
**PROVENANCE OF OLIGOCENE CONGLOMERATES AND ASSOCIATED SANDSTONES
FROM THE SIAMANÁ FORMATION, SERRANÍA DE JARARA, GUAJIRA, COLOMBIA:
IMPLICATIONS FOR OLIGOCENE CARIBBEAN-SOUTH AMERICAN TECTONICS**

**PROVENIENCIA DE ARENISCAS Y CONGLOMERADOS OLIGOCENOS PERTENECIENTES A
LA FORMACION SIAMANÁ, SERRANÍA DE JARARA, GUAJIRA, COLOMBIA:
IMPLICACIONES EN LA TECTÓNICA OLIGOCENA DEL CARIBE Y SUR AMERICA**

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ABSTRACT

Analyses of composition and sedimentological attributes of conglomerate clasts together with petrographical and heavy mineral analyses and detrital geochronology from sandstones of the Oligocene Siamaná Formation in the Serranía de Jarara, are presented in order to reconstruct the provenance of this sedimentary sequence and contribute to the knowledge of the tectono-sedimentary evolution of the Guajira Peninsula and the Caribbean.

The results indicate that the source areas are proximal and are located to the southeast. The presence of plutonic igneous and medium- to low-grade metamorphic rocks, as well as high-pressure metamorphic rocks, indicate that the lithostratigraphic units (Parashi Stock and Jarara Formation) of the Serranía de Jarara and an unidentified unit to the southeast, are the main rock sources. The heavy minerals and the detrital zircon distribution with peaks at approximately 50 Ma, 207 Ma, 245 Ma, 463 Ma, 963 Ma and 1044 Ma, confirm that this is the source area. The extremely proximate sources and the rapid burying of the basin, which is evident due to the presence of marine sediments that overlie this sequence, indicate that this siliciclastic unit is related to the initial phases of a pull-apart basin. This basin was probably formed as a result of the movement of the Caribbean plate towards the east. The origin of the high-pressure clasts is unknown, and is possibly linked to a tectonic mélange. The U-Pb ages of approximately 50 Ma and the presence of fragments from the Parashi Stock, suggest exhumation during the Eocene and Upper Oligocene, possibly linked to the formation of the basin.

KEY WORDS: Colombia, Guajira, Caribbean plate, Oligocene, pull-apart basin, provenance.

RESUMEN

Se presentan los resultados de análisis de composición y de atributos sedimentológicos de clastos de conglomerados, junto con la caracterización petrográfica, el análisis de minerales pesados y geocronología detrítica U-Pb en circones de areniscas de la Formación Siamaná de edad Oligoceno de la Serranía del Jarara, para reconstruir la procedencia y contribuir al conocimiento de la evolución tectono-sedimentaria de la Península de la Guajira y el Caribe.

El conjunto de resultados indican que las áreas de aporte son de carácter proximal y están localizadas al sureste. La presencia de material derivado fundamentalmente de rocas ígneas plutónicas y metamórficas de medio a bajo grado así como fragmentos de rocas de alta presión indica que la Serranía de Jarara y sus unidades litoestratigráficas (Stock de Parashi y Formación Jarara), y un área no reconocida al sureste representan las áreas de aporte fundamental de esta secuencia. Los resultados de minerales pesados y las poblaciones de circones detríticos con picos de distribución de aproximadamente 50 Ma, 207 Ma, 245 Ma, 463 Ma, 963 Ma and 1044 Ma confirman esta área de aporte. Las fuentes extremadamente proximales de esta secuencia y el posterior hundimiento de la cuenca, evidenciado por los sedimentos marinos que los suprayacen, indican que esta secuencia siliciclástica está asociada a las fases iniciales de un ambiente de pull-apart, que formó esta cuenca por el avance hacia el este de la placa Caribe. El origen de los clastos de alta presión de fuente desconocida posiblemente están ligados a un mélange tectónico. Las edades U-Pb de aproximadamente 50 Ma y la presencia de clastos afines con el Stock de Parashi implican una importante fase de exhumación durante el Eoceno y Oligoceno Superior, que estaría en parte asociada a la formación de la cuenca.

PALABRAS CLAVES: Colombia, Guajira, Placa Caribe, Oligoceno, cuencas pull-apart, procedencia.

1. INTRODUCTION

Following the Late Cretaceous to Paleogene arc-continent collision between the Caribbean front and the northwestern South American Continent in the southern margin of the Caribbean plate (Pindell et al., 2005; Weber et al., 2009), Eocene to Miocene basin formation and infill recorded in the Upper Guajira Peninsula of Colombia indicate a subsequent oblique to strike-slip convergence of the Caribbean plate and the South American plate (Pindell, 1993; Avé Lallemant and Sisson, 1993; Macellari, 1995; Pindell et al., 1998; Montes et al., 2005; Ramirez, 2006; Gorney et al., 2007; Vence, 2008; Pindell and Keenan, 2009).

The Siamaná Formation of the Guajira Peninsula represents a major Oligocene unconformity, related to the formation of one of the major Oligocene to Neogene pull-apart basins built by the west to east migration of the Caribbean plate and the segmentation of the once coherent Andean blocks (Pindell 1993, Avé Lallemant and Sisson, 1993; Macellari, 1995, Montes et al., 2005; 2009; Ramirez, 2006; Gorney et al., 2007; Vence, 2008).

In this contribution we reconstruct the provenance record from an Oligocene conglomerate and associated sandstone sequence of the Siamaná Formation, which lies on the northwestern foothills of the Serranía de Jarara, by means of clast counting, sandstone petrography, heavy mineral analysis and detrital zircon geochronology. Due to limited transport of this type of sedimentary material (Boggs, 2009), conglomerate provenance is used to constrain the uplift and exhumation history in the source area, and to test the regional tectonic model for pull-apart basin formation, which predicts that at the source of the basin sediments must be extremely proximal.

2. GEOLOGICAL SETTING

The Guajira Peninsula is located in northern Colombia, and is formed by small and isolated hilly massifs (Serranías), separated by Oligocene basins filled by Cretaceous and Cenozoic sediments (MacDonald, 1964; Lockwood, 1965; Alvarez, 1967; Vence, 2008) (Figure 1). The central massif is the Serranía de Jarara, which has a roughly southeast to northwestern trend.

The Serranía de Jarara can be divided into two main metamorphic belts: (1) a southeastern belt of amphibolites, mica schists and associated orthogneisses (Macuira Group), intruded by Jurassic granitoids (Lockwood, 1965; Cardona-Molina et al., 2006; Weber et al., 2009). Recent U-Pb geochronology on the orthogneisses have yielded Early Triassic ages of ca. 245 Ma, which may be linked to a late metamorphic event (Weber et al., 2010). (2) To the northwest, two major Cretaceous metamorphic units are exposed: (a) The Jarara Formation formed by graphitic phyllites, muscovite schists, chlorite schists and meta-volcanic rocks, biotite schists and gneisses, and calcite marbles (Lockwood, 1965). (b) The Etpana Formation, formed by phyllites, greenschists, large bodies of serpentinites, gabbros and rodingites (Lockwood, 1965; Arredondo, 2005) (Figure 1). These rocks are intruded by quartzdiorites and porphyritic rocks of the Eocene Parashi Stock (Lockwood, 1965; Cardona et al., 2007).

Farther to the west, Weber et al. (2009) have identified the existence of an accreted island arc remnant that collided with the continental margin in the Maastrichtian. This collision is evident in the metamorphism of the Jarara and Etpana formations (Weber et al., 2010).

The sedimentary record of the Guajira Peninsula includes major Jurassic to Cretaceous rocks exposed in the southeast (MacDonald 1964; Rollins, 1965; Toussaint, 1996) (Figure 1), with stratigraphic features that can be correlated with the sedimentary record of the adjacent eastern Andes of Colombia (Toussaint, 1996; Villamil, 1999).

During the Eocene, the migration of the Caribbean plate towards the east was responsible for the formation of several pull-apart basins (Muessig, 1984; Macellari, 1995; Gorney et al., 2007). In the Guajira region this scenario was marked by the dextral displacements of the Cuisa and Oca faults, and the generation of pull-apart or graben-type basins in the Baja and Alta Guajira (Vence, 2008; Macellari, 1995) (Figure 1). This new period of sedimentation apparently included the deposition of a series of conglomerates, marls and calcareous shales of the Siamaná Formation on top of the older

Macarao Formation or directly on the crystalline rocks (Lockwood, 1965). Deep water sediments of the Uitpa Formation and Miocene shallow water Formations like Jimol and Castilletes were deposited on top of the Siamaná Formation confirming the deepening of the basin.

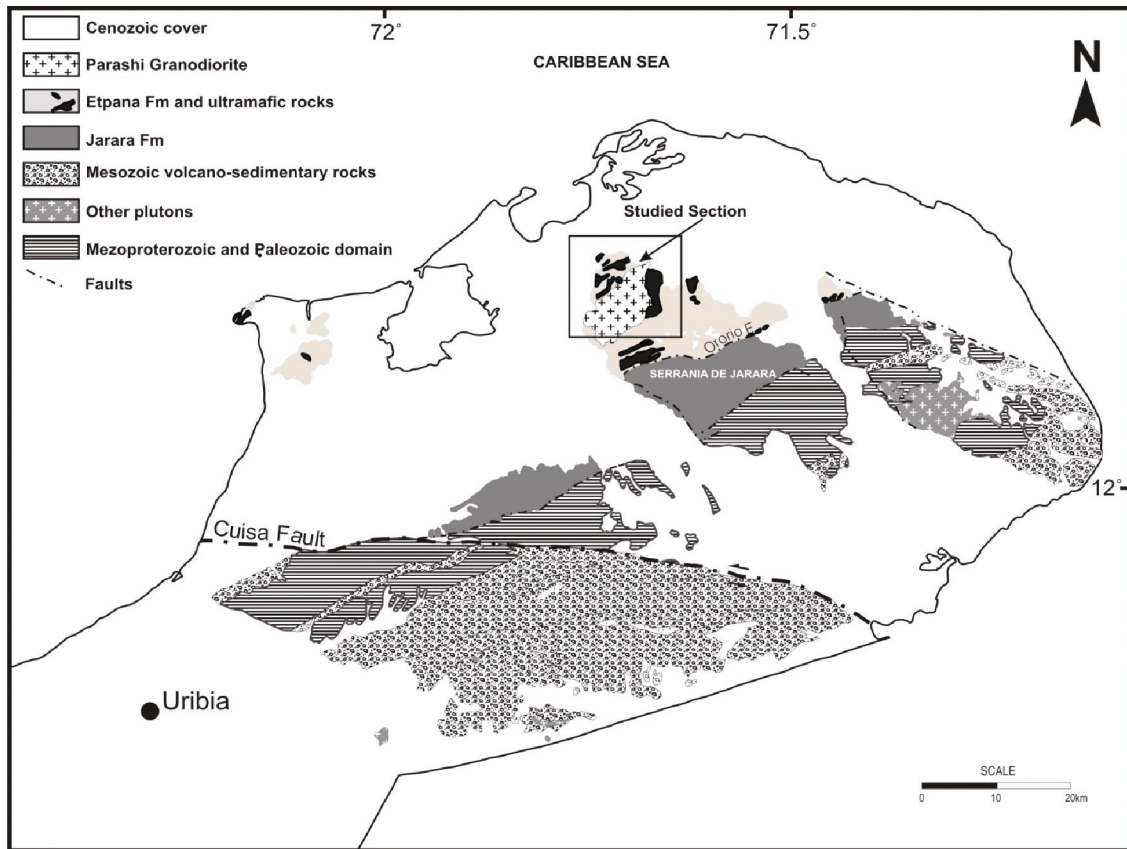


Figure 1. Geological settings and location of the studied section of the Siamaná Formation, modified from the Geological Map of Colombia (Ingeominas, 1997).

The conglomerate unit selected for provenance analysis is part of the Siamaná Formation in the Serranía de Jarara (Lockwood, 1965). This conglomerate contains a series of high-pressure Cretaceous metamorphic clasts whose origin is linked to the subduction and collision of the Caribbean arc front against the South American continent (Green et al., 1968; Zapata, 2005; Weber et al., 2007). Finding the in-situ origin of these high-pressure rocks has proven to be challenging (Lockwood et al., 1965; Green et al., 1968; Weber et al., 2007; 2009), however their regional petrotectonic evolution link them to the adjacent rocks of the Etpana Formation (Weber et al., 2007; 2010).

3. ANALYTICAL TECHNIQUES

Heavy minerals were extracted after crushing and washing, using LST liquid with a density of 2.89. Grains were mounted on a glass slide using meltmount® resin, that has an refraction index of 1.54.

Detrital zircons were extracted from sandstones following standard procedures for manual crushing and heavy liquid and magnetic separation at the University of Arizona, in Tucson. Once separated, the detrital zircons were encased in epoxy within one-inch ring mounts, which were then sanded and polished to produce a smooth flat surface that exposed the interiors of the zircon grains. Analytical procedures followed Gehrels et al. (2006, 2008). Zircon grains were selected randomly from all sizes and shapes, although grains with obvious cracks or inclusions were avoided. U/Pb ages of detrital zircons were obtained using an LA-MC-ICP-MS (GVI Isoprobe; GV Instruments, Manchester,

UK). The interiors of the zircon grains were ablated using a New Wave DUV193 Excimer laser (New Wave Instruments, Provo, UT, USA, and Lambda Physik Inc., Ft. Lauderdale, FL, USA) operating at a wavelength of 193 nm and using a spot diameter of 35-50 μm ; laser ablation pits are $\sim 20 \mu\text{m}$ deep. With the LA-MC-ICP-MS, the ablated material is carried via argon gas to the plasma source of a Micromass Isoprobe, which is configured in such a way that U and Pb can be measured simultaneously. Measurements were made in the static mode using Faraday collectors for ^{238}U , ^{232}Th , ^{208}Pb , ^{207}Pb , ^{206}Pb and an ion counting channel for ^{204}Pb . Analyses consist of one 20-s integration with the peak centered but no laser firing (checking background levels), and 20 1-s integrations with the laser firing on the zircon grain. At the end of each analysis, a 30-s delay occurs during which the previous sample is purged from the system and the peak signal intensity returns to background levels. The contribution of Hg to the ^{204}Pb is accounted for by subtracting the background values.

Common lead corrections were made using the measured ^{204}Pb of the sample and assuming initial Pb compositions from Stacey and Kramers (1975). A fragment of a zircon crystal of known age ($564 \pm 4 \text{ Ma}$, 2s error; G. E. Gehrels, unpublished data) was analyzed after every fifth zircon analysis to correct for inter-element and Pb isotope fractionation. The ages presented are $^{206}\text{Pb}/^{238}\text{U}$ ages for grains with ages $< 1000 \text{ Ma}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ages for grains with ages $> 1000 \text{ Ma}$. All uncertainties of individual grains were reported at the first level and include only measurement errors; systematic errors would have increased age uncertainties by 1-2%. Those analyses with or more than 20% discordance or 5% reverse discordance were omitted from further consideration. The data from each sample were displayed on concordia diagrams and age probability plots/ histograms using the programs of Ludwig (2003). Age probability plots

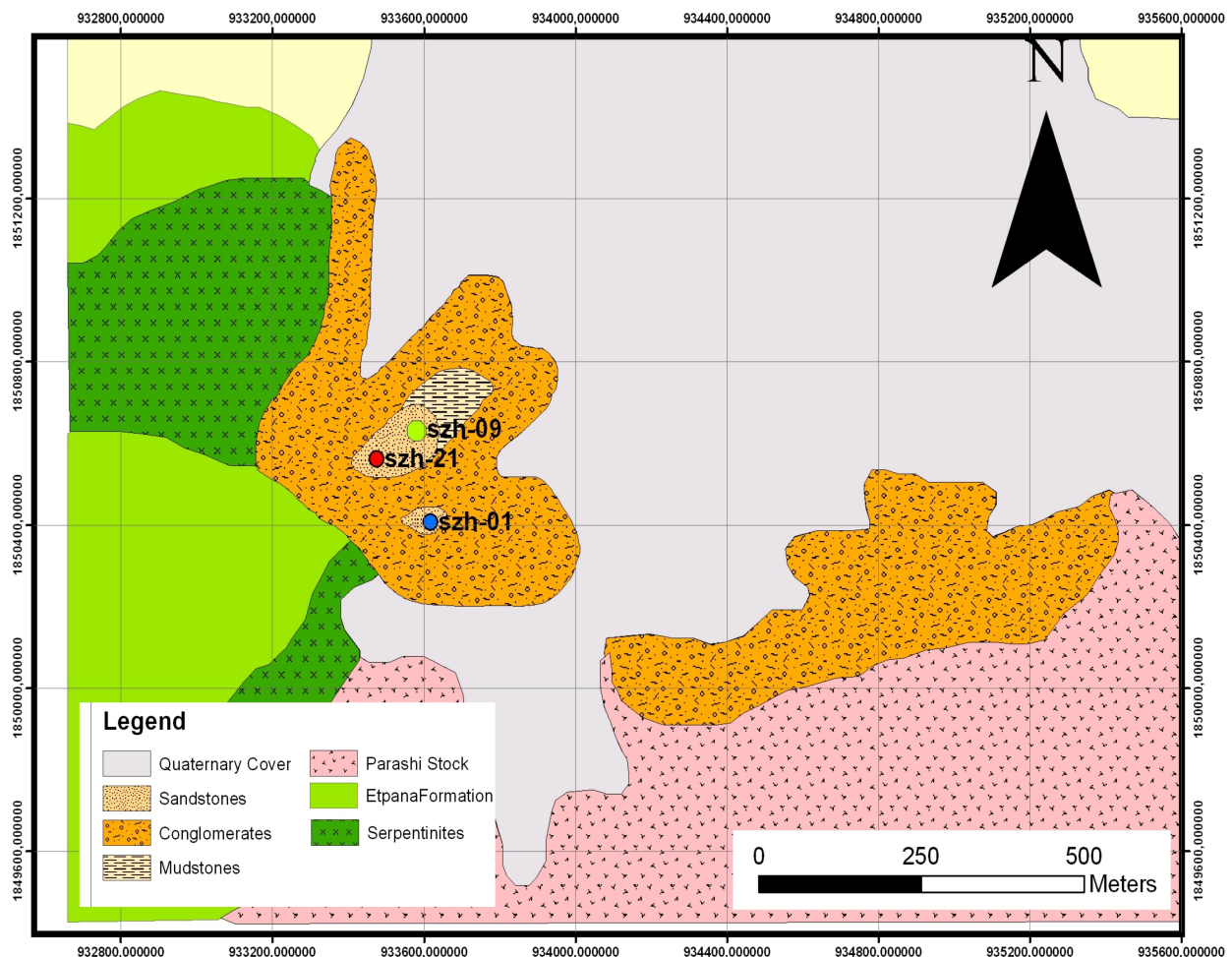


Figure 2. Studied section located in the NW of the Serranía de Jarara. Symbols represent collected sandstone samples.

depicted each age and its uncertainty as a normal distribution, summing all ages from the analyzed zircons of a sample into one curve, which was then divided by the total number of analyzed zircons.

4. RESULTS

The study section is located in the northwestern boundary of the Serranía the Jarara. The size of this section is approximately 1 Km² and 24 m thick (Figures 2 and 3). This conglomerate rests on top of ultramafic rocks and schists that are part to the Etpana Formation (Figure. 2). Although not studied, another conglomerate exposed to the east, apparently rests directly on top of the Eocene Parashi Granitoid. It is possible to distinguish three units in the studied section of the Siamaná Formation (Figure 3). The lower unit comprises a 20 m thick conglomerate, which is overlain by a 3 m thick layer of calcareous sandstones. Also present is a 4 m mudstone lens associated to the sandstones and resting on top of the conglomerates (Figure. 3).

5. CONGLOMERATE PROVENANCE ANALYSIS

Sediment sorting, composition, size, and roundness were quantified in 9 stations (C1 to C9, Figure 4) of a single conglomeratic layer. Distribution maps of sedimentological properties were drawn from the collected data.

Systematic observation of clastic elements has shown that materials tend to decrease in size towards the current direction (Pettijhon, 1975) and therefore, the average clast size distribution is an indicator of the possible location of the depocenter of the materials found in the conglomeratic unit. In general in the studied section the largest rocks are located to the southwest, decreasing in a radial pattern towards the northeast (Figure 4B).

Variation in sediment sorting is directly related to decrease of grain size and can be used to identify flow direction (Pettijohn, 1975). Sorting of the conglomerate in station C1 is very poor, with sizes ranging between 2 cm to 60 cm (Figure 4A). In station C3, located towards the center of the unit, sorting is defined by an unimodal grain distribution, whereas stations C6 and C9, which are located on the edges of the conglomerate, show good sorting, with sizes of ca. 35 cm and 25 cm respectively (Figure 4A). This trend clearly shows a general increase in sediment sorting towards the northeast.

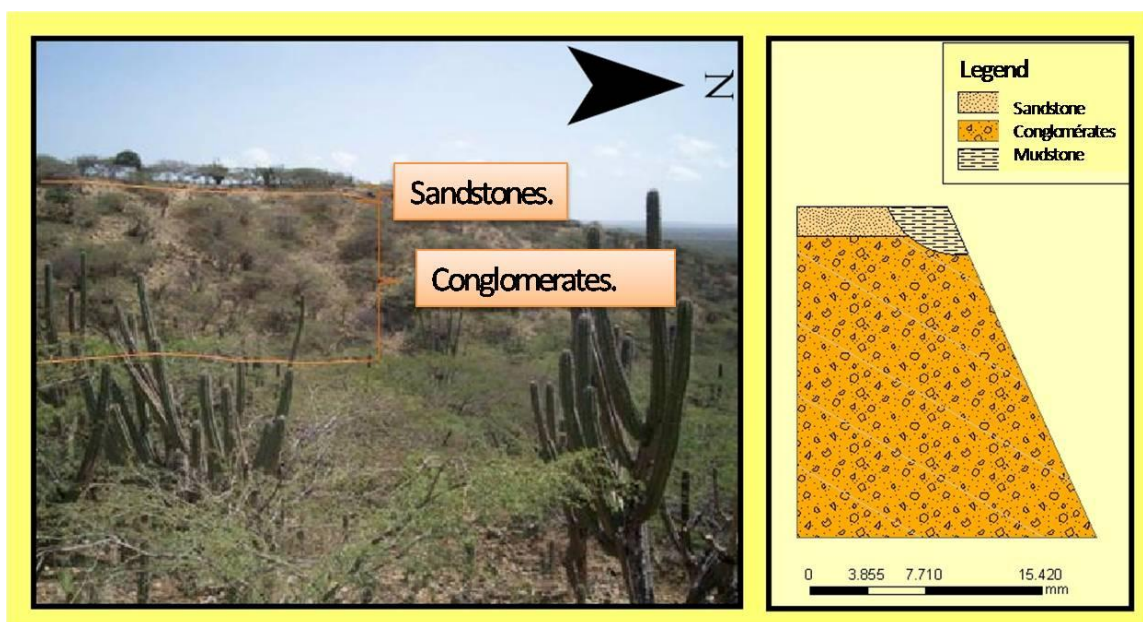


Figure 3. Studied stratigraphic section of the Siamaná Formation.

These features and the fact that the sorting pattern is inversely related to grain size (Figures 4A, 4B), confirms that the stream direction was to the northeast.

The composition of the clasts includes granodiorites and porphyritic rocks, quartzites, serpentized ultramafic rocks, high-pressure metapelites, eclogites and muscovite-quartz schists. Figure 4C shows the percentages of abundance of each composition in representative stations.

Roundness and sphericity are considered to increase with the amount of sediment transport (Pettijhon, 1975). In the case of the conglomerate of the studied section, roundness of the clasts increases towards the fringes, and is lowest to the center-southwest of the deposit (Figure 4D), indicating that the clasts to the southeast were exposed to longer travel distances and therefore were subjected longer to sediment transport.

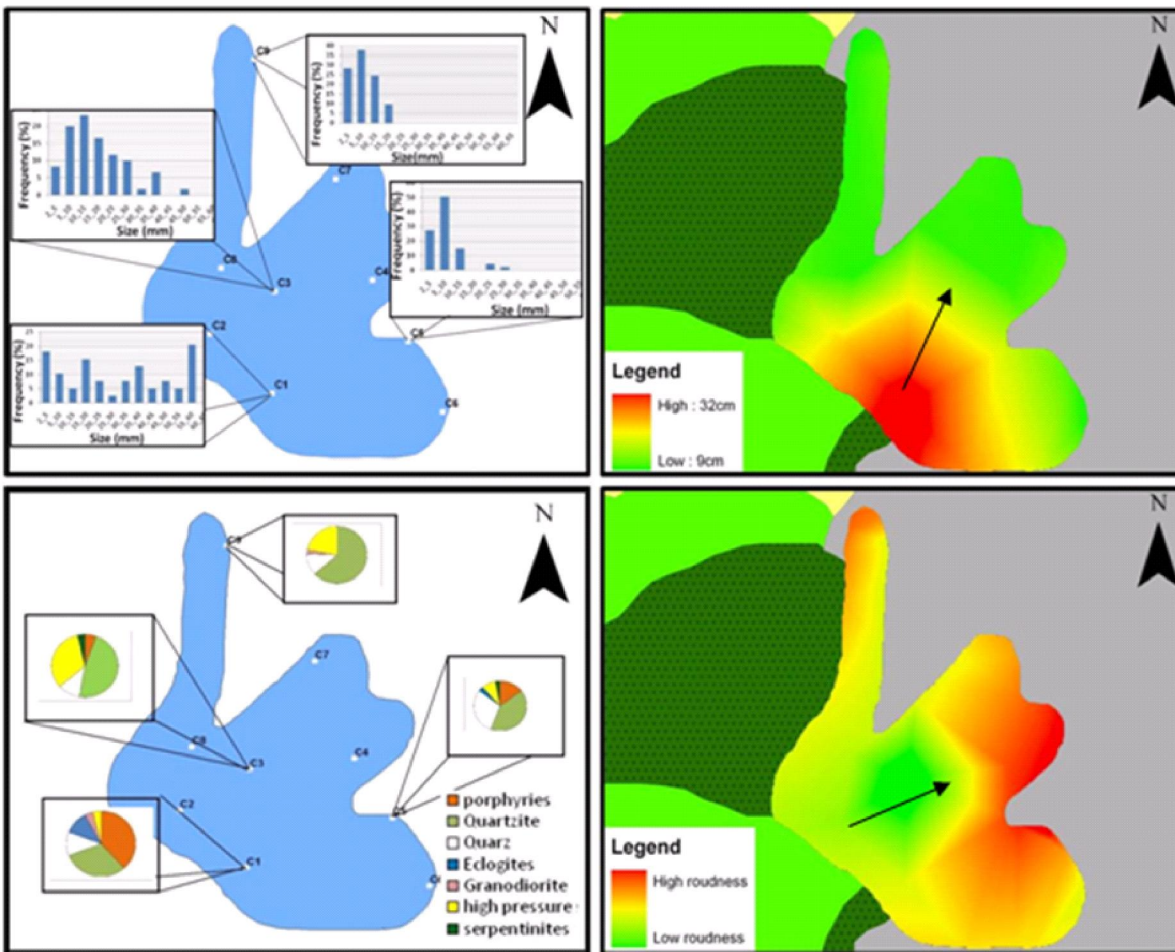


Figure 4. Distribution of the sediment properties in the studied section of the Sianamá Formation. (A) Sorting distribution histograms for some of the representative stations. (B) Size distribution integrated map. (C) Composition pie-charts from some of the representative stations. (D) Roundness distribution integrated map. The black arrow indicates the average paleoflow direction.

Eclogite and high-pressure metapelite clasts tend to be more rounded and spherical compared to the other rock types. This is either due to the fact that these rocks suffered more transport, or they reflect a particular characteristic of the source. The source of these rocks is probably a tectonic *mélange* (Zuluaga et al., 2008; Weber et al., 2009), and therefore we consider that the ductile deformation associated to the shearing created rounded lens shaped fragments before exposing them to the sedimentary processes. Consequently, the exposure to transport increased the roundness and sphericity of these rocks, compared to the porphyries, granodiorites, quartzites and low-grade schists, also present in the conglomerate.

6. SANDSTONE PETROGRAPHY

Three samples (SZH 01, SZH 02 and SZH 03) from the sandstone unit of the studied section were collected for petrographic analysis (Figure 1). At least three hundred points were counted following the Gazzi-Dickinson method (Gazzi, 1966; Dickinson, 1970; Ingersoll et al., 1984).

The sandstones are medium-grained rocks with highly angular fragments and poor sorting. They include mono and polycrystalline quartz, feldspar and igneous and metamorphic clasts (Figure 5). A clay matrix with carbonate cement represents over 15% of the rock.

Detrital modes are included in Table 1. The samples are classified as lithic arkose with high quartz content (Folket al., 1974) (Figure 6-A). The abundance of quartz and lithic fragments suggests that the tectonic environment during sandstone deposition is likely to be a recycled orogen (Dickinson and Suczek, 1979; Dickinson et al., 1983; Figure 6-B). This environment is commonly related to the erosion of active orogenic belts and subduction complexes (Dickinson et al., 1983), where upper crustal rocks are deformed and rapidly exposed to erosion.

Table 1. Detrital modes of the sandstone samples. Qm (monocrystalline quartz), Qp (polycrystalline quartz), F (feldspar), P (plagioclase), Lhp (porphyritic lithic fragments), Lm (metamorphic lithic fragments).

	Qm%	Qp%	F%	Pl%	Lh%	Lm%	Otros%
SZH 01	29,5	35,8	5,2	7,4	4,8	13,6	3,7
SZH 09	25,8	31,3	12,7	5,5	6,6	14,5	3,5
SZH 21	30,6	31,7	3,1	12,6	4,8	13,1	4,1

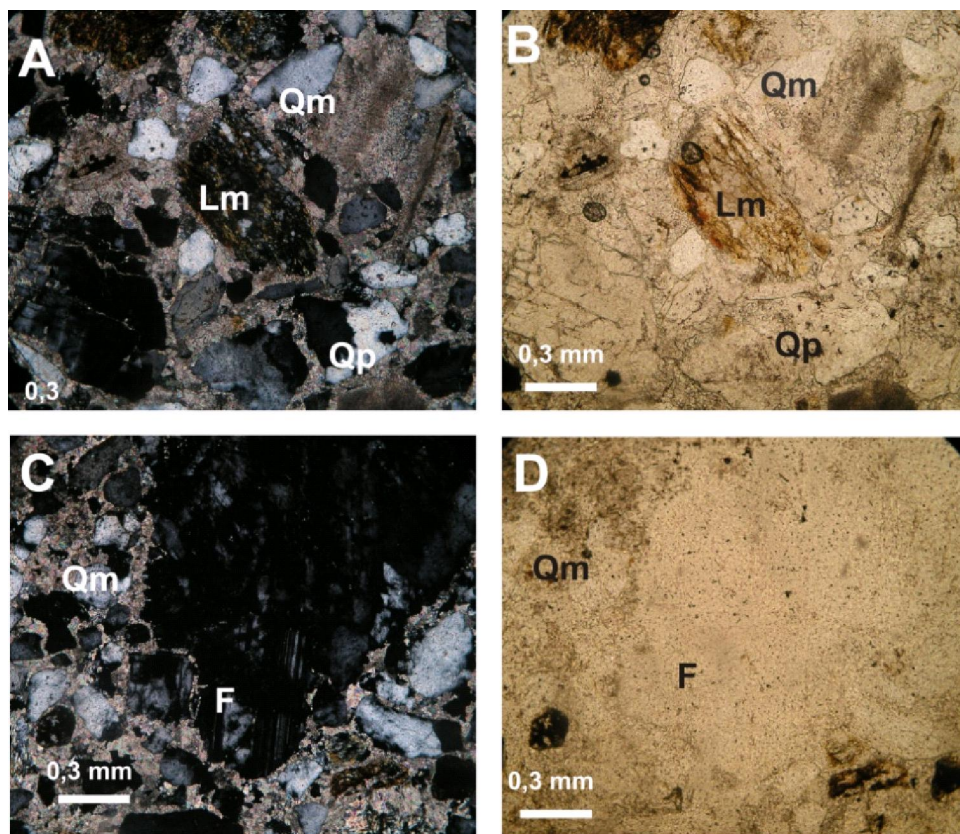


Figure 5. Representative thin sections of analyzed sandstones. Qm (monocrystalline quartz), Qp (polycrystalline quartz), F (feldspar), Lm (metamorphic lithic fragments).

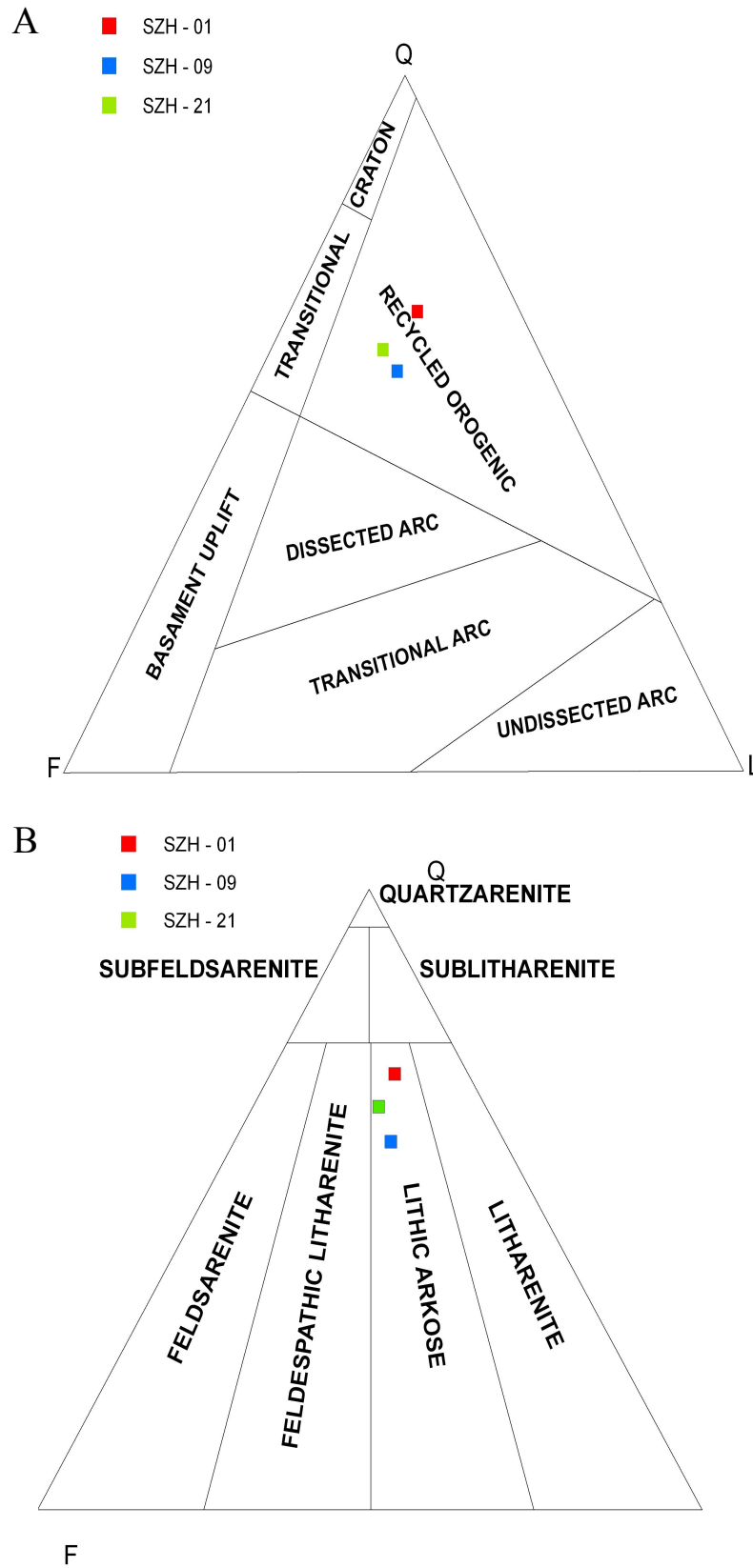


Figure 6. Three sandstone samples plotted on the sample classification QFL diagram from Folk (1974) (A) and the sandstone tectonic discrimination diagram from Dickinson (1983) (B).

7. HEAVY MINERALS

Heavy mineral suites provide important information on the sedimentary provenance (Pettijhon, 1975). The same three sandstone samples were selected for detailed heavy mineral analysis. In each section at least three hundred grains of non-opaque heavy minerals were counted. Identified minerals include epidote group minerals (zoisite, clinozoisite, epidote), garnet, amphibole, rutile, biotite and pyroxene (Figures 7 and 8). The heavy minerals show a similar geographic variability in relation with the composition of the rock clasts seen in the conglomerates.

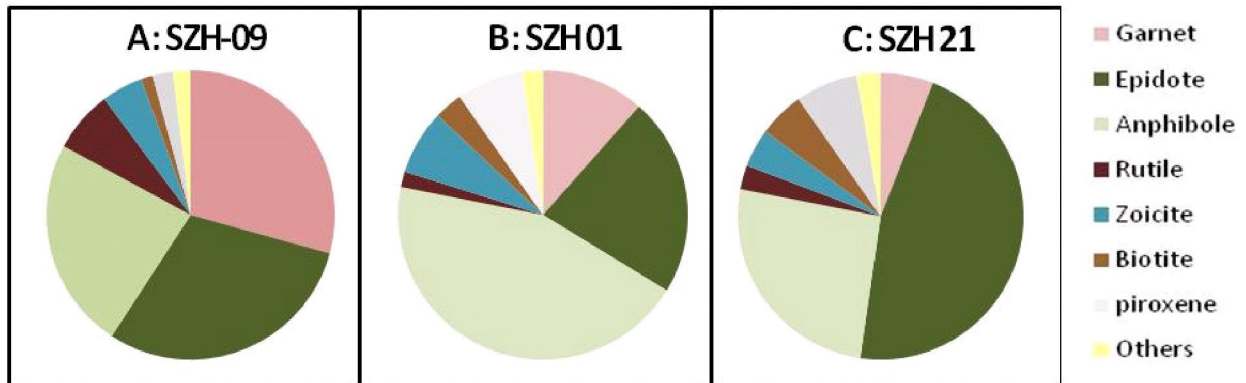


Figure 7. Heavy mineral suite for the three studied samples. (A) Sample SZH-09. (B) sample SZH-01. (C) sample SZH. 21

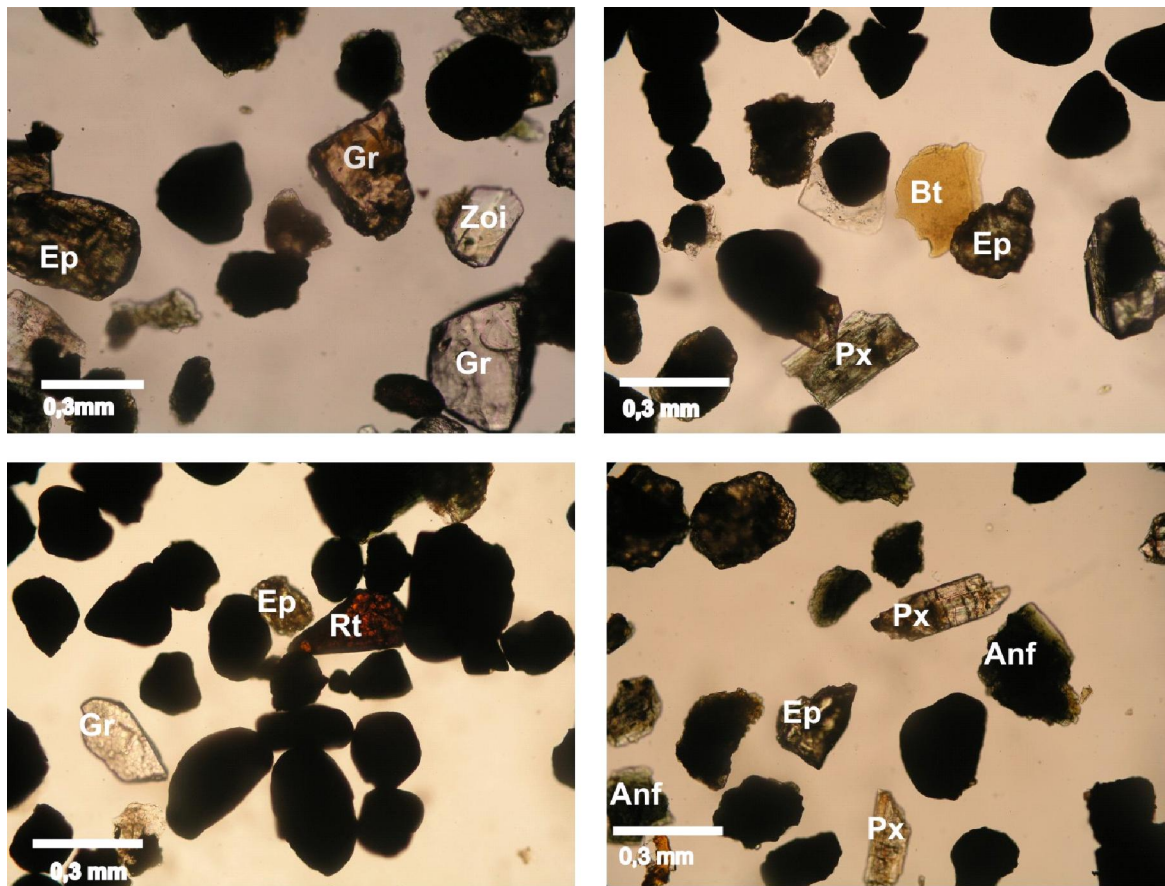


Figure 8. Heavy minerals in thin section from selected samples of the Siamaná Formation sandstones. Gr= garnet, Ep= epidote, Zoi= zoisite, Bt= biotite, Px= pyroxene, Rt= rutile, Anf= amphibole.

8. U-Pb DETRITAL ZIRCONS

One hundred and five detrital zircon grains were analyzed from sample MSZH-01. Results are presented in Table 2. Zircons younger than 1200 Ma are concordant. Older zircons are generally also concordant, but include some grains that fall outside of the Concordia (Figures 9A).

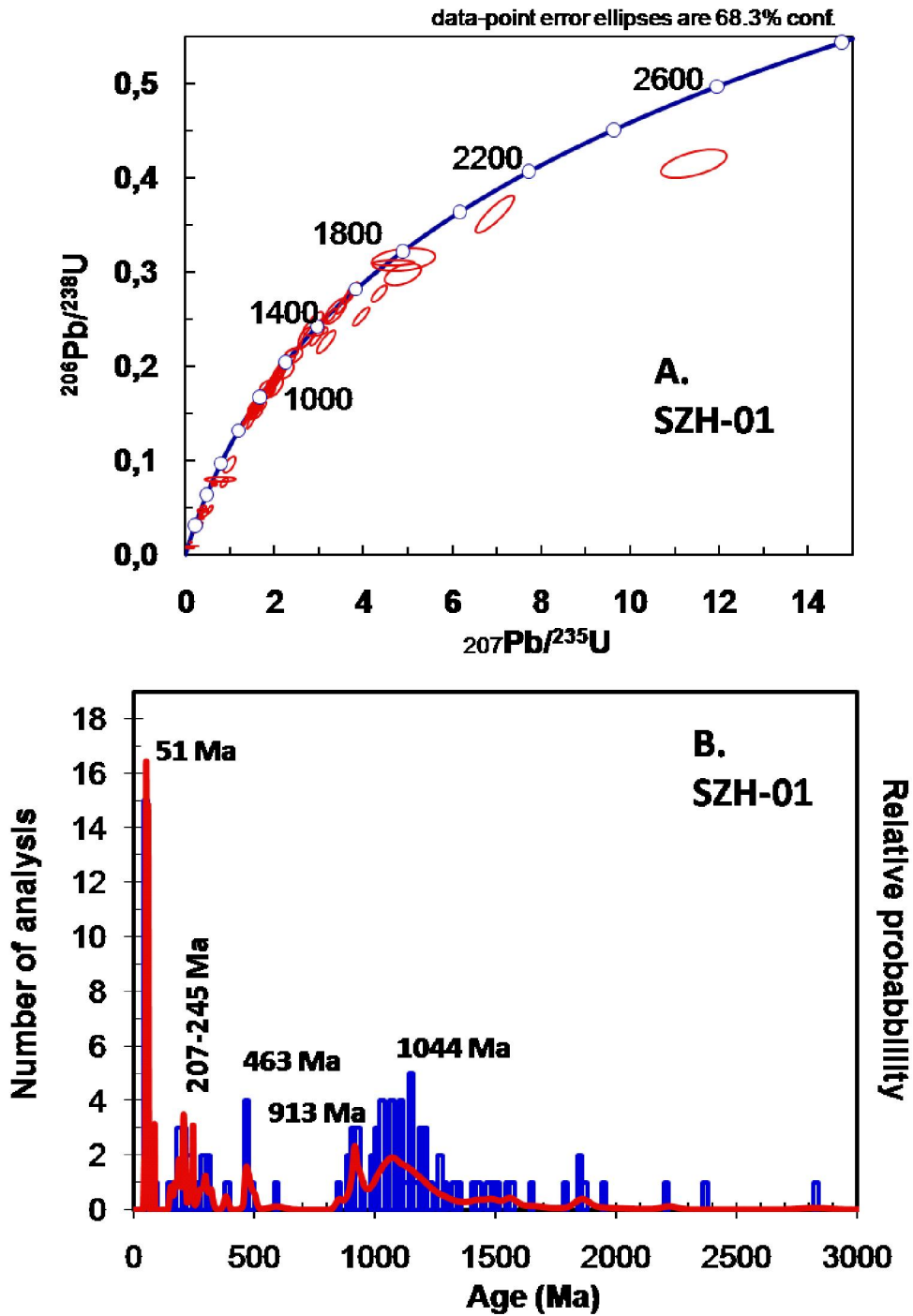


Figure 9. U/Pb detrital zircon results from sample SZH-01. (A) Concordia diagram, (B) Detrital age distribution histogram.

The major age distribution peak comprises 10 zircons with an age of approximately 50 Ma. (Figure 9B) and also represents the youngest age recorded for this sample. The rest of the zircons show five different age distribution peaks at 207 Ma, 245 Ma, 463 Ma, 913 Ma and 1044 Ma (Figure 9B). The Mesozoic and Grenvillian peaks are included in relatively continuous age intervals, which suggest a highly mixed and recycled source of zircons, probably linked to sediments or metasediments.

Single grains with Meso and Paleoproterozoic and Archean ages were also analyzed. These zircons suggest that there are in fact older ages, however they do not comprise a statistically well defined particular population (Gehrels et al., 2006). Young Eocene zircons limit sedimentation to this time span. With the exception of three grains, all of the analyzed zircons have U/Th ratios < 12 which is typical of magmatic zircons (Rubatto, 2002). The other three grains include Permian (2) and Grenvillian age with higher ratios that must be related to a metamorphic source.

9. DISCUSSION AND CONCLUSIONS

9.1 Provenance of the Siamaná siliciclastics

Bad sorting, low roundness, presence of non-altered feldspars and biotite, and an unstable heavy mineral fraction suggest that conglomeratic and sandy materials deposited in the Siamaná Formation were not exposed to long transport and derived from a very proximal source.

Sorting, size and clast composition have shown that the conglomerates were derived directly from a source located to the south to southeast. Igneous (porphyries and granodiorites) and low-grade schist clasts and polycrystalline quartz in the conglomerate and the sandstones of the studied siliciclastic sequence of the Siamaná Formation can be correlated to the erosion of the immediately adjacent Jarara and Etpana Formations and the Parashi Stock. The presence of amphibole and biotite can be also related to the erosion of the Parashi Stock and Jarara or Etpana Formations, and their presence, together with additional unstable pyroxene, clearly indicate short travel distances and fast deposition, that result in lack of transient weathering. U-Pb detrital zircon ages can also be compared to de adjacent Parashi Stock with ages of approximately 50 Ma (Cardona, Weber and Valencia unpublished data). The older ages are similar to the detrital ages recorded by the metasedimentary rocks of the Etpana Formation and the high-pressure metamorphic clasts (Weber et al., 2009).

Tectonic setting sandstone discrimination diagrams after Dickinson et al. (1983) and Suczek et al. (1983) show that the samples fall within the field of a recycled orogen. Normally tectonic provenance patterns are more related to the composition of the source area than the specific basin or source area tectonic setting (Augustsson and Bahlburg, 2003). It is therefore suggested that pre-Oligocene magmatic and metamorphic rocks filled the basin, such as those found in the Serranía de Jarara.

Unfortunately the source of the high-pressure metamorphic fragments remains not found (Lockwood, 1965; Weber et al., 2007; 2009). However, their limited spatial exposure and roundness suggest that they were probably derived from the Cretaceous tectonic mélange postulated by Weber et al. (2007, 2009) and Zuluaga et al. (2008), where the high-pressure rocks are most likely to be minor blocks in a schistose matrix (Weber et al., 2007, 2009; Zuluaga et al., 2008, Zapata, 2005). And have been rounded during shearing.

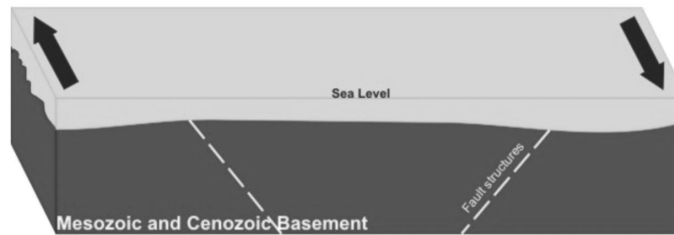
9.2 Tectonosedimentary implications

In general, the Siamaná Formation has been considered of Middle to Late Oligocene in age (Renz, 1960; Lockwood, 1965). The presence of marine fossils of shallow environments described by Rollins (1965) and of carbonate cement in the conglomerate and sandstone sequence suggests that the studied section was deposited in a shallow marine environment, and that the relatively thick and coarse conglomerate deposits are related to a marine type fan delta (McPherson et al., 1987).

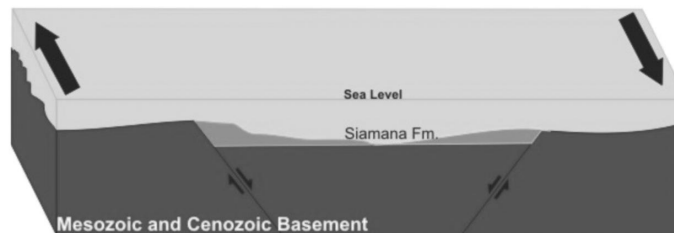
Tectonic reconstructions have shown that following the Paleogene collision and frontal convergence with the northern margin of Colombia, the Caribbean plate changed to a relative eastern migration that allowed the formation and transition to several back-arc and pull-apart basins on the margins (Muessig, 1984; Macellari, 1995; Pindell et al., 1998; Ramirez, 2006; Gorney et al., 2007; Vence, 2008; Pindell and Keenan, 2009). It is therefore suggested that the conglomerate described here is related to the opening of a pull-apart basin during the Oligocene that caused the formation of a basin and the simultaneous proximal uplift or push-up of blocks such as the adjacent Serranía de Jarara (Figures 10A and 10B). Fan deltas derived from this uplifted block were deposited in shallow water environments within adjacent pull-apart basins. The continuous subsidence and opening of these basins may be responsible for the marine transgression, represented by the deep marine sediments of the Uitpa Formation (Rollins, 1960, in Hall and Cediel, 1971; Lockwood, 1965) (Figure 10C).

Finally, the presence of rock clasts and zircons from the Eocene Parashi Stock (ca. 50-46 Ma) suggest that following the emplacement of this granitoid, there was a major post 50 Ma unroofing event, which could include exhumation related to the basin formation, which is common in extensional settings (Ring et al., 1999; Horton and Schmitt, 1998).

A) Late Eocene



B) Early Oligocene - Middle Oligocene



C) Late Oligocene

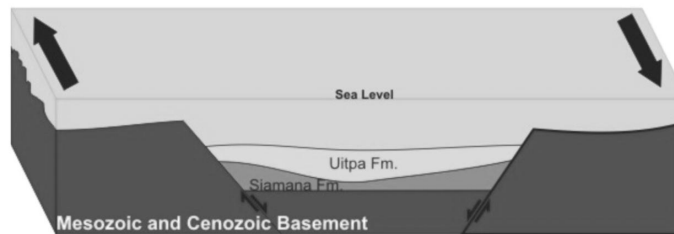


Figure 10. Simplified model for the formation and filling for pull-apart basins in the NW margin of South America. (A) The first stage before the breakup of the basement, (B) Sintectonic filling of the basin and Siamaná Formation deposition and (C) Subsidence of the basin and deposition of the Uitpa Formation.

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