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Current tufa sedimentation in a high discharge river: A comparison with other synchronous tufa records in the Iberian Range (Spain)

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The results from sedimentological, isotopic and hydrochemical analyses of current tufa sedimentation conducted in a high-discharge river (Ebrón River, northeastern Spain; 1.49 m^3/s) through six-month monitoring over 3.5 years are discussed in terms of the factors that control local carbonate deposition through space and time, and compared with results from other synchronous tufa records in the same climatic domain. The findings allow for discerning the influence of the riverbed slope, hydrochemistry, discharge and groundwater inputs on tufa attributes and assess the significance of tufa as archives of certain climatic events on a regional scale.

In the Ebrón River, the dominant upstream karstic springs from a Jurassic-rock aquifer determined the river's HCO_3–Ca composition. Two river stretches were differentiated according to localised increments in both pCO_2, resulting from additional groundwater inputs, and SO_4 content, influenced by evaporite-bearing units. The variations in tufa's thickness through space were strongly controlled by CO_2-rich springs and local slope variations. The monitored sites represent four primary subenvironments with distinct sedimentary facies, whose attributes suggest that 1) the tufa deposition rates in each fluvial subenvironment are mainly controlled by the CO_2-outgassing intensity linked to local flow conditions and the biological substrate type, and 2) stromatolites represent the thickest and most complete record. The six-month variations in tufa thickness and calculated calcite mass in the Ebrón River were controlled by temperature-dependent physico-chemical and biological parameters, coupled with high-discharge events that provoked tufa erosion.

The smaller deposition of the Ebrón River compared to two other synchronous tufa records in the Iberian Range is linked to 1) the absence of long areas of increased slope, 2) the occurrence of significant CO_2-rich groundwater springs in the middle reach, and 3) the higher discharge and water depth. Certain high-discharge events were recorded as lower deposition rates concurrent in the three rivers. Moreover, anomalous water temperatures calculated from the calcite $\delta^{18}O$ in the three rivers for a coincident time span support a regional anomaly in the precipitation $\delta^{18}O$. Thus, the evolution of the short-term tufa deposition rates and calcite $\delta^{18}O$ composition through time can detect regional climate and hydrology changes and therefore can be robust criteria for correlation in the geological record.

1. Introduction

Studies on modern carbonate sedimentation in the fluvial environment have proven the ability of tufas and associated deposits to record diverse environmental information at different time scales (Drysdale and Gillieson, 1997; Kano et al., 2003; Shiraishi et al., 2008; Vázquez-Urbez et al., 2010). The short-term periodic monitoring of physical, chemical and biological parameters and high-resolution analysis of associated deposits, both in natural and laboratory contexts, are facilitated by the generally high deposition rates (Pentecost, 1978; Gradziński, 2010; Arenas et al., 2014). These studies commonly involve hydrochemical (Lorah and Herman, 1988; Liu et al., 1995; Kawai et al., 2006; Auqué et al., 2013), sedimentological (Drysdale and Gillieson, 1997; Manzo et al., 2012; Arenas et al., 2014), isotopic (Chafetz et al., 1991; Hori et al., 2009; Osácar et al., 2013a, b) or biological (Pedley et al., 2009; Arp et al., 2010; Santos et al., 2010) analyses. The study of these rapid-evolving fluvial contexts is better approached through a combination of these techniques. The results over a long time span for a number of sites along fluvial courses provide reliable patterns for the carbonate deposition rates, stable-isotope composition and textural attributes of the deposits. Ultimately, the aim of these studies is to explain the variations in the above-mentioned parameters through space and time in terms of climate and hydrology interpretation.

The deposition rates and sedimentary facies largely vary within a single stream or river as a result of varying depositional conditions, mostly depending on physical flow attributes and associated biota, which are recorded through the diverse textures and structures of

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deposits. In addition, changes in the riverbed slope and hydrology can account for variations in the deposition rates along the rivers (Drysdale et al., 2002; Auqué et al., 2013, 2014; Arenas et al., 2014).

Many tufa-depositing streams are primarily fed through ambient-temperature, and less commonly low-thermal, water springs sourced from carbonate aquifers (Capezzuoli et al., 2010; Auqué et al., 2013). These springs are mainly located at the headwaters and, occasionally, along their courses, although the contribution of intermediate springs is usually smaller. Nonetheless, groundwater input along a river can exert a significant influence on tufa deposition downstream depending on the discharge volume and chemical composition of the new inputs to the river (Auqué et al., 2013; Arenas et al., 2014). Therefore, coupled hydrochemical and sedimentological analyses are crucial to decipher the factors that control the variations in the tufa deposition's attributes through space and time. Moreover, the stable-isotope composition of the water and related sediment can record short-term climatic and hydrological changes on different time scales (i.e., seasonal, interannual and decadal); thus this type of analysis is useful to infer high-resolution environmental changes (Lojen et al., 2004; Andrews, 2006; Osácar et al., 2013a, b).

In the Iberian Range (northeastern Iberian Peninsula), studies of several tufa-depositing rivers (e.g., the Añamaza, Mesa and Piedra Rivers; Auqué et al., 2013, 2014; Arenas et al., 2014) indicated that there are large variations in the deposition rates among them that should result from differences in the discharge, water composition, riverbed slope, temperature, etc. The Ebrón River is another tufa-depositing river in the Iberian Range, in the continental Mediterranean climate zone, that stands out due to its high mean discharge (1.49 m^3/s) compared to the discharge in other rivers (e.g., the Añamaza River, 0.21 m^3/s, and Piedra River, 1.26 m^3/s) and the occurrence of significant ambient-temperature groundwater inputs along its course. The present river has a moderate-gradient longitudinal profile (mean slope of 1.4%), close to that of the Piedra River (1.3%) but smaller than that of the Añamaza River (1.9%). These circumstances make the Ebrón River a distinct scenario to assess the influence of such factors on the attributes of tufa deposition.

Therefore, this work presents sedimentological, isotopic and hydrochemical data obtained from periodic monitoring (every six months from October 2006 to March 2010) along this high-discharge and moderate-slope river (i.e., the Ebrón River). The aim was to analyse the factors that control carbonate deposition through space and time in that river. In addition, the comparison between these results and those obtained through the same monitoring method in other rivers in the Iberian Range over a similar time span provides valuable information that can be used to interpret the climatic and hydrological characteristics of ancient carbonate fluvial systems. The findings underscore the significance of tufa deposits as high resolution records of climate and hydrology changes and, more importantly, their use as correlation tools on a regional scale.

2. Location, geological context, climate and hydrology

The valley of the Ebrón River is located in the southern part of the Iberian Range, an Alpine intraplate chain in the Iberian Peninsula (Fig. 1A). The Ebrón River is a 42-km long tributary of the Turia River that flows from northwest (1370 m a.s.l.) to southeast (730 m a.s.l.). The Turia River enters the Mediterranean Sea in the city of Valencia (Fig. 1B). The drainage area of the Ebrón River occupies ca. 245 km^2; its altitude ranges between 1723 and 730 m a.s.l. The present study covers a section along which the river has volume from the Las Amanaderas creek (*The Sourcers* creek; ≈1050 m a.s.l.) to the gauging station in Los Santos (≈740 m a.s.l.) (Figs. 1C, 2A). Upstream of Las Amanaderas, the Ebrón River is dry for most of the year. The mean slope of the studied section is 1.4%, including an 8-m high vertical waterfall (Calicanto waterfall) in the most upstream area (Fig. 2A).

From northwest to southeast, the river flows across Lias–Dogger limestones and dolostones affected by faults that are mostly oriented in a NE–SW to N–S direction, Triassic dolostones (Muschelkalk) and strongly folded gypsum-rich mudstones (Keuper), south-dipping Upper Cretaceous limestones and dolostones and, further south, subhorizontal, mostly detrital Miocene rocks of continental origin (Figs. 1C, 2B). From Castielfabib to Los Santos, the river also cuts down thick Quaternary tufa deposits (Lozano et al., 2012).

The climate is continental Mediterranean with strong seasonal differences in temperature and precipitation. In the studied period in this work (October 2006–March 2010), the mean monthly air temperature was highest in July (mean: 19.9 °C) and lowest in January (mean: 2.6 °C) (Fig. 3). The annual precipitation (mean: 508 mm) was roughly distributed across two maxima, namely, April–May or April to June (205 mm) and September–October or September to November (121 mm), and two minima, namely, July–August and November to February, mostly below 40 mm/month (Fig. 3).

The Ebrón River is mainly fed from the aquifer of the Montes Universales (*Ministerio de Obras Públicas y Urbanismo*, 1988). North of Tormón, the river is fed by the middle interval of this aquifer, which consists of 300–400 m thick fissured and karstified Lias–Dogger limestones. Close to the north of the village of El Cuervo, the river receives further water inputs from the same aquifer (El Yogo and La Poza springs; Figs. 1C, 2A). The available discharge measurements of the La Poza spring varied between 150 L/s (in 2007–08) and 317.7 L/s (in 2008–09) (data from *Confederación Hidrográfica del Júcar*; *http://www.chj.es/es-es/Organismo/Paginas/Organismo.aspx*). The mean annual discharge of the Ebrón River (measured at the Los Santos gauging station) was 1.49 m^3/s from October 2006 to March 2010 (*http://hercules.cedex.es/anuarioaforos/default.asp*).

In the studied period, the monthly discharge varied between 0.733 m^3/s in October 2006 and 3.53 m^3/s in January 2010, but the maximum instantaneous discharge reached 7.57 m^3/s in June 2008, 5.60 m^3/s in November 2008 and 8.85 m^3/s in January 2010 (Fig. 4). A comparison between the precipitation and discharge diagrams (Figs. 3, 4) shows a delay between the precipitation and subsequent discharge increase that is shorter than one month. Between sites 7 and 8 (Fig. 1C), the Ebrón River receives water from a microhydropower station, which is sourced from river water taken between sites 4 and 5 and between sites 6 and 7 (Hermosilla and Peña, 2008) (Figs. 1C, 2A). The diverted water flows along channels of very small and uniform slope as far as the penstock located between sites 7 and 8.

3. Methods

A total of 9 sites were chosen along the Ebrón River for the periodic (six-month) monitoring of physical and chemical parameters from October 2006 to March 2010. The topographic and hydrological features (sites of groundwater inputs, riverbed slope, water velocity and depth) and sediment characteristics (primarily structure and texture, including floral associations) were considered when selecting these sites (Figs. 1C, 2A). No sites were monitored along a 4-km long narrow section (between sites 3 and 4) due to the difficulty in accessing the area (the topographic features made this section infeasible for systematic monitoring), but it is known that tufa deposition occurs in successive small jumps. Hydrodynamical and hydrochemical features, sediment attributes, tufa sedimentation rates and sediment and water stable isotopes were periodically examined at the different monitored sites.

3.1. Sedimentation rate monitoring

A total of 9 limestone tablets (25 × 16 × 2 cm) were installed parallel to the floor (one at each of the 9 selected sites) from October 2006 to March 2010 in the different subenvironments along the Ebrón River (Figs. 1C, 2A). The tablets were removed at the end of summer (approximately September 22) and the end of winter (approximately March