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Apatite LA-ICP-MS U-Pb and fission-track geochronology of the Caño Viejita gabbro in E-Colombia: Evidence for Grenvillian intraplate rifting and Jurassic exhumation in the NW Amazonian Craton.

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1 **Apatite LA-ICP-MS U-Pb and fission-track geochronology of the Caño Viejita gabbro in**
2 **E-Colombia: Evidence for Grenvillian intraplate rifting and Jurassic exhumation in the**
3 **NW Amazonian Craton.**

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5
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15
16 **ABSTRACT**

17 The 1.80-1.76 Ga crystalline basement in Colombia as part of the W-Amazonian Craton is
18 composed mainly of gneisses, granitoids and migmatites, affected later by several
19 compressive and extensional events resulting for example in A-type granites, but also mafic
20 intrusions and dikes. Here we present, after a revision of main geological features, research
21 results obtained on the NW-SE trending ilmenite-apatite-rich Caño Viejita gabbro in the SW-
22 Vichada department some 500 km east of Bogota. Petrographic and geochemical data hint to
23 a metaluminous continental alkaline gabbro enriched in K, Ti and P, possibly due to
24 continental crust reworking or magma mixing, as also confirmed by trace elements
25 characteristics in the apatites like HREE enrichment (Ce/Yb)_{cn} 12-13, negative Eu-anomaly,
26 and Y, Th, Sr, Mn ratios. LA-ICP-MS U-Pb apatite geochronology suggests an early
27 Neoproterozoic emplacement age between 975±9 and 1002±21 Ma related with rifting
28 triggered by the Amazonia-Baltica-Laurentia collision during the Rodinia Supercontinent
29 assembly and associated Grenvillian events. These events also caused mafic intrusions in
30 other parts of the craton. Apatite fission track thermochronometry and thermal history

31 modelling on one sample suggest the onset of the final exhumation stage during Jurassic
32 (~180 Ma), which brought the rocks slowly to their current outcrop position.

33

34 **Keywords:** U-Pb apatite chronology, apatite fission-track thermochronology, olivine gabbro,
35 Amazonian Craton, Neoproterozoic, Grenvillian.

36

37 **1. Introduction**

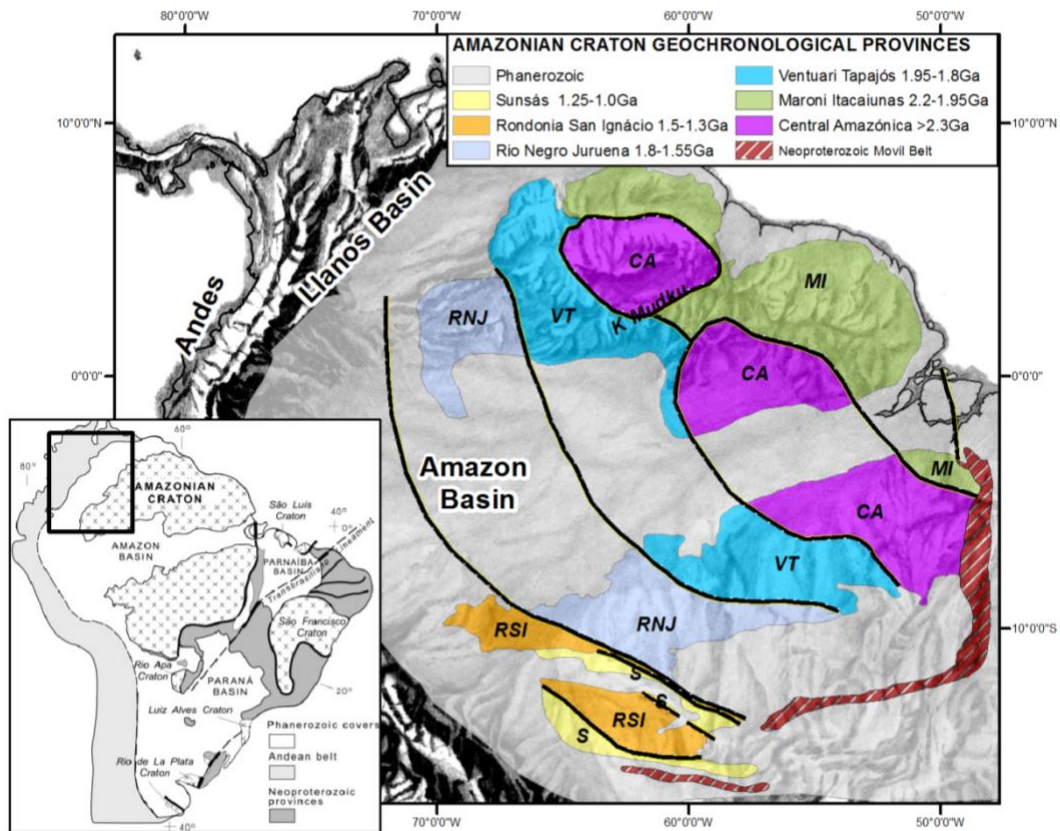
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39 The Amazonian Craton is one of the largest Precambrian continental nuclei in the world
40 comprising huge parts of NW-South America, mainly in Brazil, but also in Venezuela,
41 Guyana, Suriname, French Guyana and NE-Colombia. It formed during the Paleo-
42 Mesoproterozoic due to several accretion events, was affected by extensional and crust
43 consuming episodes, which all resulted in complex geochronological provinces (**Error!**
44 **Reference source not found.**). These provinces have been (re)defined and refined over the
45 last years and the exact positions of their boundaries is still a matter of debate (Cordani et al.,
46 2009, 1979; Kroonenberg, 2019; Santos et al., 2000; Tassinari and Macambira, 1999;
47 Teixeira et al., 1989). The NW Amazonian Craton that outcrops in Eastern Colombia yields
48 ages between ~1.86-1.70 Ga and is defined as part of the Mitú Migmatitic Complex (Galvis et
49 al., 1979; Rodríguez et al., 2011) or better the Mitú Complex (Bonilla et al., 2019; López et
50 al., 2007). This Mitú Complex is itself a portion of the 1.86-1.55 Ga Rio Negro-Juruena
51 Geochronological Province (Tassinari et al., 1996; Tassinari and Macambira, 1999). Older
52 (~1.98 Ga) metavolcanic rocks of the Atabapo-Río Negro Gneiss may testify remains of the
53 Trans-Amazonian basement (Kroonenberg, 2019) and not of the Mitú Complex accretion.
54 This complex was affected by several magmatic and tectonic episodes during the
55 Mesoproterozoic (1.6-1.0 Ga), among them (in Colombia 1.40-1.34 Ga) intraplate A-type

56 granite emplacements like the Parguaza and Matraca rapakivi granites (Bonilla et al., 2013;
57 Bonilla et al., 2016; Gaudette et al., 1978) and the Nickerie-K'Mudku thermal event 1.3-1.0
58 Ga ago deduced from far-reaching K/Ar and Rb/Sr ages resetting.

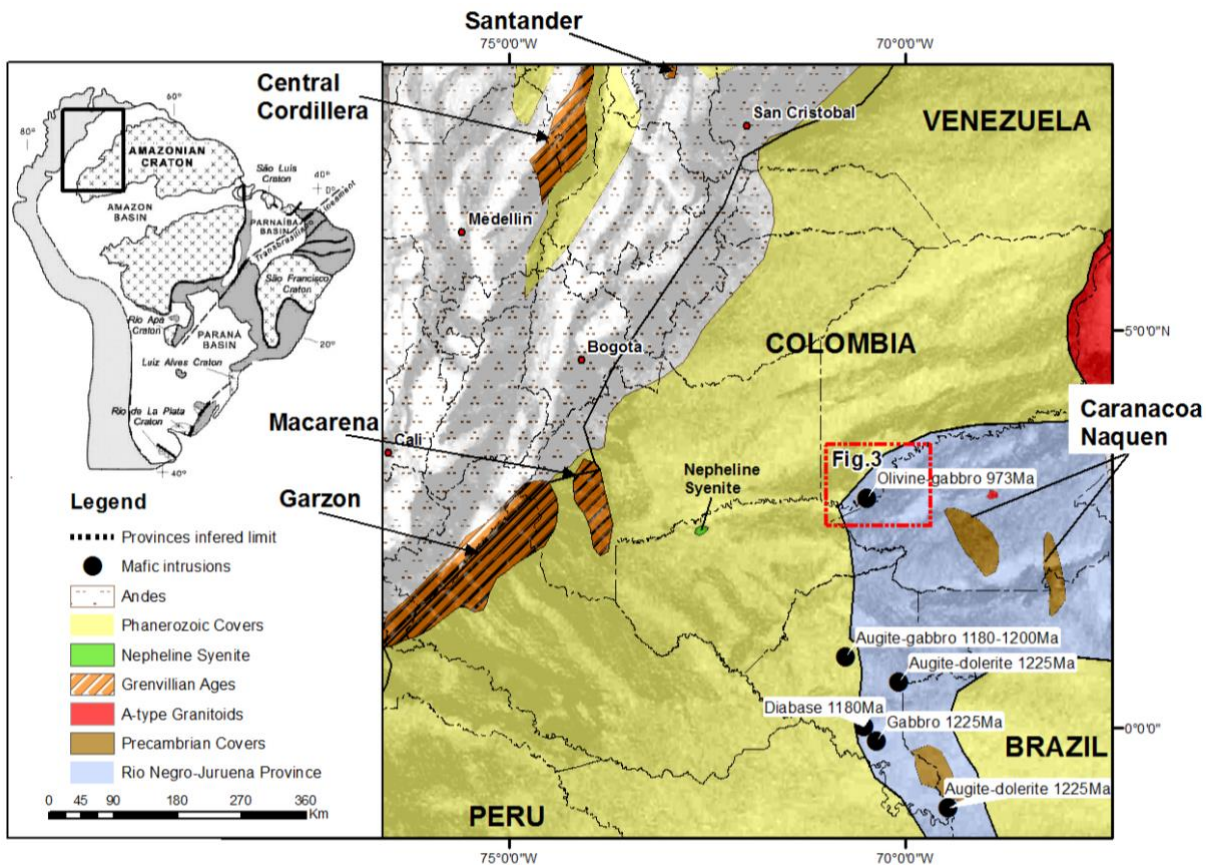
59

60 The youngest of the geochronological Amazonian Craton provinces identified hitherto is the
61 1.25-1.0 Ga old Sunsás Province (**Error! Reference source not found.**), a late
62 Mesoproterozoic collisional metamorphic belt in the southwestern margin of the Amazonian
63 Craton which constitutes an important paleogeographic link between the late Meso- and the
64 early Neoproterozoic, when Amazonia, Baltica and Laurentia became part of the Rodinia
65 supercontinent first proposed by Hoffman (1991) and confirmed by further studies (Cardona
66 et al., 2010; Cordani et al., 2010, 2009; Dewanckele et al., 2014). There is no reason why
67 younger accretionary belts, like the Rondonia-San Ignacio (1.55–1.3 Ma) and the Sunsás
68 (1.25–0.99 Ga) orogenic belts in the southern block, should not extend below the Amazon
69 Basin until the North Andean foreland. Covered by thick Cenozoic sediments (Cordani et al.,
70 2009; Santos et al., 2000; Tassinari and Macambira, 1999, 2004) and with dense tropical
71 forest and soils, their identification is difficult. However, several Grenvillian-age basement
72 inliers were identified in the northern Andes of Colombia (Figure 2), Ecuador and Peru (see
73 e.g. Restrepo-Pace and Cediél, 2010), although their lithostratigraphic and tectonic history
74 seem to differ somehow from that of the Sunsás belt.



75

76 **Figure 1** The Amazonian Craton in South America and Geochronological Provinces after
 77 Tassinari and Macambira (1999). CA: Central Amazonica, MI: Maroni-Itacaiunas, VT:
 78 Ventuari-Tapajós, RNJ: Rio Negro-Juruena, RSI: Rondonia-San Ignacio, S: Sunsás. The
 79 extended Phanerozoic sediments W of the Andes as those filling the Llanos Basin cover large
 80 parts of the Pre-Cenozoic rocks, and only small portions of Precambrian units like the Sunsás
 81 geochronological province the area of the (S) were identified hitherto in Colombia.



82

83 **Figure 2** Location of the study area (red rectangle within the blue-marked Rio Negro-Juruena
 84 Province) in the Colombian part of the NW Amazonian Craton. Also shown are A-type
 85 granitoids to the East (Parguaza and Matraca rapakivi granites), Grenvillian-age remnants to
 86 the West near and within the Andes, the Ecarian to Cambrian Nepheline Syenite of San Jose
 87 de Guaviare, Precambrian (Caranacoa and Naquén) to Phanerozoic covers and ages of
 88 some mafic rock outcrops (Table 1). Modified after Cordani et al., 2010; Tassinari and
 89 Macambira, 1999; Ibañez et al., 2011, 2016; Bonilla et al., 2016.

90

91 Consequently, this belt could represent a separate composite orogeny (Cardona et al., 2010;
 92 Ibañez, 2010). Based on drill core sample analyses, Ibañez (2010) suggested the existence
 93 of a younger orogenic belt in Colombia called the “Putumayo Orogen” assumed to be coeval
 94 with the Sunsás belt. Both have a distinctly different posterior geological evolution, resulting,
 95 amongst others, in different structure and fabric. The Putumayo Orogen is marked by two
 96 evolutionary stages in a Rodinian context: i.e. an early tectonometamorphic event (1.05 Ga),
 97 followed by anatexis melting (1.01 Ga) resulting from an inferred arc-continent collision

98 followed by a final continent-continent collision and associated granulite-facies
99 metamorphism (~0.99 Ga) (Ibañez et al., 2015; Ibañez, 2010). Relics of both events are
100 found sporadically along the Colombian Andes as basement inliers (Figure 2) with U-Pb
101 zircon ages of ~1.1- 0.99 Ga (Cardona et al., 2010; Ibañez et al., 2015; Ibañez, 2010;
102 Restrepo-Pace, 1995) possibly as product of a continent-continent collision (Amazonia-
103 Baltica in this case) during the aggregation of the Mesoproterozoic supercontinent Rodinia,
104 as first proposed by Hoffman (1991). Rivers (1997) suggested three orogenic pulses in the
105 Canadian Grenville province, the Elzevirian (starting ~1.35 Ga), Ottawan (~1.15 Ga) and
106 Rigolet (~1.0 Ga). Only the last episode (Rigolet) has affected the entire magmatic-tectonic
107 Grenville-province where indeed the Sunsás-belt acted as the Amazonia-Baltica counterpart
108 of the Grenville belt on the Laurentia side during the collision that culminated in the final
109 amalgamation of the Rodinia supercontinent.

110

111 Several intraplate rifting events have been recognized in the Amazonian Craton as responses
112 to the collisions at its borders (Cordani et al., 2010; Santos et al., 2008; Teixeira et al., 2010).
113 In the whole Rio Negro-Juruena Province, anorogenic granite intrusions with ages between
114 1.6-0.97 Ga are reported (Bettencourt et al., 1999; Bonilla et al., 2013; Dall'Agnol et al., 1999;
115 Gaudette et al., 1978; Bonilla et al., 2016), whereas the less common mafic to ultramafic
116 intrusive rocks yield Rb-Sr and K-Ar whole-rock isochron ages between 1.20-0.94 Ga (Priem
117 et al., 1982; Tassinari et al., 1996; Teixeira and Tassinari, 1976). In the SW-Amazonian
118 Craton some mafic rocks associated with a rift system as response to the Sunsás orogeny
119 form part of a well-defined convergent active margin (Cordani et al., 2010; Santos et al.,
120 2008; Teixeira et al., 2010). This indicates that while the western side of the Amazonian
121 Craton (Amazonia) was colliding against Baltica and Laurentia to build Rodinia, expressing

122 itself in the Grenvillian-Sunsás orogeny, rifting had already initiated further inland during the
123 Late Mesoproterozoic-Early Neoproterozoic (Cordani et al., 2010; Teixeira et al., 2010).

124

125 In this work, we show further evidence of Grenvillian-age mafic rift or intraplate magmatism in
126 the NW Amazonian Craton in Colombia based on petrographic, geochemical and U-Pb
127 apatite LA-ICP-MS analysis of the NW-SE trending ilmenite-apatite-rich Caño Viejita gabbro
128 in the SW-Vichada department some 500 km east of Bogota. Apatite fission-track
129 thermochronometry suggests furthermore a continuous exhumation and denudation process
130 of these rocks since the Jurassic until their current outcrop position.

131

132 **2. Geological and tectonic setting**

133

134 The Colombian part of the Amazonian Craton, which represents less than 10% of this
135 Precambrian nucleus in South America, outcrops in Vichada, Guainía, Vaupés, Caquetá and
136 Guaviare departments (**Error! Reference source not found.** and Figure 2) but is largely
137 covered by thick sedimentary sequences in the Amazonas and Llanos basins as weathering
138 and erosion products of its complex history.

139 **2.1 Eastern Colombian basement (1800-1500Ma)**

140

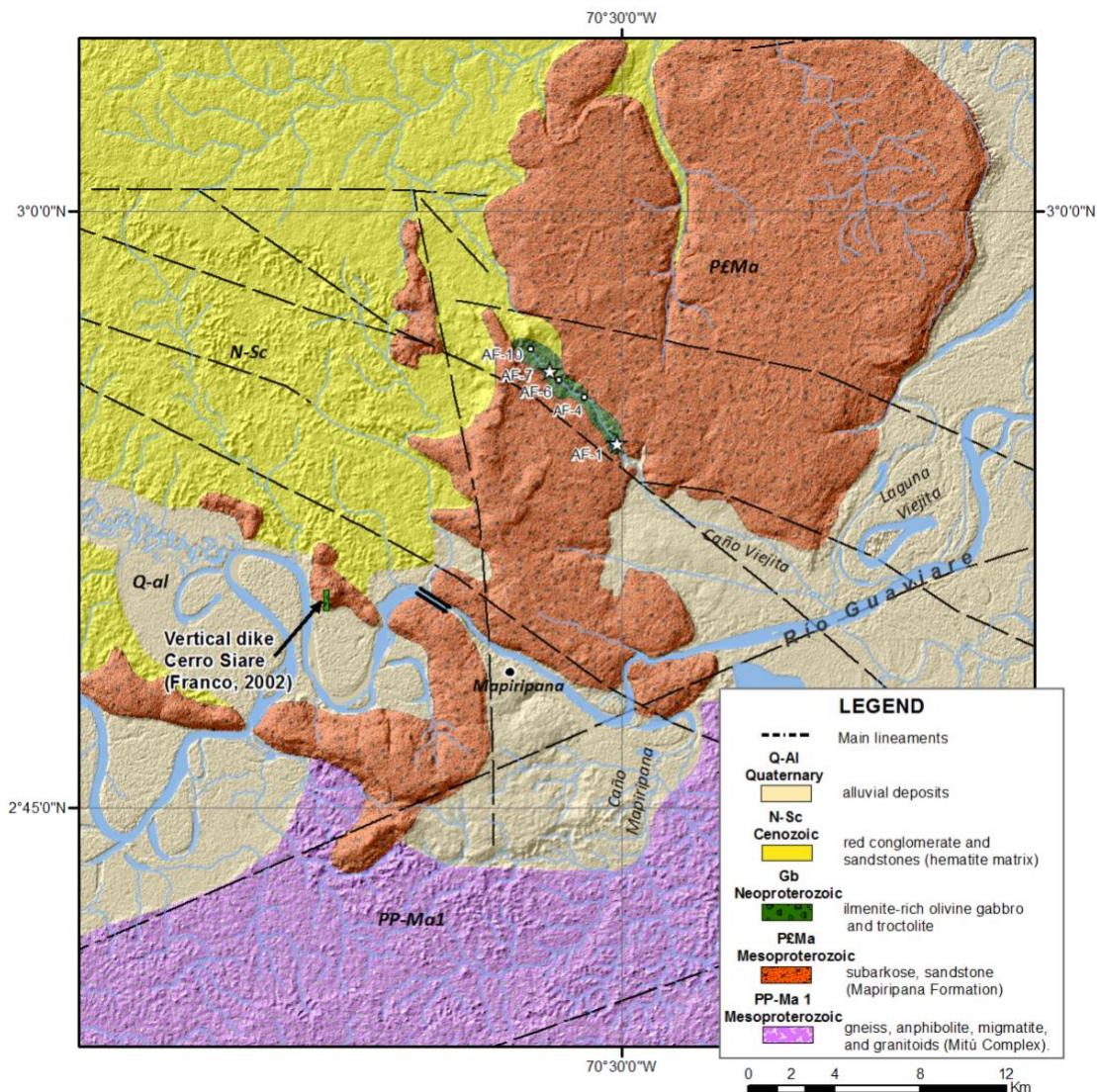
141 Since the 1960's, important progress has been made in the understanding of the geological
142 evolution of this region which was initially simply named the Basement Group (Gansser,
143 1954). Especially different national remote sensing programs (e.g. Departamento Nacional da
144 Produção Mineral, 1976; Huguet, 1977; Kroonenberg and de Roever, 2010; PRORADAM,
145 1979; Putzer, 1984) and dedicated field work produced a wealth of new data. These studies
146 have led in the 70th to the recognition of the Mitú Migmatitic Complex (Galvis et al., 1979;
147 Rodríguez et al., 2011), later called the Mitú Complex (Bonilla et al., 2019; López et al., 2007)

148 as part of the 1.80-1.55 Ga Rio Negro-Juruena Geochronological Province (Figure 2) in
149 Colombia (Tassinari et al., 1996; Tassinari and Macambira, 1999). Large parts of the Mitú
150 Complex (Figure 3) are composed of monzogranites with calc-alkaline characteristics, and
151 meta- to peraluminous affinity with an U-Pb LA-MC-ICPMS age for the Mitú granite of $1574 \pm$
152 10 Ma (Ibáñez-Mejía et al. 2011), as well as of other granites: Among the clearly
153 metamorphic rocks prevail quartzo-feldspathic gneisses with zircon U-Pb ages between
154 1800-1760 Ma (Bonilla et al., 2019; Cordani et al., 2016; Kroonenberg, 2019; López et al.,
155 2007). Medium grade amphibolite facies metamorphic rocks within a series of essentially
156 juvenile magmatic arcs in the Rio Negro Juruena province are interpreted as subduction-
157 related by several workers (Cordani et al., 2016; Tassinari and Macambira, 1999).

158 Younger granitoids in its SE-part (especially Guainia Department) exhibit variable
159 compositions, porphyritic textures and may contain ovoid feldspar phenocrysts that
160 crystallized some 1750 Ma ago during the Statherian (Bonilla et al., 2019).

161 On this Statherian basement, a metasedimentary sequence, associated with the Tunui Group
162 in Brazil (Almeida et al., 2004; Santos et al., 2003) was deposited about 1720 - 1600 Ma ago
163 (Bonilla et al., 2019) and extends to the north into the Naquen and Caranacoa mountains
164 (Figure 2). This Precambrian cover in the south of Guainia Department contains an upper
165 quartzite facies, partly tourmalinized, locally influenced by metasomatism which may be
166 responsible for gold deposits in this area and associated with a two-mica granite intrusion
167 some 1600-1550 Ma ago (Bonilla et al., 2019). The latter is probably part of the Rio Içana
168 Intrusive Suite described in Brazil (Almeida et al., 2004; Almeida and Larizzatti, 1996;
169 Carneiro et al., 2017a, 2017b; Veras, 2012), and evolved by partial melting of cratonic
170 protoliths (Almeida et al., 1997). In a similar way, other ~1600 – 1500 Ma old granites have

171 been described along the whole Colombian eastern territory (Cordani et al., 2016; Ibañez,
 172 2010; Priem et al., 1982; Rodriguez et al., 2011).



173
 174 **Figure 3** Geological map of the study area (red rectangle in **Figure 2**) with sampling points
 175 AF in the NW-trending gabbro surrounded by possibly Mesoproterozoic sedimentary rocks
 176 (modified from Franco et al., 2014; Franco et al., 2002; Gómez Tapias et al., 2015). Observe
 177 also the vertical gabbro dike at Cerro Siare crosscutting the sediments described by Franco
 178 et al. (2002).

179
 180 **2.2 Anorogenic magmatism (1500-1000 Ma)**
 181

182 Several rapakivi intrusive suites in the Brazilian SW-Amazonian Craton (e.g. Santo Antonio,

183 Teotónio, Alto Candeias) represent extensional anorogenic magmatism associated with the
 184 terminal stages of the Rondonian–San Ignacio Orogeny ~ 1.50 to 1.30 Ga (Bettencourt et al.,
 185 1999). Also in the NW-part of the Rio Negro-Juruena Province in Colombia, evidence of rift or
 186 intraplate magmatism exists, including ~1.40 to 1.34 Ga rapakivi granite intrusions like the
 187 Parguaza and Matraca rapakivi granites (Bonilla et al., 2013; Bonilla et al., 2016; Gaudette et
 188 al., 1978). Later, the regional tectono-thermal “Nickerie-K’Mudku” event affected the area and
 189 temperatures above 300°C resetted (partially) the Rb-Sr and K-Ar systems, leaving 1300 –
 190 1000 Ma cooling ages (Cordani et al., 2016; Galvis et al., 1979; Priem et al., 1982).

191
 192 Younger <1.0 Ga intra-plate A-type granites in the SW-Amazonian Craton (Teixeira et al.,
 193 2010) produced by extensional tectonics and rifting resulting from collisional events ~1.25 to
 194 1.0 Ga (Teixeira et al., 2010) are until now unknown in the NW Amazonian Craton.

195
 196 Less prominent than the felsic intrusions, but locally important, mafic intrusions and dikes
 197 occur in the Amazonian Craton, as for example on its western margin, where they are mainly
 198 of Grenvillian age (**Error! Reference source not found.**). Unfortunately, the current tropical
 199 climate and associated strong weathering reduce the number of outcrops for this rare rock
 200 types even more. Where they are visible, they cross-cut the basement or the overlying meta-
 201 sedimentary sequences along pre-existing major NE–SW or NW–SE trends forming dikes
 202 dated by Rb/Sr-whole-rock analyses between 1225-1100 Ma (Priem et al., 1982). Teixeira et
 203 al. (2010) describe mafic dikes, sills and graben basins as product of post-tectonic to
 204 anorogenic stages in the SW Amazonian Craton that took place after ca. 1 Ga.

205 **Table 1** Mafic rocks of Grenvillian age reported in the NW and SW Amazonian Craton
 206 margin.

Location and Rock type	Age (Ma)	Method and Reference
<i>NW Amazonian Craton</i>		
Papuri River: Augite-dolerite	1225	Rb/Sr whole rock, Priem (1982) Figure 2

Serra Traira, NW Brazil: Dolerite dikes	940–980	K–Ar, Tassinari (1996)
North of Manaus, Amazonas: Gabbro intrusion	1100	K–Ar, Teixeira (1978); Tassinari (1996)
Pira-Parana River: Diabase dike,	1180	Rb/Sr, whole rock Priem (1982) Figure 2
Augite-gabbro	1200	Rb/Sr whole rock, Priem (1982) Figure 2
Augite-gabbro	1180	Rb/Sr whole rock, Priem (1982) Figure 2
<i>SW Amazonian Craton</i>		
Northern Rondonia State of Brazil: dolerite dikes, gabbros and alkaline intrusions	1050– 1200	K–Ar + Rb–Sr Teixeira (1978), Tassinari (1996)
Southern Rondonia State of Brazil: dolerite dike swarms	1000– 1100	K–Ar Teixeira (1978), Tassinari (1996)

207

208 **2.3 Post Mesoproterozoic events**

209

210 The youngest known intracratonic magmatic episode in the NW Amazonian Craton is a rift-
211 related alkaline subsiliceous event (Nepheline Syenite of San José del Guaviare) with
212 Neoproterozoic-Ediacaran to Cambrian ages (U-Pb zircon emplacement ages) of ~578 Ma
213 (Mejia et al., 2012) and biotite K-Ar and Rb-Sr cooling ages of 445 – 495 Ma (Pinson et al.,
214 1962). Recent own LA-ICP-MS U-Pb zircon ages of ~ 609 Ma (Franco et al., 2018; Muñoz
215 Rocha et al., 2019) near Jordan to the SE of the intrusion, suggest a long emplacement and
216 cooling history for this large body that is probably associated with the Pan-African - Brazilian
217 orogeny. Further west, no intracratonic intrusions are reported.

218

219 Since early Phanerozoic, predominant uplift and erosion of the NW Amazonian Craton are
220 evidenced by large stratigraphic hiatus, interrupted by several transgressions and marine
221 depositional regimes during the Paleozoic (e.g. Silurian (?) sandstone Araracuara Formation,
222 NW-trending Güejar- Apaporis Graben filled with marine platform and continental sediments).

223 The Colombian Cretaceous Transgression, which extended at least to the modern Eastern
224 Cordillera at the western Amazonian Craton boundary, was the most prominent expression of
225 a Pre-Andean extension. It encompassed various back-arc zones with recognizable syn- and
226 post-rift phases of basin evolution (Horton, 2018) as result of an intensification of the Nazca
227 plate subduction below the incipient South American continent in its modern form. The related
228 rapid uplift, erosion and exhumation of the Amazonian Craton caused widespread Mesozoic
229 stratigraphic gaps all over the craton's cover and a high flux of recycled Precambrian sourced
230 sediments filling the Andes or Llanos Basin (Cardona et al., 2011) mainly in east – west
231 directed fluvial systems.

232

233 The Cenozoic Andean history shows a less pervasive extension in the midst of the Andean
234 orogeny and affected specific fore-arc lowlands, elevated hinterland regions, and isolated
235 retro-arc settings (Horton, 2018). Also, since the Paleogene, the Andean orogeny changed
236 the fluvial systems in the Colombian Amazonian Craton with its continental sedimentary cover
237 now directing the rivers eastwards to the Orinoco Basin or to the Amazonian Basin.

238

239 **3. Methods**

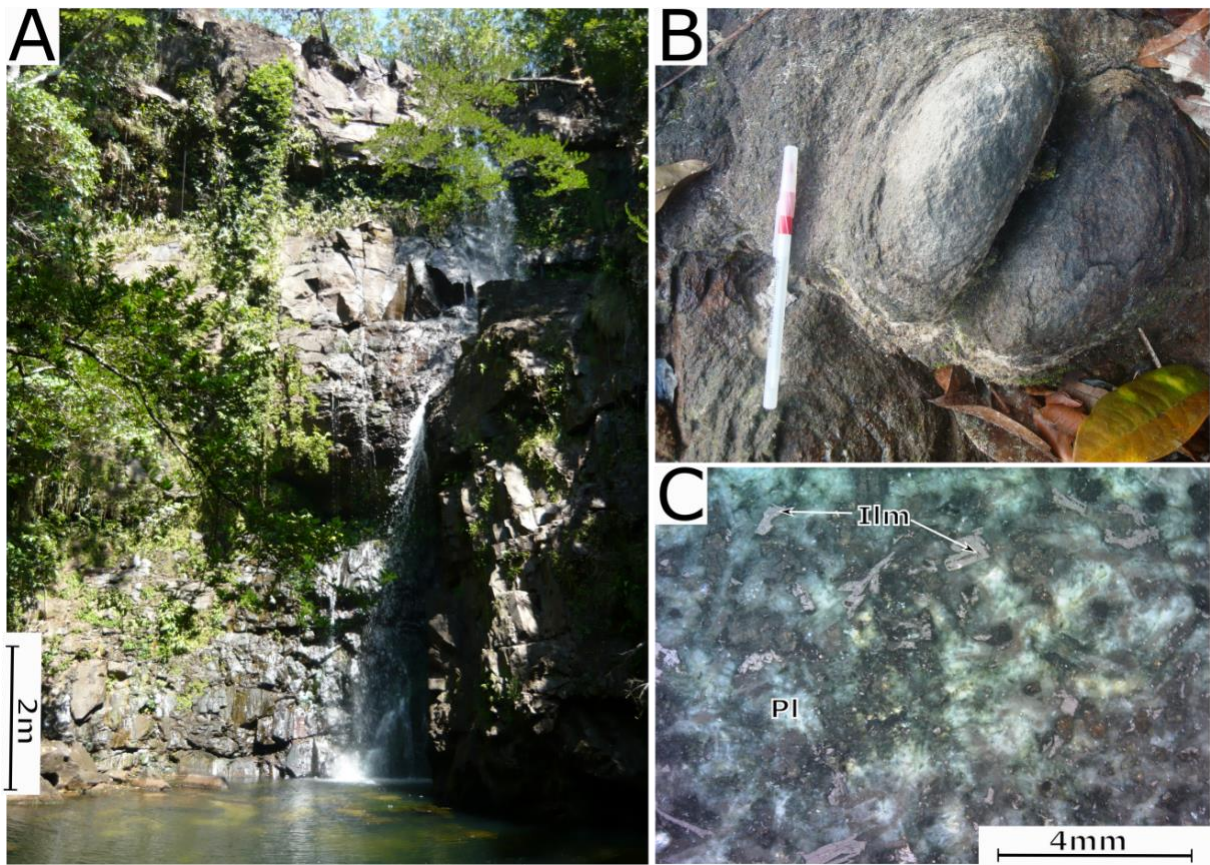
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241 **3.1 Field work**

242

243 During a 2010 exploration survey in a black sands mining concession area (#18557 mining
244 cadaster code), we found that the main ore minerals there were alluvial ilmenite concentrates
245 which obviously resulted from the weathering of a mafic intrusive body in the SW of the
246 Vichada Department. The source gabbro outcrops along a 6 km small creek called “Caño
247 Viejita”, a tributary of the Guaviare River (Figure 3). The elongated gabbro trends N40W with
248 unclear extension, as to the north it is limited by a river and a ~50 m thick sedimentary

249 sequence that outcrops as “Tepui” with $<10^\circ$ N dip, and is fringed by vertical cliffs (Figure 4A).
250 The tropical climate produced abundant spheroidal weathering forms (Figure 4B) and
251 yellowish weathering rims on the rock samples; it is not clear until which point abundant
252 secondary minerals like chlorite and serpentine are product of this weathering or syn- to
253 postmagmatic fluids. More field data are presented in the result and discussion chapters.
254 High ilmenite content visible in the fresh rock (Figure 4C) results in placer deposits as
255 weathering product of the gabbro. For this area, where presumably the ilmenites were mined
256 as titanium ore, also a mining license had been emitted years ago by the Colombian
257 authorities for wolframite, coltan and other alluvial “black sands” which served mainly for
258 “laundering” of wolframite and coltan illegally mined from other deposits in E-Colombia like
259 Cerro Tigre in the Guainía department. This illustration of the complex interaction between
260 geology, mining, lack of knowledge and both social, political and environmental issues
261 portrays the challenges of geologists in Colombia, but thanks to further exploration efforts of
262 the title owner in this case facilitated field recognition and sampling of black sands, soils and
263 fresh rocks which were brought to Bogotá for further analyses.



264

265 **Figure 4** Some geological features in the study area: A) sub-horizontal layers of the
 266 Mesoproterozoic sedimentary sequence with characteristic waterfall of the Viejita creek with
 267 ilmenite concentrates; B) spheroidal forms resulting from tropical weathering of the gabbro;
 268 C) Binocular image (10x) of ilmenite crystals in plagioclase and pyroxene, within an
 269 undeformed gabbro texture.

270

271 **3.2 Petrography and whole rock geochemistry**

272

273 Seven thin sections from different parts of the gabbro were analyzed under a Zeiss Axio
 274 Scope A1 petrographic microscope. Whole rock geochemistry by means of XRF was carried
 275 out on 3 samples (Af-1, Af-7 and Af-4, the first two were also used for U-Pb apatite
 276 geochronology, and sample Af-4 was measured one year later for quality control). The
 277 samples were pulverized and mixed with Merck spectromelt wax at sample/wax ratio of 10/1
 278 and measured with a Phillips MagixPro PW - 2440 X-ray fluorescence spectrometer (4 kW,
 279 Rh-tube, reported detection limit 20 ppm for heavy elements) at the National University of

280 Colombia. For interpretation and diagrams, mainly the GCDkit5.0 software (Janousek et al.,
281 2008) was used. By means of LA-ICP-MS, REE of extracted apatites were measured, which
282 will be discussed later.

283

284 **3.3 Apatite U-Pb LA-ICP-MS geochronology**

285

286 Mineral separation procedures on two crushed gabbro samples (Af-1 and Af-7) at
287 Universidade Federal do Rio Grande do Sul (Brazil) yielded too low datable zircon or
288 baddeleyite contents in the concentrates, but sufficient apatite crystals of good quality after
289 applying conventional mineral separation techniques. From the non-magnetic heavy fraction,
290 apatite grains were carefully handpicked under a binocular microscope, embedded in epoxy
291 resin and afterwards grounded and polished with a 6, 3 and 1 μm diamond suspension
292 successively.

293

294 In the first sample (Af-1), apatite cathodoluminescence (CL) images were acquired using a
295 Reliotron CL system equipped with a digital color camera at Géosciences University Rennes,
296 where also LA-ICP-MS U-Pb geochronology was conducted using an ESI NWR193UC
297 Excimer laser coupled to a quadrupole Agilent 7700x ICP-MS equipped with a dual pumping
298 system to enhance sensitivity (Paquette et al., 2014). During the analyses, we used an
299 ablation spot diameter of 50 μm , a repetition rate of 5 Hz and a fluence of 6.5 J/cm². Data
300 were corrected for U-Pb and Th-Pb fractionation and for the mass bias by standard
301 bracketing with repeated measurements of the Madagascar apatite standard (Cochrane et
302 al., 2014). The apatite standards McClure (523.51 \pm 2.09 Ma (Schoene and Bowring, 2006))
303 and Durango (31.44 \pm 0.18Ma (McDowell et al., 2005)) which were used during the
304 measurements to monitor precision and accuracy of the analyses, yielded ages of 520 \pm 9

305 (McClure, N = 3, MSWD = 0.47) and 32.3 ± 0.8 Ma (Durango, N = 5, MSWD = 0.76). For
306 instrumental conditions and protocols used in this study see Pochon et al. (2016) and Table
307 3.

308

309 A different protocol was necessary for the second apatite samples (Af-7), on which also
310 fission track analysis were performed, as well as additional trace elements determinations
311 (mainly Cl, Ca, REE) using the same shots as for the U-Pb ages. The same LA-ICP-MS
312 facility as described above was used, but with a spot size of 30 μm , a repetition rate of 7 Hz
313 and a fluence of 6 J/cm². The full instrumental conditions and U-Pb dating protocol are
314 reported in Table 3, too. In the same way as the first sample, data were corrected for U-Pb
315 and Th-Pb fractionation and for the mass bias by standard bracketing with repeated
316 measurements of the Madagascar apatite standard (Cochrane et al., 2014). The same apatite
317 standards as above used as secondary standard yielded a weighted mean ²⁰⁷Pb-corrected
318 age of 528.9 ± 7.0 (McClure, N = 11, MSWD = 0.41) and 31.7 ± 2.2 Ma (Durango, N = 24,
319 MSWD = 0.55).

320

321 **3.4 Apatite Fission Track Thermochronology and trace elements patterns**

322

323 The apatite fission track (AFT) method is a low-temperature thermochronological technique
324 based on the spontaneous fission of ²³⁸U in the apatite crystal lattice. The fission decay
325 produces lattice damage trails, the fission tracks, which can accumulate over time. At
326 geological timescales, fission tracks in apatite are considered stable at temperatures lower
327 than $\sim 60^\circ\text{C}$, while they anneal completely at temperatures above $\sim 120^\circ\text{C}$ (Ketcham et al.,
328 1999; Wagner and Van den Haute, 1992). Between these two temperature thresholds, fission
329 tracks (initially $\sim 16\mu\text{m}$) in apatite are gradually shortened, defining the Apatite Partial

330 Annealing Zone (APAZ), which depends to some extent on the chemical composition of the
331 apatite crystals (Wagner and Van den Haute, 1992). With a minimum of ~100 measured
332 confined fission track lengths, it is statistically viable to model or reconstruct the low-
333 temperature thermal history of the apatite-bearing rock sample (e.g. Ketcham et al., 1999),
334 but 40 track lengths are considered the absolute minimum (Rahn and Seward, 2000). If
335 significantly less than 100 confined tracks could be measured, only a qualitative (and rather
336 speculative) model can be retrieved, and interpretation of the AFT data and accompanied
337 time-temperature model has to be done with care.

338

339 Fission tracks were counted on 800x magnification with a Nikon Eclipse NI-E microscope
340 system and imaged with a DS-Ri2 camera attached to the microscope system. The
341 determination of the uranium concentration for fission track dating followed the analytical
342 protocol of Cogné et al. (2019). In contrast to the LA-ICP-MS absolute calibration approach of
343 Hasebe et al. (2004), which employs the ^{238}U fission-decay constant, a fission-track
344 registration factor and a calibration factor for etching and observation, Cogné et al. (2019)
345 used a modified zeta calibration approach (cf. Hurford and Green, 1983) for LA-ICP-MS
346 apatite U concentration measurements, building on Donelick et al. (2005). The method
347 assumes that the apatite ^{43}Ca signal intensity during a given LA-ICP-MS session acts as a
348 proxy for the volume of apatite ablated, and hence the apatite $^{238}\text{U}/^{43}\text{Ca}$ ratio yields relative U
349 concentration measurements. In this study, an extensive primary LA-ICP-MS session was
350 undertaken on Durango apatite crystals (31.44 ± 0.18 Ma (2σ)) (McDowell et al., 2005)
351 previously counted for fission tracks to yield a primary LA-ICP-MS zeta factor. The
352 uncertainty on the calibration procedure (including the age uncertainty and the counting
353 statistics related to the number of spontaneous tracks counted in the Durango standard) was
354 propagated through to the final zeta calculation. These same Durango apatite crystals were

355 then analyzed in subsequent LA-ICP-MS (along with apatite unknowns for fission-track
356 dating) to yield a session-specific calibration factor on the primary zeta value. Inter-session
357 drift in both the primary and subsequent LA-ICP-MS sessions was corrected for by monitoring
358 the $^{238}\text{U}/^{43}\text{Ca}$ ratio of NIST612 standard glass. Depth-related variations in U concentration
359 were accounted for by incorporating a function within the Lolite “Trace elements” data
360 reduction scheme that weights appropriately the $^{238}\text{U}/^{43}\text{Ca}$ ratio with depth. Chlorine
361 measurements are calibrated with a synthetic “Bamble” apatite (e.g. Chew et al. 2016).

362

363 Data reduction for trace-element data acquired on the same spots was undertaken using the
364 freeware Lolite package of Paton et al. (2011), with the “Trace Elements” data reduction
365 scheme. NIST612 was used as primary reference material. Cl concentration measurements
366 followed the analytical protocol of Chew et al. (2016). The ^{35}Cl background-corrected signals
367 for each apatite analysis were normalized to the internal standard (^{43}Ca) and then sample-
368 standard bracketing was employed using synthetic apatites of known Cl concentration
369 (chlorapatite end member 6.81 wt% Cl, (Klemme et al., 2013)) and Durango fluorapatite (0.37
370 wt% Cl).

371

372 **4. Results**

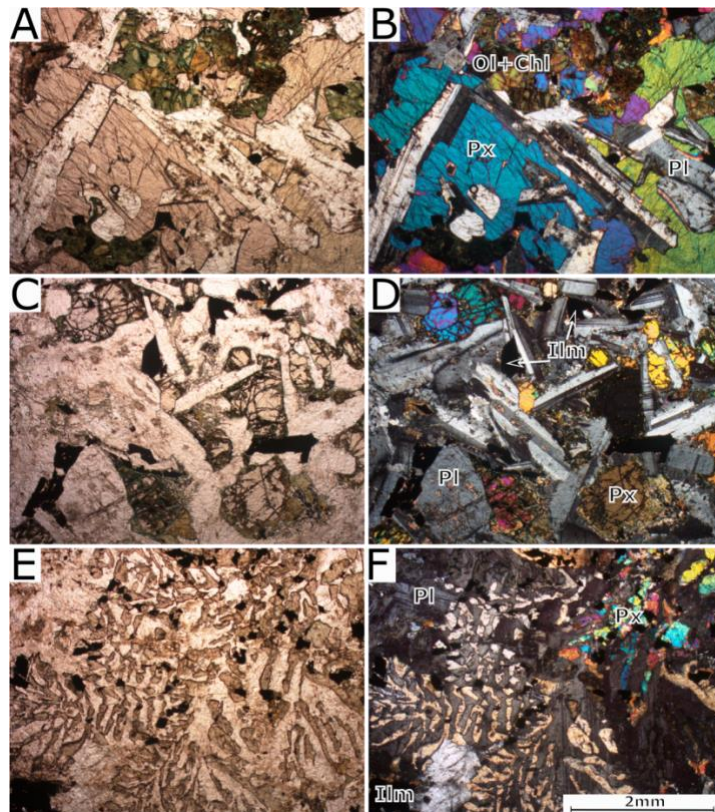
373

374 **4.1 Petrological and geochemical results**

375

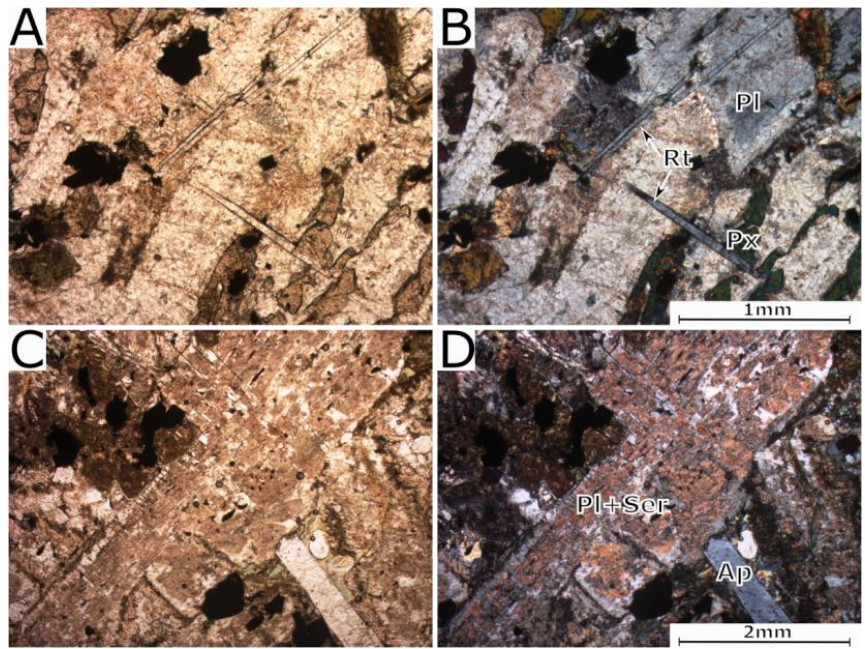
376 As the N40W trending gabbro body (Figure 3) is covered to the north by thick sedimentary
377 sequences, its real extent is difficult to assess. The vertical cliffs (Figure 4A) with abundant
378 spheroidal weathering forms (Figure 4B) as well as the high ilmenite content in the fresh rock
379 (Figure 4C) and alluvial “black sands” allow to assume that the body is rather large and
380 affected by active (at least until recently) uplift processes. The continuous supergenic

381 processes are evidenced in the yellowish weathering rims, secondary chloritization and
382 abundant serpentine, although the contribution of syn- or postmagmatic hydrothermal fluids is
383 not clear, and no signs of metamorphic remobilization are visible, neither macro nor
384 microscopically, nor geochemically.



385

386 **Figure 5** Thin-sections micro-photographs of gabbro samples from Caño Viejita, right side
387 crossed nicols. A-B) olivine-gabbro with interstitial texture showing plagioclase, pyroxene and
388 olivine crystals altered to chlorite; C-D) gabbro with intergranular texture, abundant ilmenite
389 and pyroxene partially altered to chlorite; E-F) gabbro with poikilitic texture where pyroxene
390 laths are enclosed by plagioclase.



391

392 **Figure 6** Thin-sections micro-photographs (right XPL) of gabbro samples from Viejita creek,
 393 A-B) plagioclase and pyroxene, traversed by acicular rutile crystals; C-D) pronounced
 394 replacement of plagioclase by sericite and of olivine by serpentine + chlorite. Observe
 395 large apatite crystals and, in both sections, abundant opaque ilmenite grains.

396

397 Petrographically, the rock is a gabbro to olivine-gabbro with 58-67% plagioclase (An70), 7-
398 13% clinopyroxene and 4-10% olivine. Abundant accessory minerals (~12%) are ilmenite,
399 rutile, large apatite crystals and pyrite. Neither enough baddeleyite nor zircon were identified
400 for geochronology analyses, thus testifying Si-subsaturation and low Zr-contents (but see
401 note below). Parts of the gabbro exhibit poikilitic texture where large plagioclase phenocrysts
402 enclose skeletal pyroxene crystals (Figure 5E-F) while other portions show interstitial and
403 intergranular textures. Fe-rich olivine (fayalite) is identified due to its slightly higher relief than
404 pyroxene, as well as its fracturing and alteration products like chlorite and serpentine visible
405 in some parts, whereas in the prevailing pyroxenes chlorite alteration dominates. Other
406 alteration minerals are sericite, epidote and iron oxides, as in sample Af-1. Some ~1% biotite
407 in samples Af-6 and Af-7 are associated with ilmenite or pyrite surrounding some olivine
408 crystals. Titanite traces were found in sample Af-1.

409

410 XRF data for major and some trace elements are shown in Table 2, together with continental
411 crust gabbro (CCG) values after Le Maitre (1976), cited in Wedepohl (1995) and “normal”
412 gabbro after Nockolds (1954, cited in Perkins, 2014). The geochemistry of the three samples
413 is rather similar, suggesting that they are part of a homogeneous body. The SiO₂ content
414 varies from 46.46 % to 48.15%, which is in the range of a normal gabbros, although with
415 some Si-subsaturation (cf. e.g. <https://earthref.org/GERMARD/>). High Fe₂O₃ (~13%) reflects
416 itself in fayalite, Fe-pyroxene and, together with high TiO₂ content from 3.12% to 3.43%, in
417 abundant ilmenite and much less rutile in the gabbro. While Al₂O₃ content from 15.55% to
418 15.83% is typical, K₂O content from 1.86% to 2.04% is rather high for a normal gabbro, thus
419 nearly reaching shoshonite composition, although no K-main minerals were found. On the
420 other hand, CaO from 7.36% to 8.24% and MgO from 4.27% to 4.99% are lower than in
421 oceanic-crust associated gabbro, but CaO is higher than in CCG. High P₂O₅ from 1.54-1.72%

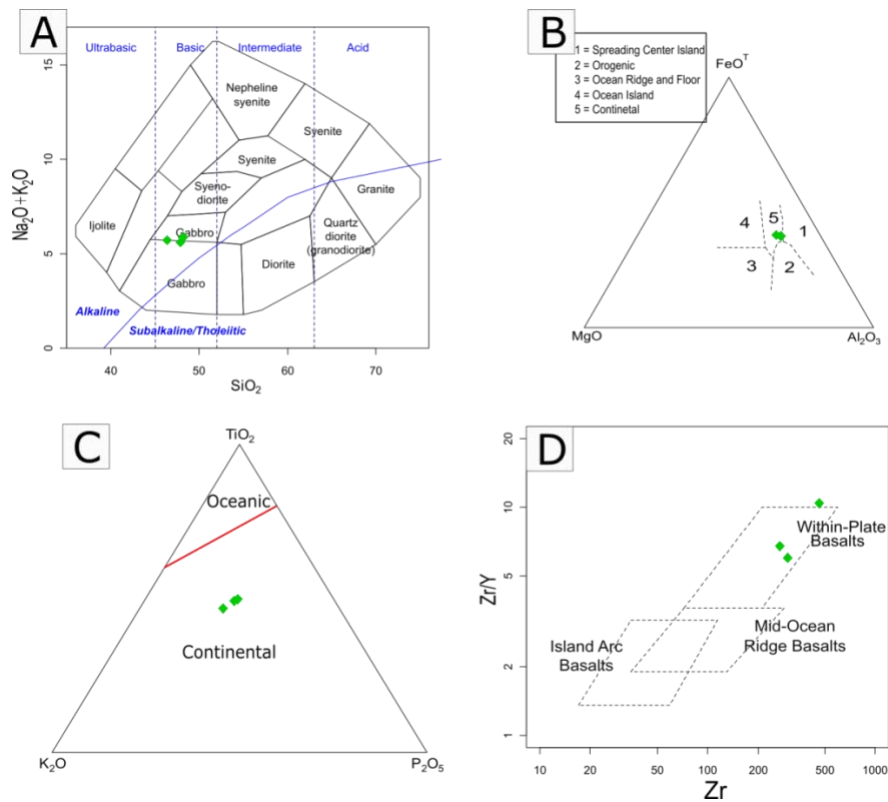
422 expresses itself in abundant apatite, whereas the low Zr-contents together with Si-
 423 subsaturation did virtually not allow zircon crystals to form, although the surely not very
 424 precise XRF Zr-values (Table 2) are apparently above the 140 ppm Zr reported for basalts
 425 and also a lot of granitic rocks (e.g. Mielke, 1979). Geochemical-petrotectonic discrimination
 426 patterns (**Error! Reference source not found.**) such as Na₂O+K₂O vs. SiO₂ (Cox et al.,
 427 1979), MgO-FeO_T- Al₂O₃ (Pearce et al., 1977) and TiO₂-K₂O-P₂O₅ (Pearce et al., 1975)
 428 locate this intrusive in the field of continental alkaline metaluminous gabbro of Within-Plate
 429 characteristics based on the Zr-Y relationship (Pearce and Norry, 1979). Low content
 430 together with XRF-detection limits and deficient precision did not allow using other common
 431 trace elements like Nb, Ta or most REE for further confident geotectonic interpretations of the
 432 gabbro samples.

433 **Table 2** XRF geochemistry of gabbro samples AF-1, AF-4 and AF-7 and of Continental Crust
 434 Gabbro (CCG) after Wedepohl (1995, citing Le Maitre (1976)) and “normal” gabbro after
 435 Nockolds (1954, cited in Perkins, 2014). Observe the lower SiO₂ and MgO but much higher
 436 Na₂O, TiO₂, K₂O and P₂O₅ contents in comparison with CCG and “normal” gabbro, which
 437 express in minerals like rutile, and abundant ilmenite and apatite. Only CaO lies between the
 438 two gabbro types, possibly reflecting the anorthosite component. Oxides reported in wt.% and
 439 trace elements in ppm.

Element	Af 1	Af 4	Af 7	CCG	Gabbro Nockolds (1954)
SiO ₂	48.152	46.46	47.854	50.1	50.78
Al ₂ O ₃	15.833	15.72	15.551	15.5	15.68
Fe ₂ O ₃ incl. FeO	13.074	13.82	12.746	11.5	2.26
Feo					7.41
CaO	7.395	7.36	8.245	4.58	10.85
MgO	4.455	4.99	4.279	7.6	8.35
Na ₂ O	3.831	3.85	3.696	2.4	2.14
TiO ₂	3.122	3.42	3.431	1.1	0.81
K ₂ O	2.045	1.86	1.897	0.9	0.56
P ₂ O ₅	1.541	1.70	1.720	0.24	0.05
MnO	0.156	0.18	0.172	0.12	0.18

H ₂ O					0.76
Ba	1050	1700	840		
Sr	790	740	800		
Cl	560	1030	1200		
S	480	590	1400		
V	0	0	500		
Ce	390	380	200		
Zr	300	270	400		
Zn	170	130	200		
Cr	90	0	0		
Rb	50	70	44		
Y	50	40	38		
Nb	0	0	25		

440



441

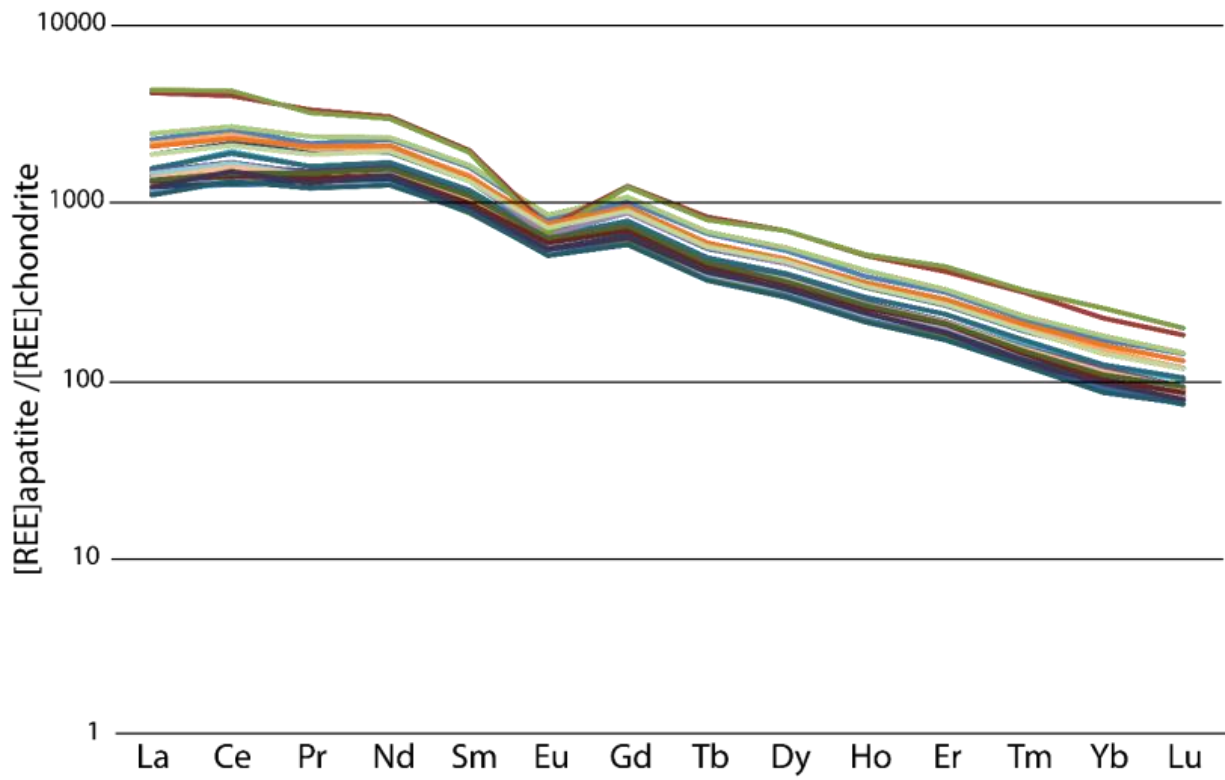
442 **Figure 7** Gabbro samples plotted in A) Na₂O+K₂O vs SiO₂ diagram after Cox *et al.* (1979); B)
 443 MgO-FeO_T- Al₂O₃ after Pearce *et al.* (1977); C) TiO₂-K₂O-P₂O₅ after Pearce *et al.* (1975); D)
 444 Zr/Y vs Zr for basalts after Pearce and Norry (1979).

445

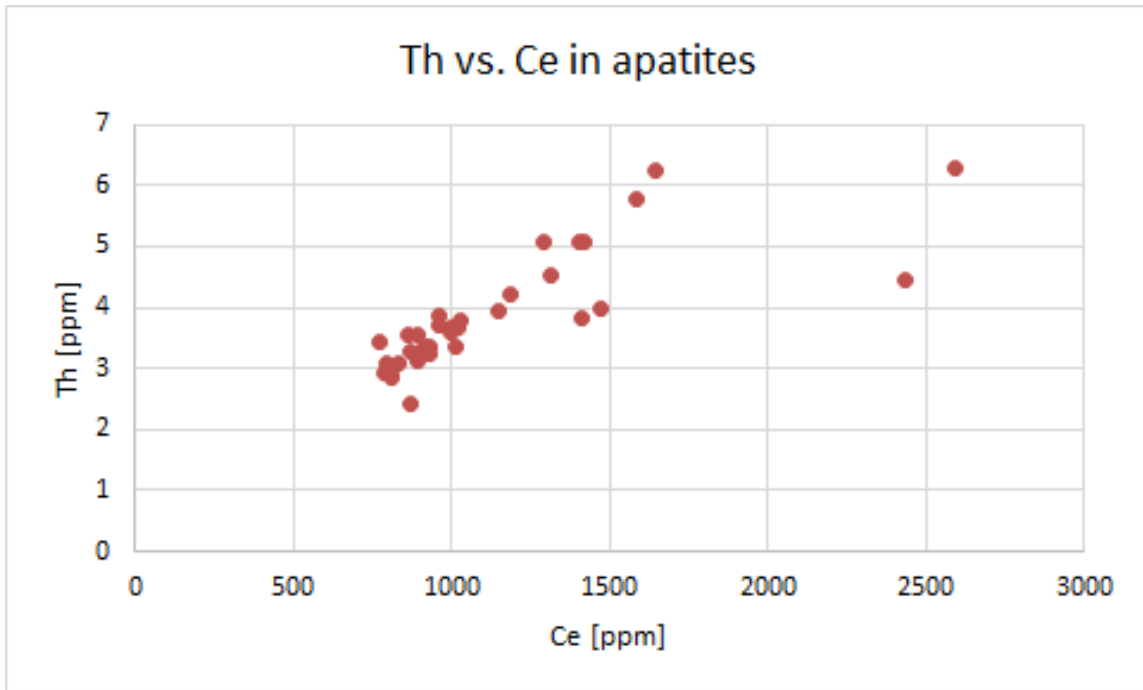
446 Apatites are versatile geological materials not only useful for geochronological and thermal
447 evolution studies as below but also, for example, to decipher magma-fluid interactions and
448 differentiation (e.g. Harlov 2015). CI-normalized (Anders and Grevesse,1989) Rare Earth
449 Elements values of the 35 apatite crystals from the Caño Viejita gabbro sample Af-7 (**Error!**
450 **Reference source not found.**) analyzed by means of LA-ICP-MS during the U-Pb dating
451 show a strong enrichment mainly of the LREE with a decreasing slope to heavier REE
452 ((Ce/Yb)_{cn} of 12-13)) and a moderate negative Eu-anomaly (2Eu/(Sm+Gd))_{cn} of 0.62-0.7),
453 common patterns observed in many apatites. The latter was probably controlled by former or
454 simultaneous plagioclase crystallization (e.g. Rollinson, 1993) much more than the own
455 apatite redox-state. REE-distribution patterns at first glance are similar to apatites from
456 syenites and associated jacupirangites reported by Belousova et al. (2002). However, other
457 parameters differ, like the lower sum of REE between 0.2-0.6wt.%. A slight positive Ce-
458 anomaly (2Ce/La+Pr)_{cn} of 1.1-1.2, Y 328-934ppm, Mn 358-478ppm, Sr 516-747ppm, Th 2.4-
459 6.3ppm, U from 1.1-2.25ppm and mainly radiogenic Pb from 2-8ppm with rather high ²⁰⁴Pb
460 give some clues about the apatite and gabbro crystallization process, using for example the
461 discrimination patterns proposed by Belousova et al. (2002). The Sr/Y values (Sr 516-
462 747ppm / Y 328-934ppm) occupy the granitoid but more the mafic rocks to Fe-ore fields of
463 Belousova et al. (2002). (Ce/Yb)_{cn} of 12-13 and Sum REE 0.2-0.6 wt.% are in the granitoid
464 and near the dolerite field. Sr 516-747ppm/ Mn 358-478ppm correlations are in the larvikites,
465 jacupirangite and iron ore fields, Y 328-934ppm/ Eu/Eu* 62-0.7 occupy the granitoids, mafic
466 rocks and iron ore fields. The absence of observable concurrent phosphate minerals
467 (monazite or xenotime) or garnets which tend to scavenge REE and other incompatible
468 elements as well of zircons explain a good part of this behavior.

469 Thus, both the apatite as the gabbro characteristics hint to a somehow enriched gabbro
470 mantle source.

471



472



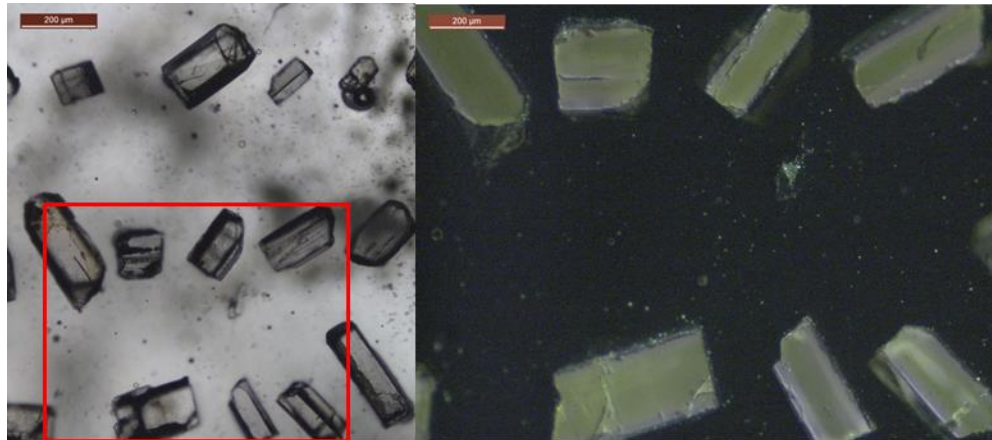
473

474 **Figure 8A** CI-normalized (Anders and Grevesse, 1989 in McDonough and Sun, 1995) REE
 475 contents of 35 apatite crystals from Caño Viejita gabbro sample Af-7 showing strong
 476 enrichment mainly of LREE with nearly log-linear decrease tendency of heavier REE and a
 477 moderate negative Eu-anomaly. **B**: Positive correlation Th vs. Ce in the apatite samples.

478 **4.2 Apatite U-Pb and FT geochronology**
479

480 As zircon and baddeleyite contents in the gabbro samples are very low and only a few zircon
481 grains were found in thin sections mainly as inclusions inside ilmenite or at the boundary
482 between plagioclase and pyroxene grains, not sufficient material could be obtained for U-Pb
483 geochronology in neither of the Zr-minerals. However, the high amount of good-quality apatite
484 grains allowed applying apatite U-Pb dating. Two samples (Af-1 and Af-7) with large and
485 abundant apatite grains, which exhibit perfect euhedral prism shapes and grain sizes
486 between 100 to 500 μm were selected using binocular, petrological microscope and CL-
487 imaging. CL-images of sample Af-1 exhibit yellow-grayish luminescence free of visible
488 internal structures like cores or zoning (Figure 9).

489 The U-Pb data of twenty-five apatite grains from this sample Af-1 (Table 4) plotted in a Tera-
490 Wasserburg diagram (Figure 10) show discordant ages with a rather high proportion of
491 common (non-radiogenic) Pb and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios between 0.38 and 0.49. They yield a
492 lower intercept age of 1001 ± 59 Ma with a $^{207}\text{Pb}/^{206}\text{Pb}$ initial value of 0.945 (Figure 10). If the
493 discordia is forced to a $^{207}\text{Pb}/^{206}\text{Pb}$ value of 0.909 ± 0.004 , calculated for an age of 1000 ± 50
494 Ma following the Pb evolution model of Stacey and Kramers (1975), we obtain a similar age,
495 although with lower scattering, of 975 ± 9 Ma (MSWD=0.95) (Figure 10). The weighted
496 average ^{207}Pb -corrected date is in agreement at 979 ± 10 Ma (Figure 10).

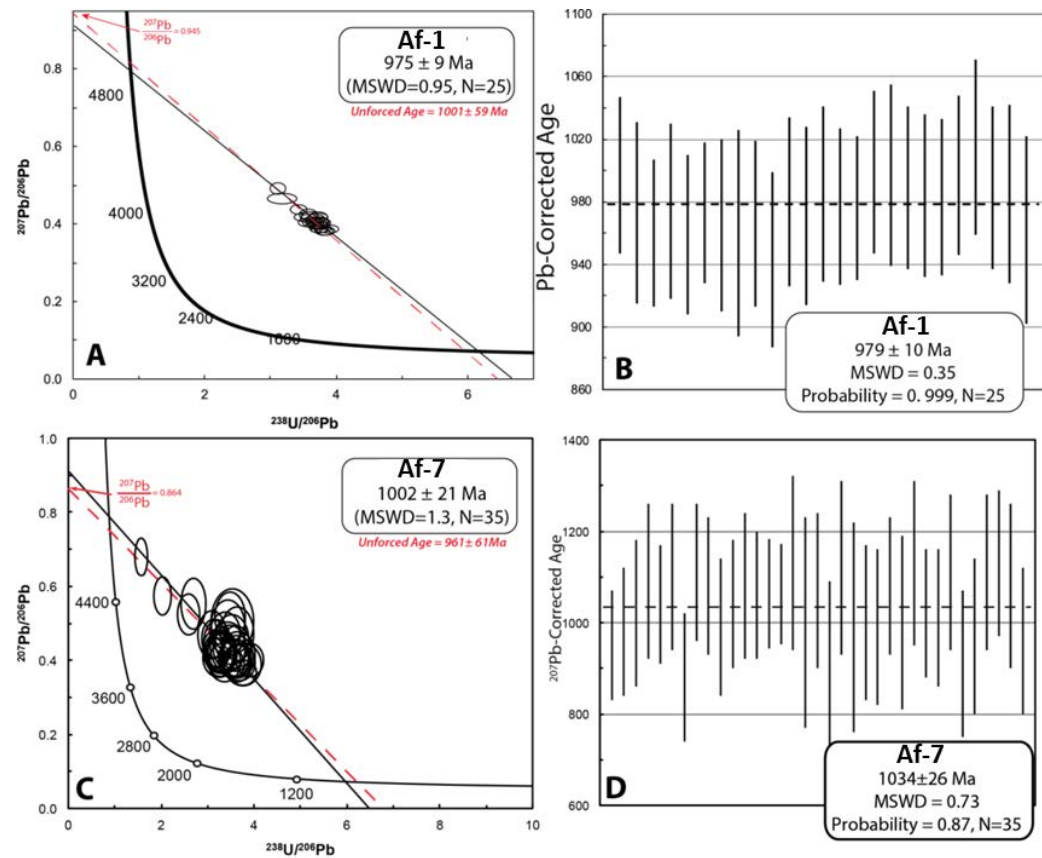


497

498 **Figure 9** Embedded apatite crystals under the transmitted light microscope (left) and
499 magnified CL-images from Af-1 showing homogeneous yellow-grayish luminescence (right).

500

501 U-Pb data of the 35 apatite grains from the second sample (Af-7 in Table 4) yield a lower
502 intercept age of 961 ± 61 Ma with a $^{207}\text{Pb}/^{206}\text{Pb}$ of 0.864 (Figure 10). The forced regression
503 with an initial common Pb value of 0.909 ± 0.004 yield an age of 1002 ± 21 Ma (Figure 10)
504 coherent with the weighted mean ^{207}Pb -corrected age of 1034 ± 26 Ma (Figure 10).
505 Therefore, the unforced age is coherent with the lower intercept and the corrected age of Af-1
506 sample. The corrected age (based on Stacey and Kramers 1975 single evolution model) of
507 1034 ± 26 Ma is the oldest of all obtained ages. In spite of the scatter, both samples share a
508 common history.

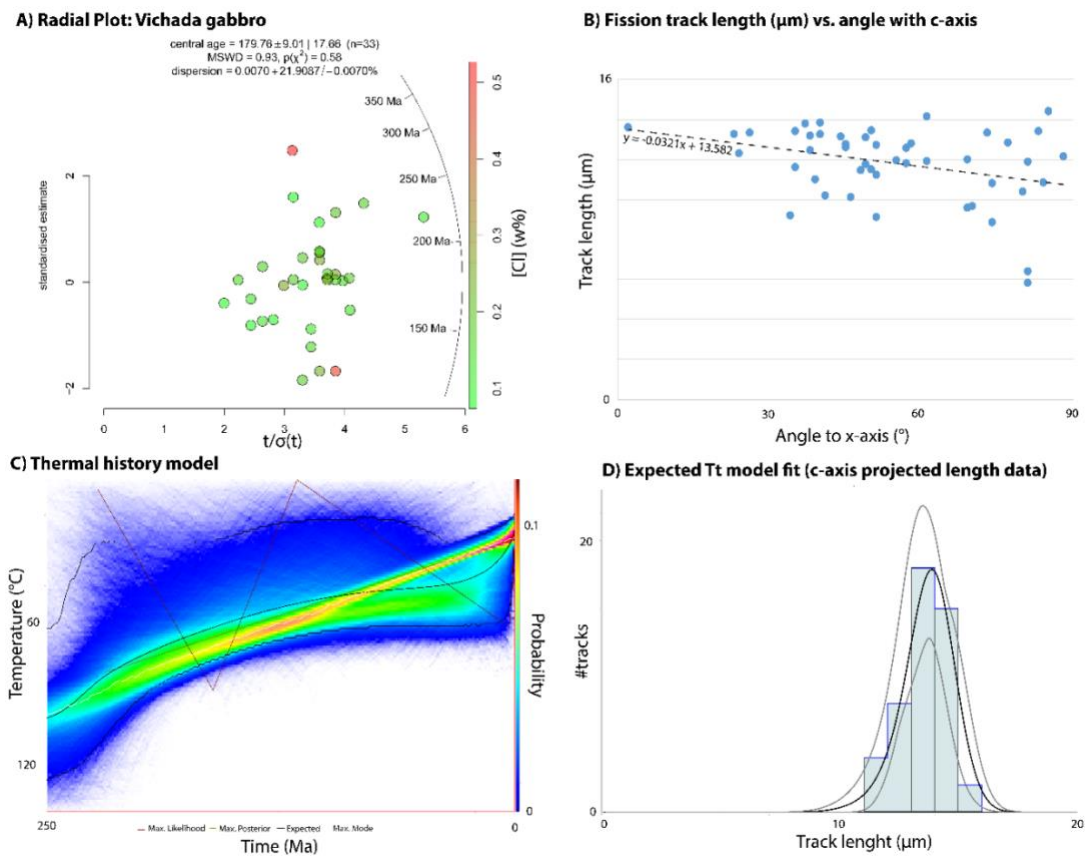


509

510 **Figure 10** Tera–Wasserburg Concordia diagrams and weighted average ^{207}Pb -corrected
 511 ages for the 25 single apatite grains from olivine gabbro sample Af-1 (A+B) and 35 single
 512 grains from gabbro Af-7 (C+D).
 513

514 A Lower Jurassic (Toarcian) AFT central age of 179.8 ± 9.0 Ma (Figure 11A) based on 33
 515 grain analysis could be calculated (Table 4, Figure 11). The chlorine content for the gabbro
 516 apatite is 0.28 ± 0.13 wt%, and single grain ages are not related to Cl-content (Figure 11).
 517 The spontaneous fission track density is rather low, and only 47 horizontal confined tracks
 518 could be measured. The mean track length from this limited data set is short at $11.8 \mu\text{m}$, with
 519 a large standard deviation of $1.9 \mu\text{m}$. An attempt for a thermal history reconstruction must
 520 consider that it is based on an absolute minimum of track length information. C-axis
 521 projection (Ketcham et al., 2007) of the apatite fission tracks was performed because the data
 522 showed anisotropic annealing and follows the model of Donelick et al. (1999) (Figure 11B)

523 and give a narrower distribution with a c-axis-projected mean length of 13.5 μm .
 524 Subsequently, the C-axis-projected length data and the compositional data (i.e. the chlorine-
 525 content) were modelled (Figure 11C) with the QTQt software (v5.6.0) (Gallagher, 2012),
 526 according to the strategies reported in Van Ranst et al. (2019). After c-axis projection, the
 527 mean track length of the sample increased from 11.8 to 13.5 μm and the distribution of the
 528 track length histogram was much narrower (Figure 11D).



529

530 **Figure 11** Apatite fission track results of the Vichada gabbro sample Af-7. (A) Radial plot of
 531 the analyzed sample with compositional data added as colour scale (using IsoPlotR;
 532 (Vermeesch, 2018)). (B) Scatter plot indicating the decreasing trend for apatite fission track
 533 length with angle to the c-axis. (C) Thermal history model performed with QTQt (Gallagher,
 534 2012) illustrating the slow cooling through the apatite partial annealing zone ($\sim 60^{\circ}$ - 120°C).
 535 (D) Model fit of the expected Tt model (i.e. the black curve in panel C) with the c-axis
 536 projected length data.

537

5. Discussion and conclusions

As the “Caño Viejita” gabbro is limited to the north by a ~50 m thick sedimentary sequence (Figure 4A) which begins north of the intrusion in a creek valley, no clear contact was visible nor a confident extension estimate can be made. Thus, simple field observations did not allow concluding if the gabbro intruded the sediments or if on the contrary the sediments covered the exhumed intrusion at a later stage. This issue will be discussed later in this section.

Lacking quartz and low SiO₂ contents as well as the occurrence of fayalite, pyroxene and bytownite-anorthite as main minerals, point to a mafic to ultramafic primary magma. These observations are consistent with the Al₂O₃ contents from 15.55% to 15.83%, and the low Zr-contents are in agreement with a continental alkaline metaluminous gabbro of Within-Plate characteristics as confirmed by the geochemical-petrotectonic discrimination diagrams (**Error! Reference source not found.**). However, alkali feldspar, mentioned as characteristic of the latter two (Le Maitre et al., 2002), were not found in thin-section nor XRD.

The former seems somewhat in contradiction with the rather low CaO and MgO concentrations and high K₂O and Na₂O content (Table 2). However, the latter can be explained by the influence of continental crust reworking and/or magma mixing as part of an aborted rifting process. The high FeO_{tot} (~11%) and TiO₂ content (3.12% to 3.43%) is expressed in abundant ilmenite and fayalite, and the high P₂O₅ (1.54-1.72%) evidenced in the numerous large apatite crystals may reflect the initial formation of immiscible Ti-Fe-P melts, that, due to their higher density, typically reflect the bottom of mafic intrusions. Interestingly, titanian pyroxene was not found, showing that Ti was hugely scavenged before by ilmenite and to a lesser extent rutile crystallization. The iron incorporation into ilmenite, pyroxene and

562 olivine of very fayalitic composition is also in agreement with the low Mg content. Virtually no
563 magnetite was found in spite of some rutile needles. This all indicates a rather low fO_2 and
564 low liquidus temperature in a highly evolved mafic magmatic system, although still far away
565 from peralkaline miaskitic or much less agpaitic rocks (Marks and Markl, 2017).

566 This work also confirms the utility of apatite trace elements analysis for petrogenetic or
567 exploration purposes (e.g. Mao et al. 2016 and references herein). Although the LA-ICP-MS
568 data acquisition was not especially performed for apatite trace elements analysis, using for
569 example the discrimination patterns proposed by Belousova et al. (2002) some light is put on
570 the apatite and gabbro genesis, considering also the absence of observable concurrent
571 phosphate minerals (monazite or xenotime) or garnets which tend to scavenge most of
572 incompatible and RE elements.

573

574 The strong enrichment mainly of the LREE with a nearly log-linear decrease slope to heavier
575 REE (Ce/Yb)_{cn} of 12-13)) and a moderate negative Eu-anomaly ($2Eu/(Sm+Gd)$)_{cn} of 0.62-0.7)
576 (**Error! Reference source not found.**) are common patterns observed in many apatites. The
577 negative Eu-anomaly was probably controlled by former or simultaneous plagioclase
578 crystallization (e.g. Rollinson, 1993) much more than the own apatite redox-state, and would
579 decrease with further magmatic differentiation as observed e.g. in granites. In contrast, mid-
580 ocean ridge gabbro apatites nearly don't show LREE enrichment in comparison with HREE
581 (see Mao et al. 2016). The dispersion in the apatites of LREE (e.g. La 261- 1030 ppm, Ce
582 770-2590ppm) exceeding for example the dispersion of HREE and Y (328-984ppm) is much
583 more pronounced than the nearly invariant trace elements Sr (516-747ppm) or Mn (358-
584 478ppm). Mn decreases slightly together with Sr, whereas between Y and Sr a strong scatter
585 exists. However, the clear positive correlation between Th and Ce (Fig. 8B) as well as

586 between Y and the REE-sum, evidences their enrichment during the crystallization process.
587 Also both the Th/Ce and Y/REE contents and ratios indicate a more reducing environment
588 (Belousova et al., 2002), whereas for the redox sensitive Mn the picture is not so clear:
589 assuming higher Sr as indicator of less differentiated and more reduced magma, the coupled
590 decrease of Sr and Mn may be caused by the preferred incorporation of Mn²⁺ instead of Mn³⁺
591 or Mn⁴⁺ in apatite where it substitutes directly for Ca²⁺ in the two Ca-sites. This assumption is
592 also supported by the slightly positive Ce-anomaly with the preferential incorporation of Ce³⁺
593 on the ⁹⁹Ca1-site and the corresponding valence balancing through, e.g. Na⁺.

594

595 The comparison with the discrimination diagrams of Belousova et al. (2002) give the following
596 picture: The Sr/Y values (Sr 516-747ppm / Y 328-934ppm) occupy the fields of granitoid but
597 more the mafic rocks to Fe-ore fields. (Ce/Yb)_{cn} of 12-13 and Sum REE 0.2-0.6 wt.% are in
598 the granitoid and near the dolerite field. Sr 516-747ppm/ Mn 358-478ppm correlations are in
599 the larvikites, jacupirangite and iron ore fields, Y 328-934ppm/ Eu/Eu* 62-0.7 occupy the
600 granitoids, mafic rocks and iron ore fields. The high P concentrations in the Fe-ore fields like
601 Durango or Kiruna, but also in some of the Fe-Ti-P deposits worldwide as well as the
602 enrichment of K are in agreement with the overlapping of most of these mafic to granitoid
603 and immiscibility magma fields.

604 Neither etching nor the CL images reveal zonation or growth patterns in the apatites. Zircons
605 seem to have crystallized first and were then enclosed by ilmenites or later between nearly
606 coeval plagioclase and pyroxene grains, where also early formed rutile needles are frequent.
607 Altogether, petrologic evidence and main elements as the high K, P, and Na content of the
608 gabbro as well as the apatite trace element geochemistry (high Ce/Yb etc.) plaid against an
609 ophiolite subduction-related origin of the Vichada Viejita Creek gabbro, favoring instead an

610 aborted continental rifting process with relatively low f_{O_2} , little water (no amphiboles nor mafic
611 pegmatites) and low Cl content. As fluxing agent, phosphorous may have played an important
612 role in the system. Some of the gabbro whole-rock and apatite geochemical characteristics
613 hint to sediment or continental crust recycling, but also to magma mixing with some
614 lamprophyre, carbonatite or anorthosite associated Fe-Ti-P signatures.

615

616 The two U-Pb principal ages obtained from 25 (Af-1) and 35 (Af-7) apatite grains,
617 respectively, are discordant and show a scattering of individual grain ages. They yield lower
618 intercept ages of 1001 ± 59 Ma (Af-1) and 961 ± 61 Ma (Af-7) with a $^{207}\text{Pb}/^{206}\text{Pb}$ initial value
619 of 0.945 (Figure 10). Adjusting them to the Pb evolution model of Stacey and Kramers (1975),
620 we obtain similar ages of 975 ± 9 Ma (Af-1) and 1002 ± 21 Ma (Af-7), with Af-1 showing no
621 lower scattering. This rather broad range in ages may have two principal reasons: either
622 analytical-procedural based dispersion, or geological-mineralogical factors and their
623 interaction. The low scatter of analytical data of the different standard apatites used during
624 measurement suggest a rather stable instrument configuration and no measuring
625 disturbance. However, apart from differences between the two sample groups from different
626 parts of the gabbro also the different analytic procedures have contributed, as in the second
627 case also AFT data were to be obtained. Among the geological-mineralogical factors, first the
628 rather high proportion of common (non-radiogenic) Pb is to be mentioned, inhomogeneities of
629 HFSE incorporation during the crystallization process as also evidenced by the high REE
630 scattering in the apatite samples from gabbro Af-7; the homogeneous CL-images of apatites
631 from Af-1 suggest no zonation during apatite growth. Although the U-Pb apatite closure
632 temperature of $\sim 500^\circ\text{C}$ is much lower than for zircons (Chew and Spinkings, 2015) and than
633 the magma emplacement temperature ($>1000^\circ\text{C}$ or perhaps lower due to continental
634 contaminants, fluids and high P) neither diffusion effects during the cooling process nor later

635 thermal peaks can be ruled out. So there is no doubt that both apatite U-Pb ages show a
636 common history related to the magmatic emplacement and cooling process and much more
637 unlikely posterior thermal events. Small mafic bodies as the Viejita Creek gabbro tend to
638 solidify and cool below the apatite closure temperature in less than ~100 years. Additionally,
639 the absence of metamorphic overprinting signs both in rocks and thin-sections, rule out
640 stronger posterior thermal events.

641 This Early Neoproterozoic Viejita Creek gabbro exhibit strong similarities with other mafic
642 bodies outcropping hundreds of kilometers to the south near to the Vaupés and Apaporis
643 rivers extending at least until Brazil (Figure 2). Their radiometric ages are considerably older
644 (100-200 Ma), however, but also were obtained by other radiometric methods (K/Ar + Rb/Sr).
645 The Rb/Sr isochrons are considered to give too low regional ages with very large error
646 margins (Kroonenberg et al., 2016). Such a large time difference only caused because of
647 analytical differences is not very probable, but we don't have enough elements for a definite
648 conclusion, at the moment.

649

650 The reported time window of Neoproterozoic mafic magmatism in the western Amazonian
651 craton span from 940 to 1225 Ma (Table 1). To the East (Brazilian Taraira) are some of the
652 youngest reported ages ~ 940 to 980 Ma (Tassinari, 1996), and moreover there seems to be
653 a South-to-North trend from older to younger magmatism, possibly indicating several cycles
654 of cortical opening and closing in different parts of the craton. About 200km to the East of our
655 study area, the youngest known intracratonic magmatic rocks in the NW Amazonian Craton,
656 the Nepheline Syenite of San José del Guaviare, of Neoproterozoic-Ediacaran to Cambrian
657 ages of ~578 Ma (Mejia et al., 2012) and biotite K/Ar and Rb/Sr cooling ages of 445 – 495 Ma
658 (Pinson et al., 1962) outcrops over > 10 square kilometers. Recently obtained own LA-ICP-

659 MS U-Pb zircon ages of ~609 Ma in the southern extension near Jordan (Franco et al., 2018;
660 Muñoz Rocha et al., 2019) suggest a long emplacement and cooling history for this large
661 body. Further west, no intracratonic intrusions are reported until now. Anyhow, the San José
662 del Guaviare Nepheline Syenite is another indication of tectonic reactivation of structural
663 weakness zones in the crust, possibly representing older suture or rift zones. Whilst in the
664 case of the older Viejita Creek gabbro the Grenvillian orogeny as partial response to the
665 Rodinia Supercontinent assembly some 1 Ga ago was the most likely cause producing a
666 distinctive enrichment of Ti, K, P and REEs in apatites from the mantle-derived magma, the
667 magmatic differentiation of the Nepheline Syenite, coeval but not necessarily caused by the
668 Pan-African-Braziliano orogeny, produced more agpaitic rocks and characteristic minerals
669 such as large zircon crystals.

670

671 Also other alkaline to carbonatitic intrusions in the NW Amazonian Craton may be related to
672 Grenvillian sequences s.l. (Cordani et al., 2010) or later events. The Nepheline Syenites of
673 the Muri Alkaline Complex are dated between 1026 ± 28 Ma (Issler et al., 1975) and 1090 Ma
674 (Kroonenberg et al., 2016). For the Nb-rich Seis Lagos Carbonatite Complex (SLCC) in Brazil
675 near to the Colombian border, Rossoni et al. (2017) established an U-Pb zircon maximum
676 age of 1328 Ma, at the very beginning of the Grenvillian, but other authors attribute much
677 younger ages, which span from the Cambrian to the Triassic (Pinheiro et al., 1976). For the
678 diamondiferous Guaniamo layered kimberlite sheets in Venezuela, ages between 840 and
679 710 Ma are claimed (Channer et al., 2001).

680

681 These examples illustrate sufficiently, how much work is still to be done in the often difficult to
682 access and covered areas of the Amazonian Craton in order to get an indisputable and
683 generally accepted reconstruction of the Craton's history. Much better defined in this sense

684 are the anorogenic granites such as the Parguaza Rapakivi Batholith from 1392 ± 5 Ma to
685 1402 ± 2 Ma in Colombia (Bonilla et al., 2013), although this is younger than the ages of the
686 batholith reported in Venezuela of ~ 1545 Ma. The comparable felsic Matraca rapakivi
687 granites (Bonilla et al., 2016) seem to have a narrow correlation with U-Pb LA-ICP-MS ages
688 of $1381 - 1343$ Ma from pegmatitic monazite and xenotime of the Chorrobocon colluviums in
689 the Colombian Guainía Department (Franco et al., 2019), where granitic intrusions and
690 associated mineralizations prove to be much more prominent than in other portions of the
691 Mitú Complex (Bonilla et al., 2019).

692

693 With respect to the relation between the intrusive and the sandstone cover mentioned in the
694 beginning of this chapter, another gabbro outcrop ~ 10 km to the west of the study area (Cerro
695 Siare, Figure 3) may give some hints. This gabbro consists of 55-60% plagioclase, 3-5%
696 pyroxene, 2-8% olivine and 25-30% chlorite and crosscuts as a vertical dike the sandstone
697 sequence, as reported by Franco (2002). Initially, Vesga & Castillo (1972) described the
698 sedimentary sequence informally as “Raudales-Iteviare Sandstone”. However, in the updated
699 Colombian Geological Map (Gómez Tapias et al., 2015) these sediments are now correlated
700 with the Ordovician Araracuara Formation (without reported ages). But the detailed
701 description of this unit by Franco (2002), who recognized a detailed column of 372 m thick
702 sub-arkoses to quartz sandstones and conglomeratic sandstones as part of the Mapiripana
703 Formation of Mesoproterozoic age is very convincing, although much more study including
704 field work and geochronology has to be done for a final conclusion. The Mapiripana
705 Formation as well as the La Pedrera Formation are more likely part of a northern extension of
706 the Tunui Group (Pinheiro et al., 1976), which also forms the gold-rich Naquén and
707 Caranacoa mountains of Mesoproterozoic age. All of them seem to represent molasse
708 deposits of different oogenesis eroded long after the consolidation of the Roraima Formation.

709 In the latter, detrital zircon U-Pb ages of 2171-1958 Ma (Santos et al., 2003) indicate a Trans-
710 Amazonian Orogeny origin of the sediments (Kroonenberg et al., 2016), with more or less
711 well developed metamorphic overprinting. The series of Neoproterozoic gabbros could have
712 intruded and cut rocks of the Mitu Complex (Bonilla et al., 2019; Galvis et al., 1979; López et
713 al., 2007; Rodríguez et al., 2011) as part of the 1.80-1.55 Ga Rio Negro-Juruena
714 Geochronological Province (Figure 2) in Colombia (Tassinari, 1996; Tassinari and
715 Macambira, 1999) and also the 1.87-1.5 Ga Roraima-Formation-like sedimentary covers
716 (Tunui Group). The oldest metamorphic overprint of those sediments was dated at ~1.3 Ga
717 and related with the incipient Grenvillian event (Kroonenberg and de Roever, 2010).

718

719 The Amazonian Craton as a whole seems to have behaved as a rigid block where
720 deformation mostly concentrated along pre-existing major shear zones that could accompany
721 the uplift of the intervening blocks, the development of rift basins, emplacement of bi-modal
722 magmatic suites and extensional fractures which were filled by mafic dike swarms (Cordani et
723 al., 2010) or intrusions. This suggests that granitic, mafic and syn-sedimentary sequences of
724 Grenvillian age outcropping in the Colombian Rio Negro Juruena Province would be the
725 result of different stages of intraplate rifting and shearing induced by continent-continent
726 collision (Putumayo Orogen and Sunsás belt). This tectonic regime hence also created easier
727 pathways for the ascent of magmas. The Viejita Creek Gabbro represents such a mafic body
728 associated with intraplate rifting, as a response to the Rodinia Supercontinent assembly. This
729 mafic intrusion contains a rare lithology in this part of the Amazonian Craton where felsic
730 rocks of the Rio Negro-Juruena province predominate. This points to a mantle origin with high
731 crustal influence or magma mixing and rifting caused by significant collisions like those
732 assumed to have occurred during the Grenvillian.

733

734 The NE-SW and NW-SE structural trends in the Eastern Colombian basement are visible as
735 main lineaments all over the Amazonian Craton. They were interpreted mainly as the result of
736 compression during Mesoproterozoic accretion stages (Galvis et al., 1979; Tassinari and
737 Macambira, 1999) such as the Rondonian-San Ignacio orogeny, or the Sunsás orogeny
738 (Cordani et al., 2010). In this context, our data and other research suggest that the mafic
739 intrusion occurred related with a NW-SE trending intra plate or rifting event some 970 Ma ago
740 (or slightly before) affecting the Rio Negro Juruena Province. This may have been associated
741 with the Putumayo Orogeny (Ibañez et al., 2015) proposed for the late phases of the

742 Amazonia-Baltica-Laurentia collision. Possibly in this context or earlier, a sedimentary basin
743 opened, accommodating the deposition of sediments during the late Mesoproterozoic.

744

745 In relation to the gabbro's exhumation process, the apatite fission track central age of $179.8 \pm$
746 9.0 Ma extracted from 47 measurements of high-quality apatite crystals (Figure 11), allow
747 some preliminary conclusions for developing a thermal history model. The time-temperature
748 path with the highest probability suggests continuous and slow cooling through the Apatite
749 Partial Annealing zone during the Meso- and Cenozoic, since the Jurassic.

750

751 The understanding of the thermal history of the Colombian part of the Amazonian craton is in
752 its beginning and requires more thermochronological data. Apatite and zircon fission track
753 thermochronology until now focused mainly on the Andes Cordillera, where mostly Andean,
754 i.e. Cenozoic ages are retrieved from basement rocks (Amaya et al., 2017; Parra et al., 2009;
755 Villagómez and Spikings, 2013). The analyzed samples exhumated ~400km southeastwards
756 of the Andean thrust front or Borde Llanero Fault System (Restrepo-Pace and Cediél, 2010),
757 did not cool rapidly as would result from an Andean orogeny uplift, but rather experienced a
758 gradual, slow cooling through the 120°-60°C temperature window (Apatite Partial Annealing
759 Zone). This slow cooling occurred in the regional context of Mesozoic extension during which
760 backarc and marginal basins developed in western South America (Coney and Evenchick,
761 1994; Dalziel, 1986; Mpodozis and Ramos, 1989). The source-material for these basins were
762 predominantly clastic sediments originating from the cratonic lithosphere (e.g. Horton, 2018
763 and references therein). Further possible geochronological evidence for the gradual slow
764 erosion of the Grenvillian remnants are found in the Llanos basin to the west of our study
765 area, in which the 950-1050 Ma age population is one of the most dominant zircon U-Pb age

766 populations of the sedimentary record from the Paleozoic to the Late Cenozoic (Horton et al.,
767 2010).

768

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774

775 **7. Bibliography**

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1116 **Table 3** Operating conditions of the LA-ICP-MS equipment

Laboratory & Sample Preparation	
Laboratory name	Géosciences Rennes, UMR CNRS 6118, Rennes, France
Sample type/mineral	Magmatic apatite
Sample preparation	Conventional mineral separation, 1 inch resin mount, 1 μ m polish to finish
Imaging	CL: RELION CL instrument, Olympus Microscope BX51WI, Leica Color Camera DFC 420C
Laser ablation system	
Mark, Model & type	ESI NWR193UC, Excimer
Ablation cell	ESI NWR TwoVol2
Laser wavelength	193 nm
Pulse width	< 5 ns
Fluence	6.5 J/cm ² sample AF-4, 6.5 J/cm ² sample AF-7
Repetition rate	5 Hz sample AF-4, 7 Hz sample AF-7
Spot size	50 μ m sample AF-4, 30 μ m sample AF-7
Sampling mode / pattern	Single spot
Carrier gas	100% He, Ar make-up gas and N ₂ (3 ml/mn) combined using in-house smoothing device
Background collection	20 seconds
Ablation duration	60 seconds
Wash-out delay	15 seconds
Cell carrier gas flow (He)	0.75 l/min
ICP-MS Instrument	
Mark, Model & type	Agilent 7700x, Q-ICP-MS
Sample introduction	Via conventional tubing
RF power	1350W
Sampler, skimmer cones	Ni
Extraction lenses	X type
Make-up gas flow (Ar)	0.87 l/min
Detection system	Single collector secondary electron multiplier
Data acquisition protocol	Time-resolved analysis
Scanning mode	Peak hopping, one point per peak
Detector mode	Pulse counting, dead time correction applied, and analog mode when signal intensity > $\sim 10^6$ cps
Masses measured	⁴³ Ca, ²⁰⁴ (Hg + Pb), ²⁰⁶ Pb, ²⁰⁷ Pb, ²⁰⁸ Pb, ²³² Th, ²³⁸ U
Integration time per peak	10-30 ms

Sensitivity / Efficiency	28000 cps/ppm Pb (50µm, 10Hz)
Dwell time per isotope	5-70 ms depending on the masses
Data Processing	
Gas blank	20 seconds on-peak
Calibration strategy	Madagascar apatite used as primary reference material, Durango and McClure apatites used as secondary reference material (quality control)
Reference Material info	Madagascar (Thomson et al., 2012) Durango (McDowell et al., 2005) McClure (Schoene and Bowring, 2006)
Data processing package used	lolite (Paton et al., 2010), VizualAge_UcomPbine (Chew et al., 2014)
Quality control / Validation	Durango: Wtd ave ^{207}Pb corrected age = 32.29 ± 0.76 Ma (N=5, MSWD=0.76; probability=0.92) McClure: Wtd ave ^{207}Pb corrected age = 520.3 ± 8.8 Ma (N=3, MSWD=0.47; probability = 0.78)

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1118 **Table 4** U-Pb LA-ICP-MS data of apatite crystals from Caño Viejita gabbro samples AF-1 and
1119 AF-7.

ANALY SIS #	$^{238}\text{U}/$ ^{206}Pb	PropErr 2Sig%	$^{207}\text{Pb}/$ ^{206}Pb	PropErr 2Sig%	Approx_ U_PPM	Approx_P b_PPM	Final ^{207}Age	PropErr2S igAbs.
AF-1.1	3.178	5.7	0.4660	2.4	1.4	1.2	997	50
AF-1.2	3.617	5.8	0.4180	2.6	1.3	1.0	973	58
AF-1.3	3.890	3.1	0.3872	2.2	1.7	1.2	960	47
AF-1.4	3.601	3.0	0.4199	2.3	1.2	0.9	974	56
AF-1.5	3.778	2.9	0.4041	2.1	1.2	0.9	959	51
AF-1.6	3.769	3.0	0.3952	1.9	1.5	1.1	973	45
AF-1.7	3.754	3.0	0.4060	2.5	1.1	0.9	965	55
AF-1.8	3.113	3.1	0.4920	2.4	1.2	1.2	960	66
AF-1.9	3.736	3.0	0.4062	2.2	1.2	0.9	966	53
AF-1.10	3.729	3.0	0.4190	2.4	1.1	0.8	943	56
AF-1.11	3.730	3.0	0.3990	2.5	1.1	0.8	980	54
AF-1.12	3.575	3.1	0.4250	2.6	1.2	0.9	971	57
AF-1.13	3.428	3.0	0.4378	2.3	1.3	1.1	985	56
AF-1.14	3.840	3.0	0.3823	2.3	1.4	1.0	977	50
AF-1.15	3.792	2.8	0.3883	1.8	1.7	1.2	976	46
AF-1.16	3.733	2.9	0.3884	2.3	1.5	1.1	999	52
AF-1.17	3.617	2.9	0.4050	2.5	1.2	0.9	997	58
AF-1.18	3.818	2.9	0.3816	2.2	1.6	1.1	989	52

AF-1.19	3.586	2.9	0.4148	2.1	1.2	0.9	984	52
AF-1.20	3.658	3.0	0.4074	2.3	1.4	1.0	983	50
AF-1.21	3.744	3.0	0.3883	2.2	1.3	0.9	997	51
AF-1.22	3.552	3.0	0.4045	2.2	1.3	1.0	1015	56
AF-1.23	3.689	2.9	0.3965	2.1	1.4	1.0	989	52
AF-1.24	3.675	3.0	0.4030	2.7	1.1	0.8	985	57
AF-1.25	3.685	3.0	0.4140	2.4	1.1	0.8	962	60
AF-7.1	3.906	6.2	0.4010	9.2	2.3	1.3	950	120
AF-7.2	3.610	7.2	0.4320	11.6	1.4	0.9	980	140
AF-7.3	3.623	8.0	0.4120	10.9	1.3	0.9	1020	160
AF-7.4	3.268	8.8	0.4210	10.7	1.2	0.8	1090	170
AF-7.5	3.636	6.9	0.3920	10.5	1.6	0.9	1040	130
AF-7.6	3.195	7.7	0.4310	9.7	1.2	0.9	1100	160
AF-7.7	3.484	7.7	0.5170	10.6	1.7	1.3	880	140
AF-7.8	3.300	7.3	0.4220	10.7	1.3	0.8	1110	150
AF-7.9	3.300	8.3	0.4180	10.3	1.1	0.7	1080	150
AF-7.10	3.759	8.6	0.3890	12.1	1.2	0.8	990	150
AF-7.11	3.597	7.6	0.4070	10.1	1.6	1.0	1040	140
AF-7.12	3.322	7.6	0.4250	10.6	1.2	0.9	1080	160
AF-7.13	3.559	7.5	0.4030	10.2	1.2	0.9	1060	140
AF-7.14	3.521	6.3	0.3900	7.7	1.9	1.2	1063	120
AF-7.15	3.759	6.4	0.3670	7.6	2.3	1.5	1062	110
AF-7.16	2.591	7.5	0.5240	8.6	1.4	1.3	1130	190
AF-7.17	2.695	8.1	0.5530	10.1	0.9	0.8	1000	230
AF-7.18	3.096	8.0	0.4690	11.3	1.5	1.0	1070	170
AF-7.19	3.534	10.6	0.5050	14.3	1.0	0.5	900	190
AF-7.20	2.028	7.5	0.5740	7.3	1.6	1.9	1120	190
AF-7.21	1.570	7.1	0.6790	6.2	1.4	2.4	990	230
AF-7.22	3.521	8.5	0.4560	12.1	1.3	0.8	1000	170
AF-7.23	3.436	8.9	0.4360	12.6	1.1	0.6	990	170
AF-7.24	3.125	6.6	0.4590	9.2	1.9	1.4	1080	150
AF-7.25	3.436	8.9	0.4860	13.0	1.0	0.7	1000	190
AF-7.26	3.367	8.4	0.3950	10.9	1.1	0.7	1130	180
AF-7.27	3.690	7.4	0.3930	9.9	1.8	1.0	1020	140
AF-7.28	3.650	8.4	0.4150	12.3	1.3	0.7	1010	150
AF-7.29	3.279	7.9	0.4150	11.6	1.4	0.8	1110	170
AF-7.30	3.636	8.0	0.4720	12.5	1.4	0.8	910	160

AF-7.31	3.472	8.3	0.4350	11.3	1.1	0.6	970	170
AF-7.32	3.279	7.2	0.4270	11.9	1.3	0.7	1110	170
AF-7.33	3.247	8.8	0.4070	10.6	1.1	0.6	1130	160
AF-7.34	3.205	7.4	0.4460	11.7	1.2	0.9	1080	180
AF-7.35	3.378	7.8	0.4740	9.7	1.1	0.9	960	160

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Table 5 Apatite fission tracks results. N is the number of analyzed grains, N_s represents the number of spontaneous tracks counted in total, A represents the total area in which N_s were measured distributed over all 33 grains. The Average and Average Weighted ²³⁸U/⁴³Ca ratios are based on each individual ²³⁸U/⁴³Ca ratio and are used as a proxy for the Uranium concentration of each apatite grain. The samples pass the chi-squared probability test (>0.05). Chlorine content given in weight percentage and with synthetic apatite (**6.81 wt% Cl**, Klemme et al., 2013). The mean length (l_m), number of tracks lengths (n_i) and standard deviation is also displayed.

Sample	N	N _s	A (10 ⁻³ cm ²)		Average ²³⁸ U/ ⁴³ Ca	Average Weighted ²³⁸ U/ ⁴³ Ca	Central age ± 1σ (Ma)	Pooled age ±1σ (Ma)	P(χ ²)	Chlorine content ±1σ (w%)	l _m (μm)	n _i	σ (μm)
AF-7	33	404	3.35		0.0888	0.00934	179.8±9.0	173.3±9.2	0.58	0.28±0.13	11.84	47	1.87