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Research paper

Investigation of optically stimulated luminescence behavior of quartz from crystalline rock surfaces: A look forward

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ABSTRACT

Optically stimulated luminescence (OSL) dating has recently been applied to crystalline (i.e. igneous and metamorphic) rock surfaces. With the advent of this technique, early studies can guide improvements to the methodology that will lead to more robust age constraints. Low OSL sensitivity, poor measurement reliability, and equivalent dose scatter are common problems with dating quartz from crystalline rock surfaces. We investigate OSL characteristics of quartz extracted from crystalline Antarctic beach cobbles. Comparison of OSL behavior with cathodoluminescene characteristics and mineral composition and texture does not show a distinct relationship, suggesting luminescence behavior results from the natural radiation environment and post-crystallization transport history, rather than provenance source and the nature of crystal defects. Elemental composition of processed samples used for OSL measurements indicates standard methods of chemical preparation are not always suitable to extract pure quartz samples. Additionally, heterogeneous radiation production and attenuation poses a problem for estimating dose rates, in particular regarding beta contributions that dominate effective dose rates. We determine the sensitivity of effective dose rates to water content parameters and crystal size needed to calculate dose rates for crystalline rock surfaces. An increase in the value of all modelled parameters serves to reduce effective dose rates and, thus increase OSL ages. Dose rates are most sensitive to crystal size, which can introduce large uncertainty in burial ages from crystalline rocks due to heterogeneous crystal morphology (i.e. size and shape). This study provides a step forward in understanding the challenges and improving the methodology of luminescence dating of quartz from crystalline rock surfaces.

1. Introduction

Optically stimulated luminescence (OSL) is a useful tool for dating Quaternary deposits with ages beyond the range of radiocarbon dating and in settings where other dating techniques are problematic. Traditional OSL measurement techniques are suitable for sedimentary sand- and silt-sized quartz and feldspar grains, such as loess, dunes, and beach sand (e.g. Rhodes, 2011). Recent studies apply OSL dating to coarser-grained deposits and rocks, including alluvial gravels (Kenworthy et al., 2014), calcitic rocks (Liritzis et al., 2010) and crystalline (i.e. igneous and metamorphic) rock surfaces (Vafiadou et al., 2007; Simms et al., 2011, 2012; Sohbati et al., 2011; Simkins et al., 2013a, 2015). Environments where sedimentary deposits are lacking pose challenges for obtaining reliable Quaternary chronologies and feed the motivation to apply luminescence dating methods to crystalline rock surfaces. Additionally, an improved understanding of luminescence behavior of minerals directly derived from rocks is necessary for the application of thermochronology to estimate exhumation and erosion rates (e.g. Herman et al., 2010; Guralnik et al., 2015; King et al., 2016). Although studies demonstrate success in dating crystalline rock surfaces, poor luminescence characteristics, most notably low OSL sensitivity, limited OSL measurement reliability, and equivalent dose scatter, are commonly reported.

Poor luminescence and dosimetric characteristics of crystalline

Abbreviations: OSL, Optically stimulated luminescence; CL, cathodoluminescence; EDS, energy dispersive spectroscopy; SAR, single-aliquot regenerative-dose; IR, infrared; IRSL, infrared stimulated luminescence.

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rock surfaces can result from: (1) crystallization thermal history; (2) post-crystallization transport history; and (3) microdosimetric effects. Crystal defects are responsible for trapping free electrons that produce luminescence. The type and amount of crystal defects in silicate minerals is largely controlled by crystallization temperature (Dennen et al., 1970; Götze et al., 2001; Wark and Watson, 2006; Preusser et al., 2009; Sawakuchi et al., 2011). These defects result from the incorporation of impurities (e.g. Al and Ti) and point defects (e.g. Si- and O-vacancies) within quartz crystal lattices (Preusser et al., 2009), as well as solid mineral inclusions (Götze, 2012). Electron traffic between crystal defects increases with repeated exposure-burial cycles (McKeever et al., 1996; Moska and Murray, 2006; Preusser et al., 2006; Pietsch et al., 2008; Fitzsimmons et al., 2009; Zheng et al., 2009; Sawakuchi et al., 2011). For example, coastal deposits from Brazil (Sawakuchi et al., 2011) and fluvial deposits from Australia (Pietsch et al., 2008) have higher OSL sensitivities than their respective source rocks and sediments. Whereas crystallization temperature dictates the nature of crystal defects, transport history is the dominant control on OSL sensitivity (Sawakuchi et al., 2011). Therefore, crystalline rocks that have experienced different crystallization temperature and transport histories display a range of luminescence behaviors.

Equivalent dose scatter is common for sedimentary sand and silt due to grain-to-grain variability in light exposure (e.g. Fuchs and Owen, 2008). On the contrary, a single crystalline rock surface experiences the same exposure history. Quartz crystals extracted from crystalline rocks should favor more homogenous equivalent doses due to the absence of grain mixing. Sohbati et al. (2011) demonstrate that partial bleaching is not responsible for the observed equivalent dose scatter from quartz and feldspar extracted from metamorphosed sediment, gneiss, and granite clasts. It is, however, possible that minerals have variable bleaching rates that would produce heterogeneous bleaching in crystalline rocks. In crystalline rocks, an assemblage of minerals contributes to the production and attenuation of radiation doses. Microdosimetric effects produced by different minerals, including proximity to potassium feldspar 'hotspots', result in spatially-variable radiation environments that could cause equivalent dose scatter (Vandenberghe et al., 2003; Mayya et al., 2006).

Beta radiation is attenuated during its passage through a grain, so that the beta dose rates depend on grain size (Wintle and Aitken, 1977; Armitage and Bailey, 2005). Mean grain size is used to correct for beta dose rate attenuation within OSL-dated minerals (Mejdahl, 1979). Minerals in crystalline rocks often have heterogeneous crystal size and shape; therefore, rock surfaces are likely plagued by microdosimetric effects resulting from heterogeneous crystal morphology. The use of mean crystal size and assumption of spherical crystals does not account for variations in morphology that can cause microdosimetry (Duval et al., 2015). Consequently, heterogeneous crystal size and shape likely contribute to equivalent dose scatter.

In addition to heterogeneous dose rates resulting from crystal morphology, water absorbs radiation and reduces the effective dose rate. Although water content in crystalline clasts is negligible, water content between clasts can be highly variable. Consequently, several factors have an influence on the water content between clasts including: (1) space between clasts (i.e. pore volume); (2) amount of pores filled with water; and (3) duration of water-filled pores. These factors have undoubtedly not remained constant throughout burial history, causing spatial and temporal changes in the radiation environment. One of the lingering questions associated with dose-rate assumptions for crystalline rock surfaces is how much the dose rate – and subsequently the age – of samples will change if water content and crystal size vary.

We use igneous beach cobbles from Calmette Bay (68° 03′S 67° 10′W) and the South Shetland Islands (62°S 58°W) along the western Antarctic Peninsula to explore OSL behavior and dose-rate sensitivity for crystalline rock surfaces (Fig. 1). These samples have previously been dated and published in Simms et al. (2011, 2012) and Simkins et al. (2013a, 2015). Cathodoluminescence (CL) was measured for thin-sections of the beach cobbles. The traps that produce luminescence utilized for OSL dating also produce CL in the visible range; therefore, CL analysis provides qualitative insight on the crystal defects available for producing luminescence. Mineralogic analysis was conducted to identify rock types and mineral assemblages and texture. We compare the findings from the CL and petrographic analyses to OSL behavior to identify the controlling factors on luminescence behavior. As only part of the age stems from OSL measurements, we assess the sensitivity of dose-rate calculations to a range of values for crystal size and water content parameters.

2. Methods

2.1. OSL measurements

Buried cobbles were extracted from Antarctic beaches (Fig. 1) under a light-proof tarpaulin and wrapped in layers of light-proof black plastic. The dimensions of the cobbles are listed in Table 1 Material surrounding the dated cobbles was collected for

Fig. 1. Beaches preserved above sea level in Calmette Bay, western Antarctic Peninsula. (a) Beach berms visible between snow-covered portions of the beaches. (b) Open-framework coarse-clastic beach material composed of crystalline rocks rounded by wave action. (c) Brash ice on the modern beach.