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Laminae development in opal-A precipitates associated with seasonal growth of the form-genus *Calothrix* (Cyanobacteria), Rehai geothermal area, Tengchong, Yunnan Province, China

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ABSTRACT

The western discharge apron at Meinuquan (Rehai geothermal area, Yunnan Province, China), which incorporates the upper terrace, terrace front, and lower terrace, is covered with laminated opal-A precipitates that have formed from the spring waters that flow across its surface. Laminae are formed of silicified *Calothrix* mats or featureless opal-A that contains no microbes, scattered spherical and rod-shaped microbes, and/or rare *Calothrix*. Rapid silicification of the *Calothrix* led to preservation of their basal heterocysts, vegetative cells, trichomes, tapering filaments, and laminated and splayed sheaths.

The *Calothrix* mats grew during the dry season when there was maximum sunlight because of low cloud cover. During this time, the mats grew under stable conditions because the water that flowed across the discharge apron was sourced from the springs, and temperature and water geochemistry was more or less constant. Growth of the *Calothrix* mats decreased during the wet season (April to late September) when sunlight is reduced due to the extensive cloud cover associated with the monsoonal rains. During the wet season, water flowing over the discharge apron is a mixture of rainwater, runoff from the surrounding hillsides, and spring water. Such variable flow conditions, water temperatures, and water geochemistry curtailed microbe growth and impacted silica precipitation.

The precipitates at Meinuquan are like those associated with some Icelandic hot springs. Although growth of *Calothrix* is controlled by sunlight in both settings, the periods of maximum sunlight in China (October–March) and Iceland (June–August) are at different times of the year because of their geographic locations.

1. Introduction

The form-genus *Calothrix*, first described and defined by Agardh (1824), is a common filamentous cyanobacterium found in modern spring systems throughout the world, including those in Yellowstone National Park (Weed, 1889; Tilden, 1897, 1898; Copeland, 1936; Norris and Castenholz, 2005), Iceland (Konhauser et al., 2001), New Zealand (Cassie, 1989), India (Roy et al., 2014), and Bulgaria (Lukavský et al., 2011). Although some species of *Calothrix* can survive in water temperatures up to 52–54 °C (Castenholz, 1969, his Table 3; Colwell and Fuentes, 1975, their Fig. 2), most thrive where the water temperatures are in the 20–40 °C range (Copeland, 1936; Nash, 1938; Walter, 1976; Cady and Farmer, 1996; Walter et al., 1996). Many other environmental factors also influence the growth and development of *Calothrix*, including UV radiation (Brenowitz and Castenholz, 1997; Dillon and Castenholz, 2003; Dillon et al., 2003; Norris and Castenholz, 2005). *Calothrix* has commonly been used to assess microbe silicification because naturally silicified specimens are abundant (Hugo et al., 2011) and this cyanobacterium is susceptible to silicification under controlled laboratory conditions (Phoenix et al., 2000, 2002; Yee et al., 2003; Benning et al., 2004, 2005).

This study focuses on laminated opal-A deposits that cover a the Meinuquan (Beauty Spring) hot-spring discharge apron that is located in the Rehai geothermal area, which is situated ~13 km southwest of Tengchong in the Yunnan Province of China (Fig. 1). The stratigraphic architecture of these opal-A deposits is fundamentally controlled by the silicification of the *Calothrix* mats that thrived on this discharge apron. Using these samples, this paper focuses on (1) preservational aspects of *Calothrix* from different parts of the discharge apron, (2) the significance of the pigmentation that is evident in the silicified sheaths of some of the *Calothrix*, and (3) interpretation of the cyclic alternation between laminae formed of silicified *Calothrix* and laminae devoid of

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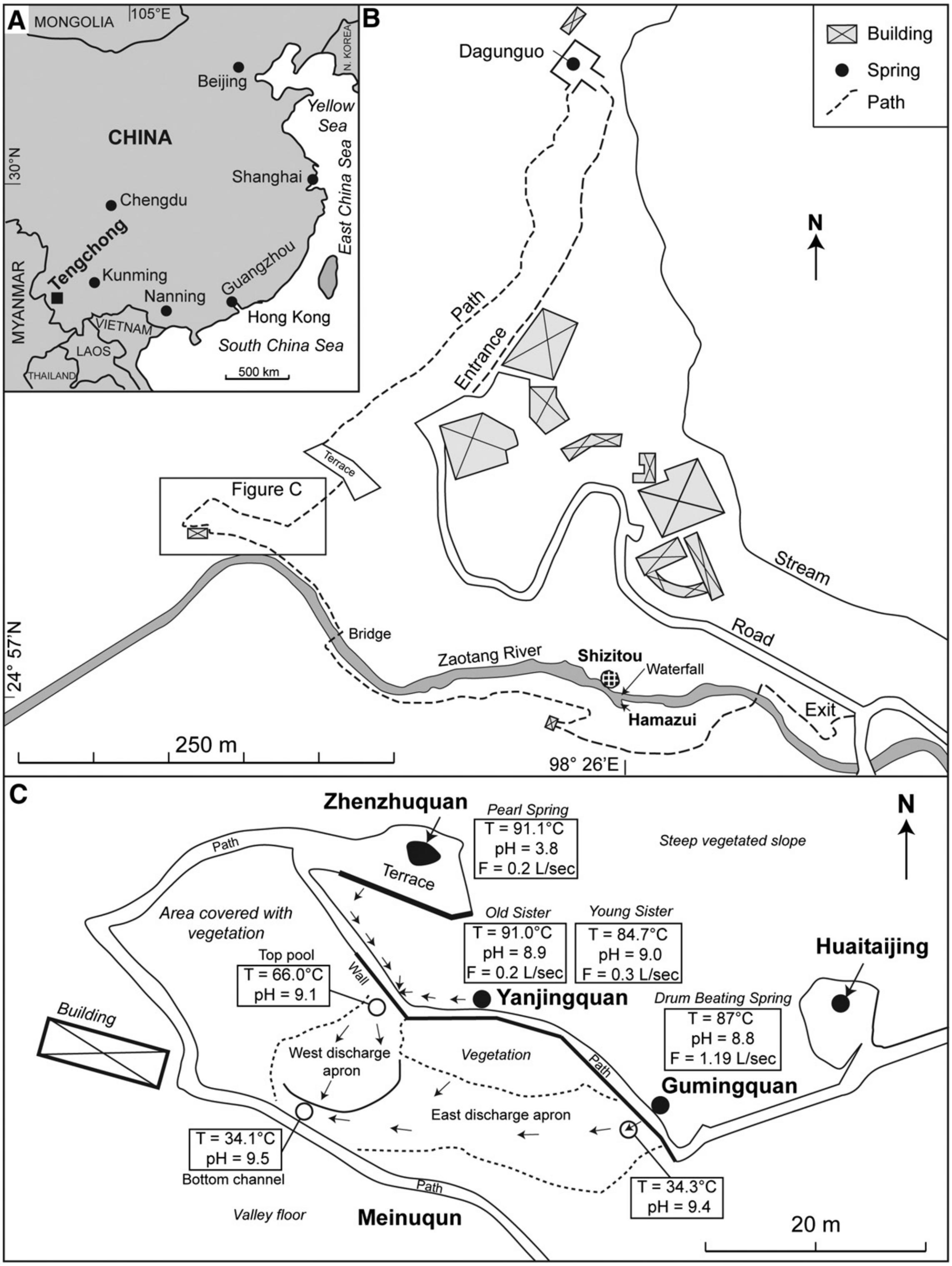

Fig. 1. (A) Location of Tengchong in western China. (B) Map of Rehai geothermal area, located about 13 km SW of Tengchong, showing locations of main springs. (C) Map of Meinuquan area (see panel B) showing location of Gumingquan, Yanjingquan, and Zhenzhuquan springs along the north margin that discharge water onto the main discharge area. The discharge apron is topographically divided into the east and west segments (see Fig. 2). Small black arrows indicate water flow directions based on observations in the field. Water temperatures (T) and pH shown for each spring were measured on April 28, 2013. Flow rates (F) provided by Rehai Geothermal area.

Calothrix. Through careful examination of the textures in the siliceous sinters, this research shows that the dry season, which is characterized by low rainfall and low cloud cover but many hours of sunshine, encouraged growth of the *Calothrix* mats whereas the onset of heavy rain and reduced hours of sunlight in the wet season led to the death of the *Calothrix* mats.

2. General setting

2.1. Geological setting

The Rehai Geothermal Field (Fig. 1B), characterized by numerous active springs with highly variable water temperatures, pH values,