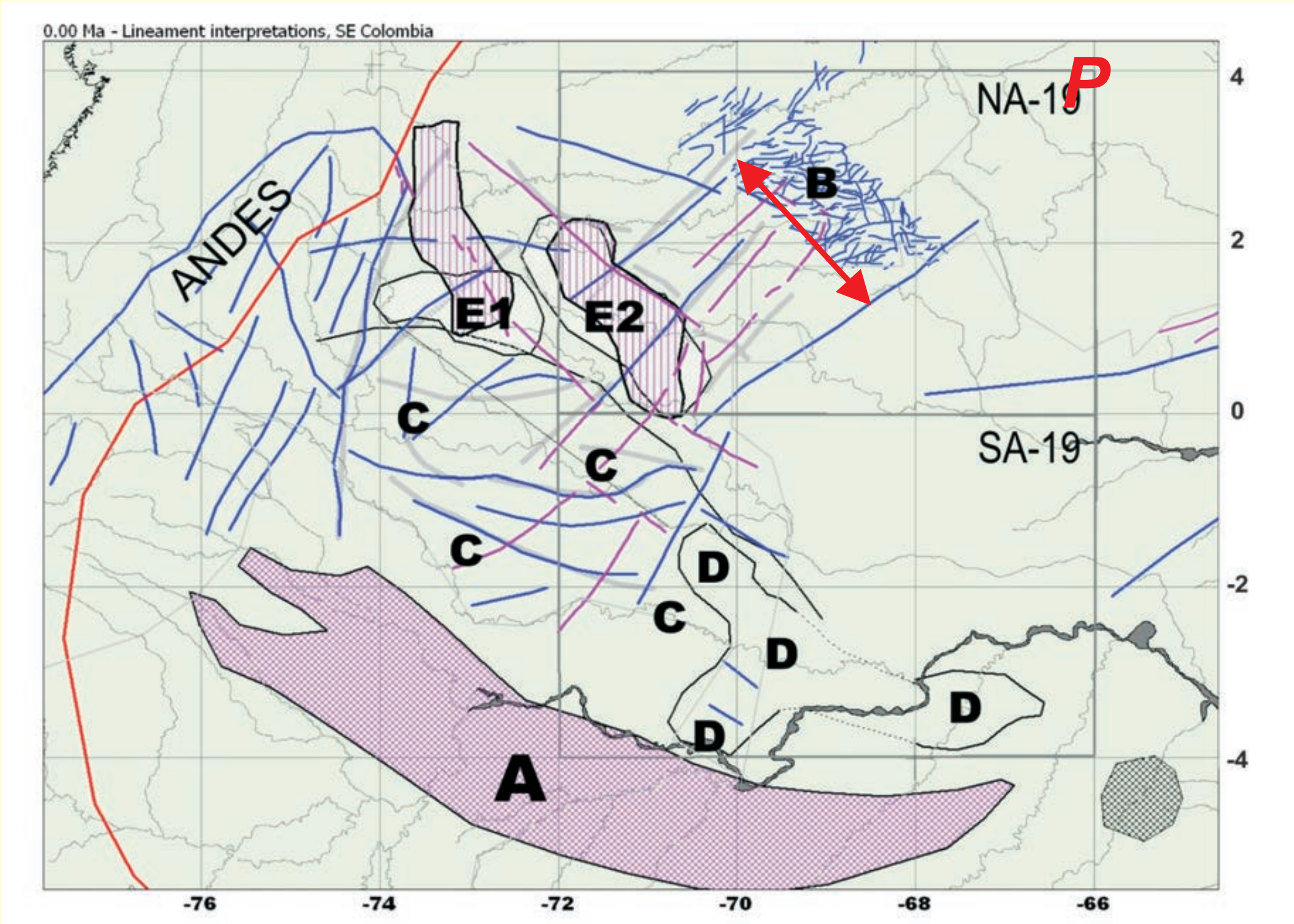

*Fig. 3 Compilation of lineaments from radar (pink), gravity (grey) and magnetic (blue) data interpretation. Modified after [2], with indication of width (red - double arrowed bar) of belt of multiple SW-NE striking regional lineaments, ca. 200 km wide, extending northeastward to the Parguaza batholith (P), and the lateral displacement of magnetic anomalies observed in Fig. 2. These lineaments may represent a major shear belt.*

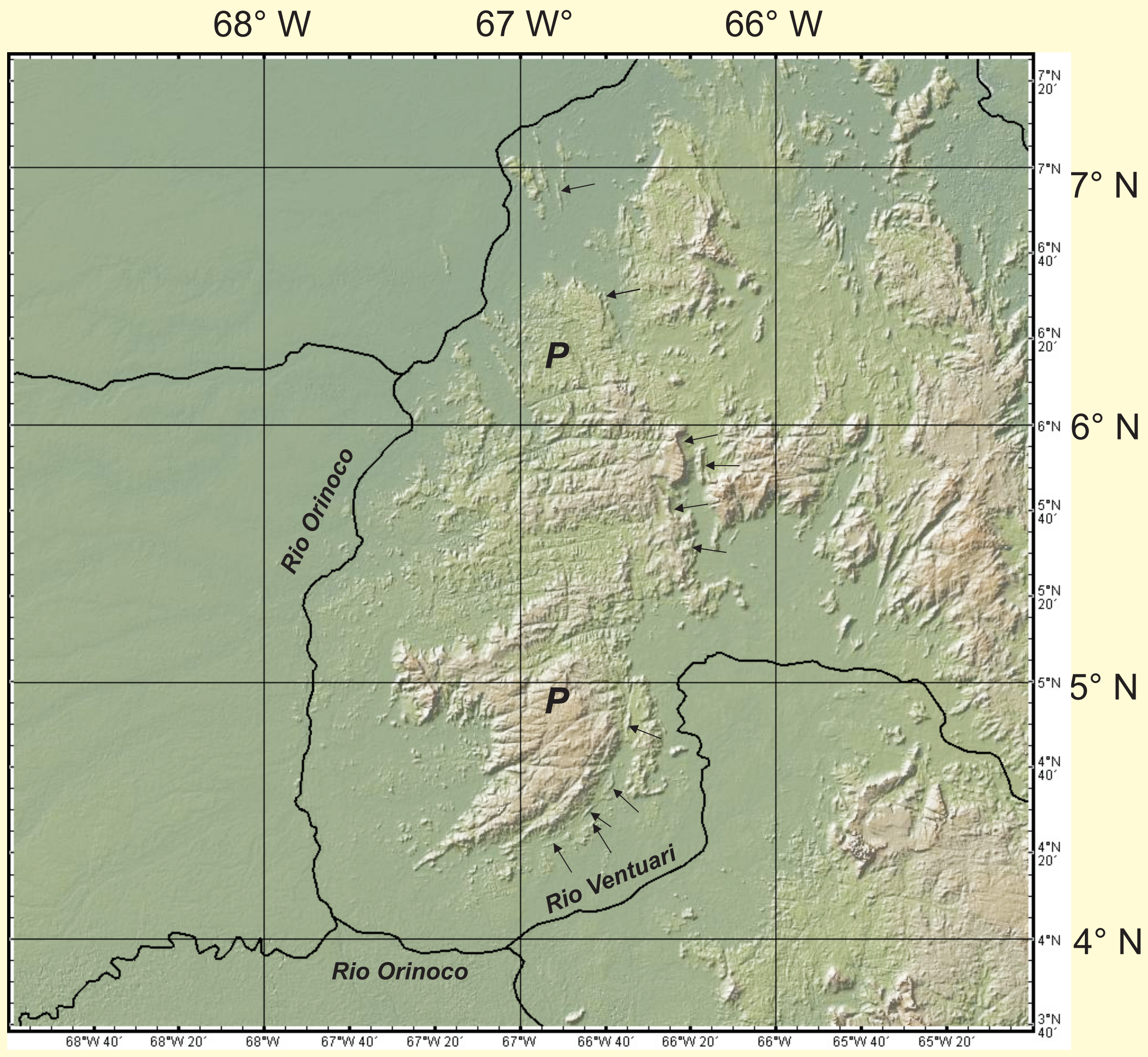

*Fig.4 The margins of the Parguaza batholith (P) of Rapakivi-type granite show short linear ridges, indicated by small arrows, whose strike grades from ENE at the southern apex of the batholith to NE and N along the eastern perimeter. I suggest these ridges may represent foliation (schistosity, gneissosity) due to deformation during consolidation of the magmas [5, 6, 7]. The extensional setting of the batholith [4] suggests the magmas were emplaced in an extensional jog of a much longer strike-slip shear. Topography after Ryan et al., http://www.geomapapp.org [8].*

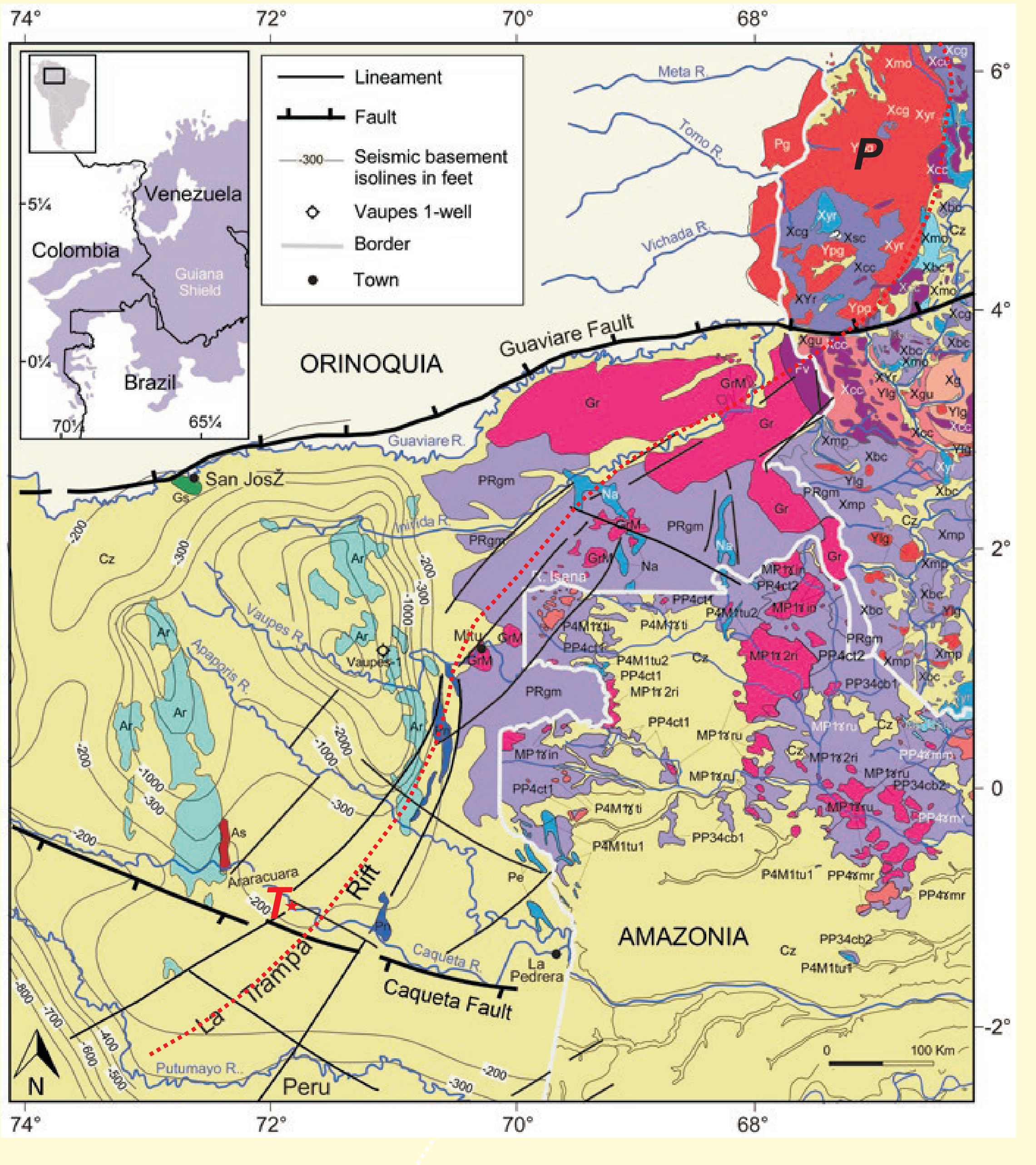

*Fig. 5 Geological map of the border area of Colombia, Venezuela and Brazil, (modified after [4]), with indication of axis of the inferred La Trampa structure (dotted red line) from the Rio Putumayo to the Rio Orinoco and continuing northward along the eastern margin of the Parguaza Batholith (P). Small plutons (GrM; T - Tijereto Granite), comparable to Parguaza granite [4], appear confined to La Trampa belt.*

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**In view of the transcurrent shear belt (Fig. 2), its NE strike (Figs. 2, 3), the setting of the Parguaza batholith in an extensional jog where the shear zone turns to the north (Fig. 4), and the distribution of small anorogenic plutons (Fig. 5) limited to the La Trampa domain as far south as the Tijereto Granite on the Rio Caqueta, a major strike-slip shear belt is suggested in the western Guiana Shield (Fig. 5).**

11th Inter Guiana Geological Conference: The Tectonics & Resource Potential of NE South America

# Stratigraphy of Guyana & the Greenstone Belts

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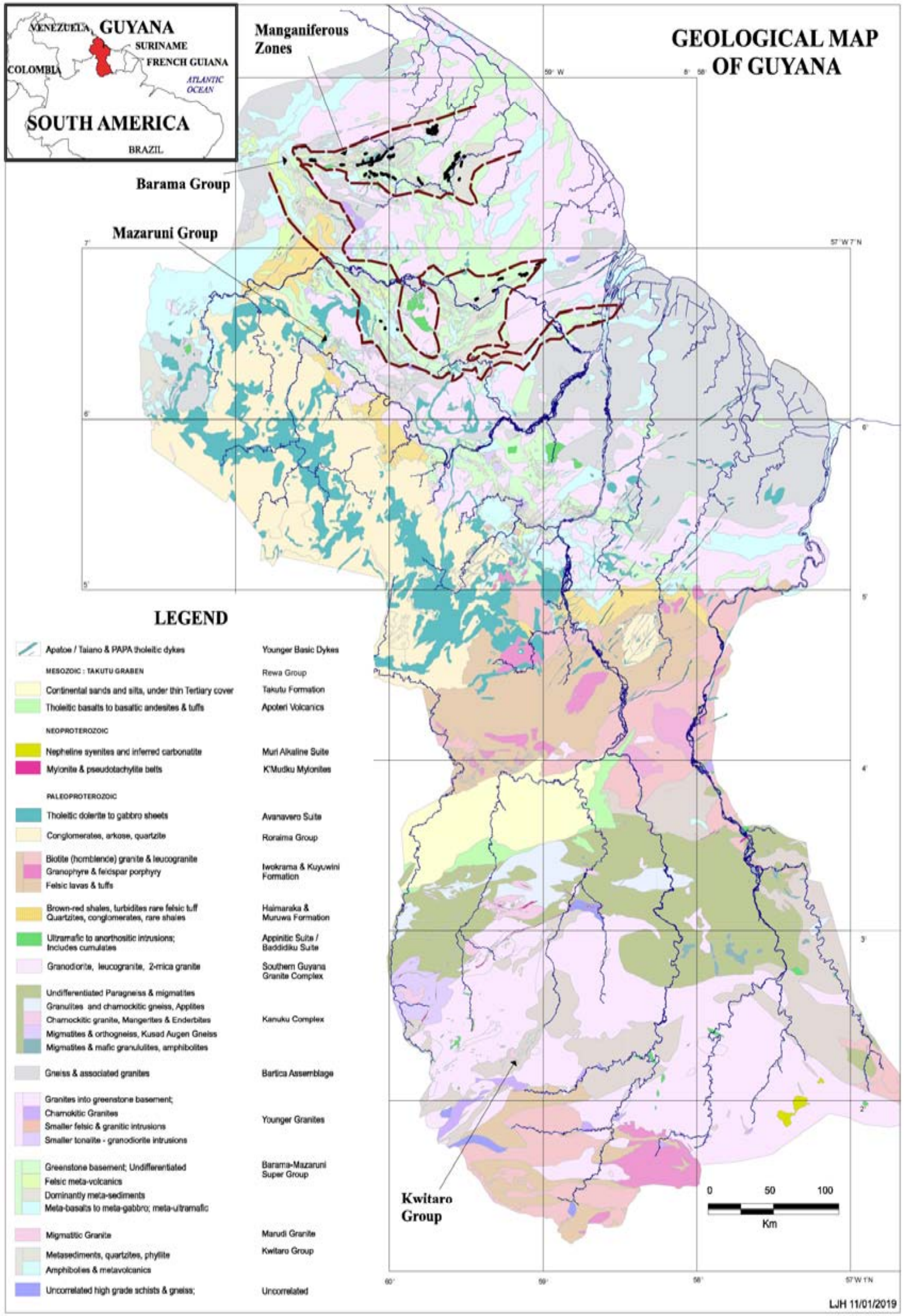
# DATA SOURCES

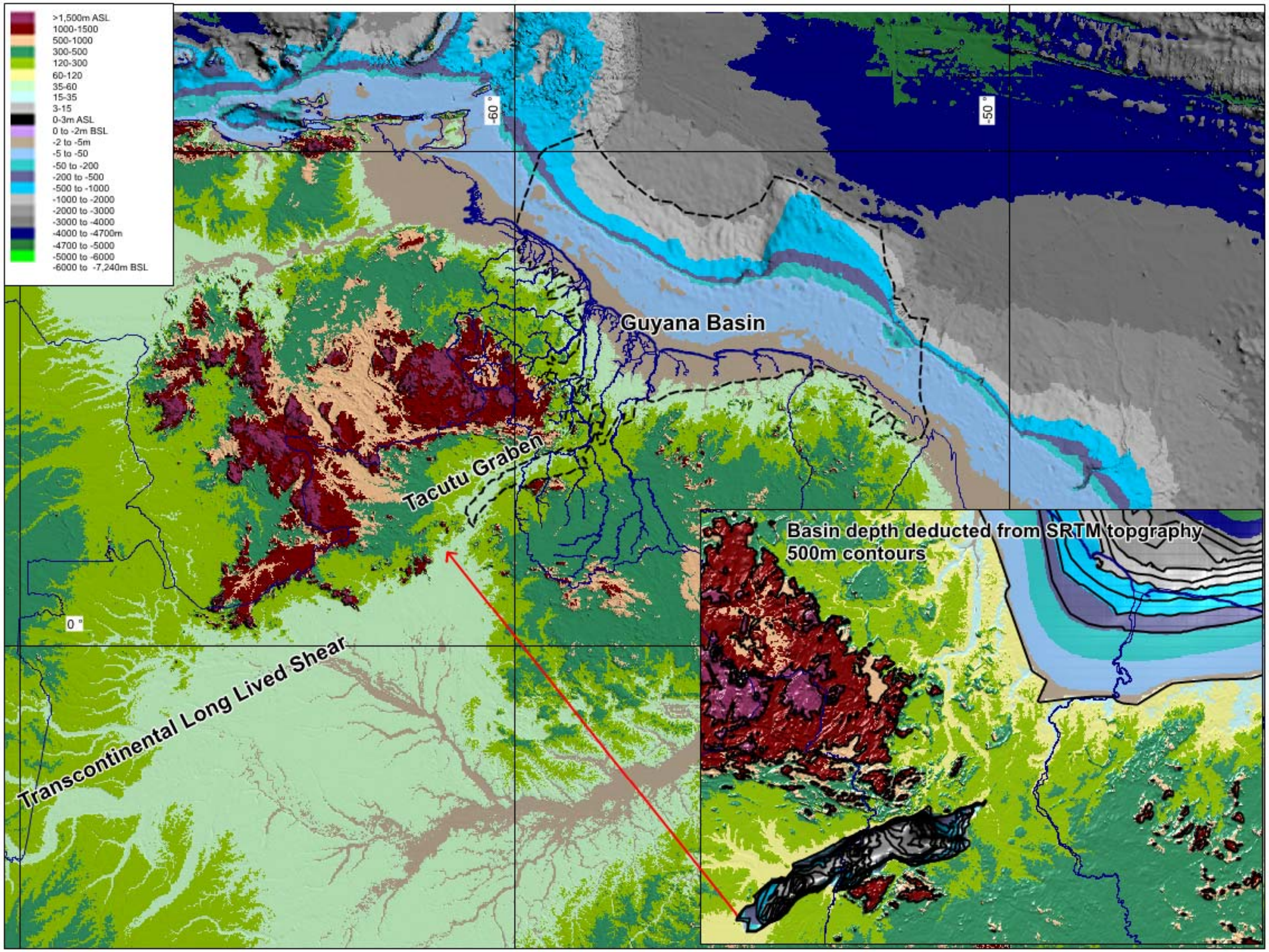
- 3 bibliographies on older literature; Dixon & George (1964), MacDonald (1968) and Sidder (1989).
- Gibbs & Barron 1993.
- Post 1992 MSc & PhD theses (9).
- Publications based on thesis and / or company mineral exploration.
- Company websites & reports – eg 43-101
- Guyana Geology & Mines Commission (GGMC)
  - Drainage & rock geochem, outcrop data, petrology, scanned historical maps all part of digital project reports. Historical company reports; digital & GGMC library – available for purchase

# Guyana Geological Map - updated from GGMC



# North & South Guyana: divided!

- Two halves of Guyana separated by the Jurassic-Cretaceous Takutu Graben.
- Pull-apart basin on a continent scale shear
- Basement depth under the sediment is over 5km deep – same as the ocean depths.
- Adjacent Kanuku Mountains only 500m high
- Two halves have different older geology, yet must have been adjacent since ~ 2Ga since the Muruwa Formation and Roraima Group also occur in Suriname



SRTM Topography with baisin depth deducted – Takutu Basin > 5km; as deep as the ocean!

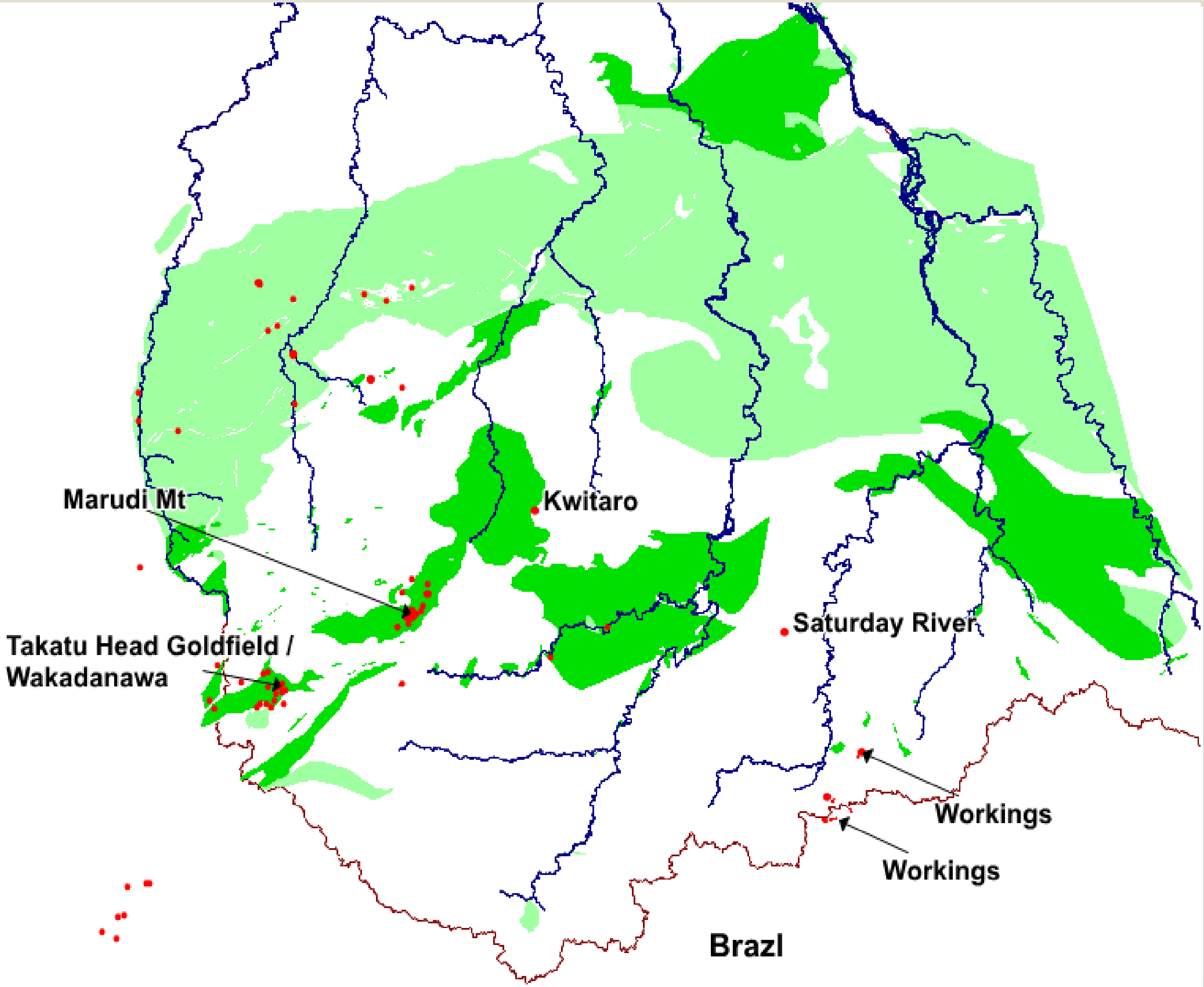
# Geology southward of the Takutu Graben

- Kanuku Complex gneiss & assoc. granites incl. charnockites (1.96 Ga). Rare alluvial Au.
- Southern Guyana Granite Complex; >100km wide zone (1.93-1.98 Ga).
- Enclaves of Kwitaro Group in the granite complex– some with gold.
- Marudi Granite intrudes Kwitaro – 2.22Ga
- Uncorrelated gneiss & charnockites
- Kuyuwini Group; mod met felsic volcanics & assoc intrusions. 1.89-1.81 Ga – younger than the Iwokrama rocks 1.99-1,96 Ga

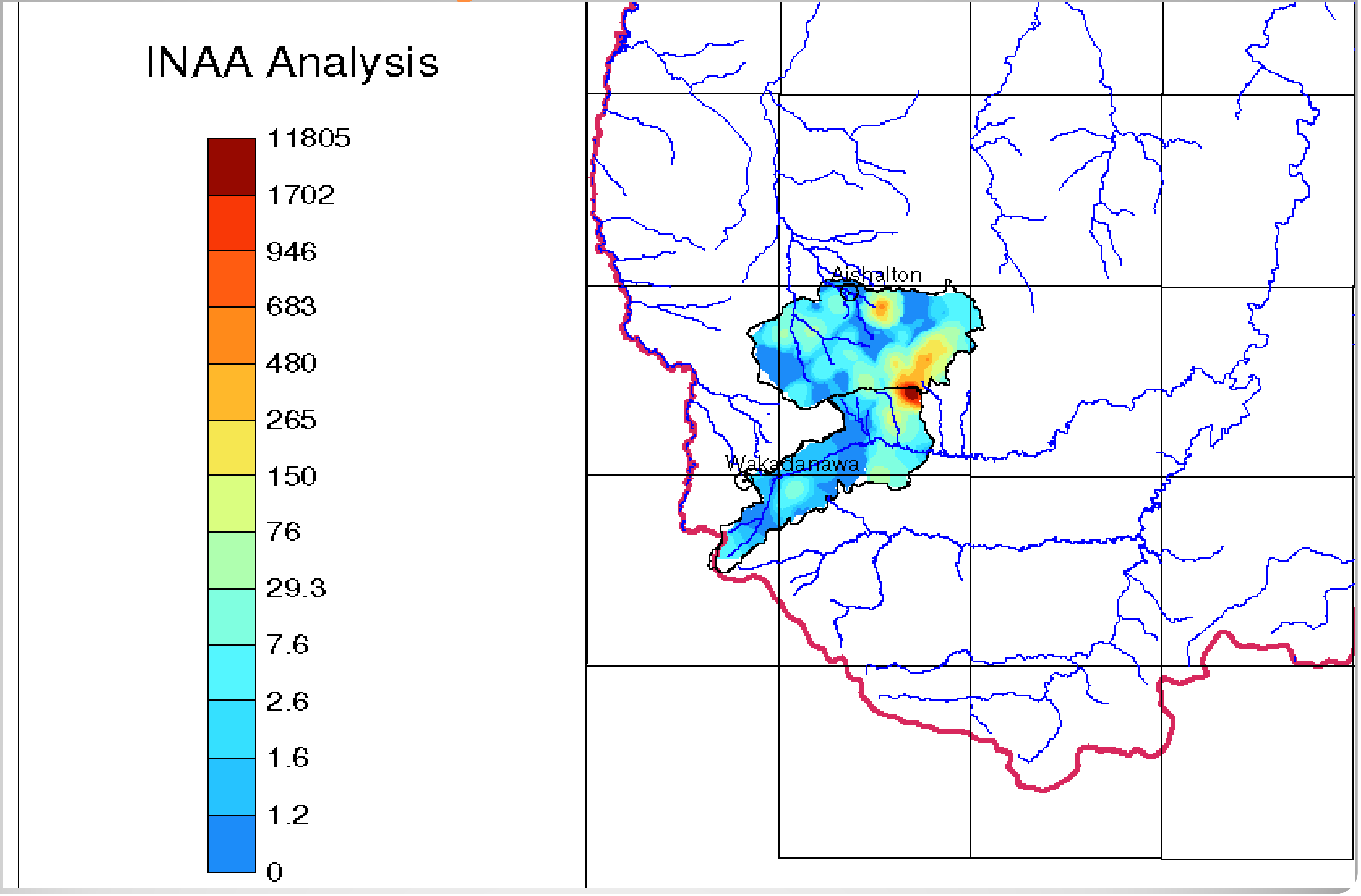
# SOUTHERN GUYANA: the KWITARO GROUP

Mostly meta-sediments, some andesite, locally gneissose.
More of a supracrustal formation than a greenstone, but locally gold-bearing.

Is minor gold in the Kanuku gneiss areas because it includes Kwitaro protolith?



# Southern Guyana: SS Au



From GGMC website 2015

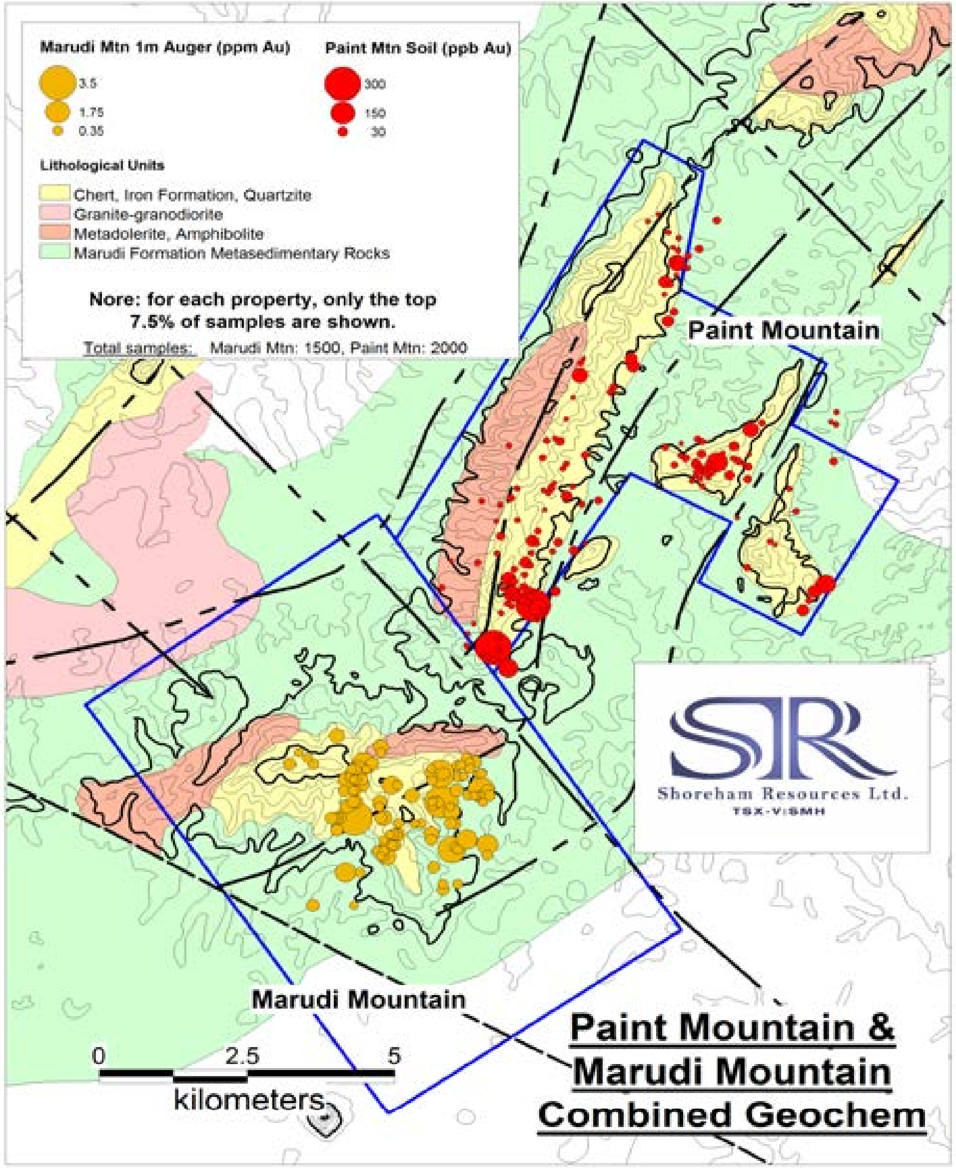
# Kwitaro Group Lithologies

- Marudi Mountain: phyllite, metachert ("quartzite"), then meta-andesite with subordinate tuff and ironstone are overlain by amphibolite / meta-basalt
- Some layers of BIF-like rocks at both Marudi and Wakadanawa

- Post metamorphism feldspar porphyry dykes

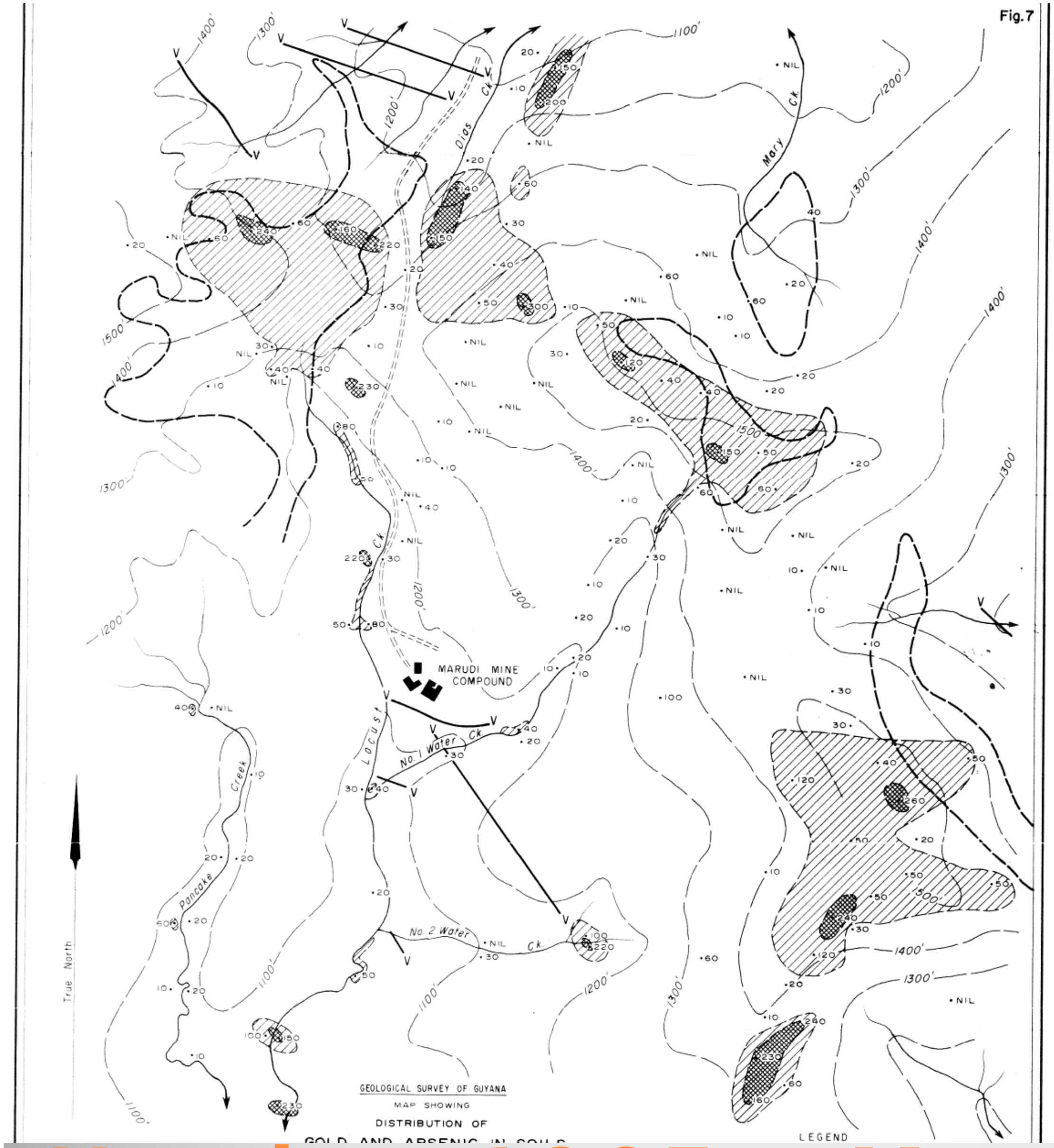
# Kwitaro quartzite & BIF

# Kwitaro at Marudi Mountain



Phyllite, amphibolite, chert & BIF intruded by Marudi Granite.
2 phases of folding

Kwitaro & Marudi granite as enclave in Southern Guyana Granite Complex.

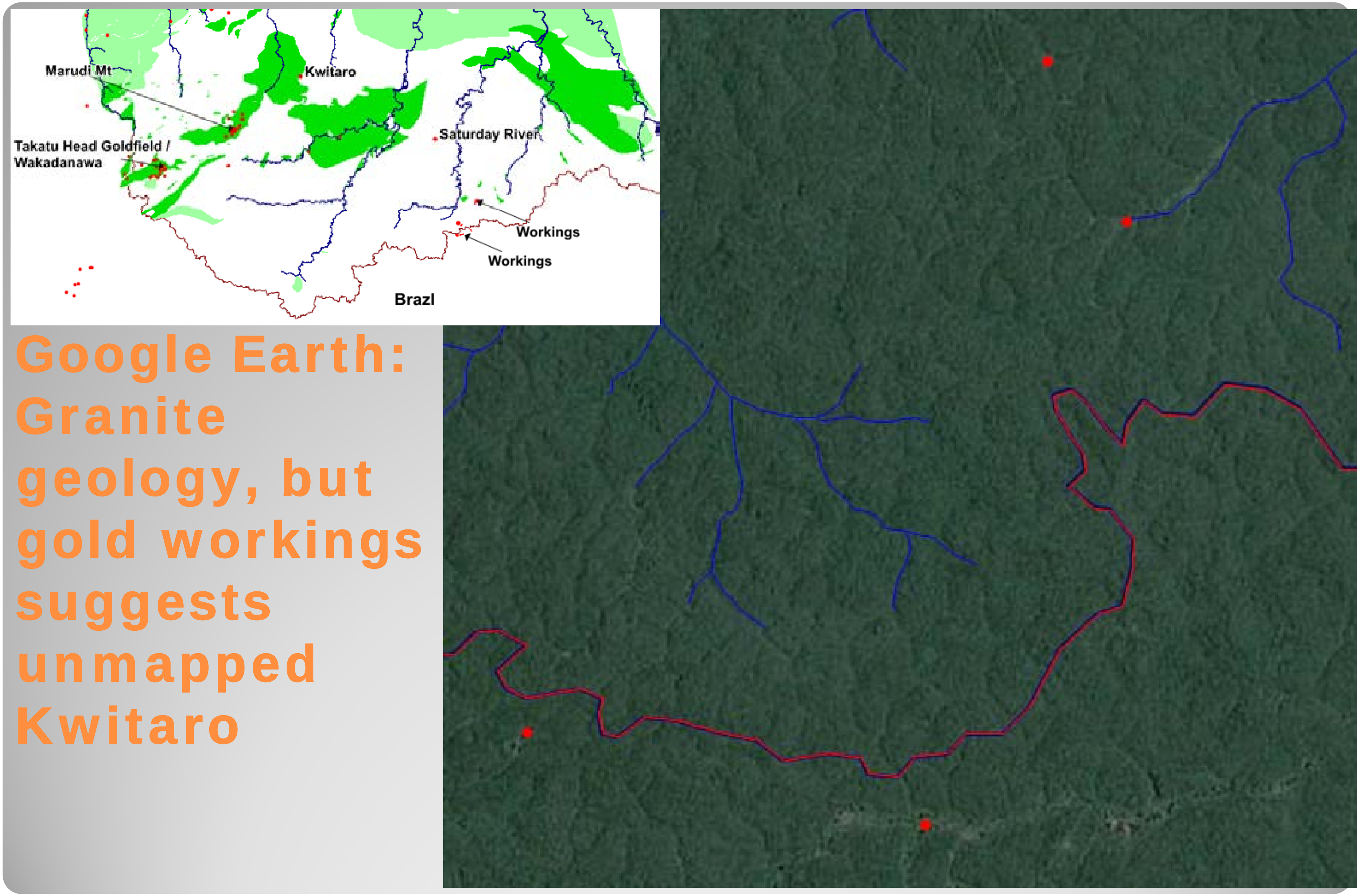


At Marudi good correlation Au & As.

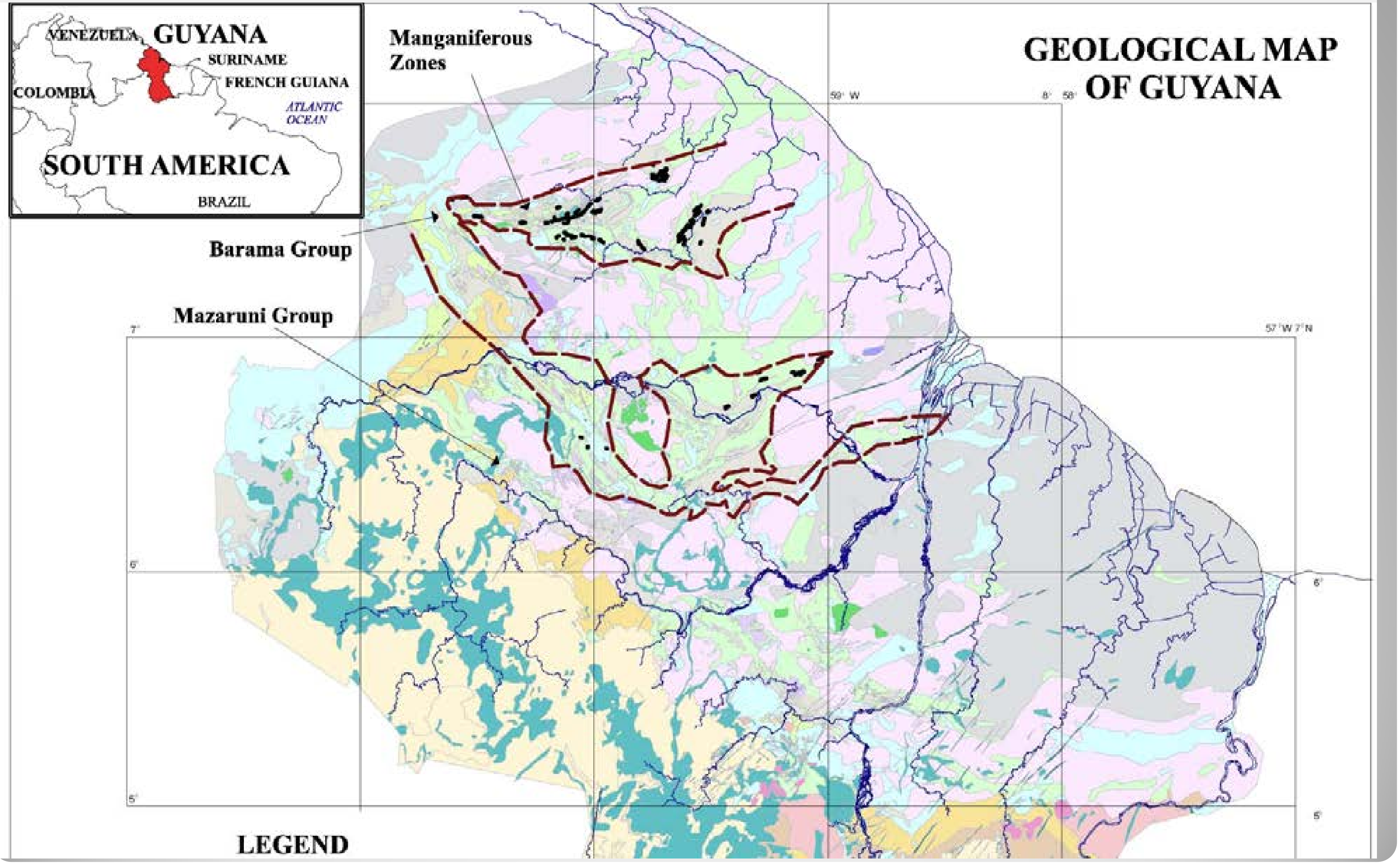
Along strike (~25km) GGMC drainage geochemistry shows a consistent gold anomaly, but only spotty SS As – highest at Marudi – 21ppm. Amphibolitic geology can be traced by anomalous SS Ni, Co, Cu etc

# Hawkes 1965 – Marudi Au & As

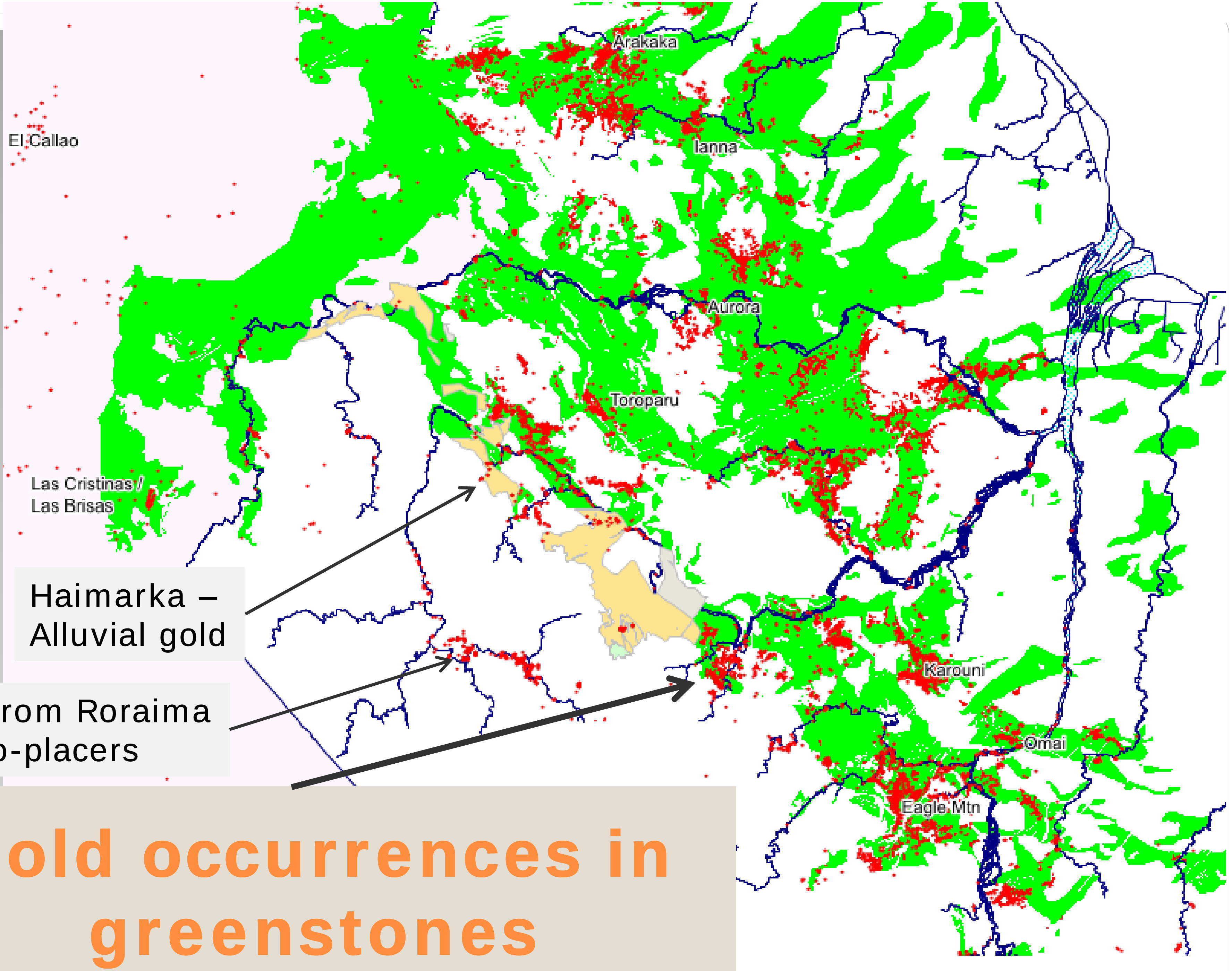
# Google Earth: Granite geology, but gold workings suggests unmapped Kwitaro



# North Guyana; Barama-Mazaruni Super Group



# Gold occurrences in greenstones



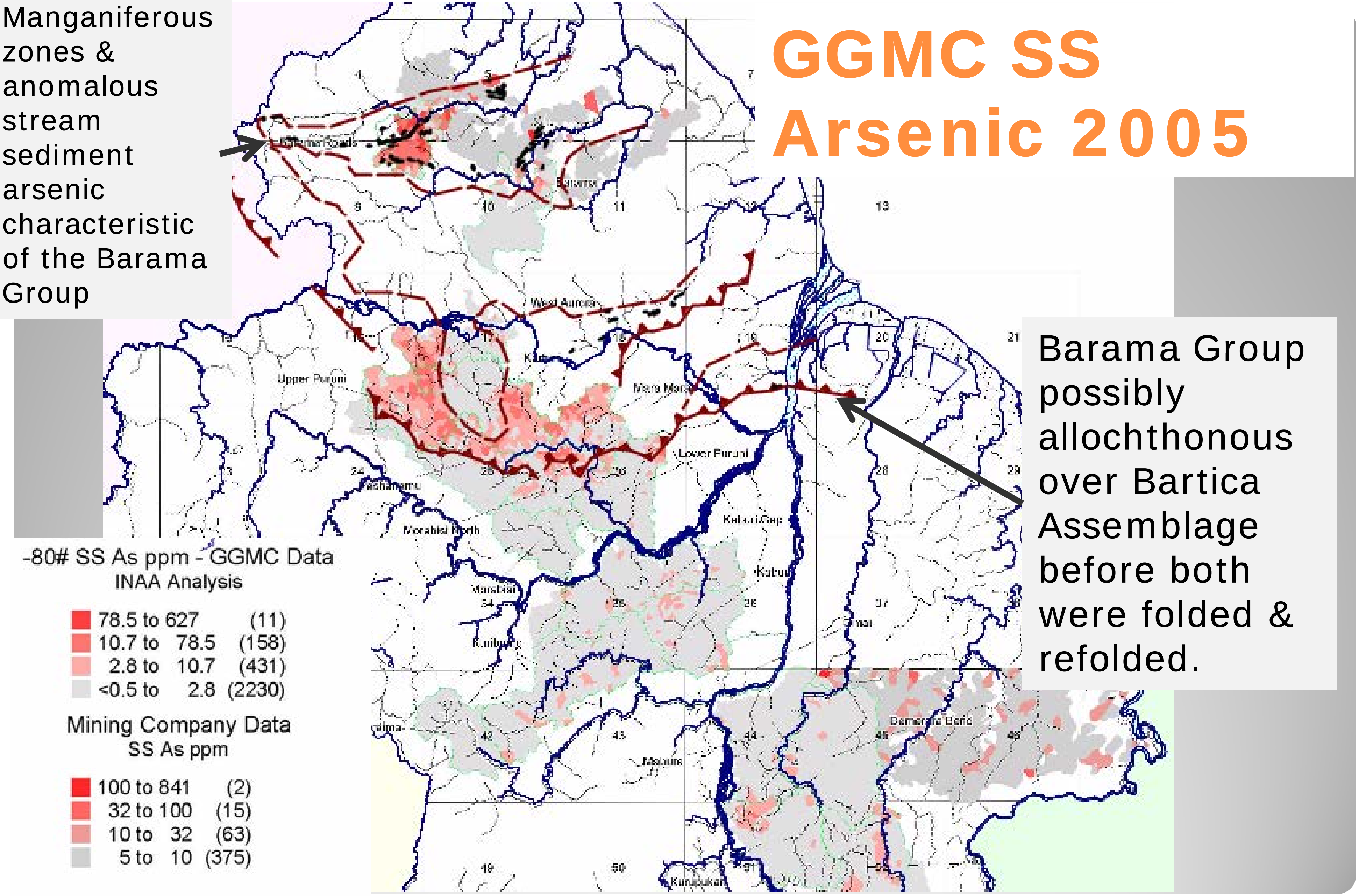
Haimarka – Alluvial gold

Gold from Roraima Palaeo-placers

# Barama Group

- Named after the Barama River.
- Meta-basic rocks overlain by increasingly felsic meta-volcanics and then the dominant meta-sedments.
- Can be traced westwards to Venezuela – El Callao Formation / Pastora Super Group
- Manganiferous sediments / gondites act as marker horizons
- Refolded folds / locally dome / basin structure
- Distinctive regional drainage geochemistry – almost always detectable arsenic, locally very high – 1000 ppm As near Arakaka.
- Low level, but common 1-2ppm Sb

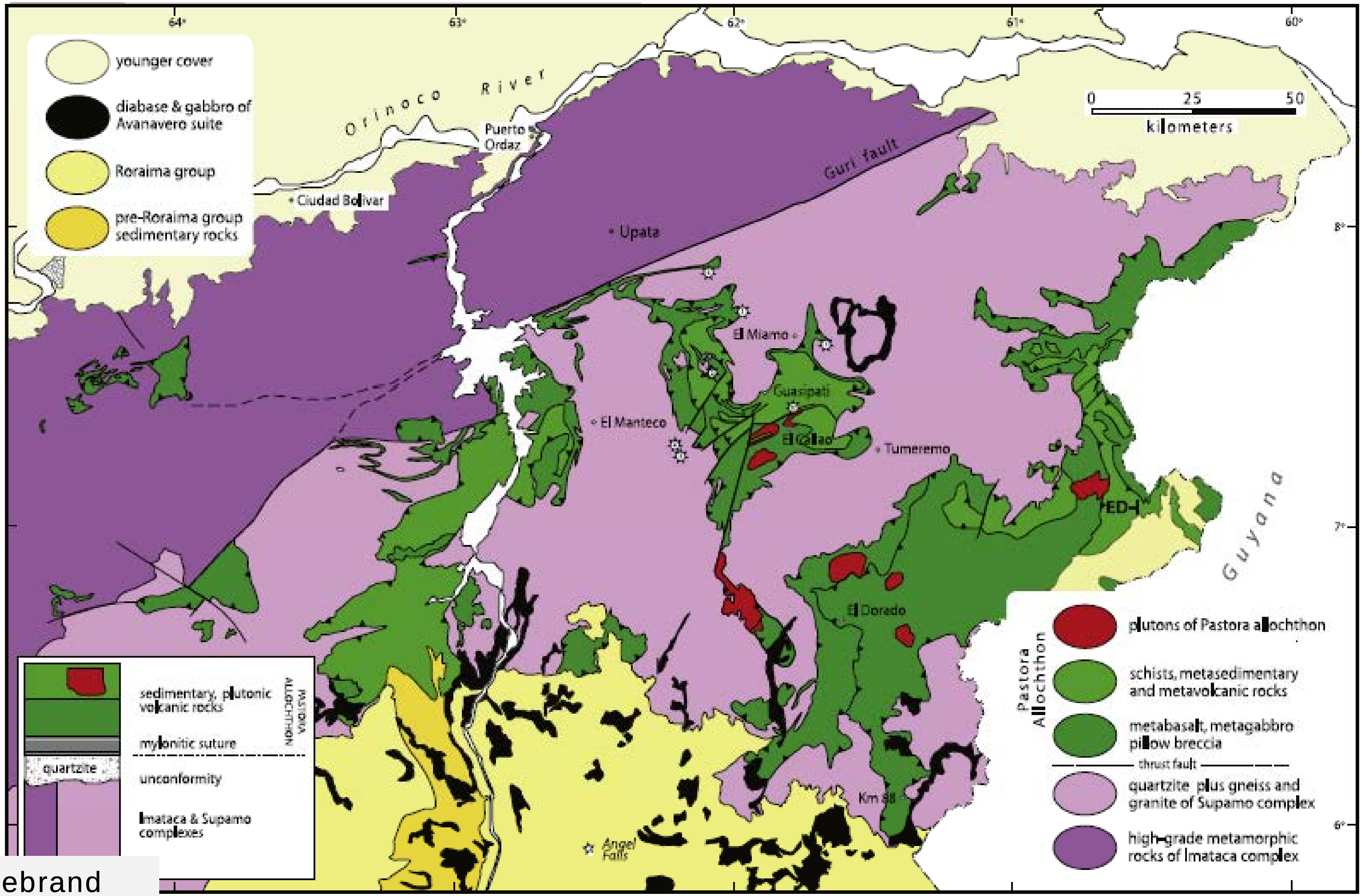
# GGMC SS Arsenic 2005



Manganiferous zones & anomalous stream sediment arsenic characteristic of the Barama Group

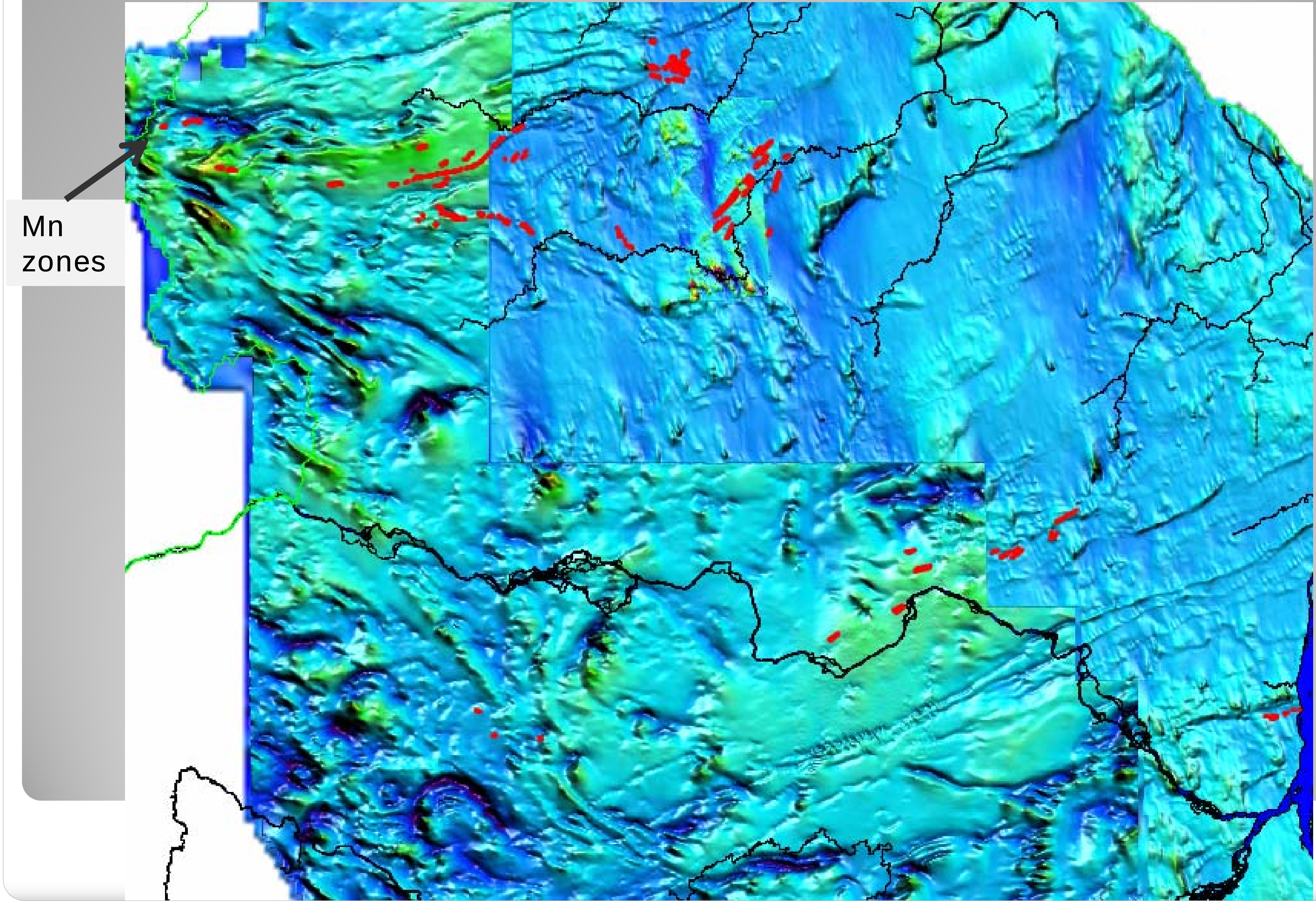
Barama Group possibly allochthonous over Bartica Assemblage before both were folded & refolded.

# In Venezuela Greenstones are thrust over Granite & Gneiss then folded and refolded



Hildebrand 2018

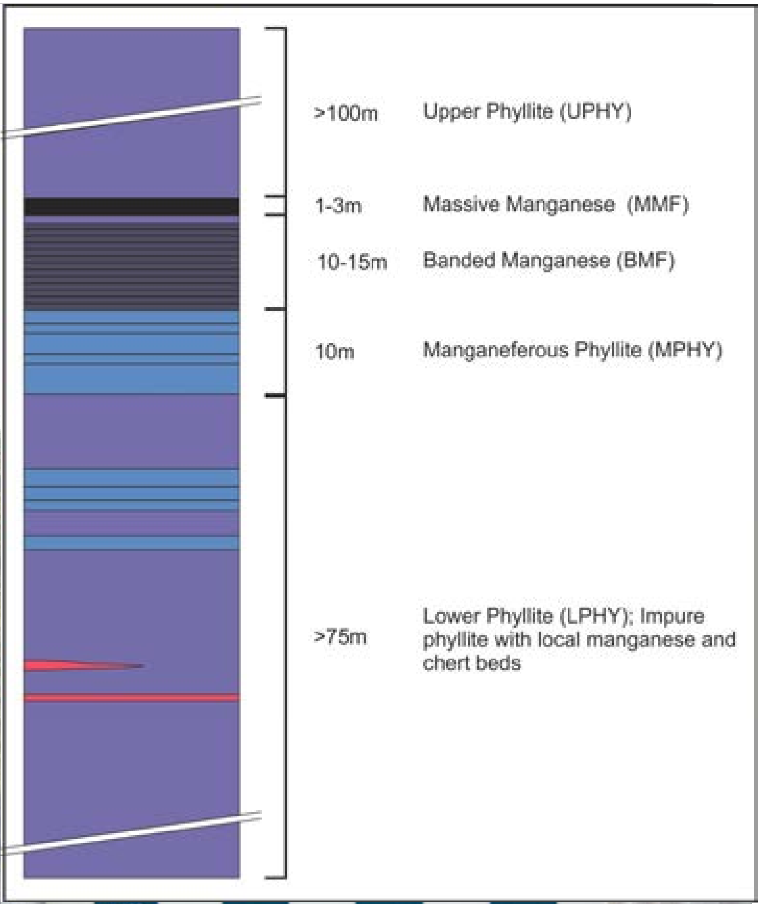
# Aeromag shows mega-folds



Mn zones

# Barama Group Stratigraphy

- amphibolites, chlorite schists and pillow basalts – Tenapu Formation
  - serpentinites and talcose rocks – Komatiites?
- calc-alkaline flows, tuffs and sub-volcanic porphyry stocks – Arawanta Formation
  - Shoshonitic hornblende-porphyries in the west
- Meta-sediments – quartzites (after chert?), red-brown phyllites, Mn zones - Matthews Ridge / Arawanta Formation
  - Eastern end some tuffaceous rocks (Tassawini)
- Lots of small diorite sills / stocks
- Unconformable greywackes / volcaniclastic conglomerates & fine igneous rocks in the east– Kokrit Formation.



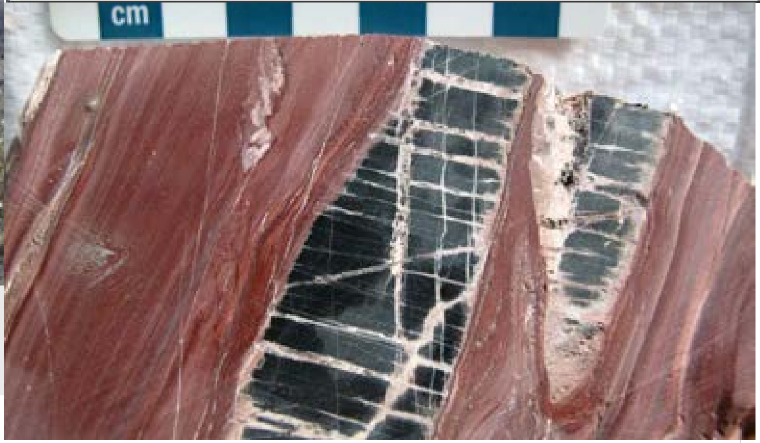
>100m Upper Phyllite (UPHY)

1-3m Massive Manganese (MMF)

10-15m Banded Manganese (BMF)

10m Manganeferous Phyllite (MPHY)

>75m Lower Phyllite (LPHY); Impure phyllite with local manganese and chert beds



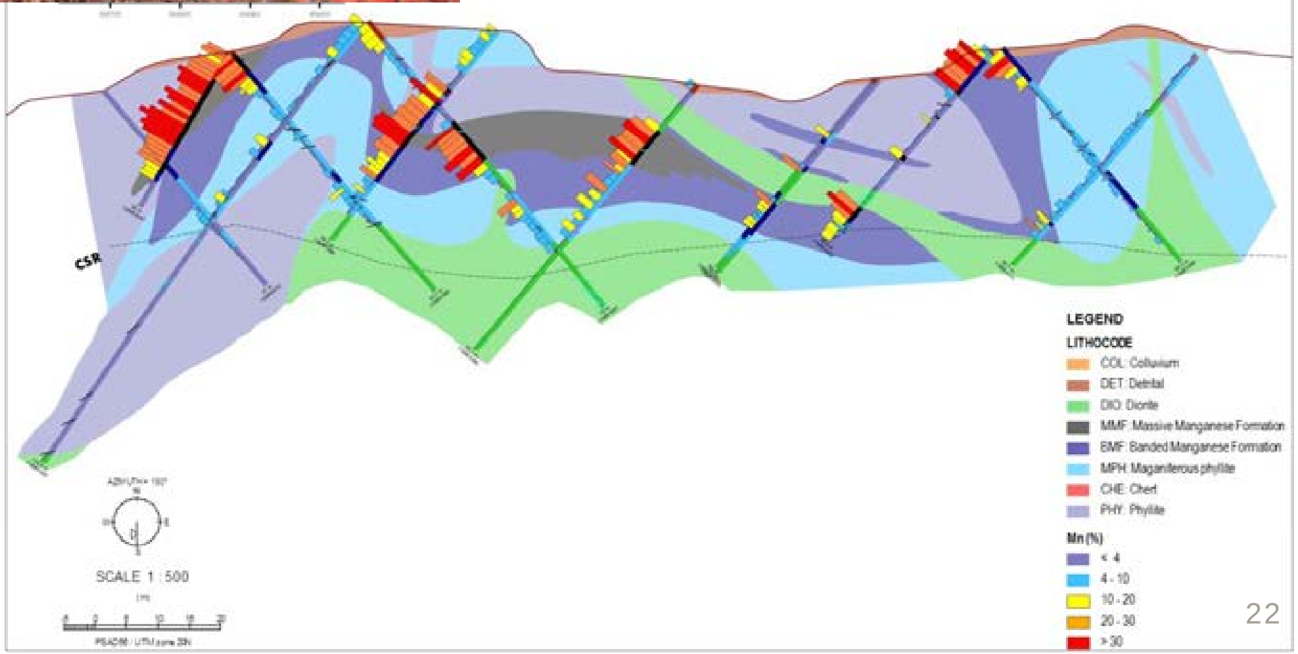
# Matthews Ridge Mn

From
Reunion
Gold 2013

## Folding – before intrusion of diorite?

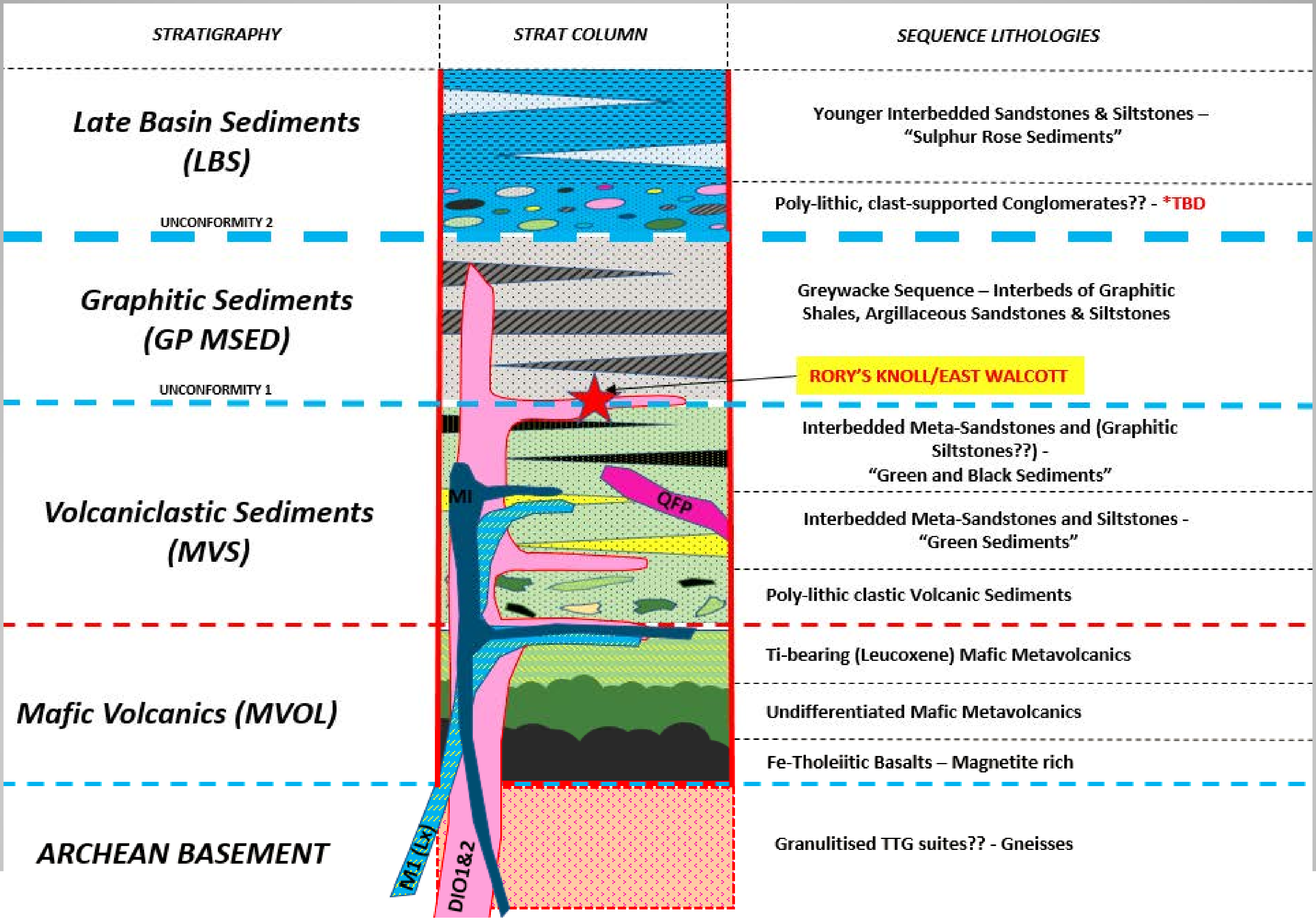
Hill 9C: 808750E

REUNION MANGANESE INC.



From Reunion Gold 2013

# Aurora: Cuyuni Group = Barama Group



STRATIGRAPHY

STRAT COLUMN

SEQUENCE LITHOLOGIES

*Late Basin Sediments (LBS)*

UNCONFORMITY 2

*Graphitic Sediments (GP MSED)*

UNCONFORMITY 1

*Volcaniclastic Sediments (MVS)*

*Mafic Volcanics (MVOL)*

*ARCHEAN BASEMENT*

Younger Interbedded Sandstones & Siltstones – "Sulphur Rose Sediments"

Poly-lithic, clast-supported Conglomerates?? - *TBD

Greywacke Sequence – Interbeds of Graphitic Shales, Argillaceous Sandstones & Siltstones

RORY'S KNOLL/EAST WALCOTT

Interbedded Meta-Sandstones and (Graphitic Siltstones??) - "Green and Black Sediments"

Interbedded Meta-Sandstones and Siltstones - "Green Sediments"

Poly-lithic clastic Volcanic Sediments

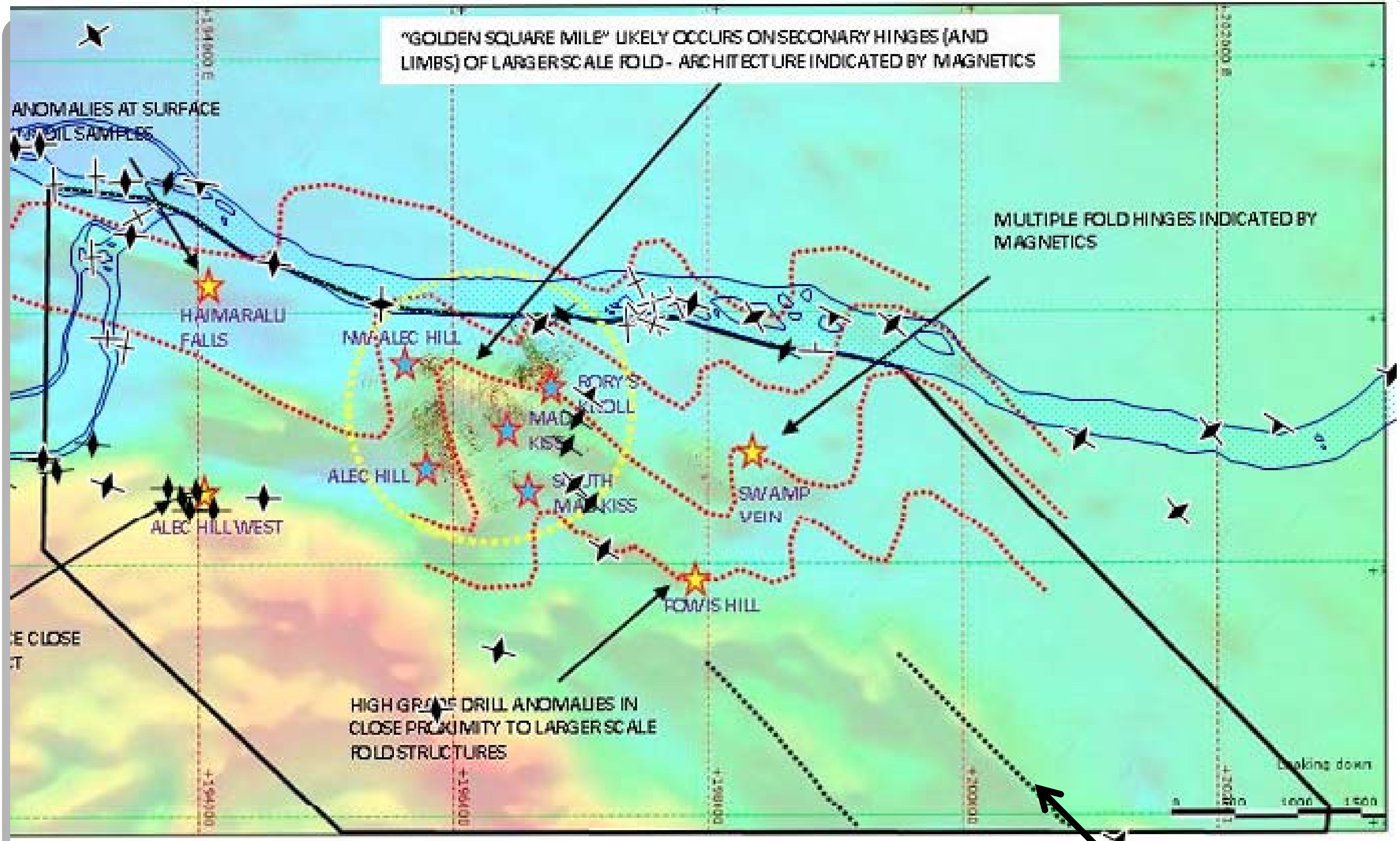
Ti-bearing (Leucoxene) Mafic Metavolcanics

Undifferentiated Mafic Metavolcanics

Fe-Tholeiitic Basalts – Magnetite rich

Granulitised TTG suites?? - Gneisses

From Guyana Goldfields 2018



# Aurora folding

Serictic shear;
Mapped as meta-sediment
by Bracewell 1948

From Guyana Goldfields presentation 2018
with GGMC 2003 & historical structural data

- Low angle structures:
  - Arakaka
  - Sona Hill (Toroparu)
  - Quartzstone
  - Eagle Mountain
  - Million Mountain

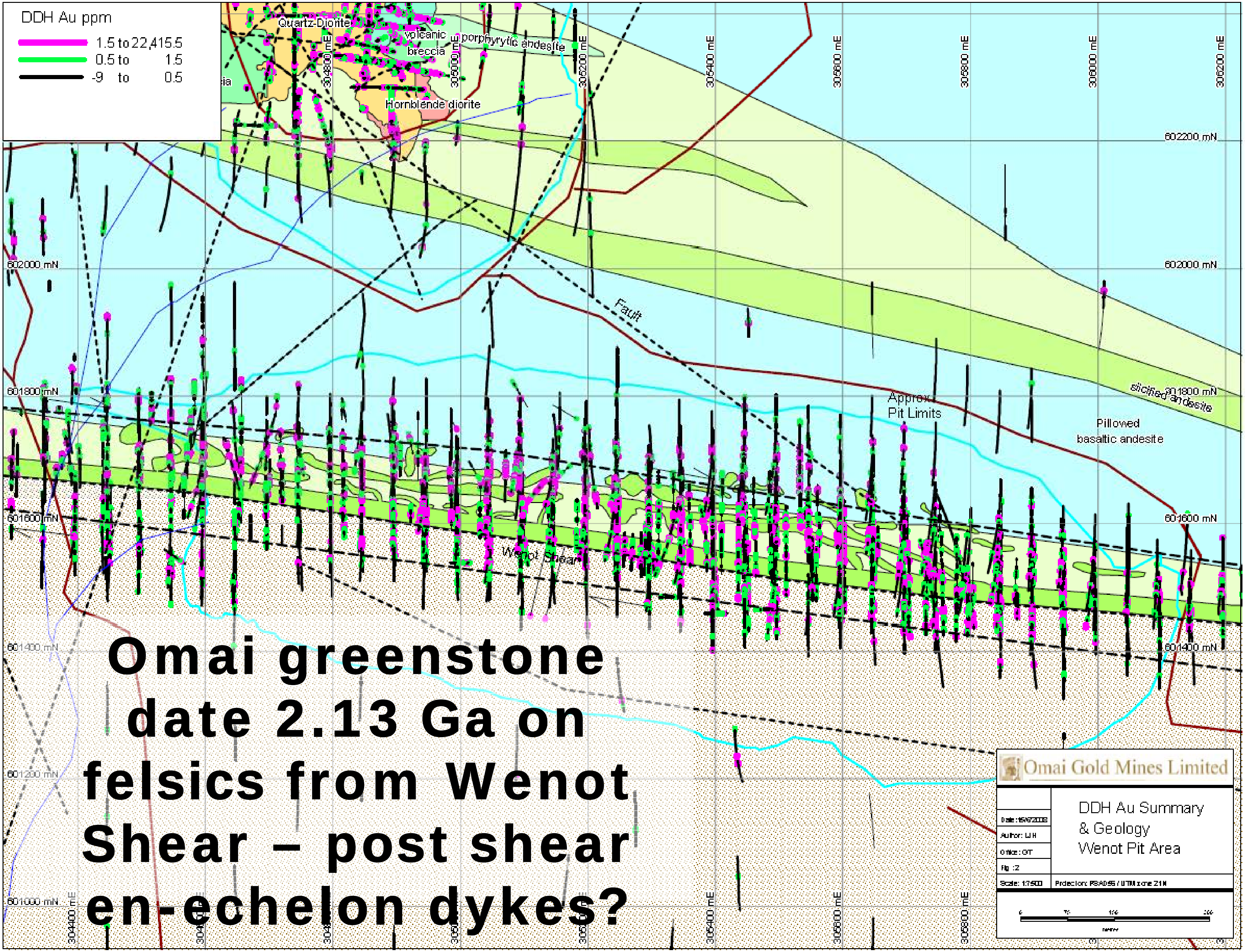
**Evidence of thrusts in Guyana: maybe**
**Low angle structures - yes**

# Mazaruni Group

- Issineru-Haimaraka area considered as the "Type Area" by Gibbs & Barron 1993 & Renner & Gibbs 1987
  - Because it is less deformed & faulted.
- Issineru Formation
  - Basalt & gabbro, some tuffs & cherts
  - Upwards predominantly intermediate and felsic volcanics
  - Gradually more sediment zones
  - Greenschist facies
- Haimaraka Formation
  - Graywackes derived from Issineru
  - Some only zeolite facies

# Mazaruni group - Omai

- Very similar geology to Barama Group
- Larger volumes of mafic metavolcanics / greenschists
- Intermediate and felsic volcanics
- Greywackes / meta-volcaniclastics, locally phyllitic
- Diorite intrusion into basaltic & andesitic rocks 2.09 Ga
- Some felsics post shearing – 2.13 Ga en-echelon intrusions in Wenot Shear, Omai
- Greywackes, locally conglomeratic
- No significant arsenic in GGMC Stream Sediments
- Minor SS As in the immediate Omai Mine area



# Omai greenstone date 2.13 Ga on felsics from Wenot Shear – post shear en-echelon dykes?

# Omai Pillow Basalts and mafic meta-volcaniclastics

# Haimaraka Formation = pre-Roraima, Not Mazarui Group

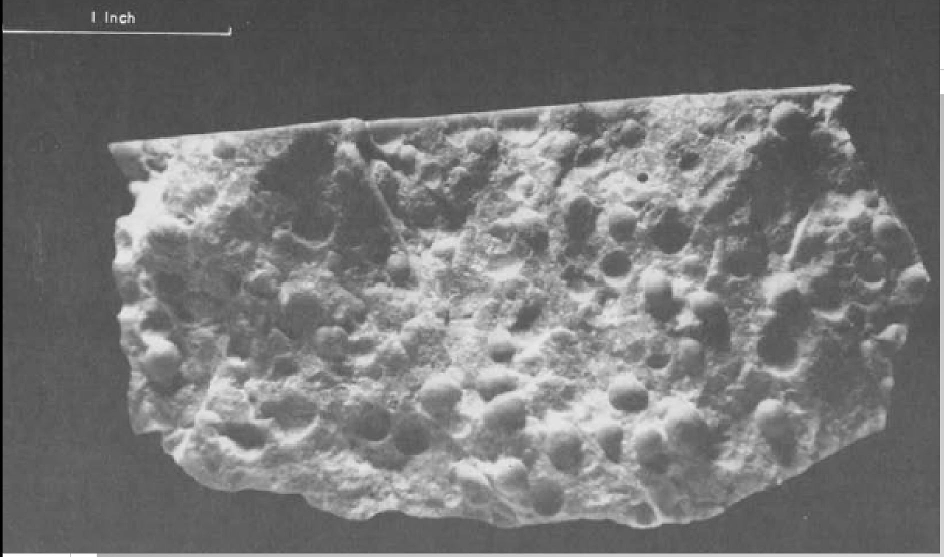
- Cuyuni River (Venezuela border) – unconformity between folded greenstones and the quartzitic / conglomeratic Los Caribes / Muruwa Formation. Originally called the "Western Cuyuni Formation"
- Conglomerate at the top with porphyry clasts
- Overlain by Haimaraka Formation – red/brn graywackes & shales – locally only zeolite facies
- Both show 2 phases open folding
- Covered by semi-flat Roraima Group

- No known primary gold occurrences in the Haimaraka, only alluvial gold & diamonds
- Primary gold in the Issineru Formation - Tamakay

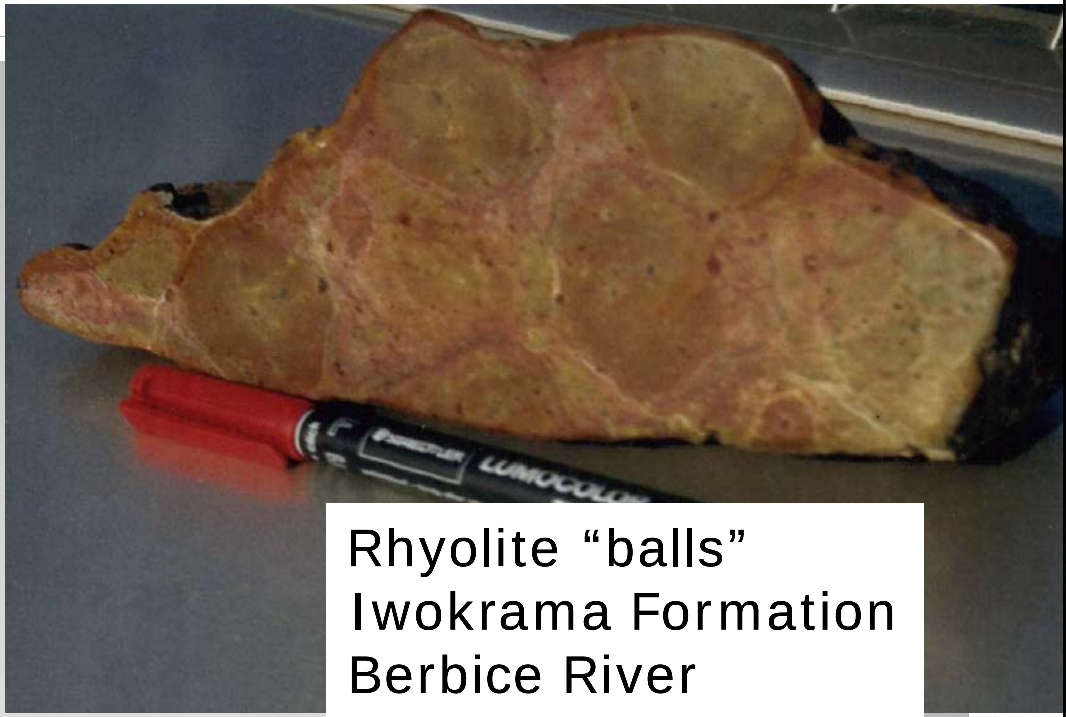
# Basement & “pre-Roraima rocks”

- In the Muruwa River west of the Essequibo a conglomeratic contact was drilled by Cogema between Muruwa and greenstone basement
- In the Essequibo & Corentyne Rivers Muruwa xenoliths occur in granite – so these Iwokrama associated granites are younger than the “Younger Granites”
- The Muruwa Formation also shows 2 phases of gentle folding
- East of the Essequibo there is a ~conformable contact of Muruwa with Iwokrama felsic and then ~flat Roraima Group
- West of the Berbice ~ conformable Iwokrama overlies Muruwa
- Lots of Iwokrama Formation south of the Pakaraima Mts
- North side only Muruwa & Haimaraka
- **Haimaraka is lateral equivalent of the Iwokrama**

# Haimaraka & Iwokrama “Balls”

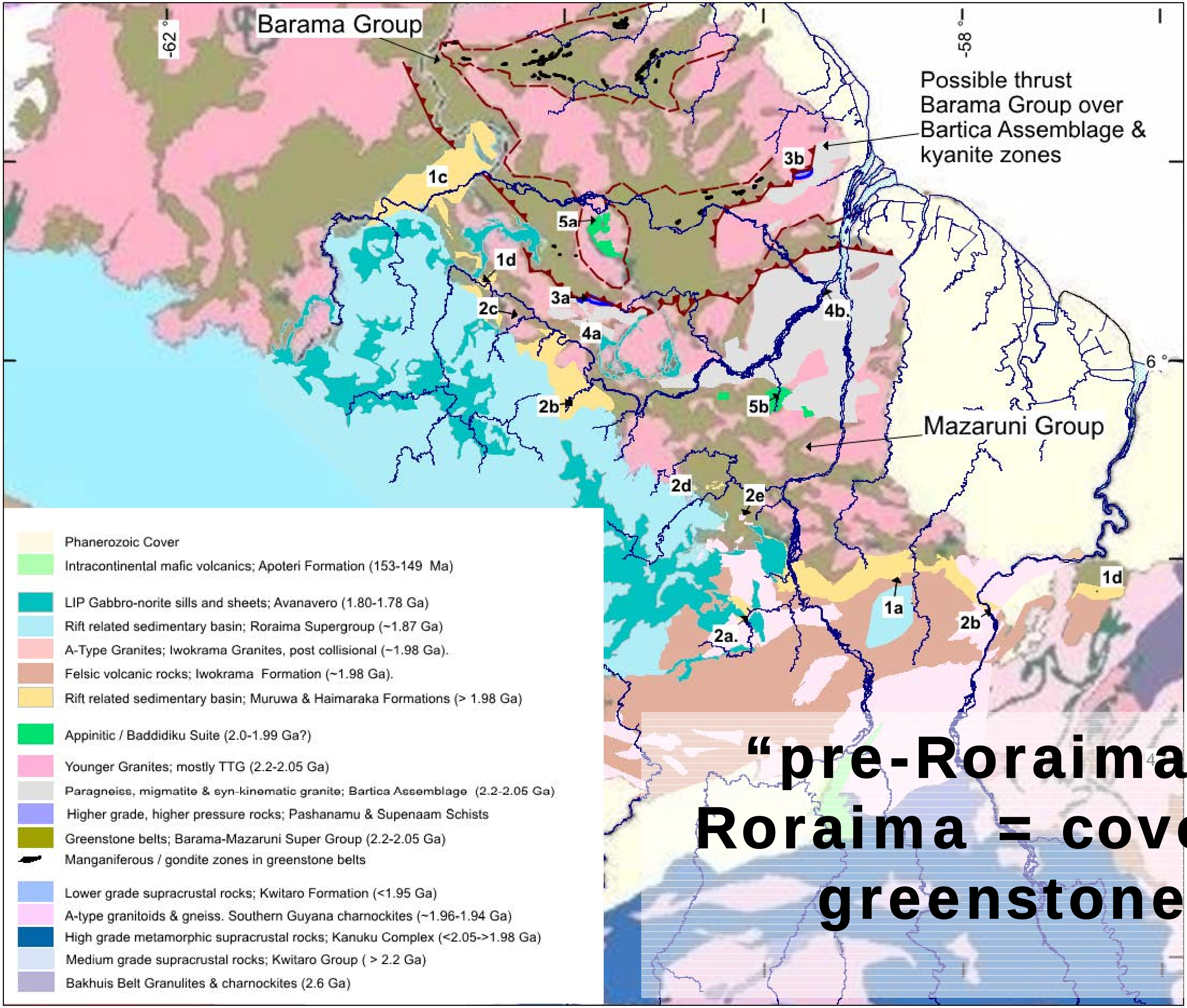


Felsic tuff – accretionary lapilli in Haimaraka Formation
Merume River



Rhyolite “balls”
Iwokrama Formation
Berbice River

Bedded “balls”
Each bed has “balls” of approx same size.
Iwokrama Formation
Berbice River



# "pre-Roraima" & Roraima = cover on greenstones

Geology & gold hidden under even younger / Phanerozoic cover 100km inland; Edge of the Guiana Basin

# Conclusions?

- Kwitaro Group – completely different
- Mazaruni group probably the same as the Barama group / Pastora Super Group but distal to the manganiferous / arsenic rich areas
- Brought into proximity by thrusting?
- Roraima Group & "pre-Roraima" rocks unconformable on greenstones – post mineralisation
- What about the other graywackes / conglomerates – not sure
- Dating on post sediment felsic intrusions needed! – the Haimaraka is metamorphosed by granite near Enachu

# Hopefully a few cogs turning!

This one from small scale workings 4m deep from the base of the Phanerozoic cover / White Sand – Mahdia area

# Questions?

# *From Small scale miners to Discovery: the Nassau Project and the Discovery of the Merian Mine*

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**dennis.lapoint@gmail.com**

**11th Inter Guiana Geological**
**Conference: The Tectonics &**
**Resource Potential of NE**
**South America**
**February 19, 2019**

# Thanks to Suralco and their team.

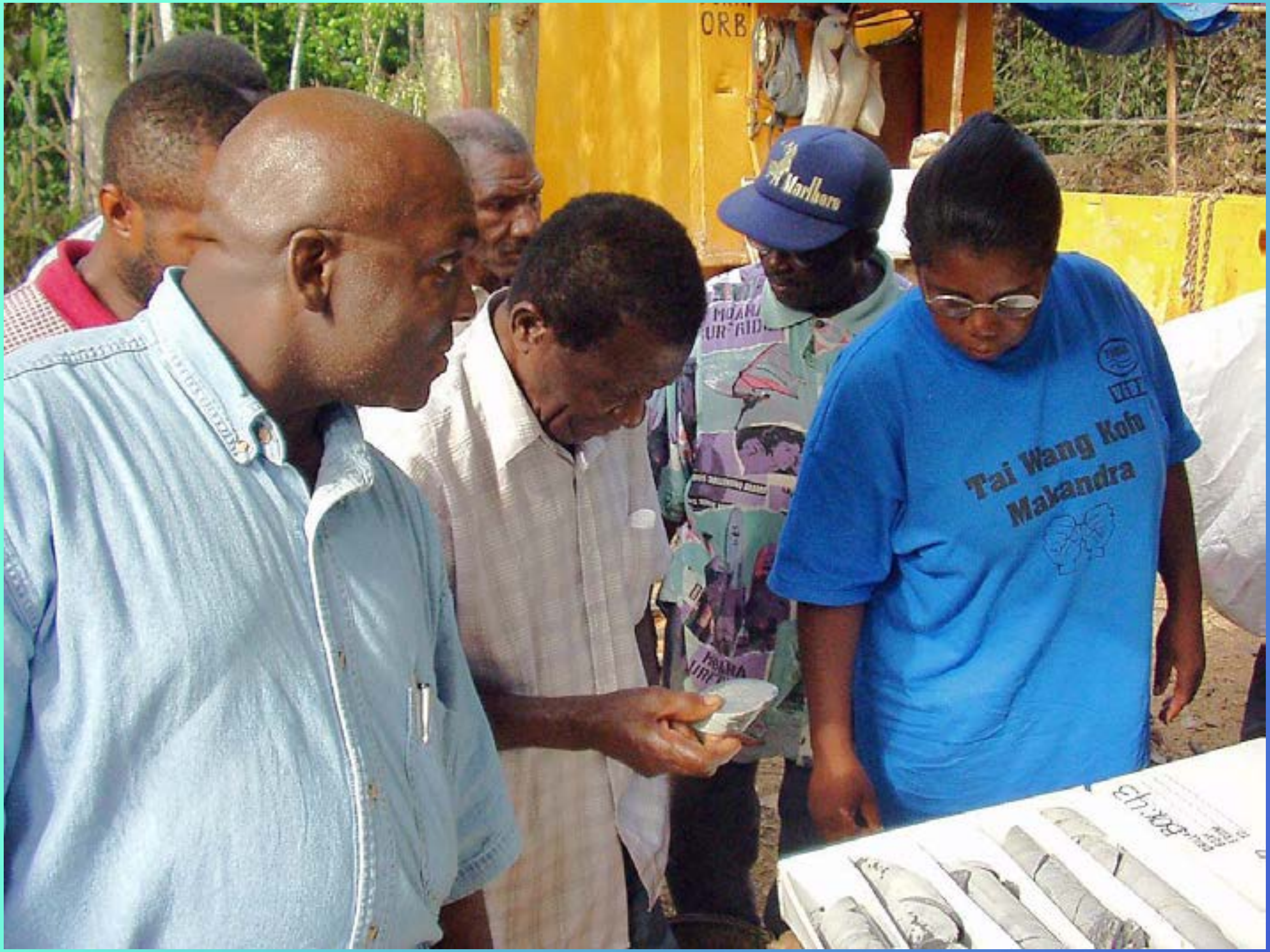
Charlie Soh in Alcoa

Especially Anton Brandon and Herman Alendy in Suralco

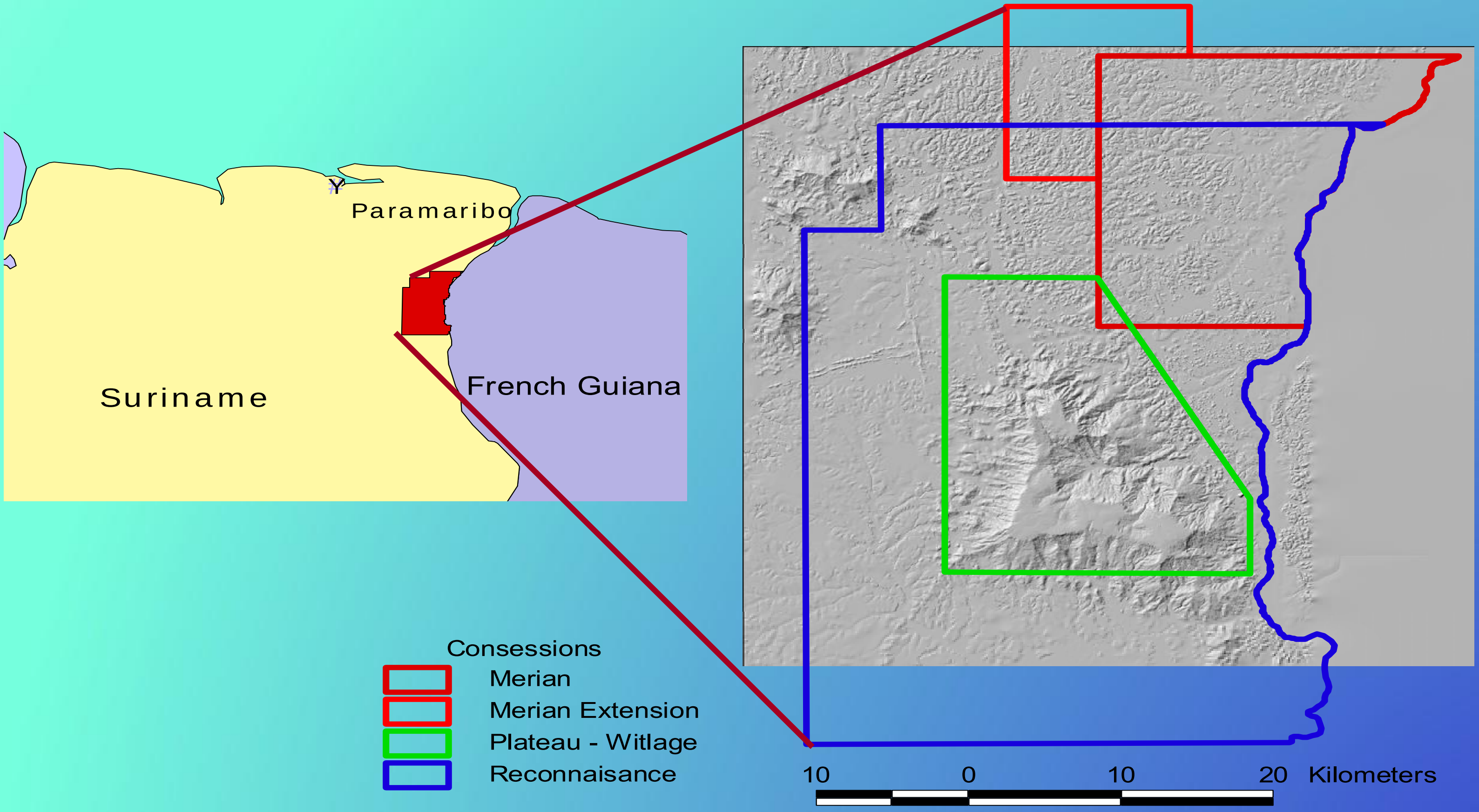
# Mandate from Suralco

- Find a Gold Mine to support funding for infrastructure to develop bauxite resource on Nassau Plateau
- Train and develop a Suriname team of geologists and technicians with minimal expat support
- Drill: converted 140,000 hectares from reconnaissance to exploration concessions in order to drill.
- Maintain good relations with local community
- **Merian (Nassau) Is a Greenfields Gold Discovery made as a *TEAM* of Suriname Geologists and support of Suralco**
- Program started 2000. Discovery holes September 2002

# Community Relations: Visit by Granman in September 2003



# How to Evaluate Large Area with Minimal Data?

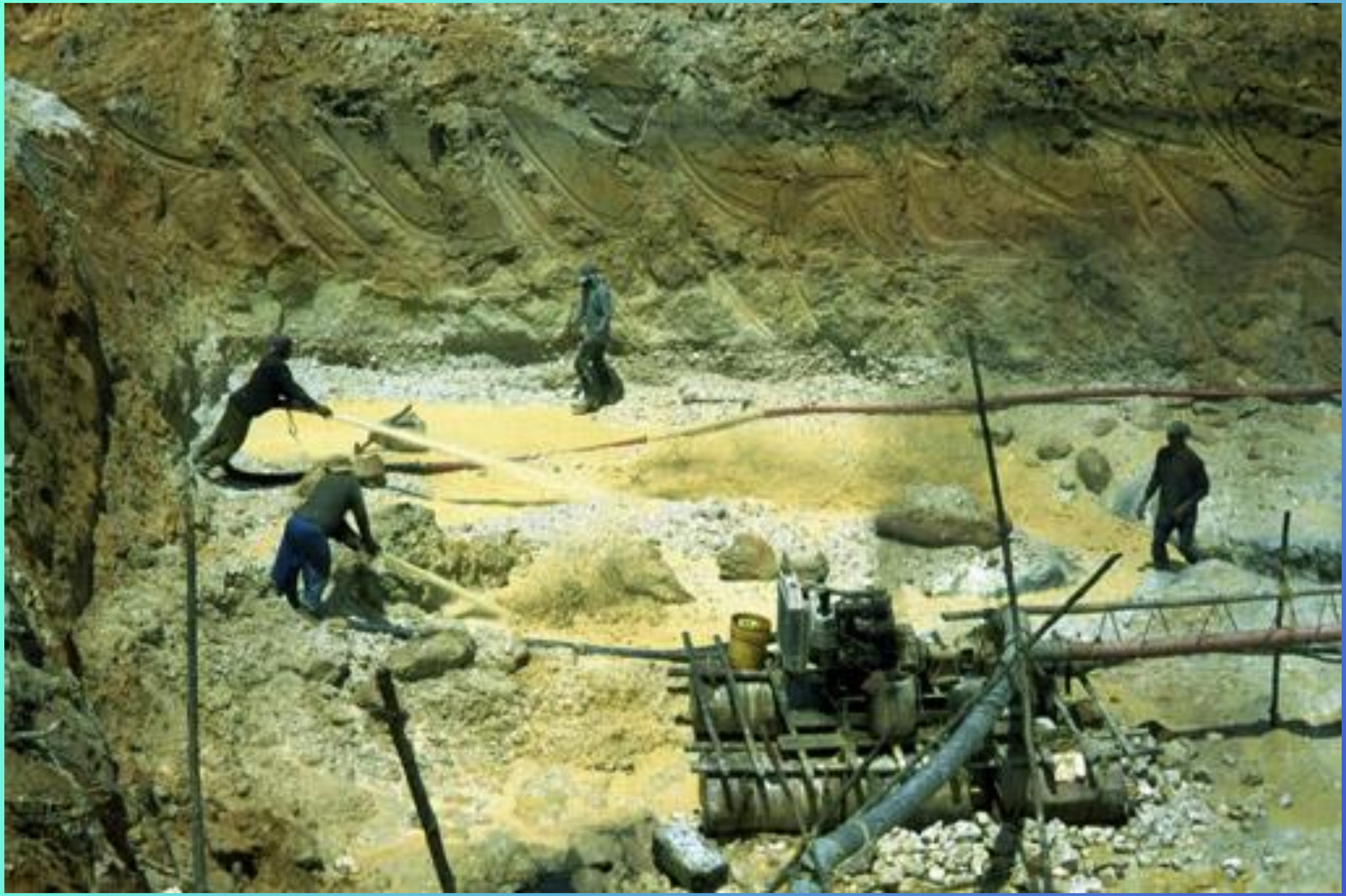


# Data Sources

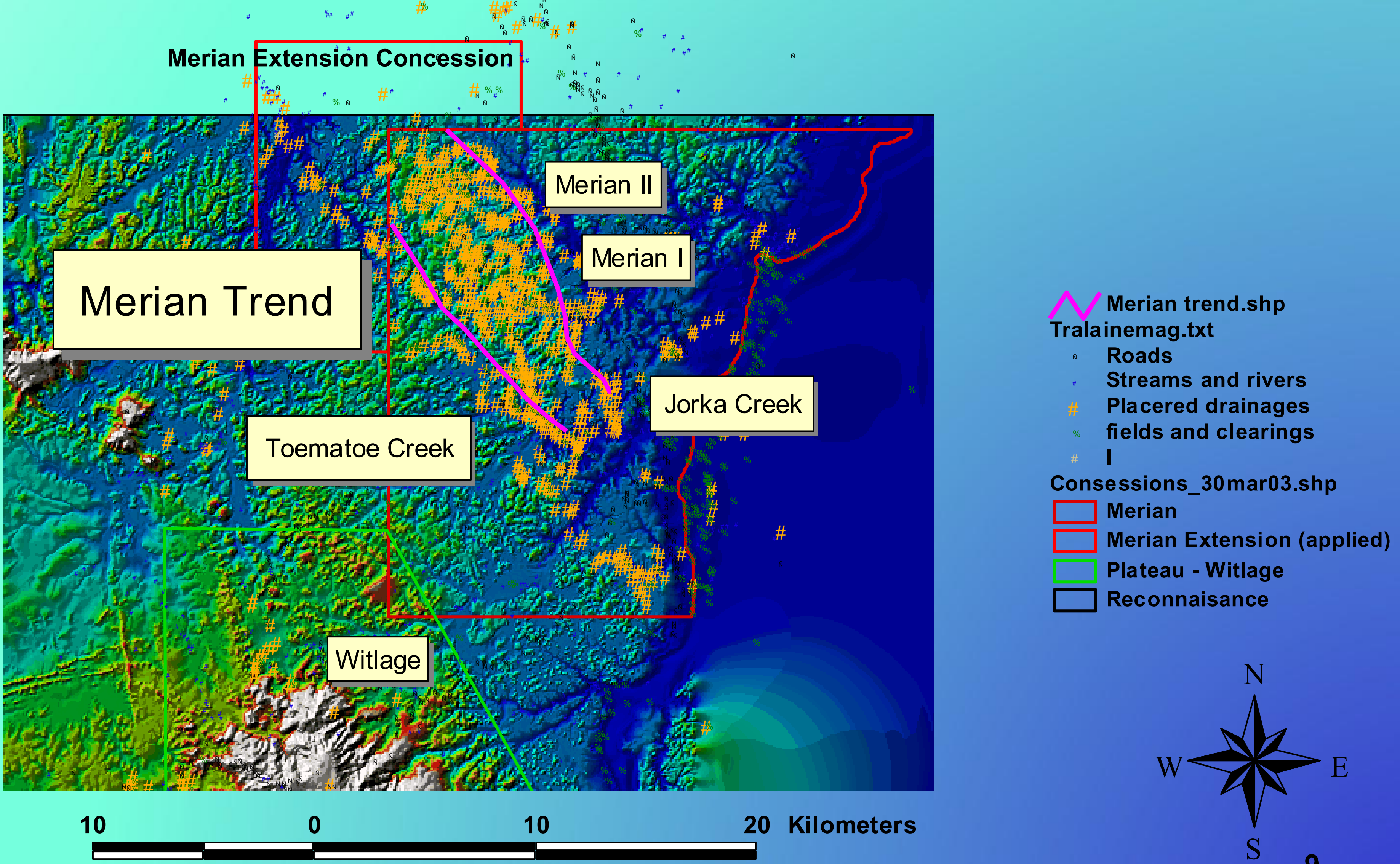
- NO KNOWN PRIOR EXPLORATION OR REGIONAL SURVEYS
- Greenstone belt within country geologic map
- Porkknocker mining of alluvial gravels and access
- Landsat Satellite and Radar images (no Google Earth!)
- Topographic maps on local grids with significant errors and issues converting to WGS 84 Zone 21N
- GPS in jungle difficult (2000-2003)

# MERIAN CREEK SMALL SCALE MINING
# 2000

# Porkknockers



# SMALL SCALE MINING ACTIVITY
# NASSAU 2000



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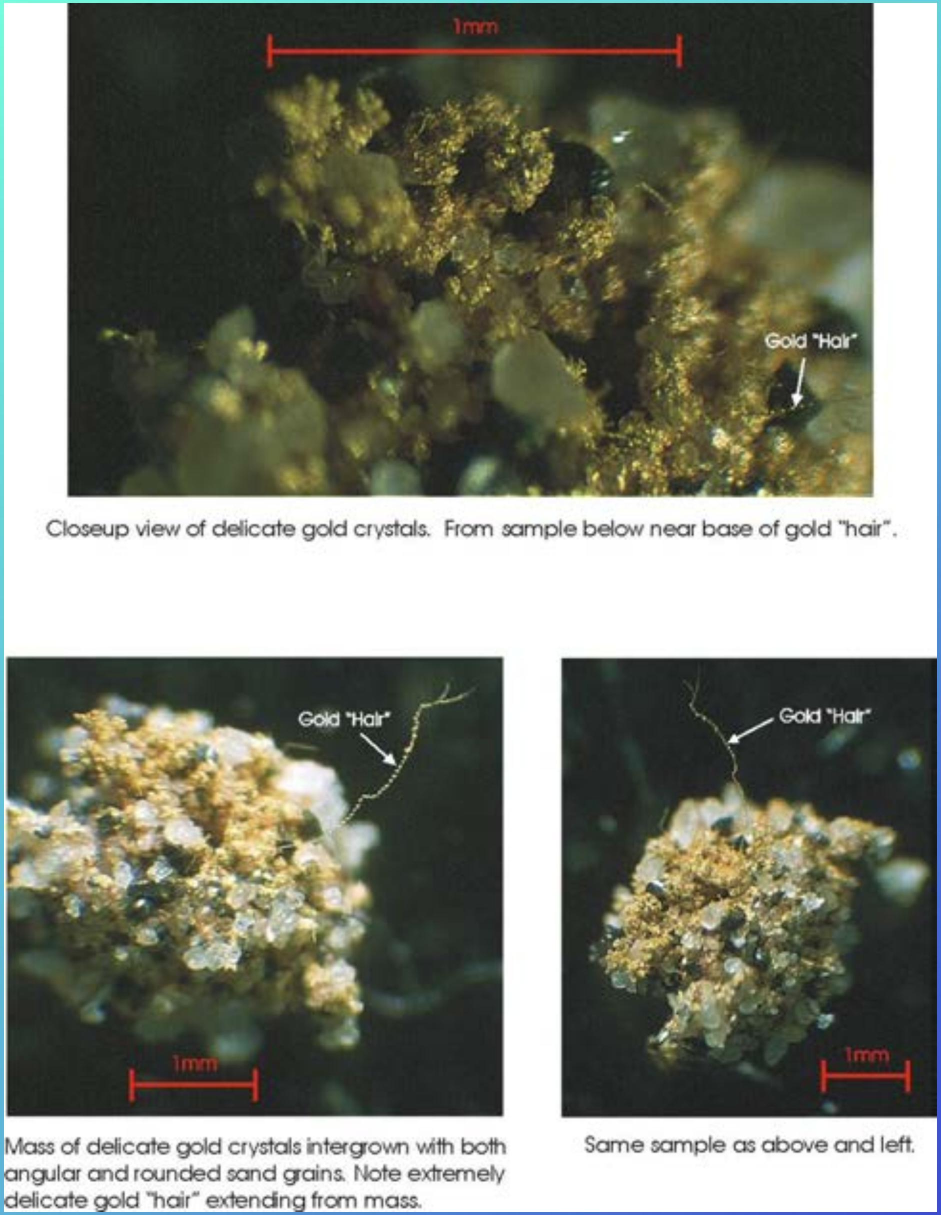
# Gold locally produced by bacterial action in streams



Closeup view of delicate gold crystals. From sample below near base of gold "hair".

Mass of delicate gold crystals intergrown with both angular and rounded sand grains. Note extremely delicate gold "hair" extending from mass.

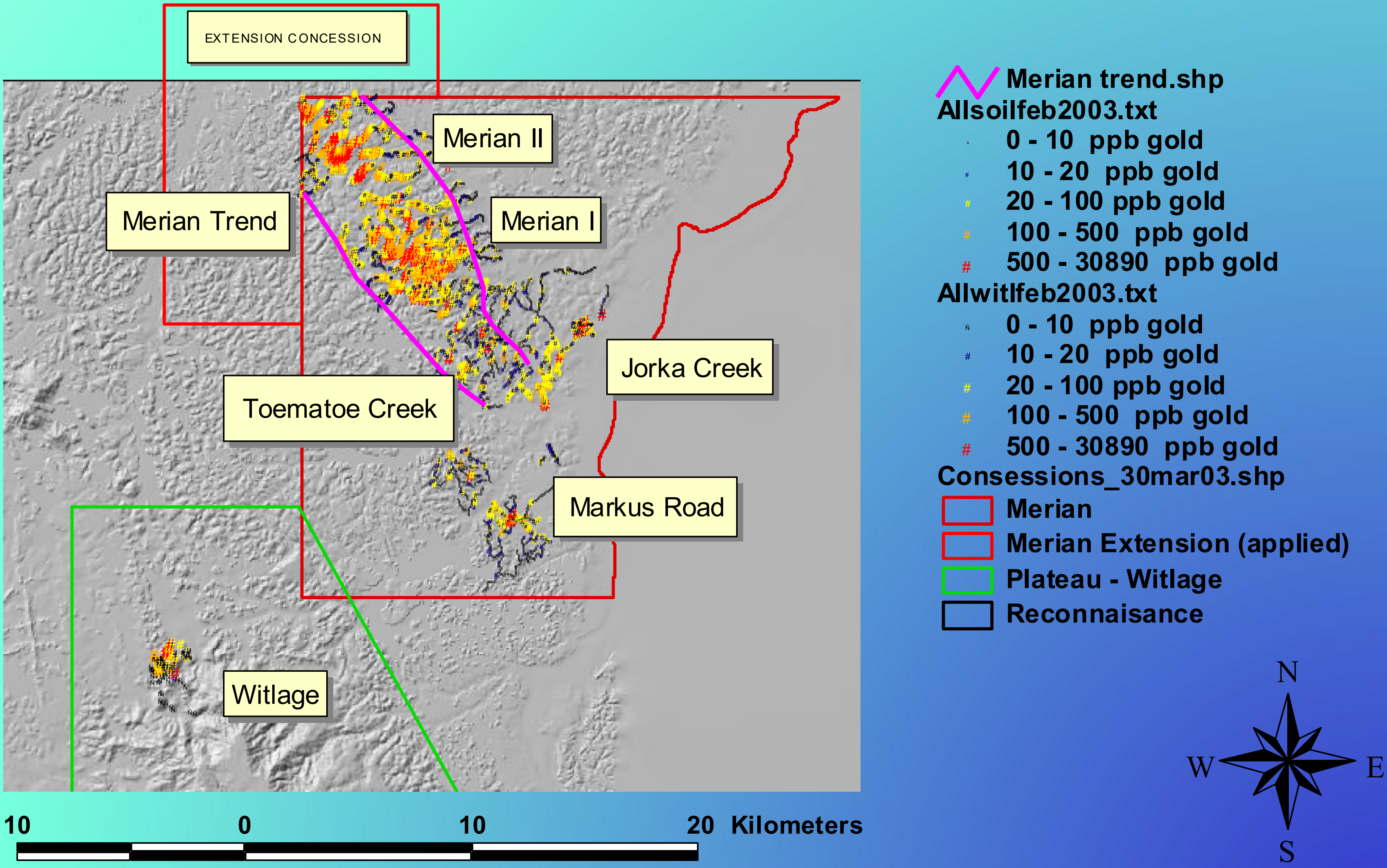
Same sample as above and left.

# Exploration Tools

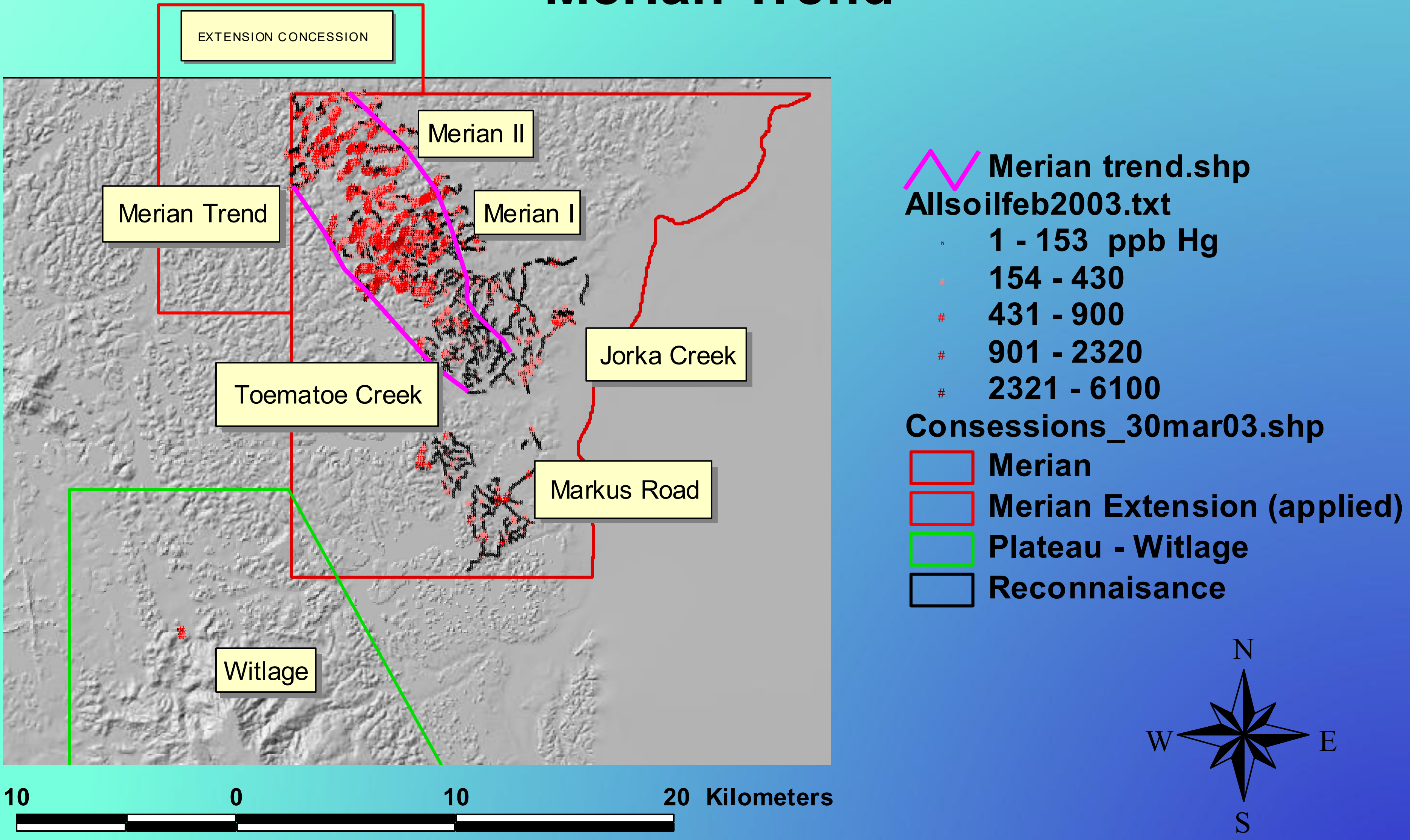
- Remote sensing and airborne geophysics
- Porkknocker pits and access they provided
- Panning and heavy mineral analysis
- Ridgecrest auger sampling (2 meters): gold and multielement
- Mapping and sampling of lines and porkknocker pits
- Trenching
- Deep Auger grids on Merian Gold trend
- Hollow stem auger core drilling.
- Diamond core drilling
- Team of US based geologists for interpretation of Merian in February to July, 2003
- First resource estimate July 2003

# Auger Sampling along Ridgecrests

# Ridgecrest Soil Samples to Locate Targets

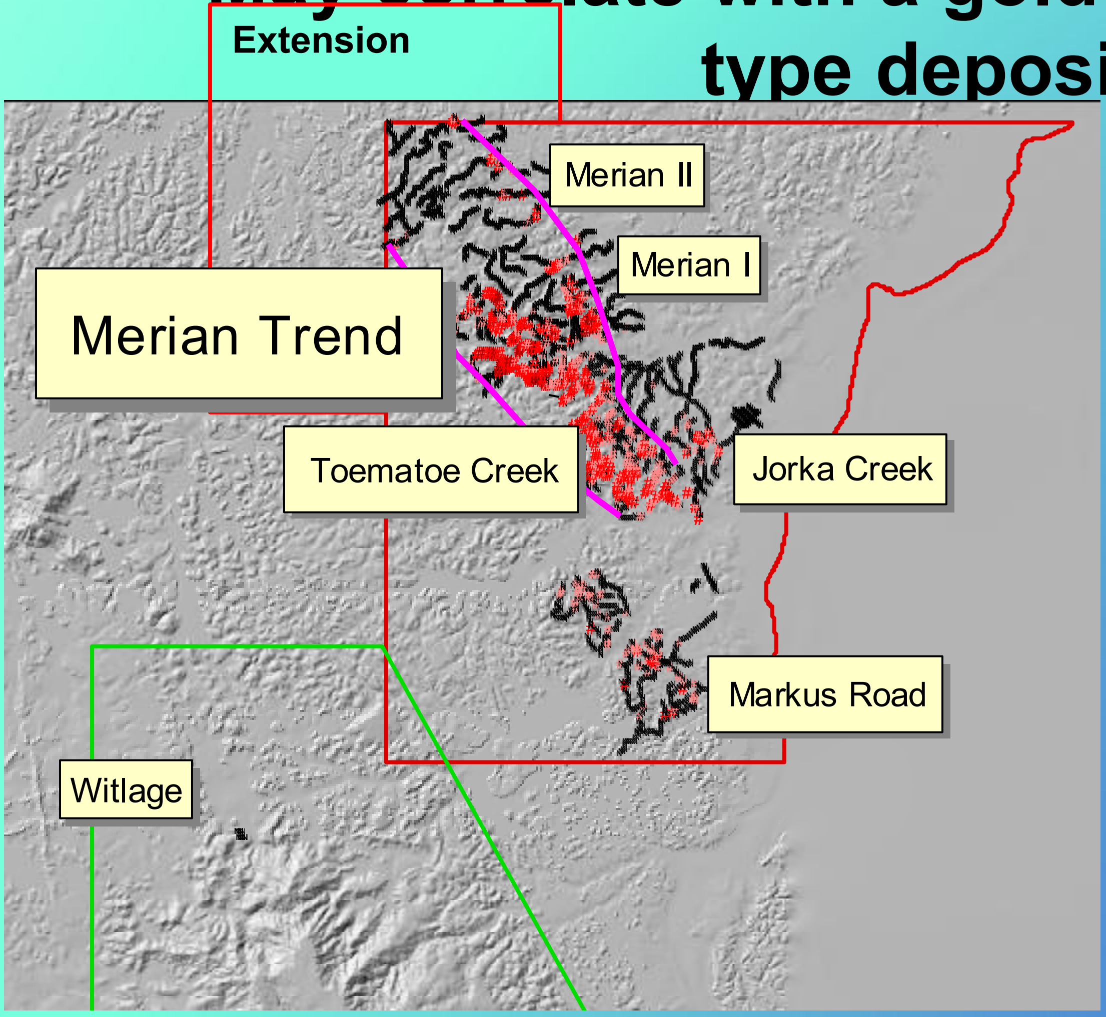


# High mercury values correlate with gold on Merian Trend



# Arsenic anomalies Merian Trend

## May correlate with a gold-arsenic-quartz type deposit



Merian trend.shp

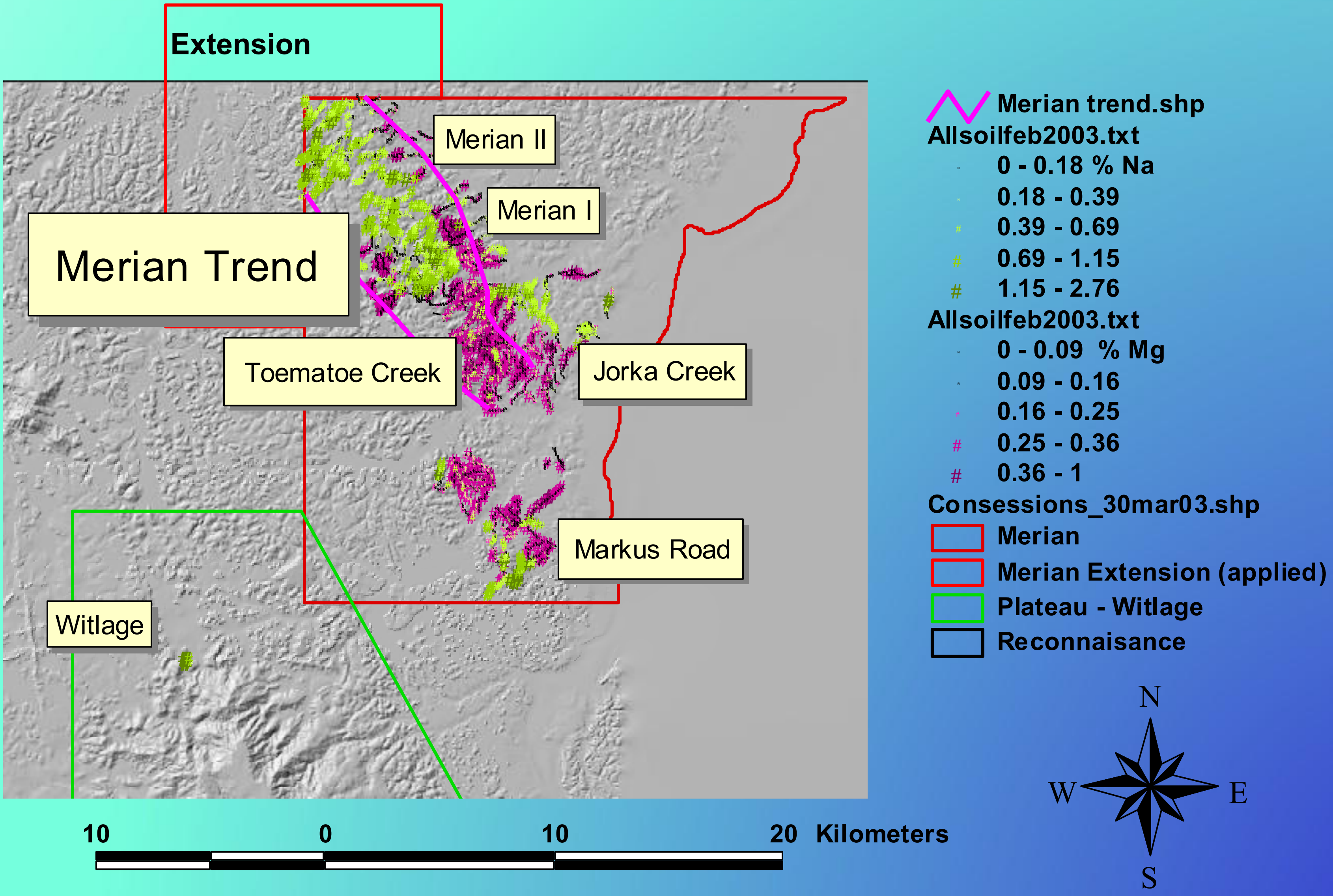
Allsoilfeb2003.txt

- 0 - 100 ppm As
- 100 - 200
- 200 - 500
- 500 - 1000
- 1000 - 2115

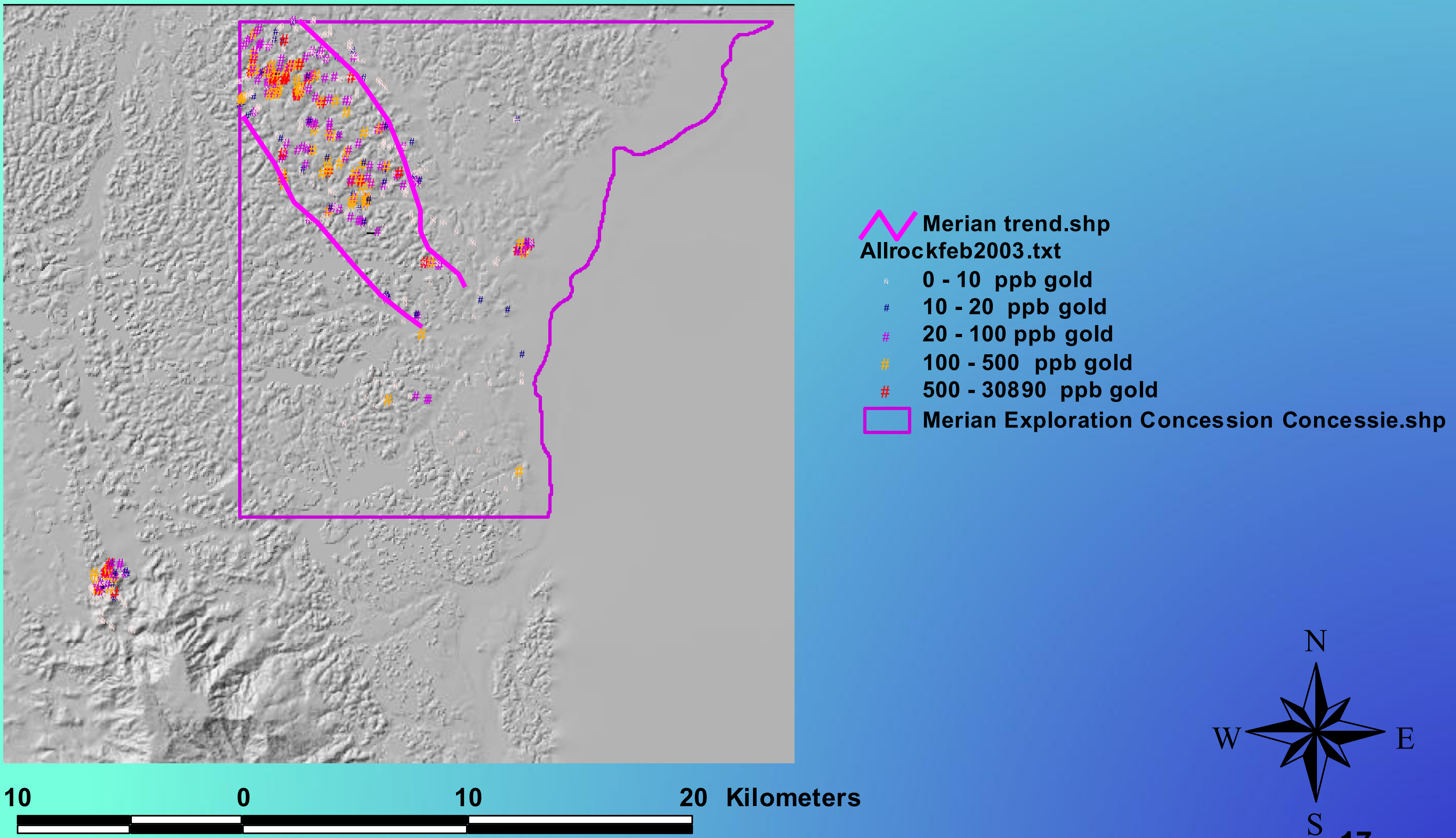
Consessions_30mar03.shp

- 🟥 Merian
- 🟥 Merian Extension (applied)
- 🟩 Plateau - Witlage
- ⬛ Reconnaisance

# Gold associated with higher sodium values



# ROCK SAMPLES
# NASSAU PROJECT



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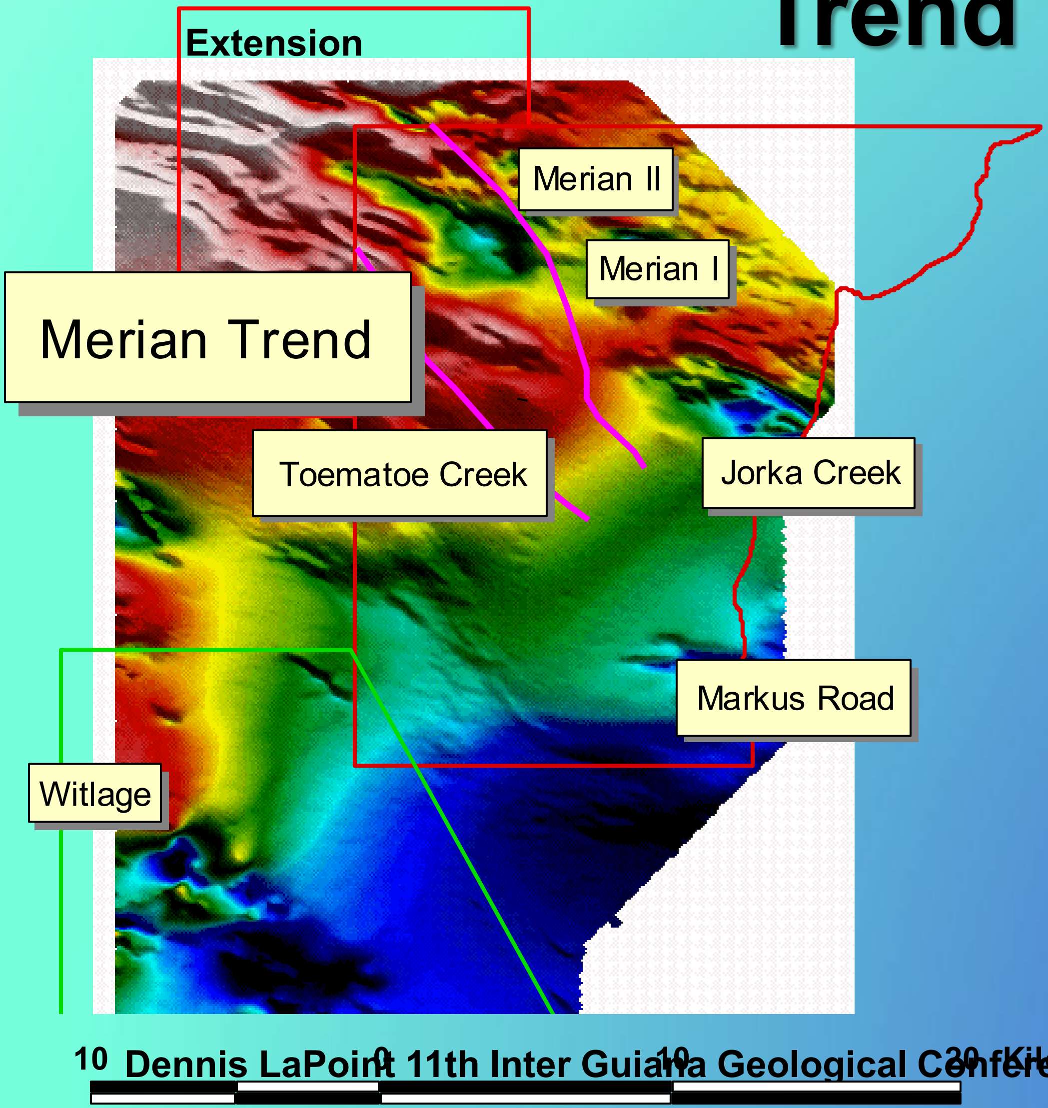
# Magnetic Total Field and Merian Trend



**Merian trend.shp**

**Consessions_30mar03.shp**

- 🟥 **Merian**
- 🟥 **Merian Extension (applied)**
- 🟩 **Plateau - Witlage**
- ☐ **Reconnaisance**

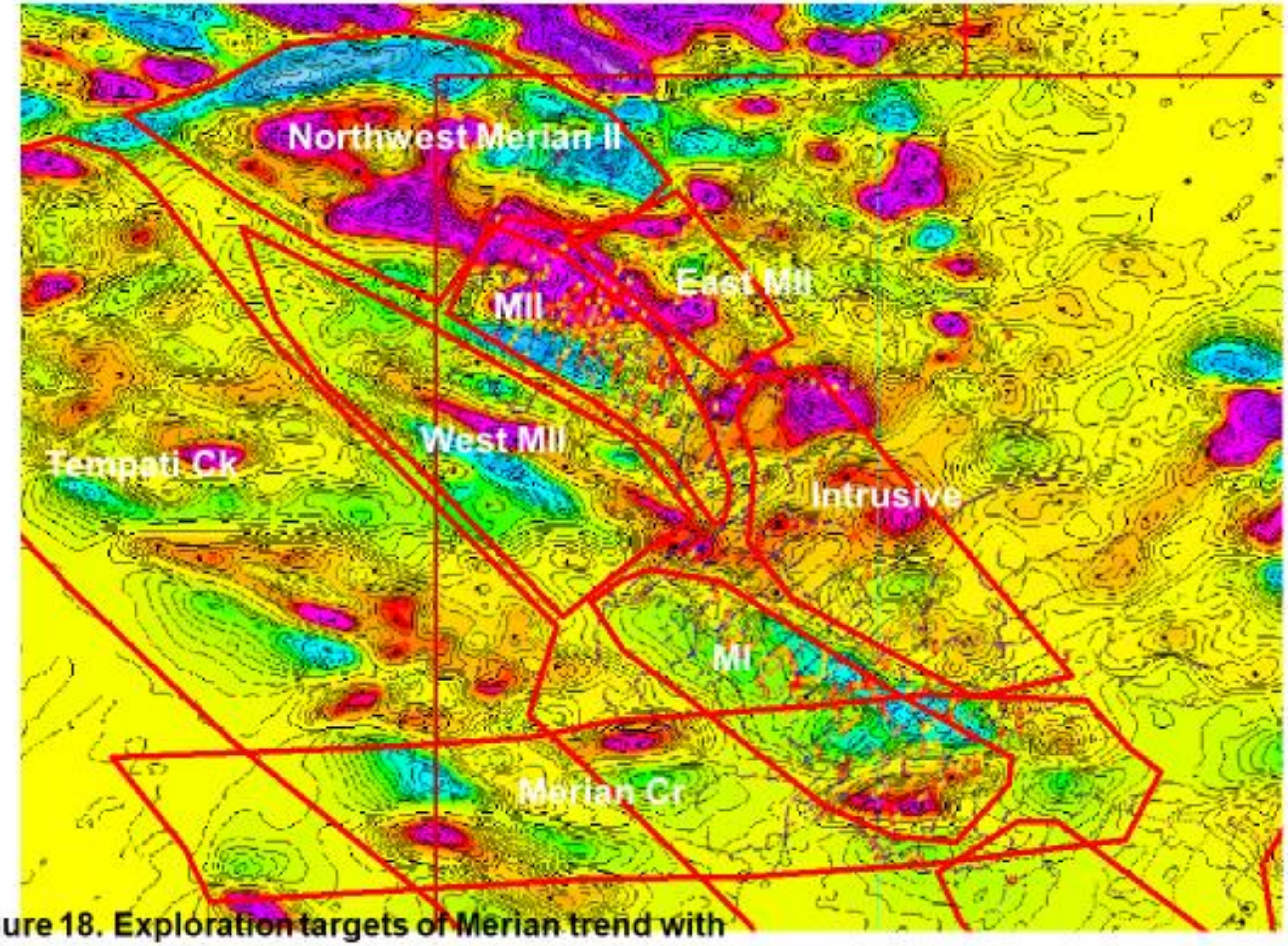


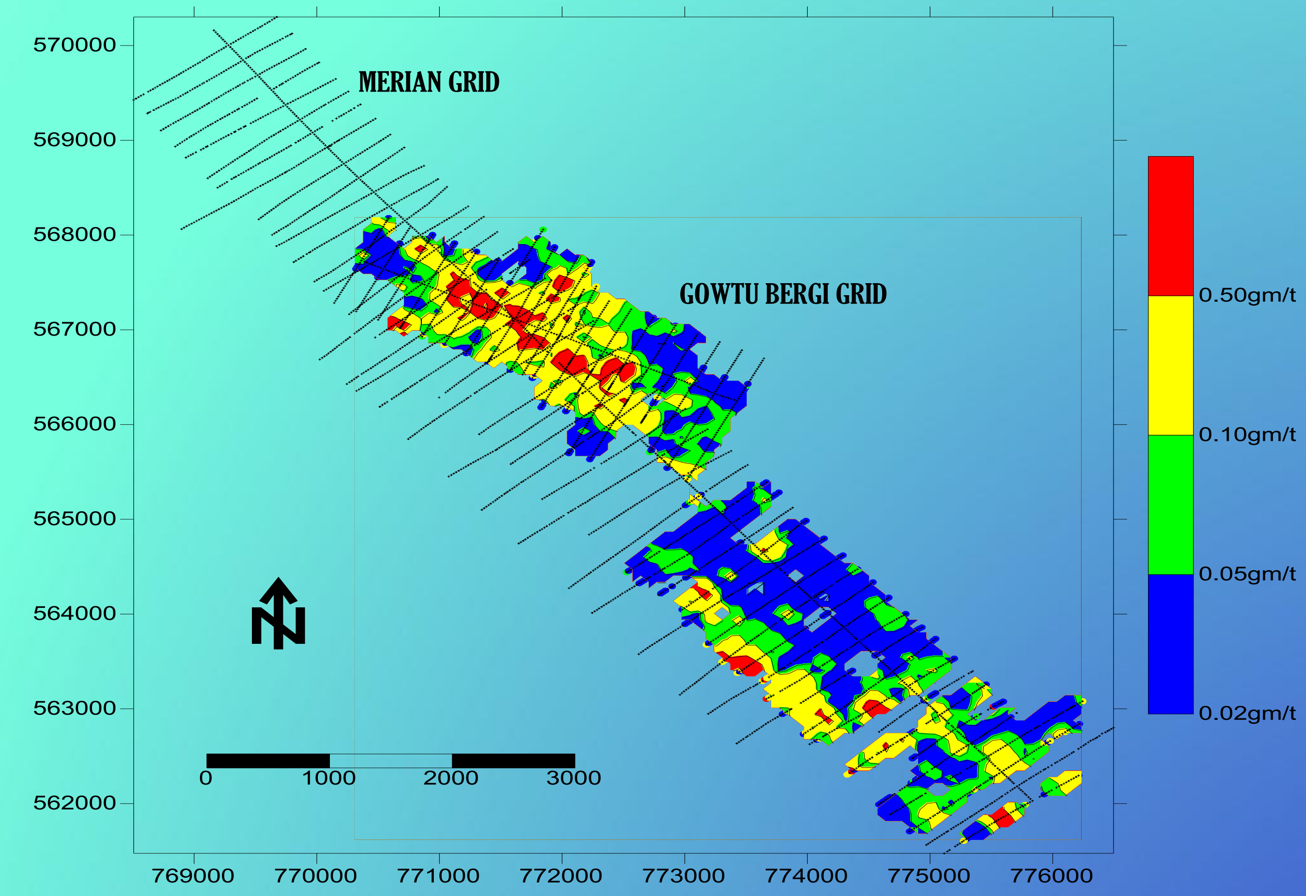
Figure 18. Exploration targets of Merian trend with magnetic, soil and deep auger data.

# Mining at Gowtu Bergi June 6, 2002 visit

# Sampling at Gowtu Bergi July 2002

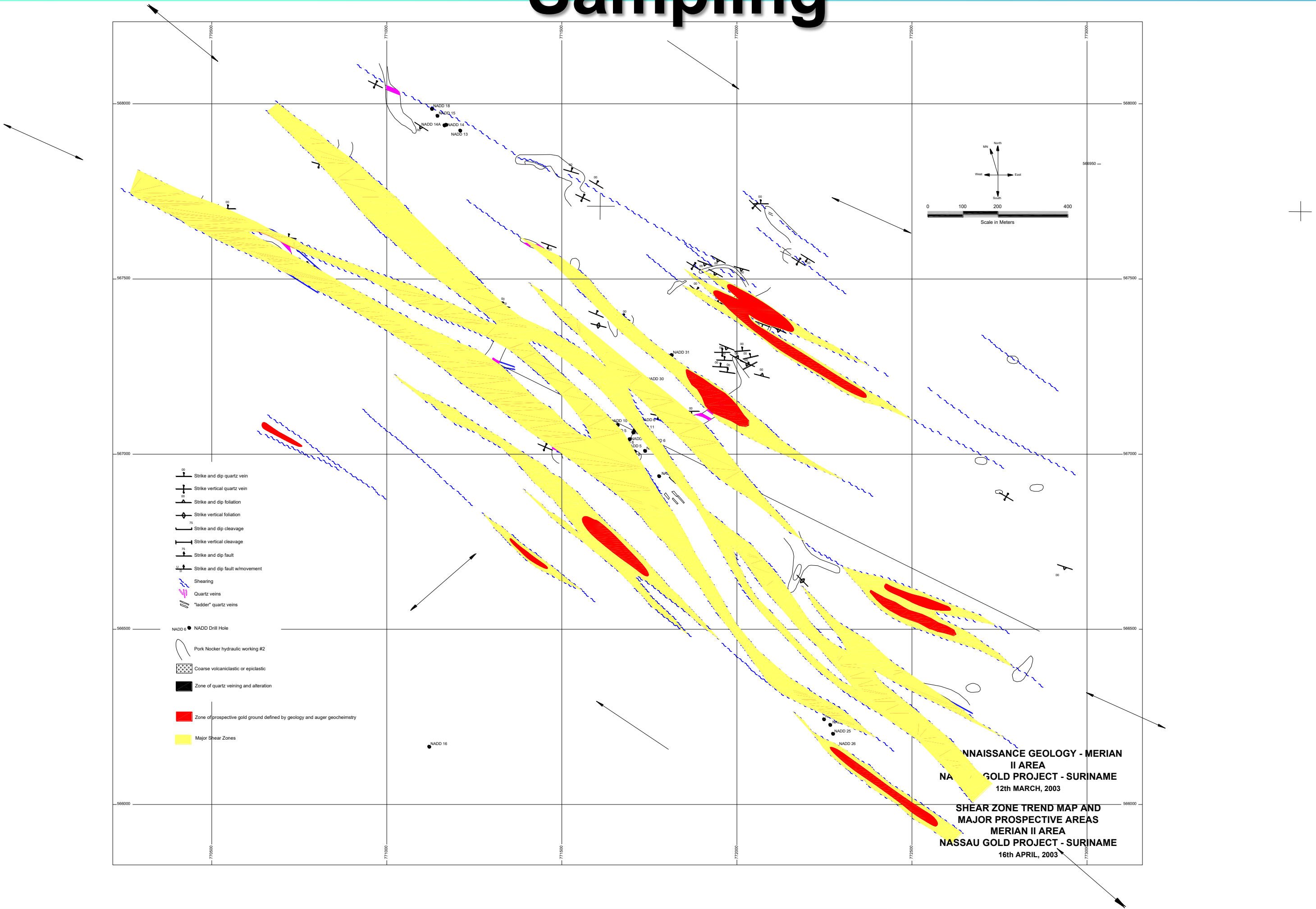
# Police Assistance – Merian Village

# Porkknocker Trail To Gowtu Bergi



GOLD VALUES DEEP AUGER MERIAN TREND

# Gold Targets and Structural Zones Merian II based on Mapping and Deep Auger Sampling



# Saprolite Core Drilling and Logging with Diedrich Drill

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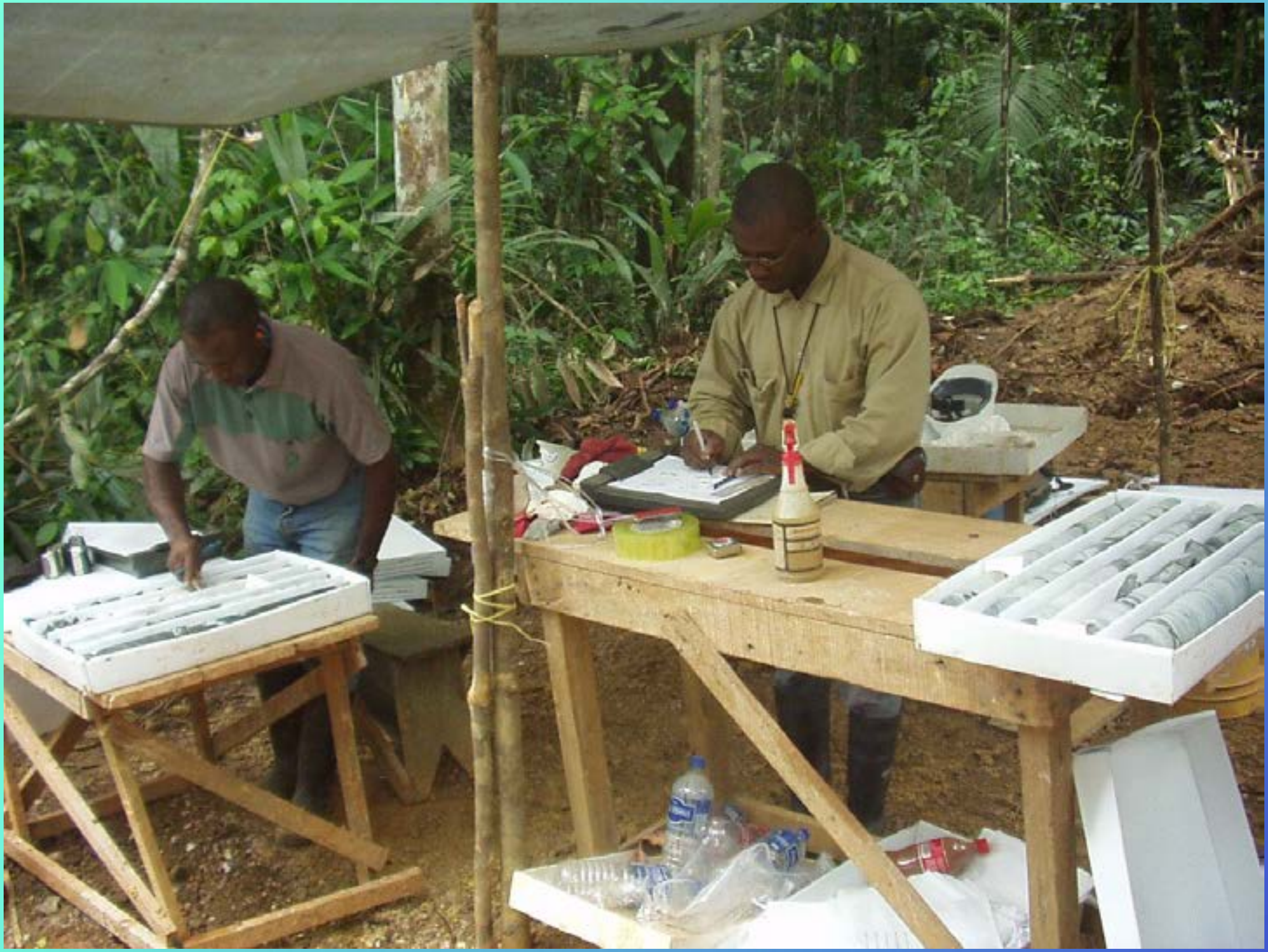
# First Core hole August 31, 2002

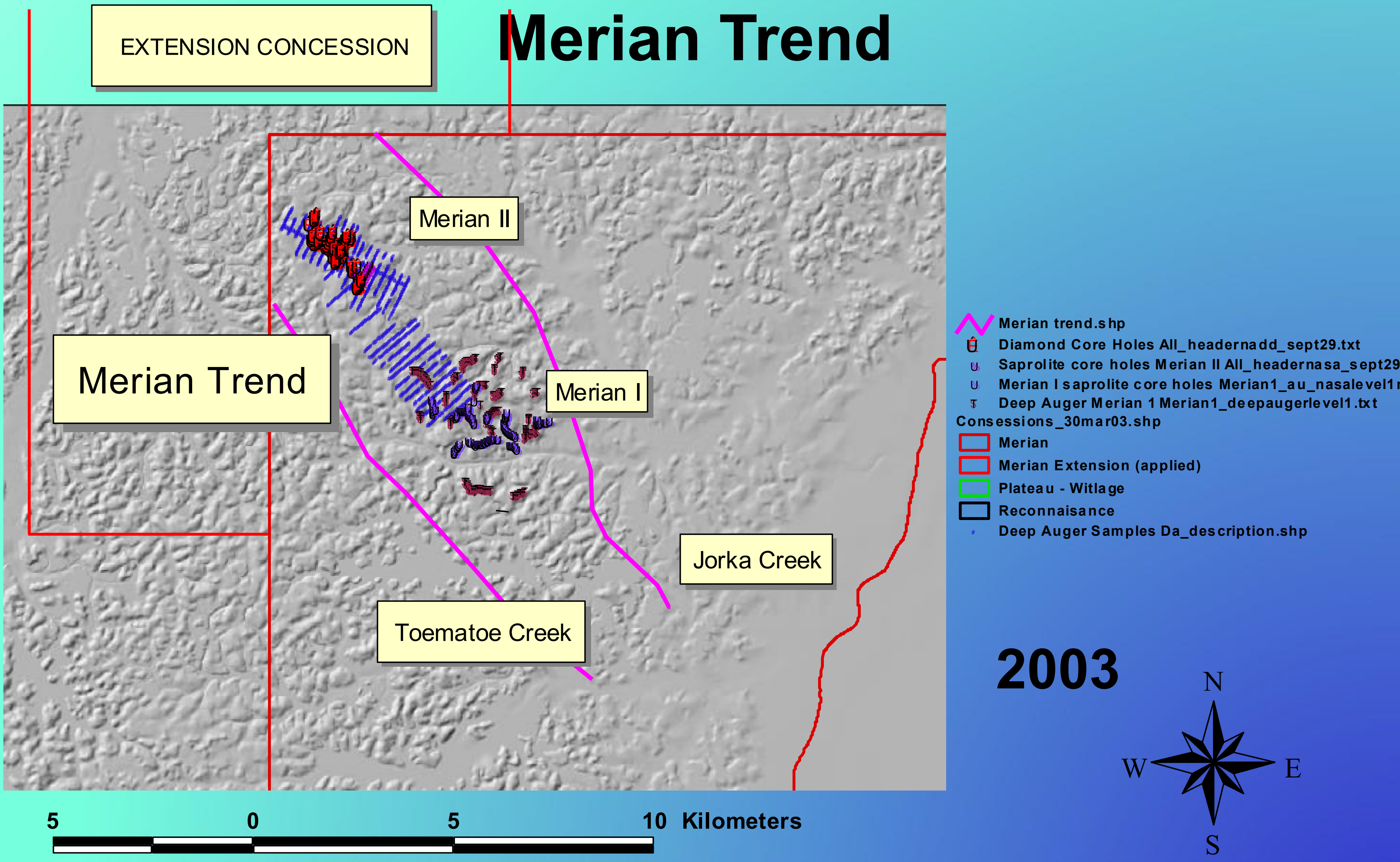
# Diamond Core Drilling by Forage Orbit: 12 holes all ore holes

# Descriptive Logging



# Mineralized Ore Zones Hole NADD-011: Oxidized Saprolite and Saprock (unoxidized)

# All Drill Hole and Deep Auger Sites
# Merian Trend



2003

# Resource Modeling

- From February to July, 2003 there was an intense period of evaluation on the understanding of mineralization while drilling and modelling was on-going. Geologists Dr. Criss Capps, Robert J. Moye, Dave Christensen, Mary Stollenwerk, and Tom Watson from the United States were retained to assist the Suriname geologic team of Aroena Ramlal, Manuella Fung, Deepak Narsing, Ryan Kambel, and Linus Diko.

# Interpretation and Modeling

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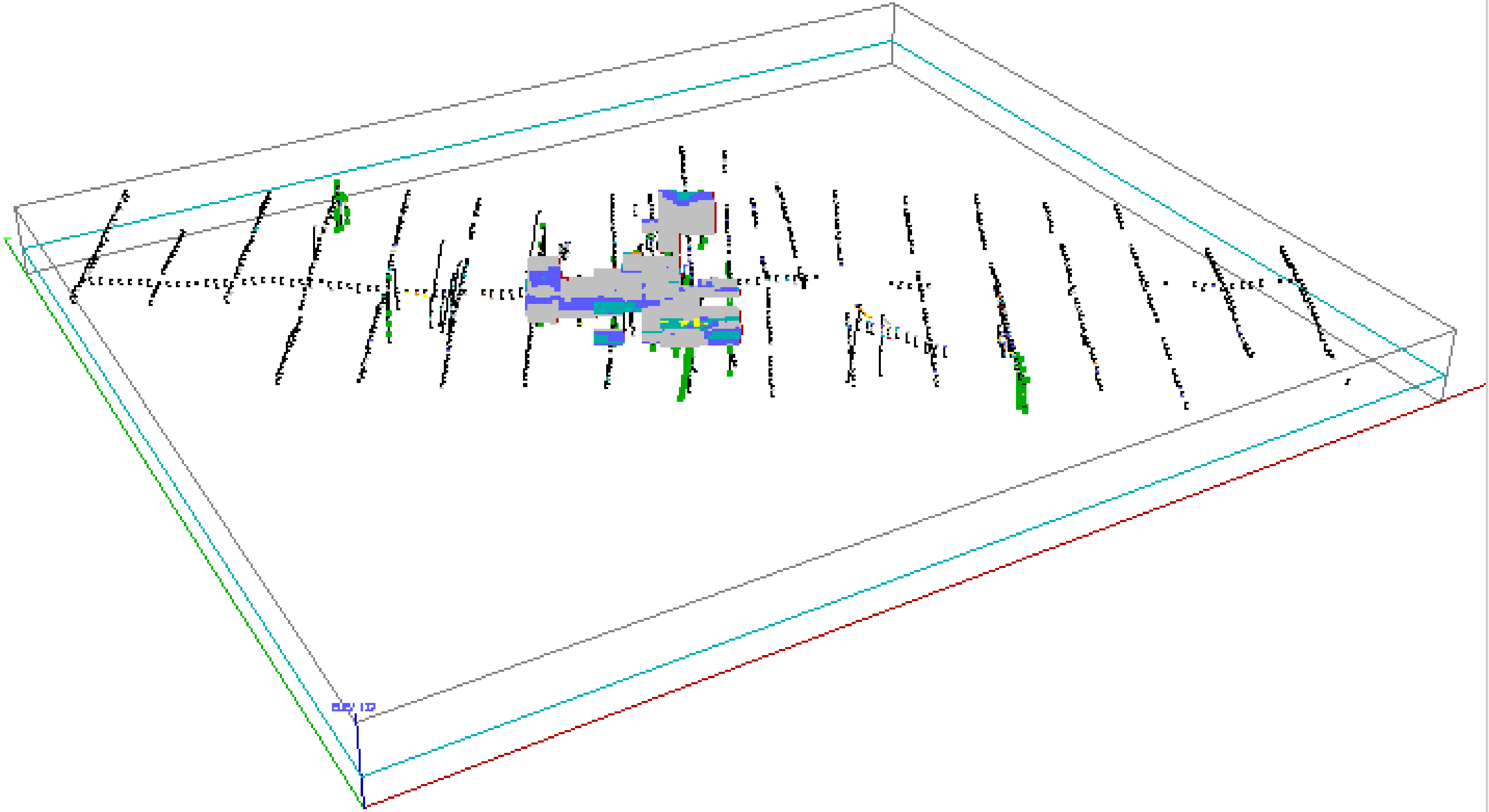
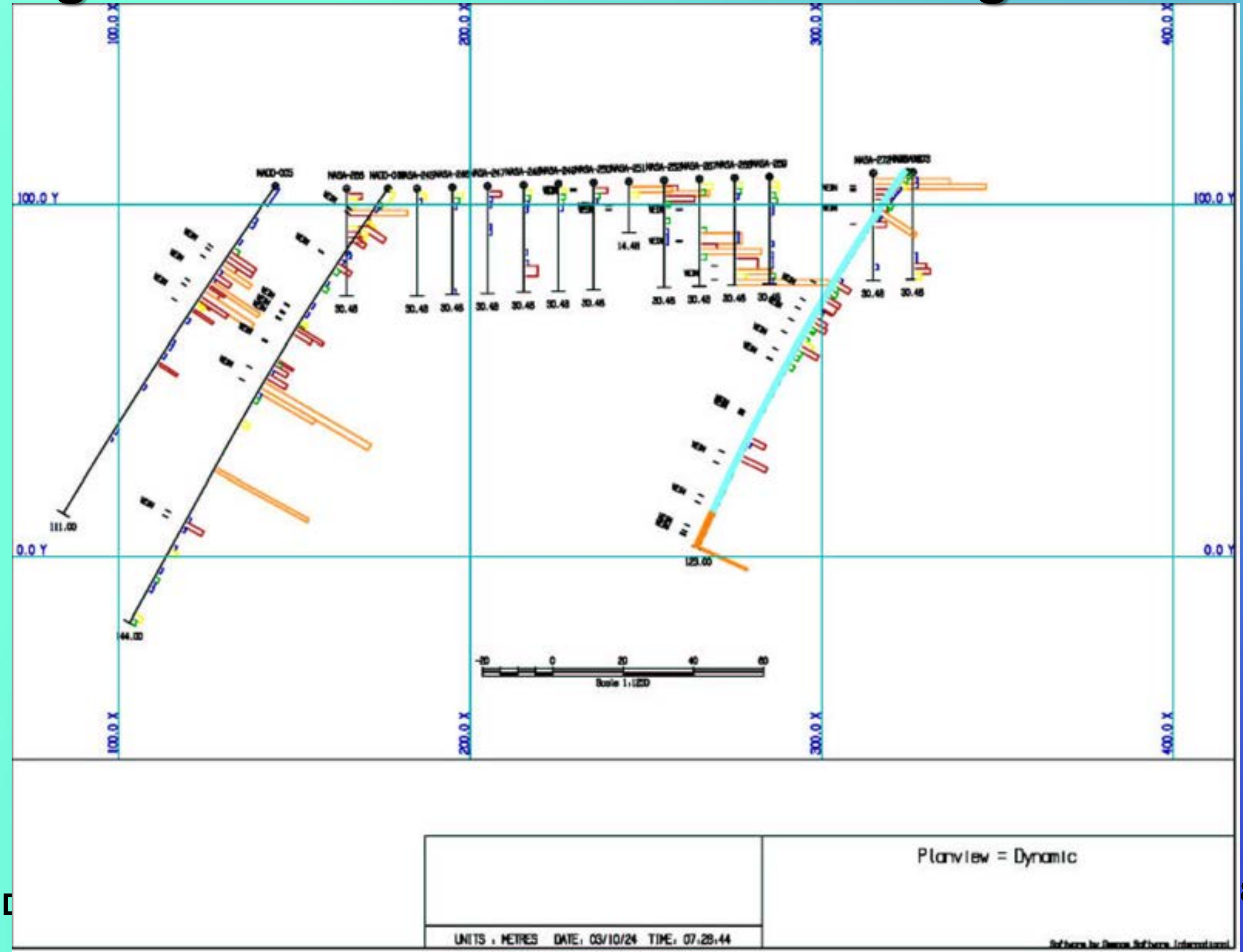
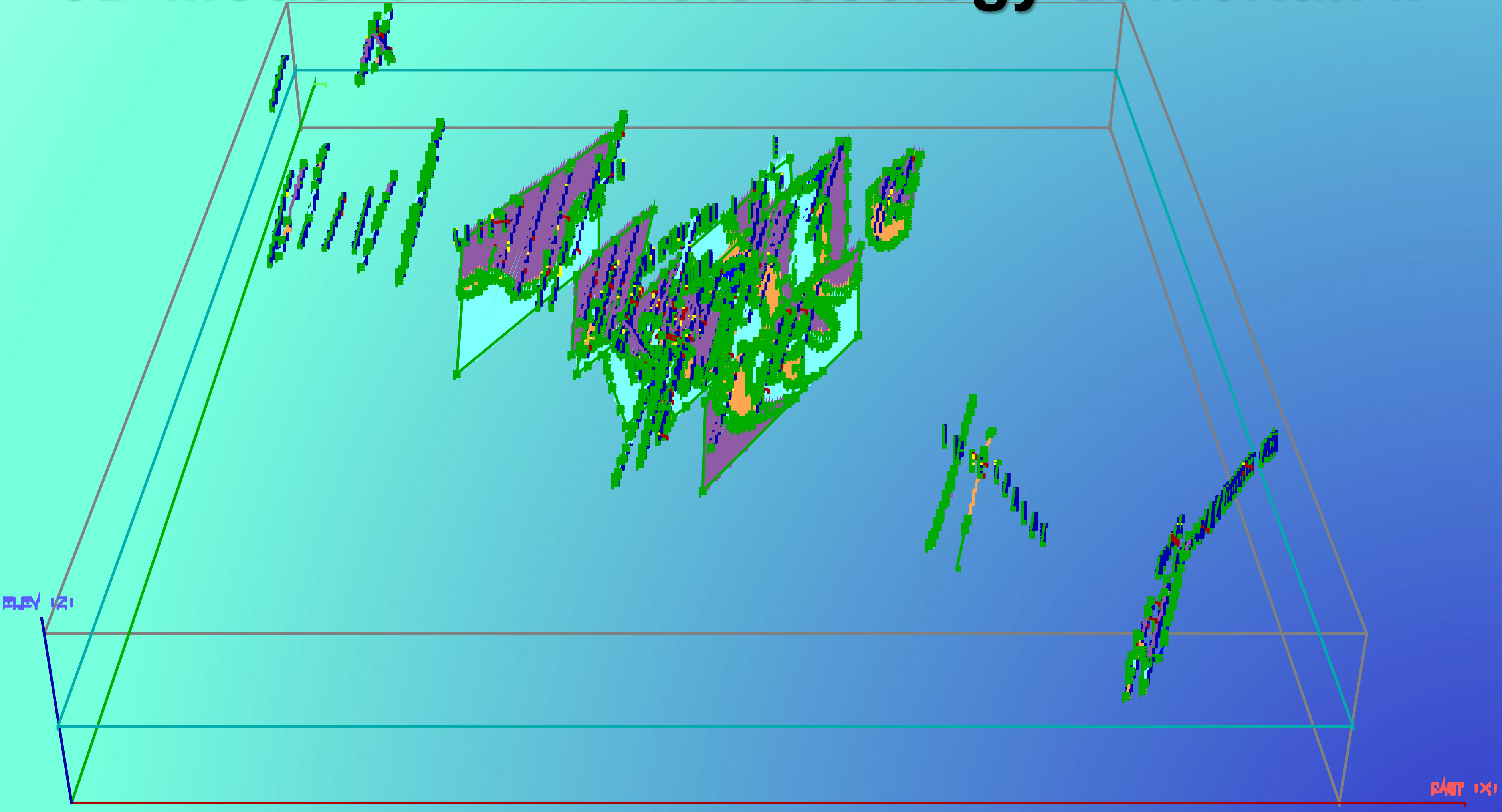
# 3D PERSPECTIVE VIEW OF BLOCK MODEL AND SURROUND GRID AND DRILLING



# Construct Cross Sections using computer programs to evaluate resource and gold trends



# 3D Model of Drill Hole Geology at Merian II

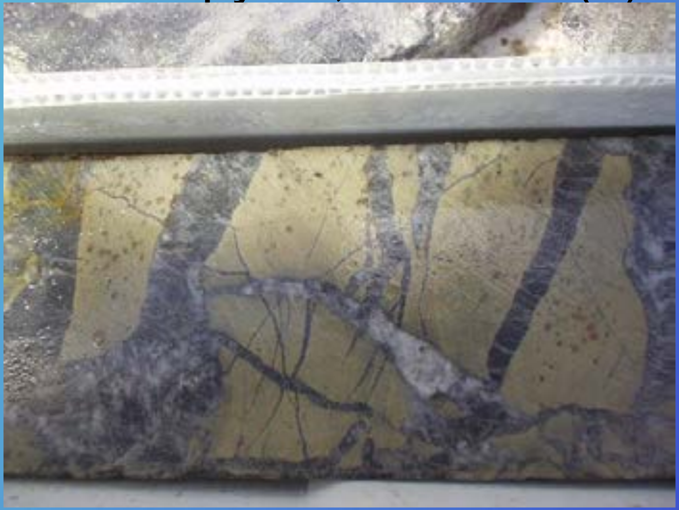


# Host: Fine- to Coarse-Grained Siliciclastic Sediments

- Poorly-sorted litharenite and intercalated discontinuous quartz arenite (arkosic?) Are about 20 percent of the stratigraphic section.
- Most litharenite clasts are subangular to subrounded quartz and heterolithic rock fragments.
- This unit is a good marker horizon.

# Three Vein Sets: Vein Set 2 Most Extensive

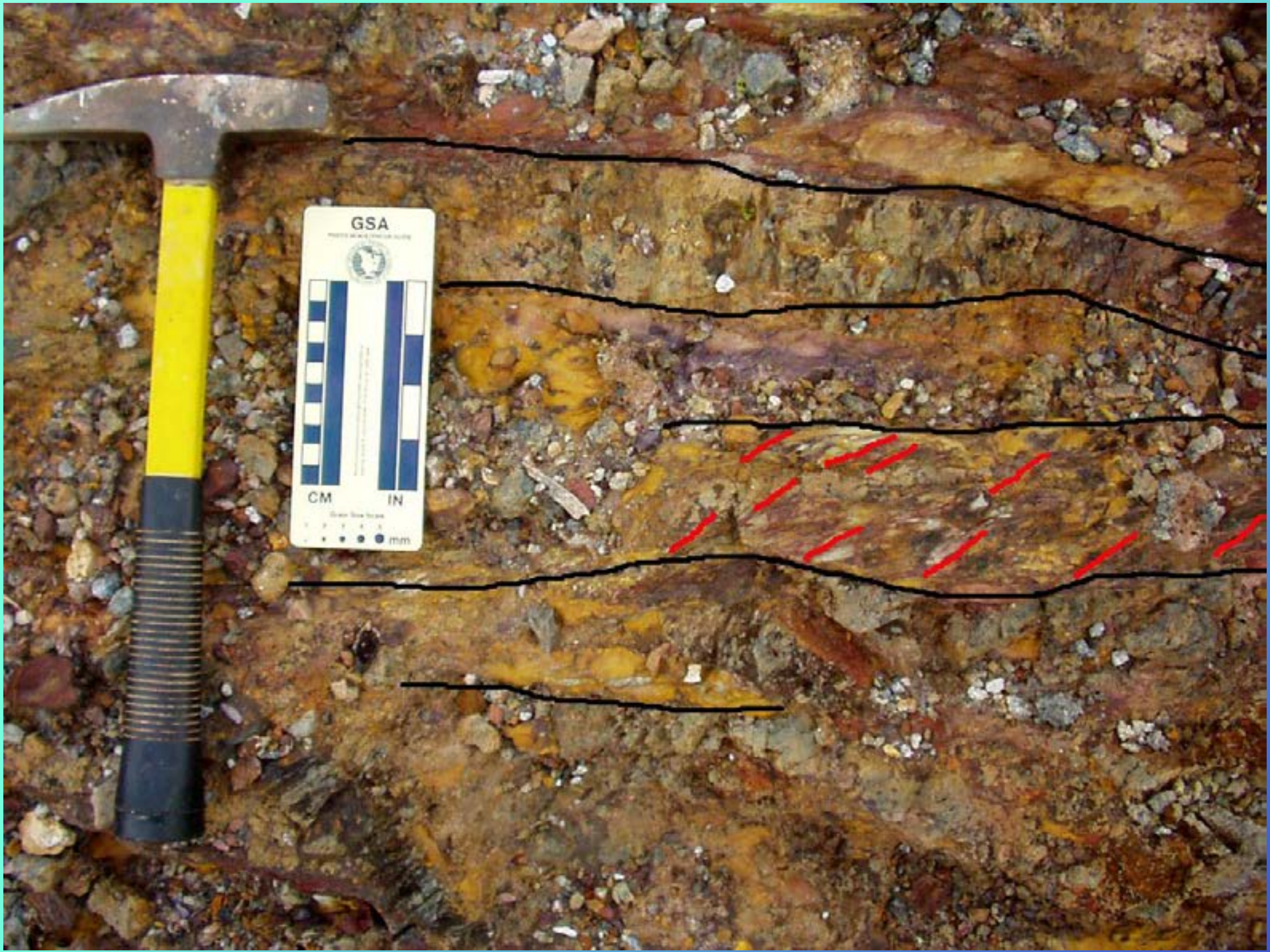
- Most extensive vein set
- Marked interval runs 8 grams/tonne
- Vein minerals are: quartz, carbonate (ankerite? & calcite), white mica, alkali feldspar, pyrrhotite?, pyrite, gold, and chalcopyrite, & carbon(?).



# Shortening Increases Vein Material

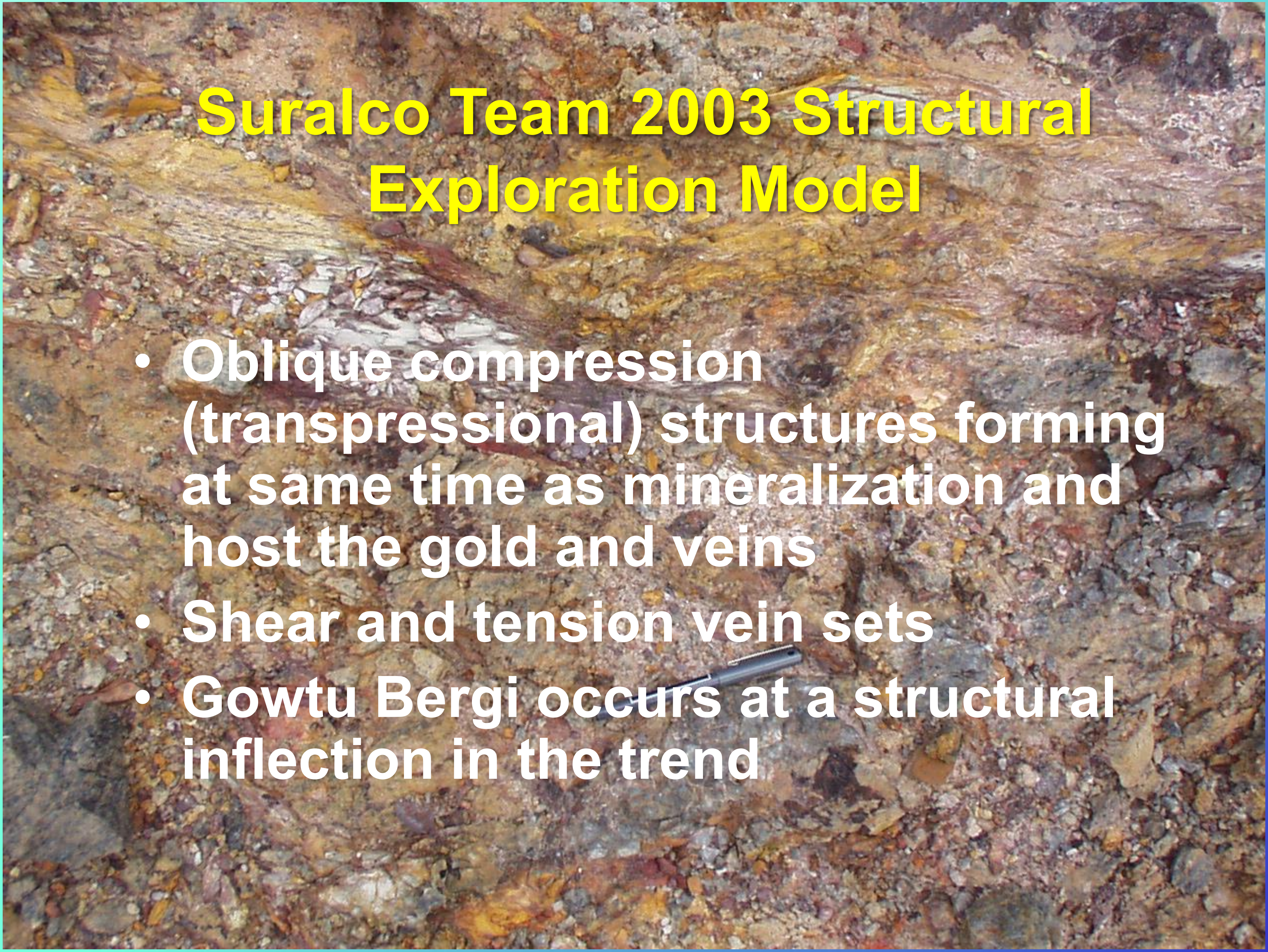
- fold limbs are sheared and highly attenuated, forming an imbricate system of shear zones dipping 35° to 60° northeast.
- anticlinal structures are highly attenuated - this results in *extreme* shortening.
- Preferentially removes micas and chlorite (argillites, thin-bedded lithologies, and vein wall alteration) and concentrates all earlier quartz vein material into the shear zones.

**Zone of intense subvertical quartz veining and alteration flanked by swarms of tension gash ladder veins, Gowtu Bergi Pit, Merian 2 Area, Nassau Au Project**



Well developed c-s fabric indicating dextral shear, center of Gowtu Bergi pit, Merian 2 Area, Nassau Au Project

# Suralco Team 2003 Structural Exploration Model



- Oblique compression (transpressional) structures forming at same time as mineralization and host the gold and veins
- Shear and tension vein sets
- Gowtu Bergi occurs at a structural inflection in the trend

# Arc volcanism and sedimentation in a synkinematic Paleoproterozoic basin: Rosebel Gold Mine, northeastern Suriname

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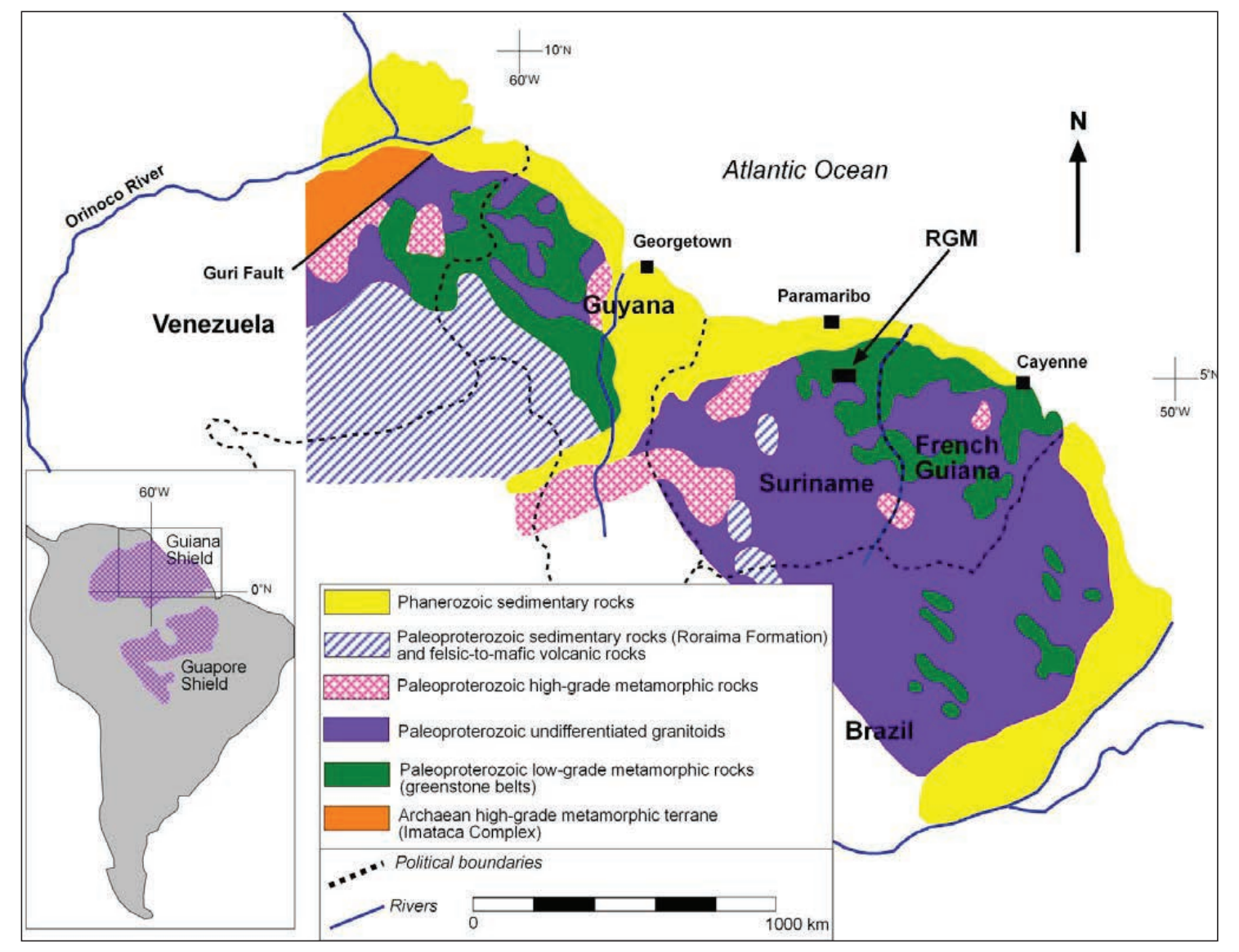
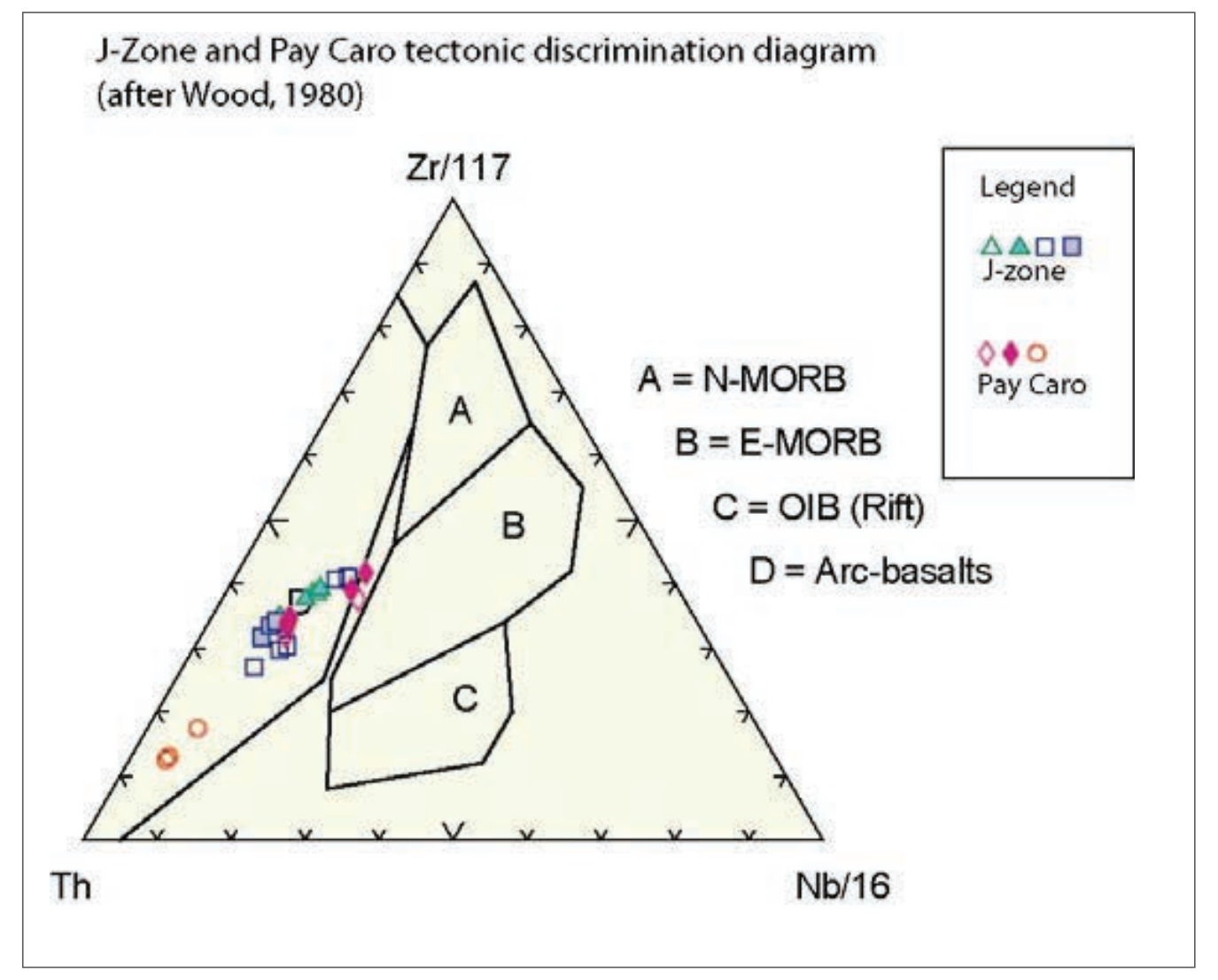



J-Zone and Pay Caro tectonic discrimination diagram (after Wood, 1980)

## SUMMARY

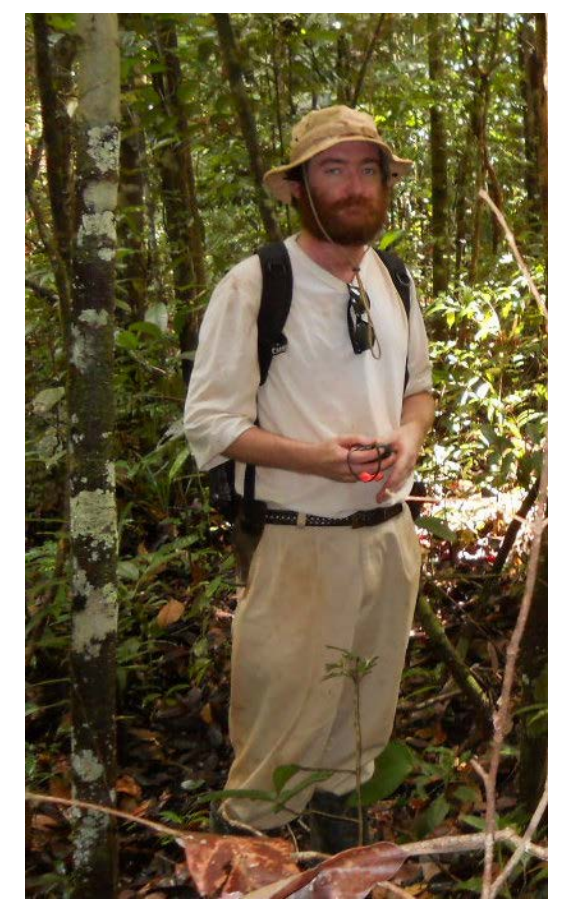
The rocks at RGM represent different types of volcanism and sedimentation attributable to changing tectonic setting, and the development of different depositional environments during the Paleoproterozoic. Igneous rocks range from mafic to felsic, and show tholeiitic to calk-alkaline affinities. The tholeiitic rocks show REE patterns similar to those of other Paleoproterozoic volcanic arcs, and the intermediate to felsic rocks have REE distributions consistent with island arcs as well. Royal Hill mafic volcanic rocks represent the earliest phase of volcanism, and are relatively un-enriched in incompatible REE's, although they are still 10 to 20 times more enriched in REE's than chondrites, and are therefore probably arc- basalts. Pay Caro rocks represent intermediate phase of volcanism, and have a greater enrichment in incompatible REE's. Finally, Mayo rocks are the most enriched in incompatible REE's, and probably represent the last phase of volcanism. Brinck's granite is similarly enriched in incompatible REE's as are the Mayo igneous rocks, and is therefore also associated with a later phase of magmatism than the other igneous rocks at RGM.

The sedimentary rocks at RGM show four different lithofacies associations. (1) A deep-water, turbiditic series of wackes, conglomerates, and mudstones comprise the Koolhoven and J-Zone rocks. These rocks consist of distal to proximal facies and deposit mafic and felsic clastic material in a submarine slope environment. (2) Steep, syn-deformational sub-aerial to shallow-water alluvial processes disperse mafic and felsic sediment of the Royal Hill deposit. These deposits probably originated in an alluvial fan - braided stream environment. (3) Alluvial deposits in the Mayo area show bimodal volcanic association and are related to late-phase volcanism. (4) A clastic marine deposit in which volcanic and terrigenous material comprise proximal facies, and mainly terrigenous material comprises distal facies is evident in the rocks of Pay Caro. This sequence is unconformably overlain by a younger, mainly terrigenous conglomeratic sandstone, locally, the Rosebel Group.

The sedimentary rocks at RGM range in provenance from undissected arc to transitional arc, to recycled orogen. This is probably reflective of contemporaneous erosion of different source material. A unique and not obviously correlative rock sequence is present in the turbidites of the north-trend, and this probably represents an earlier phase of deposition in a pelagic environment, that was later juxtaposed with the younger rocks to the south, through thrusting. The sequence most likely represents: (1) The formation of an island arc system, related to the convergence of the West African and South American cratons; (2) deposition of volcanogenic turbidites in either forearc or back-arc basin positions; (3) continued convergence of the cratons, and the formation of thrust sheets and horizontal folds along the northern margin of the South American craton; (4) erosion of these thrust sheets and primary deposition of the basal conglomerates and wackes; (5) sinistral shearing and felsic plutonism.

The structure of the RGM property resembles a synclinorium, about 30 kilometers wide, and trending 110°. The northern limb of the synclinorium is delineated by the hill-forming rocks of the north trend, and the southern limb is thought to be delineated by the hill-forming rocks of Brownsberg, approximately 18 kilometers southwest of the RGM property. The geometry of the rocks at RGM is indicative of at least three episodes of deformation, reflecting a changing stress regime during the Transamazonian Orogeny, resulting in folds, refolded folds, faulted folds, and folded faults. Most commonly, the rocks are isoclinally folded, with axial surfaces of folds striking parallel to the regional foliation (110°). Structural evolution of the RGM rocks is polyphase, and probably represents three deformational events:
(1) Early thrusting and nappe-folding related to the initial stages of the Transamazonian orogeny; (2) Refolding of early nappe-style folds, and development of a penetrative axial planar foliation; (3) Sinistral strike slip deformation related to the final stages of the Transamazonian orogeny.

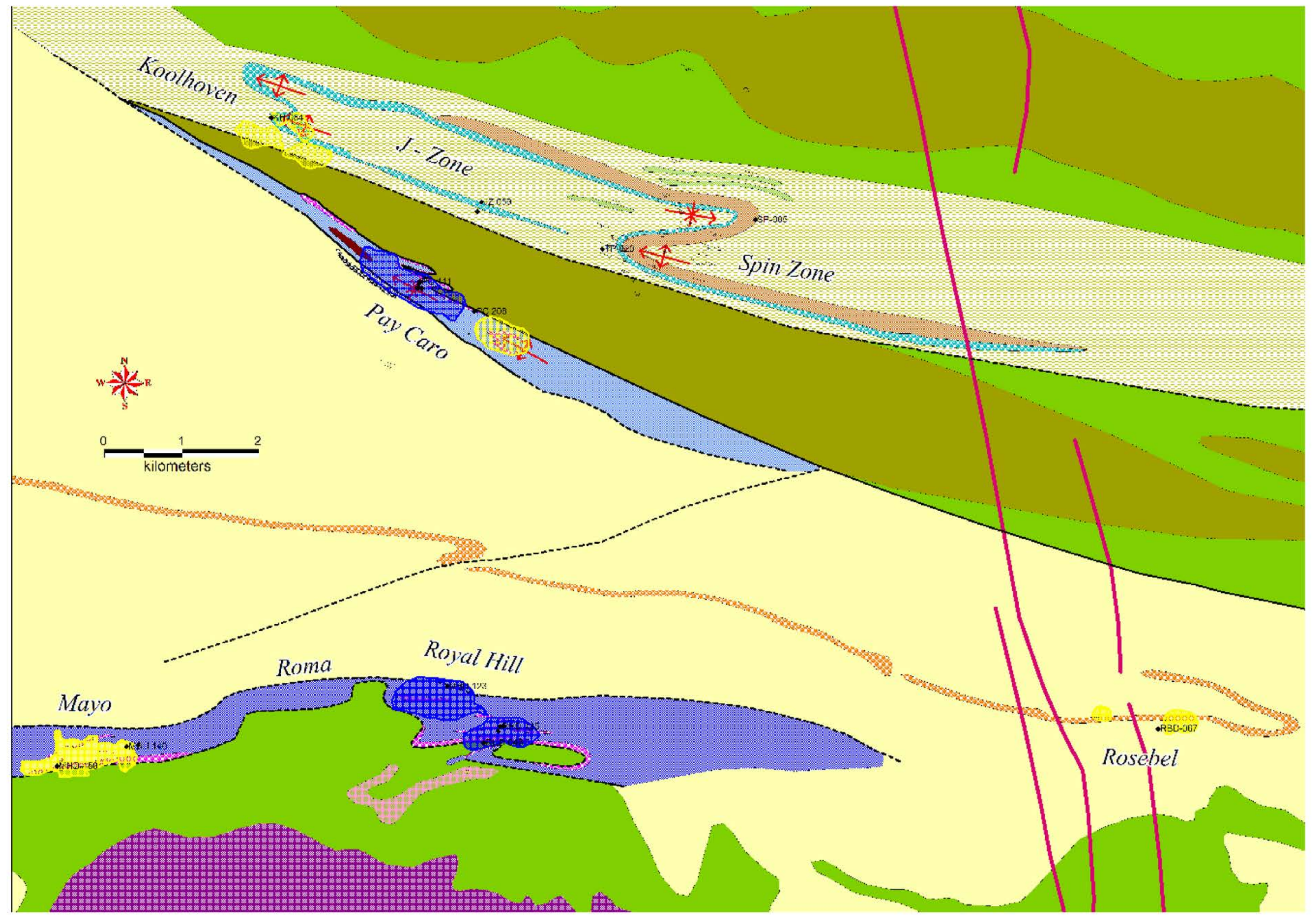
The rocks at RGM are analogous to a great number of Archaean and Proterozoic greenstone-belts described throughout the world. Examples from the Rio das Velhas greenstone belt in Brazil, the Birimian greenstone belts in west Africa, arc-related rocks in the Canadian shield, greenstone belts in India.



## In Memory of Tom Watson

**Tom Watson passed away much too soon in February 2013. This work constituted a major part of his M.S. thesis completed in 2008 and Tom's work gave us new insight into the geologic history of this important area.**

## Geologic map of Rosebel Concession



## Lithostratigraphy

Dolerite dikes

| | |
|---|---|
| 🟨 Arenite<br>▩ Conglomeratic sandstone (monomict)<br>▨ Conglomeratic sandstone (polymict) | Fluvial sedimentary rocks |

Granite and tonalite ▨ 🟪

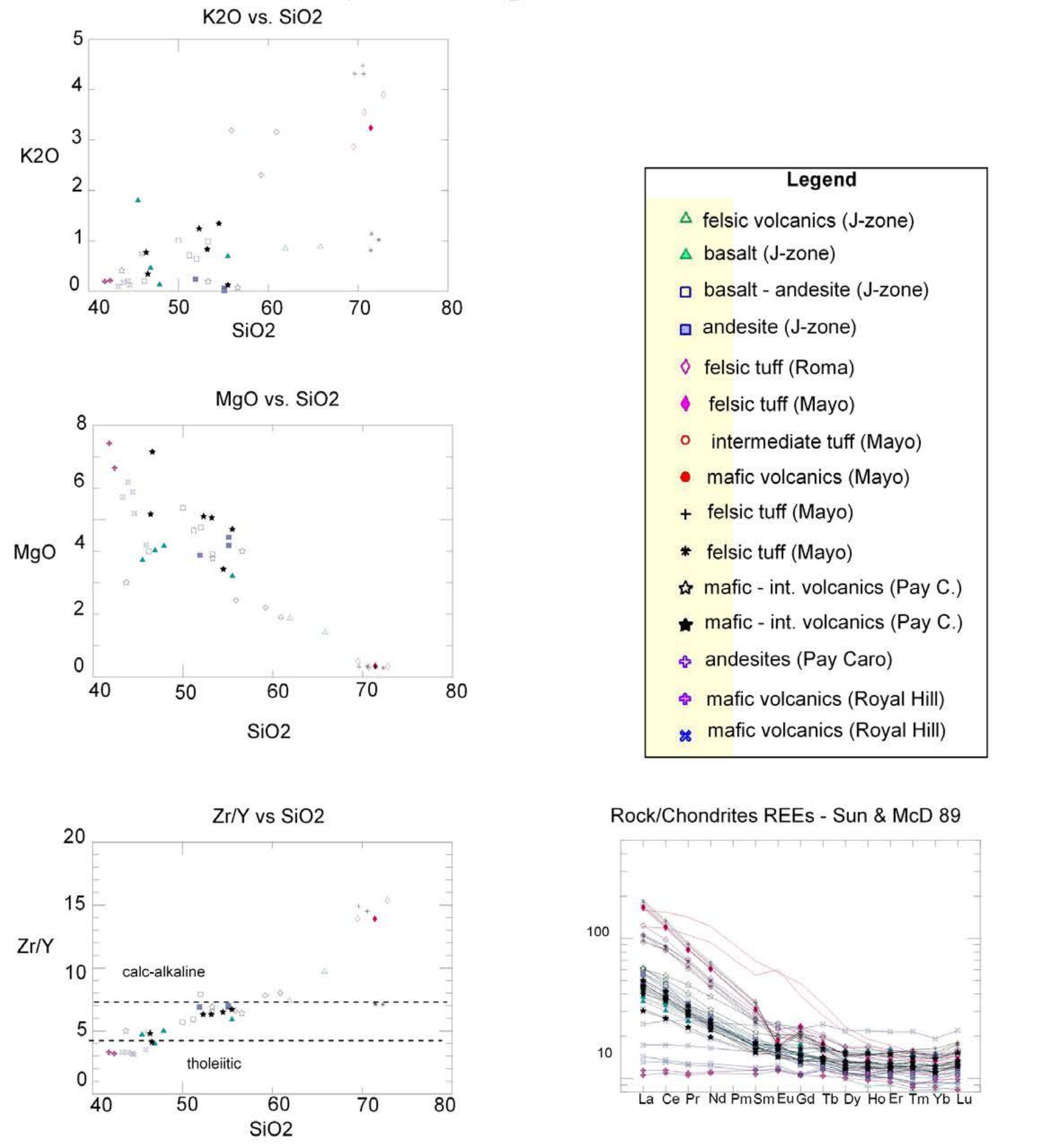
| | |
|---|---|
| 🟥 Mudstone<br>🟦 Lithic wacke<br>▨ Polymict congomerate | ▨ Turbiditic mudstones, siltstones, and wackes<br>▨ Polymict conglomerate |
| Shallow marine facies | Deep marine facies |

🟩 Undifferentiated volcanic and volcaniclastic rocks
🟫 Mafic volcanic rocks

## Map Legend

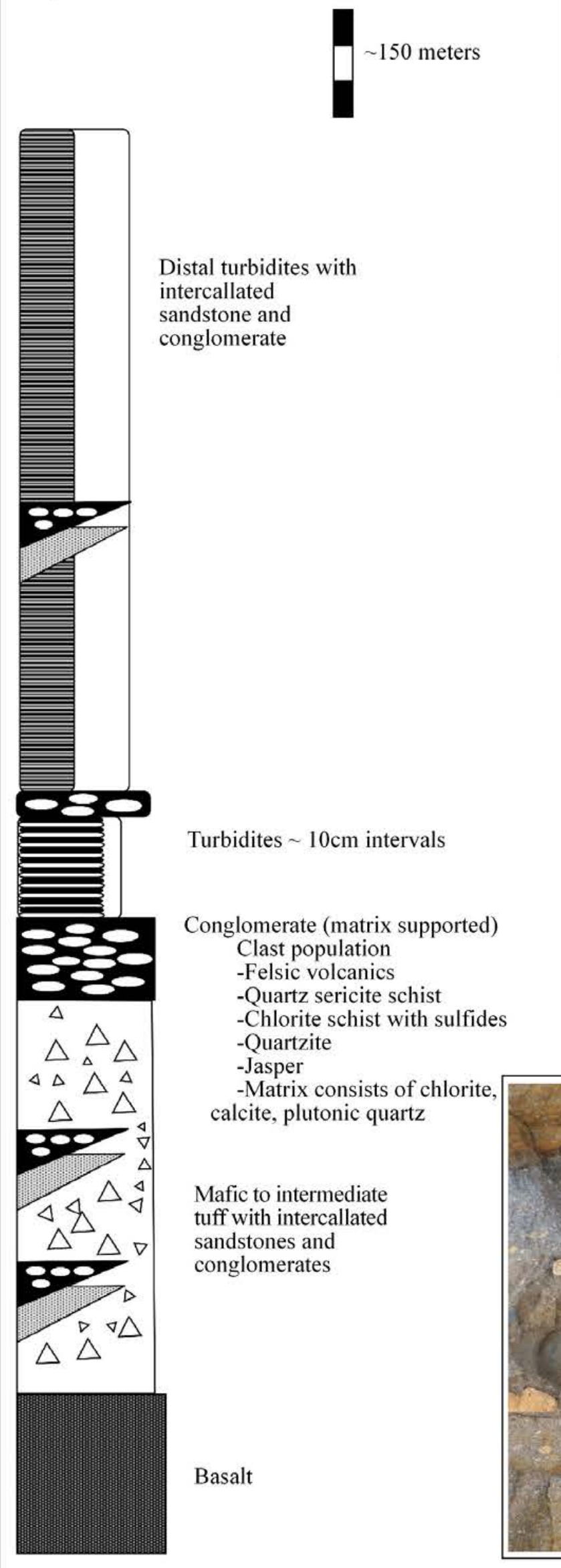
- Contact (certain)
- Contact (inferred)
- Fault (certain)
- Fault (inferred)
- Fold axis showing direction of plunge
- Orientation of bedding
- Orientation of foliation
- Petrographic sample locations
- Known gold deposits
- Active mines

## Geochemical analyses of igneous rocks



## Generalized stratigraphic columns for RGM deposits (refer to map above for location names)

### Spin-Zone and North Trend


~150 meters

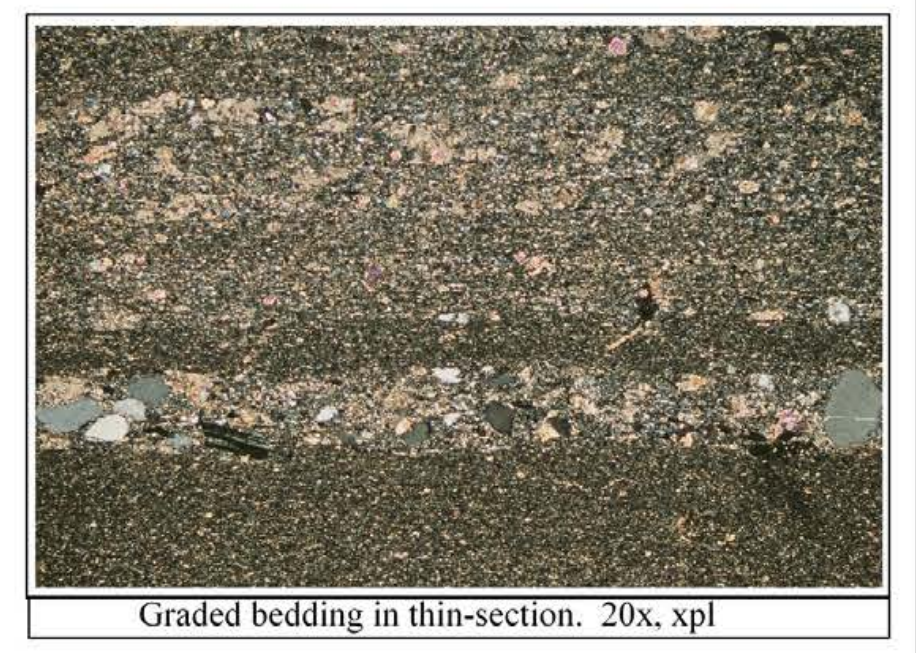
Distal turbidites with intercallated sandstone and conglomerate

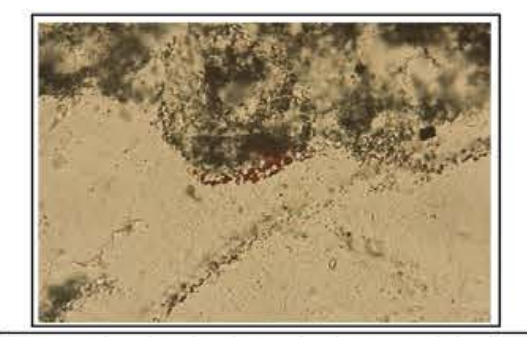
Turbidites ~ 10cm intervals

Conglomerate (matrix supported)
Clast population
-Felsic volcanics
-Quartz sericite schist
-Chlorite schist with sulfides
-Quartzite
-Jasper
-Matrix consists of chlorite, calcite, plutonic quartz

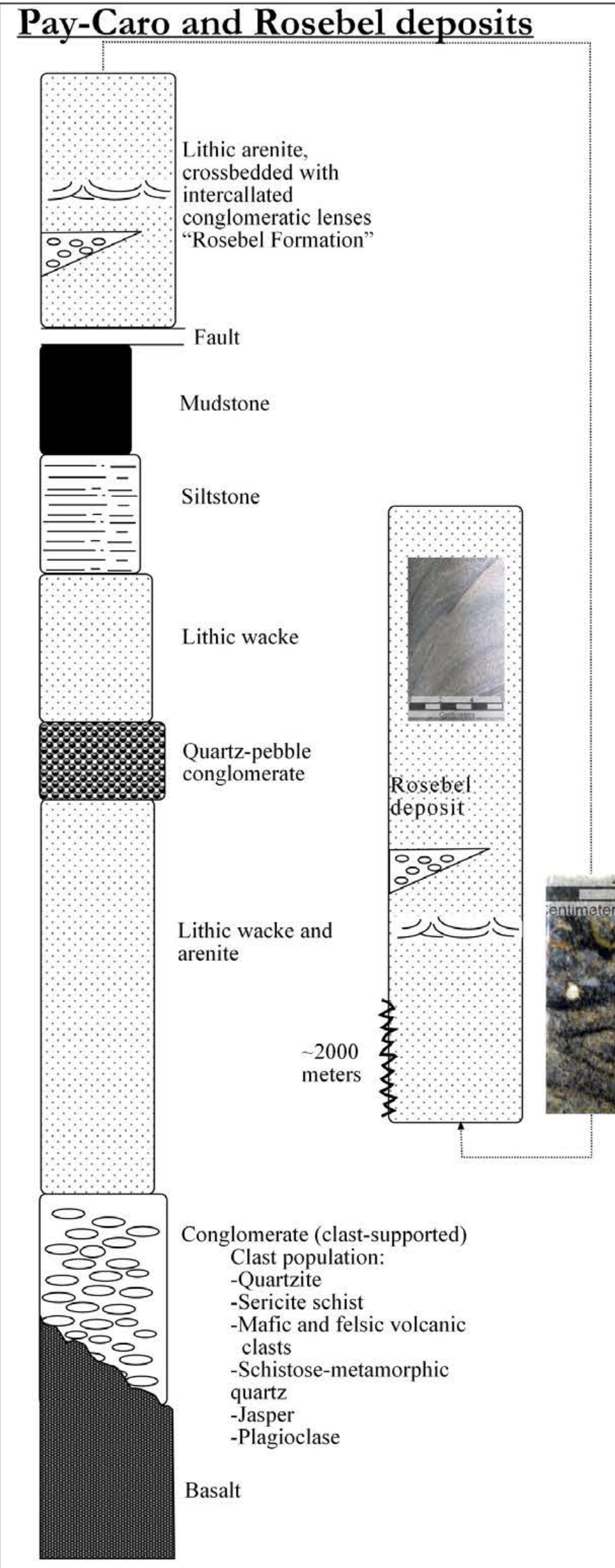
Mafic to intermediate tuff with intercallated sandstones and conglomerates

Basalt


Graded bedding in thin-section. 20x, xpl


Hematite inclusions in jasperoid clast 400x, ppl

### Pay-Caro and Rosebel deposits


Lithic arenite, crossbedded with intercallated conglomeratic lenses "Rosebel Formation"

Fault

Mudstone

Siltstone

Lithic wacke

Quartz-pebble conglomerate

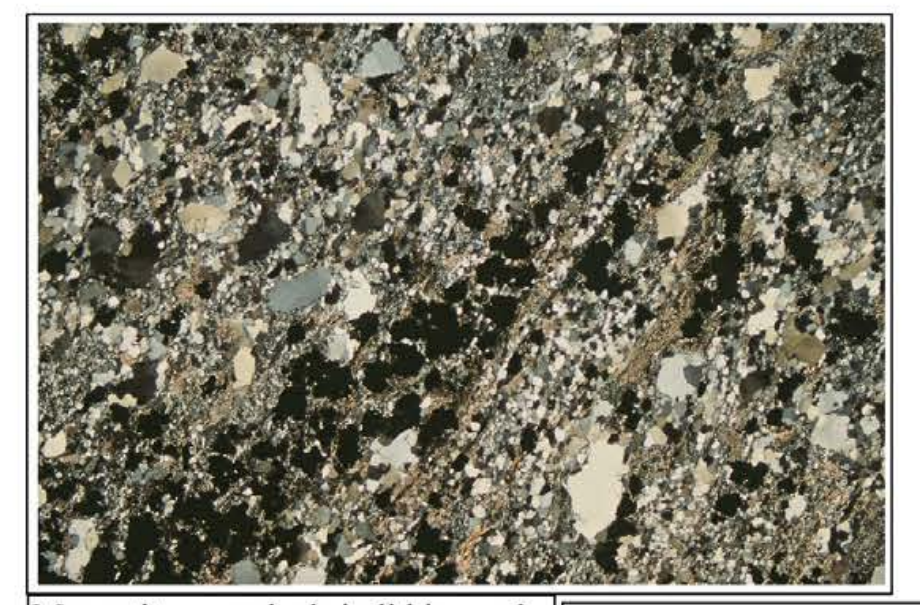
Rosebel deposit

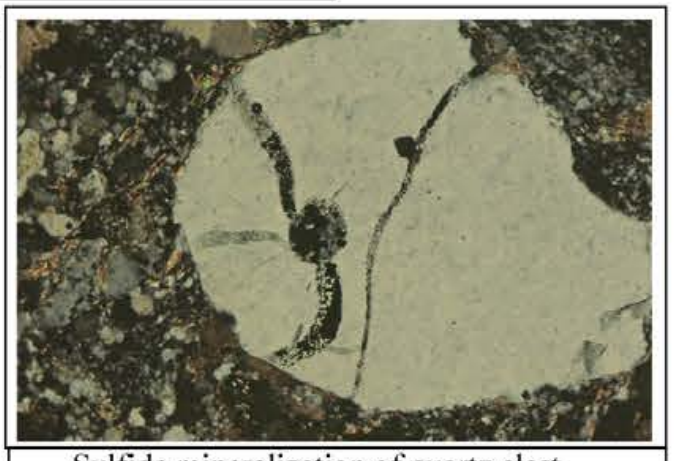
Lithic wacke and arenite

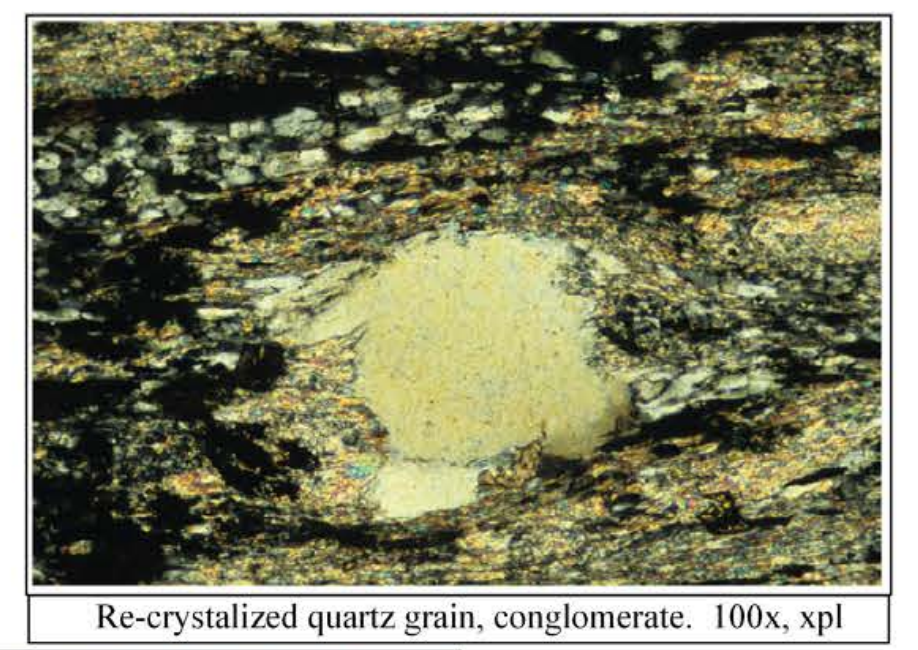
~2000 meters

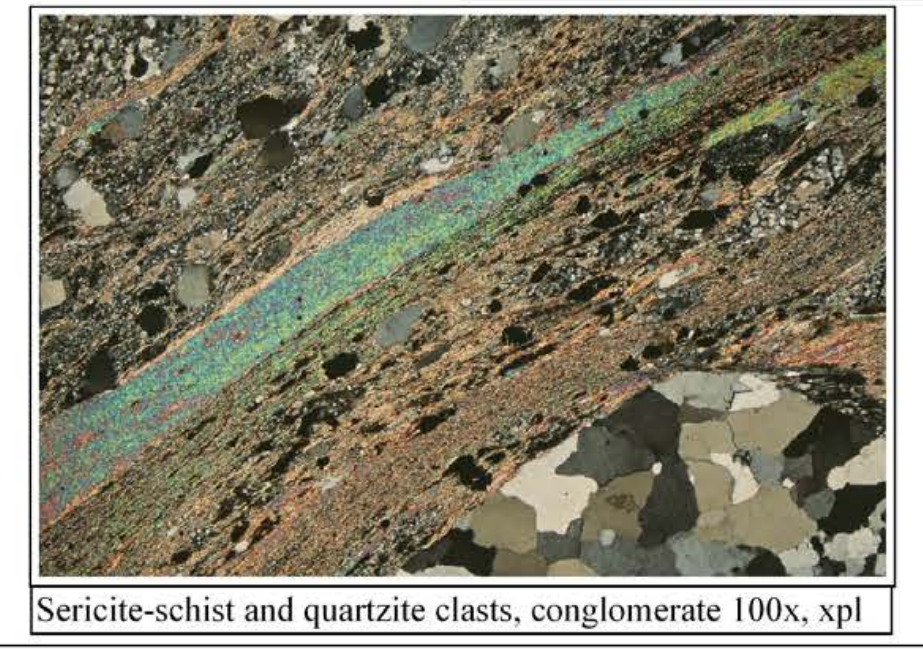
Conglomerate (clast-supported)
Clast population:
-Quartzite
-Sericite schist
-Mafic and felsic volcanic clasts
-Schistose-metamorphic quartz
-Jasper
-Plagioclase

Basalt

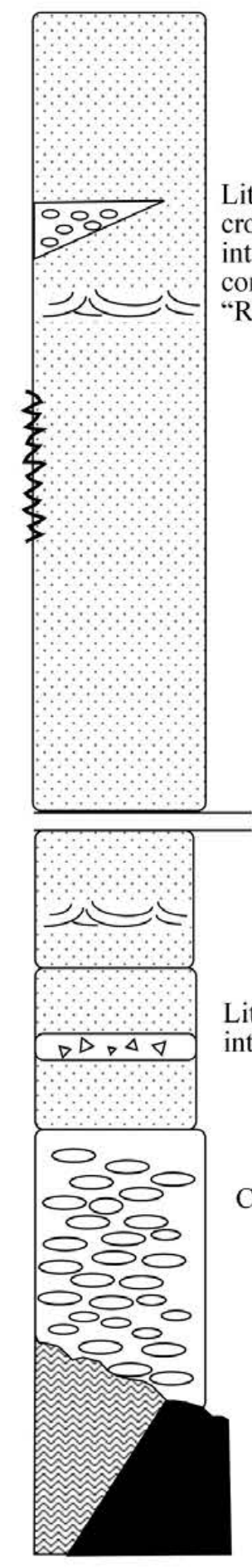

Magnetite cross-beds in lithic-wacke 20x, xpl


Sulfide mineralization of quartz clast. Evidence for previous mineralization event? 100x, xpl


Re-crystalized quartz grain, conglomerate. 100x, xpl


Sericite-schist and quartzite clasts, conglomerate 100x, xpl

### Mayo deposit

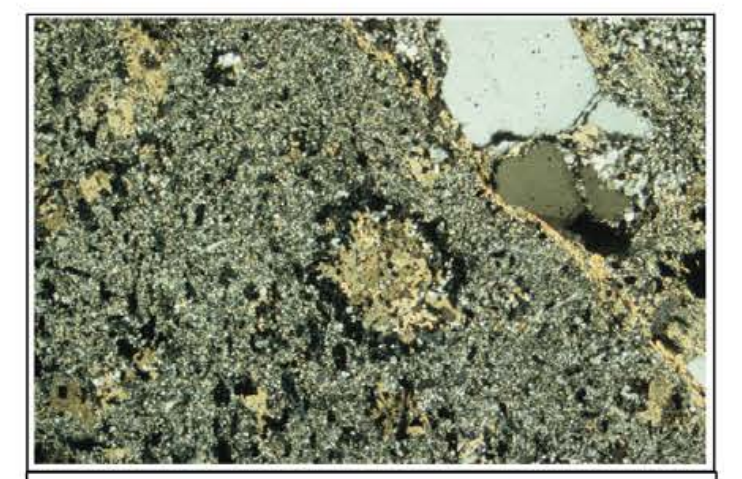

Lithic arenite, crossbedded with intercallated conglomeratic lenses "Rosebel Formation"

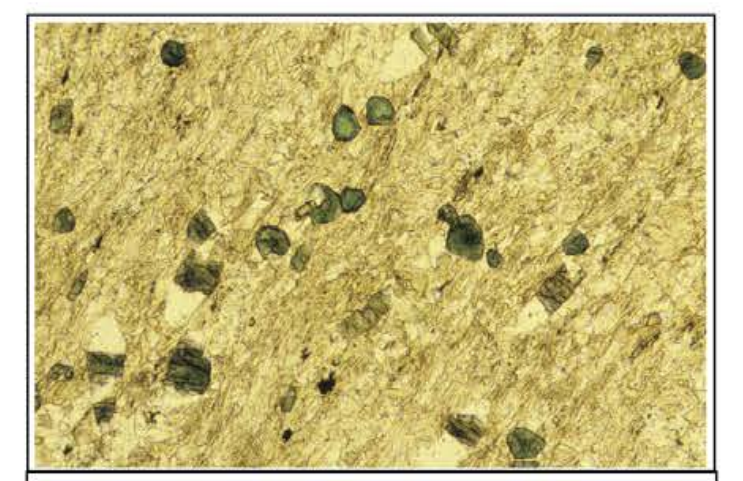
Fault?

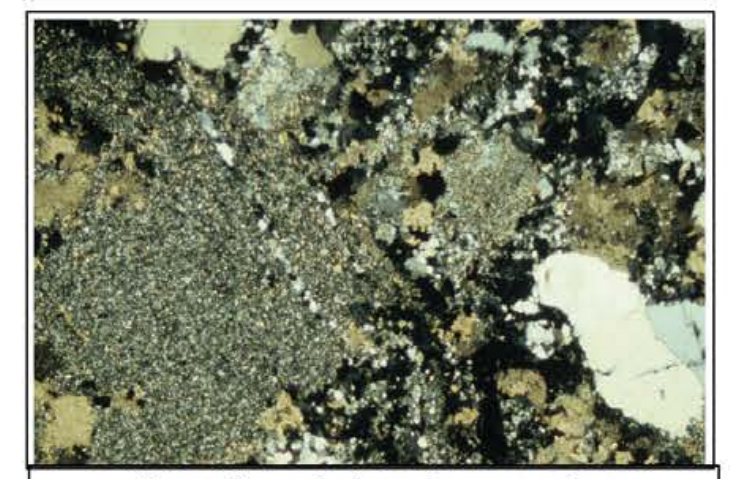
Lithic wacke with intercallated felsic tuff

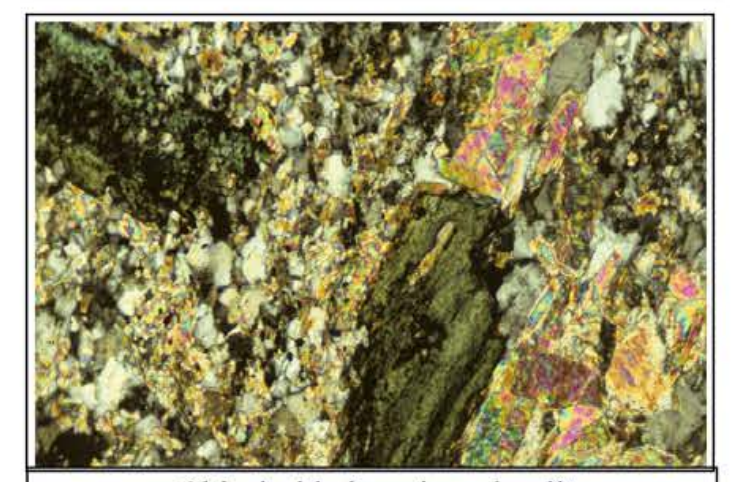
Conglomerate:
Clasts population
-Felsic volcanics
-Chlorite schists
-Schistose-metamorphic quartz
-Plutonic quartz
-Plagioclase

Bimodal volcanic rocks (felsic-mafic)

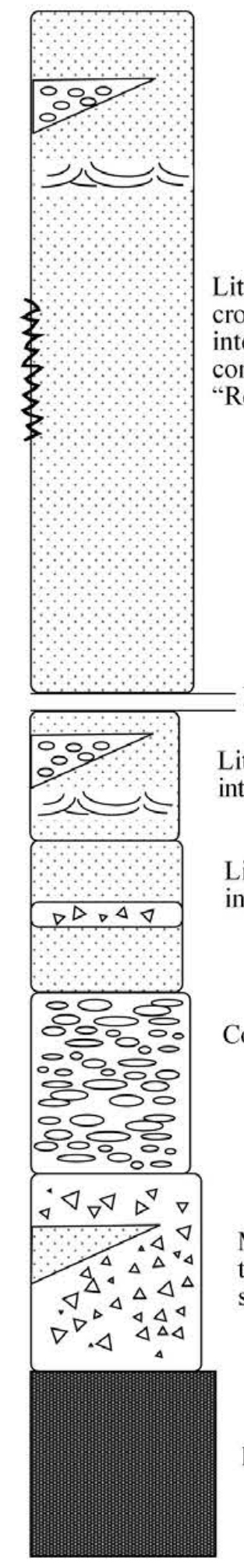

Chlorite-carbonate porphyroblast in volcanic clast. 20x, xpl


Tourmaline alteration, conglomerate 100x, ppl


Quartzite and plutonic quartz clasts, conglomerate. 100x, xpl


Chloritoid alteration, rhyolite. 100x, xpl

### Royal-hill deposit


Lithic arenite, crossbedded with intercallated conglomeratic lenses "Rosebel Formation"

Fault?

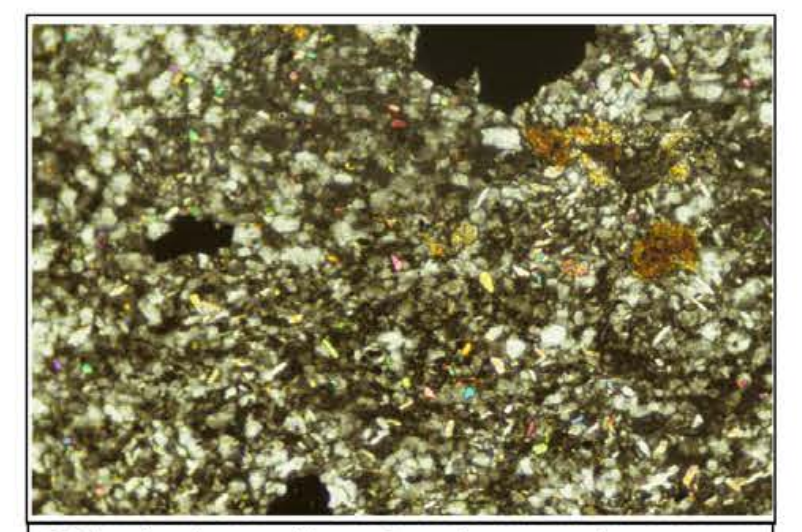
Lithic wacke with intercallated conglomerate

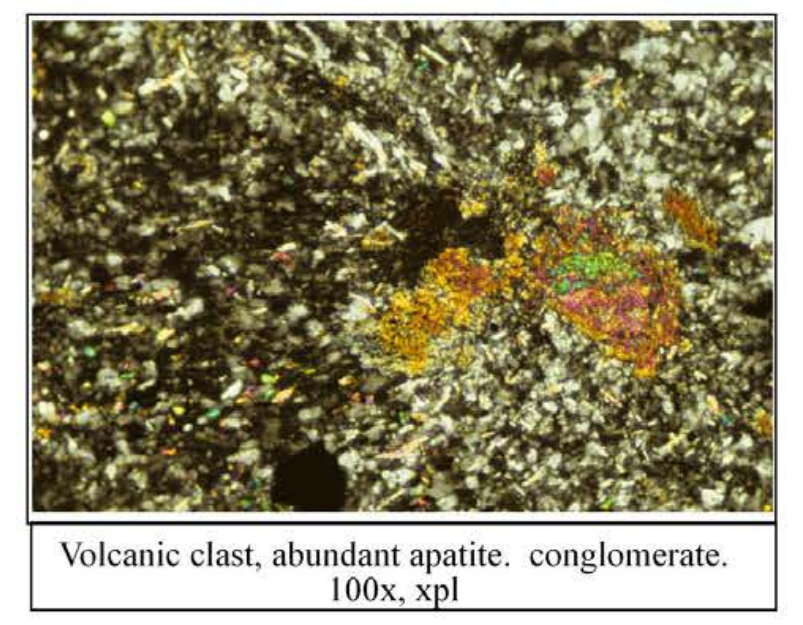
Lithic wacke with intercallated felsic tuff

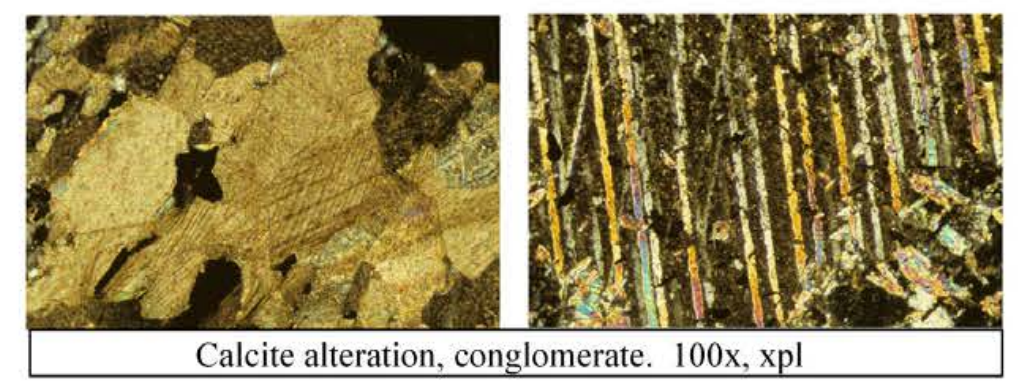
Conglomerate
Clast populaton
-Mafic volcanics
-Felsic volcanics
-Quartzite

Mafic to intermediate tuff with intercallated sandstone

Basalt


Volcanic clast, epidote alteration. conglomerate. 100x, xpl


Volcanic clast, abundant apatite. conglomerate. 100x, xpl


Calcite alteration, conglomerate. 100x, xpl