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Distribution patterns and morphological classification of climbing dunes in the Qinghai-Tibet Plateau

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ABSTRACT

In this study, the climbing dunes in the Qinghai-Tibet Plateau were digitalized through Google Earth images and field examinations in order to facilitate the investigation of their distribution patterns and to allow their classification. The results of this study showed that the total area covered by climbing dunes in the Qinghai-Tibet Plateau is about 30,075 km^2, which represents 7.5% of the total area of aeolian landforms in the plateau, and 1.15% of the entire plateau area. The climbing dunes of the Qinghai-Tibet Plateau were densely distributed in the Qaidam Basin, Gonghe Basin, Kumukuri Basin, foothills of the Qilian Mountains, foothills of the Altun Mountains, and the Southern Tibet Valley. Sporadic distributions were also observed in the river and lake basins of the Hengduan Mountains, Qiangtang Plateau, and the Ali Plateau. The average climbing height of the climbing dunes in the Plateau was 191 m, with the maximum and minimum climbing height being 1416 m and 3 m, respectively. Based on morphogenetic principles, we have established a classification diagram for climbing dunes of the Qinghai-Tibet Plateau; on going from the base of a slope to the crest, the morphologies of the dunes increased in complexity and the age of their formation grows earlier. The development of climbing dunes is related to interactions between wind regime, sand materials, dry climate, undulating terrain and accommodation space. The research results of the climbing dunes on the Qinghai-Tibet Plateau could contribute to the understanding of aeolian landforms.

1. Introduction

The Qinghai-Tibet Plateau (QTP) has received worldwide attention as a result of its unique geographical location and ecological environment. Over the past few decades, aeolian deposition landforms (dunes) have become increasingly pronounced in the Plateau owing to the combined actions of global climate change and human activity (Dong, 1999). The current area of aeolian geomorphology in the Qinghai-Tibet Plateau is approximately 400,000 km^2 (Zhang, 2009; Li et al., 2010; Dong et al., 2012; Li et al., 2016). The basic aeolian landforms of the Plateau (Wu, 2003) include mobile sands, semi-mobile sands, semi-anchored sands, and anchored sands, which cover an area of 140,000 km^2 (Wang et al., 2005). These are mainly located in the diluvial plains or alluvial fans of the following locations: the foothills of the Kunlun Mountains and Qilian Mountains within the Qaidam Basin (Wang et al., 2005; Chen et al., 2016), the source regions of the Yangtze River and the Yellow River (which includes the Gonghe Basin), the Ruoergai Basin (Dong et al., 2012), the Qinghai Lake Basin (Zhang, 2009), the intermountain basin of the Kunlun Mountains, the Kumukuri desert and its surrounding sporadic aeolian landforms (Li, 1991), the river and lake basins of Qiangtang and the Ali Plateau, vales in the upstream and midstream regions of the Yarlung Zangbo River and Lhasa River Valley, and the mid and downstream regions of the Pengqu River (Li et al., 2010). Among them, the widely distributed climbing dunes are the important manifestations of wind-sand movement of the Qinghai-Tibet Plateau (Li et al., 2010; Zhang, 2009).

Traditional dune geomorphology studies tend to concentrate on the formation mechanism and evolution process of dunes that are in area unaffected by terrain (Pye and Tsoar, 1990; Tsoar and Blumberg, 2002). However, the topographically influenced dunes are common in nature

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and topographically controlled accumulations of aeolian sand are found in many high-relief areas of desert regions. Complex topography can decelerate, accelerate and otherwise control the direction of the air or wind-blown sand flow. These changes in wind-blown sand movement lead to different erosion and deposition near the terrain, forming a variety of sand dunes, including echo dunes, climbing dunes, sand ramps, cliff-top dunes, falling dunes and shadow dunes (Evans, 1962; Cooke and Warren, 1973; Tsoar, 1983).

The concept of climbing dunes was firstly put forward when Hack (1941) described the aeolian landforms of Western Navajo in the United States. Bagnold (1941), the pioneer of blown-sand research, regarded these as a class of shadow dunes. Smith (1954)、Evans (1962) initially proposed the definition of climbing dunes and regarded the climbing dunes and falling dunes as a Climbing-Falling Dune System. Studies on climbing dunes have been undertaken in numerous parts of the arid world, such as Peru (Howard, 1985; Haney and Grolier, 1991), Sahara (Clos-Arceduc, 1967), Negev (Tsoar, 1983), and many localities in the Basin and Range Province of the western United States (Hack, 1941; Smith, 1954, 1978; Koscielniak, 1973; Tchakerian, 1991). It is found that sand accumulates in front of topographical barriers as a result of the deceleration of the wind and subsequent deposition. Tsoar (1983) revealed the formation mechanism of climbing dunes through wind tunnel experiments and found that when a topographical barrier is inclined, the size of the reverse-flow eddy decreases. However, when the slopes are great than 55°, the small reverse-flow eddies have no effect on the sand, thus forming a climbing dunes. Climbing dunes have the potential to provide detailed palaeoenvironmental records, such as palaeowind directions, precipitation, temperature and chronologies sequence (Thomas, 1997).

Besides, sand ramps are relatively widespread landforms in drylands regions which have the potential to provide rich palaeoenvironmental information and past sediment dynamics (Lancaster and Tchakerian, 1996; Rowell et al., 2018). Sand ramps and climbing dunes are regarded as part of a continuum of topographically controlled slope landforms because of the similar formation mechanism. They are formed by the accumulation of migrating sand on the upwind side of topographic barriers where aeolian sand transport paths across undulating terrain (Thomas, 1997). Sand ramp generally have gradients and are an amalgamation of aeolian sands, talus materials, fluvial and colluvial sediments, as well as palaeosols which were formed during geomorpgically stable periods (Lancaster and Tchakerian, 1996; Thomas, 1997; Bateman et al., 2012), however, climbing dunes are the purely aeolian topographic features and more mobile than sand ramps (Thomas, 1997). Since the Google Earth remote sensing images cannot distinguish between pure aeolian and mixed aeolian-slope forms (ramps), climbing dunes and sand ramps are sometimes interdigitated in the field. So we temporarily regarded sand ramps as generalized climbing dunes system in this paper.

Many desert geomorphologists consider that classification is a vital first step in the understanding and explanation of sand dune forms (Livingstone and Warren, 1996). At present, it mainly concentrates on the classification of inland aeolian landforms (Liu et al., 2008; Liu et al., 2012), coastal aeolian landforms (Dong, 2004, 2006), aeolian landforms in river valley (Li et al., 1997). The most extensive classification indicators are based on the wind characteristics, location, contributing factor, degree of stability, sediment provenance, structural characteristics, morphological, age and so on. There are few classification systems about topographically controlled slope landforms. Rowell et al (2018) initially put forward the classification schematic of sand ramps based on the presence/absence of morphological features such as: size, whether connected to hillslope, surface characteristics and presence of secondary dunes (Rowell et al., 2018). He divided the sand ramps into four categories, these results are groundbreaking and provide a guidance for the classification study of topographically controlled landforms.

In general, most of the studies which related to climbing dunes focus on inland (Evans, 1962; White and Tsoar, 1998; Li et al., 1997, 1999; Howard, 1985; Tirsch et al., 2012; Blight et al., 2013), coastal climbing dunes (Li et al., 2007) and Mars (Chojnacki et al., 2010, 2014). Their formation and mechanism, morphological characteristics, flow field characteristics and granularity features are mainly focus on small-scale simulation experiments and sporadic field observations, systematic research and broader distribution patterns of climbing dunes in the Qinghai-Tibet Plateau remain relatively scarce. we have conducted an investigation into the distribution patterns of climbing dunes in the Plateau by using Google Earth remote sensing imagery, based on a 1:100,000 map of deserts in China. In addition, we have constructed a climbing dune database for the QTP. The findings presented in this work provide basic data for subsequent studies on the dynamics and formative processes, the relationship between the formation of climbing dunes and the river, the mechanisms of their formation and evolution, while also serving as a scientific framework for the refinement of studies on environmental conservation, regional anti-desertification projects, and the desertification of the Plateau.

2. Overview of the study area and research methodology

2.1. Study area

The Qinghai-Tibet Plateau is located in the southwestern region of China. It is both the largest plateau in China and the highest plateau in the world, and is often referred to as the “Roof of the World” and the “Third Pole” (Li et al., 2001). The plateau is surrounded by the Pamirs and Hindu Kush to the west, the Hengduan Mountains to the east, the Kunlun Mountains and Qilian Mountains to the north, and the southern edge of the Himalayas to the south. The average elevation of the plateau is more than 4000 m above sea level, and its total area is approximately 2,596,340 km^2. The QTP can be topographically divided into six regions: Qiangtang Plateau, the Southern Tibetan Valley, Qaidam Basin, Qilian Mountains, Qinghai Plateau, and the Sichuan-Tibet Gorge; these regions include large portions of Tibet and Qinghai, and some parts of Xinjiang, Gansu, Sichuan, and Yunnan. As a result of the high terrain, wide area, and the middle latitudes of the Plateau, its climate is characterized by strong sun and long hours of daylight, as well as low temperatures that exhibit a small annual range, but a large diurnal range. This region also has distinct wet and dry seasons; the winters are long, cold, and very windy, while the summers are wet and cool, with frequent hailstorms. The spatial distribution of rainfall is extremely heterogeneous in this region; rainfall decreases gradually from the southeastern region toward to the northwestern region, and significant differences in precipitation are observed between the southern and northern foothills of the Himalayas. The soils of the Plateau have distinct horizontal and vertical zonations, and alpine meadow soils and alpine desert soils are widely distributed throughout the region. The vegetation in this region includes the majority of vegetation types that are found in China, with the exception of the vegetation types typical for the Arctic tundra. The landscapes are dominated by alpine meadows and grasslands, and alpine deserts (Lu et al., 2017), which are physiologically wind-resistant and salt-tolerant.

2.2. Research methodology

The identification and extraction of climbing dunes based on field observations and Google Earth imagery includes three phases: (1) preliminary selection of study area or field observation site using Google Earth, (2) field observations, and (3) batch digitalization of the images. The preliminary image selection is based on a 1:100,000 map of deserts in China; areas with a high concentration of deserts, diverse dune types, and distinct dune morphologies were selected as regions for field observations. Each climbing dune was located via GPS, and its properties were recorded, including its geological characteristics, underlying topography, dune type, dune orientation, dune height, dune