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Notes

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ABSTRACT

Quartz sand in the eastern Mediterranean coastal plain is supplied through an extended transport system, which includes the Nile River, east Mediterranean longshore currents, and inland eolian transport. While the concentrations of cosmogenic nuclides (^{26}Al and ^{10}Be), and their ratio, in modern sand deposited along the coast of the eastern Mediterranean reflect the combined effect of exposure and burial during transport, the concentrations of these nuclides in buried sands are the result of decay of this initial dosing. Samples of modern exposed sand (n = 3) collected from the coastal plain of Israel yield an average ^{26}Al/^{10}Be ratio of 4.8 ± 0.2, significantly lower than the expected ratio of 6.8 for exposed quartz grains at the surface. A similar ratio of 4.5 ± 0.3 was measured in a late Pleistocene sand sample, indicating similar exposure-burial histories during transport in spite of the difference in climatic conditions. The results imply a steady, preburial cosmogenic nuclide ratio related to the Nile River's ability, through storage and recycling, to buffer the effects of climatic and tectonic perturbations on cosmogenic nuclide concentrations in the transported quartz. All ancient and buried sand samples (n = 11) fall on a decay path that originates from the concentrations and ratio of ^{26}Al and ^{10}Be in modern sand, suggesting steady preburial concentrations of cosmogenic nuclides in quartz sand over the past 2.5 m.y.

INTRODUCTION

Long and complex transport systems such as the Nile River are expected to affect terrestrial cosmogenic nuclide (TCN) concentrations in quartz grains by means of sediment storage at depth and recycling of the grains along their paths. Therefore, the TCN concentrations in sandy sediment deposited in the Nile delta, or in sandy sediment transported from the Nile delta to other locations along the eastern coast of the Mediterranean Sea, will reflect the long and complex exposure-burial-mixing history of the sediment. Studies in small basins have shown the effect of glacial/interglacial changes on cosmogenic nuclide concentrations in sediment (Schaller et al., 2002), although limitations to this correlation have been discussed (Schaller and Ehlers, 2006). In large fluvial systems, sediments are collected from a wide area and from multiple sources that differ in their climate, level of tectonic activity, exposed lithology, and relief. We hypothesize that in large systems such as the Nile River, the enormity of the system may act to buffer the effects of possible climatic and tectonic perturbations that occur in the subbasins on the properties of the mixed sediment, including their TCN abundances, and to maintain fairly constant concentrations at the outlet of the main trunk channel.

Wittmann et al. (2011a, 2011b) show that in the lower Amazon basin, TCN concentrations of modern sediments reflect a mixture of active and buried sediments and that the Amazon has the ability to dampen short-term, high-amplitude fluctuations caused by climatic variability in source areas and anthropogenic soil erosion. In our study, we expand on this idea to the temporal dimension and focus on the concentrations of the cosmogenic nuclides ^{10}Be and ^{26}Al in quartz sand transported over the past 2.5 m.y. by the Nile River system and eastern Mediterranean longshore currents to the coastal plain of Israel (Fig. 1).

^{10}Be and ^{26}Al start accumulating when bedrock is weathered to sediment. The rate of bedrock weathering, which is a function of climate, lithology, and level of tectonic activity, is the major process that determines the initial concentrations of cosmogenic nuclides in sediment (Lal and Arnold, 1985). As sediment travels downstream, its concentrations of cosmogenic nuclides change for several reasons: (1) mixing of sediment from different sources (when these sources differ in their TCN concentrations) (Davis et al., 2011); (2) the overall time sediment spends in the alluvial system at the surface (allowing the production and accumulation of nuclides to continue); and (3) the time sediment spends buried in alluvial terraces and fans (Wittmann and von Blanckenburg, 2009), causing a partial or an effectively total termination of nuclide production. Burial periods increase the total average transport time in general and increase the time sediment is shielded from cosmic radiation, both of which allow cosmogenic nuclide decay to dominate the change in isotopic concentrations and ratios.

We consider the transport stages of quartz grains in the Nile system (Fig. 1) as a "black box." We do not attempt to distinguish the relative contribution of each stage (i.e., slope transport, alluvial transport and storage, or eolian transport along the Western Desert dunes; Fig. 1) to the total dose of cosmogenic nuclides. Any particular quartz grain could experience one or more, partial or complete, stages. Nevertheless, the mixture of a great number (>10^5) of grains deposited in the Nile delta (and later on transported along the Mediterranean coast) yield cosmogenic nuclide concentrations that may be considered as representing some kind of an average sedimentary history prior to the final deposition along the coast of the eastern Mediterranean. Once these grains are buried at their final and current location under tens of meters of overburden, the ^{26}Al/^{10}Be ratio decreases and its value may reflect the burial time of this last burial episode (Granger, 2006).

STUDY SITE

The Nile extends 35° of latitude across northeast Africa, and its tributaries drain the great lakes region of equatorial Africa and the Ethiopian highlands before uniting as the main Nile, which continues its path through the eastern Sahara and spills into the eastern Mediterranean Sea (Fig. 1). Quartz is a major component of Nile sediments and is derived from large provinces of Nubian sandstone and crystalline basement rocks (e.g., Garzanti et al., 2006). A fraction of the sands supplied to the Nile delta is transported via longshore and seabed currents to the coastal plain of Israel (Emery and Neev, 1960; Golik, 2002). These sands are then transported inland by eolian processes (Yaalon and Laronne, 1971). Dip directions of cross-beds measured in Pliocene–Holocene eolianites suggest southwest to northwest wind directions, similar to those of modern sand-transporting prevailing winds (Yaalon and Laronne, 1971).

Dunes and eolianites of the coastal plain of Israel form a sedimentary wedge of Quaternary age that covers the area, and they are closely linked to the evolution of the Nile cone (Gvirtzman et al., 1997). Numerous

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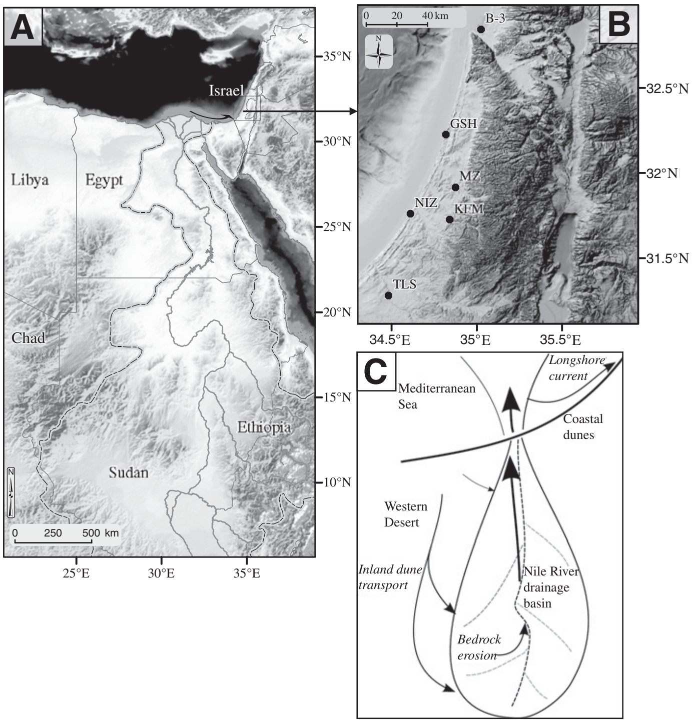

Figure 1. A: Northeast Africa and the eastern Mediterranean showing the Nile River and its drainage area (marked by a shaded dashed line). Also shown are the Nile delta and the 200 m water depth line marking the seaward buildup of the Nile cone. B: Coastal plain of Israel and sample locations. Linear features along the coast are eolianite ridges. The depression in the east is the Jordan Rift valley. C: Conceptual diagram depicting transport paths and storage sites for quartz grains along the Nile transport system. In the eastern Sahara, prevailing winds transport sand grains to the south (through the Western Desert), while the Nile transports them back northward (Embabi, 1998).

studies of heavy-mineral assemblages in modern sediments between the Nile delta and the coastal plain of Israel (reviewed by Stanley, 1989) and in Quaternary sands of the coastal plain (Greenberg, 1975) indicate a Nilotic source for the sands. In contrast, inland from the coastal plain, the surface geology of Israel is dominated by carbonate rocks with very few quartz-bearing lithologies (Sneh et al., 1998). Furthermore, remote eastern sediment sources in Jordan and the Arabian Peninsula have been disconnected from the coast by the Dead Sea Rift valley since the Pliocene (Fig. 1) (Ginat et al., 2000; Zilberman et al., 1996). Thus, local and remote eastern sources of quartz sand to the coastal plain are not probable.

We test the hypothesis described above, in which sediment supplied by a huge alluvial system such as the Nile River will retain its isotopic signature in spite of possible environmental changes over time, by applying terrestrial cosmogenic burial dating to dunes and eolianites in the coastal plain of Israel.

METHODS

Fifteen samples were collected for ^{10}Be and ^{26}Al measurements (Fig. 1; Table 1) (see Table DR1 in the GSA Data Repository[1]). Three modern beach sand samples (NIZ-1, NIZ-2, and GSH-3) were collected from two locations separated 55 km along the shore. Another sample was collected from an eolianite dated by optically stimulated luminescence to ca. 50 ka (Porat et al., 2004) (GSH-2; ~50 m burial). Five samples were collected from a Pliocene–Pleistocene section in the northwestern Negev Desert (TLS-1 through TLS-5; 20–40 m burial) (Menashe, 2003; Zilberman et al., 1994), and one sample was collected from eolianite sands at the bottom of a quarry (KFM-1; 24 m burial). Three samples were collected from buried sands in the central part of the coastal plain (MZWS-1, MZWS-2, and MZOS-1; 6.5–10 m burial) exposed recently by a roadcut. We also include in the data set two samples from an offshore core (B-3; ~60 m sediment burial and 14.1 m water depth). Sample locations are spread over the entire coastal plain, and the collected samples are of different sediment types: cross-bedded eolianites, nonstratified sands, sandy calcic paleosols, and unconsolidated beach sands. Most sand samples

TABLE 1. COSMOGENIC NUCLIDE CONCENTRATIONS

Sample	Description	Burial depth (m)	^{10}Be (10^4 atoms/g quartz)	^{26}Al (10^4 atoms/g quartz)	$^{26}Al/^{10}Be$
TLS-1	Pliocene–Pleistocene sands. Numbered in stratigraphical order.	~40	9.31 ± 0.22	13.9 ± 2.4	1.55 ± 0.27
TLS-2			9.54 ± 0.30	13.3 ± 1.8	1.45 ± 0.20
TLS-3			6.35 ± 0.20	11.9 ± 2.5	1.96 ± 0.42
TLS-4			6.61 ± 0.22	12.6 ± 2.9	1.99 ± 0.47
TLS-5		~20	8.38 ± 0.35	15.2 ± 4.6	1.88 ± 0.67
NIZ-1	Modern beach	0	27.12 ± 0.78	126 ± 9	4.66 ± 0.28
NIZ-2	Modern beach	0	27.00 ± 0.65	132 ± 8	4.90 ± 0.31
GSH-2	Last glacial	~50	22.73 ± 0.55	101 ± 6	4.46 ± 0.28
GSH-3	Modern beach	0	26.86 ± 0.61	132 ± 9	4.92 ± 0.35
KFM-1	Pliocene–Pleistocene eolianite	24	9.84 ± 0.26	13.1 ± 2.1	1.33 ± 0.22
MZWS-1	Dune sand	10	9.44 ± 0.25	18.9 ± 1.8	2.00 ± 0.19
MZWS-2		7	9.36 ± 0.25	21.5 ± 2.6	2.30 ± 0.28
MZOS-1	Fluvial/dune sand	6.5	11.1 ± 0.4	20.0 ± 2.3	1.81 ± 0.22
B3-60.3	Sand	60.3 + 14.1 water	23.0 ± 0.8	82.0 ± 4.4	3.58 ± 0.22
B3-62.35	Reddish clayey fine sand	62.35 + 14.1 water	27.0 ± 0.9	96.0 ± 5.9	3.61 ± 0.25

All uncertainties are 1σ.

Scaling factors for spallation were calculated using Dunai (2001) with an average axial magnetic dipole moment for 0–2 Ma of 5.3×10^{22} Am^2 (Ziegler et al., 2011). Sea-level high-latitude production rates due to spallation for ^{10}Be and ^{26}Al in quartz are 4.45 ± 0.52 and 30.0 ± 3.5 atoms g^{-1} yr^{-1}, respectively (Balco et al., 2008; Balco, 2010). Muon production rates and altitude scaling are based on Braucher et al. (2011). Attenuation lengths for neutrons, negative muons, and fast muons are 160, 1500, and 4320 g/cm^2, respectively (Gosse and Phillips, 2001; Heisinger et al., 2002). The resultant $^{26}Al/^{10}Be$ production rate ratio is 6.87. Half-lives for ^{10}Be and ^{26}Al are 1.39 ± 0.01 m.y. and 0.705 ± 0.02 m.y., respectively (Chmeleff et al., 2010; Korschinek et al., 2010; Nishiizumi, 2004).

[1]GSA Data Repository item 2012098, Table DR1 (description of sample locations) and Table DR2 (sample data, AMS analytical data, and ^{10}Be and ^{26}Al concentrations), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

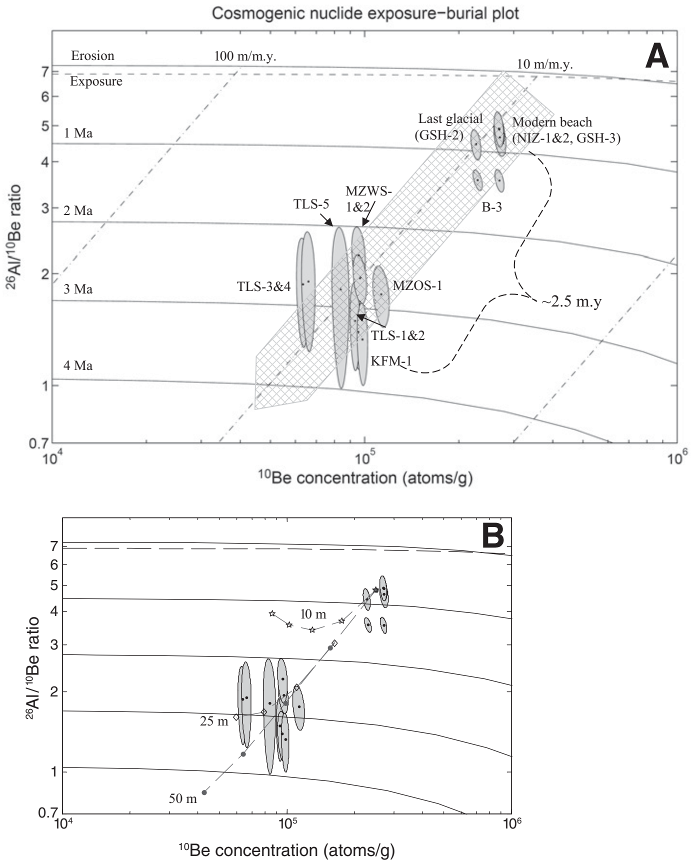

Figure 2. A: ^{26}Al-^{10}Be exposure-burial plot of samples from the coastal plain of Israel. All the samples plot on a relatively restricted decay path (shaded arrow). Simple burial ages of the buried sands range between 3.2 and 1.2 Ma. However, when corrected for the initial ratio, as expressed by the modern and late Pleistocene samples, these ages reduce to 2.6–0.6 Ma. B: Effects of postburial production at different burial depths and 1 m.y. time steps are shown, using muon productions from Braucher et al. (2011). The effects of postburial production are not significant in burial depths >25 m (true for most of the samples) and ages <2.5 Ma. Erosion and burial isochrones are shown only as a general reference and are based on steady erosion at a mean basin altitude of 500 m at 20°N and source rock density of 2.5 g/cm^3. Postburial production is calculated based on latitude 32°N, altitude 100 m, and density of 1.8 g/cm^3. 1σ error ellipses are shown.

(excluding the modern beach sands) were overlain by a sedimentary overburden of tens of meters and were exposed by roadcuts, quarries, recent stream incision, or beach erosion, thus effectively eliminating postburial production (see the Results and Discussion section). All samples were processed following standard techniques (Bierman and Caffee, 2001). Isotopic ratios were measured by accelerator mass spectrometer at the Lawrence Livermore National Laboratory. ^{10}Be/^{9}Be ratios were normalized to 07KNSTD3110 = 2.85 × 10^{-12}, and ^{26}Al/^{27}Al ratios were normalized to KNSTD10650 = 1.065 × 10^{-11}.

RESULTS AND DISCUSSION

When the cosmogenic nuclide data (Table 1) are plotted on a ^{26}Al-^{10}Be exposure-burial plot (Fig. 2A), several observations stand out: (1) modern sand samples have a ^{26}Al/^{10}Be ratio of 4.8 ± 0.2 (equivalent to an apparent burial age of 600–700 ka); (2) the isotopic concentrations and ratio of the last glacial late Pleistocene sample are similar to those in the modern sand samples; and (3) all data points plot along a relatively restricted decay path that spans ~2.5 m.y. and passes through the modern and late Pleistocene samples. We find that the effects of postburial production are not significant for burial depths >25 m (true for most of the samples) and ages <2.5 Ma (Fig. 2B). However, at 10 m depth, the effects are significant and these relate to three samples with burial depths shallower than 10 m (MZ samples). However, the low ^{26}Al/^{10}Be ratios (~2) of these samples do not conform to their current burial depth and may indicate that their shielding depth had to be greater until recently.

The apparent burial age of modern beach sands (ca. 600 ka) is the result of storage and recycling of sediments along the complex transport system of the Nile River. This huge system provides time for the decay of ^{26}Al and ^{10}Be in sediment during its long transport from the various sources in eastern Africa to its depositional locations along the eastern Mediterranean coast. Similar phenomena have been presented at other locations as well. Modern sediments at the mouth of the Orange River in South Africa also yield a ^{26}Al/^{10}Be ratio lower than 6.8, corresponding to an apparent age of ca. 250 ka (Vermeesch et al., 2010). A recent study by Wittmann et al. (2011a, 2011b) has shown low ^{26}Al/^{10}Be ratios in modern sediments within the Amazon basin. Eolian systems can also serve as storage sites on million-year time scales, as seen in the Namib Desert (Vermeesch et al., 2010), Australia (Fujioka et al., 2009), and South Africa (Matmon et al., 2011), and may also be a factor contributing to the low ^{26}Al/^{10}Be ratio supplied by the Nile River.

Changes over time in the concentrations of the cosmogenic nuclides in quartz sand may indicate significant variations in source bedrock erosion rates, transport time along the Nile River system, and burial time in alluvial terraces, fans, and the Nile delta. In contrast, relatively constant concentrations of ^{26}Al and ^{10}Be may suggest either that significant changes in erosion, and in other geomorphic processes, have not occurred over time, or that the enormity of the Nile system dampens effects caused by environmental changes on the concentrations of cosmogenic nuclides. A conceptual answer is provided by ^{26}Al and ^{10}Be concentrations measured in the late Pleistocene sample (GSH-2). This sample was collected from an eolianite that was deposited during the last glacial period under climatic conditions significantly different from the present ones (Bar-Matthews et al., 1999). As only ~50 k.y. have passed since its burial, we don't expect measurable changes in the ^{26}Al/^{10}Be ratio due to cosmogenic nuclide decay. Thus, the similar ^{26}Al and ^{10}Be concentrations and ratio in late Pleistocene sand relative to the modern active sand suggest that ~50 k.y. ago sand derived from the Nile was deposited along the eastern coast of the Mediterranean after experiencing a similar exposure-burial-mixing history as the modern sand in spite of the obvious differences in climatic conditions. The similarity between modern sands and late Pleistocene sands raises the possibility that in the Nile system all sands, regardless of age, experienced the same exposure-burial-mixing history and were deposited along the eastern coast of the Mediterranean with similar TCN concentrations. Indeed, ^{26}Al and ^{10}Be concentrations and their ratio in all Pliocene–middle Pleistocene sands plot along a relatively restricted decay path that includes, close to its origin, the modern and late Pleistocene sand samples. Also, ^{26}Al/^{10}Be ratios in samples from the same section (TLS) conform to their stratigraphical order (lower ratios for older samples). Samples TLS-1 and KFM-1, which are separated by 60 km, are both placed close to the bottom of the Quaternary eolianite section and at the eastern extent of the coastal plain sands. These samples yield identical burial ages of ca. 2.5 Ma, overlapping with the Quaternary climate shift and the initiation of Northern Hemisphere glaciations (Bartoli et al., 2005).

CONCLUSIONS

Our results suggest that the Nile River system has supplied the coastal plain of the eastern Mediterranean quartz sands with relatively constant ^{26}Al and ^{10}Be concentrations over the past 2.5 m.y. The steady concentration of cosmogenic nuclides in quartz supplied to the eastern Mediterranean may indicate the capacity of the long and complex transport systems to homogenize the output of many sources and buffer the possible effect of changes in climate and tectonic activity through time (on a 10^6 yr time scale) on the concentrations of cosmogenic nuclides in alluvial sediment.

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