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# The genesis of actively growing siliceous stromatolites: Evidence from Lake *Specchio di Venere*, Pantelleria Island, Italy

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ABSTRACT

This study documents the attributes of siliceous stromatolites growing in the Lake *Specchio di Venere*, on the volcanic island of Pantelleria, Italy, in a setting characterized by very shallow cold waters and pools and by scattered hydrothermal activity, which exhales mainly $CO_2$, at emission point temperatures of 34 to 58 °C. The saturation indexes indicate that the lake waters are saturated with respect to tridymite, cristobalite, chalcedony and quartz, and slightly undersaturated with respect to amorphous silica. Common roughly laminated and poorly lithified stromatolites show scanning electron microscope (SEM) evidence for silicified microbial mat structures, including biofilms, filamentous and coccoid cells, and extracellular polymeric substances (EPS). The screening of bacterial 16S rRNA libraries indicates that autotrophic and heterotrophic bacterial communities colonize surface and core levels of the stromatolites. Locally the stromatolites show a granular non-porous fabric, where filaments and silica sheets are not apparent. Inhomogeneity in the stromatolite fabric corresponds with varying DNA content and different structures of the colonizing bacterial communities, non-porous stromatolite levels being microbially colonized to a lesser extent. Based on Fourier Transform (FT)–Raman and FT-infrared investigations, the laminated stromatolite contains early diagenetic tridymite in addition to amorphous silica (opal-A), whereas the non-porous stromatolite shows an essentially amorphous character. The laminated stromatolite is thought to form at relatively low rates of silica precipitation and with a possible microbial mediation in terms of microbial cells and their EPS accelerating the onset of amorphous silica nucleation. It is suggested that high porosity probably favoured a consistent flux of silica-rich fluids that triggered the opal-A to tridymite transformation, thus strengthening the preservation of biosignals. Non-porous stromatolite growth could reflect temporal or localised changes in environmental conditions that caused variations in the degree of silica saturation in the lake waters inducing abiotic silica accumulation. Accelerated opal-A deposition could have obscured primary filamentous fabrics and limited the flux of pore fluid needed for sustaining the process of silica maturation.

## 1. Introduction

Stromatolites (i.e. laminated microbialites) are organosedimentary deposits produced by the mediation of growth and activity of microorganisms. Cycling microbial communities facilitate mineral precipitation, trap and cement small grains with extracellular organic material, and promote lithification (Kalkowsky, 1908; Awramik, 1984; Burne and Moore, 1987; Reid et al., 2000; Tucker, 2001; Baumgartner et al., 2009; Budakoglu, 2009). They were common in the Precambrian and represent some of the earliest macroscopic evidence of life in the fossil record (Schopf, 1993), potentially containing important paleoenvironmental and biological information (Andres and Reid, 2006). Living, modern stromatolites are considered their contemporary analogues based on morphology and hence their study has the potential to elucidate the mechanisms of colonization of the early Earth.

The most widespread modern and fossil stromatolites display carbonate compositions, and numerous studies have recognized the biogenically mediated origin of specific mineralized fabrics, textures, and mineral assemblages (Reid et al., 2000; Riding, 2000; Webb and Kamber, 2000; Van Lith et al., 2003, Allwood et al., 2006; Olivier and Boyet, 2006; Cavallazzi et al., 2007). Siliceous stromatolites have been reported from many active geothermal systems (Campbell et al., 2002; Rodgers et al., 2004, Handley et al., 2005; Jones et al., 2005; Handley et al., 2008). In these settings microbial activity can result in microbial fossilization, chemical sediment formation, and silica transport (Yee et al., 2003; Benning et al., 2004a, b; Konhauser et al., 2004; Handley et al., 2008), although the precise role of

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microorganisms in silica precipitation and its diagenetic maturation is incompletely known. Mechanisms invoked have included processes acting in modern hot spring settings at moderate to low temperatures (less than 73 °C), where microbial activity is common (Handley et al., 2005). Even if there is no evidence to suggest that prokaryotes actively precipitate silica (Walters et al., 1977; Mountain et al., 2003; Konhauser et al., 2004), functional groups on their cell walls and within extracellular polymeric substances (EPS) are thought to provide reactive sites for biologically passive silica deposition followed by autocatalytic silica polymerization (Krumbein and Werner, 1983; Urrutia and Beveridge, 1993; Westall et al., 1995; Konhauser and Ferris, 1996; Farmer, 1999; Phoenix et al., 2000; Benning et al., 2004a, b). Silica accumulation has been demonstrated to be proportional to the availability of electrostatically favourable substrates (Rimstidt and Barnes, 1980; Fleming, 1986) provided by a filamentous network (Nicholson and Aquino, 1989; Handley et al., 2005). In contrast, possible abiotic mechanisms refer to silica precipitation induced by (1) rapid cooling to ambient temperatures, (2) changes in pH, and (3) increased silica oversaturation and polymerization caused by combined cooling and evaporation or by wind-induced waves providing subaerial transport of silica charged waters (White et al., 1956; Iler, 1973; Brown and McDowell, 1983; Mroczek and Reeves, 1994; Jones et al., 1997; Renaut et al., 1998; Mountain et al., 2003; Handley et al., 2005). Whether microbial surfaces play a crucial role in silica fixation or have a negligible effect on silica nucleation is still controversial. There is however agreement on the need to further investigate mechanisms that control silica–microbe interactions (e.g., Yee et al., 2003).

Actively growing siliceous stromatolites have been recently found in the Lake *Specchio di Venere*, on the volcanic island of Pantelleria, Italy (Fig. 1), in a setting characterized by very shallow cold waters and pools and by scattered hydrothermal activity. Owing to their extensive deposition, variable morphology, association with a saline lake ecosystem the stromatolites have the potential to provide new insight into the processes involved in the microbial fossilization and to enhance recognition of geobiologically relevant imprints in ancient rocks. In this paper, we use an integrated approach combining petrographic, geochemical, mineralogical and molecular microbiology studies with the aim of contributing to the understanding of biotic and abiotic factors controlling the initial growth and the early diagenetic transformation of the silica stromatolites.

## 2. Geological setting and lake features

The island of Pantelleria is a quiescent strato-volcano located in the Strait of Sicily, about 100 km SW of Sicily and 70 km NE of Tunisia, on the axis of the Sicily Channel Rift Zone (Fig. 1). The island is entirely covered by volcanic products from both effusive and explosive activity, with dominant peralkaline rhyolites ("pantellerites") and trachytes and minor alkali basalts (Civetta et al., 1984). At present, volcanic activity is limited to low temperature fumarolic emissions and thermal springs reaching temperature up to 90 °C (Parello et al., 2000; Favara et al., 2001; Aiuppa et al., 2007). Many of these hydrothermal rises occur in the north-east island sector, particularly in the area of Lake *Specchio di Venere*. This is an endorheic lake located inside a calderic depression (Caldera Cinque Denti, Fig. 1) which has a sub-circular shape, being *ca* 450 m long and *ca* 350 m wide, and a maximum depth of 12.5 m (Bocchi et al., 1988) with steeper slopes in its north-eastern zone (Fig. 2A). The surface area is strongly controlled by the rainfall rate, varying from 136.000 to *ca* 200.000 $m^2$ (Aiuppa et al., 2007). In addition to runoff, the lake receives a contribution from the thermal aquifer and loses the water surplus through seepage to groundwater (Aiuppa et al., 2007). Hydrothermal activity, exhaling mainly $CO_2$ (98%) together with low percentages of $N_2$, $O_2$, Ar, $CH_4$, $H_2$ and He (D'Alessandro et al., 1994; Parello et al., 2000; Aiuppa et al., 2007) affects the south-west lake shoreline in proximity to the intersection of the underground water table with the topographic surface. At the emission points, temperatures are between 34 and

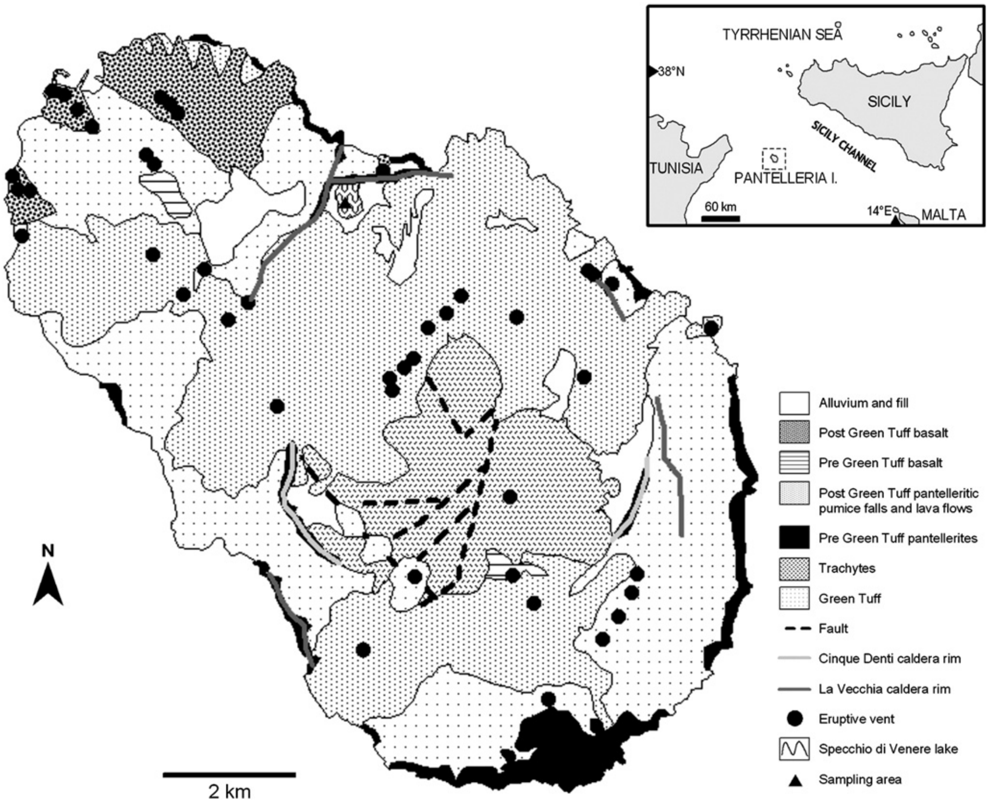

**Fig. 1.** General geological setting of Pantelleria Island, Italy (simplified from Rotolo et al., 2007) showing the location of the sampling area.