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Soil erosion rates in South Africa compared with cosmogenic ^3He -based rates of soil production

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ABSTRACT

Soil erosion has been considered a major problem in South Africa since the early 20th Century, yet the degree to which rates of soil erosion may exceed rates of soil production has not been well constrained by previous studies. Here we present 22 cosmogenic ³He-based maximum denudation rates of Karoo dolerite bedrock surfaces, and interpret these values as local rates of soil production. These generally low soil production rates (< 4 m/Myr measured over a 10^5 yr timescale) are in all instances lower than various literature estimates for the corresponding rates of soil erosion in the same catchments, by up to two orders of magnitude. This significant contrast between long term rates of soil production and short term rates of soil erosion suggests that current agricultural practices are unsustainable under prevailing geological conditions.

Introduction

The increasing movement of rock and soil by humans correlates strongly with the development of human societies. Humans are now arguably the most significant geomorphic agents that sculpt the Earth's landscape ("manscaping"), and anthropogenic rates of erosion are estimated to have surpassed those resulting from all natural processes at the end of the first millennium A.D. (Hooke, 2000; Wilkinson, 2005). Following from the exponential growth of the human population, it has been projected that the total amount of solid earth materials moved by humans over the past 5000 years could double within the next 100 years, and that high rates of global sediment production may thus be considered a distinct lithostratigraphic signal typical of a discrete geological epoch: the "Anthropocene" (Hooke, 2000 and references therein; Zalasiewicz *et al.*, 2008). On the other hand, modern global sediment yields may be higher than the geological average partly because of increased sediment delivery following the Quaternary/late Neogene glaciations (Wilkinson, 2005 and references therein). However, most material eroded by humans is not delivered to the oceans, but is deposited within catchments if the carrying capacity of rivers is exceeded. Thus, local soil erosion rates may be an order of magnitude greater than the net sediment yield to the oceans (Martin, 1987; Garland *et al.*, 1999; Wilkinson and McElroy, 2007; Keay-Bright and Boardman, 2009).

Soil erosion has been a cause for concern in southern Africa since the early 20th Century (Garland *et al.*, 1999; Fey, 2010), and it has been proposed that severely degraded areas in the region are likely to become even more vulnerable in future, according to predicted climate change scenarios (Meadows and Hoffman, 2003). In particular, studies of badland and gully development focused on the Karoo region are

indicative of recent land degradation, probably due to extensive stock farming during the past 150 years of European settlement (Boardman *et al.*, 2003; Keay-Bright and Boardman, 2006; 2009). However, absolute estimates of regional soil erosion rates in southern Africa are variable and generally poorly constrained (Garland *et al.*, 1999). Furthermore, knowledge of the rate of soil formation relative to the rate of soil erosion is required in order to assess the long-term sustainability of agricultural practices (Le Roux, 1990). Here we use the cosmogenic nuclide abundances in bare dolerite bedrock surfaces in southern Africa to determine rates of soil production, and compare these values with rates of soil erosion in the same locations, as estimated in the literature.

Cosmogenic nuclides and rock denudation

Cosmogenic nuclides are produced through the interaction of high-energy cosmic ray particles with target nuclei in the earth's atmosphere (Libby, 1946), in meteorites (Paneth *et al.*, 1952), and in terrestrial rocks (Davis and Schaeffer, 1955). Because cosmic ray particles interact with the earth's atmosphere during their descent, the cosmogenic nuclides produced *in situ* in terrestrial surface rocks are several orders of magnitude less abundant than in meteorites, and it is only in the last two decades that technological advances have enabled their routine analysis and application to studies of earth surface processes (e.g. Gosse and Phillips, 2001; Niedermann, 2002; Dunai, 2010).

For geomorphological applications, where the cosmogenic nuclide production rate at the earth's surface P_0 is well constrained, the cosmogenic nuclide abundance in a surface rock may be used to place constraints on its exposure history. For the simple

case of instantaneous surface exposure of the rock with no subsequent denudation, an exposure age T may be determined as follows:

$$T = \frac{C}{P_0} \quad (1)$$

where C is the measured abundance of a stable cosmogenic nuclide, such as ^3He or ^{21}Ne , at the surface (e.g. Niedermann, 2002). As this assumes no denudation of the surface, T is in fact the minimum exposure age compatible with the data, and is only likely to be appropriate for rock surfaces that erode episodically through large mass wasting events (e.g. cliff faces). Instead, for rock surfaces that denude more gradually through weathering processes, a denudation rate ε may be defined:

$$\varepsilon = \frac{\Lambda P_0}{\rho C} \quad (2)$$

where ρ is the rock density and Λ is the effective attenuation length for cosmogenic nuclide production (the amount of mass penetrated by cosmic rays which reduces production rates by a factor of $1/e$; e.g. Niedermann, 2002). Thus, nuclide production is assumed to attenuate approximately exponentially with depth. Because the denudation rate ε assumes that denudation has proceeded at a steady rate for an effectively infinite period, ε is actually the maximum denudation rate compatible with the data, and is by definition valid for the characteristic time period taken to remove the thickness of rock equivalent to the cosmogenic nuclide production attenuation length, e.g. ~ 53 cm for a horizontal and unshielded dolerite surface where $\rho = 3 \text{ g/cm}^3$ and $\Lambda = 160 \text{ g/cm}^2$ (Gosse and Phillips, 2001). This characteristic time period for the denudation rate is numerically equivalent to the minimum exposure age T .

Because cosmogenic nuclides typically yield constraints on surface exposure histories on an intermediate timescale of 10^3 - 10^6 years, they are useful for the solution of a range of geomorphological problems. Previous cosmogenic nuclide studies in southern Africa (Fleming *et al.*, 1999; Cockburn *et al.*, 1999; 2000; Bierman and Caffee, 2001; Van der Wateren and Dunai, 2001; Kounov *et al.*, 2007; Codilean *et al.*, 2008; Dirks *et al.*, 2010; Vermeesch *et al.*, 2010) have been primarily concerned with testing models of long term landscape evolution, yet cosmogenic nuclide data can also provide a natural baseline against which the rates of present-day surface processes may be assessed (e.g. Hewawasam *et al.*, 2003; Vanacker *et al.*, 2007).

For the purposes of this study, we interpret the maximum denudation rates of sub-aerial bedrock surfaces as sediment production rates, which we also assume to be local soil production rates. This contrasts with studies from elsewhere in the world which have used cosmogenic nuclides to determine sub-surface rock weathering rates, based on the assumption of a local steady state regolith thickness (e.g. Heimsath *et al.*, 1997, 1999, 2000, 2002; Burke *et al.*, 2007; Dixon *et al.*, 2009). In our study, we did not analyse samples from beneath soils and saprolites, partly because our measurements rely on the analysis of fresh pyroxene, which was generally absent in such field settings. Even some apparently fresh rock samples that we collected could not be analysed due to pyroxene weathering. In addition, we did not assume that soils at our sample sites were necessarily in a steady state, because we observed apparently exhumed dolerite tors in the field (Decker, 2010), and because previous studies have shown some soils in the region to be relicts that are millions of years old (e.g. van Niekerk, 1999). A number of studies have focused on the effect of soil cover on

weathering rates, and results generally indicate that sediment production rates decline with soil depth, although a threshold soil cover may be required for soil formation processes (e.g. biological activity) to occur at optimum rates (Heimsath *et al.*, 1997; 1999; 2000; Gaillardet *et al.*, 1999; Oliva *et al.*, 2003; Burke *et al.*, 2007; Dixon *et al.*, 2009). Our approach also assumes that the total mass flux from these subaerial bedrock surfaces is deposited as soil. Although some mass is lost from these surfaces in solution, this dissolved rock mass may be precipitated in soils before eventual transport to the ocean.

Despite these assumptions, the results of our study and those of complimentary studies suggest that our approach is sound, particularly with respect to our general conclusions (see discussion below). Our data also suggests that, in retrospect, a long-term steady state assumption might be valid - at least on a regional scale - although this steady state has now been disrupted through human activities.

Sampling and analysis

In this study, 22 samples of the early Jurassic (~183 Ma; Encarnación *et al.*, 1996; Duncan *et al.*, 1997; Jourdan *et al.*, 2007; Svensen *et al.*, 2007) Karoo dolerite suite were collected for cosmogenic noble gas analysis from a number of drainage basins in the south-central parts of South Africa's arid Karoo region, and also from the Pongola river basin in north-eastern parts of KwaZulu-Natal (Figure 1). This presents an additional limitation, in that, for analytical reasons (the availability of suitable minerals such as pyroxene for noble gas analysis) and methodological reasons beyond the scope of this paper, we have assessed denudation rates for only one lithology. Nevertheless, soil production rates from Karoo dolerites are of particular importance,

because soils derived from Karoo dolerites are typically more fertile than those derived from their Karoo sedimentary host rocks, a fact reported to have been well known amongst traditional African farmers (Walker and Poldevaart, 1949).

Information on sample sites, including geographical coordinates and site descriptions, is summarised in Table 1, and an example of a sample site is shown in Figure 2. More detailed descriptions of sample sites are presented by Decker (2010). Each rock sample was recovered in the field with a hammer and chisel once its location and altitude was recorded with a GPS, its surface inclination measured with a clinometer, and the extent of cosmic ray shielding by obstructions on the horizon measured with an Abney level and a compass.

Horizontal surfaces were selected if they were the highest points locally, in order to minimize the chances of a complex exposure history (i.e. intermittent sediment cover). Similarly, vertical surfaces were selected that did not appear to have been influenced by human activities (e.g. road construction). Care was also taken not to sample rocks that may have experienced an influx of cosmic-ray neutrons from more than one surface (e.g. small boulders and the crests of cliffs) or collect samples that may have experienced movement during their exposure history. Only dolerite outcrops that appeared to be fresh enough to potentially yield pristine pyroxenes suitable for cosmogenic noble gas analysis were selected. As such, sampling was biased towards less weathered dolerite outcrops. As indicated above, some samples collected in the field were later rejected during sample preparation as they did not yield sufficient fresh pyroxene.

For each sample, the top 5 cm of the exposed rock surface was removed with a circular saw, crushed with a jaw crusher, sieved, and the 250-600 μm fraction washed with distilled water in an ultrasonic bath. Approximately 650 mg of pyroxene mineral grains were then handpicked for each sample after being concentrated through the application of magnetic and density separation techniques. A split of ~ 500 mg was used for noble gas mass spectrometry, and ~ 150 mg was used for major element determination through ICP-AES (inductively-coupled plasma atomic emission spectrometry) so that mineral chemistry-dependent nuclide production rates could be calculated. Extra pyroxene was sometimes handpicked in order to confirm the success of the mineral separation procedure through X-ray diffraction analysis.

Noble gas analysis was performed at the noble gas laboratory of Deutsches GeoForschungsZentrum in Potsdam, Germany, using a MM5400 noble gas mass spectrometer equipped with an ultrahigh vacuum furnace, an ultrahigh vacuum mechanical crusher, a gas preparation line and a cryogenic adsorber. All samples were analysed through stepwise heating, and some were also analysed through crushing. For crushing analyses, the sample was loaded into the ultrahigh vacuum crusher and baked at $100\text{ }^{\circ}\text{C}$ for 24 hours. The sample was then crushed between two hard metal jaws in order to release gases trapped between grain boundaries and within fluid inclusions, and the extracted gas was expanded into the gas preparation line. After crushing, the crushed sample material was then recovered and used in subsequent heating analyses.

For all heating analyses (i.e. for both previously crushed and uncrushed samples), the samples were wrapped in aluminium foil, deposited in a sample carousel, placed

under vacuum and baked for at least one week at 100°C. For noble gas extraction each sample was dropped into a tantalum crucible and heated by means of a graphite heating jacket. Samples were degassed in two or three temperature steps: 600°C and/or 900°C and 1750°C, and after each temperature step the gas was expanded into the gas preparation line and ultimately into the mass spectrometer for separate analysis. In the gas preparation line, condensable gases such as H₂O were frozen in a dry-ice cooled trap, and other chemically active gases (e.g. O₂, N₂, CO₂, H₂, hydrocarbons etc.) were absorbed in two titanium sponge and two ZrAl getters, with two additional ZrAl getters in the source and detector parts of the mass spectrometer, in order to maintain a low background of active gases during the measurements.

For each analysis (crushed, 600 °C, 900 °C, or 1750 °C), the measurement of noble gas spectra (and other associated spectra for interference corrections) was performed in three separate stages - first for He, then for Ne, and finally for Ar, Kr and Xe together. Sequential release of these gases into the mass spectrometer was achieved with the use of the cryogenic adsorber which could be cooled to 12 K, and then heated in separate steps. Gases were then ionized through electron bombardment with a modified Nier-type ion source, accelerated by a 4.5 kV voltage, focused through a system of electric lenses, and deflected through a 90° magnetic sector field according to their mass to charge ratio, for measurement by a Faraday cup or an electron multiplier detector, depending on the ion current strength. The data evaluation and reduction procedures discussed by Niedermann *et al.* (1997) were subsequently followed, and are also presented in detail by Decker (2010).

Noble gas results

The cosmogenic noble gas nuclides ^3He , ^{21}Ne and ^{38}Ar in pyroxene may all be used to determine surface denudation rates (e.g. Niedermann, 2002; Kounov *et al.*, 2007; Niedermann *et al.*, 2007). However, for the purpose of simplicity, we limit our discussion here to the determination of maximum denudation rates based on ^3He measurements. This proved to be the most analytically robust dataset, although the corresponding Ne and Ar datasets did yield consistent interpretations.

^4He abundances and $^3\text{He}/^4\text{He}$ ratios for all samples are given in Table 2. From this data, the cosmogenic ^3He excesses were determined according to the following relation:

$$^3\text{He}_{ex} = \left[\left(^3\text{He}/^4\text{He} \right)_m - \left(^3\text{He}/^4\text{He} \right)_{tr} \right] \times ^4\text{He}_m \quad (3)$$

where the subscripts *ex*, *m* and *tr* denote excess, measured and trapped respectively (e.g. Niedermann, 2002). Thus, in addition to the measured ^4He abundance and $^3\text{He}/^4\text{He}$ ratio, it is also required for the $^3\text{He}/^4\text{He}$ ratio of the trapped (non-cosmogenic) component to be assumed. For $(^3\text{He}/^4\text{He})_{tr}$, measurements of $^3\text{He}/^4\text{He}$ made after crushing *in vacuo* were considered, as these measurements reflect the $^3\text{He}/^4\text{He}$ ratio of He trapped in fluid inclusions and grain boundaries. Crushing of samples DV5, GD2 and IT1 yielded $^3\text{He}/^4\text{He}$ ratios of $(0.022 \pm 0.010) \times 10^{-6}$, $(0.050 \pm 0.036) \times 10^{-6}$ and $(0.060 \pm 0.011) \times 10^{-6}$ respectively (Table 2). However, these measurements are likely overestimates of the true $^3\text{He}/^4\text{He}$ ratio of the total non-cosmogenic He, because additional (radiogenic) ^4He is produced *in situ* within the crystal lattice of these relatively old pyroxenes. Therefore, a $(^3\text{He}/^4\text{He})_{tr}$ value of $(0.035 \pm 0.035) \times 10^{-6}$ was assumed for all samples in this study.

$^3\text{He}_{\text{ex}}$ values were calculated for each heating step according to Equation 3. The total $^3\text{He}_{\text{ex}}$ value for each sample is given in Table 3 with 2σ analytical errors. Some $^3\text{He}_{\text{ex}}$ values bear asymmetric errors, because for analyses where 2σ relative errors for $(^3\text{He}/^4\text{He})_{\text{m-tr}}$ are greater than 100 %, the negative 2σ error was set to 100 %. Similarly, where $(^3\text{He}/^4\text{He})_{\text{m-tr}}$ was less than zero, this value was set to zero to calculate $^3\text{He}_{\text{ex}}$ and the negative 2σ error, and set to $(^3\text{He}/^4\text{He})_{\text{m}}$ when calculating the positive 2σ error for $^3\text{He}_{\text{ex}}$. $^3\text{He}_{\text{ex}}$ values are given in atom/g, converted from cm^3 STP/g according to the Loschmidt Constant, i.e. with 2.686×10^{19} atom/ cm^3 STP.

Rock denudation and soil production rates

Minimum exposure ages and maximum denudation rates for bedrock surfaces were calculated from the ^3He excesses with the use of the Microsoft Excel add-in CosmoCalc version 1.6 (downloadable free of charge from <http://cosmocalc.googlepages.com>). Details of the CosmoCalc program are reported by Vermeesch (2007). Default settings were used, with the exception of the exponent of topographic shielding, $m = 2.3$ (e.g. Gosse and Phillips, 2001; Niedermann, 2002) and the rock density, $\rho = 3.0 \text{ g/cm}^3$ (e.g. Maré and Cole, 2006). Unshielded cosmogenic ^3He production rates normalised to sea level and latitudes $> 60^\circ$ are given in Table 3. These values were calculated on a sample specific basis, through the application of the mineral chemistry-dependent production rates proposed by Fenton *et al.* (2009). Our chemistry-dependent ^3He production rates, which range from 111.8 atom/g/yr to 115.9 atom/g/yr, are generally about 10 % lower than, but within error of, Goehring *et al.*'s (2010) chemistry-independent average ^3He production rate of 124 ± 12 atom/g/yr for pyroxenes and olivines, as determined according to Dunai (2000) scaling. On the other hand, our rates are very close to the value of 113

atom/g/yr given by Balco *et al.* (2008). Table 3 also lists the respective topographic shielding factors used, as determined in CosmoCalc according to the surface inclination and horizon shielding for each sample. Due to the complex dependence of the effective attenuation length on slope angle, true maximum denudation rates (ε) for non-horizontal surfaces were derived from apparent rates determined in CosmoCalc (ε^*), according to the numerical approximation employed by Hermanns *et al.* (2004):

$$\varepsilon = \frac{\varepsilon^*}{\left(1 + \frac{\alpha^2}{5000}\right)} \quad (4)$$

where α is the slope angle in degrees. Altitudinal and latitudinal controls on the cosmogenic nuclide production rate were compensated for with scaling factors calculated according to Dunai (2000).

Minimum exposure ages and maximum denudation rates for all surfaces are given in Table 4. Only 3 out of 22 samples (2 out of 5 vertical/inclined surfaces: CB1 and BW3, and 1 out of 17 horizontal/sub-horizontal surfaces: GR2) yielded maximum denudation rates greater than 4 m/Myr. These consistently low values for most samples suggest that the maximum denudation rate provides a plausible approximation of the true denudation rate, and that most surfaces, particularly those that are horizontal, lose mass gradually through weathering. For the three samples with higher maximum denudation rates, the ε value is likely to be an overestimate of the true denudation rate, as these surfaces have probably also lost mass episodically through rockfalls (BW3 and CB1) or exfoliation (GR2). If so, ε values are also likely to overestimate the rate of soil production at these sites, as the formation of soil will require the subsequent weathering of the large rock pieces lost from these surfaces. As

indicated by the corresponding minimum exposure ages for these surfaces, maximum denudation rates < 4 m/Myr are integrated over time periods on the order of 10^5 yr.

As stated above, maximum denudation rates for Karoo dolerite bedrock surfaces may only necessarily reflect rates of soil production from this lithology, although Karoo dolerites are abundant throughout most of the late Carboniferous-early Jurassic (~ 300 -180 Ma; Johnson *et al.*, 2006) Main Karoo Basin and thus also across much of South Africa. The mudstones and shales typical of Karoo sedimentary rock units are probably more easily eroded than harder Karoo dolerites in response to tectonically-driven fluvial incision, but their relative weathering rates are not known. However, the weathering rates of these sedimentary rocks are likely reflected in the overall denudation rate of the Orange River drainage basin, which, according to Vermeesch *et al.*'s (2010) cosmogenic ^{10}Be and ^{26}Al data, is 4.0 ± 0.9 m/Myr. The good agreement between this catchment-averaged value and our maximum denudation rates for dolerite surfaces (average value = 3.1 m/Myr) suggests that our rates are representative of local sediment production in the region. The corollary of this is that regionally, the landscape has approximated a steady state over the cosmogenic nuclide-integrated timescale, with the rate of sediment delivery to the ocean approximating the rate of sediment production.

Based on off-shore stratigraphy for the Holocene, Compton *et al.* (2010) concluded that mud from the Orange River had accumulated along southern Africa's west coast at an average rate of 5.1×10^{12} g/yr. These authors also noted that 5/6th's of the historical (20th Century) discharge from the 953 200 km² Orange River basin is mud (Dingle and Hendey, 1984; Bremner *et al.*, 1990; Compton *et al.*, 2010). Assuming a

parent rock density of 2.6 g/cm³ (e.g. Le Roux, 1990), this translates into a mean denudation rate of 2.5 m/Myr across this basin. However, given that the particulate load for rivers globally is estimated to be only 75 % to 90 % of the total load (Wilkinson, 2005) with the dissolved load being the remainder, an average Holocene denudation rate of 3.3 - 3.7 m/Myr may be assumed for the Orange River basin. This is within error of the value determined over a longer period by Vermeesch *et al.* (2010), although Compton *et al.* (2010) considered Holocene denudation rates to be heterogeneous across the region. In addition, the observation that *in situ*-produced soils in southern Africa (fluvial and aeolian deposits excluded) are generally < 1 m thick and thinner in arid areas of Karoo sedimentary rock outcrop (Schulze, 2007) is compatible with steady state, weathering-limited soil erosion rates for the Quaternary/late Neogene.

Present soil erosion rates

Present soil erosion rates in South Africa are poorly constrained, and future regional studies applying improved monitoring, modeling and remote sensing technologies are required to address this deficiency (Le Roux *et al.*, 2007). Nevertheless, some general inferences may be made through recourse to the available published data. To perform a spatial comparison of soil production rates with soil erosion rates, soil erosion maps (or spatial databases) are a necessary reference source. Four such sources were made use of in this study, namely:

1. Rooseboom (1978): By extrapolating sediment yield rates determined from measuring stations and dam accumulations over larger areas of presumed similar erodibility, this author presented a map of maximum potential

sediment yield rates in South Africa, Lesotho and Swaziland. Sediment yield values ranged from 50 ton/km²/yr to 1000 ton/km²/yr (i.e. denudation rates of 19 m/Myr to 385 m/Myr, assuming a rock density of 2.6 g/cm³).

2. Le Roux (1990): This author produced a contoured map of denudation rates in this same area, based on dam accumulations, with contours ranging from 25 mm/kyr to 150 mm/kyr (units equivalent to m/Myr).
3. Schulze (2007): This reference source is a GIS dataset of catchment-specific model sediment yields for the region, based on the Modified Universal Soil Loss Equation (MUSLE; Williams, 1975). Variable inputs for this model include the volumes and peak discharges of stormflow events, a soil erodibility factor, slope length and slope gradient (Schulze *et al.*, 2007).
3. Compton *et al.* (2010): These workers estimated soil erosion rates for magisterial districts within the Orange River catchment by combining literature estimates of the qualitative degree of soil degradation, measured rates of soil loss, and land use indices. It may be noted that Compton *et al.* (2010) also reported that the modern mud flux of the Orange River basin prior to the building of large dams (1930-1969) was ten times greater than the mean Holocene mud flux, and attributed this to modern agricultural practices.

Other soil erosion rate estimates for southern Africa have been made by du Toit (1933 and references therein) and Martin (1987). Du Toit (1933 and references therein) estimated from the sediment flux below the Orange and Vaal river junction that soil

erosion was lowering the landsurface by an average rate of 1 foot per 1500 years, i.e. ~200 m/Myr. For southern Africa's east coast rivers and the Limpopo river catchment, Martin (1987) reported the sediment yield to be 323 ton/km²/yr and 265 ton/km²/yr, equivalent to average surface denudation rates of 124 m/Myr and 102 m/Myr, respectively, assuming a parent rock density of 2.6 g/cm³.

Comparison and discussion

Estimated soil erosion rates in the vicinity of Karoo dolerite sample sites according to Rooseboom (1978), Le Roux (1990), Schulze (2007) and Compton *et al.* (2010) are given in Table 5. These values were extracted from scanned and georectified maps or from databases with the use of ArcGIS 9.3 software. Note that values are presented here after conversion to denudation-equivalent units (surface lowering per unit time). These estimates are compared graphically with ³He maximum denudation rates for Karoo dolerites in Figure 3. For every sample site, all literature estimates of the soil erosion rate are greater than the corresponding Karoo dolerite maximum denudation rate, and therefore also greater than the soil production rate from dolerite. The degree to which soil erosion rates exceed soil production rates varies by a factor of between ~2 and ~280. As shown in Table 5, the average soil erosion rate at all the cosmogenic nuclide sample sites is variously estimated to be 198 m/Myr (Rooseboom, 1978), 70 m/Myr (Le Roux, 1990), 76 m/Myr (Schulze, 2007) and 57 m/Myr (Compton *et al.*, 2010). Note, however, that Rooseboom's (1978) estimates are maximum values, and that Compton *et al.*'s (2010) estimates are restricted to sample sites that lie within the Orange River catchment.

The mean maximum denudation rate for the Karoo dolerite surfaces sampled in this study is 3.1 m/Myr, although the probable mean rate of dolerite weathering (i.e. the mean ϵ value excluding the ϵ values of the 3 samples BW3, CB1 and GR2) is still lower, at 1.9 m/Myr. Comparison of the latter value with the mean soil erosion rate estimates given above suggests that, on average, soils in southern Africa are presently being lost 30 to 100 times faster than they are being replaced. Le Roux (1990) tentatively assumed rock weathering rates in southern Africa to be considerably higher than shown in this study, at 10-40 m/Myr, and thus proposed that soil was being lost more than 2 or 3 times faster than it was being produced. In fact, soil erosion and production rates in southern Africa are apparently even further from equilibrium than Le Roux (1990) calculated. The results of this comparison are instead similar to the findings of Hewawasam *et al.* (2003), who compared natural erosion rates in Sri Lanka, based on cosmogenic ^{10}Be in quartz from sediments and soils, with present-day rates of soil loss. They observed that sediment was being lost 1 to 2 orders of magnitude faster than it was being produced, and attributed this to extensive deforestation. Similarly, Vanacker *et al.* (2007) noted that in deforested catchments in the Ecuadorian Andes, present-day sediment yields were at least 1 order of magnitude higher than the maximum long-term (cosmogenic nuclide-based) denudation rates. Encouragingly, these workers also showed that the effect of human activities on sediment yield was minimal in catchments where surface vegetation cover had been restored, even by non-indigenous vegetation.

Concluding remarks

Cosmogenic ^3He abundances in Karoo dolerite bedrock surfaces reveal slow rates of denudation, with maximum denudation rates of most surfaces being less than 4

m/Myr. These maximum denudation rates may be interpreted as long-term rates of local soil production, and reveal that for all sites, rates of short-term soil loss are estimated to be higher than rates of soil production, by up to 2 orders of magnitude.

Although absolute soil erosion rates in South Africa are admittedly poorly constrained, the generally high rates that are proposed are apparently unprecedented in the Cenozoic. It is sobering to consider that the region has not experienced long-term denudation rates in excess of 50 m/Myr since the Cretaceous (Brown *et al.*, 2002; Tinker *et al.*, 2008; Kounov *et al.*, 2009), and it may thus be said that humans are now mimicking the “Kalahari epeirogeny” (de Wit, 2007) in sculpturing the landscape. On the other hand, the rates of irregularly occurring processes such as erosion are timescale-dependent (Gardner *et al.*, 1987), and thus present soil erosion rates might be less geologically significant for South Africa than a direct comparison with long-term rates would suggest. What is apparent, however, is that “Anthropocene” rates of soil erosion in South Africa are unsustainable under prevailing tectonic and climatic conditions.

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FIGURE AND TABLE CAPTIONS

Figure 1. Site locations of Karoo dolerite samples ($n = 22$) from the south-central Karoo region and north-east KwaZulu-Natal (yellow circles) in the Republic of South Africa. The geographical coordinates of individual sample sites are given in Table 1. Surface elevations according to the SRTM digital elevation model (Jarvis *et al.*, 2006) as well as provincial boundaries and the outcrops of the Karoo dolerite suite (red) after Veselinovic-Williams and Frost-Killian (2002) are also shown.

Figure 2. Example of a dolerite sample site (DV9) viewed to the south; sample indicated by arrow. The dolerite sill from which the sample is collected forms a slight local topographic high on low relief plains south of the Great Escarpment in the southern Karoo (Table 1). The mountains of the Cape Fold Belt are faintly visible on the horizon. The ^3He maximum denudation rate for this surface was determined to be $2.17 \pm 0.27/-0.37$ m/Myr (Table 4).

Figure 3. Comparison between ^3He maximum denudation rates for Karoo dolerites (red line) and corresponding estimates of modern soil erosion rates at these sites (blue, grey, green and orange lines), according to Rooseboom (1978), Le Roux (1990),

Schulze (2007) and Compton *et al.* (2010). Error bars for dolerite maximum denudation rates represent 2σ analytical uncertainties. Note that the vertical axis is logarithmic. If Karoo dolerite maximum denudation rates are assumed to represent soil production rates, soil erosion rates are higher than long-term production rates at any site by a factor of between ~ 2 and ~ 280 .

Table 1. Location, elevation, surface dip and type, river catchment and brief site description corresponding to each Karoo dolerite sample site.

Table 2. ^4He abundances and $^3\text{He}/^4\text{He}$ ratios for step-heating and crushing measurements. Total values from heating measurements are also given for each sample.

Table 3. Total ^3He excesses, unshielded cosmogenic ^3He production rates normalised to sea level and latitudes $> 60^\circ$, and topographic shielding factors for all samples.

Table 4. ^3He minimum exposure ages and maximum denudation rates for all samples.

Table 5. Literature estimates for modern soil erosion rates in areas corresponding to Karoo dolerite sample sites.

FIGURE 2

FIGURE 3

TABLE 1

Sample	Latitude (°)	Longitude (°)	Elevation (m)	Surface dip (°)	Surface type
BW3	-32,2552	22,5818	1121	90	Vertical
CB1	-31,2623	24,9396	1632	44	Inclined
DV5	-32,5217	22,8831	855	0	Horizontal
DV6	-32,5216	22,8836	858	0	Horizontal
DV9	-32,5762	23,1796	907	10	Sub-horizontal
GD1	-30,6122	25,4923	1494	90	Vertical
GD2	-30,6128	25,4920	1494	10	Sub-horizontal
GD3	-30,6128	25,4920	1494	12	Sub-horizontal
GR1	-32,1066	24,6029	1176	0	Horizontal
GR2	-32,1065	24,6020	1187	0	Horizontal
GR3	-32,0528	24,6110	1260	10	Sub-horizontal
GR5	-31,8117	24,8762	1647	0	Horizontal
IT1	-27,5579	31,3586	1101	0	Horizontal
IT3	-27,5905	31,3156	1252	0	Horizontal
IT5	-27,4824	31,2918	919	4	Sub-horizontal
IT6	-27,4774	31,2969	876	90	Vertical
IT8	-27,5713	31,2756	1386	0	Horizontal
IT9	-27,5713	31,2756	1386	0	Horizontal
IT10	-27,5705	31,2766	1393	0	Horizontal
OR1	-29,8958	24,6319	1163	30	Inclined
OR2	-29,8963	24,6447	1205	0	Horizontal

OR3	-30,1993	24,7119	1236	6	Sub-horizontal
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River catchment	Site description
Gouritz	Exfoliating scarp face at southern Great Escarpment east of Beaufort West
Orange	Exfoliating scarp face immediately north of the Orange River's southern drainage divide
Groot	Low relief plains to the south of the southern Great Escarpment between Beaufort West and Graaff-Reinet
Groot	Low relief plains to the south of the southern Great Escarpment between Beaufort West and Graaff-Reinet
Groot	Low relief plains to the south of the southern Great Escarpment between Beaufort West and Graaff-Reinet
Orange	Scarp face of a <i>koppie</i> overlooking Gariep Dam on the Orange River
Orange	Summit of a <i>koppie</i> overlooking Gariep Dam on the Orange River
Orange	Summit of a <i>koppie</i> overlooking Gariep Dam on the Orange River
Sundays	Exfoliating ridge north of Graaff-Reinet
Sundays	Exfoliating ridge north of Graaff-Reinet
Sundays	Plain within the Great Escarpment zone north of Graaff-Reinet
Great Fish	Surface from the top of Lootsberg Pass, north of Graaff-Reinet
Pongola	Locally flat surface on the edge of an escarpment overlooking the Pongola River
Pongola	Exfoliating dolerite pavement littered with loose dolerite boulders
Pongola	Horizontal surface of a dolerite sill above the incised Pongola River
Pongola	Scarp face overlooking the incised meanders of the Pongola River
Pongola	Exfoliating dolerite pavement at the summit of a hill south of the Pongola River
Pongola	Exfoliating dolerite pavement at the summit of a hill south of the Pongola River
Pongola	Boulder surface at the summit of a hill south of the Pongola River
Orange	Inclined hillslope overlooking the Orange River downstream of Vanderkloof Dam
Orange	Hill summit overlooking the Orange River downstream of Vanderkloof Dam

Orange

Top of an inselberg/tor comprising a pile of *in situ* dolerite
corestones

TABLE 2

Sample	Mass g	T °C	⁴ He		³ He/ ⁴ He	
			10 ⁻⁸ cm ³ STP/g	± 2σ	10 ⁻⁶	± 2σ
BW3	0,50102	600	13,91	0,70	0,449	0,083
		900	112,6	5,6	0,090	0,013
		1750	141,4	7,1	0,0251	0,0079
		Total	267,9	9,1	0,0744	0,0081
CB1	0,48028	900	129,9	6,5	0,194	0,020
		1750	59,8	3,0	0,045	0,011
		Total	189,8	7,2	0,147	0,015
DV5	0,50352	900	207	10	0,669	0,031
		1750	140,2	7,0	0,035	0,011
		Total	347	13	0,413	0,022
	0,51124	Crushed	59,2	3,0	0,022	0,010
DV6	0,50356	900	234	12	0,923	0,037
		1750	513	36	0,049	0,018
		Total	748	38	0,322	0,023
DV9	0,50052	900	377	19	0,439	0,028
		1750	544	38	0,0496	0,0083
		Total	921	43	0,209	0,015
GD1	0,50352	600	5,27	0,26	3,92	0,30
		900	15,30	0,77	4,43	0,33
		1750	22,0	1,1	1,044	0,083
		Total	42,6	1,4	2,62	0,14
GD2	0,51466	900	25,1	1,3	8,89	0,55
		1750	17,5	1,2	1,56	0,15
		Total	42,6	1,8	5,88	0,36
	0,52240	Crushed	14,43	0,72	0,050	0,036
GD3	0,48336	900	17,40	0,87	14,57	0,55
		1750	27,1	1,4	2,36	0,18
		Total	44,5	1,6	7,14	0,32
GR1	0,50178	900	178,0	8,9	0,734	0,037
		1750	422	21	0,0600	0,0027
		Total	600	23	0,260	0,015
GR2	0,50070	900	289	14	0,220	0,014
		1750	236	12	0,0425	0,0090
		Total	525	19	0,140	0,009
GR3	0,52566	900	329,8	16	0,401	0,028
		1750	148,7	7,4	0,128	0,020
		Total	478	18	0,316	0,021
GR5	0,48144	900	118,7	5,9	2,031	0,078
		1750	318	16	0,207	0,011
		Total	437	17	0,702	0,034
IT1	0,52212	900	885,9	63	0,150	0,018
		1750	1236	88	0,054	0,011
		Total	2120	110	0,094	0,010
	0,53060	Crushed	866	61	0,060	0,011
IT3	0,50018	900	1063	75	0,342	0,025
		1750	1920	140	0,100	0,011
		Total	2980	150	0,187	0,013
IT5	0,50190	900	258	13	0,984	0,035
		1750	308	15	0,161	0,013
		Total	566	20	0,536	0,023
IT6	0,50024	600	62,9	3,1	0,490	0,044
		900	268	13	0,164	0,011
		1750	607	43	0,0989	0,0079
		Total	938	45	0,144	0,007
IT8	0,50388	900	795	56	0,497	0,057
		1750	966	68	0,151	0,016
		Total	1761	88	0,307	0,028
IT9	0,49022	900	1240	88	0,311	0,022
		1750	643	32	0,1382	0,0088

		Total	1883	94	0,252	0,015
IT10	0,50202	900	933	66	0,509	0,032
		1750	981	69	0,151	0,014
		Total	1914	96	0,326	0,019
OR1	0,50602	900	91,1	4,6	0,993	0,067
		1750	35,9	1,8	0,638	0,063
		Total	127,0	4,9	0,893	0,052
OR2	0,50038	900	49,3	2,5	3,25	0,16
		1750	21,3	1,1	1,40	0,11
		Total	70,7	2,7	2,69	0,12
OR3	0,50940	900	72,6	3,6	1,709	0,082
		1750	198,1	9,9	0,254	0,013
		Total	271	11	0,644	0,031

TABLE 3

Sample	³ He excess (10 ⁶ atom/g)	2σ (+)	2σ (-)	³ He production rate (atom/g/yr)
BW3	3,2	1,5	1,2	115,8
CB1	5,7	1,6	1,4	115,2
DV5	35,3	3,4	3,1	114,5
DV6	57,7	6,9	4,6	113,7
DV9	43,1	7,3	5,4	114,2
GD1	29,5	1,8	1,8	115,8
GD2	66,9	4,8	4,8	115,6
GD3	84,9	4,5	4,5	115,5
GR1	36,3	5,0	4,1	115,5
GR2	14,8	3,8	3,1	115,0
GR3	36,2	4,6	4,6	114,6
GR5	78,3	5,3	5,3	115,8
IT1	34	16	12	113,6
IT3	121	24	24	111,8
IT5	76,3	5,7	5,7	112,4
IT6	27,4	6,6	6,6	112,5
IT8	129	19	19	113,4
IT9	110	17	17	113,5
IT10	149	18	18	113,3
OR1	29,3	2,3	2,3	115,2
OR2	50,4	3,1	3,1	115,9
OR3	44,3	3,2	3,2	115,7

Topographic shielding factor
0,460
0,926
1,000
1,000
0,999
0,499
0,999
0,999
0,997
1,000
0,999
0,999
1,000
1,000
1,000
1,000
0,499
1,000
1,000
1,000
0,977
1,000
1,000

TABLE 4

Sample	Minimum exposure age (ka)	2σ (+)	2σ (-)
BW3	33	16	12
CB1	20,3	5,6	5,2
DV5	205	20	18
DV6	337	40	27
DV9	241	41	30
GD1	219	13	13
GD2	248	18	18
GD3	315	17	17
GR1	165	23	19
GR2	67	17	14
GR3	155	20	20
GR5	251	17	17
IT1	184	85	63
IT3	600	120	120
IT5	483	36	36
IT6	359	86	86
IT8	568	83	83
IT9	484	73	73
IT10	656	78	78
OR1	146	12	12
OR2	236	15	15
OR3	201	14	14

Maximum denudation rate (m/Myr)	2 σ (+)	2 σ (-)
6,2	2,3	3,0
18,9	4,8	5,2
2,60	0,23	0,25
1,58	0,13	0,19
2,17	0,27	0,37
0,929	0,057	0,057
2,11	0,15	0,15
1,644	0,088	0,088
3,23	0,37	0,44
8,0	1,6	2,1
3,37	0,43	0,43
2,13	0,14	0,14
2,9	1,0	1,3
0,89	0,17	0,17
1,101	0,082	0,082
0,57	0,14	0,14
0,94	0,14	0,14
1,10	0,17	0,17
0,813	0,097	0,097
3,10	0,25	0,25
2,26	0,14	0,14
2,63	0,19	0,19

TABLE 5

Sample site	Soil erosion rate estimates ($\text{m}^3/\text{km}^2/\text{yr} = \text{mmr}$)			
	Rooseboom (1978) ¹ Max.	Le Roux (1990) ² Min. Max.		Schulze (2007) ³
BW3	385	25	50	23
CB1	308	25	50	47
DV5	58	25	50	16
DV6	58	25	50	16
DV9	58	25	50	278
GD1	231	25	50	163
GD2	231	25	50	163
GD3	231	25	50	163
GR1	58	75	100	30
GR2	58	75	100	30
GR3	58	75	100	57
GR5	308	50	75	25
IT1	231	100	125	22
IT3	231	100	125	22
IT5	231	100	125	78
IT6	231	100	125	78
IT8	231	100	125	78
IT9	231	100	125	78
IT10	231	100	125	78
OR1	231	-	25	41
OR2	231	-	25	41
OR3	231	-	25	139
Average	198	62	78	76

¹Converted from map of maximum averaged sediment yields in ton/ha/yr, assuming an average rock density of 2.6 g/cm³

²Determined from map of surface lowering rate contours, given as mm/kyr for a rock density of 2.6 g/cm³

³Converted from dataset of catchment-specific sediment yields in ton/ha/yr, assuming an average rock density of 2.6 g/cm³

⁴Determined from supplementary table of erosion rates in ton/km²/yr for magisterial districts in the Orara catchment, assuming an average rock density of 2.6 g/cm³

v/kyr = m/Myr)
Compton <i>et al.</i> (2010) ⁴
-
57
-
-
-
56
56
56
-
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-
-
-
-
-
-
57
57
58
57

ensity of 2.6 g/cm³
n³
density of 2.6 g/cm³
nge River catchment, assuming an