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Occurrence and genesis of Quaternary microbialitic tufa at Hammam Al Ali, Oman

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ABSTRACT

Remnants of late Quaternary microbialitic tufa occurs within a shallow depression in the Hammam Al Ali hot spring area, which is located approximately 14.5 km to the southwest of Muscat, Oman. The tufa precipitated from hot spring water supersaturated with respect to calcium carbonate and is mostly of a porous phytogenic type, with occasional detrital and stromatolitic types. Microscopic and nanoscopic examination revealed that the tufa deposits developed through two successive processes of calcite precipitation, biotic and abiotic, preceded by limited precipitation of unstable aragonite. It is suggested that biologically mediated precipitation results in the construction of incomplete skeletal calcite crystals. The latter provide a base for classical physiochemical precipitation and, eventually, the development of complete sparry calcite crystals. The initiation of dendritic calcite crystals in the stromatolitic tufa as incomplete biogenic skeletal crystals and their characteristic growth pattern indicates that the tufa represents a clear example of hot spring calcitic microbialite.

1. Introduction

Tufa deposits are from a spectrum of fresh-water terrestrial carbonates that mainly precipitate under subaerial conditions from calcium bicarbonate-rich waters in a large variety of depositional and diagenetic settings (Pedley, 1992; Pentecost, 2005). In addition to tufa, these carbonates include travertines and speleothems. Confusingly, the terms 'tufa' and 'travertine' have been used to describe several different types of carbonate deposits. Capezzuoli et al. (2014) endeavoured to decode the terms to avoid this confusion: 'the term tufa *should be applied to deposits consisting dominantly of calcite that are produced from low depositional rate, shallow cycled and karstic-derived, ambient temperature waters which are characterized by poorly bedded, highly porous fabrics. Microbiota and macrobiota are very common, and δ^{13}C is always low, while primary aragonite is typically absent except in spring waters with a high Mg/Ca ratio*.'

A plethora of studies have examined the carbonate fabrics and nanofabrics of naturally occurring and experimentally produced tufa to understand its genesis within various depositional environments (Chafetz and Folk, 1984; Guo and Riding, 1999; Fouke et al., 2000; Turner and Jones, 2005; Perri and Tucker, 2007; Bontognali et al., 2008; Jones and Renaut, 2008; Spadafora et al., 2010; Fouke, 2011; Perri et al., 2012; Pedley, 2013; Jones and Peng, 2014; Cangemi et al., 2016). The consensus is that tufa mostly consists of low-Mg calcite and is the product of both physiochemical and biogenic precipitation associated with biofilm colonisation. Tufa diagenesis and the conditions controlling the habit and form of its calcite components have been adequately investigated (Jones and Renaut, 1995; Meldrum, 2003; Meldrum and Colfen, 2008; Brasier et al., 2011; Peng and Jones, 2013; Richter et al., 2015). Until the last decade, most studies of naturally occurring and experimentally developed tufa focused on the biochemical processes leading to carbonate precipitation and were often limited to traditional thin section petrography. More recently, application of SEM techniques has facilitated the study of crystal nucleation mechanisms and mineral ultrastructures, which are essential to discriminate between biotic and abiotic origins of tufa (Benzerara and Menguy, 2009; Perri et al., 2012; Jones and Peng, 2014).

Studies of modern and ancient tufa have mostly been conducted in Europe, North and South America, Australia, Africa, and China, while Arabian tufa has received comparatively less attention. Tufa deposits have been described in the Kharga Oasis in Egypt (Smith et al., 2004), the Tadrat Acacus Mountains in Libya (Cremaschi et al., 2010), the Imouzzer Ida Ou Tanane in Morocco (Weisrock, 1981), Gafsa in southwestern Tunisia (Henchiri, 2014), and the

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Jabal Farasan-Wadi Qedid area in southern Saudi Arabia (Kabesh and Abdel-Motelib, 2014). The Sultanate of Oman is characterized by abundant early to late Holocene terrestrial carbonates, which mostly occur as travertine and calcite veins that were produced by precipitation from hyperalkaline springs (Clark and Fontes, 1990). Despite the abundance of Quaternary travertines, tufa, and cave speleothems in Oman's northern mountains, their petrography and microfabrics, particularly those associated with hot springs, have not received adequate attention. The present study addresses this gap by providing detailed petrographic and nanoscopic description of late Quaternary tufa deposits that surround a hot spring in the foothills of Oman's northern mountains. It also discusses their genesis and provides additional evidence for the non-classical microbialitic crystallization of tufa calcite.

2. Field occurrence

The study area is located within the Hammam Al Ali hot spring at 23°28′41.7″ N and 58°19′25.9″ E, approximately 30 km to the southwest of Muscat, the Sultanate of Oman (Fig. 1). The hot spring seeps along a thrust plane of the Samail ophiolite and underlying Triassic dolostones at the foothills of Oman's northern mountains. In recent years the spring water level has dropped by several metres and water has to be pumped from the spring. The temperature has been measured as 65 °C.

The spring occurs within a depression that is bounded by hard Triassic dolostone highs and low foothills of extensively weathered peridotite rocks. At present, most of the tufa deposits in the Hammam Al Ali area have been eroded, and their remnants are preserved within conglomeratic terraces that surround the peridotite and dolostone hills (Fig. 2A), while some deposits crust the footwall of the weathered peridotite hills (Fig. 2B). The depression is filled by at least three layered sheets of conglomerates, each reaching 1.5 m in thickness and interlayered with thin tufa deposits that are approximately 0.7 m thick. The conglomerates mostly consist of well-rounded dolomitic gravels and boulders and are crusted with tufa. The tufa investigated in this study has been designated a late Quaternary age (Clark and Fontes, 1990; Burns et al., 2001; Fleitmann et al., 2004, 2007).

3. Climate

The Sultanate of Oman is located within the northern equatorial

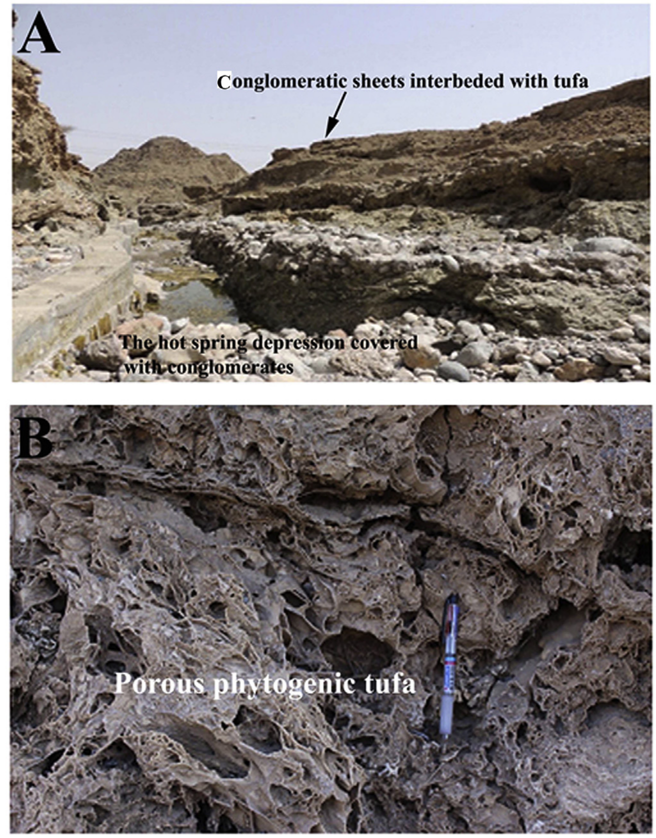

Fig. 2. Field photographs of the Hammam Al Ali hot spring area: (A) eroded remnants of interbedded conglomeratic sheets and tufa; (B) porous phytogenic tufa crusting the footwall of the weathered peridotite hills.

desert belt, which extends from eastern North Africa to the Thar Desert in India. The region is characterized by a subtropical dry hot desert climate with mean annual rainfall of the order of 100 mm for most of the country and summer temperatures that regularly exceed 45 °C. However, evidence shows that palaeoclimatic conditions in Oman during the Quaternary were considerably more humid. Clark and Fontes (1990) established that the area experienced a wet period extending from the Late Pleistocene to 19 ka BP, followed by a period of hyperaridity from ca. 16.3 ka to 13 ka BP. A

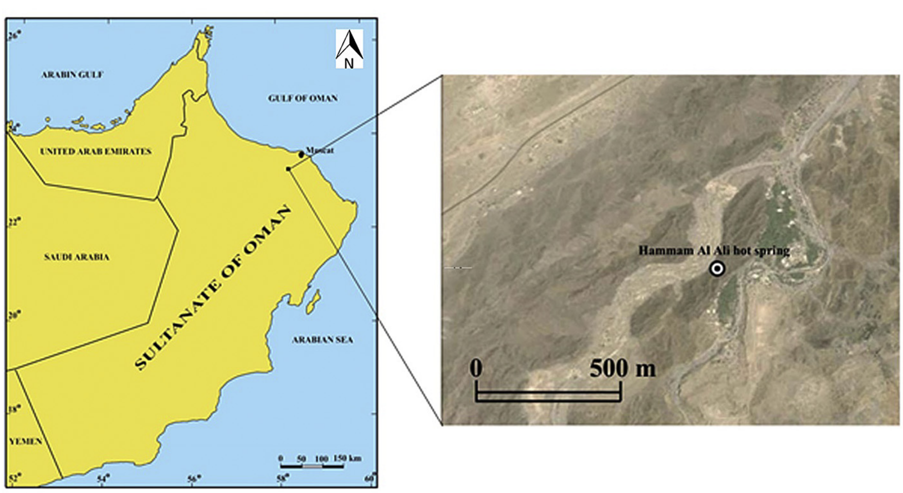

Fig. 1. Location of the Hammam Al Ali hot spring.