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Stratigraphy, petrophysical characterization and 3D geological modelling of the historical quarry of Nueva Tabarca island (western Mediterranean): Implications on heritage conservation

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ABSTRACT

The historical quarry of the Nueva Tabarca fortress (Mediterranean Sea, SE of Spain) was developed in a complex sedimentary Miocene deposit. Five lithostratigraphic units have been defined, including different lithologies such as breccias and microconglomerates (Unit 1), massive and laminated lithoarenites (Units 1, 3 and 5), calcarenites and biocalcirudites (Units 2 and 4). A complete stratigraphic description of this sequence has been carried out, as well as the petrophysical characterization of the most significant lithologies including the analysis of rock durability as well as hydraulic and mechanical properties. Regarding durability, the softest rocks correspond to those from the Unit 4, whilst samples from Units 2 and 5 are the most durable. Three weathering patterns were observed during the artificial ageing test according to both the velocity and intensity of the sample decay. Each pattern is explained according to water-circulation possibility through the rock, its porous system, and the mechanical strength. Rock weathering in monuments of Nueva Tabarca is quantified and discussed according to the results found in the laboratory. Several decay forms are observed in the building stones (mainly differential erosion, alveolization, and rounding forms). Both 3D photogrammetric and 3D geological model of the historical quarry were elaborated in order to quantify the extracted volume of building stones, differentiating the specific quarried percentage of each lithology. Correlation between the results obtained in the volumetric analysis of the historical quarry and the building stones used in the monuments has been carried out. 3D models were also used for determining the remaining rock volume in the current outcrops. Finally, a set of recommendations for future conservation works of the architectural heritage are proposed after the current availability of the different rock varieties and their petrophysical behaviour.

1. Introduction

The location and study of historical quarries is a fundamental task for the restoration of a monument. When the stones in monuments are deeply weathered, they require replacement by new ones. However, the use of inappropriate replacement stones can result in significant damage to the heritage. The literature shows the problems resulting from the use of inadequate replacement stones (Sasse and Snethlage, 1996; Dreesen and Dusar, 2004; Hyslop, 2004; Rozenbaum et al., 2008; Graue et al., 2011). Therefore, the choice of the replacement stone should be appropriate in physical and aesthetic terms and, ideally, it should be of the same type as the original building stone, or the nearest possible equivalent (Pereira and Marker, 2016). Therefore, knowing the location of original stone source, as well as the petrographical and petrophysical properties of the rock, helps guarantee effective restoration work. Consequently, the interest of research groups in historical quarries has been increasing in recent years (Cooper, 2010; Hyslop, 2004; Fronteau et al., 2010; Baltuille et al., 2012; Pereira et al., 2013).

It is generally accepted that the main physical properties for stone compatibility include their hydro-mechanical performance in terms of properties such as water absorption, capillarity or mechanical strength, which in turn depend on the porous system of the rock (Andriani and Walsh, 2003; Rozenbaum et al., 2008). The pore network of building stones, and consequently, most of their petrophysical properties, is strongly related to the microfacies of the source rock (i.e. to their sedimentary and diagenetic history). Hence, a full characterization requires a multi-perspective approach to understand the natural variability of stone resources (Bednarik et al., 2014; De Kock et al., 2017). Rock microfacies can be relatively constant over large bodies of rock or they can fluctuate strongly on a subcentimetre to decimetre scale (De

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Kock et al., 2017). Consequently, it is essential to have accurate knowledge of the stratigraphic sequence (in sedimentary rocks) as well as the geometry of the rock bodies and their spatial distribution. The combination of traditional geological work with new photogrammetry techniques enables a highly precise 3D outcrop characterization. In these terms, the historical quarry of Nueva Tabarca island constitutes an exceptional study case due to the lithological variations throughout the stratigraphic sequence and the volumetric distribution of the regular and irregular layers.

The fortified village of Nueva Tabarca constitutes an valuable example of homogeneous baroque architectural heritage (Beviá and Giner Martínez, 2012). The singularity of the monuments was recognized by several local and national protective measures. The initial plans for this fortified city were focused on the building of a strong wall around the west part of the island and the construction of several buildings with military, religious, and civil functions. The reason for this important intervention was to offer a stronger resistance against the Barbary pirates. The construction works began in the mid 18th century, and were stopped in 1770, due to economic, political, and logistical problems. The result was the construction of most of the wall, the church, the governor's house and a complex hydraulic system in order to supply the population with fresh water. Due to the insularity conditions, the supply of the building materials was restricted to the local resources. In this context, the most appropriate rock for carving the ashlars and sculptural elements was a yellowish calcarenite which outcrops in one of the rocky islets surrounding the main island (*La Cantera* islet, which means “the quarry” in Spanish).

Unfortunately, the current conservation state of the city-walls and buildings is alarming. The sea-salt crystallization in the porous system of rocks, the wind abrasion, and human damage are some of the most significant decay causes. On the other hand, not all the materials present the same weathering resistance. Despite that the whole rock blocks were extracted from the same local quarry, several lithofacies can be recognized and each presents different petrophysical and petrographical properties. As a result, the 3D geological characterization of the historical quarry is extremely useful for determining the current susceptibility of monuments to weathering as well as for establishing a petrophysical criterion to select the best replacement stones for future restoration.

The aim of this paper is the geological characterization of the historical quarry of Nueva Tabarca island from a multi-perspective point of view. The main points in this study are: i) the determination of the complete stratigraphic section of the Miocene deposits outcropping in the island; ii) the modelling of the 3D spatial distribution of the different lithostratigraphic units of the *La Cantera* islet; iii) the petrophysical characterization of the main lithotypes recognized in the islet; and iv) the correlation of the data gathered from the volumetric analysis and the petrophysical characterization with the weathering state observed in the rocks of the architectural heritage of the Nueva Tabarca fortress.

2. Geological setting

The Betic Cordillera makes up the westernmost part of the Mediterranean Alpine chains. It spreads along > 600 km, in the southeastern part of the Iberian Peninsula (fig. 1). Two great geological realms are distinguished: the Internal and the External Zones. The Internal Zones are made up of three overthrusting units (Nevado-Filábride, Alpujárride, and Maláguide) which are composed mainly of Triassic and Palaeozoic rocks. The External Zones are represented by a sedimentary rock belt making up the northern sector of the chain. Neogene-Quaternary sedimentary deposits cover the Internal Zones, filling the basins developed during the extensional tectonics occurring since the Early-Middle Miocene.

The Bajo Segura Basin is one of the so-called post-Orogenic Neogene Basins of the Betic Cordillera (Fig. 1). The infill units outcropping in the Bajo Segura Basin include Tortonian to Quaternary sediments, with the strong tectonic control exerted by the Trans-Alboran shear zone, which is still active (Montenat et al., 1990; Soria et al., 2001, 2008a). The sedimentary record of this basin represents one of the most complete Neogene sedimentary records of the Mediterranean margins (Soria et al., 2008a,b; Caracuel et al., 2011; García-García et al., 2011). According to Soria et al. (2008a), the marine sedimentary record of this basin is divided into five major allostratigraphic units (synthems) with bounding unconformities represented by erosional surfaces that correspond to palaeogeographic and tectosedimentary changes (Tortonian I, Tortonian II, Tortonian-Messinian I, Messinian II, and Pliocene).

Nueva Tabarca island is located in the eastern sector of the Internal Zones of the Betic Cordillera (Fig. 1). The main rocks observed in the island are: fine-grained metagabbro (weakly metamorphosed), marl, black limestone, porous limestone (calcarenite), red silt and marine conglomerate. According to the chronostratigraphic sequence proposed by Estévez et al. (1985), the oldest rocks correspond to the Triassic materials of the Alpujárride complex, being consequently the easternmost outcrop of this complex in the Betic Cordillera. The Triassic set is formed by the fine-grained metagabbro (constituting the base of this Triassic level), the black limestones and the marls. The calcarenites (Late Miocene in age according to Kampschuur and Simon, 1969) appear in the western sector overlying an erosive unconformity with the lower Triassic materials. This sedimentary deposit forms the *Tabarca Unit* (Calvet et al., 1996), and is interpreted as an open carbonate platform grading upwards to more distal deposits. According to Calvet et al. (1996), the presence of the *Globorotalia pseudomiocenica* (included in the *Globorotalia menardii* group), previously identified by Kampschuur and Simon (1969), dates these deposits as Tortonian, being included in the synthem Tortonian II of the Bajo Segura Basin (Montenat, 1977; Corbí, 2010; Corbí and Soria, 2016). Finally, the red silts and the marine conglomerates correspond to Quaternary deposits and are separated from the Triassic and Neogene sediments by an unconformity.

3. Methodology

3.1. Stratigraphic analysis

Three stratigraphic sections of the Miocene deposits were studied (Fig. 2): Moll Vell (MV), San Gabriel (SG) and Cantera (C) sections. The most representative stratigraphic levels were sampled bed-by-bed in order to carry out a complete petrophysical characterization at laboratory.

Description at mesoscopic level was focused on layer thickness, bed geometry, rock texture and sedimentary structures. Petrographic components and fossil record were also studied, paying special attention to the relative content between both lithoclasts and bioclasts (specially rhodoliths), as well as the medium size of the predominant component, subsequently defining lithofacies. According to these criteria, four basic lithofacies were defined. On the one hand, when the medium clast size is larger than 2 mm, the lithofacies is named *microconglomerate* when lithoclasts are predominant or *calcirudite* when bioclasts dominate. On the other hand, lithofacies with components smaller than 2 mm are classified as *biocalcarenite* or *lithoarenite* after the predominance of bioclasts or lithoclasts, respectively.

3.2. Photogrammetry and 3D geological model

Geoscientist have used photogrammetry for many years through stereoscopic analysis of overlapping pairs of aerial photographs (e.g. Eardley, 1942; Pillmore, 1964). In recent years, structure-from-motion (SfM) photogrammetry software has been providing powerful tools for geosciences (Favalli et al., 2012; Bemis et al., 2014), enabling automated 3D model production from a suite of overlapping two-dimensional images (e.g. James and Varley, 2012; Westoby et al., 2012;

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