Field Trip September 3-5 2011

GEOLOGICAL TRANSECT THROUGH AN ACCRETIONARY MARGIN, WESTERN COLOMBIA

Prepared by

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Introduction (by James Pindell)

Thanks to the efforts of many workers in different geological disciplines, our understanding of the Caribbean regional tectonic evolutionary framework has evolved to the point where predictions may now be made for the finer-scale evolution of more local areas around the Caribbean. One such area is Colombia (northern Andes), and the integration of specific aspects of Colombian geology within the Caribbean framework is leading to new levels of understanding for Colombia's tectonic and basinal evolution.

Rigorous paleogeographic evolutionary interpretation requires the balanced integration of information from both the orogenic zones and sedimentary basins, which are genetically linked in many ways. This is why it is vital for subsurface information from energy and ore exploration to be made public once it is commercially practical to do so; the future success of Colombian exploration is highly dependent on the results of past exploration efforts.

Paleogeography is best portrayed on quantitative palinspastic reconstructions that 1) progressively restore the effects of tectonism (compression, extension, strike-slip), and 2) progressively remove allochthonous accreted terranes back through time. This process should begin by assessing neotectonic deformations, which can be extrapolated back some amount of time until the geologic record suggests a change from another tectonic phase. In addition, constructing a quantitatively constrained Early Jurassic restoration of western Pangea is helpful for unraveling paleogeography, because it provides a starting point in regional evolution. Once these efforts have been made, then the time between them can be interpreted as the information and regional framework warrants, paying particular attention to periods of tectonic change.

Evolving concepts of Caribbean evolution since 1970 show advantages of considering regional evolution in the mantle reference frame, because subducted slabs in the mantle can only migrate forward/backward at a fraction of plate motion rates. Thus, the "room" for error in tectonic models is much less (Pindell and Kennan, 2009). From Triassic to Early Cretaceous, northern South America remained attached to northern Africa, with both continental blocks moving little relative to the mantle. This contrasts strongly with North America's Late Triassic-Jurassic and later NW-ward migration from northern Africa, which led to rifting and drifting between the Americas. At a finer scale, this is believed to have led to rifting and drifting between Colombia and the continental blocks of southern Mexico/Chortis/Yucatán. This created a western segment of the Proto-Caribbean Seaway, which Pindell (1993) called the Colombian Marginal Seaway. In the Aptian (~125 Ma), opening of the Equatorial Atlantic began, and northern South America has migrated westward across the mantle ever since then. Thus, the Jurassic-Neocomian extensional tectonism of Colombia became compressional, and offshore subduction systems and intra-arc basins along the northern Andes were thrown into E-W or SW-NE compression (sensu Dewey, 1980), with a probable dextral strike slip component. This long-lived compressive period comprises unique phases of convergent tectonic style between the NW corner of South America (Colombian continental promontory) and lithosphere that was either driven by, or directly belonged to, the Caribbean Plate.

In Early to Middle Jurassic, granitic intrusives were produced and cooled in a "Central Cordilleran" belt from Guajira into Ecuador, usually presumed to be arc magmas resulting from E-dipping subduction. However, they may relate to rifting within a zone of crustal anatexis caused by Alleghanian-Gondwanan crustal thickening of Late Paleozoic arc-related terrane. Following the arc model, the opening of an intra-arc basin has been proposed as a means of terminating this "arc" by 140-150 Ma (Pindell, 1993), but the alternative anatexis model (Pindell, this conference) requires only Jurassic rifting of Mexico/Chortis from Colombia, without any active subduction at all. The continental overlap between Colombia and Mexico/Chortis shown by Pindell and Dewey (1982) and many others since then is one reason to suspect the anatexis option as viable. Redbed deposition on phaneritic intrusive rock (e.g., Saldaña Fm on Ibague pluton) attests to syn-magmatic extension and exhumation of deep terrane, fitting EITHER model. But the arc model predicts evolution of an offshore active arc from 145-125Ma; such ages on arc rocks are rare in Colombia/southern Caribbean, making the identification of an active allochthonous arc at that time an issue for future investigation.

The NW-ward flight of North America probably created an archipelago underlain by arc, oceanic, and continental blocks, torn from from Mexico and Chortis, stretching along a SE-trending and lengthening sinistral shear zone/transform to South America. This shear zone may have ended at the north Andean Trench, which at the latitude of Colombia, was likely situated outboard of an intra-arc basin (Pindell et al. 2011), which can be called the Quebradagrande Basin. If our confidence about the existence of an arc outboard of that basin increases, then that arc might be called the Quebradagrande Arc, which now comprises a terrane known along the Cauca Valley of Colombia.

When the opening of the Equatorial Atlantic began at 125 Ma, we can predict a resultant end of back arc basin development, and the onset of north Andean compression. A simple way to view the effect of this development is that this basin and its supposed outlying Quebradagrande Arc began to collapse, achieved by dextral and W-dipping "subduction" within the backarc basin. This could have proceeded until the Central Cordilleran margin (former remnant arc) choked the trench during arc collision. Such a history has been well documented on Margarita (Venezuela), which has been interpreted to host a far-travelled portion of the HPLT metamorphic belt that was created by this event (Maresch, this volume; Maresch et al., 2009; Maresch et al., 2010). In additioin, the arc-continent collision appears to have involved propagation of transpressive faults into the continental margin, parts of which were uplifted and cooled around 115 Ma (Villagomez, 2010) as they were carried northward along orogen-parallel shears. However, E-dipping subduction of the Farallon Plate from outside (west of) the Quebradagrande Arc, marked by the Arquia HPLT complex, probably continued throughout closure of the weak backarc basin, and then continued after arc accretion from the Albian on. This view suggests that young, weak backarc basins can close without causing interference to the primary outboard subduction zone, where presumably stronger crust is subducted.

The Caribbean-Colombian intra-oceanic plateau (CCOP) then formed on Farallon crust from about 110-88 Ma (Kerr, 2003; J. Wright, pers. com., 2011) and progressively converged with Colombia, accreting slices of the plateau into a wide subduction prism as it encountered the E-dipping trench outboard the Quebradagrande/Arquia belts. Subduction-related magmas intruded inner parts of this prism (e.g., Buga Batholith) and adjacent continental margin (e.g., Antioquia and other batholiths) from about 100-74 Ma. Margarita was situated beyond the northern end of this setting, where a lengthening NE-trending dextral shear zone connected the Colombian trench to the eastern, W-dipping, Caribbean trench. The CCOP followed Margarita in this northerly position, and, like Margarita, began to receive Caribbean arc magmas (i.e., due to subduction of Proto-Caribbean crust) by 89 Ma as the Great Caribbean Arc was lengthened in the southerly direction to include the Aves Ridge, Margarita and the Leeward Antilles, by a combination of (1) dextral shear and arc-parallel extension, and (2) the simple fact that these terranes initially migrated along the western flank of the Central Cordillera-Guajira (no arc magmas) but eventually cleared Guajira and thus became situated above the Proto-Caribbean slab (onset of arc). Wright and Wyld (2010) present a general version of this scenario; a more precise synthesis awaits improved understanding of the allochthoneity of the Central Cordilleran/Guajiran terranes. One final note about the Upper Cretaceous is that subduction at the Panama-Costa Rica arc was underway by about 70-75 Ma (Buchs et al., 2009). We infer therefore that the Caribbean Plate had been carved out of the Farallon Plate by this time, and in turn that the Caribbean Plate was able to move on its own relative to other plates from that time onward. However, as shown by Pindell and Kennan (2009), the Caribbean Plate actually moved very little in the mantle reference frame during the Cenozoic, due to the fact that it was anchored by its two opposing Benioff zones since about 70 Ma.

The Late Cretaceous Andean setting of plateau subduction/accretion prevailed until the Maastrichtian, during which upper crustal components (CCOP) were accreted (Western Cordillera) while deeper Farallon crust and upper mantle continued to subduct and produce arc magmas (Antioquia). In the Paleocene-Eocene, Andean "Laramide" orogenesis began due to (1) acceleration of Caribbean orthogonal subduction once the Greater Antilles had encountered the Bahamas and could not move NE relative to the Americas any longer (Pindell and Kennan, 2009); and (2) westward acceleration of South America across the mantle, which further threw the Andes into compression (Pindell and Tabbutt, 1995). By the Middle Eocene, much of Colombia had become subaerial with multi-kilometric uplift and erosion of material from the Colombian hanging wall (Central Cordillera, Lower Mag basement, Santa Marta and Guajira) as it was more effectively telescoped across the trace of the Caribbean Benioff Zone, thereby effecting flat slab subduction. Cenozoic Caribbean arc magmas appear to be limited to Early Paleogene partial melts (re-melts, hence tonalite) of downgoing slab in the Santa Marta region (Cardona et al., 2010). Late Eocene reduction of plate convergence rate allowed deposition to resume in Colombia (Pindell and Tabbutt, 1995), but by the Late Oligocene, the Caribbean's relatively buoyant west-facing arc ridge (Panama) began to enter and choke the trench. This, combined with rejuvenated plate compression at 25 Ma as a result of another westward acceleration by South America (Pindell and Tabbutt, 1995), initiated the "Andean" Orogeny that persists today.

A key issue regarding our perception of the tectonic style of Andean orogenesis, as well as the pre-Neogene palinspastic reconstruction, is the amount of strike slip on the Santa Marta, Ibague, Oca, and collective Mérida Andes faults. Estimates of shortening in the Eastern Cordillera range from perhaps 50 to 250 km (!), but the fact remains that if Campbell's (1965) original estimate of 110 km for slip on the Santa Marta Fault is correct, then there must be AT LEAST that much shortening in the Eastern Cordillera because the fault is effectively a lateral ramp to Eastern Cordilleran thrusts. There is no sense further suggesting a low shortening value for the Eastern Cordillera until a correspondingly low offset for the Santa Marta Fault is accepted, which is not yet the case and it is this writer's present opinion (Pindell) that this will not be forthcoming. Resolving these incompatibilities is an important area for continued work.

Some the critical points and areas for debate of the above discussion can be highlighted by the following questions, which can be taken up in discussion on the field trip.

1. Was there a Jurassic continental arc along Guajira-Central Cordillera? If so, then where was Mexico/Chortis, OR, where was Guajira/Central Cordillera?

2. Is there evidence for arc magmatism from 140 through 125 Ma, and is it the Quebradagrande? If so, can this be modeled by the opening of a back arc basin? Or, did the subduction zone step out, leaving a trapped ocean basin between the arc and Central Cordillera? Alternatively, can we derive the Quebradagrande from farther afield, such that there was no arc along western Colombia in the Neocomian?

3. Can we reconcile Central Cordilleran uplift data with the Aptian arc-continent collision model for Quebradagrande?

4. Above, initial accretion of CCOP is suggested by Albian, so that arc magmatism within CCOP can be driven by east-dipping subduction. This avoids the speculation of a west-dipping subduction system along the eastern flank of the CCOP AS it was formed, as demanded by Kerr (e.g., 2003) and the lack of arc contamination of in the CCOP. Can we prove that accretion of CCOP began this early? Can we accept that Buga and Antioquia and all the other Upper Cretaceous arc plutons pertain to this east-dipping subduction zone?

5. The outline above places the Margarita HPLT rocks at the north end of the Quebradagrande back arc basin upon its closure, and the Arquia HPLT rocks OUTSIDE of the Quebradagrande arc. However, is it possible that Margarita and Arquia are related, and that Margarita needs to lie outboard of the arc too? Or that Arquia was originally situated inboard of the Quebradagrande arc?

6. Where is the southeastern terminus of the Panama Ridge (and arc)? Are the Dabeiba Arch and the Eocene Mande Batholith definitely part of the Panama magmatic arc? Does Panama continue south past Buenaventura all the way to the Piñon Terrane of Ecuador as suggested by Pindell and Kennan (2009)? This implies that Gorgona and the entire basement of the coastal basins are part of a "Greater Panama Terrane". Can we disprove this? And if we entertain it, how does the Miocene Nazca Plate-related magmatic arc propagate all the way to the Combia Valley? Is there not a problem with subcreted Caribbean lithosphere underlying the arc trend? Or, has the Caribbean slab broken off and subducted far beneath Colombia-Ecuador, such that the "Greater Panama Terrane" is merely an accreted terrane now, no long connected to the slab? And if this is so, then the Nazca arc does NOT need to cut up through the Caribbean lithosphere. Perhaps the slab tearing northwards, and the point of tearing is just reaching the Mande Batholith area?

1. GEOLOGICAL OVERVIEW

The northwestern margin of South America is characterized by the interaction of the South American, Caribbean and Pacific plates. This interaction involved multiple episodes of accretion of oceanic terranes (MORB, island arc and plateau) against the Pre-Mesozoic continental margin since the Lower Cretaceous. This interaction resulted in formation of subduction-accretion complexes that underwent a complex transition from primitive to more evolved crust.

Over the last five years, new radiometric, geochemical and field data has enabled the revision of current geodynamic models for the northwestern Andean and Caribbean realms, allowing to readdress long-standing and important questions regarding subduction-accretion models. Such questions include: the nature of accreted terranes; the growth of batholiths within continental and oceanic plates; and the role of major shear zones responsible for the redistribution of litho-tectonic elements in the margin.

Physiographically speaking the westernmost segment of the Colombian Andes encompasses the Central and Western Cordillera as well as the Atrato basin and the Baudó Ranges (Fig. 1).

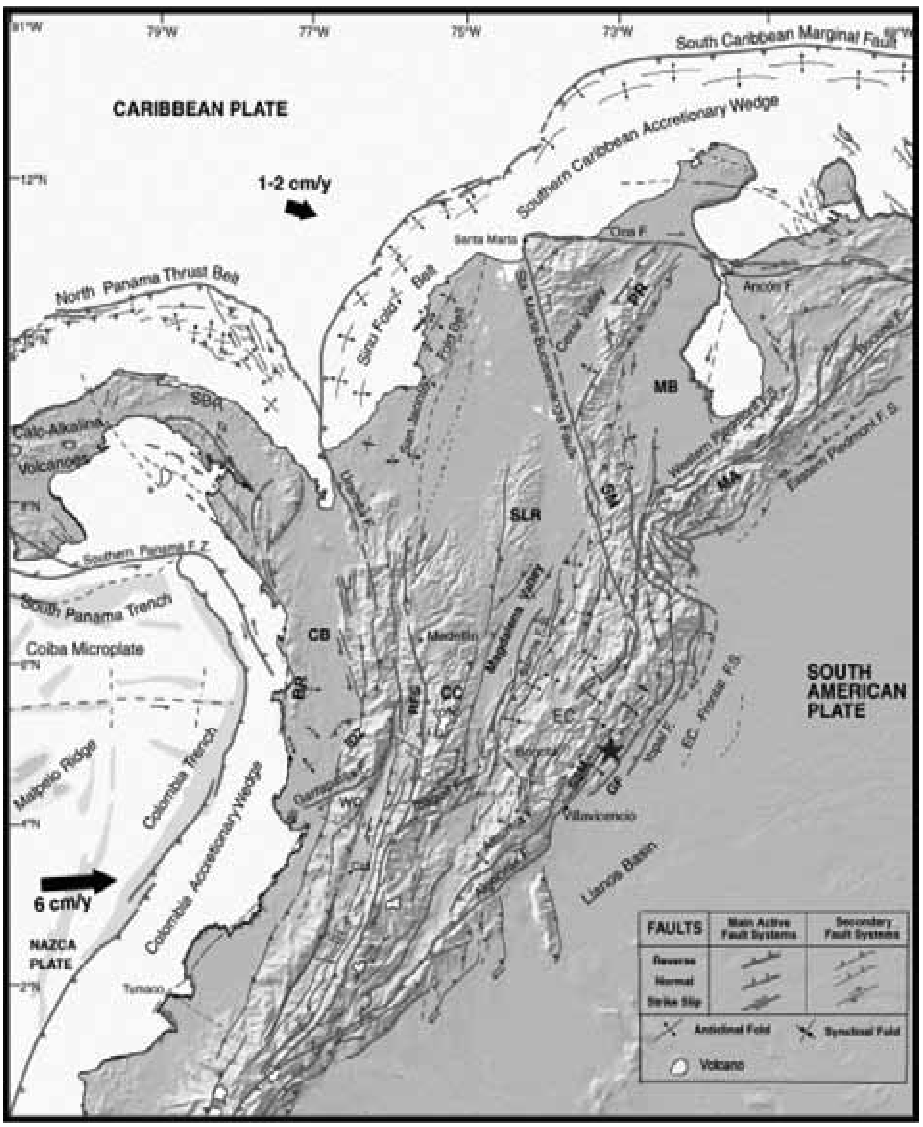

Fig 1. Neotectonic map of the Northern Andes indicating the main active fault systems (after Taboada et al., 2000). Solid arrows indicate plate velocity relative to South American Plate. BR=Baudo Range, CB=Chocó Block, CC=Central Cordillera, EC=Eastern Cordillera, GF=Guaicaramo Fault, MA=Merida Andes, MB=Maracaibo Block, PR=Perija Range, RFS=Romeral Fault System, SLR=San Lucas Range, SM=Santander Massif, SSM=Servitá–Sta. Maria Fault, WC=Western Cordillera.

The Central and Western Cordilleras are separated by the Cauca River depression. The geological configuration closely follows the physiographic trend whereby the two cordilleras belong to two contrasting domains separated by the Romeral Fault System (RFS) (Fig. 1). The RFS encloses a series of units (including the Arquía Complex, Quebradagrande Complex, Sinifana Schist, mafic intrusive belts, etc.), that is interpreted here as an extensive shear zone (kilometric-scale) composed of multiple lithological units of varying ages, diverse origins, polydeformed, and in faulted contact. The Pre-Mesozoic continental margin worked as a Meso-Cenozoic back stop, which is roughly defined by the Central Cordillera. The accreted terranes are in turn represented by the Western Cordillera, some of the components of the Arquía Complex and rocks of the Baudó Range.

Despite the complex distribution of reported ages for the Central Cordillera block, which suggests the presence of pre-Mesozoic constituents, an Upper Paleozoic – Lower Mesozoic event is perhaps the most important orogenic event recorded for the block. This event could be associated with the build up of Pangea driven by the collision between Laurentia and Gondwana during the Alleghenian orogeny (Vinasco et al., 2006), and is responsible for the subsequent closure of the proto Atlantic ocean (Pindell and Dewey, 1982; Pindell, 1985; Pindell and Kennan, 2002). The Triassic tectonic regime recorded for the Pueblito Diorite (Fig. 2, # 6) suggests a dominant left lateral regime by this time, in contrast to the dextral dominant regime for the Cretaceous.

The Central Cordillera block has been described and given various names through time including: Cajamarca Group (Nelson, 1957); Cajamarca Complex (Maya and González, 1995); the Tahamí terrane (Toussaint and Restrepo, 1989); the Central Cordillera Polymetamorphic Complex (Toussaint and Restrepo, 1989) and the Cajamarca – Valdivia Terrane (Cediel et al., 2003).

In general the Central Cordillera basement can be regarded as a Paleozoic – Permian metamorphic sequence, with detrital U/Pb zircon ages ranging from 270-380 Ma, (and a single point about 234 Ma) (Vinasco et al. in prep.; Villagómez et al., 2008) intruded by crustal syn-tectonic Permian and post tectonic Triassic granitoids with arc imprints and Jurassic calc-alkaline granites like the Ibague Batholith (160 ± 3 Ma U/Pb)

Other well-documented geochronological events in the region occurred during Devonian and Cretaceous times (Hall et al., 1972; González, 1980; Toussaint and Restrepo, 1989). This latter event is particularly relevant, as it includes the extensive Late Cretaceous Antioquia Batholith (Fig. 2, #1), (U/Pb ages between 83.75 ± 0 and 94.5 ± 1.7 Ma (Ibañez-Mejía et al., 2007; Villagómez et a., 2008), which is related to a well-established western subduction zone characteristic of an active Upper Cretaceous continental margin (Botero, 1963; Saenz, 2003; Restrepo-Moreno et al., 2009), responsible for regional resetting of the the K-Ar system.

Discrete Precambrian age populations indicate that the Palaeozoic-Triassic sedimentary rocks were probably derived from the Guyana Shield and are derived from the South America authoctonous basement
(Vinasco et al. In prep; Villagómez et al., 2011).

Finally, other events are recorded during the entire Tertiary. These events are mainly associated to deformational processes, syntectonic sedimentation and Mio-Pliocene volcanism (e.g., the Amagá and Combia Formations respectively- Fig. 2).

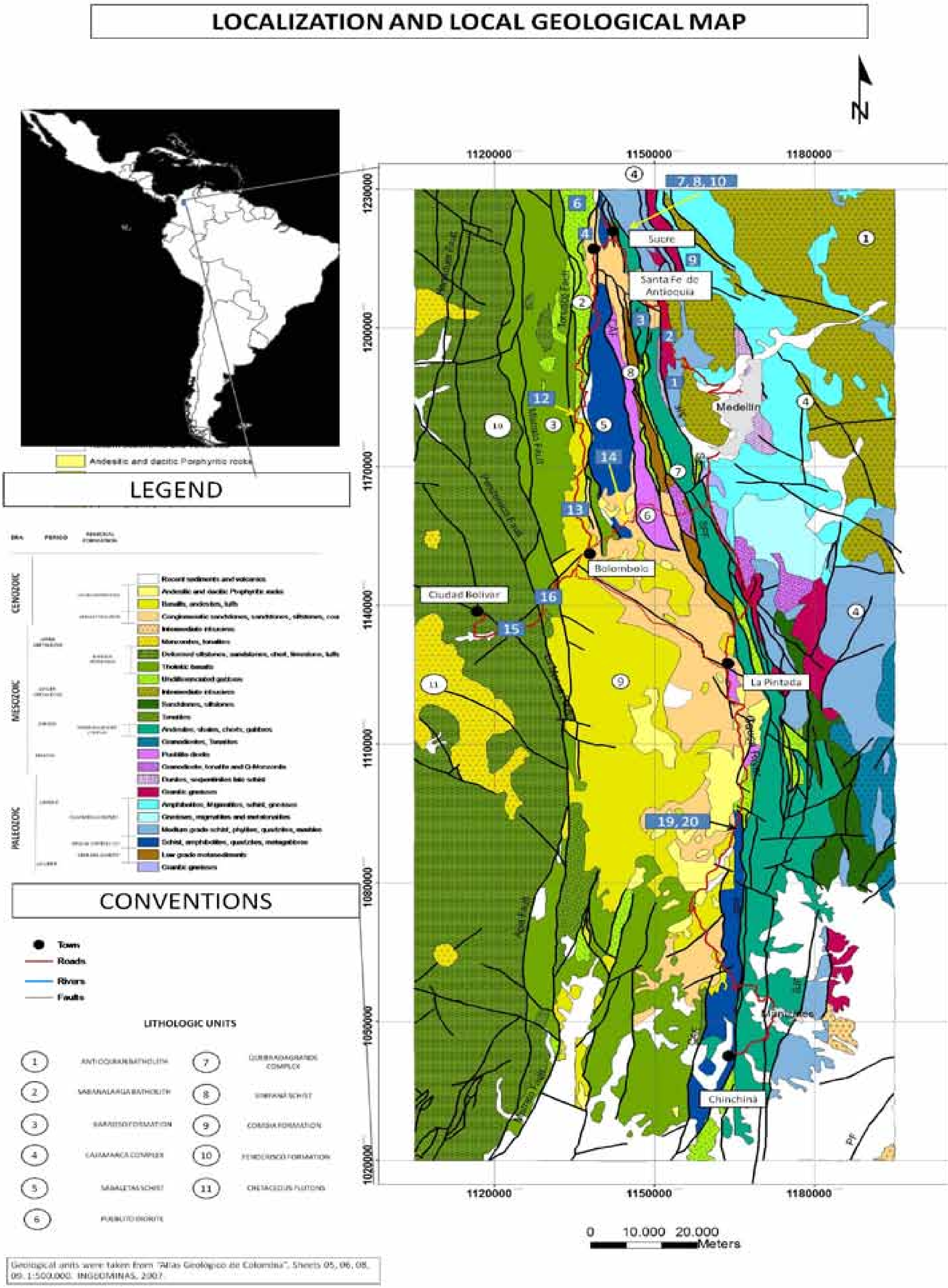

Fig 2. Localization and geological map.

The Central Cordillera has been compared with the Loja terrane in Ecuador, which in turn comprises most of the Cordillera Real and El Oro province to the SW of the country where metamorphic Paleozoic rocks associated with Triassic foliated plutons have been described (Litherland et al., 1994).

The easternmost trace of the RFS is defined by the San Jerónimo fault (Maya and González, 1995) (Fig. 2 SJF). This fault defines the beginning of a broad boundary that separates the Central Cordillera in the east from the accreted terranes to the west. Regionally, this broad boundary corresponds to a kilometric shear zone hosting a series of rocks including: (1) Cretaceous sedimentary-volcanic sequence of the Quebradagrande Complex (Fig. 2, #7); (2) low grade Devonian(?) metasedimentary rocks of Sinifaná Metasediments (Fig. 2, #8); (3) mafic and ultramafic Triassic supra subduction intrusives (Fig. 2, #6) and finally (4) Permian (?) and/or (?) Cretaceous (?) low to medium grade meta vulcano-sedimentary N-MORB type sequences of the Arquía Complex (Fig.2, #5). The Amagá Formation, a coal-bearing, Oligo-Miocene sedimentary sequence (Grosse, 1926; Silva et al., 2008) unconformably covers the older lithological units. Mio-Pliocene volcanic and subvolcanic rocks of the Combia Formation covered and intruded the Amagá Formation and other older rocks. Geometrically, the RFS shear zone is characterized by an anastomosed arrange of faults yielding a block tectonics configuration. The rocks and structures inside the shear zone are the main focus of the field trip.

The accreted Cretaceous terranes occur to the west of the regional RFS (Cauca-Almaguer Fault) in the western flank of the Central Cordillera (Fig. 2 CAF). They consist of basalts, gabbros, ultramafic cumulates and flysh-type sedimentary rocks (Amaime Formation, Bolívar Complex, Volcanic and Barroso Formation.), which are characterized by flat mantle-normalized REE patterns (Kerr et al., 1997, Villagómez et al. 2011) representing a portion of the large late-Cretaceous Colombian-Caribbean Oceanic Plateau CCCP (Kerr et al., 1997). These rocks have available radiometric ages about 95 Ma (U-Pb in zircon, Bolivar Complex) (Villagómez et al., 2011) and Ar-Ar ages between 84-90 Ma (Barroso and Amaime Formations) (González, in prep.). Several authors have used radiometric and biostratigraphic evidence to show that the plateau rocks exposed in the Caribbean, Colombia and Ecuador (and elsewhere) range between 92 and 88 Ma (Kerr et al., 1997; Kerr et al., 1999; Sinton et al., 1997, 1998; Luzieux et al., 2006; Vallejo et al., 2009) with a minor pulse at 76–72 Ma (Kerr et al., 1997). In a recent model presented by Serrano et al. (2011), the authors argument that the CCCP formed when the proto-Caribbean Arc intersected the Great Caribbean Arc, and suggest the possibility that that an oceanic slab window setting alone may be responsible for its formation.

The boundary with the meta-vulcano sedimentary sequences of the Arquía Complex is not clear. Recently, García et al. (2010) suggested that the westernmost metabasic rocks of the Arquía Complex are transitional to volcanic rocks of the western Cordillera implying that at least some components of the Arquía complex belong to this sequence.

Late Cretaceous to early Cenozoic tectonic evolution of the northern South American margin was controlled by its interaction with the margins of an allochthonous, anomalously thick Caribbean oceanic plate and its associated arc (Burke, 1988; ; Pindell et al., 1998; Montes et al., 2005; Spikings et al., 2005; Luzieux et al., 2006; Vallejo et al., 2006; Maresh et al., 2009; Weber et al., 2009, Kerr et al., 1997; Cardona et al., 2011). Timing of accretion is constrained by the Buga Batolith, which yields an U-Pb age of c. 90 Ma, the Santa Fe Batholith, which yields an Ar-Ar age of c. 92 Ma (Weber et al., 2011), and the Córdoba Batholith which yields an U-Pb age of c. 80 Ma and 85 Ma (Villagómez et al., 2011; González et al., in prep.). This magmatism represents the initial stages of island arc activity that formed at the juvenile active margin of the eastward migrating CCOP (Villagómez et al., 2011). This magmatic event is also registered in the southern Caribbean by the Aruba

(White et al., 1999) and in Ecuador by the Pujilí Granite (Vallejo et al., 2009), which yields Ar-Ar ages about 92 Ma. Direct dating of fault reactivation of SJF is presented by Vinasco (2001) through Ar-Ar results in neoformed micas in milonitic bands. Plateau ages ranging from 72-81 Ma in sericite and 87-90 Ma in biotite were obtained. Whole rock K-Ar ages ranging between 65-68 Ma record final episodes of tectonic reactivation of SJF associated with accretion of the CCOP.

Additionally, several preliminary fission track (FT) ages presented by Villagómez et al. (2011) for the Central Cordillera ranging between 77 and 36 Ma and results from best-fit modelling, indicate rapid cooling between 80 and 70 Ma, followed by slower cooling from 70 to 10 Ma indicative of an important tectonic event. This event produced exhumation in the paleocontinental margin during the late Cretaceous associated to the accretion of the CCOP (Villagómez et al., 2011). In Ecuador, accretion occurred in Campanian – Mastrichtian times (75-65 Ma), slightly later than in Colombia (Vallejo et al., 2006). Tectonostratigraphic evidence and position of depocenter evolution studies for Colombia suggest that the regional axis of deposition had a tectonic origin and migrated eastward with gradual uplift of the Central Cordillera, evidenced by westerly derived coarse clastic sediments (the Campanian 'El Cobre' Sandstone and the Maastrichtian Monserrate, La Tabla and Cimarrona formations) (Villamil, 1999). During the Cretaceous–Tertiary boundary, parts of the eastern margin of the Eastern Cordillera were uplifted. This event is evidenced by a regional paraconformity in Colombia, by a localized unconformity in the present-day Llanos foothills and by a localized unconformity in the Barinas Basin (Villamil, 1999). In the Sierra Nevada Province, to the north of the country, exhumation at elevated rates are recorded during 65-58 Ma in response to the accretion of the Caribbean Colombian Oceanic Province.

Regional reconstructions given by Pindell (in prep.) involve the eastward subduction of Farallon plate under the continental margin represented by the Central Cordillera. Oceanward, back-stepping of the slab during the earliest Cretaceous due to fragmentation of the Jurassic slab is bracketed by Ar-Ar cooling ages obtained from crystalline rocks located to the south of Ibagué fault about ~133–139 Ma (Villagomez, et al. 2011). These cooling ages are contemporaneous with the cessation of Jurassic arc-magmatism, which gave rise to the early Cretaceous Quebradagrande oceanic arc sequence (Villagomez, et al., 2011). The collision of the Quebradagrande arc against the margin was accompanied by the obduction of medium-high P–T metamorphic rocks of the Arquía Complex, which are probably a relict of the late Jurassic - early Cretaceous subduction channel (Villagomez, et al., 2011). These arcs were closed against the Central Cordillera and continuous subduction lasting until 70 Ma. The SJF would be formed during this time by the accretion of the complex onto the continent, which occurred between 117–107 Ma based on thermochronological data (Villagomez et al., 2011). The Sabaletas greenchists (Arquia complex) with Ar-Ar plateau age of 127±5 Ma and integrated ages between 102-115 Ma (Vinasco, 2001) eventually record this episode.

Concurrently, offshore in the Pacific, the Caribbean-Colombian Oceanic Plateau (CCOP) was being extruded at intra-oceanic hotspots onto the Farallon lithosphere from 100 to 88 Ma (Kerr et al., 2003). Alternative models, invoking an oceanic slab windows mechanism are presented by Serrano et al., (2011) to explain the origin of the CCOP, with no mandatory presence of an asthenospheric plume. The eastward dipping subduction of Farallon crust beneath the now composite terranes of Colombia allowed the plateau to converge against the Colombian margin. The Farallon lithosphere continued to be subducted beneath the accreted upper crustal material, albeit at a low dipping Benioff Plane. Panamanian subduction began in the Maastrichtian, thus isolating a Caribbean Plate out of the Farallon.

In the model depicted above, the Quebradagrande belt corresponds to an autochthonous arc contemporaneous to the Arquía belt produced by eastward subduction of the Farallon plate. Alternatives hypothesis suggest that Arquía Complex is a composite collection of rocks including pre-Mesozoic and Upper Cretaceous fragments. Some of these fragments would be remobilized pieces from both Central and Western Cordillera in a long lasting shear zone, developed to the continental margin since Triassic times, as suggested by ASM studies in the Pueblito Diorite (Fig. 2, #6) (Rodriguez et al., 2010). The Quebradagrande complex could represent an intracratonic marginal basin trapped during the collision of the CCOP, which accreted west of the Arquía Complex in the Early Eocene (Nivia et al., 2006).

On the other hand, Moreno Sánchez et al. (2007) stands that there is not prove of the existence of any metamorphic basement to the west of the Quebradagrande Complex. Instead, they invoke the presence of a magmatic arc in that position.

Finally, a complete different line of argumentation for the origin of the Caribbean plate is given by James (2006) who suggests an inter-American origin for the plate. Arguments are based mainly in the existence of coeval of Caribbean and neighbouring continental areas of regional deposits of Albian shallow water limestones, Paleocene - Middle Eocene flysch deposits, Middle Eocene limestones, and the presence of a regional Late Eocene hiatus compatible with an inter-American location, not with a changing Pacific-Caribbean development. Additionally, the internal structural conformity of the Caribbean Plate and of the Maya and Chortis blocks with regional geology of Middle America shows that no major migrations or rotations have occurred (James, K., 2006), aspects invoked by models of pacific origin

Subsequent Palaeogene orogenic phases seem to be related to variations in plate convergence (velocity and angle) or to accretionary phenomena (Pindell et al., 1998; Restrepo-Moreno et al., 2009; Vallejo et al., 2009; Jaillard et al., 2010). Cardona et al. (2011) suggest magmatic quiescence and block uplift after 50 Ma as a product of shallow subduction and oblique convergence. However, a pulse of exhumation is recorded during 50-40 Ma due to underthrusting of the Caribbean Plate beneath northern South America (Villagómez et al., 2011). The Central Cordillera exhumed at moderate rates during the Eocene (~45–30 Ma), which is also observed over widely dispersed regions along the Andean chain. The greatest amount of middle - late Miocene exhumation occurred in southern Colombia, and spatially corresponds with elevated exhumation rates in northern Ecuador in response to collision and subduction of the buoyant Carnegie Ridge (Villagómez et al., 2011).

During the Tertiary, South America overthrust more and more the Caribbean Plate in a flat slab geometry. Thus, after accretion of the Western Cordillera at the start of this overthrusting, first the Central Cordillera (Paleocene-Middle Eocene; Laramide) and then the Eastern Cordillera (Late Oligocene-Miocene; early Andean) have been thrust over the eastern leading edge of the underthrusted Caribbean lithosphere. Presently, seismic tomography indicates that the Caribbean slab occurs beneath northern Colombia all the way to the Llanos Basin (Van der Hilst and Mann, 1994). Final episodes of deformation in the chain are related to the collision of the Panama-Choco block in Early Miocene-early Pliocene (Pennington, 1981; Toussaint and Restrepo, 1988; Duque-Caro, 1990; Mann and Corrigan, 1990; Van der Hilst and Mann, 1994; Taboada et al., 2000; Trenkamp et al., 2002). Collision drives changes in the RFS kinematics from right-lateral in the south to left-lateral in the north (Suter el at, 2008). The Panamá-Chocó block collides with NW South America in an E to ESE direction (Duque-Caro, 1990; Taboada et al., 2000). It is considered as a rigid indenter, which induces deformations north of 5°N reaching the lowlands of the Eastern Cordillera some 600 km east (Suter, et al. 2008). The collision is considered to be responsible for the latest and major phase of uplift in the Colombian Andes which corresponds to the Andean tectonic phase that affected the three cordilleras (Taboada et al., 2000; Cortes et al., 2005).

We hope that new data to be presented during the special session will contribute to better elucidate the r egional models. More importantly though is promoting the opening of new ways of cooperation and the looking for research paths yet unexplored.

1.1 EAST OF ROMERAL FAULT SYSTEM BASEMENT

Basement rocks of the Central Cordillera are found east of the RFS. The term Cajamarca Complex was introduced by Maya and González (1995) to group various lithological units, which are situated between the Otú-Pericos Fault in the eastern flank of the Cordillera Central and the SJF to the west. The Cajamarca complex is composed of low- to medium-grade schists, quartzites, marbles and orthogneisses. Thus, the Central Andes of Colombia roughly correspond to a polimetamorphic pre-Mesozoic complex intruded by Meso-Cenozoic batholiths and covered by recent continental volcanic rocks (Botero, 1963; Restrepo and Toussaint, 1982; Gonzaléz, 1988).

Zircon U-Pb anlyses in metasedimentary samples of the Cajamarca Complex in the area of interest show important differences in U-Pb age distribution diagrams. Metapsamite MS001B near Palmitas (Est. 1, Fig. 3), registers an important input of Paleozoic ages, whereas metapsamite ARQ-14 near Sucre (Est. 9, Fig. 4), displays a significant Permo-Triassic signature. In contrast, metapsamite COLC-56 from the southeast of Medellin (Fig. 5) virtually lacks any Phanerozoic input, being the younger age obtained ~530 Ma. These preliminary results indicate an intricate spatio-temporal pattern of metamorphic rocks in the paleomargin related to a complex geologic history.

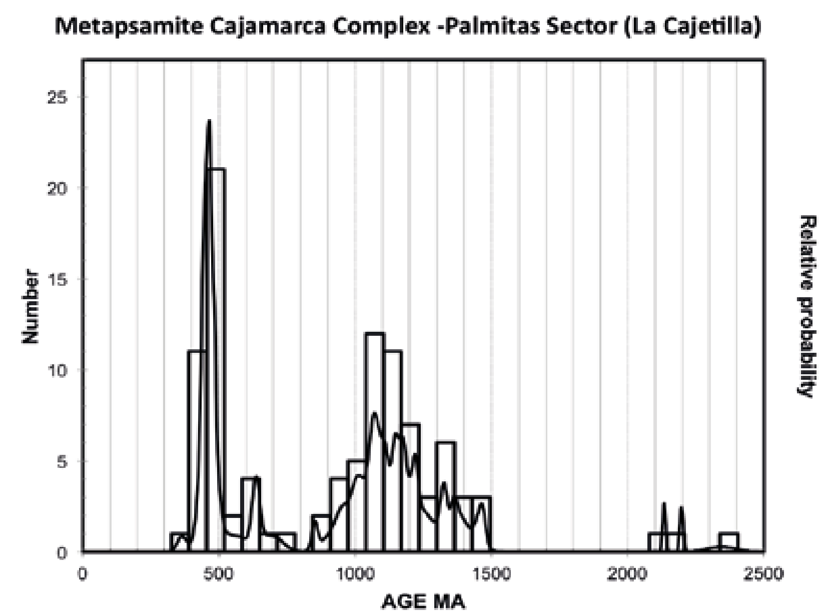

Fig 3. U-Pb distribution ages for metapsamite of Cajamarca Complex, La Cajetilla sector.

1.1.1 WITHIN THE ROMERAL SHEAR ZONE

The geological boundary between the Central and the Western Cordilleras of Colombia is defined by an accretionary system formed by several independent tectonic blocks, deformed by the Romeral Fault system (RFS) configuring a kilometre-long shear zone. Some of the blocks are however autochthonous or para-autochthonous, and accretion of these blocks onto the paleo - South American margin occurs between the Upper Cretaceous and the Middle Eocene during the pre-Andean cycle, which probably reflects the arrival of the Western Cordillera volcanic rocks, i.e. the Colombian Caribbean Oceanic Plateau (CCOP).

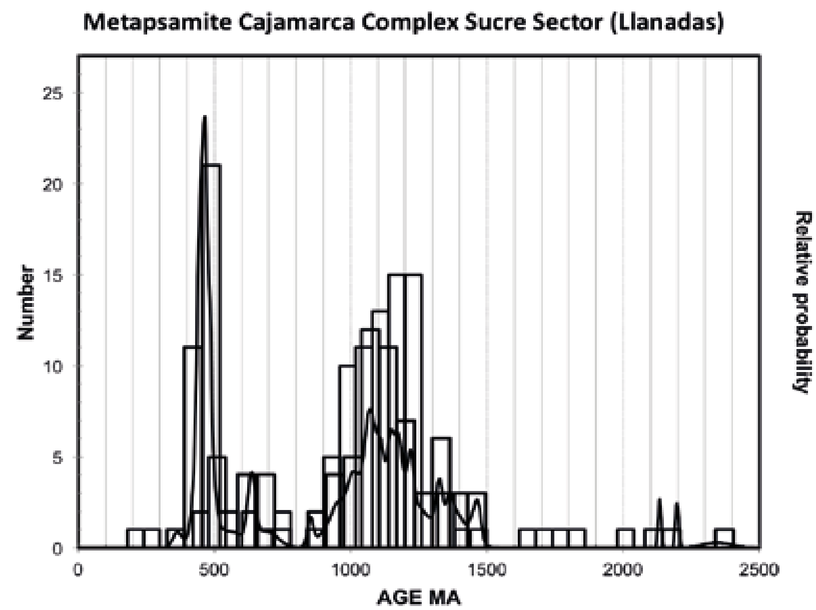

Fig 4. U-Pb distribution ages for Metapsamite Cajamarca Complex Sucre Sector (Llanadas)

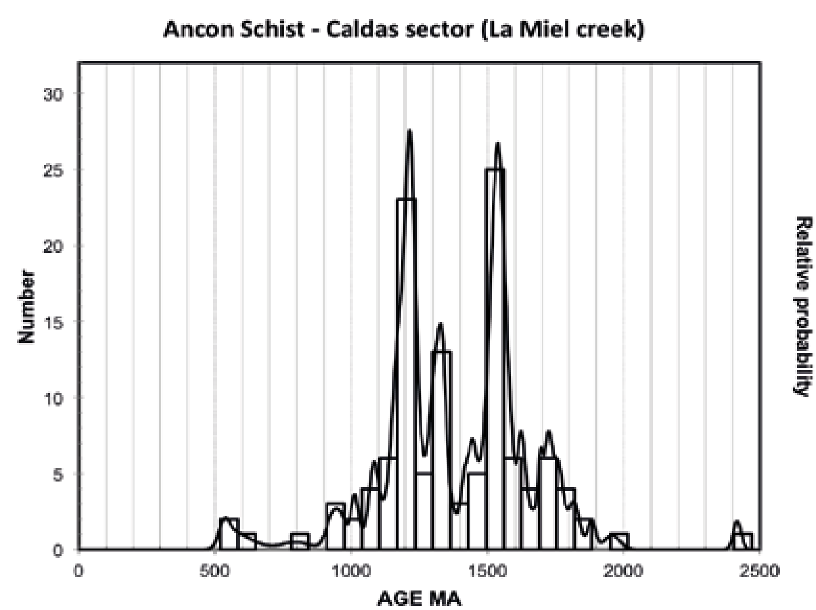

Fig 5. U-Pb distribution ages for Ancon Schist - Caldas sector (La Miel creek)

Pre-Andean structures were subsequently deformed during the Andean cycle in Miocene times, which mark t he arrival of western oceanic terrenes in the final closure of the Panamá isthmus. The structural style is dominated for tight isoclinal folds with vertical axial planes, east vergent thrusts and west vergent back thrusts characterizing the nor-western margin of the Central Cordillera of Colombia.

1.1.1.1 SINIFANÁ METASEDIMENTS

These are low grade metamorphic rocks which outcrop in the western flank of the Central Cordillera. They appear in fault contact relative to the west margin of the Quebradagrande Formation (Fig. 2 #8). These rocks have been ascribed to the Devonian, based primarily on weak paleontological evidence (Gonzalez, 2000) and on stratigraphic relations with the Triassic Amagá Pluton (Grosse, 1926; Gonzalez, 2000) that intrudes the Sinifaná unit. Correlation with other metamorphic rocks of the Central Cordillera has been difficult due to the paucity of geochronological evidence and the complexity of regional tectonic patterns.

The Sinifaná metadesiments encompass a variety of rocks such as silts, slates, metagrawackes, metapsamites, and quartzites metamorphosed up to greenschist facies conditions (González, 2000), although sometimes they appear as very low-grade metasediments.

Recent data obtained from a sample collected near the town of Sucre in the quebrada Seca (zircon U-Pb ages (in situ) for 37 laser spots) (Fig. 6) indicate an important contribution of Permo-Triassic input, since about 30% of data correspond to this period. This implies a younger age than traditionally considered for this sequence. Sinifana metasediments, at least in this area, pose a Triassic maximum age for sedimentation. Two younger zircon ages of about 160 Ma and 73 Ma are considered as meaningless on the basis of statistical uncertainty. New geochronological data is currently being generated in order to help to constrain the possible meaning of such younger ages. There is also a significant Neoproterozoic and Grenvillian contribution to the sediments, and an almost absence of the Paleozoic record (except by a single age of roughly 450 Ma), suggesting that these rocks formed in proximity to the continental South American margin, configuring an autochthonous or para-autochthonous basin position. The lack of Paleozoic ages could imply absence of Paleozoic massifs at this margin.

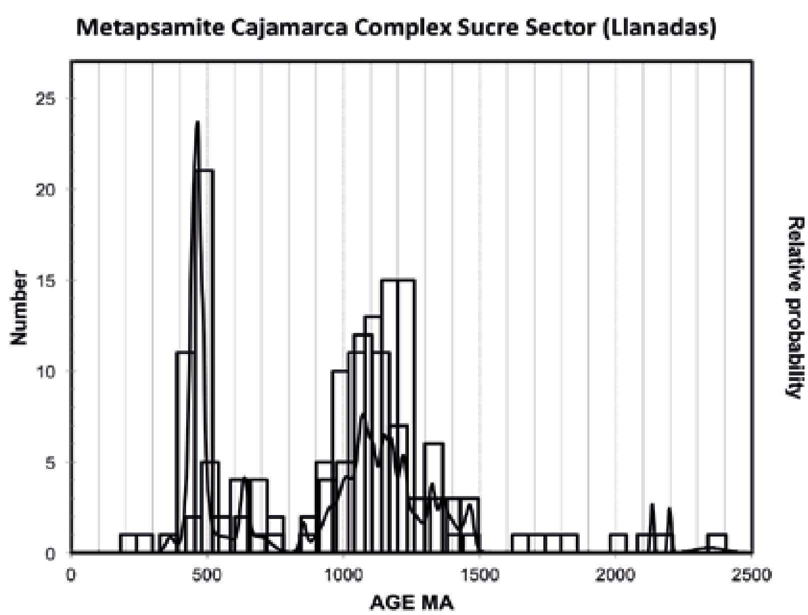

Fig 6. U-Pb distribution ages for low grade metasediments of Sinifana Schist

The age assigned to the sequence based on relationship with The Amagá Stock must be revised. However, it is possible that the sample collected in La Seca creek, some miles north of the main body belongs to a different unit.

This is a plausible explanation because at this point it is likely that the mapped Sinifaná Metasediments comprises several units not yet individualized.

1.1.1.2 ARQUIA COMPLEX

The Arquía Complex (Central Colombia) represents an accretionary complex containing rock bodies of d ifferent origin and composition including (meta)sediments, (meta)volcanics and (meta) ultramafites (Fig. 2 #5). According to the metamorphic grade, metabasites can be grouped into greenschist and epidote-amphibolites. Their major element composition indicates basaltic compositions of tholeiitic affinity with SiO_2=48.25-51.59 wt%, FeO+MgO=17.63-20.45 wt% and K_2O+Na_2O=1.51-3.07 wt%. The REE patterns are characterized by slightly depleted LREE, with $(La/Yb)_n$ <0.72, and no Eu anomaly (Eu/Eu*= 0.90-1.05). The trace element composition indicates enrichment in LILE (principally in Cs, Ba, and Pb). These features, and the Th/Yb and Ta/Yb ratios (0.03-0.24 and 0.05-0.23 respectively), indicate a MORB composition modified by infiltration of LILE-bearing fluids during metamorphism.

Epidote-garnet amphibolite rocks from the Arquía complex (central Colombia) are composed of magnesio hornblende + garnet + epidote + quartz + plagioclase + calcite, plus rutile + titanite + apatite as accessory phases. The rocks are fine- to medium-grained, with grains up to 1 mm in size, though grain size reduction is related to foliation development during an intense and retrograde deformation stage overprinting an earlier higher-T foliation. Locally, fine veins of leucocratic materials appear parallel to the main foliation, suggesting partial melting of amphibolite. The cores of magnesiohornblende are relatively rich in AlVI, NaB and Ti (1.01, 0.49 and 0.06 apfu, atoms per formula units, respectively), approaching barroisite composition, while retrograde amphibole is actinolite (AlVI<0.26, NaB<0.15 and Ti<0.02 apfu). Garnet porphyroblasts are euhedral, partly replaced by chlorite, and rich in almandine (Xalm=0.46-0.60) and grossular (Xgrs=0.25-0.32). Plagioclase is mostly albitic, locally reaching oligioclase composition (max. Xan=0.18). Epidote is clinozoisite with Xpistacite up to 0.27. Thermobarometric calculations indicate peak metamorphic conditions of ca. 630 ± 30 ºC and 10.5 ± 1.2 kbar, close to the wet solidus for basaltic rocks and in agreement with melting at peak conditions. The apparent geothermal gradient at peak conditions suggests a collision-related metamorphic event, probably related to collision and obduction of the Caribbean-Colombian Oceanic Plateau during the late Cretaceous.

1.1.1.3 MAFIC AND ULTRAMAFIC IGNEOUS ROCKS

These rocks are mainly represented by the Pueblito Diorite and Gabbro (Fig. 2# 6) and numerous small and discontinuous lenses of ultramafic rocks. The Pueblito Diorite comprises an elongated body disposed N-S, 55 km long. It was syntectonically emplaced into metasedimentary rocks of the Sabaletas Schist (Arquía Complex?). The characteristic elongate shape is sub parallel relative to the Romeral fault system, indicating some tectonic control during emplacement. It is closely associated to foliated gabbros and ultramafic rocks as part of an ophiolitic complex (Gonzalez, 2000).

Similar intrusive units to the south, which include the Cambumbia stock suggest the presence of an extensive Triassic magmatic belt, which affected the lithologic units mainly of the Arquía complex (Aspden et al., 1987).

The southern part of the body is uplifted against Oligo-Miocene sedimentary Amagá Formation while to the northern termination seems to thin out and disappear under the Cenozoic sedimentary cover.

Emplacement models presented by Rodriguez et al. (2010), indicates a NW-SE general transpresive regime in a subduccion environment. The fabric is mainly magmatic with some evidence of deformational component implying sintectonism during the final stages of regional deformation. Contact metamorphism, the presence of diorite dikes and schist roof pendants characterize an intrusive contact between the Pueblito Diorite and the Sabaletas Schist (i.e. Arquía Complex?).

Zircon U–Pb data yields crystallization ages of ca. 233 Ma (Rodriguez et al., 2010; Restrepo-Moreno et al., in review), while Ar/Ar ages (Vinasco, 2001), suggest rapid cooling and epizonal crystallization. Apatite fission-track low temperature thermochronology from samples collected near the Palomos Coal mine defines a clear exhumation pulse at ~43-45 Ma similar to erosion-realted cooling events in the Central Cordillera at a similar latitude (Restrepo-Moreno et al., 2009; Restrepo-Moreno et al., in review). Inherited zircon U–Pb data yield similar results compared to granitoids of the Central Cordillera, to the east of San Jerónimo Fault. This record suggests a potential relationship with Central Cordillera basement.

1.1.1.4 MAFIC AND ULTRAMAFIC IGNEOUS ROCKS

Associated to the RFS are various lenses of ultramafic rocks, the origin of which is still uncertain. These are relatively small in size (less that a few Km), and are possibly part of various of the oceanic elements related to the interaction of the Caribbean and the South American plates.

These rocks are composed of olivine + tremolite ± spinel ± chromite (Acevedo et al., 2011), indicating that they suffered metamorphic conditions in the range 600-700 ºC. The presence of tremolite also suggests that Cpx was a stable phase in the protolith, and the lack of anthophyllite suggests pressures above 6 kbar. Further retrogression and hydration is denoted by partial to total replacement by serpentine minerals.

1.1.1.5 QUEBRADAGRANDE COMPLEX

The Quebradagrande Complex outcrops as a discontinuous fringe along the western flank of the Central Cordillera of Colombia (Fig. 2 # 7). To the east and west is limited by fault zones with the metamorphic rocks of the Cajamarca and Arquía Complexes respectively (Maya and González, 1995). Geophysical studies carried out between 4° and 5.5° latitude north (Case et al., 1971; Meissner et al., 1976) show that these rocks overlie the metamorphic basement of the Central Cordillera. This lithodemic unit was proposed by Maya and González (1995), in order to group several "lithostratigraphic units" that were named in the region, because the tectonic complexity prevent the recognition of the base and top of the sedimentary sequences and, in many cases, the original relationships between the lithologic bodies. From north to south the following units are included in this complex: the "Formación Porfirítica" (Grosse, 1926);"Quebradagrande"(Botero, 1963), "Abejorral" (Bürgl y Radelli, 1962) and "Valle Alto" (González et al., 1977; González, 1980) formations; the "Valle Alto", "San Fèlix" and "El Establo" Stratigraphic-Tectonic Intervals (Rodríguez and Rojas, 1985); "Grupo Quebradagrande" and "Complejo Ofiolítico de Pácora" (Alvarez, 1987); "Eastern" and "Western" intervals of Manizales (Gómez et al., 1995); "Aranzazu-Manizales" Metasedimentary Complex (Lozano et al., 1975; Mosquera, 1978); "Quebradagrande" Formation (McCourt et al., 1984). In southern Colombia this Complex has not been differentiated from the volcanic and sedimentary units of the western Cordillera; however, similar rocks are reported as far south as the area of Puyana in Ecuador ("Basal Greywackes", "Bosque de Piedra", "Puyango", "Alamor" and "Celica" formations; see Jaillard et al., 1999; 2009), and in the "Melange ofiolítico de Peltec", "turbidites of Maguazo" and the greenstones of the "División de Alao" (Aspden and Litherland, 1992).

The Quebradagrande Complex is composed of an ophiolitic assemblage of ultramafic rocks, gabbros, diorites, diabases, basalts, basaltic andesites, andesites, mudrocks, cherts, feldspathic and quartzitic sandstones, lithic and quartzitic conglomerates, and pyroclastic rocks, usually affected by dynamic metamorphism (Moreno-Sánchez & Pardo-Trujillo, 2003; Moreno-Sánchez et al., 2008) and zeolite, prhenite–pumpellyite, and greenschist facies metamorphism (Nivia, 2006). The complex is crossed by a braided system of north-south faults with separating blocks where a stratigraphic and a tectonic trend may be recognized. The dip of this tectonic "pile" is vertical or inclined to the east but most of the sedimentary structures suggest inverted stratigraphic polarity (Moreno-Sánchez & Pardo-Trujillo, 2003). Internal changes in the degree of deformation are common and in some areas fault bounded Paleozoic (?) metamorphic blocks, similar to the Cajamarca Complex rocks occur, hindering the distinction from adjacent metamorphic complexes (e.g. in the Manizales region. Moreno-Sánchez & Pardo-Trujillo, 2003). Intruding Cretaceous-Paleocene granite bodies (e.g. the Stock of Manizales) and Upper Miocene-Pliocene hypabyssal rocks also occur. These lithologies are partially covered by Pliocene to recent volcano-sedimentary deposits (Thouret et al., 1985; Kronemberg et al. 1990).

The depositional environments deduced from the sedimentary rocks vary from fluvial, coastal, coarse grained deltas, platform (Rodríguez and Rojas, 1985), slope and submarine fans associated with volcanism (Gómez et al., 1995). The composition of the clastic fragments suggests a continental margin to the east (see Rodríguez and Rojas, 1985 and Gómez et al., 1995) and strong volcanic influence to the west ("Western" Interval of Gómez et al., 1995). Nivia et al. (2006) demonstrated that the basalts mostly display calc-alkaline affinities typical of volcanic rocks generated in supra-subduction zone mantle wedges, in an island arc, marginal basin, or active continental margin, independent of the Caribbean-Colombian Cretaceous Igneous Province (CCCIP of Kerr et al., 1997). Some basalts and gabbros of the Quebradagrande Complex located along the western flank of the Central Cordillera are characterized by flat to positive slopes on chondrite-normalized REE plots (La/Yb 0.8-1.1), high Zr/Th ratios (>650) and low Th/Co ratios (<0.004) that are indicative of a depleted mantle source origin such as at a mid-oceanic ridge, or perhaps enriched ORB material (Villagómez et al., 2011). All basaltic andesites and andesites and a diorite studied by Villagómez (2011) are less altered and metamorphosed than the basalts and gabbros. These magmatic rocks differ from the previous group because they yield negative Nb–Ta and Ti anomalies on a primitive-mantle normalized multi-element plot, high La/Yb ratios of 7.9-26.9, low Zr/Th values (<55) and Th abundances of >1ppm, suggesting they are petrogenetically related to subduction and have a calc-alkaline signature (Villagómez et al., 2011).

Based on fossil remains a Berriasian-Albian (140-100 Ma) age is proposed (González, 1980; Botero and González, 1983; Etayo-Serna, 1985; Gómez et al., 1995). Euhedral zircon crystals from a metatuff of the Quebradagrande Complex, yields a zircon U–Pb age of 114.3±3.8 Ma (Villagómez et al., 2011), which overlaps with early Cretaceous fossil ages indicated above. Euhedral, zoned zircons from the Córdoba granodiorite, which intrudes the Quebradagrande Complex along the western flank of the Central Cordillera, yielded a mean age of 79.7±2.5 Ma, which is considered to represent the time of emplacement (Villagómez et al, 2011). New U/Pb LA-ICP-MS analysis (Pardo et al., in preparation) in detrital circon performed in the quartz rich unit in the Manizales area yielded three main age populations: 1) Carboniferous-Triassic (220-300 Ma), 2) Neoproterozoic-Ordovician (440-600 Ma) which can be associated with the Tahami Terrane basement (cf. Toussaint, 1996) (e.g. Paleozoic orthogneisses and schists of the Cajamarca Complex) and 3) Mesoproterozoic (1000 -1100 Ma), probably derived from the Grenville-related rocks from the eastern Andes. In contrast, the western volcanic deposits contain mainly a Cenomanian-Aptian (95-115 Ma) population, derived from the lower cretaceous Caribbean volcanic arc. A minor proportion of Triassic-Late Permian (220-270 Ma) and Ordovician-Cambrian (460-500 Ma) detrital zircon populations could indicate the influence of the Central Cordillera basement in the sedimentary record at least at 100 Ma (Albian) in the western part of the Quebradagrande Complex. Currently, two main hypotheses have been proposed for the origin of the Quebradagrande Complex: 1) An intracratonic marginal basin produced by spreading-subsidence, where the progressive thinning of the lithosphere generated gradually deeper sedimentary environments, eventually resulting in the generation of oceanic crust (Nivia et al., 2006). 2) An accretionary complex composed of passive-margin deposits (organic mudrocks and quartz-rich sediments), a volcanic arc and some portions of the Proto-Caribbean Plate, which were accreted to the NW border of South America during the uppermost Early-Late Cretaceous (Moreno-Sánchez & Pardo-Trujillo, 2003; Pindell & Kennan, 2009;.Villagómez, 2011).

1.1.1.6 AMAGA FORMATION

Siliciclastic successions in the region bear critical geologic information that may help unravel the Oligocene-Miocene paleotectonic and paleogeographic evolution of NW South America. However, a litho and chronostratigraphic framework for the Oligocene-Miocene sedimentary successions in NW Colombia is still deficient.

Fig 7. Cauca River Valley near La Pintada (Ant.). Landscape is formed by the Mio-Pliocene Combia Formation and Oligo-Miocene sediments of the Amagá Formation (low lands).

An important sedimentary sequence, which currently occupies the Interandean depression of the Cauca River (between the Central and Western cordilleras), will be found during the fieldtrip as an interesting element of the landscape and a fundamental lithologic unit (Fig. 2). It is a narrowly confined, N-S elongate (less than 25 km wide and 150 km long), segmented, sedimentary basin Oligo-Miocene in age (Fig. 7). This sequence was meticulously studied by E. Grosse who wrote the seminal report "El Terciario Carbonifero de Antioquia"(Grosse, 1926). Without major modifications, with regards to its understanding or to the addition of new stratigraphic differentiation, subsequent studies have suggested several new names. Its current designation is that of Amagá Formation (Gonzalez, 2001) and it refers to a coal-bearing siliciclastic succession deposited in a low elevation, fluvial environment (continental). Based on the presence of coal layers, Grosse (1926) proposed a subdivision of the sequence into three members: lower member (conglomeratic, no coal), middle member (alternating sandstones and claystones, coal rich), and upper member (arkosic, no coal layers). Alternative subdivisions have been also proposed (for details see Correa and Silva, 1999; Sierra et al. 2004). To this date, The AF embodies a dilemma with respect to its evolution either as an Interandean basin without any marine influence (Campuzano, 1977; Guzmán, 2003; Sierra et al., 2004; Silva et al., 2008), or as a peneplain (Dueñas, 1986; Grosse, 1926) with a potential for marked marine influence from the west (Dueñas, 1986; Escobar, 1983; Schuler and Doubinger, 1970; Zegarra, 1993).

The Amagá Formation unconformably overlies the Paleozoic metamorphic basement of the Central Cordillera of Colombia and is unconformably covered by late Cenozoic volcaniclastic successions from the Combia and Irra formations (Fig. 2 #9; Fig. 7) (Guzmán, 1991; Guzmán and Sierra, 1984; Hernández, 1998; Murillo, 1998; Silva et al., 2008). In its current configuration the Amagá Formation is in fault contact, along the RFS, with Paleozoic turbiditic metasediments (Sinifana metasediments - Fig. 2 #8) and with oceanic metavolcanic-sedimentary successions from the Arquía Complex (Fig. 2 # 5). It is also in fault contact with volcano-sedimentary successions and ultramafic rocks of oceanic affinity Jurassic–Cretaceous in age e.g., the Cañas Gordas and Quebrada Grande complexes, and with Triassic S-type intrusives such as the Amagá Pluton and the Pueblito Diorite. (Fig. 2 #6). All these lithologic units topographically flank the modern Amagá formation and are considered potential detrital source areas for the Amagá Basin (Correa and Silva, 1999; Silva et al., 2008; Grosse, 1926; Restrepo et al., in review).

The depositional age of the Amagá Formation is well constrained. On the basis of palynologic assemblages observed in floodplain deposits from the lowermost portions of the Lower Member, Van der Hammen (1958) and Pons (1984), concluded a middle Oligocene age for the onset of deposition. The upper limit of sedimentation is considered middle-late Miocene, as suggested by the palynologic assemblages reported by the same authors. The 7.8 ± 1 Ma K–Ar age obtained from tholeitic sills intruding the Upper Member (Aspden et al., 1987; Maya, 1992) can be considered as a minimum age. Recent palynologic information permits to refine the age and the environment of deposition for the Amaga Formation. Based on similarities with the palynology zoning of Jaramillo and Rueda (2004), the section could be placed in the zones Ca-04 (Retitricolporites esponjosus) and Ca-08 (Retistephanoporites minutiporus) yielding and age range from Early Oligocene to Early Miocene. Fossil leafs, stems and tree trunks, and the presence of Mauritiidites franciscoi, plus the absence of marine palynomorphs (e.g. dinoflagellates and foraminiferan) are evidence of a continental character apparently supported by other sedimentologic studies (Campuzano, 1977; Guzmán, 1991, 2003; Silva et al., 2008).

Silva and others (2008) reported three stages in the evolution of the Amagá Formation that are marked by changes in the sedimentologic and stratigraphic characteristics of the sequence and by changes in the compositionl mode of the sandstones. Such changes reflect major fluctuations in base level resulting from significant geologic episodes since the middle Cenozoic. The initial stage was related to a pulse of uplift recognized for the Central Cordillera at ~25 Ma, episodes (Restepo-moreno et al., 2009; Van der Hammen, 1961; Gomez et al., 2005) which triggered moderate subsidence and high rates of sediment supply into the basin. This stage favored the development of aggradational braided rivers and widespread channel amalgamation resulting in poor preservation of both, low energy facies and geomorphic elements (Silva et al., 2008). A second stage of increased subsidence and enhanced accommodation space during the Late Oligocene favored the developing of meandering rivers thus allowing the formation of extensive swamps deposits where a number of coal beds formed (from 90 to 3 m thick). High preservation of geomorphic elements and high diversity of sedimentary facies characterize this stage resulting in the most symmetric stratigraphic cycles of the entire Amagá Formation. Stage two was attributed to the migration of the Pre-Andean tholeitic magmatic arc from the Western Cordillera towards the Cauca depression that generated extensional movements along the Amagá Basin. The final stage of evolution for the Amagá Basin was related to the development of late Miocene tholeitic volcanism (~10-8 Ma). The extensive thrusting and folding associated with this volcanism reduced subsidence rates and accommodation space leading to the development of highly aggradational braided rivers. Little preservation of low energy facies, poor preservation of the geomorphic elements and a complete obliteration of important swamp deposits (coal beds) within the basin are reflected by the most asymmetric stratigraphic cycles of the whole formation (Silva et al., 2008). This stages however, may be related to the changing nature of convergence of the PCB since the Oligocene.

Recently produced zircon U-Pb ages and apatite fission-track thermochronology data from the Amagá Formation and some neighboring igneous massifs (detrital and magmatic samples) in conjunction with recent sedimentologic, stratigraphic and compositional characteristics of Oligocene-Miocene siliciclastic successions exposed along the Cauca River depression (e.g., the Amagá Formation to the North and the Cinta de Piedra, Mosquera, and Esmita formations to the south) were used to assess the morphotectonic and paleogeographic history of the region, and to constraint the evolution of these basins in the geodynamic milieu implied by the docking of the Panama-Chocó block (PCB) and the establishment of the Western Cordillera and the Paleo-Cauca fluvial network (Restrepo-Moreno et al., in review). Contrasting evolution between the northern and southern sediment-stratigraphic domains and a marked provincialism (backed by U-Pb and AFT data) are taken to entail two juxtaposed and yet disparate morphotectonic and paleogeographic histories defined by the point of collision between the PCB and the North Andean block in South America (~ 4º N): The Interandean and continental Amagá Formation to the north, and the marine -dominated sedimentary sequences to the south (i.e., Cinta de Piedra, Mosquera and Esmita formations).

1.1.1.7 COMBIA FORMATION

The Combia Formation (González, 1976) comprises basal volcanic rocks covered by poorly consolidated sediments and recent volcanics. Originally described by Grosse (1926), the Combia Formation includes conglomerates, sandstones, silts, conglomeratic tuffs, tuffitic sandstones, tuffs, ashes, agglomerates and basaltic and andesitic lavas reaching 600 m thickness (González, 2000). These rocks discordantly cover the siliciclastic sequence known as the Amagá Formation (Fig. 7) (Grosse, 1926; Calle and Gonzalez, 1980), representing the Neogene volcanism of western Colombia (Mariner and Millward, 1984). The Combia Formation outcrops in northwestern Colombia along the Cauca Basin between the Central and Western cordilleras (Fig. 2 #9), and record volcanic pulses between 10 and 6 Ma and deposited under fluvial and lacustrine conditions (Lopez et al., 2006).

Combia magmatism occurred under a transpresional regime associated with the accretion of oceanic material of the Panama-Choco Block along traces of the Romeral fault system (Lopez et al., 2006)
With the final docking of the Serranía de Baudó and the Plio-Quaternary closure of panama isthmus , magmatism migrated towards the axis of the Central cordillera, currently affecting only the region below 6ºN (Sierra, 1994; Toussaint, 1999), where modern Ruiz Tolima volcanic complex is situated.

Regionally, the Western Cordillera is composed of Upper Cretaceous rocks, including massive basalts and pillows of the Volcanic Formation (Barrero, 1979; Aspden, 1984; Kerr et al., 1997; Sinton et al., 1998), gabbronorites of the Bolívar Ultramafic Complex geochemically similar to the Volcanic Fm. (Kerr et al., 2004), and finally Albian–Maastrichtian turbidites of the Espinal and Cisneros formations (Barrero, 1979; Etayo-Serna, 1985a) to the south of the country. To the northern part of the cordillera, in Antioquia, equivalent rocks are known as Cañasgordas Group (Alvarez, 1970; Alvarez y Gonzalez, 1978), which comprise a volcanic-sedimentary sequence informally divide into Barroso Formation (volcanic member) (Fig. 2 # 3) and Penderisco Formation (turbidites and chemical and biogenic sediments) of upper cretaceous age.

Reecent data reported by INGEOMINAS (González, pers. com.) shows very similar ages for volcanic formations of Western Cordillera (Volcanic and barroso Formation) and Central Cordillera (Amaime Formation). Ar-Ar results are mainly grouped about 84-89 Ma. Diabasic group to the south reports slightly younger ages about 81 Ma. Plutonic rocks in the northern part of Western Cordillera yields Ar-Ar ages about 92 Ma (Anserma Gabbro), 80 and 114 Ma (Mistrato Pluton), 80 Ma (Guayabillas Pluton). In the Central cordillera, mafic intrusives yields 2 Ar-Ar ages of c. 85 and 89 Ma (Cordoba igneous Complex).

The western Cordillera form part of the Caribbean Large Igneous Province (e.g. Kerr et al., 1997). Ultramafic to mafic rocks formed in response to Late Cretaceous, mantle plume-related volcanism in the eastern Pacific (Kerr et al., 1997; Luzieux et al., 2006; Pindell, 1990, 1993) erupted above the Galapagos Hot Spot (Kerr et al., 2004; Luzieux et al., 2006; Pindell and Kennan, 2009; Sinton et al., 1998) and then accreted against northwestern South America in the Upper Cretaceous (Hughes and Pilatasig, 2002; Jaillard et al., 2004; Spikings et al., 2001, 2010; Vallejo et al., 2009).

1.1.2 WESTERN CORDILLERA BASEMENT (CCOP)

1.1.2.1 BARROSO FORMATION

The Barroso formation comprises a tectonic association of basalts (with some pillows), dolerites, hyaloclastites, thin tuffs, volcanic breccias, with occasional lenses of pelites and chert and terrigenous rocks of Upper Cretaceous age (Pardo and Moreno; Barrero, 1979;Etayo-Serna et al, 1980; Etayo-Serna et al, 1982;Aspden y McCourt, 1986a; Etayo-Serna, 1989; Ossa y Pardo, 1989; Nivia, 1996; Pardo et al, 1999) limited to the east by the Cauca Fault system (Pardo and Moreno), part of the RFS. The sequence is intruded by late cretaceous, paleogene and Miocene granitoids (Brook, 1984, Aspden and MacCourt, 1986) (Fig. 2 #3)).

In the northern section of the Western Cordillera, sediments associated with Barroso formation make up more than half of the outcrop. These sediments, the Penderisco Formation, consist of a sequence of cherts, black micritic limestones and deposits with possible turbiditic characteristics (Alvarez & González, 1978).

Ar-Ar ages in volcanic rocks yields a plateau age of 91•7±2•7 Ma (Kerr. Et al., 1997), consistent with palaeontological evidence from the intercalated sediments (Kerr. Et al., 1997). The lavas and intrusives of the Western Cordillera are tholeiitic in character and geochemical evidence suggest an origin in plume-derived oceanic plateau (Kerr. Et al., 1997).

The volcanism associated with the Colombian portion of the Caribbean oceanic plateau appears to be of three distinct ages: two well-dated events (40Ar/39Ar; fossils from intercalated sediments), one of Late Cenomanian– Turonian (88–92 Ma) and another of Late Campanian– Early Maastrichtian (72–78 Ma), plus another eruptive episode older than 100 Ma (Kerr. Et al., 1997).

1.1.2.2 SANTA FE BATHOLITH

The Santa Fe Batholith is a roughly N-S elongated unit, that outcrops to the west of the Cauca-Almaguer Fault (Fig. 2 #2)(sensu Maya & González, 1995). It intrudes the mafic lava sequence of the Barroso Formation, which is generally accepted to be part of the Colombian Caribbean Plateau. The Santa Fe Batholith is mainly composed of gabbros and tonalities, whereby the tonalites generally contain gabbro and microdiorite enclaves (Fig. 8). Contacts range from straight to diffuse often strongly aligned and assimilated, suggesting that the gabbros crystallised before the tonalite facies, but where still relatively hot during tonalite emplacement. These rocks are intruded by late microdiorite dykes and more silicic porphyritic rocks (felsites).

The rocks are phaneritic, alotriomorphic, medium-grained, often slightly to intensely oriented. They comprise plagioclase, amphibole, pyroxene and sometimes quartz and opaques, and accessory minerals are apatite and sphene. Both rock-types range from pyroxene-rich to amphibole-rich. Amphiboles surround and sometimes completely replace the pyroxene, and various stages of replacement can be observed, indicating late-stage hydration.

The tonalitic rocks have some characteristics similar to Low-SiO2 adakites (Martin et al., 2005) and primordial mantle-normalized spidergrams are characterized by negative Nb-Ta and Ti anomalies, suggesting a subduction related signature. Sr and Nd isotopic data are homogenous (87Sr/86Sr – 0.70366, Ndi – + 6.7) and are compatible with melt generation from a mafic source. A new incremental heating 40Ar/39Ar date indicates that cooling of the Batholith occurred around 92 Ma.

Fig 8. Magmatic structures in Santa Fe Batholith. Note the mafic enclaves and diffuse transition with the main dioritic body suggesting mingling mechanisms

The geochemical characteristics and field relations are very similar to those described for the Aruba Batholith (White et al., 1999), the Buga Batholith (Villagómez et al., 2008), and the Pujilí Batholith (Vallejo et al., 2009), and therefore a similar tectonic setting is probable for all four units. The most likely tectonic scenario for these rocks, is the west dipping subduction zone, that initiated along the eastern margin of the Colombian Caribbean plateau, enabling the emplacement of mafic to intermediate magmas into basaltic rocks of the CCOP. During the Maastrichtian these units were accreted onto the South American margin, prior to the formation of a post-collisional continental arc at 65-55 Ma.

The Santa Fe Batholith has traditionally been mapped as part of the Cretaceous Sabanalarga Batholith (see González and Londoño, 2001), which outcrops to the east of the Cauca-Almaguer Fault. This unit intrudes the Cajamarca Complex, which is the makeup of the Central Cordillera basement, considered as the Pre-Triassic continental Andean margin.

The separation of the Santa Fe Batholith into two separate units was first proposed by Nivia and Gómez (2005), based on petrographical and tectonic evidence. K-Ar ages in biotite and hornblende of the Sabanalarga Batholith are 97 ± 10 Ma and 98 ± 3.5 Ma respectively. If both, the Santa Fe and Sabanalarga Batoliths are considered as one unit, the accretion of the Colombian Caribbean Plateau onto the South American plate margin would have had to have occurred before the Turonian.

2. FIELD GUIDE

A 3-day fieldtrip "Geological transect through the evolution of an accretionary margin" will guide us through the various elements that formed the current western South American margin (Fig. 1,2). These include the pre-Mesozoic South American basement rocks, accreted metamorphosed mixed oceanic domains (Arquía Complex), an earlier Cretaceous unit with arc-affinity (Quebradagrande Complex), the Colombian-Caribbean plateau (CCP), and various magmatic rocks that range from Cretaceous to Miocene, suggesting active magmatic activity through time.

The trip will take us from modern Medellín city to the historical colonial town of Santa Fe de Antioquia, along the Cauca River, heading afterwards to the mountainous city of Manizales, where coffee and volcanoes are part of the landscape.

General information

Figure 2 shows the main roads linking Medellin - Santa Fe de Antioquia – Bolombolo – La Pintada – Manizales. The map includes field points of observation (yellow stars) on a geological base map, which in turn shows the main lithological units referred in the text.

Santa Fe de Antioquia is a national historical monument given its colonial architecture. It possess 6 churches and houses of the XVI, XVII y XVIII centuries. The town is located at 550 m.a.s.l and a mean of 25Co. It is recommended wearing proper cloths for warm climate and keep enough liquid.

Pictures of the area, including panoramical views and rock characteristics are available at this link:
https://picasaweb.google.com/116714157401905796743/PanoramicalPicturesNearSantaFeDeAntioquia?feat=directlink

Itinerary

The field trip is intended to show an overview of the complex transition of the Central Cordillera into the Western Cordillera through the RFS (Figs. 1, 2, 9 and 10). The first day we will cross the Cauca Valley in the northern part of the area until reach rocks of the Western Cordillera represented by the Santa Fe batholith Batolith (Fig. 2 #2). During the journey we will observe outcrops of the Amaga Formation and deformed rocks of the Arquía complex. The second day we will head to Ciudad Bolivar (Fig. 2) to see exposures of Barroso and Combia Formations. The third day we will go to La Pintada (Fig. 2) and Rio Arquia (Est. 20) to observe mafic schist and garnetiferous amphibolites of the Arquía Complex. At the end of the afternoon we will back to Medellin.

Day 1 (September 3)

The field trip begins in the Medellin city heading NW to the Santa Fe de Antioquia town. The first field point is known as the Boquerón (Est. 1)). This point allows the observation of the Aburra Valley to the east where Medellin is located. It is possible either observe the Cauca Valley to the North.

In this area we can observe Tr (?) Amphibolites of the Central Cordillera and medium grade schist belonging to the Cajamarca Complex. Amphibolites are probably related to deformed gabbros and amphibolites located within the RFS although some authors considered it as allocthonous blocks obducted in the lower Cretaceous (Toussaint and Restrepo, 1989).

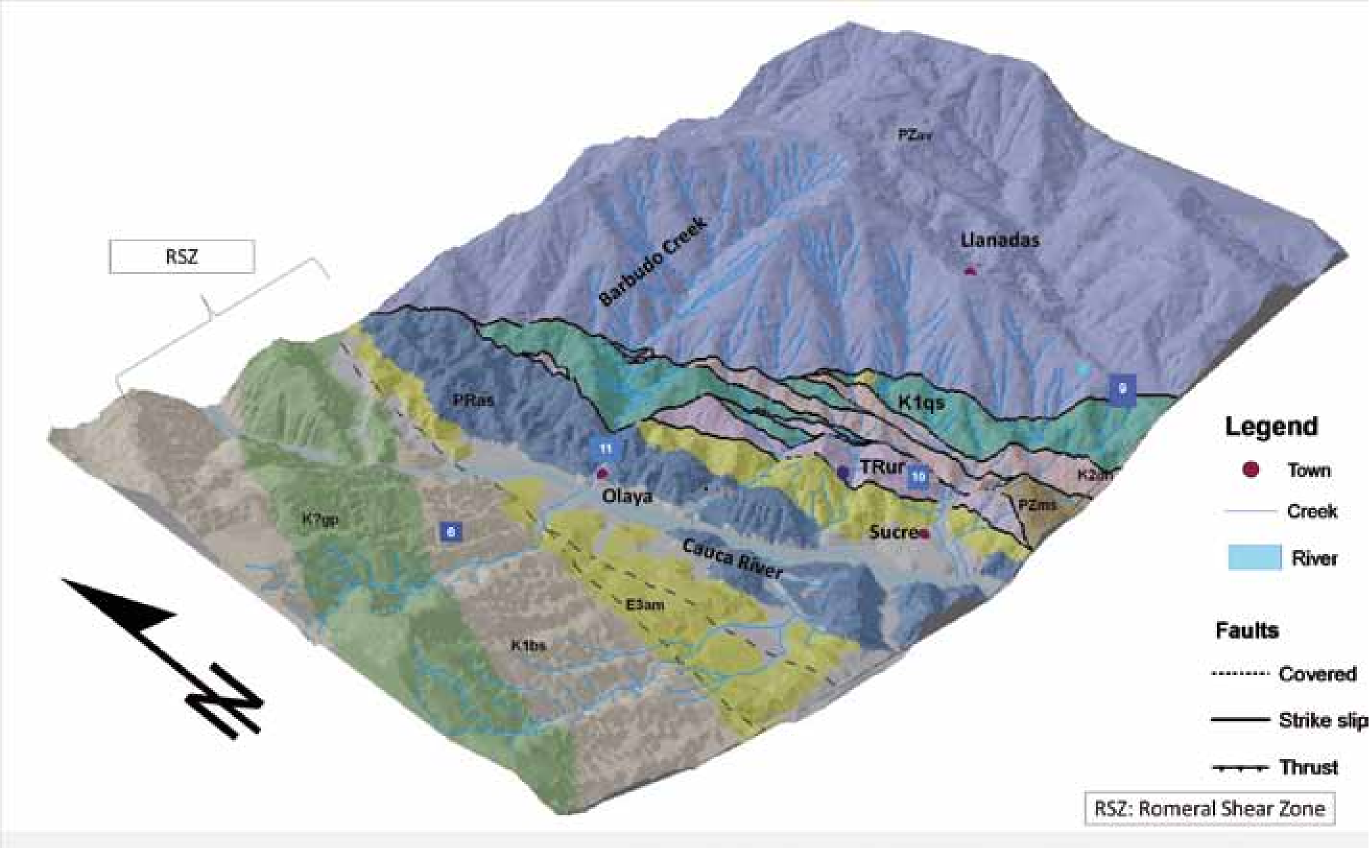

Fig 9. Digital 3D-terrane model and geological map for the area of interest. Map includes localization of samples for provenance U-Pb studies in zircon. Main geological units are numbered.

The journey takes us to the Cauca Valley where Oligo-Miocene sediments of the Amaga Formation outcrops. The siliciclastic Oligo-Miocene successions in the region bear key geologic information to unravel the paleotectonic and paleogegraphic evolution of NW South America. Two models are actually being considered, and interandean depression model for deposition (Guzmán, 2003; Sierra, 2003; Silva, 2008), or a peneplain configuration model (Grosse, 1926) with a potential for marine influence (Escobar, 1990; Schuler and Doubinger, 1970).

Passing 5 kms in NW direction from Santa Fe de Antioquia, we are now fully located in the western cordillera domain. In this point outcrop the lower Mesozoic Santa Fe Batholith Batolith (Est. 4,5 and 6). Some pictures of landscapes are taken from this place (Fig. 11).

We spend the night in Santa Fe de Antioquia where there are plenty of nice places for diner and drinking.

Day 2 (September 4)

Most part of the day will be dedicated to the neighboring areas of Santa Fe de Antioquia within the RFS area of influence. We will visit the Puente de Occidente, a bridge over the Cauca river (Est.7) (see link of pictures - panoramical pictures). In this place outcrops L-tectonites Tr(?) gabbros and amphibolites (Fig. 12). These mafic rocks are continuous with Pueblito diorite further south (Fig. 2 #6). Rodriguez et al. (2010) present evidence of intrusive contact with schist of Sabaletas (Fig. 13), implying a pre-mesozoic age for at least some fragments of the Arquía Complex (see link pictures – structures in schist). Other authors consider the contact as being regionally faulted of Sabaletas schist with Tr Pueblito diorite.

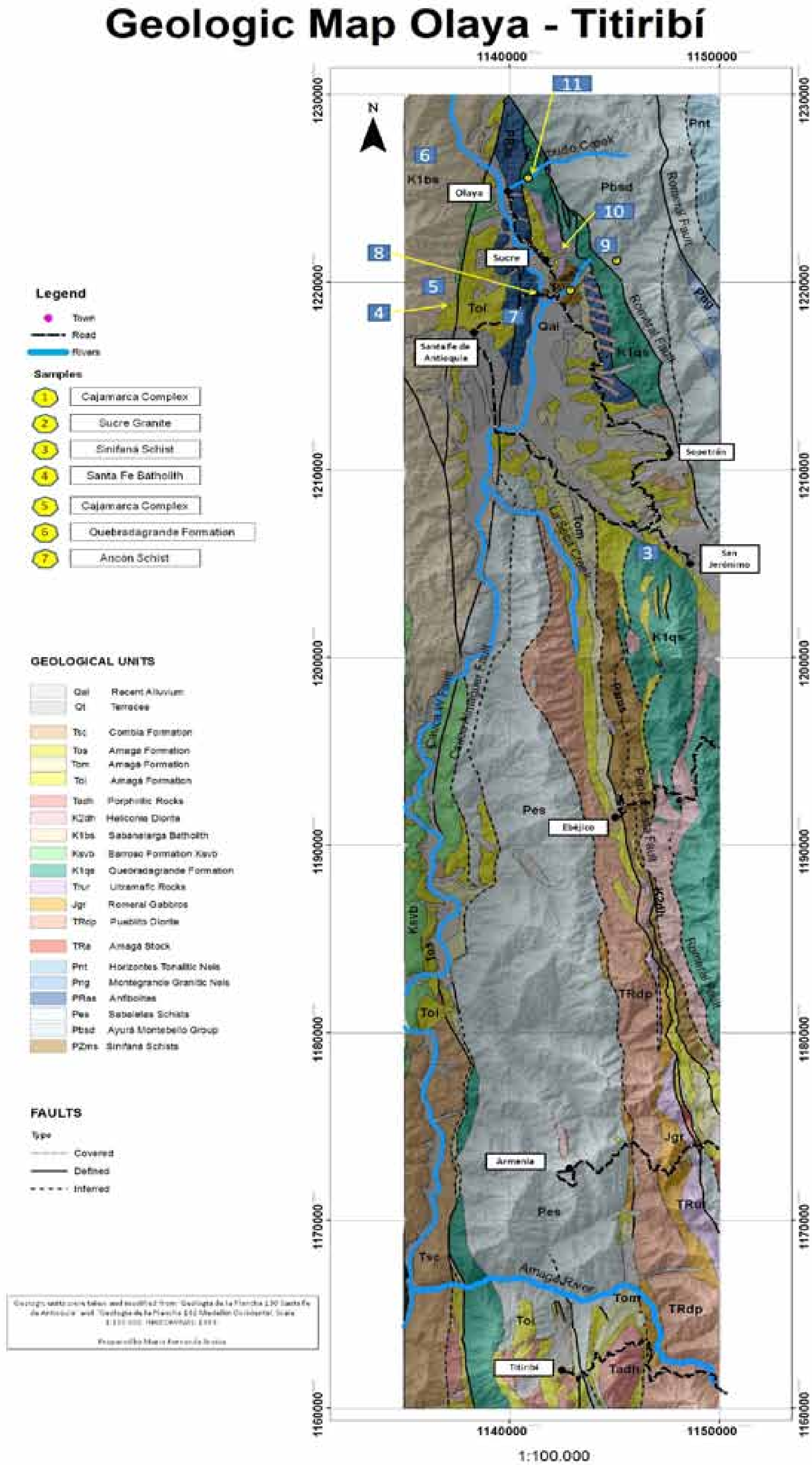

Fig 10. Digital 3D-terrane model for the northern part of the study area and geological map for the area of interest. Topography is a very useful indicator of lithology and structure for mapping and tectonic interpretation.

Fig 11. Panoramical View to the Cauca River (To the East) from Carretera al Mar, near Santafe de Antioquia.

Next, we will cross the Cauca River heading to the small town of Sucre. We can observe west verging thrusting structures of ultramafic rocks over low grade metasediements. If hiking some 30 minutes along Quebrada Seca we can observe a thrust of Quebradagrande rocks over Tertiary (?) syenogranites verging to the west. The west verging of structures is a generalized characteristic of the area. Almost all of the actual contacts between units inside the shear zone (RFS) are low angle thrusts verging to the W-SW. This is probably a Cenozoic structure.

Fig 12. L-Type tectonites developed in gabbros and textural variations.

Hiking along the Barbudo creek is an option; it would depend of the weather. Along the creek it is possible observe structures associates with deformed Tr gabbros and amphibolites (see link pictures – Barbudo creek), deformed sediments and volcanics of Quebragrande formation (Fig. 14)(see link pictures – structures in Quebradagrande). The Barbudo creek is the best route in the area to see structures associated with RFS. Includes discrete shear zones, associated folding, stretched boudins, etc. Some granitic sills are observed intruding the shale sequence (see link pictures – Barbudo creek). Ultramafic rocks can be seen few kms east of Sucre along a local road. They correspond to lense shape bodies parallel to regional NNW structures. Finally we will ascend towards Llanadas village to the east. In this point outcrops schist of Cajamarca Complex again. This is an excelent point to observe landscapes to the west and south-west (see link pictures – panoramical pictures).

In the afternoon we will head to the south looking for La Ciudad Bolivar (Fig. 2). During the journey it is possible observe volcanics rocks of Barroso Formation and Mio-Pliocene Combia Formation and landscapes associated (see link pictures – panoramical pictures).

We will spend the night in Ciudad Bolivar.

Fig 13. Mafic dike crosscutting rocks of Sabaletas schist (Arquia Complex).

Day 3. (September 5)

From Ciudad Bolivar we will head to the East to La Pintada. Passing la Pintada, We will visit the Guavita creek where massive serpentinite with peridotite cores appears. One km from this point we will visit the Rio Arquía w(Est. 20) here outcrops black and green intercalated schists intruded by andesitic and dacitic Mio-Pliocene porphyritic rocks. These rocks normally host important deposits of gold and basic metals actually being exploted in the Marmato mine district. Locally the schists presente faulted contact with garnetiferous amphibolites. Finally, getting back to Medellin.

Fig 14. Discrete metrical shear zone developed in sediments of Quebradagrande Formation. Structure marks the regional west verging thrusting over Triassic (?) L-tectonite gabbros (Sucre Amphibolite).

Stop	Coordenates		Locality	Comments	Day/ Journey	Time
1	1.154.768	1.192.221	Alto de Boquerón	Metamorphic rocks of the Central Cordillera. Cajamarca Complex. Low P metamorphism shown by pre-tectonic Andalusite. Upper Cretaceous porphyritic dykes from the Altavista stock (¿). Fig. 15. **Page 13** (east of Romeral fault system).	1	AM
2	1.153.149	1.195.585	Finca La Primavera - Palmitas	Permian S-Type Palmitas orthogneiss. Record Ar-Are ages about 68 Ma, likely associated with regional uplift because collision of CCP. **Page 13** (east of Romeral fault system).	1	AM
3	1.147.473	1.205.250	San Jerónimo - Santa Fe road	Volcanic rocks of the Quebradagrande Formation. **Page17** Quebragarande complex	1	AM
4	6. 34´23.1"	75.5´ 31.84"	Via al Mar road	Faulted contact between Amagá Formation and Santa Fe Batholith. Fig. 16. Beautiful fossil leaves in the Amagá Formation. **Page 19** Amagá Formation **Page 22** santa fe batholith	1	AM
5	6.34´ 51.7"	75.5´ 20.4"	Via al Mar road	Volcanic rocks of the Barroso Formation, intruded by intermediate to felsic dikes. Fracture cleavage in Volcanic rocks not seen in Oligo-Miocene rocks. Fig. 17. **Page 22** barros formation	1	AM
6	6.36´52.2"	75.5´13.5"	Via al Mar road	Banded gabbros. Magmatic structure is locally obliterated by deformation. **Page 22** santa fe batholith	1	AM
7	1.140.214	1.218.237	Santa Fe – Pte de Occidente road	Deformed schist of the Arquía Complex and mafic dikes. **Page 16** arquia complex	1	PM
8	1.141.306	1.219.531	Puente de Occidente observation point	L-Type Triassic (?) gabbros and amphibolites. Fig. 12 **Page 16** mafic and ultramafic igneous rocks.	1	PM
9	1.144.957	1.221.211	Sucre-Llanadas road	Panoramical View to the West. Topography is a very useful indicator of lithology and structure for mapping and tectonic interpretation. Fig. 11.	2	AM
10	1.142.304	1.221.774	Near Sucre	Lense of ultramafic rock. **Page 17** ultramafic units	2	AM
11			Olaya	Q. La Barbudo- Hiking to observe mainly volcano-sedimentary rocks of the Quebradagrande Formation. Fig. 14. **Page 17** Quebradagrande complex	2	AM
12	6.21´52.9"	75.51´20.7"	Near the road to Anzá	Volcanic rocks of the Barroso Formation and gabbroic dike. 200 m away the deformed Cretaceous marine sediments of Penderisco Formation	2	PM

Stop	Coordenates		Locality	Comments	Day/ Journey	Time
12	6.21´52.9"	75.51´20.7"	Near the road to Anzá	Volcanic rocks of the Barroso Formation and gabbroic dike. 200 m away the deformed Cretaceous marine sediments of Penderisco Formation can be seen. **Page 22** barroso formation	2	PM
13	6.3´8.5"	75.52´11.5"	Q. El Abejorro	Volcanic rocks from the Combia Formation. **Page 21** combia formation	2	PM
14			Bolombolo-Amagá road	Panoramical view of Venecia - Cerro Tusa	2	PM
15	1.137.200	1.127.600	Bolombolo - Ciudad Bolivar road	Rocks from the Penderisco Formation-Urrao Member	3	AM
16	1.149.170	1.129.500	Rio Barroso	F. Barroso (Alternative). Massive to columnar basalt lavas.	3	AM
17	1.144.680	1.131.000	Bolombolo - Ciudad Bolivar road	Rocks from the Barroso Formation	3	AM
18	1.145.000	1.131.300	Q. La Herradura	Rocks from the Barroso Formation (Hiking). Morphological manifestation of Mistrató fault, which is the contact between Miocene Volcanics of the Combia Formation and the Cretaceous volcanic rocks of the Barroso Formation. **Page 22** barroso formation	3	AM
19	5.3325"	75.34´35"	Q. Chirapotó/Q. La Guadita	Amphibolites and schists of the Arquía Complex/Ultramafic lenses. **Page 16** arquia complex	3	PM
20	5.30´57"	73.34´41"	Rio Arquía	Amphibole schist and Q-Sericitic schists of the Arquía Complex intruded by Mio-Pliocene porphyritic dikes. **Page 16** arquia complex	3	PM

Fig 15. Andalucite cristal developed in metasediments.

Fig 16. Faulted contact between Amaga Formation and Santafe batholith.

Fig 17. Intermediate to felsic dykes intruding Volcanic rocks of Barroso F.

Notes

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