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Freshwater tufa record from Spain supports evidence for the past interglacial being wetter than the Holocene in the Mediterranean region

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ABSTRACT

The sedimentation of spring-fed tufa deposits is subject to two main factors: the ground water discharge from the spring and the supersaturation of such waters with respect to carbonate at the surface. In Trabaque Canyon (central Spain), several spring tufa deposits were formed during the Pleistocene and Holocene, mostly during mild periods. They were linked to the outflow of ground waters that in each period cropped at a different site along the canyon, depending on the intersection of the water table and the thalweg. Recent lowering of the water table due to changes in land uses have resulted in a downstream shift of the spring location along the bottom of the valley, confirming the relationship between the water table level and the spring location. The elevation of the deposits is independent of their age and geomorphologic evidence suggests that although over ten metres of tufa has been repeatedly deposited and eroded, there was not a lowering of the base level in the canyon since the last interglacial. Thus, it is possible to compare the water table levels during the last two interglacial periods. Due to the link of the spring and the tufa deposits, the location of the latter has been considered an indicator of ancient water table and consequently as a proxy of the recharge by rainwater to the aquifer. Geomorphic comparison of deposits from the previous interglacial to those from the Holocene indicates that the former are at higher elevations along the valley, suggesting that this period was wetter than the Holocene. Comparison of Trabaque Canyon record with other paleo-hydrological reconstructions from Southern Europe and the Mediterranean agree, supporting the scarce number of continental records in which interglacial comparisons are possible in the region.
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1. Introduction

In regions where carbonates are common rocks, the existence of springs, rivers or lakes causing the precipitation of carbonates in the surface is relatively common in warm and temperate climates (Pentecost, 1995a). In this context the term tufa is considered to represent precipitates of cool water carbonates (Pedley, 1990), in order to differentiate them from travertines, which have a thermal origin (e.g., Guo and Riding, 1992). Tufas have been considered an outstanding archive to record paleo-environmental information (Pentecost, 2005; Andrews, 2006; Pedley, 2009). Several approaches have been used to obtain information from tufas including sedimentology, geomorphology, geochemistry, palynology or paleontology among others, demonstrating the importance of the preserved records (e.g., Mania, 1990; Pedley et al., 1996; Peña et al., 2000; Andrews and Brasier, 2005; Viles et al., 2007).

Tufa deposits are fed in most cases by ground water and their occurrence depends on the specific hydrochemical composition. In carbonate regions, dissolution of the aquifer host rock is enhanced by the input of CO_2 from soils, yielding hard waters with elevated bicarbonate and Ca^{2+} concentrations (Ford and Williams, 2007). When those hard waters intersect the surface, tufa precipitation occurs as a consequence of CO_2 out-gassing, although evaporation or bio-mediation can also be significant factors (Shiraishi et al., 2008). Intersection of ground waters with the surface occurs as springs (Pedley et al., 2003), in connexion with the course of rivers (Lojen et al., 2009) or even in lake systems (Ordoñez et al., 2005), and they can extend from some metres to tens of kilometres, depending on the water chemistry and the existence of one or multiple springs in the system. The relationship of tufa precipitation with the soil CO_2 production is well known, and changes in soil thickness, vegetation or land use have been reported as major causes for tufa cessation (Goudie et al., 1993; Baker and Simms, 1998). This is possibly the reason why tufas are found more abundantly during interglacial periods in the geological record in Europe (Hennig et al., 1983; Baker et al., 1993; Durán, 1996; Horvatinčić et al., 2000), since warm and more humid climates favour the development of forest in contrast to

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the steppe vegetation that dominates during glacial/stadial times (e.g., Woillard, 1978).

The precipitation of tufa deposits does not depend exclusively on the chemistry of the waters, but also on the hydrological regime. The ground water can crop out at the surface in (1) confined springs due to the existence of geological structures, (2) it can flow with a free drainage through the vadose zone, springing before reaching the water table favoured by karst conduits, or (3) being connected to the local water table (Ford and Williams, 2007). Although most of the spring tufas are not related to their local water table (e.g., Peña et al., 2000), there are descriptions of tufas precipitated from springs in connexion with the local water table (e.g., Martín-Algarra et al., 2003; Pedley et al., 2003). In these cases, large changes in the aquifer recharge result in significant water table fluctuations which may affect the position of the spring and then the continuity of the formation of a tufa deposit at a specific location. Studies of tufa deposits in valleys have frequently shown that their altitude is not age-dependent (e.g., Soligo et al., 2002). Thus, in cases where there is no evidence for a long-term fluvial incision in the valley, the occurrence of spring tufas in clear relationship to their water table showing different elevations may be a physical evidence of shifts in the water table and a strong argument for comparing the aquifer recharge in different ages.

Composition and structure of tufas make this material suitable to be dated by numerous techniques (Bischoff et al., 1988; Pedley, 1993; Eikenberg et al., 2001; Ihlenfeld et al., 2003; Ortiz et al., 2009). The dating method most frequently used is the application of U-series disequilibrium (Garnett, et al., 2004), commonly U-Th, since it is able to date tufa deposits from at least the last 3 glacial cycles (Rihs et al., 2000; Wang et al., 2004). However, the accuracy of reported ages is based upon two main assumptions: (1) the existence of a chemically closed system since deposition, and (2) the low or negligible initial thorium content. Both assumptions can be easily tested by replicating cogenetic samples and checking the ^{230}Th/^{232}Th ratios of individual samples. The occurrence of an open system represents differential leaching of U and in rare cases Th atoms from the crystal lattice, providing isotope ratios that do not depend exclusively on the radiometric decay of the U-series. Thus, age reported from those values cannot be trusted. Replication of successive cogenetic samples in different locations demonstrates whether the ages are consistent, and allows the evaluation of a closed system. On the other hand, detrital and/or organic contamination can introduce initial ^{230}Th into the carbonate. This implies that not all the ^{230}Th detected in the sample is a product of its parent nuclide decay, but derives from other sources. Initial ^{230}Th contamination biases the calculated dates towards older ages. However, by measuring the ^{232}Th concentration, which belongs to a different decay series, the possibility of any substantial contamination can be determined and with the existence of cogenetic samples, corrections can be performed by isochron methods (e.g., Ludwig and Titterington, 1994). Although tufa carbonates can contain large amounts of detrital particles due to their sedimentological context, some environmental settings are favourable for the collection of samples for U-Th dating avoiding in part the problem of initial thorium contamination (Frank et al., 2000; Mallick and Frank, 2002).

Here we present the tufa system from the Trabaque Canyon in Cuenca, central Spain. Geomorphologic, sedimentologic, stratigraphic and chronologic surveys have been carried out in the canyon. This research focuses on the significance of one of the deposits regarding the connexion between the position of the tufa deposit and the paleo-hydrology in the canyon. The geomorphologic evolution of the valley, together with the current tufa formation system provides the basis to interpret the past. The detailed sedimentologic study carried out was essential in order to choose the best possible samples to be dated according to the requirements of the U-series dating technique. Additionally, the sedimentology and stratigraphy studies were necessary to evaluate the coherence of the tufa deposit evolution, confirming that the surveyed section was precipitated in continuity without major hiatuses and hence, the age calculated is representative for the whole section. Finally, the integration of the chronological information of different deposits available from previous studies in the valley, together with the new data provided within this research, allows comparison of local paleo-hydrologic conditions at discrete time intervals and their correlation in a more general context.

2. Regional setting

The Trabaque Canyon is located in the Iberian Range, in central Spain (Cuenca province). This study focuses on a small sector of tufa deposits within one of the largest tufa systems in Europe (Torres et al., 2005) that includes the Guadiela, Escabas and Trabaque rivers (Fig. 1). The three rivers originate in the Iberian Range which in this region consists of Mesozoic sedimentary rocks, mostly carbonates. The confluence of rivers takes place in the Cenozoic Loranca Basin, dominated by detrital sediments, where most of the tufa system is located. A sharp relief exists between the range and the basin, and the rivers cross through deep (several hundred metres) canyons just before entering the basin. The karstic ground waters from the range aquifer rise to the surface near the boundary between the ranges and the basin as a consequence of the large topographic gradient. Thus, tufa carbonates precipitate along different springs that feed this sector of the three rivers.

In this region the climate is Mediterranean with continental influence. Meteorological data from Albalate de las Nogueras, which is the town nearest to Trabaque Canyon (Figs. 1and 2), has a mean annual temperature of 12 °C and the annual amount of precipitation exceeds 450 mm, although precipitation in the range around the river watershed can double that amount. Precipitation is concentrated from October to March, whereas drought characterises the summer. Despite the significant magnitude of the Trabaque catchment area upstream of this location (~300 km^2), the river along the canyon is dry most of the year except for some periods ranging from weeks to months during winter and/or spring. This is due to the karstic control on the Trabaque River hydrology and the importance of the summer drought. However, shortly downstream of the canyon, near Albalate de las Nogueras, a sluggish water flow is permanent throughout the year. A major spring from the range aquifer is responsible for this continuous water supply. Below the spring the river flows continuously for the rest of its course. The ground water springs at the thalweg of the river without any specific morphology indicating its presence. The water simply flows out from the sediments of the river bed and, as is the case of springs without major conduits (Alfaro and Wallance, 1994), the ground water rises to the surface by a series of minor spots within a limited area (~10^1 m). This spring is connected to the local water table and the site where the ground water rises to the surface changes slightly along the thalweg in relation to its oscillations. Despite these minor oscillations, the elevation of the spring can be located within a precision of 2 m.

The tufa carbonates in the region have been previously surveyed (Pérez-González and Virgili, 1971; Torres, 1990; Torres et al., 1994, 1996, 2005; Ortiz et al., 2009). Tufa deposits occur at different elevations and up to six tufa terraces have been differentiated and an attempt to correlate them has been carried out (Torres et al., 1994, 1996). Chronological studies have been based on α-spectrometric U-Th dates (Torres et al., 1994, 1996), and racemization of amino acids from ostracods (Torres et al., 2005; Ortiz et al., 2009). Previous studies have shown the complexity of the system. So, our research focuses exclusively on the Trabaque Canyon area near the town of Albalate de las Nogueras, where previous studies have only partially covered the tufa system. This site was selected because the tufa deposits are constrained to a narrow canyon where the connexions of the current spring and the water table are clear, providing an analogue to

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