The Bakhuis ultrahigh-temperature granulite belt (Suriname): II. implications for late Transamazonian crustal stretching in a revised Guiana Shield framework

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La ceinture de granulites d'ultra-haute température des Monts Bakhuis (Suriname) : II. implications en termes d'étirement crustal tardi-transamazonien argumenté dans le cadre d'un schéma structural révisé du Bouclier guyanais

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Key words: Paleoproterozoic, Granulite, Transamazonian orogeny, Suriname, Guiana Shield.

Abstract

The development of the Bakhuis ultrahigh-temperature (UHT) granulite belt, northwestern Suriname, is discussed in the light of an updated geological framework for the Guiana Shield. In the Shield Archean basement is present only in the far western and eastern parts, i.e. Imataca (Venezuela) and south Amapá / northwestern Pará (Brazil). The huge Shield region in between is the result of Paleoproterozoic growth and reworking, during a Rhyacian "Main Transamazonian event" (2.26-2.08 Ga) producing tonalite(TTG)-greenstone belts and a subsequent granitic suite, and a Late-Rhyacian to Orosirian "Late Transamazonian event" (2.07 - 1.93 Ga) characterized by granulite belts and synchronous magmatism.

For the Main Transamazonian event, the timing and geometry of the greenstone belts and TTG magmatism are defined in terms of plutono-volcanic pulses occuring between 2.18 Ga and 2.13 Ga. They are interpreted as the result of progressive consumption of juvenile oceanic crust during a tectonic stage (D1) witnessing N-S convergence of north-Amazonian and west-African Archean blocks, with southward subduction. The subduction is reflected in an apparent diachronous island-arc accretion in the eastern part of the Guiana Shield, with a 2.15-2.13 Ga central TTG domain located between northern and southern TTG domains dated at 2.18-2.16 Ga. The D1 tectonothermal stage is closely associated with that major stage of plutonism, as shown by low-pressure thermal aureoles and gravity-driven deformation.

The transition from N-S frontal plate convergence to oblique NE-SW convergence with major sinistral shear marks the onset of a later stage (D2) of the Main Transamazonian event, at ca. *2.10 Ga. The production of dominant granite magmatism and the formation of pull-apart basins at 2.11-2.08 Ga witness a first part of this event (D2a).*

The Late-Transamazonian event leads to further structuring of the TTG-greenstone belts and the granitic suite during prolonged sinistral wrenching (D2b). At a regional scale, our new Shield compilation map highlights the trends of the TTG-greenstone belts, which display an overall "pinch and swell" structuring, with two E-W continental-scale boudins limited by three granulite domains, Imataca, Bakhuis and eastern Amapá. The Bakhuis belt shows granulite-facies metamorphism under UHT and

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near-UHT conditions. This granulite metamorphism and associated charnockite magmatism were dated at 2.07-2.05 Ga. We interpret both continental-scale boudinage and UHT metamorphism in terms of late-Transamazonian crustal stretching, as the result of prolonged sinistral shearing (D2b). The exceptional, UHT, conditions of the Bakhuis metamorphism require a mantle-derived thermal perturbation, situated probably in a zone of maximum crustal stretching. The counterclockwise prograde P-T path of the metamorphism witnesses a very high thermal gradient during burial, in response to mantle upwelling, while subsequent isobaric to near-isobaric cooling reflects the progressive return to a normal geothermal gradient, in a moderately thickened crust.

In eastern Amapá, 2.06-2.05 Ga charnockite magmatism is also interpreted as the result of late-Transamazonian crustal stretching. In Imataca, Paleoproterozoic granulitic metamorphism might be connected to the same mantle-driven thermal regime.

*There is evidence for even younger Late-Transamazonian high-grade metamorphism and magmatism, as shown by granulite-facies metamorphism poorly constrained at about 2.0 Ga and charnockite magmatism at 1.97-1.93 Ga in the central part of the Shield. At the scale of the Guiana Shield the belt of 2.01-1.96 Ga old acid volcanics and hypabyssal granites (*pro parte *the so-called Uatumã) shows the same veering as the nearby TTG-greenstone belts. This, and the presence of open folding, suggest that this acid magmatic belt has suffered N-S to NE-SW regional shortening during the waning stages of the Late-Transamazonian event.*

In conclusion, the Transamazonian tectonometamorphic continuum associated to oblique plate convergence (D2) may have been a rather protracted multi-stage event. D2 metamorphism culminated with the formation of granulite belts, and more specifically with UHT metamorphism in the Bakhuis belt at 2.07-2.05 Ga, as the result of Late-Transamazonian crustal stretching, enhanced by prolonged sinistral shearing of early formed Rhyacian crust.

Résumé

Ce travail discute la formation de la ceinture de granulites d'ultra-haute température (UHT) des Monts Bakhuis à la lumière d'un schéma géologique actualisé du Bouclier Guyanais. La présence d'un socle archéen est reconnu uniquement dans les secteurs les plus occidentaux de l'Imataca (Vénézuela), et les plus orientaux du sud Amapá / nord-ouest du Pará (Brésil). Entre ces deux extrêmes secteurs, la croissance crustale et les processus thermo-tectoniques d'âge paléoprotérozoïque sont présentés comme l'aboutissement d'un « événement transamazonien majeur » Rhyacien (2,26–2,08 Ga) ayant produit des ensembles TTG-ceintures de roches vertes, ainsi qu'une suite granitique et d'un « événement tardi-transamazonien » tardi-Rhyacien à Orosirien (2,07–1,93 Ga) caractérisé par la formation de ceintures de granulites et un magmatisme de même âge.

Au sein de l'événement transamazonien majeur, la chronologie et la géométrie du magmatisme TTG et des ceintures de roches vertes, sont déclinées en termes de pulsations plutono-volcaniques entre 2,18 Ga et 2,13 Ga. Ce magmatisme est interprété comme le résultat de la destruction progressive d'une croûte juvénile océanique pendant un épisode tectonique D1 témoignant de la convergence N-S des blocs archéens nord-amazonien et ouest-africain, et d'une zone de subduction majeure à pendage sud. A l'est du Bouclier Guyanais, la croissance des ensembles TTG-ceintures de roches vertes est diachrone avec mise en évidence d'un domaine central d'accrétion d'âge 2,15-2,13 Ga, entre deux domaines de TTG nord et sud d'âge 2,18-2,16 Ga. Associées à ce stade majeur de plutonisme, des auréoles thermiques et des déformations gravitaires caractérisent l'épisode thermo-tectonique D1.

A 2,10 Ga, la transition des directions de convergence de plaques, de N-S (frontale) à NE-SW (oblique) se traduit par un stade de déformation sénestre majeur, qui marque le début d'un épisode thermo-tectonique D2 plus tardif au sein de l'événement Transamazonien majeur. Un magmatisme granitique dominant ainsi que la formation de bassins pull-apart *à 2,11-2,08 Ga (événement D2a) lui sont associés.*

L'événement transamazonien tardif est responsable de la structuration ultérieure des ensembles TTG-ceintures de roches vertes et de la suite granitique, au cours d'un stade de coulissage sénestre prolongé (D2b). A l'échelle régionale, notre nouvelle carte synthétique du Bouclier Guyanais met en exergue les directions structurales des ceintures TTG-roches vertes, en soulignant la géométrie d'ensemble de domaines pincés et élargis (« pinch and swell »), correspondant à deux « boudins » E-W d'échelle continentale encadrés par trois domaines granulitiques : Imataca, Bakhuis et Est-Amapá. D'un intérêt spécifique pour notre étude, la ceinture des Monts Bakhuis révèle un métamorphisme granulitique atteignant des conditions de UHT. Ce métamorphisme granulitique et un magmatisme charnockitique associé sont datés à 2,07-2,05 Ga. Nous interprétons le boudinage d'échelle continentale et le métamorphisme UHT en termes d'étirement crustal D2b tardi-transamazonien, résultant d'un contexte prolongé en cisaillement sénestre. Nous proposons que le métamorphisme des trois domaines granulitiques, et de façon plus spécifique le métamorphisme UHT des Monts Bakhuis tardi-rhyacien, résultent d'une perturbation thermique tardi-transamazonienne de nature mantellique dans les zones d'étirement crustal maximum. Le trajet Pression-Température anti-horaire du métamorphisme granulitique des Monts Bakhuis témoigne d'un gradient thermique très élevé au cours d'un stade d'enfouissement, en *réponse à une remontée mantellique. Le refroidissement isobare reflète le retour progressif à un gradient géothermique normal, au sein d'une croûte affectée par un épaississement crustal modéré.*

A l'est de l'Amapá, la présence d'un magmatisme charnockitique à 2,06-2,05 Ga est aussi interprétée comme le résultat de cet étirement crustal tardi-transamazonien. Dans le secteur Imataca, le métamorphisme granulitique pourrait être lié au même régime thermique activé par une perturbation mantellique.

*Par ailleurs, il existe des signes de métamorphisme et magmatisme encore plus jeunes dans la partie centrale du bouclier, comme en témoignent les évidences de métamorphisme granulitique mal contraint vers 2,0 Ga et de magmatisme charnockitique daté à 1,97-1,93 Ga. De plus, à l'échelle du bouclier Guyanais, la ceinture volcano-plutonique acide datée à 2,01-1,96 Ga (*pro parte *« Uatumã ») montre des virgations de directions identiques à celles des ceintures TTG-roches vertes contiguës. Ce constat et l'observation de plis ouverts au sein des formations volcaniques, suggèrent qu'au moins une partie de ce magmatisme acide a été impliqué dans un raccourcissement régional de direction N-S à NE-SW durant les stades terminaux de faible amplitude de l'événement tardi-transamazonien.*

En conclusion, le continuum thermo-tectonique transamazonien associé au stade de convergence oblique (D2) semble avoir été un événement relativement étalé dans le temps, et caractérisé par plusieurs étapes. Le métamorphisme D2 a atteint son paroxysme avec la formation de domaines granulitiques, et de façon spécifique avec le métamorphisme UHT des Monts Bakhuis daté à 2,07-2,05 Ga. La formation de ces domaines granulitiques résulte, à l'échelle continentale, de l'étirement de la croûte précoce rhyacienne au tardi-transamazonien, sous l'effet prolongé d'un contexte cisaillant sénestre.

Resumo

*Esse trabalho discute a formação da faixa granulítica de ultra-alta temperatura (UHT) dos Montes Bakhuis, NW do Suriname, à luz de um esquema geológico atualizado do Escudo das Guianas. A presença de um embasamento arqueano é reconhecida apenas nos setores mais ocidentais do Imataca (Venezuela) e mais orientais, no sul do Amapá / noroeste do Pará (Brasil). A extensa área entre esses dois extremes é resultado de crescimento crustal e retrabalhamento paleoproterozóicos durante um "Evento Transamazônico Principal" riaciano (2,26–2,08 Ga), produzindo associações TTG-*greenstone belts *e, em seguida, uma suíte granítica e de um "Evento Tardi-Transamazônico", tardi-riaciano a orisiriano (2,07-1,93 Ga), caracterizado pela formação de faixas granulíticas e de um magmatismo contemporâneo.*

Para o Evento Transamazônico Principal, a cronologia e a geometria do magmatismo TTG e das seqüências greenstones são interpretadas em termos de pulsos plutono-vulcânicos entre 2,18-2,13 Ga. Este magmatismo é considerado como o resultado da destruição progressiva de uma crosta juvenil oceânica durante um episódio tectônico D1, testemunhando a convergência N-S dos blocos arqueanos norte amazônico e oeste africano, e a existência de uma zona de subducção com vergência para sul. Na porção oriental do Escudo das Guianas, o crescimento dos terrenos TTG-greenstones ocorre de forma diacrônica com um domínio central de acresção com idade de 2,15-2,13 Ga entre dois domínios de TTG norte e sul com idades de 2,18-2,16 Ga. A estreita associação do episódio termo-tectônico D1 com esse importante episódio plutónico, é demonstrada pela presença de auréolas térmicas e deformações gravitarias.

A mudança de convergência frontal de placas de direção N-S para uma convergência obliqua de direção NE-SW se traduz por um estágio de deformação sinistral, o qual marca o início de um episódio termo-tectônico D2 mais tardio, do Evento Transamazônico Principal a 2,10 Ga. Um magmatismo predominantemente granítico e a formação de bacias pull apart *a 2,11-2,08 Ga estão associados às primeiras etapas deste estágio (D2a).*

*O Evento Tardio Transamazônico é responsável pela estruturação posterior dos terrenos TTG-*greenstones *e da suíte granítica, durante um estágio de deformação sinistral prolongado (D2b). Em escala regional, o novo mapa sintético do Escudo das Guianas enfatiza as direções estruturais das associações TTG-*greenstones, *e a geometria dos domínios* pinch and swell, *correspondendo a dois* boudins *E-W de escala continental, bordejados por três domínios granulíticos (Imataca, Bakhuis e Leste-Amapá). A faixa dos Montes Bakhuis revela um metamorfismo granulítitico que alcança condições UHT ou próximas a estas condições. Esse metamorfismo granulítico e o magmatismo charnoquítico associado foram datados em 2,07-2,05 Ga. O "boudinage" em escala continental e o metamorfismo UHT são interpretados em termos de estiramento crustal D2b tardi-transamazônico, como resultado de um episódio em cisalhamento sinistral durante um período prolongado. As condições excepcionais do metamorfismo UHT tardi-riaciano dos Montes Bakhuis requere uma perturbação térmica de natureza mantélica, em uma zona de estiramento crustal máximo. As trajetórias Pressão–Temperatura anti-horárias do metamorfismo granulítico dos Montes Bakhuis retratam um gradiente térmico muito elevado durante um estágio de soterramento, em resposta a uma subida mantélica. O subseqüente resfriamento isóbaro ou quase isóbaro reflita uma volta progressiva a um gradiente geotérmico normal, de uma crosta com espessamento crustal moderado.*

No leste do Amapá, a presença de um magmatismo charnoquítico a 2,06-2,05 Ga é também interpretado como

o resultado deste episódio de estiramento crustal tardi-transamazônico. No setor do Imataca, o metamorfismo granulítico poderia também ser ligado ao mesmo regime térmico, ativado por perturbação mantélica.

*Existem evidências de um episódio metamórfico transamazônico ainda mais tardio na porção central do Escudo, identificado por gnaisses granulíticos, com idade mal definida em torno de 2,0 Ga e um magmatismo charnoquítico datado em torno de 1,97-1,93 Ga. Na escala do Escudo das Guianas, a faixa vulcano-plutônica félsica datada a 2,01-1,96 Ga (*pro-parte *Uatumã) mostra virgações de direções idênticas àquelas das associações TTG-greenstones vizinhas. Essa constatação e a observação de dobras abertas dentro das formações vulcânicas sugere que pelo menos parte deste magmatismo félsico foi envolvida em um episódio de encurtamento regional de direção N-S a NE-SW, durante os estágios finais de baixa amplitude do evento tardi-transamazônico.*

Em conclusão, o continuum termo-tectônico transamazônico associado ao estágio obliqua (D2) parece ter constituído um evento relativamente espalhado no tempo e caracterizado por várias etapas. O metamorfismo D2 atingiu o seu paroxismo com a formação de domínios granulíticos, em particular, com o evento metamórfico de UHT dos montes Bakhuis, datados em 2,07-2,05 Ga. A formação desses domínios granulíticos resulta, em escala continental do estiramento tardi-transamazônico da crosta precoce riaciana, sob o efeito prolongado de um contexto em cisalhamento sinistral.

Introduction and geological setting

The Guiana Shield, extending from Venezuela, through Guyana, Suriname and French Guiana, to Brazil, constitutes the northern part of the Amazonian Craton, one of the largest cratonic areas in the world, with an area of about 1.5 10^6 km^2. Archean protoliths, dated between 3.3 Ga and 2.6 Ga, have been documented at its borders both in the west (Imataca Complex in Venezuela: Montgomery and Hurley, 1978, 1980; Tassinari *et al*., 2001) and in the east (central and south Amapá and northwestern Pará in Brazil: e.g. João and Marinho, 1982; Montalvão and Tassinari, 1984; Ricci *et al.*, 2001; Avelar *et al*., 2003; Rosa Costa *et al.*, 2003). In between, the Proterozoic succession shows evidence of a southwestward-younging crustal growth and/or reworking (Tassinari *et al*., 2000; Santos *et al*, 2000). The northeastern part of the Shield along the Atlantic margin, often referred to as the “Maroni-Itacaiúnas” province (see Tassinari *et al*., 2000), comprises Paleoproterozoic formations made up essentially of greenstone belts and plutonic complexes emplaced during the so-called Transamazonian orogeny - the major tectonothermal event between 2.25 and 1.95 Ga. Further younging tectonothermal activity and, in part, crustal growth is documented towards the southwest, with Late-Paleoproterozoic plutono-volcanic activity (2.1 - 1.8 Ga) and sedimentary basin deposition (1.89 - 1.78 Ga) and predominantly Mesoproterozoic alkaline magmatism (1.7 - 1.3 Ga).

The present architecture of the Guiana Shield results mainly from these successive Paleo- to Mesoproterozoic geodynamic events at a time when the Guiana Shield and the West African Craton belonged to a single Proterozoic continental landmass (Choubert, 1974; Rowley and Pindell, 1989). Neoproterozoic events in the Shield would appear to be restricted to the emplacement of dyke swarms (Santos *et al.*, 2002; Delor *et al.*, 2001, 2003). The Phanerozoic formations (sediments and dykes) reflect the subsequent continental break-up from basin opening during the Paleozoic (Amazonian trough) to ultimate tectonic activity during the Mesozoic culminating with the opening of the Atlantic Ocean.

To account for the ca. 3 Ga span in the succession of geological events, the existing sketch maps of the Guiana Shield (Gibbs and Barron, 1993; Tassinari, 1996; Tassinari and Macambira, 1999; Tassinari *et al*., 2000; Santos *et al*., 2000 – Fig. 1a, b, c) are based on a schematic distinction of predominant Precambrian provinces. The studies insist on contrasting global ages of crustal accretion, i.e. protolith reworking versus new crustal genesis, but do not enable an accurate tectonic analysis of the prominent Paleoproterozoic domain. More accurate maps do, nevertheless, exist in the various Guiana Shield countries, and we have been able to compile those maps at 1:500,000 to 1:1,000,000 scale in order to extract a more detailed, although still synthetic, lithostructural framework. This compilation includes a refined transboundary legend based on the most recent isotopic data, especially for the eastern part of the Shield where more than 200 age determinations have been published over the last 5 years - mainly U-Pb and Pb-Pb on single zircons, and Sm-Nd model ages (Vanderhaeghe *et al*., 1998; Lafrance *et al*., 1999; Nogueira *et al*., 2000; Delor *et al*., 2001; Ricci *et al*., 2001; Avelar *et al*., 2001, 2002, 2003; Lafon *et al*., 2001, 2003; Lafon and Avelar, 2002; Pimentel *et al*., 2002; Rosa Costa *et al*., 2003). In the light of our earlier brief framework analysis (Delor *et al*., 1998, 2000, 2001), we first present a revised geology for the Guiana Shield, then concentrate on the development of the Bakhuis granulite belt whose ultrahigh-temperature (UHT) metamorphism is discussed in a companion paper (de Roever *et al*., 2003). Building on petrological and isotopic arguments for a counterclockwise P-T path in response to mantle upwelling at 2.07 - 2.05 Ga, we discuss the Transamazonian tectonothermal evolution of the Shield in terms of plate-tectonic convergence, strike-slip motion, and progressive crustal stretching.

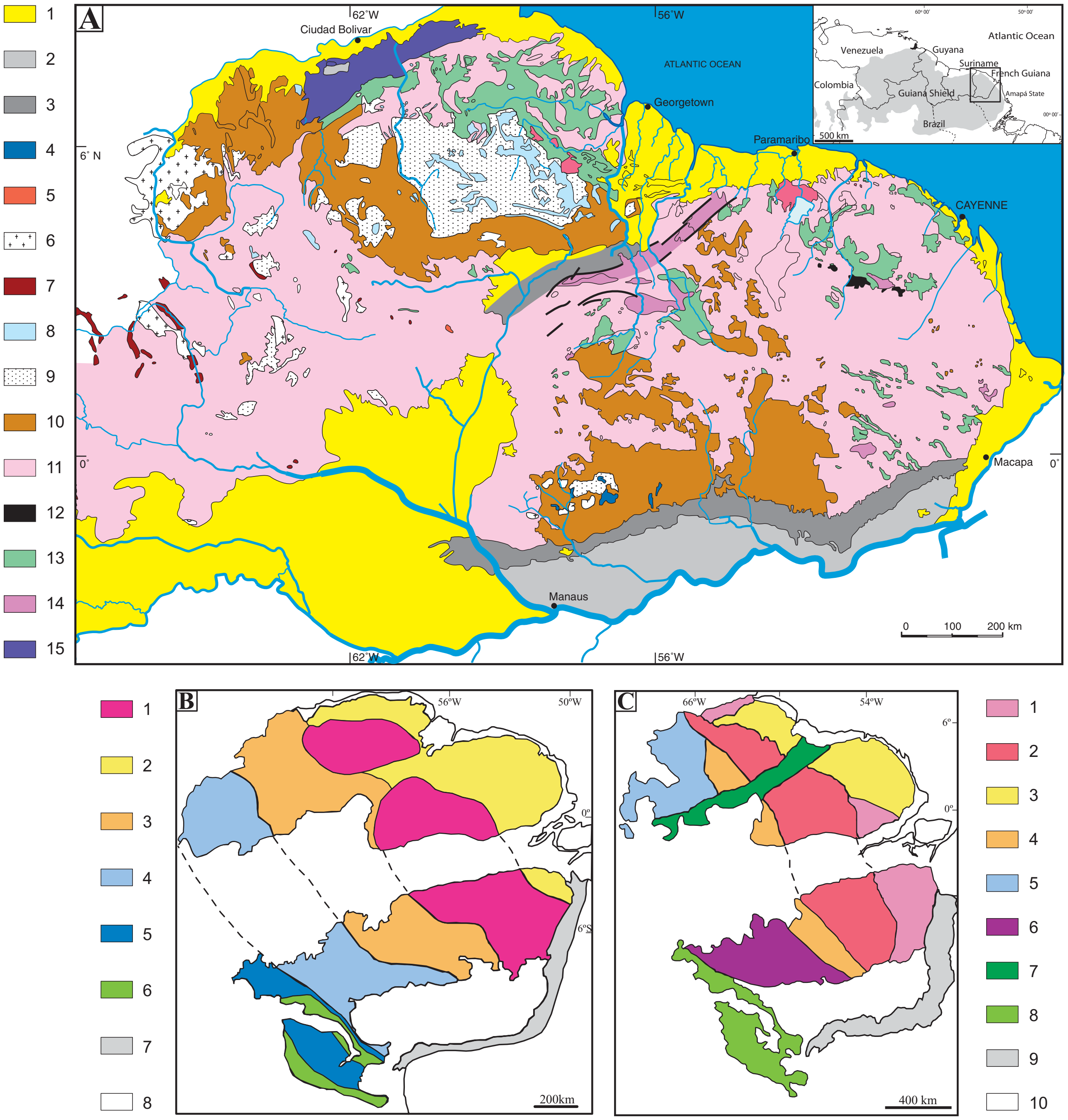

Fig. 1.- Simplified geological sketch maps of the Guiana Shield according to A: Gibbs and Barron, 1993; B: Tassinari *et al.* (2000) and C: Santos *et al.* (2000).
A) CENOZOIC: 1 - Alluvium cover; MESOZOIC: 2 - dolerite and sediment; PALEOZOIC: 3 - Amazon margin sediment; NEOPROTEROZOIC: 4 - alkaline basalt (Cachoeira Seca), 5 - alkaline plugs (Muri); MESOPROTEROZOIC: 6 - granite (Parguaza), 7 - sediment (Vaupes supergroup), 8 - basic sill/dyke (Avanavero), 9 - sediment (Roraima Group), 10 - acid plutono-volcanism (Uatumã); TRANSAMAZONIAN tectonothermal episode: 11 - granitoid, 12 - ultrabasic plug (Badidku), 13 - greenstone belt, 14 - granulite (Central Guiana); ARCHEAN: 15: granulite and migmatite (Imataca).
B) 1 - Central Amazonian (> 2.3 Ga), 2 - Maroni-Itacaiúnas (2.2-1.95 Ga), 3 - Ventuari-Tapajós (1.95-1.8 Ga), 4 - Rio Negro-Juruena (1.8-1.55 Ga), 5 - Rondonian-San Ignacio (1.55-1.3 Ga), 6 - Sunsas (1.25-1.0 Ga), 7 - Neoproterozoic mobile belt, 8 - Phanerozoic cover.
C) 1 - Carajás-Imataca (3.10-2.53 Ga), 2 - Central Amazon (1.88 - 1.70 Ga), 3 - Transamazonian (2.25-2.00 Ga), 4 - Tapajós-Parima (2.10-1.87 Ga), 5 - Rio Negro (1.86 -1.52 Ga), 6 - Rondônia-Juruena (1.80-1.50 Ga), 7 - K'Mudku (1.33-1.10 Ga), 8 - Sunsas (1.33-0.99 Ga), 9 - Neoproterozoic mobile belt, 10 - Phanerozoic cover.

Fig. 1.- Schémas géologiques simplifiés du Bouclier guyanais selon A: Gibbs et Barron, B : Tassinari et al. *(2000) et C: Santos* et al. *(2000).*
A) CENOZOÏQUE: 1 - couverture alluvionnaire; MESOZOÏQUE: 2 - dolérite et sédiment; PALEOZOÏQUE: 3 - sédiment de la marge amazonienne; Neoproterozoique: 4 - basalte alcalin (Cachoeira Seca), 5 - plutonisme alcalin (Muri); MESOPROTEROZOÏQUE: 6 - granite (Parguaza), 7 - sédiment (super groupe Vaupes), 8 - sill/dyke basique (Avanavero), 9 - sédiment (Roraima Group), 10 - plutono-volcanisme acide (Uatumã); épisode thermo-tectonique TRANSAMAZONIEN: 11 - granitoïde, 12 - pluton ultrabasique (Badidku), 13 - ceinture de roche verte, 14 - granulite (Central Guiana); ARCHEEN: 15: granulite et migmatite (Imataca).
B) 1 - Amazonie centrale (> 2,3 Ga), 2 - Maroni-Itacaiúnas (2,2-1,95 Ga), 3 - Ventuari-Tapajós (1,95-1,8 Ga), 4 - Rio Negro-Juruena (1,8-1,55 Ga), 5 - Rondonian-San Ignacio (1,55-1,3 Ga), 6 - Sunsas (1,25-1,0 Ga), 7 - zone mobile néoprotérozoïque, 8 - couverture phanérozoïque.
C) 1 - Carajás-Imataca (3,10-2,53 Ga), 2 - Amazonie centrale (1,88 - 1,70 Ga), 3 - Transamazonien (2,25-2,00 Ga), 4 - Tapajós-Parima (2,10-1,87 Ga), 5 - Rio Negro (1,86 -1,52 Ga), 6 - Rondônia-Juruena (1,80-1,50 Ga) , 7 - K'Mudku (1,33-1,10 Ga), 8 - Sunsas (1,33-0,99 Ga), 9 - zone mobile néoprotérozoïque, 10 - couverture phanérozoïque.

A revised lithostructural framework for the Guiana Shield paleoproterozoic domain

The proposed revised shield lithological map as given in figure 2 is discussed in the following sections. This map being focussed on the Paleoproterozoic domains, our discussion will not take into account the Rio Negro Province with its Mesoproterozoic fingerprint, in the westernmost part of the Guiana shield (Santos *et al*., 2000; Tassinari *et al.*, 2000).

Archean basement

In Venezuela, the 450-km-long, 100-km-wide Imataca Complex is limited to the south by the Guri Fault. Its formations are considered to be of igneous origin, reworking an Archean protolith dated at *ca*. 3.7 Ga and 2.6 Ga (Montgomery and Hurley, 1978; Montgomery, 1979; Teixeira *et al*., 1999; Tassinari *et al*., 2001).

In French Guiana, Choubert (1964) proposed the existence of Archean remnants in the Île de Cayenne high-grade gneiss along the Sinnamary River, on the basis of ages obtained from pioneering Pb-Pb dating on zircon. However, these assumptions have never been confirmed by subsequent work on the Île de Cayenne series (Teixeira *et al.*, 1985; Delor *et al*., 2001).

In Amapá (Brazil), Rb-Sr ages obtained on tonalitic and enderbitic gneiss range from 2.9 Ga to 2.45 Ga (João and Marinho, 1982; Montalvão and Tassinari, 1984), and similar Sm/Nd model ages on tonalite reinforce the assumption that an Archean crust was reworked by the Transamazonian orogeny in central Amapá (Sato and Tassinari 1997; Pimentel *et al.*, 2002). New geochronological results presented by Ricci *et al*. (2001) and Rosa Costa *et al*. (2001, 2003) from the frontier between Amapá and Pará states, confirm the existence of a significant Archean nucleus, with ages ranging from 2.58 Ga to at least 2.80 Ga, that was reworked by the Transamazonian orogeny.

Avelar (2002) and Avelar *et al.* (2003) have presented new evidence of preserved Archean nuclei in southern and central Amapá, which can be traced indirectly northward into southeastern French Guiana as detrital zircons in quartzite and as an inherited component in Paleoproterozoic granite. Their Sm-Nd ages indicate a period of crustal growth between 3.29 Ga and 2.92 Ga in central Amapá, while in southeastern French Guiana model ages up to 2.55 Ga correspond to mixing of a Proterozoic juvenile source and an Archean reworked source, rather than to a Siderian episode of crustal growth. The available Pb-Pb zircon ages in Amapá point to a magmatic event at about 2.85 Ga, and another one at about 2.58 Ga, the latter being poorly recognized throughout the Amazonian craton. This suggests that the Amapá region could be an extension of the Carajás Archean crust (south of the Amazon River) reactivated by a Neoarchean event and involved in the Transamazonian orogeny. Tassinari (1996) depicted the eastern Guiana Shield as a southern domain showing ensialitic characteristics and a northern domain showing juvenile simatic characteristics, with the boundary between the two domains being located along the Oyapok River. Taking into consideration all the recent Archean isotopic data, we agree with Tassinari's (op. cit.) assumption of two crustal domains, as refined by Avelar *et al*. (2003), but with a roughly WNW-ESE trend rather than the NNE-SSW trend of the Oyapok River. Integration of the whole set of recent data from Amapá, and especially the work of Rosa Costa *et al*. (2001, 2003), shows that these easternmost Archean terrains constitute an elongated domain, of ca 50 km wide and about 200 km in length, limited to the north by Paleoproterozoic terrains of French Guiana and to the south by Paleoproterozoic terrains of Carecuru-Paru. It is therefore not directly connected to the more southern Carajas Archean domain. Laterally, the NE-SW trends of this Amapá-Pará Archean domain are hidden to the east under the Phanerozoic cover of the Amazon River mouth. To the west its extension towards Suriname needs further support.

The possible existence of Archean basement in the broad area between the Imataca Complex to the west and the large, partly reworked, Archean sector in the southeastern part of the Guiana Shield has been widely discussed, in particular for the Bakhuis horst zone (Gaudette *et al.*, 1976; Priem *et al.*, 1978; Bosma *et al.*, 1983; Gibbs and Barron, 1993; Lima *et al.*, 1991; Vanderhaeghe *et al.*, 1998; Tassinari and Macambira, 1999). However, the most recent Pb-Pb zircon ages and Sm-Nd model ages (de Roever *et al*., 2003) indicate a lack of reworked Archean crust in the Bakhuis Mountains and point to a major episode of Paleoproterozoic juvenile crustal accretion during eo-Transamazonian times. These results are in good agreement with the U-Pb zircon data and previous whole-rock Sm-Nd results in the region (Priem *et al*., 1978; Ben Othman *et al.*, 1984).

Paleoproterozoic crustal growth and reworking

The entire evolution of the so-called Transamazonian orogeny, between *ca*. 2.25 Ga and 1.95 Ga, took place mainly within the Rhyacian. However, whereas the main tectonothermal activity in the easternmost part of the Shield ended at 2.08 Ga, with only subsequent cooling, the central and western parts of the Shield underwent a further Orosirian tectonothermal event that lasted until about 1.93 Ga. We shall therefore refer to the main Rhyacian evolution (2.26 - 2.08 Ga) as the "Main Transamazonian event", and to the subsequent Late-Rhyacian to Orosirian evolution (2.07 - 1.93 Ga) as a "Late Transamazonian event".

The relationships between the Uatumã magmatism and the Transamazonian events will be discussed at the end of this chapter.

Main Transamazonian event (Rhyacian: 2.26-2.08 Ga)

The northern side of the Guiana Shield includes TTG–greenstone belts and granitic suite domains. Plutonic terms include a wide range of chemical compositions, within which two representative types can be distinguished - 1) a tonalitic-granodioritic-trondhjemitic (TTG) suite, and 2) a granitic *sensu lato* suite.

This lithological duality, originally inferred by Choubert (1974) as "Guyanais" magmatism and "Caraibe" magmatism, has been refined and geodynamically modeled in the light of plate tectonic processes (Vanderhaeghe *et al*., 1998; Delor *et al*., 2003).

Ocean-floor tholeiitic magmatism

The "Île de Cayenne" gabbro and associated trondhjemite, which are exposed along the Atlantic coast, have always been considered as one of the oldest terrains of the Guiana Shield. The initial Archean age proposed by Choubert (1964) for these areas has not been confirmed by later age determinations; for example, Teixeira *et al.* (1985) obtained early Rb-Sr ages at *ca*. 1.9 Ga for the Île de Cayenne series, and Milesi *et al.* (1995) obtained precise Pb-Pb zircon ages at 2216 ± 4 Ma and 2174 ± 7 Ma for the trondhjemite. On the basis of the geochemical characteristics of the rocks, considered to be derived from tholeiitic rocks emplaced at mid-oceanic ridges or within an oceanic back-arc basin, the youngest age has been postulated as representing a stage of oceanization (Vanderhaeghe *et al*., 1998). A new isotopic study accompanying a recent reappraisal of the geology of French Guiana has provided zircon ages as old as 2208 ± 12 Ma for the Fe-gabbro of "Pointe des Amandiers", and similar ages from zircons of the migmatized TTG in southern French Guiana (Delor *et al.*, 2001, 2003). These arguments, together with Sm-Nd data on French Guiana sediments and granitoids (Delor *et al.*, 2001, 2003) and on the Ipitinga greenstone in Amapá (McReath and Faraco, 1997) show that the formation age of the early Transamazonian oceanic crust may be as old as 2.26 Ga.

TTG plutonism and greenstone belts

The Paleoproterozoic tonalite/trondhjemite/granodiorite - greenstone belt (TTG-GS belt) can be traced for about 1000 km in the northern part of the Shield, from the Amazon delta in the east to the Orinoco River in the west. It does not, however, form one continuous belt, but consists of two main sections separated by the Bakhuis horst: a western, Venezuela - Guyana, belt and an eastern, Brazil - French Guiana - Suriname belt. The geological map of Suriname (Bosma *et al*., 1978) shows a large greenstone occurrence to the northwest of the Bakhuis horst, which resembles the western belt and the greenstone occurrences to the northeast of the horst. A clear continuation between the two belts is lacking and, moreover, the eastern belt narrows towards the horst. Nevertheless, available data reveal a large lithological similarity between the two belts, apart from the absence of an Upper Detrital Unit in the western belt.

The eastern belt was formed between 2.18 Ga and 2.13 Ga (Delor *et al.,* 2001, 2003), whereas the western belt contains indications of a similar younger age limit, with felsic volcanics dated at 2.13 Ga (Venezuela; Day *et al.*, 1995) and 2.12 Ga (Omai, Guyana; Norcross *et al*., 2000). The more precise ages determined for the TTG suite of the eastern belt indicate the following evolution:

A first stage of ocean-floor "consumption" with the production of TTG melts dated at *ca*. 2.18 - 2.16 Ga in the northern and southern parts of French Guiana (Delor *et al*., 2001, 2003). Along the Atlantic margin, these early TTG products can be traced fairly continuously from the Cayenne area in French Guiana to the Blakawatra area (south of Paramaribo) in eastern Suriname (Fig. 2). In the southern part of French Guiana, they form a 50-km-wide E-W-trending unit that can be traced i) eastward into Amapá with the same strike, and, ii) westward into Suriname with the main trend progressively rotating from E-W to WNW-ESE. Between these northern and southern exposures of 2.18 - 2.16 Ga TTG, we find a significantly younger TTG suite, dated between *ca*. 2.15 Ga and 2.13 Ga, forming a large batholith in the central part of the French Guiana - this has been termed the Central TTG Complex (Delor *et al*., 2003).

Greenstone belts associated with the TTG suite include volcanic members (ultramafites, basalts, intermediate to acid volcanics) and sedimentary terms. The regional terminology for these greenstone successions varies from country to country: "Pastora" in Venezuela, "Barama-Mazaruni" in Guyana, "Marowijne" in Suriname, "Paramaca" in French Guiana, and "Vila Nova" in Brazil. In French Guiana, the volcanosedimentary units are caught up in two "synclinoria" lying to the north and south of the Central TTG Complex: a southern greenstone belt (Gruau, 1980; Marot, 1988) and a northern greenstone belt (Ledru *et al*., 1991; Manier, 1992; Vernhet *et al*., 1992; Manier *et al*., 1993; Egal *et al*., 1994, 1995; Milesi *et al*., 1995; Vanderhaeghe *et al*., 1998; Delor *et al*., 2001, 2003), which merge westward in Suriname into a single greenstone belt (Delor *et al*., 2003) whose trend, south of Paramaribo, veers to the west (Bosma *et al*., 1983; Gibbs and Barron, 1983, 1993). The western belt in Venezuela and Guyana consists of three greenstone "sub" belts (see Gibbs and Barron, 1993).

The detailed lithological and isotopic studies in French Guiana show that the greenstones consist essentially of submarine lavas and pyroclastic rocks (Ledru *et al*., 1991; Manier *et al*., 1993; Egal *et al*., 1994, 1995; Milesi *et al*., 1995; Vanderhaeghe *et al*., 1998) with compositions ranging from basalt to rhyolite, intercalated with scarce sericite-chlorite schist. Pb-Pb ages ranging from 2156 ± 6 Ma to

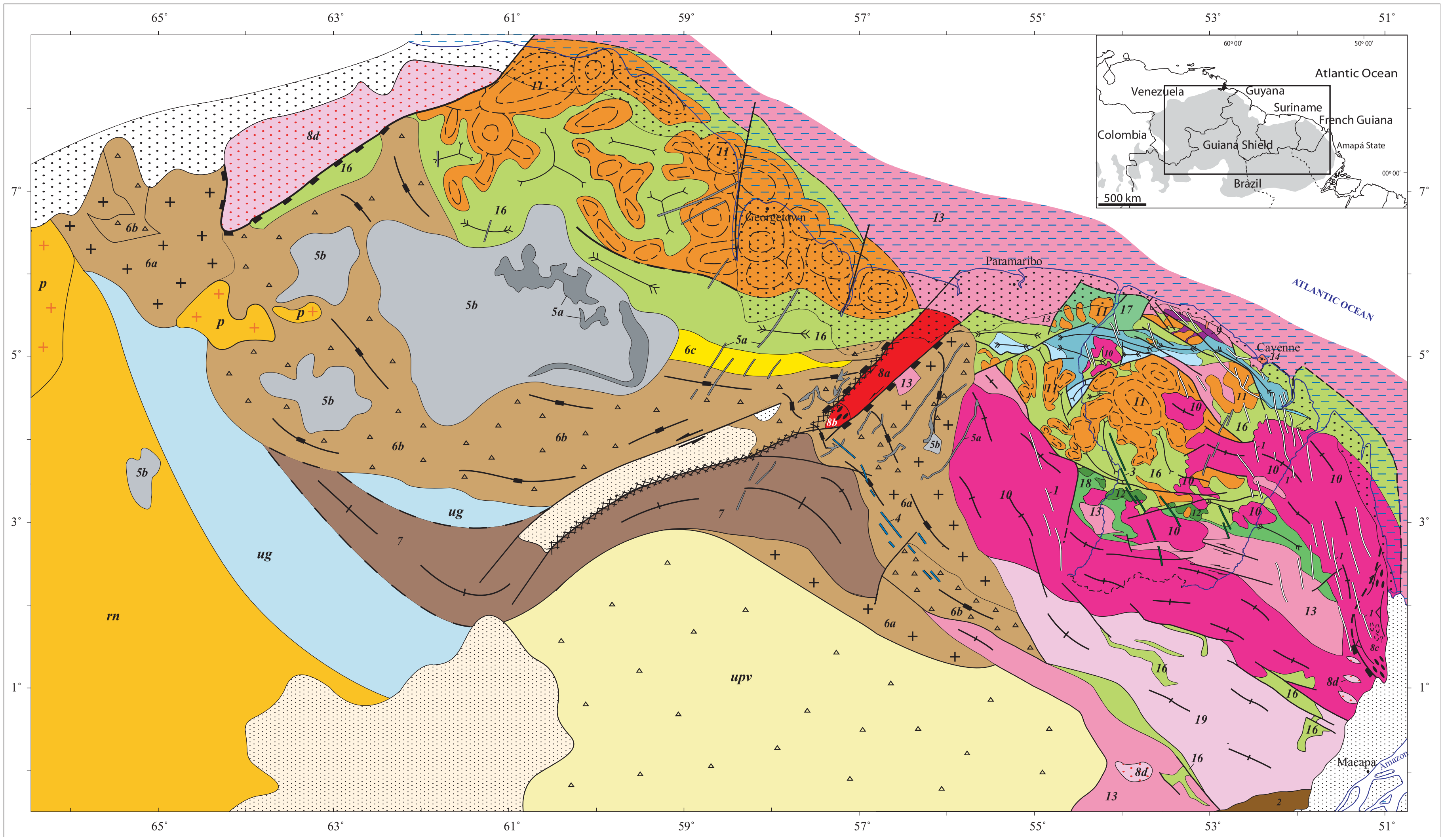

Fig. 2a.- Revised structural sketch map of the Guiana shield.

Fig. 2a.- Nouveau schéma structural du Bouclier guyanais.

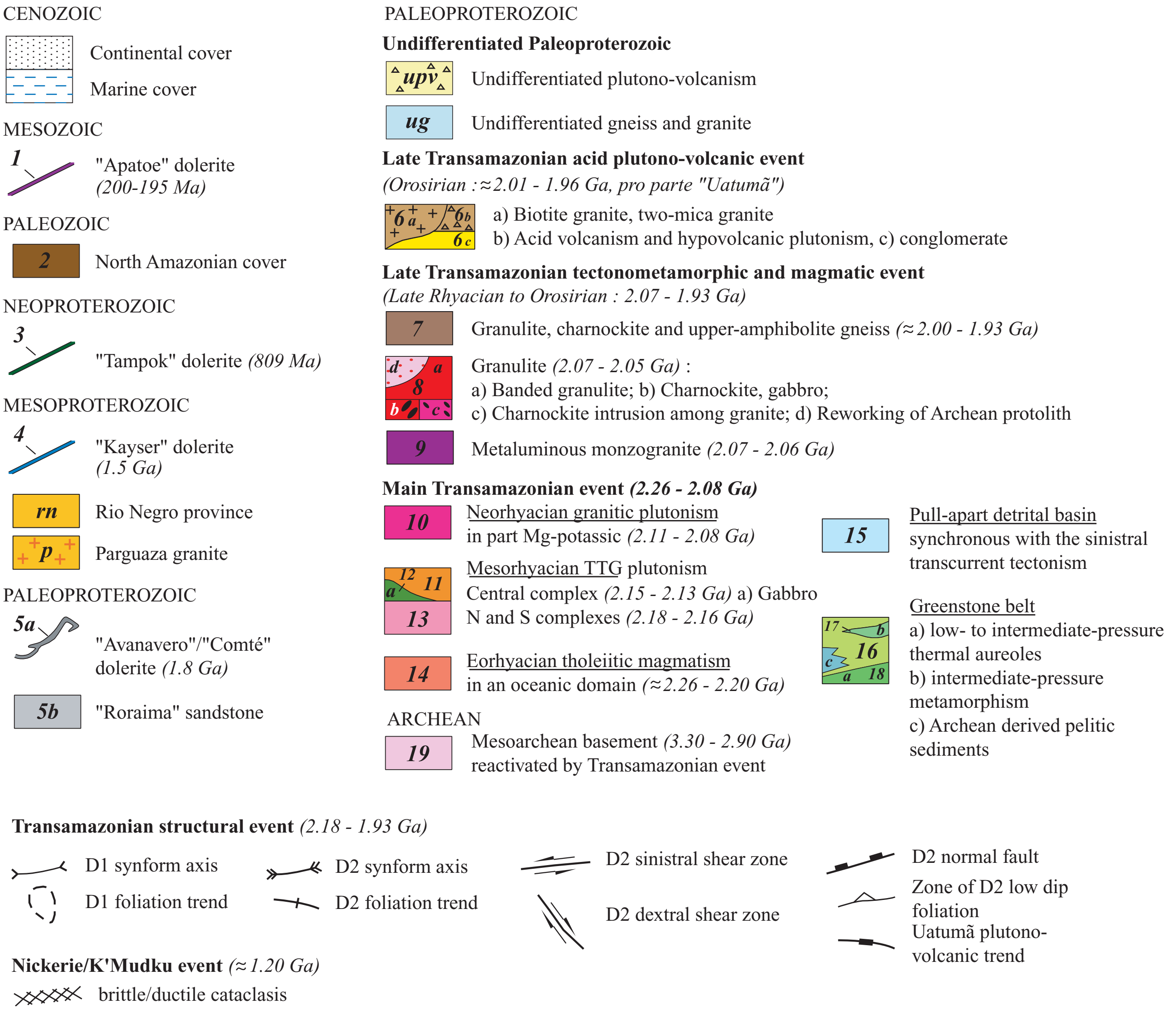

Fig. 2b.- Geological legend for Fig. 2a.

Fig. 2b.- Légende géologique de la Fig. 2a.

2137 ± 6 Ma have been obtained on acid to intermediate volcanics (Delor *et al.*, 2003). The positive $\varepsilon_{(Nd)t}$ values both of the acid metavolcanic rocks and metagreywacke from the greenstone belts and of associated TTG (Lafrance *et al.*, 1999; Delor *et al.,* 2001; also in Guyana, Venezuela and Amapá, Lafrance *et al.*, 1999; Teixeira *et al.*, 2002b; Nogueira *et al.*, 2000) confirm the juvenile character of the TTG-greenstone complexes and preclude the involvement of significant pre-Transamazonian crust in their genesis. Archean fingerprinting is only displayed by negative $\varepsilon_{(Nd)t}$ values on metapelite and by inherited Archean zircon in quartzite and in some granitoids (Delor *et al.*, 2003).

In Guyana, the volcanic section consists of lower units of tholeiitic basalt and minor komatiite, and middle and upper units of basalt with interstratified andesite, dacite and rhyolite. Tuff, greywacke, shale and less abundant chemical sediments are interbedded with the volcanics (see Gibbs and Barron, 1993). A similar lithology (excluding komatiite) has been described from Suriname (Bosma *et al.*, 1978, 1984), with a greywacke and shale sequence on top of the metavolcanics. These metasediments were derived predominantly from erosion of the associated volcanics, and show widespread graded bedding indicative of deposition by turbidity currents (Maas, in Bosma *et al.*, 1984).

In a number of respects these greenstone belts resemble arc-type Archean greenstone belts. For example, they exhibit a basic to acid succession. The lower units comprise primitive low-K Fe-rich tholeiitic basalt with a near-horizontal chondrite-normalized REE pattern (10x chondrite), thus differing from oceanic-floor tholeiite (Veenstra, 1978) and showing a strong affinity to island-arc tholeiite (Elliott, 1992; Gibbs and Barron, 1983, 1993;

Voicu *et al.*, 1997). This is overlain by and partly alternates with calc-alkaline andesitic rock with a characteristic island-arc signature (Veenstra, 1978; Elliott, 1992; Gibbs, 1980; Voicu *et al.*, 1997) in the higher units. Associated greywacke and shale, with graded bedding, were deposited by turbidity currents, probably in an arc-trench environment (Bosma *et al.*, 1983). Furthermore, the belts in part show an asymmetric structure (e.g. with respect to the position of the basic volcanics and sediments). These data suggest an island-arc to back-arc marginal basin tectonic setting (Bosma *et al.*, 1983; Voicu *et al.*, 1997). Voicu *et al.* (2001) suggest successive back-arc closure and extensional oceanic-arc systems caused by migrating spreading ridges.

Detrital series

Unconformably overlying the greenstone belts and TTG suite is an Upper Detrital Unit that crops out in the north of Suriname (Rosebel Formation) and French Guiana (Orapu Formation); it has not been found in the western belt or in Amapá. Composed of sandstone and conglomerate, including monogenic gold-bearing conglomerate, and 5000 m thick, it has been recently referred to as the “North Guiana Trough” (Milesi *et al.*, 1995). Milesi *et al.* (op. cit.) have inferred the maximum age of deposition to be 2115 ± 4 Ma on the basis of detrital zircon dating. As with the reworked greenstone pelitic terms, the $\varepsilon_{(Nd)t}$ values of the unit are negative.

In Suriname, the Rosebel sandstone and conglomerate contain pebbles of basic and intermediate volcanics, schist and phyllite, and rare granitic rocks. They exhibit current bedding, scour-and-fill, and other sedimentary structures that indicate deposition in a torrential fluvial environment as alluvial-fan and braided-river deposits (Maas, *in* Bosma *et al.*, 1978, 1984). Felsic volcanics are intercalated locally. The Rosebel deposits show low-grade metamorphism and several stages of folding, including isoclinal folding. However, the presence of enclosed pebbles of phyllite and schist point to an earlier event of deformation and metamorphism (Bosma *et al.*, 1984).

Granitic Plutonism

The youngest magmatic units are represented by a granitic suite consisting of massive intrusives with granular texture. This suite, dated at 2.11-2.08 Ga, is widely developed in southern and western French Guiana (Delor *et al.*, 2001) where it is associated with a migmatitic facies containing variably preserved greenstones and TTG from which the migmatites originated. The whole set of transitions from metatexite and diatexite to granite with unequivoquial magmatic textures strongly suggests that granite genesis involved melting of the TTG-greenstone belt. Such evidence of a *ca*. 2.10 Ga melting process can be seen along the northern Oyapok River on the eastern limb of the Mesorhyacian central TTG complex (2.15-2.13 Ga), and along the southern and northern Mesorhyacian TTG complexes (2.18-2.16 Ga). At a regional scale, this *ca.* 2.10 Ga granitic suite is constituting two elongated WNW-ESE trending domains, which merge to the east in Amapá. To the west, only the southern domain is represented and veers progressively from WNW to N-S trends.

Forming part of this *ca*. 2.10 Ga granitic suite, Mg-K magmatic compositions (amphibole ± pyroxene-bearing granite) and anatexite have been encountered specifically in southern French Guiana and along the Oyapok River. Such hornblende and pyroxene granites apparently extend farther west in central Suriname, in the area of the classical Gran Rio granite described by IJzerman (1931). They are heterogeneous in grain-size and colour and show an inhomogeneous and/or migmatitic aspect, or vague banding and schlieren (Bosma *et al.*, 1978, 1983). Clinopyroxene, usually mantled by hornblende and biotite, is common in the pyroxene granites, and orthopyroxene is present in some of them. The pyroxene granites are associated with high-grade metamorphic enclaves. The granulite-facies rocks of these enclaves are assimilated by the granite (as shown e.g., by xenoliths), which implies that the high-grade metamorphism should be older than the granite (2.11-2.08 Ga), and hence, older than the high-grade metamorphism in the Bakhuis belt.

Recent U-Pb and Pb-Pb results on zircons in Amapá suggest that the Transamazonian magmatic episodes in this area are similar to those recognized in French Guiana (Nogueira *et al.*, 2000; Avelar *et al.*, 2001). Nevertheless, late metaluminous monzogranite and pegmatite rock types have been dated at 2.07 - 2.06 Ga and appear to be restricted to the northern part of French Guiana (Vanderhaeghe *et al.*, 1998; Delor *et al.,* 2001, 2003).

Late-Transamazonian high-grade tectonometamorphic and magmatic events (Late-Rhyacian to Orosirian: 2.07-1.93 Ga)

Three northeasterly granulitic domains are known in the Guiana Shield, the well-known Imataca belt (Venezuela) and Bakhuis belt (Suriname), and a co-eval but less-developed remnant of granulites in Amapá and northwest Pará (Brazil). The three domains all belong to the Late Rhyacian granulitic event (2.07-2.05 Ga).

The Central Guyana granulite belt is considered to be limited (see below) to amphibolite- and granulite-facies rocks of northeastern Roraima State in Brazil (Fraga, 1997, 2000), the granulites and high-grade metamorphics from the Kanuku complex in Guyana (Berrangé, 1977), and the Coeroenie high-grade gneisses from southwestern Suriname (Kroonenberg, 1977). This Roraima-Kanuku-Coeroeni belt has an arcuate shape, from NE-SW to NW-SE (Fig. 2). A younger Orosirian charnockitic magmatic event (≈ 1.97-1.93 Ga) has been found in the western extension, in

Roraima State (Fraga *et al.*, 1997; Fraga, 2000), whereas the age of the granulitic metamorphism in this region and the other parts has not yet been dated precisely.

Late Rhyacian granulite domains (2.07-2.05 Ga)

i) The northeasterly trending Imataca belt, in the northwesternmost part of the Guiana Shield, consists of orthopyroxene granulite, subordinate two-pyroxene granulite and minor metasediments (Dougan, 1974). From an isotopic point of view, U-Pb, Rb-Sr and Sm-Nd results on the metamorphic and igneous rocks reveal a complex Archean/Paleoproterozoic history (Montgomery and Hurley 1978; Montgomery, 1979; Teixeira *et al.*, 1999, Tassinari *et al.*, 2001). Granulitic metamorphism has first been inferred to have occurred at around 2.10 Ga (Montgomery and Hurley, 1980). More recent analysis by Tassinari *et al.* (2001) emphasised the Archean nature of granulites in the core of the Imataca complex, with high-grade Transamazonian resetting on its northeasterly margin. However, recent thermochronological study of the São Felix - Upata granulites from the Imataca complex indicates a late Transamazonian age for the granulite-facies metamorphism (Tassinari *et al.*, 2003).

ii) The high-grade metamorphic rocks of the Falawatra Group, in western Suriname, occur in a northeast-trending horst in the Bakhuis Mountains (de Roever, 1973, 1975; Dahlberg, 1973). The horst is bounded to the north and south by mylonitized faults attributed to the 1.2 Ga Nickerie Metamorphic Event (Priem *et al.*, 1971). The central part of the horst consists almost entirely of a 30-40-km-wide, 100-km-long zone of charnockite-suite rocks that show a conspicuous, neat and ubiquitous compositional banding on a centimetre to metre scale, and foliation of both mafic and felsic minerals. They almost invariably contain hypersthene. The conspicuous and fairly regular character of the compositional banding suggests a predominantly metasedimentary (and/or metavolcanic) nature. This is also indicated by intercalations of obvious metasediments, such as pelitic gneiss, sillimanite quartzite, spessartine quartzite (gondite), calc-silicate rocks (calcite-scapolite quartzite), and graphite-bearing (enderbitic) bands. Discordant syn- to postkinematic metadolerite dykes are common. The SW of the horst consists mainly of orthopyroxene granites to tonalites, and gabbroic-ultramafic rocks. An anorthosite body was found in the core of the horst.

The P-T conditions for the peak UHT metamorphism have been estimated as 950 °C and 8.5 - 9.0 kb. The UHT metamorphism shows evidence of a counterclockwise P-T path passing from an early cordierite-sillimanite assemblage via a subsequent sapphirine-quartz assemblage to the peak metamorphic assemblage of orthopyroxene-sillimanite-quartz (de Roever *et al.*, 2003). Late retrograde assemblages have recorded mainly a near isobaric or steeper cooling path.

Single zircon Pb-evaporation and whole-rock Sm-Nd dating on the Bakhuis granulite demonstrate that the high-grade metamorphism in the Bakhuis Mountains occurred at 2070 - 2050 Ma, without significant Archean inheritance. On the basis of these integrated petrological and isotopic studies, de Roever *et al.* (2003) conclude that the UHT metamorphism and associated counterclockwise P-T path in the Bakhuis belt are better interpreted as the result of Late Transamazonian mantle upwelling. Contemporaneous magmatism probably related to the mantle upwelling is formed by the ubiquitous metadolerite dykes in the granulite belt, whereas anorthosite and gabbroic–ultramafic bodies may represent younger magmatic pulses.

iii) The limits of a granulitic domain in eastern Amapá have, hitherto, been imprecisely determined, due to the difficulty of distinguishing metamorphic granulitic rocks and magmatic charnockite. The extent of the easternmost domain shown on Figure 2 takes into account a) our own observations, b) the occurrence of two-pyroxene-bearing assemblages documented by João and Marinho (1982) and c) the field work by Avelar (2002). This zone is located at the junction of the elongated granitic domains extending from French Guiana, and is characterized by flat-lying to low-westward-dipping foliations. At a regional scale these westward-dipping foliations exhibit an arcuate shape from N030 trends (at 2°30 latitude) to N145 trends (at 1°30 latitude). Charnockite is encountered on both northern and southern sides of this arcuate shape. A charnockitic body in the south has been dated at 2.05 Ga by Pb-evaporation on zircon (Avelar *et al.*, 2001), while in the north, close to Calçoene, zircons from another charnockitic pluton furnished a Pb-Pb age of 2.06 Ga (Lafon *et al.*, 2001). Melt veins associated to ductile normal faulting along the southern N145 trends have also been dated at 2.05 Ga. This set of arguments points to a poorly constrained northeasterly trending zone characterized by the presence of 2.06-2.05 Ga charnockite, and by upward movement relative to surrounding granitic gneiss. However, relationships between the charnockitic magmatism and granulitic rocks in central Amapá are not clear, as yet. The 2.45 Ga Rb-Sr age obtained by João and Marinho (1982) and Pb-Pb zircon minimum ages of 2.58 Ga obtained on two samples of granulite by Avelar *et al.* (2003) are considered to be related to the magmatic protoliths of the granulite; they do not constrain the age of the metamorphism. Sm-Nd dating on garnet from the granulite gave an age of about 2.03-2.0 Ga (Oliveira *et al.,* 2002), which suggests a Paleoproterozoic age for the high-grade metamorphism. However, as in the Imataca belt, the existence of at least two high-grade episodes, one Archean and the other Transamazonian in age, cannot be discarded. Furthermore, there is evidence for a close relationship between charnockite magmatism and ductile normal faulting at 2.05 Ga, pointing to partial contemporaneous exhumation in easternmost Amapá.

Orosirian granulite domains (≈ 2.0-1.93 Ga)

The “Central Guyana Granulite belt” (Kroonenberg, 1976) stretches from W Suriname across S Guyana (Kanuku horst) into Brazil, State of Roraima. The belt supposedly would also contain the Bakhuis high-grade rocks but aeromagnetic evidence (Hood and Tyl, 1973) and lack of relief E of the Kanuku horst do not support a continuation toward the Bakhuis belt but to the SE, to the Coeroeni area in SW Suriname. It is this continuous arcuate trend that we have represented on Figure 2; in the following paragraphs we discuss i) the western branch in Roraima State, Brazil, ii) the NE-SW Kanuku horst in Guyana, and iii) the eastern, NW-SE-trending, Coeroeni branch in Suriname.

i) Fraga *et al*. (1997) and Fraga (2002) emphasized the presence of true magmatic charnockite in Roraima State, which yielded Pb-Pb zircon ages between 1966 ± 37 Ma and 1933 ± 2 Ma. The Paleoproterozoic T_{DM}(Nd) model ages obtained for these rocks between 2.19-2.08 Ga (Fraga, 2002) are compatible with the 2.2 Ga T_{DM} model age obtained for a sample of Kanuku granulite (Ben Othman *et al.*, 1984), but the Pb-Pb zircon ages are significantly younger than that of the Bakhuis granulite metamorphism and contemporaneous charnockitic magmatism, 2.07-2.05 Ga (de Roever *et al*., 2003).

ii) In Guyana, the Kanuku granulite and migmatite were distinguished by Berrangé (1977). The granulite includes mainly acid granulite and enderbite, and may have been derived from magmatic rocks (Gibbs and Barron, 1993). The migmatite is mainly paragneiss in which the metamorphic grade ranges from amphibolite facies in the southeast (with muscovite) and east, to granulite facies (including orthopyroxene) in the Kanuku horst to the west (Berrangé, 1977).

iii) In southwestern Suriname, the Coeroeni gneiss comprises mainly quartzofeldspathic gneiss and sillimanite gneiss, with minor amphibolite (Kroonenberg, 1976), metamorphosed in the amphibolite or granulite facies. It commonly shows intense folding as well as extensive migmatization. Rb-Sr dating of the gneiss from drill cores and river samples gave an age of 2001 ± 97 Ma (Priem *et al*., 1977). The Coeroeni gneiss represents a predominantly supracrustal series with few volcanics, and probably formed in an intracontinental surrounding. This would be in line with the finding of reworked Archean zircons in a sample of Coeroeni gneiss (unpublished data, Delor *et al.*, 2000, 2001).

Orosirian acid plutonovolcanic event, *pro parte* Uatumã (≈ 2.01-1.96 Ga)

A plutono-volcanic acid suite occurs in a wide, long zone across the Guiana Shield (Venezuela, northern part of Roraima state, central Guyana, western Suriname) whereas a smaller zone or branch occurs in southern Roraima State and south Guyana and meets the other zone near the Amazon north of Manaus, in Brazil. The suite (≈2.01-1.96 Ga) postdates all northernmost Transamazonian formations. In western Suriname extensive areas with acid to intermediate metavolcanics occur (Dalbana Formation), which show low-grade metamorphism and wide, open folding (Verhofstad, 1970; Maas and van der Lingen, 1975). They have partly an ignimbritic origin, show a calc-alkaline chemistry and are closely associated with (intrusive) leucogranites, granophyric granites and fine-grained granites. These hypabyssal granites are considered to be comagmatic with the metavolcanics. Widespread biotite granites with K-feldspar megacrysts postdate the metavolcanics and hypabyssal granites (Bosma *et al*., 1978, 1984). In French Guiana and to the east in Amapá, such volcanics have not been found, although a Late Transamazonian age has been suggested for the Mount Belvédère rhyolites in French Guiana, which needs isotopic confirmation.

To the west, the acid to intermediate volcanics and associated hypabyssal granites, referred in the past as Uatumã, form a huge belt in central Guyana (Berrangé, 1977), the Roraima State of Brasil and Venezuela. The Surumu volcanics and related Pedra Pintada granite in Roraima State were dated by zircon dating at 2.01-1.96 Ga (Schobbenhaus *et al.*, 1994; Almeida *et al*., 1997; Fraga *et al*., 1997), the Cuchivero volcanics in Venezuela at 1.98 Ga (Brooks *et al*., 1995). The acid to intermediate volcanics and hypabyssal granites of southern Guyana were described by Berrangé (1977).

The suite commonly shows a basal sequence of mature sandstones and monomict conglomerates, called Murua formation in Guyana, Ston in Suriname and Cinaruco in Venezuela (Berrangé, 1977). The basal sequence is conformably overlain by Uatumã volcanics, and both are folded in large open folds (Gibbs and Barron, 1993; Bosma *et al.*, 1984). This is a clear distinction from greenstone belt metasediments which show intense folding.

The age and geodynamical position of the Uatumã Suite has been the subject of a long, ongoing debate. At one side the Uatumã volcanics were considered to represent anorogenic magmatism, with ages as young as the Roraima supergroup, then dated at 1.6-1.7 Ga (e.g., Gibbs and Olszewski, 1982). Two main arguments were given, a) the presence of only mild open folds and absence of intense folding; and b) younger, post-Transamazonian ages. E.g. in Venezuela Rb-Sr WR dating showed an age of 1.70 Ga for the volcanics (Gaudette *et al.*, 1985). Therefore, Gibbs and Barron (1993) describe the Uatumã and Roraima Supergroups together, as the Mesoproterozoic cover of the Guiana Shield, and give an approximate median age of 1.8 Ga for the Uatumã supergroup.

The opposite view, such as expressed by geologists from Suriname was that the Uatumã volcanics represent a late, posttectonic phase within the Transamazonian orogeny. In Suriname acid metavolcanics, hypabyssal granites and surrounding biotite granites were dated at 1874 ± 40 Ma (Rb-Sr WR; Priem *et al*., 1971). Field relations and xenoliths showed the widespread biotite granites to be younger than the acid metavolcanics and hypabyssal granites. The age was taken as clear evidence for a Trans-Amazonian, orogenic nature of the metavolcanics and granites.

More precise dating by zircon Pb/Pb and U/Pb in the 90's and after has changed the age framework considerably. Zircon dating of Roraima supergroup sediments showed ages of 1860 and 1875 Ma (Santos *et al.,* 2002, 2003; compared to previous 1.65 Ga ages by Rb-Sr whole rock dating), setting also a minimum age for the end of the Transamazonian orogeny. Zircon datations of Uatumã volcanics and hypabyssal granites are still low in number, but available ages fall in the 2.01-1.96 Ga range (Schobbenhaus *et al*., 1994; Almeida *et al*., 1997; Brooks *et al*., 1995). Therefore, Schobbenhaus *et al.* (1994) and Reis *et al.* (2000) include the dated Uatumã volcanics in the Transamazonian orogeny.

The Uatumã suite continues south of the Amazon, in the Guapore Shield. One of the causes of the long debate is that south of the Amazon more rocks were ranged with the Uatumã Suite, because of their similarity. However, in the Iriri Group of the Uatumã Supergroup in the Tapajos Gold Province two volcanic sequences (each with associated granites) can now be distinguished by zircon dating, one formed at 2.00 -1.97 Ga, the other one at 1.89-1.87 Ga, demonstrating the heterogeneity of the Uatumã Supergroup (Lamarão *et al*., 2002). The two sequences differ in geochemical characteristics, the older one is attributed to subduction-related arc magmatism, the younger one to an anorogenic, intracontinental event (Lamarão *et al*., 2002). Also in the nearby Carajas Province the 1.87 Ga magmatism is widespread and ranged with the Uatumã Suite (Teixeira *et al*., 2002; showing Nd model ages of *ca*. 3.0 Ga).

Reis *et al*. (2000) proposed the name of "Oracaima volcano-plutonism" for the 2.0-1.95 volcanoplutonic rocks in northern Roraima State, Brazil, to avoid the confusion related to the name Uatumã. Younger, *ca*. 1.89 Ga, zircon ages have been reported for acid volcanics and related granites from S Roraima and near Pitinga (Reis *et al*., 2000; Costi *et al*., 2000). Reis *et al.* (2000) found a considerable geochemical difference between the 2.0-1.95 and 1.89 volcano-plutonic sequences, at considerable variance with an anorogenic signature for the 2.0-1.95 "Uatumã" event.

Many rather small gabbroic-ultramafic intrusions occur in W Suriname (De Goeje Gabbro, Bosma *et al*., 1978, 1984), central Guyana (Appinite Suite, Berrangé, 1997; Badidku Suite, Gibbs and Barron, 1993) and northern Roraima State. The intrusions have not yet been dated by modern isotopic methods. They are essentially undeformed and intrusive in e.g. the acid (meta-) volcanics, but in turn intruded by the biotite granite of western Suriname (Bosma *et al*., 1984), ranged with the Uatumã plutono-volcanic suite. Therefore, they may be broadly similar in age with that suite. The large PGM-bearing gabbroic-ultramafic De Goeje body in E Suriname, is definitely older and can be ranged with the greenstone belt; its continuation in French Guiana (Tampok), was dated at approximately 2.15 Ga (Delor *et al*., 2003).

Late Paleoproterozoic post-orogenic cooling and subsequent magmatism and basin deposits

Apart from the Roraima area marked by abundant Orosirian magmatic activity, thermal assessment of the Transamazonian event by Rb-Sr and K-Ar methods shows that the Guiana shield basement has cooled down below the 500-600°C isotherm between 2.08 Ga and 1.76 Ga (Montalvão and Tassinari, 1984; Nomade *et al*., 2002). This was without major regional thermal resetting and therefore without a subsequent orogenic cycle. Nevertheless, tectonic and magmatic events of restricted extent argue for regional reactivation in a continental context.

Magmatic activity

i) In Pitinga in the South, 200 km N of Manaus, the Agua Boa and Madeira granites, in part with rapakivi structure, are associated with major Sn deposits. They were dated at 1.83-1.79 Ga and are considered as anorogenic, intracratonic granites (Lenharo, 1998; Costi *et al*., 2000). Slightly younger granite intrusions occur in Amapá, 1.75 Ga (Vasquez and Lafon, 2001; zircon).

ii) Large dolerite sills and dykes of the Avanavero type, dated with *ca*. 1.79-1.78 Ga ages by zircon and baddelyite dating, are reported from Venezuela, Brazil (Roraima State), Guyana and Suriname (Norcross *et al*., 1998; Santos *et al*., 2001). They are much older than indicated by Rb-Sr whole rock dating (Priem *et al*., 1968; Snelling and McConnell, 1969). A poorly constrained Ar-Ar age of 1.8 Ga has been also obtained on a N030°-trending dolerite dyke in French Guiana. This indication of a Late Paleoproterozoic dyke generation has been extended to the whole set of NE-SW trending dykes in French Guiana (Delor *et al*., 2001, 2003).

Roraima Supergroup

The thick sedimentary sequences of the Paleoproterozoic Roraima Supergroup postdate all Paleoproterozoic formations and include a variety of sedimentary lithologies that mainly include sandstones, feldsphatic sandstones, conglomerates and dark shales. The deposition of the Roraima Supergroup was developed in the following major environments: fluvial, deltaic, coastal lagoon, beach and shallow marine environments (Ghosh, 1981). The paleocurrent measurement on sedimentary sequences of the Roraima Group (Keats, 1973 and Ghosh, 1981), suggest a northeasterly, easterly and southeasterly source of sediments. Santos *et al*. (2003) conclude that the sequences represent a fill in a foreland basin that was derived mostly of the Transamazonian orogenic belt to the north and northeast. An outlier of Roraima sediments occurs to the E, in central Suriname (Tafelberg), and near Pitinga in the South; in French Guiana and more to the east the sediments are absent.

Recent datation of Avanavero dolerite sills and dykes (Santos *et al.*, 2001) intruded in the sediments, and of horizons of pyroclastic volcanics interbedded with the middle and upper Roraima sediments, showed that these sediments are substantially older than previously thought (1860 ± 15 Ma and 1875 ± 5 Ma for two horizons, Santos *et al.*, 2001; Santos *et al.*, 2003). Detrital zircons with an age of 1.95 Ga and older were found in the sediments (Santos *et al*., 2001, 2003). The 1875 Ma age was interpreted as approx. the maximum age of the Roraima Supergroup, the dolerite intrusion age of 1.78 Ga as the minimum age (Santos *et al.*, 2003).

Post Paleoproterozoic Intracontinental evolution

Mesoproterozoic and Neoproterozoic

For more data on the Rio Negro Province in the extreme W of the Shield the reader is referred to the recent papers by Santos *et al*. (2000) and Tassinari *et al*. (2000).

Significant anorogenic acid magmatism of Mesoproterozoic age took place in the far west of the Shield, near Pitinga in the south, and locally in areas in between. The Parguaza rapakivi granite pluton in the far west, occupying an area of over 10000 km^2, was dated at 1546 ± 20 Ma by U-Pb on zircons (Gaudette *et al*., 1987). Also the Surucucus intrusive suite (Roraima State), dated at around 1.55 Ga, consists in part of rapakivi granites and is associated with Sn deposits. Ages at 1.56 Ga have also been obtained by Fraga *et al*. (1997) for charnockite from Roraima State. In this state also an example of a complete AMCG, anorthosite-mangerite-charnockite-(rapakivi)granite suite, has been suggested by Dall'Agnol *et al*. (1999) and demonstrated by Fraga (2002).

A swarm of NW-SE trending dolerite dykes of alkaline affinity, the Käyser dolerite, is associated with a major fault system and a graben structure in W Suriname (de Roever *et al.*, 2003, this volume). The dykes were dated by Ar/Ar dating on biotite at about 1.50 Ga. In the eastern part of the shield, evidence for Mesoproterozoic rocks is scarse.

Neoproterozoic tectonometamorphic evidence is of restricted occurrence in the Guiana Shield

i) Throughout the western half of Suriname and in Guyana, Rb-Sr and K-Ar mica dating of Transamazonian granitoids and K-Ar dating of basic rocks indicated a resetting of the ages by the Nickerie Metamorphic Episode at around 1.2 Ga (Priem *et al*., 1971). In the eastern half of Suriname such resetting has not been found. Long mylonitic zones along the Bakhuis horst in W Suriname, both affecting its high-grade rocks and Transamazonian granites and metavolcanics, as well as the horst formation itself, are also attributed to the Nickerie Metamorphic Episode (Priem *et al.*, 1971). Similar NE-SW mylonite zones are seen along the Kanuku horst in southern Guyana due to the K'Mudku event (Snelling and McConnell, 1969), and along the Guri Fault, near the Imataca Complex in Venezuela, due to the Orinoquean Event.

ii) In French Guiana, a sample from NW-SE trending dolerite dykes has been dated at 809 ± 29 Ma by the K-Ar method (Delor *et al.*, 2003). An analysis of the paleomagnetic poles confirms its inconsistency with younger Mesozoic dolerite dykes (Théveniaut and Delor, 2003).

iii) Alkaline complexes of varying age have been found locally. They consist mainly of nepheline syenite and strongly weathered rocks, which in cases were interpreted as carbonatites. An example is the Muri/Mutum intrusion at the border of Brazil and the Guyana-Suriname disputed territory. K-Ar dating gave an age of 1026 ± 28 Ma (Oliveira *et al.*, 1975). Other alkaline complexes such as the Seis Lagos carbonatite may be more recent. Alkaline intrusions of the Mapari Suite in Amapá have been dated at *ca*. 1.7, 1.5 and 1.3 Ga (Lima *et al.*, 1974).

iv) Alkali basalts and troctolites of alkaline affinity of the Cachoeira Seca suite occur near the Amazon, N of Manaus. They were dated at 1.19 Ga (Santos *et al.*, 2002; baddelyite).

Phanerozoic continental breakup

Phanerozoic formations (sediments and dykes) when observed, give account of subsequent continental breakup during the Paleozoic (Amazonian basin) and the Mesozoic (Atlantic margin).

i) A widespread magmatic event is represented by the emplacement of Apatoe-type dolerite dykes in Venezuela, Guyana, Suriname, French Guiana and Brazil. Large dyke swarms in eastern Suriname and French Guiana cut all the above-described lithologies. In French Guiana they are oriented NNW-SSE and, more rarely, WNW-ESE. K-Ar whole-rock ages range from the Late Triassic to Early Liassic (Priem *et al*., 1968) because of the weathering and excess argon, but accurate Ar-Ar data obtained in French Guiana and Suriname point to an Early Jurassic age (Deckart *et al.*, 1997; Nomade *et al.*, 2000, 2001a,b). The major dyke swarm is located in the northeastern part of French Guiana, close to the mouth of the Oyapok river. The Apatoe dykes mark the precursor stages of the Atlantic ocean opening (see for more details de Roever *et al.*, 2003, this volume).

ii) A tensional event resulted in the fault-bounded subsidence of the North Savannas/Takutu graben in central

Guyana and extrusion of the Apoteri basalt outflows in the graben at 180-150 Ma, synchronous with the opening of the southern North Atlantic (Berrangé and Dearnley, 1975). The graben has been explored extensively for oil.

iii) Restricted Tertiary and Quaternary sedimentary basin deposits are known along the Atlantic margin. They also occur in western Guyana (in the Mesozoic Takutu Basin).

The setting of the Bakhuis belt in the Paleoproterozoic framework of the Guiana Shield

The study of the petrology and geochronology of the granulite-facies metamorphism in the Bakhuis belt showed the following features:

- The granulite-facies metamorphism occurred at approximately 2.07-2.05 Ga, rather late in the Transamazonian orogeny.

- The metamorphism occurred partly at ultrahigh-temperature (UHT) conditions, reaching temperatures of approximately 950 °C, at 8.5-9 kb. Such exceptional conditions would require a heat source, for which mantle upwelling was suggested.

- The metamorphism followed a counterclockwise path, which suggests a position of the UHT rocks below a zone where voluminous magma was introduced. Charnockites were at least locally produced contemporaneous with the UHT metamorphism. Voluminous charnockites to enderbites were found in a zone which probably represents a higher level within the belt.

The timing and geodynamical conditions under which the UHT metamorphism took place, should be considered within the broader context of the Paleoproterozoic development of the Shield, and compared e.g., with the timing and geodynamical conditions of the regional metamorphism in the greenstone belts and in the upper detrital unit.

Comparison with tectonic, metamorphic and intrusive events in the greenstone belts and the upper detrital unit

Deformation events

The chronological discussion of Transamazonian tectonic, metamorphic and magmatic events is mainly based on recent work in French Guiana, where, over the last decades structural constraints have been established through extensive study of the volcanosedimentary greenstone belts and regionally associated plutonic rocks. In the northern part of French Guiana two major tectonometamorphic events have been recognised, called D1 and D2 (Ledru *et al*., 1991; Milesi *et al*., 1995; Vanderhaeghe *et al*., 1998). A further subdivision of the D2 event has been proposed by Delor *et al.* (2003) on the basis of contrasting thermomechanic regimes, associated thermal gradients and intrusions. Using these definitions of D1 and D2, we discuss below the succession of tectonothermal events, with special reference to the eastern part of the Shield, i.e., French Guiana and contiguous Suriname and Amapá.

i) Evidence for the earliest deformations associated to a D1 tectonic event has been found both in greenstone volcanosedimentary formations and in the TTG suite, mainly from areas in the northern and central part of French Guiana where D2 reworking was minimal. There, D1 is highlighted by round imbricated magmatic fabrics in the central French Guiana TTG batholith (2.15-2.13 Ga). D1 thermal aureoles around *ca* 2.13 Ga tonalites in the northern Guiana basin are marked by down-dip andalusite-staurolite lineations associated with normal movements (Delor *et al*., 2001, 2002). Such evidence of gravity-driven deformation and thermal aureoles is found in southern French Guiana for the oldest TTG and for the gabbroic suite dated at 2.15 Ga (Delor *et al*., 2003).

A study of the metamorphism and folding of the greenstone metavolcanics and metasediments in central Suriname (Veenstra, 1978) showed a stage of low-grade regional metamorphism associated with folding, followed by a stage of localised lower-amphibolite-facies metamorphism in zones around diapiric TTG intrusions. Combined with the geochronological data for the (younger) TTG intrusions from French Guiana, this would point to early regional deformation and metamorphism in the greenstone belt before 2.13 Ga. Similar evidence of earliest deformation in TTG as old as 2.17 Ga has been observed in Amapá during our field checking campaigns.

These arguments point to the close relationship between the D1 structures and TTG magmatism which has been interpreted in terms of N-S-directed plate convergence (Vanderhaeghe *et al.*, 1998; Delor *et al.*, 2003).

ii) A second, transcurrent tectonic event (D2) gives rise to large zones of E-W to NW-SE sinistral strike-slip faults mapped throughout French Guiana (Marot, 1988; Lasserre *et al.*, 1989; Ledru *et al.*, 1991; Egal *et al*., 1994, 1995; Milesi *et al*., 1995; Vanderhaeghe *et al*., 1998; Delor *et al*., 2001, 2002).

D2a stage: In southern French Guiana this sinistral shearing can be seen at a regional scale with the development of sigmoidal shapes of foliation trajectories (Delor *et al*., 2001) between major crustal discontinuities such as the South Guiana shear zone (Lasserre *et al*., 1989; Jegouzo *et al*., 1990). The 2.11 - 2.08 Ga granitic suite widely documented in southern and western French Guiana (Milesi *et al*., 1995;

Delor *et al.*, 2001) was emplaced during this initial D2a structural event. It is accompanied there by migmatization of TTG and greenstones. K-Mg magmatism is characterized by pyroxene- and/or amphibole-bearing granites, dated at 2.10 Ga. They were emplaced syntectonically during D2a. These Mg-K granites are known only from easternmost French Guiana along the Oyapok river and from southern French Guiana and extend westward into central Suriname (where their co-eval age needs to be confirmed).

In northern French Guiana, D2a sinistral shearing is contemporaneous with the opening of the “North Guiana Trough” which consists of a series of “pull-apart” type basins aligned approximately E-W (Ledru *et al.*, 1991; Egal *et al.*, 1994, 1995). In Amapá no evidence of a detrital basin has hitherto been shown (nor in Guyana-Venezuela).

D2b stage: Late metaluminous monzogranite plutons and pegmatites dated at 2.07-2.06 Ga (Delor *et al.,* 2001, 2003) were emplaced during a second stage, D2b, characterised by a corridor of WNW-ESE dextral shearing (Delor *et al*., 2003) in northern French Guiana. Dextral shear with strong *in-situ* migmatization is also witnessed by contiguous TTG gneisses. The presence of such major dextral-shear corridors is not incompatible with the global sinistral-shearing context during the D2 event and can be interpreted in terms of conjugated shear. Besides such high-temperature conditions related to D2b shearing, further unequivocal evidence of D2b metamorphism is found in the upper detrital unit (see discussion below).

P-T conditions of metamorphism

Regional metamorphism associated with both deformation events is of greenschist (muscovite-chlorite associations) to medium-amphibolite (biotite ± garnet) facies, whereas thermal metamorphism occurred near the very abundant granitoids (Ledru *et al.*, 1991; Egal *et al.*, 1994, 1995; Milesi *et al.*, 1995; Vanderhaeghe *et al.*, 1998; Delor *et al.*, 2002).

Metamorphism associated to the D1 event has been considered as a low-pressure type (Milesi *et al*., 1995, Vanderhaeghe *et al.*, 1998; Delor *et al.*, 2003). In central French Guiana greenstones, such metamorphism is essentially in the greenschist facies (Milesi *et al*., 1995).The pervasive presence of andalusite in the inner parts of thermal aureoles around diapirs dated at 2.15 Ga and 2.13 Ga show that pressure conditions have not exceeded 4 kb (Delor *et al.*, 2003). In central Suriname the metavolcanics and metasediments were metamorphosed in the pumpellyite-actinolite and greenschist facies, accompanied by regional development of schistosity (Veenstra, 1970). A later low-amphibolite-facies metamorphism, accompanied by deformation, only affected the metavolcanics and metasediments in the vicinity of the TTG batholiths and also affected the outer zones of the batholiths themselves. The metamorphism and deformation probably occurred during later stages of diapiric ascent of the batholiths.

Intermediate-pressure regional metamorphism associated to D2a migmatization has been documented in the southern greenstone terrains of French Guiana through the succession biotite-garnet-staurolite-kyanite-sillimanite isometamorphic zones (Marot, 1988; Delor *et al.*, 2003). Further P-T conditions for D2b metamorphism have been discussed specifically for the French Guiana upper detrital unit which has undergone only the D2 event. Pressure conditions have been re-evaluated to 3-4 Kb with temperatures below 550 °C (Delor *et al*., 2003), with a specific counterclockwise PT path argumented on the basis of an andalusite/kyanite retrograde path, first described by Vanderhaeghe *et al*. (1998).

From a petrological point of view, and despite an apparent higher-temperature imprint in some parts of the greenstone belt, D1 and D2 metamorphic gradients in French Guiana and Suriname are symptomatic of medium to low pressure. For both D1 and D2 tectonothermal events, the metamorphism is considered to be due to both TTG and granitic plutonism, with evidence of thermal aureoles, in a global context of low to moderate crustal thickening (Delor *et al.*, 2003).

The data presented above indicate that:

- D1 regional metamorphism and deformation in the French Guiana-Suriname greenstone belt is at least as old as the *ca*. 2.15-2.13 Ga central TTG complex of French Guiana and co-eval greenstone metavolcanics preserved from D2 reworking (Delor *et al.*, 2003). This predates considerably the UHT metamorphism in the Bakhuis belt at 2.07-2.05 Ga. With D1 being interpreted as the result of N-S plate convergence, leading to oceanic crust consumption and TTG island-arc magmatism (Voicu *et al*., 1997; Vanderhaeghe *et al.*, 1998; Delor *et al.*, 2003), D1tectonometamorphism may have started as early as 2.18 Ga (age of the oldest TTG: Delor *et al.*, 2003) and has lasted down to 2.13 Ga (age of the youngest TTG: Delor *et al*., 2003).

- D2 deformation starting at *ca* 2.10 Ga was accompanied by syntectonic emplacement of a granitic suite in a regional context dominated by sinistral shearing, and led to the formation of pull-apart basins (D2a) with detrital sequences. Subsequent deformation and metamorphism of these detrital series at 2.07-2.06 Ga was associated to local dextral shearing (D2b), and to contemporaneous metaluminous monzogranite and pegmatite emplacement. D2 is considered as marking the change from N-S to oblique plate conve rgence. The D2b metamorphism in the greenstone belt at 2.07-2.06 Ga is co-eval with the UHT metamorphic climax and deformation in the Bakhuis belt at 2.07-2.05 Ga.

- The D1 to D2 tectonothermal continuum in the greenstone belt is characterised by low to moderate crustal thickening (Milesi *et al.*, 1995; Delor *et al.*, 2003), and further by low erosion rates as pointed out by Voicu *et al.* (2001). These data do not allow an interpretation of the higher-grade metamorphic domains of the Guiana Shield in terms of a modern collision orogenic style where crustal melting and associated granulite genesis reflect late intracontinental crustal thickening.

The Bakhuis UHT metamorphism does not appear to be the final stage of Transamazonian metamorphism. There is evidence for even younger metamorphism and related magmatism in the central part of the Shield, as shown by granulite-facies metamorphism poorly constrained at about 2.0 Ga and charnockite magmatism at 1.97-1.93 Ga. Both high-grade metamorphism and magmatism occurred at least 50 - 100 Ma later than in the Bakhuis belt.

In conclusion, the Transamazonian tectonometamorphic continuum associated to oblique plate convergence may have been a rather protracted event with successive stages D2a, dated at *ca*. 2.11-2.08 Ga, D2b, dated at *ca* 2.07-2.05 Ga and probably D2c dated at *ca*. 2.0-1.93 Ga. D2 metamorphism culminated to granulite metamorphism first in the Bakhuis belt, at 2.07-2.05 Ga (D2b), and as late as 1.93 Ga along D2 strike in the Roraima-Kanuku-Coeroenie belt.

Continental-scale relationships between the Bakhuis belt and the other Paleoproterozoic domains

Paleoproterozoic structuring shows superimposed, but easily distinguishable, unconformable or crosscutting domains. Moreover, the major WNW-ESE trends of the Paleoproterozoic domains are well dated as being mainly the result of D2 transcurrent shearing (Fig. 2). Here we describe the overall partitioning of the Paleoproterozoic plutonometamorphic domains in order to extract a geodynamic scenario.

i) The Early Paleoproterozoic tonalite/trondhjemite/granodiorite – greenstone belts (hereafter TTG-GS) formed between 2.18 and 2.13 Ga (Delor *et al.*, 2000, 2003) and can be traced for about 1000 km in the northern part of the Shield, from the Amazon delta to the Orinoco River. Apart from internal structures in TTG complexes, where concentric fabrics trends are attributed to the D1 event (Delor *et al.*, 2003), the dominant structural trends in the Shield are the result of a pervasive Late Transamazonian structuring (D2).

From east to west, the dominant northwesterly trend of the southern part of the TTG-GS belt seen in Amapá and French Guiana, progressively veers to a northerly direction in Suriname, where it abuts against the northeasterly trending granulite belt of the Bakhuis Mountains. The northern part of the belt, i.e. along the coastlines of French Guiana and Suriname, exhibits a symmetrical, though less pronounced, bend and also converges onto the Bakhuis Mountains. The TTG-GS belt re-appears on the western side of the Bakhuis granulite belt and extends again to the west with a progressive trending curve from northeasterly (near the Bakhuis belt) to East-West (in Guyana) and finally to southeasterly trends against another granulite belt - the Imataca complex. At the shield scale, the TTG-GS belts show clearly a “pinch and swell” structuration

ii) High-grade (amphibolite- and granulite-facies) rocks from the Roraima-Kanuku-Coeroenie belt follow conformably the southern limit of the TTG belts and are in the Coeroeni area in SW Suriname at a right angle with the Bakhuis granulite belt. It is of special interest for this study to note the lithological continuity from the NE-SW trends in the Roraima and Kanuku branch to the NW-SE trend of the Coeroeni branch, with an intermediate E-W trend in East Guyana near the Essequibo river and Corantine rivers, at the border with Suriname.

iii) The prominent Uatumã acid plutono-volcanic suite displays the same regional curving trends as the TTG-GS belts, although it postdates the TTG-GS belts and partly hides the boundary between the Bakhuis granulites and western and eastern TTG-GS belts. To the SW, the suite is interrupted locally by the Mesozoic Takutu basin (Fraga *et al.*, 1997). The western extension of this acid plutono-volcanic suite, although partly hidden below Roraima Paleoproterozoic detrital basins, can be traced to the extreme North-West where it interrupts the Imataca granulite belt.

At the Shield scale, the Transamazonian D2 structural trends display an apparent “pinch and swell” structuration with two E-W continental-scale TTG-GS boudins limited by three granulite domains, Imataca, Bakhuis and Eastern Amapá. The Imataca and Bakhuis belts exhibit clear N-E trends, at a right angle with the contiguous continental scale boudins. For the eastern Amapá belt, along the Amazon River mouth, a N-E trend is only suggested by the zone of low-dip foliation inside which 2.05 Ga charnockite occurs.

From a chronological point of view, Sm-Nd data for the Bakhuis belt are also pointing to dominant Paleoproterozoic model ages and imply that the high-grade rocks in the belt were not formed by reworking of previous Archean basement, but result from the filling of a basin/trough from Paleoproterozoic juvenile TTG-greenstone areas.

Mantle upwelling at 2.07-2.05 Ga has been interpreted as the cause of the UHT metamorphism in the Bakhuis belt (de Roever *et al.*, 2003). The counterclockwise P-T path recorded by the Bakhuis granulites shows that a high-T gradient due to this mantle upwelling was accompanying initial burial of Bakhuis supracrustals, without substantial

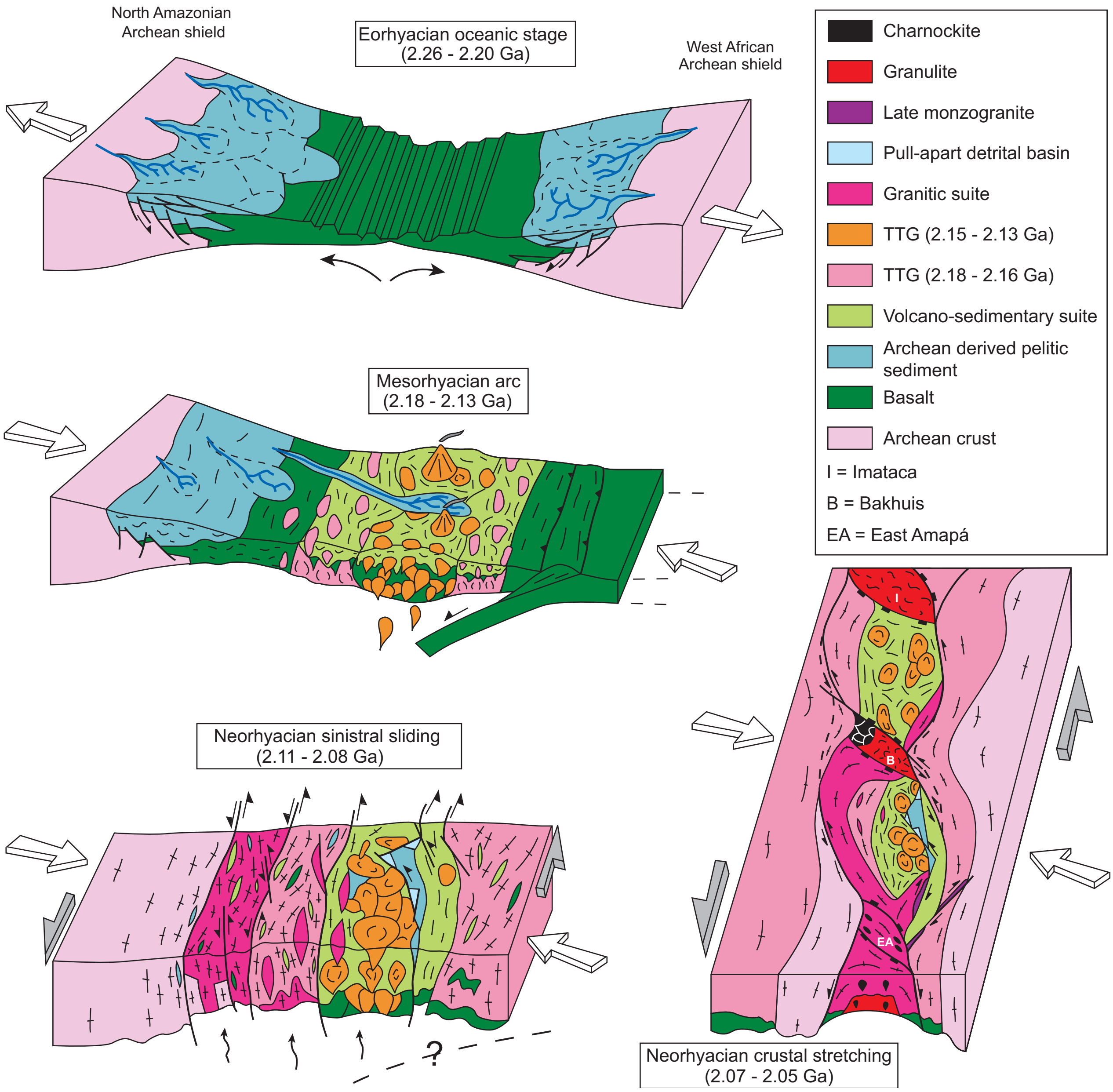

Fig. 3.- A geodynamic evolution model for the Guiana shield Paleoproterozoic terrains.

Fig. 3.- Evolution géodynamique des terrains paléoprotérozoïques du Bouclier guyanais.

crustal thickening. The absence of substantial crustal thickening is also indicated by the isobaric to near isobaric cooling path registered by the UHT rocks.

As conclusion we propose that the 2.07-2.05 Ga Bakhuis granulite belt is the result of continental-scale boudinage, enhanced by sinistral shearing of pre-existing Transamazonian (2.25-2.08 Ga) greenstone crust. Furthermore, we tentatively propose that the 2.0-1.93 Ga granulites and charnockites from the western end of the Roraima-Kanuku-Coeroenie belt represent a still later stage of sinistral shearing, postdating the Bakhuis belt. This is further discussed in the next chapter as part of a comprehensive Transamazonian geological scenario from i) earliest juvenile oceanic crust, followed by ii) TTG-Greenstone belt crustal growth by plate consumption, then iii) intracontinental sinistral shearing with granitic magmatism, and late iv) crustal stretching and mantle upwelling leading to granulitic metamorphism.

Geodynamic discussion

Integrating the whole set of available petrostructural and isotopic data, we propose a revised geodynamical model for the Guiana Shield (Fig. 3). For the earlier stages of

Transamazonian structuration, this proposal builds on the geodynamic model proposed by Vanderhaeghe *et al*. (1998) and recently refined by Delor *et al.* (2000, 2003), for the spatial relationships and chronology of TTG and granitic domains during the 2.26-2.08 Ga period. The articles mentioned have provided detailed arguments about the early Transamazonian stages of ocean formation and consumption in a model of island-arc genesis. Therefore, this chapter will present only briefly the discussion of Eorhyacian to Mesorhyacian geodynamic evolution, and the reader should refer to Delor *et al*. (2003) for further details. Following brief accounts at the 34th international geological congress and 7th symposium on Amazonian geology (Delor *et al.*, 2000, 2001) this paper gives more attention to the time period younger than 2.10 Ga, with specific reference to the development of Late-Transamazonian granulite belts.

Eorhyacian: juvenile oceanic crust (2.26-2.20 Ga)

Mantle extraction processes, starting at 2.26 Ga, between the once joined southern (Amazonian) and northern (African) Archean plates, have led to the individualization of an oceanic crust of which gabbroic remnants have been recognized in French Guiana (Vanderhaeghe *et al*., 1998; Delor *et al*., 2003). The "Île de Cayenne" trondjhemitic/gabbroic formations have provided zircon ages as old as 2.21-2.22 Ga for some gabbros and for some trondhjemites derived from intra-continental tholeiitic magma. On the southern limb of the French Guiana TTG-greenstone domain, inherited ages in migmatitic gneisses point to protolith ages as old as *ca.* 2.2 Ga. Sm-Nd data for the Ipitinga greenstones (MacReath and Faraco, 1997) point to Eorhyacian oceanic crust as old as 2.26-2.20 Ga.

Mesorhyacian: D1 convergence versus multi-pulse TTG growth (2.18-2.13 Ga)

The Tonalite-Trondjhemite-Granodiorite (TTG) suites and co-eval greenstone belts can be traced out from the western Archean margin of Imataca in Venezuela through Guyana to Suriname, French Guiana and Brazil. They reflect the consumption of juvenile crust during early frontal (NS) collision stages of Transamazonian plate tectonics. The timing and geometry of TTG magmatism has been deciphered quite precisely in French Guiana, with diachronous pulses occuring between 2.18 Ga and 2.13 Ga. An apparent internal younging direction of accretion is indicated by the position of the 2.15-2.13 Ga Central French Guiana TTG domain between northern and southern TTG domains dated at 2.18-2.16 Ga. This is interpreted in terms of a progressive consumption of juvenile crust during N-S convergence of the Amazonian and African Archean blocks resulting from a major southward-directed subduction. The fingerprint of Archean inheritage in the greenstone pelitic terms is witnessed by negative $\varepsilon_{(Nd)t}$ values and Archean zircons, while the positive $\varepsilon_{(Nd)t}$ characteristics of TTG and greenstone volcanics do support the juvenile character of early Transamazonian magmatism (Delor *et al*., 2003).

Neorhyacian: D2a sinistral sliding versus granitic magmatism (2.11-2.08 Ga)

Syntectonic granitic accretion reflects the evolution from early N-S oriented plate convergence (D1) to a progressively stronger imprint of sinistral shearing as the result of left-lateral sliding (D2a) motions between a north-Amazonian Archean plate at south and a west-African Archean plate at north. This D2a sinistral deformation event also led to the formation of pull-apart basins (Fig. 3).

Delor *et al.* (2003) described *in-situ* migmatization of TTG under low- to moderate-pressure conditions. This would point to anomalous thermal gradients, which can best be interpreted in terms of a mantle perturbation. The authors also point to the occurrence of Mg-K magmatism (amphibole- and/or pyroxene-bearing granite/granodiorite); mantle-crust interactions might be responsible for such high-temperature granites.

Neorhyacian: D2b crustal stretching versus granulite-belt formation (2.07-2.05 Ga)

The formation of Paleoproterozoic granulite belts in the framework of TTG-greenstone and granitic domains is the ultimate product of continental sinistral shearing between 2.07 and 2.05 Ga (Fig.3). The revised geological synthetic map of the Guiana Shield emphasizes the late-Paleoproterozoic crustal stretching with two E-W TTG continental-scale boudins limited by three granulite belts, Imataca, Bakhuis and eastern Amapá. The ultrahigh-temperature metamorphism in the Bakhuis belt can only be explained by mantle upwelling, to account for the very high geothermal heating during burial. Exhumation by normal faulting may have initiated as early as *ca*. 2.05 Ga This interpretation is at considerable variance with Santos *et al*. (2000) model according which the Bakhuis belt is highlighted in terms of a main K'Mudku event dated at *ca*. 1.2 Ga. Despite their lower peak-metamorphic temperatures, the Imataca belt and Amapá charnockitic zone probably reflect a similar normal faulting process initiated at 2.05 Ga. In Amapá, melting veins controled by low-angle southwest-dipping normal faults have been dated at 2.05 Ga (Avelar, 2002). The retrograde path marked by cooling at constant to slightly decreasing pressures in the Bakhuis belt implies the absence of substantial crustal thickening.

Synchronous with granulite-facies metamorphism late metaluminous monzogranite was emplaced along WNW-ESE dextral strike-slip corridors in northern French Guiana. The corridors are "accommodating" the E-W stretching of the

Transamazonian crust between 2.07 and 2.06 Ga (Fig. 2a, 3). This D2b shearing postdates the formation of pull-apart basins. The sediments in the basins underwent low-grade metamorphism with a counterclockwise P-T path, which also gives account of a thermal perturbation during burial followed by isobaric cooling (Delor *et al*., 2003).

Orosirian: D2c deformation versus granulites (2.0-1.93 Ga)

In the high-grade Roraima-Kanuku-Coeroenie belt, the granulite metamorphism and synkinematic folding occurred around 2.0 Ga in the Coeroenie area (Priem *et al*., 1977) and the generation of (magmatic) charnockites in the Roraima state at 1.97-1.93 Ga (Fraga *et al*., 1997; Fraga, 2002). The regional trends of these granulites are parallel to pre-2.0 Ga strikes in the greenstone belts. At the scale of the Guiana Shield, and in terms of the proposed crustal-boudinage model, these 2.0-1.93 Ga rocks exhibit an arcuate shape, localised along the narrowest ("pinch") zone between the widest ("swell") zones of the greenstone belts. We tentatively propose that this late Orosirian granulite-facies metamorphism witnesses the final stages (D2c) of continental-scale stretching. Further isotopic studies in the Kanuku and Coeroenie areas are needed to support such a hypothesis.

Orosirian acid magmatism (ca. 2.01-1.96 Ga)

At the scale of the Guiana Shield the northern limit of the acid plutono-volcanic belt shows the same veering as the nearby Rhyacian TTG-GS belts and granitic domains. This and the observation of open folding suggest that at least part of this acid magmatic belt has suffered N-S to NE-SW regional shortening during the waning stages of Late-Transamazonian deformation. The rather few available zircon ages for the plutono-volcanic suite point to an age of 2.01-1.96 Ga (Schobbenhaus *et al*., 1994; Almeida *et al*., 1997; Brooks *et al*., 1995), which places them at the end of - but still within - the Transamazonian Orogeny. Also Reis *et al.* (2000) relate the suite to the end of the Transamazonian Orogeny.

The calc-alkaline characteristics of the Suite have been interpreted in terms of subduction-related arc magmatism, in a post-collisional setting (Reis *et al*., 2000). Nd isotopic characteristics of the acid volcanics and related granites from Venezuala (Cuchivero group) show that they are juvenile in nature, with model ages up to 2.2 Ga (Teixeira *et al*., 2002).

The 2.01-1.96 ages of the acid-plutono-volcanic belt support an emplacement synchronous with the high-grade metamorphism of the Roraima-Kanuku-Coeroenie belt, and therefore suggest some, as yet not understood, relationship.

Extensive further studies need to be carried out to bracket the full span of this Orosirian magmatic event, the more so since it covers one of the largest zones of acid volcanics in the world. We do not propose a tectonic sketch map for the Orosirian period. That type of study will certainly merge as a new challenge to check Orosirian geodynamic driven forces either as a continuation of previous Neorhyacian crustal stretching and mantle upwelling, or as a the initiation of a new orogenic cycle.

Conclusion

In this study, we discuss the development of the Bakhuis UHT belt in the light of an updated geological framework for the Guiana Shield. After debating the limits of an Archean basement in the southeastern part of the Shield, and presenting evidence of Mesoarchean growth and Neoarchean reworking, we summarize the initial growth of Paleoproterozoic terrains from the formation of a juvenile oceanic crust (2.26-2.20 Ga) to its consumption to produce TTG-greenstone belts (at 2.18-2.13 Ga) during D1 frontal plate convergence, between west-African and north-Amazonian Archean blocks. We then bring specific emphasis on the development of a second phase, D2, of oblique plate convergence. Its first stage, D2a, is marked by granitic magmatism and opening of pull-apart basins during the onset of major sinistral deformation (at *ca*. 2.11-2.08 Ga), while the subsequent stage D2b is marked by granulite metamorphism and charnockite magmatism at *ca*. 2.07-2.05 Ga.

At a regional scale, we highlight the trends of the TTG-greenstone belts which display an overall "pinch and swell" structure, with two E-W TTG-GS continental-scale boudins limited by three granulite belts, Imataca, Bakhuis and Amapá. We interpret that continental-scale boudinage in terms of late-Transamazonian crustal stretching, as a response to prolonged sinistral shearing at a continental scale. The Bakhuis belt shows granulite-facies metamorphism (dated at 2.07-2.05 Ga) and contemporaneous charnockite magmatism. Its granulitic metamorphism, at ultrahigh-temperature (UHT) and near UHT conditions, occurred as a response to a late-Transamazonian, mantle-driven thermal perturbation in a zone of maximum crustal stretching associated with normal faulting. The counterclockwise prograde PT path of the metamorphism in the Bakhuis belt is due to the very high thermal gradient during burial, which requires mantle upwelling as a heat source. Subsequent isobaric cooling in the Bakhuis belt reflects the progressive return to a normal geothermal gradient, in a moderately thickened crust.

We also propose that high-grade metamorphism at *ca*. 2.0-1.93 Ga reflects prolonged late-Transamazonian crustal stretching during D2. The contemporaneous character and nearby, side-by-side occurrence of acid volcanism and granulite metamorphism (associated with charnockitic magmatism) strongly suggests some relationship. The occurrence of granulite-facies metamorphism and intense folding as late as 2.0-1.93 Ga in the nearby high-grade belt indicates that the limited deformation and open folding of the acid volcanics cannot be considered anymore as an argument for their supposed anorogenic character.

In terms of prospective ideas, further studies will have to test the hypothesis of a possible Archean link between Amapá and southwestern Suriname (Coeroeni area), and to conclude (or not) on the existence of a preserved Archean margin along the western coastal limb of the Amazon. The westward extension of this Archean basement should help to refine the relative geometry and movement of the converging Amazonian and African Archean blocks, as well as possible links with magmatic provinces. As far as the Paleoproterozoic is concerned, isotopic constraints on TTG growth would have to be carried out in the light of recent data in French Guiana, to test the hypothesis of multi-stage or continuing growth, and the intra-arc younging direction highlighted in French Guiana. Also further evidence of UHT metamorphism should be searched for, as well as the significance of the Rhyacian-Orosirian transitional tectonothermal regime with emphasis on the initiation of the so-called Uatumã episode of acid volcanism. In the course of this ongoing re-appraisal, lithostructural analysis and absolute isotopic dating will have to be carried out together. Paleomagnetic investigation as recently developed successfully in Precambrian rocks from French Guyana (Théveniaut and Delor, 2003) will certainly merge as a third invaluable tool to bring further constraints of paleolatitudes, and their implications in terms of plate-tectonics vergence.

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