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Catchment-scale denudation and chemical erosion rates determined from ^{10}Be and mass balance geochemistry (Mt. Lofty Ranges of South Australia)

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ABSTRACT

Global biogeochemical cycles have, as a central component, estimates of physical and chemical erosion rates. These erosion rates are becoming better quantified by the development of a global database of cosmogenic radionuclide ^{10}Be (CRN) analyses of soil, sediment, and outcrops. Here we report the denudation rates for two small catchments (~0.9 km^2) in the Mt. Lofty Ranges of South Australia as determined from ^{10}Be concentrations from quartz sand from the following landscape elements: 1) dissected plateaux, or summit surfaces (14.10 ± 1.61 t km^{-2} y^{-1}), 2) sandstone outcrops (15.37 ± 1.32 t km^{-2} y^{-1}), 3) zero-order drainages (27.70 ± 1.42 t km^{-2} y^{-1}), and 4) stream sediment which reflect a mix of landscape elements (19.80 ± 1.01 t km^{-2} y^{-1}). Thus, the more slowly eroding plateaux and ridges, when juxtaposed with the more rapidly eroding side-slopes, are leading to increased relief in this landscape.

Chemical erosion rates for this landscape are determined by combining cosmogenic denudation rates with the geochemical mass balance of parent rock, soil and saprolite utilizing zirconium immobility and existing mass balance methods. Two different methods were used to correct for chemical weathering and erosion in the saprolite zone that is shielded at depth from CRN production. The corrected values are higher than uncorrected values: total denudation of 33.24 or 29.11 t km^{-2} y^{-1}, and total chemical erosion of 15.64 or 13.68 t km^{-2} y^{-1}. Thus, according to these methods, 32–40% of the denudation is taking place by chemical weathering and erosion in the saprolite below CRN production depth. Compared with other similar areas, the overall denudation and chemical erosion rates are low. In most areas with sub-humid climates and tectonic uplift, physical erosion is much greater than chemical erosion. The low physical erosion rates in these Mt. Lofty Range catchments, in what is a relatively active tectonic setting, are thought to be due to low rainfall intensity during the winter wet season, which inhibits physical erosion such as land-sliding and debris flows.

1. Introduction

Earth's surface is a dynamic place where rocks and minerals weather to soil and produce secondary soil minerals, sediment, and dissolved solutes. Quantifying the rates at which sediment and solutes are generated from landscapes by chemical and physical weathering and exported from drainage basins by rivers is critical for understanding biogeochemical cycles (Bierman and Nichols, 2004; Granger and Riebe, 2007, 2014; Portenga and Bierman, 2011). The balance between soil production and removal determines whether soil exists on any given landscape, its thickness and its geochemical characteristics (Heimsath et al., 1999). Soils contain vital nutrients for life; because weathering and erosion supply sediment and solutes to rivers and the oceans, they are important regulators of aquatic habitat quality, and set the rate of sedimentation in reservoirs and navigational channels (Granger and Riebe, 2007, 2014). Chemical weathering aids the acid neutralization capacity of soil (Kirchner and Lydersen, 1995) and, over much longer timescales, silicate mineral weathering and erosion moderates ocean alkalinity, which affects atmospheric CO_2 concentrations and thus is part of regulating global climate (Berner, 1992). Over geologic time-scales, changes in weathering and landscape-scale erosion rates have been investigated across major geologic boundaries with the aim to quantify their contribution to global change (Raymo et al., 1988; Bestland, 2000).

Cosmogenic nuclides form in rocks and sediments from the interaction between secondary cosmic rays and mineral grains near the Earth's

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surface. Because cosmogenic nuclide production rates are rapidly attenuated with depth, the concentration of such nuclides in a mineral grain allows the time it has spent near the Earth's surface, or how rapidly material has been removed from above it, to be calculated (Lal, 1991). Cosmogenic nuclide analysis is the primary data used to determine surface exposure dating, erosion rates and the determination of catchment-averaged denudation rates (Lal, 1988; Granger et al., 1996). For the latter two cases it is assumed that, at secular equilibrium, CRN production balances loss via erosion and decay, such that concentrations of cosmogenic nuclides are effectively determined by the magnitude of the erosion rate (Heimsath et al., 2001a). Beryllium-10 measurements allow the quantification of rates at which sediments are generated, transported and deposited over timescales ranging from 10^3 to 10^6 years. Samples from rock exposures are used to estimate erosion rates at points on the landscape, whereas samples of fluvial sediment provide quantification of basin-scale rates of denudation integrated over <1 to >10^4 km^2 (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996; Bierman et al., 2001). Cosmogenic nuclide analysis has made it possible to obtain numerical data pertaining to the erosion history of stable landscape features, such as Australian inselbergs and similar features elsewhere (Bierman and Caffee, 2001; Bierman and Caffee, 2002). Cosmogenic nuclide analysis of sediment, soil and bedrock at the catchment scale can identify sediment source areas and erosion mechanisms (Clapp et al., 2002; Belmont et al., 2007).

The quantification of sediment generation rates has made it possible to examine relationships between landscape erosion rates and landscape parameters such as mean annual precipitation (*MAP*), mean annual temperature (*MAT*), slope, relief, and other factors. For example, Riebe et al. (2001a, 2001b, 2004) and Granger et al. (2001) have shown that the erosion rate (thereby the soil production rate) did not correlate with either annual precipitation values (spanning 200–1800 mm) or with mean annual temperatures (ranging 4–5 °C) at seven climatically diverse sites in the Sierra Nevada, California. Factors driven by tectonics and rock types such as: 1) changes in base level, 2) rock strength (in particular the spacing of joints and fractures), and 3) trunk stream incisions are more likely to influence erosion rates than climate (Riebe et al., 2001a, 2001b; Bierman and Nichols, 2004). In landscapes where uplift or incision have recently changed, erosion rates seem to be variable as relief becomes larger or smaller, and the transient response will persist until stream incision and erosion rates match uplift rates in all parts of the landscape (Granger et al., 1996). In regions of tectonic stability, erosion rates are uniform across a wide range of hillslope gradients. For example, in the highlands of tropical Sri Lanka the erosion rate is slow even on slopes up to 30° (Hewawasam et al., 2003), and in the Smoky Mountains in the Appalachians (USA) the denudation rates are nearly constant over various lithologies and slope gradients (Matmon et al., 2003). These results have been called into question by the realization that in many landscapes a major component of weathering in the saprolite zone has been shielded from CRN production and, therefore, a significant component of the weathering and erosion is not incorporated in CRN estimates of denudation (Dixon et al., 2009; Riebe and Granger, 2013). Other studies (Heimsath, 2006; Heimsath et al., 1997, 2001b) used cosmogenic data to understand how bedrock conversion to a mobile soil regolith layer depends on local soil thickness. In these studies the objective was to determine whether soil production varies inversely with soil thickness or if it peaks under certain soil depths.

In the work reported here we collected 12 soil, sediment and bedrock samples in two small sub-catchments (<1 km^2), of Mackereth Creek and Fern Gully in the Mt. Lofty Ranges, a few km east of Adelaide, South Australia (Fig. 1). This hilly area is dissected by ephemeral, seasonal and permanent streams. From ^{10}Be measurements we infer: 1) the steady state erosion rate for exposed bedrock surfaces, assuming that samples have had simple exposure histories and have been eroding at nearly constant rates; and 2) the catchment-averaged erosion rates, based on nuclide concentrations in stream sediments. These data are used as representative of erosion rates for the Mt. Lofty Ranges and then compared to erosion rates determined for the Flinders Ranges to the north in arid South Australia (Quigley et al., 2007), to the Blue Mountains in New South Wales (Wilkinson et al., 2005), and to inselbergs on the Eyre Peninsula, South Australia (Bierman and Caffee, 2002). These comparisons are useful because they provide context for the results reported here of landscape-scale erosion rates. Thirdly, chemical erosion rates are calculated using mass balance geochemistry of parent rock, regolith/soil and saprolite samples. This chemical erosion is based on assumed immobility of zirconium under the studied catchment conditions. Thus, with erosion rates calculated from both chemical depletion and ^{10}Be data at the catchment scale, chemical erosion rates are determined from equations developed by Granger and Riebe (2007, 2014). These chemical and physical erosion rates are compared with other studies from elsewhere in the world. In addition, chemical depletion determined from mass balance geochemistry allows for the weathering that occurs below the CRN production depth to be calculated.

2. Geological setting

The two catchments are broadly representative of much of the Mt. Lofty Ranges (MLR) in terms of bedrock geology, soil types, relief, degree of dissection, presence of remnant plateaux surfaces, climate and elevation (Figs. 2 and 3; Table 1). The Mt. Lofty Ranges in the Adelaide area have elevations ≤700 m above sea level and rise abruptly from the coastal plain. They are tectonically active and have been uplifted several hundreds of meters over the last few million years (Sandiford et al., 2003). The plateaux or "summit surface" (Twidale, 1976) has long been recognised as a geomorphic feature which appeared on explorer Matthew Flinders sketch map of the area made in 1803. The "surface" has an associated lateritic profile, possibly dating back to the Mesozoic (Twidale, 1976) and has a complicated weathering and erosional history since the Mesozoic (Milnes et al., 1985; Bourman, 1995).

Both catchments are among the least human impacted areas that can be found in the Mt. Lofty Ranges (Fig. 4). They are in a conservation area (Scott Creek Conservation Park) with no current human habitation. Land clearing has been minimal and kept to a few small valley bottoms and some logging. Bulldozed fire tracks are present on ridge lines, as is common in woodland settings throughout the Mt. Lofty Ranges and in hilly, wooded areas of Australia generally.

The Mackreath Creek study site is a sub-catchment of Scott Creek Catchment and has 100–300 m of relief, moderately steep slopes in many areas and narrow riparian-floodplain zones (Fig. 5). The study area, as is most of the MLR, is underlain by metamorphosed late Precambrian sedimentary rocks consisting of meta-shales, sandstone-quartzite, and minor carbonate units (Preiss, 1987). The hydrogeology of the area is that of a fractured rock aquifer (FRA) with large variations in hydraulic conductivity and groundwater salinity (Harrington, 2004a, 2004b; Banks et al., 2009; Bestland and Stainer, 2013). Small local aquifers are present where alluvial deposits are widespread (Bestland et al., 2009).

The Mackreath Creek area has four landscape-soil units: 1) a narrow and shallow alluvial bottom land with sandy silty and clayey soils and deposits, 2) moderate gradient slopes underlain by meta-shale with clayey soils (Xeralfs; Soil Survey Staff, 2010) that have strong texture contrasts between A and B horizons of the Red Brown Earth to Red Podzolic soil types (Taylor et al., 1974), 3) sandstone dominated moderate to steep slopes with Yellow Podzolic and skeletal stony and sandy soils (Xerents; Soil Survey Staff, 2010), and 4) broad ridge tops with eroded relict and podzolized soils and in places lateritic horizons (Fig. 2). Of these four landscape areas, the clayey texture contrast soils and yellow podzolic soils comprise the vast majority of the catchment. Soil thickness is typically between 0.5 and 1 m. Weathered bedrock or regolith of several meters in thickness typically occurs beneath the soil horizons (Fig. 5). A number of 2–3 m deep backhoe trenches have been dug in the area