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Sedimentary provenance and low-temperature thermochronology from northwestern
Colombia: a record of the Neogene transition from the Panama collision to Nazca subduction
controlled tectonics

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Abstract

The occurrence of major plate reorganization during the Neogene, reflects the complex interactions between the Caribbean, Farallon and South-American plates, and the Panama Arc. These, have influenced the tectono-stratigraphic record of the northwestern Colombian Andes, which has been scarcely studied near the suture between the Panama and South-American domains. New sandstone petrography, heavy minerals analyses, U-Pb detrital zircon geochronology, whole-rock geochemical data, and thermal inverse modeling of multiple thermochronometers, carried along a 50 km southeast-northwest transect, allow to reconstruct the deformation and exhumation/erosional history of the Late Cretaceous to Pliocene rocks from the western flank of the Western Cordillera. The onset of exhumation of Late Cretaceous sedimentary rocks, associated with the South-American margin, occurred between 45-20 Ma, as suggested by the initial cooling from temperatures within the zircon helium partial retention zone (ZPRZ, ~ 180 - 200°C). These rocks also experienced a substantial pulse of exhumation during the Middle Miocene, which is characterized by moderately rapid rates between ~ 0.3 km/my and 0.7 km/my. Moreover, a Pliocene period of rapid cooling is also documented with maximum exhumation rates of ~ 1.3 km/my. The Middle Eocene rocks from the intra-oceanic Panama Arc, which are separated by a highly-deformed zone from the Late Cretaceous rocks of the Western Cordillera, record an initial cooling at ca. 15 Ma from the apatite partial retention zone (APRZ, ~ 80 - 60°C) at rates around 0.6 km/my. Detrital thermochronology of post-collisional sequences and modern river sediments also record these exhumation events. The results can be related to more regional-scale tectonic processes including: the Late Oligocene rapid and frontal convergence between the newly formed Nazca plate and the continental South-American plate following the fragmentation of the former Farallon plate, the Middle Miocene collision of the Cretaceous-Eocene Panama Arc that triggered generalized exhumation-deformation widespread in the upper NW South-American plate, and the Middle to Late Miocene initiation of the Nazca subduction and installation of a Late Miocene-Pliocene flat-slab to the north. The latter is likely to represent the mechanism that triggered surface uplift in eastern Colombia and ongoing uplift-deformation of western coastal ranges and eastern foreland basins north of 5°N .

Keywords: Panama arc collision, Northern Andes, Inverse thermal modeling, sedimentary provenance, subduction.

Resumo

A ocorrência de uma grande reorganização de placas durante o Neógeno reflete a complexa interação entre as placas do Caribe, Farallon, e América do Sul, e o arco intra-oceânico de Panamá. Isto, tem influenciado o registro tectono-estratigráfico dos Andes nor-ocidentais da Colômbia, o qual tem sido escassamente estudado perto da sutura entre os domínios de Panamá e da América do Sul. Novos dados de petrografia de arenitos, análises de minerais densos, geocronologia detrítica em zircão, geoquímica de rocha total, e modelamento termal inverso de múltiplos termocronômetros, realizados em um transepto de 50 km com direção SE-NW, permitem reconstruir a história de deformação e exumação/erosão das rochas do Cretáceo Superior ao Plioceno do flanco ocidental da Cordilheira Ocidental. O início da exumação das rochas do Cretáceo Superior associadas com a margem continental Sul-americana, ocorreu entre 45 e 20 Ma, o qual é sugerido pelo resfriamento inicial desde temperaturas dentro da zona de retenção parcial do hélio em zircão ($\sim 180\text{-}200^{\circ}\text{C}$). Essas rochas, também sofreram um pulso de exumação considerável durante o Mioceno Médio, o qual caracteriza-se por taxas moderadamente rápidas entre 0.3 km/my e 0.7 km/my. Adicionalmente, um período de resfriamento rápido também é documentado com taxas máximas de exumação ~ 1.3 km/my. As rochas do Eoceno Médio do arco oceânico de Panamá, as quais estão separadas das rochas do Cretáceo Superior da Cordilheira Ocidental por uma faixa de deformação, registram um resfriamento inicial em ~ 15 Ma desde a zona de retenção parcial de hélio em apatita (APRZ, $\sim 80\text{-}60^{\circ}\text{C}$, com taxas perto de 0.6 km/my. Termocronologia detrítica em sequências pós-colisionais e sedimentos modernos, também registram estes períodos de exumação. Os novos resultados podem ser relacionados com processos tectônicos de escala regional, que incluem: Convergência rápida e frontal no Oligoceno Superior, entre a recentemente formada placa de Nazca e a placa continental Sul-americana, depois da fragmentação da antiga placa de Farallon, a colisão do Arco de Panamá do Cretáceo Superior-Eoceno durante o Mioceno Médio, o qual resultou exumação geral ao longo do segmento NW da placa Sul-americana, é o início da subducção da placa de Nazca é a instalação de um segmento plano ao norte durante o Mioceno Superior-Plioceno. Este é provavelmente o mecanismo responsável pelo soerguimento da superfície recente na Colômbia nor-oriental e a contínua deformação-soerguimento das serras costeiras ocidentais e das bacias orientais de foreland ao norte de 5°N .

Palavras chave: Colisão do arco de Panama, Andes do norte, Modelamento termal inverso, Proveniência sedimentar, Subducção

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1. Introduction

The northern Andes have been considered as a particular segment of the entire South-American chain, since its Meso-Cenozoic growth has been influenced by the accretion of oceanic terranes, such as island-arcs, oceanic plateaus, seamounts or offscraped sediments from the subducting plate, interspersed with different phases of oceanic crust subduction (Gansser, 1973; Ramos, 1999).

These changing tectonic settings result from the complex interaction between the Caribbean, Farallon and South-American plates (Bayona et al., 2012; Cardona et al., 2011; Pindell and Kennan, 2009; Spikings et al., 2015) that is also responsible for the middle Miocene collision of the Panama Arc and the subsequent Isthmus closure that constitutes one of the most influencing phenomena on the modern oceanographic and biogeographic global configuration (Coates et al., 2004; Duque-Caro, 1990a, 1990b; Escalona and Mann, 2011; Ibaraki, 1997; Iturralde-Vinent and MacPhee, 1999; Montes et al., 2015; Tsuchi, 1997; Webb, 2006)

The growing of accretionary orogens like the northern Andes is characterized by the incorporation of oceanic crust of different age composition and thickness, generation of magmatic arcs and the formation of distinct types of upper-plate sedimentary basins (i.e. back-arc, forearc, marginal and foreland basins) (Cawood et al., 2009; Kusky et al., 2013; Pubellier and Meresse, 2013). The continuous accretion of these elements and changes in characteristics and factors controlling the geometry of the subduction zone (i.e. slab-dip, obliquity, convergence rates, and structural inheritance) is responsible for the over-imposition of multiple magmatic, sedimentary and deformation events, which requires appropriate temporal constraints and an integrated multi-technical approach in order to be reconstruct the overlapped tectonic facies (Boutelier et al., 2012; Cloos, 1993; Spikings and Simpson, 2014; von Huene and Scholl, 1991).

Although major advances have been made in order to recognize the timing of the establishment of an emerged Central American land-bridge between South and North America, and its implications on ecological and environmental phenomena, the timing and nature of the

geological processes involved are still matter of debate (i.e. collision of the Panama Arc, subduction of the Nazca and Cocos plate) (Farris et al., 2011; Lonsdale, 2005; Mann, 1995; Vannucchi et al., 2006; Wegner et al., 2011; Whattam et al., 2012). Therefore, ages ranging from 23 Ma and ca. 3 Ma, have been proposed for both the early interaction and the ultimate establishment of a land connection between the Americas. (Bacon et al., 2015; Coates et al., 2004; Duque-Caro, 1990a, 1990b; Montes et al., 2015; O' Dea et al., 2016).

In this contribution, we present integrated field observations, sedimentary provenance, U-Pb geochronology, geochemistry of magmatic rocks and low-temperature thermochronology analyses, carried out throughout a ~50 km-long NW-SE transect between the axis and western flank of the Western Cordillera of Colombia. This transect crossed the Uramita Fault Zone, which represent a major expression of the suture between the Panama Arc and South-American margin (Duque-Caro, 1990a; Toussaint and Restrepo, 1994) (**Figure 1**).

The integration of this multidisciplinary approach, together with published geochemical, geochronological, stratigraphic, and thermochronological constraints from western Colombia are used to reconstruct different tectonic scenarios that shaped the continental margin during the Neogene. We specifically attempt to differentiate the Panama and South-American blocks by means of contrasting their provenance and particular geochemical signature and to identify periods of rapid exhumation and deformation potentially conditioned by their structuration, and correlate them with global and local plate kinematic models for the Neogene.

The new results presented here elucidate a more complicated Mio-Pliocene tectonic scenario of transition from collisional to subduction-dominated regimes, which must be considered when the paleogeographic and tectonic models of the interaction between South-America and the Panama Isthmus are discussed.

Figure 1. Regional tectonic map and main geological features considered for discussion. Geological data compiled from (Gómez et al., 2015; Montes et al., 2012a, 2012b; Rodríguez et al., 2013; Valencia-Giraldo et al., 2016).

2. Geological framework

The over-imposition of b-type subduction of oceanic crust and the accretion of exotic terranes, has imprinted a peculiarity to the evolution of the Colombian and Ecuadorian Andes (Gansser, 1973; Ramos, 1999; Restrepo and Toussaint, 1988) with respect to the central and southern segments, where mountain building and continental growth are solely controlled by subduction processes (Kay and Coira, 2009; Ramos, 2010). Since the Eocene, the NW corner of South-America has been affected by major plate re-adjustments, including changes in plate convergence obliquity (Bayona et al., 2012), breaking-up of the former Farallon oceanic plate and formation of the Nazca and Cocos plates (Lonsdale, 2005), the arc-continent collision with the Panama Arc (Duque-Caro, 1990a; Montes et al., 2015), and the apparent onset of a flat-slab subduction in northern Colombia (Chiarabba et al., 2015; Syracuse et al., 2016). Such major changes are recorded in the filling and deformation of the Late Cretaceous-Pliocene sedimentary basins exposed along the northwestern flank of the Western Cordillera of Colombia and the Atrato Valley (**Figure 1**). However, in contrast with the great amount of thermochronological, structural, sedimentological and stratigraphic analysis carried out in the Eastern and also in the Central Cordillera of Colombia (Parra et al., 2012, 2010, 2009b; Reyes-Harker et al., 2015; Spikings et al., 2015; Villagómez et al., 2011; Villagómez and Spikings, 2013), limited rock exposure obscured by a dense vegetation cover, deep soil profiles, and limited access roads, including political conflicts, have complicated the acquisition of similar data in western Colombia. Such situation hinders the proposition of integrative models that allows understanding the upper-plate effects from the forearc to the foreland regions, associated with the different tectonic scenarios experienced by the continental margin during the Neogene.

In this section, we summarize the major regional tectonic events that may have affected the continental margin of northern South-America since the Oligocene and discuss the relation that such events apparently have with the geological record.

We present a summarized tectono-stratigraphic chart that allows comparing the timing and nature of major changes in sedimentary facies within the forearc, intermontane, and foreland

basins of Colombia. We also highlight the periods of ongoing exhumation in the adjacent mountain ranges (**Figure 2**).

Figure 2. Summarized tectono-stratigraphic chart for the main sedimentary basins of Colombia. Shaded zones indicate periods of moderate to rapid exhumation: blue (Central Cordillera), yellow (Panama Arc), Green (Eastern Cordillera). Data is compiled from (ANH-Universidad de Caldas, 2008; Coates et al., 2004; Duque-Caro, 1990a, 1990b; Geotec, 2003; Haffer, 1967; Montes et al., 2012a, 2012b; Mora et al., 2013; Reyes-Harker et al., 2015; Rodríguez et al., 2013; Villagómez and Spikings, 2013).

2.1. Farallon break-up

The fragmentation of the Farallon plate and the consequent formation of the Cocos and Nazca plates took place at ca. 23 Ma (Lonsdale, 2005). Such event was responsible for changes in the convergence angles (increased orthogonality) and rates between the newly formed Nazca

oceanic plate and the South-American margin, which apparently reached the highest Cenozoic values around 15 cm/yr (Pardo-Casas and Molnar, 1987; Somoza, 1998; Somoza and Ghidella, 2012). Some authors have suggested that this event might be a controlling mechanism for moderately-rapid exhumation observed in a thermochronological age-elevation profile carried out in the Cretaceous plutons of the northern Central Cordillera (Restrepo-Moreno et al., 2009). Whereas based on stratigraphic, thermochronometric and structural analyses, a period of rapid exhumation has been identified on the Eastern Cordillera during that time (Horton et al., 2010; Mora et al., 2013; Parra et al., 2009a; Reyes-Harker et al., 2015). Arc magmatism seems to become important during the Late Oligocene-Early Miocene (Schütte et al., 2010) and followed a Late Eocene magmatic hiatus in the Colombian Andes (Bayona et al., 2012)

2.2. Middle to Late Miocene docking of the Panama Arc

The Miocene evolution and continental growth of the NW corner of South-America have been mainly related to the collision of the Panama Arc against the NW Andean continental margin, and the subsequent re-establishment of a subduction zone (Duque-Caro, 1990a). This oceanic terrane is composed of Late Cretaceous-Eocene magmatic rocks geochemically akin with an island arc setting, which were constructed over an Early to Late Cretaceous oceanic plateau probably linked with the *Caribbean Large Igneous Province* (CLIP) (Burke, 1988; Kerr et al., 1996; Sinton et al., 1998). Volcanic and plutonic rocks from the Santa Cecilia-La Equis Complex, and the Mandé and Acandí batholiths in the Western Cordillera, and other correlatable units in Panama, constitute this domain (Buchs et al., 2011, 2010; Kerr et al., 1997; Montes et al., 2012a; Wegner et al., 2011; Wörner et al., 2009) (**Figure 1**). The tectonic limit that marks the suture zone of this block in NW Colombia, referred as the Uramita Fault Zone (Duque-Caro, 1990a) or the Dabeiba-Pueblo Rico Fault (Toussaint and Restrepo, 1994), is defined by a regional fault-system with quaternary activity, whose southern tip is characterized by the occurrence of a high-strain zone (Isthmina deformed belt) (Cediel and Shaw, 2003; Duque-Caro, 1990a; Noriega-Londoño et al., 2013)

As suggested above, no consensus has been achieved in the scientific community on the timing and nature of the geological processes involved in the collision of the Panama Arc with the NW

Andes. In fact, we claim that one of the main issues could be anchored to the confusion related to terms used to refer some specific phenomenon (seaway closure, full establishment of a land-bridge, tectonic collision that drives rock cooling and exhumation). Within this scenario, ages that span from 23 Ma to 3 Ma, which individually are interpreted to document one of those phenomena above-mentioned, are cited together when discussing in a general way the timing of the formation of the Panama isthmus and its collision and connection with northwestern South-America (Bacon et al., 2015; Duque-Caro, 1990a; Montes et al., 2015; O' Dea et al., 2016; Pindell and Kennan, 2009).

The Eocene to Pliocene strata deposited in the Atrato Basin in NW Colombia and the Chucunaque-Tuira Basin from SE Panama, include a series of unconformities, shallowing of sedimentary environments, and switching from marine to nonmarine sedimentation, which initiate in the Middle Miocene (Coates et al., 2004; Duque-Caro, 1990a, 1990b; Haffer, 1967; Montes et al., 2012b; Ramírez et al., 2016), and are probably influenced by the ongoing collisional event at ca. 15 Ma. that also potentially influenced the occurrence of subsequent orogenic uplift and deformation inboard the continent as suggested for the accumulation of thick syn-tectonic conglomeratic sequences, increased sedimentation rates, and regional unconformities identified in foreland and intermontane basins in eastern Colombia (Gómez et al., 2005, 2003; Mora et al., 2013; Pardo-Trujillo et al., 2015; Reyes-Harker et al., 2015; Rodríguez et al., 2016; Suter et al., 2008).

2.3. Mio-Pliocene subduction-dominated tectonics

Widespread upper-plate magmatism since the Middle-Late Miocene (ca. 13 Ma) in northwestern South-America, indicates the establishment of a renewed continental arc following the re-initiation of subduction of the Nazca oceanic plate underneath South-America after the accretion of the Panama Arc (Leal-Mejía, 2011; Rodríguez-García and Bermúdez-Cordero, 2015; Rodríguez and Zapata, 2012; Zapata and Rodríguez, 2011).

Based on the seismicity registered by the Colombian national network, Chiarabba et al. (2015) and Syracuse et al. (2016) have proposed the existence of a flat-slab subduction beneath the

Eastern Cordillera northward of 5°N. The Late Miocene-Pleistocene ongoing deformation in the foreland basins (Veloza et al., 2015), regional uplift of the Eastern Cordillera (Mora et al., 2013; Parra et al., 2009a), together with shallowing of forearc basins (Duque-Caro, 1990a, 1990b; Haffer, 1967), and exhumation of the northern segment of the Western Cordillera (Pardo-Trujillo et al., 2015; Restrepo-Moreno et al., 2015), took place during this time interval and therefore, may suggest a causal link with the flat-slab configuration, that needs to be evaluated.

The new results from the selected transect in western Colombia, will allow testing if these distinct tectonic scenarios are constrained in the hinterland, near the suture of the Panama Arc

3. Methods

3.1. Fieldwork

The study area is comprised between the localities of Cañasgordas and Dabeiba, approximately 170 kilometers west of the city of Medellín (**Figure 3**). The main lithological and structural features of the rock units cropping out along an SE-NW oriented cross-section of ca. 50 km long and 5 km wide were described in ~100 field stations. Ninety-seven samples were collected during this stage, and representative samples from each major geological unit were selected for further analyses. Locations, lithological units and analytical methods applied for all samples are summarized in **Appendix 1**.

3.2. Petrography

Forty thin sections, including magmatic and sedimentary rocks from all mapped units, were analyzed. Characteristic compositional and textural features of each sample were described using an Olympus BX51 polarizing microscope at the Laboratory of Low-Temperature Thermochronology (LABTER) of the Instituto de Energia e Ambiente of the Universidade de São Paulo. Modal mineral proportions of igneous rocks were determined by point-counting of at least one hundred grains on each sample. Petrographic analyses of magmatic rocks were also used to determine the grade of alteration, which was considered when interpreting the whole-rock geochemistry data. Petrographic analyses of seventeen sedimentary rocks from the Penderisco, Cruces and Beibaviejo formations, where done by counting of at least 400 points including framework, matrix and cement, and following methods suggested by Dickinson (1985), Folk (1980), and Garzanti (2016).

3.3. Conglomerate clast-counting

During the field work, four localities of the Late Miocene Guineales Formation were clast-counted using the ribbon method (Howard, 1993). A total of one-hundred clasts with a diameter greater than 2 cm were counted to assess the sedimentary provenance of this unit.

3.4. Heavy Minerals Analyses

Eleven sandstone samples were crushed, sieved and hydraulically concentrated on the Wilfley table. The 63-250 μm fraction was selected to minimize the hydraulic sorting effect and the apparent discrepancies between mineral proportions induced by the presence of large grain-size differences on the mounts (Mange and Maurer, 1992; Morton, 1985). Subsequently, minerals with a density above 2.89 gr/cm^3 were obtained using sodium polytungstate. Mounts were prepared using the Meltmount[®] resin with a refraction index of 1.539. At least 300 translucent grains were optically identified following the ribbon method (Mange and Maurer, 1992). Additionally, apatite and zircon concentrate for U-Pb geochronology, and fission-track and (U-Th)/He thermochronology analysis, were obtained by magnetic separation and using diiodomethane (3.32 gr/cm^3).

3.5. U-Pb Geochronology

LA-ICP-MS U-Pb analyses were obtained from three samples at the Washington State University Geoanalytical lab, using a New Wave Nd: YAG UV 213-nm laser coupled to a ThermoFinnigan Element 2 single collector, double-focusing, inductively coupled plasma-mass spectrometer (ICP-MS), according to procedures described in (Chang et al., 2006). The Plešovice zircon with an age of 337.13 ± 0.37 Ma (Sláma et al., 2008), was used as a standard during the analysis. Laser spot-size and repetition rates were 30 μm and 10 Hz respectively. Each analysis consisted of a short blank analysis followed by 250 sweeps of 30 s through masses 202, 204, 206, 207, 208, 232, 235 and 238. Fractionation was corrected by normalizing U/Pb and Pb/Pb ratios of the unknowns to the zircon standards (Chang et al., 2006). U and Th abundances were monitored by comparison to NIST 610 trace-element glass. U-Pb ages were calculated using Isoplot 4.15 (Ludwig, 2003). We also used the Excel macro available from the Arizona Laserchron Center ([www. geo.arizona.edu/alc](http://www.geo.arizona.edu/alc)), in order to identify the age peaks present in the detrital samples. Individual ages older than 150 Ma that exceeded 20% of discordance were discarded. No filter was applied for ages younger than 150 Ma, given the difficulty of determining robust $^{207}\text{Pb}/^{206}\text{Pb}$ ages (Gehrels, 2012).

3.6. Whole-rock geochemistry

Whole-rock geochemical analyses of five magmatic rocks from the Santa Cecilia-La Equis Complex were conducted at the ALS Minerals laboratories in Lima, Peru.

After crushing, splitting and pulverizing, an aliquot of 0.1 g is added to a $\text{LiBO}_2 / \text{Li}_2\text{B}_4\text{O}_7$ flux, mixed and fused in a furnace at 1000°C . The resulting melt is then cooled and dissolved in 100 mL of 4% HNO_3 / 2% HCl . This solution is then analyzed for major oxides by inductively coupled plasma – atomic emission spectroscopy (ICP-AES) and the results are corrected for spectral inter-element interferences. For trace and rare-earth elements, an aliquot of 0.1 g is added to a $\text{LiBO}_2 / \text{Li}_2\text{B}_4\text{O}_7$ flux (1.8 g), mixed and fused in a furnace at 1025°C . The resulting melt is cooled and dissolved in a mixture containing HNO_3 , HCl , and HF . This solution is then analyzed by ICP-MS. Data handling, plotting, and interpretation were performed using the software GCD Toolkit 4.1. (Janoušek et al., 2006). Additionally, a compiled database of ~270 geochemical analyses from rocks exposed along the Western Cordillera of Colombia and Panama, were used to compare the new data presented here, and look for an appropriate discrimination of the main magmatic units (Buchs et al., 2010; Farris et al., 2011; Kerr et al., 1997; Montes et al., 2012a; Rodríguez et al., 2012; Rodríguez and Arango, 2013; Villagómez et al., 2011).

3.7. Low-temperature thermochronology

Aiming to reconstruct the thermal history of the Late Cretaceous to Miocene rocks exposed on the northwestern segment of the Western Cordillera, we implemented a multi-thermochronometer approach on each representative unit present in the study area (**Figure 3**). Combined apatite fission-track (AFT) with apatite and zircon (U-Th)/He analyses were employed to unravel the T-t evolution of the northwestern Andes between the $\sim 180^\circ$ and 60° isotherms gave the suggested closure temperatures for these systems (Reiners and Brandon, 2006). Hence, the exhumation history through upper-crustal depths could be assessed.

3.7.1. Zircon (U-Th)/He dating (ZHe)

Daughter He and parent U-Th nuclides were measured at the University of Arizona following the procedures of Reiners (2005). Preferably tetragonal, inclusion-free zircon grains with prism widths $>75\mu\text{m}$ were hand-picked and packed into a slightly closed ~ 1 mm Nb foil. Before packing, two dimensions perpendicular to the a_1 and a_2 crystallographic axes of the selected grains were measured, and its morphology described in order to calculate the alpha-ejection correction (Farley, 2002; Farley et al., 1996). Subsequently, foil packets were placed on a Cu planchet in a high-vacuum chamber connected to the He purification-measurement line. Each Nb foil was heated to $\sim 1100^\circ\text{C}$ - 1250°C by focusing a $10\mu\text{m}$ Nd-YAG 1064 nm laser beam, for 15 min extraction intervals. At least two re-extractions were performed for each sample to assess the extent of degassing of the crystal. The $^4\text{He}/^3\text{He}$ ratio is measured following gas release and nominal equilibration time. Measured ratios were corrected for background and interferences on mass 3 (HD^+ and H_3^+) and then compared with $^4\text{He}/^3\text{He}$ measured on pipetted aliquots of a manometrically calibrated ^4He standard. U and Th parent nuclides in degassed zircons were measured by isotope dilution and solution ICP-MS. This method requires spiking with an isotopically distinctive U-Th spike, sample spike equilibration, and dissolution to a final solution appropriate for ICP-MS. Zircon dissolution was attained using HF-HNO_3 mixtures in Parr bombs, which can entirely dissolve the Nb foils. $^{238}\text{U}/^{233}\text{U}$ and $^{232}\text{Th}/^{229}\text{Th}$ ratios were quantified by 2000 measurements of the average intensities in the middle 10% of peak-widths in low-resolution mode on an Element2 high-resolution ICP-MS. Pt contamination and mass fractionation were checked measuring the $^{238}\text{U}/^{235}\text{U}$ ratio. U and Th abundances were calculated from multiple determinations of isotope ratios on a pure spike and spiked normal containing 1-4 ng of isotopically normal U and Th. A 2σ uncertainty is reported for all ages. The potential effect of radiation damage on the ZHe data dispersion was assessed by comparing the effective uranium $e[\text{U}]$ with individual ages, following the model of (Flowers et al., 2007) and (Guenther et al., 2013).

3.7.2. Apatite fission-track (AFT) analyses

AFT analyses were conducted on 6 samples collected along the studied section following the External Detector Method (EDM) (Gleadow, 1981). A detailed description of this method, as well as its theoretical principles, is presented in **Appendix 12**.

Apatite concentrates were mounted in an epoxy resin and polished to expose the internal grains surfaces. Mounts were chemically etched in 5.5 HNO₃ for 20 s at 20°C ± 1°C to reveal spontaneous fission-tracks. After the attaching of the external detector low-U mica, samples were irradiated at the Oregon State University research reactor. Subsequently, induced fission-tracks were revealed by etching with 40% hydrofluoric acid at 21°C for 45 min. Spontaneous and induced fission-tracks density were determined at the Low-Temperature Thermochronology Lab of the University of São Paulo using an Olympus BX51 microscope with a digitalizing tablet and a coupled computer-controlled stage driven by the FTStage 4.05 software (Dumitru, 1993). Ages and errors were calculated using the zeta calibration method (Hurford and Green, 1983) with the Trackkey software (Dunkl, 2002). A zeta calibration factor of 126.5 ± 4.1 (CN1 glass; Santiago León) was used. Chi-square test was used to evaluate whether individual ages belong to a unique population. Datasets with a $P(\chi^2) > 5\%$ are considered to represent a concordant age (Galbraith, 1981). The software DensityPlotter version 7.3 were used as a visualization tool for detrital and non-detrital samples (Vermeesch, 2012, 2009). The Kernel Density Estimator (KDE) was used to evaluate the detrital AFT age distribution, a bandwidth of 5 Ma was chosen in order to avoid over- or under-smoothing (Vermeesch, 2012).

3.7.3. Apatite U-Th/He (AHe) dating

Five samples were selected for AHe. Four to five individual apatite grains for each sample were hand-picked, photographed and packed in 1 mm Pt tubes using an Olympus SZX16 stereo microscope following the procedure suggested by Farley (2002). Grain dimensions and the number of terminations were determined to calculate the retentivity (F_T) correction factor

(Farley et al., 1996). The platinum tubes were loaded into a 25-spot laser chamber of an ASI Alphachron He extraction and analysis system, equipped with a 30W Coherent 978 nm diode laser and a Pfeiffer Prisma 200 Quadrupole mass spectrometer, at the University of Potsdam, Germany. Routinely, blank tubes and age standards were analyzed together with unknown samples. Samples were heated by the laser system at 8 amps (~3.5W) for 5 minutes to release all He from the apatite grains. After exposing for 1 minute to a hot getter, designed to remove chemically active gas species, the released gas after heating was purified. The abundance of ^4He in the purified gas was measured by isotope dilution using a ^3He tracer, calibrated against a manometrically determined ^4He standard. A second analysis or re-extraction was done for each sample in order to ensure that the grain was completely degassed. Analysis of U, Th and Sm were carried at the clean lab at GFZ Potsdam by isotope dilution ICP-MS. Samples were placed in 3ml Savillex PFA screw-cap vials, spiked with an HNO_3 -based ^{235}U - ^{230}Th spike and an HNO_3 -based ^{149}Sm spike, and dissolved with a ~0.5 ml 7N HNO_3 . The spikes were calibrated against NIST-traceable Certified Reference Material ICP concentration standards. Aiming to ensure the total sample dissolution and isotopic homogenization between sample and spikes, the vials were placed on a hotplate at ~100°C for at least 24 hours. The solution was then evaporated to dryness and re-dissolved for another 24 h in 1.5 ml 2% HNO_3 . Then, the solution was analyzed for U, Th, and Sm isotopic composition on a Thermo Element 2 XR ICP-MS at GFZ Potsdam, equipped with a CETAC ASX-520 auto-sampler system, and run in the low-resolution mode to maximize transmission of ions. Mass 234 was also analyzed to detect potential Pt-Ar isobaric interferences on the U mass spectrum. Repeated analyses of $^{149}\text{Sm}/^{147}\text{Sm}$ ratio, and of the NIST SRM material U-500, were used to monitor instrumental mass fractionation. Age calculations followed the procedure of (Meesters and Dunai, 2005). A 2σ uncertainty is reported for all ages.

The potential effect of radiation damage on AHe data was assessed by comparing the effective uranium $e[\text{U}]$ with individual ages, following the model of (Flowers et al., 2007).

3.7.4. Thermal Modeling

Thermal modeling was performed using the HeFTy v. 1.80 software. Input data include AHe, ZHe, fission-track ages, track lengths when available, and Dpar as a kinetic parameter. Between 20000 and 195000 iterations were done using a Monte-Carlo search method, until at least 20 to 50 good models (Goodness of Fitness > 0.5) were obtained (Ketcham, 2005). For fission-track annealing, we used the kinetic model of (Ketcham et al., 2007), for AHe and ZHe we used the models of (Farley, 2000) and (Guenther et al., 2013) respectively.

Additional constraints, as stratigraphic ages and provenance criteria, were included allowing the software to search for a wide range of a coherent T-t spectrum. For discussion an estimation of burial/exhumation rates, we use a geothermal gradient of 15°C/Km, which has been suggested as a mean value for subduction-related settings (Dumitru, 1991; Henry and Pollack, 1988).

4. Results

4.1. Field and petrographic observations

The study area is located on the northwestern flank of the Western Cordillera at ~7°N and can be separated in three genetically distinct N-S trending belts, limited by high-angle thrust-faults (**Figure 3**). These major units are presented from east to west, initially following the published nomenclature.

The eastern belt comprises Early to Late Cretaceous volcano-sedimentary rocks included within the Cañasgordas Group (Álvarez, 1971). The volcanics are characterized by a suite of tholeiitic basalts and diabbases with plateau geochemical affinity associated with the Caribbean Large Igneous Province (CLIP), that may also include Early Cretaceous chemical and fine-grained siliciclastic sedimentary rocks (Mejía et al., 1983; Rodríguez and Arango, 2013), and whose accretion to the continental margin has been considered as Late Cretaceous-Paleocene (Kerr et al., 1997; Villagómez and Spikings, 2013). Unconformably overlying this basement is a relative thick (~3000 m) marine sequence of coarse to fine-grained sandstones and mudstones, chert, siliceous mudstones and limestones, whose fossiliferous material suggest a Late Cretaceous to Paleocene accumulation age (Bourgeois et al., 1987, 1982; Etayo-Serna et al., 1982; Moreno-Sánchez and Pardo-Trujillo, 2003; Pardo-Trujillo et al., 2002; Rodríguez et al., 2013; Valencia-Giraldo et al., 2016). The central belt is defined by three distinct volcano-sedimentary units: 1) Middle to Late Miocene sequence of lithic sandstones, siliceous mudstones, and limestone nodules, with interlayered thin levels of tuffs mapped as the Beibaviejo Fm. 2) basaltic to andesitic porphyritic rocks with a shoshonitic geochemical affinity of the El Botón Basalts, with ages between 12 Ma and 11 Ma (Zapata & Rodríguez, 2011), which intrude the sediments from the Beibaviejo Fm., and 3) a Late Miocene-Pliocene ~2 km thick conglomeratic sequence of the Guineales Fm. overlying the volcanic rocks from the El Botón Basalts.

The westernmost belt includes a thin Eocene-Oligocene sedimentary cover made up of interlayered tuffs, volcanic sandstones, mudstones and limestones regionally known as the Cruces Formation (Buchely et al., 2009; Mejía and Salazar, 1989; Rodríguez et al., 2013). These rocks are nonconformably overlying a volcanic basement predominantly composed by porphyritic basalts and andesites mapped as the Cretaceous-Eocene Santa Cecilia-La Equis Complex (González, 2001). Intermediate arc-related plutonic rocks from the Mandé and Acandí Batholith with ages ranging from 56 Ma to 38 Ma (Leal-Mejía, 2011; Montes et al., 2012b) are found intruding the volcanic rocks of the Santa Cecilia-La Equis Complex toward the SW and NW from the studied area respectively (Álvarez & Parra, 1979; González, 2001; Sillitoe et al., 1982). Both, the volcanic and the plutonic rocks have been correlated with the Panama Arc (Duque-Caro, 1990a; Montes et al., 2012a). A major regional fault (Dabeiba-Pueblo Rico Fault), separates the easternmost and westernmost belts and is apparently covered by the Miocene-Pliocene central belt.

Although detailed sedimentological and stratigraphic analyses are beyond the focus of this work, here we describe the main lithological features of the units exposed in the studied area (**Figure 3**).

Figure 3. Local geological map and summary of the geochronological and thermochronological results.

4.1.1. Eastern Belt

4.1.1.1. San José de Urama Diabase

This unit, defined by Rodríguez & Arango (2013) due to its geochemical signature akin with oceanic-plateau related rocks from the CLIP, crops out as structural sheets (**Figure 4A, 4B**), dipping to the SE-SW, within the Penderisco Formation towards the eastern and central segment of the study area. It comprises a series of gray-greenish deformed effusive volcanic and subvolcanic rocks with a predominant massive and pillow structure of basic composition.

In thin section, rocks are inequigranular with ophitic, sub-ophitic, intersertal and seriate textures. Phenocrysts are principally subhedral clinopyroxene and minor plagioclase with maximum sizes around 3-4 mm (**Figure 5A, 5B**). Matrix, when present, is holocrystalline and hypocrystalline. Glassy portions within the matrix are commonly altered to palagonite. Hydrothermal alteration grade varies within the unit extent and is characterized by the presence of epidote and clay minerals replacing plagioclase, chloritization of pyroxenes and matrix, opaque minerals are abundant.

Plagioclase phenocrysts show tabular euhedral-subhedral habits and their abundance ranges between 40-50%. Composition, based on the extinction angle, varies from An₄₆ (andesine) to An₆₀ (labradorite). Clinopyroxene is augite-pigeonite and its abundance is around 35-45%. Crystals exhibit short tabular subhedral habits in longitudinal sections and polygonal subhedral forms when found in basal sections. Subhedral sphene is the most common accessory phase. Deformational textures of this unit are more clearly defined in the western sector, where basaltic rocks are included within mélangé fabrics related with strongly sheared fine-grained sediments, near the influence area of the Dabeiba-Pueblo Rico Fault, and close to the limit with the central belt that includes the Miocene magmatic and sedimentary rocks (**Figure 3**)

4.1.1.2. Penderisco Formation

Along the axial zone of the Western Cordillera, to the east of transect along the road between Uramita and Dabeiba (**Figure 3**), outcrops a series of sequences that include interlayered fine to coarse-grained sandstones, gray siliceous and carbonaceous mudstones, limestones and minor chert. This unit is comprises tabular beds with sharp-planar bedding ranging in thickness from centimeters to few meters (**Figure 4C, 4D**). However, they are preferentially massive with some discontinuous gradation structures. Hemipelagic sediments, composed by thin tabular interbedded of fossiliferous limestones and siliceous mudstones, as well as minor carbonaceous mudstones, which are exposed along the western limit of this unit, suggesting a possible lateral facies variation marked by a westward basin deepening.

Sandstones are moderate to well-moderately sorted, fine to coarse-grained, with subangular and low-sphericity grains. Thin plane-parallel lamination and cross-bedding structures are frequently observed. In thin section, samples show a dominant clast-supported structure with punctual and longitudinal contacts. Framework particles include dominantly anhedral undulatory quartz, euhedral plagioclase, sedimentary, metamorphic and volcanic lithics, whereas epidote, biotite, and muscovite are present as minor phases (**Figure 5C**). Carbonates, clay minerals, and epidote are present as alteration products, principally after plagioclase. Siliceous and calcareous veins were observed, together with poorly developed cleavage.

Mudstone are laminated, strongly siliceous and usually varies in color from gray to black-gray when fresh, depending on the carbonaceous content. Foliation is normally defined by plane-parallel orientated micas and shows a major increase towards the western limit of this Early to Late Cretaceous block.

Non-siliciclastic rocks are constituted by interlayered chert, siliceous mudstones, and limestones of few centimeter-thick beds. In thin section, they are classified as fossiliferous micrites and sparse biomicrite following the framework of (Folk, 1962). Allochems abundance range from 5% to 30% of the sample, and are mainly represented by ooids, and foraminifera (**Figure 5D**). As mentioned above, pelagic rocks are preferentially exposed toward the western limit of this

unit, where they are included within a ca. 10 km wide *mélange* zone, which includes siliceous mudstone and basaltic blocks, embedded into a fine-grained highly-sheared matrix.

Scarce polarity structures and complex structural arrangements render stratigraphic analyses complicated. However, the interlayering between fine to coarse-grained sandstone with siliceous and carbonaceous mudstones, and its association with fossiliferous limestones and chert suggest a turbiditic to mores distal pelagic-hemipelagic marine depositional environment close to a continental mass, given the presence of material derived from metamorphic and sialic sources. Double-vergent bedding planes dipping between 20° to 80° W-NW and E-SE, together with parasitic folding suggest a regional structural arrangement characterized by east-vergent asymmetric folding. High to moderate-angle (30°-90°) east-dipping and west-dipping normal and inverse fault zones with shear zones with a few meters wide, indicative of a transpressional kinematics, were found as well, pointing out for a more complex deformational history and geometry.

Figure 4. A), B) Typical outcrops of the San J. de Urama Diabase found in the study area, note the fracturing and intense deformation, as well as the surrounding fine-grained sheared matrix. C) Interbedded conglomeratic sandstones, sandstones, and thin-layers of mudstones with sharp-planar geometry from the Penderisco Fm. D) Tabular shape of the limestones and siliceous mudstones strata from the Penderisco Fm.

Figure 5. Microphotographs of rocks from the eastern Cretaceous belt. A) Fine-grained gabbroic rock from the San J. de Urama Diabase. B) Ophitic texture of a gabbroic rock from the San J. de Urama Diabase. C) Quartzose sandstone from the Penderisco Fm. D) Allochems and micritic matrix of non-siliciclastic rocks from the Penderisco Fm.

4.1.2. Central Belt

Although bed-tilting is a common feature of the units included within this belt, these are younger rocks respect to the eastern and western belts and are lacking strong ductile deformation. As will be presented later, the units of this central belt are probably covering the suture zone between the South-American continental margin and the Panama Arc.

4.1.2.1. Beibaviejo Formation

This unit has limited outcrops within the study area. It includes levels of massive grayish medium-grained sandstones and dark limestones, which are intruded by fine-grained subvolcanic rocks (**Figure 6A, 5B**).

In thin section, samples are clast-supported fine to coarse-grained sandstones, moderately sorted, with fragments of low-sphericity mainly composed of quartz and lithic particles of sandstones, chert, mudstones, volcanic rocks and mica-schists (**Figure 7A, 7B**). Plagioclase and strongly altered pyroxene and amphiboles are also present as minor components.

4.1.2.2. El Botón Basalts

Towards the central segment of the studied transect, west of Dabeiba, a north-trending volcanic belt with an average width of 8 kilometers is exposed (**Figure 3**). It includes altered basaltic rocks with a porphyritic texture as the dominant lithology. Matrix is typically reddish with feldspar and pyroxene phenocrysts. In some outcrops, grayish volcanic xenoliths with porphyritic texture were found. Additionally, middle to late Miocene basic to intermediate plutonic rocks exposed in the vicinities of the study area, alike with that found intruding the sediments from the Beibaviejo Fm., have been correlated with this volcanic unit (Rodríguez and Zapata, 2012).

In thin section, volcanic rocks present seriate and vesicular textures, defined by an altered hypocrystalline matrix with euhedral plagioclase and subhedral clinopyroxene phenocrysts (**Figure 7C, 7D**). Plagioclase composition ranges between An₄₂-An₆₀ (andesine to labradorite) and shows typical oscillatory zoning. Clinopyroxene is probably augite-pigeonite and varies in abundance between 30-70%. When present, vesicles are filled by zeolites and represent less than 5% of the sample. The xenoliths found within this unit are intermediate volcanic rocks with trachytic texture and augite and plagioclase phenocrysts.

Deformation structures are rarely observed and include minor fractures and faults of predominantly brittle character.

4.1.2.3. Guineales Formation

A thick sequence of polymictic conglomerates crops out along the road from Dabeiba to Mutatá, between the Guineales and the Choromandó rivers (**Figure 3**). It is composed of matrix-supported bladed fragments. The matrix consists of medium to coarse sand with a sublitharenite composition. Bladed and rounded fragments are mainly composed of mudstones, sandstones, porphyritic and massive volcanic rocks, similar to the lithology described before within the Santa Cecilia-La Equis, Cruces and Penderisco Formations (**Figure 6C**). Minor plutonic fragments, diorite-tonalite in composition, and reddish porphyritic rocks similar to those described in the El Botón Basalts are also included.

The absence of well-defined bedding planes renders thickness estimation difficult. However, based on its extension along the study cross-section and the apparent bedding planes dipping around 70° to the E, is possible to infer a thickness of few kilometers for this sequence.

Rarely, fine-grained sandstones lenses of up to 30 cm thick were found embedded in the conglomeratic sequence. Sandstones are typically gray, with subrounded fragments and a composition similar to the conglomerate matrix. Leaves prints and stems were discovered in these fine-grained blocks, suggesting continental environments (**Figure 6D**).

The particle size and composition, and the preservation of organic matter suggest a high-energy fluvial depositional system. The different lithological units already described above sourced this conglomeratic sequence. Deformational features found in this unit are mainly represented by brittle fracturing and tilting, as suggested by bedding planes dipping ~60° to the SE-NE.

Figure 6. Outcrop photographs of the Miocene sedimentary units from the central belt. A) Lithic sandstone from the Beibaviejo Fm. intruded by a fine-grained gabbroic unit. B). Brittle fracturing of rocks from the Beibaviejo Fm. and gabbroic intrusive. C) Bladed matrix-supported conglomerates from the Guineales Fm. D) Leave prints and stems found within interlayered sandstones from the Guineales Fm.

Figure 7. Microphotographs of the volcanic and sedimentary rocks from the Miocene central belt. A) Lithic conglomeratic sandstone from the Beibaviejo Fm., note the presence of volcanic rocks fragments. B) Lithic conglomerate from the Beibaviejo Fm., note the quartzose sandstone fragment. C) Seriate texture of the volcanic rocks from the El Botón Basalts, note the plagioclase zoning. D). Seriate texture of the volcanic rocks from the El Botón Basalts, note the plagioclase twinning and the presence of alteration carbonates.

4.1.3. Western belt

This belt comprises volcanic and sedimentary from the Santa Cecilia-La Equis Complex and the Cruces Fm., respectively, which are part of the Panama Arc.

4.1.3.1. Santa Cecilia-La Equis and Cruces Formations

It includes volcanic, volcano-clastic and calcareous rocks that are well exposed along the Dabeiba-Mutatá road and the Chichiridó River (**Figure 3**). Stratification is not well-defined and the different rocks forming this unit are structurally mixed, including tuffs and agglomerates with massive volcanic sandstones, mudstones, and limestones (**Figure 8A, 8B**). Distinct

calcareous reddish limestones is an important feature of this unit. Although the stratigraphic relations between the volcanics and the sediments were not observed, previous works have reported a nonconformable contact farther to the west (Rodríguez et al., 2013).

The sedimentary rocks from the Cruces Formation include irregularly interlayered tuffs, volcanic sandstones, gray-greenish mudstones, and reddish limestones. Sandstones are poorly sorted, with subangular and low-sphericity fragments. In thin section, sandstones are matrix or clast-supported with fragments of euhedral feldspar, clinopyroxene, epidote, and chlorite; lithics fragments of massive and porphyritic volcanic rocks and chert are also found as important components. Quartz, amphibole, biotite and intermediate plutonic lithics exhibit a more variable proportions (**Figure 9A**). Carbonates and siliceous veins are included as alteration products. Strongly chloritized pyroxenes and matrix, plagioclase epidotization, and the abundance of opaque minerals are interpreted as evidence of the high degree of hydrothermal alteration.

Volcanic rocks are represented by gray-greenish massive, porphyritic basalts and andesites, and pillow-lavas (**Figure 8C, 8D**), with pyroxene and plagioclase phenocrysts. Strongly altered agglomerates with massive basaltic fragments and mafic crystals and crystal tuffs composed of plagioclase and chlorite are found as well. Subhedral plagioclase phenocrysts, andesitic in composition (An_{42}), are surrounded by a hypocrySTALLINE matrix in which the glassy portions are altered to chlorite (**Figure 9A, 9B, 9C**).

All rocks that are forming this western Cretaceous-Eocene block show both brittle and ductile deformation fabrics, they include inverse faults, fractures, and foliation planes. Such structures affect more intensely the eastern sector, where chaotic or *mélange* structures are found near the contact with the central Miocene belt.

Figure 8. Outcrop photographs of the sedimentary and volcanic rocks from the Cruces Fm. and the Santa Cecilia-La Equis Complex. A) Structurally mixed red limestone and siliceous mudstone from the Cruces Fm. B) Deformed mixture of agglomerates and volcanic sandstones from the Cruces Fm. C) Altered pillow-lava from the Santa Cecilia-La Equis Complex. D) Pillow-lava structures of rocks from the Santa Cecilia-La Equis in the Chichiridó River.

Figure 9. Microphotographs of sedimentary, volcano-clastic and volcanic rocks from the Cruces Fm. and the Santa Cecilia-La Equis Complex. A) Arkose from the Cruces Fm. B) Crystal tuff from the Cruces Fm. C) Trachytic texture of the volcanic rocks from the Santa Cecilia-La Equis. D). Altered glassy portions of the volcanic rocks from the Santa Cecilia-La Equis

4.2. Sedimentary provenance

The results of the integrated sandstone petrography and conglomerate clast-counting provenance analysis is summarized in (Figure 10).

Figure 10. Summarized results from the sandstone petrography and conglomerate clast-counting provenance analysis. A) Classification and tectonic discrimination diagrams (Dickinson, 1985; Folk, 1980; Garzanti, 2016)

4.2.1. Sandstone petrography

Results of the sandstone petrography analysis is presented in **Appendix 2**. As described above, sandstones from the Late Cretaceous to Paleocene Penderisco Fm, are compositionally and texturally mature. On the QFL classification diagram of Folk (1980), they mainly plot within the lithic arkose and feldspathic litharenite. In the QFL diagram of Garzanti (2016), due to its quartz-rich composition and variable ratio between lithic components and plagioclase, samples are principally classified as litho-feldspatho-quartzose and feldspatho-lithic-quartzose sandstones, whereas on the Dickinson (1985) and Garzanti (2016) tectonic discrimination diagrams, they mainly plot within the recycled orogen and mixed provenance fields, suggesting the existence of multiple sources and regionally uplifted regions (**Figure 10A**).

The seven samples from the Eocene-Oligocene Cruces Fm. (Buchely et al., 2009; Mejía and Salazar, 1989), are texturally and compositionally immature. They plot within the arkose field on the Folk (1980) diagram. They are classified as quartz-feldspathic, litho-quartz-feldspathic, quartzo-litho-feldspathic and litho-feldspathic sandstones on the Garzanti (2016) scheme, according to with their high abundance of plagioclase and volcanic lithic fragments, as well as by the variable quartz content. On the Dickinson (1985) and Garzanti (2016) tectonic discrimination diagrams, samples plot within the basement uplift and continental block fields respectively (**Figure 10A**), suggesting an erosional trend of a magmatic arc with a considerable amount of uplift.

Two sandstones from the Beibaviejo Fm. was also point-counted. Its lithic-rich composition makes it plot in the lithic arkose and feldspathic litharenite on the QFL diagram of Folk (1980). On the tectonic discrimination diagram after Dickinson (1985), the sandstones plot within the dissected arc and quartzose recycled fields, whereas in the Garzanti (2016) classification and tectonic discrimination diagrams, they plot within the quartzo-litho-feldspathic and feldspatho-lithic-quartzose sandstone fields, and the recycled orogen field, respectively (**Figure 10A**), suggesting that the lithic-rich composition of this unit is related with extensive reworking of older sedimentary units, formerly sourced by continental terranes, and limited time of residence within sedimentary systems, which allowed the preservation of unstable components.

The above petrographic analysis demonstrates major differences between units exposed within the study area, including a quartz-rich composition for the Penderisco Fm. that changes to a more feldspar-rich composition for the Cruces Fm., and the lithic dominance of the Beibaviejo Fm.

4.2.2. Conglomerate clast-counting

Clast-counting were performed in four localities from the Guineales Fm. Results are presented in **Appendix 3**. Conglomerates from this unit are cobble-sized, polymictic and matrix-supported. They are composed of rounded bladed fragments of sedimentary, volcanic and few plutonic rocks. The more abundant clasts are chert (19-30%), siliceous mudstones (11-51%) and quartz-rich sandstones (10-52%) which are similar to those described within the Penderisco Fm. Massive basalts, diabase and porphyritic rocks with plagioclase and plagioclase-pyroxene phenocrysts are the main volcanic components (1-14%) (**Figure 10B**). These fragments, exhibit textural and compositional features similar to those described for the Santa Cecilia-La Equis Complex, as well as the San José de Urama Diabase. Grayish and greenish mudstones, as well as red limestones, similar to those reported within the Cruces Formation, were also found. Intermediate plutonic rocks fragments are probably sourced by intrusive rocks correlated with El Botón Basalts.

Based on U-Pb detrital geochronology and geochemical analyses performed on the clasts from this conglomeratic unit, the recent work of Rodríguez et al. (2016), has demonstrated that older volcanic units from the San J. de Urama Diabase, the Santa Cecilia-La Equis, and the El Botón Basalts, sourced the Guineales Fm.

4.2.3. Heavy Minerals

Heavy mineral analyses were conducted on ten samples from the Penderisco, Cruces, Beibaviejo and Guineales formations (**Figure 11**); the summarized results are presented in **Appendix 4**. Samples from the Penderisco Fm. (samples BTU-004, BTU-010, UDB-011, UDB-024, UDB-032 and UDB-063) are characterized by a suite of ultrastable (zircon, tourmaline, and rutile),

unstable and stable minerals (clinopyroxene, epidote, garnet, biotite, zoisite, apatite, muscovite, clinozoisite), which are akin to a mixed recycled sedimentary, metamorphic (probably metapelitic), and basic igneous rocks probably hydrothermally altered, as suggested by the presence of epidote-group minerals. In contrast, the analyzed sample DMT-020 from the Cruces Fm. is mainly composed of stable and unstable minerals (clinopyroxene, epidote, zoisite and muscovite), with a significantly high clinopyroxene content, indicating basic to intermediate sources.

Samples from the Beibaviejo Fm. (UDB-017 and UDB-022) are characterized by a high content of ultrastable and stable minerals, like zircon, rutile, and tourmaline, kyanite, garnet, muscovite, and epidote-group minerals, suggesting the increase in sedimentary recycling. Finally, sample DMT-010 from the Guineales Fm. resembles the pyroxene-rich composition described for the sample from the Cruces Fm.

Figure 11. Summarized results of the heavy minerals analysis.

4.2.4. U-Pb Geochronology

Three sandstone samples from the Penderisco Fm., the Beibaviejo Fm., and the Guineales Fm. were analyzed. Detailed analytical results including isotopic ratios, and ages are presented in **Appendix 5**. Additionally, cathodoluminescence images from samples analyzed during this work are also presented in **Appendix 6**. Probability density and Tera-Wasserburg Concordia plots are presented in (**Figure 12**).

One hundred grains were analyzed from the Late Cretaceous-Paleocene Penderisco Fm. (sample GR-30). Th/U ratios range in a wide spectrum of values between 0.1 and 1.7, as expected for a suite of zircons probably derived from a mixture of igneous and metamorphic sources (Hoskin and Schaltegger, 2003). Analyzed zircons yielded major age-peaks of Late Cretaceous (80-96 Ma), Permo-Triassic (220-290 Ma), and less representative, Early Paleozoic and Proterozoic (400-1800 Ma). The youngest detrital population has a peak at 81 Ma and is defined by twelve grains. Age peak analysis results are presented in (**Table 1**). The youngest zircon analyzed from this sample yielded an age of 42.6 ± 6.1 Ma, however, it could be related to Pb loss or analytical uncertainty. Older detrital age of 2480.0 ± 12.4 Ma, is likely to represent reworked material originally derived from cratonic sources (Chew et al., 2011).

Table 1. Age peak analysis of the sample GR-30 from the Penderisco Fm.

MIN AGE	MAX AGE	# GRAINS	PEAK AGE	# GRAINS
68	122	28	81	12
197	293	20	96	11
394	403	0	240	13
419	594	17	477	9
635	735	3	540	5
746	877	6	679	3
1203	1255	3	807	6
1538	1550	1	1226	3
1552	1556	0	1768	3
1751	1790	2		

One hundred and twenty-four grains were analyzed from the sample UDB-022 from the middle to late Miocene Beibaviejo Fm. Zircon grain-sizes ranges between 40 and 400 μm and can be separated into two different groups. The first group is characterized by a prismatic morphology with Length:Width (L:W) ratios around 3:1 and oscillatory patterns as typical of igneous rocks. A second group is characterized by prismatic and sub-rounded shapes with stubby and homogeneous overgrowths typical of metamorphic rocks (Vavra et al., 1999). Th/U ratios range in a wide spectrum of values between 0.38 and 5.51, as expected for a suite of zircons probably derived from a mixture of igneous and metamorphic sources (Hoskin and Schaltegger, 2003). The sample has Eocene-Oligocene (42-23 Ma), and Late Cretaceous (73-91 Ma) dominant age peaks, and less representative, Neoproterozoic and Mesoproterozoic zircons. The youngest detrital zircon age for this sample is represented by an age peak at 23 Ma estimated from seven grains, which suggest a maximum Late Oligocene accumulation age. Age peak analysis results are presented in (**Table 2**).

Table 2. Age peak analysis of the sample UDB-022 from the Beibaviejo Fm.

MIN AGE	MAX AGE	# GRAINS	PEAK AGE	# GRAINS
20	28	10	23	7
33	45	27	38	11
69	94	42	42	14
565	583	3	73	6
679	686	0	78	14
968	1024	4	84	13
1198	1203	0	89	9
1234	1244	0	91	8
1349	1366	1	573	3
			993	4
			1362	3

Eighty-four grains from the late Miocene to Pliocene Guineales Fm. (sample DMT-010) were analyzed. Zircon crystals are characterized by sizes between 50 and 320 μm , some crystals are prismatic with L:W ratio between 3:1 and 2:1. The cathodoluminescence images show the presence of oscillatory patterns characteristic of igneous sources. Conversely, another set of analyzed grains shows a sub-rounded shape with oscillatory patterns, although some crystals show homogeneous overgrowths, which suggest the metamorphic character of the source rocks. Th/U values range between 0.19 and 4.54, as expected for mixed igneous and metamorphic source terranes (Hoskin and Schaltegger, 2003). Analyzed zircons exhibit age peaks of Middle Eocene (46-40 Ma), Late Cretaceous (70-90 Ma), Triassic (230 Ma) and Mesoproterozoic (~1000 Ma), also indicating the existence of mixed sources. The youngest age peak of 40 Ma is estimated from four grains, which suggest a maximum Middle Eocene accumulation age. Age peak analysis results are presented in (**Table 3**).

Table 3. Age peak analysis of the sample DMT-010 from the Guineales Fm.

MIN AGE	MAX AGE	# GRAINS	PEAK AGE	# GRAINS
38	47	7	40	4
68	93	40	46	3
228	235	3	70	9
1056	1093	3	78	9
1096	1116	1	84	4
			90	12
			230	3
			1064	3
			1071	3
			1074	5
			1076	5
			1103	3

One volcanic rock recovered from the Cruces Fm. (sample DMT-003), was selected for U-Pb zircon geochronology. Zircons are characterized by sizes between 70 and 270 μm , most of the crystals are prismatic with L:W ratio between 3:1 and 2:1. The cathodoluminescence images show oscillatory well-developed growth, characteristic of igneous rocks. Single crystal present magmatic a resorbed without overgrowths pattern, that is a typical feature of pyroclastic volcanic rocks (Corfu et al., 2003). The igneous character of analyzed zircons is also demonstrated by a Th/U ratio ranging from 0.39 to 2.28. 25 grains yielded a weighted average age of 41.98 ± 0.37 Ma (**Figure 13**).

Figure 12. Probability density plots and Tera-Wasserbur Concordia diagrams for detrital U-Pb analyses.

Figure 13. Weighted average age calculation and Tera-Wasserburg Concordia diagram for sample DMT-003 from Cruces Fm.

4.3. Geochemistry

Results from whole-rock geochemical analyses of five volcanic samples from the Late Cretaceous-Eocene Santa Cecilia – La Equis Complex, located with limited exposures at the westernmost segment of the study area, are presented in **Appendix 7**. These samples are compared with the compiled geochemical database, to appropriately characterize the tectono-magmatic origin of this volcanic unit. Rare-earth elements (REE) allows discriminating three main groups which are defined for comparison and correlation, before describing the new results. The Azuero Arc and protoarc, Golfito Complex and San Blas Range from Panama and Costa Rica, the Santa Cecilia-La Equis Complex (including the newly analyzed samples), the Mandé Batholith (with ages between 56 and 38 Ma), share common characteristics and might be included as part of the Panama Arc (Buchs et al., 2010; Calle and Salinas, 1984; Farris et al., 2011; Montes et al., 2012a; Rodríguez and Zapata, 2012; Villagómez et al., 2011). A second category includes rocks from the Azuero Marginal Complex, San Blas Range (Group I), Baudó Basalts (with ages ranging from ~72 to ~78 Ma), which are exposed in Panama and the Pacific coast of Colombia, are considered to represent the main basement of the Panam Arc, and can be related with an oceanic-plateau. San José de Urama Diabase, Amaime Fm., Western Cordillera Unit, and Buriticá Stock are included within the Plateau Rocks group (Buchs et al., 2010; Kerr et al., 1997; Montes et al., 2012a).

The San J. de Urama Diabase, the Amaime Fm. and the Buriticá Stock, Early Cretaceous (Albian-Aptian) in age, are also associated with oceanic-plateau related rocks (González, 2001; Rodríguez and Arango, 2013; Villagómez et al., 2011; Weber et al., 2015), which were already accreted to the western margin of South-America in the Late Cretaceous (Villagómez and Spikings, 2013). This oceanic plateau unit is overlaid and intruded by intra-oceanic arc-related rocks from the Barroso Fm., the Buga Batholith and Santa Fé Batholith (Rodríguez and Zapata, 2013; Villagómez et al., 2011; Weber et al., 2015) from the Volcanic and Barroso Formations, and the Buga and Santa Fé Batholiths are grouped as the Barroso Arc (Rodríguez and Zapata, 2013; Villagómez et al., 2011; Weber et al., 2015), which are also Late Cretaceous in age (~100 to 80 Ma) (Villagómez et al., 2011; Weber et al., 2015; Zapata et al., 2017)

The SiO₂ values from the five new analyzed samples range from 49.4% to 67%, Al₂O₃ between 14.45% and 18.55%, and MgO varies between 1.82% and 3.84%. The K₂O, Na₂O, and loss on ignition (LOI) values, oscillate between 0.32% - 3.06%, 3.07% - 5.06%, and 2.57%-8.61% respectively. The relatively high alkalis and LOI values, and the absence of a linear correlation with silica suggest that the samples have experienced elemental mobility. For this reason, immobile elements are preferentially used when interpreting and discussing the results (Pearce, 2008, 1996, 1982; Ross and Bédard, 2009). They are classified as andesites and basaltic-andesites based on the Nb/Yb and Zr/Ti ratios (Pearce, 1996) (**Figure 14A**). Similarly, on the Y vs. Zr magmatic classification diagram (Ross and Bédard, 2009) they plot close to the limit between the transitional and calc-alkaline fields (**Figure 14B**), nearly following the distribution of the volcanic rocks from the Panama Arc and the Santa Cecilia – La Equis Complex (Buchs et al., 2010; Calle and Salinas, 1984).

Figure 14. A) Classification diagram of Pearce (1996). B) Magmatic classification diagram of Ross & Bédard (2009).

REE abundance normalized to the chondrite composition after Nakamura (1974), show a strongly enriched pattern in the LREE (Light Rare-Earth Elements), as evidenced by the $(La/Yb)_N$ and $(La/Sm)_N$ ratios, which range from 4.17 to 5.95, and from 2.11 to 3.01, respectively (**Figure 15A**). Whereas the HREE (Heavy Rare-Earth Elements), show a slightly enriched to a flat pattern, as indicated by $(Gd/Yb)_N$ values ranging between 1.53 and 1.73. Plagioclase fractionation is also suggested by the negative Eu anomalies, with Eu/Eu^* values between 0.71 and 0.98.

When normalized to MORB composition (Pearce, 1983), the multi-elemental patterns are characterized by moderate LILE (Large Ione Lithophile Elements) enrichment, including Sr, K, Rb, Ba and Th, and depletion of the HFSE (High Field Strength Elements) (**Figure 15B**). The strong Nb and Ti negative anomalies, and the LREE and LILE enrichment are characteristic of magmas originated in a modified mantle by the incorporation of slab-derived fluids in subduction systems.

Figure 15. A) REE diagram normalized to chondrite composition after Nakamura (1974). B) Multielemental diagram normalized to MORB composition after Pearce (1983).

As observed in the normalized trace and rare-earth elements concentrations the analyzed samples are similar to the Panamá Arc compositional signature. Their island arc affinity is also corroborated in the Zr vs. Ti (**Figure 16A**) and Nb/Yb vs. Th/Yb (**Figure 16B**) diagrams, where samples plot within the island arc lavas field, and overlap with the Panamá Arc and Santa Cecilia – La Equis Complex.

Figure 16. Tectonic discrimination diagrams of A) Pearce (1982) and B) Pearce (2008).

4.4. Low-Temperature Thermochronology

4.4.1. Zircon (U-Th)/He (ZHe)

Analytical results of the ZHe analyses are presented in **Appendix 8**. Sixteen individual ages were obtained from zircons recovered from samples from the Penderisco Fm. (samples UDB-032 and UDB-063), the Cruces Fm. (sample DMT-003), and from the Buriticá Tonalite (sample BTU-015). The Buriticá Tonalite, with U-Pb crystallization ages of ca. 100 Ma (Weber et al., 2015) yielded three reproducible ages with a weighted average of 52.7 ± 1.1 Ma. Five grains analyzed from the sample UDB-032 yielded ages ranging from 114 Ma to 29 Ma. Those ages that span from 67 Ma to 29 Ma exhibit an apparent negative correlation between $e[U]$ and ZHe age, and will be considered for thermal modeling, as this dispersion may be varying degrees of radiation damage, according to recent kinetic models of He diffusion in zircon (Guenther et al., 2013). Similarly, five individual grains of the sample UDB-063 from the Penderisco Fm. also yielded ages between 123 Ma and 30 Ma. For this sample, the grains with ZHe ages ranging 68 Ma and 30 Ma, exhibit an apparent positive correlation between effective uranium value ($e[U] = U + 0.235Th$, Flowers et al., 2007) (~ 605 - 67 ppm) and age, except by one zircon with a 50.0 ± 3.4 Ma age, which has a greater $e[U]$ of ~ 2200 ppm. Grains with a ZHe dates older than the stratigraphic age (~ 75 - 65 Ma) (Moreno-Sánchez and Pardo-Trujillo, 2003; Pardo-Trujillo et

al., 2002), were not considered for the thermal modeling, and are here interpreted to potentially represent detrital non-reset ages, or may be related with crystal micro-inclusions that tend to produce older ages (Fitzgerald, 2006).

Finally, the tuff sample DMT-003 from the Cruces Fm. yielded three concordant ages with a weighted average of 44.7 ± 0.8 Ma. Given that twenty-five zircons recovered from the same sample yielded a weighted average U-Pb age of 41.98 ± 0.37 Ma, we infer that the older ZHe age is likely the result of an over-correction of the raw age by the geometric factor (Farley, 2002; Farley et al., 1996). For this reason, ZHe data for the Cruces Fm. was not included in the thermal modeling, but we are confident that overlapping of the U-Pb, ZHe and AFT ages around 42 Ma, reflect the rapid cooling associated with volcanic extrusion, and that the AHe age of ~ 15 Ma, reflect resetting of the AHe system and renewed Neogene uplift.

4.4.2. Apatite Fission-Track (AFT)

A summary with the results of the AFT analysis is presented in **Appendix 9**. Fission-tracks analyses were conducted on six samples from sedimentary and volcanic rocks, and modern sediments. Two sandstones from the Penderisco Fm. yielded concordant pooled ages of 14.2 ± 2.2 Ma (sample UDB-063, $P(\chi^2)=81.2\%$) (**Figure 17A**) and 13.1 ± 1.6 Ma (sample UDB-032, $P(\chi^2)=39.3\%$) (**Figure 17B**). One sample from the Cruces Fm. (sample DMT-003) yielded a concordant age of 40.2 ± 4.6 Ma with $P(\chi^2) = 100$ (**Figure 17C**). We were also able to measure only a limited amount of horizontal confined tracks (up to 10) for the sample DMT-003 from the Cruces Fm., which yielded a mean track length of 15.0 ± 0.9 μm , indicative of rapid cooling through the partial annealing zone (PAZ).

Figure 17. Radial plots for samples that yielded reset AFT ages.

Detrital samples from the Guineales Fm. and the modern Sucio River, show similar distribution pattern with most of the individual ages clustered in 3 groups ranging from 12 to 20 Ma, 36 to 44 Ma, and 56 to 70 Ma, respectively (**Figure 18**). Although the sample DMT-008 passed the chi-square test ($P(\chi^2)=58\%$), it is interpreted as a detrital age given its lithological similarities and proximity with sample DMT-010

Figure 18. Radial plots and Kernel Density Estimator (KDE) for detrital AFT samples.

4.4.3. Apatite (U-Th)/He (AHe)

Analytical results of the AHe analysis is presented in **Appendix 10**. Twenty apatite grains from the Buriticá Tonalite, Penderisco Fm., Cruces Fm., and Guineales Fm. were analyzed. Five aliquots from the sample BTU-015 from the Buriticá Stock (U-Pb age 100.9 ± 0.9 Ma; Weber

et al., 2015) yielded reproducible ages between 3.9-7.5 Ma, which exhibit a clear positive correlation with the grain size. However one of the individual ages was discarded because of its high analytical error (>400%), therefore a weighted-mean age of 6.7 ± 1.1 Ma was obtained. Five grains analyzed from the sample UDB-063 from the Penderisco Fm. yielded ages that span from 5.6 to 9.7 Ma, which show a fair positive correlation between the effective uranium $e[U]$ ($U + 0.235Th$, Flowers et al. 2007), indicating the potential effect of radiation damage. For this sample, a weighted-mean age of 8.9 ± 0.7 Ma was calculated. No weighted mean age is reported for the sample UDB-032 from the Penderisco Fm., since only one out of four aliquots yielded a reasonable age of 3.3 ± 0.9 Ma, being the other three non-apatites with abnormal negative ages

Three apatites from the Cruces Fm. (sample DMT-003, with U-Pb age of 41.98 ± 0.37 Ma), yielded reproducible individual ages ranging from 13.1 to 37.6 Ma. Individual grains with AHe dates younger than 35 Ma were considered for the inverse modeling, since we assume that they are partially-reset ages that would potentially indicate the maximum temperature attained and the timing for the onset of cooling, as supported by the large MTL of 15.0 ± 0.9 μm that suggest rapid cooling through the apatite partial annealing zone (PAZ), and no further reheating above the minimum temperatures for the partial annealing zone $\sim 80^\circ C$ (Reiners and Brandon, 2006).

Sample DMT-010 from the Guineales Fm. yielded individual helium ages of 4.9 ± 1.2 Ma, 6.5 ± 2.0 Ma, and 13.9 ± 2.0 Ma. The comparison between $e[U]$ and grain size failed to explain the dispersion among individual ages from this sample, and therefore may be detrital cooling ages derived from already exhumed sources. The fact that, these individual ages closely resemble the AHe cooling ages obtained for the samples UDB-063 from the Penderisco Fm., and DMT-003 from the Cruces Fm., buttress the hypothesis of a detrital non-reset origin.

4.4.4. Thermal Modeling

Inverse thermal modeling of fission-track and (U-Th)/He ages were conducted in four samples from the Buriticá Tonalite, Penderisco, and Cruces Fms. Results are summarized in **(Figure 19)**

For the ca. 100 Ma Buriticá Tonalite (Weber et al., 2015), ZHe and AHe data show a 52.7 ± 1.1 Ma and 6.7 ± 1.1 Ma, respectively, which likely reveal moderate cooling rates during the Paleogene-Neogene. In order to explore viable thermal histories, we consider the hypothesis of the Buriticá Tonalite being a source rock of the Penderisco Fm., as suggested by the ca. 100 Ma detrital U-Pb ages found in the sample GR-30 from this unit, and thus, it must have been close to the surface during sediment accumulation. In this first scenario, we added a constraint to the thermal model that forces the T-t trajectory to reach near-surface temperatures at the depositional age corresponding to ~75-65 Ma (Moreno-Sánchez and Pardo-Trujillo, 2003; Pardo-Trujillo et al., 2002). Under this assumption, the T-t path that best fit the data, suggest that this unit were buried to depths greater than the equivalent zircon partial retention zone (ZPRZ, 180-200°C) anytime ~65 Ma until the onset of cooling at ca. 37 Ma. A cooling rate since the onset of exhumation ~2°C/my was continuous until ~15 Ma when a major pulse of accelerated exhumation is suggested by an increase in the cooling rate to ~6.5°C/my which remains to the present. An alternative scenario, in which the sample BTU-015 from the Buriticá Tonalite was not a source rock for the Penderisco Fm. sediments were also modeled. All good paths, show an almost gradual cooling through temperatures from 300°C to 240°C at a rate of ~3°C/my. Subsequently, the sample cooled at an increased rate of ~5.7°C/my, until ca. 48 Ma, when the cooling rate decreased again to ~1.2°C/my. Finally, a renewed phase of rapid exhumation started at ca. 12 Ma, when cooling rates reached the highest value at ~8°C/my.

After running more than 3000 paths attempting to reconstruct the thermal history of the samples UDB-032 and UDB-063 from the Penderisco Fm., including all ZHe dates younger than the depositional age, and using the radiation damage kinetic model of Guenthner et al. (2013), no acceptable or good models were obtained. We interpret the dispersion among individual ages as an evidence which suggest that both samples reached maximum temperatures close or within the helium Partial Retention Zone (PRZ), at around 180-200°C (Reiners, 2005; Reiners and Brandon, 2006), and given the distinct e[U] values, helium diffusivity behaved differently for each grain (Flowers et al., 2007; Guenthner et al., 2013). We also noted, that in the sample UDB-032, the zircon that yielded the youngest ZHe age, has the highest value of e[U] (~870 ppm). Conversely, in the sample UDB-063, the grain with the youngest age, has the lowest value of e[U] (~67 ppm). Therefore, we interpret that the above described is the result of the different

degrees of radiation damage, that may in some cases increase the He retentivity, but after a threshold, act in an opposite way, facilitating He diffusion. The dated zircon from the UDB-063, given its low abundance of U and Th, was probably lacking “traps” for He retention, and thus the activation energy needed for He diffusion was lower than that for the other zircons that yielded older ages, which have greater $e[U]$ values and a higher probability of have formed traps within their lattice (Farley, 2000; Flowers et al., 2007). On the other hand, the system apparently worked in the opposite way for the youngest zircon recovered from the sample UDB-032, in this case, the very high U and Th content, is probably responsible for the occurrence of a lot of crystallographic defects or traps, to the point that they got interconnected and served as paths for diffusion of He atoms. As a consequence, the activation energy required for He diffusion was lower than that for other grains where radiation damage was absent or not enough to convert traps in pathways (Guenther et al., 2013).

Based on the above assumption, we only used the younger ZHe ages for the thermal modeling of both samples from the Penderisco Fm., because they are likely to represent the timing when rocks achieved their maximum temperature and therefore the onset of cooling/exhumation (Parra et al., 2012).

The paths that better reproduce the thermochronological data of the sample UDB-032, suggest protracted burial at approximately constant rate of $\sim 10^{\circ}\text{C}/\text{my}$, until 45 Ma to 30 Ma (~ 42 Ma as suggested by the model with the best fit), when sample began to exhume at a cooling rate of $\sim 5^{\circ}\text{C}/\text{my}$. An episode of rapid exhumation occurred at ca. 2 Ma, when cooling rate dramatically increased to $20^{\circ}\text{C}/\text{my}$, as suggested for the young AHe age of 3.3 ± 0.9 Ma.

Sample UDB-063 was continuously buried at an approximate rate of $\sim 5^{\circ}\text{C}/\text{my}$, until 30 Ma to 20 Ma when it started to being exhumed at $\sim 6.7^{\circ}\text{C}/\text{my}$. A significant increase in the cooling rate occurred at ca. 12 Ma, attaining its highest value of $\sim 10.6^{\circ}\text{C}/\text{my}$. The above as suggested by the path that best fit the data. Subsequently, the cooling rate decreased to $\sim 4^{\circ}\text{C}/\text{my}$ until present.

When putting together the thermal histories from the samples UDB-032 and UDB-063 from the Penderisco Fm., we are not able to identify the precise onset of cooling/exhumation. Instead, we

are allowed to say that it should start at any time between 45 and 20 Ma. Moreover, the acceleration of the exhumation rates at ca. 2 Ma suggested by the thermal modeling of the sample UDB-032, is not registered in the thermal histories obtained for the sample UDB-063, although both samples belong to the same stratigraphic unit and are spatially close. This could be controlled by the fact that the ca. 2 Ma event, is shaped by only one individual AHe age that would be masking the real T-t path. However, it could also be explained by differential exhumation patterns, even within a narrow area, controlled by the occurrence of local-scale faults, or punctual episodic thermal perturbations (e.g. high-temperature fluid circulation along fractures).

We were not able to obtain good paths during the inverse modeling for the volcanic sample DMT-003 from the Cruces Fm., when including all AHe analyses with dates between 20-13 Ma, even using the radiation damage model of (Flowers et al., 2007). The above, suggest the existence of differential resetting among individual grains. For this reason, we only include for thermal modeling the two youngest individual ages. Therefore, good models indicate that after formation, this rock was buried until ca. 16 Ma, reaching maximum temperatures within the Apatite Helium Partial Retention Zone (APRZ, ~80-60°C) (Farley, 2000; Reiners and Brandon, 2006). At this moment, the cooling started with a rate of ~9°C/my, which decreased at ca. 12 Ma to ~2°C/my. Finally, after 5 Ma cooling rate attained the lowest values <2°C/my.

Figure 19. Results of the inverse thermal modeling. Purple lines represent the good paths (GOF>0.5), and green lines represent the acceptable paths. Shaded zones highlight the periods of time discussed below.

5. Discussion

Despite the controversies associated with the precise temporal constraints and evidences for the different elements involved in the tectonic processes, the fragmentation of the Pacific Farallon plate, to form the Nazca and Cocos plates (Lonsdale, 2005), and the approach of the Panama Arc to collide against the NW South-American continental margin (Duque-Caro, 1990a; Montes et al., 2015; O' Dea et al., 2016), are considered as the major tectonic events that may have influenced the growth of the Andean chain and the Central America isthmus since the Late Oligocene-Early Miocene.

The connection of these events with the evolution of the northern Andes have been inferred from supposed temporal correlations between deformation, exhumation, and changes in sedimentary facies in the intermontane and foreland basins of eastern Colombia (Caballero et al., 2013; Mora et al., 2013; Parra et al., 2010, 2009a), which suggest tectonic protracted tectonic instability since the Oligocene. Moreover, recent provenance constraints from the Middle Miocene basins of northern Colombian Caribbean region, that show the existence of deposits feed by rivers that drained the Panama Arc, is interpreted as outstanding evidence for the occurrence of major events that might ultimate exert some influence in that framework of tectonic instability (Montes et al., 2015).

In spite of these results, there is still great controversy regarding the precise timing and nature of the collisional and subduction-related mechanisms involved.

The new results presented in this contribution allows to reconstruct the main geological features of the tectonic limit between Panama and South-America, and recognize the exhumation, sedimentological and magmatic behavior of the lithological units exposed close to the suture, which it is expected to appropriately constrain the timing and nature of tectonic events. A summarized sketch of the Cenozoic paleogeography is presented in (**Figure 21**).

5.1. Pre-collisional building of the Panama and South-American blocks

The Early to Late Cretaceous San J. de Urama Diabase and the Barroso Fm., that constitute most of the eastern flank of the Western Cordillera, are considered as an accreted segment of an oceanic plateau included within the Caribbean Large Igneous Province (CLIP) (Burke, 1988; Kerr et al., 1997; Rodríguez and Arango, 2013; Sinton et al., 1998; Villagómez et al., 2011). Despite their oceanic affinity, these units were already forming part of the South-American margin since the Late Cretaceous-Paleocene, as suggested by rapid exhumation of the continental rocks from the Central Cordillera, which were probably triggered during the collisional episode (Parra et al., 2012; Villagómez and Spikings, 2013). Additionally, major changes in the sedimentary provenance patterns, as well as the occurrence of regional stratigraphic unconformities in the Middle Magdalena Basin, the Eastern Cordillera and the Llanos Basin (Bayona et al., 2013; Gómez et al., 2005, 2003; Parra et al., 2010; Reyes-Harker et al., 2015).

The Penderisco Fm., that is discordantly deposited over the oceanic terranes include sandstones with unstable framework material, such as plagioclase, epidote, biotite, clinopyroxene and volcanic lithic fragments, which indicate that these sediments were rapidly accumulated in the proximity to the source terranes in a transitional to marine environment, given the coexistence with chert and fossiliferous limestones. The above is also suggested by modeled burial rates between ~0.3-0.6 km/my on samples UDB-063 and UDB-032 (thermal gradient of 15°C/km). The quartz-rich composition and the presence of micaceous metamorphic lithic fragments, together with a mixed suite of heavy minerals such as clinopyroxene, epidote, clinozoisite, kyanite, rutile, garnet, and tourmaline, suggest that medium to high-grade metamorphic and intermediate-acid plutonic rocks, as well as basic igneous units, were the main sources for this unit

The U-Pb detrital signature of one sandstone from the Penderisco Fm. (sample GR-30) characterized by Cretaceous, Permo-Triassic and older populations, is akin with intermediate-acid plutonic rocks exposed along the axis of the Central Cordillera (e.g. Antioqueño Batholith) (Leal-Mejía, 2011; Villagómez et al., 2011), some basic-intermediate intrusives rocks from the

Western Cordillera (e.g. Buriticá Tonalite, Buga Batholith and Altamira Gabbro) (Villagómez et al., 2011; Weber et al., 2015; Zapata et al., 2017), and the main pre-Jurassic metamorphic and igneous basement units of the Central Cordillera (Cardona et al., 2010; Restrepo et al., 2011; Vinasco et al., 2006). Therefore, the Penderisco Fm. is interpreted as a syn to post-collisional sequence of this Late Cretaceous-Paleocene accretionary event, and represent the continental reference margin of the Mio-Pliocene tectonic phases.

The above volcano-sedimentary units, are separated by the Uramita deformed zone, from intra-oceanic arc-related rocks from the Santa Cecilia-La Equis Complex, that together with the Mandé Batholith, in spite of that available geochronological data include Ar/Ar, K/Ar, Rb/Sr, and few U-Pb zircon ages from plutons, are suggested to be part of a Late Cretaceous to Late Eocene island arc, which is a continuation of the Panama Arc, whose magmatic activity began at ca. 70 Ma (Buchs et al., 2010; Wegner et al., 2011; Wörner et al., 2009).

In the studied area, the Cruces Fm. is deposited over the basaltic-andesitic rocks of the Santa Cecilia-La Equis, and is included as the volcano-clastic expression of this unit, from which a tuff yielded a U-Pb age of 41.98 ± 0.37 Ma, similar to the ages reported for the Mandé Batholith (Montes et al., 2015). Sandstones associated with this volcanic unit, include texturally immature sedimentary rocks strongly-volcanic in composition, as indicated by the high content of euhedral plagioclase, clinopyroxene and volcanic lithic fragments, as well as the dominance of a heavy minerals suite characteristic of basic igneous sources, and compositional characteristics alike with the erosional trends of magmatic arcs (Dickinson, 1985; Folk, 1980; Garzanti, 2016). These features also demonstrate that the Colombian side of the Panama Arc system was built on subaerial conditions in the Middle Eocene.

The inverse thermal modeling conducted on samples from the Penderisco Fm. and the Buriticá Tonalite, suggest that protracted burial at constant rates characterized the evolution of these units during the Paleocene to Late Eocene, pointing for a tectonic regime without a strong contractional component in the western margin, that contrasts with identified ongoing deformation and exhumation for this period in eastern Colombia (Parra et al., 2009b; Restrepo-Moreno et al., 2009; Reyes-Harker et al., 2015; Villagómez and Spikings, 2013). The continuous

burial of the Penderisco Fm. probably required constant subsidence for accumulation-space generation, which could be related to its position in a forearc setting, which might suffer subsidence, potentially triggered either by subduction-erosion or plate decoupling (Clift and Vannucchi, 2004; Underwood et al., 1995), or the highly-oblique subduction of the Caribbean plate underneath South-America that could be conditioned by strong trench-parallel convergence and a subsequent decrease in the relative plate motion velocities (Bayona et al., 2012; Faccenna et al., 2017; Pardo-Casas and Molnar, 1987; Somoza, 1998).

5.2. Constraints for the Farallon break-up

As observed in the modeled thermal histories from the Buriticá Tonalite and Penderisco Fm., that represented the NW South-American continental margin, T-t trajectories that better fit the thermochronological data, suggest the onset of cooling between 45-20 Ma, which could be related to the switching from extension-dominated tectonics to a geodynamic regime with a stronger compressive component.

Based on thermochronological elevation profiles, carried out on the Cretaceous intrusives emplaced into the pre-Mesozoic metamorphic rocks from the Cordillera Central, suggest the existence of a pulse of moderately-rapid exhumation at rates around 0.2 to 0.4 km/my during the Late Oligocene.

The sedimentary record of the Eastern Cordillera and Magdalena Valley, suggest a period of intense reworking of Paleogene units and provenance marked by an increase in the abundance of material derived from deeper stratigraphic sequences, which is associated with the ongoing exhumation and denudation at this area during the Oligocene (Horton et al., 2010; Mora et al., 2013; Parra et al., 2009a, 2009b; Reyes-Harker et al., 2015). Increased sediment rates in both the Magdalena Valley and the eastern flank of the Eastern Cordillera between ca. 35 Ma to 25 Ma, as well as the switching from muddy marine sedimentary facies to more coastal and transitional sandy facies, are also evidence of the active uplift/erosion of the adjacent mountain ranges.

The above geological features, are likely to represent the upper-plate consequences correlated to the breaking of the Farallon Plate and the formation of the Cocos and Nazca Plates (Lonsdale, 2005), when the perpendicularity and convergence rate between the latter and the South-American Plate, reached the highest values around 15 cm/yr (Pardo-Casas and Molnar, 1987; Somoza, 1998; Somoza and Ghidella, 2012).

5.3. Middle to Late Miocene Panama arc-continent collision

Great controversy still exists about the timing of the final closure of the Isthmus of Panama, and the subsequent atmospheric and biogeographic consequences widespread throughout the globe (Bacon et al., 2015; Ibaraki, 1997; Iturralde-Vinent and MacPhee, 1999; Montes et al., 2015; O’Dea et al., 2016; Tsuchi, 1997; Webb, 2006). However, we claim that one of the main issues with this debate is rooted in the confusion about the referred phenomena (e.g. seaway total or partial closure, land-bridge establishment, the tectonic collision of genetically distinct terranes). The data presented here, and additional constraints compiled from previous studies, are used to document the tectonic collision of the oceanic Panama Arc with the NW continental margin of South-America. Therefore, any attempt to document the timing of the occurrence of biogeographic or atmospheric global changes are beyond the scope of this work.

Our new thermochronological data suggest that rocks from the Buriticá Tonalite and the Penderisco Fm. experienced a pulse of exhumation during the Middle-Late Miocene at moderate to high rates between 0.3 and 0.7 km/my. Moreover, a short period of rapid exhumation (0.6 km/my) at ca. 15 Ma is also observed for the Cruces Fm., which was followed by slow cooling until present.

As described in previous chapters, the geochemical data suggest that the volcanic and subvolcanic rocks from the San José de Urama are geochemically akin with an oceanic plateau, on which an island arc (Barroso Fm.) were constructed until ca. 80 Ma (Rodríguez and Arango, 2013; Weber et al., 2015; Zapata et al., 2017). Conversely, the Santa Cecilia-La Equis together with the Cruces Fm. constitute the volcanic member of an island arc built over a thick oceanic crust during the Late Cretaceous-Eocene (Buchs et al., 2010; Leal-Mejía, 2011; Montes et al.,

2012b; Villagómez et al., 2011). These genetically distinct oceanic terranes are separated by a mélange zone up to 10 km wide, as evidenced by the occurrence of high-strain zones towards the western limit of the Penderisco Fm. and the eastern limit of the Cruces Fm, which coincides spatially with the Uramita Fault Zone of Duque-Caro (1990b). Similarly, the highly-deformed zone described within the study area, also agree with the previously suggested location for the suture zone between the Western Cordillera Late Cretaceous rocks and the Eocene accreted oceanic units (Cuna Terrane of Restrepo & Toussaint, 1988 and Toussaint & Restrepo 1994).

Based on the whole tectono-stratigraphic constraints presented above, together with our new thermochronological results that evince a generalized period of moderate-rapid exhumation widespread throughout the northern segment of the Colombian Andes, suggest that both the Panama Arc and the Late Cretaceous NW continental margin, share a common tectonic history since the Middle Miocene, which is here interpreted as an evidence for the collision of this allochthonous oceanic terrane with the NW South-American Plate, as previously suggested (Duque-Caro, 1990a; Montes et al., 2015). An outstanding key-point that strongly supports our interpretations, arises from the new geochronological data presented here, which reveal the mixed detrital U-Pb signature found in rocks from the Middle Miocene to Pliocene (Beibaviejo and Guineales formations) located right over the suture zone, represented by both the pre-Mesozoic age-peaks related with the continental basement, and the unique Late Eocene-Oligocene signal from the Panama Arc (Buchs et al., 2010; Montes et al., 2015; Ramírez et al., 2016). No zircon U-Pb ages between 44 Ma and 24 Ma, have been reported in Colombia so far (Gómez et al., 2015).

Analogously, stratigraphic studies performed on the Cenozoic rocks from the Atrato and Chucunaque Basins, have identified major changes in sedimentary facies following the occurrence of regional discordances during the Middle Miocene (Coates et al., 2004; Duque-Caro, 1990a, 1990b; Haffer, 1967; Montes et al., 2012b). The Tapaliza Fm., and the Sierra Fm. define the shift from marine-dominated to more terrestrial-influenced environments within the Chucunaque and Atrato Basin, respectively (Coates et al., 2004; Duque-Caro, 1990b).

Here we present one tectonic subsidence curve, reconstructed through back-stripping (using the Backstrip Software version 4.3 of Nestor Cardozo, available at <http://www.ux.uis.no/~nestor/work/programs.html>) of stratigraphic data from the Atrato Basin (exploratory well Opogadó-1), compiled from Duque-Caro (1990a, 1990b) and Haffer (1967). The input parameters are presented in **Appendix 11**. The obtained tectonic subsidence curve (**Figure 20**), show that the combined effect of basin floor uplift (blue curve) and increased sediment accumulation (red curve) contribute to the dramatic Late Miocene-Pliocene decrease of 2.5 km in paleobathymetry, which started at ca. 15 Ma, as suggested by the progressive changes towards shallower sedimentary environments (Duque-Caro, 1990b). However, we highlight that despite the accumulation of a thick sedimentary column, 1D back-stripping shows that the basin indeed underwent tectonic uplift since 15 Ma, which correlates very well with the ~15 Ma onset of renewed uplift seen in AHe and AFT data.

Figure 20. Tectonic subsidence curve of the Opogadó-1 well from the Atrato Basin. Input data after Duque-Caro (1990a, 1990b). Shaded zone highlight the period of increased exhumation rates suggested by the new AFT and AHe results.

Exhumation on the Eastern Cordillera was still active during Early to Late Miocene, as suggested by tectono-stratigraphic analyses (Parra et al., 2009b; Ramirez-Arias et al., 2012). A major change from transitional mudstones to continental conglomerate and sandstone deposits,

as recorded by the accumulation of the Cenozoic thickest conglomeratic unit in the northern Andes foreland, and a general increase in the accumulation rates and eastward migration of the provenance axis both in the Magdalena Valley and the eastern foothills of the Eastern Cordillera, demonstrate the considerable tectonic activity in the orogen and consequent subsidence of in the adjacent basins (Bayona et al., 2013; Mora et al., 2013; Parra et al., 2010; Reyes-Harker et al., 2015).

All these dramatic changes experienced along the continental margin, including the studied regional suture, may be compatible with the arc-continent collision event already established by ca. 15-13 Ma, as suggested by the reinstallation of subduction and renewed construction of a continental magmatic arc (Rodríguez-García and Bermúdez-Cordero, 2015; Zapata and Rodríguez, 2011).

5.4. Late Miocene-Pliocene Nazca subduction

The new thermochronological data presented here, suggest that rocks from the Early Cretaceous Buriticá Tonalite and the Late Cretaceous Penderisco Fm., have been exhumed at rates between 0.3 and 1.3 km/my since 10 Ma. The highest cooling/exhumation rate is defined by an inflection on the T-t path of the sample UDB-032 from the Penderisco Fm. at ca. 2 Ma. Moreover, the dispersion between AHe individual ages obtained from four aliquots from the Guineales Fm. (sample DMT-010), could not be explained by the e[U] and the grain-size. Therefore, we interpret that they represent non-reset detrital cooling ages probably sourced from the Penderisco and Cruces formations, which yielded similar AHe ages to those found within this late Miocene-Pliocene conglomeratic unit. Our interpretation is also supported by the integration of our provenance analyses with previously published geochronological and geochemical analyses performed on conglomerate clasts from the Guineales Fm., which suggest that the Penderisco and Cruces formations, as well as the volcanic rocks from the Santa Cecilia-La Equis Complex, San José de Urama Diabase, and El Botón Basalts, probably sourced the late Miocene-Pliocene sedimentary unit (Rodríguez et al., 2016). Therefore, we used the youngest AHe date of 4.9 ± 1.2 Ma, as a marker of the maximum depositional age (Gehrels, 2012). In this scenario, the accumulation of the conglomeratic Guineales Fm. through high-

energy fluvial systems could be the response of active exhumation/erosion of the adjacent mountain ranges during the late Miocene-Pliocene, as also suggested by detrital U-Pb signature defined by a mixture between accreted Cretaceous to Eocene terranes, and reworked material from pre-Mesozoic continental sources.

The late Miocene-Pliocene period is also marked by the occurrence of a great magnitude surface uplift of the northern segments of the three main Cordilleras of Colombia (Anderson et al., 2016; Kroonenberg et al., 1990; Van der Hammen et al., 1973). In this context, it is worth noting the ~2000 m of surface uplift occurred after 5-4 Ma of the Bogotá Altiplano (Van der Hammen et al., 1973). Additionally, J. L. González et al. (2014) and Veloza et al. (2015), have independently identified Pleistocene ongoing deformation and uplifting both in the western coastal Baudó Range and the eastern foreland Llanos Basin, respectively.

The ongoing exhumation/deformation indicated by the new thermochronological data, together with surface uplift, and the coexistence of an active magmatic arc in the Colombian continental margin since the Late Miocene (Leal-Mejía, 2011; Mantilla et al., 2009; Rodríguez and Zapata, 2012; Zapata and Rodríguez, 2012, 2011), evidence the active subduction of the Nazca plate beneath South-America by that time.

Recently, based on a 3-D velocity model constructed from the seismic record of Colombia, Chiarabba et al. (2015) and Syracuse et al. (2016) also document the subduction of the oceanic Nazca plate. The spatial distribution of intermediate-depth earthquakes, together with the absence of magmatism to the north of 5°N, also demonstrates that the subduction system has a major segmentation at this latitude, and marks a transition from “normal” subducting slab dip-angle to a flat-slab, as previously suggested by Ramos & Folguera (2009).

Figure 21. Paleogeographic models from Late Cretaceous to Pliocene summarizing the all geological data discussed above. Modified after (Pindell, 1994). The white arrow indicates the relative direction of the Caribbean plate motion.

6. Conclusions

The integration of new sedimentary provenance, whole-rock geochemical analyses, and thermochronological data, together with regional tectono-stratigraphic and geochronological constraints along an east to west transect in the northwestern segment of the Western Cordillera allows to reconstruct the exhumation/deformation periods that affected the South-American continental margin since the Oligocene, and explore the potential causal link between these events with the over-imposition of collisional and subduction dominated tectonics. The new results suggest that the construction of the Late Cretaceous continental margin was initially controlled by the accretion of an Early to Late Cretaceous oceanic plateau, on which syn to post-collisional sediments from the Penderisco Fm. were accumulated. Protracted burial of this sedimentary sequence was followed by a period of contractional tectonics that triggered the onset of its exhumation/cooling from depths equivalent to temperatures within the zircon helium partial retention zone (ZPAZ, ~180-200°C) at any time between 45-20 Ma, which overlaps with a period of high tectonic instability in eastern Colombia, and with the suggested age for the Farallon plate break-up and the subsequent formation of the Cocos and Nazca plates. A subsequent pulse of moderately-rapid exhumation (~0.3 to 0.7 km/my) at ca. 15 Ma of the Early to Late Cretaceous of the Western Cordillera, is also constrained by the new AFT ages. This Middle Miocene pulse of exhumation is also registered by cooling of the volcano-clastic rocks from the Eocene Cruces Fm. from temperatures within the apatite helium partial retention zone (APAZ, ~60-80°C), as suggested by the AHe ages ca. 14 Ma obtained from this unit. A period of combined increased sedimentation rates and uplifting of the forearc Atrato Basin at ca. 15 Ma, correlates well with the pulse of exhumation/erosion documented for the adjacent orogens. The above together with changes in the sedimentary and provenance patterns on intermontane and foreland basins of eastern Colombia indicates a period of intense tectonic activity during the Middle-Late Miocene in the northern Colombian Andes. The collisional nature of this event is suggested by the mixed U-Pb detrital ages of sediments being accumulated at this time, that include both pre-Mesozoic continental-basement signature and Late Eocene ages, which are uniquely sourced from the intra-oceanic Panama Arc. The suture zone between this accreted oceanic terrane and the South-American continental margin is defined by a regional highly-deformed zone that extends from the southern Istmina deformed belt to the Dabeiba area, and

further to the northwest towards the Urabá Gulf. The younger AHe ages presented here document ongoing exhumation of the Western Cordillera rocks since the Late Miocene-Pliocene until present, which together with the occurrence of great-magnitude surface uplift mainly recorded in the Eastern Cordillera and southern massifs of Colombia (Garzon and Quetame), as well as the coexistence of an active magmatic arc, suggest that Nazca subduction beneath South-America initiated right after the Middle Miocene collisional episode and is still active today.

7. References

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Appendix 1. Details of samples used in this work

Sample	Longitude	Latitude	Lithological Unit	Lithology	Petrography	Heavy Minerals
BTU-004	-76.06184	6.78367	Penderisco Fm.	Sandstone	X	X
BTU-005	-76.09414	6.81294	Penderisco Fm.	Sandstone	X	
BTU-007	-76.11458	6.83518	S. J. de Urama Diabase	Diabase	X	
BTU-008	-76.12392	6.84433	S. J. de Urama Diabase	Basalt	X	
BTU-010	-76.15292	6.87955	Penderisco Fm.	Sandstone	X	X
BTU-012	-76.15835	6.88629	Penderisco Fm.	Limestone	X	
BTU-014	-76.16325	6.88915	S. J. de Urama Diabase	Diabase	X	
BTU-015	-75.92072	6.6877	Buriticá Stock	Tonalite		
DMT-001	-76.38847	7.03295	Cruces Fm.	Sandstone	X	
DMT-002	-76.39023	7.04331	Cruces Fm.	Mudstone	X	
DMT-003	-76.38934	7.04022	Cruces Fm.	Tuff	X	
DMT-004	-76.38896	7.04003	Cruces Fm.	Tuff	X	
DMT-005	-76.38953	7.03892	Cruces Fm.	Sandstone	X	
DMT-006	-76.39163	7.03802	Cruces Fm.	Sandstone	X	
DMT-007	-76.3947	7.0373	Cruces Fm.	Sandstone	X	
DMT-008	-76.35173	7.03302	Guineales Fm.	Conglomerate		
DMT-010	-76.32279	7.02214	Guineales Fm.	Conglomerate Matrix (Sandstone)	X	X
DMT-012	-76.33788	7.02623	Sucio River	Modern Sediments		
DMT-013	-76.39650	7.04081	Santa Cecilia-La Equis Complex	Volcanic	X	
DMT-014	-76.39677	7.0413	Cruces Fm.	Sandstone	X	

DMT-015	-76.41167	7.04501	Santa Cecilia-La Equis Complex	Volcanic	X	
DMT-016	-76.41467	7.04536	Santa Cecilia-La Equis Complex	Volcanic	X	
DMT-017	-76.42371	7.05298	Santa Cecilia-La Equis Complex	Volcanic	X	
DMT-018	-76.4259	7.06083	Santa Cecilia-La Equis Complex	Volcanic	X	
DMT-020	-76.42044	7.07165	Cruces Fm.	Sandstone	X	X
UDB-006	-76.30207	7.01131	El Botón Basalts	Volcanic	X	
UDB-007	-76.30207	7.01131	El Botón Basalts	Volcanic	X	
UDB-009	-76.2514	6.99227	S. J. de Urama Diabase	Volcanic	X	
UDB-011	-76.25639	7.00084	Penderisco Fm.	Sandstone	X	X
UDB-015	-76.30226	7.01484	El Botón Basalts	Volcanic	X	
UDB-017	-76.29475	7.01376	Beibaviejo Fm.	Conglomeratic Sandstone	X	X
UDB-018	-76.2905	7.01281	Nudillales	Gabbro	X	
UDB-019	-76.28841	7.01224	S. J. de Urama Diabase	Volcanic	X	
UDB-020	-76.28841	7.01224	Penderisco Fm.	Limestone	X	
UDB-021	-76.2852	7.01711	Nudillales	Volcanic	X	
UDB-022	-76.2852	7.01711	Beibaviejo Fm.	Sandstone	X	X
UDB-024	-76.2609	6.99829	Penderisco Fm.	Sandstone	X	X
UDB-030	-76.25845	6.98615	Penderisco Fm.	Sandstone	X	
UDB-032	-76.26706	6.93975	Penderisco Fm.	Sandstone	X	X
UDB-041	-76.24651	6.9173	Penderisco Fm.	Tuff	X	
UDB-045	-76.23618	6.91551	Penderisco Fm.	Limestone	X	

UDB-054	-76.2318	6.89642	S. J. de Urama Diabase	Volcanic	X	
UDB-063	-76.24501	6.88585	Penderisco Fm.	Conglomeratic Sandstone	X	X
GR-30	-76.149542	6.876722	Penderisco Fm.	Sandstone		

Sample	Whole Rock Geochemistry	U-Pb Geochronology	Apatite Fission-Tracks	Apatite (U-Th)/He	Zircon (U-Th)/He
BTU-015				X	X
DMT-003		X	X	X	X
DMT-008			X		
DMT-010		X	X	X	
DMT-012			X		
DMT-013	X				
DMT-015	X				
DMT-016	X				
DMT-017	X				
DMT-018	X				
UDB-022		X			
UDB-032			X	X	X
UDB-063			X	X	X
GR-30		X			

Appendix 2. Sandstone Petrography Results

Sample	Unit	Grain-Size (mm)	Roundness	Sphericity	Sorting	Number of Grains
BTU-004	Penderisco Fm.	0.1-0.3	Subangular	Low-Medium	Well-Sorted	406
BTU-005	Penderisco Fm.	0.1-0.3	Angular-Subangular	Low-Medium	Well-Sorted	409
BTU-010	Penderisco Fm.	0.1-0.6	Subangular-Angular	Low-Medium	Moderately-Sorted	416
UDB-011	Penderisco Fm.	0.1-0.5	Subangular	Low-Medium	Moderately-Sorted	463
UDB-017	Beibaviejo Fm.	0.2-2.5	Subangular	Low	Poorly-Sorted	458
UDB-024	Penderisco Fm.	0.3-1	Subangular	Low-Medium	Moderately-Sorted	424
UDB-030	Penderisco Fm.	0.1-0.5	Angular	Low-Medium	Poorly-Sorted	454
UDB-032	Penderisco Fm.	0.3-1	Subangular	Low-Medium	Moderately-Sorted	454
UDB-063	Penderisco Fm.	0.4-2	Subangular	Low-Medium	Poorly-Sorted	436
DMT-001	Cruces Fm.	0.4-0.7	Subangular	Low-Medium	Moderately-Well-Sorted	410
DMT-005	Cruces Fm.	0.3-1.5	Subangular	Low-Medium	Poorly-Sorted	440
DMT-006	Cruces Fm.	0.4-1	Subangular	Low	Poorly-Sorted	427
DMT-007	Cruces Fm.	0.3-1	Subangular	Low	Poorly-Sorted	424
DMT-013	Cruces Fm.	0.2-0.5	Subangular-Subrounded	Low-Medium	Moderately	358
DMT-014	Cruces Fm.	0.1-0.9	Subangular-Subrounded	Low-Medium	Poorly-Sorted	407
DMT-020	Cruces Fm.	0.1-0.3	Subangular	Low-Medium	Moderadamente Buena	411
UDB-022	Beibaviejo Fm.	0.1-0.4	Angular-Subangular	Low-Medium	Moderately-Sorted	465

Sample	Pg	Qpf	Qpi	Qpc	Qrec	Qond	Lss	Lsm	Lmm	Lmgs	Lp	Lv
BTU-004	104			18	25	102		2	5			
BTU-005	38	1	9	23	27	216		19	6			
BTU-010	99		6	18	32	124	1	11	7	2		11
UDB-011	115	3	7	19	69	146		24	8	5		18
UDB-017	141	2	3	17	22	111	30	33				51
UDB-024	57	5	14	21	13	226		16	10			7
UDB-030	62		8	24	22	228		24	9	3		23
UDB-032	49	4	16	19	28	221	3	23	6			33
UDB-063	86	1	16	4	4	208	18	20	10			35
DMT-001	197		2	17	10	26		4				14
DMT-005	293		1	3	10	2						62
DMT-006	147		3	2	29	52					5	26
DMT-007	197		1	1	4	35					4	26
DMT-013	175		3	6	8	24						30
DMT-014	239			6	28	26					6	19
DMT-020	258				32	9					3	25
UDB-022	56	3	23	34	25	187	1	33	10			39

Sample	Msk	Ep	Bt	Px	Ap	Zr	Chl	Rt	Ox	Amp	Op	Zs
BTU-004	14	37	30	5		4	33	5	22			
BTU-005	17	7	30				14	2				
BTU-010	16	29	15	2	3		14	3	19			4
UDB-011	6	6	6		2	1	17		11			
UDB-017		13	1	12	1	1	4	2	14			
UDB-024	27		2		1	1	17	1	6			
UDB-030	8	6	9			2	19	2	5			
UDB-032	6	11	4	4	2		18	1	6			
UDB-063	5	6	3				20					
DMT-001		7	5	63			22			10	33	
DMT-005		2	37			1	29					
DMT-006		17	11	83			39			13		
DMT-007		22	2	92			37			3		
DMT-013		18		71			23					
DMT-014		27	15				41					
DMT-020		24		49			11					
UDB-022	10	1	2	1		2	28	2	8			

Appendix 3. Conglomerate clast-counting results.

Loc.	Chert	Siliceous Mudstone	Greenish Mudstone	White Mudstone	Red Limestone	Sandstone	Qz	Px-Fd Porphyry	Massive Volcanic	Diabase	Fd Porphyry	Diorite	Gabbro
DMT -014	30	51				10	7	1	1				
DMT -016	20	26	6		1	42			4			1	
DMT -018	19	11				52		2	6	2	5	3	
DMT -021	23		2	6	8	28	1	10	4		14	3	1

Appendix 4. Heavy minerals analysis results.

Sample	Cpx	Opx	Hbl	Bt	Chl	Ep	Zs	Czs	Ap	Zr	Msk	Cc	Sph	Grt	Tur	Rt	Ky	Str
BTU-004	11			16	35	64	15	4	5	38	123	5		8	24			2
BTU-010	75		4		31	114	33	1		25	22	12		8				
UDB-011					3		53	207		11	20		1		5			
UDB-017	199		3	4	1	1	32	15	1	5	35			3	2			
UDB-022	26		8		8	6	11	20	1	91	97		1	5	9	16	1	
UDB-024	4		5	13	53		12	117		3	82	3		1	3	1		
UDB-032	134		5	6	14	22	4	2		42	69				2			
UDB-063	234						32		3		22			9				
DMT-010	271		28			14	2											
DMT-020	263	21				9	1				12							

Appendix 5. U-Pb Geochronology Results

Name	U ppm	Th/U	U/Th	²³⁸ U/ ²⁰⁶ Pb	1s % error	²⁰⁷ Pb/ ²⁰⁶ Pb	1s % error	²⁰⁶ Pb/ ²³⁸ U age	1s abs err	²⁰⁷ Pb/ ²⁰⁶ Pb age	1s abs err	Selected age	1s abs err
UDB-022_1	53.2	1.3	0.8	52.4	1.9	0.1	3.1	121.8	2.2	383.9	67.9	121.8	2.2
UDB-022_2	374.8	2.4	0.4	11.2	1.0	0.1	0.7	550.0	5.3	554.7	14.7	550.0	5.3
UDB-022_3	104.6	0.6	1.7	278.8	2.5	0.0	5.8	23.1	0.6	43.9	134.1	23.1	0.6
UDB-022_4	36.1	2.1	0.5	7.9	1.2	0.1	1.0	764.6	8.3	847.3	21.2	764.6	8.3
UDB-022_5	658.3	0.9	1.1	3.1	1.0	0.1	0.5	1802.6	15.0	2070.2	8.4	2070.2	8.4
UDB-022_6	577.9	2.3	0.4	158.0	1.2	0.0	1.6	40.7	0.5	0.0	28.1	40.7	0.5
UDB-022_7	352.4	0.4	2.6	3.2	1.0	0.1	0.5	1753.5	15.4	1778.3	9.8	1778.3	9.8
UDB-022_8	517.1	1.7	0.6	158.0	1.2	0.0	1.7	40.7	0.5	0.0	17.4	40.7	0.5
UDB-022_9	103.9	0.7	1.5	73.5	1.6	0.0	2.7	87.1	1.4	109.0	61.6	87.1	1.4
UDB-022_10	110.0	0.8	1.3	298.4	2.4	0.0	7.4	21.6	0.5	15.0	168.9	21.6	0.5
UDB-022_11	164.6	0.8	1.2	247.8	1.7	0.0	4.9	26.0	0.5	0.0	0.0	26.0	0.5
UDB-022_12	67.2	1.1	0.9	90.4	1.7	0.0	4.3	70.9	1.2	34.1	99.9	70.9	1.2
UDB-022_13	48.0	0.9	1.2	79.9	2.1	0.0	4.7	80.2	1.6	0.0	105.9	80.2	1.6
UDB-022_14	640.9	2.1	0.5	148.6	1.2	0.0	1.3	43.2	0.5	63.8	30.1	43.2	0.5
UDB-022_15	125.4	0.8	1.2	81.2	1.4	0.0	2.5	78.9	1.1	104.0	57.8	78.9	1.1
UDB-022_16	21.0	1.0	1.0	71.8	2.8	0.1	6.0	89.2	2.5	415.2	128.9	89.2	2.5
UDB-022_17	219.3	1.1	0.9	172.0	1.4	0.1	3.2	37.4	0.5	384.0	70.1	37.4	0.5
UDB-022_18	124.2	1.1	0.9	167.8	1.7	0.0	3.6	38.3	0.7	98.0	83.1	38.3	0.7
UDB-022_19	81.3	0.6	1.7	69.8	1.5	0.0	3.0	91.7	1.4	108.9	69.3	91.7	1.4
UDB-022_20	630.6	0.6	1.6	86.9	1.1	0.0	1.0	73.8	0.8	39.4	24.4	73.8	0.8
UDB-022_21	172.3	0.9	1.1	77.7	1.3	0.0	2.2	82.4	1.1	0.0	0.0	82.4	1.1
UDB-022_22	81.8	2.2	0.5	8.9	1.0	0.1	0.9	688.6	6.7	859.4	19.2	688.6	6.7
UDB-022_23	456.5	2.2	0.5	71.7	1.1	0.0	1.1	89.3	0.9	84.0	26.9	89.3	0.9
UDB-022_24	78.1	1.7	0.6	76.3	1.5	0.0	2.5	83.9	1.3	117.9	59.0	83.9	1.3
UDB-022_25	38.5	1.3	0.7	325.1	4.5	0.0	9.3	19.8	0.9	19.3	209.1	19.8	0.9

UDB-022_26	112.3	1.3	0.8	7.8	1.0	0.1	0.7	775.8	7.5	782.7	14.1	775.8	7.5
UDB-022_27	272.4	1.3	0.8	10.3	0.9	0.1	0.6	596.6	5.3	575.0	14.0	596.6	5.3
UDB-022_28	65.3	1.3	0.8	88.3	2.0	0.0	3.6	72.6	1.4	127.0	83.7	72.6	1.4
UDB-022_29	383.4	0.9	1.1	6.4	0.9	0.1	0.6	942.3	8.2	990.1	11.2	990.1	11.2
UDB-022_30	191.6	2.0	0.5	76.8	1.2	0.0	1.8	83.4	1.0	142.1	42.8	83.4	1.0
UDB-022_31	420.6	1.5	0.7	148.6	1.2	0.0	1.7	43.2	0.5	79.8	39.6	43.2	0.5
UDB-022_32	282.5	1.5	0.7	177.4	1.5	0.0	2.3	36.2	0.5	0.0	0.0	36.2	0.5
UDB-022_33	335.7	1.8	0.5	160.0	1.1	0.0	2.3	40.2	0.5	96.9	53.4	40.2	0.5
UDB-022_34	248.0	1.1	0.9	70.5	1.5	0.1	1.6	90.8	1.3	868.3	32.2	90.8	1.3
UDB-022_35	278.5	2.6	0.4	160.3	1.5	0.0	2.7	40.1	0.6	13.1	62.6	40.1	0.6
UDB-022_36	164.9	2.0	0.5	153.5	1.4	0.0	3.1	41.9	0.6	22.0	72.0	41.9	0.6
UDB-022_37	53.4	0.9	1.1	69.8	1.5	0.0	4.1	91.7	1.3	91.5	95.1	91.7	1.3
UDB-022_38	72.9	0.8	1.3	81.9	1.5	0.0	3.5	78.2	1.2	78.0	80.1	78.2	1.2
UDB-022_39	103.8	0.8	1.3	86.1	1.7	0.0	2.3	74.5	1.2	106.9	54.4	74.5	1.2
UDB-022_40	63.5	0.9	1.1	5.0	1.1	0.1	0.7	1165.1	11.9	1177.0	13.0	1177.0	13.0
UDB-022_41	144.4	1.9	0.5	151.5	1.6	0.0	3.1	42.4	0.7	0.0	11.4	42.4	0.7
UDB-022_42	99.8	1.3	0.8	80.7	1.7	0.0	2.6	79.4	1.3	74.0	61.6	79.4	1.3
UDB-022_43	181.4	2.7	0.4	10.5	1.1	0.1	0.8	586.2	6.2	602.9	16.5	586.2	6.2
UDB-022_44	167.1	0.9	1.1	83.1	1.3	0.0	2.0	77.1	1.0	0.0	0.0	77.1	1.0
UDB-022_45	297.1	1.0	1.0	6.4	1.0	0.1	0.6	934.2	8.8	918.4	11.3	918.4	11.3
UDB-022_46	143.9	1.2	0.8	77.0	1.3	0.0	1.9	83.2	1.1	119.3	44.9	83.2	1.1
UDB-022_47	281.9	1.9	0.5	81.7	1.2	0.0	1.5	78.4	0.9	68.6	35.1	78.4	0.9
UDB-022_48	126.7	5.5	0.2	6.1	1.0	0.1	0.7	984.7	9.4	995.8	13.6	995.8	13.6
UDB-022_49	730.3	1.2	0.8	83.6	1.0	0.0	1.1	76.7	0.8	49.1	26.1	76.7	0.8
UDB-022_50	177.8	1.1	0.9	87.6	1.2	0.0	1.8	73.2	0.9	51.1	42.4	73.2	0.9
UDB-022_51	187.0	1.4	0.7	181.5	1.5	0.0	2.6	35.4	0.5	113.6	60.9	35.4	0.5
UDB-022_52	118.6	0.5	1.8	72.3	1.4	0.0	2.7	88.5	1.2	74.9	63.1	88.5	1.2
UDB-022_53	879.0	0.8	1.3	75.8	1.4	0.1	1.2	84.5	1.1	218.5	26.8	84.5	1.1

UDB-022_54	86.8	0.9	1.1	82.8	1.6	0.1	3.2	77.4	1.2	197.7	72.7	77.4	1.2
UDB-022_55	167.5	1.7	0.6	8.8	1.0	0.1	0.7	693.2	6.8	682.4	14.9	693.2	6.8
UDB-022_56	210.8	1.8	0.5	149.5	1.5	0.0	2.1	43.0	0.6	75.7	48.9	43.0	0.6
UDB-022_57	68.4	0.7	1.5	269.1	3.5	0.0	5.3	23.9	0.8	0.0	178.1	23.9	0.8
UDB-022_58	190.3	1.2	0.8	10.7	1.0	0.1	0.8	575.4	5.3	644.5	17.5	575.4	5.3
UDB-022_59	1091.8	0.5	2.0	10.8	1.0	0.1	0.5	573.4	5.5	540.3	11.4	573.4	5.5
UDB-022_60	71.5	0.8	1.3	5.7	1.0	0.1	0.8	1044.4	9.9	990.1	17.2	990.1	17.2
UDB-022_61	350.3	2.6	0.4	24.9	1.0	0.1	0.9	253.4	2.5	224.3	20.9	253.4	2.5
UDB-022_62	199.9	2.6	0.4	2.2	0.9	0.2	0.5	2376.5	18.6	2419.5	8.1	2419.5	8.1
UDB-022_63	217.3	1.7	0.6	167.4	1.4	0.0	3.1	38.4	0.5	32.9	72.1	38.4	0.5
UDB-022_64	354.7	1.8	0.5	179.3	1.5	0.1	2.5	35.9	0.5	646.7	51.9	35.9	0.5
UDB-022_65	410.8	1.2	0.8	150.9	1.2	0.0	1.7	42.6	0.5	77.0	40.4	42.6	0.5
UDB-022_66	70.8	5.5	0.2	2.0	0.9	0.2	0.5	2601.8	20.0	2589.0	8.7	2589.0	8.7
UDB-022_67	54.7	1.6	0.6	4.5	1.1	0.1	0.8	1300.8	12.4	1356.3	14.4	1356.3	14.4
UDB-022_68	356.3	1.5	0.7	171.4	1.3	0.0	2.1	37.5	0.5	35.8	50.4	37.5	0.5
UDB-022_69	62.5	1.0	1.0	93.7	1.9	0.1	3.2	68.4	1.3	349.6	71.5	68.4	1.3
UDB-022_70	484.0	0.9	1.1	5.0	0.9	0.1	0.5	1165.1	10.0	1366.8	9.5	1366.8	9.5
UDB-022_72	270.0	1.1	0.9	78.2	1.2	0.0	1.4	81.9	1.0	111.2	33.8	81.9	1.0
UDB-022_73	423.3	2.0	0.5	167.8	1.2	0.0	2.0	38.3	0.5	0.0	0.0	38.3	0.5
UDB-022_74	188.2	0.8	1.2	76.4	1.3	0.0	2.0	83.9	1.1	92.5	47.3	83.9	1.1
UDB-022_75	166.6	1.0	1.0	149.3	1.5	0.0	2.8	43.0	0.6	0.0	72.3	43.0	0.6
UDB-022_76	108.2	1.5	0.7	5.6	1.0	0.1	0.6	1060.9	10.0	1344.5	11.2	1344.5	11.2
UDB-022_77	168.8	0.6	1.7	5.9	1.0	0.1	0.6	1010.8	9.3	1015.3	11.9	1015.3	11.9
UDB-022_78	69.8	1.3	0.7	4.8	1.0	0.1	0.7	1219.0	11.0	1260.5	13.1	1260.5	13.1
UDB-022_79	117.9	0.7	1.4	5.6	0.9	0.1	0.7	1051.2	9.0	1051.0	13.3	1051.0	13.3
UDB-022_80	128.2	2.3	0.4	9.6	1.0	0.1	0.8	635.8	6.2	629.0	16.3	635.8	6.2
UDB-022_81	84.9	1.6	0.6	5.9	1.1	0.1	0.7	1013.1	10.0	1223.8	13.2	1223.8	13.2
UDB-022_82	39.7	2.0	0.5	4.3	1.1	0.1	0.8	1361.9	13.7	1442.2	15.7	1442.2	15.7

UDB-022_83	39.7	0.7	1.4	69.7	2.0	0.0	4.7	91.8	1.8	40.6	108.5	91.8	1.8
UDB-022_84	86.4	1.3	0.8	248.7	2.3	0.0	5.7	25.9	0.6	35.6	131.7	25.9	0.6
UDB-022_85	143.0	1.5	0.6	80.2	1.4	0.0	2.0	79.9	1.1	149.2	47.2	79.9	1.1
UDB-022_86	655.2	1.6	0.6	182.3	1.1	0.0	1.7	35.3	0.4	94.2	39.6	35.3	0.4
UDB-022_87	396.9	2.3	0.4	142.9	1.2	0.0	1.6	44.9	0.5	0.0	18.5	44.9	0.5
UDB-022_88	276.3	2.0	0.5	4.0	1.1	0.1	0.6	1428.4	14.5	1535.4	10.7	1535.4	10.7
UDB-022_89	86.0	0.7	1.4	76.7	1.6	0.0	2.7	83.5	1.4	125.0	61.2	83.5	1.4
UDB-022_90	158.1	0.9	1.1	4.7	1.0	0.1	0.6	1251.9	11.5	1219.9	11.5	1219.9	11.5
UDB-022_92	378.9	2.5	0.4	80.7	1.1	0.0	1.3	79.4	0.9	52.7	30.9	79.4	0.9
UDB-022_93	309.8	1.5	0.7	12.3	1.0	0.1	0.7	505.4	4.9	576.8	14.7	505.4	4.9
UDB-022_94	41.9	1.0	1.0	72.5	2.3	0.0	3.7	88.3	2.0	0.0	38.5	88.3	2.0
UDB-022_95	90.7	30.8	0.0	7.3	1.1	0.1	0.8	832.1	8.3	1083.5	16.0	1083.5	16.0
UDB-022_96	83.1	1.2	0.8	4.8	1.1	0.1	0.8	1227.2	12.3	1293.9	14.6	1293.9	14.6
UDB-022_97	103.1	3.1	0.3	9.6	1.1	0.1	1.0	636.0	6.8	602.5	21.4	636.0	6.8
UDB-022_98	301.1	0.4	2.6	27.3	1.0	0.1	0.9	232.3	2.3	200.5	20.0	232.3	2.3
UDB-022_99	62.3	0.7	1.3	79.7	1.6	0.0	3.2	80.4	1.3	0.0	157.2	80.4	1.3
UDB-022_100	843.8	0.0	35.9	5.8	1.0	0.1	0.5	1030.2	9.8	963.0	10.2	963.0	10.2
UDB-022_101	132.3	2.7	0.4	11.4	1.0	0.1	0.8	544.1	5.4	549.4	18.4	544.1	5.4
UDB-022_102	200.2	1.5	0.7	210.2	1.5	0.1	3.1	30.6	0.5	309.2	70.0	30.6	0.5
UDB-022_103	287.7	1.5	0.7	159.2	1.3	0.0	2.2	40.4	0.5	108.3	51.6	40.4	0.5
UDB-022_104	266.4	2.5	0.4	13.7	1.0	0.1	0.7	455.6	4.2	498.1	15.6	455.6	4.2
UDB-022_105	189.8	1.8	0.5	223.7	1.5	0.0	3.4	28.8	0.4	71.0	78.2	28.8	0.4

UDB-022_106	601.5	1.5	0.7	143.6	1.1	0.0	1.4	44.7	0.5	63.2	34.1	44.7	0.5
UDB-022_107	142.7	1.9	0.5	10.8	1.0	0.1	0.8	568.4	5.6	559.7	16.8	568.4	5.6
UDB-022_108	147.4	1.2	0.9	257.3	1.8	0.0	4.5	25.0	0.4	82.7	104.1	25.0	0.4
UDB-022_109	312.5	1.2	0.8	170.4	1.3	0.0	2.1	37.7	0.5	32.6	50.7	37.7	0.5
UDB-022_110	450.6	2.0	0.5	187.6	1.3	0.0	1.7	34.3	0.4	27.7	40.1	34.3	0.4
UDB-022_111	205.4	0.9	1.1	302.2	1.8	0.0	4.0	21.3	0.4	18.6	93.2	21.3	0.4
UDB-022_112	291.4	1.9	0.5	152.5	1.5	0.0	2.2	42.1	0.6	64.9	51.2	42.1	0.6
UDB-022_113	194.6	1.0	1.0	75.7	1.3	0.0	2.0	84.6	1.1	154.7	46.6	84.6	1.1
UDB-022_114	55.8	1.4	0.7	74.7	1.8	0.1	3.6	85.7	1.5	742.6	74.1	85.7	1.5
UDB-022_115	212.9	0.9	1.1	275.3	1.9	0.0	4.0	23.4	0.4	0.0	91.1	23.4	0.4
UDB-022_116	889.6	0.8	1.3	92.1	1.1	0.0	1.1	69.6	0.7	83.6	26.8	69.6	0.7
UDB-022_117	123.8	1.4	0.7	76.4	1.6	0.0	2.2	83.8	1.3	179.0	49.4	83.8	1.3
UDB-022_118	151.0	1.0	1.0	81.5	1.6	0.0	2.0	78.6	1.2	0.0	71.9	78.6	1.2
UDB-022_119	99.1	1.5	0.7	88.2	1.3	0.1	2.5	72.7	0.9	372.1	54.4	72.7	0.9

UDB-022_120	63.4	2.8	0.4	3.5	1.1	0.1	0.6	1623.4	15.1	1649.5	11.0	1649.5	11.0
UDB-022_121	268.4	0.9	1.1	279.0	1.6	0.0	3.0	23.1	0.4	47.7	69.5	23.1	0.4
UDB-022_122	56.4	1.0	1.0	82.1	1.9	0.0	3.8	78.1	1.5	120.7	88.3	78.1	1.5
UDB-022_123	78.4	0.9	1.2	73.1	1.6	0.0	2.4	87.6	1.4	10.7	56.3	87.6	1.4
UDB-022_124	420.7	2.9	0.4	154.9	2.1	0.1	2.1	41.5	0.9	571.8	45.4	41.5	0.9
UDB-022_125	219.9	0.7	1.3	9.1	1.0	0.1	0.7	674.5	6.3	703.8	14.1	674.5	6.3
UDB-022_126	156.3	1.7	0.6	82.8	1.4	0.0	2.2	77.4	1.0	115.3	50.6	77.4	1.0
DMI-010_1	246.2	1.7	0.6	83.6	1.3	0.0	1.7	76.6	1.0	188.0	38.4	76.6	1.0
DMI-010_2	199.5	1.3	0.7	2.7	1.1	0.1	0.5	2012.1	19.6	2020.1	9.0	2020.1	9.0
DMI-010_3	167.6	1.3	0.8	4.4	1.1	0.1	0.6	1313.0	13.0	1321.6	11.9	1321.6	11.9
DMI-010_4	346.6	0.9	1.1	5.6	1.0	0.1	0.6	1067.3	9.4	1060.9	11.1	1060.9	11.1
DMI-010_5	255.5	0.3	3.3	26.6	1.1	0.1	1.0	237.6	2.6	212.9	22.3	237.6	2.6
DMI-010_6	197.5	1.4	0.7	70.0	1.4	0.0	1.8	91.4	1.2	26.0	42.4	91.4	1.2
DMI-010_8	232.5	1.5	0.7	5.4	1.0	0.1	0.6	1098.3	10.0	1209.0	12.4	1209.0	12.4
DMI-010_9	256.0	1.5	0.7	25.5	1.1	0.1	0.9	248.1	2.6	279.8	20.5	248.1	2.6
DMI-010_10	74.1	3.4	0.3	8.6	1.1	0.1	1.0	710.0	7.1	775.0	20.5	710.0	7.1
DMI-010_11	302.6	2.1	0.5	2.7	1.0	0.1	0.5	2038.1	16.9	1980.6	8.7	1980.6	8.7
DMI-010_12	74.2	2.0	0.5	19.0	2.1	0.1	1.7	330.7	6.9	1018.8	33.5	330.7	6.9
DMI-010_13	416.0	3.1	0.3	156.8	1.3	0.0	1.8	41.0	0.5	29.1	43.0	41.0	0.5
DMI-010_14	268.5	1.6	0.6	202.7	1.4	0.1	2.3	31.7	0.4	384.2	51.3	31.7	0.4

DMI-010_15	160.9	0.9	1.1	9.8	1.1	0.1	0.8	624.2	6.4	598.6	16.2	624.2	6.4
DMI-010_16	138.8	2.4	0.4	81.2	1.4	0.0	2.3	78.9	1.1	9.4	54.1	78.9	1.1
DMI-010_17	640.5	1.4	0.7	81.3	1.0	0.0	1.0	78.8	0.8	92.1	24.1	78.8	0.8
DMI-010_18	417.0	4.1	0.2	61.2	1.0	0.1	1.2	104.5	1.1	656.0	24.5	104.5	1.1
DMI-010_19	413.4	1.1	0.9	88.9	1.2	0.1	1.5	72.1	0.9	307.0	34.3	72.1	0.9
DMI-010_20	228.4	0.5	2.1	27.5	1.0	0.1	1.0	230.1	2.3	227.6	23.8	230.1	2.3
DMI-010_21	859.1	3.5	0.3	144.2	1.1	0.1	1.2	44.6	0.5	208.0	27.2	44.6	0.5
DMI-010_22	374.4	0.2	5.3	11.2	1.4	0.1	1.3	549.4	7.3	910.7	26.4	549.4	7.3
DMI-010_23	702.5	0.5	1.9	5.6	0.9	0.1	0.5	1065.4	9.3	1073.8	9.5	1073.8	9.5
DMI-010_24	112.0	2.6	0.4	5.9	1.0	0.1	0.7	1004.7	9.2	1003.0	14.4	1003.0	14.4
DMI-010_25	301.8	3.2	0.3	85.6	1.2	0.0	1.5	74.9	0.9	0.0	55.0	74.9	0.9
DMI-010_26	152.7	4.3	0.2	7.0	1.1	0.1	0.7	863.5	8.5	918.8	15.2	918.8	8.5
DMI-010_27	84.5	1.5	0.7	73.7	1.6	0.1	3.0	86.9	1.3	201.4	67.1	86.9	1.3
DMI-010_28	249.6	0.8	1.3	5.8	0.9	0.1	0.6	1024.5	8.9	1093.7	11.2	1093.7	11.2
DMI-010_29	242.2	1.6	0.6	174.8	1.5	0.1	2.8	36.8	0.5	236.6	62.4	36.8	0.5
DMI-010_31	158.3	1.5	0.7	83.7	1.3	0.0	1.4	76.6	1.0	83.1	32.4	76.6	1.0
DMI-010_32	262.1	1.0	1.0	27.6	1.1	0.1	0.9	229.3	2.5	234.2	21.2	229.3	2.5
DMI-010_33	349.4	1.6	0.6	91.6	1.2	0.0	1.3	70.0	0.9	104.1	30.1	70.0	0.9
DMI-010_34	119.1	0.9	1.1	80.8	1.7	0.0	2.8	79.3	1.3	130.8	63.9	79.3	1.3
DMI-010_35	196.3	1.3	0.8	91.6	1.6	0.0	2.0	70.0	1.1	80.7	46.1	70.0	1.1
DMI-010_36	103.9	0.8	1.3	65.3	1.5	0.1	2.0	97.9	1.5	296.0	45.5	97.9	1.5
DMI-010_37	185.1	2.1	0.5	139.0	1.7	0.0	2.4	46.2	0.8	100.5	56.6	46.2	0.8
DMI-010_38	266.2	1.0	1.0	70.5	1.2	0.0	1.5	90.7	1.1	88.8	36.0	90.7	1.1
DMI-010_39	287.3	0.9	1.2	71.9	1.2	0.0	1.2	89.0	1.1	110.6	28.3	89.0	1.1
DMI-010_40	220.6	0.9	1.1	91.4	1.3	0.1	1.8	70.2	0.9	220.7	41.7	70.2	0.9
DMI-010_41	333.0	0.3	3.4	7.2	1.3	0.1	0.7	835.3	9.8	989.2	13.3	989.2	13.3
DMI-010_42	709.2	2.6	0.4	90.1	1.4	0.0	1.2	71.2	1.0	132.7	27.6	71.2	1.0
DMI-010_43	330.7	1.5	0.7	157.1	2.0	0.0	1.8	40.9	0.8	5.2	43.1	40.9	0.8

DMI-010_44	607.0	0.9	1.1	8.0	1.8	0.1	0.6	762.2	13.0	1066.9	12.7	1066.9	12.7
DMI-010_45	94.5	0.9	1.1	84.4	1.7	0.0	2.9	75.9	1.3	150.2	66.5	75.9	1.3
DMI-010_46	287.7	2.1	0.5	161.3	2.2	0.1	2.0	39.8	0.9	230.9	45.3	39.8	0.9
DMI-010_47	590.8	0.6	1.5	91.0	2.0	0.0	1.2	70.5	1.4	47.8	29.1	70.5	1.4
DMI-010_48	278.5	1.0	1.0	5.7	1.7	0.1	0.7	1046.6	16.1	1100.7	14.4	1100.7	14.4
DMI-010_49	128.4	0.5	1.9	258.4	2.4	0.0	4.6	24.9	0.6	135.7	104.2	24.9	0.6
DMI-010_50	238.9	1.4	0.7	81.8	1.4	0.0	1.8	78.4	1.1	147.9	41.7	78.4	1.1
DMI-010_51	137.6	1.3	0.8	71.6	1.9	0.0	2.4	89.4	1.7	29.5	57.3	89.4	1.7
DMI-010_52	228.2	1.1	0.9	3.6	1.4	0.1	0.5	1587.1	19.9	1534.6	9.8	1534.6	9.8
DMI-010_53	125.2	1.6	0.6	85.5	1.6	0.0	2.5	75.0	1.2	37.7	59.8	75.0	1.2
DMI-010_54	115.9	3.5	0.3	23.5	1.8	0.1	1.9	269.2	4.6	733.2	40.0	269.2	4.6
DMI-010_55	315.2	0.3	3.1	25.4	1.6	0.1	1.0	249.3	3.9	283.4	22.6	249.3	3.9
DMI-010_56	463.3	2.0	0.5	140.5	3.1	0.1	2.9	45.7	1.4	750.2	59.5	45.7	1.4
DMI-010_57	246.3	1.2	0.8	69.8	1.3	0.0	1.6	91.7	1.2	56.4	38.5	91.7	1.2
DMI-010_58	356.1	1.7	0.6	75.5	3.1	0.1	2.0	84.9	2.6	399.6	44.2	84.9	2.6
DMI-010_59	209.1	1.2	0.9	75.9	1.5	0.0	1.6	84.4	1.3	73.9	36.5	84.4	1.3
DMI-010_60	51.6	4.5	0.2	4.8	1.3	0.1	0.8	1227.4	14.0	1200.8	15.2	1200.8	15.2
DMI-010_61	229.3	1.9	0.5	72.8	1.3	0.0	1.6	88.0	1.1	45.2	37.3	88.0	1.1
DMI-010_62	84.9	3.9	0.3	3.5	1.2	0.1	0.7	1620.8	17.5	1568.5	12.3	1568.5	12.3
DMI-010_64	102.6	2.6	0.4	3.2	1.4	0.1	0.8	1774.2	21.2	1934.9	14.1	1934.9	14.1
DMI-010_65	158.8	0.9	1.1	71.1	1.4	0.0	2.1	90.0	1.3	126.4	48.3	90.0	1.3
DMI-010_66	141.6	1.3	0.8	76.7	1.3	0.0	2.2	83.5	1.1	22.8	51.4	83.5	1.1
DMI-010_67	79.0	1.5	0.7	88.5	1.9	0.0	4.3	72.4	1.4	24.9	100.9	72.4	1.4
DMI-010_68	838.4	0.9	1.2	7.5	1.4	0.1	0.5	810.8	11.0	1621.1	9.4	1621.1	9.4
DMI-010_69	840.2	4.0	0.2	71.1	1.3	0.1	0.8	90.1	1.1	220.9	18.2	90.1	1.1
DMI-010_70	129.6	1.3	0.8	27.0	1.4	0.1	1.6	234.3	3.2	386.7	35.0	234.3	3.2
DMI-010_71	480.6	1.7	0.6	88.2	1.2	0.0	1.3	72.6	0.9	141.0	30.5	72.6	0.9
DMI-010_72	304.0	0.7	1.4	90.9	1.2	0.0	1.5	70.5	0.8	54.8	34.3	70.5	0.8

DMI-010_73	179.1	1.2	0.9	80.8	1.2	0.1	2.4	79.3	0.9	620.7	51.6	79.3	0.9
DMI-010_74	169.2	1.0	1.0	73.7	1.2	0.0	1.6	86.9	1.0	134.2	37.7	86.9	1.0
DMI-010_75	868.5	2.4	0.4	71.8	1.0	0.1	0.9	89.1	0.9	267.9	20.1	89.1	0.9
DMI-010_76	384.4	1.7	0.6	159.5	1.3	0.0	1.7	40.3	0.5	64.3	39.8	40.3	0.5
DMI-010_77	163.3	0.9	1.1	71.2	1.3	0.0	1.8	89.9	1.2	80.9	42.7	89.9	1.2
DMI-010_78	274.9	1.3	0.8	70.3	1.2	0.0	1.3	91.0	1.1	188.1	29.7	91.0	1.1
DMI-010_80	123.2	2.1	0.5	10.8	1.0	0.1	0.8	569.3	5.5	592.4	18.0	569.3	5.5
DMI-010_81	294.4	0.8	1.3	7.1	1.0	0.1	0.6	848.1	8.3	1117.5	11.3	1117.5	11.3
DMI-010_82	311.1	2.1	0.5	75.6	1.1	0.1	1.5	84.7	1.0	310.9	33.8	84.7	1.0
DMI-010_83	621.9	0.8	1.3	86.9	1.1	0.0	1.0	73.8	0.8	65.5	23.5	73.8	0.8
DMI-010_84	1011.0	1.0	1.0	82.9	1.0	0.0	1.1	77.3	0.8	133.1	24.5	77.3	0.8
DMI-010_86	358.4	0.6	1.5	90.6	1.2	0.0	1.6	70.8	0.9	79.5	38.1	70.8	0.9
DMI-010_87	184.7	0.8	1.3	68.8	1.4	0.0	1.3	93.0	1.3	101.8	31.5	93.0	1.3
GR30_100	211.9	0.5	2.1	5.3	3.8	0.1	1.0	1117.2	39.2	985.4	19.6	42.6	6.1
GR30_99	661.3	0.8	1.3	11.2	3.9	0.1	1.0	552.0	20.6	1435.8	18.1	62.2	4.2
GR30_98	298.2	1.0	1.0	66.3	5.7	0.0	3.1	96.5	5.4	116.3	72.4	75.8	4.0
GR30_97	375.9	0.5	2.2	75.8	4.7	0.1	3.1	84.5	4.0	527.3	65.5	76.3	3.2
GR30_96	462.9	0.4	2.2	25.7	4.1	0.1	1.8	245.9	9.9	261.1	41.5	76.6	2.7
GR30_95	255.9	0.8	1.3	7.4	3.6	0.1	1.1	820.8	28.0	798.8	23.7	79.1	2.8
GR30_94	283.4	1.3	0.8	2.1	3.8	0.2	0.6	2475.3	77.9	2447.4	10.1	79.5	3.3
GR30_93	255.9	0.8	1.3	7.4	3.6	0.1	1.1	820.8	28.0	798.8	23.7	80.3	20.4
GR30_92	462.9	0.4	2.2	25.7	4.1	0.1	1.8	245.9	9.9	261.1	41.5	82.1	3.4
GR30_91	157.1	0.5	2.1	25.3	4.6	0.0	3.1	250.2	11.2	157.7	70.0	82.3	2.9
GR30_90	1915.2	1.4	0.7	69.4	3.6	0.0	1.5	92.2	3.3	115.7	34.2	82.4	3.3
GR30_89	1470.1	0.7	1.5	62.2	4.3	0.1	2.6	102.7	4.4	538.3	56.2	83.1	3.0
GR30_88	2572.5	1.4	0.7	59.0	3.5	0.0	1.0	108.4	3.8	109.0	23.3	84.5	4.0

GR30_87	365.8	1.0	1.0	3.3	3.9	0.1	0.7	1717.7	58.1	1777.3	13.1	87.6	3.3
GR30_86	714.7	1.1	0.9	67.8	4.3	0.0	2.7	94.4	4.0	88.0	62.7	88.2	3.1
GR30_85	1990.7	0.7	1.4	78.0	4.2	0.0	1.7	82.1	3.4	111.8	40.2	90.7	3.4
GR30_84	543.5	0.9	1.2	3.4	3.4	0.1	0.5	1644.3	49.3	1532.0	8.9	92.2	3.3
GR30_83	242.6	0.4	2.4	4.0	3.5	0.1	0.7	1450.3	45.2	1229.1	13.5	94.4	4.0
GR30_82	2536.0	0.3	3.5	16.5	3.4	0.1	0.5	378.8	12.4	452.2	11.6	96.0	2.8
GR30_81	1358.9	0.1	9.0	12.5	3.4	0.1	0.6	496.1	16.2	474.4	12.9	96.5	5.4
GR30_80	386.0	0.6	1.6	23.5	4.3	0.1	1.4	268.6	11.4	471.3	29.9	96.9	3.3
GR30_79	523.0	0.6	1.6	70.5	3.8	0.0	1.7	90.7	3.4	133.8	39.6	97.4	7.8
GR30_78	769.2	0.7	1.4	72.6	3.5	0.1	1.3	88.2	3.1	380.8	29.7	98.1	3.9
GR30_77	1336.8	0.9	1.1	22.1	3.4	0.1	0.8	285.8	9.6	282.0	18.0	98.6	3.3
GR30_76	780.9	0.6	1.7	6.2	4.2	0.1	1.5	967.0	37.9	1203.3	30.0	102.7	4.4
GR30_75	454.4	0.7	1.3	56.1	3.8	0.0	1.7	113.9	4.3	119.3	38.4	107.4	5.1
GR30_74	407.4	1.5	0.7	3.5	3.4	0.1	0.5	1605.8	48.7	1538.3	8.8	108.4	3.8
GR30_73	1006.5	0.5	2.2	8.9	3.8	0.1	0.6	685.3	24.7	708.4	13.2	113.9	4.3
GR30_72	810.5	0.9	1.2	12.1	3.5	0.1	0.7	511.4	17.2	542.5	15.0	117.0	9.2
GR30_71	863.9	0.6	1.6	77.1	3.6	0.0	1.5	83.1	3.0	120.8	34.3	119.4	11.0
GR30_70	1107.2	0.4	2.5	26.3	3.5	0.1	0.8	240.8	8.2	259.9	17.8	166.5	4.6
GR30_69	267.6	1.0	1.0	54.6	8.0	0.1	0.8	117.0	9.2	552.3	18.0	206.4	10.1
GR30_68	1016.5	0.1	8.9	59.5	4.8	0.1	3.0	107.4	5.1	1053.7	59.3	216.5	9.5
GR30_67	160.3	0.8	1.2	27.2	3.1	0.1	1.0	233.1	7.0	235.9	22.9	217.0	12.2
GR30_66	969.9	0.3	3.2	79.8	25.6	0.1	14.7	80.3	20.4	415.1	297.9	227.2	12.5
GR30_65	324.3	0.7	1.4	53.5	9.3	0.0	4.6	119.4	11.0	97.0	106.1	231.2	9.1
GR30_64	1193.7	0.2	6.4	27.9	5.6	0.1	3.0	227.2	12.5	345.3	67.1	233.1	7.0
GR30_63	909.1	0.5	2.0	13.2	5.8	0.1	2.2	470.8	26.4	498.6	48.2	234.9	8.2
GR30_62	429.9	0.2	5.5	103.2	6.8	0.0	3.4	62.2	4.2	77.4	78.0	237.3	7.3
GR30_61	663.1	0.5	2.0	12.9	4.6	0.1	2.3	481.2	21.1	477.5	49.6	240.8	8.2
GR30_60	442.6	0.2	5.6	24.9	5.6	0.1	2.0	253.4	13.9	1158.5	39.3	245.9	9.9

GR30_59	585.9	0.4	2.4	4.5	3.8	0.1	0.9	1305.0	44.7	1571.6	17.3	245.9	9.9
GR30_58	550.3	0.8	1.3	6.6	3.9	0.1	1.3	905.1	32.5	1015.8	26.3	247.0	7.9
GR30_57	452.6	1.5	0.7	3.2	3.6	0.1	1.2	1750.4	54.5	1748.9	21.9	250.1	8.0
GR30_56	1157.2	0.6	1.6	7.9	4.0	0.1	1.2	765.7	28.6	1027.9	24.5	250.2	11.2
GR30_55	928.5	0.7	1.4	11.3	4.0	0.1	1.1	546.8	21.2	666.9	22.7	253.4	13.9
GR30_54	666.8	0.9	1.1	4.2	3.3	0.1	0.7	1367.2	40.2	1576.1	12.4	255.4	7.4
GR30_53	1577.0	0.4	2.6	9.1	3.4	0.1	1.0	670.8	21.6	983.4	19.6	263.2	8.2
GR30_52	1248.5	0.3	3.6	30.7	5.0	0.1	2.2	206.4	10.1	1134.5	44.0	268.6	11.4
GR30_51	623.7	1.4	0.7	73.1	3.8	0.0	2.0	87.6	3.3	119.0	45.4	272.7	9.9
GR30_50	1509.1	1.2	0.8	10.5	3.2	0.1	1.2	588.9	17.8	617.5	24.7	285.8	9.6
GR30_49	605.9	0.7	1.4	7.0	4.1	0.2	0.7	864.1	33.1	2481.0	12.4	296.0	10.0
GR30_48	1265.4	1.2	0.8	4.8	3.3	0.1	0.9	1228.8	36.6	1108.5	17.1	378.8	12.4
GR30_47	616.3	0.4	2.6	24.0	3.2	0.1	1.5	263.2	8.2	271.4	33.2	434.4	20.1
GR30_46	857.8	0.2	5.5	3.4	4.3	0.1	1.3	1677.5	63.8	1837.6	23.0	435.1	32.3
GR30_45	46.8	1.3	0.7	84.5	5.3	0.0	1.7	75.8	4.0	101.3	39.8	468.2	21.8
GR30_44	311.4	0.5	1.8	66.7	3.0	0.0	1.1	96.0	2.8	136.9	25.9	469.6	13.5
GR30_43	2355.1	1.7	0.6	12.9	3.1	0.1	0.8	479.5	14.4	505.7	18.5	470.8	26.4
GR30_42	1047.0	1.2	0.9	25.6	3.3	0.0	1.4	247.0	7.9	150.3	33.3	472.6	14.7
GR30_41	329.9	0.7	1.5	25.3	3.3	0.0	1.5	250.1	8.0	136.5	34.1	479.5	14.4
GR30_40	338.7	0.7	1.5	12.1	2.9	0.1	0.7	511.5	14.5	501.6	16.3	481.2	21.1
GR30_39	1216.4	0.6	1.7	13.1	3.2	0.1	0.8	472.6	14.7	496.0	18.3	496.1	16.2
GR30_38	2100.8	0.3	3.9	13.2	3.0	0.1	1.1	469.6	13.5	603.9	23.5	511.4	17.2
GR30_37	650.3	0.6	1.6	2.2	2.9	0.1	0.6	2458.5	59.4	2307.9	10.8	511.5	14.5
GR30_36	420.8	1.1	0.9	65.2	4.0	0.0	2.6	98.1	3.9	72.6	61.6	539.9	18.3
GR30_35	184.6	0.4	2.4	7.6	2.9	0.1	0.7	796.6	22.0	816.6	14.9	544.3	19.1
GR30_34	696.6	0.5	1.9	66.0	3.4	0.1	1.9	96.9	3.3	253.7	42.6	546.8	21.2
GR30_33	402.1	0.9	1.2	26.7	3.1	0.1	1.4	237.3	7.3	258.4	30.7	552.0	20.6
GR30_32	479.4	0.6	1.8	24.7	3.0	0.1	0.8	255.4	7.4	246.7	18.5	581.8	18.5

GR30_31	1918.8	1.0	1.0	29.2	5.7	0.1	3.1	217.0	12.2	478.9	67.8	588.9	17.8
GR30_30	516.7	0.5	2.1	65.7	8.1	0.0	4.6	97.4	7.8	0.0	0.0	670.8	21.6
GR30_29	1220.6	0.2	5.3	14.3	7.7	0.1	3.8	435.1	32.3	535.4	80.8	685.3	24.7
GR30_28	393.8	0.2	5.5	150.9	14.5	0.1	9.0	42.6	6.1	721.6	180.5	692.2	37.1
GR30_27	375.9	0.5	1.8	13.3	4.8	0.1	2.8	468.2	21.8	393.9	60.5	765.7	28.6
GR30_26	299.4	0.6	1.6	4.7	4.9	0.1	1.6	1237.0	54.8	1203.5	31.1	796.6	22.0
GR30_25	707.0	0.3	2.9	29.3	4.5	0.1	2.0	216.5	9.5	224.8	46.0	802.2	28.1
GR30_24	554.6	0.6	1.8	77.9	3.5	0.1	1.5	82.3	2.9	198.7	34.7	820.8	28.0
GR30_23	1325.6	0.0	21.4	7.5	3.7	0.1	0.9	802.2	28.1	896.5	18.5	820.8	28.0
GR30_22	291.9	0.5	1.9	2.5	3.8	0.1	0.9	2194.8	70.5	2170.1	14.9	852.5	29.4
GR30_21	810.3	0.3	2.9	77.7	4.0	0.0	2.2	82.4	3.3	45.4	52.3	905.1	32.5
GR30_20	1877.4	0.5	2.1	81.0	3.5	0.0	1.4	79.1	2.8	0.0	4.0	985.4	19.6
GR30_19	600.7	0.5	1.9	11.4	3.7	0.1	0.9	544.3	19.1	591.1	19.3	1108.5	17.1
GR30_18	1699.5	0.4	2.4	27.4	4.0	0.1	1.3	231.2	9.1	274.7	28.7	1203.3	30.0
GR30_17	790.2	1.1	0.9	2.5	3.5	0.1	0.7	2134.6	63.1	2039.7	13.2	1203.5	31.1
GR30_16	3117.9	0.5	2.1	64.9	3.4	0.0	1.0	98.6	3.3	118.2	23.7	1229.1	13.5
GR30_15	776.4	0.6	1.7	3.1	3.5	0.1	0.8	1791.6	54.2	1677.2	14.1	1532.0	8.9
GR30_14	1006.9	0.4	2.3	21.3	3.5	0.1	0.9	296.0	10.0	363.3	20.7	1538.3	8.8
GR30_13	455.3	0.6	1.6	11.4	3.5	0.1	0.9	539.9	18.3	626.2	20.1	1571.6	17.3
GR30_12	929.2	0.2	5.8	8.8	5.7	0.1	0.9	692.2	37.1	965.5	18.2	1576.1	12.4
GR30_11	675.0	1.1	0.9	38.2	2.8	0.0	8.7	166.5	4.6	170.5	190.9	1677.2	14.1
GR30_10	716.2	0.4	2.7	4.6	5.6	0.1	1.2	1262.9	63.7	1972.0	21.2	1748.9	21.9
GR30_9	1094.3	0.4	2.8	10.6	3.3	0.1	1.1	581.8	18.5	1020.1	22.6	1757.5	16.1
GR30_8	760.7	0.7	1.5	3.5	3.6	0.1	0.9	1600.3	50.3	1757.5	16.1	1777.3	13.1
GR30_7	1088.7	0.7	1.3	23.1	3.7	0.1	1.1	272.7	9.9	287.7	25.2	1837.6	23.0
GR30_6	700.5	0.5	2.2	26.9	3.6	0.0	1.3	234.9	8.2	160.3	30.3	1972.0	21.2
GR30_5	470.4	0.6	1.7	84.0	4.2	0.1	0.6	76.3	3.2	353.1	13.6	2039.7	13.2
GR30_4	2955.5	1.5	0.7	80.6	4.1	0.1	1.2	79.5	3.3	350.1	27.2	2170.1	14.9

GR30_3	4251.0	1.1	0.9	83.7	3.5	0.0	1.0	76.6	2.7	103.3	23.3	2307.9	10.8
GR30_2	441.8	0.9	1.1	14.3	4.8	0.1	1.1	434.4	20.1	572.2	23.8	2447.4	10.1
GR30_1	641.3	0.4	2.5	7.1	3.7	0.1	0.8	852.5	29.4	1055.6	16.5	2481.0	12.4
DMI-003_1	265.7	0.7	1.4	158.6	1.2	0.0	2.4	40.5	0.5	11.5	55.9	40.5	0.5
DMI-003_2	212.9	0.7	1.4	154.8	1.7	0.0	2.1	41.5	0.7	0.0	133.5	41.5	0.7
DMI-003_3	327.8	0.8	1.2	155.2	1.2	0.0	2.1	41.4	0.5	59.7	50.1	41.4	0.5
DMI-003_4	252.7	0.6	1.8	143.9	1.5	0.1	1.9	44.6	0.7	569.7	41.8	44.6	0.7
DMI-003_5	229.1	0.5	2.0	156.9	1.5	0.0	2.7	41.0	0.6	158.5	61.1	41.0	0.6
DMI-003_6	373.1	0.8	1.3	156.0	1.3	0.1	2.9	41.2	0.5	390.6	64.6	41.2	0.5
DMI-003_7	322.8	0.7	1.4	149.6	1.5	0.0	2.0	43.0	0.6	0.0	17.1	43.0	0.6
DMI-003_8	382.8	0.7	1.5	151.5	1.4	0.0	1.7	42.4	0.6	128.0	40.4	42.4	0.6
DMI-003_9	105.1	2.3	0.4	85.9	1.7	0.1	2.5	74.6	1.3	1077.2	49.0	74.6	1.3
DMI-003_10	282.8	0.7	1.4	151.9	1.3	0.0	2.5	42.3	0.6	71.7	57.8	42.3	0.6
DMI-003_11	396.4	0.9	1.1	151.6	1.3	0.1	2.2	42.4	0.6	342.5	49.0	42.4	0.6
DMI-003_12	419.2	0.9	1.1	151.0	1.3	0.0	2.5	42.5	0.6	109.4	58.1	42.5	0.6
DMI-003_13	362.7	0.8	1.3	148.3	1.3	0.0	2.0	43.3	0.5	109.1	47.5	43.3	0.5
DMI-003_14	315.2	1.0	1.0	152.3	1.3	0.0	1.5	42.2	0.6	79.5	35.4	42.2	0.6
DMI-003_15	342.1	1.0	1.0	150.8	1.2	0.0	2.0	42.6	0.5	189.1	45.2	42.6	0.5
DMI-003_16	248.8	1.0	1.0	152.0	1.3	0.0	2.5	42.3	0.5	0.0	58.4	42.3	0.5
DMI-003_17	388.2	0.9	1.2	152.9	1.3	0.0	1.8	42.0	0.5	79.4	42.1	42.0	0.5
DMI-003_18	245.4	1.0	1.0	153.5	1.3	0.0	1.7	41.9	0.6	101.9	39.7	41.9	0.6
DMI-003_19	485.9	0.8	1.3	152.5	1.5	0.1	1.5	42.1	0.6	291.5	34.4	42.1	0.6
DMI-003_20	462.7	0.5	2.1	158.2	1.3	0.0	1.9	40.6	0.5	0.0	5.8	40.6	0.5
DMI-003_21	234.9	0.7	1.4	155.6	1.3	0.0	2.6	41.3	0.5	63.3	60.5	41.3	0.5
DMI-003_22	130.5	1.0	1.0	148.1	1.9	0.1	2.7	43.4	0.8	1654.2	49.9	43.4	0.8
DMI-003_24	92.9	2.3	0.4	120.2	1.6	0.1	3.5	53.4	0.8	789.0	72.4	53.4	0.8
DMI-003_25	415.5	0.9	1.2	149.9	2.9	0.0	2.3	42.9	1.3	129.3	52.6	42.9	1.3

DMI-003_26	310.7	0.7	1.5	154.6	1.3	0.1	2.2	41.6	0.6	199.0	50.3	41.6	0.6
DMI-003_27	290.9	1.5	0.7	115.3	2.0	0.1	1.9	55.7	1.1	869.9	38.8	55.7	1.1
DMI-003_28	379.6	0.6	1.7	155.6	1.4	0.0	2.1	41.3	0.6	45.7	48.3	41.3	0.6
DMI-003_29	536.0	0.4	2.6	153.3	1.2	0.0	1.4	41.9	0.5	192.9	31.4	41.9	0.5
DMI-003_23	298.5	0.7	1.5	131.8	3.2	0.1	1.9	48.7	1.5	1693.5	34.4	1693.5	1.5

Appendix 6. Cathodoluminescence images of samples analyzed for U-Pb zircon geochronology conducted during this work

Appendix 7. Whole-rock Geochemistry Results

Sample	Lithology	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	MnO	Ni	LOI	Sum
DMT-013	Basalt	57.7	17.75	7.12	3.17	6.6	3.97	0.32	0.47	0.13	0.14	11	3.05	100.52
DMT-015	Basalt	62.3	13.55	7.26	3.84	1.99	3.07	3.06	0.67	0.27	0.11	5	4.64	100.83
DMT-016	Basalt	67	14.45	5.48	1.82	2.17	5.06	2.29	0.67	0.25	0.1	1	2.57	101.95
DMT-017	Basalt	51.4	18.55	8.58	3.08	7.25	4.37	1.11	0.69	0.15	0.12	11	5.87	101.27
DMT-018	Basalt	49.4	17.7	8.94	3.19	6.6	3.86	1.18	0.72	0.18	0.13	12	8.61	100.64
UDB-006	Basalt	46.2	15.15	12	4.53	10.5	1.6	3.42	1.21	0.64	0.26	5	4.68	100.42

Sample	Ba	Co	Cs	Ga	Hf	Nb	Rb	Sn	Sr	Ta	Th	U	V	W	Zr	Y	La	Ce	Pr	Nd	Sm	Eu
DMT-013	261	13	0.13	18.6	1.8	1	4.2	1	586	<0.1	0.88	0.38	172	1	59	13.5	9	18.8	2.81	12.8	2.62	0.8
DMT-015	489	14	0.36	19	4.3	2.9	51.8	1	168	0.1	3.43	1.93	149	1	153	36.3	29	48.8	6.79	30.2	5.92	1.45
DMT-016	621	8	0.1	15.4	4.6	5.1	34.1	1	134.5	0.2	4.98	1.31	110	2	175	28.9	26.4	55.3	7.9	34.3	7.38	1.6
DMT-017	313	21	0.32	19.6	2.2	2.1	14.8	1	441	0.1	1.71	0.44	319	1	74	15.1	11.7	23.8	3.44	15.3	3.18	1.01
DMT-018	346	22	2.18	18.2	2.2	2	17.5	2	771	0.1	1.87	0.54	351	2	81	16.8	12.6	25.5	3.69	16	3.33	1.06
UDB-006	886	36	0.48	19.6	2.6	5.8	48.9	1	1080	0.2	1.6	0.98	427	4	96	23.1	16.7	33.9	4.59	22.5	5.1	1.54

Sample	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Mo	Cu	Pb	Zn	Cr	As	Cd	Ag	Tl	Sc
DMT-013	2.77	0.42	2.3	0.5	1.47	0.26	1.44	0.23	1	57	4	74	40	<0.5	<0.5	<0.5	<10	15
DMT-015	6	0.93	5.13	1.16	3.75	0.55	3.56	0.51	1	106	12	101	20	<0.5	<0.5	<0.5	<10	16
DMT-016	6.42	0.95	4.97	1.07	2.98	0.49	2.96	0.51	1	18	4	62	20	<0.5	<0.5	<0.5	<10	15
DMT-017	3.27	0.49	2.65	0.54	1.72	0.27	1.52	0.26	1	329	6	70	30	<0.5	<0.5	<0.5	<10	23
DMT-018	3.85	0.58	3.05	0.66	1.89	0.28	1.96	0.29	<1	62	3	73	30	<0.5	<0.5	<0.5	<10	24
UDB-006	5.83	0.86	3.96	0.83	2.4	0.33	1.99	0.31	<1	263	3	114	20	<0.5	<0.5	<0.5	<10	29

Appendix 8. Zircon (U-Th)/He Results

Samples	U (ppm)	Th (ppm)	4He nmol/g	eU (ppm)	Raw Age (Ma)	2s ± Age (Ma)	Rs (μm)	Ft	Corrected Age (Ma)	2s ± Age (Ma)
DMT_003_Zr1	259.9	70.7	54.2	276.5	36.3	1	64.1	0.807	45.0	1.2
DMT_003_Zr2	285.9	87.6	56.5	306.5	34.1	1	46.5	0.739	46.1	1.2
DMT_003_Zr4	291.3	90.4	51.8	312.6	30.7	1	43.3	0.722	42.5	1.4
BTU_015_Zr2	968.1	343.7	215.4	1048.9	38.0	1.4	42.0	0.714	53.2	2.0
BTU_015_Zr3	919.0	299.7	204.0	989.4	38.1	1.4	51.6	0.763	50.0	1.8
BTU_015_Zr4	174.5	87.4	40.3	195.0	38.2	1.4	38.7	0.690	55.3	2.0
UDB_032_Zr1	306.2	98.1	92.9	329.3	52.1	2	55.7	0.780	66.8	2.4
UDB_032_Zr2	774.0	411.0	103.9	870.6	22.1	0.8	51.9	0.763	29.0	1.2
UDB_032_Zr3	289.5	101.9	108.1	313.5	63.6	2.8	58.6	0.790	80.6	3.6
UDB_032_Zr4	348.5	59.1	161.2	362.4	82.0	3.6	42.4	0.719	114.1	5.2
UDB_032_Zr5	575.0	277.4	133.9	640.2	38.7	1.6	57.6	0.785	49.2	2.2
UDB_063_Zr1	364.2	68.9	194.3	380.4	94.0	6.2	50.7	0.762	123.4	8.2
UDB_063_Zr2	2184.7	296.5	465.4	2254.4	38.2	2.6	51.3	0.763	50.0	3.4
UDB_063_Zr3	583.8	90.5	159.0	605.1	48.6	3.2	42.6	0.719	67.5	4.6
UDB_063_Zr4	61.2	25.2	8.4	67.1	23.1	1.6	52.9	0.768	30.1	2.0
UDB_063_Zr5	286.9	132.9	45.7	318.1	26.6	0.6	47.7	0.744	35.7	1

Appendix 9. Summary of Fission-Track Analysis

Sample	Unit	Stratigraphic Age (Ma)	# of Grains	Rho-S (Ns)	Rho-I (Ni)	Rho-D (Nd)	P(x ²) %	Age ± 2s (Ma)	Dpar (µm)	SD (µm)	# Lengths	Mean Track Length (µm)	Error (µm)
UDB-032	Penderisco Fm.	Late Cretaceous	33	0.41 (75)	4.14 (745)	20.5 (12924)	39.3	13.1 ± 1.6	2.60	0.10	0	NA	NA
UDB-063	Penderisco Fm.	Late Cretaceous	30	0.33 (47)	3.02 (430)	20.6 (12924)	81.2	14.2 ± 2.2	2.49	0.11	0	NA	NA
DMT-003	Cruces Fm.	42.0 ± 0.4	30	0.98 (108)	3.18 (351)	20.7 (12924)	100.0	40.2 ± 4.6	2.96	0.31	10	15.0	0.9
DMT-008	Guineales Fm.	Late Miocene-Pliocene	44	0.80 (141)	4.06 (711)	20.8 (12924)	57.9	26.1 ± 2.6	2.29	0.20	0	NA	NA
DMT-010	Guineales Fm.	Late Miocene-Pliocene	41	0.61 (132)	3.03 (658)	20.9 (12924)	0	26.5 ± 2.7	2.48	0.20	0	NA	NA
DMT-012	Modern Sediments	Present	49	1.04 (210)	7.1 (1435)	21.0 (12924)	0	19.5 ± 1.6	2.23	0.15	0	NA	NA

Rho-S and Rho-I are the spontaneous and induced track density, respectively ($\times 10^5$ tracks/cm²). Ns and Ni are the number of counted spontaneous and induced tracks, respectively, which were used for estimating Rho-S and Rho-I

Rho-D is the induced track density measured in the external mica detector, attached to a CN1 dosimetry glass ($\times 10^5$ tracks/cm²).

Nd is the number of counted tracks for estimating Rho-D

P(x²) is the chi-square probability. Values above 5% are considered to represent a single population ages (Galbraith, 1981)

Appendix 10. Apatite (U-Th)/He Results

Sample	U (ppm)	Th (ppm)	Sm (ppm)	eU (ppm)	Raw Age (Ma)	2s ± Age (Ma)	Rs (µm)	Ft	Corrected Age (Ma)	2s ± Age (Ma)
DMT-003 1	13.1	218.4	85.7	64.4	9.3	0.7	43.2	0.7	14.2	1.1
DMT-003 2	6.2	62.4	63.3	20.9	14.3	1.1	51.5	0.7	20.2	1.6
DMT-003 3	16.6	55.5	73.7	29.6	26.0	1.4	48.6	0.7	37.6	2.1
DMT-003 4	12.5	17.2	66.6	16.5	12.4	1.3	48.3	0.7	18.0	1.9
DMT-003 5	6.6	109.0	44.6	32.2	8.8	1.0	46.4	0.7	13.1	1.5
BTU-015 1	14.4	35.3	482.7	22.7	4.7	1.1	40.6	0.6	7.5	1.7
BTU-015 2	14.6	30.9	239.6	21.8	3.5	2.2	35.0	0.6	6.2	3.8
BTU-015 3	19.4	33.6	189.4	27.2	4.0	1.1	44.2	0.7	6.1	1.7
BTU-015 4	6.5	22.4	240.4	11.7	4.0	3.2	37.9	0.6	6.5	5.3
BTU-015 5	3.7	12.4	182.5	6.6	2.1	8.9	32.1	0.5	3.9	16.7
DMT-010 1	7.4	24.9	45.6	13.3	3.6	0.9	57.5	0.7	4.9	1.2
DMT-010 2	10.4	37.3	56.1	19.2	4.2	1.3	42.6	0.6	6.5	2.0
DMT-010 3	7.2	24.4	45.0	12.9	3.4	2.3	44.7	0.7	5.2	3.4
DMT-010 4	8.3	28.1	52.0	14.9	9.8	1.4	50.6	0.7	13.9	2.0
UBD-063 1	11.3	69.3	86.7	27.6	6.9	0.6	53.1	0.7	9.7	0.8
UBD-063 2	6.6	23.2	50.7	12.1	5.4	1.4	52.0	0.7	7.6	2.0
UBD-063 3	7.9	35.6	62.2	16.2	4.6	1.6	42.1	0.6	7.1	2.6
UBD-063 4	7.2	23.7	42.8	12.7	4.0	2.3	43.1	0.7	6.1	3.5
UBD-063 5	7.7	36.0	67.7	16.1	3.7	1.9	44.7	0.7	5.6	2.8
UDB-032 1	45.1	65.4	33.1	60.5	2.0	0.6	38.9	0.6	3.3	0.9

Appendix 11. Input parameters for back-stripping of the Atrato Basin stratigraphic data

Name	Base Depth (km)	Age of Base (Ma)	Sea-Level at Base (km)	Water Depth at Base (km)	Top Depth (km)	Age of Top (Ma)	Sea-Level at Top (km)	Water Depth at Top (km)	Density (kg/cm3)	Porosity Coefficient	Surface Porosity (%)	Basin Type
Uva Fm.	3.185	29.4	0.02	2.5	2.758	14.8	0.15	2	2700	0.6	60	Marine
Napipí Fm.	2.758	14.8	0.15	2	2.225	13.8	0.12	1.5	2700	0.51	63	Marine
Unconf.	2.225	13.8	0.12	1.5	2.225	11.8	0.05	1	0	0	0	Marine
Sierra Fm.	2.225	11.8	0.05	1	1.42	7	-0.02	0.5	2700	0.6	67	Marine
Munguidó Fm.	1.42	7	-0.02	0.5	0	3.4	0.05	0.15	2700	0.6	67	Marine

Appendix 12. Principles of the Apatite Fission-Track External Detector Method

Spontaneous decay of radioactive nuclides, either alpha decay or fission decay, constitutes the basis of the entire series of methods for radiometric dating of rocks (i.e. $^{238}\text{U} - ^{206}\text{Pb}$, $^{235}\text{U} - ^{207}\text{Pb}$, $^{87}\text{Rb} - ^{87}\text{Sr}$, $^{176}\text{Lu} - ^{176}\text{Hf}$, fission-tracks, etc.). Basically, the proportional abundance of the radiogenic product (daughter nuclei) and the radioactive isotope (parent nuclei), knowing the decay rate or constant, enable to determine the approximate time since the radiometric system has been at temperatures low enough for retention of the daughter product in the mineral's crystal lattice. (Dickin, 2005; Dodson, 1973; Faure, 1986). Among the great variety of radioisotopic systems, those with the lowest ranges of closure temperatures ($< 300^{\circ}\text{C}$) are known as Low-Temperature Thermochronometers (Reiners and Ehlers, 2005) and are used to reconstruct thermal histories of rocks through middle-upper crustal levels ($< 10\text{-}15\text{ Km}$), where geological processes like evolution of sedimentary basins, hydrocarbon generation, and long-term landscape evolution, can be addressed (Donelick et al., 2005; Farley, 2002; Gallagher et al., 1998; Reiners & Brandon, 2006).

Figure 22. Estimated closure temperatures for different thermochronometers and geochronometers. Modified from (Reiners et al., 2005)

3.5.1. Apatite Fission-Track

3.5.1.1. Spontaneous Fission of ^{238}U

The radioactive isotope ^{238}U spontaneously decays by a series of α (^4He nuclei) and β (transformation of a neutron into a proton and an electron, the latter being expelled from the atom) particle emissions. Additionally, nuclear fission of ^{238}U , when an unstable nucleus splits into a pair of highly charged fragments, produces a micrometric scale damage trail into the lattice of the host mineral (i.e. apatite, zircon, monazite, titanite) called latent spontaneous fission-track (Tagami and O'Sullivan, 2005). The most accepted theory about how fission-tracks are formed is the “ion explosion spike” model proposed by Fleischer et al. (1975). The model suggests that rapid moving of a positively-charged particle and consequent repulsion of the positively-ionized lattice atoms yields vacancies.

Figure 23. Schematic representation of the “ion explosion spike” model. Modified from (Gallagher et al., 1998)

3.5.1.2. Annealing of Fission-Tracks

Fission-tracks begin to anneal as they are formed at temperatures above $\sim 100^\circ\text{C}$ (Donelick et al., 2005; Reiners and Brandon, 2006). Nonetheless, both natural and laboratory experiments have demonstrated that temperatures at which fission-tracks in apatite are partially or totally annealed are also a function of the cooling rate and the chemical composition (i.e. proportional abundance of Cl, F or OH) (Ketcham et al., 2007). The intersection of tracks with a polished and etched internal surface of an apatite crystal has the form of a rhomboid called *etch-pit*. The

length of its longer axis, known as the *Dpar*, is a parameter that has empirically been suggested to constitute a proxy for the annealing kinetics of the fission-tracks (Donelick et al., 2005; Ketcham, 2005; Ketcham et al., 2007; Tagami and O’Sullivan, 2005). Therefore, the length distribution of apatite fission-tracks records a protracted cooling history of a rock sample instead of a simple cooling age through a certain closure temperature (Gallagher et al., 1998). Despite of the complexity of the kinetics for fission-track annealing, a temperature range of approximately between 60°C and 130°C, called the *Partial Annealing Zone (PAZ)*, is widely accepted in the scientific community (Gleadow and Duddy, 1981; Reiners and Brandon, 2006).

3.5.1.3. On the Visualization of Fission-Tracks

The nanometric scale of the width of natural latent fission-tracks render their observation only possible using transmission electron microscopes (TEM’s). For this reason, chemical etching of fission-track host materials has been a widely used technique in order to enlarge and make them visible under an optical microscope. Fission-tracks lengths are enlarged because the atomic disordered nature of the region where they form make it more susceptible to dissolution and chemical etching than the surrounding area (Tagami and O’Sullivan, 2005). Etching with 5.5 M HNO_3 for 20 s at 21°C of apatite grains mounted and polished in an epoxy resin is the most common routine used for fission-track analysis in this mineral (Donelick et al., 2005) and was the routine adopted in the present work.

Figure 24. A) Schematic illustration of an apatite grain mount; B) Polished surface before and after etching.

3.5.1.4. Fission-Track Ages Determination

As mentioned before, apatite fission-track (AFT) dating is analogue to most commonly used geochronological systems in that, knowing the decay constant, the concentration of a parental (radioactive) and a daughter (radiogenic) isotope must be measured in a host material in order to retrieve an age. Particularly, in the AFT system, the parental isotope is ^{238}U , and the radiogenic product is not an isotope but the physical damage called fission-track. On this basis, the fundamental equation of geochronological systems,

$$D = N(e^{\lambda t} - 1) \quad (1)$$

where D is the daughter or radiogenic nuclei, N is the abundance of the parental nuclei at the time t , and λ is the decay constant, has been modified for fission-track single-grain age determination in accordance with the equivalent terms.

$$N_s = \frac{\lambda_f}{\lambda_d} N(e^{\lambda_d t} - 1) \quad (2)$$

Here, N_s is the number of spontaneous fission-tracks (number of tracks per unit volume), λ_f is the decay constant for spontaneous fission of ^{238}U , λ_d is the decay constant of ^{238}U by α -emission ($1.55125 \times 10^{-10} \text{y}^{-1}$), and N_{238} is the number of atoms of ^{238}U per unit volume. N_s is directly determined by counting the number of fission-tracks from a selected area within an etched apatite crystal. However, the determination of ^{238}N , the parental nuclei abundance at the time t , is not straightforward. For this, two principal analytical techniques are commonly used: Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) and the External Detector Method (EDM) (Donelick et al., 2005; Gallagher et al., 1998; Hasebe et al., 2004; Tagami and O'Sullivan, 2005). Here I briefly describe the EDM method, the one used in this work, following the procedures described in Donelick et al., (2005). The age calculation equations and its derivations are taken and modified from Tagami & O'Sullivan (2005).

3.5.1.5. Determination of ^{238}N using the External Detector Method (EDM) and Age Calculation

In order to measure the concentration of ^{238}U atoms, a fission-track-free external detector with low-uranium concentration (typically a muscovite sheet) is attached to an apatite grain mount and then irradiated with thermal neutrons in a nuclear reactor facility aiming to induce fission of ^{235}U .

Figure 25. A) Schematic illustration showing the external detector attaching; B) Generation of induced fission-tracks after thermal neutron irradiation

Then, the resultant number of induced fission-tracks is given by:

$$N_i = {}^{235}\text{N} \sigma_f \varphi \quad (3)$$

where ^{235}N is the abundance of ^{235}U per unit volume, σ_f is the cross-section for induced nuclear fission, and φ is the thermal neutron fluence. Therefore, after equations (2) and (3):

$$t = \frac{1}{\lambda_d} \ln \left\{ 1 + \left(\frac{\lambda_d}{\lambda_f} \right) \left(\frac{N_s}{N_i} \right) I \sigma_f \varphi \right\} \quad (4)$$

where I is the isotopic ratio $^{235}\text{U}/^{238}\text{U}$ (7.2527×10^{-3}). Given that only tracks that intersect the surface of etched mounts are visible under microscope, an integrated factor of registration efficiency Q , and an integrated geometry factor of etched surface G , are added to the equation (4), thus:

$$t = \frac{1}{\lambda_d} \ln \left\{ 1 + \left(\frac{\lambda_d}{\lambda_f} \right) \left(\frac{\rho_s}{\rho_i} \right) I \sigma_f \varphi Q G \right\} \quad (5)$$

where ρ_s and ρ_i are the surface density of spontaneous and induced fission-tracks respectively. Apatite fission-tracks are observed in a polished and etched surface that intersect tracks both from above and below (removed and remaining parts of the grain respectively). This registration geometry for fission-tracks is referred as a 4π geometry, where $G=0.5$ (Donelick et al., 2005). ρ_i is determined by counting an area on the mica detector that was directly coupled with the counted area in the apatite grain. Induced tracks hosted in the external detector are previously revealed by etching with 49% HF during 15 min at $20 \pm 1^\circ\text{C}$ (Sobel and Seward, 2010).

Figure 26. Schematic illustration of counting area selection. A) Apatite grains-mount; B) Mica detector

Since the measurements of the thermal-neutron-flux is extremely difficult, standard glasses with known uranium concentration, and their respective external detectors, are positioned at the top and the bottom of a series of stacked mounts being irradiated. Induced fission-track density is determined for each glass, and then a corresponding induced track density ρ_d is calculated for each sample according to its position in the sample stack by linear interpolation. Now, given that:

$$\varphi = B \rho_d \quad (6)$$

where B is a calibration constant empirically determined, the age calculation equation results in:

$$t = \frac{1}{\lambda_d} \ln \left\{ 1 + \left(\frac{\lambda_d}{\lambda_f} \right) \left(\frac{\rho_s}{\rho_i} \right) I \sigma_f B \rho_d Q G \right\} \quad (7)$$

Nevertheless, although it is possible to determine the parameters B , λ_f , and Q , the subcommission on Geochronology of the International Union of Geological Science (IUGS), recommend the use of the zeta ζ age calibration factor, which is based on the analysis of known ages standards (Hurford, 1990). The zeta factor is defined by:

$$\zeta = B \frac{I \sigma_f}{\lambda_f} \quad (8)$$

Because Q is always the same between age standards and age-unknown samples, as long as they are analyzed following the same experimental conditions, this parameter is ignorable. Finally, the age calculation equation for apatite fission-track, using the EDM and the zeta age calibration method is given by:

$$t = \frac{1}{\lambda_d} \ln \left\{ 1 + \lambda_d \zeta \rho_d \left(\frac{\rho_s}{\rho_i} \right) G \right\} \quad (9)$$

Then, the symmetrical error for an apatite single-grain age is given by:

$$\sigma_t = \sqrt{\left\{ \frac{1}{N_s} + \frac{1}{N_i} + \frac{1}{N_d} + \left(\frac{\sigma_\zeta}{\zeta} \right)^2 \right\}} \quad (10)$$

where, N_d is the number of induced fission-tracks counted in the mica detector of the standard glasses irradiated with the samples, used to determine ρ_d . When determining the fission-track age of a bedrock sample, around 20-30 individual ages are obtained, then a pooled age is calculated using:

$$t_{pooled} = \frac{1}{\lambda_d} \ln \left\{ 1 + \lambda_d \zeta \rho_d \left(\frac{\sum N_s}{\sum N_i} \right) G \right\} \quad (11)$$

Otherwise, when treating detrital samples, 50-100 individual ages are needed to characterize the cooling signal derived from the sources (Bernet and Spiegel, 2004; Brewer et al., 2003). In this case, a classical Probability Density Function (PDF) is used to examine data distribution (Garver et al., 1999; Ruhl and Hodges, 2005)

$$PDF = \frac{1}{\sigma_t \sqrt{2\pi}} e^{\left\{ -\frac{1}{2} \left(\frac{t-t_c}{\sigma_t} \right)^2 \right\}} \quad (12)$$

where, t_c is the measured age and σ_t the respective error.