Erg deposition and development of the ancestral Taklimakan Desert (western China) between 12.2 and 7.0 Ma

Richard V. Heermance1, Jozi Pearson1, Annelisa Moe1, Liu Langtao2, Xu Jianhong3, Chen Jie3, Fabiana Richter4, Carmala N. Garzione4, Nie Junsheng5, and Scott Bogue6

1Department of Geological Sciences, California State University Northridge, Northridge, California 91330-8266, USA
2Department of Prospecting Engineering, Hebei University of Engineering, Handan, Hebei, 056038, China
3State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, P.O. Box 9803, Chaoyang District, Beijing, 100029, China
4Department of Earth & Environmental Sciences, University of Rochester, Rochester, New York 14627, USA
5Key Laboratory of Western China's Environment System (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou, Gansu 730000, China
6Department of Geology, Occidental College, Los Angeles, California 90041, USA

ABSTRACT

The Taklimakan Desert in western China contains the second largest shifting sand desert on Earth. The onset of this desert formation has been debated between the Eocene, early Miocene, late Miocene, or Pliocene, with each hypothesis having profound implications for the climatic and tectonic evolution of this region. We provide stratigraphic evidence for desert formation based on a new 3800-m-thick stratigraphic section in the northwestern Tarim Basin. Magnetostratigraphy defines 50 magnetozones and constrains the age of these strata to between ca. 15.1 and 1.5 Ma. Fluvial and lacustrine strata at the base of the section change abruptly to eolian sandstone (~1100 m thick) at 12.2 Ma and persist until 7.0 Ma, implying development of an erg system that represents the ancestral Taklimakan Desert. The appearance of sand dunes at 12.2 Ma has no global climate parallel, and resulted from aridification in the rain-shadow behind a growing Tian Shan and Pamir that isolated the Tarim Basin.

INTRODUCTION

The Tarim Basin in northwest China contains the Taklimakan Desert, one of the largest erg systems on Earth. Ergs, also known as sand seas, are large regions (105–106 km2) where sand covers >20% of land area, and are typically unvegetated and arid desert environments (Wilson, 1973). The Tarim Basin formed between the Tibetan Plateau, Pamir, and Tian Shan orogens, and contains a 3–8-km-thick Cenozoic stratigraphy. Since the early Miocene, the fluvial and lacustrine Wuqia Group, Atushi Formation and Xiyu Formation have been deposited there (e.g., Heermance et al., 2007; Zheng et al., 2015), but there is little evidence for thick eolian deposits similar to that being deposited today, and thus the age of desert formation and associated aridification is unresolved. Thin (<100 m) eolian strata appeared as early as 39 Ma in the Tajik Basin (Tajikistan; Carrapa et al., 2015), isolated dunes are interpreted to be between 26.7 and 22.6 Ma at the Aertashi section in the southwestern Tarim Basin (Zheng et al., 2015), and Wang et al. (2014) interpret eolian strata intermittently throughout the Miocene in the Pamir-Tian Shan convergence zone (Fig. 1A). The first evidence of thick eolian successions, however, don’t appear until 7.0 Ma or 4.2 Ma at the Mazatagh section (M in Fig. 1A; Sun et al., 2009, 2011).

Shifts to eolian deposition resulted from the retreat of the Tethys seaway and/or global climate change in the late Eocene, or rain-shadow development behind the Pamir and Tian Shan at the Oligocene-Miocene and Miocene-Pliocene boundaries (e.g., Sun et al., 2011; Bosboom et al., 2014; Licht et al., 2014; Carrapa et al., 2015; Zheng et al., 2015; Bougeois et al., 2018). Mountain uplift would block westerly airflow and moisture, producing a rain shadow within the Tarim Basin (e.g., Caves et al., 2015). Although parts of the Pamir may have been high prior to 35 Ma, northward indentation and uplift was most pronounced after ca. 25 Ma, with pulsed episodes from 21–13 Ma, 20–16 Ma, 20–8 Ma, 25–16 Ma, and 6–0 Ma, depending on location (Sobel and Dumitru, 1997; Amidon and Hynek, 2010; Bershaw et al., 2012; Lukens et al., 2012; Thompson et al., 2015; Blayney et al., 2016). Similarly, the southwestern Tian Shan had pulsed deformation and uplift initiating at 25–20 Ma, with southward migration of deformation at 16.3, 13.5, and 4 Ma (Sobel et al., 2006; Heermance et al., 2007). This study provides new age constraints on eolian strata from the Tarim Basin, to test the hypothesis that growth of the Tian Shan and Pamir are linked to desert development.

RESULTS

Stratigraphy

Five of six described lithostratigraphic units within the WK section correlate with strata from the Kashgar Basin, and we define lithofacies after Heermance et al. (2007) (Fig. 1A). Details on stratigraphy are provided in the Data Repository and in Figure 2. Units include: 0–270 m: Wuqia Group Unit B, interpreted as meandering fluvial deposition; 270–318 m: Wuqia Group Unit C, interpreted as shallow lacustrine and playa; 318–525 m: Wuqia Group Pakabulake Formation, interpreted as meandering river and floodplain; 1698–3285 m: Atushi Formation (also called the Artux Formation), interpreted as channelized fluvial and floodplain; 3285–3800 m: Xiyu Formation, interpreted as braided stream and alluvial fan.

Between 525 and 1698 m, the stratigraphy changes dramatically to well-sorted, pale red, fine-grained sandstone characterized by >1-m-thick, planar, continuous beds with meter-scale cross-bedding (Fig. 3A). Sand grains are well-sorted, rounded, and show evidence of pits, depressions and upturned plates (Fig. 3B; Figs. DR1 and DR2). Beds contain 0.2–1.5 m amplitude tabular cross-bedding (Figs. DR3A–DR3F) and have 1–3 mm upward-coarsening laminations (Fig. DR2). These strata are interpreted as eolian dune deposits based on the following rationale:

1. The pitted sand grain textures are diagnostic of grain impacts in wind-blown sand (Krlnsley and Doornkamp, 1973).
2. Reverse-graded laminations imply grain flow on the slip face of eolian dunes (Kocurek and Dott, 1981).
3. Large-amplitude cross-beds contain 20–30° dipping foresets (median = 22°) that imply subaerial deposition on dune slip faces rather than the 5–10° (median = 8°) dips observed on fluvial lateral-accretion surfaces (Figs. DR3 and DR4).
4. The base of the eolian sandstone beds are laterally continuous, do not show scour, and are interpreted as Type 1 bounding surfaces, after Brookfield (1977), that bound sets of cross strata and represent dune migration across other dunes. Type 2 bounding surfaces are also present and represent the passage of dunes across draas (very large-scale dune bedforms; Fig. 3A; Fig. DR5B). In contrast, the lower contacts of fluvial channel sandstones are laterally discontinuous and show scour into the underlying mudstone (Fig. DR5A); these define type 3 fluvial surfaces, after Miall (1996).
5. The reddish color and pinstripe lamination are consistent with eolian strata (Fig. DR3; Ahlbrandt, 1979; Fryberger and Schenk, 1988).

Grain-size data are equivocal between our eolian and fluvial strata (mode [particle size most commonly found in the distribution] of 0.07 and 0.09 mm, respectively), but eolian grain sizes overlap with sizes observed in Pliocene eolian strata from the central Tarim Basin (Fig. DR6; Sun et al., 2011).
model provides ages for deposition of the Wuqia Group Unit B (15.1–13.6 Ma), Wuqia Group Unit C (13.6–13.3 Ma), Pakabulake Fluvial Member (13.3–12.2 Ma), Pakabulake Eolian Member (12.2–7.0 Ma), Atushi Formation (7.0–2.2 Ma), and Xiyu Formation (2.2 to ca. 1.5 Ma).

**DISCUSSION**

**Erg Deposition at 12.2–7.0 Ma**

Our observations of a thick (~1100 m) sequence of eolian dune and interdune strata are unequivocal evidence for a long-lived erg system between 12.2 and 7.0 Ma, when paleoenvironmental conditions may have been similar to that of the present-day Taklimakan Desert (Fig. 4B). This new member of the Pakabulake Formation is laterally continuous for ~70 km, from the north-south-trending Pqiqiang fault at ~77.75° E to where it pinches out to the west into fluvial strata near the Darenkou Valley (Fig. 1B). The southern extent is buried within the Tarim Basin to the south, but similar eolian strata are not observed farther west or east along the Tian Shan foreland (e.g., Heermance et al., 2007; Charreau et al., 2006) except at one poorly dated location ~150 km west of Kashgar (Wang et al., 2014). Nonetheless, the exposed area gives this unit a minimum size of ~240 km², making it the earliest documented erg within the Tarim Basin, and implies a long-lived desert from at least 12.2 to 7 Ma. After 7 Ma, erg deposition terminated, as fluvial deposition engulfling the study area, likely due to encroachment of the Tian Shan from the north, and may have pushed the erg system into the central Tarim Basin where it occurs today (Fig. 4B).

**Global versus Tectonic Forcing of Tarim Paleoenvironments**

Depositional environments within the western Tarim Basin were remarkably consistent and spanned at least 500 km during the late Oligocene–early Miocene (ca. 25 Ma), characterized by fluvial and playa-lacustrine deposition within the lower Wuqia Group (Fig. 4A; Huang et al., 2006; Wang et al., 2014; Zheng et al., 2015; Cao et al., 2015; Blayney et al., 2016). Westerly winds traveling across Eurasia likely brought substantial moisture to the region, which fed distal river catchments from the south (Pamir), east, and north that flowed into the relatively low-relief landscape of the Tarim Basin (Caves et al., 2015; Bougeois et al., 2018). After 25 Ma, the Pamir experienced rapid tectonic growth, including commencement of movement on oblique slip faults bounding the eastern Pamir and initial closure of the Alai Valley at ca. 25 Ma (Coutand et al., 2002; Blayney et al., 2016), followed by rapid exhumation and orogen-wide growth between 21 and 13 Ma (Sobel et al., 2006; Heermance et al., 2007). By 12 Ma, the mountain ranges had developed into a high-elevation topographic barrier with an associated rain shadow that cut off west-erly moisture (e.g., Bougeois et al., 2018). Widespread Xiyu Formation deposition at this time implies that course-grained alluvial fans flanked the ranges, and fluvial deposition was limited to narrow corridors where rivers emerged from the mountains (Fig. 4B; Heermance et al., 2007; Cao et al., 2015; Zheng et al., 2015; Blayney et al., 2016). In the Pamir/Tian Shan rain shadow, reduced vegetative cover, combined with uplift of weak foreland basin strata, would have created a source for sand and silt to create an erg against the developing Tian Shan. The influence of this tectonically driven rain shadow at ca. 12 Ma may have affected a broad area, as similar observations of aridification were reported by workers in the northeastern Tibetan Plateau (e.g., Dettman et al., 2003; Zhuang et al., 2011; Li et al., 2016).

**CONCLUSIONS**

We present a 3800 m record of paleo-environmental changes between ca. 15.1 and 1.5 Ma.
from the northern Tarim Basin. Based on magnetostratigraphic age correlation, these strata define a relatively humid middle Miocene until 12.2 Ma, when an erg system developed due to aridification of the region. Erg deposition at 12.2 Ma most likely resulted from rain-shadow development behind the growing and colliding Tian Shan and Pamir Mountains. The Taklimakan Desert therefore represents a long-lived desert since at least 12 m.y. ago, due to isolation of the Tarim Basin.

ACKNOWLEDGMENTS

This project was supported by an American Chemical Society Petroleum Research Fund grant (50776-UN18) and National Science Foundation grants to Heerman (grant 1348075) and Garzione (grant 1348005). J. Cook helped with paleomagnetic analysis at Occidental College. We thank the editor, J. Charreau, G. Dupont-Nivet, and two anonymous reviewers for their constructive reviews.

REFERENCES CITED


