A progress report on the use of in-situ-produced cosmogenic isotopes to evaluate rates of landscape development in central Namibia

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We report on our on-going research into the rate and mode of landscape development in central Namibia using analysis of in-situ-produced cosmogenic isotopes in quartz. Long-term (>10^6 a), regional estimates of denudation are available from previous studies that have used fission-track thermochronology and investigation of the terrestrial and offshore sedimentary record. However, complementary, intermediate-term (10^4-10^6 a) denudation rates are currently lacking but are required to fully constrain landscape evolution. To date, bedrock samples from two of the key morphological elements of the central Namibian landscape have been analysed, namely the escarpment and the granite bornhardts on the coastal plain. Abundances of cosmogenic ^{10}Be and ^{26}Al in quartz indicate an escarpment retreat rate of ~10 m Ma^{-1} and a mean surface lowering rate for the bornhardts of ~5 m Ma^{-1}. These values are incompatible with the rapid denudation and retreat rates typically inferred for passive margin landscapes and therefore challenge traditional geomorphic models of landscape development. Our research demonstrates the potential of cosmogenic isotope analysis to provide previously unobtainable, quantitative data that increases our understanding of the Namibian landscape, and presents opportunities for more applications in the future.

Introduction

Quantifying how fast landscapes change is fundamentally important to understanding how they evolve. Therefore, to fully appreciate the evolutionary history of the Namibian landscape between continental rifting (~130 Ma BP) and the present-day, it is necessary to establish the rate and pattern of denudation across the south-west African margin. Long-term (10^6-10^8a), regional-scale data on denudation for the margin are available from apatite fission track studies (Brown *et al.*, 1990, 1994 and 1999), analysis of the offshore sedimentary record (Dingle and Hendy, 1984; Rust and Summerfield, 1990) and investigation of on-shore geology (Gilchrist *et al.*, 1994). However, there is a distinct lack of quantitative data on rates of denudation at the finer spatial resolutions required to assess the role of individual morphological components in landscape development. In addition, data are needed at an intermediate time-scale (10^4-10^6a) between long-term techniques and modern day process studies (Summerfield and Hulton, 1994). Data are also required at greater spatial and temporal resolutions to constrain numerical surface process models of landscape evolution (e.g. van der Beek and Braun, 1998).

In-situ-produced cosmogenic isotope analysis (CIA) is a valuable recent addition to the range of techniques currently available to measure denudation rates (Cerling and Craig, 1994). Based on the accumulation of isotopes produced in the upper layers of rocks that are exposed to cosmic radiation at the Earth's surface, the technique can place site-specific, quantitative constraints on the exposure history of a rock surface in terms of a uniform denudation rate (Lal, 1991). The technique yields data on time-scales from 10^3-10^6a and as such provides an important link between short and longer-term geomorphic information.

Here we present an overview of research carried out using cosmogenic isotopes ^{10}Be and ^{26}Al in quartz to quantify denudation on key morphological elements of the Namibian landscape. Our overall aim is to test existing hypotheses regarding landscape evolution in passive margin settings and to provide empirical constraints for quantitative surface process models. Our objectives have been to constrain a rate of escarpment retreat and an average rate of bornhardt surface lowering in central Namibia. More detailed accounts of bornhardt and escarpment studies are given by Cockburn *et al.* (1999) and Cockburn *et al.* (2000).

Background to Research

The main topographic elements along the south-west African continental margin are typical of many high-elevation passive margins (Gilchrist and Summerfield, 1994). In central Namibia there is a well defined major escarpment, with a relief of ~1000 m, located ~150 km inland of the present coastline separating a gently inclined coastal plain with a regional slope of 0.3° from an interior plateau with a mean elevation of ~1800 m. It has been generally assumed that the evolution of this topography has been dominated by the steady inland migration of the escarpment since its initial formation at the continental edge during the break-up of Gondwana (King, 1951; Ollier, 1985; Gilchrist and Summerfield, 1990; Seidl *et al.*, 1996). Average retreat rates of ~1000 m Ma^{-1} are required for this model to apply. A problem with geomorphic models of this type is that they are largely qualitative and lack supporting evidence from quantitative field based studies. At the same time, surface process modelling studies are questioning the validity of the styles of landscape development proposed in these traditional models. Specifically, numerical modelling has shown that uniform escarpment retreat is an unlikely mode of landscape development because the position and evolution of major escarpments is strongly influenced by antecedent topography and the location of inland drainage divides (Gilchrist *et al.*, 1994; Tucker and Slingerland, 1994; van der Beek and Braun, 1998).

Below the escarpment, the Namib Desert occupies the ~150 km wide coastal plain. In the central Namib, north of the Namib Sand Sea, the main significant relief forming features are inselbergs and ephemeral channels of the Kuiseb, Swakop and Tumas River systems. The inselbergs are often formed in granite with a domed morphology rising on average 100 m above their fringing bedrock pediments. Southern Africa is the type locality for these domed granite inselbergs, or bornhardts as they are commonly known (Willis, 1934; Thomas, 1994). Bornhardts in Namibia have been extensively studied and their origin has been attributed largely to structural control (Selby, 1977, 1982), yet rates of denudation on these features are very poorly constrained. Knowledge of how fast they are eroding is not only important to understand the evolution of the bornhardts themselves but also because they are key morphological elements which can provide important quantitative constraints on landscape evolution across the south-west African margin.

Central Namibia was selected as the field site not only because it displays typical passive margin morphology with good sampling sites for CIA, but also because the area has a well documented, relatively stable climatic history. Investigation of the sedimentary record indicates that arid to semi-arid conditions, similar to the present-day climate (Lancaster *et al.*, 1984), have prevailed over at least the past 10-12 Ma but possibly throughout most of the Cenozoic (Ward *et al.*, 1983; Lancaster, 1984a and b; Ward, 1987; Ward and Corbett, 1990; Wilkinson, 1991). This exceptionally stable history allows for tentative extrapolation back in time of our denudation rates based on cosmogenic isotopes in the coastal plain region.

Sampling Strategy

Namibia is an ideal environment in which to apply the cosmogenic technique due to large areas of exposed bedrock free from vegetation and remote from intensive human activity. However, sampling sites must be selected carefully as the information obtained from CIA is very site specific. Our strategy involved two contrasting sampling locations in central Namibia: the escarpment at the Gamsberg and granite bornhardts on the coastal plain. Sampling sites are shown in Figure 1.

Fourteen surface bedrock samples for analysis of cosmogenic ^{10}Be and ^{26}Al were collected from the Gamsberg in order to place quantitative constraints on the rate of escarpment retreat in central Namibia (Table 1). The Gamsberg (2347 m) is second only to the Brandberg in elevation in Namibia and is an impressive landscape feature. Situated directly on the escarpment on the western edge of the Khomas Hochland it is the highest and one of the simplest expressions of the escarpment on the south-west African margin. It consists of a uniform quartz arenite caprock with a cliff edge overlying basement Gamsberg Granite which gives it a conspicuous table-top shape (Schalk, 1983). A profile of samples across the Gamsberg was collected in order to assess denudation rates of the three principal topographic elements, namely the caprock summit, the

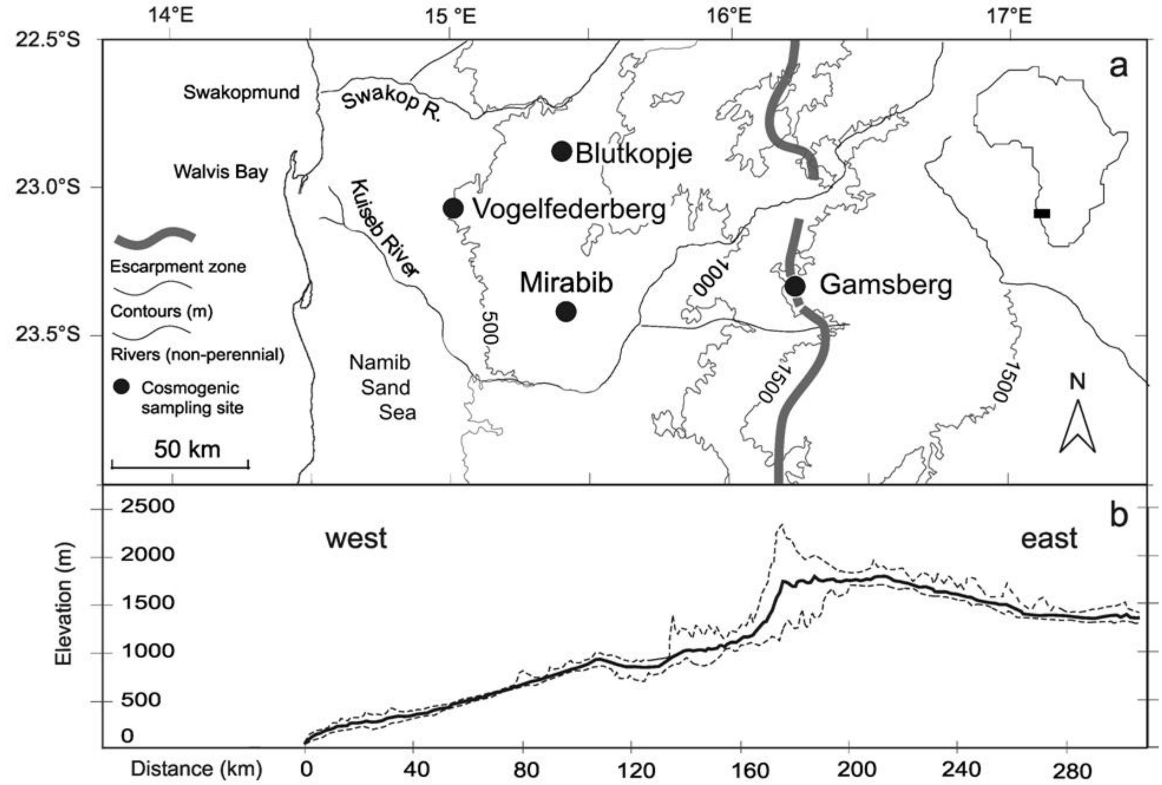

Figure 1: a) Location map showing sampling sites for cosmogenic isotope analysis.
b) Mean elevation (solid black line) and maximum and minimum (dashed lines) elevations across the central Namibia margin along a 20 km wide transect through the Gamsberg . The Gamsberg is the highest point of the escarpment. (Data from the GTOPO 30 digital data set.)

caprock cliff face and the granite ridges extending from the base of the caprock.

Three granite bornhardts in the central Namib Desert located on the coastal plain below the escarpment were also selected for sampling (Fig. 1). There are abundant similar features throughout the central Namib suggesting that rates of denudation on just three may be representative of many more. Two surface bedrock samples were analysed from Blutkopje, Vogelfederberg and Mirabib respectively (Table 1).

Results

A summary of denudation rates for the different morphological elements sampled are presented in Table 2. Gamsberg samples yielded denudation rates ranging from 0.28 ± 0.07 m Ma^{-1} to 0.52 ± 0.11 m Ma^{-1} for the slowly eroding summit samples, 4.53 ± 0.96 m Ma^{-1} to 12.50 ± 2.93 m Ma^{-1} for the retreating caprock cliff face, and 2.09 ± 0.49 m Ma^{-1} to 15.64 ± 3.70 m Ma^{-1} for the granite ridge samples. Ratios of ^{10}Be and ^{26}Al concentrations indicate that all Gamsberg samples have probably experienced simple exposure histories and attained isotopic secular equilibrium, thereby supporting the assumptions of the steady-state model (Lal, 1991). Transforming the rates for the granite slope samples into horizontal retreat rates using a simple trigonometric conversion and combining them with the caprock cliff retreat rates suggests an overall rate of escarpment retreat at the Gamsberg of ~10 m Ma^{-1}. In order to satisfy the assumptions of secular equilibrium and prolonged denudation inherent in the steady-state erosion model, these rates are necessarily integrated over a minimum of the past ~10^6 a for the slowly eroding summit samples and ~8 x 10^4 a for escarpment retreat.

Denudation rates on the coastal plain bornhardts range from 2.70 ± 0.56 m Ma^{-1} to 8.00 ± 1.79 m Ma^{-1}. Analysis of the Al/Be ratio for the bornhardt samples reveals that although samples 16B and 17A, from Vogelfederberg and Mirabib respectively, support the assumptions

Table 1: Field and sample data for Namibian cosmogenic samples.
* Full details of exposure geometry and production rate shielding corrections for each sample can be found in Cockburn (1998).

Sample Number	Location	Longitude & Latitude	Altitude (m)	Lithology	Surface Slope (°)	*Exposure Geometry
Escarpment Profile at the Gamsberg						
1/95	Ridge	16° 12' 35" 23° 20' 56"	2130	Gamsberg Granite	37	partial shielding
2/95	Ridge	16° 12' 40" 23° 21' 01"	2183	Gamsberg Granite	47	partial shielding
3/95	Ridge	16° 12' 42" 23° 21' 02"	2246	Quartz Vein	33	partial shielding
4/95	Ridge	16° 12' 12" 23° 20' 52"	2119	Gamsberg Granite	0	partial shielding
5/95	Ridge	16° 14' 13" 23° 20' 49"	2191	Gamsberg Granite	0	partial shielding
6/95	Ridge	16° 14' 10" 23° 20' 40"	2293	Gamsberg Granite	0	partial shielding
15/94	Caprock Cliff Face	16° 14' - 23° 20' -	2327	Gamsberg Quartz-ite	80	partial shielding
8/95	Caprock Cliff Face	16° 12' 53" 23° 21' 01"	2321	Gamsberg Quartz-ite	65	partial shielding
9/95	Caprock Cliff Face	16° 12' 49" 23° 21' 04	2325	Gamsberg Quartz-ite	70	partial shielding
11/95	Caprock Cliff Face	16° 14' 10" 23° 20' 38"	2330	Gamsberg Quartz-ite	80	partial shielding
14/94	Gasmberg Summit	16° 14' - 23° 20' -	2343	Gamsberg Quartz-ite	0	full exposure
10/95	Gamsberg Summit	16° 12' 52" 23° 21' 02"	2346	Gamsberg Quartz-ite	0	full exposure
12/95	Gamsberg Summit	16° 13' 26" 23° 20' 57"	2339	Gamsberg Quartz-ite	0	full exposure
Coastal Plain Bornhardts						
15A	Blutkopje	15° 22' 58" 22° 50' 36"	849	Donkerhuk Granite	0	full exposure
15B	Blutkopje	15° 22' 56" 22° 50' 33"	846	Donkerhuk Granite	0	full exposure
16A	Vogelfederberg	14° 59' 12" 23° 03' 22"	531	Donkerhuk Granite	0	full exposure
16B	Vogelfederberg	14° 59' 12" 23° 03' 23"	520	Donkerhuk Granite	0	full exposure
17A	Mirabib	15° 21' 35" 23° 27' 08"	785	Donkerhuk Granite	28	partial shielding
17B	Mirabib	15° 21' 27" 23° 27' 04"	750	Donkerhuk Granite	55	partial shielding

of the steady-state model, samples 15A, 15B, 16A and 17B do not. These samples have lower $^{26}Al/^{10}Be$ ratios than would be expected for a simple exposure history and have therefore experienced some complexity in their exposure, possibly involving phases of burial or non-steady denudation, both of which invalidate the assumptions of the steady-state model (Lal, 1991). Under these circumstances the best approximation to the true rate of denudation is an average from many samples assuming that the cause of complexity has not been synchronous at all sites (Small *et al.*, 1997). Assuming this to be the case, we infer an average rate of bornhardt surface lowering of ~ 5 m Ma^{-1} (Table 2). This rate is necessarily integrated over the past $\geq 10^5$ a. However, given the apparent persistence of arid conditions similar to those of the present throughout the Quaternary, and possibly throughout much of the Cenozoic (Ward *et al.*, 1983; Lancaster 1984 a and b; Ward, 1987; Ward and Corbett, 1990; Wilkinson, 1991), it is probable that rates broadly similar to 5 m Ma^{-1} have prevailed over at least the late Cenozoic.

Discussion

Denudation rates calculated on the escarpment at the Gamsberg and on bornhardts in the coastal plain clearly demonstrate the potential of CIA to provide quantitative constraints for landscape change in central Namibia. Denudation rates in the escarpment zone are, on average, somewhat higher than denudation rates of coastal plain bornhardts. The bornhardts, however, probably provide a minimum denudation rate for the coastal plain as a whole. This is because they form positive relief and must have been downwearing more slowly than the surrounding landscape for at least the time period over which the cosmogenic data apply ($\geq 10^5$ a).

$^{26}Al/^{10}Be$ concentration ratios in the bornhardt samples are lower than expected and suggest that there has been some complexity in the exposure history for four out of six sampling sites. There is no unique quantitative or geomorphic solution for the observed $^{26}Al/^{10}Be$ concentration ratios. However, the close proximity of samples which indicate complexity and those that support the continuous exposure model argues against a geomorphic explanation that involves complete burial of the bornhardts, for example by dune encroachment or weathering mantle development. Field observations revealed that bornhardt mass-wasting progresses by small-scale granular disintegration and displacement of thin laminar sheets as well as by the spalling of ~1m thick sheets or blocks. Non-synchronous phases of burial as well as non-steady denudation at nearby sampling sites can be explained by a combination of these two styles of weathering. We propose that the complexity in our samples comes from a combination of both weathering mechanisms.

At the Gamsberg, CIA has suggested an overall retreat rate of ~10 m Ma^{-1} for the escarpment. It is likely that this rate is generally representative of the escarpment as a whole for several reasons. The morphological setting of the Gamsberg is found repeatedly along the length of the escarpment. In addition, the overall distance of the escarpment from the coast is uniform, suggesting that large-scale variation in rates of retreat have not been maintained for significant periods of time. Further sampling is needed to fully address this issue but whatever the representativeness of the rate of escarpment retreat calculated at the Gamsberg for the rest of the margin, an average rate of ~10 m Ma^{-1} is two orders of magnitude slower than the commonly assumed rate of retreat for Great Escarpments on passive margins (King, 1951; Ollier, 1985; Gilchrist and Summerfield, 1990; Seidl *et al.*, 1996). Our data therefore suggest that the landscape of Namibia, in the vicinity of the Gamsberg at least, has not evolved through the progressive inland migration of a major escarpment. Given the very large differ-

Table 2: Mean denudation rates for key morphological elements from cosmogenic isotope analysis of ^{10}Be and ^{26}Al.

Location/Morphological Element	Number of Samples	*Mean ^{10}Be and ^{26}Al Denuation Rate: m Ma^{-1}
Escarpment Profile at the Gamsberg		
Ridge	6	7.23 ± 1.45
Face	4	7.56 ± 1.51
Summit	3	0.42 ± 0.08
Coastal Plain Bornhardts		
Summit	6	5.07 ± 1.13

*Mean denudation rate is the mean surface lowering rate calculated for each sample using production rates from Nishiizumi *et al.* (1989), scaled to the latitude and altitude of the sites (Lal, 1991). Production rates were corrected for the dip and exposure geometry of the sampling site based on the angular dependence of cosmic radiation (Nishiizumi *et al.*, 1989). The cosmic ray attenuation coefficient for flat surfaces (Brown *et al.*, 1992) was adjusted for the effects of angled sampling surfaces as described by Dunne *et al.* (1999) and Fleming *et al.* (1999). Horizontal retreat rates (escarpment retreat) were determined using a simple trigonometric conversion whereby the retreat rate = surface lowering rate/sin θ where θ is the ridge or slope angle. Uncertainty includes all measurement error at 2σ level as well as a 20% propagated uncertainty on the production rates.

ence between the two rates it is unlikely that the very slow retreat rate for the recent past can be explained by variations in lithological resistance or climate. Preliminary cosmogenic ^{36}Cl data from the significantly more humid, basalt escarpment in the Drakensberg on the southeast margin of Africa imply an average retreat rate of ~50 m Ma^{-1} (Fleming *et al.*, 1999). Although the exact relationship between denudation, climate and lithology for the two locations cannot be ascertained at present, escarpment retreat rates may have been consistently overestimated in the past. Low rates of retreat (<100m Ma^{-1}) may be characteristic of high-elevation passive margins in general.

Confidence in our average values can be assessed by comparing the data with other quantitative evidence for denudation in the region. Of the range of techniques that have been used to provide quantitative constraint on patterns of denudation in Namibia, apatite fission track thermochronology (AFTT) has provided the best regional-scale insight into denudation in the study area for the past 10^7-10^8 a (Brown *et al.*, 1990, 1994 and 1999). The data suggests that in central Namibia the margin has been subject to extensive crustal cooling across the whole region. Mean denudation rates between the time of break-up and the end of the Eocene (36 Ma BP) average ~40 m Ma^{-1} for the coastal plain and about 10 m Ma^{-1} inland of the escarpment. Post Eocene, mean rates for the coastal plain drop to ~5 m Ma^{-1} and remain relatively constant at ~10 m Ma^{-1} for the inland area (Cockburn *et al.*, 2000). The AFTT data are therefore compatible with and support the cosmogenic results by implying a coastal plain denudation rate of ~5 m Ma^{-1} for the recent past and slightly greater activity in the escarpment zone. The AFTT data also support our extrapolation of rates of bornhardt denudation in the central Namib throughout most of the Cenozoic based on limited climatic fluctuation.

The CIA data, combined with the AFTT data, suggest an initial post-rifting phase of rapid denudation in the coastal zone, possibly promoted by the establishment of new baselevels at rifting, followed, at the end of the Eocene to the present by a period of much lower denudation rates and slow escarpment retreat. This pattern is consistent with a model of landscape evolution in which any initial escarpment that may have been formed at the coast at the time of break was degraded by river systems flowing from an inland drainage divide and adjusting to a new base level at the coast. We speculate that the position of the present-day escarpment was controlled by a major inland drainage divide and probably originated only a few kilometres oceanward of it present position and the subsequent low rate of retreat, implied by the CIA results, has been controlled by pinning at the drainage divide. This interpretation is supported by recent numerical surface process modelling results which highlight the importance of drainage divides in controlling the location and evolution of major escarpments. The extent to which our model is applicable to other parts of Namibia, and other passive margins, requires further investigation.

Conclusion and Future Directions

The development of *in-situ* CIA presents a valuable opportunity to estimate previously unobtainable rates of denudation in a range of geomorphic settings on a time-scale that is needed to fully understand landscape development in Namibia. Denudation rates estimated from CIA are site-specific and therefore provide the necessary detail to monitor the role of specific landforms, in this case coastal plain bornhardts and the escarpment, in contrast to the regional information provided by other techniques. Our data show that bornhardts in the coastal plain are lowering at an average rate of ~5 m Ma^{-1}, whereas the escarpment at the Gamsberg is retreating at an average rate of ~10 m Ma^{-1} with a summit lowering rate of ~0.4 m Ma^{-1}. Our data are supported by regional-scale information from apatite fission track thermochronological studies. The research presented here is on-going and further work at other locations on the escarpment, as well as below and further inland of the escarpment is in progress. Continuing research with CIA in Namibia, as well on other passive margins, will reveal whether the denudation rates presented here are representative of the Namibian escarpment and coastal plain as a whole and whether or not our rate of escarpment retreat is characteristic of passive margins in general.

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