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Wind as the primary driver of erosion in the Qaidam Basin, China

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ABSTRACT

Deserts are a major source of loess and may undergo substantial wind-erosion as evidenced by yardang fields, deflation pans, and wind-scoured bedrock landscapes. However, there are few quantitative estimates of bedrock removal by wind abrasion and deflation. Here, we report wind-erosion rates in the western Qaidam Basin in central China based on measurements of cosmogenic ^{10}Be in exhumed Miocene sedimentary bedrock. Sedimentary bedrock erosion rates range from 0.05 to 0.4 mm/yr, although the majority of measurements cluster at 0.125 ± 0.05 mm/yr. These results, combined with previous work, indicate that strong winds, hyper-aridity, exposure of friable Neogene strata, and ongoing rock deformation and uplift in the western Qaidam Basin have created an environment where wind, instead of water, is the dominant agent of erosion and sediment transport. Its geographic location (upwind) combined with volumetric estimates suggest that the Qaidam Basin is a major source (up to 50%) of dust to the Chinese Loess Plateau to the east. The cosmogenically derived wind erosion rates are within the range of erosion rates determined from glacial and fluvial dominated landscapes worldwide, exemplifying the effectiveness of wind to erode and transport significant quantities of bedrock.

1. Introduction

Knowledge of bedrock erosion rates on Earth's surface over timescales of 10^2–10^6 yr is limited, yet fundamental in assessing the dynamics of landscape evolution and sediment production as a function of tectonic processes, climate, and lithology and their superposed forcing factors (Molnar, 2004; Whipple, 2004). Significant advances have been made in recent decades in quantifying bedrock and drainage-basin erosion rates in regions where fluvial and glacial processes dominate. Short-term landscape sedimentary flux and erosion rates (10^0–10^2 yr) have been recorded by sedimentary traps and gauging stations on rivers (Meade, 1988; Kirchner et al., 2001; Lavé and Burbank, 2004), whereas on longer timescales (10^3–10^6 yr) concentrations of in situ cosmogenic radionuclides (i.e. ^{10}Be) in fluvial sediments have been used (e.g., Granger et al., 1996; Gosse and Phillips, 2001; Von Blanckenburg, 2005, Owen et al., 2001; Portenga and Bierman, 2011). In contrast, few studies have quantified eolian erosion processes in deserts (e.g., McCauley et al., 1977; Ward and Greeley, 1984; Bristow et al., 2009; Fig. 1), particularly on timescales >5000 yr (Inbar and Risso, 2001; de Silva et al., 2010; Ruszkiczay-Rüdiger et al., 2011). This is despite the recognition of wind as an important transport agent (Pye, 1995; Uno et al., 2009), that loess is one of the most important fertilizers for plankton growth in the open ocean (Pye, 1995; Hanebuth and Henrich, 2009), and the ubiquity of wind-deflated and abraded landforms in many desert regions on Earth (Goudie, 2007) and extraterrestrial bodies such as Mars and Jupiter's moon Titan (e.g. Bridges et al., 2004; Sullivan et al., 2005; Thomson et al., 2008; Rubin and Hesp, 2009).

The in-situ produced cosmogenic nuclide ^{10}Be can be used to quantify in-situ bedrock erosion because of its long half-life ($\sim 1.3 \times 10^6$ yr), short attenuation length (<2 m), and known production rate in quartz at the Earth's surface (Lal, 1991), making it useful for studying bedrock erosion processes and assessing rates of landscape evolution in general (e.g., Bierman and Caffee, 2002; Bookhagen and Strecker, 2012). In this study, we quantify eolian erosion rates by measuring cosmogenic ^{10}Be in quartz from wind-scoured and deflated sedimentary bedrock surfaces in the Qaidam Basin (Fig. 2). We then compare our results with worldwide bedrock erosion studies in an effort to document the significance of wind as a global erosion agent.

1.1. *Deflation vs. abrasion and evidence for wind erosion*

In general, wind erosion is effective in arid, windy regions characterized by sparse to no vegetation cover. Wind erosion is viewed as being the result of both deflation and abrasion processes

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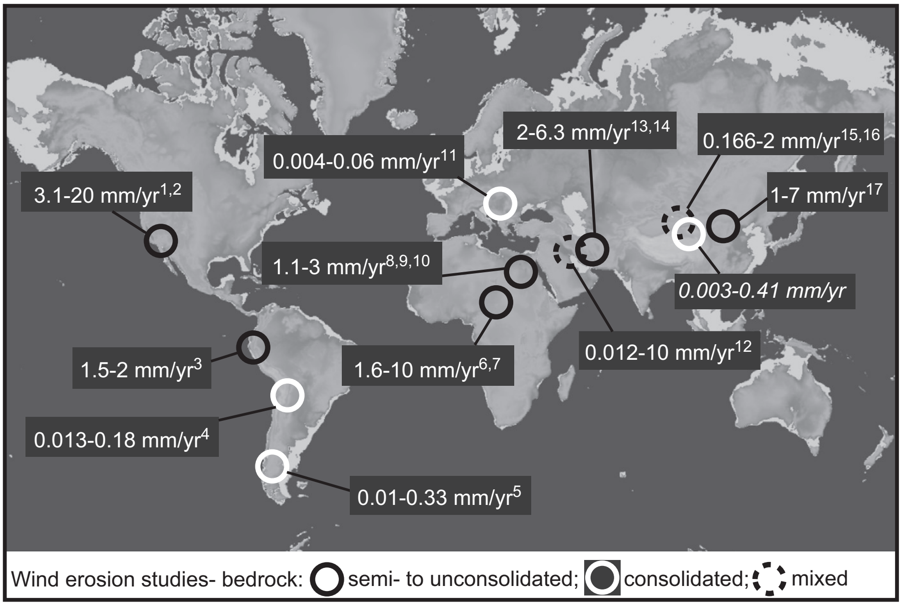

Fig. 1. Global compilation of wind erosion estimates reporting erosion by deflation (semi- to unconsolidated) and abrasion (consolidated) or both. Erosion rate estimates are based on ^{14}C-dating, optical luminescence-dating (OSL), cosmogenic ^{10}Be-dating or U–Pb dating of eroded rocks. Where no rates were reported, a conservative erosion rate was estimated using the age of the deposit and wind removed material by geometric considerations, e.g. yardang troughs; inverted channels; elevated lake beds or paleosoils above the general basin floor. Note the order of magnitude difference between wind erosion by deflation and abrasion, suggesting bedrock strength controlling the effectiveness of wind erosion. References: 1. Clarke et al. (1996), 2. Ward and Greeley (1984), 3. Beresford-Jones et al. (2009), 4. de Silva et al. (2010), 5. Inbar and Risso (2001), 6. Washington et al. (2006), 7. Bristow et al. (2009), 8. Haynes (1980), 9. Goudie et al. (1999), 10. Brookes (2003), 11. Ruszkiczay-Rüdiger et al. (2011), 12. Al-Dousari et al. (2009), 13. Krinsley (1970), 14. Kehl (2009); 15. McCauley et al. (1977), 16. Dong et al. (2012), 17. Ritley and Odontuya (2004). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

(Laity, 2011). Disagreements exist about the correct use of these terms, since both processes can spatially and temporally overlap and contribute to the overall wind-erosion signal. Deflation is defined here as the passive entrainment of loose material at the Earth's surface into the air-flow. In contrast, abrasion is the physical process of actively eroding material by the impact of wind-blown grains onto a bedrock surface (Goudie, 2009; Laity and Bridges, 2009). Deflation dominates wind erosion in areas where unconsolidated sediments or poorly lithified rocks are exposed at the surface. In bedrock-dominated areas floored by either consolidated sedimentary or crystalline rocks, only abrasion is able to remove material from bedrock surfaces (Laity and Bridges, 2009; Laity, 2011). However, other factors such as water (e.g. gullying, mudflow, sheet wash), temperature (freeze–thaw), and chemical weathering (salt corrosion and expansion) also impact bedrock surfaces and are able to produce loose material covering bedrock (Aref et al., 2002). Loose sediment is prone to deflation, resulting in bedrock lowering without physical abrasion. In many places it is impossible to distinguish between deflation or abrasion because of the complex relationships among weathering, climate, and bedrock lithology. Thus, information on rates and time scales of either deflation or abrasion alone are scarce.

The primary evidence for wind erosion, and specifically abrasion, in the Qaidam Basin and elsewhere are yardangs (Fig. 3A, B and E), ventifacts (Fig. 3B, foreground), and scoured, low-relief bedrock landscapes devoid of a fluvial network (Fig. 3C and D). Yardangs are wind eroded narrow ridges up to 100 m high and up to hundreds of meters in length (Hedin, 1903; Goudie, 2007). They are sculpted into poor-to-well consolidated bedrock by saltating particles that are transported by strong, uni-directional winds (McCauley et al., 1977; Dong et al., 2012). The few estimates available for the time scales of yardang formation range from thousands of years for small yardangs (1–10 m) (Halimov and Fezer, 1989) to millions of years for large yardangs (> 50 m) (Goudie, 2007).

Ventifacts provide evidence for the strong abrasive power of wind at much smaller scales (Laity, 1994; Knight, 2008). Ventifacts are rocks that exhibit grooves, facets, or polishing as a result of abrasion by wind-entrained sand and typically consist of crystalline and well consolidated sedimentary rocks; they are found in most deserts and periglacial environments (Spate et al., 1995; Knight, 2002; Laity and Bridges, 2009). Reported abrasion rates associated with ventifacts are generally between 0.015 and 6.8 mm/yr (Knight 2008), although one study reported a maximum abrasion rate of 36 mm/yr over a time period of 15 yr (Sharp, 1980).

Most wind erosion occurs in the large, windy, semi-arid to arid region stretching from North Africa to central China and parts of North and South America (Fig. 1). Here, bedrock removal by wind is ubiquitous and reported wind deflation rates from semi- to unconsolidated sediment range from 1 to 20 mm/yr over short (< 5000 yr) time periods (Fig. 1; Krinsley, 1970; McCauley et al., 1977; Haynes, 1980; Ward and Greeley, 1984; Clarke et al., 1996; Goudie et al., 1999; Inbar and Risso, 2001; Brookes, 2003; Ritley and Odontuya, 2004; Washington et al., 2006; Beresford-Jones et al., 2009; Bristow et al., 2009; Al-Dousari et al., 2009; Kehl, 2009; de Silva et al., 2010; Ruszkiczay-Rüdiger et al., 2011; Dong et al., 2012). Most of the presented compilation in Fig. 1 is based on studies of wind eroded features (yardangs, tree roots, channels, lake beds, lava flows) with ages quantified by ^{14}C-dating, optical luminescence-dating (OSL), and ^{40}Ar–^{39}Ar dating. There are, however, very few studies from well-lithified bedrock in areas affected by wind erosion, where abrasion should be dominant (Inbar and Risso, 2001; de Silva et al., 2010; Ruszkiczay-Rüdiger et al., 2011). Recently, Ruszkiczay-Rüdiger et al. (2011) reported cosmogenically derived eolian erosion rates between 0.003 and 0.056 mm/yr from consolidated sedimentary bedrock in the Pannonian Basin of Hungary (Fig. 1). Although this technique is promising, there have been few studies of long-term (> 5000 yr) erosion rates from Central Asia (e.g. Lal et al., 2003). Here, the hyper-arid and windy conditions prevalent in northern Tibet may have enhanced eolian erosion and transport, as testified by the widespread and locally thick (hundreds of meters) accumulations of loess in eastern Asia,