REACTIVATION EPISODES OF THE ROMERAL FAULT SYSTEM IN THE NORTHWESTERN PART OF CENTRAL ANDES, COLOMBIA, THROUGH ^{39}AR-^{40}AR AND K-AR RESULTS

EPISODIOS DE REACTIVACIÓN DEL SISTEMA DE FALLAS DE ROMERAL EN LA PARTE NOR-OCCIDENTAL DE LOS ANDES CENTRALES DE COLOMBIA A TRAVÉS DE RESULTADOS ^{39}AR-^{40}AR Y K-AR

CESAR VINASCO

Ph.D., Universidad Nacional de Colombia, Medellin, cvinasco@unal.edu.co

UMBERTO CORDANI

Ph.D., Universidade de Sao Paulo, Brazil

Recibido para evaluación: 30 Octubre 2012/Aceptación: 15 Noviembre: 2012 / Recibida Versión Final: 29 Noviembre 2012

ABSTRACT: Direct dating of reactivation of the San Jerónimo Fault (SJF), easternmost limit of the Romeral fault system (RFS), is presented through ^{39}Ar-^{40}Ar and K-Ar results in neo-formed micas and mylonitic bands of strongly hidrothermalized gabbros. Published cooling and crystallization ages from sin-tectonic magmatic rocks exposed in the western flank of the Central Cordillera have suggest that tectonic evolution of the paleo-fault system began since Triassic and Lower Jurassic before the installation of Central Cordillera in its present position relative to the South American margin (SOAM). The Sabaletas greenchists (Arquía complex) yields ^{39}Ar-^{40}Ar plateau age of 127±5 Ma and integrated ages between 102-115 Ma eventually recording the initial accommodation of the Albian-Aptian volcano-sedimentary sequence of the Quebradagrande Complex to the continental margin.

Direct dating of fault reactivation of SJF through ^{39}Ar-^{40}Ar analysis in neo-formed micas in mylonitic bands and K-Ar ages in a hidrothermalized gabbro belonging to the Quebradagrande volcanic rocks shows plateau ages ranging from 87-90 Ma in biotite and 72-81 Ma in sericite, whereas K-Ar whole rock ages in samples collected in the area of influence of the SJF range between 91-102 Ma.
The predominance of Upper Cretaceous ages suggest that activity of the fault system rich the major and most important peak during this time spam. This age interval is most likely related to the oblique arrival and collision of the Caribbean-Colombian Oceanic Plateau (CCOP) episodically during the upper cretaceous.

Final deformational episodes in the Central Cordillera and RFS are related to the collision of the Panamá-Chocó block in Early Miocene-early Pliocene, and are recorded by ^{39}Ar-^{40}Ar and K-Ar ages in Mio-Pliocene intrusives along the Cauca depression.

Keywords: Romeral, Ar-Ar, Quebadagrande, Arquía, Central Cordillera, Colombia, Caribe, Plateau.

RESUMEN: Resultados de geocronología ^{39}Ar-^{40}Ar and K-Ar en micas neoformadas, bandas miloniticas y gabros intensamente hidrotermalizados expuestos a lo largo del sistema de San Jerónimo (FSJ) son utilizados para establecer la historia de reactivación tectónica de este segmento oriental del sistema de fallas de Romeral.

Edades de cristalización y enfriamiento de granitos sin-tectónicos expuesto en el flanco occidental de la Cordillera Central sugieren que la evolución tectónica de esta falla comenzó en el Triásico-Jurásico Inferior en una posición paleogeográfica diferente a la actual. Los Esquistos de Sabaleta (Grupo Arquía) presentan una edad ^{39}Ar-^{40}Ar de meseta de 127±5 Ma que estarían asociados al adosamiento del Complejo Quebradagrande a la margen continental.

Dataciones directas de la reactivación de la FSJ fueron obtenidas por el método ^{39}Ar-^{40}Ar en micas neoformadas y bandas miloníticas y por el método K-Ar en rocas volcánicas y gabros hidrotermalizados del Complejo Quebradagrande. Los resultados indican edades de meseta en biotita y sericita entre 87-90 Ma y 72-81 Ma y edades K-Ar entre 91-102 Ma.

La mayor parte de las edades obtenidas se encuentran en el Cretácico Superior y sugieren que durante este período la actividad tectónica fue bastante significativa, asociada probablemente a la aproximación oblicua y episódica del borde la placa oceánica del Caribe.
Los episodios finales de deformación en la Cordillera Central y en FSJ estarían relacionados a la colisión del bloque Panamá Chocó en el Mioceno Temprano-Plioceno Temprano y se encuentran documentadas en las edades ^{39}Ar-^{40}Ar and K-Ar de los intrusivos Mio-Pliocenos expuestos en la depresión del Cauca.

Palabras Claves: Romeral, Ar-Ar, Quebadagrande, Arquía, Central Cordillera, Colombia, Caribe, Plateau.

1. INTRODUCTION

The geological boundary between the Central and the Western Cordilleras of Colombia is defined by an accretionary system formed by several independent tectonic blocks, bounded and deformed by the RFS configuring a kilometric-scale shear zone. Accretion of these blocks onto the paleo-South American margin occurs mainly in lower and upper Cretaceous times (McCourt, et al., 1984, Restrepo and Toussaint, 1988).

The Romeral Fault System (RFS) and associated deformed rocks, represent the western limit of the Central Cordillera of Colombia, which configure the cretaceous paleo-margin of northwestern South America. The temporal and geological evolution of the RFS is closely associated to this margin formed in a dominantly para-autochtonous proto-Andean configuration, although several other models suggest a completely allocthonous evolution (Restrepo and Toussaint, 1988). Given the complex nature of the rocks exposed along the RFS and diverse nature and age of constituent rocks, some of them even pre-Triassic in age, constraining the initiation of the tectonic activity and subsequent reactivation episodes of the system is not an easy task.

Over-imposed ductile deformation and hydrothermal processes are common in the area, as a major reflect of structural reactivation during the main tectonic events. Therefore direct dating of deformation can be achieved if minerals associated with this processes and the deformation are properly date.

The ^{40}Ar-^{39}Ar methodology is an applicable tool to a wide spectrum of geological problems. In the case of thermochronology of shear zones and mylonitic dating it has allow to directly constraint the timing of tectonic and structural reactivation of continental and oceanic margins (Dunlap, 1997, Freeman et al., 1998). In this contribution we constraint the timing of the major tectonic reactivation events for the RFS (Fig 1.) through direct dating of neo-formed and recrystalized minerals using the ^{40}Ar-^{39}Ar methodology. K-Ar analysis in mylonitic, volcanic and hidrothermalized rocks were also carried out as complementary results. The main advantage of the method consists on the possibility of obtaining reliable results with little amount of sample, such as individual crystals or small mineral concentrates of fine micas carefully selected.

2. GEOLOGICAL OVERVIEW

The westernmost segment of the Colombian Andes encompasses the Central and Western Cordillera as well as the Atrato basin and the Baudó Ranges (Figure 1). The geological configuration of the northern Andes closely follows the physiographic trend whereby the Central and Western cordilleras belong to two contrasting domains separated by the RFS (Figure 1). Multiple processes of plutonism, volcanism and metamorphism have been specially recorded in the Central Cordillera and can be traced with reasonable certainty at least until the Devonian (McCourt et al., 1984, Restrepo and Toussaint, 1988, Vinasco, et al. 2006). The Western Cordillera (WC) includes volcanic rocks of oceanic affinity related to Caribbean plate, that were obliquely accreted to the western margin of South America (e.g. Pindell and Dewey, 1982, Kerr et al., 1997, McCourt et al., 1984) in the Late Cretaceous. The accreted Cretaceous terranes are exposed to the west of the regional RFS (Cauca-Almaguer Fault) (Figure 2). They consist of basalts, gabbros, ultramafic cumulates and flysh-type sedimentary rocks. Some of these remnants present geochemical features akin with oceanic plateau that can be related to the Late-Cretaceous Colombian-Caribbean Oceanic Plateau CCCP (Kerr et al., 1996, Villagómez et al., 2011). These rocks have available U-Pb radiometric ages about 95 Ma in zircon for the Bolivar Complex (Villagómez et al., 2011) and ^{39}Ar-^{40}Ar ages between 84-90 Ma for Barroso and Amaime Formations (González, pers. comm.).

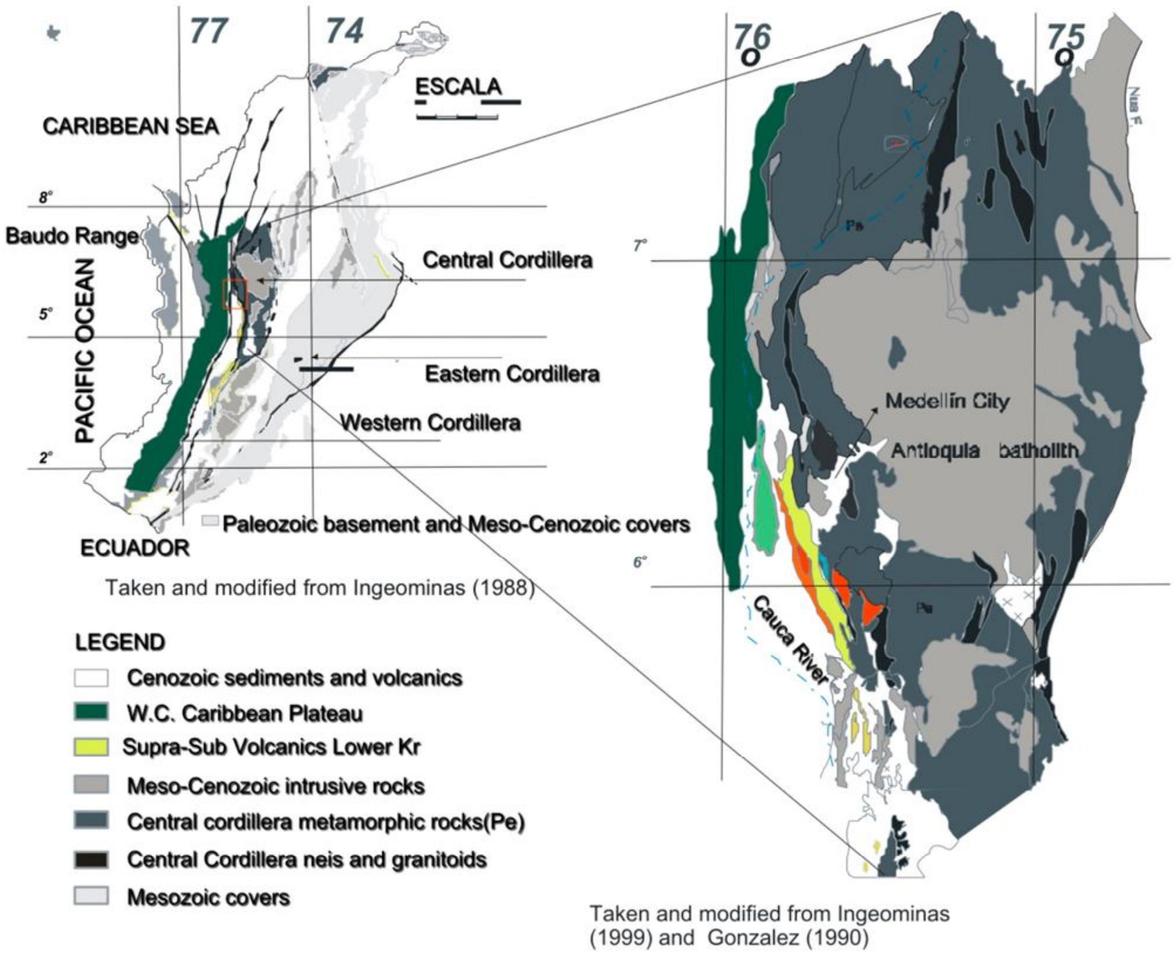


Figure 1. Simplified geological map of Colombia and Central Cordillera in the northern part, including the Antioquia Batholith and Medellin city.

Regionally, the broad boundary separating Central from Western cordillera, i.e. RFS, corresponds to a kilometric shear zone hosting a series of rocks (Figure 2): (1) Early Cretaceous volcano sedimentary rocks of the Quebradagrande Complex, characterized by both MORB and arc-related rocks (Villagómez et al., 2011) , (2) low grade Paleozoic (?) meta-sedimentary rocks grouped as the Sinifaná Meta-sediments, (3) mafic and ultramafic Triassic intrusives and finally (4) Permian (?) and/or (?) Cretaceous (?) low to medium grade meta-vulcano-sedimentary N-MORB type sequences of the Arquía Complex. The Amagá Formation, a coal bearing, Oligo-Miocene sedimentary sequence (Grosse, 1926) unconformably covers the older lithological units. Mio-Pliocene volcanic and sub-volcanic rocks of the Combia Formation covered and intruded the Amagá Formation and older rocks.

Geometrically, the RFS shear zone is characterized by an anastomosed arrange of faults yielding a block tectonic configuration, interpreted here as an extensive shear zone (kilometric-scale) composed of multiple lithological units of varying ages, diverse origins, poly-deformed, and in faulted contact, which Gonzalez (1980) named the Romeral Mélange. The system has been traditionally considered as a strike-slip shear zone, however, systematic observation of thrust faults suggests the importance of a compressive component of the system, configuring a dominant transpressive regime at least for the Cenozoic and eventually the Upper Cretaceous. Evidences for post- Coniacian thrusting of Quebradagrande volcanics over a feldspar granitoid, and post- Miocene thrusting of ultramafic rocks over oligo-miocene clastic rocks of Amagá Formation are reported.

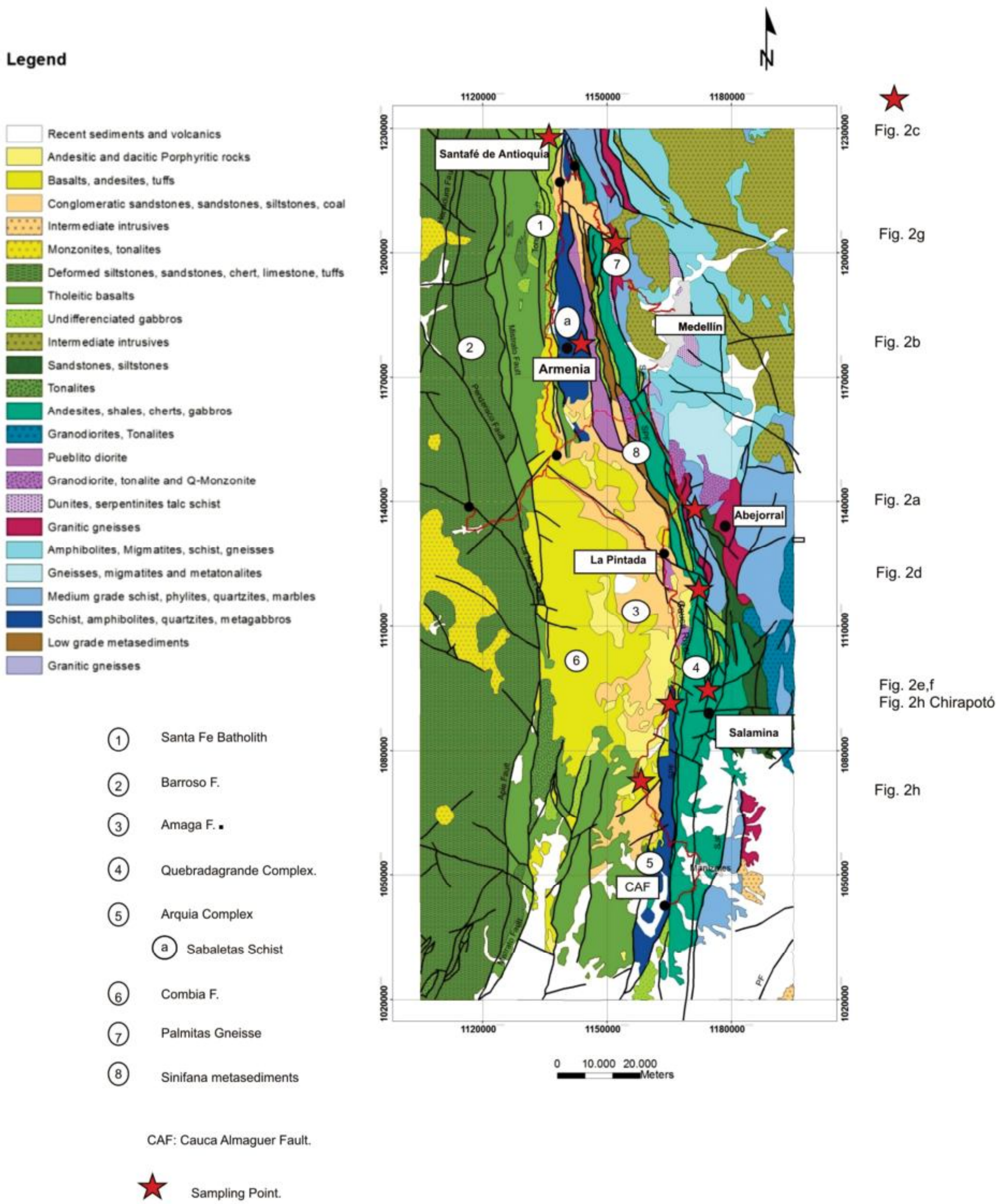


Figure 2. Detailed geological map, including sampling points, geological and geographical references cited in the text.

The Triassic position of the Central Cordillera relative to the South American margin is actually matter of debate. Vinasco et al. (2006) placed it somewhere between the southern United States and northern Venezuela, in the leading edge of Gondwana. Pindell and Kennan (2009), in turn, place the Central Cordillera for Jurassic times just outboard the South American margin in a non-defined strike position. Bayona, et al. (2006), based in paleo-magnetic results in the

Eastern Cordillera, shows an along-margin northward translation of Andean Colombian terranes. These are located between the Borde LLanero and Romeral faults during the Early-Middle Jurassic while do not record any further change in paleo-latitude since then. This model, however, doesn't take into account the probably exotic character of the Central Cordillera relative to eastern Cordillera (Restrepo and Toussaint, 1988). On the other hand, Pindell and Kennan (2009) and references therein, based on the geometrical requirements of Pangaea assembly, place the pre-Jurassic Central Mexican, Southern Mexican, Chortís, Tahami–Antioquia (Central Cordillera of Colombia), and Chaucha–Arquía terranes outboard of the more stable cratonic areas of northeast Mexico and the Guayana Shield. Precambrian U-Pb age populations obtained by different authors indicate the Paleozoic-Triassic sedimentary rocks were probably derived from the Guyana Shield and are native to South America (Vinasco et al., 2006, Villagómez, 2011).

Post-Triassic evolution of the northwestern Margin of South America is mainly controlled by the break-up of Gondwana in the Jurassic and subsequent drifting of the Caribbean plate in Cretaceous times after installation of the Central Cordillera of Colombia in Albian times on its present position. The Central Cordillera, consequently, serves as a backstop for installation of pre Caribbean subduction zones (related to the Trans American plate boundary), lower Cretaceous arc and back arc basins and accretion of exotic blocks Restrepo and Toussaint, 1988, Villagómez, 2011). The Meso-Cenozoic subduction system (the Trans American plate boundary - Pindell and Kennan, 2009) at the western margin of the Americas plays a key role in the entire evolution of the margin and subsequent development of the Caribbean plate.

Finally, other events are well known for the entire Cenozoic. These events are mainly related to variations in plate convergence or to terrene accretion (Pindell et al., 1988, Restrepo-Moreno et al., 2009, Vallejo et al., 2009, Jaillard et al., 2009), and include syn-tectonic sedimentation and Mio-Pliocene volcanism along the RFS (e.g., the Amagá and Combia Formations respectively- Figure 2).

Sampling and experimental methods

The sampling area for this study is located to the south and southwest of Medellin, within the RFS (Figure 2). Three metamorphic rocks, five magmatic rocks, and five mylonitic rock samples were selected for analysis. Selection of samples for ^{39}Ar-^{40}Ar analyses was defined during a detailed petrographic study supported by X ray and SEM studies especially for the finest grained rocks. Samples were crushed, ultrasonicated with ethanol, and dried. Ten to fifteen single crystals of hornblende, biotite or muscovite from each sample were picked with metal tweezers, placed in wells in Al-irradiation disks, and irradiated, together with Fish Canyon sanidine fluence monitors, in the IEA-R1 nuclear reactor at IPEN, São Paulo, Brazil. After 2-3 weeks, three grains from each sample were analyzed by the laser incremental heating ^{40}Ar-^{39}Ar method at the CPGeo-USP laboratory. Irradiation, analysis, and interpretation procedures follow the methodology presented in Vasconcelos et al. (2001). Additionally, K-Ar whole rock analysis for six mylonitic rocks and three hidrothermalized volcanic rocks for comparison purposes were carried out.

Grain size, alteration conditions and macroscopic fabrics were the main criteria for selection of samples in the field. For dating deformational events using K-Ar methodology, samples may present hydrothermal alteration because the neo-crystallization process is related to fluid activation, while hydrothermalism and deformation are closely associated in time

Mylonitic rocks are direct representatives of activation episodes of fault systems in ductile medium crustal levels. Good spectrums were obtained from mylonitic rocks in neo-formed fine mica concentrates, yielding in most cases concordant plateau ages for different samples and similar K-Ar ages in the same rocks. Mineral concentrates were analyzed instead of individual grains because of the fine grain size and the necessity of obtaining enough quantity of gas for reliable measurements.

A plateau age is here defined as a segment of the ages spectrum composed by several fractions of released gas. Such fractions together must represent more than 50% of released gas in a sample. They cannot yield an age difference that can be detected within a 95% of confidence (Fleck et al., 1977 in McDougall and Harrison, 1999). Each sample is analyzed for 2-3 independent separate of grains or concentrates in order to check final results.

3. RESULTS

Upper Triassic-Lower Jurassic deformational episodes are recorded by quartz-sericitic schist with minor biotite of the Cajamarca Complex (sample CJ-30) collected near the town of Abejorral (Figure 2). The amount of gas released overcomes blank values for the first steps while plateau ages for two separate grains (Mu), yields ages of 189 ± 9 Ma and 214 ± 9 Ma (Figure 3a)

^{39}Ar-^{40}Ar cooling ages between 127-119 Ma (CJ-19 and CJ-28) were obtained in a sample from the Sabaletas Schist and a meta-gabbro near Abejorral town (Figure 2). Sample CJ-19 is quartz micaceous schist characterized by fine aggregates of sericite and graphite intercalated with bands of quartz. One of the concentrate yielded a plateau age (Mu) of 127.5 ± 2.0 Ma (Figure 3b). This age coincides with some values releassed during degassing of a second concentrate of the same (Figure 3b). The plateau age is here considered close of the deformational event. Sample CJ-28 is a cataclastic metagabbro with evident hydrothermal alteration and a well-defined foliation texture. Amphibole replaces pyroxene and commonly appears as aggregates. Integrated ages of 119 ± 5.0 and 141 ± 7 were obtained in the final steps of degasification in a pattern consistent with minor Ar loss (Turner, 1968).

Samples CJV-09 and CJV-07 correspond to the Santa Fe Batholith, traditionally mapped as part of the Cretaceous Sabanalarga Batholith (Weber et al., 2011). This unit is a syntectonic quartz-dioritic to gabbro-dioritic body emplaced in the eastern margin of the Western Cordillera to the west of the Cauca-Almaguer Fault (Figure 1). Samples are not appreciable neither deformed nor altered except for plagioclase near veinlets. A plateau ^{39}Ar-^{40}Ar age about 90 Ma was obtained on amphiboles from sample CJV-09 (Figure 3c), is considered as cooling ages after crystallization. The disturbed spectrum shows evidences of excess argon yielding integrated ages of 145 Ma for one of the analyzed minerals. Sample CJV-07 yielded a very low amount of gas resulting in significant error during the first steps, but stabilizes in the final steps when the level of gas overcomes the blank level. The integrated ages obtained for this sample are in the range of 90-108 Ma while the plateau ages of the intermediate steps range between 92 and 106 Ma (Figure 3c). The ca. 90 Ma is considered as the cooling age of the granitoid near the 450°C closure temperature for amphiboles.

Direct dating of reactivation at the SJF was achieved through ^{39}Ar-^{40}Ar analyses in neo-formed micas in mylonitic bands and K-Ar ages in a hidrothermalized gabbros belonging to the Quebradagrande volcanic rocks. Plateau ages ranging from 87-90 Ma in biotite and 72-81 Ma in sericite were obtained. Samples are strongly deformed or brecciated, defining mylonitic textures. Pressure shadows in quartz, plagioclase, micas and amphiboles are common. Micro-folding and recrystallization textures in micas are often observed. SEM analysis of mylonitic rocks shows homogeneity in color and brightness for micas which define the foliated structure. These characteristics are indicative of neo-formation or fully recrystallization during mylonitization.

Samples CJ-47, CJ-42B, and CJ-42A correspond to rocks intensely deformed within basic volcanic strata of the Quebradagrande Formation, SE of the La Pintada town (Figure 2**)**. These rocks outcrop continually for more than 300 meters, exhibiting variable degree of deformation. Less deformed sections correspond to metric strata of basic tuffs while the most deformed areas correspond to centimetric mylonitic zones where samples were collected.

Tuffaceous mylonitic rocks of basic (CJ-42B) and acid (CJ-42A) composition were collected in the same outcrop. CJ-42B sample shows a homogeneous spectrum for more than 80% of gas released (Figure 3d), yielding plateau ages in biotite of 89.8±1.1 Ma and 87.8±0.7 Ma. A whole rock K-Ar age on the same sample yielded an age of 91±2 Ma.

Sample CJ-42A (Figure 3d) present an-heterogeneous spectra (Figure 3d)- ca. 90% of gas release above the blank level was achieved at the first stages of fusion. The integrated ages of 93±14 Ma and 89±5 Ma are considered a reasonable approach for the deformational episode. Sample CJ-47 corresponds to a tuffaceous mylonitic rock of intermediate composition with plateaus ages in sericite of 74±2 Ma and 81±5 Ma (Figure 2d).

Sample CJ-54 corresponds to sericite-graphite phylonite rock. Although the amount of gas obtained was very low, an integrated age of 84±4 Ma (Figure 3e) reflect the upper cretaceous deformational episode similar to the others samples.

In the same volcanic sequence of Quebradagrande Formation, a set of ^{39}Ar-^{40}Ar and K-Ar ages between 81-62 Ma were obtained. A phylonite sample (CJ-55) from deformed sediments near Salamina town yielded a plateau age of 72±4 Ma (Figure 3f). This age is corroborated by K-Ar ages of 65 ± 3 Ma for the same sample and 66±3 Ma for sample CJ-54.

Sample CJ-50 from a intensely altered basic pyroclastic rock from the volcanic sequence, yield a whole rock K-Ar age of 68±5 Ma, interpreted as hydrothermal alteration related to activity of the RFS. Finally, the Palmitas gneiss (CJV-01, Figure 3) yield very well defined ^{39}Ar-^{40}Ar plateaus ages in biotite of 68.13 ± 0.12 Ma (Figure 3g) considered as a resetting age.

Sample CJ-69 corresponds to a deformed amphibolite collected in the Chirapotó creek, south of La Pintada town. The amount of gas obtained was very low, yielding spectra with high error and complex geometries. However, one of the analyzed grains yield a plateau age in biotite for 50% of released gas of 5.6 ± 0.4 Ma (Figure 2h). Finally, ^{40}Ar-^{39}Ar biotite plateau ages of 6.75±0.06 Ma for sample CJ-61 were obtained for an andesitic porphyritic rock collected south of La Pintada town (Figs. 2, 3h)

4. DISCUSION

^{39}Ar-^{40}Ar results yield temporal constraints through mineral growth during deformation for magmatic and deformational episodes. Cooling ages obtained, along with previously published geochronological results allows to established the different tectonic episodes experienced by the RFS, the western flank of the Central Cordillera and the eastern flank of the Western Cordillera as well. These events will be discussed in a temporal and spatial framework compared with available paleo-tectonic models and described through independent tectonic domains.

4.1. Triassic-jurasic

4.1.1. Romeral Fault System:

The sinistral syn-tectonic intrusive character of Triassic mafic rocks (Pueblito diorite) intruding meta-sedimentary rocks (Rodriguez, 2010) is probably the older documented activity of the paleo-continental margin. Although, this record took place when the Central Cordillera was still in an outboard position relative to the South American paleo-margin, sinistral regime, lasting at least until Jurassic times is probably due to east dipping subduction along the American Cordilleran margin.

4.1.2. Central Cordillera:

Upper Triassic-Lower Jurassic deformational episodes are recorded by a quartz-sericitic schist of the Cajamarca Complex (CJ-30). Plateau ages of 189 ± 9 Ma and 214 ± 9 Ma (Figure 2a) are probably related to the main Triassic sin-tectonic magmatic event. The age around 200 Ma as an important event is corroborated by the wide amount of ^{39}Ar-^{40}Ar resetting ages of Lower Jurassic, around 200-170 Ma, obtained by Vinasco (2001). Rocks recording these cooling ages include different granitoid bodies such as the Horizontes Gneiss (bi-Mu), stock del Buey (bi), Abejorral gneiss (bi) and the Stock de Cambumbia (bi).

4.1. Lower cretaceous

4.1.2. Romeral Fault System:

^{39}Ar-^{40}Ar cooling ages between 127-119 Ma for CJ-19 (Figure 2a) and CJ-28 from the Sabaletas Schist, collected near Armenia town (Figure 1) and a cataclastic metagabbro of the Quebradagrande complex collected near Santa Bárbara town, respectively, are related to the accretion of Quebradagrande arc-back-arc rocks and pre-triassic meta-sediments of the Sabaletas schist to the western margin of the Andes. Although precise paleo-geographic position cannot be defined with the available data, these rocks configure the cretaceous paleo-margin of Northern Andes. The spatial position of Pre-Cretaceous rocks of the Sabaletas schist west of Quebradagrande Complex, suggest that both the Quebradagrande and the basement rocks were in a continental para-autochtonous position because both records provenance of sediments from the ancient Central Cordillera.

The RFS reaches its “actual” configuration when the trans-American plate boundary (the fundamental pre-aptian east-dipping subduction zone located to the west of the American margin) underwent a major transformation to a southwest dipping subduction zone

Boletín Ciencias de la Tierra, Nro. 32, pp. 111-124. Medellín, diciembre de 2012. ISSN 012-3630

beneath the future Caribbean Arc (Pindell and Kennan, 2009) impelling the closure of the Quebradagrande oceanic arc-back arc system. Initiation of this arc is likely constrained by HP-LT metamorphic rocks present in the circum-Caribbean subduction complexes (Pindell and Kennan, 2009) including examples from Colombia in the Barragan area (Valle del Cauca) (Bustamante et al, 2011).

4.3. Upper cretaceous

4.3.1. Western Cordillera:

Plateau ^{39}Ar-^{40}Ar ages in amphibole about 90 Ma for sample CJV-09 for the Santa Fe batholith (Figure 2c) are considered as cooling ages after crystallization. The integrated ages are in the range of 90-108 Ma and the plateau ages of the intermediate steps ranges between 92 and 106 Ma (Figure 2c), values in general considered as cooling ages, suggesting that construction of the arc occurred at least since Albian times, some time earlier than previously considered. This magmatic event is also registered by the Buga Batholith, which yields an U-Pb age of c. 90 Ma Villagómez, 2011), and the Córdoba Batholith which yields an U-Pb age of c. 80 Ma and 85 Ma (Villagómez et al., 2011, González, pers. Comm). In the southern Caribbean it is recorded by the Aruba batholith (White et al., 1999) and in Ecuador by the Pujilí Granite (Vallejo et al., 2009), which yields ^{39}Ar-^{40}Ar ages about 92 Ma

The Santa Fe Batholith (Sabanalarga Batholith) (Weber et al., 2011), which outcrops to the west of the Cauca-Almaguer Fault (Figure 1), constraint the beginning of an east-dipping subduction system west to the Colombian margin around 100 Ma and the initial stages of island arc activity that formed at the juvenile active margin of the eastward migrating CCOP (Villagómez et al., 2011).

The plateau rocks exposed in the Caribbean, Colombia and Ecuador ranges 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). This unit constraint as well the accretion of the Quebradagrande and Arquía rocks against the margin in pre-Albian times, because intrudes the Sucre Amphibolite (within the RFS), meta-sediments of the Cajamarca Complex and the Barroso Formation (Gonzalez, 2001), implying that accretion of the CCOP probably began episodically since mid cretaceous times.

4.3.2. Romeral Fault System:

At almost the same period of time, direct dating of fault reactivation of SJF through ^{39}Ar-^{40}Ar analyses in neo-formed micas in mylonitic bands and K-Ar ages in a hidrothermalized gabbro belonging to the Quebradagrande volcanic rocks were obtained. Samples CJ-47, CJ-42B, and CJ-42A (Figure 2e) correspond to rocks intensely deformed within a basic volcanic stratum of the Quebradagrande Formation, SE of the La Pintada town. These samples yield plateau ^{39}Ar-^{40}Ar and whole rock ages about 90 Ma and K-Ar whole rock ages ranging between 91-102 Ma. Sample CJ-54 corresponds to a phylonite analyzed for sericite and graphite concentrates with integrated age of 84±4 Ma (Figure 2e). These deformational ages are concomitant with syntectonically intrusion of the Santa Fe batholith, which intrudes the eastern border of the CCOP.

Reactivation ages for this period of time probably represent a dextral transpressive character of the margin because the NE drifting of the Caribbean plate and beginning of accretion of the CCOP against the margin. This happens soon after the beginning of an east-dipping subduction system west to the Colombian margin around 100 Ma (Pindell and Kennan, 2009).

Another set of ^{39}Ar-^{40}Ar and K-Ar ages from Quebradagrande Formation have yield age interval betwee 76-62 Ma. A phylonite sample (CJ-55) from deformed sediments near Salamina town, yielded a plateau age of 72±4 Ma (Figure 2f). This age is corroborated by K-Ar ages of 65 ± 3 Ma for the same sample and 66±3 Ma for a phylonite (CJ-54). Sample CJ-50 from an intensely altered basic pyroclastic rock from the volcanic sequence, yield a whole rock K-Ar age of 68±5 Ma. These ages are probably recording the final accretion of the CCOP against the margin in an episodically fashion.

Due to the presence of chlorite and neo-formed sericite, ribbons in quartz with important recovery textures, maximum temperatures are in the green schist facies (Simpson, 1985). Therefore ages are then interpreted as true deformational episodes. On the other hand, ^{39}Ar-^{40}Ar results from a Permian gneiss located at the eastern border of the SJF (Palmitas gneisse,Figure 1) have yielded similar ^{39}Ar-^{40}Ar plateaus ages in biotite of 68.13 ± 0.12 Ma (Figure 2g), re-enforcing the upper Cretaceous reactivation of the RFS. Finally, similar ^{40}Ar/^{39}Ar ages presented by Bustamante et al. (2011) about 63 Ma in micas from blue schists southward of the study area, records the timing of exhumation of metamorphic rocks. Therefore it´s seems that the new and already published ^{40}Ar/^{39}Ar ages together with available thermochronological data records the collision and accretion of the CCOP and associated arcs in Campanian times (Villagómez, 2010, Cardona, et al. 2011).

4.4. Cenozoic

4.4.1. Central Cordillera:

^{40}Ar/^{39}Ar systematic applied for mylonitic rocks performed during this work didn't record deformational ages directly associated to reactivation of the fault system. There are several reasons to explain the absence of ages in this time spam, which are beyond the scope of this contribution. Some of them, however, are probably related to more brittle deformation compared to cretaceous deformation. On the other hand, there is not data available for thrust systems associated with the RFS in the area, which are potential areas for precisely dating Cenozoic deformation episodes for the chain.

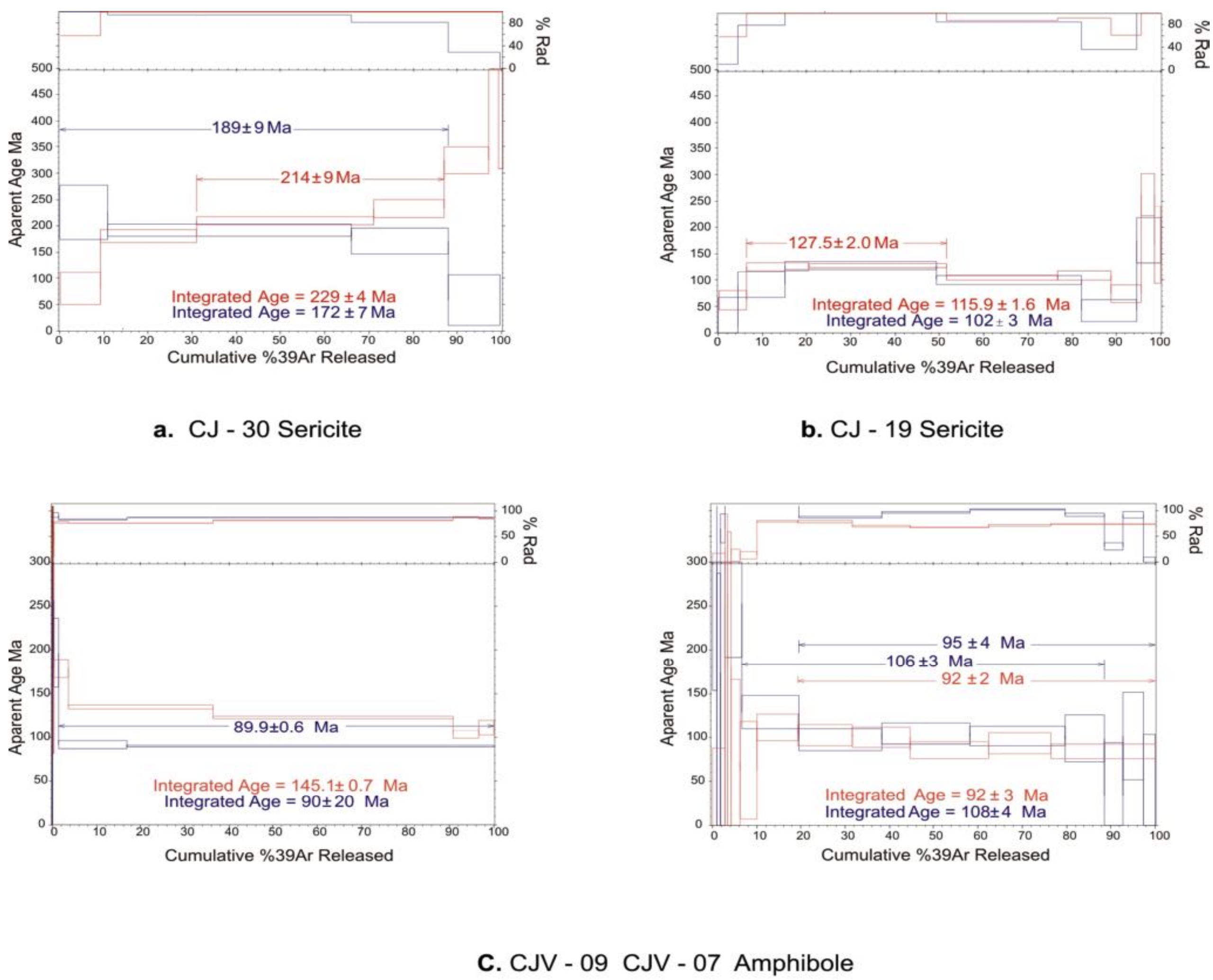
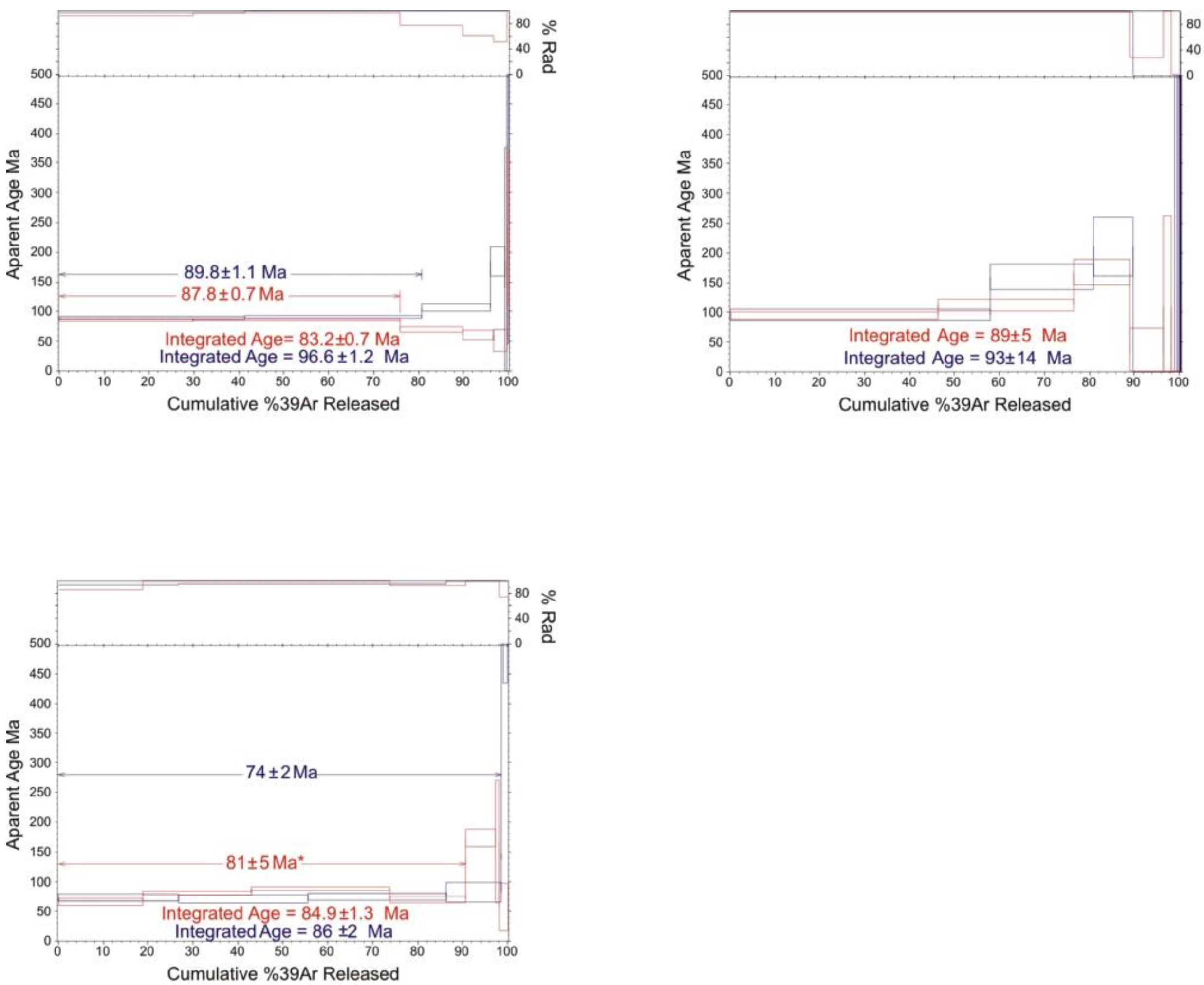
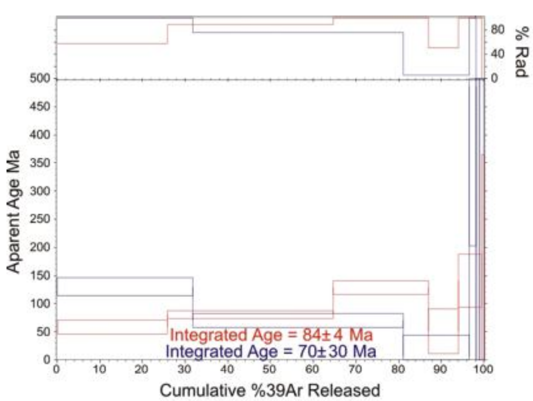


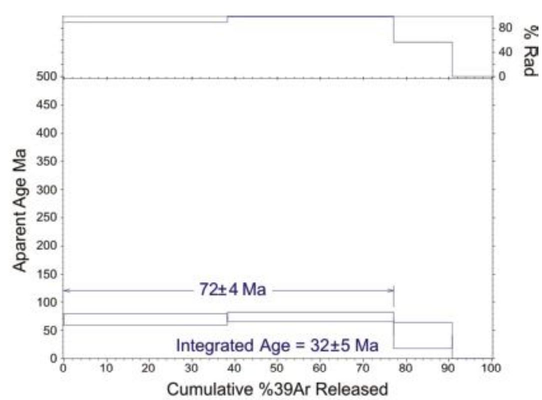
Figure 3. Single crystal duplicate analysis by the laser incremental heating ^{40}Ar/^{39}Ar method at the CPGeo-USP laboratory, Brazil.



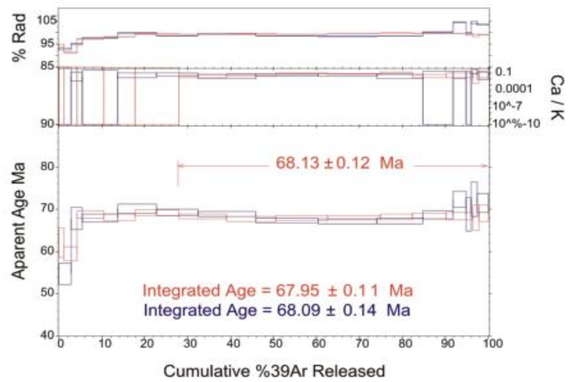
d. CJ - 42B Biotita; CJ - 42A Sericite; CJ - 47 Sericite



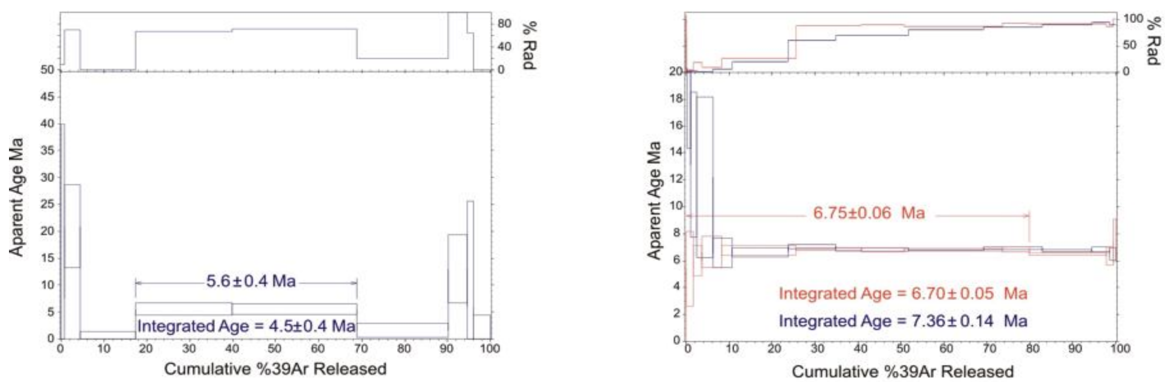
e. CJ - 54 Sericite



f. CJ 55 Sericite



g. CJV - 01 Biotite



h. CJ - 69 Biotite, CJ - 61 Biotite

Figure 3. (cont).

Palaeogene orogenic phases in Central Cordillera seem to be related to variations in plate convergence or to accretionary phenomena (Pindell et al., 1988, Restrepo-Moreno et al., 2009, Vallejo et al., 2009, Jaillard et al., 2009). The Central Cordillera exhumed at moderate rates during the Eocene (~45–30 Ma) (Villagómez et al., 2011), which is also observed over widely dispersed regions along the Andean chain. The greatest amount of middle - late Miocene exhumation occurred in southern Colombia, corresponding with elevated exhumation rates in northern Ecuador in response to collision and subduction of the buoyant Carnegie Ridge (Villagómez et al., 2011).

Final episodes of deformation in the chain are related to the collision of the Panamá-Chocó block in Early Miocene-Early Pliocene (Restrepo and Toussaint, 1988, Duque-Caro, 1990, Mann and Corrigan, 1990, Taboada et al., 2000, Trenkamp et al., 2002). 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).

5. CONCLUSIONS

Results obtained suggest that the Romeral Fault System (RFS) has been active since the Triassic. The initial phases may be part of a paleo-system formed when the Central Cordillera when still located in outboard position. The oldest deformational activity is represented by 175-200 Ma thermal event related to the post orogenic final stages of the upper Triassic orogenic event (Vinasco et al., 2006).

A lower cretaceous thermal event is registered in quartz-sericitic schist, reflecting the cooling age related to the dynamo thermal regional event thoroughly recorded in the Central Cordillera by several K-Ar ages. This event record the first accretion of mafic to intermediate volcanic rocks including the Quebradagrande Formation.

^{40}Ar-^{39}Ar and K-Ar results from mylonites for Upper Cretaceous times are perhaps the most important contribution to this work. A widely range of ages are obtained for this entire time spam. As these ages are interpreted as direct dating of activation of the fault system, it is possible to conclude that the regional event is long lasting and is eventually episodic in character. Regional reactivation of RFS is likely associate to accretion of the CCOP to the margin, configuring a major geological tectonic episode for northwestern Andes. Accretion began probably about 90 Ma reaching the onset of collision afterwards in Campanian-Maastrichtian times.

Subsequent deformation episodes couldn't reset the ^{40}Ar-^{39}Ar system. Important episodes during the Cenozoic were not recorded in this study. They are widely documented through other isotopic system, including (U-Th)/He in apatite and FT in zircon along with stratigraphic and structural evidence. These events apparently do not record ductile deformation and none of the analyzed neoformed mineral record younger Cenozoic events.

REFERENCES

[1] Bayona, G., A. Rapalini, et al. (2006). "Paleomagnetism in Mesozoic rocks of the Northern Andes and its Implications in Mesozoic Tectonics of Northwestern South America." Earth Planets and Space 58(10): 1255-1272.

[2] Bustamante, A., C. Juliani, et al. (2011). "Ar-40/Ar-39 ages from blueschists of the Jambalo region, Central Cordillera of Colombia: implications on the styles of accretion in the Northern Andes." Geologica Acta 9(3-4): 351-362.

[3] Cardona, A., V. A. Valencia, et al. (2011). "Early-subduction-related orogeny in the northern Andes: Turonian to Eocene magmatic and provenance record in the Santa Marta Massif and Rancheria Basin, northern Colombia." Terra Nova 23(1): 26-34.

[4] Cortes, M., J. Angelier, et al. (2005). "Paleostress evolution of the northern Andes (Eastern Cordillera of Colombia): Implications on plate kinematics of the South Caribbean region." Tectonics 24(1).

[5] Dunlap, W. J. (1997). "Neocrystallization or cooling? 40Ar/39Ar ages of white micas from low grade mylonites." Chemical Geology. 143: 22.

[6] Duque-Caro, H. (1990). "The Choco Block in the northwestern corner of South America: Structural, tectonostratigraphic, and paleogeographic implications." Journal of South American Earth Sciences 3: 13.

[7] Freeman, S. B., R, Cliff, R.A. (1998). "Direct dating of mylonite evolution: a multi-disciplinary geochronological study from the Moine thrust zone, NW Scotlaand." Journal of the Geological Society. 155: 13.

[8] Gonzalez, H. (1980). "Geología de las planchas 167 (Sonsón) y 168 (Salamina). Boletín Geológico. 23: 174.

[9] Gonzalez, H. (2001). "Mapa Geológico del departamento de Antioquia. Escala 1:400.000. Memoria Explicativa. Ingeominas.

[10] Grosse, E. (1926). "Estudio Geológico del Terciario Carbonífero de Antioquia en la parte occidental de la Cordillera Central de Colombia." Berlín, Verlag Von Dietrich Reimer (Ernst Vohsen). 361p.

[11] Jaillard, E., Lapierre, H., Ordonez, M., Alava, J.T., Amortegui, A., Vanmelle, J. (2009). "Accreted oceanic terranes in Ecuador: southern edge of the Caribbean Plate? ." Geological Society of London Special Publication 328: 16.

[12] Kerr, A. C., Iturralde-Vinent, M.A., Saunders, A.D., Babbs, T.L., Tarney, J. (1999). "A new plate tectonic model of the Caribbean: Implications from a geochemical reconnaissance of Cuban Mesozoic volcanic rocks." Geological Society of America Bulletin 111: 18.

[13] Kerr, A. C., Marriner, G.F., Tarney, J., Nivia, A., Saunders, A.D., Thirlwall, M.F., Sinton, and C.W. (1997). "Cretaceous Basaltic Terranes in Western Colombia: Elemental, Chronological and Sr-Nd Isotopic Constraints on Petrogenesis." Journal of Petrology 38: 25.

[14] Kerr, A. T., J.,Nivia, A., Marriner, G.,Saunders, A. (1996). "The geochemistry and tectonic setting of late Cretaceous Caribbean and Colombian volcanism. Journal of South American Earth Sciences 9(1-2).

[15] Luzieux, L. D. A., Heller, F., Spikings, R., Vallejo, C.F., Winkler, W. (2006). "Origin and Cretaceous tectonic history of the coastal Ecuadorian forearc between 1°N and 3°S:

[16] Paleomagnetic, radiometric and fossil evidence." Earth and Planetary Science Letters 249: 14.

[17] Mann, P., Corrigan, J. (1990). "Model for late Neogene deformation in Panama." Geology 18: 4.

[18] McCourt, W., J, Aspden, J.A, Brook, M. (1984). "New Geological and geochronological data from the Colombian Andes: continental growth by multiple accretion." Journal of the Geological Society 141: 14.

[19] McDougall, I. H., T. (1999) (1999). "Geochronology and Thermocronology by the 40Ar-39Ar method." Oxford University Press. New York.: 269p.

[20] Pindell, J. D., J. (1982). "1982) Permo-Triassic reconstruction of western Pangea and the evolution of the gulf of Mexico/Caribbean region. Tectonics 1: 32.

[21] Pindell, J. K., L. (2009). "Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update." Geological Society of London Special Publication 328: 55.

[22] Pindell, J. L., Cande, S.C., Pitman Iii, W.C., Rowley, D.B., Dewey, J.F., Labrecque, J., Haxby, and W. (1988). A plate-kinematic framework for models of Caribbean evolution. Tectonophysics 155: 17.

[23] Restrepo, J., Toussaint, J. (1988). "Terranes and Continental accretion in the Colombian Andes." Episodes 11(3): 4.

[24] Restrepo-Moreno, S. A., D. A. Foster, et al. (2009). "Long-term erosion and exhumation of the "Altiplano Antioqueno", Northern Andes (Colombia) from apatite (U-Th)/He thermochronology." Earth and Planetary Science Letters 278(1-2): 1-12.

[25] Rodriguez, J. V. (2010). "Fábrica y emplazamiento de la Diorita de Pueblito, NW Cordillera Central de Colombia: análisis de fábrica magnética y mineral. Master Dissertation." Universidad Nacional de Colombia: 61p.

[26] Simpson, C. (1985). "Deformation of granitic rocks across the brittle-ductile transition. Journal of Structural Geology 7(5): 8.

[27] Sinton, C. W., Duncan, R.A., Denyer, P. (1997). "Nicoya Peninsula, Costa Rica: A single suite of Caribbean oceanic plateau magmas." Journal of Geophysical Research 102: 13.

[28] Taboada, A., Rivero, L., Fuenzalida, A., Cisternas, A., Philip, H., and O. J. Bijwaard, Rivera, C. (2000). "Geodynamics of the northern Andes: Subduction and intracontinental deformation (Colombia). Tectonics 19(5): 26.

[29] Trenkamp, R., J. N. Kellogg, et al. (2002). "Wide plate margin deformation, southern Central America and northwestern South America, CASA GPS observations. Journal of South American Earth Sciences 15(2): 157-171.

[30] Turner, G. (1968). "The distribution of potassium and argon in chondrites." Origin and distribution of the elements (ed. L. H. Ahrens). p. 387-398. : 11.

[31] Vallejo, C., Winkler, W., Spikings, R.A., Luzieux, L., Heller, F., Bussy, F. (2009). Mode and timing of terrane accretion in the forearc of the Andes in Ecuador. Geological Society of America Memoir 204: 19.

[32] Vasconcelos, P. O., A, Kawashita, K, Soares, A, Teixeira, W. (2001). "40Ar/39Ar Geochronology at the Instituto de Geociências, USP: Instrumentation, Analytical procedures an Calibration." Anais da Academia Brasileira de Ciências.

[33] Villagomez, D. (2010). "Thermochronology, geochronology and geochemistry of the Western and Central cordilleras and Sierra Nevada de Santa Marta, Colombia: The tectonic evolution of NW South America." Thesis, Faculté des sciences de l'Université de Genève.

[34] Villagómez, D., R. Spikings, et al. (2011). "Geochronology, geochemistry and tectonic evolution of the Western and Central cordilleras of Colombia." Lithos 125(3-4): 875-896.

[35] Vinasco, C. (2001). "A utilização da metodologia 40Ar – 39Ar para o estudo de reativações tectônicas em zonas de cisalhamento. Paradigma: o falhamento de Romeral nos andes centrais da Colômbia.Master dissertation. Universidade de Sao Paulo, Brazil.

[36] Vinasco, C., U. Cordani, et al. (2006). "Geochronological, isotopic, and geochemical data from Permo-Triassic granitic gneisses and granitoids of the Colombian Central Andes." Journal of South American Earth Sciences 21(4): 355-371.

[37] Weber, M., Duarte, E., Gómez-Tapias, J., Cardona, A., Vinasco, C. (2011). "Geochemistry of the Santa Fe Batholith in NW Colombia – remnant of an accreted Cretaceous arc." XIII Congreso Colombiano de Geologia, Medellin.

[38] White, R. V., Tarney, J., Kerr, A.C., Saunders, A.D., Kempton, P.D., Pringle, M.S., Klaver, and G.T. (1999). "Modification of an oceanic plateau, Aruba, Dutch Caribbean: Implications for the generation of continental crust." Lithos 46: 25.