Palaeogeography, Palaeoclimatology, Palaeoecology 417 (2015) 66–79

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

The role of climate and aeolian dust input in calcrete formation in volcanic islands (Lanzarote and Fuerteventura, Spain)

Pedro Huerta [a,*], Álvaro Rodríguez-Berriguete [b,c], Rebeca Martín-García [b], Andrea Martín-Pérez [d], Ángel La Iglesia Fernández [c], Ana María Alonso-Zarza [b,c]

[a] Departamento de Geología, Escuela Politécnica Superior de Ávila, Universidad de Salamanca, Avd/Hornos Caleros, 50, 05003 Ávila, Spain
[b] Departamento de Petrología y Geoquímica, Fac. CC. Geológicas, Universidad Complutense de Madrid, C/José Antonio Novais, 2, 28040 Madrid, Spain
[c] Instituto de Geociencias, IGEO (CSIC, UCM), C/José Antonio Novais, 2, 28040 Madrid, Spain
[d] Institute of Palaeontology ZRC SAZU, Novi trg 2, SI 1000 Ljubljana, Slovenia

ARTICLE INFO

Article history:
Received 16 June 2014
Received in revised form 30 September 2014
Accepted 5 October 2014
Available online xxxx

Keywords:
Calcrete
Canary Islands
Geochemistry
Strontium
Vegetation

ABSTRACT

Calcretes are widely described in non-marine settings with carbonates in their catchment, or vicinity areas, but in volcanic islands without carbonates in their substrate, calcretes are not very common. In Lanzarote and Fuerteventura Canary Islands, characterized by impressive volcanic landscapes, the sedimentary carbonate rocks are rare except for some recent marine and aeolian deposits. In these settings very well-developed calcretes cover large areas of the present landscape. The source of calcium required for the formation of these calcretes has not been discussed in much detail till now, although its role is critical to an understanding of the climatic conditions in which calcium was transported and fixed and of the calcrete formation processes. The petrological and geochemical studies ($^{87}Sr/^{86}Sr$ ratios, $\delta^{13}C$, $\delta^{18}O$, major, trace and REE) carried out in this paper do confirm the important role of aeolian dust input in the formation of these calcretes. Canarian calcretes were mainly generated by pedogenic processes and are composed of various irregular carbonate lamina interbedded with fine clastic deposits. Our study indicates that these interbeddings were the result of several stages in which, during dry periods, aeolian dust deposition alternated with leaching and calcite precipitation during wetter periods when plants, insects and bacteria played an important role in carbonate precipitation. The $\delta^{18}O$ (-2.70 to $+2.22$‰ VPDB) and $\delta^{13}C$ (-8.21 to $+0.24$‰ VPDB) values indicate that calcretes were formed by pedogenic processes. Comparison of calculated $\Delta^{18}O$ values for the Canary calcretes with continental mid-latitude calcrete values reflects the more homogeneous temperature regimes of calcrete formation in island (oceanic) settings. Calcrete $^{87}Sr/^{86}Sr$ ratios (0.706357 to 0.709208) show strong affinity with those obtained in aeolian carbonate dust and marine deposits, and are relatively different from those obtained in basalts. REE, major and trace element concentrations show that Ca-bearing minerals from volcanic host rock contributed little to calcrete formation and most of the calcium was supplied by aeolian deposits such as the aeolian dust coming from the Sahara and Sahel or sand dunes.

1. Introduction

Pedogenic calcretes are terrestrial carbonate materials whose formation, within a soil profile, results from the introduction of mostly vadose carbonate into soils, rocks or sediments (Goudie, 1973; Watts, 1980). Biogenic and non-biogenic mechanisms of calcium precipitation within calcretes have been widely discussed. In most cases it seems that semi-arid climates favoured calcrete formation (Wright, 2007; Alonso-Zarza and Wright, 2010). However, the formation of thick calcrete profiles requires long periods of time under which, climate and soil organisms may have varied (Wright, 2007). These variations, recorded in calcrete features, make calcretes an important palaeoenvironmental archive. Most of the palaeoenvironmental information extracted from calcretes is contained in their macro- and micro-morphological features, their biological content or their carbon and oxygen isotope signatures (Tanner, 2010). Weathering of parent-rocks, local inputs from nearby calcareous deposits, the biota, aeolian dust or sea spray in coastal areas have been considered as the main sources of Ca (Goudie, 1983; Capo and Chadwick, 1999; Cailleau et al., 2004). The strong chemical affinity of Sr and Ca makes $^{87}Sr/^{86}Sr$ ratio a good tracer for Ca provenance (Dart et al., 2007). Several studies using that ratio have shown that in most cases the contribution of Ca from weathering of the host rock seems to be very limited in comparison with the contribution of Ca from aeolian dust or atmospheric input (Chiquet et al., 1999), even in the presence of nearby carbonate formations (Hamidi et al., 2001). Determining the provenance of Ca may provide information on the

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[*] Corresponding author. Tel.: +34 920353500.
E-mail addresses: phuerta@usal.es (P. Huerta), arberriguete@geo.ucm.es (Á. Rodríguez-Berriguete), rmarting@ucm.es (R. Martín-García), andreamartin@geo.ucm.es (A. Martín-Pérez), iglesia@geo.ucm.es (Á. La Iglesia Fernández), alonsoza@ucm.es (A.M. Alonso-Zarza).

http://dx.doi.org/10.1016/j.palaeo.2014.10.008
0031-0182/

atmospheric conditions and pathways that allowed Ca transport, and in cases where calcretes developed on siliceous rocks, the weathering of these rocks consumes CO_2, so calcretes may play a role as a natural sink for CO_2 (Lal and Kimble, 2000).

The eastern Volcanic Canary Islands, Lanzarote and Fuerteventura (Fig. 1) are an excellent laboratory for the study of Ca sources and geochemical mechanisms for the accumulation of calcium carbonate within the thick pedogenic calcrete profiles (Alonso-Zarza and Silva, 2002). In some cases, calcretes developed directly on the volcanic host rock, in the apparent absence of older carbonates in the surroundings. In other cases calcretes developed on alluvial-fan volcanic-sourced clastic deposits or on bioclastic aeolian deposits (Genise et al., 2013). As a result of island proximity to the Sahara desert, they are regularly affected by dust (Menéndez et al., 2007) sourced from northern Africa, the largest source area on earth for mineral dust (Goudie and Middleton, 2001; Laurent et al., 2008; Scheuvens et al., 2013). Several Ca sources can be considered in these islands, 1) the basalt plagioclases, 2) the Sahara and Sahel wind-blown dust (Coudé-Gaussen and Rognon, 1988; Mizota and Matsuhisa, 1995; Muhs et al., 2010), 3) marine sands during the last glacial (Coudé-Gaussen and Rognon, 1988), and 4) marine spray (Hamidi et al., 1999; Whipkey et al., 2000).

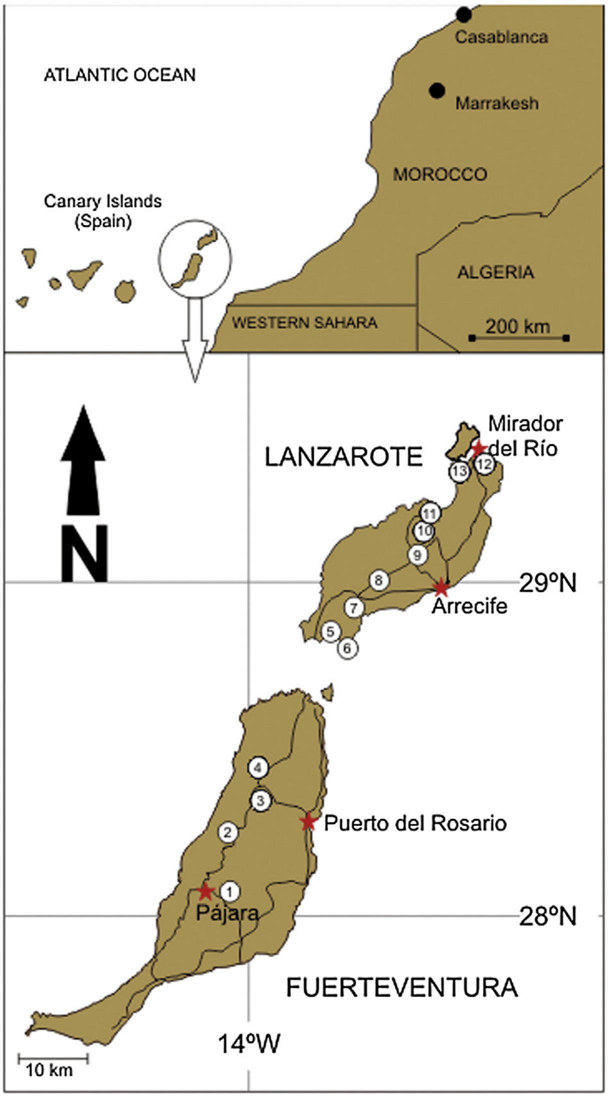

Fig. 1. Map showing the location of the Canary Islands and the outcrops studied in Lanzarote and Fuerteventura Islands (1. P. del Holandés; 2. Betancuria: 3. Ampuyenta; 4. Tefía; 5. Playa Blanca; 6. Pta. Papagayo; 7. Femés; 8. Macher (IES Basalt; IES Yaiza); 9. S. Bartolomé; 10. Tao; 11. Jable; 12. Mirador del Río; 13. Ye).

The aim of our study is to unravel how calcium is supplied to calcretes, and to discuss their palaeoclimatic significance. In this paper we perform mineralogical, petrological, including macro- and micromorphological features, and geochemical ($^{87}Sr/^{86}Sr$, $\delta^{13}C$, $\delta^{18}O$, major, trace and REE) analyses of various calcretes selected from Lanzarote and Fuerteventura Islands. The varied host rock in which the calcretes developed under the influence of the Saharian dust, makes them unique to understand the mechanisms of calcrete formation in volcanic settings.

2. Geological setting

The Canary Islands are a volcanic archipelago (Fig. 1) which lies on the continental margin of the Africa plate, on oceanic crust of early Jurassic age (Schmincke et al., 1998; Steiner et al., 1998a, 1998b; Ancochea et al., 2004; Carracedo et al., 2008). The origin of the islands is attributed to the activity of a hot spot. Age of the islands decreases from East to West. The younger islands are about 1.2 Ma, whereas the eastern-most islands, Lanzarote and Fuerteventura, situated closer to Africa, are about 20–21 Ma (Carracedo et al., 1998; Carracedo et al., 2002, 2008; Hoernle and Carracedo, 2009).

Lanzarote and Fuerteventura are in a senile evolutive stage dominated by erosive and sedimentary morphologies and processes, containing a large variety of marine, aeolian deposits and calcretes (Meco, 2008). Age of these deposits ranges from Pliocene to present times. Reworking of Quaternary bioclastic marine deposits by prevailing winds transporting sand grains gives place to the formation of large dune fields in the eastern-most Canary Islands during the more arid glacial periods. On the contrary, calcretes were formed after the Pliocene in the relatively less arid interglacial periods (Criado, 1988; Alonso-Zarza and Silva, 2002; Genise et al., 2013). Palaeoclimatic trends for the eastern Canary Islands were established on the basis of previous pedological, sedimentological, and palaeoecological studies (Petit-Maire et al., 1987; Damnati, 1997; Zazo et al., 1997; Meco et al., 2011).

Present-day climatic conditions reflect the scarcity of water, and predominant arid conditions within Lanzarote and Fuerteventura. Their climate is controlled by the cold Canary Current, which reduces precipitation and causes high temperatures equivalent to those recorded in the Western Sahara. Both islands have a mean annual precipitation of 105 mm. Marine trade winds affect the Canary Islands during most of the year and the scarce precipitation is mostly brought by westerly cyclones occasionally following southern tracks (Damnati, 1997; von Suchodoletz et al., 2009). At present the islands receive important amounts of Saharian dust. In winter the dust is brought by the "Calima" low-level continental African winds, which are deflected towards the northwest by Atlantic cyclones (Criado and Dorta, 2003). The northern branch of the high altitude Saharian Air Layer (SAL) transports the dust to latitudes north of the Canary Islands mostly during the summer (Prospero and Lamb, 2003). The main direction of dust transport in the SAL is to the west at latitudes between 15° and 21°N (south of the Canary Islands). A south-to-north component of flow can occur in the lee of an easterly wave (Pye, 1987; Muhs et al., 2010). Part of the dust carried by the SAL sinks into the lower atmosphere and is transported to the islands by northeast trade winds (Bozzano et al., 2002; von Suchodoletz et al., 2009; von Suchodoletz et al., 2010).

3. Methods

Samples were taken from different calcrete profiles representative of the entire variety of host rock on which calcrete developed and in selected points of Lanzarote and Fuerteventura Islands to check the possible changes in aeolian dust distribution (Fig. 1). Some profiles were previously studied because of their content in insect trace fossils (Genise et al., 2013). Thin sections were done to perform the petrographical analysis and to characterize the textures and microstructures.

Mineralogical composition of bulk-rock samples was determined by X-ray diffraction using a Bruker D8 diffractometer equipped with a