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Morpho-stratigraphic characterization of a tufa mound complex in the Spanish Pyrenees using ground penetrating radar and trenching, implications for studies in Mars

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ABSTRACT

The Isona tufa mound complex (ITMC), associated with artesian springs of the Areny-Montsec aquifer, Spanish Pyrenees, is a potential analog for water constructed landforms on Mars. We used Ground Penetrating Radar (GPR), trenching, sedimentological description of exposures, and radiocarbon and U-series dating methods for the geological characterization of the ITMC. Preliminary geomorphological mapping combined with sedimentological analyses permitted the recognition of the different facies and their spatial distribution. GPR surveys conducted next to an outcrop and a trench provided electromagnetic wave velocity in tufas (0.09 and 0.11 $m\,ns^{-1}$) and determined the correspondence of the radar signatures with facies types. This was used to reconstruct the tufas internal structure and the depositional stages for two different contexts: (1) an upper unit representing the morpho-stratigraphic record of paleosprings – Tufa 1 – composed of relict tufa mounds older than 350 ka BP; and (2) a lower unit – Tufa 3 – associated with groundwater aquifer outlets (Basturs Lakes). The GPR data allowed depicting the signatures for the vent, pool, rimstone, palustrine, dam, cascade and slope facies. A relationship was inferred between the age of the tufas and the radar signature, in terms of relative amplitude and signal attenuation. Older dry tufas with advanced diagenesis and karstification are characterized by well-defined GPR reflectors and lower attenuation than younger tufas, associated with aquifer discharge and shallower water tables. U-series and radiocarbon ages obtained from the Basturs Lakes tufas indicate that these have been active since 106 ka BP during both cold and mild Marine Isotopic Stages (MIS). We hypothesize that tufas related to the deep-seated Areny-Montsec confined karst aquifer were insensitive to climate variations. Landforms reminiscent of the ITMC have been detected during the last decade on Mars. Since GPR will be part of the ExoMars Rover of the European Space Agency (ESA) mission projected for 2018, we anticipate that our results may be able to constrain the interpretation of landforms possibly related to water on Mars.

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1. Introduction

The Isona tufa mound complex (ITMC) developed within the Tremp Basin, an artesian structural basin that forms part of the south-central Pyrenean piggy-back thrust-propagation sequence located in the Spanish Pyrenees. This thrust unit is composed of Mesozoic and Cenozoic rocks tectonically transported southwards and comprises three main thrust sheets: the Bóixols-Sant Corneli, the Montsec and the Marginal ranges (Ardèvol et al., 2000; Gutiérrez et al., 2012). The Tremp Basin is located on the footwall of the Bóixols-Sant Corneli Thrust (Fig. 1a).

The ITMC includes eleven dome-shaped mounds primarily composed of highly porous freshwater calcareous rocks. Although travertine mounds associated with geothermal springs are widely described in the literature (e.g. Bargar, 1978; Scheuer and Schweitzer, 1985; Hancock et al., 1999; Akdim and Juliá, 2005; Kele et al., 2008), the ITMC formed concomitant with non-thermal artesian springs of calcium-carbonate-saturated waters (Linares et al., 2010). These mounds are generally breached by one or more channels extending away from the primary groundwater discharge vent and contain most of the autochthonous landforms defined by

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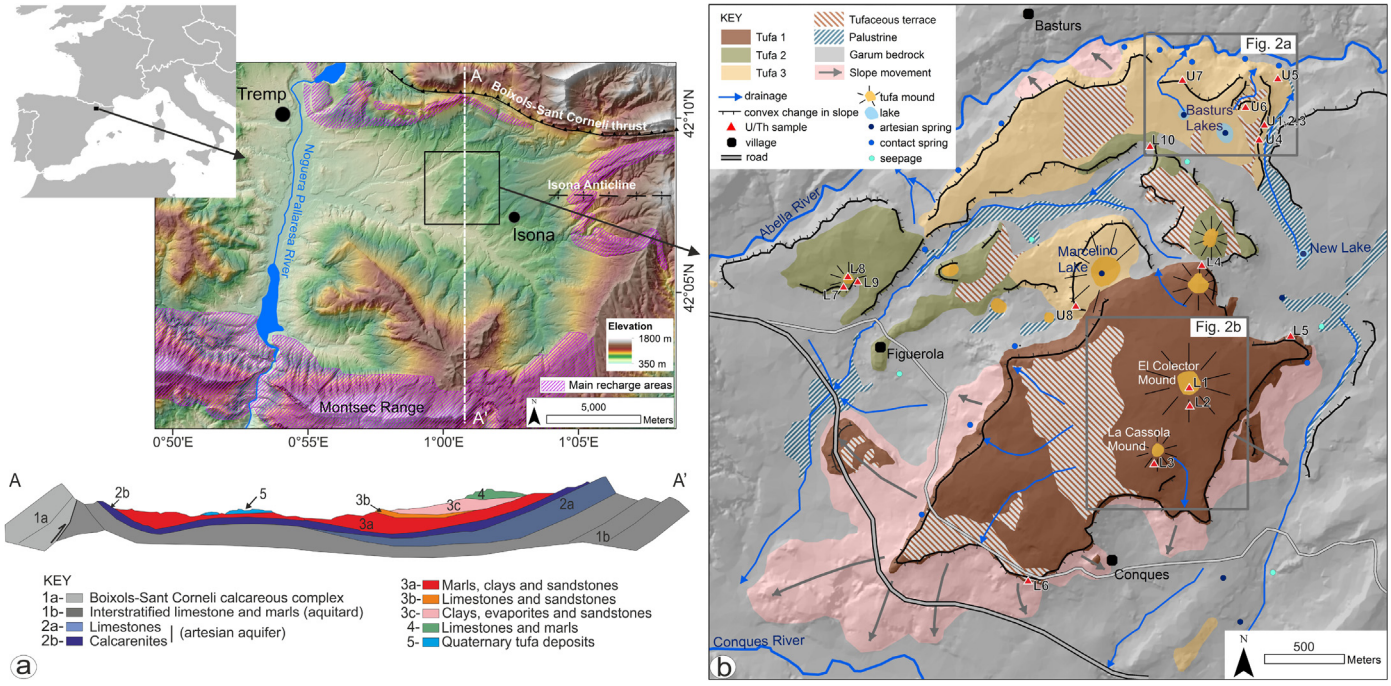

Fig. 1. (a) Location of the Tremp Basin with chief structural elements, aquifer recharge areas and cross-section illustrating the main hydrogeological units associated with the Areny-Montsec aquifer; (b) geomorphological map of the study area showing the spatial distribution of tufas, main drainages, slope movements, location of springs, main geographical features and U/Th samples (Table 2). The location of sites investigated using GPR are outlined in gray.

Pentecost and Viles (1994), such as mound, palustrine, cascade, dam, and/or lacustrine flats.

Previous investigations of tufa mounds are limited. Tufa deposits showing geomorphic features analogous to those in the ITMC have been described as fresh water built mounds in the Rocky Mountains, USA (McBride et al., 2012), forming part of perched springline tufa systems in Spain (Pedley et al., 2003), associated with seepage in the UK (Pentecost, 1981) and as lacustrine subaqueous features in Turkey (Kempe et al., 1991) and USA (Rosen et al., 2004; Guo and Chafetz, 2012). Furthermore, tufa mounds associated with superambient groundwater outlets in the Great Artesian basin of Australia were proposed as potential analogs for similar landforms discovered on Mars (Kerr and Turner, 1996; Mudd, 2000; Clarke and Bourke, 2011; Keppel et al., 2011, 2012). Ground Penetrating Radar (GPR) has been used to describe fluvial barrage tufas in UK (Pedley et al., 2000; Pedley and Hill, 2003) and the internal architecture of a thermogene tufa mound in Utah, USA (McBride et al., 2012), aiding in the reconstruction of the depositional environment.

Relatively recent sedimentary volcanism may have led to the formation of spring mounds on Mars (e.g. Allen and Oehler, 2008; Oehler and Allen, 2008; Rossi et al., 2008). Comparative geomorphologic studies indicate that gradual groundwater discharges from artesian aquifers likely comprised an important water/sediment supply (e.g. Crumpler, 2003; Mann et al., 2004; Clarke and Bourke, 2011; Linares and Rodriguez, 2011). The terrestrial mounds are finely layered suggesting a long-lived history of precipitation from thin surface flows. An equivalent mode of formation for the Martian mounds would be indicative of a sustained interconnection between subsurface and surface hydrologic systems in Mars. The ExoMars mission by the European Space Agency (ESA) is planning to launch a rover on the surface of Mars by 2018. The rover will be carrying the first space-borne GPR system (WISDOM – Water Ice and Subsurface Deposit Observation on Mars) with the objective of characterizing the top 3 m of the Martian subsurface searching for evidence of past and present life (Plettemeier and Ciarletti, 2011). Our results demonstrate the usefulness of GPR-derived subsurface stratigraphy to investigate the hydrologic processes involved in tufa mound development.

We used geophysical, trenching and dating methods to asses and further develop a previous evolutionary model of tufa mound formation for the ITMC (Linares et al., 2010). The objectives of the work include: (1) characterizing GPR signatures in tufas by comparing geophysical transects over exposed tufa deposits with sedimentological analyses; (2) describing the internal architecture of the tufa mound facies and inferring their evolution, by combining sedimentological analyses, the interpretation of radar signatures, and isotopic dating; (3) validating the evolutionary model of tufa mound formation presented by Linares et al. (2010). We anticipate that this work may have implications for research on water constructed landforms in Mars.

2. The Isona tufa mound complex (ITMC)

The structural and sedimentological settings of the Tremp Basin, an artesian structural basin developing on the footwall of the Bóixols-Sant Corneli Thrust (Rosell, 1996), favored the development of the ITMC. The basin geological sequence consists of five main hydrostratigraphic units: (i) Upper Cretaceous interstratified limestones and marls acting as an aquitard; (ii) the Upper Cretaceous Areny-Montsec aquifer system, composed of up to 200 m of calcarenites underlain by limestones; (iii) a 60–400 m thick clay, marl, and sandstone unit of the Upper Cretaceous-Lower Paleocene Garum Facies that confines the Areny-Montsec aquifer and is overlain to the south by interstratified limestones, sandstones, and clays (Rosell et al., 2001); (iv) Lower Eocene limestones and marls; and (v) the Quaternary ITMC in the main discharge area of the Areny-Montsec artesian aquifer (Fig. 1a). The ITMC is composed of three morpho-stratigraphic tufa units (Fig. 1b). The upper unit, locally named “Mont de Conques” (Tufa 1) consists of three inactive tufa mounds up to 40 thick. The second unit (Tufa 2) includes fossil tufa mounds at a lower altitude northwest of the upper unit. The younger unit (Tufa 3), reaching 10 m thickness, is associated with groundwater outlets (Basturs Lakes) formed at lower altitudes.

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