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Structural control on the presence and character of calas: Observations from Balearic Islands limestone rock coast macroforms

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ABSTRACT

Calas are characteristic embayed rocky coastline landforms related to steep-sided drowned valleys that were deeply incised during low sea-level stages into carbonate plateaus. This paper studies the factors that control the presence and character of calas in three different islands of the Balearic Archipelago (Mallorca, Menorca and Formentera) by means of Digital Elevation Model (DEM) reconstructions, embayment and catchment morphometric analysis and through the compilation of fault and joint orientations. All islands exhibit emerged carbonate platforms (Upper Miocene in age) characterised by horizontal or very gently-dipping bedding. Two distinct patterns observed at all study sites are the absence or poor development of calas when carbonate plateaus exhibit strong coast-parallel structures and a greater variability of cala embayment size according to stream catchment size, lithology or their catchment distance from the coastline. Furthermore, the amount of stream incision, and consequently the characteristics of a cala at its mouth, depends on the proportion of impermeable rocks exposed in each drainage basin and on the density and spacing of fractures. Karst collapse, dolines and valley infilling associated with Quaternary sea-level oscillations are also important in determining the shape and size of calas.

1. Introduction

There has been an increase in rock coast geomorphology research in recent years, which is reflected in a large number of papers and researchers involved with these environments and their related processes (Naylor et al., 2010). Nevertheless, most of these recent contributions tend to explore processes and erosion rates shaping cliffs and shore platforms (Trenhaile, 2002; Stephenson and Brander, 2003; Dasgupta, 2010; Moses and Robinson, 2011) whereas descriptive evolutionary-scale studies that dominated rock coast geomorphology until the seventies are still very few (Trenhaile, 1987; Sunamura, 1992; Bird, 1993; Kench et al., 2008). However, there are many new investigations that contribute to our knowledge of rock coast evolution from cliff and shore platform modelling (Trenhaile, 2001) to sedimentological and/or structural studies on cliff retreat and/or fossilisation (Fornós et al., 2005; Trenhaile et al., 1998, 1999). Despite these advances, there are few current contributions on major rock coast landforms or morphological assemblages such as rias, fjords and calas or calanques as features in their own right. In fact, because of their condition as drowned valleys and the complex and unbalanced relationship between coastal and fluvial processes, among others, some authors consider these rock coast macroforms as a generic type of estuary or fluvial feature rather than rock coast landscapes (Bird, 2008).

Calas or calanques are canyon-like coastal inlets described from a number of areas in the Mediterranean (Kelletat and Scheffers, 2009), including Malta (Nicod, 1951; Paskoff and Sanlaville, 1978; Odette, 2006), Croatia and Slovenia (George, 1948; Ambert, 1978), Provence (Blanchard, 1911; Berard, 1927; Denizot, 1934; Chardonnet, 1948, 1950; Corbel, 1956; Froget, 1963), Corsica (Chardonnet, 1948) and Mallorca (Butzer, 1962; Rosselló, 1964).

The word *cala* can be traced back to pre-Indo-European origins (Kranjc, 1998). It stems from *kal* — initially meaning stone, later shelter made of stone, and finally house, fortress, or village, and its derivatives are found in many languages of Europe (Alessio, 1935). 'Cala', with a constrained meaning of small bay or coastal inlet, appears in Catalan, Occitan, Sardinian, Spanish, Portuguese, Italian and Maltese (*qala*) (Rosselló, 1995). One of the oldest usages of cala appeared in the Roussillon documents that date from 1123 AD, "ad calam de Maruano" (Coromines, 1981), much earlier than the French word 'calanque',

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which is derived from the Occitan word 'calanco' (a form of the word 'calo') — a typical term in the Provence coast.

Penck (1894) provided one of the earlier scientific descriptions of calas influenced by Erzeherzog –archduke– Ludwig Salvator von Österreich-Toskana (1847–1915). Ludwig-Salvator lived in Mallorca from 1872 to 1913 and wrote an extensive natural history and human geography of the Balearic Islands (Ludwig-Salvator, 1884–1891). According to Penck, the term "cala" relates to a submerged, short, eroded valley in a rocky coast. Although calas can exist in any kind of lithology according to this earlier definition, for most investigators a key factor for the development of this macroform is the presence of an emerged carbonate platform. In that sense, Rosselló (2005) considers the term 'cala' to mean marine indentations in the coastline related to eustatic flooding of ancient, often non-functional, stream-valleys in limestone plateaus (Fig. 1).

Calas can be preliminary understood as a sub-class of ria. Nevertheless, the coastal limestone rock nature is a key issue as it introduces a larger complexity that reduces the previously considered primary fluvial nature that actually plays a secondary role. In that sense, the development of the karstic processes related to the mixing of phreatic waters in the coastal zone (Ford and Williams, 2007) and Quaternary sea-level fluctuations highlights the role played by the karst. The development of cavities and conduits (the so-called flank margin caves) following the classical Carbonate Island Karst Model (Mylroie and Carew, 1990; Mylroie and Mylroie, 2007) is the necessary prerequisite for generation of collapse cavities. Thus, the karstic evolution of the carbonate plateau influenced by mixing waters and sea-level fluctuations at the coast can subordinate the drainage network evolution, with doline captures (Fornós, 2004) and cliff retreat and morphological shaping.

Most authors have concentrated in separating different types of calas according to the relative contribution of both the sea drowning of karstic valleys and the collapse of subterranean systems or doline captures. The karstic dry valleys drowned by the Holocene transgressions are classified as true calas or calanques–rias, whereas those inlets related to sinuous coastlines (an expression of selective erosion of weaker lineaments and areas of weak rock) are known as calanques–cirques (Trenhaile, 1987). Beginning with Chardonnet (1948) and Paskoff and Sanlaville (1978), many authors stressed the contribution of karst processes in the formation of calas. They concluded that true calas are best developed in thick and homogenous limestone formations when dry valleys are enlarged by the collapse of subterranean void systems. On the other hand, calanques–cirques seem to be related to the capture of dolines by sea-cliff retreat or to the erosion of weaker lineaments that connect karst conduits not connected with the main stream to the cliff (Nicod, 1972). Additionally, there are other major issues in calas research, such as the fault control in cala morphology (Paskoff and Sanlaville, 1978), or the existence of different phases of cala evolution and therefore of the stream-profile geometry that result in either short ravines with steep slopes and well-defined thalwegs or in wider channels with poorly defined thalwegs (Denizot, 1934).

Considering this background, the present work aims to: (i) study the influence of the tectonic structure of the carbonate plateaus on the occurrence of calas, and (ii) evaluate the structural control on drainage development and overall cala gross-morphology. This work is carried out in four areas of the Balearic Islands with lithologic and climatic uniformity, which facilitates cross-comparisons and interpretation of the role of other factors, such as the geological structure, that may have contributed to shaping the drainage network and the coastal embayment.

2. Study area

2.1. Regional setting

The Balearic Archipelago is located at the centre of the western Mediterranean (Fig. 2) and includes four major islands: Mallorca, Menorca, Eivissa and Formentera. Rock coasts represent close to 90% of the Balearic Islands shoreline and calas are an abundant macroform (Gómez-Pujol et al., 2006).

Wave climate over Balearic coastal areas is characterised by a mean significant wave height greater than 1 m during autumn–winter months and less than 1 m (approx. 0.3 m) during the spring–summer months. Waves of 5 m height, although rare, are associated with 10-year return period (Cañellas et al., 2007). Forcing by tides is almost negligible in the Mediterranean, the spring tidal range not exceeding 0.25 m, although changes in atmospheric pressure and wind stress can account for considerable fluctuations in coastal water levels (Gómez-Pujol et al., 2007).

The Balearic Islands have a typical Mediterranean climate, with hot, dry summers and mild, wet winters. The mean annual temperature is approximately 17 °C, with mean winter and summer values of 10 °C and 25 °C, respectively. The mean annual precipitation is 500 mm and is mostly concentrated in autumn (Guijarro, 1986). Hydrologically, the

Fig. 1. Cala Magraner in southeastern Mallorca, an archetypical example of a cala: a marine indentation in the coastline related to the eustatic flooding of an ancient, often non-functional, stream-valley developed in a limestone plateau.