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The provenance of Taklamakan desert sand

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ABSTRACT

Sand migration in the vast Taklamakan desert within the Tarim Basin (Xinjiang Uyghur Autonomous region, PR China) is governed by two competing transport agents: wind and water, which work in diametrically opposed directions. Net aeolian transport is from northeast to south, while fluvial transport occurs from the south to the north and then west to east at the northern rim, due to a gradual northward slope of the underlying topography. We here present the first comprehensive provenance study of Taklamakan desert sand with the aim to characterise the interplay of these two transport mechanisms and their roles in the formation of the sand sea, and to consider the potential of the Tarim Basin as a contributing source to the Chinese Loess Plateau (CLP). Our dataset comprises 39 aeolian and fluvial samples, which were characterised by detrital-zircon U–Pb geochronology, heavy-mineral, and bulk-petrography analyses. Although the inter-sample differences of all three datasets are subtle, a multivariate statistical analysis using multidimensional scaling (MDS) clearly shows that Tarim desert sand is most similar in composition to rivers draining the Kunlun Shan (south) and the Pamirs (west), and is distinctly different from sediment sources in the Tian Shan (north). A small set of samples from the Junggar Basin (north of the Tian Shan) yields different detrital compositions and age spectra than anywhere in the Tarim Basin, indicating that aeolian sediment exchange between the two basins is minimal. Although river transport dominates delivery of sand into the Tarim Basin, wind remobilises and reworks the sediment in the central sand sea. Characteristic signatures of main rivers can be traced from entrance into the basin to the terminus of the Tarim River, and those crossing the desert from the south to north can seasonally bypass sediment through the sand sea. Smaller ephemeral rivers from the Kunlun Shan end in the desert and discharge their sediment there. Both river run-off and wind intensity are strongly seasonal, their respective transport strength and opposing directions maintain the Taklamakan in its position and topography.

1. Introduction

The Taklamakan is the largest desert in China and one of the largest sand seas in the world, second only to the Rub‘ al-Khali in Arabia. At an altitude of >1000 m, it occupies the central part of the internally drained Tarim Basin. This basin is surrounded by some of the world's highest mountain ranges, including the Kunlun Shan and Altun Shan (south), Tian Shan (north) and Pamir (west), which are the latest expressions in a succession of tectonic events that have shed sediments of regionally varying thickness up to ∼15 km (Kao et al., 2001) onto the continental Tarim Block since the Jurassic (Sobel, 1999). The Taklamakan itself may have formed as early as 26.7–22.6 Ma (Zheng et al., 2015) and is currently a major source of fine grained dust (<2–3 μm) in East Asia that influences both the regional and global climate through scattering of solar radiation and changing cloud properties (Huang et al., 2014). Taklamakan dust storm events are known to have global reach, delivering dust to the Pacific Ocean, North America, Greenland and the Atlantic Ocean (Svensson et al., 2000; Yumimoto et al., 2009). Some of this dust may be carried across the Hexi Corridor to the

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Loess Plateau region and southeastern China (e.g. Liu et al., 2011; Yumimoto et al., 2009), although the role of the Taklamakan as a source of loess-forming dust in the past and the present-day is controversial (Sun, 2002; Bird et al., 2015). Despite this significance as a globally important dust source, the nature of the sand sources to the Taklamakan itself has not been explored in detail. Some bulk geochemical data from Taklamakan dune sand from the eastern part of the basin have been published (Chen et al., 2007; Yang et al., 2007; Xu et al., 2011), as well as a single detrital zircon U–Pb age data set (Xie et al., 2007), but the precise source regions of the desert sand and their spatial heterogeneity are not known. This is of special interest in light of recent detrital zircon U–Pb dating of desert sands from the Mu Us desert in central northern China, that showed stark spatial heterogeneity in sand source (Stevens et al., 2013). Without proper characterisation of the sand sources to the desert itself, its role and impact as a past dust source remains unclear.

The origin of the word 'Taklamakan' has been lost over time, but according to popular tradition, it means "he who goes in shall never come out". It is because of this inaccessibility that the interior parts of the desert remained unexplored until petroleum was found in the 1990s, and two desert-crossing highways were constructed (Dong et al., 2000). Taking advantage of these new access points, we here present a comprehensive provenance study of this desert, using a combination of multiple provenance proxies and state-of-the art statistical analysis.

There is an ongoing debate in sedimentology and in Quaternary paleoclimatology about the production of desert sands and silt in arid and semi-arid regions. In summary, the main views on desert sand generation are either fresh sediments being delivered from surrounding areas and "maturing" in the desert area, or alternatively, potentially multi-phase, in-place recycling of older sediments derived from in-situ weathering of bedrock and/or sedimentation during a different climatic phase. For the generation of loess, it is debated whether the bulk of the silt-sized quartz fraction is delivered by glacial processes, aeolian abrasion on sand dunes, or weathering (Knippertz and Stuut, 2014; Amit et al., 2014; Crouvi et al., 2010; Smith et al., 2002). The role of fluvial transport interaction with arid sandy areas is also an active field of research (e.g. Bullard and McTainsh, 2003; Stevens et al., 2013; Field et al., 2009). Whatever the mechanism of sediment generation and transport, for large aeolian dune fields to continue to exist, there must be a steady supply of transportable material, and yet in many cases, the sediment pathways and sources are not well known.

At the outset of this study, we may consider two competing sand transport mechanisms: wind and water. Current Resultant Drift Potential for sand transport by wind is from the north to the south (Wang et al., 2002). According to geological evidence from up to >1500 m thick Pliocene deposits including windblown sands along the southern margin of the Tarim Basin, these conditions have persisted since at least 5.3 Ma (Sun and Liu, 2006) and possibly the late Oligocene (Zheng et al., 2015). However, the main rivers flow in the opposite direction, from south to north and then east, aided by a gentle slope from elevations of ca. 1500 m in the south of the basin to ca. 900 m in the north and east (Fig. 1). Most of these rivers are ephemeral, only the Hotan He and the Yarkan He cross the desert year long, though fluvio-lacustrine sediments in the dune valleys across large parts of the desert testify to floods and water flow occurring during the snow melt in June–August. Given the current prevalent wind directions and thick stratigraphic successions preserved along the southern margin, it might appear that a large part of the sand must be blown from the north, derived from the fluvial fans coming off the Tian Shan, or even transported over long distances from Central Asian sources including the Junggar Basin. Yet, it may equally be argued that the northward flowing rivers, following topographic gradient, could achieve a constantly large supply of sediment outweighing basin subsidence. So far, few studies have considered the interplay of fluvial and aeolian sediment transport in a comparable setting to the study area (e.g. Field et al., 2009; Bullard and McTainsh, 2003).

To gain a more complete understanding of sand transport in the Tarim Basin, we collected a large multivariate provenance dataset based on detrital-zircon geochronology (dZ), heavy-mineral (HM) and bulk-petrography (PT) analyses of 39 sand samples from the main tributaries and representative alluvial fans feeding into the Tarim Basin, and from Taklamakan dunes. The dataset includes several samples from the Junggar Basin and the southern Altai for comparison, to test whether these areas may have been a source of sediment carried by winds from this basin into the Tarim area (Fig. 1). A previous small-scale study across the central Tarim Basin, based on visual comparison of whole-rock geochemical data from samples collected along the eastern desert-crossing highway and from the Keriya River (Yang et al., 2007), suggested that it should be possible to discriminate local source areas due to a low degree of E–W mixing. In order to recognise sediment pathways, our more detailed study required the interpretation of large multiple proxy datasets, so we used an established statistical method known as multidimensional scaling (MDS) that has been adopted for provenance studies (Vermeesch, 2013; Stevens et al., 2013; Vermeesch and Garzanti, 2015). This provides an efficient, unbiased way to visualise relations within multi-sample datasets, and greatly helps to subsequently interpret the full data set in detail.

2. Regional overview

The Tarim Basin (Fig. 1) covers an area of over 600 000 km^2 and stretches some 1100 km E–W and 600 km N–S. The basin is fringed by tectonically active mountain ranges: the Tian Shan to the north and the Kunlun and Altun Mountains (Altyn Tagh) to the south. The central parts of the basin contain the active sand desert that covers more than half of the total area of the basin (330 000 km^2). Atmospheric circulation is dominated by a high-pressure centre which sits above the northwestern part of the desert and produces winds that blow from the north in the northern part of the desert and from the east in the central and southern parts (Fig. 1). Thus, net aeolian sand transport is in a south-westerly direction (Dong et al., 2000; Wang et al., 2002), which generally coincides with the orientation of larger dune features (Tsuchiya and Oguro, 2007), including large-scale (1–2.5 km wide and 50–200 m high) linear sand dunes, large (100 s of m high) star dunes (Tsuchiya and Oguro, 2007), and areas of complex, smaller-scale compound dunes (Wang et al., 2002). Mean annual precipitation decreases from 100 mm in the northeast to 50 mm in the central region.

The main Tarim river originates at the confluence of the Yarkan and the Kashgar Rivers, draining the eastern Pamir and westernmost Kunlun Mountains, respectively, and flows eastward around the northern edge of the Taklamakan desert (Fig. 1). 60–80% of its annual run-off is confined to the flood season between June and August. During this period, the river carries more than 80% of its annual sediment load (Ye et al., 2014), and for most of the remaining months, river levels are low, allowing the flood plains to dry out and potentially be remobilised by wind erosion. As the Tarim River is dependent on glacial melt waters for ca. 48% of annual run-off (Chen et al., 2006), tributaries with glaciated catchments are important sources of sediment. The Tarim River receives water from three rivers that have catchments in glaciated mountains: the Hotan drains the Kunlun, the Yarkan the Karakorum, Pamir and Kunlun, and the Aksu (including Toshkan) the Tian Shan. The Aksu drains the most heavily glaciated part of the Tian Shan and thus,