Journal of Asian Earth Sciences 134 (2017) 281–292

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Full length Article

Microclimatic, chemical, and mineralogical evidence for tafoni weathering processes on the Miaowan Island, South China

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ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form 26 September 2016
Accepted 21 November 2016
Available online 23 November 2016

Keywords:
Tafoni
Microclimate
Chemistry
Mineralogy
Miaowan Island, China

ABSTRACT

Tafoni were widely distributed around the world; however, their processes of development remain unclear. In this study, the roles of microclimatic, geochemical and mineralogical processes on tafoni development along the subtropical coastline of the Miaowan Island, south China, are investigated. Field observations were carried out during three visits to the island over a four-year period (2011–2015). The orientation of 184 tafoni openings were measured, and micrometeorological changes of three tafoni on opposite sides of the island were monitored by pocket weather trackers (Kestrel 4500) in two periods. Samples of residual debris inside three tafoni hosted in a large boulder, the parent rock of the tafoni, and from the weathering profile of a nearby bedrock outcrop were collected for X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses. The field observations showed that tafoni were of different sizes and constantly produced flakes and debris inside the tafoni caves, indicating their on-going active development. An increase in Na in residual debris in tafoni caves on the Miaowan Island is the most obvious evidence of salt weathering. Salt weathering inside tafoni caves is not intense and does not match the salt-rich environment outside the caves, indicating that the influence of salt is not strong. The loss of K, Ca, and Mg in the residue samples, and the appearance of the clay mineral montmorillonite are caused by chemical weathering. Most of the tafoni openings face mountains, demonstrating the effect of humidity in tafoni weathering. Tafoni cave shapes are related to the distribution of humid water vapour, which tends to collect at the top of the cave, and leads to more intensive development here than in other parts. Drastic daily changes in relative humidity inside tafoni caves accelerate mechanical weathering owing to swelling and shrinking of salt and clay minerals. The Miaowan Island tafoni are formed by weathering, but they cannot be simply interpreted as the product of a single weathering process.

1. Introduction

Tafoni (tafone is the singular noun for a single cavern) are a type of cavernous weathering widely distributed across the world. Tafoni usually develop on inclined or vertical rock surfaces and occur in groups. The most accepted morphological characterizations of tafoni are probably cavities with arch-shaped entrances, concave inner walls, overhanging visors, and debris-covered floors (Cook et al., 1993; Mellor et al., 1997; Goudie, 2004). Since such geographical terms as "cavernous weathering", "alveolar weathering", "honeycomb weathering", and "tafoni" are not precisely defined, it is sometimes quite difficult to tell them apart in terms of their physical form (Trenhaile, 1987). In this study, use of the term tafoni incorporates similar features such as "cavernous weathering", "honeycomb weathering", and "tafoni" found in the study area. Over the past centuries, tafoni have been found in different climatic environments, such as Mediterranean sites (Reusch, 1882; Mellor et al., 1997; Hejl, 2005), arid deserts (Smith, 1978; Viles, 2005), temperate regions (Paradise, 2013), and Antarctica (Guglielmin et al., 2005; Hall and André, 2006). Tafoni are also distributed in coastal areas (Gill et al., 1981; Mottershead and Pye, 1994; Matsukura et al., 1999; Hejl, 2005). At geological timescales, tafoni may be partially responsible for rapid coastal landscape retreat. Gill et al. (1981) estimated that tafoni weathering processes were responsible for 10% of all coastal retreat. Tafoni occur on different kinds of substrates, most commonly on granular rocks, such as granite (Dragovich, 1969; Strini et al., 2008), sandstone, conglomerate, and tuff (Mellor et al., 1997; Matsukura et al., 1999; McBride and Picard, 2000), and to a lesser extent on other kinds of rocks, such as various metamorphics (Kejonen et al., 1988) and limestone (Smith, 1978; Norwick and Dexter, 2002).

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http://dx.doi.org/10.1016/j.jseaes.2016.11.023
1367-9120/

A variety of theories have been used to explain the formation and development of tafoni (Bradley et al., 1980; Norwick and Dexter, 2002). Tafone weathering mostly develops in salt-rich regions such as arid deserts and coastal areas. Hence, salt weathering was traditionally believed to be the main cause of tafone formation and growth (Mustoe, 1982; McGreevy, 1985; Young, 1987; Matsukura and Matsuoka, 1991; Cook et al., 1993; Mottershead and Pye, 1994; Mellor et al., 1997; McBride and Picard, 2000; Strini et al., 2008). However, Campbell (1999) has suggested that salt weathering does not play a major role in the formation of tafoni. Chemical weathering and differential mineral weathering processes have also been regarded as general causes of tafone development (Dragovich, 1969; Mellor et al., 1997). In polar regions, erosion and abrasion by ice have been used to explain tafoni formation (Blackwelder, 1940). Recent studies suggested that thermal stresses in Antarctica and valley wind deflation in China could be important contributors to tafone development (Hall and André, 2006; Strini et al., 2008; Zheng et al., 2009).

This study focuses on the roles of microclimate, geochemical composition, and mineralogy in the weathering processes that contribute to tafoni formation on the Miaowan Island, southern China. The study concludes that the Miaowan Island tafoni are in a state of active development and constantly produce debris. Tafoni formation is not simply related to a single cause, such as a salt-rich environment, because salt weathering intensity inside the tafoni is far lower than that outside. High relative humidity inside the cave is the main cause of chemical weathering. It leads to the loss of K, Ca, and Mg in tafoni residues, and to the appearance of the clay mineral smectite. Marked daily changes in the water vapour content inside a cave leads to swelling (mechanical disruption) of smectite and salt crystals. The process of tafoni cave shaping is related to weathering variations caused by differential distribution of water vapour inside the cave.

2. Study area

Miaowan Island (21°52′N, 114°01′E) is located in the northern part of the South China Sea, approximately 48.8 km south of Hong Kong (Fig. 1). The island covers an area of 1.437 km^2 and the climate is monsoonal subtropical, with warm-dry winters and hot-wet summers. There is no weather station on the island; therefore, weather data were obtained from the nearest meteorological station on the Cheung Chau Island, Hong Kong,[1] which is located 36 km from the Miaowan Island. Annual average rainfall in the study area is 1583 mm, with approximately 80% between May and September, the mean temperature ranges from 15.8 °C in January to 27.7 °C in July, and the prevailing wind directions are 90–120° and 0°, which correspond to SE and north, respectively. Miaowan Island is mostly hilly and steep, with slopes between 30° and 60°, and the maximum altitude of 228 m (Fig. 1). Geologically, the island mainly comprises coarse-grained Yanshanian biotite and porphyritic granite, with small outcrops of migmatitic granite and basalt (Huang et al., 1985). A total of 184 tafoni were identified in this study. The tafoni are developed in groups on the vertical surfaces of boulders and/or bedrock in a narrow belt in the central Miaowan Island and are distributed in five sites, marked on the map in the alphabetical order from A to E (Figs. 1 and 2). Tafoni of A and B are developed on two separate large boulders while tafoni of C, D, and E are developed on bedrock.

[1] Hong Kong Observatory http://gb.weather.gov.hk/cis/regionc.htm.

3. Study methods

3.1. Field work

The orientation of 184 tafoni openings was measured with a geological compass at five sites on the island. Tafoni A1 and A2, positioned on a large boulder at site A on the northwestern coast, and tafone E1, at site E on the southeastern coast of the island (Figs. 1 and 2a and b), were selected for the location of pocket weather monitors (Kestrel 4500) to detect external and internal meteorology of tafone caves. Tafoni A2 and E1 were measured in two time periods: 12–14 April 2012 and 1–14 January 2015. Tafone A1 was also measured in two time periods: 10–12 April 2012 and 1–16 January 2015. Variations in external and internal meteorological indices (such as temperature, relative humidity, and wind speed) of each tafone were detected by two monitors, the locations of which are shown in Fig. 3b and c. Three sensors were installed at different positions of the internal surface of tafone A1 (visor, lip, and backwall near the top) to detect differences in relative humidity (Fig. 3a). Temperature, relative humidity, and wind speed were measured at 10 min intervals. The measurement ranges and accuracies of the Kestrel 4500 are −45 to 125 °C ±1 °C for temperature, 0–100% ±3% for relative humidity, and 0–60 m/s ±3% for wind speed. Rainfall was recorded as events within the monitoring periods.

Very few studies of tafoni development have examined tafoni interior residual debris (Matsukura and Tanaka, 2000), and none have directly sampled fresh debris accumulation within a known time period. During field investigation, one weathering crust profile sample, three tafoni residue samples, and one tafoni parent rock sample were collected. The weathering crust sample was collected from 1 m above a profile on the northern slope of the Miaowan Island (40 m asl), which dark red[2] (Fig. 2a and h). The three tafoni residues samples (e.g. A1, A2, and A3) were collected from inside the tafoni cave at location A. The tafoni parent rock sample was collected from the surface rock of the boulder on which tafoni A1, A2, and A3 are developed. The samples of tafoni residue, parent rock, and weathering crust profile collected from the field were analysed for their major element and mineral contents. Tafone A2 was initially cleaned by removing all the residual debris piled up on the cave floor in the first survey of the island on 23 October 2011. New debris that accumulated inside the cave was collected on 9 April 2012, and 31 December 2014. Debris collected from the two sampling periods was dried and weighed to determine the quantity produced in each period. In addition, the extent of biological activity (e.g. lichen growth) and the occurrences of salt in the tafoni caves or on the surface of bedrock were also recorded in the field.

3.2. Laboratory analysis

3.2.1. Major element analysis

The major elements (oxides) of samples taken from debris inside the tafoni (A1, A2, and A3), the parent rock, and the weathering profile were analysed by means of X-ray fluorescence using a Rigaku XRF instrument (model ZSK 100e) at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The following steps were conducted for the major elements analysis. The samples were ground and sifted through a 200-mesh screen and dried in the oven at 105 °C. They were then baked in a high-temperature oven at 920 °C, and the LOI (loss on ignition) of samples was determined. A certain number of burnt samples were mixed with alkaline reagents (Li28407) at a ratio of 1:8. The mixture was placed in

[2] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.