Quaternary International xxx (2016) 1–22

Contents lists available at ScienceDirect

Quaternary International

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

Facies architecture, geochemistry and palaeoenvironmental reconstruction of a barrage tufa reservoir analog (Betic Cordillera, S. Spain)

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Analog
Continental carbonates
Guadix
Quaternary
Resevoir
Tufa

ABSTRACT

Continental carbonates are currently of high interest for the oil and gas industry, as they have proved to be good reservoir rocks in Brazil and Angola offshore oil fields. In this article, a tufa system in which continental carbonates formed mainly in the Pliocene (Rambla Becerra Tufa System, Guadix Basin, Betic Cordillera, S. Spain), is described in detail, and a model proposed for its formation and evolution through time. Several stages of tufa growth have been identified in the field, intercalated between stages of progradation of alluvial fan sediments. The tufa system connects laterally with the fluvial system developed in the axial valley of the Guadix Basin during the Pliocene and the Pleistocene, indicating that the tufa formation was coetaneous with the periods of lateral expansion of the fluvial system floodplain, that in previous works have been interpreted as more humid stages and potentially warmer. The absence of extraclasts in the tufa sediments points to the low activity of the alluvial fans during the tufa formation and therefore supports the idea that the main tufa growth happened during more humid stages, and the alluvial fans developed further during the more arid periods, which is consistent with other recent findings in the Guadix Basin. The tufa growth is represented by four main stages, the second one bearing the best example to study as a potential reservoir analog, as the main outcrop is a discrete body with a specific geometry and facies distribution. This main outcrop is a mound-shaped tufa build-up formed by prograding sigmoids of clastic tufa, interpreted as the ramp-like buttresses developed after a barrage in a barrage tufa system. From a preliminary isotopic study of the carbonates forming the barrage tufa system and by comparison with other tufas and travertines, the oxygen and carbon stable isotopes point to an intermediate situation between a palustrine tufa and a travertine. This information, when added to the sedimentological data, supports the idea that water feeding the tufa system probably had different sources: a meteoric one, coinciding with the surface runoff and a groundwater one, probably in the form of springs fed by groundwater from the nearby aquifers that still exist in the Mesozoic carbonates that form the External Zones of the Betic Cordillera in the area.

1. Introduction

The tufas and travertines outcropping in the Neogene-Quaternary basins of the Betic Cordillera in Southern Spain (see examples in Fig. 1) have received little attention until recently. There are only a few studies on them (Martín-Martín et al., 2002; Martín-Algarra et al., 2003; Díaz-Hernández and Julià, 2006; Prado-Pérez, 2011; García del Cura et al., 2012; García-García et al., 2014) and most of them focus on a travertine outcrop in the Alicún area (Baños de Alicún spa, Guadix Basin, S. Spain). However, there are other tufa and/or travertine outcrops that need further studies, such as the examples presented in this article. The importance of these calcareous deposits as potential analogs for hydrocarbon reservoirs such as the ones currently being exploited in Brazil (Bosence et al., 2015) and Angola (Koning, 2014) makes

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http://dx.doi.org/10.1016/j.quaint.2016.05.022
1040-6182/

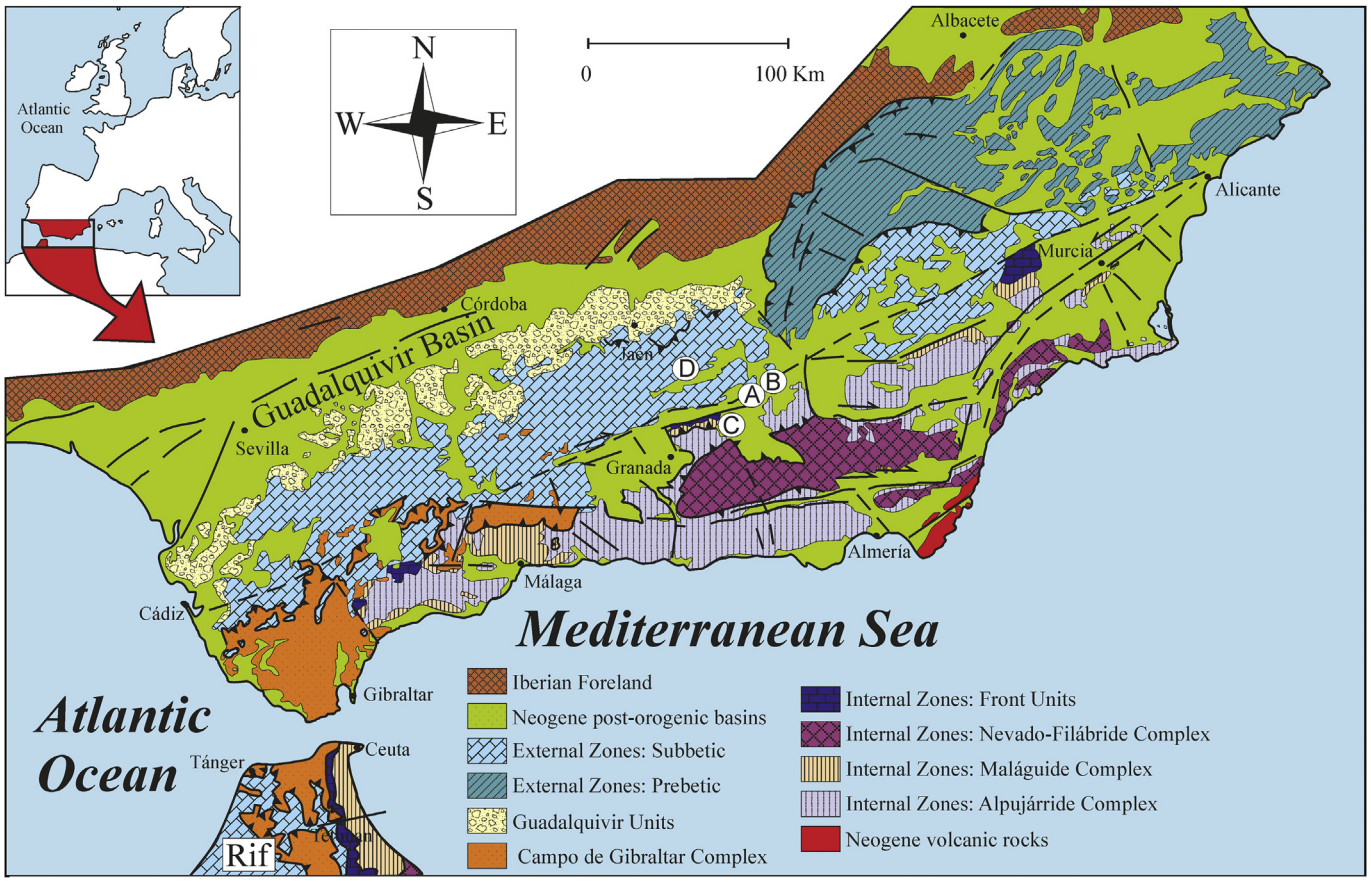

Fig. 1. Major geological domains of the Betic Cordillera (from Pla-Pueyo et al., 2009a). The location of four different microbialite systems developed close to the External Zones of the Betic Cordillera is indicated in the figure: the Rambla Becerra Tufa System (letter A), the Baños de Alicún travertine (letter B) (Prado-Pérez, 2011) and the Vereda de las Yeguas palustrine tufa (letter C) (Pla-Pueyo et al., 2009, 2013), all within the Guadix Basin, and the Frailes tufa outcrop (letter D), in the Alcalá Basin (García-García et al., 2014).

them valuable examples that deserve a thorough study. From the point of view of reservoir characterisation, the architecture of the tufa build-ups, together with any information regarding the processes affecting the facies formation, the facies distribution within the tufa system and the evolution of the system through time may be of interest for the oil industry (Awramik, 2013; Arenas et al., 2013a).

In order to clarify the concept of tufa used in this article, the definition by Ford and Pedley (1996) will be followed, so the term tufa will be used for meteogenic, ambient-temperature precipitated carbonate in the context of a stream or river (mainly meteoric water), and the term travertine will be used for warm/hot water thermogenic carbonates related to hydrothermalism and/or deep groundwater. The terms microbialite or microbial carbonate, widely used in the recent literature related to continental carbonate hydrocarbon reservoirs (e.g. Bosance et al., 2015), will be avoided in this article. Although some of the facies that will be discussed here are effectively "organosedimentary structures that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation" as defined by Burne and Moore (1987) (pp. 241–242), both physico-chemical and biological processes occur in these different precipitation environments, so these terms will not be used, to avoid their misuse. Moreover, there is still some controversy on whether the deposits bearing oil in Brazil are in fact microbialites or not (Wright, 2013).

The present study focuses on the Rambla Becerra Tufa System (Guadix Basin, Betic Cordillera, S. Spain) (Fig. 1). This system is formed by several stages of tufa formation. These tufa-forming stages occur in lateral association with the fluvio-lacustrine facies of an axial system flowing towards the NE during Pliocene and Pleistocene times and in vertical and lateral association with alluvial fan facies.

In the present article, the different stages will be described, with a stronger focus on the second stage of tufa growth, dominated by the development of a barrage tufa system, with dammed areas represented by palustrine carbonates and post-barrage buttresses formed by detrital tufa clasts from the destruction of the phytoherm forming the main barrage. This outcrop has been briefly described in previous works (Pla-Pueyo et al., 2009a, 2013), but no satisfactory interpretation was proposed for the formation of such facies in the study area. However, recent geochemical results, supported by scientific discussions in a recent conference (Pla-Pueyo et al., 2015a, 2015b), together with a visit to a field example of a similar system in the Háj Valley in Slovakia (Gradzinski et al., 2013) has led to the integrated interpretation of the whole tufa system that is presented in this article.

2. Geological setting

The Rambla Becerra Tufa System is located in the northern part of the Guadix Basin. This is a Pliocene-Quaternary basin situated in the central sector of the Betic Cordillera (Fig. 1), within the Granada province (S. Spain), that seals the contact between the two main structural realms of the Betic Cordillera (Viseras et al., 2005): the External Zones (formed mainly by Mesozoic marine carbonates in the study area) and the Internal Zones (corresponding to the folded

Please cite this article in press as: Pla-Pueyo, S., et al., Facies architecture, geochemistry and palaeoenvironmental reconstruction of a barrage tufa reservoir analog (Betic Cordillera, S. Spain), Quaternary International (2016), http://dx.doi.org/10.1016/j.quaint.2016.05.022