Geomorphology 211 (2014) 43–51

Contents lists available at ScienceDirect

Geomorphology

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

A new sand-wedge–forming mechanism in an extra-arid area

Hongshou Li [a,b,*], Wanfu Wang [a,b], Fasi Wu [a,b], Hongtao Zhan [b], Guobing Zhang [a,b], Fei Qiu [b]

[a] The Conservation Institute of Dunhuang Academy, Dunhuang, 736200 Gansu, China
[b] National Research Centre for Conservation of Ancient Wall Paintings, Dunhuang, 736200 Gansu, China

ARTICLE INFO

Article history:
Received 10 September 2013
Received in revised form 26 December 2013
Accepted 27 December 2013
Available online 7 January 2014

Keywords:
Landmarks
The Mogao Grottoes
Polygon structures
Salts
Water

ABSTRACT

A survey found that sand wedges are widely distributed in the extremely extra-arid Gobi region of Dunhuang, China. The sand wedges are still developing. Well-developed sand wedges are surrounded by polygonal areas showing fractal structures. The depth of a well-developed sand wedge is 50–60 cm and its maximum width is 50–60 cm, so the depth/width ratio is 1.0. The interface between the wedge and matrix is arc-shaped. The mechanical composition of the sand wedges compared to the matrix is such that 76.72% of the particles have diameters ≤0.25 mm and show vertical sand laminations in the sand wedge, while 55.19% of the particles in the matrix are ≥2.00 mm in diameter. The particle diameters are consistent with the width of the sand-wedge fractures. The salt content in the sand wedges is 3.13 g/kg, while that of the matrix is 40.86 g/kg. The large salinity difference shows that the sand in the wedges comes from drift sand or cladding layers where salinity is lower, and that the sand wedge was formed in an arid climate. Displacement and pressure are closely associated with the daily temperature variation; they fluctuate significantly following the temperature. Measurements reveal the movement of thermal-contraction fissures. Pressure monitoring identified that wet expansions occurred after rainfall, which made the sand wedges become tightly joined to the matrix. Following this, as the soil became desiccated and shrank, a crack opened in the middle of the sand wedge. This was then filled with drift sand. With the next rainfall, the system moved into another development cycle. The current article reveals a new mechanism for forming sand wedges in extra-arid conditions. Arid sand wedges are a unique drought-induced surface landmark resulting from long-term, natural, dry-climate processes.

1. Introduction

Sand wedges are widely distributed in the cold tundra of high northern and southern latitudes near the poles (Black, 1976; Washburn, 1979; Andersland and Ladanyi, 1994; Marchant et al., 2002). Sand wedges are generally believed to be a result of chill-induced splits filling with sand, a process which repeats with the cycles of freezing and thawing year-by-year in frigid climates (Bockheim et al., 2009a,b). A sand wedge is one of the most important materials for paleoclimate reconstruction (Mears, 1981; Liang and Cheng, 1984; Wang and French, 1991; Murton, 1996; Adam et al., 2002; Murton and Bateman, 2007; Bateman et al., 2010).

When sand wedges were found to be widespread in mid-latitudes, the observation became important evidence in the judgment of the southern/northern edges of the periglacial regions in the late Pleistocene in the northern/southern hemispheres (French et al., 2003; Kovács et al., 2007). In China, sand wedges have been found in Daxinganling in northeastern China (Guo and Li, 1981), in the southern Ordos Plateau in Inner Mongolia (Dong et al., 1985, 1996; Cui et al., 2004), in the Datong Basin of Shanxi Province in northern China (Yang et al., 1983), in the Hexi Corridor area (Cui and Song, 1992; Wu et al., 2007), and the 'Third Pole' in northwestern China, as the Tibetan Plateau is often called (Guo, 1979; Pan and Chen, 1997; Shi et al., 1997; Chang et al., 2011). Where sand wedges have been found, they are generally thought to belong to the places where the periglacial southern edge existed in the late Pleistocene.

Along with the fact that sand wedges have been found in low latitudes near equatorial areas of Australia and northern Africa (Deynoux, 1982; Williams and Tonkin, 1985; Sohl et al., 1999), such observations are seen as key evidence in favor of the Snowball Earth hypothesis (Williams, 1975, 2001).

In order to more exactly reconstruct paleoclimate using sand-wedge data, the latter's formation mechanisms and formation conditions have been studied using dynamics (Lachenbruch, 1962), mechanics (Kaplar, 1963; Rist et al., 1999), model experiments (Li and Yang, 2000; Adam et al., 2002), electromagnetic induction (Singleton et al., 2010), paleodosing (D_e) (Bateman et al., 2010), etc. The temperature of formation of sand wedges has been tested by Romanovsky in the Siberian tundra, which is used as the basis for reconstructing paleoclimate (Wang et al., 2001, 2003). Bockheim et al. (2009a,b) believe that the sand wedges only form in Antarctica today when the mean annual air temperatures are −4 to −8 °C or colder. But Murton et al. (2000) advocate that care and caution are required in the use of ancient/relict primary sand-wedge data as quantitative paleoenvironmental indicators

* Corresponding author at: Dunhuang Academy, Dunhuang, Gansu Province 736200, China. Tel.: +86 937 8869046; fax: +86 937 8869103.
E-mail address: dhlhs69@163.com (H. Li).

0169-555X/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.12.028

because the modern active wedge distribution is still poorly known. Hence, they infer that the thermal climatic threshold values are questionable. We also think that all of these traditional studies are based on *wet* soil, which can freeze into ice as a precondition. In a periglacial climate, repeated freezing and thawing are the bases of sand-wedge formation. However, in recent years, we have found well-developed sand wedges in the dry Gobi Desert location of the famous Dunhuang Mogao Grottoes in China, where the climate has been in a state of drought since the last glacier disappeared (Liu, 2009). Further investigation found that sand wedges lurk in far-ranging locations in the Gobi Desert of the Dunhuang, which are developed to different levels and are still developing. Moreover, exploration has found that polygon vein structures exist on Mars as well as on Saturn's moon, Titan, and other planets (Mellon, 1997; Siebert and Kargel, 2001; Levy et al., 2009; Buczkowski et al., 2012). This suggests that other ways of forming such structures are possible apart from the freeze–thaw mechanism, i.e., other formation ways probably exist in extra-arid areas.

In addition, we found that deep-buried phreatic water evaporation occurs in extra-arid areas (Li et al., 2010a,b), and salt sources on the Gobi surface have been revealed. The salts come from deep underground as a result of groundwater migration — when the water evaporates, the salts are left in the soil and thus accumulate in the land's surface. They become a foundation material for a binder that is different from ice (Bockheim, 2007; Bockheim et al., 2009a,b). They can combine and consolidate loose gravel together and then, along with wet soil expansion and shrinking upon drying, form cracks.

Recently, soil researchers have made great progress in their field concerning expansion and contraction under alternating dry and wet conditions (Xiong et al., 2006; Huang and Shao, 2008). Shao and Lu (2003) presented a model to identify the relationship between a contracting feature index and the physical qualities of soil (Lu and Shao, 2003; Shao et al., 2007). A wet soil study indicated that lateral expansion occurs in wet sand soil (Luo and Fu, 2007). These studies have provided a new research platform for studying the formation of arid sand wedges. Thus, we suggest that sand wedges in extra-arid areas are formed by wet expansion when it rains and, following the polygon's dry shrinking, drift sands or surface sands entering into the cracks so developed. In this study, we describe and characterize sand-filled wedges and polygon matrices and propose a new descriptive model for their formation in extra-arid regions. Our proposals are based on detailed analyses of excavated sand wedges and rainfall experiments on wet expansion. By revealing the arid sand-wedge formation mechanism we hope to understand the historical landscape changes of the Mogao Grottoes and to provide a scientific basis for reasonable, accurate, and proper use of the unique landmarks formed by arid sand wedges.

2. Study areas

The city of Dunhuang is situated in the Eurasian heartland, at the Kumtag Desert fringe, where there are two modern alluvial fans (western and eastern). The Mogao Grottoes are located on the southern edge of the Dunhuang basin in the valley between the Sanwei and Mingsha mountains, in the Gansu Province of northwest China. The study areas are shown in Fig. 1. The main research region is a Gobi mesa located in the piedmont of Mingsha Mountain. It has an area of only about 10 km^2, and 0–60 cm of its depth is sand soil belonging to the Gobi

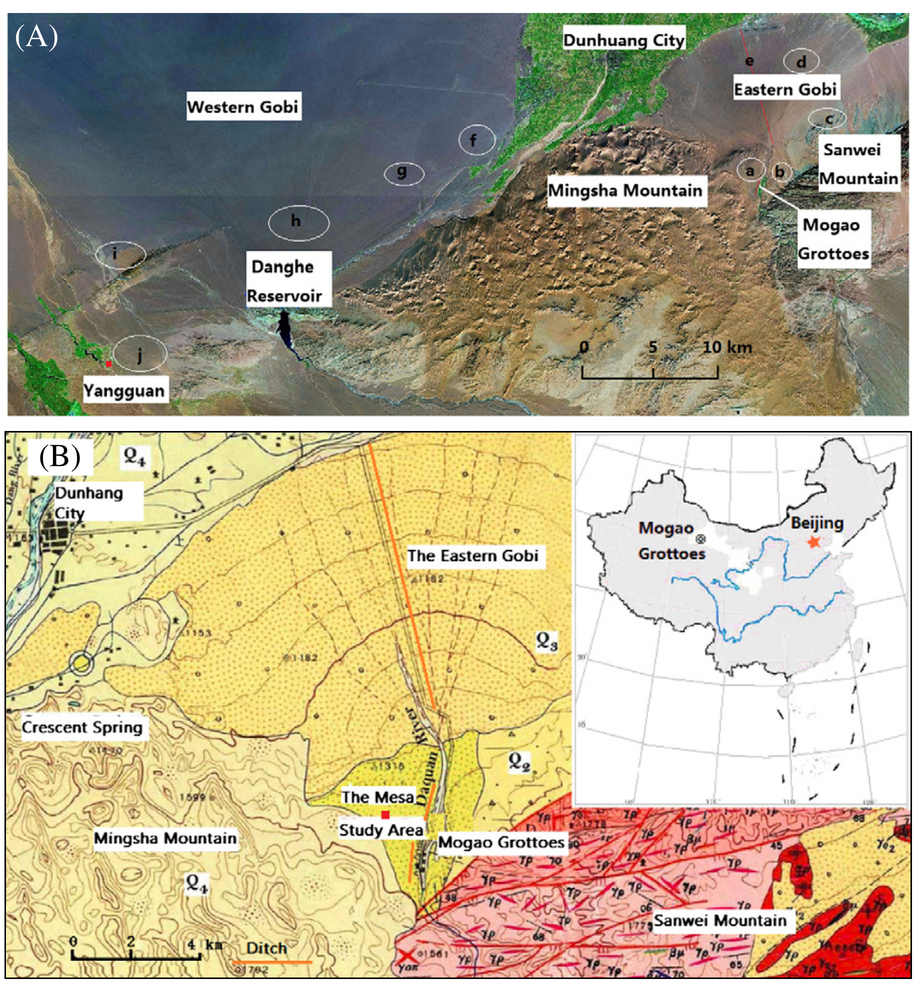

Fig. 1. The surveyed areas (A) and the geography around the Mogao Grottoes (B).