An integrative geologic, geochronologic and geochemical study of Gorgona Island, Colombia: Implications for the formation of the Caribbean Large Igneous Province

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A R T I C L E   I N F O

Article history:
Received 24 January 2011
Received in revised form 7 July 2011
Accepted 11 July 2011
Available online 3 August 2011

Editor: R.W. Carlson

Keywords:
Gorgona Island
Caribbean Large Igneous Province
geochronology
Galapagos hotspot
slab window

A B S T R A C T

The genesis of the Caribbean Large Igneous Province (CLIP) has been associated to the melting of the Galapagos plume head at ~90 Ma or to the interaction between the plume and the Caribbean slab window. Gorgona Island, offshore western Colombia, is an accreted fragment of the CLIP and its highly heterogeneous igneous suite, ranging from enriched basaltic to depleted komatiites and picrites, was assumed to have formed at ~89 Ma from different part of the plume. Here we present new geologic, geochronologic and geochemical data of Gorgona with significant implications for the formation of the CLIP. A new set of 40Ar–39Ar ages documents a magmatic activity spanning the whole Late Cretaceous (~88 ± 7 to 64.4 ± 5 Ma) followed by a shallower, picritic pyroclastic eruption in the Paleocene. Trace element and isotope geochemistry confirm the existence of an enriched (EDMM:La/Sr ≥ 1 and εNd of 5.7 to 7.8) and a depleted (DMM:La/Sr < 1 and εNd of 9.5 to 11.3) mantle sources. A progressive increase in the degree of melting and melt extraction with time occurred in both groups. Petrologic modeling indicates that low but variable degrees of wet melting (~5%) of an EDMM can produce the LREE-enriched rocks. Higher degree of melting (~10%) of a mixed DMM + EDMM (40 to 60%) may reproduce the more depleted rocks with temperatures in the range of ambient mantle in absence of plumes. Our results contradict the notion that the CLIP formed by melting of a plume head at ~90 Ma. Multiple magmatic pulses over several tens of Ma in small areas like Gorgona, also recognized in other CLIP areas, suggest a long period of diffuse magmatism without a clear pattern of migration. The age span of this magmatism is broadly concurrent with the Caribbean slab window. During this time span the Farallon oceanic lithosphere (later becoming the Caribbean plate) advanced eastward ~1500 km, overriding the asthenosphere feeding the proto-Caribbean spreading ridge. This hotter mantle flowed westward into, and mixed with, the opening mantle wedge, promoting increasing melting with time. The fortuitous occurrence of a plume passing through the slab gap area cannot be excluded but not required to produce the observed composition and degree of melting.

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1. Introduction

Oceanic plateaus are the most voluminous large igneous provinces on Earth and usually considered the result of short-lived (few Ma) periods of intense submarine volcanism marking the arrival of mantle plumes at the base of the lithosphere (Kerr and Mahoney, 2007). This major pulse of volcanism should be followed by a volcanic chain with ages decreasing away from the site of the plume head impact. One such event is postulated to have formed most of the Caribbean plateau at ~90 Ma, when the Galapagos plume head impacted the Farallon plate (Duncan and Hargraves, 1984; Hastie and Kerr, 2010; Sinton et al., 1998; Storey et al., 1991). At present, the remnants of the Caribbean plateau form the irregularly thickened and locally deformed oceanic crust of the Caribbean Sea (Mafffret and Leroy, 1997; Driscoll and Diebold, 1998) as well as several highly deformed fragments obducted in northern South America, Central America and the Antilles (Fig. 1), collectively defined as the Caribbean Large Igneous Province (CLIP).

The island of Gorgona, offshore western Colombia, is one of the less deformed and last accreted pieces of the Caribbean plateau. Widely known for its ultramafic occurrences that includes one of the few world occurrences of Mesozoic komatiites (Echeverría, 1980), Gorgona rocks are among the most thoroughly studied from a geochemical and isotopic point of view (see review in Kerr, 2005). By contrast, geologic and geochronologic studies are scarce and the entire Gorgona suite has been considered roughly concurrent with the initial volcanism of the Caribbean plateau based on a three-step plateau
age of 87.9 ± 2.1 Ma and a three-point isochron of 86.1 ± 6.1 Ma of basaltic lavas (Sinton et al., 1998). Previous studies showed that Gorgona rocks are heterogeneous, with slightly enriched to strongly depleted varieties and a relatively large spread in isotope values (Dupré and Echeverría, 1984; Echeverría, 1980; Hauff et al., 2000a; Kerr et al., 1997; Revillon et al., 2002; Thompson et al., 2003). The trace element and isotope geochemistry of most rocks is similar to MORB and the first model for its formation was in fact related to an oceanic ridge (Dieterich et al., 1981). On the other hand, high volatile contents (H$_2$O, B, Cl) in olivine melt inclusions (Kamenetsky et al., 2010) indicate a hydrated mantle source, possibly related to subduction fluids. However, over the past two decades Gorgona has been associated to a hotspot and, given the only available age, all the rock varieties were assumed to have formed at roughly the same time (~89 Ma) within a complex, compositionally and thermally heterogeneous mantle plume (e.g. Kerr, 2005). Despite three decades of studies the tectonic setting and the petrogenesis of Gorgona are still not completely understood. Clearly, a better stratigraphic and geochronologic control of Gorgona geology is critical to solve what has been termed the “petrologic enigma” of the island (Kerr, 2005) and its implication for the formation of the CLIP.

2. Age and tectonic setting of the Colombian CLIP fragments

The highly deformed belt west of the Romeral suture in Colombia (Fig. 2) is composed of mafic and ultramafic igneous rocks as well as marine sediments that are considered part of the CLIP based on its geochemical affinity and gravimetric and magnetic signature (Cediel et al., 2003; Kerr et al., 1996). These rocks are affected by large scale folds, thrust, and right-lateral faults developed during the oblique convergence between the Caribbean plateau and the northwestern margin of South America. Although differing in details, regional plate reconstructions indicate that the accretion process was accomplished by a progressive docking of discrete slivers of the CLIP from the end of Cretaceous through the Cenozoic (Cediel et al., 2003; Kennan and Pindell, 2009; Pindell et al., 2006). In this process the slivers now forming the Western Cordillera (Dagua-Piñon terrane) were the first to be accreted, followed by the Gorgona and later the Baudó ones (Figs. 1 and 2)( Cediel et al., 2003; Kennan and Pindell, 2009). Multichannel seismic profiles northeast and southwest of Gorgona show that the island is part of a series of NNE trending axial basement bulge formed in Late Eocene times (Cediel et al., 2003; Kerr, 2005). The latter represents one of the few exposures of the CLIP intrusive complexes and was chosen for comparison with the intrusive complex of the island. Our results, which are consistent with field geologic relations, greatly expand the age range of the magmatic activity and, coupled with new geochemical and Sr and Nd isotope data, allow to assess the petrologic evolution of the Gorgona suite. We then discuss these new data in the frame of the previous models for the formation of the CLIP.
Colombia proved difficult to date. These ages are broadly consistent with those obtained for the Cordillera dated at ~89 Ma and samples from four sites in the eastern side of the Western terrane accretion has been accomplished by the end of Miocene deformation observed in the San Juan basin indicates that the Baudó faulting. 

Because of the intense deformation, pervasive weathering and low grade metamorphism the accreted fragment of the CLIP in restricted to three samples from Serranía del Baudó in the range ~73–76 Ma and samples from four sites in the eastern side of the Western Cordillera dated at ~86–96 Ma (Kerr et al., 1997, 2002, Kerr et al., 2004). These ages are broadly consistent with those obtained for the submerged part of the Caribbean plate where igneous rocks were dated at ~94–90 Ma at DSDP Site 150 and ~81 Ma at ODP site 1001 (Sinton et al., 1998, 2000), and between ~81 and ~75 Ma at Beata Ridge (Revillon et al., 2002) (Fig. 1).

3. Sampling and methodology

During three field campaigns we revised the geology of the island and collected a large suite of fresh samples from all the geologic units. Additional sampling was conducted in the Western Cordillera in an effort to sample the intrusive part of the CLIP. After a petrographic study the best samples were crushed and the least altered fragments were selected for geochronology and geochemistry. Representative pictures of field geology (Fig. A1) and of dated rocks (Fig. A2) are provided in the Electronic Supplementary Material.

The 40Ar–39Ar analyses were performed at the Geochronology Laboratory of the Departamento de Geología, CICESE, Baja California, Mexico. With the exception of samples GOR 28 and CORW 9, all samples were step-heated and the argon isotopes were analyzed in two different mass spectrometers. One set of experiments was done on less than 0.1 mg of sample using a laser as a heat source and a VG5400 mass spectrometer. To insure that the argon was released from a homogeneous phase, a second set of experiments was conducted with a temperature controlled Ta furnace on line with a MS 10 mass spectrometer. In order to compensate for the lower sensitivity of the MS 10 mass spectrometer aliquots of 0.5 to 1.0 g were used for these experiments. All technical details and results of the experiments are reported in the Electronic Supplementary Material.

Major elements were analyzed by X-ray fluorescence (XRF) at Instituto de Geología, UNAM, according to the procedures outlined in Lozano-Santa Cruz et al. (1995). Trace elements were obtained by inductively coupled plasma mass spectrometry (ICP-MS) using a Thermo Series X® instrumentation at Centro de Geociencias, UNAM, Querétaro, Mexico. Sr and Nd isotope ratios were determined on whole rock at the Dipartimento di Scienze della Terra, Università degli Studi di Firenze, using a Thermo Finnigan Triton-Ti® mass spectrometer equipped with nine Faraday cups in a dynamic mode. Analytical procedures are given in Avanzinelli et al. (2005). Further details of procedures and measurements are given in the Electronic Supplementary Material.

4. Results

4.1. Geology

Dense pluvial forest and deep lateritic soil cover most of the island so that rock units can be observed along the coast but are rarely exposed in the interior. Fig. 3 shows our revision of the original geologic mapping of Echeverría (1980) and the main sampling and observation sites. Peridotites and dunite were reported to form the axial core of the island by Echeverría (1980) who was able to map the island when large parts of the forest had been cleared. At present these ultramafic rocks may be only seen in a few small outcrops in the uppermost part of the island. Serpentinized cumulate peridotites were observed along a major NNE striking fault zone in contact with lavas at 205 m asl in the upper part of a stream west of the Park facilities toward Cerro La Trinidad (Fig. 3). According to the mapping of Echeverría (1980) the peridotites are surrounded by massive gabbros although the relations with the other units are rarely observed. Massive poikilitic gabbros were observed to lie below komatiitic lavas in the upper part of the Pizarro stream (site 28, Fig. 3). A microgabbroic sill was also observed at site GOR 15–2 in the northeastern part of the island (Fig. 3; Fig. A1a). In the rest of the island gabbros are seen in blocks, metric to decimetric in size, along the northwestern coast and near La Azufra (Fig. 3). These areas correspond to large rockfall fan from the upper part of the island. Extrusive rocks are dominated by picro-basalts (MgO = 6–10 wt.%) and, to a lesser extent, komatiitic and picritic lavas (MgO = 16–20 wt.%) (Fig. A1b). The relations among these rock units are almost always obscured, but in a few cases the komatiites were observed interspersed with the basalts, as it is also suggested by the frequent occurrence of the two lithologies in adjacent outcrops. In the southern part of Gorgona and at the small Gorgonilla Island, basaltic and komatiitic lavas are covered by a younger unit made of picritic (MgO = 22–23 wt.%) tuff breccias with hyaloclastic texture (Fig. 3; Fig. A1c). Described in detail by Echeverría and Aitken (1986), this pyroclastic deposit represents a change to a shallower environment in the submarine eruptive activity forming the island. The breccias are tilted to the south and covered in angular unconformity by different packages of marine sedimentary rocks. The oldest ones are steeply tilted (Fig. A1d) arenaceous limestones and siliceous shales intercalated with volcanic glass and ash levels in the southernmost part of Gorgonilla that were assigned to the Late Eocene by Gansser (1950). Other sedimentary rocks exposed in the southern part of Gorgona are siliceous sandstone and silty shale (Fig. A1e) for which a maximum age can be deduced from the scarce pollen recovered from samples GOR 30, 34 (fallen blocks along the coast), and 44 (in situ), which was processed by the standard method of Traverse (2007). The
assemblage was composed by Psilatriletes (ferns), Mauritiides franciscoi franciscoi (palm), Spirosyncolpites spiralis (angiosperm), Monoporopollenites annulatus (Poacea), Trilites sp. (ferns), Retipollinates sp., Echitriletes sp. (ferns), Laevigatosporites sp. (ferns), Baculatisporites sp. (ferns), the dinoflagellate Lingulodinium, and reworked material including the Cretaceous dinoflagellate Dinogymium. An age not older than Eocene can be deduced by the co-occurrence of M. franciscoi, S. spiralis, and M. annulatus (Jaramillo et al., 2009; Muller et al., 1987).

4.2. Geochronology

The two sets of geochronology experiments were generally comparable and produced eight reliable ages for basalts and gabbros. The results are presented in Table 1 and Fig. 4 and combine the experiments performed with both mass spectrometers. The relevant 40Ar–39Ar data for all the experiments of each sample are presented in Table 3 of the Electronic Supplementary Material, together with a detailed discussion of each age.

The oldest age at Gorgona was obtained from a poikilitic gabbro (GOR 28) that forms the axial intrusive core of the island sampled in the Pizarro stream (Fig. 3). Mafic minerals were completely altered but we were able to separate a small amount of plagioclase that could be analyzed in a few steps only. An isochron age of 98.7 ± 7.7 Ma, is well defined by five data points (MSWD = 0.3, see Fig. 4a). Four are from the step heating experiments and one from a one-step laser fusion. Sample GOR 20 is a basaltic lava exposed on the western side of the island. The rock is holocrystalline with olivine and orthopyroxene crystals with plagioclase inclusions defining a subophitic and poikilitic texture. Two experiments conducted in the temperature controlled Ta-furnace yielded comparable results (Fig. 4b). Our best estimate for this sample is taken from the well defined plateau age of 85.7 ± 1.6 Ma (84.6% of 39Ar released; MSWD = 0.3, for n = 4). This age is in agreement within 1σ errors with the only available 40Ar–39Ar age for Gorgona (87.9 ± 2.1 Ma; Sinton et al., 1998), although a direct comparison is precluded since the exact location of the previously dated samples was not provided. Sample GOR 15 comes from an olivine basalt flow in the northeastern part of the island. The rock is hypocrystalline characterized by anhedral olivine intergrowth with plagioclase (andesine). The two laser step-heating experiments yield comparable results (Fig. 4c). The 75.3 ± 1.2 Ma age, was calculated from the weighted mean of five consecutive fractions which represent 77.5% of the 39Ar released with a MSWD = 1.5. This age is indistinguishable from the isochron age of 76.4 ± 1.4 Ma calculated with the combined fractions of two experiments (MSWD = 1.1 for n = 12). At the same location we sampled a microgabbro that intruded below the GOR 15 basalt (Fig. A1a). The rock has an equigranular texture dominated by subhedral olivine and fine plagioclase crystals. Reproducible results were obtained in the four step-heating experiments, two with the laser using only a few rock fragments and two with the temperature controlled Ta-furnace, where bulk
samples of 0.5 and 1.0 g were analyzed. Our best age estimate of 69.5 ± 1.9 Ma (Fig. 4d) for this microgabbro comes from the plateau age, which was obtained from the weighted mean of the last three fractions of the laser step-heating experiment (76.5% of 39Ar; MSWD = 0.9). Sample GOR 8 is a basalt sampled at the northern tip of the island. It is a hypocrystalline rock with fine highpseudomorphic clinopyroxene (augite), subhedral plagioclase and anhedral olivine. Two laser step-heating experiments yield comparable results (Fig. 4e). The last six fractions of the second experiment were used to calculate a plateau age of 69.6 ± 1.6 Ma (73.4% of 39Ar; MSWD = 1.2), which we consider our best estimate for this basalt. Finally, we dated a sample from a basaltic komatiite that substitute diopside in a subhedral plagioclase and anhedral olivine. Two laser step-heating experiments yield comparable results (Fig. 4f). The last six fractions of the second experiment were used to calculate a plateau age of 69.5 ± 1.9 Ma (76.5% of 39Ar; MSWD = 0.9), which we consider our best estimate for this basalt. Given the stratigraphic relations, the 64 ± 5 Ma age can be taken as the maximum age for the picritic breccias, whereas their minimum age is set by the overlying sediments.

In addition to the Gorgona igneous suite we dated the Bolivar Ultramafic Complex (BUC) located in the Western Cordillera (Nivia, 1996) (Fig. 2). The BUC represents the largest exposure of the intrusive complex of the CLIP thus a comparison with the intrusive bodies exposed at Gorgona would be worthwhile. The complex is located about 100 km north of Cali along the eastern edge of the Western Cordillera (Fig. 2). A 40Ar/39Ar age of 90.5 ± 0.9 was previously published by Kerr et al. (2004) for a weighted mean of four different samples whereas Villagomez (2010) report U–Pb zircon ages of 94.0 ± 2.4 and 95.5 ± 1.0 Ma. Our sample CORW10 is an isotropic gabbro rich in labradorite collected 2.5 km southwest of Bolivar village. An experiment performed with 1.0 g of bulk sample with the MS 10 mass spectrometer using a 1.02 g sample yielded measurable argon. A plateau age of 64 ± 5 Ma (see Fig. 4f) was calculated with three fractions released above 900 °C, these represent 82.6% of the 39Ar released (MSWD = 0.9). Given the stratigraphic relations, the 64 ± 5 Ma age can be taken as the maximum age for the picritic breccias, whereas their minimum age is set by the overlying sediments.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rock</th>
<th>Material dated</th>
<th>Lat. N</th>
<th>Long. W</th>
<th>Plateau age (Ma)</th>
<th>Isochron age (Ma)</th>
<th>(36Ar/39Ar)b</th>
<th>MSWD/nb</th>
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</thead>
<tbody>
<tr>
<td>GOR 28</td>
<td>Gabbro</td>
<td>plg</td>
<td>2.984159°</td>
<td>78.17362°</td>
<td>69.7 ± 7.7</td>
<td>372 ± 24</td>
<td>0.3/5</td>
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<tr>
<td>GOR 20</td>
<td>Basalt</td>
<td>wr</td>
<td>2.978139°</td>
<td>78.18956°</td>
<td>85.7 ± 1.6</td>
<td>881 ± 1.6</td>
<td>0.6/9</td>
<td></td>
</tr>
<tr>
<td>GOR 15</td>
<td>Olivine basalt</td>
<td>wr</td>
<td>2.996299°</td>
<td>78.16716°</td>
<td>75.3 ± 1.2</td>
<td>764 ± 1.4</td>
<td>0.7/12</td>
<td></td>
</tr>
<tr>
<td>GOR 15-2</td>
<td>Micro gabbro</td>
<td>wr</td>
<td>2.996299°</td>
<td>78.16716°</td>
<td>69.5 ± 1.9</td>
<td>73.7 ± 3.1</td>
<td>0.4/7</td>
<td></td>
</tr>
<tr>
<td>GOR 8</td>
<td>Basalt</td>
<td>wr</td>
<td>3.000970°</td>
<td>78.16868°</td>
<td>69.6 ± 1.6</td>
<td>68.6 ± 2.3</td>
<td>0.7/14</td>
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<tr>
<td>GOR 43</td>
<td>Komatiitic basalt</td>
<td>wr</td>
<td>2.939246°</td>
<td>78.21058°</td>
<td>64 ± 5</td>
<td>60 ± 12</td>
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<tr>
<td>CORW 10</td>
<td>Gabbro</td>
<td>wr + plg</td>
<td>2.984159°</td>
<td>78.17362°</td>
<td>98.4 ± 2.4</td>
<td>99.5 ± 2.7</td>
<td>250 ± 9</td>
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<tr>
<td>CORW 9</td>
<td>Gabbro</td>
<td>amph</td>
<td>74 ± 5</td>
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</table>

Preferred age in bold, complete data for all the experiments performed is given in the Electronic Supplementary Data. The equations presented in York et al., 2004 were used to calculate the straight line parameters. All errors are 1σ.

Table 1 Summary of 40Ar–39Ar ages.

4.3. Tectonics

The spatial distribution of the rock units on the Gorgona island depicts a faulted anticline structure with an axial zone exposing the intrusive complexes and the flanks made by the extrusive succession (Fig. 3). The fold axis trends NNE and is moderately dipping to the SSW. This broad structure is partly disrupted by reverse oblique and normal brittle faulting, which affect more intensely the southwestern side of the island. Normal faults cut the southern part of the island so that the youngest rocks (breccias and sediments) are exposed there. A normal fault appears also to cut the northern tip of the island, as peridotite and gabbros do not outcrop around Boca el Horno (Fig. 3), where the youngest ages of basaltic lavas were obtained instead (see previous section). Gorgonilla island and the NNE trending submarine ridge continuing to the south may represent a second fold or a continuation of the Gorgona faulted anticline (Figs. 2 and 3). A NNE trending, WNW dipping reverse or oblique fault zone is inferred to pass through the Tasca strait (Fig. 3) as rocks on both sides of the strait display pervasive faulting and fracturing (Fig. A1f). Although nowhere kinematic indicators such slickensides are preserved most of these faults are inferred to result from contractile oblique deformation based on dip, drag structures and rotation of blocks in the fault gouge. At Gorgona lava flows dip dominantly toward the west whereas sediment beds dip broadly to the south (Fig. 3, inset) indicating different phases of deformation. In particular, sedimentary rocks attributed to the Eocene in the southern part of Gorgonilla (Gansser, 1950) are strongly tilted to the SSW (50° to 60°, Fig. A1d). By contrast sediments in the southernmost part of Gorgona are only slightly tilted (5° to 10°) and are not faulted (Fig. 3; Fig. A1e).

These field observations broadly agree with the interpretation of the seismic profiles in the Tumaco basin south of Gorgona (Marcallou and Collot, 2008) and in proximity of the island (Cediel et al., 2010) (Fig. 2). They show an angular unconformity between the Cretaceous igneous
Fig. 4. Age spectra and 36Ar/40Ar vs. 39Ar/40Ar correlation diagrams for basalts and gabbros from Gorgona and Gorgonilla islands and the Western Cordillera of Colombia. With the exception of gabbro GOR 28, all the samples yielded reliable plateau ages. In the age spectra, the weighted mean of the fractions close to the arrow, were used to calculate the plateau age. For sample CORW 9 the data did not constrain a straight line to calculate a reliable isochron age. All errors are 1 sigma. Preferred age is highlighted in bold typeface.
basement and the first sedimentary unit, dated at the Oligocene, and thought to be deposited once this part of the CUP had been accreted to the continental mainland. We consider that the formation of the NNE trending Gorgona anticycle was related to the accretion process, which likely occurred during the early Eocene, prior to the deposition of the oldest sedimentary rocks exposed in the southern part of Gorgonilla, as the latter dip in a different direction than the lavas. The southward tilting of the fold axis and deformation of this older sedimentary succession may have occurred as a result of an episode of right-lateral transpression associated with the development of the Garrapatas fault zone and the accretion of the Serranía del Baudó to the NE (Fig. 2) in the Miocene. Additional Late Miocene to Pliocene transtensional or extensional faulting observed in seismic lines passing only few km to the north and to the south of the island (Fig. 2) may be responsible for the remaining brittle faulting affecting the Gorgona fold.

4.4. Geochemistry

Previous works have reported a high compositional heterogeneity in Gorgona rocks, which were nevertheless assumed to have originated at the same time. Our new ages and stratigraphic constraints allow for the first time to recognize secular patterns of variation in the geochemistry of Gorgona rocks. Fig. 5 shows the trace- and rare-earth-element pattern of our samples (Table 2, Electronic Supplementary Material) compared with previously published data. A two-fold subdivision can be put forward on the basis of depletion in LREE in incompatible elements. Indeed, a LREE-enriched (La/SmN > 1) group and a LREE-depleted (La/SmN < 1) group are clearly recognizable. Basalts and gabbros are found in both groups; komatiites and picrites are mostly in the LREE-depleted group with the exception of GOR 26, which is a LREE-enriched komatiite. While the LREE-depleted group has slightly older starting age in respect with the LREE-enriched group (98.7 ± 7.7 Ma vs. 85.7 ± 1.6 Ma), the more LREE-depleted samples are the younger ones in both groups indicating that depletion in LREE and incompatible elements increases with decreasing age. The La/SmN and La/YbN values decrease in time, from 1.45 to 2.56 respectively for the LREE-enriched GOR 20 to 0.94 and 0.99 for GOR 8. Similarly these values decrease from 0.30 to 0.28 for the oldest LREE-depleted GOR 28 to 0.14 and 0.06 for GOR 13 and GOR 40 picrites, which are also the lowest among the whole set of analyzed samples. Tb/YbN is well above 1 for all the samples except GOR 13 and GOR 40, implying melting within the garnet stability field for all rocks older than the picrites. La/Sm, La/Yb and Ce/Sm are proxies for degree of melting: the higher these ratios, the lower the degree of melting. The Nb/Zr ratio is moderately affected by partial melting as garnet is left in the residue. The low values observed for the youngest unit suggest progressive melt extraction and increasing degree of melting with time as confirmed by the correlation between La/Yb vs. Nb/Zr and Ce/Sm vs. Ce (Fig. 6a, b). This is particularly evident for the LREE-enriched group. Although the youngest rocks of the LREE-depleted group show the lowest La/Yb and Nb/Zr ratios pointing to high degree of melting, this secular variation is less evident in this group.

Initial Sr and Nd isotope ratios (Table 2) are shown in Fig. 6c. LREE-depleted rocks have higher εNd (9.46–11.34) than the LREE-enriched group (εNd, 5.68–7.80) and mostly fall in the field of Gorgona komatiites reported in Kerr (2005) and close to the EPR MORB field. The anomalous high 87Sr/86Sr value of the youngest rock (GOR 13 picrite) might be due to secondary seawater alteration. A secular variation is shown by the LREE-enriched group also in isotope ratios as εNd increases from the older rock (GOR 20, 89.6 Ma) to the youngest (GOR 8, 69.6 Ma) at the same or slightly decreasing 87Sr/86Sr ratios. The oldest and less radiogenic rock of the LREE-enriched group shows isotope composition similar to enriched-basalt, suggesting the presence of an enriched mantle source component. The less radiogenic composition of LREE-depleted rocks suggests the involvement of a DMM (Depleted MORB Mantle) source in their genesis. These two groups of rocks (i.e. LREE-depleted and LREE-enriched) also having distinct εNd confirm the existence of two mantle components (e.g. Hauff et al., 2000a; Revillon et al., 2002): a depleted source having εNd of ~ +10 and an enriched source with εNd of ~ +6. The secular variation shown by the LREE-enriched younger rocks toward the less radiogenic composition of LREE-depleted rock also claims for a possible mixing of enriched and depleted mantle sources.

Nd isotopic system is insignificantly affected by seafloor alteration and metamorphism in contrast to the Sr isotopic system, thus the variability in the initial values of Nd isotope ratios shown by Gorgona rocks can only be explained by the presence of a heterogeneous mantle in which the two components interact and mix together. At the same time, the good correlation between (143Nd/144Nd) and the
proxies of melting (i.e., Ce/Sm, Fig. 7a) clearly points to variable degree of partial melting affecting the heterogeneous (enriched–depleted) mantle source. We test this model quantitatively and the results are shown in Fig. 7. Mantle source compositions have been recalculated at 89 and 55 Ma to show the time-integrated Nd isotope variability of DMM, EDMM (Enriched DMM), recycled MORB and recycled MORB+lower continental crust (Stracke and Bourdon, 2009; Workman and Hart, 2005) over the ~34 my life-time of Gorgona magmatism (Fig. 7a). A simple mixing model has been applied in order to model quantitatively the isotope and trace elements composition of the mixed EDMM-DMM mantle source. Partial melting trace elements variability (Ce/Sm, Zr/Nb, Fig. 7a and b) has been modeled through the fractional melting equation of Langmuir et al. (1992) using partition coefficients for garnet and spinel lherzolite eventually under hydrous condition (~H$_2$O 1 wt.%) from Johnston and Schwab (2004), Gaetani (2004) and McDade et al. (2003). Different degrees of melting modeled (F=1.5, 4.4, 7.2, 12.5 and 20%) correspond to variable mantle temperatures (T=1300, 1330, 1345, 1360 and 1390 °C respectively) according to the used clinopyroxene partition coefficients (Johnston and Schwab, 2004). The model clearly shows the effect of fractional melting over a heterogeneous mantle source. Low degree of melting (<2%) of the EDMM garnet lherzolite mantle component is able to reproduce the oldest and most enriched composition of the LREE-enriched group. Higher degree of melting of a mixed EDMM+DMM (~70% EDMM+30% DMM) will match the younger less radiogenic and less enriched composition of the LREE-enriched group. Nd isotope compositions of the LREE-depleted group claim for a larger proportion of the DMM
component in the mixed mantle source (≤40% DMM + 60% DMM). Variable but higher degrees of fractional melting (F > 10%) of this garnet or eventually spinel lherzolite mantle source will match Nd-isotopic and trace elements composition shown by LREE-depleted group.

5. Discussion

5.1. The Galapagos plume and the Caribbean slab window in the formation of the CLIP

The formation of the Caribbean plateau has been traditionally linked to the impact of a mantle plume located at the Galapagos hotspot at ~90 Ma (Hastie and Kerr, 2010 and references therein). This model, mostly based on geochemical and petrologic arguments, revealed problematic when compared with plate tectonic reconstructions. In fact, if fixed in a mantle reference frame, the Galapagos hotspot would have been located about 1000 km west of the CLIP site (Meschede, 1998; Pindell et al., 2006). On the other hand, plate tectonic reconstructions indicate that the Caribbean plateau formed to the west of a slab window produced by the intersection of the proto-Caribbean spreading ridge with the Great Caribbean Arc during the Cretaceous, which was therefore suggested as an alternative mechanism for the generation of the CLIP (Pindell et al., 2006). More recently, Pindell and Kennan (2009) incorporate the motion of the Galapagos hotspot relative to the indo-atlantic reference frame (Wessel and Kroenke, 2008) plus “a subjective correction” following the plume deviation model of Steinberger (2002) and noted that in this way part of the CLIP would overlap the possible location of the Galapagos hotspot and of the Caribbean slab window (Fig. 8). Their revised hybrid model, suggest that a deep mantle plume would fortuitously arrived at the base of the Farallon lithosphere passing through the slab gap. We now evaluate these models in light of the new results for Gorgona considering three set of constraints: geodynamic setting deduced by plate reconstructions, timing of magmatic activity, and geochemical composition of volcanism.

5.2. Geodynamic setting during the formation of the CLIP

The large set of geologic and geophysical data accumulated in the past decade on the Caribbean region allowed a refined reconstruction of the geodynamic setting during the Cretaceous. Plate kinematics indicate that NW–SE divergence between the Americas began to produce oceanic crust by the end of Jurassic in the Colombian Marginal Seaway (Pindell and Kennan, 2009), separating the continental crusts of the Chortis Block and Colombia (Fig. 8a). Timing of arc magmatism and HP-LT metamorphic belts in the eastern Caribbean realm also indicate that the onset of SW-dipping subduction has occurred at 135–130 Ma at the site of the former inter-American transform and that a steady-state subduction zone producing the Great Caribbean Arc was in place by about 120–115 Ma (Pindell et al., 2011) (Fig. 8b). Relative motion between North and South America with at least a component of divergence continued until ~66 Ma (Pindell et al., 2006; Somoza and Zafferana, 2008). Therefore a proto-Caribbean spreading ridge must have intersected the Great Caribbean Arc between ~115 and 66 Ma, with the unavoidable consequence of the formation of a slab window in the region to the west. During this time span the Farallon oceanic lithosphere (later becoming the Caribbean plate) advanced toward the east–northeast by 1500 km (Pindell et al., 2006, 2011), overriding the asthenosphere feeding the proto-Caribbean spreading ridge, which, in turn, would flow westward into the mantle wedge of the retreating Great Caribbean subduction zone through the slab window.

5.3. Timing of formation of the CLIP

The time distribution of available CLIP ages, including our new Gorgona and BUC ages, is shown in Fig. 9. It shows a long period of igneous activity spanning the whole Late Cretaceous, with peaks at 74–76, 80–82, and 88–90 Ma in decreasing order of importance even older, Early Cretaceous ages, have been reported for the CLIP in Costa Rica (Hauff et al., 2000b; Hoernle et al., 2004) and Curacao (Wright and Wyld, 2011) and led Hoernle et al. (2004) to suggest that the CLIP formed during a 70 Ma period spanning the whole Cretaceous. A straightforward interpretation of these data indicates that the concept of the Caribbean plateau as an igneous unit mostly formed at the initial impact of a plume is now untenable. A prolonged period of igneous activity over several tens of Ma is not consistent with a short, voluminous outburst of magmatism from a plume head at ~91–89 Ma.
as proposed by Sinton et al. (1998) and reiterated until recent times (e.g. Kerr, 2005; Hastie and Kerr, 2010). Hoernle et al. (2004) proposed that the CLIP could be the result of the accumulation of intraplate volcanic structures produced by a pulsing Galapagos hotspot. However, the geographic distribution of ages in the CLIP does not point to a definite pattern of migration (Fig. 1) as it would be expected if magmatism would be the result of the passage of the Farallon plate over a stationary, or slowly moving, hotspot. Particularly, the persistence of magmatic activity at the small Gorgona Island, which is only 12 km², is at odds with the model of a volcanic chain with ages decreasing away from the initial impact site of a plume head. The distribution of ages rather suggests a long period of pulsing magmatism in areas over 1000 km apart (Fig. 1). A diffuse and irregular magmatism is also consistent with the crustal structure of the Caribbean plateau. Seismic profiles show that CLIP magmatism added a very variable amount but no more than 10 km of igneous material to the original crust of the Farallon plate (Mauffret and Leroy, 1997) making the Caribbean plateau thinner and more irregular than other oceanic plateaus, a feature that also explains its widespread internal deformation (Mauffret and Leroy, 1997; Driscoll and Diebold, 1998).

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**Fig. 8.** Simplified tectonic maps of the Caribbean region at 141 Ma (a), 130 Ma (b) (redrawn from Pindell et al., 2011) and 84 Ma (c) (modified from Pindell and Kennan, 2009) showing the creation and evolution of the Caribbean slab window. After the initiation of southwestern subduction at the site of the former inter-American transform a portion of the Farallon plate moved to the ENE ~1500 km overriding the region occupied by the Proto-Caribbean spreading center. The Caribbean plateau formed over the region formerly underlain by the ascending mantle that then flowed into the slab gap. Serranía del Baudó (Bau), Gorgona (Gor), and Western Cordillera (WC) are envisioned as the southern part of the Caribbean plateau that were progressively accreted to northern South America in Campanian, Eocene, and Miocene, respectively (see text). Star denote arc magmatism.

**Fig. 9.** Distribution of available ages for the CLIP according to sources in Fig. 1. Early Cretaceous ages reported for Costa Rica (Hauff et al., 2000b; Hoernle et al., 2002) and Curaçao (Wright and Wyld, 2011) not shown. CLIP ages are distributed throughout the Late Cretaceous with relative peaks at 74–76, 80–82, and 88–90 Ma.
5.4. Geochemistry and isotope constraints

The isotope and trace element compositions of Gorgona rocks, the secular variation and the correlation of initial Nd-isotope ratios with trace element proxies of melting, can be explained by variable degree of fractional melting affecting a heterogeneous mantle. Our data and modeling (Fig. 7) show the presence of an EDMM and a DMMM source which mix in time at variable degree, giving the variable Nd-isotope composition observed for the Gorgona rocks. Low but variable degrees of melting (max 4–5%) of the EDMM mantle source produce the LREE-enriched group. Subsequent higher degree of melting (>10%) of a mixed mantle source with prevalence of the more depleted DMM component (the higher F the more DMM melts) will originate the LREE-depleted group. Effect of variable degrees of fractional melting will produce the variable depletion in incompatible elements shown by the LREE-depleted rocks.

The increasing degree of melting with time observed at Gorgona does not fit a classic plume model, as the temperature in a plume is expected to decrease after the initial impact, producing lower degrees of melting. This is particularly important as another argument for the existence of a mantle plume has been the high temperature presumably needed to produce the high Mg rocks found at Gorgona. However, the only dated komatiite basalt (GOR 43) and the picrites, which have the highest MgO content, were emplaced over 30 Ma after the beginning of the Gorgona igneous activity. Our modeling indicates temperatures of ~1300–1390 °C (Fig. 7) positively correlated with partial melting degrees and secular variation eventually suggesting higher degree of melting from a hotter mantle source with time.

5.5. The origin of the CLIP in a slab window setting: with or without plume?

Given the problems posed by a classic plume head model for the formation of Gorgona and the CLIP highlighted in the previous sections we analyze here the possibility that an oceanic slab window setting alone may be responsible for this magmatism. In the Cretaceous tectonic setting of the Caribbean region the eastward advance of the Great Caribbean arc implies an eastward retreating subduction zone that, in turn, is expected to produce a westward counterflow of Proto-Caribbean (Atlantic) asthenosphere through the roughly triangular-shaped area of the slab window (Fig. 9). This relatively dry and hot asthenosphere will thus mix with a wet mantle wedge enhancing its melting. In this model melting may occur in an area wider than that of the slab gap because the asthenosphere is expected to flow toroidally around the sides of the window (and these locations may be prone to higher degree of melting as they are richer in fluids). The melting will continue for as long as the oceanic ridge is active (~70–66 Ma) and the degree of melting will likely increase as the slab window enlarges. Decompression melting of a heterogeneous and partly wet mantle within this tectonic setting may explain the prolonged period of diffuse magmatism at Gorgona and other parts of the CLIP as well as the increasing degree of melting with time.

The existence of an enriched and a depleted mantle source at Gorgona has been referred to different parts of a plume recycling altered upper oceanic crust and lower oceanic crust or oceanic lithospheric mantle, respectively (Hauff et al., 2000a). More recent studies have shown that the oceanic upper mantle is highly heterogeneous (e.g. Anderson, 2006; Helffrich, 2006; Harvey et al., 2006) with both highly depleted and highly enriched domains (O’Reilly et al., 2009; Anderson, 2010) that need not to be related to deep mantle plumes but may be the result of lithospheric delamination or removal of deep continental roots (Lustrino, 2005; O’Reilly et al., 2009) and ancient episodes of mantle melting (Simon et al., 2008). We speculate that the EDDM can be associated to fragments of refertilized lithospheric roots removed during the Atlantic rifting (O’Reilly et al., 2009) while the DMMM may reside in ancient fragments present in the Pacific mantle. The Caribbean slab window evolution depicted in Section 5.2 would have allowed the mixing of the Farallon (Pacific) and proto-Caribbean (Atlantic) mantle domains.

While the Cretaceous Caribbean slab window is a requirement of plume tectonics the fortuitous arrival of a mantle plume in the Caribbean area would be only needed if the Gorgona high Mg melts are proved to be produced in a mantle hotter than an oceanic slab window. Estimates of mantle potential temperature for Gorgona komatiites and picrites are 1550 and 1600 °C, respectively, under dry conditions (Herzberg et al., 2007). Similar potential temperatures were estimated by Hastie and Kerr (2010) for the most primitive rocks of Curacoa. However, under hydrous conditions, as expected in an opening mantle wedge and confirmed by Gorgona olivine melt inclusions (Kamenetsky et al., 2010) and geochemistry of the Bolivar Ultramafic Complex (Kerr et al., 2004), the temperature of formation of komatiites may be as low as ~1300–1500 °C (Inoue et al., 2000; Parman et al., 2001). In fact, Kamenetsky et al. (2010) calculated an initial crystallization temperature of 1330–1340 °C for Gorgona komatiites, which matches the range of temperature obtained in our petrologic modeling to reproduce the Gorgona suite (1300 to 1390 °C; Fig. 7). These values are well within the ambient mantle potential temperature in absence of plumes (Lee et al., 2009; Presnall and Gudfinnsson, 2011). Therefore, even if the coincidental occurrence of a mantle plume hitting the slab gap area cannot be excluded, it is probably not required to produce the observed composition and degree of melting. Three dimensional thermal numerical modeling constrained by geodynamic reconstructions may quantitatively confirm the possibility of formation of the CLIP igneous suite, and particularly the Gorgona komatiites and picrites, in an oceanic slab window setting. Nevertheless, we have shown that the thermal and geochemical consequences of the Cretaceous Caribbean slab window are consistent with the formation of the CLIP.

Supplementary materials related to this article can be found online at doi:10.1016/j.epsl.2011.07.011.

Acknowledgments

The research was funded by grant UNAM-PAPIIT IN114508 (to LF) and by the CICESE Geochronology Laboratory (MLM). LSD was supported by a M.Sc. scholarship from Instituto Panamericano de Geografía e Historia. V. Kamenetsky, EPSL editor R. Carlson and an anonymous reviewer provided important criticism and suggestions that greatly improve the final manuscript. We thank J. Pindell for useful discussions and the review of an earlier version of the manuscript. We also thank M. A. García and A. S. Rosas for assistance with the 40Ar–39Ar experiments, A. Gómez-Tuena and O. Pérez for supervising ICP-MS geochemistry, S. Tommasini and E. Braschi for help in measuring Sr and Nd isotopes. G. Serrano, P. de Greiff, R. López and the Gorgona Natural Park guides are greatly acknowledged for their assistance during the fieldwork. We acknowledge Parques Nacionales Naturales de Colombia for granting the access to Gorgona island and collecting samples between 2006 and 2009.

References


