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Evidence for subaerial development of the Caribbean oceanic plateau in the Late Cretaceous and palaeo-environmental implications

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ABSTRACT

The formation of oceanic plateaus in the Pacific in the Mesozoic has been proposed to create major environmental impacts, including global anoxic events OAE-1 in the Aptian (ca. 120 Ma) and OAE-2 in the Cenomanian–Turonian (ca. 90 Ma). However, our understanding of the formation of these large volcanic systems and their environmental effects are strongly limited by difficulties in accessing them and characterising their volcanic evolution. In particular, it remains significant to determine whether Pacific oceanic plateaus experience a phase of subaerial volcanic activity as this has critical implications in terms of their environmental impacts. Herein we provide the first unequivocal evidence for an emergent volcanic phase of the Caribbean oceanic plateau in the Late Cretaceous. This subaerial phase is evidenced by accreted oceanic sequences in Colombia that include fallout tuffs with accretionary lapilli and lahar deposits. This facies assemblage, recognised for the first time in an oceanic plateau, reflects phreatomagmatic eruptions coeval with subaerial erosion on an oceanic island. This result, combined with previous evidence of subaerial development of the Ontong Java Plateau and Shatsky Rise, suggests that syn-volcanic emergence of oceanic plateaus was common in the Pacific during the Mesozoic. Although temporal and spatial scales of these emergences remain poorly constrained it confirms that emergence of the Caribbean plateau in the Late Cretaceous (ca. 90 Ma) could have actively contributed to atmospheric changes and the establishment of OAE-2. Significantly, emergence of the Caribbean plateau occurred synchronously to the beginning of its tectonic displacement between the Americas. We propose that this unusual volcanic and tectonic evolution led to drastic reduction of the flow of Pacific oxygenated bottom waters into the early Atlantic basin, leading to a series of regional anoxic events previously documented between the Coniacian and Santonian (OAE-3, ca. 89 to 84 Ma). In addition, emergence of the Caribbean Plateau in the early inter-American seaway could have facilitated migration of terrestrial organisms between the Americas in the Late Cretaceous. The formation of the Caribbean plateau had therefore a large range of possible environmental effects, from atmospheric to palaeo-oceanographic and biotic impacts.

1. Introduction

Oceanic plateaus are a type of large igneous province that develop in the oceans and represent some of the largest volcanic systems on Earth. The formation of oceanic plateaus in the Pacific Ocean during the Cretaceous (i.e., Ontong Java, Manihiki, Hikurangi, Caribbean, Shatsky Rise and Hess Rise) was associated with rapid release of large volumes of magmatic gases and volcanic nutrients that could have triggered global oceanic anoxia and mass extinctions (Sinton and Duncan, 1997; Kerr, 1998; Kuroda et al., 2007; Yasuhara et al., 2017). If these oceanic plateaus experienced a phase of subaerial volcanism, their formation could have more severely affected the atmosphere, with significant implications for the nature and extent of their global environmental impact (e.g., Kuroda et al., 2007).

Cretaceous oceanic plateaus in the Pacific have a considerable crustal thickness of approximately 10 to 30 km (e.g., Eldhom and Coffin, 2000), but evidence for their emergence remain very limited, relative to their large surface area (i.e., typically of the order of 1×10^6 km^2). Wood fragments, shallow-marine sediments and

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subaerial fallout tuff with accretionary lapilli have been locally described in drill cores from the Ontong Java Plateau (Thordarson, 2004) and Shatsky Rise (Yasuhara et al., 2017). However, these occurrences lack thick coastal to subaerial deposits commonly observed in the geological record of modern and ancient Pacific oceanic islands (Garcia et al., 2007; Buchs et al., 2011, 2018). Some uplifted sections of the Caribbean plateau on Aruba Island and in the Western Cordillera of Colombia suggest that this volcanic edifice could have developed partly subaerially in the Cretaceous (White et al., 1999; Moreno-Sanchez and Pardo-Trujillo, 2003; Kerr, 2014). However, observations from these areas are ambiguous due to their complex geological settings and lack of detailed lithological and geochemical constraints. Overall, a limited record of subaerial activity on top of Pacific oceanic plateaus may reflect a fundamental characteristic of these volcanic edifices, but it could also be an observational bias due to logistical difficulties in conducting subsurface observation and sampling of very large, deep marine volcanic sequences.

In this paper we present new field observations and geochemical data from volcanic sequences of the Caribbean plateau that formed in the Pacific in the Cretaceous and were subsequently accreted and exposed along the northern margin of South America in Colombia (Fig. 1). These sequences offer a unique access to the main volcanic phase of the plateau, before renewed volcanism associated with the inter-American evolution of the Caribbean Large Igneous Province. Notably, these sequences preserve volcaniclastic deposits not recognised before on top of Pacific oceanic plateaus, and so provide novel and compelling evidence for subaerial development of the Caribbean plateau. We show that this development was associated with a specific palaeogeographic context that could have triggered anoxic events in the early Atlantic basin from the Coniacian to Santonian (OAE-3, ca. 89 to 84 Ma, Wagreich, 2012), and could have facilitated inter-American exchange of terrestrial organisms in the Late Cretaceous.

2. Geological background

The studied oceanic sequences are exposed in the Western Cordillera of Colombia approximately 30 km west of Medellin close to Altamira village on the western side of the Cauca valley (Fig. 1). The sequences include tuffs with accretionary lapilli recently interpreted to be part of an accreted fragment of the Caribbean plateau (Zapata-Villada et al., 2017). However, this work did not undertake a detailed characterisation of the origin and implications of these sequences for the volcanic evolution of the plateau. The tuffs occur in a complex area comprising imbricated, fault-bounded igneous and sedimentary units west of the Cauca fault. This fault marks a significant boundary with the Quebradagrande Complex to the east, which formed in an extensional, supra-subduction continental margin setting in the Early Cretaceous (Bourgois et al., 1987; Nivia et al., 2006; Villagómez and Spikings, 2013; Spikings et al., 2015; Jaramillo et al., 2017). Eastward migration of the Caribbean plateau between the Americas in the Late Cretaceous led to tectonic inversion of this margin and accretion of units in the region that now comprises the Western Cordillera (Kennan and Pindell, 2009). The accreted units are generally considered to be composed of igneous rocks of the Caribbean plateau (Barroso formation, *sensu* Kerr et al., 1997 and Villagómez et al., 2011) and its Upper Cretaceous pelagic to near-trench sedimentary cover (Penderisco formation) (Kerr et al., 1997; Moreno-Sanchez and Pardo-Trujillo, 2003; Villagómez et al., 2011). The igneous sequences consist of massive and pillowed basalts with dolerites and subordinate gabbroid intrusions that have oceanic plateau geochemical affinities and Ar–Ar and U–Pb zircon ages of approximately 100 to 91 Ma (Kerr et al., 1997, 2004; Villagómez et al., 2011). Similar sequences with plateau affinities occur in the studied area, including a gabbro dated at 89.9 ± 1.5 Ma (U–Pb zircon age, Zapata-Villada et al., 2017).

It has been suggested that possible coral remains found in tuffs from the Antioquia area (Hall et al., 1972) and sedimentary rocks including colonial corals and conglomerate with carbonized fragments of tree trunks in the Belen de Umbría region (Moreno-Sanchez and Pardo-Trujillo, 2003) could reflect subaerial volcanic activity of the Caribbean plateau exposed in the Western Cordillera (Moreno-Sanchez and Pardo-Trujillo, 2003; Kerr, 2014). However, the sedimentary rocks in the Belen de Umbría region contain detrital quartz of possible terrigenous origin and have been dated to the Campanian–Maastrichtian based on ammonite fossils (Moreno-Sanchez and Pardo-Trujillo, 2003); these clearly postdate published ages of Caribbean plateau volcanism in the Western Cordillera. In addition, recent studies reveal that the northern Western Cordillera also includes Lower Cretaceous arc-related units, which crosscut or are tectonically (?) intercalated with Caribbean plateau sequences (Rodríguez and Arango, 2013; Weber et al., 2015). This makes the interpretation of the origin of tuffs reported by Hall et al. (1972) and parts of the Barroso formation uncertain, in particular where detailed field observations and geochemical constraints are lacking. This also questions the validity of previous regional tectonic and palaeogeographic reconstructions. The tuff locality that is the focus of the present study therefore provides a rare and valuable opportunity to test and characterise subaerial volcanic activity associated with the formation of the Caribbean plateau. The age of this activity ca. 90 Ma is constrained by geochronological data in the western Cordillera (Villagómez et al., 2011; Rodríguez and Arango, 2013; Zapata-Villada et al., 2017) that are consistent with a main magmatic pulse of the Caribbean plateau ca. 90 Ma (e.g., Hoernle et al., 2004), as well as tectono-stratigraphic relationships and geochemical similarities of the volcaniclastic deposits with the dated sequences (see below).

3. Methods

In order to test a plateau origin and characterise volcanic processes associated with the emplacement of volcaniclastic deposits in the studied area, we used a field-based lithological, petrographic and geochemical approach building upon regional work by Zapata-Villada et al. (2017) and the Geological Survey of Colombia (e.g., Rodríguez and Arango, 2013). We carried out detailed observations and sampling along a track to Altamira village that is accessible from Santa Fé and offers good road cut exposures perpendicular to the strike of the bedding (Fig. 1B). Geochemical analysis of whole rock samples and clinopyroxene was used to assess the geochemical affinity of subaerial sequences, including several populations of clasts in primary and secondary volcaniclastic deposits. GPS coordinates of our samples are reported in Table S1.

Analysis of major and trace elements of 19 whole rock samples was conducted at Stellenbosch University (Table S2, including analysis of certified samples). Fusion disks were prepared for XRF and LA-ICP-MS analysis by an automatic Claisse M4 Gas Fusion instrument and ultrapure Claisse Flux, using a ratio of 1:10 sample:flux. Major elements were measured by XRF (Rh Tube, 3 kW). A Resolution 193 nm Excimer laser from ASI connected to an Agilent 7700 ICP-MS was used for the analysis of trace elements. Ablation was carried out in He gas at a flow rate of 0.35 L/min, then mixed with argon (0.9 L/min) and Nitrogen (0.004 L/min) just before introduction into the ICP plasma. Three spots of 228 μm were ablated on each sample using a frequency of 10 Hz and fluence of $\sim$5 J/cm^2, and later averaged to produce the final results. Trace elements were quantified using NIST 612 for calibration and SiO_2 from XRF measurements as internal standard. The calibration