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Centennial- to millennial-scale hard rock erosion rates deduced from luminescence-depth profiles

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ABSTRACT

The measurement of erosion and weathering rates in different geomorphic settings and over diverse temporal and spatial scales is fundamental to the quantification of rates and patterns of earth surface processes. A knowledge of the rates of these surface processes helps one to decipher their relative contribution to landscape evolution – information that is crucial to understanding the interaction between climate, tectonics and landscape. Consequently, a wide range of techniques has been developed to determine short- ($<10^2$ a) and long-term ($>10^4$ a) erosion rates. However, no method is available to quantify hard rock erosion rates at centennial to millennial timescales. Here we propose a novel technique, based on the solar bleaching of luminescence signals with depth into rock surfaces, to bridge this analytical gap. We apply our technique to glacial and landslide boulders in the Eastern Pamirs, China. The calculated erosion rates from the smooth varnished surfaces of 7 out of the 8 boulders sampled in this study vary between $<0.038 \pm 0.002$ and 1.72 ± 0.04 mm ka^{-1} (the eighth boulder gave an anomalously high erosion rate, possibly due to a recent chipping/cracking loss of surface). Given this preferential sampling of smooth surfaces, assumed to arise from grain-by-grain surface loss, we consider these rates as minimum estimates of rock surface denudation rates in the Eastern Pamirs, China.

1. Introduction

The erosion of the Earth's surface results from a combination of physical, chemical and biological weathering and the subsequent removal of weathering products by various transport agents. Erosion of rock surfaces may result from a range of processes such as dissolution, grain-by-grain attrition, chipping/frost cracking, and even massive bedrock landslides. Quantifying the rates and timing of such processes over various spatial and temporal scales is fundamental to determining the relative contribution of each process and thereby understanding landscape evolution. Bare hard rock surfaces are the most durable surficial features in the landscape and thus can have a long memory of the erosional history. Consequently, a wide range of methods have been developed to quantify erosion rates of subaerially exposed rock surfaces (Turowski and Cook, 2017). These include: i) the direct/indirect measurement of surface loss over laboratory timescales, or by comparison with resistant natural or anthropogenic reference features of known-age (Stephenson and Finlayson, 2009; Moses et al., 2014), ii) the analysis of cosmogenic nuclides (CNs) produced within mineral grains from exposed rock surfaces as a result of bombardment by secondary cosmic rays (Nishiizumi et al., 1986; Lal, 1991), and iii) thermochronology using a wide range of radiogenic processes to determine the thermal history of rocks, and thus their exhumation rates (Braun et al., 2006). Depending on the length of the observation period or the age of the reference feature, the rates measured by the techniques in category (i) are integrated over sub-annual to multi-decadal timescales (Moses et al., 2014), while the rates derived using CNs and thermochronology are averaged over thousands to millions of years, respectively (Lal, 1991; Braun et al., 2006). The short (i.e. $<10^2$ a) and long (i.e. $>10^4$ a) timescales of these techniques leave an intermediate time interval

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of 10^2–10^4 a over which there is currently no technique available for quantifying the erosion rates of rock surfaces. The centennial to millennial time intervals are of particular importance and interest to human society for evaluating the effects of climate change or anthropogenic activity on landscape evolution.

One of the major challenges in geomorphology is to make a link between different scales of observation (Schumm and Lichty, 1965; Warke and McKinley, 2011). Specifically, the timescale over which the rates of earth surface processes are averaged directly influences the apparent rates (e.g. Gardner et al., 1987; Viles, 2001; Koppes and Montgomery, 2009). Such measurement-interval bias can result in either underestimation (e.g. Kirchner et al., 2001) or overestimation (e.g. Lal et al., 2005) of short-term measurements compared to long-term average rates, hindering a linkage by simple extrapolation between the rates averaged over timescales that are orders of magnitude different (Gardner et al., 1987). It is clear that the development of a new analytical tool to bridge the gap between the decadal and millennial timescales would be of considerable value in erosion studies.

Several studies have shown that when a rock surface is first exposed to daylight, the latent luminescence, mainly from the constituent minerals quartz and feldspar, starts to decrease. The rate of this resetting (or ‘bleaching’) process decreases with depth as the incident light is attenuated (e.g. Habermann et al., 2000; Laskaris and Liritzis, 2011). Based on this phenomenon, Sohbati et al. (2011, 2012a, 2012b) proposed a new surface-exposure dating technique, which utilizes the time and depth dependence of the residual latent luminescence. The longer the rock is exposed to daylight, the deeper is the transition zone between the region of bleached latent luminescence at the surface and saturated latent luminescence at depth. After calibration, the depth of this “optical bleaching front” can be translated to an exposure time (Sohbati et al., 2011, 2012a, 2012b).

CN-depth profiles are influenced by the effect of erosion; Lal (1991) points out that the rock depth equivalent to one absorption mean free path for cosmic rays is ∼50 cm. In contrast, the corresponding absorption mean free path for light penetration into rocks is on the scale of millimeters (Sohbati et al., 2011, 2012a, 2012b). Thus, luminescence-depth profiles are expected to be ∼2 orders of magnitude more sensitive to the effect of erosion. In contrast to the effect of daylight exposure, the transition zone between the surface bleached latent luminescence and the saturated latent luminescence will become shallower, the higher the erosion rate. Nevertheless, this effect has been considered to be unimportant in all published applications, because the technique was applied to surfaces where archaeological evidence suggested negligible erosion (e.g. Pederson et al., 2014). However, the application of the technique to geological features, where constraints on surface preservation are rare on the centimeter scale (Lehmann et al., 2018 being an exception), necessitates the effect of erosion be taken into account (Sanderson et al., 2011). Here, we present a further development of the luminescence surface-exposure dating model (Sohbati et al., 2012b) that includes the effect of erosion on luminescence-depth profiles. We then use the new model to derive steady-state centennial- to millennial-scale hard-rock erosion rates from several surface-exposed glacial and landslide boulders from the Pamir plateau, China.

2. Theoretical framework

The ubiquitous rock-forming minerals quartz and feldspar can store energy (in the form of trapped charge) through the absorption of ionizing radiation resulting from the decay of naturally-occurring radionuclides (mainly ^{238}U and ^{232}Th and their decay products, and ^{40}K) and cosmic rays. This trapped charge can be released during exposure to heat or light. Some of the energy released during the resetting is emitted as photons (i.e. as UV, visible, or near infrared luminescence); if the trapped charge is released by light (i.e. photon stimulation of trapped electrons), the luminescence emitted from the mineral is called optically stimulated luminescence (OSL; Aitken, 1998). OSL is now a well-established Quaternary dating method usually used to determine the time elapsed since mineral grains were last exposed to daylight (i.e. the burial age) (Aitken, 1998). Recently, luminescence has also been shown to be useful in surface exposure dating (Sohbati et al., 2012a, 2012b).

2.1. Luminescence surface exposure age

In any rock sample that has been deeply buried and therefore shielded from light for an extended length of time (typically >0.5 Ma) the trapped electron population in the constituent quartz and feldspar crystals will usually be in field saturation due to finite trapping capacity (e.g. Guralnik et al., 2013). If the rock is then exposed to daylight by an exhumation event (e.g. fracture, ice-scouring) the trapped electron population will begin to decrease. The electron detrapping rate decreases with depth as a result of the attenuation of incident light with depth, following Beer–Lambert law (e.g. Laskaris and Liritzis, 2011). The rate of change of trapped electron population at a particular depth is a result of competition between two effects: (i) the accumulation rate of trapped electrons due to ambient ionizing radiation, and (ii) the eviction rate of trapped electrons due to the daylight flux at a given depth. Thus, in a rock that has been exposed to daylight, the residual luminescence forms a sigmoidal profile that continues to evolve with time until it reaches secular equilibrium, when electron trapping and detrapping rates are equal at all depths (Fig. 1a). For a given exposure time and daylight conditions, the penetration depth and form of a luminescence profile depend on the opacity of the rock-forming minerals and the relevant photoionization cross section(s). Assuming that luminescence signal is proportional to the trapped electron population, Sohbati et al. (2011, 2012a, 2012b) developed a mathematical model describing the luminescence-depth profiles in rock surfaces and demonstrated its application in surface exposure dating. According to this model, which assumes first-order kinetics for electron trapping and detrapping, the instantaneous concentration of trapped electrons n (mm^{-3}) at a depth of x (mm) can be expressed as:

$$\frac{dn}{dt} = (N - n)F(x) - nE(x) \tag{1}$$

where t (ka) is time, N (mm^{-3}) is the concentration of electron traps, and $F(x)$ and $E(x)$ (both ka^{-1}) are the rate constants describing electron trap filling and emptying, respectively.

$E(x)$ (ka^{-1}) decreases with depth due to attenuation of daylight intensity into the rock following the Beer–Lambert law:

$$E(x) = \overline{\sigma\varphi_0} e^{-\mu x} \tag{2}$$

where $\overline{\sigma\varphi_0}$ (ka^{-1}) is the time-averaged detrapping rate constant at the surface of the rock and μ (mm^{-1}) is the inverse of the mean free path of photons in the rock.

The coefficient $F(x)$ describes the trapping rate constant:

$$F(x) = \dot{D}(x)/\, D_0 \tag{3}$$

where $\dot{D}$ (Gy ka^{-1}) is the natural dose rate and D_0 (Gy) is the characteristic dose that fills ∼63% (i.e. $1 - e^{-1}$) of the traps (Wintle and Murray, 2006). D_0 is an intrinsic property of the dosimeter and not expected to have any systematic dependence on depth. $\dot{D}$ may have a weak dependence on depth into the rock, especially close to