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Depositional architecture of a mixed travertine-terrigenous system in a fault-controlled continental extensional basin (Messinian, Southern Tuscany, Central Italy)

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ABSTRACT

The extensional Neogene Albegna Basin (Southern Tuscany, Italy) includes several thermogene travertine units dating from the Miocene to Holocene time. During the late Miocene (Messinian), a continental fault-controlled basin (of nearly 500-km^2 width) was filled by precipitated travertine and detrital terrigenous strata, characterized by a wedge-shaped geometry that thinned northward, with a maximum thickness of nearly 70 m. This mixed travertine–terrigenous succession was investigated in terms of lithofacies types, depositional environment and architecture and the variety of precipitated travertine fabrics.

Deposited as beds with thickness ranging from centimetres to a few decimetres, carbonates include nine travertine facies types: F1) clotted peloidal micrite and microsparite boundstone, F2) raft rudstone/floatstone, F3) subrounded radial coated grain grainstone, F4) coated gas bubble boundstone, F5) crystalline dendrite cementstone, F6) laminated boundstone, F7) coated reed boundstone and rudstone, F8) peloidal skeletal grainstone and F9) calci-mudstone and microsparstone. Beds of terrigenous deposits with thickness varying from a decimetre to >10 m include five lithofacies: F10) breccia, F11) conglomerate, F12) massive sandstone, F13) laminated sandstone and F14) claystone.

The succession recorded the following three phases of evolution of the depositional setting: 1) At the base, a northward-thinning thermogene travertine terraced slope (Phase I, travertine slope lithofacies association, F1–F6) developed close to the extensional fault system, placed southward with respect to the travertine deposition. 2) In Phase II, the accumulation of travertines was interrupted by the deposition of colluvial fan deposits with a thickness of several metres (colluvial fan lithofacies association, F10 and F12), which consisted of massive breccias, adjacent to the alluvial plain lithofacies association (F11–F14) including massive claystone and sandstone and channelized conglomerates. Travertine lenses, of 2–3-m thickness, appeared intermittently alternating with the colluvial fan breccias. 3) In the third phase, the filled fault-controlled basin evolved into an alluvial plain with ponds rich in coated reed travertines, which record the influence of freshwater (travertine flat lithofacies association, F7–F9).

This study shows the stratigraphic architecture and sedimentary evolution of a continental succession, wherein the hydrothermal activity and consequent travertine precipitation were driven by the extensional tectonic regime, with faults acting as fluid paths for the thermal water. Fault activity created the accommodation space for travertine and colluvial fan accumulation. Erosion of the uplifted footwall blocks provided the source of sediments for the colluvial fan breccias, which alternated with the thermogene travertine precipitation. Climatic oscillations might have led to the recharge of the aquifer that fed the hydrothermal vents.

The studied continental succession in an extensional basin provides valuable information about the interplay between thermogene travertine and alluvial/colluvial deposition, which in turn might improve the understanding of similar fault-controlled continental depositional systems in outcrops and the subsurface.

1. Introduction

Continental rift and strike-slip basins, such as the present-day examples of the East African Rift (McCall, 2010) and the Dead Sea Basin in the Middle East (Stein, 2001), present a variety of depositional environments and lithofacies including lacustrine carbonates, hydrothermal vent-related travertines as well as alluvial and fluvial deposits. In ancient cases of such fault-controlled basins, with deposition being influenced by varying rates of tectonic subsidence (Blair, 1987), mixed siliciclastic–carbonate successions occur alternately, as observed in the

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Jurassic–Lower Cretaceous of the Todos Santos Formation in Mexico (Blair, 1987), the Pliocene Ridge Basin in California (Link et al., 1978) and the Namibe Basin in southern Angola (Beglinger et al., 2012).

An important prerequisite for the development of travertine deposits is groundwater enriched in calcium and bicarbonate ions (Pentecost, 2005). Two classes of travertines are defined based on the two sources from which CO_2 can be derived: a) meteogene travertines are precipitated by groundwater enriched in meteoric carbon dioxide derived from soils and the atmosphere (Pentecost and Viles, 1994) and b) thermogene travertines are produced by thermally generated CO_2 (Pentecost, 2005). The signature of stable oxygen isotopes in meteogene travertines varies between −13‰ and 4‰ Vienna Pee Dee Belemnite (V-PDB), whereas the $\delta^{13}C$ values range from −12‰ to 4‰ V-PDB (Pentecost, 2005). In thermogene travertines, the oxygen isotope values range from −18‰ to −1‰ V-PDB, whereas carbon isotopes vary between −3‰ and 11‰ V-PDB (Pentecost, 2005). Some authors use the term 'travertines' exclusively to address continental carbonates precipitated by thermal water and the term 'calcareous tufa' to denote those carbonates associated with groundwater of ambient temperature (Pedley, 1990; Ford and Pedley, 1996; Capezzuoli et al., 2014). However, according to Jones and Renaut (2010), classifications based on the water temperature or water sources do not consider the diagenetic processes, which is problematic in the case of ancient deposits. In this study, due to the sedimentological and geochemical results, the terminology proposed by Pentecost (2005) is used.

In the last decade, thermogene travertine deposits accumulated in rift basins have been increasingly studied as a valuable archive of information about Quaternary palaeoclimate, palaeohydrology and groundwater isotope geochemistry (Minissale et al., 2002a,2002b; Minissale, 2004; Faccenna et al., 2008; Kele et al., 2008, 2011; Özkul et al., 2014) and tectonics (Hancock et al., 1999; Altunel and Karabacak, 2005; Brogi et al., 2010). In addition, recent discoveries of Lower Cretaceous hydrocarbon reservoirs in the subsurface of the South Atlantic, offshore Brazil and West Africa, have led to more studies on travertines and lacustrine carbonates accumulated in continental rift basins (Abilio and Inkollu, 1989; Dorobek et al., 2012; Wright, 2012; Ronchi and Cruciani, 2015; Wright and Barnett, 2015). Despite extensive study, the present knowledge on continental carbonate facies, their precipitation processes and the extrinsic and intrinsic factors controlling their depositional architecture is still limited (cf. Wright, 2012; Della Porta, 2015). However, only few known fossil travertine deposits have been noted in the pre-Quaternary geological record. The Messinian mixed carbonate–terrigenous succession of the Albegna Basin (Southern Tuscany, Central Italy), of nearly 70-m thickness, has not been studied in detail, despite being a valuable example of the interaction between travertines and colluvial–alluvial terrigenous deposits in a kilometre-scale fault-controlled rift basin. This study assesses the lithofacies characteristics and architecture as well as the factors controlling the sedimentary evolution over time of a mixed travertine–terrigenous succession. Thus, interpretative geological models are provided, which could prove useful in comparable outcrop and subsurface rift systems.

2. Geological setting

2.1. Structural and stratigraphic framework of Southern Tuscany

The Neogene Albegna Basin (Fig. 1) developed on the Cenozoic Apennine fold-and-thrust belt from the Tortonian (Late Miocene) Age, when the inner northern part of the Apennine orogen was subjected to extensional tectonics, which was equivalent in time to the eastward migration of the thrust propagation (Patacca et al., 1990; Carmignani et al., 1994). Extensional structures were superimposed on the previous contractional structures (Pasquarè et al., 1983; Zanchi and Tozzi, 1987; Brogi et al., 2015). The Albegna Basin substrate includes the following pre-extension superimposed tectonic units (Kligfield, 1979 and references therein): 1) Ligurian and Sub-Ligurian Units, composed of remnants of the Jurassic oceanic crust and its Jurassic–Cretaceous sedimentary cover, as well as Cretaceous–Oligocene turbidites; 2) Tuscan Nappe, composed of non-metamorphic sedimentary succession including the Upper Triassic Anidrite di Burano/Calcare Cavernoso Formation and Cretaceous–Lower Miocene marine clastic deposits; and 3) the metamorphic Tuscan succession.

The Miocene extensional phase led to the development of hinterland basins separated by NW–SE-oriented transverse lineaments (Pascucci et al., 2007). During the Pliocene, structural depressions developed controlled by WSW–ENE-oriented tectonic lines (Zanchi and Tozzi, 1987; Pascucci et al., 2007; Cornamusini et al., 2011 and references therein), such as the Albegna Line (Fig. 1). These extensional basins were filled by upper Tortonian lacustrine clays and fluvial conglomerates (Unit T in Bossio et al., 2003–2004; cf. Fig. 2), overlain by brackish deposits that denoted an early Messinian marine transgression (Unit M1 in Bossio et al., 2003–2004). The following uplift of the Middle Tuscany Ridge during the late Messinian promoted the deposition of fluvio-lacustrine conglomerates and clays (M3 in Bossio et al., 2003–2004). In the study area, unit M3 is represented by the Poggio Capraio Formation, which unconformably overlies the Ligurian Unit (Fig. 3). The Albegna Basin was oriented SSW–NNE during the Pliocene when at least 200 m of marine claystone were deposited (Blue Clays; Unit-P1 in Bossio et al., 2003–2004; Figs. 1,2). The Late Pliocene to Holocene sedimentary history of the Albegna Basin was characterized by tectonic uplift as well as glacio-eustasy and climate changes, with the deposition of various continental lacustrine to brackish successions (Units P2, P3 and Q1–Q3; cf. Bossio et al., 2003–2004 and Fig. 2) unconformably overlying the Lower Pliocene marine Blue Clays.

2.2. Distribution of travertine outcrops in Albegna Basin

The Albegna Basin includes several Neogene to Holocene thermogene travertine units, which are distributed along faults and fractures, are related to hydrothermal activity, and occur close to the Manciano, Montemerano, Saturnia and Marsiliana localities (Fig. 1c; Zanchi and Tozzi, 1987; Bosi et al., 1996; Barilaro et al., 2011, 2012; Ronchi and Cruciani, 2015). Bosi et al. (1996) distinguished five travertine units of different ages from the Messinian to the Holocene (Tr1–Tr5 in Fig. 2). These authors determined the relative ages of these units based on their stratigraphic positions, sedimentary and tectonic features and, for the youngest units, their occurrence with respect to three orders of Quaternary fluvial terraces developed in the Albegna River valley, labelled as A1, A2 and A3 (Fig. 2). Tr1 represents the Holocene travertine deposits at Bagni di Saturnia (Fig. 1), which developed on the youngest and lowest (25–80 m above sea level, a.s.l.) fluvial terrace A1 (Bosi et al., 1996). This active system is characterized by a water temperature of 37 °C and a pH of 6.3 (Minissale, 2004). Tr2 denotes the Middle–Upper Pleistocene travertines cropping out near the Montemerano and Manciano villages, which developed on the fluvial terrace A2, from 80 to 160 m a.s.l. (Bosi et al., 1996). The Middle Pleistocene Tr3 travertines, which crop out at the village of Saturnia, are older than the A3 fluvial terrace (from 100 to 190 m a.s.l.; Bosi et al., 1996). These three travertine units are untilted and characterized by sub-horizontal stratification. Tr4 refers to Pliocene travertine deposits close to the village of Semproniano, which developed above the Pliocene deposits (Bosi et al., 1996); this unit is also characterized by horizontal stratification, although the travertines show evidence of tectonic deformation (Bosi et al., 1996). Tr5 represents the Messinian travertine deposits that crop out close to the Marsiliana village, which are the focus of this study. The Tr5 travertines overlie the Messinian deposits with a tilted appearance (dips 60–70°), and they are subjected to faults with a strike-slip component as the underlying Messinian strata (Bosi et al., 1996; Bossio et al., 2003–2004).