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Sand residence times of one million years in the Namib Sand Sea from cosmogenic nuclides

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The Namib Sand Sea is one of the world's oldest and largest sand deserts[1], yet little is known about the source of the sand in this, or other large deserts[2]. In particular, it is unclear whether the sand is derived from local sediment or comes from remote sources. The relatively uniform appearance of dune sands and low compositional variability within dune fields[3] make it difficult to address this question. Here we combine cosmogenic-nuclide measurements and geochronological techniques to assess the provenance and migration history of sand grains in the Namib Sand Sea. We use U–Pb geochronology of detrital zircons to show that the primary source of sand is the Orange River at the southern edge of the Namib desert. Our burial ages obtained from measurements of the cosmogenic nuclides ^{10}Be, ^{26}Al and ^{21}Ne suggest that the residence time of sand within the sand sea is at least one million years. We therefore conclude that, despite large climatic changes in the Namib region associated with Quaternary glacial–interglacial cycles[4,5], the area currently occupied by the Namib Sand Sea has never been entirely devoid of sand during the past million years.

The Namib Sand Sea covers an area of 34,000 km^2 along the Namibian coast[6,7]. Previous cosmogenic nuclide studies north of the sand sea have indicated that aridity in this region dates back to at least the Miocene[8,9], although it has also been proposed that the linear dunes of the Namib only formed during the Last Glacial Maximum[4]. Our study applies cosmogenic nuclide techniques to the dune sand itself, to directly determine the antiquity of the aeolian activity and investigate the response of a sandy desert to multiple cycles of Quaternary climate change[5], beyond the time-span that can be determined through optical dating of sand[10] or radiocarbon dating of organics[11].

Our method is based on the widely applied technique for erosion–burial dating[12,13] using *in situ* produced cosmogenic ^{26}Al and ^{10}Be. The principle is as follows: in quartz-bearing rocks exposed to cosmic radiation (that is, within the upper ~2 m of the Earth's surface), ^{26}Al and ^{10}Be are produced at a ratio of ~6. Namib desert sand predominantly originates from the Orange River in South Africa and quartz, therefore, enters the desert with an inherited cosmogenic nuclide signal, which is a function of the average erosion rate of the catchment area[14]. Within the desert the sand is wind-blown in a northerly direction by strong trade winds[7,15] and is then buried inside large (~100 m high[7]) linear dunes. On burial and cessation of production, the ^{26}Al and ^{10}Be concentrations start decreasing owing to radioactive decay. ^{26}Al has a shorter half-life than ^{10}Be and so the concentration of ^{26}Al will decrease more quickly, changing the ^{26}Al/^{10}Be ratio. For material that has experienced a single erosion–burial event, the ^{26}Al/^{10}Be ratio can be used to calculate the burial age. Grains of sand moving through a dune field will be exposed and buried multiple times and so the classic form of the ^{26}Al/^{10}Be erosion–burial method cannot be applied to these sands[13,16]. To be able to carry out burial dating of the sand grains in the Namib Sand Sea, we extend the method by adding a third nuclide, ^{21}Ne. Cosmogenic ^{21}Ne, also produced in quartz, is stable. Consequently, its concentration in grains of sand moving through a dune field (and being continuously re-exposed and re-buried) can either (1) increase with time, if the episodes of exposure are substantial, or (2) remain constant, if the grains spend most of their time buried. Thus by combining ^{21}Ne with ^{26}Al and ^{10}Be, we can correct for any further re-exposure events and calculate a mean burial age for the sand grains. To test these predictions, 12 samples of dune sand were collected from the edges of the Namib Sand Sea, plus one alluvial sample from the mouth of the Orange River (Fig. 1).

In addition to alluvial sediments from the Orange River, which are similar in mineralogy to the Namib sands[17], other possible sediment sources include the Great Escarpment and the Miocene Tsondab Sandstone Formation[18]. Before embarking on the cosmogenic nuclide work we need to first confirm that sand is indeed transported from south to north. To this end, we employed a zircon U–Pb provenance study, dating ~100 zircon grains in each of our samples. The resulting U–Pb age spectra look remarkably uniform, with the coastal samples (1, 2, 11, 12) being virtually indistinguishable from the Orange River sample (13). Arranging the 13 U–Pb age distributions geographically reveals an anisotropic pattern (Fig. 1), in which samples that are close together geographically do not necessarily have similar age patterns. For example, samples 2 and 3 were collected only 40 km apart but their age spectra look quite different, whereas samples 2 and 12 are separated by nearly 400 km but their age spectra are almost indistinguishable. This confirms the validity of the assumption of predominant longitudinal sediment transport from south to north, parallel to the Benguela Current and the resultant wind direction[15].

Having established the direction of sand transport, we set out to measure the time it takes for the sand to travel across the desert. Cosmogenic ^{10}Be and ^{26}Al measurements were carried out on quartz sand collected along a longitudinal transect from the mouth of the Orange River at Alexander Bay (sample 13) to the southern margin of the Namib Sand Sea at Lüderitz (sample 12), and its northern margin just south of the Kuiseb River (samples 1 and 2). The cosmogenic ^{10}Be and ^{26}Al concentrations of sample 13 are compatible[14] with steady-state erosion at a rate of 4.04 ± 0.89 mm kyr^{-1}, followed by 280 ± 230 kyr of burial decay

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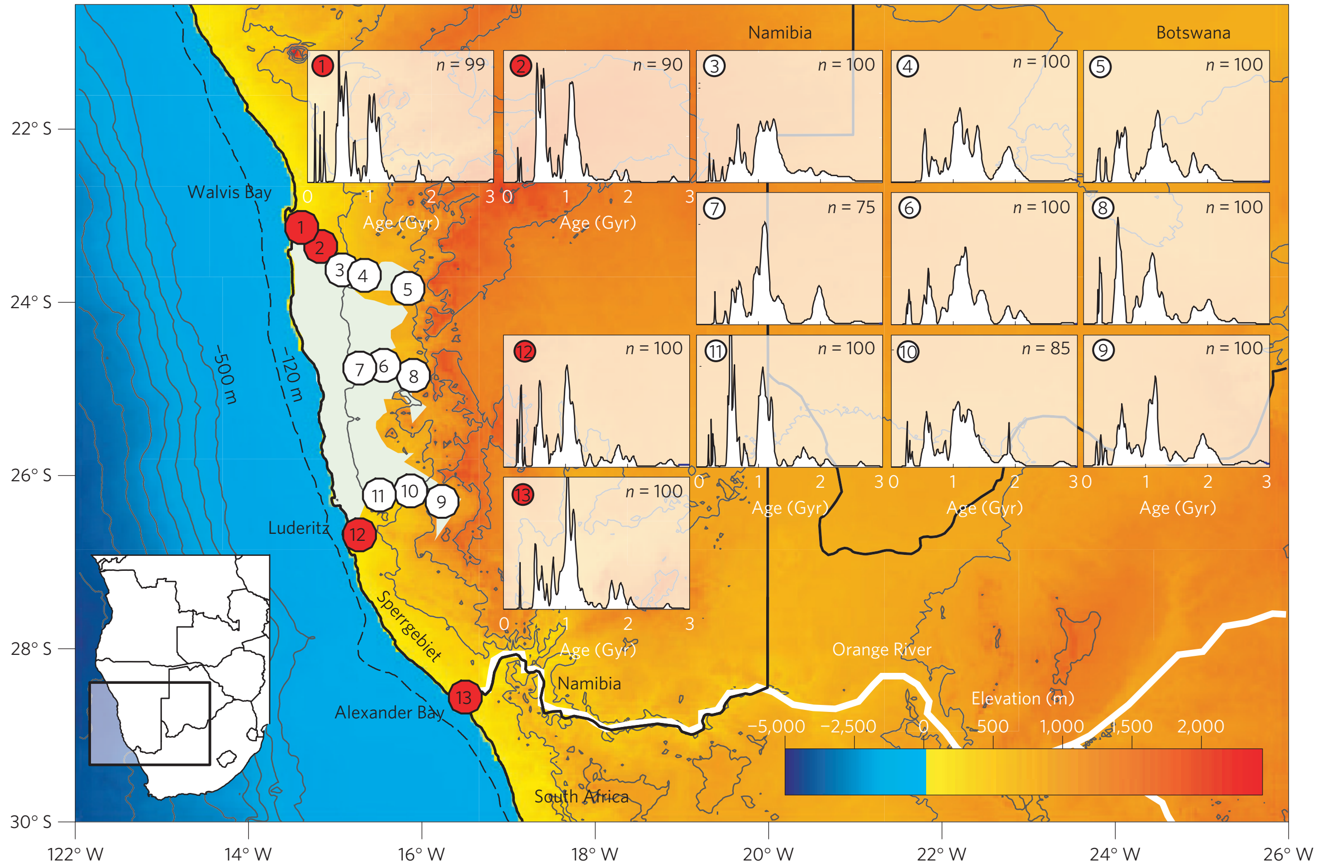

Figure 1 | The detrital U–Pb data arranged geographically. The age spectra of the coastal samples (1, 2, 11, 12 and 13) look nearly identical, indicating that coastal sands of the Namib Sand Sea are exclusively derived from the Orange River. *n* is the number of concordant ages. Samples dated with cosmogenic nuclides are marked in red.

Table 1 | Cosmogenic-nuclide data ($\times 10^4$ atoms g^{-1}).

Sample ID	^{26}Al	$\sigma(^{26}$Al)	^{10}Be	$\sigma(^{10}$Be)	^{21}Ne	$\sigma(^{21}$Ne)
1	163.0	7.1	58.6	2.0	1,990	46
2	167.0	7.5	55.5	1.9	1,716	40
12	479	15	105.0	3.7	1,840	42
13	600	19	124.6	4.4	2,005	38

due to sediment storage in the Orange River catchment. Nearly identical cosmogenic-radionuclide concentrations are found in sample 12 (Table 1), indicating that sand is quickly transported north along the coast by longshore drift and inland across the Sperrgebiet deflation area (Fig. 1), where the potential sand flow[15] exceeds 1,200 ton m^{-1} yr^{-1}. The ^{10}Be concentrations in the southern samples (12 and 13) of the transect are twice as high as those in the northern samples (1 and 2), whereas the ^{26}Al concentrations differ by a factor of three (Table 1). Plotting the coastal samples on a ^{26}Al/^{10}Be two-nuclide diagram reveals a simple trend consistent with 0.82–1.08 million years of radioactive decay (Fig. 2). The fact that all four samples plot on the same radioactive decay line, corresponding to the same palaeodenudation rate, is another strong argument in favour of the hypothesis that all samples are sourced from the same region, the Orange River catchment.

The ∼1 million year residence time is a minimum estimate for the following two reasons. First, it can be shown mathematically (see Methods section) that the apparent burial age calculated from the average nuclide concentration of multiple sand grains is less than or equal to the average burial age of these same grains. Second, every step of re-irradiation by cosmic rays would increase the ^{10}Be and ^{26}Al content of the quartz, and partially erase the burial signal. The effect of this re-exposure should be relatively minor, again for two reasons. First, cosmogenic nuclide production rates along the Namibian coast are less than half those of the Orange River catchment, which has an average elevation of 1,240 m. Second, simple geometric considerations (see Methods section for details) show that the effective cosmogenic nuclide production rate in a well-mixed, ∼90-m-high linear dune is 50 times less than the surface production rate. By combining these two effects, even one million years of recycling inside the sand sea would produce only $\sim 8 \times 10^4$ atoms g^{-1} of ^{10}Be and $\sim 40 \times 10^4$ atoms g^{-1} of ^{26}Al.

In addition to these theoretical considerations, the importance of re-irradiation of the aeolian sand by cosmic rays on its way across the Namib Sand Sea can also be directly assessed by measuring its ^{21}Ne content. Because ^{21}Ne is a stable nuclide, it does not decay while buried inside sand dunes. Therefore, the ^{21}Ne content of the quartz sand is not expected to decrease downwind, as is the case for ^{10}Be and ^{26}Al, but should remain constant or increase. The rate of increase provides a measure of the cumulative amount of re-exposure. Our measurements show nearly constant ^{21}Ne concentrations in the coastal samples (1, 2, 12 and 13, Table 1), confirming that re-exposure is minor (<75 kyr). Finally, when jointly considered with the ^{10}Be and ^{26}Al data, the ^{21}Ne content of the Orange River sand (sample 13) is not consistent with steady-state erosion, indicating an inherited component. This is not surprising given that most of the Orange River catchment is underlain by sedimentary rocks of the Karoo Supergroup with a history of one or more erosion cycles before their deposition during the Mesozoic[19].

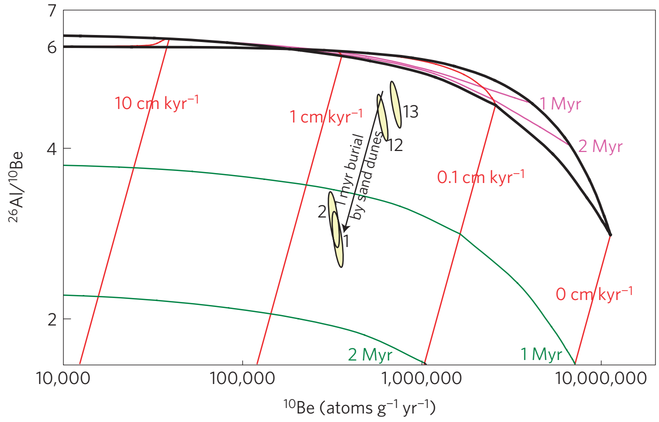

Figure 2 | ^{26}Al/^{10}Be two-nuclide plot normalized to sea level and high latitude[24,25]. The ^{26}Al/^{10}Be ratios in the southern (12 and 13) and northern (1 and 2) samples are 4.6–4.8 and 2.8–3.0, respectively, corresponding to an apparent burial age of 0.82–1.08 Myr. Their nearly exact alignment along a trend of simple radioactive decay indicates a simple burial history. Re-irradiation by cosmic rays is limited, as confirmed by the uniform ^{21}Ne content of the same samples (Table 1). Error ellipses are 2σ.

Combined ground penetrating radar measurements and optical dates for a linear sand dune in the northern Namib Sand Sea indicate complete overturning in a time period of $\sim 10^4$ years[10]. In light of these findings, the $>10^6$ year residence time measured in our cosmogenic nuclide study can be interpreted in terms of two different end-member models. Either the Namib Sand Sea has been active throughout this entire period and sand grains are, on average, buried, recycled and re-exposed at least 100 times on their northward journey across the sand sea, or the sand sea has been immobilized for extensive lengths of time during relatively humid climate conditions[20], alternating with dry conditions of increased dune mobility and sand mixing[13]. The above two models can be tested by analysing extra samples along a longitudinal transect through the central parts of the sand sea. If the sand sea is in a steady state, the ^{10}Be and ^{26}Al concentrations should decrease gradually from the south to the north. In the case of an episodic history, the ^{10}Be and ^{26}Al concentrations would be more uniform, with all but the southernmost dunes containing largely reset ^{10}Be and ^{26}Al concentrations.

Aridity in southwest Africa is at least 5 Myr old[8,9], predates the onset of the Benguela Current and may have initiated shortly after the opening of the Atlantic Ocean[1]. The present study provides the first direct evidence that the occurrence of aeolian sand is an equally old and long-lived feature. A residence time of greater than one million years for the sand compares favourably with recent estimates for the age of the Namib Sand Sea based on the speciation of endemic beetles around 2.35–2.6 Myr (ref. 21) and indicates that, although the individual dunes may be only a few thousand years old[10], the area between the Sperrgebiet deflation area and the Kuiseb River Canyon has remained covered by sand through multiple cycles of Quaternary climate change[4,5].

Methods

Proof that residence time is a minimum estimate. Consider a large number (n) of sand grains with common inherited cosmogenic radionuclide (^{26}Al or ^{10}Be) concentration N_0, but different residence times t_i in the sand sea ($1 \le i \le n$). Assuming, for the sake of simplicity, that re-irradiation is negligible, then the nuclide concentration of the i th grain is $N_i = N_0 e^{-\lambda t_i}$, where λ is the radioactive decay constant. Define $\hat{t}$ as the apparent burial age, calculated from the average nuclide concentration $\bar{N}$, that is, $\hat{t} \equiv -(1/\lambda) ln(\bar{N}/N_0)$, with $\bar{N} \equiv (1/n)\sum_{i=1}^{n} N_i$, and define $\bar{t}$ as the true average burial age of all sand grains, that is, $\bar{t} \equiv (1/n)\sum_{i=1}^{n} t_i$. Then $e^{-\lambda\hat{t}} = \bar{N}/N_0 = (1/n)\sum_{i=1}^{n} N_i/N_0 = (1/n)\sum_{i=1}^{n} e^{-\lambda t_i} = Ce^{-\lambda\bar{t}}$, with $C \equiv (1/n)\sum_{i=1}^{n} e^{\lambda(\bar{t}-t_i)}$. It can be shown that $C \ge 1$. Therefore, $e^{-\lambda\hat{t}} \ge e^{-\lambda\bar{t}}$, and hence $\hat{t} \le \bar{t}$.

Effective production rate of a linear dune. Cosmogenic-nuclide production is restricted to a surface layer with an effective thickness[22] of 160 g cm^{-2}. Using a dune density[23] of 1.7 g cm^{-3}, this is equivalent to 90 cm of sand. Approximating the linear dunes of the Namib by triangular prisms of 90 m height, the volume of this active layer is one-50th of the total dune volume. Therefore, the average production rate for the entire dune is one-50th of the surface production rate.

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Author contributions

P.V. designed the study, collected the samples, carried out the U–Pb analyses and wrote the paper; C.R.F. made the ^{10}Be and ^{26}Al measurements; F.K. carried out the noble gas analyses; G.F.S.W. provided field assistance; C.S.B. helped in writing the paper; S.X. was in charge of the accelerator mass spectrometer measurements.

Additional information

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