Chapter 3
The Proterozoic Basement of the Western Guiana Shield and the Northern Andes

Salomon B. Kroonenberg

3.1 The Amazonian and Orinoquian Basement

3.1.1 General Geology of the Guiana Shield

The Colombian Precambrian basement forms the westernmost extension of the Guiana Shield, the northern half of the Amazonian Craton (Fig. 3.1). Apart from two Archean nuclei, the Imataca high-grade belt in Venezuela (2.74–2.63 Ga; Tassinari et al. 2004a, b) and the Amapá high-grade belt in northern Brazil (2.65–2.60 Ga: Rosa-Costa et al. 2003), the largest part of the shield was formed in the Paleoproterozoic during the Trans-Amazonian Orogeny between 2.26 and 1.98 Ga. This orogeny resulted from the collision of the Archean parts of Amazonia with those of the West African Craton (Bispo-Santos et al. 2014). Two younger orogenic events are recorded along its western extremity, the Querarí Orogeny (1.86–1.72 Ga) in Colombia, western Venezuela and northwestern Brazil and the Grenvillian Orogeny in Neoproterozoic slivers in the Colombian Andes and the Andean foredeep (1.3–1.0 Ga, called Putumayo by Ibáñez-Mejía et al. 2011). Several phases of anorogenic magmatism have been distinguished as well, one around 1.89–1.81 Ga along the southern border of the shield and one Mesoproterozoic around 1.59–1.51 Ga in the western part (Fig. 3.2). All ages cited in this paper are U-Pb or Pb-Pb zircon ages unless otherwise stated.

The Trans-Amazonian Orogeny has developed in three phases, each of them producing distinguishing geological units (Kroonenberg et al. 2016). During the first phase between 2.26 and 2.09 Ga, a 2000 km long greenstone belt developed along the whole northern border of the Guiana Shield, from Venezuela (Pastora-Carichapo Group) through Guyana (Barama-Mazaruni Group), Suriname (Marowijne Greenstone Belt),

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Fig. 3.1 Guiana Shield and Brazilian Shield together form the Amazonian Craton. In black outcrops of Andean Precambrian. (Modified after Cordani and Sato 1999)

French Guiana and Amapá in Brazil (Vila Nova Group). It consists of a series of ocean-floor (ultra)mafic metavolcanics, island-arc intermediate and felsic metavolcanics, followed by turbiditic metagreywackes and epicontinental meta-arenites. The whole sequence is folded into broad synclinoria and intruded by tonalite, trondhjemite and granodiorite (TTG) plutons (Gibbs and Barron 1993; Sidder and Mendoza 1991; Delor et al. 2003; Cordani and Sato 1999; Cordani et al. 2000; Cordani and Teixeira 2007; Kroonenberg and De Roever 2010; Kroonenberg et al. 2016).

A second phase of the Trans-Amazonian Orogeny is evidenced by a discontinuous 2.08–1.98 Ga belt of high-grade rocks, consisting of the sinuous Cauarane-Coeroeni belt roughly parallel to the greenstone belt and the Bakhuis granulite belt intersecting it. It represents a rifting phase followed by sedimentation, volcanism and ultimately high-grade metamorphism with an anti-clockwise cooling path. The Cauarane-Coeroeni belt, defined by Fraga et al. (2008, 2009a) (formerly also called Central Guiana Granulite Belt), can be followed from southwestern Suriname

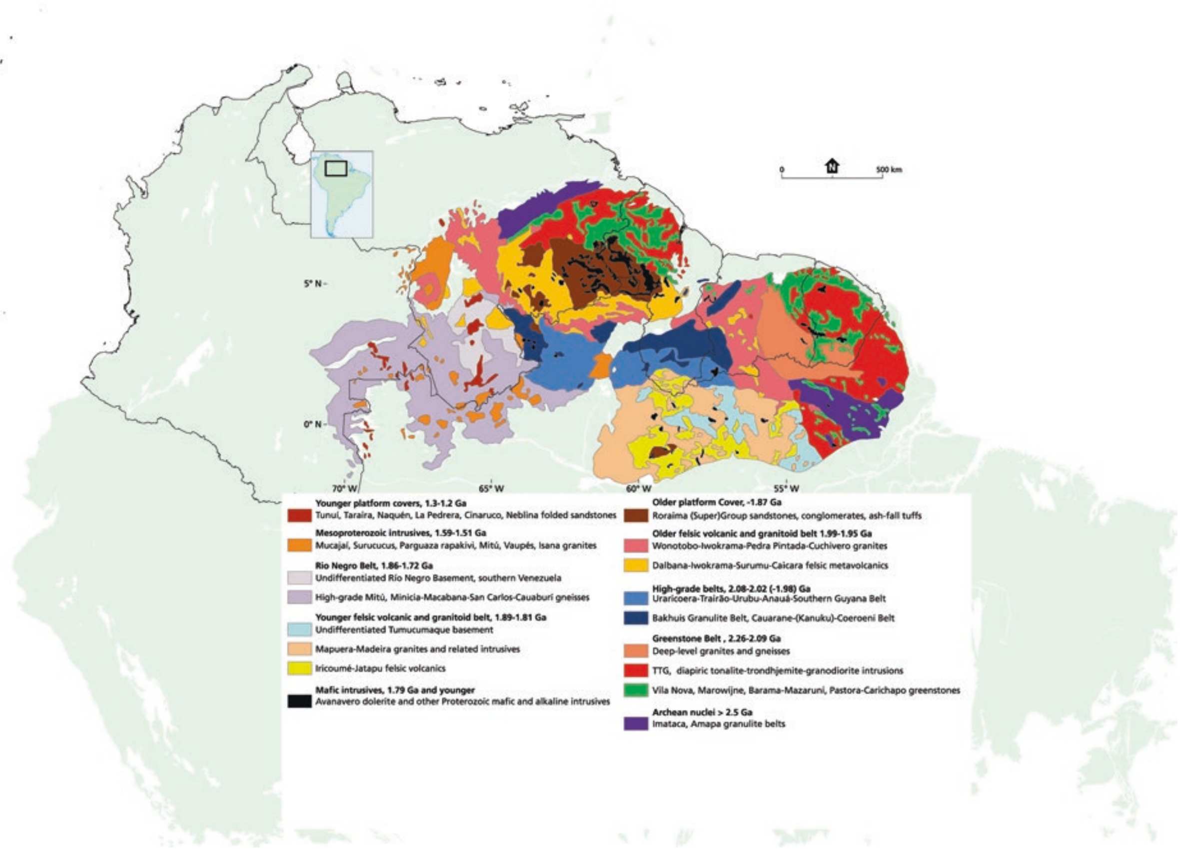


Fig. 3.2 Lithological-chronological-geological map of the Guiana Shield (Kroonenberg et al. 2016). © Cambridge University Press. Reprinted with permission

(Kroonenberg 1976; Priem et al. 1977), through Guyana (Berrangé 1977; Gibbs and Barron 1993), into the state of Roraima in Brazil (Fraga et al. 2008, 2009a, 2011). It consists of an essentially supracrustal sequence of pelitic and quartzofeldspathic metasediments, amphibolites, quartzites and calcsilicate rocks, metamorphosed to amphibolite facies to granulite facies. The Bakhuis granulite belt in Suriname is characterized by mafic to intermediate granulites and metapelitic gneisses showing ultra-high temperature (UHT) granulite-facies metamorphism around 2.08–2.03 Ga (De Roever et al. 2003; Kroonenberg et al. 2016).

The third phase of the Trans-Amazonian Orogeny is characterized by a huge outpour of mainly ignimbritic felsic volcanics and associated granitoid rocks around 1.99–1.95 Ga, in a broad W-E stretching belt, equally about 2000 km long, roughly parallel to the greenstone belt. The metavolcanics and associated plutons go by the name Caicara/Cuchivero in Venezuela, Iwokrama/Kuyuwini in Guyana, Surumú in Brazil, and Dalbana in Suriname. Charnockite and anorthosite intrusions in the Bakhuis Mountains and gabbroic plutons elsewhere in Suriname (Lucie Gabbro, formerly De Goeje Gabbro) show similar ages, together testifying of an important magmatic pulse in the whole northern Guiana Shield in an Andean-type setting, called Orocaima event by Reis et al. (2000). Inherited zircons from the Iwokrama rocks in Guyana gave the highest ages so far found in South America of 4.2 Ga (Nadeau et al. 2013).

In the southeasternmost part of the Guiana Shield, in the states of Amazonas and Roraima in Brazil, a younger series of anorogenic felsic volcanics (Iricoumé) and associated plutons (Mapuera) crops out, showing ages between 1.89 and 1.81 Ga, unrelated to the Trans-Amazonia Orogeny.

The crystalline basement of the Guiana Shield is overlain in its central part by a up to 3000 m thick platform cover of Paleoproterozoic sandstones and conglomerates with intercalations of volcanic ash, which since long have referred to as Roraima Formation or (Super)Group. There have been many speculations and geochronological analyses spent on the formation (e.g. Priem et al. 1973), until Santos et al. (2003), after an extensive review of all older data, established a very trustworthy age of the intercalated volcanics of 1873 Ma, of the underlying basement of Surumu metavolcanics of 1966 Ma and of intruding Avanavero dolerite sill of 1782 Ma. That means that the Roraima volcanic ashes are also coeval with the Iricoumé metavolcanics.

The westernmost part of the shield in Colombia, western Venezuela and northwestern Brazil is underlain by a block of much younger granitoid and high-grade metamorphic rocks, the Río Negro belt (Tassinari 1981; Tassinari and Macambira 1999), accreted to the main Trans-Amazonian part of the shield during the Querarí Orogeny (1.84–1.72 Ga). This block is intruded by a large amount of well-constrained plutons of largely anorogenic granitoid rocks dated around 1.55 Ma, the largest of which is the Parguaza rapakivi granite on the border of Venezuela and Colombia. This block is also locally overlain by slightly folded (meta)sandstone covers as in the Naquén, Pedrera and Tunuí ridges. This area will be discussed in more detail below.

Many rocks in the western part of the Guiana Shield suffered intense shearing and low-grade thermal metamorphism around 1.3–1.1 Ga (Priem et al. 1968, 1971; Gibbs and Barron 1993) probably caused by the continental collision of Amazonia and Laurentia during the Grenvillian Orogeny as evidenced by the Grenvillian granulites in the Colombian Andes and the basement in the adjacent Putumayo foredeep (Kroonenberg 1982; Cordani et al. 2010; Ibáñez-Mejía et al. 2011; see also par. 3.2.).

Several generations of mafic and alkaline intrusions have been recognized in the Guiana Shield, including the Avanavero one referred to above, but there are also younger generations such as the Käyser dolerite (1500 Ma) in Suriname and at last the ~200 Ma Jurassic dykes that mark the separation of South America and Africa (Deckart et al. 2005).

3.1.2 The Colombian Part of the Guiana Shield

In Colombia the basement crops out in large areas of eastern Amazonia and the eastern Llanos Orientales and is also exposed in many cataracts in major and minor rivers. Further westwards, towards the Andes, and southwards, towards the Amazon River, the basement is progressively covered by younger sediments of Ordovician to Cenozoic age. Nevertheless, drilling by oil companies into the Subandean foreland basins frequently struck basement (Ibáñez-Mejía et al. 2011), confirming its continuity beneath the sedimentary cover. Within the Andean cordilleras, large slices of Proterozoic rocks have been incorporated during later orogenies (Fig. 3.1).

The Colombian Precambrian constitutes the westernmost part of the Guiana Shield and comprises a small fragment of a mid-Paleoproterozoic (Late Trans-Amazonian) basement and large tracts of late Paleoproterozoic metamorphic basement, intruded by late Proterozoic syntectonic granites and Mesoproterozoic anorogenic granites. It is covered by low-grade metamorphosed and non-metamorphic sandstone plateaus and intruded by small Neoproterozoic basic and alkaline intrusions.

The first systematic description of the rocks of the Colombian part of the Guiana Shield has been published by Galvis et al. (1979) and Huguett et al. (1979) in the framework of the mapping project PRORADAM. The crystalline rocks of the Guiana Shield in Colombia south of the Guaviare River were designated by them as *Complejo Migmatítico de Mitú*. They describe it as having formed by 'sedimentation, volcanism and probably plutonism; later, the whole complex was metamorphosed and at last suffered mainly potassic metasomatism that affected the metamorphic rocks, imparting a granitoid aspect to the major part of the complex'. In their, now outdated, view, migmatization is a solid-state metasomatic process, not an anatectic process as nowadays considered. Unfortunately, their metasomatic conception coloured many descriptions, making it difficult to understand them in a modern way. In an excellent review of the Colombian Amazonian geology, Celada et al. (2006) reject the name as such, because of the inappropriate use of the term migmatitic, as many rocks in the area are clearly intrusive and not migmatitic in either sense. They propose to call the complex simply 'Complejo Mitú', a position later supported by López et al. (2007) and López (2012). We will retain the latter designation, inasmuch as we restrict the use of it to the high-grade metamorphic part of the basement.

Galvis et al. (1979) distinguish the following rock units in the Mitú complex: (1) Atabapo-Río Negro gneisses (including gneisses s.s., amphibolites, amphibolic gneisses, quartzites and quartz gneisses, quartzofeldspathic gneisses, aluminous gneisses and blastomylonites), (2) migmatitic granites and (3) Araracuara gneisses. However, these units have not been mapped separately.

Additional data are given in unpublished reports by De Boorder (1976, 1978). Kroonenberg (1985) revised the petrography of the PRORADAM samples. After PRORADAM, several mapping projects have been carried out in the basement. Bogotá (1981) and Bruneton et al. (1983) give a detailed description of the geology of the Guainía and Vichada departments in the framework of a mineral exploration project by COGEMA.

In the framework of the production of 1:100,000 geological map sheets of the country, the Servicio Geológico Colombiano has published a limited number of sheets in the Guiana Shield, in the area around Mitú (Rodríguez et al. 2010, 2011b) and near Puerto Inírida (López et al. 2010) and Puerto Carreño (Ochoa et al. 2012). On the Venezuelan side, the UGSG map of Hackley et al. (2005) is a major source of information and on the Brazilian side the 1:1 M map sheets NA.19 and SA.19 (CPRM 2004a, b). Preliminary 1:1 M geological maps of the same sheets showing the combined geology of the three countries have been prepared by the Commission for the Geological Map of the World (2009a, b). In the framework of this book, a combined map of the western Guiana Shield has been prepared, as well as a description of the sequence of events (Figs. 3.3, 3.4, and 3.5).

The following descriptions of major rock types are synthesis of observations by the authors mentioned above and own field and petrographic observations in 1979–1981 and 1985–1991.

3.1.2.1 Mid-Paleoproterozoic Caicara Metavolcanics

Along the Atabapo River and parts of the Río Negro river, fine-grained banded acid to intermediate metavolcanic rocks occur, which by their macroscopic aspect (fiamme, agglomeratic sections, banding) appear to be largely of ignimbritic origin (Figs. 3.6, 3.7, and 3.8; Kroonenberg 1985). Microscopically the very fine-grained granoblastic matrix testifies to the metavolcanic origin as well and shows that their metamorphic grade is much lower than in the other parts of the metamorphic basement. They are characterized by euhedral, normally zoned plagioclase phenocrysts and locally also bipyramidal quartz phenocrysts with deep embayments, in a typical fine-grained granoblastic groundmass (Figs. 3.9 and 3.10). Alkali feldspar phenocrysts engulfed finer-grained matrix grains. Metamorphism is evident from the preferred orientation of biotite crystals. Similar rocks also occur much further west along the rivers Yari, Mesay and Caquetá near the Araracuara Plateau.

Not all previous authors have recognized these rocks as metavolcanic. Galvis et al. 1979 and Huguett et al. 1979 call them Neises del Atabapo-Río Negro and consider them as blastomylonitic gneiss; Barrios (1985) and Barrios et al. (1985) describe them as Atabapo migmatites. López et al. (2010), referring to them as diatexites, show beautiful microscopic examples of outgrown phenocrysts and

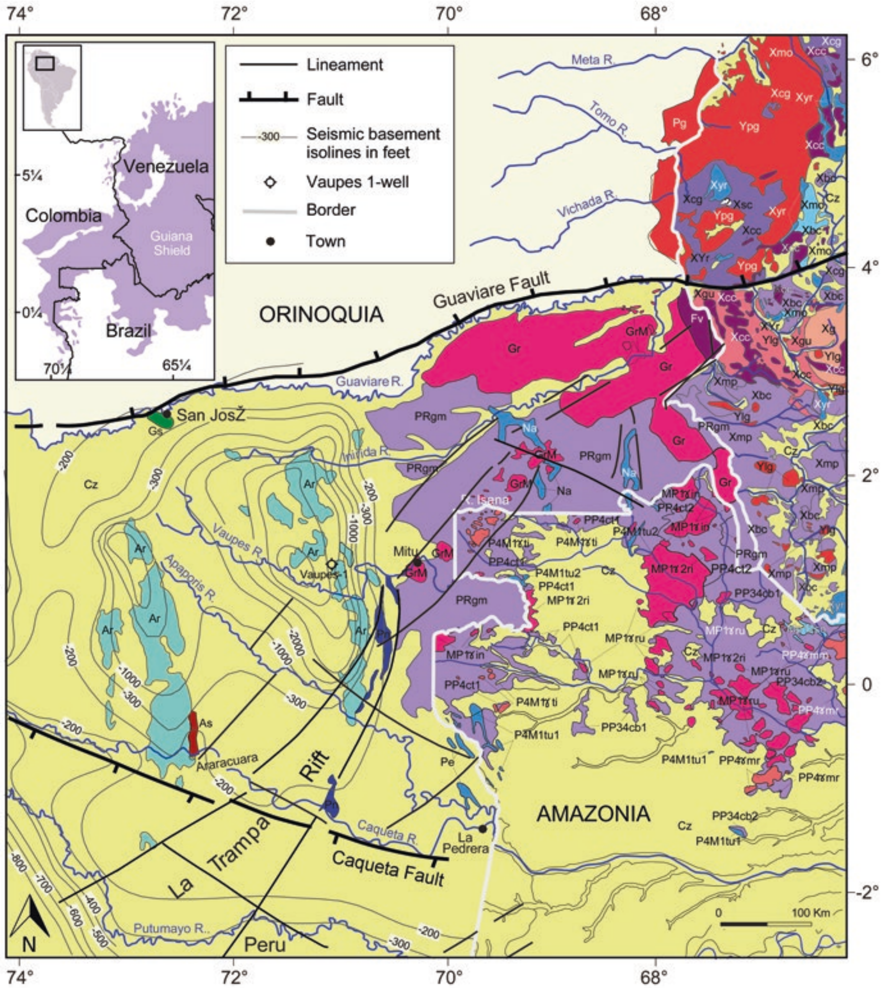


Fig. 3.3 Combined geological sketch map of Colombian, Venezuelan and Brazilian border. (Based on Bruneton et al. 1983; Gómez et al. 2007; Hackley et al. 2005; Almeida 2014 and unpublished own data)

recrystallized groundmasses from the Atabapo River outcrops without recognizing the metavolcanic character of the rocks. However, Bogotá (1981) and Bruneton et al. (1983) had already confirmed their metavolcanic origin and mapped them separately as such ('Atabapo Gneiss').

On the Venezuelan map of Hackley et al. (2005), the same rocks along the upper Atabapo River are mapped as the metavolcanic Caicara Formation (legend unit Cox et al. 1993; Wynn 1993), a name coined already by Ríos (1972), cited by Sidder and Mendoza (1991). We follow their nomenclature. In Venezuela only Rb-Sr isochrons for these rocks have been obtained: 1782 ± 72 Ma (Barrios et al. 1985) and 1793 ± 98 Ma (Gaudette and Olszewski 1985). However, in Brazil, Schobbenhaus

UNIT		Lithology	Age (Ma)	Method	Author
Cenozoic	Cz				
Araracuara Formation	Ar	Mudstones, shales, siliceous siltstones, metasiltsnones, feldspathic metasandstones and metasandstones with marble lenses.	500 - 435	Based on Acritarchs	Théry, J. M., Peniguel, T., & Haye, G. (1986)
Guaviare Syenite	Gs	Nepheline Syenite - Monzosyenite.	494 ± 5 577.8 ± 6.3 - 9	Ar-Ar U-Pb	Arango, M. I (2012)
Vaupés Basin	Subsurface	Sandstones Contact metamorphosed sandstone Granophyric diabase Intrusive granophyric gabbro	1) 804 ± 40 2) 1110 ± 51 3) 826 ± 41	1) K-Ar (Sandstones) 2) W R (Sandstones) 3) K-Ar (Gabbro)	Franks (1988)
Piraparaná Formation	Pn	Rhyodacitic volcano-sedimentary rocks quartzarenites and feldspathic sandstones.	920 ± 90	Rb-Sr	Priem *et al.* (1982)
Siliceous Intrusive Rocks	Ylg				
Parguaza Granite	Pg Ypg	Pink, rather dark-coloured very coarse grained rock with the typical rapakivi texture with large pink ovoid potassium feldspar megacrysts. Biotite and hornblende are the main mafic minerals.	1) 1545 ± 20 2) 1531 ± 39 3) 1392 ± 5 4) 1401 ± 2	1) U-Pb 2) Rb-Sr 3) U-Pb 4) U-Pb	1) Gaudette *et al.* (1978) 2) Gaudette *et al.* (1978) 3) Bonilla *et al.* (2013a, b) 4) Bonilla *et al.* (2013a, b)
Naquén Formation	Na	Metaquartzarenites. Metaconglomerates and metasandstones.	Deposition interval: 1580 - 1350 1) 1593 ± 6 2) 1880 3) 1225 4) 1334 ± 2	1) U-Pb (underlying basement) 2) U-Pb (youngest detrital zircon) 3) Rb-Sr (intruding mafic dyke) 4) Ar-Ar (mica age-metamorphic event)	1) Ibáñez-Mejía (2011) 2) Santos *et al.* (2003) 3) Priem *et al.* (1982) 4) Santos *et al.* (2003)
Pedrera Formation	Pe	Metaquartzarenites. Metaconglomerates and metasandstones.			
Tunuí Group	P4M1tu1 (Tunuí facies)	Quartzite and sericite-quartzite, with subordinated sericite-andalusite Quartzite, ferruginous quartzite, metapelite, graphite bearing pelite, phyllite and quartzarenite.			
	P4M1tu2 (Taiuacu-Cauera facies)	Banded, polideformed and migmatitic paragneisses.			
Cinaruco	Xyr	Micaceous quartzite, phyllite and conglomerate			McCandless(1962) & Cox et al (1991)
Neblina Formation	Mp12sn	Quartzarenite, quartzite and metaconglomerate.	1400 - 543	?	CPRM (2004b)
Moriche, Esmeralda Formations (undifferentiated)	Xmo	Ferruginous quartzites.			
Inhamoin Instrusive Suite	MP1γin	Porphyritic biotite monzogranite with titanite.	1) 1483 ± 2 2) 1536 ± 4	1) Pb-Pb 2) Pb-Pb	1) Almeida *et al.* (2013) 2) CPRM (2004b)
Río Uaupés Instrusive Suite	MP1γru	Porphyritic biotite monzogranite with titanite.	1518 ± 25	U-Pb	Santos *et al.* (2000)
Río Icana Instrusive Suite	MP1γ2ri	Muscovite-biotite granite, generally sheared and with magmatic flow structures, associated with a series of para-derived migmatitic sequence with cordierite, biotite and sillimanite.	1) 1521 ± 32 to 1536 ± 4 2) 1530 ± 21 to 1578 ± 27	1) Pb-Pb 2) U-Pb	1) Almeida *et al.* (1997) 2) Ibáñez-Mejía (2011)
Porphyroblastic Granite	Gr	Calc-alkaline basement.	1500 - 1550	?	?
Mitú Granite	GrM	Coarse-grained homogeneous unmetamorphosed biotite granite with pink alkali feldespar megacrysts and with very large titanite crystals as a typical microscopic characteristic.	1) 1552 2) 1574 ± 10	1) U-Pb 2) U-Pb	1) Priem *et al.* (1982) 2) Ibáñez-Mejía (2011)
Araracuara Syenogranite	As	Syenogranite.	1732 ± 17 1756 ± 08	U-Pb	Ibañez - Mejia, et al (2011)
Tiquié Granite	P4M1γti	Biotite-monzogranite, syenogranite and rarely grey-pink alkali feldespar granite, locally porphyritic.	1) 1746 ± 6 and 1756 ± 12 2) 1749 ± 5	1) Pb-Pb 2) Pb-Pb	1) CPRM (2004a) 2) CPRM (2004b)
Marie - Mirim Intrusive Suite	PP4γmm	Biotites syenogranite, monzogranite to orthogranite with riebeckite.	1756 ± 12	Pb-Pb	CPRM (2004b)
Marauiá Intrusive Suite	PP4γmr	Biotite (leuco) monzogranite, leucosyenogranite with riebeckite.	1746 ± 6	Pb-Pb	CPRM (2004b)
Calc - alkaline Granite	Xg				
Intrusive rocks (undifferentiated)	Xgu				
Cumati Complex	PP4ct1 (Querari facie) PP4ct2 (Tonú facie)	Hornblende-biotite (meta) granitoids and monzogranitic to dioritic orthogneisses. Tonalitic to granodioritic biotite orthogneiss, polideformed and locally migmatitic.	1) 1777 ± 4 2) 1785 ± 2	1) U-Pb 2) Pb-Pb	1) Almeida *et al.* (2013) 2) Almeida *et al.* (2013)
Cauaburi Complex	PP34cb1 (Tarsira facie) PP34cb2 (Santa Isabel facie)	Granitoids and monzogranitic augengneisses. Monzogranitic to tonalitic (mega) granitoids and orthogneisses, with subordinate amphibolites and migmatites.	1) 1807 ± 6 2) 1795 ± 2	1) U-Pb 2) Pb-Pb	1) Santos *et al.* (2003) 2) Santos *et al.* (2003)
San Carlos Complex	Xmp	Granite, granitic gneiss, augen gneiss and pegmatites.			
Mitú Complex	PRgm	Quartzofeldspathic gneisses, metapelitic gneisses, amphibolites, granulites.	1) 1859 2) 1740 ± 5	1) U-Pb 2) U-Pb	1) Gaudette and Olszewski (1985) 2) Cordani 2011, pers com
Basement Complex	Xbc	Granitics gneisses to foliated granodioritic and migmatitic gneisses.			
Felsic volcanics	Fv	Felsic volcanics, tuffs, agglomerates, red beds.			
Caicara Formation	Xcc	Ignimbritic acid metavolcanics.	1) 1782 ± 72 2) 1793 ± 98 3) 1966 ± 9 4) 1984 ± 9	1) Rb-Sr 2) Rb-Sr 3) U-Pb (obtained from the correlated Surumú Group 4) U-Pb (obtained fromthe correlated Surumú Group)	1) Barrios *et al.* (1985) 2) Gaudette and Olszewski (1985) 3) Schobbenhaus *et al.* (1994) 4) Santos *et al.* (2003)
Cuchivero Group	Xcg	Biotite granites, hypabyssals and granodiorites.	1) 1956 - 1932	1) Rb-Sr (Santa Rosalia and San Pedro granites)	1) Gaudette *et al.* (1978)

Fig. 3.4 Legend of geological map of 3.3

et al. (1994) published a first conventional U-Pb age of the equally correlated acid metavolcanic Surumú Group at 1966 ± 9 Ma (conventional U-Pb), and Santos et al. (2003) published a SHRIMP U-Pb age 1984 ± 9 Ma for a Surumu rhyodacite from the Roraima Province, immediately south of the Venezuelan Amazonas territory. Therefore I consider these rocks as not belonging to the Mitú complex but to an older Late Trans-Amazonian basement.

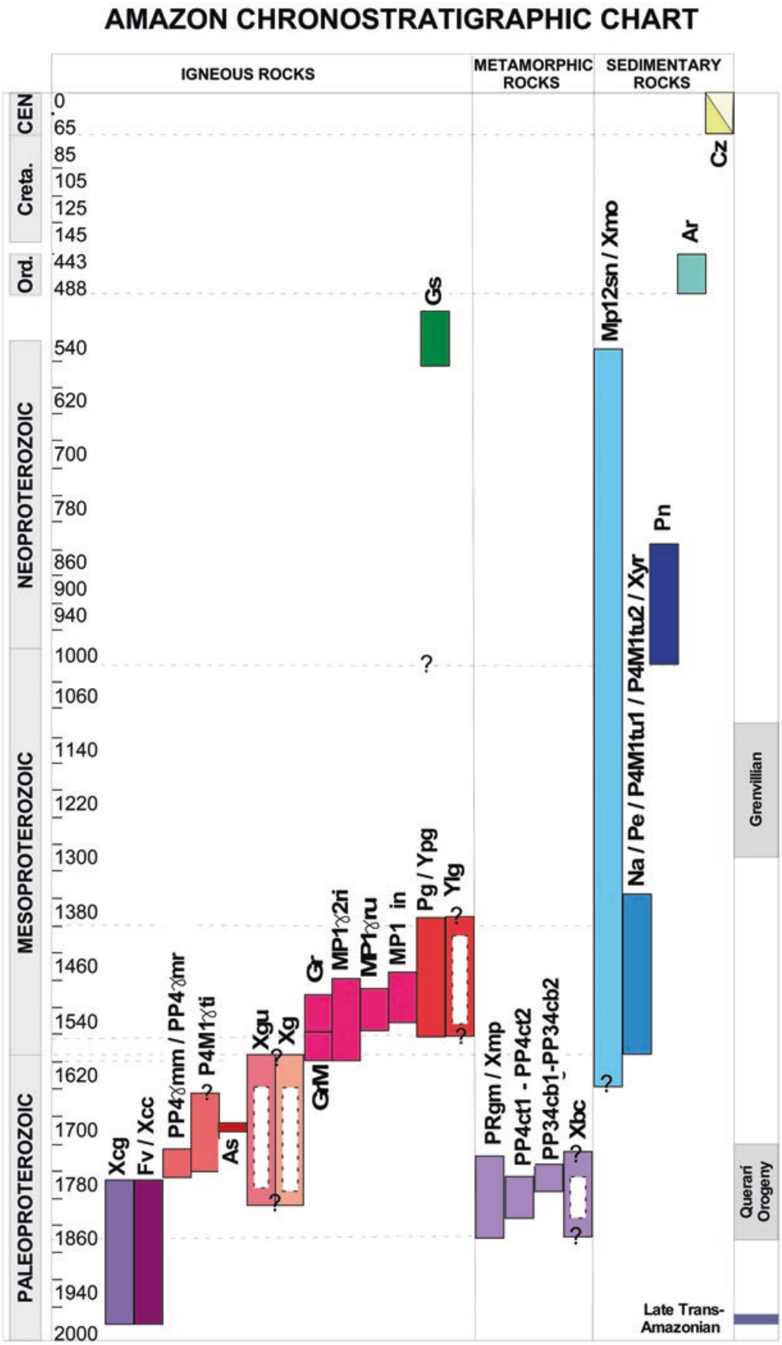


Fig. 3.5 Sequence of events in the Colombian Amazonian Precambrian

Fig. 3.6 Metaignimbrite with fiamme, Caicara Formation, río Orinoco near mouth Caño Guachapana, Venezuela. (Photo: Kroonenberg)

3.1.2.2 Late Proterozoic Metamorphic Basement (Mitú Complex)

Quartzofeldspathic gneisses Quartzofeldspathic gneisses form the bulk of the metamorphic rocks, comprising both homogeneous orthogneisses with large alkali feldspar megacrysts, such as the Caño Yí gneisses defined by Rodríguez et al. (2010, 2011b, Fig. 3.11), and migmatitic banded gneisses, which often by their compositional banding suggest a supracrustal origin (De Boorder 1978). Bruneton et al. (1983) present chemical arguments for a supracrustal origin of these rocks. Common types are (hornblende)-biotite gneisses, biotite-plagioclase (tonalitic) gneisses and biotite-muscovite gneisses, usually metamorphosed in the amphibolite facies. The latter crop out extensively along the Vaupés, Cuduyarí, Querarí and Papurí rivers. The distinction between orthogneisses and paragneisses is often difficult to make, and therefore they were not mapped separately during the PRORADAM campaign. However, Bogotá (1981), Bruneton et al. (1983) and Rodríguez et al. (2011b) did map them separately at larger scales.

On the Venezuelan side of the Guainía and Río Negro, these rocks have been mapped as belonging to the San Carlos metamorphic-plutonic terrane (Hackley et al. 2005), described by Wynn (1993) as granite, granite porphyry, granitegneiss and augengneiss, apparently largely ortho- in appearance, and to the basement complex: well-foliated, chloritized and well-foliated quartz-rich biotite-granite gneisses. Older descriptions include those of the Minicia migmatitic gneiss along the Orinoco and Macabana augengneiss along the Ventuari River in Venezuela (Figs. 3.12, 3.13, and 3.14; Rivas 1985).

On the Brazilian side of the Vaupés and Traira areas, they correspond with the facies Querarí of the Cumati series (hornblende-biotite (meta) granitoids and

Fig. 3.7 Primary layering in Caicara acid metavolcanic sequence, Guarinuma, Raudal Chamuchina, Río Atabapo. (Photo: Kroonenberg)

monzogranitic to dioritic orthogneisses: CPRM 2004a, b; Commission for the Geological Map of the World 2009a, b). In the Brazilian part of the Río Negro border area, they correspond with the Tonú facies of the Cumati series (tonalitic to granodioritic biotite orthogneisses, polydeformed, locally migmatitic) and the Cauaburí series, facies Santa Izabel (monzogranitic to tonalitic (meta)granitoids and orthogneisses, with subordinate amphibolites and migmatites).

Table 3.1 shows the U-Pb radiometric ages for the quartzofeldspathic gneisses in Colombia, Brazil and Venezuela. Priem et al. (1982) gave a conventional U-Pb age of 1846 Ma from a biotite gneiss along the Guainía River but discarded this age because of presumed older radiogenic lead. However, in view of the similar ages obtained by Gaudette and Olszewski (1985) and others, this date may indeed be a reliable age. The quartzofeldspathic gneisses in the basement therefore show a range in ages between 1.86 and 1.72 Ga. Recently ϵ_{Nd} values between +0,78 and −2,24 and T_{DM} ages between 2,40 Ga and 1,99 Ga have been obtained for these rocks, suggesting a largely juvenile character for them (Almeida et al. 2013).

Fig. 3.8 Recrystallized metavolcanic rock with grey plagioclase phenocrysts and dendritic biotite; Guarinuma, Raudal Chamuchina, Río Atabapo. (Photo: Kroonenberg)

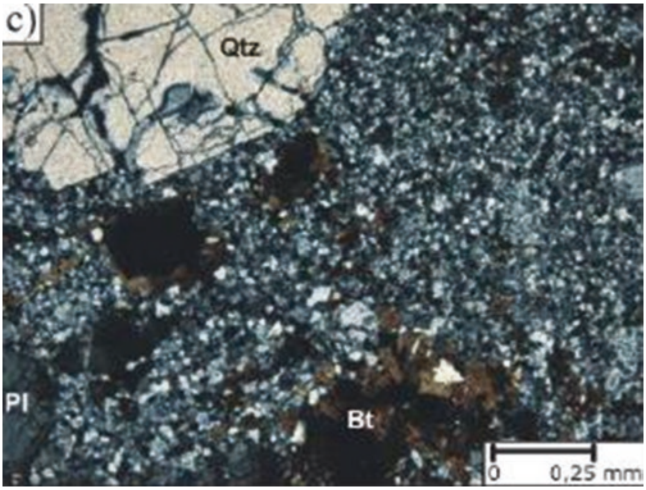


Fig. 3.9 Embayed quartz phenocryst in recrystallized groundmass in Atabapo metavolcanite (López et al. 2010)

Metapelitic gneisses Migmatitic biotite-(muscovite) gneisses of metapelitic composition, evidenced by the presence of aluminous minerals as sillimanite, andalusite, cordierite and locally also garnet, occur in isolated outcrops near Puerto Colombia in the Guainía River, in the upper Cuduyarí, in the Río Paca/Rio Papurí and in the Vaupés River just upstream from Mitú, but they have nowhere been mapped separately (Fig. 3.15; Galvis et al. 1979; Huguett et al. 1979; Kroonenberg 1980;

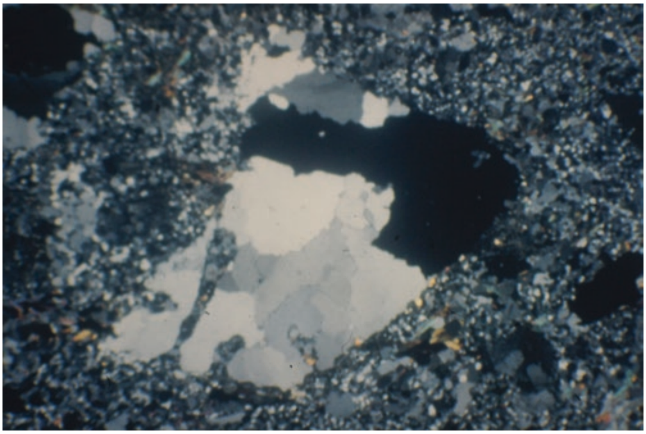


Fig. 3.10 Deformed bipyramidal quartz phenocryst with embayments in acid metavolcanic gneiss, IGM 130464 Araracuara. (Photo: Kroonenberg)

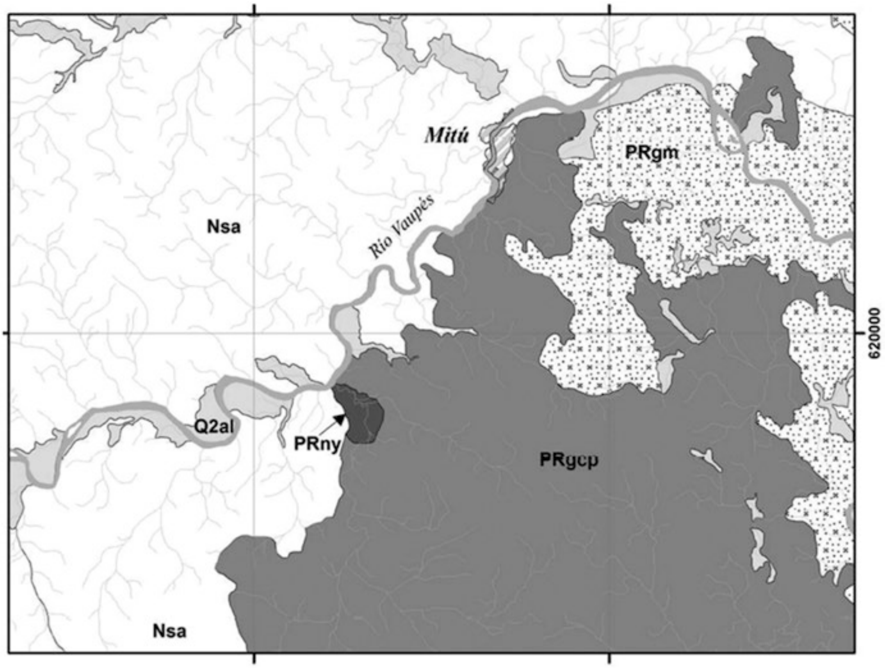


Fig. 3.11 Geological map of sheet 443, Mitú, showing PRgm, monzogranito de Mitú, PRny gneiss del caño Yi, PR gcp, granofels del Cerro Pringamosa. (After Rodríguez et al. 2011b)

Bruneton et al. 1983). Locally there is green spinel as an accessory. Metamorphic grade is in the amphibolite facies. Replacement of cordierite by higher-pressure minerals might indicate a later static phase of metamorphism (Kroonenberg 1980). No geochronological data of these rocks have been published.

Fig. 3.12 Augengneiss with aplite vein traversed by *en echelon* quartz veins: at least three phases of deformation. Guyanese geologist Chris Barron, Río Atabapo near Boca Caño Caname 1981. (Photo: Kroonenberg)

Fig. 3.13 Minicia supracrustal migmatitic quartzofeldspathic gneiss with crosscutting pegmatite vein, río Orinoco, Venezuela. (Photo: Kroonenberg)

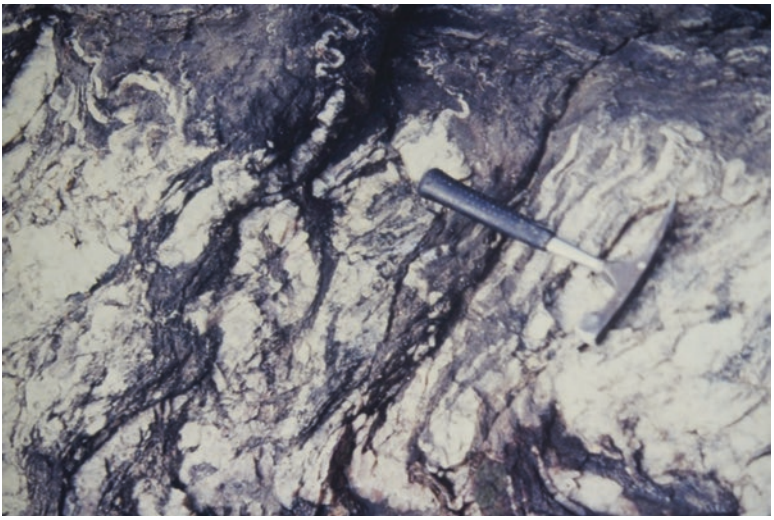


Fig. 3.14 Migmatitic quartzofeldspathic gneiss, El Chorro, río Caquetá, Araracuara. (Photo: Kroonenberg)

Table 3.1 Radiometric ages (U-Pb) for quartzofeldspathic gneisses in Colombia, Brazil and Venezuela

Sample nr.	Location, rock type	Method	Age (Ma)	Author
8697	Minicia gneiss (bi-gar)	Conventional U-Pb	1859	Gaudette and Olszewski (1985)
8699B	Macabana Gn. (bi-hbl)	Conventional U-Pb	1823	Gaudette and Olszewski (1985)
PRA 21	Guainía R, bi-gneiss	Co nventional U-Pb	1846 ± 95	Priem et al. (1982)
6850/6085	Casiquiare R., tonalite	Pb-Pb SHRIMP	1834 ± 24	Tassinari et al. (1996)
MS63	Cauaburi gneisses	U-Pb SHRIMP	1807 ± 6	Santos et al. (2003)
CG8	Cauaburi gneisses	Pb-Pb evaporation	1795 ± 2	Santos et al. (2003)
	Cumati gneisses	Pb-Pb evaporation	1785 ± 2	Almeida et al. (2013)
	Cumati gneisses	U-Pb SHRIMP	1777 ± 4	Almeida et al. (2013)
J-263	Caquetá, bi-granite	La-mc-ICP-MS	1732 ± 17	Ibáñez-Mejía et al. (2011)
PR-3215	Mesay, bi gneiss	La-mc-ICP-MS	1756 ± 8	Ibáñez-Mejía et al. (2011)
EP2Mi	Caquetá bi ms gneiss	ICP-MS	1721 ± 9.6	Cordani et al. (2016)
HB-667	Vaupés bi hbl gneiss	ICP-MS	1779 ± 3.7	Cordani et al. (2016)
J-36	Cuduyarí bi-ms granite	ICP-MS	1739 ± 38	Cordani et al. (2016)
J-127	CañoNaquén bi hbl gn	ICP-MS	1775 ± 3.7	Cordani et al. (2016)
J-199	Guainia bi-hbl gneiss	ICP-MS	1796 ± 3.7	Cordani et al. (2016)
PR-3001	Cuduyarí mig bi plag gn	ICP-MS	1740 ± 5	Cordani et al. (2016)

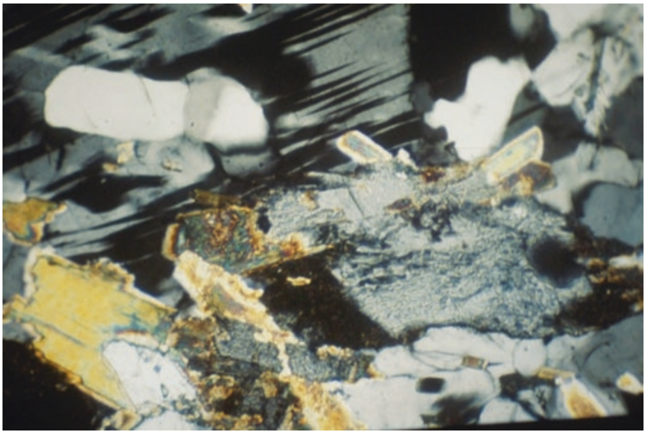


Fig. 3.15 Cordierite-sillimanite-andalusite biotite gneiss, IGM 130356, Puerto Colombia, Río Guainía. (Photo: Kroonenberg)

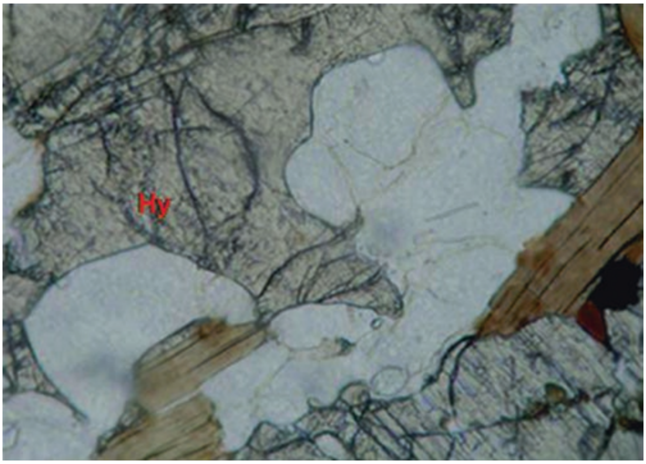


Fig. 3.16 Orthopyroxene in granulite, IGM 5000372. (Rodríguez et al. 2011b)

Amphibolites Amphibolites, consisting of hornblende, plagioclase +/− quartz and sometimes clinopyroxene or biotite, occur in thin bands and boudins intercalated in gneissic rocks, e.g. at the confluence of Querarí and Vaupés rivers.

Granulites A single granulite sample with orthopyroxene, biotite, plagioclase, quartz and subordinate alkali feldspar (Figs. 3.11 and 3.16) was described from the Sierra de Pringamosa south of Mitú by Rodríguez et al. (2010, 2011b). It is the only indication of granulite-facies metamorphism in the Colombian Amazones. No age data are available.

3.1.2.3 Late Paleoproterozoic Older Granites (Tiquié Granite)

Tiquié granite Along the Isana River in the Brazilian-Colombian border area, CPRM maps the Tiquié granite (biotite-monzogranite, syenogranite and rarely grey-pink alkali feldspar granite, locally porphyritic). Granite plutons have been mapped in this area on morphological grounds by Botero (1999), which coincide with outcrops of coarse-grained biotite granites along the Guainía River upstream from Manacacías. These A-type granites have been dated in Brazil in a range of 1746 ± 6 Ma and 1756 ± 12 Ma with some inherited ages from the Cumati-Cauaburi basement of 1784 ± 7 Ma e 1805 ± 8 Ma (Pb-Pb evaporation, CPRM 2004a). Sm-Nd data show an ϵ_{Nd} value of +4.05 and a T_{DM} model age of 1.82 Ga.

3.1.2.4 Mesoproterozoic Younger Granites (Mitú, Içana, Atabapo and Other Granites)

Mitú granite (or monzogranite; Rodríguez et al. 2011a, b) This is a coarse-grained homogeneous unmetamorphosed biotite granite with pink alkali feldspar megacrysts (up to 15 cm according to De Boorder 1976) and with very large titanite crystals as a typical microscopic characteristic (Figs. 3.17 and 3.18). The description resembles those of the El Remanso granite of the Inírida river and the San Felipe granite from the Río Negro of Bruneton et al. (1983) and on the Venezuelan side the San Carlos granite of Martínez (1985). Chemical analyses by Rodríguez et al. (2011a, b) show the metaluminous and anorogenic (A-type) character of these intrusions. On the Brazilian side of the border in the Vaupés-Papurí and Río Negro areas, these granites are mapped as Inhamoin granite and Uaupés granite, porphyritic biotite monzogranite with titanite (Dall'Agnol and Macambira 1992; CPRM (2004a, b); Reis et al. 2006; CGMW 2009a). Priem et al. (1982) obtained a conventional U-Pb zircon age of 1552 Ma for the Mitú granite. The Uaupés and Inhamoin granites have been dated at 1518 ± 25 Ma (Santos et al. 2000; CPRM 2004a) and 1483 ± 2 Ma (Pb-Pb evaporation), respectively (Almeida et al. 2013). A recent U-Pb LA-MC-ICPMS age for the Mitú granite of 1574 ± 10 Ma was obtained by Ibáñez-Mejía et al. 2011. Sm-Nd data show ϵ_{Nd} values between −1.85 and −2.37 and T_{DM} model ages between 2.05 and 1.97 Ga (Almeida et al. 2013).

Tijereto granophyre Another undeformed intrusive exposed along the Caquetá River, individualized by the PRORADAM authors as Granófiro de Tijereto, of intermediate and slightly alkaline composition (with magnesioriebeckite), shows a model Rb-Sr age of 1495 Ma according to Priem et al. (1982) and therefore fits in the same category of younger, Mesoproterozoic intrusives.

Içana medium-grained bi-mica granites Bruneton et al. (1983) mapped two distinct areas along the Río Negro, as consisting of medium-grained two-mica granites, without alkali feldspar megacrysts but locally with large muscovite flakes and

Fig. 3.17 Mitú granite, río Vaupés near Mitú hospital. (Photo: De Boorder 1976)

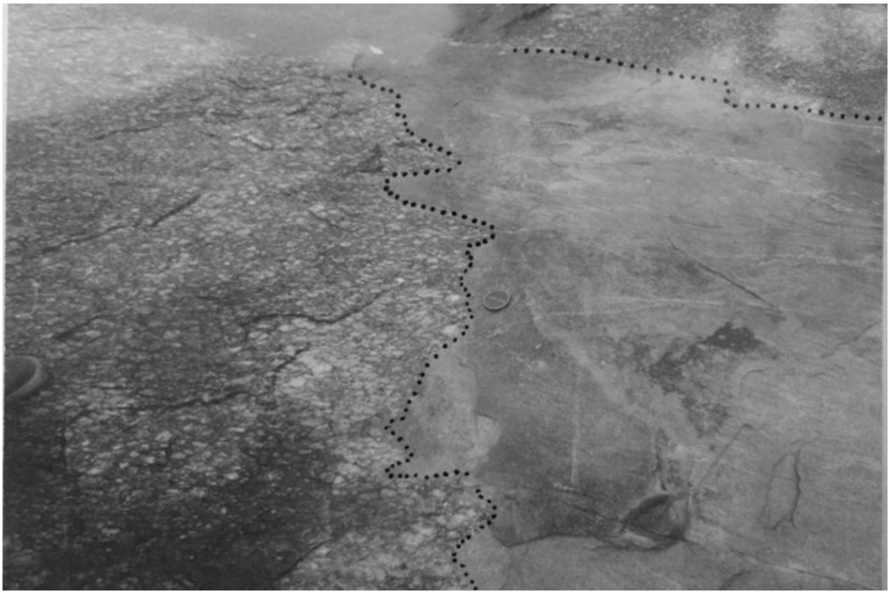


Fig. 3.18 Intrusive contact of megacryst granite into fine-grained gneisses, Río Papurí. (Photo: De Boorder 1976)

sometimes sillimanite. This would obviously be an S-type granite. This rock seems comparable with the Brazilian Río Içana Intrusive Suite, a muscovite-biotite granite, generally sheared, and with magmatic flow structures, associated with a series of para-derived migmatitic sequences with cordierite, biotite and sillimanite. The Brazilians map it along the Río Içana close to the Colombian border in the Río Negro area and along the Papurí border river near Yavaraté (CPRM 2004a; Reis et al. 2006). The Içana granites show ages ranging from 1521 ± 32 Ma (Almeida et al. 2007) to 1536 ± 4 Ma (Pb-Pb evaporation), besides some inherited ages from different basement types (1745 ± 13 Ma and 1803 ± 9 Ma; Almeida et al. 2013). Recently, Ibáñez-Mejía et al. (2011) obtained U-Pb LA-MC-ICPMS crystallization ages on zircons from two bi-mica monzogranites from the middle Apaporis River of 1530 ± 21 Ma and 1578 ± 27, apart from a considerable quantity of inherited zircons. Sm-Nd data show ϵ_{Nd} values of −3.05 and a T_{DM} model age of 2,04 Ga (Almeida et al. 2013).

Atabapo granite At San Fernando de Atabapo, a greyish-pink coarse-grained inequigranular leucocratic calcalkaline granite with characteristic blue quartz crops out over ~120 km^2 (Bruneton et al. 1983; Rivas 1985). Rb-Sr data indicate an age of 1617 ± 90 Ma (Gaudette and Olszewski 1985) or 1669 Ma (Barrios et al. 1985).

La Campana fine-grained (subvolcanic) granites Bruneton et al. (1983) distinguish various types of non-mappable fine-grained granites to aplites, supposedly late crystallization phases of the main magmatic pulses. Along the Yarí River near Araracuara, fine-grained granitic intrusions occur which appear to be related to the acid metavolcanics in this area (Fig. 3.19).

3.1.2.5 Mesoproterozoic Parguaza Rapakivi Granite

The Parguaza rapakivi granite forms a huge batholith of over 30,000 km^2, straddling the border of Venezuela and Colombia north of the Guaviare River. Most of the batholith is situated in Venezuela; in Colombia it only occupies isolated inselbergs in the Vichada department and cataracts in the Orinoco River (Gaudette et al. 1978; Bangerter 1985; Rivas 1985; Herrera-Bangerter 1989; Bonilla et al. 2013).

As Galvis et al. (1979) and Huguett et al. (1979) limit the Mitú complex to the crystalline basement *south of the Guaviare River*, the Parguaza rapakivi granite would strictly speaking not belong to the Mitú complex. In Venezuela the Parguaza rapakivi granite is known to intrude into a Paleoproterozoic basement older than the Mitú complex, the Caicara metavolcanics and the Santa Rosalia and San Pedro granites of the Cuchivero Group (Mendoza 1974; Sidder and Mendoza 1991; see above). Contact metamorphic aureoles are absent; most of the contacts are tectonic, though some apophyses of the Parguaza granite into Cuchivero rocks have been found along the Suapure River in Venezuela (Mendoza 1974; Herrera-Bangerter 1989).

The main granite is a pink, rather dark-coloured very coarse-grained rock with the typical rapakivi texture with large pink ovoid potassium feldspar megacrysts up to 8 cm, surrounded by a thin greenish plagioclase mantle (Figs. 3.20 and 3.21). Biotite and hornblende are the main mafic minerals. Apart from this main, wyborgite type, there are smaller bodies of less coarse pyterlite rapakivi granite, clinopyroxene- or sodic amphibole-bearing alkali granite and syenite (Bruneton et al. 1983;

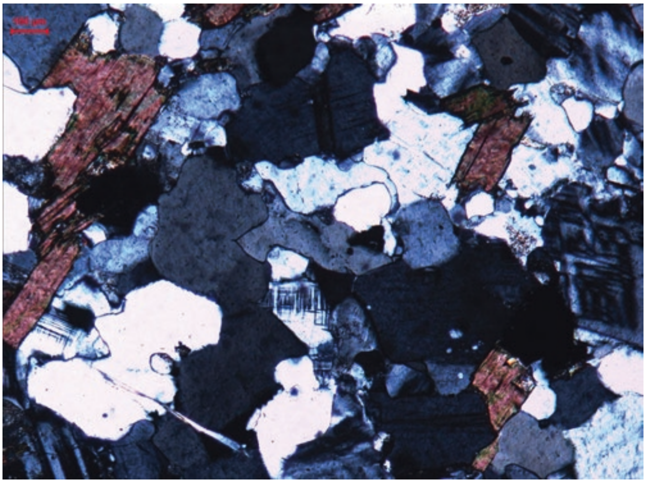


Fig. 3.19 Fine-grained subvolcanic granite, La Campana cataract, Yari river near Araracuara. (Photo: Kroonenberg)

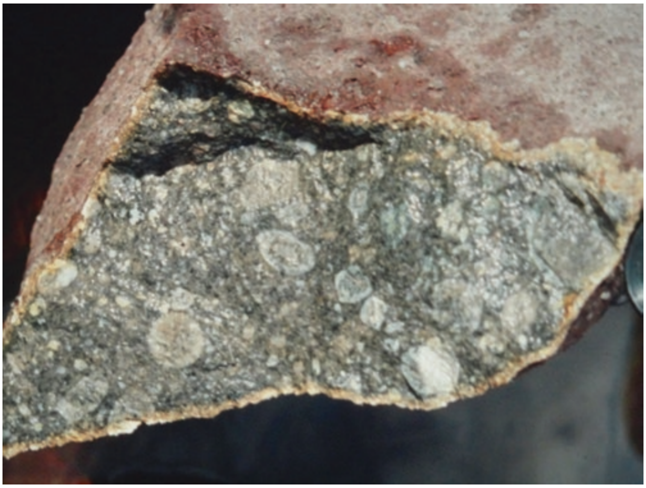


Fig. 3.20 Parguaza rapakivi granite, Caño Cupavén, Venezuela. (Photo: Kroonenberg)

Bangerter 1985; Herrera-Bangerter 1989; González and Pinto 1990; Bonilla et al. 2013, Bonilla-Pérez et al. 2013). In the main Venezuelan body, there are numerous xenoliths, abundant pink and green aplite veins, several, partly columbite-/tantalite-bearing pegmatites and late thin olivine basalt dykes with complex relationships to each other (Herrera-Bangerter 1989). Chemically it is a typical anorogenic peralkaline granite, with high FeO/MgO as many other rapakivi granites in the world. Gaudette et al. (1978) report a conventional U-Pb zircon age of 1545 ± 20 Ma and a

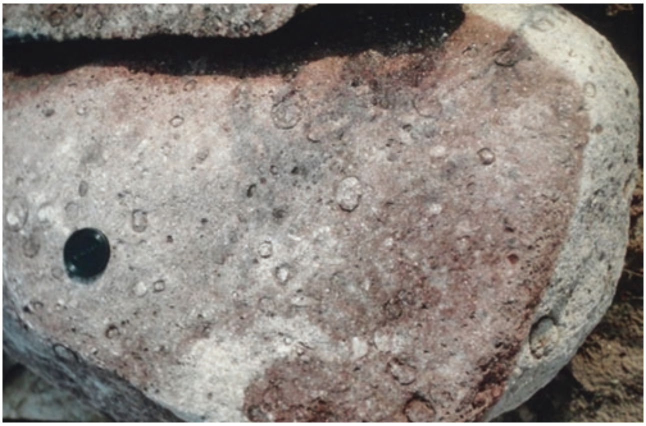


Fig. 3.21 Weathered surface of Parguaza rapakivi granite, showing differential weathering of unstable plagioclase rims around more stable alkali feldspars. Caño Cupavén, Venezuela. (Photo: Kroonenberg)

Rb-Sr isochron age of 1531 ± 39 Ma. Younger Rb-Sr isochron ages of about 1380 Ma were reported from around Puerto Ayacucho and San Pedro by Barrios et al. (1985); Bonilla-Pérez et al. 2013) present new LA-ICPMS data from the Colombian part of the batholith between 1392 ± 5 Ma and 1401 ± 2 Ma, i.e. considerably younger than the ages obtained by earlier authors. These ages not necessarily invalidate older data, as Mirón-Valdespino and Álvarez (1997) deduce from magnetic data and the distribution of Barrios (1985) Rb-Sr radiometric ages that the intrusion and cooling history of the batholith encompasses a prolonged period between 1480 and 1240 Ma, starting from an older core and a younger rim (Fig. 3.22).

3.1.2.6 Mesoproterozoic Tunuí Folded Metasandstone Formations

In the eastern part of the Colombian Guiana Shield, prominent N-S to NW-SE oriented ridges of folded low-grade metasandstones arise above the lowlands, the Naquén (Caparro in Brazil) and Caracanoa (or Raudal Alto) ridges in the Guainía Department and the Libertad (La Pedrera) and Machado (Taraíra) ridges in the Vaupés Department. The metasediments are strongly tilted, faulted and folded and form impressive escarpments up to 800 m (Fig. 3.23). Such ridges were first identified in Brazil as Tunuí Formation (Pinheiro et al. 1976; Renzoni 1989a), the name of a ridge in the continuation of the Naquén ridge into Brazil, and we will continue to use this name for the ensemble of the metasandstone formations (with the exclusion of the Piraparaná Formation, which will be discussed later). Unlike Almeida et al. (2002), we do not include in the Tunuí Formation the higher-grade migmatitic gneisses and amphibolites described by that author downstream from the Tunuí type locality in Brazil. Galvis et al. (1979) and Huguett et al. (1979) call the northern metasandstone occurrences Roraima Formation, which is unfortunate because the

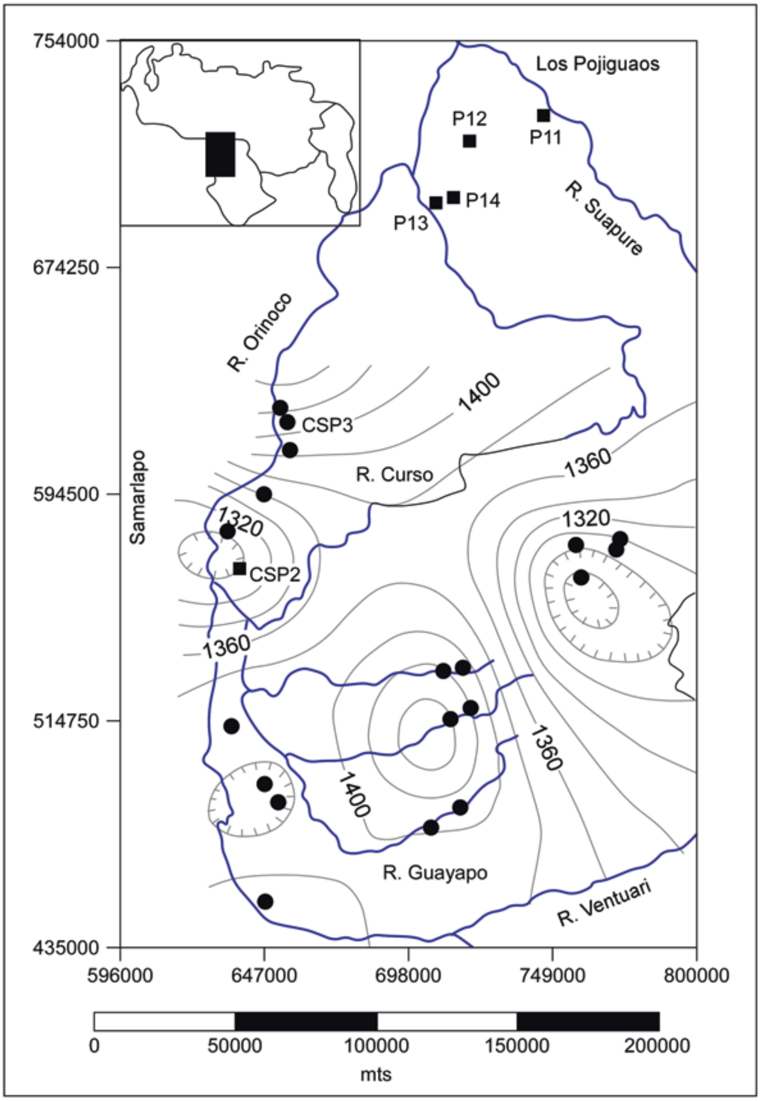


Fig. 3.22 Chrontour's Parguaza granite shows a crystallization history of >100 Ma (Mirón-Valdespino and Álvarez 1997). Reproduced with permission

Roraima Formation in Brazil, Venezuela, Guyana and Suriname is unmetamorphosed, though older (Priem et al. 1973; Santos et al. 2003).

The southern metasandstone occurrences in Colombia have received the name La Pedrera Formation from Galvis et al. (1979) because of slightly different lithologies, though the same authors admit that they offer great similarity with the northern occurrences. We include this formation into the Tunuí Formation. All metasandstone

Fig. 3.23 Northern extremity of Sierra de Naquén. (Source: Google Earth)

formations rest with unconformable and sheared contacts on top of the Complejo Mitú. Detailed stratigraphical and sedimentological studies have been made since then because of the discovery of gold in the conglomeratic sections of these formations.

Sedimentology and stratigraphy The *Naquén section* (Renzoni 1989a, b; Fig. 3.24; Galvis 1993) has a cumulative thickness of about 2000 m and consists of a non-fossiliferous series of ten fining-upwards sequences of quartz-rich metaconglomerates, metaquartzarenites and metamudstones, the latter often black and locally containing pyrite.

These sequences have been interpreted by Renzoni (1989b) as having been deposited in a fluvial environment by meandering rivers, possibly close to the sea, as some lenticular flaser-like sandstone laminae may point to tidal influence. Some of the coarse conglomerates may have been deposited in braided patterns in an alluvial fan environment. Based on the prograding character of the series, provenance of the sediments is probably from the north or northeast, though no paleocurrent data are available. The combination of fluvial with tidal characteristics leads Renzoni to infer a deltaic environment, though from the description of his sections,

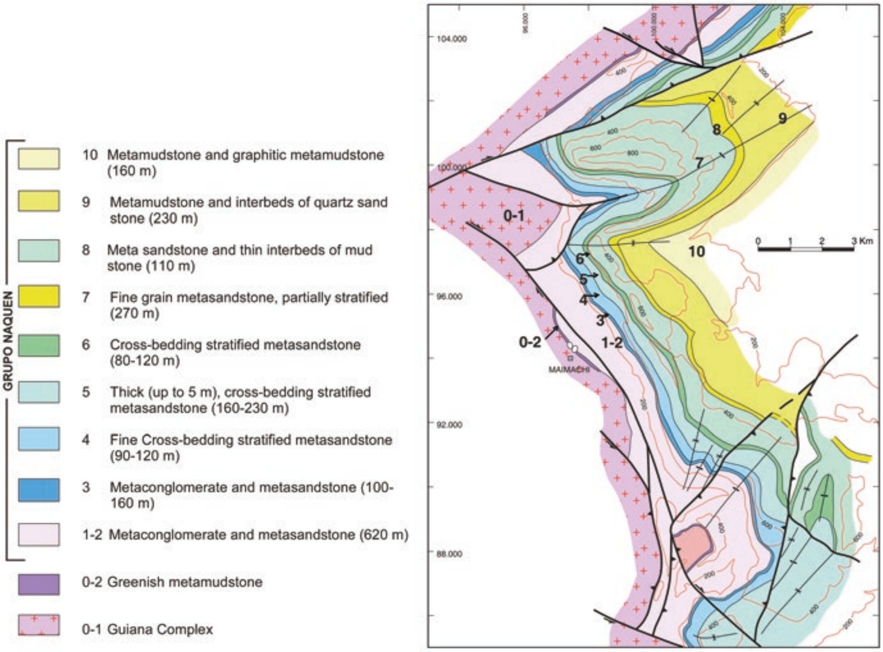


Fig. 3.24 Stratigraphy of the Tunuí Formation in the Naquén ridge, after Renzoni (1989a)

the fluvial character is largely predominant. Gold is usually concentrated in the conglomerates and conglomeratic sandstones, but also locally occurs in organic-rich mudstones close to unconformities, and is not only detrital but also remobilized by hydrothermal and supergene processes. Low-grade metamorphism is expressed in the lower parts of the sequence by complete welding of detrital grains in the sandstones and the development of coarse muscovite, though a preferred orientation is not evident. In the higher parts, metamorphism is less well expressed or not at all, and the grains are not welded (Galvis et al. 1979).

The *Caracanoa* or *Raudal Alto ridge* equally consists of at least 1000 metres of whitish quartz conglomerates and cross-bedded quartzites with phyllites at the base which rest unconformably upon the Complejo Mitú. The series is intruded by undated 'Campoalegre' diabase dykes (Galvis 1993; Carrillo 1995).

The *La Libertad range* north of the Apaporis River and close to La Pedrera has been studied in detail by Coronado and Tibocha (2000), also because of its gold potential (Fig. 3.25). The ridge is a southeast-plunging anticlinal-synclinal fold structure. They studied an 88 m sequence in which two major units are distinguished, a lower one consisting of monotonous metaquartzarenites (Fig. 3.26) and an upper one consisting of metaquartzarenites with phyllite intercalations. The quartzarenites often show trough cross-bedding and are transected by quartz veins and locally sheared. Phyllites consist mainly of muscovite. The sediments are thought to have been deposited in a fluvial to tidal environment (Fig. 3.27).

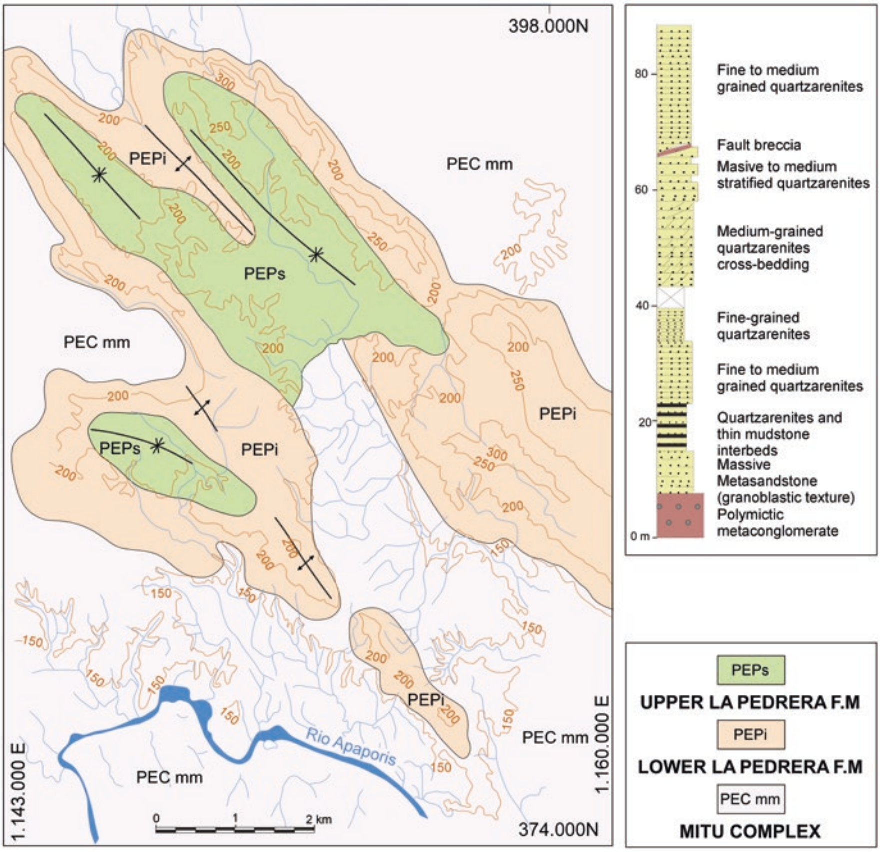


Fig. 3.25 Geological map La Libertad ridge (La Pedrera Formation), after Coronado and Tibocha (2000)

Low-grade metamorphism is evidenced by muscovite growth and locally andalusite blastesis in the finer sediments, especially in the lower parts of the sequence. Gold is mainly present in disseminated form and in narrow quartz veins in the lower part of the sequence. The contact with the underlying Complejo Mitú was observed by Galvis et al. (1979) as containing detachment folds due to shearing.

The *Machado ridge* in the Taraíra area forms a ca. 1000 m thick moderately SW-dipping monoclinal sequence (Figs. 3.28 and 3.29). It differs in several aspects from the three ridges described before. It has been explored for gold extensively by several companies, including Mineralco, Minercol, Cosigo and HorseShoe (Leal 2003; Ashley 2011), and small-scale mining is active. The sequence starts with up to 250 m of rhyolitic tuff (Mirador member of Carrillo 1995, Complejo Volcánico de Taraira de Cuéllar et al. 2003), and only on top of them the sequence of quartzconglomerates and quartz arenites starts. Two major members have been distinguished, a lower Peladero member with volcanic intercalations and horizons

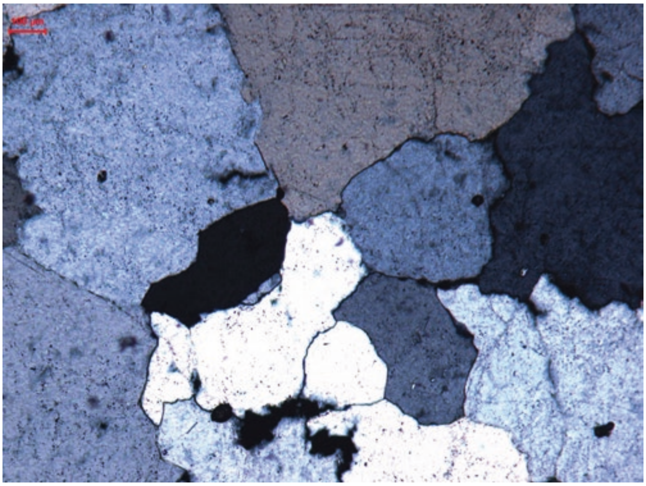


Fig. 3.26 Interlocking detrital quartz grains in La Pedrera metaquartzarenite, Quinché, río Caquetá. (Photo: Kroonenberg)

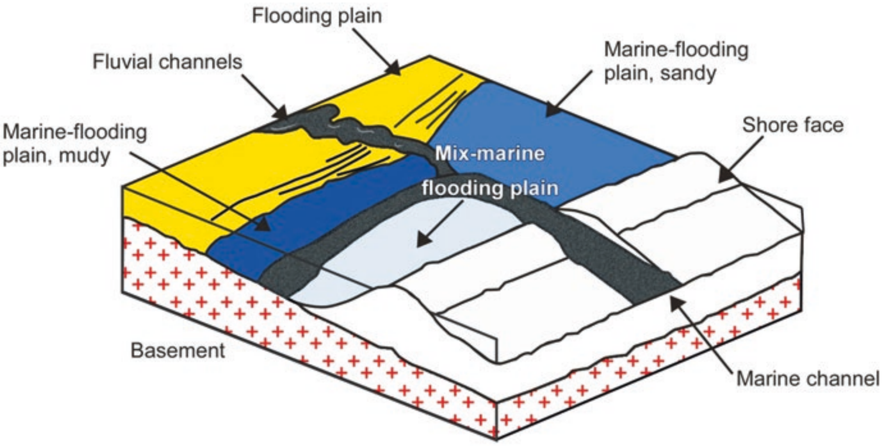


Fig. 3.27 Sedimentary environment of the La Pedrera Formation as interpreted by Coronado and Tibocha (2000)

with silica enrichment and an upper Cerro Rojo member; the latter called this way because of strong red coloration with hematite and other iron oxides, a feature not observed in the other metasandstone ridges. The base of the Cerro Rojo member is a polymict alluvial fan conglomerate, with apart from quartz also volcanic clasts. This member shows a fining-upwards sequence, terminating with finely laminated sandstone and mudstone beds, interpreted as subtidal to intertidal deposits. On top of the sequence, another sandstone formation has been distinguished, the Machado Formation, equally with strong concentrations of specular hematite

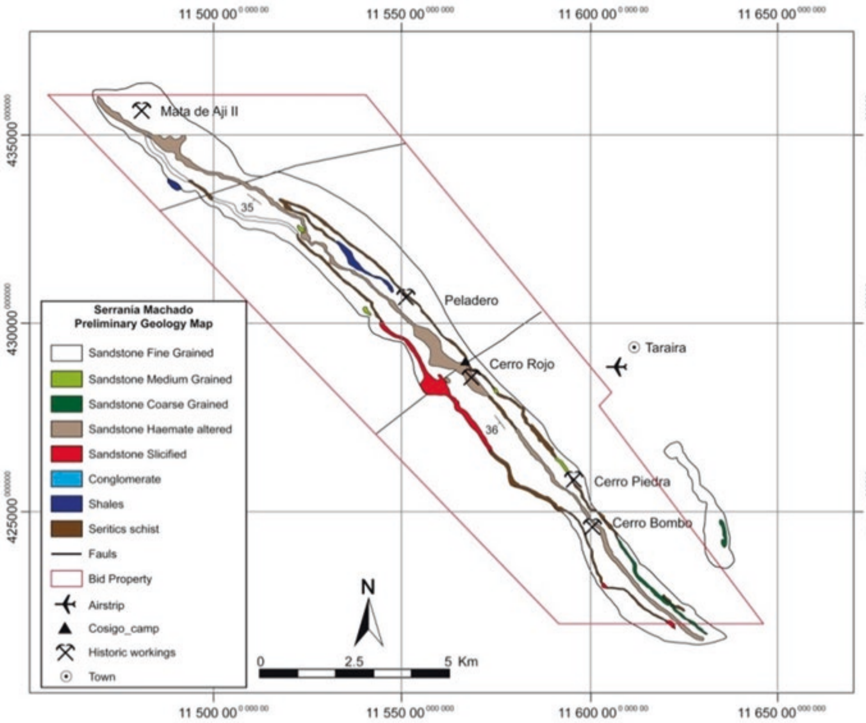


Fig. 3.28 Geological map of the Machado ridge, Ashley (2011)

(Cuéllar et al. 2003; Ashley 2011), though the designation as banded iron formation by Galvis and Gómez (1998) seems not justified (Cuéllar et al. 2003). Diabase dykes up to 10 m thick intrude into the series.

At the *Cerro El Carajo* in the Llanos Orientales of the Vichada department (Fig. 3.30), fine to coarse quartz meta-arenites with parallel and cross-bedding define a NW-striking monoclinal structure. Just like in the Tunuí sandstones, they show andalusite as a typical metamorphic mineral (González and Pinto 1990; De la Espriella et al. 1990; Ochoa et al. 2012). The contact with the crystalline basement is not exposed, but Ghosh (1985) observed andalusite in similar Cinaruco meta-arenites (Venezuela) in contact with the Parguaza rapakivi granite without stating what kind of contact.

The well Vaupés-1 drilled by Amoco in the 1980s to investigate the hydrocarbon potential of the Vaupés-Amazonas basin struck mainly Mesoproterozoic (contact) metamorphosed sandstones, intruded by a Neoproterozoic gabbro (Fig. 3.31; Franks 1988; see par. 3.1.3.9 below).

Geochronology. The age of the Tunuí metasediments has long been a controversial issue, mainly due its incorrect association with the Roraima sandstones by Galvis et al. (1979) and Huguett et al. (1979). Age data come from four different sources:

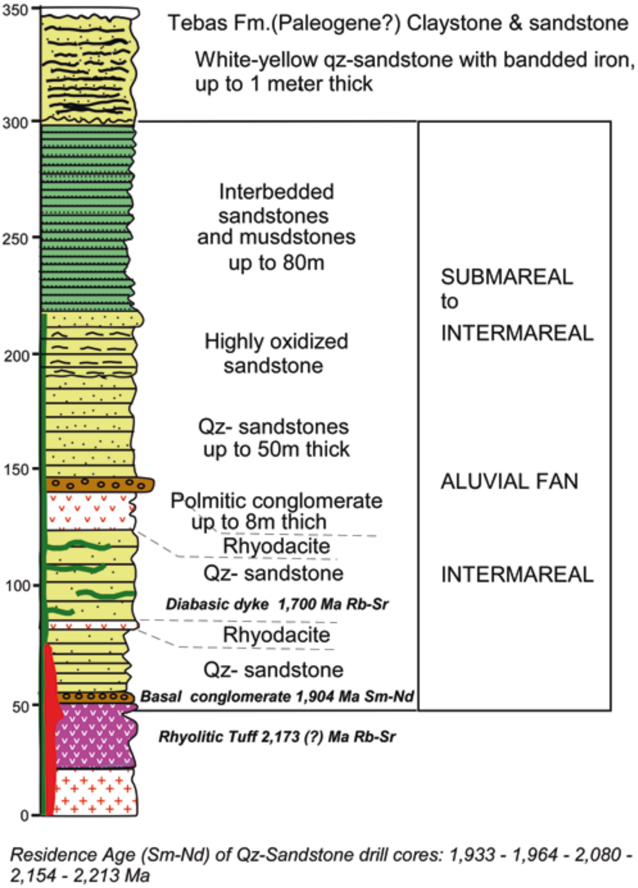


Fig. 3.29 Geological column of the Machado ridge, after Cuéllar et al. (2003)

the age of the basement underlying the sandstones, the age of detrital grains within the sandstones, the age of younger dykes intruding the sandstones and the age of metamorphism, as analysed by Santos et al. (2003).

Recent data show that the granitic basement on which the Taraira metasediments have been deposited have a U-Pb zircon crystallization age of 1593 ± 6 Ma (Ibáñez-Mejía et al. 2011), showing that the metasediments are at least 300 Ma younger than the Roraima, now dated at 1873 ± 3 Ma (Santos et al. 2003).

The youngest detrital zircon grains found in the Tunuí-like Aracá sandstone further to the east in Brazil show ages around 1.88 Ga, also younger than the age of the Roraima sandstones (Santos et al. 2003). In Brazil recently three detrital zircons populations from the Brazilian part of the Naquén (Caparro) have been dated at 1720 ± 11, 1780 ± 8 and 1916 ± 57 Ma, suggesting that the metasand-

Fig. 3.30 Large-scale cross-bedding in Cerro El Carajo metasandstone, Vichada (Ochoa et al. 2012)

stones are at least younger than the youngest of these ages (Almeida et al. 2013). No geochronological data are available from the Caracanoa and La Libertad metasandstone ridges. Fernandes et al. (1977) established the age of unmetamorphosed felsic subvolcanic rocks with quartz pebble xenoliths from the Traira (Taraira) River, associated with the Tunuí Group at 1427 ± 29 Ma (whole-rock Rb-Sr isochron). This is apparently the same age as 1498 ± 20 Ma cited by Santos et al. (2003) using modern decay constants. Fernandes et al. (1977) consider the volcanites to be younger than the metasediments because of the quarzite xenoliths, an observation confirmed by Bogotá (1981), but as discussed above there are also acid volcanics at the base of the metasediments. A mafic dyke intruding into the metasandstones in the Raudal Tente in the Taraira River fits in a 1225 Ma Rb-Sr isochron (Priem et al. 1982), whereas whole-rock K-Ar ages of 941 ± 14 and 984 ± 12 Ma (Cujubim diabase) have been obtained by Fernandes et al. (1977).

Muscovites from the Tunuí sediments have been K-Ar dated at 1293 ± 18 and 1045 ± 19 Ma by Fernandes et al. (1977), and modern Ar-Ar datings on muscovites from the Aracá sandstones in Brazil by Santos et al. (2003) give 1334 ± 2 Ma. These ages, including the mica ages from other rocks by Pinson et al. (1962) and Priem et al. (1982), are now all attributed to later metamorphism related with the K'Mudku-Nickerie Metamorphic Episode (Priem et al. 1982; Kroonenberg 1982; Santos et al. 2003; Cordani et al. 2005; Kroonenberg and De Roever 2010).

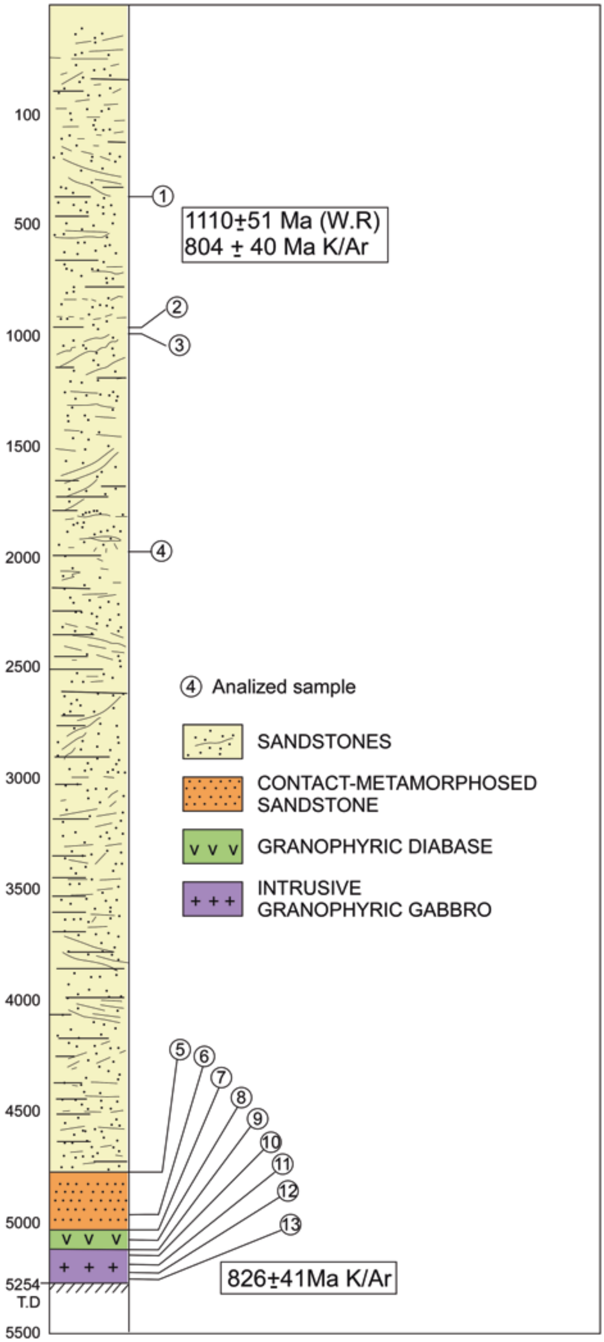


Fig. 3.31 Stratigraphy of well Vaupés-1. (After Franks 1988)

So while the field relations are not entirely clear in all cases, it is evident that the Tunuí metasediments have been deposited in the Mesoproterozoic somewhere in the interval between 1580 and 1350 Ma and if the old Brazilian field data of Fernandes et al. (1977) on crosscutting unmetamorphosed volcanics are correct, even between 1580 and 1480 Ma. In spite of its different, partly volcanic and volcaniclastic facies, the Machado-Taraira metasandstones seem to be coeval with the other metasandstones. The fact that all these metasandstone occurrences show gold mineralization also pleads for a common origin as molassic deposits in a Mesoproterozoic basin following the intrusion of the younger granites and deformed and metamorphosed during the Grenvillian Orogeny (see below).

3.1.2.7 Mesoproterozoic Mylonitization

Large areas in the Colombian Amazones and elsewhere in the Guiana Shield are traversed by important mylonite zones, often with WSW-ENE orientation (see review by Cordani et al. 2010). Although this deformation event did not result in specific mappable rock units, it is recorded geochronologically in many preexisting older rocks through a rejuvenation of mica ages. Already in the first K-Ar and Rb-Sr radiometric age, determinations on micas in rocks from Colombian Amazones gave ages around 1205 ± 60 Ma (Pinson et al. 1962); Priem et al. (1982) recorded mica ages between 1150 and 1350 for over 50 rock samples from the whole Colombian Guiana Shield and correlated this with the Nickerie Metamorphic Episode, coined by him on the base of similar mica age resetting associated with widespread shearing and mylonitization in the Precambrian of Suriname (Priem et al. 1971). Santos et al. (2003) show mica age resetting in the Aracá sandstone plateau in Brazil around 1334 Ma.

3.1.2.8 Neoproterozoic (?) Piraparaná Formation

The Piraparaná Formation has been defined by Galvis et al. (1979) and Huguett et al. (1979) in the course of the PRORADAM project as a folded series of westwards-dipping reddish volcanosedimentary rocks, cropping out in a wide arc from the Yaca-Yacá cataract in the Vaupés River along the Piraparaná river to the south, including a few outcrops along the Caquetá River. Along the Apaporis River, the formation has been seen to unconformably overlie the Complejo Mitú, and at the Raudal Jirijirimo in the same river, it is unconformably overlain by the Paleozoic Araracuara Formation. At the type locality, a thickness of 80 m has been established.

In contrast to the Tunuí rocks, the Piraparaná sediments are unmetamorphosed. They consist of polymict conglomerates (Fig. 3.32) and arkosic sands (Figs. 3.33, 3.34, and 3.35), mixed with pyroclastic material. In some levels the clasts consist

Fig. 3.32 Piraparaná conglomerate, Raudal Carurú, Río Piraparaná. (Photo De Boorder 1978)

largely of granite; elsewhere they also contain volcanites, quartzites and sandstones. At one site Galvis et al. (1979) claim to have observed carbonate cement and carbonate clasts, though the author of the present report only has seen secondary replacement by calcite in thin section. The sandstones contain feldspars, diminishing in abundance towards the top. No detailed sedimentological nor stratigraphical studies have been made, but the PRORADAM authors suppose a continental depositional environment on the base of the red coloration.

At the Raudal Yacá-Yacá in the Vaupés River, a reddish rhyodacitic lava crops out that has been included by Galvis et al. (1979) and Huguett et al. (1979), in the Piraparaná Formation on the basis of its similar colour, though no contact relations with the sediments themselves have been observed in the field. From this rock a crude six-point Rb-Sr isochron of 920 ± 90 Ma has been obtained by Priem et al. (1982). Whether this age indeed refers to the formation as a whole therefore remains uncertain. Also the relations of the Yaca-yacá lavas and Piraparaná sediments with rhyodacitic volcanics in the Machado ridge remain to be established.

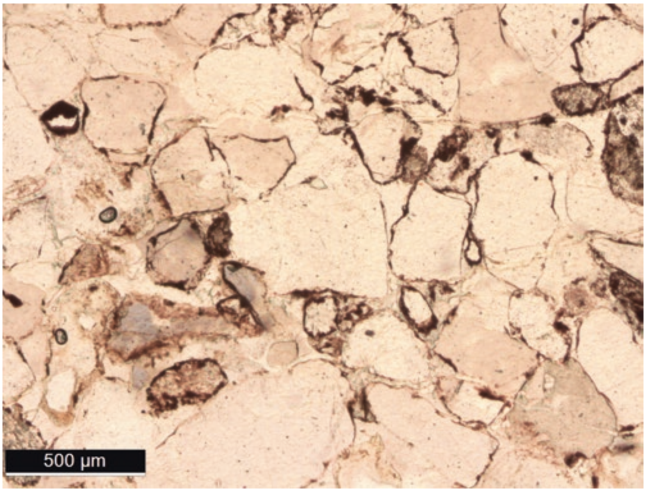


Fig. 3.33 Piraparaná sandstone, quartz-cemented, río Caquetá, 1 N .(Photo: Kroonenberg)

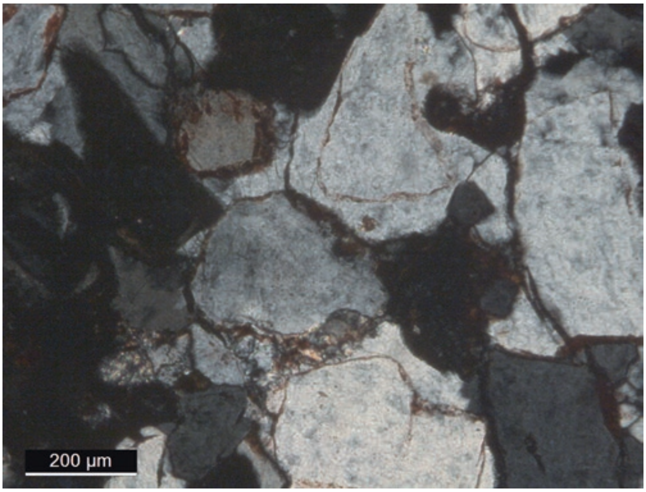


Fig. 3.34 Piraparaná sandstone, note quartz outgrowth around detrital grain, río Caquetá. (Photo: Kroonenberg)

Ibáñez-Mejía (2010) proposes 'that the Piraparana formation could represent either (1) foreland basin deposits related to Putumayo [~ Grenvillian, see below] orogenic development inboard in Amazonia, or (2) Neoproterozoic syn-rift sedimentation and volcanism associated with early extensional events of the Neoproterozoic Güejar-Apaporis graben preceding the collapse of the Putumayo orogen and related Grenville-age belts. Only detailed sedimentary provenance studies in the Piraparana formation will allow us to test these hypotheses'.

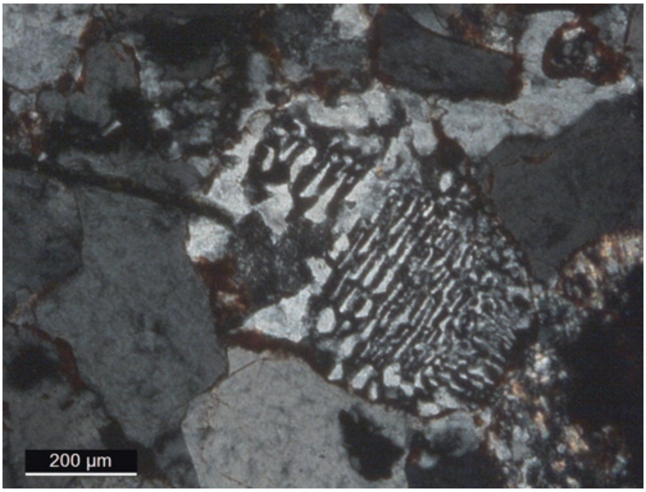


Fig. 3.35 Piraparaná sandstone, granophyre clast, río Caquetá. (Photo: Kroonenberg)

3.1.2.9 Meso-Neoproterozoic Mafic Intrusives

During the PRORADAM reconnaissance, at least 15 unmetamorphosed diabase (dolerite) dykes have been found to intrude the Complejo Mitú and the Tunuí metasediments. Petrographically they are usually pigeonite dolerites without orthopyroxene, while locally (Caño Tí) coarser, olivine-bearing granophyric gabbros occur. Priem et al. (1982) obtained a crude Rb-Sr isochron from five of them between 1225 and 1180 Ma. At the bottom of boring Vaupés-1 in Mesoproterozoic (meta)sandstone, a two-pyroxene olivine-bearing granophyric gabbro was encountered which was K-Ar dated at 826 ± 41 Ma (Franks 1988). The significance of this isolated age cannot be evaluated without additional data using other analytical methods but could fit in the same age group as the ~900 Ma diabase dykes found in the Taraira area and the 920 Ma Yacá-Yacá lavas.

3.1.2.10 Ediacaran San José del Guaviare Nepheline Syenite

In low hills near San José de Guaviare, a conspicuous body of nepheline syenite is exposed, partly unconformably overlain by a semihorizontal Paleozoic (?) sandstone sequence. This body was long considered to be of Paleozoic age as well on the base of K-Ar biotite ages between 485 ± 25 Ma and 445 ± 22 obtained by Pinson et al. (1962). However, recent U-Pb dating of zircon and ^{40}Ar-^{39}Ar dating of biotite by Arango et al. (2012) indicate an age of 577.8 ± 6.3–9 Ma (Ediacaran) crystallization and of 494 ± 5 Ma (late Cambrian) cooling.

3.1.3 Structure

3.1.3.1 Folding of the Basement Rocks

Unfortunately very little attention has been paid to the structural analysis of syntectonic deformation of the basement. The Caicara metavolcanics along the Atabapo River present generally NW strikes (N50°W, Galvis et al. 1979). The metamorphic basement of the Mitú complex shows very variable foliations. Bruneton et al. (1983) note that the foliation in the Atabapo-Río Negro is generally N110°–120°E. Along the Vaupés River, N10°E–N40°E strikes predominate elsewhere, also N70°E and N80°E, in the Papurí River however between N110°E and N170°E (De Boorder 1976). Fold axes of the Tunuí metasandstones are oriented N30°W–N50°W, and in the Piraparaná monoclinal, they are N-S to N20°E. Data are insufficient to present a deformational history of the basement. More attention has been paid to lineaments.

3.1.3.2 Lineaments

As a part of the PRORADAM project, an extensive study of lineaments from 1:200,000 radar imagery was undertaken by De Boorder (1980, 1981). At that time no geophysical information was available, and even up to now, it is the only structural information that appears on national geological maps. De Boorder distinguishes larger regional lineaments 100–300 km long, such as the WNW Carurú lineament more or less parallel to the Vaupés River, which is based on the parallel lineation of scarps of the Paleozoic sandstone plateaus. It runs more or less parallel to the grain of the Vaupés swell. Similar lineaments occur parallel to the Apaporis and Caquetá rivers. Furthermore, there are six major lineaments with orientations between NNE-SSW and ENE-WSW (Figs. 3.3 and 3.36). Surprisingly the prominent NNW-SSE alignment of the elongate Ordovician sandstone plateaus of Araracuara and Chiribiquete has not been indicated as a lineament.

A major feature is the La Trampa (The Trap) wedge, a curved segment between prominent NE-SW lineaments running from the Vaupes southwards to the Putumayo River, and identified on the basis of lineaments a.o. along the Pirá river, the large southwards bends in the Putumayo River and the occurrence of several deep earthquake foci in this area (Fig. 3.36). According to De Boorder, this could represent a possible rift structure which might be prospective for hydrocarbons. However, the aeromagnetic data do not support the presence of a rift structure (see below). The distribution of smaller lineaments in the area could give clues to important tectonic or lithological discontinuities below the cover of younger sediments (De Boorder 1980, 1981). A study of lineaments on the basis of a more detailed aeromagnetic survey in the Vichada and Guainía provinces (Obando 2006 en Celada et al. 2006) confirms the importance of the lineaments inferred by De Boorder. Older magnetic surveys are of insufficient quality to deduce structural detail (Kroonenberg and Reeves 2012).

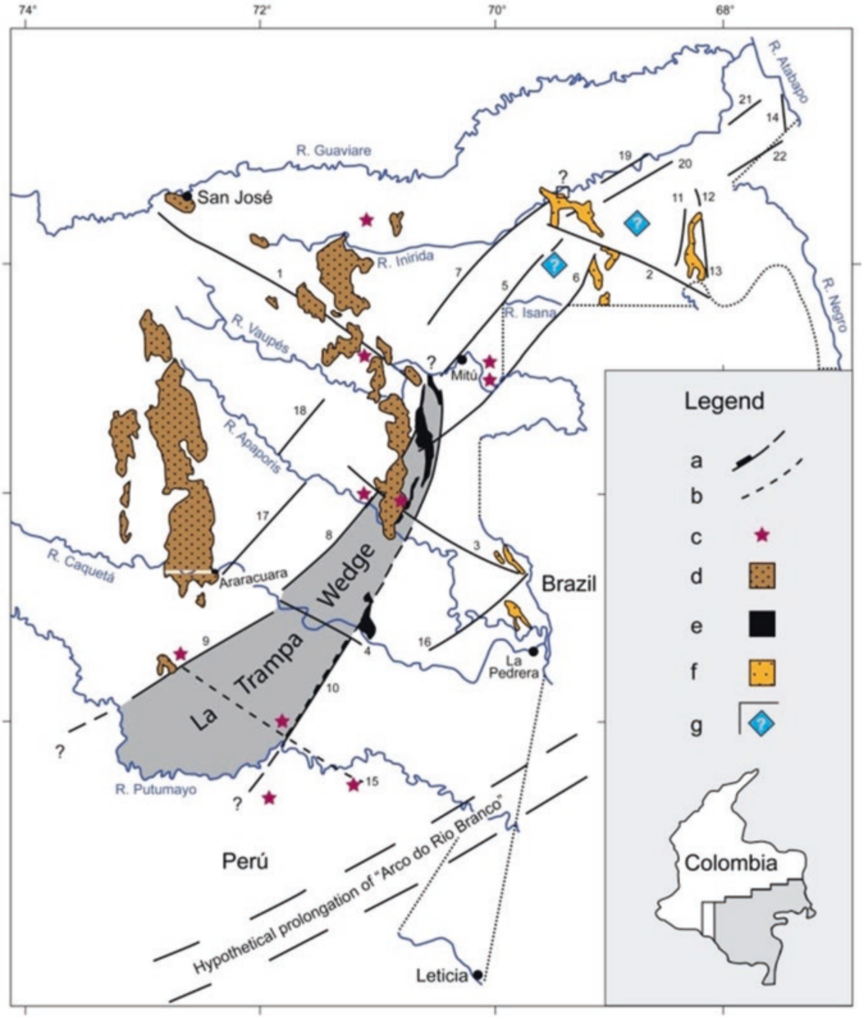


Fig. 3.36 Major lineaments derived from radar imagery (De Boorder 1980, 1981). (**a**) tectonic lineament, mainly from radar imagery; (**b**) lineament deduced from alignment epicentres of deep earthquakes; (**c**) epicentres of deep earthquakes; (**d**) major outcrop of Araracuara Formation; (**e**) major outcrop of Piraparaná Formation; (**f**) major outcrops of Tunuí Formation; (**g**) outline of area for microlineament studies

3.1.4 Geochronological Provinces in the Amazonian Craton: A Discussion

There are at least three different views on the role of the Colombian basement in the evolution of the Guiana Shield, as stated above, at least in part due to the scarcity of available data.

1. Tassinari (1981) defines it as a separate unit, the Río Negro-Juruena (RNJ) geochronological province, based on the fact that rocks from both the Río Negro area north of the Amazon basin and the Juruena area south of it all plot together in a Rb-Sr reference isochron between 1750 and 1500 Ma. Low initial Sr ratios suggested that all this material is juvenile. The RNJ province would have been the result of a volcanic arc accreted onto an older core, the supposedly Archean Central Amazonia Province (CAP) on the east, which also includes the Parguaza rapakivi granite and the basement in which it intrudes. The suture between the two provinces would roughly follow the upper course of the Orinoco River in Venezuela. In later papers (Tassinari et al. 1996; Tassinari and Macambira 1999; Tassinari et al. 2000), he maintains this vision, on the basis of additional material. Also recent ϵ_{Nd} values and T_{DM} ages suggest a largely juvenile character for the rocks of this province (Almeida et al. 2013).
2. Tassinari's vision was challenged repeatedly by Santos et al. (2000, 2006) and most eloquently in Santos (2003). In the first place, he dislodges the Juruena part from Tassinari's RNJ province, on the base of differences in lithology, structure and age, giving the Río Negro Province an identity of its own. He enlarges it considerably, encompassing almost the whole Amazonas Province of Venezuela as well as the Parguaza rapakivi granite. The Río Negro Province is now no longer bordered in the east by the Central Amazonian Province, but a new province has been squeezed between them, the Tapajós-Párima Province, characterized by the presence of the gold-bearing Parima greenstone belt in the northern part and the equally gold-bearing ~2.0 Ga Jacareacanga greenstone belt south of the Amazon basin (Santos et al. 2004). Furthermore, there appears to be no evidence at all of any Archean crust either in Santos's new Tapajós-Párima Province or in Tassinari's old CAP (Santos et al. 2004; Reis et al. 2006; Kroonenberg 2014). Therefore, whether the Río Negro indeed has accreted on the west side of an Archean nucleus has become highly questionable. Even though Santos (2003) supports the juvenile character of the rocks of the Río Negro Province, its geodynamic origin remains uncertain.
3. An entirely different view is possible if we take the Fraga et al. (2008, 2009a, b) interpretation of the structure of the Guiana Shield in consideration. As stated above, the 2.04–1.99 Ga Cauarane-Coeroeni belt (Fig. 3.2) is a major high-grade belt stretching E-W through the shield, cross-cutting all major geochronological provinces defined by Tassinari et al. (1996), Tassinari and Macambira (1999) and Santos et al. (2006). It divides the shield in a northern part with ages 2.2–1.98 Ga and a southern part, with ages generally between 1.89 and

1.74 Ga. The westernmost known extremity of the CCB is in the Complexo Urariquera in the northernmost Brazilian state of Roraima (Reis et al. 2003; Fraga et al. 2008, 2009a, b). Whether and how it continues in southern Venezuela and Colombia is unknown. On the Venezuelan map, Hackley et al. (2005) show the continuation as San Carlos metamorphic-plutonic terrane, the same unit that crops out along the Río Negro and corresponds with the gneisses of the Mitú complex at the other side of that river. No modern age data are available for the San Carlos terrane, and from the Mitú, Minicia gneisses no ages >1.85 Ga have been found, i.e. at least 100 Ma younger than the youngest CCB ages. However, the cordierite-bearing metapelitic gneisses along the Guainía River have a similar metamorphic history as those in the Cauarane-Coeroeni belt (Kroonenberg 1980), so it becomes important to date those rocks: they might correspond with the westernmost extension of the CCB. Also the recently discovered presence of granulites near Mitú (Rodríguez et al. 2011a, b) deserves further investigation.

In spite of these alternatives, the geochronological evidence available at present supports Tassinari's (1981) original concept of a younger unit accreted at the western side of a pre-existing basement (Fig. 3.2). This older basement, however, is not Archean but Paleoproterozoic in age, and some elements such as the metavolcanics along the Atabapo River and the metapelites along the Guainía River may still belong to that older basement.

3.1.5 Geological Evolution of the Colombian Part of the Guiana Shield and Adjacent Areas

The sequence of events in the Colombian part of the Guiana Shield, as appears from the descriptions above, is summarized in Table 3.2.

3.1.5.1 Late Trans-Amazonian Orogeny

The Trans-Amazonian Orogeny, as defined originally by Hurley et al. (1967), is represented in the Colombian part of the Guiana Shield only by the Caicara metavolcanics of the Cuchivero Group exposed along the upper Atabapo River. The Caicara metavolcanics are considered to be older than the Mitú complex on the base of its comagmatic association with the Santa Rosalia and San Pedro granites in Venezuela (1956–1732 Ma, Rb-Sr, Gaudette et al. 1978) and the 1.98–1.97 Ga U-Pb ages from the Surumú metavolcanics in Brazil (Schobbenhaus et al. 1994; Santos et al. 2003). The Cuchivero Group might have constituted the basement onto which the younger basement of the Mitú complex accreted, and it forms also the basement in which the Parguaza rapakivi granite intruded. Geochemically these rocks straddle the boundary between volcanic arc granites and within plate granite in the trace element discrimination diagram of Pearce et al. (1984; Fig. 3.37).

Table 3.2 Sequence of events in the Colombia Amazonian Precambrian

Age(Ma)	Formation	Events	Context
600–800	Nepheline Syenite S José, dolerite dykes, gabbro	Alkaline and mafic magmatism	Anorogenic
900?	Piraparaná	Fluvial sedimentation	Grenvillian Molasse?
1300–1100	Putumayo orogen (Subandean foreland)	Deformation, medium-high-grade metamorphism	Grenvillian collision Laurentia-Amazonia
1300–1100	K'Mudku-Nickerie metamorphic episode	WSW-ENE mylonite, thermal resetting mineral ages, deformation low-grade metam. Tunuí	Grenvillian collision Laurentia- Amazonia
1500–1400	Tunuí, etc.; metasandstones	Fluviodeltaic sedimentation	Molasse?
1550–1400	Parguaza rapakivi granite	Anorogenic magmatism	Rifting?
1550–1500	Mitú, Içana, Tijereto, Inhamoin porphyritic titanite granites	Anorogenic magmatism	Rifting?
1850–1740	Mitú complex, Minicia, Macabana gneisses; Atabapo metavolcanics? Tiquié granites	Deformation, medium-high-grade metamorphism, anatexis, syntect. Intrusives	Querarí orogeny
>1850?	Mitú complex, Minicia etc. protoliths	Deposition of graywackes(?), pelitic rocks, acid volcanics?	Continental margin? Back-arc basin? Rift?
1980	Cuchivero Gp, Caicara metavolc	Acid volcanism and shallow intrusions	Late trans-Amazonian magmatism

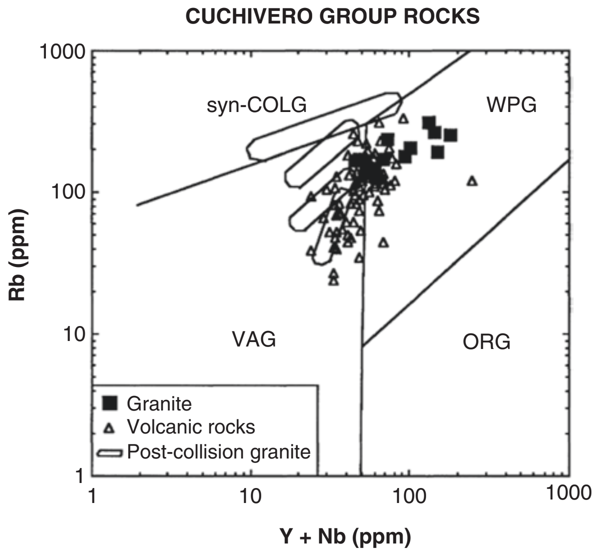


Fig. 3.37 Discrimination diagram of Venezuelan Caicara volcanics (triangles) according to the Pearce et al. (1984) classification (Sidder and Mendoza 1991)

3.1.5.2 Querarí Orogeny, 1.86–1.72 Ga: Deposition, Deformation and Metamorphism of the Mitú Complex Supracrustals

The quartzofeldspathic nature of most of the supracrustal rocks in the Mitú complex suggests that they were originally immature sediments, possibly of greywacke and/or acid to intermediate volcanogenic composition. This may point to an origin in either a passive continental margin setting or an island-arc environment. The scarcity of mafic rocks precludes an origin in a back-arc basin. Orthogneisses may represent early syntectonic intrusions. Deformation and metamorphism took place during an orogenic event between 1.86 and 1.72 Ga.

Priem et al. (1982) state that it seems obvious to correlate the 'pre-Parguazan' history of the Mitú complex with the Trans-Amazonian Orogeny. Now that many more modern U-Pb ages have been obtained from the metamorphics (see Table 3.1 above), it becomes clear that if we accept Priem's view, the Trans-Amazonian Orogeny would span almost half a billion years, from 2.2 Ga to 1.7 Ga, more than a full-fledged Wilson cycle. Moreover, nowhere else in the Guiana Shield high-grade metamorphic supracrustals with ages between 1.86 and 1.72 Ga have been found. Therefore we prefer to consider the deposition, deformation and metamorphism of the Mitú metamorphics as a separate event.

Almeida et al. (2013) recognize even two orogenic events in the adjacent part of Brazil, the Cauaburí Orogeny of 1.81–1.75 Ga and the Querarí Orogeny (1.74–1.70 Ga). In Colombia there are no compelling field or geochronological reasons to distinguish *two* orogenic events in this interval; we see rather a continuum of these ages, and therefore I propose to retain the name *Querarí Orogeny* for the whole series of deformation and metamorphic events between 1.86 and 1.72 Ga. Moreover, the Querarí river is largely situated in Colombian territory. This orogeny led to accretion of the Río Negro belt to the older Paleoproterozoic basement and was accompanied by the intrusion of the late-syntectonic S-type Tiquié granites. This marked the final cratonization of the Guiana Shield.

3.1.5.3 Mesoproterozoic Anorogenic Granitoid Magmatism: 1.55–1.4 Ga

After a gap of over 100 million years after the Querarí Orogeny, an episode of intense anorogenic magmatism started around 1.55 Ga that is widespread in the whole western part of the Amazonian Craton (Figs. 3.2 and 3.3; Dall'Agnol et al. 1999, 2006; Kroonenberg and de Roever 2010 and references therein). The Parguaza granite is the most conspicuous representative example, but the Mitú, Içana, Atabapo and other granites are from the same time interval, and typical Parguaza-like rapakivi granites (Mucajaí, Surucucus) also occur much further east in the shield (Dall'Agnol et al. 1994, 1999). There is no link with any coeval metamorphic belt, and together with the A-type geochemical characteristics of these granites, their origin is most probably related to an extensional phase in the evolution of the Guiana Shield.

3.1.5.4 Mesoproterozoic Sedimentation of Tunuí Sandstone: 1.58–1.35 Ga?

The widespread occurrence of epicontinental, partly coarse-clastic sedimentary sequences up to 2000 m in thickness over the whole western half of the shield, not only in Colombia, Venezuela (Cinaruco Formation) and adjacent Brazil but also much further eastwards in the Aracá plateau in Brazil (Fig. 3.38), suggests an episode of post-orogenic erosion and sedimentation in a huge molasse-like basin after the Querarí Orogeny, at least between 1580 and 1350 Ma.

Some occurrences may be older, as the youngest detrital zircons in the Naquén-Caparra plateau were only 1720 Ma. While sandstone plateaus rest unconformably on the crystalline basement, others may have been intruded by the anorogenic granites, as occasionally contact-metamorphic andalusite was reported at the contact with the Parguaza granite (De la Espriella et al. 1990; Ochoa et al. 2012).

3.1.5.5 K'Mudku-Nickerie Tectonometamorphic Episode: 1.3–1.1 Ga

The mylonitization and mica age rejuvenation event that affected all previously mentioned rock units was first described in Guyana by Barron (1969) as K'Mudku event and since then recognized in many areas of the shield (Fig. 3.39; Gibbs and Barron 1993; Cordani et al. 2010). Priem et al. (1971) showed that only the easternmost part of the shield was not affected by this event, called Nickerie Metamorphic Episode by him. Kroonenberg (1982) interpreted this as a result of the Grenvillian Amazonia-Laurentia collision along the western border of the Guiana Shield around 1200–1000 Ma (see below). A further correlation is possible with the 1350–1300 Rondonian-San Ignacio belt and the 1250–1000 Sunsás belt in the southwestern part of the Amazonia Craton, close to the border with Bolivia, which equally testify to the Laurentia-Amazonia collision in Elsevirian and Grenvillian times, respectively (Cordani et al. 2010). Recently similar ages around 1000 Ma were obtained from basement rocks from drill cores into the Subandean basin (Ibáñez-Mejía et al. 2011; see below). Assigning a specific geochronological province across the Guiana Shield to the K'Mudku event, as Santos et al. (2006) suggest, however, goes against existing field and geochronological data.

3.1.5.6 Late Proterozoic-Phanerozoic Events

In the Neoproterozoic the Piraparaná epicontinental rocks were deposited, possibly a far effect of the Grenvillian Orogeny along the western border of the shield. Furthermore, several isolated mafic and alkaline intrusions and extrusions took place, obviously in an intraplate setting but without clear geotectonic context. In the Phanerozoic, Ordovician sandstone plateaus (Araracuara Formation) and Neogene sediments covered large parts of the basement.

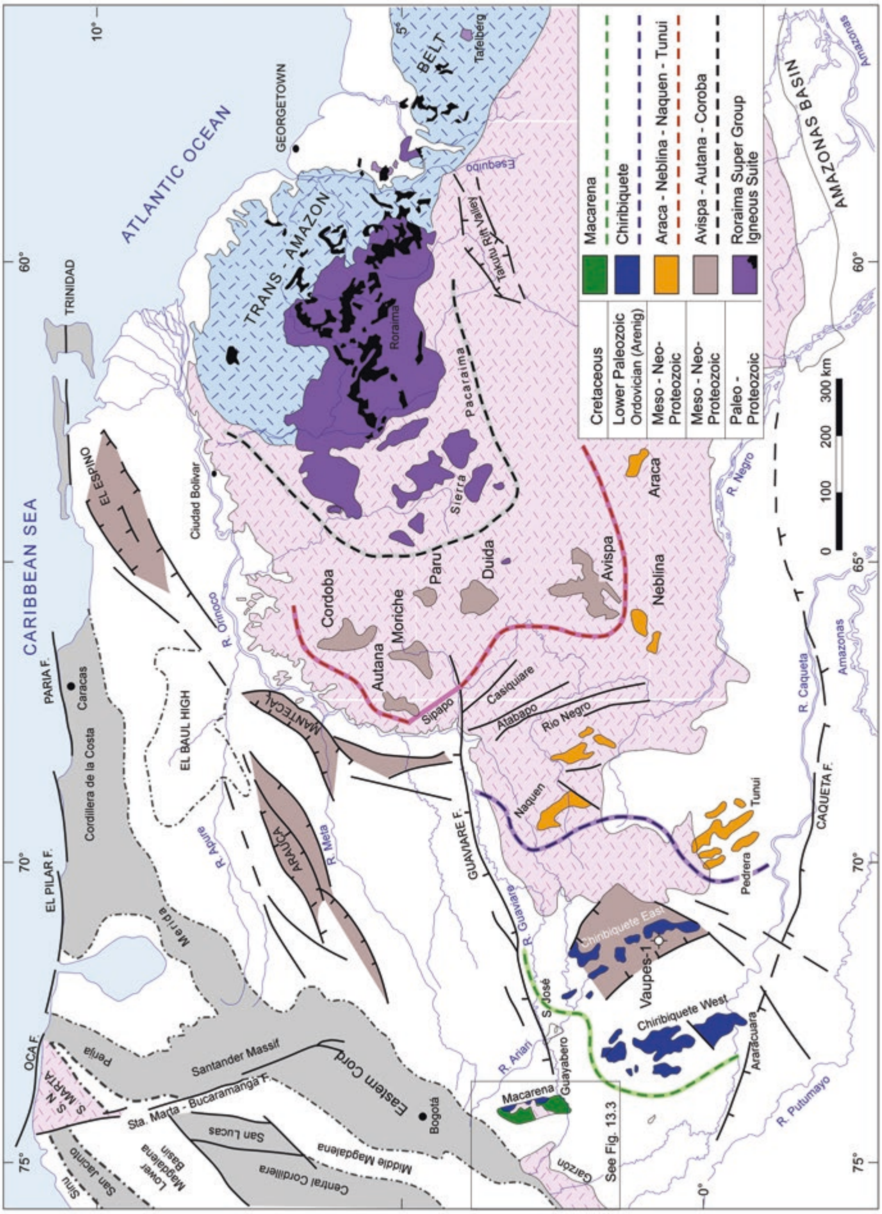


Fig. 3.38 Distribution of (meta)sandstone plateaus (tepuis) in the Guiana Shield. (see Cediel 2018)

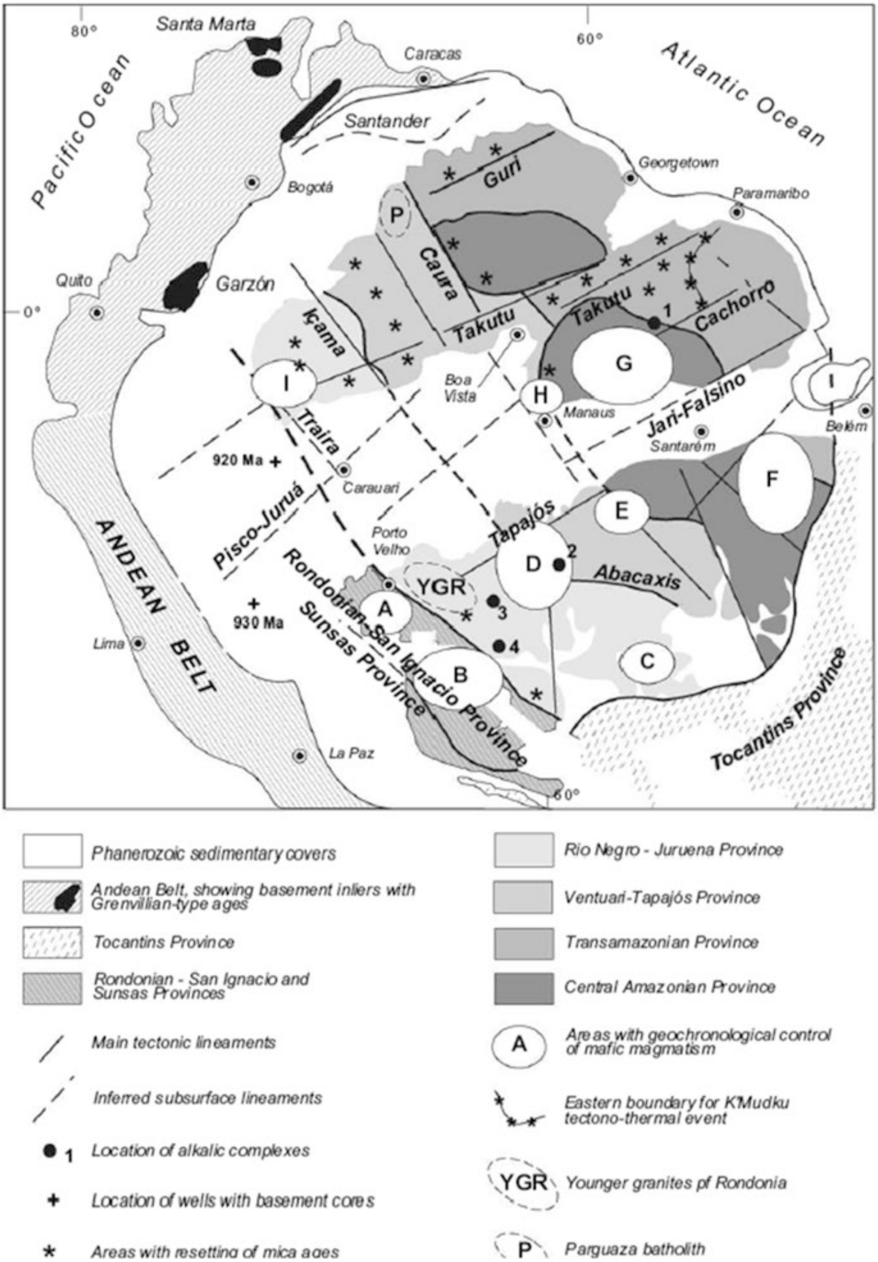


Fig. 3.39 Main lineaments and areas with mica age resetting in the Amazonian Craton (Cordani et al. 2010). Reproduced with permission

3.1.6 Geoeconomic Potential

The most important mineralizations in the area are columbite-tantalite in the Parguaza rapakivi granite and gold in the Tunuí sandstone plateaus. Columbite-tantalite occurs in coarse crystals in 'quartz-pegmatites' which never have been seen in outcrop but only as float on top of the presumed veins in the Venezuelan part of the batholith. Heavy mineral concentrates from neighbouring creeks contain up to 73% of cassiterite, further 15% of partly Ta-rich rutile and 8% of columbite-tantalite (Pérez et al. 1985; Herrera-Bangerter 1989; Bonilla et al. 2013).

Part of the gold in the Tunuí metasandstone plateaus is derived from Proterozoic paleoplacers, but hydrothermal remobilization also plays a role. Also wolframite occurrences have been reported from the metasandstone plateaus (Ashley 2011). The nearest bedrock source for the gold placers in these plateaus is in the Parima greenstone belt in the extreme NW of Roraima state in Brazil (cf. Reis et al. 2003).

Proterozoic diamondiferous kimberlites occur in the Guaniamo area, Venezuela, not far from the Colombian border (Fig. 3.40).

3.2 The Andean and Subandean Precambrian Basement

3.2.1 Distribution of Precambrian Basement in the Colombian Andes

Three major upthrusts of Proterozoic rocks exist in the Colombian Andes: the Garzón Massif and the Santander Massif in the Eastern Cordillera and the Sierra Nevada de Santa Marta (Kroonenberg 1982; Cediel et al. 2003; Cordani et al. 2005; Ordóñez-Carmona et al. 2006; Ramos 2010). The Serranía de Macarena, an isolated NW-trending outlier uplift east of the Eastern Cordillera, also has a Proterozoic basement core. Smaller tectonic slivers occur in the Guajira Peninsula and along the whole eastern flank of the Central Cordillera from the Ecuadorian border up to its northern extremities in the Serranía de San Lucas (Fig. 3.41). Furthermore recent data from the crystalline basement of the Subandean Putumayo basin in the Colombian Amazones suggest a correlation with the Andean Precambrian (Ibáñez-Mejía et al. 2011). The belt of Proterozoic outcrops continues into northwestern Venezuela (Rodríguez and Áñez 1978; Priem et al. 1989; Grande 2012; Grande and Urbani 2009).

There is no physical continuity between those separate outcrops, but their Grenvillian geochronological history between 1100 and 900 Ma and their generally high grade of metamorphism (granulite-facies or amphibolite facies) suggest a common geological history. Granulite-facies xenoliths have been erupted by the Nevado Del Ruiz volcano (Jaramillo 1978, 1980), suggesting that the Proterozoic basement of the Andes is at least present below the Central Cordillera. High-grade metamorphic rocks, partly granulites, have also been reported from the western flank of the Central Cordillera, such as Puquí, Caldas-La Miel, Nechí, San Isidro

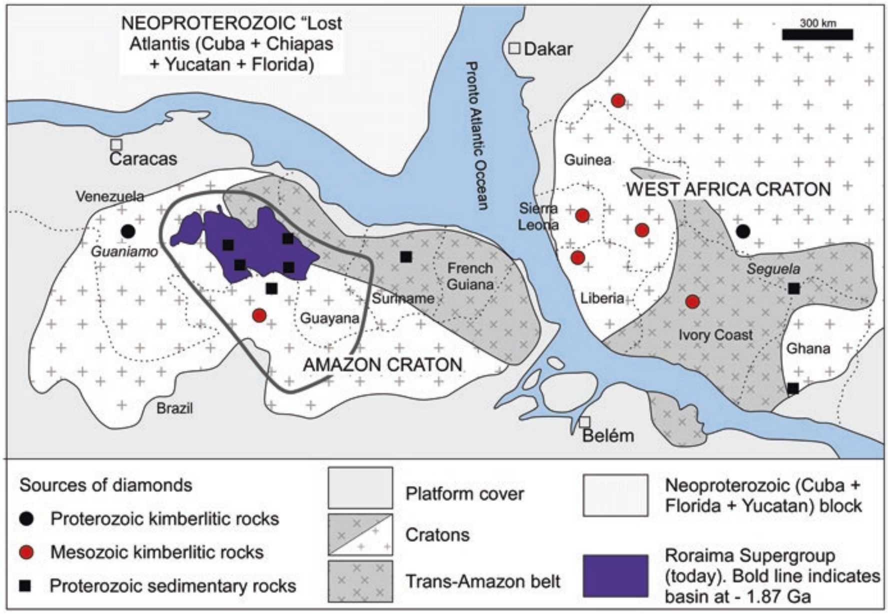


Fig. 3.40 Diamond occurrences in the Guiana Shield (Santos et al. 2003). Reproduced with permission

and Las Palmas, but so far they have been dated as Triassic, not Precambrian (Ordóñez-Carmona et al. 2001; Restrepo et al. 2009, 2011; Rodríguez et al. 2012).

Two models have been proposed for the geotectonic significance of the Proterozoic outcrops, an autochthonous and an allochthonous one. The autochthonous model considers the Garzón-Santa Marta Granulite Belt as a juvenile accretion to the Guiana Shield during the collision of Laurentia and Amazonia during the Grenvillian Orogeny (Kroonenberg 1982; Restrepo-Pace et al. 1997; Cediel et al. 2003). The argument is based mainly on the lithological similarity of the two belts and on shearing, mylonitization and thermal mineral resetting at the same time in the adjacent Guiana Shield, interpreted as indentation tectonics. The autochthonous model is also supported by the Paleozoic history of the Santander Massif (Van der Lelij 2013; Van der Lelij et al. 2016).

On the other hand, scientists especially used to accretionary tectonics in the Western Cordillera and the Serranía de Baudó prefer to subdivide the Colombian Andes in terms of fault-bounded accreted *terranes* (Etayo et al. 1983; Toussaint 1993; Ordóñez-Carmona et al. 2006). The 'terrane' concept was originally developed along the Pacific coasts of California, British Columbia and Alaska, where allochthonous, totally unrelated tectonic blocks have been displaced parallel to the mainland for hundreds to a thousand kilometres along transform faults until they became yuxtaposed into their present position. Toussaint (1993) considers only the Garzón Massif as part of the (almost) autochthonous 'Andaquí terrane' and the other massifs as part of the allochthonous 'Chibcha terrane'. Moreover, Forero (1990) considers

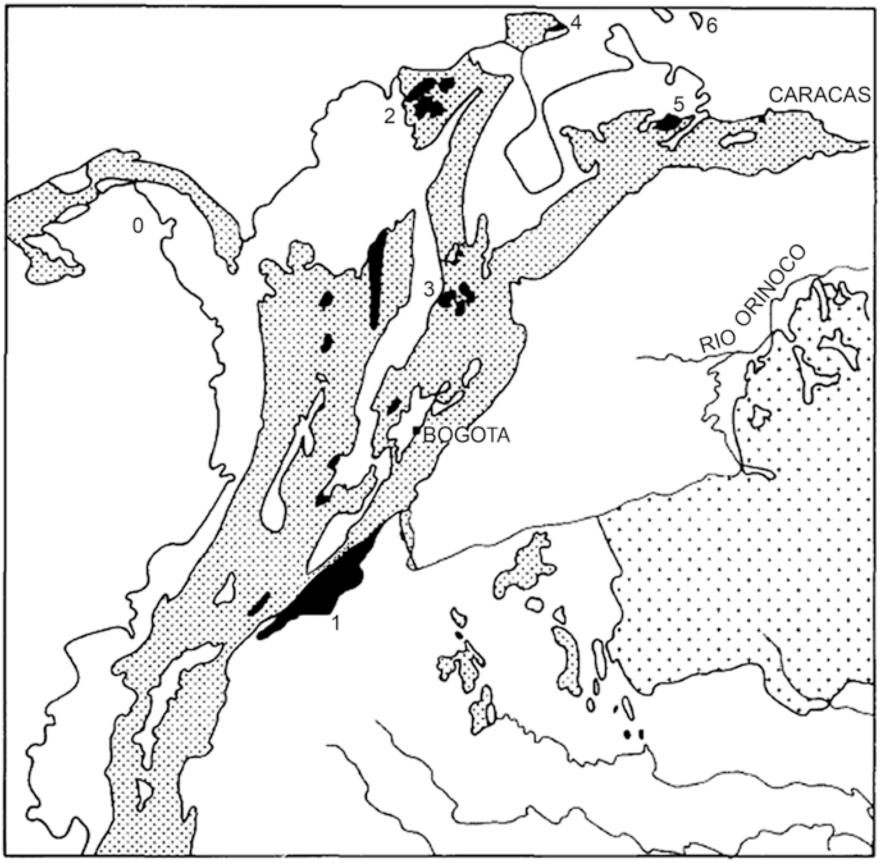


Fig. 3.41 Outcrops of Andean Grenvillian in Colombia and adjacent Venezuela: (1) Garzón Massif, (2) Sierra Nevada de Santa Marta, (3) Santander Massif, (4) Guajira, (5) Venezuelan occurrences, (6) San Lucas (Kroonenberg 1982)

on the base of paleontological evidence that the Paleozoic of the Eastern Cordillera belongs to Laurentia, and not to South America, and accreted to the Guiana Shield in Silurian-Devonian times. This is also the line followed by Cordani et al. (2005). Furthermore, Bayona et al. (2010) present palaeomagnetic evidence from the Sierra Nevada de Santa Marta for large-scale northwards along-margin displacements of basement-cored tectonic blocks in Jurassic-Cretaceous times.

However, in our view the common protoliths, metamorphism and age history plead against an allochthonous character. The lateral displacements along still active major faults do not invalidate the fact that all Grenvillian segments along the whole length of the Colombian Eastern and Central Cordilleras originally formed a continuous belt along the western margin of the Guiana Shield. Nor is there any sign of unrelated microcontinents which were docked against the mainland. The strongest argument for the integrity of the Andean Precambrian is the fact that the Grenvillian basement continues eastwards at the base of the Subandean Putumayo foredeep, beyond the eastern boundary thrust fault of the Eastern Cordillera (Ibáñez-Mejía et al. 2011), and hence forms an integral part of the Guiana Shield since the Grenvillian Orogeny. It is not illogical to suppose that a continuous Grenvillian basement is present in the deeper continental crust below the Eastern and eastern Central Cordillera. Below we discuss the Precambrian outcrops, first in the Eastern Cordillera and the Subandean basement, then in northern Colombia and at last in the eastern flank of the Central Cordillera. At the end we will discuss their wider geodynamic significance.

3.2.2 The Garzón Massif

The Garzón Massif forms the backbone of the southern part of the Eastern Cordillera over a distance of over 250 km, covering about 10,000 km^2 and reaching elevations up to about 3000 m (Fig. 3.42). Both its eastern and western boundaries are thrust faults, in which the Proterozoic basement is thrust over Mesozoic and Tertiary rocks. Towards the north and south, the massif pinches out between other thrust faults. Small slivers reappear further north, such as the El Barro Gneiss near the village of Alpujarra (Fuquén and Osorno 2002). Final uplift of the Garzón Massif took place between 12 and 3.3 Ma (Van der Wiel 1991).

Lithology The Garzón Massif consists mainly of Proterozoic banded granulites of charnockitic-enderbitic composition, mafic and ultramafic granulites, metapelitic granulites, marbles and quartzites (Fig. 3.43a–d). Compositional banding testifies to a supracrustal origin of the rocks. Moreover, their migmatitic aspects testify of incipient melting, and in some areas advanced anatexis has proceeded to a certain homogenization of the rocks. Metamorphic grade is in the granulite facies, but along the peripheries of the massif, also amphibolite-facies rocks are common. Two bodies of syntectonic megacryst granites have been described, the Guapotón-Mancagua granites. Discordant pegmatite and aplite veins are common (Kroonenberg 1982; Restrepo-Pace et al. 1997; Murcia 2002; Jiménez et al. 2006; Ibáñez-Mejía et al. 2011). The Proterozoic sequence is locally overlain by Upper Paleozoic unmetamorphosed sediments (Stibane and Forero 1969; Mojica et al. 1987) and is intruded by various large Triassic-Jurassic granitic batholiths and small lamprophyric dykes.

Subdivision The first comprehensive description of the Garzón rocks was by Luigi Radelli (1962a, 1967), who concentrated on the migmatitic aspect, but does not mention the presence of granulites, although in one sample he describes orthopyroxene. He interprets the rocks as being of metasomatic origin ('granitization'). Kroonenberg (1982, 1983) subdivided the Proterozoic rocks in the Garzón Group (the banded granulites and associated rocks) and the syntectonic Guapotón-Mancagua granites (later called augengneisses; Priem et al. 1989).

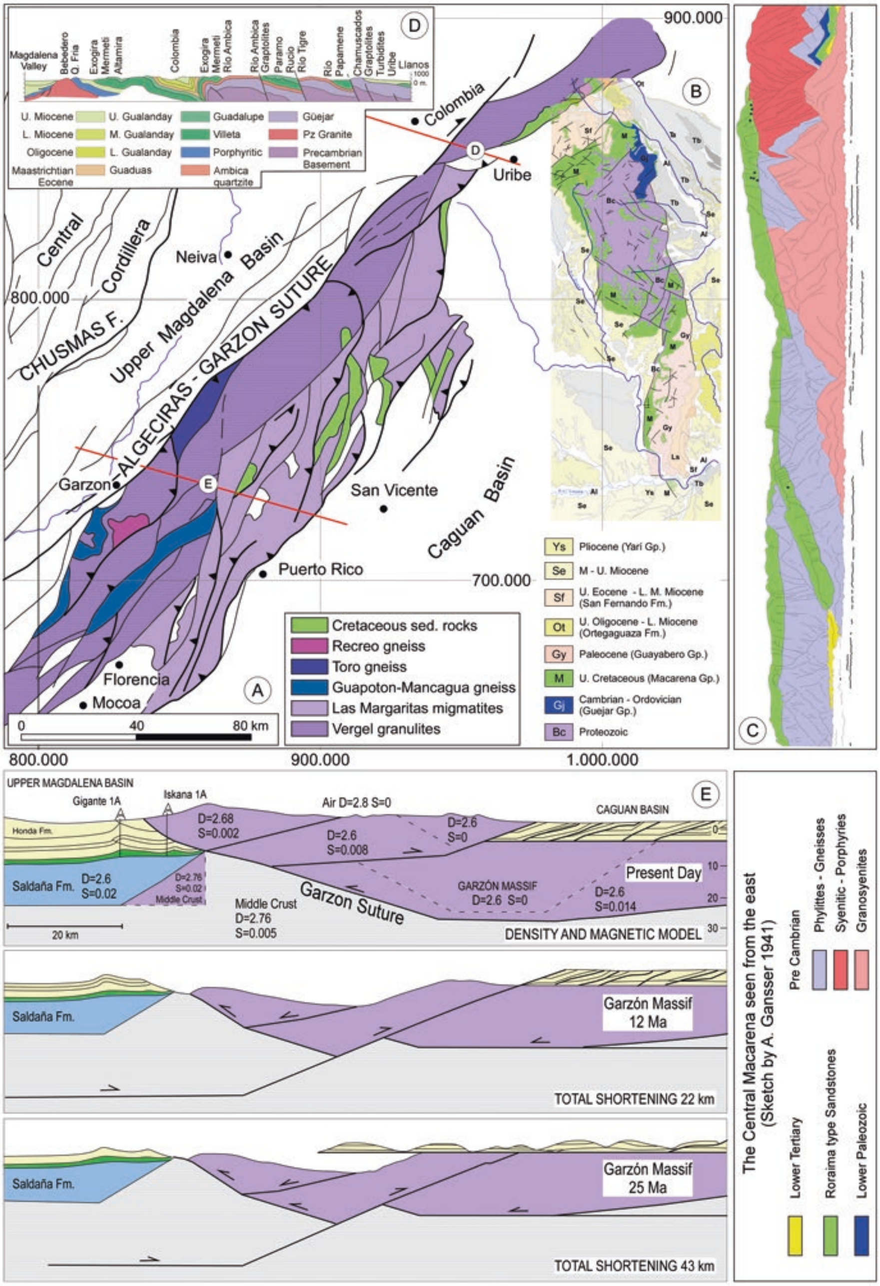


Fig. 3.42 Simplified geological map of the Garzón Massif and Sierra de la Macarena. (see Cediel 2018)

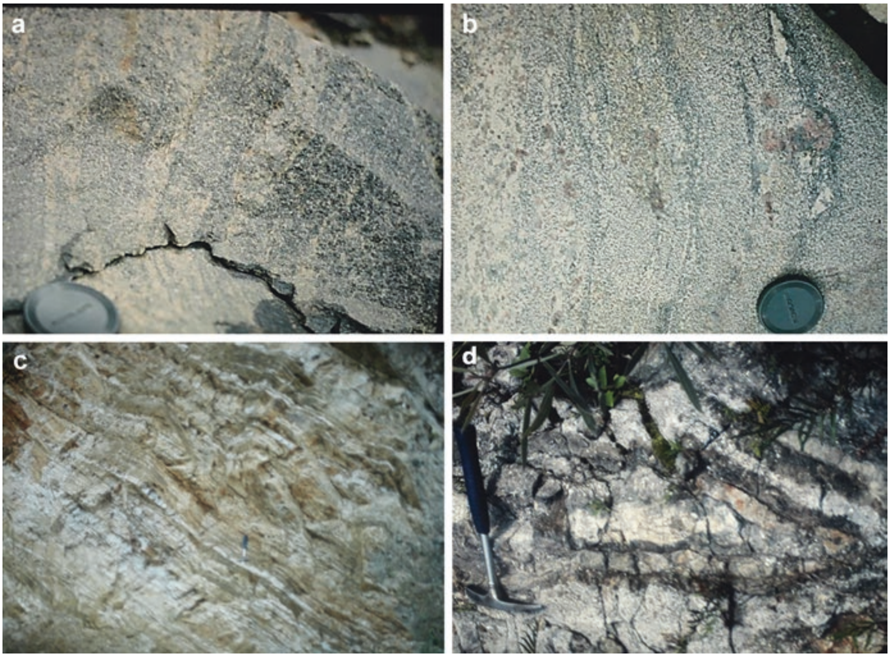


Fig. 3.43 Typical outcrops of (**a**) grey charnockitic granulites, (**b**) migmatitic mafic granatiferous granulites, (**c**) migmatitic and compositionally banded granulites, and (**d**) folded forsterite marble and calcsilicate rocks (Photo: Kroonenberg)

The Geological Survey of Colombia Ingeominas (now Servicio Geológico Colombiano) started a mapping campaign in the 1990s, resulting in the publication of several 1:100,000 map sheets of the area. In that framework Rodríguez (1995a) distinguished an additional unit in the map sheet Garzón, the El Recreo Anatectic Granite, for the more homogenized granulites in the highest part of the massif, but invoking, as Radelli, a metasomatic origin, unfortunately based on incorrect and outdated petrogenetic concepts. Transitions between the Garzón Group and the El Recreo Anatectic Granite are gradual. In a later mapping campaign of the Garzón map sheet, Velandia et al. (2001) reformulate the name as El Recreo Granite. Ingeominas and Geoestudios (1998–2001) map adjacent areas using only macroscopic descriptions of the rocks; change the name into El Recreo Gneiss, because of its more metamorphic than igneous character; and introduce new units, Toro Gneiss, Las Margaritas Gneiss and El Vergel Granulites. Fuquén and Osorno (2002) distinguish the El Barro Gneiss near the town of Alpujarra. Jiménez (2003) drew a detailed map of the whole Garzón Massif based on the subdivisions of Ingeominas and Geoestudios (Fig. 3.42). Rodríguez et al. (2003) change the name Garzón Group into Garzón complex and divide it into El Recreo granite-granofels and Florencia migmatites, discarding the names introduced of Ingeominas and Geoestudios (1998–2001) on the basis of their new petrographic data. Amidst this confusion and in the absence of clear-cut distinguishing criteria between the proposed subunits, we prefer to retain the old twofold subdivision in modern in Garzón complex and Guapotón-Mancagua Gneiss.

Geochemistry No whole-rock geochemical data have been published so far from the Garzón Massif, except for a few graphs in Kroonenberg (1990) and Restrepo-Pace (1995) (Figs. 3.44, 3.45, and 3.46). In principle the common discrimination diagrams are meant for igneous rocks, so interpretation of the data for the Garzón Massif granulites should be taken with caution because of the superimposed effect of metamorphism and concomitant mobility of several elements. Nevertheless, the bulk of the granulites plot in the calc-alkaline field in the K_2O-SiO_2 diagram of Peccerillo and Taylor (1975; Fig. 3.44), suggesting a possible volcano-sedimentary origin in an active continental-margin setting of the protoliths. This is in harmony with mafic granulites plotting in the calc-alkaline field of the Ti-Zr-Sr triangular plot and intermediate samples plotting in or near the orogenic granite field in the discrimination diagrams by Pearce et al. (1984; Fig. 3.45).

REE spider diagrams of charnoenderbitic and mafic granulites and of the Guapotón orthogneiss show weak Eu anomalies, suggesting an origin by fractional differentiation from a plagioclase-rich magma source; a single ultramafic granulite (opx-cpx-hbl-spinel) SK 132 shows an almost flat REE profile (Fig. 3.46a–d). The same wide range in profiles is seen in Restrepo-Pace (1995).

Metamorphism Granulite-facies metamorphism is evident from the ubiquitous development of granoblastic orthopyroxene in both felsic and mafic granulites and by the frequent mesoperthitic character of exsolved feldspars. The presence of orthopyroxene in the leucosomes indicates that anatexis also took place in the granulite facies (Kroonenberg 1982, 1983). According to Jiménez et al. (2006), the geothermobarometric data define a clockwise, nearly isothermal decompression path (ITD) for rocks from Las Margaritas migmatites, ranging from 780–826 °C and 6.3–8.0 kbar down to 630 °C and 4 kbar (cf. Fig. 3.47). For a garnet-bearing charnockitic gneiss from the Vergel Granulites, the path is counterclockwise, from 5.3–6.2 kbar and 700–780 °C to 6.2–7.2 kbar and 685–740 °C. Altenberger et al. (2012) argue for much higher values in the Vergel Granulites, reaching UHT (ultrahigh temperature) conditions, up to 900–1000 °C, on the basis of ternary feldspar diagrams, titanium in quartz and mineral chemistry of exsolved pyroxenes.

Geochronology The first radiometric ages on charnockitic granulites of the Garzón Massif were obtained by Álvarez and Cordani (1980) and Álvarez (1981) and show a Rb-Sr isochron of 1180 Ma, while a hornblende K-Ar age of 925 ± 50 Ma was obtained from a basic granulite by Álvarez and Linares (1984). Priem et al. (1989) show a 1172 ± 90 Ma Rb-Sr errorchron but do not exclude the presence of an older basement on the basis of a six-point best-fit line of 1596 ± 300 Ma for the Guapotón gneisses. Rb-Sr mineral ages of 918 ± 27 for phlogopite and 895 ± 16 for K-feldspar were obtained, next to Phanerozoic biotite ages. The first U-Pb zircon ages were published by Restrepo-Pace et al. (1997), showing an age of 1088 ± 6 Ma for El Vergel Granulites. Cordani et al. (2005) obtained SHRIMP U-Pb zircon ages of 1158 ± 23 Ma for igneous cores of zircons from the Guapotón Gneisses and 1000 ± 25 Ma for their metamorphic rims, 1015 ± 8 Ma for the leucosome of Las Margaritas gneisses and for the Vergel Granulites a protolith age of ~1100 Ma and

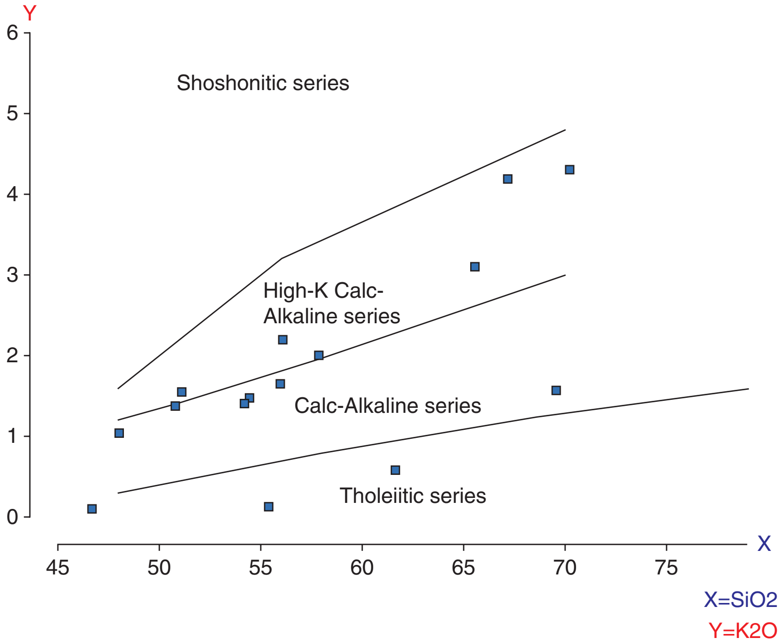


Fig. 3.44 K2O-SiO2 diagram after Peccerillo and Taylor (1975) showing calc-alkaline nature of charnockitic, enderbitic and mafic granulites. Unpublished XRF data and Kroonenberg (1990). Analyst F, Stephan, Utrecht (1982)

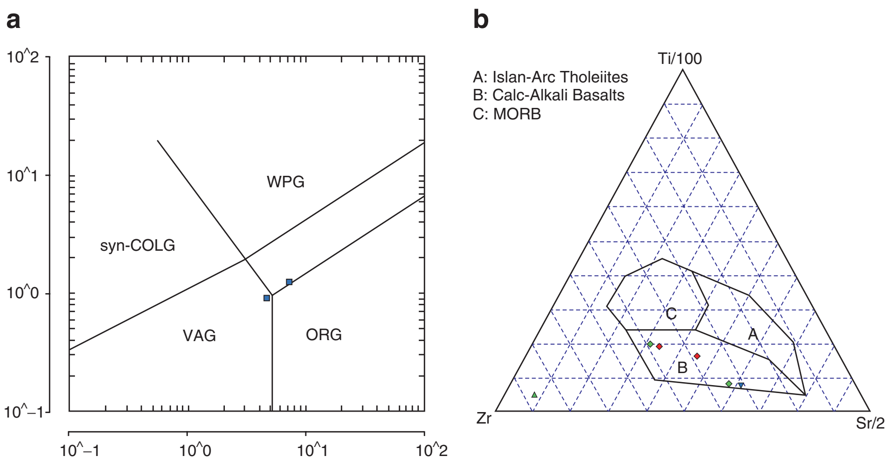


Fig. 3.45 Discrimination diagrams for intermediate and mafic granulites according to Pearce et al. (1984). Unpublished XRF data and Kroonenberg (1990). Analyst F. Stephan, Utrecht (1982)

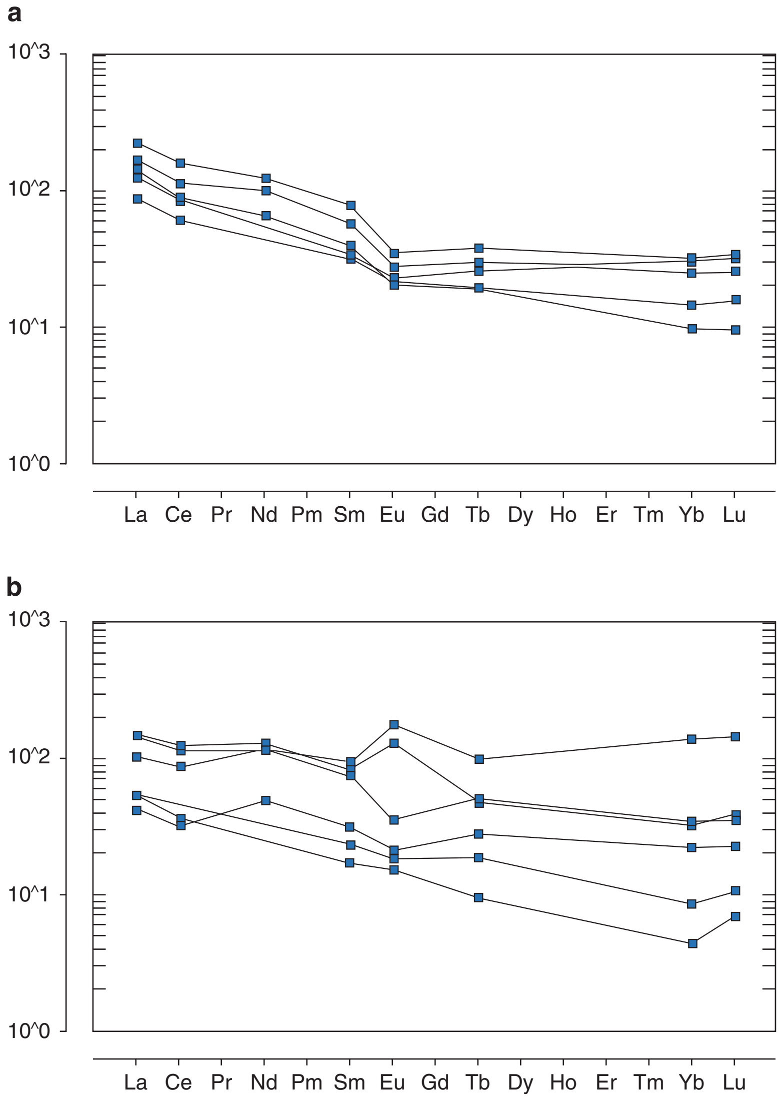


Fig. 3.46 REE diagrams for (**a**) charnoenderbitic granulites, (**b**) mafic granulites (positive Eu anomalies: garnet-bearing), (**c**) ultramafic granulite SK132 (opx, cpx, hbl, spinel), (**d**) REE Guapotón orthogneiss. (Unpublished INAA data, Delft 1983; and Kroonenberg 1990)

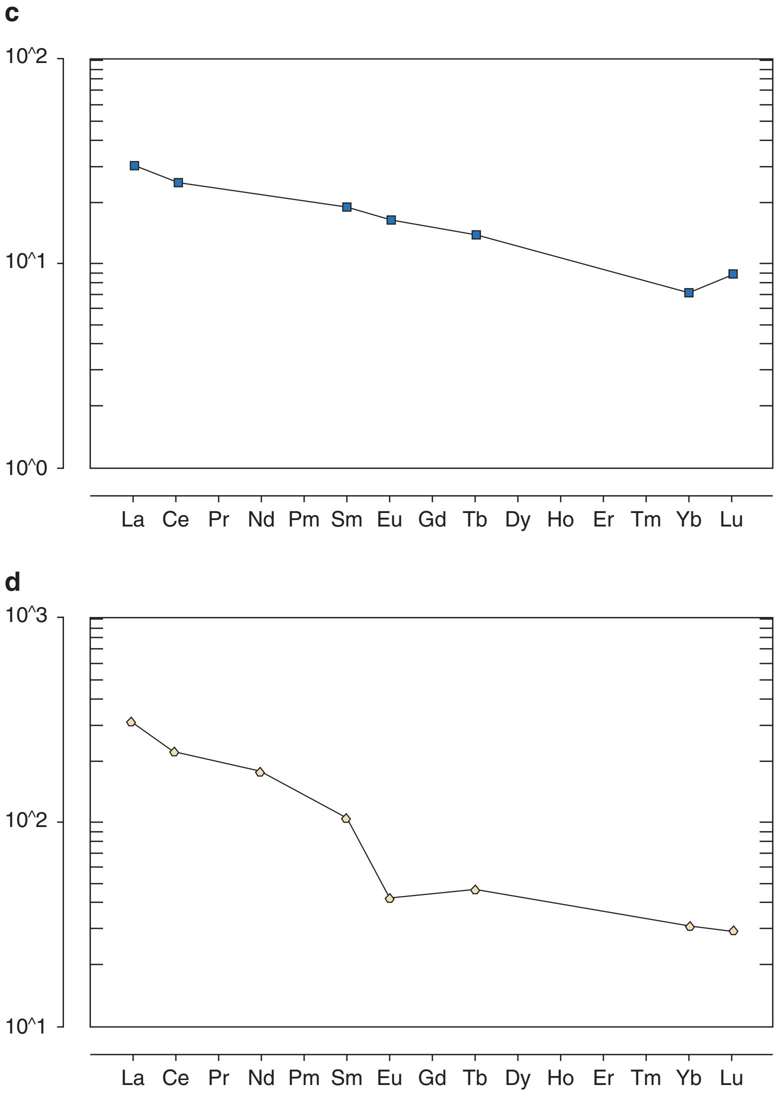


Fig. 3.46 (continued)

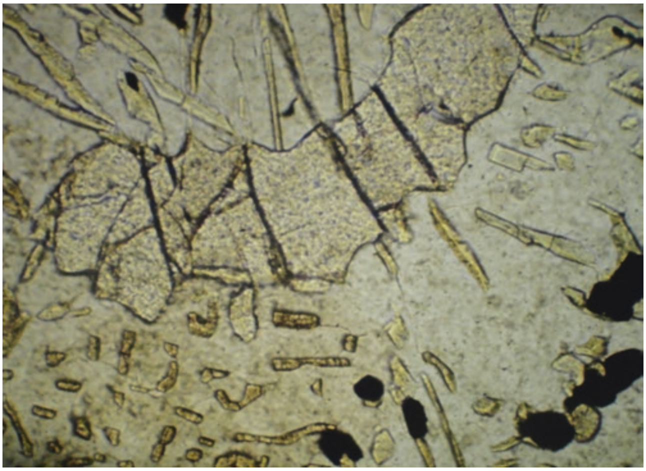


Fig. 3.47 Garnet being replaced by cordierite + orthopyroxene + magnetite symplectites in metapelitic granulite, SK 274, Garzón Massif, Río Neiva: evidence for isothermal decompression?

a metamorphic age around 1000 Ma. This pattern was confirmed by the most recent analyses by Ibáñez-Mejía et al. (2011), showing a youngest detrital age for zircon cores of 1135 ± 4 Ma and an age of 990 ± 5 for their metamorphic overgrowths (Fig. 3.48).

The ages obtained from the Garzón Massif concur in the formation of a calcalkaline volcano-sedimentary protolith between 1200 and 1100 Ma and granulite-facies metamorphism around 1000 Ma. Average model T_{DM} ages are around 1.55 Ga (Restrepo-Pace et al. 1997). Below we will discuss this in more detail.

3.2.3 The Subandean Basement

In the Putumayo basin, the southern part of the Subandean foredeep adjacent to the Garzón Massif, Precambrian basement has been found at the bottom of cores drilled by oil companies at depths between 940 and 2350 m (Ibáñez-Mejía et al. 2011, 2015). The basement in the Payara-1 well consists of granulite-facies metapelitic gneisses, from which igneous cores of zircons have been dated at 1606 ± 6 Ma and the metamorphic overgrowths at 986 ± 17 Ma (Ibáñez-Mejía et al. 2011). This author considers the protolith as igneous because of the zoned character of the zircons, but in view of the mineral paragenesis of the rock with orthopyroxene, garnet and sillimanite, it is rather a metapelitic gneiss with detrital zircons from a common igneous source rock. The Solita-1 well shows amphibolite-facies migmatitic amphibole gneisses, with zircons showing a metamorphic event at 1046 ± 43 Ma and with xenocrystic cores up to 1.85 Ga. Migmatitic gneisses from the Mandur-2 well show

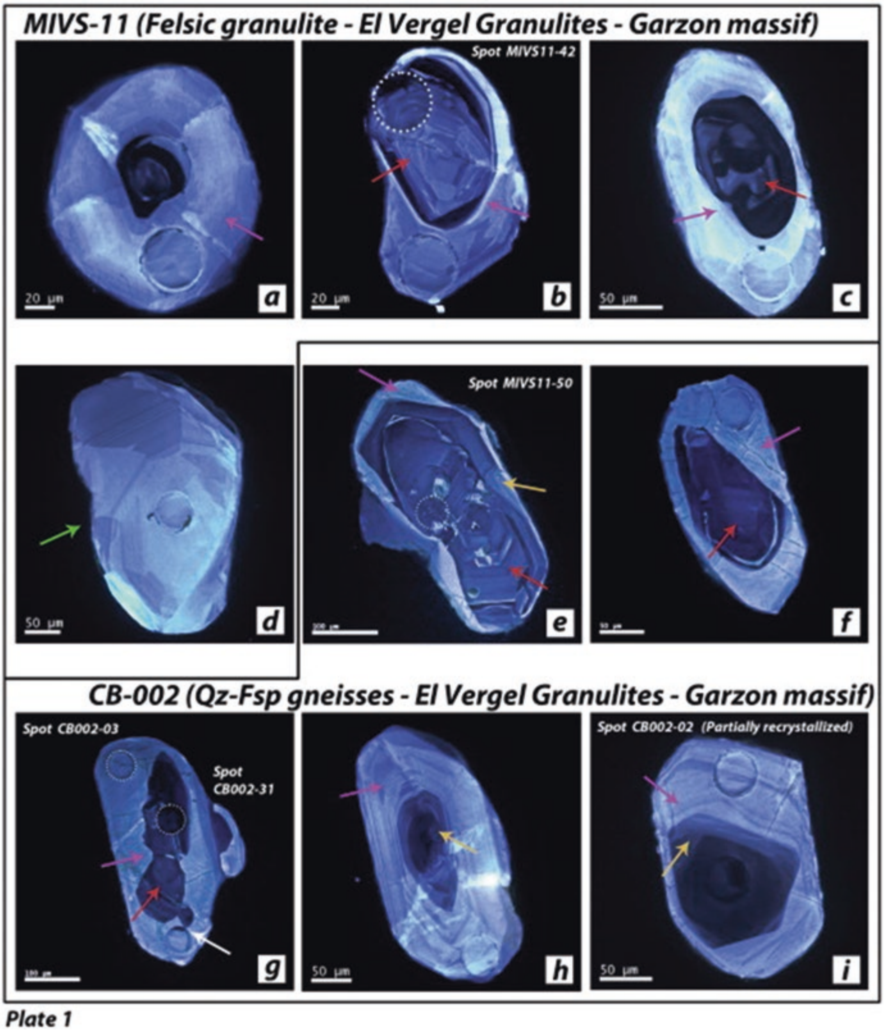


Fig. 3.48 Zircons from granulites of the Garzón Massif: igneous and/or detrital core, metamorphic overgrowths (Ibáñez-Mejía et al. 2011). Reproduced with permission (Elsevier)

amphibolite-facies metamorphism of 1019 ± 8 Ma in overgrowth rims in zircons from the melanosome and 1592 ± 8 Ma from their protolith cores. Leucosome zircons show ages of 1017 ± 4 Ma. The Caiman well consists of migmatitic biotite gneisses cut by leucogranite. The metamorphic overgrowths on zircons from the migmatites gave an age 989 ± 14 Ma; xenocrystic cores gave ages between 1470 and 1680 Ma. The crystallization age of the leucogranite was 952 ± 21 Ma, while xenocrystic zircon cores range between 1440 and 1700 Ma (Ibáñez-Mejía et al. 2011, 2015).

All these data suggest that the Precambrian basement of the Putumayo basin has been metamorphosed by the same Grenvillian event as in the Garzón Massif but that the ages of the protoliths are in the same order of those of the adjacent Guiana Shield. As Ibáñez-Mejía et al. (2011, 2015) concluded, this supports the idea that the Mesoproterozoic Amazonian basement stretched all the way to the Andean cordilleras. It also lends more confidence to the hypothesis of the autochthonous nature of the Garzón Massif.

3.2.4 Serranía de Macarena

The Serranía de Macarena forms an NNW-SSE oriented fault-bounded uplifted outlier of the Eastern Cordillera, projecting into the Llanos Orientales. Little has been published on the geology of this area after Trümpy (1943). The basement here consists of 'mica schists and alkali feldspar gneisses, hornblende gneisses, amphibolites, and injection gneisses with all intermediate types from sericitic schist to highly injected granosyenitic gneiss' (Trümpy 1943). A Precambrian age was suspected because Cambrian-Ordovician sediments cover the basement unconformably. Recently a zircon U-Pb age of 1461 ± 10 Ma was obtained from a mylonitic biotite-muscovite-epidote-plagioclase-quartz gneiss from this area, reflecting the age of the igneous precursor (Ibáñez-Mejía et al. 2011).

3.2.5 Santander Massif

While the Eastern Cordillera in southern Colombia strikes approximately NE, near the town of Bucaramanga, it suddenly turns NW. The NNW striking western boundary fault of the Eastern Cordillera in this area, the sinistral Bucaramanga-Santa Marta fault, also forms the western limit of the Santander Massif, an uplifted crustal segment consisting mainly of the Precambrian Bucaramanga Gneiss and the Paleozoic Silgará schists, intruded by Jurassic batholiths (Ward et al. 1973, 1974; Restrepo-Pace et al. 1997) and covered by younger rocks (Fig. 3.49). Three main fault-bounded blocks have been mapped, one east and north of Bucaramanga, a second one near the town of Berlín and a small one near Chitagá.

The main rock types distinguished by Ward et al. (1973) in the Bucaramanga Gneiss are metapelitic gneisses with biotite, locally muscovite, and often cordierite and sillimanite, semipelitic gneisses, sillimanite-biotite quartzites, meta-arenitic (quartzofeldspathic) biotite gneisses, calcsilicate rocks, marbles and locally hornblende gneisses and amphibolites. Migmatitic character is common. Garnet is rare except in the garnetiferous amphibolites from the second zone, which may also contain pyroxene (Urueña and Zuluaga 2011). These authors also present a detailed geochemical study of leucosomes, mesosomes and melanosomes of the migmatites from the second block. They reconstruct a metamorphic history under amphibolite-facies conditions between 660 and 750 °C and from 5.5 to 7.2 kbar. Amaya (2012) reports the presence of orthopyroxene-bearing garnetiferous mafic granulites and reconstructs a clockwise metamorphic history – still essentially within the amphibolite facies – with a prograde part ranging from 580 to 670 °C, and 6.7 to 8.6 Kbar, caused by injection of leucosome liquids.

The first Precambrian radiometric datings from the Bucaramanga Gneiss give a Rb-Sr whole-rock age of 680 ± 140 Ma for a biotite gneiss and a K-Ar hornblende age of 945 ± 40 Ma (Goldschmidt et al. 1971). Two hornblendes from an amphibolitic gneiss dated by Restrepo-Pace et al. (1997) gave integrated Ar-Ar ages of 574 ± 8 Ma and 668 ± 9 Ma. Restrepo-Pace and Cediel (2010) show a 981 ± 85 Ma U-Pb concordia age for a migmatite, apparently already obtained in 1995. U-Pb SHRIMP data by Cordani et al. (2005) show a great range of zircon ages, between 1550 and 900 Ma, of which perhaps the most tell-tale are a cluster of three zircons around 1057 ± 28 Ma and a single one of 1112 ± 24 Ma. A younger group shows ages around 864 ± 66 Ma, possibly related to a later metamorphic episode.

3.2.6 Sierra Nevada de Santa Marta

The Sierra Nevada de Santa Marta is a triangular massif, reaching from the Caribbean coast up to 5775 m, the highest coastal relief in the world. It is bounded by the left-lateral Bucaramanga-Santa Marta fault in the west, the right-lateral Oca fault along the coast in the north and the right-lateral Cerrejón fault in the southeast: a Colombian promontory that has projected itself already for over 100 km in a NW direction into the Caribbean Sea since the Tertiary (Tschanz et al. 1974; Montes et al. 2010). The Neogene uplift history has been reconstructed thermogeochronologically by Cardona et al. (2011), Villagómez (2010), and Villagómez et al. (2011).

It has a complex geological structure, in which three geological provinces separated by thrust faults have been distinguished: from NW to SE the Santa Marta Province (the NW promontory of the massif), the Sevilla Province and the Sierra Nevada Province which forms the core of the complex (Fig. 3.50). The Cesar-Ranchería depression along the SE border is still underlain by Sierra Nevada rock units (Villagómez et al. 2011). Precambrian basement crops out on five widely spaced sites within the Sierra Nevada Province, separated by huge Jurassic batholiths, as well as on the western and northern side of the Sevilla Province (Tschanz et al. 1974; Ordóñez et al. 2002; Cardona et al. 2006; Colmenares et al. 2007).

The basement rocks have been denominated Los Mangos Granulites by Tschanz et al. (1974), a name retained by Ordóñez et al. (2002) and by the recent extensive mapping project in the Sierra Nevada de Santa Marta of the Servicio Geológico

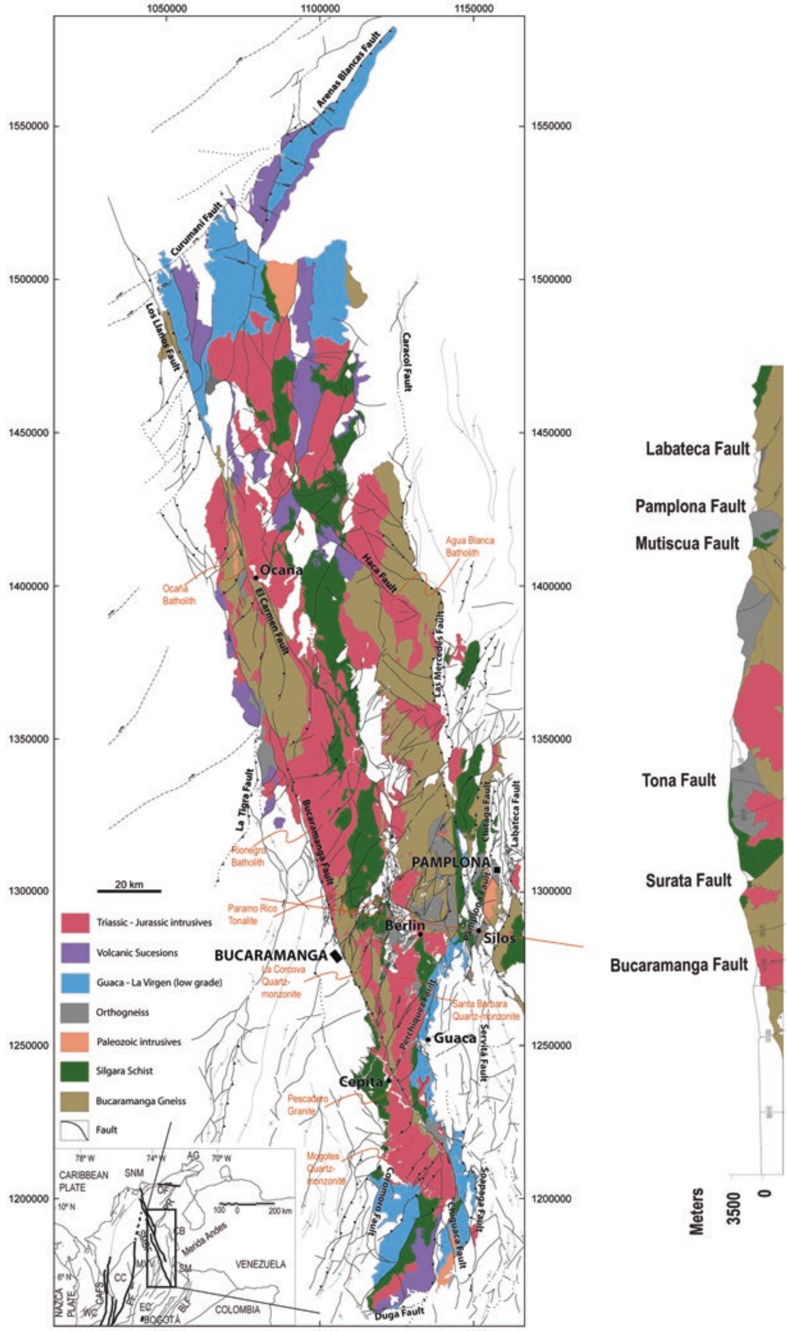


Fig. 3.49 Geological map Santander Massif near Bucaramanga, from Zuluaga et al., (2017)

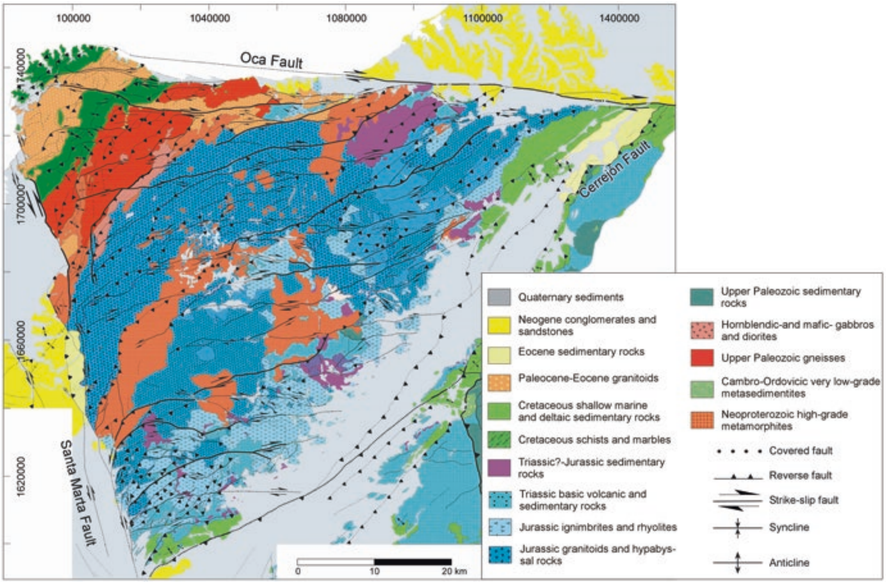


Fig. 3.50 Simplified geological map of the Sierra Nevada de Santa Marta. (see Colmenares et al. 2018)

Colombiano (Colmenares et al. 2007). The Los Mangos Granulites consist of banded and often migmatitic, granoblastic rocks including quartz-perthite granulites; intermediate granulites; mafic, calcareous and ultramafic granulites; garnet-rich granulites; and anorthosites. The migmatitic character of these units was already described by Radelli (1962b, 1967). Colmenares et al. (2007) describe also hornblende gneisses, garnetiferous biotite-muscovite gneisses, amphibolites and granulites. No orthopyroxene is mentioned, and the criteria used by Colmenares et al. (2007) to postulate granulite-facies metamorphism are insufficient. Tschanz et al. (1974) and Ordóñez et al. (2002) state that many granulites contain orthopyroxene. Also the apparent absence of metapelitic rocks is unusual. Amphibole-plagioclase thermobarometry on amphibolites indicates minimum metamorphic conditions of 6.0–7.6 kbar and 760–810° within the amphibolite-granulite-facies transition (Cordani et al. 2005). Anorthosites and anorthositic gneisses consisting almost exclusively of calcic plagioclase with accessory amphiboles and uralitized pyroxenes occur as separate concordant bands up to 1 metre in thickness within banded hornblende gneisses and garnet-biotite gneisses of the Los Mangos granulites in the Sevilla Province on the W side of the massif (Fig. 3.51; Cortes, 2013).

MacDonald and Hurley (1969) obtained a Rb-Sr isochron 1300–1400 Ma for a biotite-plagioclase gneiss and a hornblende gneiss (Dibulla Gneiss) near the northern shore of the Sierra Nevada Province. Tschanz et al. (1974) give Rb-Sr whole-rock ages of 752 and 1300 for two widely separated but similar quartz-perthite

Fig. 3.51 Río Sevilla anorthositic gneiss with amphibole lenses, Road to El Palmor. (From Colmenares et al. 2007).

granulites (Los Mangos Granulite) in the Sierra Nevada Province and a K-Ar age of 940 ± 30 Ma for a hornblende from hornblende-pyroxene-garnet-plagioclase gneiss from the western side of the Sevilla Province. Restrepo-Pace et al. (1997) give an integrated Ar-Ar age for biotite from quartz-pyroxene-garnet-biotite gneisses or granulites of 561 ± 6 Ma and a total fusion age of 845 Ma for another biotite. The upper and lower intercepts on the discordia line in the U-Pb concordia diagram of nine abraded zircons from a garnet-pyroxene-biotite-quartz-plagioclase granulite from the Guatapurí River are 1513 ± 35 Ma and 456 ± 60 Ma, respectively, but their significance is not clear because of the large error margins (Restrepo-Pace et al. 1997). Sm-Nd systematics show T_{DM} ages of 1.72–1.77 Ga. Ordóñez et al. (2002) show a Sm-Nd isochron for garnet and whole rock of 971 ± 8 Ma, and T_{DM} model ages between 1.47 and 1.92 Ga, so in the same order of magnitude as Restrepo-Pace et al. (1997). U-Pb SHRIMP analyses by Cordani et al. (2005) on rounded zircons from a biotite gneiss show apparent ages between 1400 Ma and 980 Ma. Five typical magmatic zircons yielded an age of 1374 ± 13 Ma, two other nearly concordant zircons yielded an age of 1145 ± 14 Ma and two more concordant grains presented 1081 + 14 Ma and 991 + 12 Ma. According to Cordani et al. (2005), the c. 1370 Ma age can be attributed to the magmatic crystallization of the zircons within a magmatic protolith. The zircon ages around 1140 ± 14 Ma might be related to a strong metamorphic event and the 991 ± 12 Ma age to a younger metamorphic event.

3.2.7 Guajira Peninsula

In the northernmost Guajira Peninsula, two pre-Mesozoic rock units have been recognized as possibly Precambrian, the Uray Member and the Jojoncito leucogranite (Fig. 3.52; MacDonald 1964; Lockwood 1965; Álvarez 1967; see review by Rodríguez and Londoño 2002 and López and Zuluaga 2012). The Uray Gneiss in the Macuira Mountains is a (often garnetiferous) hornblende-plagioclase gneiss body with incipient migmatitic character (cf Radelli 1961, 1967), calcsilicate rocks and diopside marbles, mostly metamorphosed under amphibolite-facies conditions, with some retrograde features. The Uray Member forms part of the Macuira Formation and is intruded by a Triassic (?) Siapana granodiorite body, but further contact relations are unclear (MacDonald 1964). A Precambrian age is suspected by Radelli (1961), but so far only Phanerozoic ages have been obtained.

A second unit, the Jojoncito leucogranite in the Simarua range (Álvarez 1967), is a leucocratic quartzofeldspathic gneiss with mesoperthite as a striking petrographic feature, suggesting granulite-facies metamorphism, but without its diagnostic minerals (Rodríguez and Londoño 2002). A 1250 Ma zircon age from this unit was mentioned by Irving (1971) and Case and MacDonald (1973), without further detail. Cordani et al. (2005) analysed zircons from the Jojoncito leucogranite and found three main groupings with apparent U-Pb SHRIMP ages of 1529 ± 43 Ma, 1342 ± 25 Ma and 1236 ± 16 Ma. These groups might reflect detrital ages from a sedimentary parent rock. High-grade metamorphic overgrowth rims gave ages of c. 1165 ± Ma and 916 ± 19 Ma. Sm-Nd systematics show a T_{DM} model age of 1.85 Ga. (Cordani et al. 2005). In the eastern, Venezuelan part of the Guajira Peninsula, also Grenvillian rocks have been reported, as well as offshore in the adjacent Venezuelan Falcon basin (Grande and Urbani 2009; Baquero et al. 2015).

3.2.8 Eastern Flank of Central Cordillera

Along the whole eastern flank of the Central Cordillera, numerous small outcrops of Precambrian rocks occur, often isolated fault-bounded uplifted blocks, often intruded by younger plutons or covered with younger deposits. From south to north, the following units have been distinguished.

Río Téllez-La Cocha Migmatitic Complex South of the Garzón Massif, in the western flank of the Central Cordillera, extending to the frontier with Ecuador, several small, elongate, fault-bounded outcrops of partly migmatitic biotite-hornblende gneisses, muscovite gneisses and garnet-sillimanite-biotite schists showing amphibolite-facies or greenschist-facies metamorphism have been reported by Ponce (1979), París and Marín (1979) and Núñez (2003). Ponce (1979) considers these rocks as Precambrian, and though Jiménez (2003) suggests that these rocks

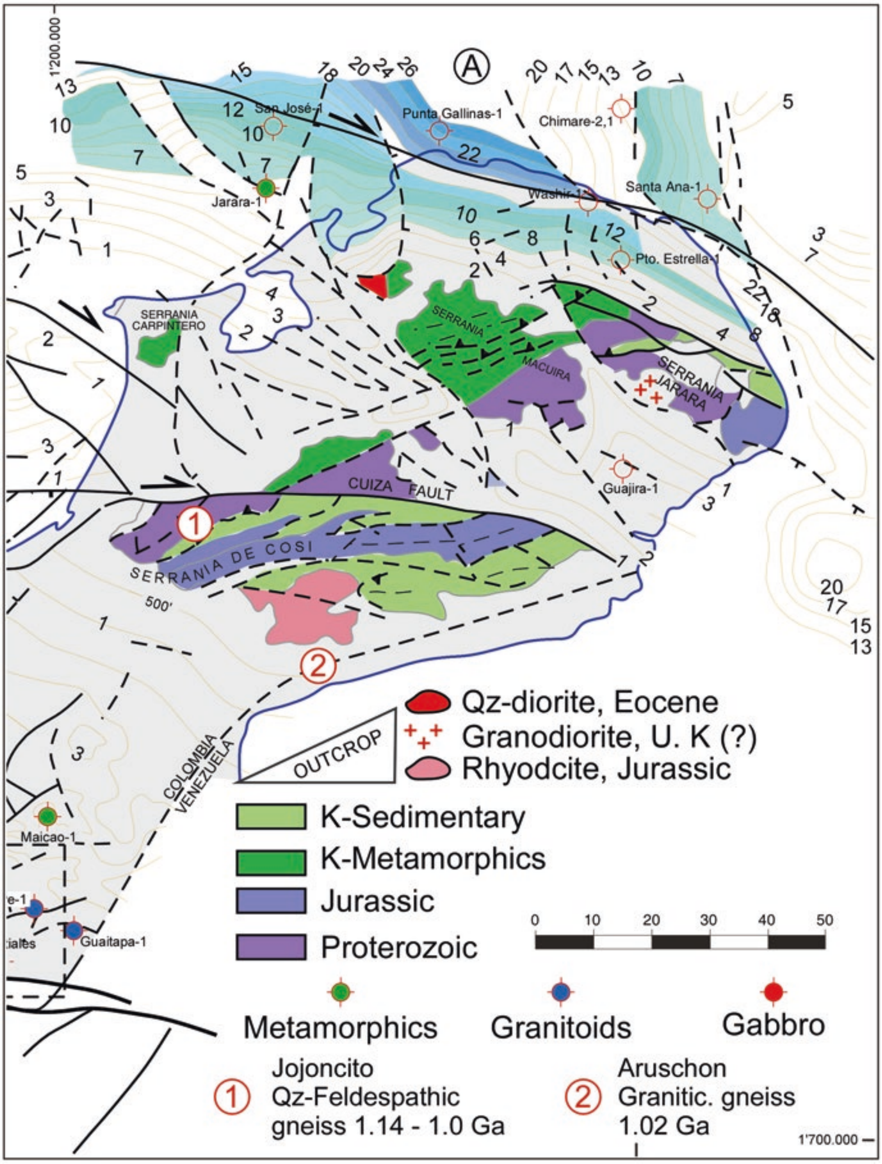


Fig. 3.52 Simplified geological map of the Guajira Peninsula Macuira, Uray rocks: dense vertical hatching, 4 is Jojoncito gneissic leucogranite. (Case and MacDonald 1973; Cediel 2018)

are much younger on the base of a U-Pb age of 166 ± 3.8 Ma from a granodiorite, we suspect that this age refers to a Jurassic intrusive body and prefer to maintain the Precambrian age of this unit, in harmony with the opinion of Ordóñez-Cardona et al. (2006).

Las Minas Massif and La Plata Massif Along the eastern flank of the Central Cordillera, just west of the Garzón Massif in the Eastern Cordillera, two smaller fault-bounded Precambrian Massif have been mapped, the Las Minas Massif and the La Plata Massif. The Las Minas Massif consists of migmatitic biotite gneisses; hornblende gneisses and amphibolites, partly garnet-bearing; and calcsilicate rocks. Slightly further north the La Plata Massif shows hornblende-biotite gneisses, orthopyroxene- and clinopyroxene-bearing quartzofeldspathic granulites as well as anatectic monzogranites (Kroonenberg 1982, 1985; Priem et al. 1989; Velandia et al. 2001; Marquínez et al. 2002a, b; Rodríguez 1995b; Ibáñez-Mejía et al. 2011). Restrepo-Pace et al. 1997 obtained an Ar-Ar hornblende cooling age obtained from a Las Minas amphibolite of 911 ± 2 Ma. Ibáñez-Mejía et al. (2011) obtained a U-Pb zircon detrital age of 1005 ± 23 Ma for a felsic gneiss near Pital and a detrital age of 1088 ± 24 Ma and a metamorphic age of 972 ± 12 for a mafic gneiss of the Las Minas Massif.

Icarcó Complex (Muñoz and Vargas 1981a, b; Murillo et al. 1982; Esquivel et al. 1987). In the southern part of the Tolima Department between the rivers Mendarco and Ambeima, three different outcrops of Precambrian have been mapped, designated Icarcó Complex by Esquivel et al. (1987). They consist of amphibolites, migmatitic hornblende gneisses, quartzofeldspathic gneisses and biotite-sillimanite gneisses and furthermore garnet-bearing quartzites, granulites and virtually pure marble lenses. On the basis of major elements of chemistry, the amphibolites are thought to be of igneous origin; the other rocks are metavolcanic-metasedimentary deposited in a continental shelf environment (Muñoz and Vargas 1981a, b). The mineral parageneses indicate mainly amphibolite-facies and locally granulite-facies metamorphism. The main foliation strikes between N-S and N10°E, and there is a pervasive cataclastic foliation striking 70–90°. Contacts with surrounding rock units are partly tectonic, but locally the migmatites are intruded by the Jurassic Ibagué batholith (Muñoz and Vargas 1981a, b). Roof pendants of similar rocks within the Ibagué batholith are mapped as Davis Biotite Gneisses (Esquivel et al. 1987). No radiometric data are available.

Tierradentro gneisses and amphibolites Migmatitic biotite gneisses (locally with muscovite and sillimanite), quartzofeldspathic gneisses, hornblende gneisses and amphibolites and occasionally quartzites and marbles have been described from the Río Coello near Ibagué (Tolima) by Barrero (1969), Barrero and Vesga (1976) and Mosquera et al. (1982) (Fig. 3.53). This unit is intruded by the Jurassic Ibagué batholith. In the absence of radiometric data, these rocks have been correlated with the granulites of the Sierra Nevada de Santa Marta (Barrero 1969; Kroonenberg 1985). West of Lérida and Armero another fault-bounded sliver of Precambrian rocks has been mapped by Barrero and Vesga (1976, 2010), continuing northwards along the hanging wall of the eastern boundary fault of the Eastern Cordillera at least as far north as Honda. They consist of schists, quartzofeldspathic biotite gneisses and amphibolites. The only available radiometric age is a K-Ar age of 1365 ± 270 Ma on hornblende from an amphibolite (Barrero and Vesga 1976; Vesga and Barrero 1978).

Fig. 3.53 Tierradentro amphibolites and migmatitic gneisses, Río Coello, Tolima. (Photo: Kroonenberg)

San Lucas Metamorphic Complex West of Puerto Berrio, the strip of Precambrian rocks in the eastern foothills of the Central Cordillera reappears, but it continues far northwards, with some interruptions, to form the western flank of the San Lucas Mountains, the northernmost extremity of the Central Cordillera (Fig. 3.54; Bogotá and Aluja 1981; Toussaint 1993; Ordóñez-Carmona et al. 1999, 2006; Figueroa et al. 2006; Cuadros et al. 2014; Clavijo et al. 2008). The Otú fault on the western side of the Serranía de San Lucas is generally considered as the westernmost limit of the Precambrian basement in this part of the Colombian Andes (Feininger et al. 1972; Ordóñez-Carmona et al. 1999, 2006; Clavijo et al. 2008; Cuadros et al. 2014). The basement is unconformably overlain by graptolite-bearing Ordovician shales (Feininger et al. 1972 and references cited therein). However, also west of this fault, occasionally high-grade metamorphic rocks occur, such as the Puquí gneiss and the Pantanillo granulite, from which so far only Phanerozoic Ar-Ar whole rock and K-Ar hornblende ages have been obtained (Rodríguez et al. 2012; Rodríguez and Albarracin 2012).

Lithologically the San Lucas rocks are migmatitic quartzofeldspathic gneisses, amphibolites, marbles, mafic granulites, leucogranite gneiss and metaquartzmonzonite apparently intruding the other rocks (Feininger et al. 1972; Ordóñez et al. 1999; Clavijo et al. 2008; Zapata et al. 2014; Cuadros et al. 2014). Ordóñez-Carmona et al. (1999) obtained a Rb-Sr isochron for the El Vapor mylonite of 894 ± 36 Ma, a single zircon Pb-Pb (Kober method) age of 1100 Ma and Sm-Nd T_{DM} model ages of 1829 and 1757 Ma. Similar values were obtained by Figueroa et al. (2006): they obtained a zircon U-Pb age of 1124 ± 22 Ma age, a whole-rock Sm-Nd age of 1312.5 ± 3.2 Ma and a T_{DM} model age of 1.6 Ga on a granulite near the Poporopo Pb-Zn mine.

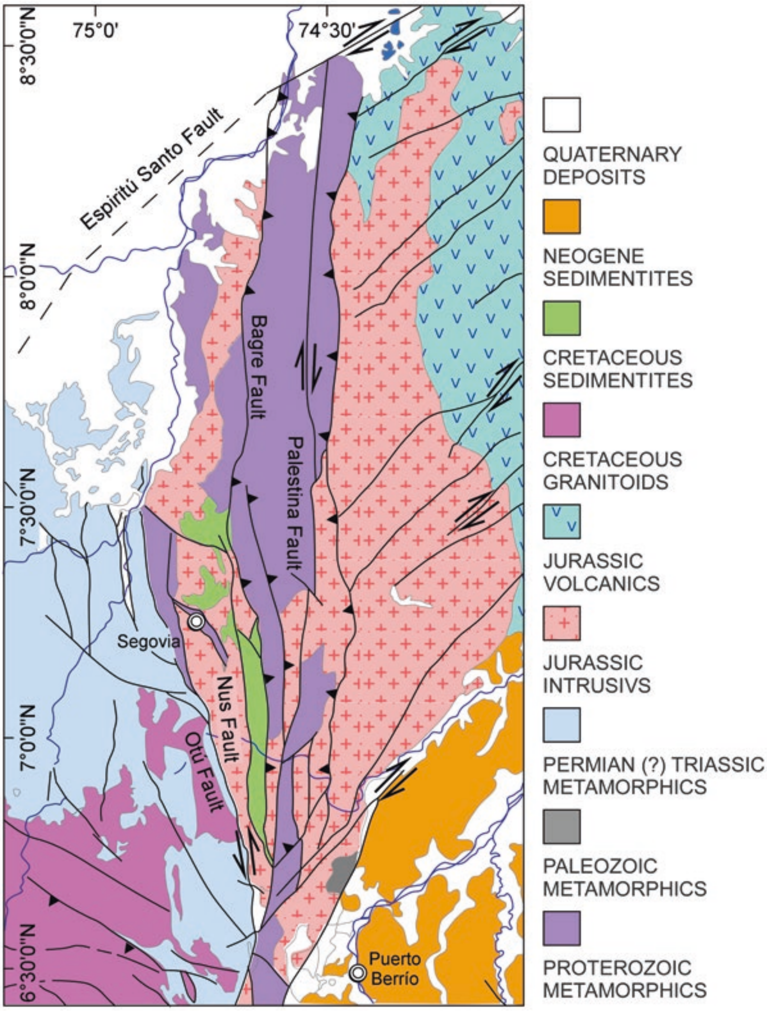
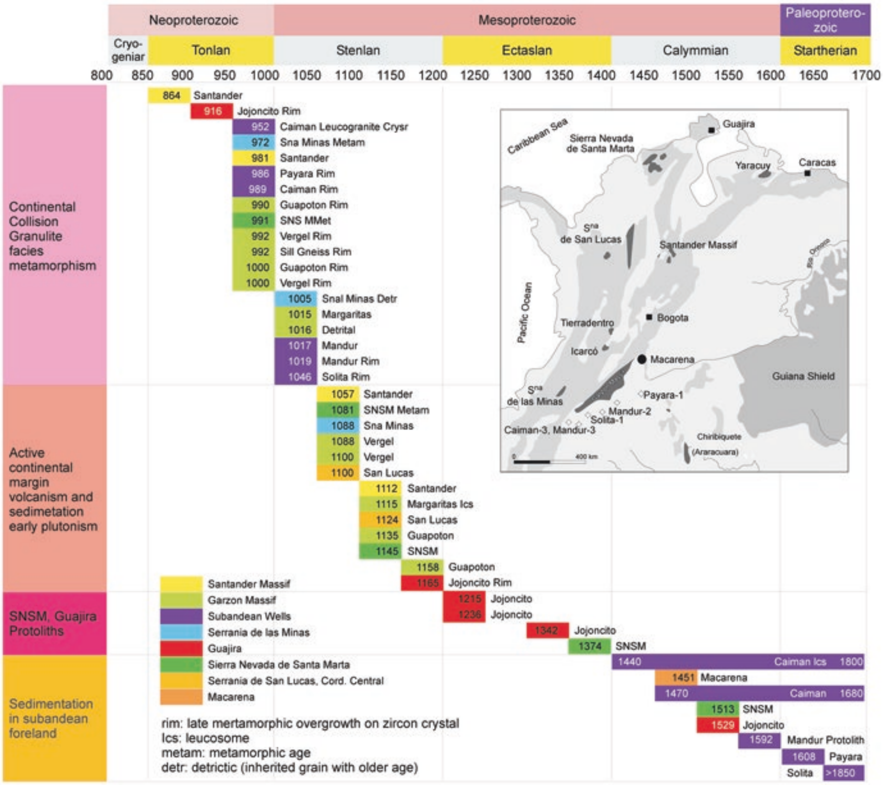


Fig. 3.54 Precambrian of the Serranía de San Lucas modified after Cuadros et al. 2014

3.2.9 Geological Evolution of the Andean Precambrian: The Grenvillian Orogeny

From the data presented above, it is clear that the Andean Precambrian in Colombia differs strongly from the Amazonian Precambrian in age, lithology and metamorphism. The great majority of the rocks show zircon U-Pb ages between 1150 and 950 Ma, granulites and gneisses of widely different compositions predominate and granulite-facies metamorphism is widespread (Table 3.3). This warrants the distinction of the Andean Precambrian as a separate geological province, termed the

Table 3.3 U-Pb chronogram of the Colombian Andean Precambrian



Garzón-Santa Marta Granulite Belt by Kroonenberg (1982). The orogenic event that gave rise to this unit is variably termed Grenvillian Orogeny (Kroonenberg 1982; Cordani et al. 2005; Cardona et al. 2010), Nickerian (Toussaint 1993, after Priem et al. 1971), Orinoquian (Restrepo-Pace et al. 1997; Martín-Bellizzia 1972) and Putumayo (Ibánez-Mejía 2011). We will retain the designation Grenvillian Orogeny, as it is generally accepted that this orogeny was the result of the collision of the Amazonian Craton with Laurentia and one of the key events in the assembly of Rodinia (Kroonenberg 1982; Cordani et al. 2005; Cardona et al. 2010; Ramos 2010).

Eastern boundary of Grenvillian Orogeny The boundary between the Amazonian and Andean Precambrian is hidden below the sediment cover of the Subandean foreland basins. The Precambrian basement rocks retrieved from boreholes in the basin by Ibáñez-Mejía et al. (2011) are largely metasedimentary gneisses and granulites subjected to Grenvillian metamorphism. They contain detrital zircons apparently derived from the adjacent Amazonian basement, but the age of sedimentation is unknown so far. The maximum age of sedimentation is given by the 1444 ± 15 Ma age of detrital zircons from the Caiman-3 well (Ibáñez-Mejía et al. 2011). There is no firm evidence that Amazonian basement rocks themselves have been subjected to Grenvillian high-grade metamorphism, and so how far the Amazonian basement extends westwards and the Grenvillian high-grade metamorphism eastwards is still unknown. However, far-field effects of the Grenvillian Orogeny are well discernible in almost the whole Guiana Shield through shearing, mylonitization and thermal resetting of mineral ages: the K'Mudku, Nickerie or Orinoquian event (see above).

1530–1230 Ma: Early stages of the Grenvillian Orogeny In spite of the common characteristics of all Andean Precambrian tectonic blocks, there are also interesting differences between them. Detrital zircons between 1530 and 1230 Ma are known from the Guajira Peninsula, the Sierra Nevada de Santa Marta and the Serranía de Macarena, but not from the other Andean outcrops. Furthermore, Cordani et al. (2005) suggest a magmatic protolith around 1370 in the Sierra Nevada de Santa Marta. The significance of those isolated early dates cannot be evaluated but suggests that some tectonic activity already started at that time, as is the case in the Grenville Province in Laurentia (Rivers 1997).

1150–1050 Ma: Active continental margin sedimentation and early magmatic activity There is a great similarity in the lithology of all Andean outcrops; quartzofeldspathic gneisses and granulites predominate, while metapelitic, metabasic, calcsilicate and quartzitic lithologies are also common. They point to a largely supracrustal, metasedimentary origin of the precursor rocks. Compositional banding on centimetre to metre scale, apart from migmatitic effects, is also evidence of a supracrustal origin. The bulk of the sediments is feldspar-rich, suggesting an immature character of the sediments. In view of the calc-alkaline affinities of the Garzón quartzofeldspathic granulites, it is logical to suppose that there is an important volcanogenic contribution, probably deposited as greywackes in an active continental margin (Kroonenberg 1982; Jiménez et al. 2006; Cordani et al. 2005). Some mafic rocks may represent metamorphosed basaltic sills or dykes, or synsedimentary lava flows into the basins, but their general scarcity does not favour an important back-arc spreading stage as envisaged by Ibáñez-Mejía et al. (2011). Only the anorthosites in the Sierra Nevada de Santa Marta are unknown from the other areas: their significance as individual bands within gneiss-granulite complexes has still to be evaluated. They also occur in Precambrian outliers in western Venezuela (Grande and Urbani 2009). Metapelitic rocks have not been recorded from the Sierra Nevada.

Orthogneisses like the Guapotón-Mancagua augengneisses intruded between 1158 and 1135 Ma may represent the deeper substructures of acid volcanic edifices. Also the early Jojoncito leucogranites (~1215–1236) may belong to this category. Early metamorphism and anatexis around Ma 1115 are evident from the Margaritas leucosomes in the Garzón Massif and in the Sierra Nevada de Santa Marta.

1050–950 Ma: Continental collision, granulite-facies metamorphism and migmatization Peak metamorphism in the granulites and gneisses is recorded in the metamorphic rims of zircons between 1050 and 950 Ma within all blocks of Andean Colombia as well as in the Subandean basement. Granulite-facies metamorphism is often concomitant with migmatization, as is evident from the presence of orthopyroxene in leucosome and from leucosome zircon dates, but anatexis did not result in large-scale plutonism. The clockwise metamorphic history of the Vergel

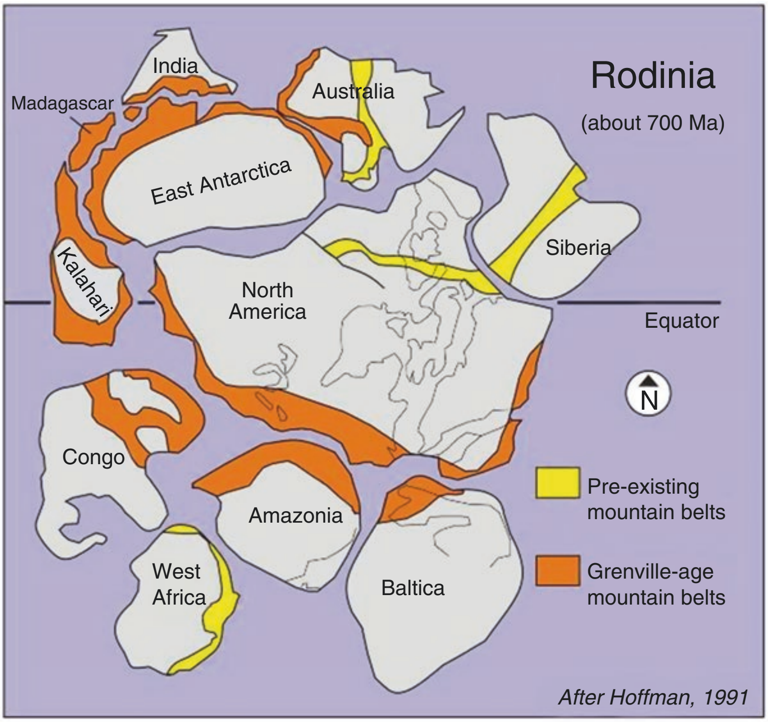


Fig. 3.55 Position of Amazonia and Laurentia in Rodinia supercontinent. (After Hoffman 1991)

Granulites suggests an isobaric cooling path, caused by thickening of the crust as a result of the collision (Jiménez et al. 2006). Younger Ar-Ar and Rb-Sr mineral ages, not included in Table 3.3, reflect different stages of cooling.

The continental collision between Amazonia and Laurentia plays a key role in the assembly of the Rodinia supercontinent around 1 Ga (Fig. 3.55; Hoffman 1991). Other continental fragments involved are the Oaxaquia and Baltica (Ruiz et al. 1999; Cordani et al. 2005, 2010; Ibáñez-Mejía et al. 2011; Geraldes et al. 2015), and there is discussion to which part of Laurentia Amazonia collided, but this discussion remains outside the scope of this chapter.

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