



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 1 October 2016

Keywords:

Analog
Continental carbonates
Guadix
Quaternary
Reservoir
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 sigmoides of clastic tufa, interpreted as the ramp-like buttresses developed after 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.

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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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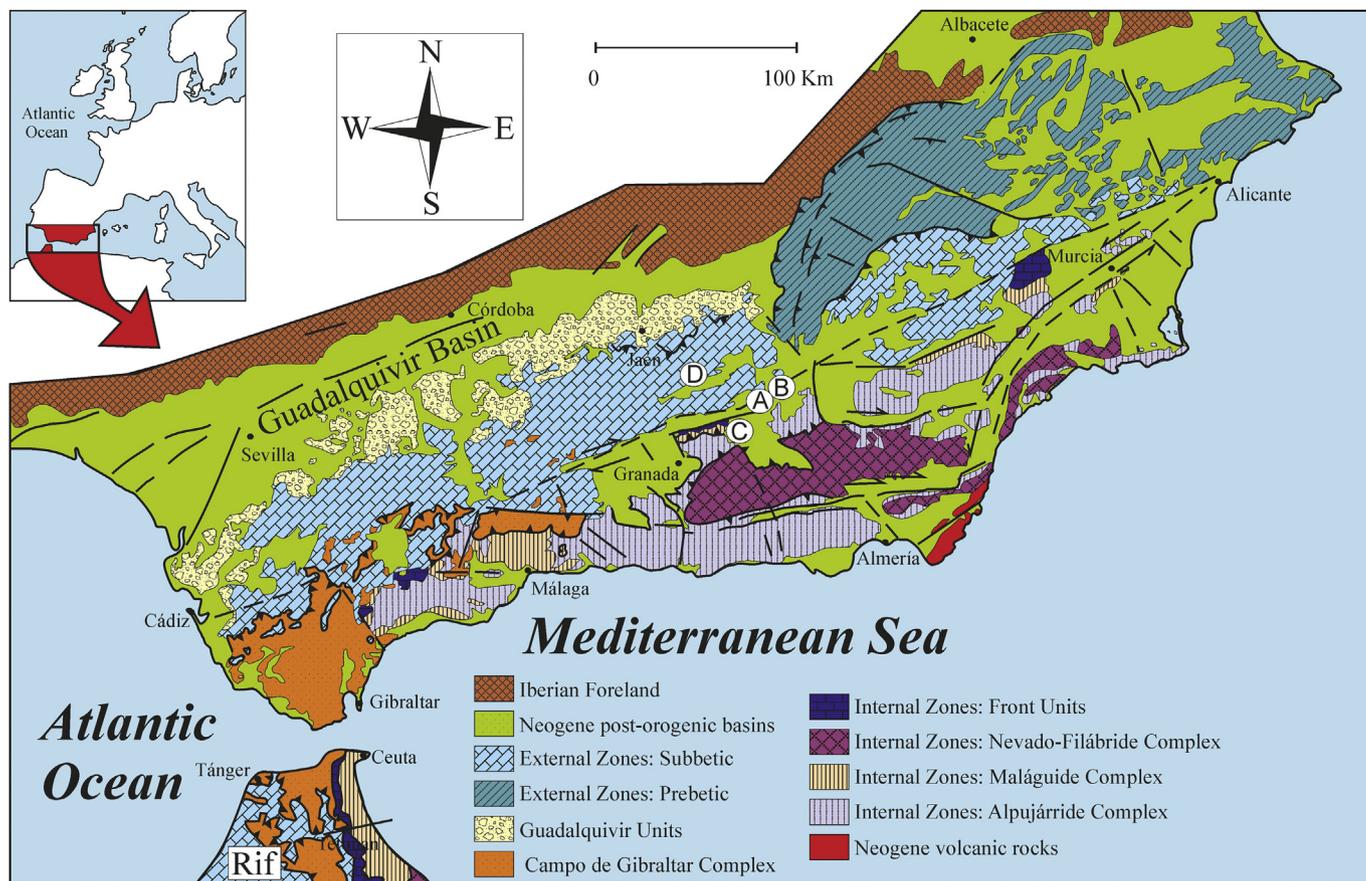


Fig. 1. Major geological domains of the Betic Cordillera (from Pla-Pueyo et al., 2009a). The location of four different microbialite systems developed close to the External Zones of the Betic Cordillera is indicated in the figure: the Rambla Becerra Tufa System (letter A), the Baños de Alicún travertine (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 meteorogenic, 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

and faulted South Iberian palaeomargin, which in the study area encompasses mostly metamorphic rocks).

The continental infill of the Guadix Basin starts in the Upper Tortonian, and has been divided into six genetic units (Viseras et al., 2005), Unit I being the oldest, and Unit VI the youngest. Unit VI started 1.778 Ma ago, and the sedimentation in this unit stopped due to a fluvial capture process (Calvache and Viseras, 1997; Calvache et al., 1997; Azañón et al., 2006) that drastically changed the drainage in the Guadix and Baza Basins from endorheic to exorheic. This change marked the stop of the sedimentation and the start of an intensive erosion that has affected the most recent sediments of the basin, those in units V and VI (Pliocene–Pleistocene).

Three main drainage systems acted during Pliocene and Pleistocene (units V and VI) in the Guadix Basin (Fernández et al., 1996; Viseras et al., 2006). A main fluvial system, so-called Axial System (AS), flowed following the palaeogeographic axis of the basin towards the NE, ending in a shallow lake in the neighbouring Baza Basin (García-Aguilar et al., 2014), which acted as base level for the entire drainage system. Two transverse alluvial systems with their source area in the two main structural realms of the Betic Cordillera fed the Axial System. The so-called Internal Transverse System (ITS) was fed by the Internal Zones (mainly metamorphic) and formed by large coalescent alluvial fans, forming a bajada system (Viseras and Fernández, 1992, 1994, 1995). On the other hand, the External Transverse System (ETS) presented small isolated alluvial fans, which received their inputs from the erosion of the External Zones (mainly Mesozoic marine carbonates) of the Betic Cordillera (Fernández et al., 1991, 1993).

The Rambla Becerra Tufa System (from now on, RBTS) is located in the northern sector of the Guadix Basin (Fig. 1A), in an area where the alluvial fans from the External Transverse System connected with the floodplain facies of the fluvial Axial System. Moreover, the External Zones outcrop in the northern part of the basin, very close to the RBTS. The Mesozoic carbonate rocks from the basement outcropping in the area are faulted, and some of the faults, such as the one near the Baños de Alicún spa (Alicún de las Torres village, Guadix Basin, S. Spain) are deep enough to allow geothermally-heated groundwater to reach the surface in the form of hot springs that are related to travertine deposits (Martín-Martín et al., 2002; Martín-Algarra et al., 2003; Díaz-Hernández and Julià, 2006; Prado-Pérez, 2011; García-Aguilar et al., 2014), similarly to what happens in other locations, such as the Gafsa fault-related springs in Tunisia (Henchiri, 2014).

In this area, the alluvial fans from the Internal Transverse System and the External Transverse System are quite close, with only 1 Km of distance between them, where the Axial System facies (mainly lacustrine) appear. Previous authors have proposed the blocking of the main valley by the progradation of the alluvial fans from both systems, creating dammed areas where lacustrine deposits would take place (Viseras, 1991; Fernández et al., 1996; Viseras et al., 2006).

3. Growth stages in the Rambla Becerra Tufa System

Up to four main tufa growth stages have been identified so far within the Rambla Becerra Tufa System (Table 1, Figs. 2 and 3). The age of the different stages has not been determined by absolute dating yet, but by correlation to the facies outcropping in the central sector of the basin (Pla-Pueyo et al., 2011), the four stages would be Pliocene–Pleistocene in age.

The oldest one, to which we will refer as Stage 1, has been identified in only one location, at the bottom of the present valley, and this patchy outcrop is formed by a framework of stem moulds (carbonate coated stems), most of them vertical, preserved in life position (Figs. 1–4).

Stage 2 is represented by three main outcrops (Figs. 2 and 5). One of them (outcrop 2 in Fig. 2) is a large tufa build-up that has been described in previous publications (Pla-Pueyo et al., 2009a, 2013, 2015b, 2015c) as the Rambla Becerra outcrop (Fig. 5B), but never interpreted in a holistic way. Another one is connected laterally to this tufa build-up (outcrop 3 in Fig. 2), and is formed mainly by palustrine-lacustrine sediments (Fig. 5C). The third one is on the other side of the valley where the tufa build-up appears (Fig. 5A.), and due to the lack of correlation tools, it is difficult to know how exactly it connects to this main build-up. Stage 2, and specifically outcrop 2 (Fig. 2B and 5B) will be the main focus of this article, as it is the most complete example to be characterised as a potential reservoir analog, allowing for detailed stratigraphical, petrological and geochemical studies.

Stages 1 and 2 are restricted to a small area, and are not considered strictly belonging to the Axial System, but local tufa growths laterally connected to the Axial System to the South and contemporaneous to its sediments.

The Stage 3 tufa growth (Fig. 6) shows lacustrine features, similarly to Stage 4, and both of them are large expanses of tufaceous sediments that need further studies to be properly characterised, although preliminary results will be provided in this article for Stage 3 tufas. They are both considered Axial System lacustrine sediments.

In between each of these stages, sediments of the ETS and ITS alluvial fans can be found, eroding the top of the tufa outcrops.

4. Methods and analytical approach

4.1. Field methods

The main methods used for gathering the field data have been geological mapping, measuring of sedimentary logs and interpretation of photomosaics. Ground-penetrating radar (GPR) was used along the main outcrop (Fig. 2B and Fig. 7) of Stage 2.

The combined use of GPR data and outcrop observations is an extremely useful methodology for the characterisation of sedimentary processes in siliciclastic sediments (e.g., Neal et al., 2002, 2003; Viseras et al., 2009) but it has also proved quite useful in

Table 1
Summary of the main features of the four tufa growth stages identified in the Rambla Becerra Tufa System.

Tufa growth stage	Geometry of tufa deposit	Thickness of tufa deposit	Lateral extent of tufa growth	Geometry of individual beds	Thickness of individual beds	Dominant lithofacies	Dominant textures
Stage 4	Tabular	3–10 m	>100 m	Tabular	50 cm ⁻² m	Lph, Mm, Mg	Mudstone, wackestone,
Stage 3	Tabular	3–10 m	>100 m	Tabular	50 cm ⁻² m	Lph, Mm, Mg	Mudstone, wackestone, breccias
Stage 2	Outcrop 3	Tabular	<100 m	Tabular	50 cm ⁻¹ m	Mm, Mg, Lph	Mudstone, wackestone
	Outcrop 2	Mound-shaped	5–8 m	Sigmoids	20 cm ⁻¹ m	Lph, Lo, Loph, Lst 1, Ls, Lg	Local frameworks Rudstone-Floatstone
Stage 1	Outcrop 1	Tabular	<100 m	Tabular	50 cm ⁻¹ m	Mm, Mg, Lph	Mudstone, wackestone,
		Unknown, patchy outcrops	Unknown (partially buried)	10 s m (data from exposure)	Lenticular-tabular	50 cm ⁻¹ m	Lst, Mg

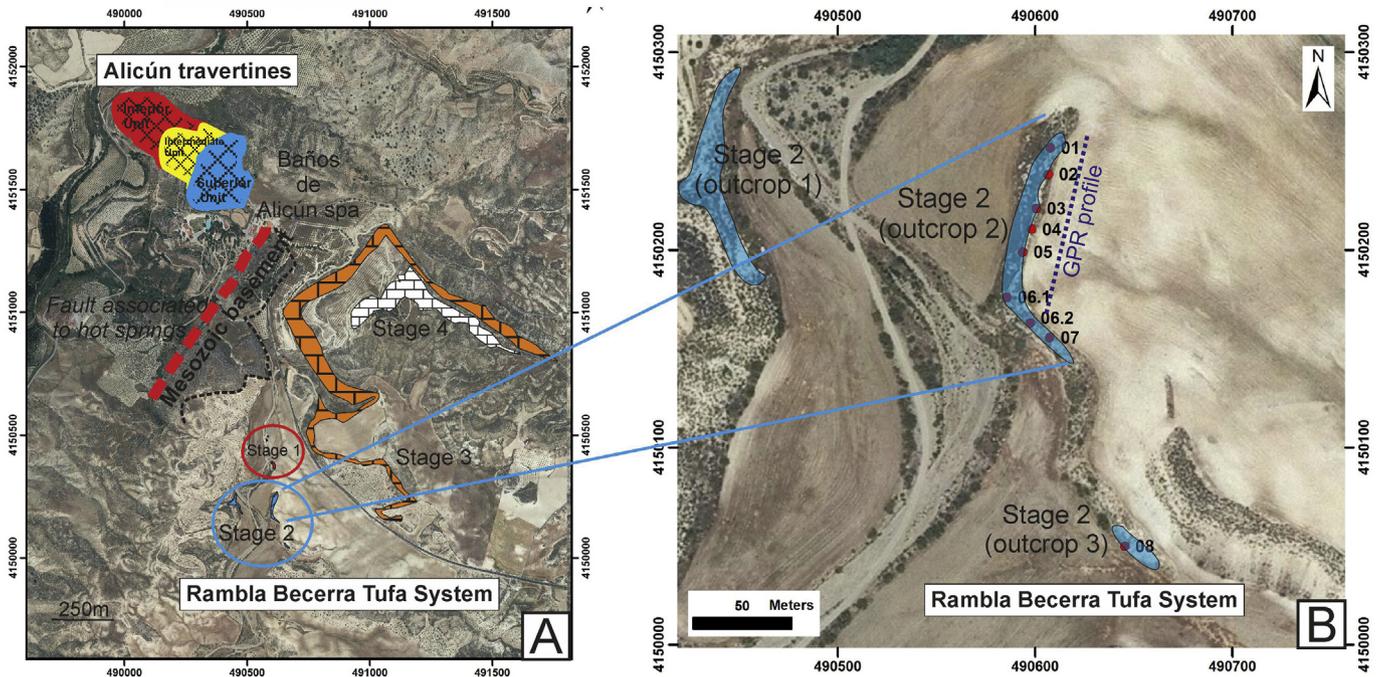


Fig. 2. A. Aerial photograph of the Rambla Becerra Tufa System, showing the four tufa growth stages identified in the area, and the nearby travertine deposits of Alicún area. B. Detail of the area where tufas from Stage 2 outcrop, showing the location of the measured stratigraphic profiles, labelled 01 to 08 in the figure. The GPR profile orientation is represented by a dotted line.

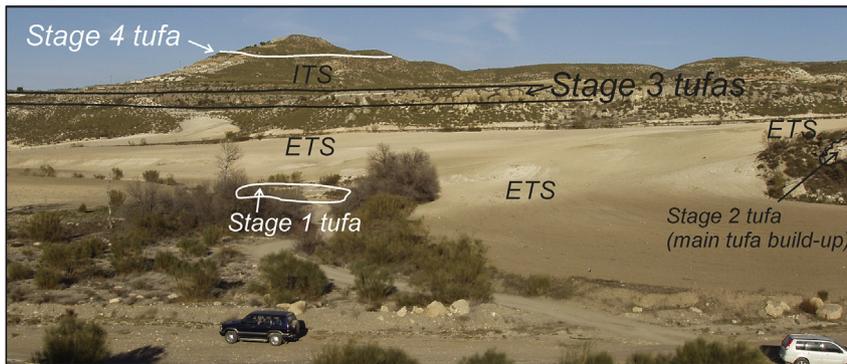


Fig. 3. In the photograph, the four tufa stages are indicated in the landscape, and the alluvial fan sediments can be observed. The External Transverse System (ETS) appears between stages 1 and 2, and 2 and 3. Mixed sediments (ancient and modern) are partially covering Stage 1 tufas. The photograph only shows the northernmost part of the main tufa build-up of Stage 2, while Stage 3 tufas are shown in full view. Stage 4 tufas, separated from Stage 3 by sediments from the Internal Transverse System (ITS) fans, are only a line in the photograph, so their location is pointed out with a white line.

tufa deposits, specially in barrage tufa systems (Pedley et al., 2000; Pedley and Hill, 2003; Luzón et al., 2017.).

The GPR methods detect, through a pulse of high-frequency electromagnetic energy, changes in dielectric properties of materials (Davis and Annan, 1989). The obtained reflections correspond to interface surfaces between materials of different dielectric properties that can be due to variations in lithology, pore fluid and/or porosity of the sediment (Skelly et al., 2003).

In the present study, the GPR survey was conducted using a Mala Geosciencies, RAMAC GPR radar with 100 MHz antenna. The original purpose of the acquisition of GPR data in the Rambla Becerra Tufa System was to check the reliability of this method in characterising subsoil data in tufa outcrops in southern Spain. Therefore, only a transect of 75 m in length

was sampled, following the same orientation of the main outcrop (NE–SW), more or less transversally to the main direction of progradation of the sigmoidal bodies identified in the outcrop.

The obtained profile (Figs. 2B and Fig. 7.) penetrated approximately 15 m in thickness, with a window of 8 ns, so the quality of the acquired data and their interpretation could be compared with the available real data.

The surfaces identified in the GPR profile coincided with the sedimentary surfaces observed in the outcrop, separating different sets of beds with a sigmoidal geometry and allowing the identification of some channel geometries. The GPR data provided here thus support the outcrop geometrical interpretation of the tufa deposits in the main outcrop of Stage 2.

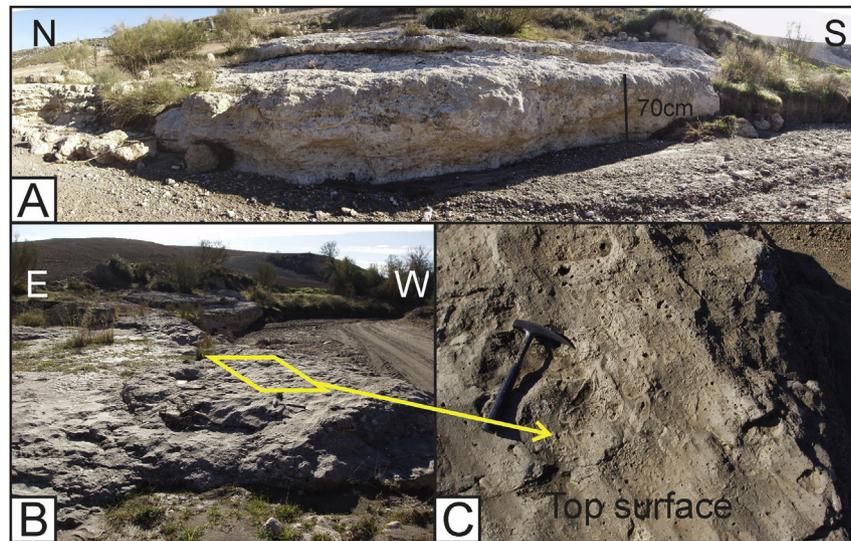


Fig. 4. Stage 1 tufa deposits. A. Photomosaic showing the main tufa outcrop of Stage 1, a phytotherm formed mainly by vertical coated stems. B. View of the tufa build-up from a different perspective, with the hammer on top for scale. C. Photograph of the top surface of the tufa body, with the hammer on it for scale, showing the transverse sections of vertical coated stem moulds and a large number of circular voids, where the stems would have been.

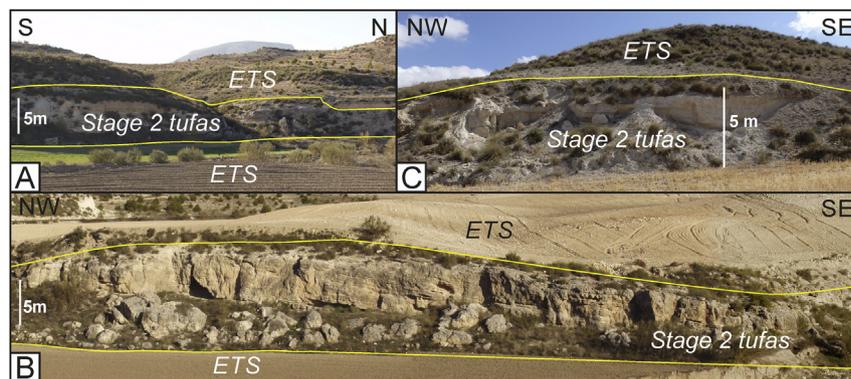


Fig. 5. Stage 2 tufa deposits. A. Photomosaic showing the upstream outcrop of Stage 2, formed mainly by marly sediments. B. Photomosaic showing the main tufa build-up, characterised in more detail as a reservoir analogue. C. Photograph showing the downstream palustrine outcrop connected laterally with the main tufa build-up.

4.2. Lab methods and analytical approach

Carbonate samples were obtained in the different outcrops in the Guadix and Alcalá Basins with a geological hammer. Thin sections from the carbonate hand samples were prepared in the facilities of the Department of Geography at Royal Holloway University (UK) and their petrology analysed using an optical microscope.

The preliminary geochemical analysis of the carbonates was performed using bulk samples. A sub-sampling was carried out in the lab at Royal Holloway before analysing their stable isotopes content. Special care was taken to ensure the freshness and the lack of contamination of the samples by avoiding pedogenically/diagenetically altered areas.

The carbonate samples were powdered using a pestle and mortar, and the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotopic composition was established by analysing CO_2 liberated from the sample reaction with phosphoric acid at 90°C . Internal (RHBNC-PRISM) and external (NBS-19, LSVEC) standards were analysed every 8 samples. The carbonate stable isotopes were analyzed using a VG PRISM series 2 mass spectrometer at the laboratories of the Royal Holloway University of London (UK). In this study, all isotopic values are quoted in reference to V-PDB.

5. Sedimentological analysis of the Rambla Becerra Tufa System

A detailed sedimentological and petrographical analysis of the tufa bodies was performed to characterise the facies and morphology of the different stages, aiding in the reconstruction of the palaeoenvironmental conditions of the system.

As we have mentioned before, the configuration of the tufas in the RBTS involve several stages of tufa development (Fig. 2) intercalated with moments of progradation of the alluvial fan sediments. In order to describe the different facies identified in each of the stages, the nomenclature proposed by Arenas-Abad et al. (2010) and used for the description of the Frailes Tufa System (García-García et al., 2014) has been applied in this article, together with the nomenclature for non-tufa facies used by Pla-Pueyo et al. (2015a). The common factor in all these publications is the use of a capital letter to describe the lithology (L = limestone, M = marl) and a small letter to specify further the nature of such facies (See Table 2 for a detailed description of the lithofacies), following the same method that Miall (1996) proposed for siliciclastic sediments.

Table 2
Lithofacies identified in the Rambla Becerra Tufa System (Guadix Basin, S. Spain). The features that characterise the lithofacies are listed first, and other features that may or may not appear are marked with an asterisk.

Facies	Textural features, sedimentary structures and biological content	Interpretation
Lst 1	Phytohermic limestones of stems (palisades and bushes of stems)	Precipitation of carbonate around stems of living macrophytes (hygrophytes) in a shallow ponded area, such as barrages and palustrine settings.
Ls	Stromatolitic limestone	Precipitation of biomediated carbonate by microorganisms (cyanobacteria, bacteria and/or algae). Two potential contexts: 1) In quiet areas, such as fluvial and lacustrine calm areas or inactive areas of waterfalls and caves. 2) In fast flowing areas on the river bed (low slope zones and cascades)
Lph	Phytoclastic limestone	Coated plant debris, eroded from existing phytohermic framestones, cemented before, during and after the deposit
Lo	Oncoidal limestone	Stromatolitic formation around a nucleus, under a fast, slow or static water regime (different resulting morphologies). They are usually related to channel fills, channel bars and lake shores.
Li	Intraclastic limestone	Flood deposits accumulating the remains of previous eroded sediments.
Lg	Limestone with gley features	Palustrine deposits in ephemeral ponds that have suffered some subaerial exposure, with colonisation by plants and affected by incipient soil processes
Ln	Nodular limestone	Palustrine deposits in ephemeral ponds that have suffered frequent subaerial exposure, with colonisation by plants and affected by soil processes
Lig	Limestone with pedogenic intraclasts and grainification	Palustrine deposits in ephemeral ponds that have suffered intense subaerial exposure and during long periods of time, showing features such as grainification and pseudomicrokarst.

Table 2 (continued)

Facies		Textural features, sedimentary structures and biological content	Interpretation
Ll	Calcrete	Coarse and uneven lamination *Breccia texture *Micrite-coated clasts *Intraclasts	Laminar horizons of pedogenic calcretes
Mm	Massive marl	Structureless, mudstone *Malacofauna and charophyte remains	Lacustrine-palustrine deposits
Mg	Marl with edaphisation features	Mudstones with: Rizholiths Marmorization Subhorizontal desiccation cracks *Circumgranular desiccation cracks and nodulisation *Malacofauna and charophyte remains *Alveolar and fenestral structures *Phreatic cements *Vadose cements *Vadose silt	Palustrine deposits in ephemeral ponds that have suffered different degrees of subaerial exposure
Ml	Laminated marl	Coarse uneven carbonate lamination Root moulds, desiccation cracks and other edaphic features *Micrite coated clasts *Intraclasts	Laminar horizons of pedogenic calcretes, developed by cementation and replacement of carbonate in edaphic profiles and existing sediments

5.1. Stage 1 tufa deposits

The first stage of tufa development is the stratigraphically lowest of the four (Table 1, Figs. 3 and 4). It has been eroded by the recent drainage network, so only a main outcrop remains (less than 10 m of lateral continuity) and a few other smaller patches, half covered by modern sediments transported by a seasonal stream, are visible.

The main outcrop (Fig. 4) is formed mostly by Lst facies (Table 2), consisting mainly of carbonate concentric casts of macrophyte stems, most of them vertical (in life position), that have been interpreted as belonging to a phytoherm (palisades and bushes of stems). The carbonate concentric coatings range between several millimetres and several centimetres, and the diametres of the stem moulds reach up to 2 cm. Some of the moulds are void, but some of them are filled by micrite. The area between stems is filled by micrite (Mm).

Apart from the field observations, no petrographical nor geochemical analyses have been performed for these facies yet.

5.2. Stage 2 tufa deposits

The second stage of tufa growth (Table 1, Fig. 3) presents three main outcrops, numbered 1, 2 and 3 in Fig. 2. The three of them seem to be in the same stratigraphical level, and they crop out at both sides of the present valley, that has eroded away a large part of the tufa sediments (Fig. 2).

5.2.1. Stage 2, outcrop 1

The first of the three outcrops (outcrop 1 in Fig. 2 and Fig. 5A) is formed by tabular beds showing mainly palustrine facies (Mm, Mg) with few phytoclasts (Lph), so it is interpreted as a low energy environment (ponded area) with formation of palustrine tufas.

5.2.2. Stage 2, outcrop 2 (main tufa build-up)

As it has been mentioned before, the main focus of the studies regarding reservoir analogs is on the main tufa-build-up developed during Stage 2, corresponding to Outcrop 2 in Fig. 2 (Fig. 5B.). This outcrop has been previously studied in a preliminary way (Pla-

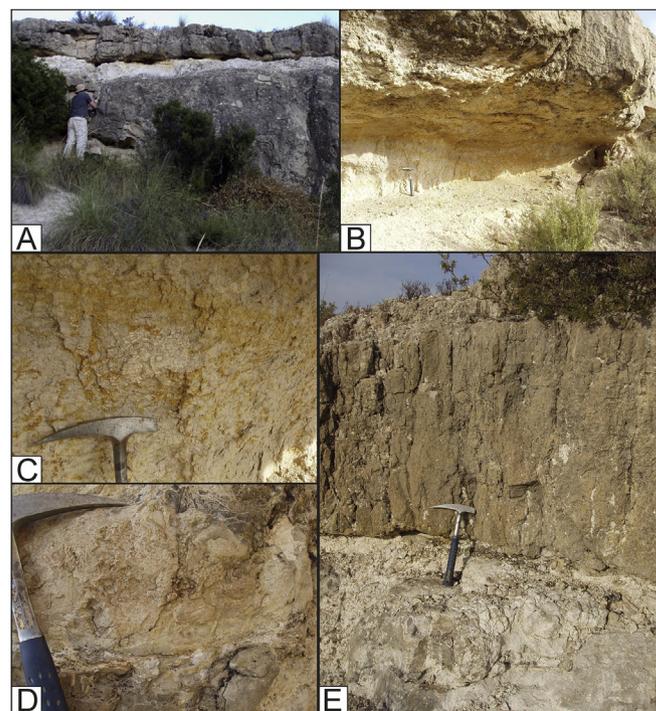


Fig. 6. Stage 3 tufa deposits. Close-up photographs of the main outcrop of Stage 3 tufas, where a palustrine carbonate can be observed at the bottom of the outcrop, and then three distinctive beds on top of it (Fig. 6A.). The middle bed is whiter than the other two, which makes this outcrop distinguishable from very long distances in the landscape. A detail of the palustrine carbonate (Fig. 6B.) is provided in Fig. 6C, showing the marly nature of the sediment and a very intense oxidation (marmorisation) interpreted as a result of pedogenic processes. The overlying greyish bed is quite thick and very well cemented, phytoclastic (Fig. 6D.). The whiter intermediate bed is mainly palustrine in nature, while the topmost grey bed is coarser, and shows a brecciated texture (see microphotographs in Fig. 11).

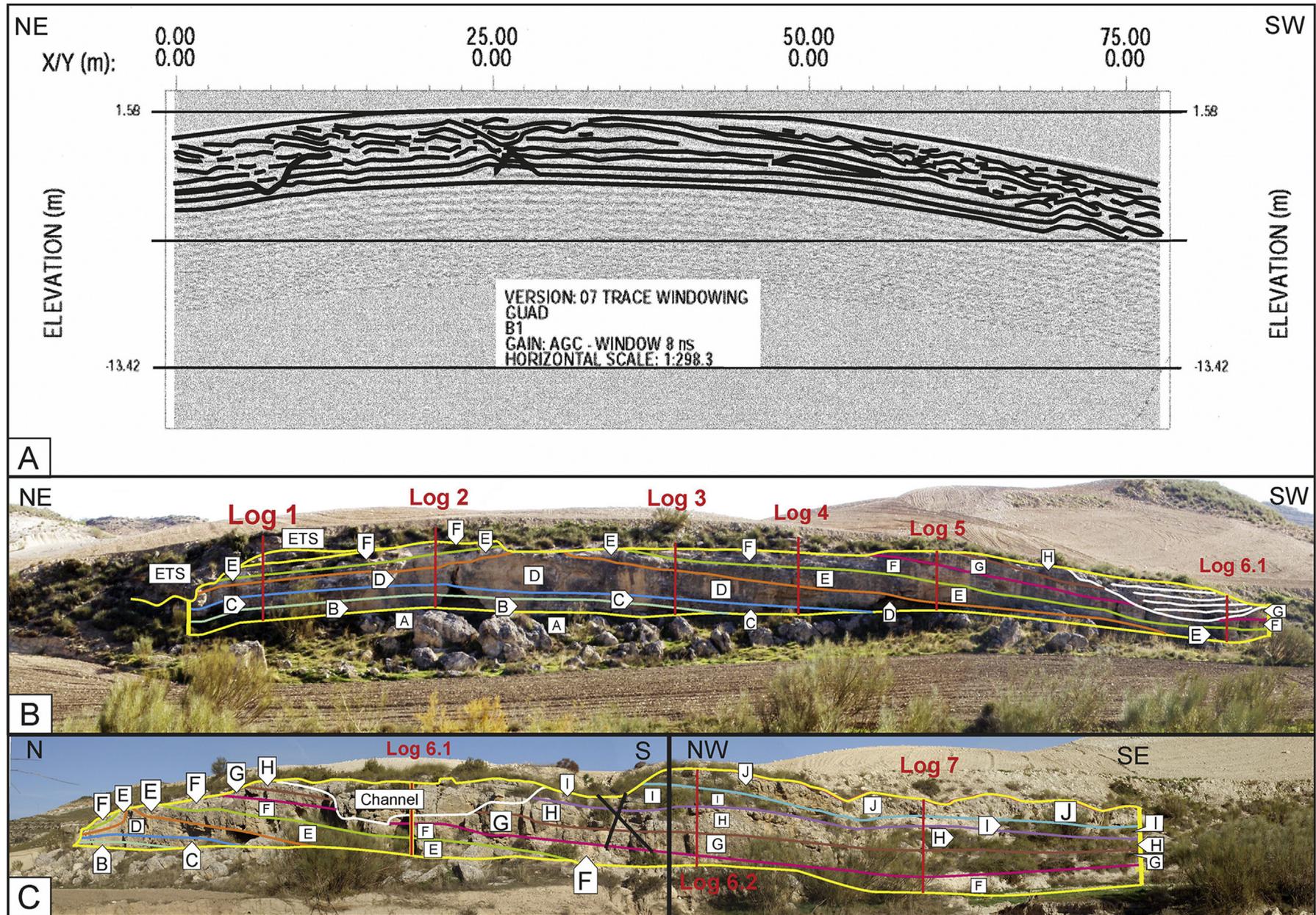


Fig. 7. A. Interpreted GPR section of the main tufa build-up in Stage 2. B. Photomosaic of the main tufa build-up, with the labels for the different sigmoids identified in the northern part of the build-up and the location of sedimentary logs 1 to 6.1. C. Southern part of the main build-up, showing the labelled sigmoids and the location of sedimentary logs 6.1 to 7.

A

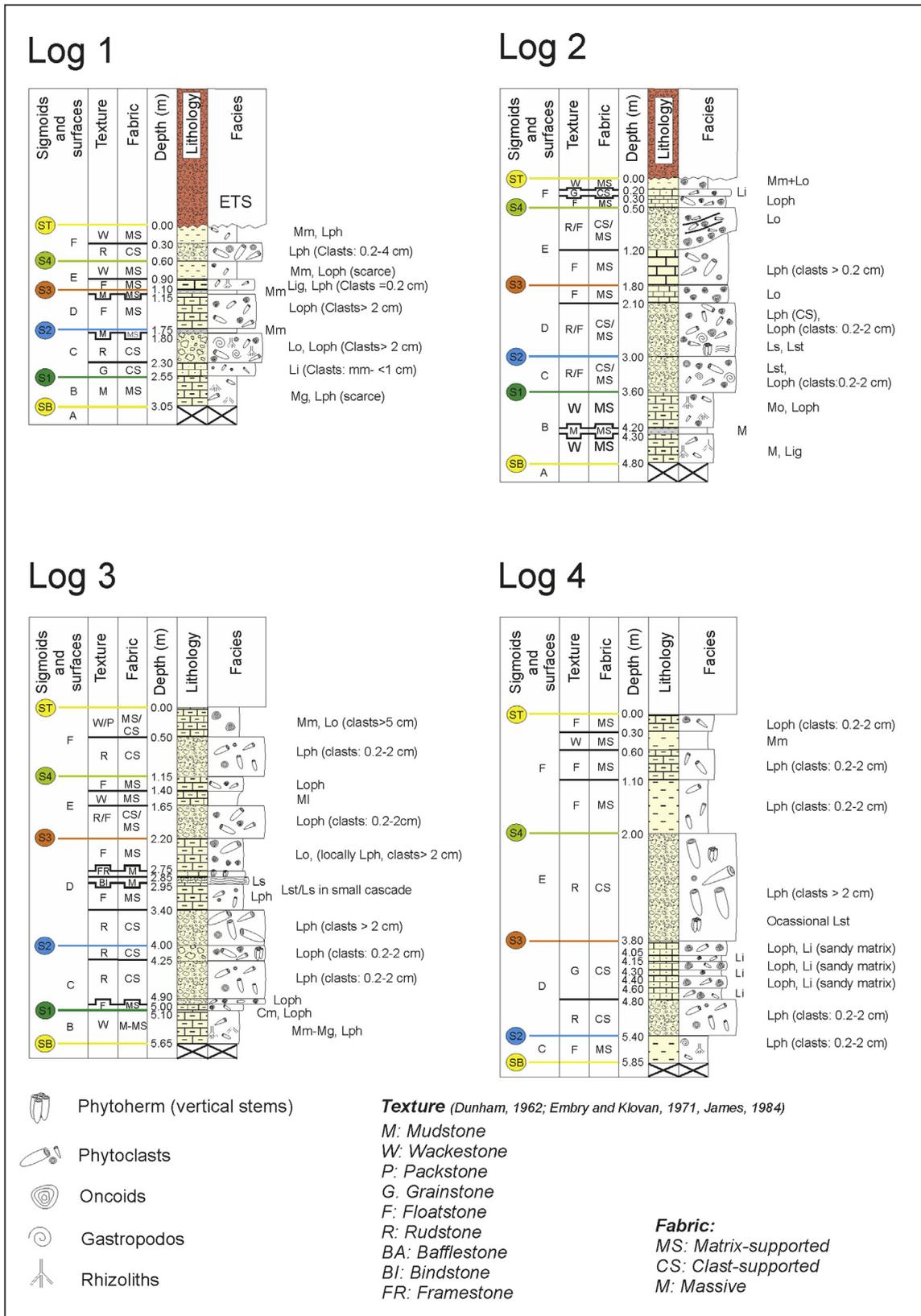


Fig. 8. A. Sedimentological logs 1 to 4 measured in the main build-up (outcrop 2 in Fig. 2) of Stage 2 tufa deposits. Sedimentological logs 5 to 7 measured in the main build-up (outcrop 2 in Fig. 2) of Stage 2 tufa deposits. The vertical scale is exaggerated $\times 10$. The predominant texture (following the modified Dunham's 1962 carbonate classification by Embry and Klovan (1971) and James (1984)) and fabric (divided in massive, clast-supported or matrix-supported) for each bed are shown in two different columns to the left of each log. The vertical length of each profile is expressed as depth from the top surface (ST), that was measured in the field using differential GPS, with the intention of using the sedimentological profiles as if they were cores in future modelling work.

B

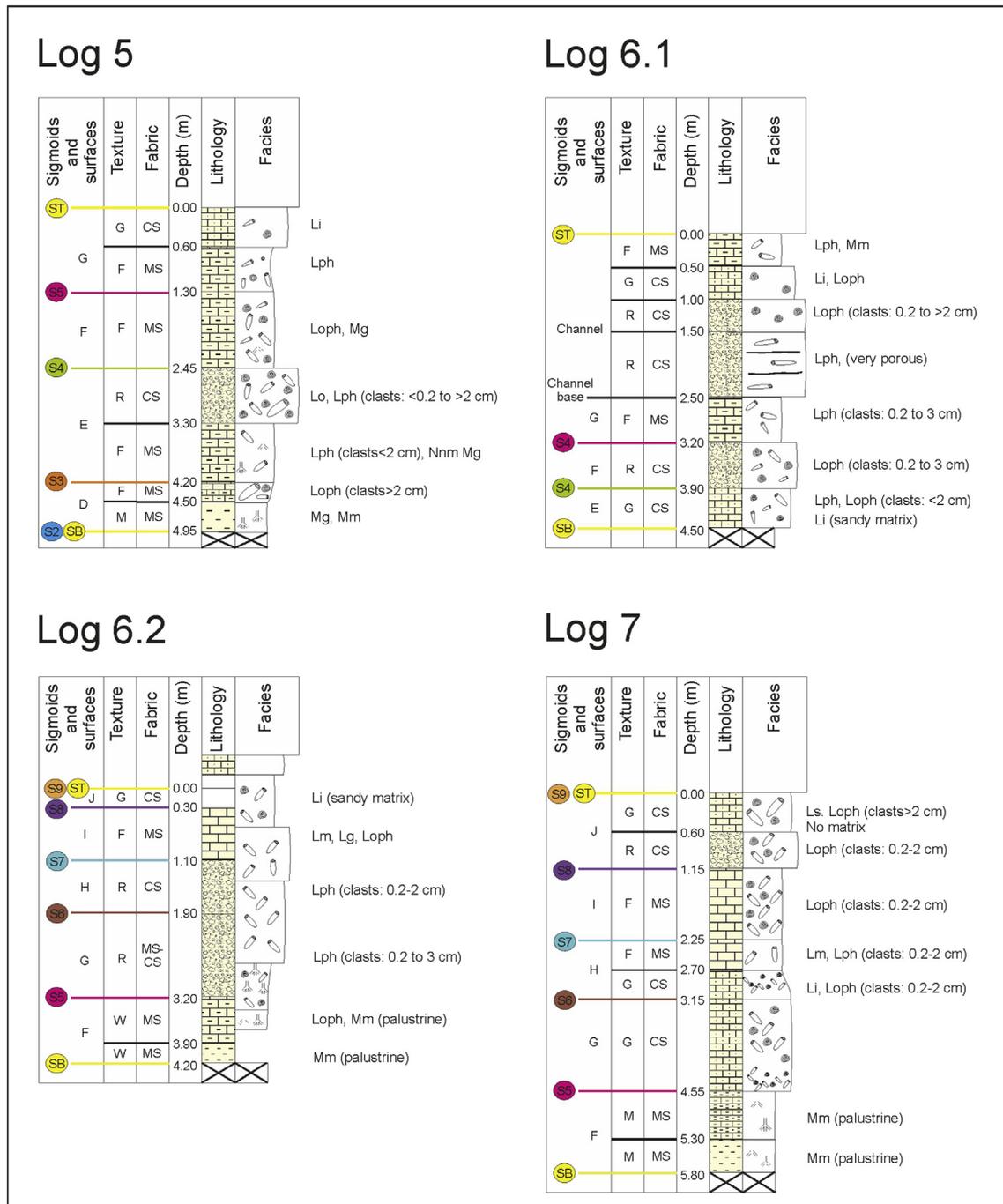


Fig. 8. (continued).

Pueyo et al., 2009a, 2013, 2015a, 2015b, 2015c) and a more detailed study about it is presented in the current section.

The initial stages of the detailed characterisation of this tufa body involved a 75 m long GPR line (Fig. 7A) on the second outcrop (Fig. 2) that supported the visual interpretations of the outcrop in the field, following the examples from Pedley and Hill (2003) and Pedley et al. (2000).

The tufa build-up is shaped as a large mound which in transverse section (outcrop view) presents tabular to sigmoidal beds dipping towards the S–SE (from almost horizontal up to 15° dip),

that have been labelled using letters, in order to facilitate the facies analysis (A to J) (Fig. 7). This dip seems to be sin-sedimentary. The top of the tufa build-up was partially eroded by a later progradation of the ETS alluvial fan (an erosive contact between the tufa build-up and the breccias of the alluvial fan can be observed in the field).

Several sedimentary logs (numbered 1 to 7) have been measured in this outcrop (Fig. 8A and B). In Logs 1 to 7, the surfaces between the different sigmoids have been identified (Figs. 7 and 8) and correlated (Fig. 9), and the facies within each sigmoid have been analysed (hand sample and optical microscope, see Table 2),

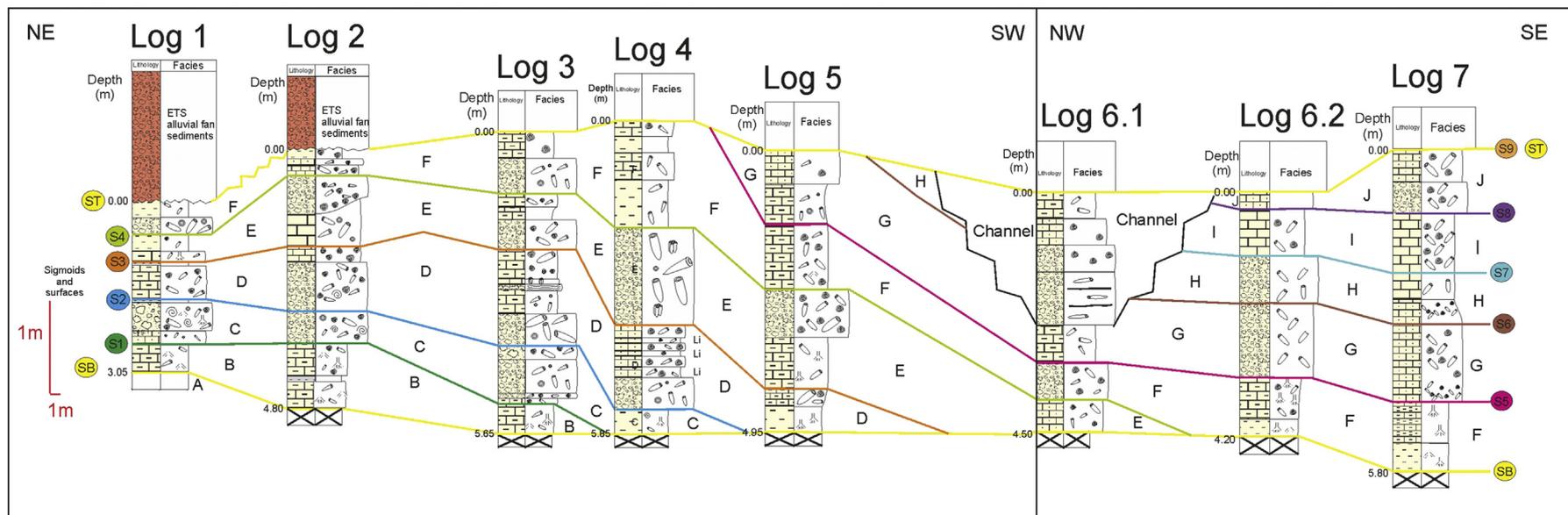


Fig. 9. Correlation among the detailed sedimentary logs measured in Stage 2 tufa build-up (outcrop 2 in Fig. 2). The vertical scale is exaggerated $\times 10$. The surfaces delimiting the bottom (SB) and top (ST) of the tufa build-up have no sedimentological meaning, but they are to be used in the modelling process to delimit the dimensions of the body. The different surfaces (S1 to S9) that can be correlated throughout the tufa build-up are shown in colours, and the sigmoids delimited by such surfaces labelled with letters from A to J. The lithology and facies are shown in two different columns. The vertical length of each profile is expressed as depth from the top surface (ST), that was measured in the field using differential GPS, with the intention of using the sedimentological profiles as if they were cores in future modelling work. For details on the represented facies, please see legend in Fig. 8A and Table 2.

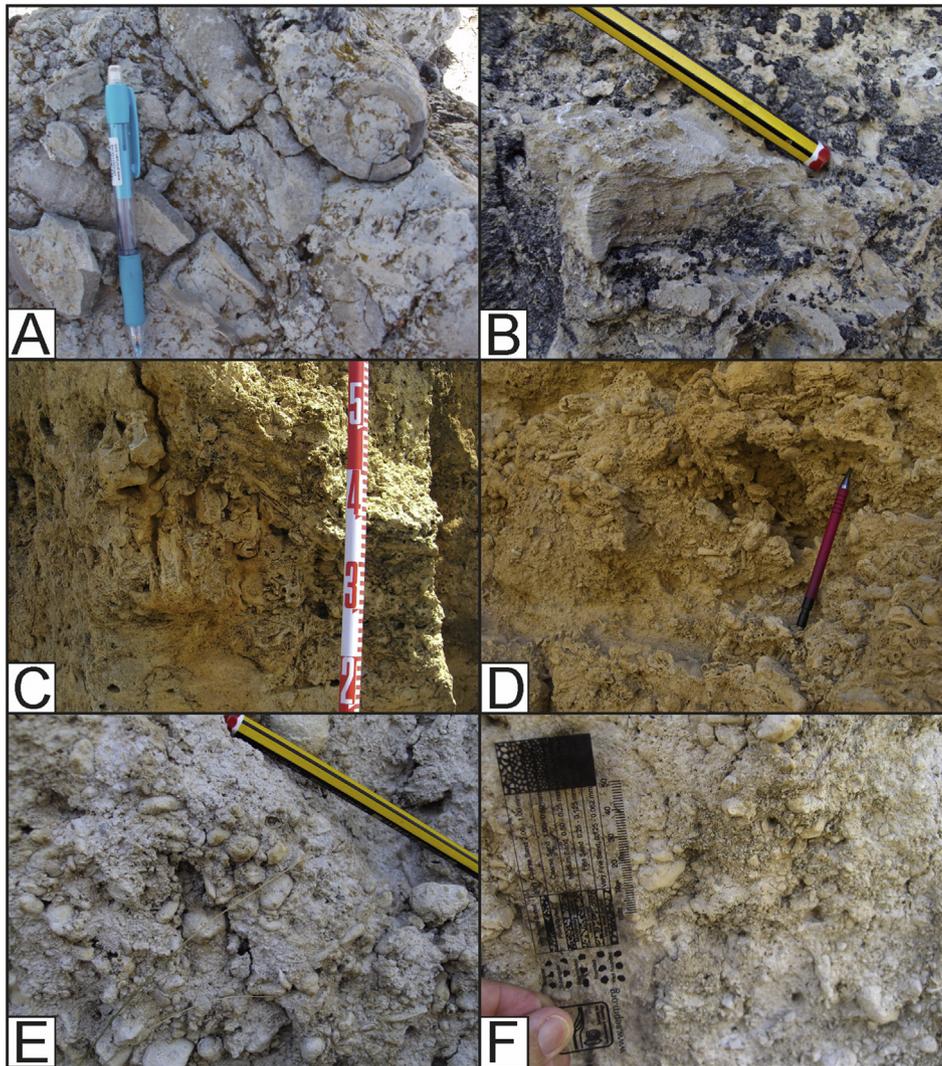


Fig. 10. Examples of lithofacies in hand sample (all of them described in Table 2). A. Facies Lst from Vereda de las Yeguas palustrine tufa (Pla-Pueyo et al., 2009, 2013). B–F. The facies in photographs B to F were all taken in the main tufa build-up of Stage 2 in Rambla Becerra Tufa System, and their description refers to the logs shown in Fig. 8. B. Facies Ls from a small cascade identified near Log 3. C. Facies Lph showing large phytoclasts in Log 4. D. Facies Loph, a mixed facies sharing the characteristics of Lph and Lo, bearing both oncooids and phytoclasts. E. Oncoidal facies (Lo) in Log 2. F. Facies Li, showing an intraclastic from Log 1, with intraclasts formed by sand-sized phytoclasts.

looking for trends in grain size (energy), texture and/or changes in predominance from in situ formed facies to detrital ones.

The sedimentary logs (Fig. 8) show mainly detrital facies (Lo, Lph, Li, phytoclastic, oncoidal and intraclastic tufa) (Table 2), most of the times with no clear grain size evolution either lateral nor vertical (only in Log 4, in sigmoid D there seem to be some finning-upward sequences). The scarce framework facies within the sigmoids (some patches of stems in life position (Lst) and a small cascade (Ls) in Log 3) (Fig. 8A) may be indicating the position of some secondary phytoterms (Pedley, 1990).

Looking at the petrographical features (Figs. 10 and 11), there are some signs of mild edaphisation, such as localised oxidation and circumgranular cracks formed by desiccation and the starting of nodulisation processes, but none of them seem to imply long exposure times for these facies. The cements filling the pores are all phreatic, indicating that all the cementation occurred under saturation (phreatic) conditions. All these features point to a system that was covered by water most of the time, with no strong

seasonal changes in the water input, at least no prolonged subaerial exposure of the tufa debris.

In terms of vertical sequences, there is not a clear pattern on how the facies are arranged vertically within each sigmoid (they tend to be poorly sorted and with no clear vertical trends in grain size). Looking at the complete vertical sequence in different points of the tufa build-up (see the detailed sedimentary logs measured in different sections of the tufa build-up in Fig. 8), there are some coarsening-upwards trends in the middle section. The only clear trend identified for all of the sigmoids is a consistent lateral facies change to marly, palustrine facies of each sigmoid downstream.

In general, these facies are interpreted as the accumulation of detritus of a large phytoterm, formed by a palisade of bushes. This phytoterm would probably slow down or even block the surface water flow, acting as a barrage for the flow. In moments of higher energy (storms, high water regime), the phytoterm would be partially destroyed and its clasts transported downstream, by the

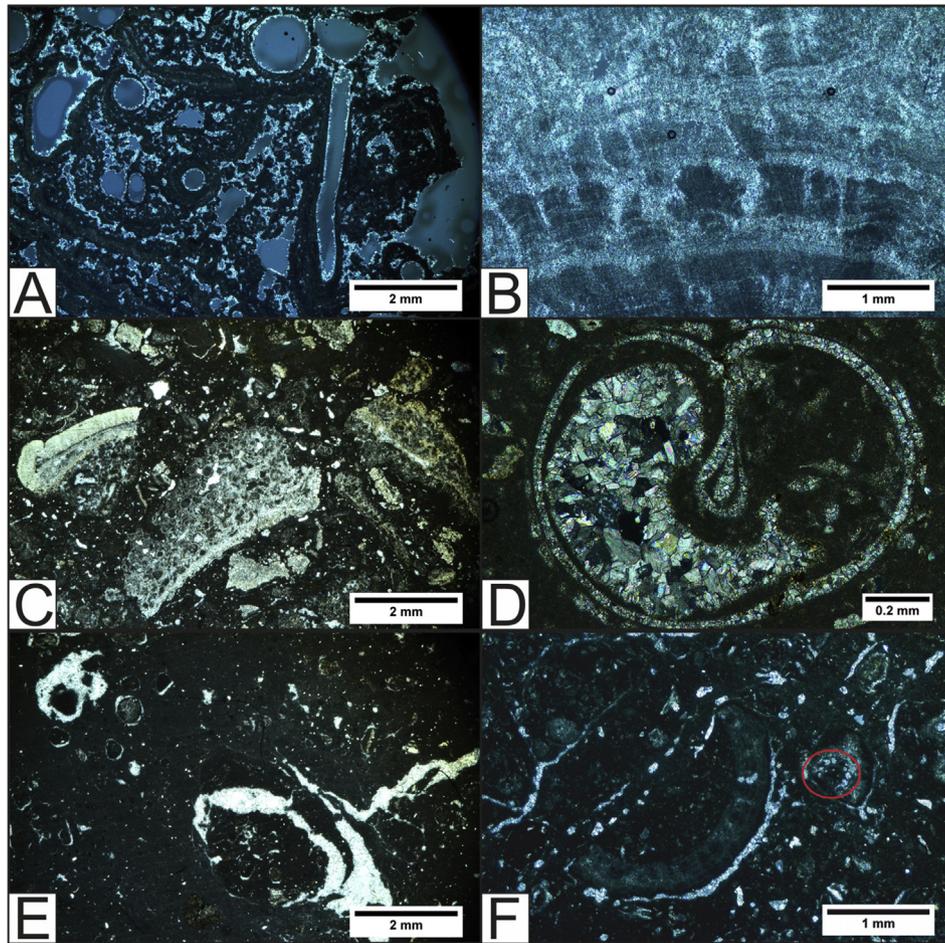


Fig. 11. Microphotographs under the optical microscope of some of the lithofacies of Rambla Becerra Tufa System. A. Phytoherm facies (Lst) under polarised light, showing framework texture (stems in life position). B. Stromatolitic facies (Ls) showing an alternation of micritic (dark) and microspar (bright) layers, with vertical cracks probably due to upward migration of bacteria. C. Packstone (Lph) with broken fragments of coated phytoclasts (stems and leaves) and ostracod shells. Clotted texture predominates in some areas (pelloids, small size) of the matrix. Pelloids seem to have been cemented later by intergranular phreatic cements. Some oxidation can be observed. D. Detail of a gastropod mould, half filled by micrite, half by phreatic spar, in a mudstone-wackestone limestone showing edaphisation features (subhorizontal and circumgranular cracks, maybe also root moulds, oxidation). E. Mudstone-wackestone palustrine limestone showing nodulisation and abundant circumgranular cracks filled by phreatic cements. F. Mudstone-wackestone limestone with clasts consisting of gastropod and ostracod shell moulds filled by cement, showing features of subaerial exposure (edaphisation), such as subhorizontal and circumgranular cracks and oxidation. A charophyte gyrogonite has been identified and circled in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water and maybe aided by gravity, forming a breccia down the slope from the barrage itself (Figs. 10 and 11).

The GPR analysis (Fig. 8), combined with the sedimentary analysis led to the interpretation of this outcrop as the remaining section (ramp-like buttresses) of a larger fluvial barrage tufa (Pla-Pueyo, 2009; Pla-Pueyo et al., 2009a) similar to other examples described in the literature (Pedley, 1987, 1990, 1993; Pedley et al., 1996, 2000; Andrews et al., 2000; Pedley and Hill, 2003; Ordóñez et al., 2005; Viles et al., 2007; Pedley and Rogerson, 2008; Valero-Garcés et al., 2008; Arenas et al., 2013b).

This large system would have a general flowing direction towards the SE (Pla-Pueyo et al., 2015b), which has been deduced from the shape and orientation of the sigmoidal bodies forming the ramp-like buttresses, that connect distally with finer palustrine-lacustrine facies that would correspond to the end term of the system downstream.

Following the interpretations of other authors for similar systems (Ordóñez et al., 2005), the sigmoids have therefore being interpreted as the downstream facing-buttruss (Pedley, 1990) or ramp-like buttruss (Ordóñez et al., 2005) and the boundaries

between sigmoids would correspond to erosion surfaces related to the fluctuations of the base level of small lakes that might have formed downstream.

The facies distribution and morphology of the main tufa build-up is similar to the one described by Pedley (1987, 1990, 1993) for the Caerwys tufa, with a downstream-facing buttruss, that he calls principal barrage, and secondary phytoherms less cemented, and therefore, more difficult to preserve (which would be the case of the Rambla Becerra Stage 2 build-up, where no phytoherm barrage has been preserved). This buttruss would be recorded in the case of Rambla Becerra build-up in Logs 1 to 6.2. The downstream deposits of the Caerwys tufa involves palustrine sediments and larger oncoids (that may be stromatolitic domes), coinciding with the observations made in Rambla Becerra build-up in log 7.

5.2.3. Stage 2, outcrop 3

The last outcrop of Stage 2 tufa deposits is Outcrop 3 (Fig. 2), 100 m further to the SE from the previous log (Fig. 2), showing mainly palustrine-lacustrine facies (Mm, Mg).

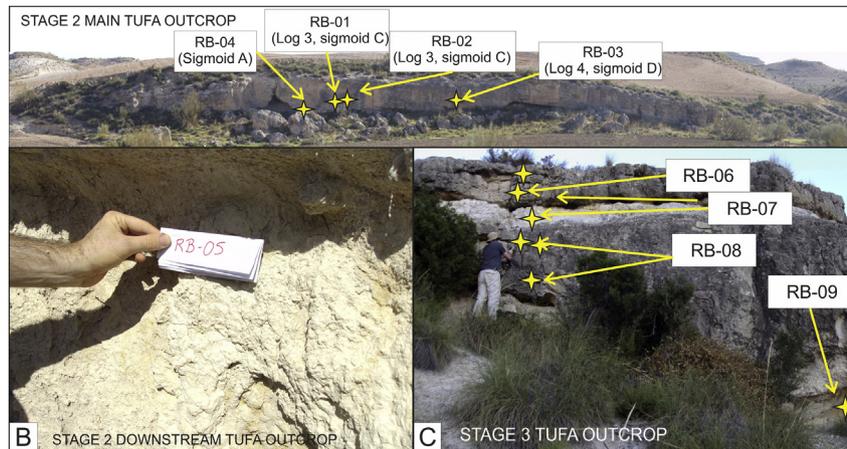


Fig. 12. Samples for thin sections and stable isotope analyses have been taken as indicated in the photographs. A and B. Photographs showing the sampling locations for Stage 2 tufas. C. Photograph showing the sampling locations for Stage 3 tufas.

The distance between logs 7 and Outcrop 3 prevented a detailed correlation of both locations, making it impossible to identify if the surfaces in Outcrop 3 correspond to any of the boundary surfaces identified between sigmoids in Log 7.

Based on field observations, Outcrop 3 is interpreted as a pond or lake formed downstream from the tufa barrage facies, at the distal part of the barrage system (Fig. 5C), and it seems to be contemporaneous with the development of AS facies in nearby areas to the South.

5.2.4. Interpretation of stage 2 tufa deposits

Once the interpretation for Outcrop 2 is provided, it is necessary to integrate the information from the three outcrops in Stage 2 in order to get a complete picture of the Rambla Becerra Tufa System as a whole.

As it has been mentioned above, the sigmoidal beds in Outcrop 2 dip downstream towards the S–SE. Therefore, this would mean that Outcrop 1 (Fig. 2), located to the W–NW of the main tufa build-up in Outcrop 2 is upstream of the system, Outcrop 2 would be in the intermediate position, and Outcrop 3 would be downstream, the distal part of the barrage tufa system.

Outcrop 1 (Figs. 2 and 5A.) has been interpreted as an upstream outcrop that would correspond to a low energy palustrine area. The erosion in the present valley does not allow a direct correlation between outcrops 1 and 2. However, the interpretation of Outcrop 2 as a ramp-like buttress resulting from the destruction of a previous barrage allows to infer that a phytoherm should have developed somewhere upstream from Outcrop 2. We can therefore infer that the main barrage (phytoherm) in the RBTS was eroded, as it should be located where the main valley currently develops and the maximum erosion has taken place.

As a result, the water dammed in Outcrop 1 upstream was retained by a phytoherm that has not been preserved, but which iterative destruction caused the formation of the prograding sigmoids in Outcrop 2. The vertical coarsening-upward sequences identified in the middle section would be recording the progressive movement or progradation of the system towards the palustrine-lacustrine area that would be connected to the flood-plain facies of the Axial System further south.

The consistent facies changes identified within the sigmoids into finer sediments downstream in Outcrop 2 is interpreted as the lateral transition of the ramp-like buttress to a ponded area

downstream (palustrine-lacustrine), and in this sense Outcrop 3, situated downstream, would be the large pond/lake where the barrage tufa system ends.

Using the classification proposed by Arenas-Abad et al. (2010) for fluvial tufas, the Stage 2 of the Rambla Becerra Tufa System would correspond to the stepped conditions with waterfall, cascade, barrage and dammed zone described as one of the possible models for tufa deposition in fluvial environments, similar to the tufa systems described by Vázquez-Urbez et al. (2012) for the Quaternary Piedra and Mesa valleys.

Another example with similar characteristics is provided by Gradzinski et al. (2013) when describing the Holocene tufa barrages in the Háj Valley (Slovakia). They correspond to a longitudinal fluvial system, with several barrages forming along the entrenched valley. The scale of the outcrops is quite similar to those in Rambla Becerra Stage 2. A visit to this outcrop by one of the authors of the present article the past summer provided very useful information to support the interpretation of the Rambla Becerra build-up. In the Háj Valley, the facies are assigned to either barrage or interbarrage facies associations. Gradzinski et al. (2013) consider the barrage facies association formed mainly by in situ precipitated facies, and the interbarrage facies association formed by detrital tufa. The barrage facies association tend to be slightly topographically higher than the interbarrage ones, creating a positive relief of several meters, and the lateral extension of the interbarrage facies association from the end of the barrage can be higher than 50 m. If we applied this terminology to the Rambla Becerra example, the outcrop would be mainly formed by interbarrage facies association, dominated by detrital tufas, extending up to 100 m from the barrage tufa association, that would have been completely eroded by the later progradation of the External Transverse System alluvial fans.

In the Háj Valley tufas, clasts from the upper slopes are sometimes incorporated in the tufa sediments, related to rockfalls. In Rambla Becerra, there are no extraclasts incorporated to the tufa facies. This is important, because the tufa barrage system in Stage 2 develops in lateral connection to the External Transverse System alluvial fans towards the NW, and in lateral connection with the fluvial Axial System towards the SE. Although the Rambla Becerra Tufa System most likely developed on the slope of the ETS fans (after field observations), if these alluvial fans were active during the deposition of the tufas, there would be traces of this activity in the form of Mesozoic marine clasts incorporated into

the tufa system from upper slopes. The lack of extraclasts points to the inactivity (or very low activity) of the alluvial fans during the tufa growth, while the important progradations of the alluvial fans are eroding the top of the tufa growths. As a result, we can assume that the intervals of tufa development alternated with moments of progradation of the fans, and that there was some allocyclic factor (climate, tectonism and/or base level) driving this alternation.

5.3. Stages 3 and 4 of tufa deposits

The tufas formed during Stage 3 and Stage 4 (Table 1, Figs. 3 and 6) have been previously defined by other authors as lacustrine sediments (Arribas et al., 1988; García-Aguilar et al., 2014) belonging to the Axial System. They are formed by several carbonate tabular beds of hundreds of meters of lateral extension (Fig. 2).

In this sense, they are really different from the previous stages both in geometry and in lateral extension. Due to the intensive erosion, first by the progradation of the External Transverse System fans and then by the modern drainage network, it is not possible to know if the earlier tufa systems developed during stages 1 and 2 were as extensive as the carbonates deposited during stages 3 and 4, although in Stage 2 the size of the prograding bodies in the tufa system gives an indication of the size of the whole barrage system, and it does not seem as extensive as the tufa deposits in Stages 3 and 4.

A preliminary study of the sediments formed during Stage 3 shows that they correspond to palustrine-lacustrine sediments (Fig. 6) of the Axial System (quite similar to those described for the central sector of the basin by Pla-Pueyo et al., 2009b), with gastropod and ostracod shells and even charophytes (this is the first time that charophytes have been identified by the authors in the central-northern sector of the Guadix Basin palustrine-lacustrine carbonates). The main textures of these carbonates are mudstones and wackestones, but the uppermost level shows a

brecciated texture including leaf moulds and broken coated stems.

There are no further detail studies yet about the carbonates in Stage 4, but from field observations, they present similar features than Stage 3 carbonates.

Whether it is suitable to talk about tufas in Stages 3 and 4 is relative, as these deposits are interpreted as lacustrine/palustrine, although they do present carbonate-coated plant remains that are typically considered tufa facies. Both terms would be applicable in this case, so just for the sake of coherence in the article, they will be named tufas.

6. Geochemical analysis

The stable isotopic record of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in tufas and travertines is an important indicator of palaeoenvironmental conditions (Andrews et al., 2000; Pedley, 2009), as it happens in general with most continental carbonates (Leng and Marshall, 2004; Candy et al., 2012).

Therefore, a preliminary sampling for geochemical analyses was performed in the Rambla Becerra Tufa System, including carbonate samples from Stages 2 and 3, but also from other tufas/travertines outcropping in other locations, in order to provide values to compare and contrast.

6.1. Sample description

A total of 26 samples of tufas and travertines were collected (Table 3, Fig. 12). Seven of them (samples labelled FR-) belonged to the Pleistocene Frailes Tufa System in the Alcalá Basin, S. Spain (data published by García-García et al., 2014), which has been interpreted as a barrage tufa system, fed mainly by surface meteoric water. Details on these samples are given in the abovementioned publication. The rest belong to carbonates from the Guadix Basin.

Table 3

Summary table showing the nature and isotopic composition of the sampled tufas/travertines by the authors.

Facies		System	Sample	d13C (‰)	d18O (‰)		
Lst	Phytohermic limestones of stems (palisades and bushes of stems)	Rambla Becerra Tufa System	RB-03	-3,05	-8,28		
		Rambla Becerra Tufa System	RB-02	-2,11	-7,11		
		Vereda de las Yeguas palustrine tufa	BP-02I	-8,34	-6,88		
		Baños de Alicún travertines	BA-03	-0,82	-10,94		
Ls	Stromatolitic limestone	Frailes Tufa System	FR-02	-7,59	-6,50		
		Frailes Tufa System	FR-06	-6,35	-5,69		
		Rambla Becerra Tufa System	RB-01	-2,64	-7,94		
		Baños de Alicún travertines	BA-01	-0,09	-9,79		
		Baños de Alicún travertines	BA-02	0,60	-8,41		
		Frailes Tufa System	FR-03	-7,00	-6,37		
Lph	Phytoclastic limestone	Frailes Tufa System	FR-04B	-6,90	-6,44		
		Vereda de las Yeguas palustrine tufa	L-1 19	-8,28	-6,32		
		Vereda de las Yeguas palustrine tufa	L-1 20	-8,30	-6,49		
		Rambla Becerra Tufa System	RB-06L	-3,30	-8,49		
		Rambla Becerra Tufa System	RB-06U	-3,30	-8,19		
		Rambla Becerra Tufa System	RB-07L	-3,26	-7,79		
		Rambla Becerra Tufa System	RB-07U	-3,75	-8,40		
		Rambla Becerra Tufa System	RB-08L	-4,84	-7,71		
		Rambla Becerra Tufa System	RB-08U	-4,25	-7,46		
		Baños de Alicún travertines	BA-04	0,21	-7,59		
		Huélago postcapture tufa	HT-01	-6,41	-9,13		
		Lg/Ln	Palustrine limestone with gley features	Frailes Tufa System	FR-01	-7,09	-6,70
				Frailes Tufa System	FR-04A	-7,07	-6,45
Rambla Becerra Tufa System	RB-04			-3,29	-7,89		
Rambla Becerra Tufa System	RB-09			-5,85	-7,76		
Ll	Calcrete	Frailes Tufa System	FR-05	-7,05	-6,66		

Eleven samples were taken from the Rambla Becerra Tufa System (Pliocene) (Fig. 12). Samples RB-1 to RB-4 were taken from the main tufa build-up of Stage 2. RB-01 sample corresponds to stromatolitic facies (Ls, see Table 2) formed in a small cascade recorded in Log 3 (Figs. 7–9). RB-02 sample was taken from phytohermic facies (vertical coated stems in life position) also in Log 3, while sample RB-03 belongs to oncoidal/phytoclastic facies in Log 4. Sample RB-04 was collected from the white palustrine facies in sigmoid A, below the surface that has been considered the base surface for the tufa build-up.

Samples RB-06 to RB-09, mainly palustrine in nature, belong to carbonates formed during Stage 3 (Fig. 6).

Four samples (labelled BA-) were taken from the Alicún area (Baños de Alicún spa, Guadix Basin, S. Spain), mentioned earlier in the text. This area is only 1 km far from Rambla Becerra system, and it is linked to a large fault affecting a tectonic height in the basement, where Mesozoic carbonates outcrop. Geothermally-heated groundwater reaches the surface through hot springs, so the area is currently a spa resort. The carbonate deposits in the area have always been referred as travertines in the literature (Martín-Martín et al., 2002; Martín-Algarra et al., 2003; Díaz-Hernández and Julià, 2006; Prado-Pérez, 2011). They will be regarded as travertines also in this article, as the predominance of laminated facies and the scarce presence of coated stem and leaf facies, together with the warm temperature of the water from which the carbonates precipitate, matches with the definition of travertine given by Ford and Pedley (1996). Moreover, the stable isotope analyses performed in these carbonates by Prado-Pérez (2011) gives a range of values (Fig. 13) that coincides with other travertine examples in the literature (Pentecost, 2005; Capezzuoli et al., 2014). There are three main units of deposition in the Alicún area. The oldest carbonate accumulation in the Alicún area (Superior Unit after Prado-Pérez, 2011) is Pleistocene in age, and there has been intermittent travertine precipitation in the area (Medium and Inferior Units after Prado-Pérez, 2011) until present. This author has interpreted that some periods had no precipitation of travertine, but his interpretation does not link the travertine precipitation only with warm periods, but also with colder ones. As there is an extensive geochemical data set produced and interpreted by Prado-Pérez (2011), only four samples were taken from the area. Samples BA-01 and BA-02 (Table 3),

both interpreted as cascade flowing facies (stromatolites) were taken at the base of the topographically higher travertine platform (Superior Unit), while BA-04 (phytoclast and flowstone/bindstone facies) was taken at the base of the lowest platform (Inferior Unit). Sample BA-03 (Table 3) was taken from a pond where travertine is currently precipitating, and it comes from a coated stem.

Another three samples (Table 3) were taken from a Pliocene palustrine tufa build-up (Vereda de las Yeguas tufa) that outcrops in the central sector of the Guadix Basin (Pla-Pueyo et al., 2009a, 2013). Sample BP-02I was taken from the concentric coating of a large stem in living position, while samples L1-19 and L1-20 came from two phytoclastic beds (data published in Pla-Pueyo et al., 2012).

The last sample of the set was taken in the Huélago area, in the SW sector of the Guadix Basin, from a phytoclast in a small Pleistocene tufa outcrop that formed after the fluvial capture took place.

6.2. Geochemical results and interpretation

The isotopic data derived from all of the tufas analysed in this study are shown in Table 2 and plotted as $\delta^{18}\text{O}$ against $\delta^{13}\text{C}$ scatter plots in Fig. 13. Whilst it is usual to calculate correlation statistics (i.e. r^2) from such data this is not done in this study because the size of the datasets from each site is too small for statistically meaningful values to be generated. It is important to stress that the data presented here is a preliminary study with the aim of producing a very general characterisation of the oxygen and carbon isotopic values of a range of tufa fabrics from the different study sites.

The scatter plot presented in Fig. 13 indicates that, on the basis of isotopic values, the tufas/travertines analysed in this study can be divided into three main groups; 1) tufa that has $\delta^{18}\text{O}$ values $> -7\text{‰}$ and $\delta^{13}\text{C}$ values $< -6\text{‰}$ (the Frailes, Vereda de las Yeguas and Huélago tufa), 2) tufa that has $\delta^{18}\text{O}$ values between -7‰ and -9‰ and $\delta^{13}\text{C}$ values between -2‰ and -6‰ (Rambla Becerra Tufa System) and 3) tufa/travertine that has a wide range of $\delta^{18}\text{O}$ values and $\delta^{13}\text{C}$ values that are ca 0‰ (the Alicún travertine). The first of these groups have oxygen and carbon values that are very typical of palustrine and riverine tufas from across Europe (Andrews et al., 1997; Andrews, 2006; Alonso-Zara and Wright, 2010; Arenas-Abad et al., 2010; Alonso-Zara et al., 2012). The carbon values indicate carbonate precipitation in association with waters that have low $\delta^{13}\text{C}$ values as a result of the input of soil respired carbon during groundwater recharge (Andrews, 2006). The $\delta^{18}\text{O}$ values are consistent with carbonates precipitating from meteoric waters in the temperate mid-latitudes (Andrews, 2006). As a consequence these tufas have isotopic values that are typical of carbonate precipitation in water bodies fed by streams and springs that allow for constant recharge and negligible isotopic modification of the source water.

The isotopic values of the Alicún tufa samples contrast strongly with those of Frailes/Vereda de las Yeguas in that their $\delta^{13}\text{C}$ values are more positive and their $\delta^{18}\text{O}$ values are more negative. These values are in agreement with the results from Prado-Pérez (2011), who analysed 766 samples for the Alicún area travertines and discussed the obtained values in the context of the travertine system and its palaeoenvironmental evolution. The $\delta^{18}\text{O}$ values obtained by this author for the fossil travertines are between -11.64 and -3.95‰ , while the $\delta^{13}\text{C}$ values range between -2.72 and 1.97‰ (V-PDB) (the values are represented by a circle in Fig. 13). These are all typical values for travertines as gathered by Capezzuoli et al. (2014) from Pentecost (2005), Gandin and Capezzuoli (2008) and references therein, providing a range of values for $\delta^{13}\text{C}$ from -1 to $+10$ in the case of the travertines, while for the tufas, they consider that the values are always negative. The high $\delta^{13}\text{C}$ values

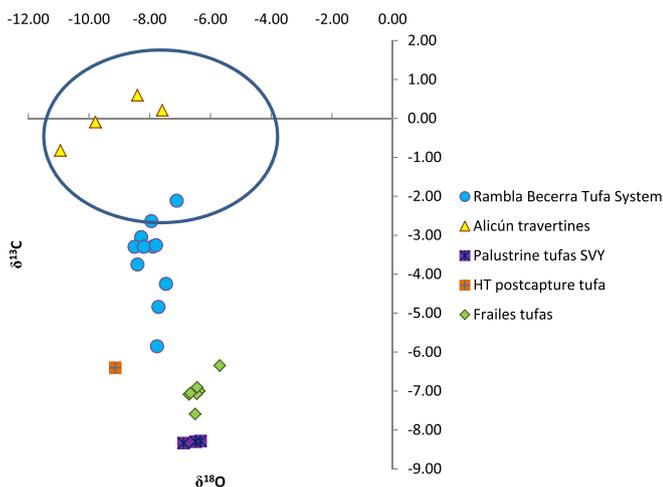


Fig. 13. Stable isotope values for tufa and travertine samples in several outcrops in the Guadix and the Alcalá basins. All values represented as dots are original data obtained by the authors and analysed in collaboration with the Royal Holloway of London labs. The circle represents the range of values obtained by Prado-Pérez (2011) for the travertine samples from Baños de Alicún outcrop.

could be explained by a number of factors; 1) low vegetation cover, 2) a dominance of C4 plants in the vegetation cover, 3) high levels of CO₂ degassing prior to carbonate precipitation and 4) the contribution of deep, potentially, thermal waters. The first two controls are here discounted because, in southern Spain during the Quaternary, there is no evidence, in lowland regions, that vegetation cover was either low enough or contained such a large component of C4 plants that $\delta^{13}\text{C}$ values of around 0‰ would be generated (Pons and Reille, 1988; Cerling and Quade, 1993). Whilst CO₂ degassing can generate high $\delta^{13}\text{C}$ values, the extent of enrichment that is seen in the Alicún tufa samples, relative to those from Frailes, would require a closed hydrological system that was undergoing significant evaporation and contraction (Leng and Marshall, 2004; Andrews, 2006). Such a situation would result in a strong enrichment in the $\delta^{18}\text{O}$ values, which is not seen within the Alicún dataset. Consequently it is considered most likely that the Alicún tufa is thermogenic, precipitating from groundwaters that have a long residence time and, therefore, significant interaction with the underlying strata (Mesozoic).

The isotopic data from the Rambla Becerra system lies in an intermediate position between the Alicún and the Frailes/Vereda de las Yeguas datasets.

The limited amount of data collected for the present study does not allow to infer any rigorous information on the link between depositional system/provenance of water and isotopic signal in the presented examples, but it has been proved by other authors that the composition and temperature of the water in which the precipitation of the carbonate occurs will affect the isotopic signal of the resulting travertines or tufas (Andrews et al., 1997; Guo and Riding, 1998, 1999; Pentecost, 2005; Andrews, 2006; Gandin and Capezzuoli, 2008; Arenas-Abad et al., 2010; Jones and Renaut, 2010; Capezzuoli et al., 2014). The simplest explanation of these isotopic values is, therefore, to propose that the Rambla Becerra tufas precipitate from waters that represent a mixture of meteoric waters (i.e. those from which the Frailes/Vereda de las Yeguas tufas precipitate) and deep thermal waters (i.e. those from which the Alicún tufas precipitate).

Such a suggestion is difficult to prove without more detailed isotopic and geochemical analysis, however, it is consistent with the existing dataset.

7. Discussion

7.1. Paleoenvironmental interpretation and evolution of the Rambla Becerra Tufa System

The results presented in this article indicate that the main tufa and travertine deposits in the Guadix Basin (Rambla Becerra Tufa System, Baños de Alicún travertines and Vereda de las Yeguas palustrine tufa) seem to be geographically close to the External Zones of the Betic Cordillera and/or connected to the deposits of the External System alluvial fans. It has been previously mentioned that the External Zones basement in these areas is formed mainly by Mesozoic marine carbonate rocks. Therefore, it seems that the proximity of the Mesozoic carbonate reliefs and the associated Plio-Quaternary alluvial fans is crucial for the saturation in calcium of the water (both groundwater and surface run off) for the formation of tufas and travertines in the Guadix Basin.

Focusing on the Rambla Becerra Tufa System, the formation and evolution of the four tufa growth stages may be explained as follows.

During the first, oldest phase of the system (Fig. 14A), a number of phytoherms (bushes growing in flooded areas, and their stems coated by carbonate while still in life position) would form in the valley, probably in the area where the change of slope of the alluvial

fan allowed for the ponding of water. Due to the fact that the sediments are mostly covered, it is not possible to know whether these phytoherms would be just palisades of bushes growing in a pond, in several connected or disconnected ponds, or whether they would even be forming barrages to the flow that could develop into a barrage system similar to the one interpreted for Stage 2. Right after Stage 1 tufa growth, a progradation of the alluvial fan of the External Transverse System eroded the topmost part of the tufa deposits.

Later in time, on top of the new deposited alluvial fan sediments, a barrage tufa system developed, represented by Stage 2 tufa deposits (Fig. 14B.). This tufa system evolved during a certain period of time and then, another progradation of the External Transverse System alluvial fans, this time more energetic than the previous one (deduced from the coarser clasts found in the channel eroding the topmost part of the main outcrop) and reaching further into the main valley eroded the topmost sediments of Stage 2 tufas and deposited several meters of sediment.

After the progradation that eroded Stage 2 tufas, a new phase begins, with the formation of Stage 3 tufas (Fig. 14C.), again progradation of alluvial fans, and then formation of Stage 4 (Fig. 14D.).

During this new phase, there seems to be a change in the basin because the Internal Transverse System fans are the ones intercalated now between the tufaceous deposits of Stages 3 and 4. This change could be tectonic, climatic or related to the base level. The External Zones of the Betic Cordillera are tectonically passive, while the Internal Zones are suffering uplift since the formation of the mountain range (Soria et al., 1998, 1999). This tectonic configuration has an impact on the morphology and extension of the alluvial fans in the Guadix Basin (Fernández et al., 1991, 1993; Viseras, 1991; Viseras and Fernández, 1992, 1994, 1995; Pla-Pueyo, 2009). A reactivation of the uplift of the Internal Zones of the Betic Cordillera during this second phase would increase the sedimentation in the ITS alluvial fans, triggering a further progradation of the fans towards the West, while the ETS fans would remain unaffected. This would restrict the Axial System to a narrower extension, and may even provoke the blocking of the drainage when the ITS fans prograded and met the ETS fans, creating the conditions for lacustrine deposition (Stages 3 and 4).

In a recent publication (Pla-Pueyo et al., 2015a), the alternation between Axial System fluvial sediments and Internal Transverse System alluvial fan progradations in the central sector of the Guadix Basin has been interpreted as a climatic cyclicity. The intervals in which the axial valley was dominated by the Axial System fluvial sediments have been interpreted as more humid (and potentially warm, as the main palaeontological sites in the area are found in these intervals (Viseras et al., 2006; Arribas et al., 2009; Pla-Pueyo et al., 2011)). The intervals dominated by the progradations of the ITS alluvial fans have been interpreted as more arid, and potentially cooler (Pla-Pueyo et al., 2015a).

Taking into account that the tufa stages are either connected laterally to the Axial System, and therefore coetaneous (Stages 1 and 2) or directly belong to the Axial System (Stages 3 and 4), we can infer that the development of the tufas coincided with the more humid periods represented by the Axial System. The best conditions for tufa to develop are typically warmer temperatures, as it has been shown in multiple examples in the literature, related to interglacial periods (e.g. Dabowski, 2012; Pazzaglia et al., 2013; Arenas et al., 2013b). Therefore, the formation of tufas at the same time that the Axial System dominates the main valley would support the hypothesis of these more humid intervals being also warmer than those of the progradation of the fans.

The progradation of the fans in the study area can then be linked to more arid periods, as it happens in the central sector of the basin (Pla-Pueyo et al., 2015a), with the tectonic activity of the Internal

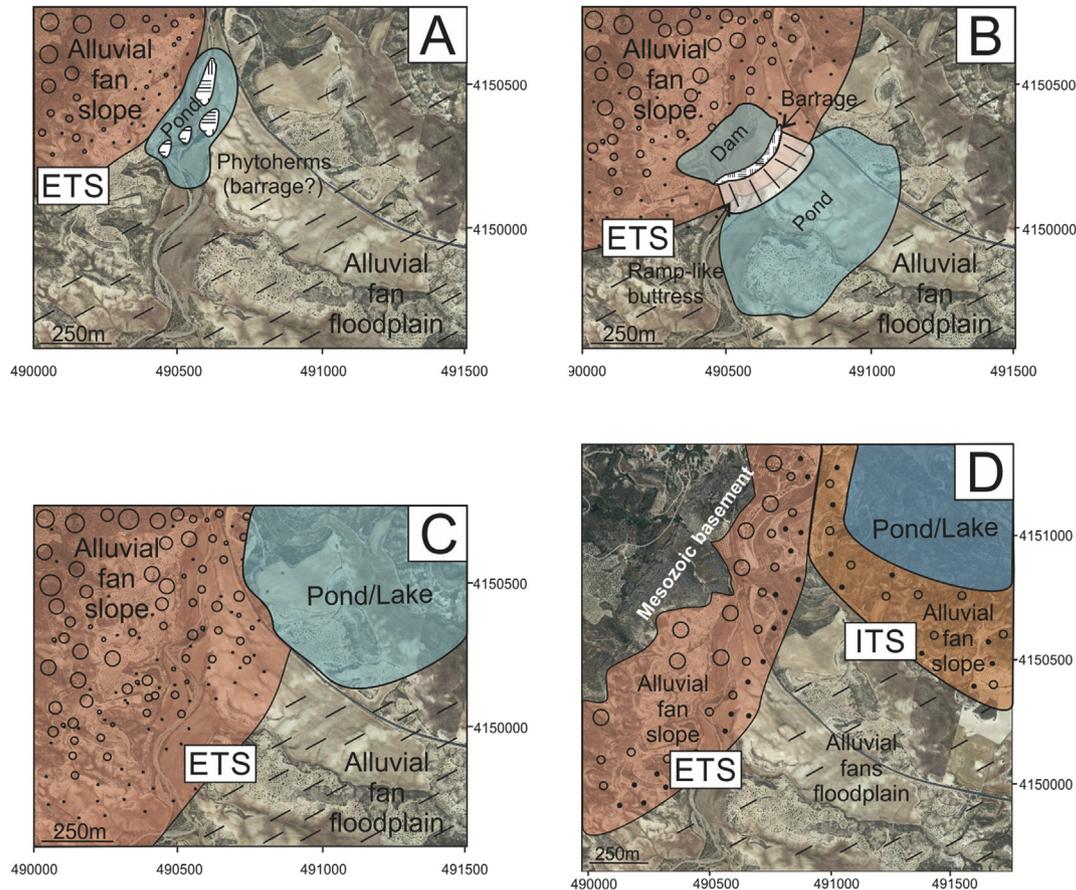


Fig. 14. Evolution of the Rambla Becerra Tufa System through time. It is important to note that most of the sediments younger than the top of Stage 2 have been eroded, so the lateral extension of the flooded areas represented in the figure is purely speculative, based on the presence of outcrops, but could be much larger than presented in the figure. A. Development of phytoherms corresponding to Stage 1 of tufa formation on the alluvial fan sediments of the External Transverse System. B. After a progradation of the External Transverse System sediments, a fluvial barrage tufa develops, corresponding to Stage 2 of tufa formation. C. After another progradation of the ETS alluvial fan sediments onto the valley, an extensive flooded area develops, and deposition of Stage 3 tufas takes place. D. After a new alluvial fan progradation, this time from the Internal Transverse System, Stage 4 tufas are formed in a flooded area. Please note that the area represented in this last image is larger than the one represented in A-C.

Zones of the Betic Cordillera potentially determining which of the transverse alluvial fan systems dominated the sedimentation in the northern part of the basin, where the Rambla Becerra Tufa System is. This explanation is supported by the tops of the tufa outcrops being eroded by alluvial fan sediments, indicating drops in the base level, one of them being recorded in an Axial System channel correlated further south (Viseras, 1991). More arid conditions are associated with less water in the drainage systems during most of the time, so entrenchment of the fluvial network and erosion of previous sediments are expected results during more arid periods.

7.2. Stage 2 tufas as outcrop analogs for reservoirs

As it has been mentioned before, the most interesting outcrop from the point of view of characterising a tufa barrage reservoir is the main tufa build-up (Outcrop 2) from Stage 2.

Engel et al. (2007) propose that the four factors that make an outcrop a good candidate to be used as an analog for a reservoir are the following: suitability to the problem, level of three dimensionality, outcrop quality, and accessibility. From this point of view, there is still a need for analogs for the continental carbonate reservoirs currently being exploited in Brazil and Angola, and Outcrop 2 is an ideal candidate. It is easy to access, and although parts of the fluvial barrage tufa system are missing, the facies preserved in Outcrop 2 would probably be the best ones

from the reservoir quality point of view, as they are carbonates that would behave more like clastic sediments than carbonates from the petrophysical point of view. Moreover, the tridimensional quality of the exposure allows the clear identification of geometries and facies changes and facies distribution in all directions (Pla-Pueyo et al., 2015b, 2016).

Starting with the information that we already have, some interesting points can be made regarding the characterisation of this outcrop as a reservoir analog from a geometrical point of view.

In this article a detailed sedimentological study has been carried out, and a preliminary geochemical study has been used to aid in the interpretation of the palaeoenvironmental conditions that determined the facies distribution and morphology of this tufa body (Figs. 5, 7–9, 15).

Other authors, such as Pimentel et al. (1996) or Evans (1999), have stressed the importance of an existing regional groundwater flow system when characterising the tufas and travertines in a certain area. In Rambla Becerra Tufa System, the sedimentology, petrology and geochemistry were studied, and after the preliminary geochemical results, that may indicate that the water feeding the tufa system probably had not only a meteoric source, but also a groundwater one, a model is proposed for the formation and evolution of the barrage tufa during Stage 2 (Fig. 15).

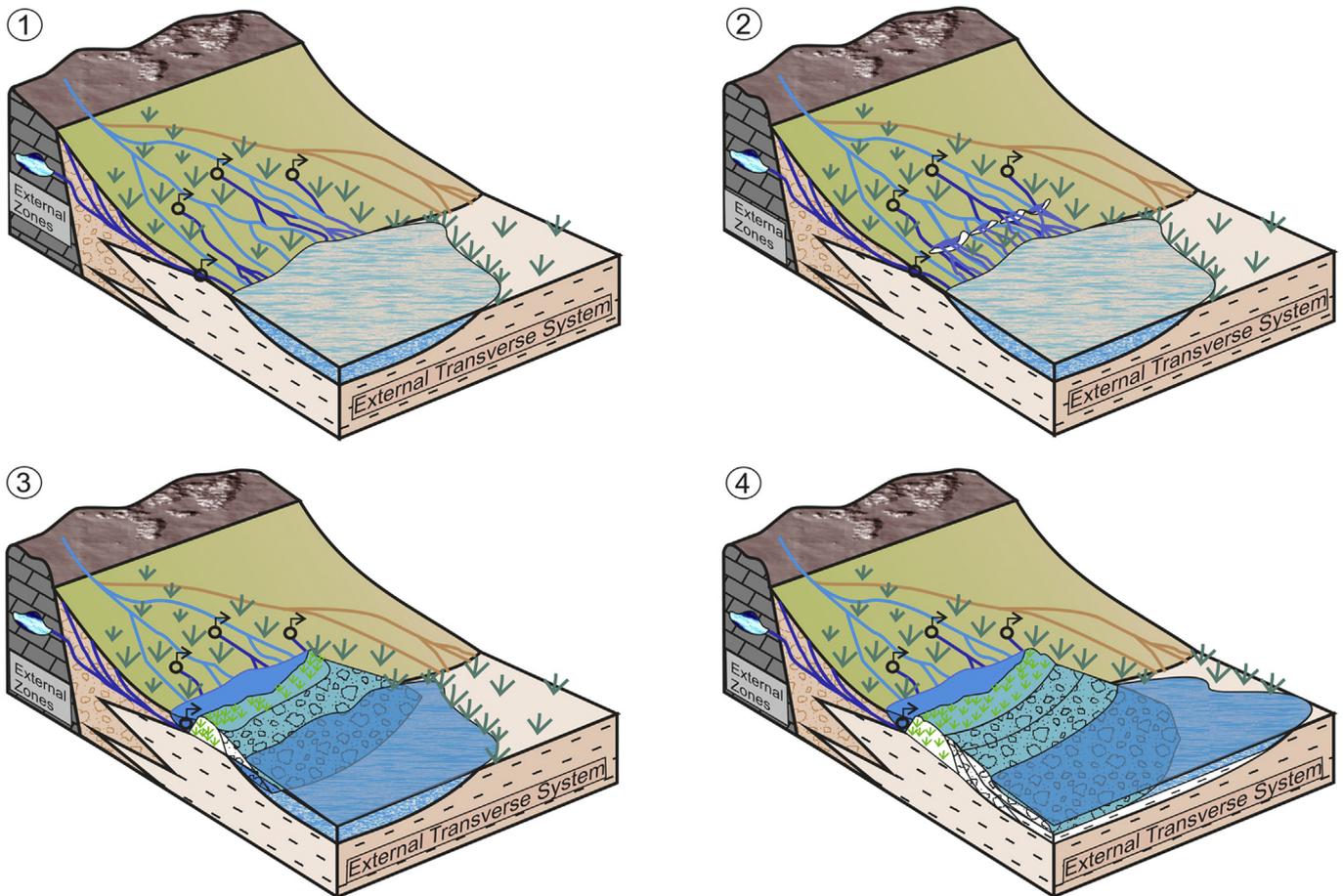


Fig. 15. Model proposed for the formation and evolution of the Stage 2 tufas in Rambla Becerra Tufa System. Number 1 corresponds to the initial stage in which groundwater springs and surface water, both saturated in calcium, start precipitating carbonate in the slope of an External System alluvial fan, around patches of vegetation that are already forming small dams. In number 2, the carbonate coated patches of vegetation begin to expand laterally, forming larger barriers to the flow and creating phytoherm barrages and a dammed area upstream. In number 3, the fluctuations in the water supply, together with normal gravity processes, produce the breakage of the top of the barrage from time to time, creating a series of sigmoids of tufa debris downstream from the barrage, entering a standing water body formed in a depressed/flat area downstream. The result will be a prograding set of bodies, represented in number 4.

In Fig. 15, step 1 shows the first step of formation of the barrage tufa on the slope of an alluvial fan from the External Transverse System. The water comes from two different sources: a meteoric one, coinciding with the surface runoff and a groundwater one. The groundwater could be related to the nearby aquifers that still exist in the Mesozoic carbonates that form the External Zones of the Betic Cordillera in the area. However, it has been described in the Paleogene alluvial fans from S. Portugal how shallow groundwater may circulate through the alluvial fans themselves, even precipitating carbonates that are not pedogenic nor groundwater calcretes, but something in between (Pimentel et al., 1996). Therefore, we may be looking at a situation in which the breaking point of the slope of the fans is the location where this shallow groundwater comes up to the surface, and mixes with the surface runoff, creating the ideal conditions for the tufas to precipitate. At this point, the saturation in calcium of the water would facilitate the precipitation of carbonate coatings around the local patches of vegetation growing in the soft slope of the alluvial fan, locally forming small puddles behind these early phytoherms.

In the next step (Fig. 15, step 2), the isolated phytoherms start connecting with each other, forming a longer, wider barrage, where more carbonate is precipitated, and creating a dammed area upstream. Step 3 (Fig. 15) represents the tufa barrage system fully

developed. The phytoherm barrage is quite extensive now, and the occasional destruction of these barrage accumulates tufa debris downstream. The iterative destruction of the barrage in time will create the sigmoids that will aggrade/prograde downstream (Fig. 15, Step 4), while entering a standing body of water where palustrine sediments are forming.

From the point of view of reservoir analogs, this interpretation is useful because it shows how the degree of development of the barrage tufa system will affect not only the type of facies being deposited in the system, but the thickness, geometry, lateral extension and connectivity of the deposits.

If the barrage tufa was just starting to develop, in a situation similar to Step 1, the only potential reservoir facies would be the phytoherm ones, and they would present a random and patchy distribution, and would be disconnected among them.

In a fully developed barrage tufa system, such as the one presented in Step 3 (Fig. 15), the main barrage would be extensive and thick, and apart from the phytoherm facies, the second best reservoir facies would be the detrital facies deposited in the ramp-like buttresses (the ones preserved in the main tufa build-up in Stage 2). Although a detailed analyses of the diagenesis is needed to assess the impact on the effective porosity, these facies would be expected to behave like siliciclastic sediments, with

sorting, grain size and other grain features affecting the primary porosity.

The amount of time that the barrage tufa system is prograding and generating new sigmoids will also affect the final geometry of the reservoir. The total thickness and the lateral extension of the sigmoidal deposits will be controlled by the base level and the water depth of the downstream lacustrine area, and the longer the system is working, the higher the amount of detrital facies accumulated.

A final issue related to the permeability is the connectivity within the facies in a sigmoid and among different sigmoids. Within each sigmoid it is expected that the downstream end, where the sediment becomes fine-grained and palustrine, would be a barrier or even a seal to the flow. Therefore, each sigmoid would have a relatively good horizontal permeability, but would be sealed downstream at some point (pinch out). Regarding the vertical permeability, a more detailed study needs to be carried out to assess whether the erosive surfaces between different sigmoids, would allow the flow to migrate vertically, or whether they would be a problem, as sometimes, but not consistently, they are coated by a thin bed of marls, that would decrease vertical permeability.

In summary, barrage tufa systems may be useful continental carbonate reservoirs analogs, and this article presents a very interesting example of it, although further studies on its geometrical and petrophysical characterisation (porosity and permeability) are needed.

8. Conclusions

The following conclusions derive from the study presented and discussed in this article:

- 1) The importance of the provenance of the calcium that saturates the water and allows for the formation of tufas and travertines is evident in the Guadix Basin, with a clear link established between the tufa and travertine formation in the basin and the proximity to the External Zones of the Betic Cordillera (dominated by Mesozoic carbonates).
- 2) Four stages of tufa growth have been identified in the northern sector of the Guadix Basin as part of the so-called “Rambla Becerra Tufa System”, in what have been interpreted as Pliocene-Pleistocene sediments by correlation to other sectors of the basin.
- 3) By correlation with the Axial System facies, a high sinuosity fluvial system that occupied the central sector of the basin, a more humid (and potentially warmer) climate has been attributed to the stages of tufa growth in the northern sector of the basin.
- 4) Progradations of the External Transverse System and the Internal Transverse System alluvial fans separate the four tufa deposit stages, eroding the top of the underlying tufa outcrops. The erosion points to falls of base level, also observed in facies of the Axial System, and by comparison to what happens in the central sector of the basin, it has been interpreted that the progradation of the alluvial fans probably occurred during moments of higher aridity (and potentially colder).
- 5) The tufas forming during Stage 2 have been studied in detail and a model of deposition is proposed for them, suggesting a mix of waters (meteoric and hydrothermal) contributing to the formation and progradation downstream (towards the S–SE) of a large barrage tufa system developed in the northern sector of the Guadix Basin.
- 6) A specific outcrop from Stage 2, showing a mound-shaped set of sigmoidal beds formed mostly by detrital carbonate facies, and

interpreted as the ramp-like buttress originated by the destruction of a tufa barrage, is proposed as an ideal case study to characterise fluvial barrage tufas as outcrop analogs for hydrocarbon reservoirs.

- 7) The results obtained in the present article are encouraging to continue the research on southern Spain tufas and travertines as potential analogs for continental carbonate reservoirs, with further studies needed, focusing on their petrophysical characterisation.

Acknowledgements

We would like to thank the two anonymous reviewers that have kindly revised this manuscript, for their time and their useful comments. This study has been financed by research projects CGL2005-06224/BTE, CLG2009-05768-E/BTE, CGL2013-43013-R (MINECO- FEDER), AHOB-3, IGME 2001-016, IGME 2005-009, SEDREGROUP and the Working Group RNM-369JA.

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