Reconstructing the history of sediment deposition in caves: A case study from Wonderwerk Cave, South Africa

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ABSTRACT

We applied cosmogenic isotope burial dating, magnetostratigraphy, and grain-size distribution analysis to elucidate the history of the sedimentary sequence, composed of fine quartz sands and silts, of Wonderwerk Cave, located on the southern edge of the Kalahari Desert, South Africa. The source for the quartz sand is the Kalahari sand dunes, presently located ~100 km to the north of the cave. Field observations and grain-size analysis suggest a sediment transport scenario that includes eolian transport of Kalahari sand, abraded to a size of 70–100 μm, to the Kuruman Hills, temporary storage on the hill slopes and valleys surrounding Wonderwerk Cave, and later transport and deposition inside the cave. Our results suggest simple burial ages for sediments from both the front and back of the cave that range between 2.63 ± 0.17 Ma and 1.56 ± 0.10 Ma following initial exposure of 310–620 k.y. However, 26Al/10Be ratios of 3.98 ± 0.24 and 4.08 ± 0.22 measured in a sand sample collected from the surface outside the cave may imply an initial burial signal equivalent to 0.78 ± 0.15 Ma, thus reducing the possible age range of the buried samples to between 1.85 ± 0.23 and 0.78 ± 0.18 Ma. The paleomagnetic results for the front of the cave gave a polarity sequence of N > R > N, where N indicates normal polarity, and R indicates reverse polarity. This sequence can be correlated with both the older and younger cosmogenic burial age ranges. The correlation suggests that in the cave front, cosmogenic burial ages and the acquisition of stable remanent magnetization were not significantly affected by chemical and physical processes and that postburial production of cosmogenic isotopes was insignificant. In contrast, at the back of the cave, the paleomagnetic polarity sequence of R > N cannot be correlated with the cosmogenic burial ages, since the temporal gap between the initial penetration of the sediment into the cave and the final acquisition of a stable remanent magnetization may have been long (~107 yr), and the single polarity transition can be correlated to any reverse-normal transition that occurred during the Quaternary. This highlights the need for caution when cosmogenic burial ages and paleomagnetic sequences are compared. The buried sediments in Wonderwerk Cave show similar grain-size distributions to the fine sand sediment presently exposed at the surface in the vicinity of the cave. Furthermore, calculated preburial 10Be concentrations for the buried sediments are similar to those measured in sediment outside the cave. These similarities suggest that the environmental conditions and rates of geomorphic processes that persisted during sand deposition in Wonderwerk Cave during the late Pliocene and early Pleistocene may have been similar to those currently experienced in the southern Kalahari, the Kuruman Hills, and the western Ghaap Plain. These conditions favor the transport of fine-grained quartz sand to the vicinity of the cave.

INTRODUCTION

Caves often act as sediment traps. As such, they become archives for past environmental conditions, including sediment generation, transport, and deposition. Dating of trapped sediments and sedimentary sequences in caves offers critical information in a number of fields. In archaeological research, it aids in establishing the chronology of human occupation (e.g., Schwarz and Rink, 2001, and references therein; Jacobs et al., 2008), while in research of geomorphic, paleoclimatic, and tectonic processes, it offers a means of establishing a chronological framework for natural events (e.g., Granger et al., 1997; Stock et al., 2004; Haeuselmann et al., 2007). To this end, a range of radiometric dating methods have been used. Radiocarbon dating has been applied where organic material is included in the buried sediment (e.g., Frumkin, 1996; Sheffer et al., 2003, 2008). Optically stimulated luminescence (OSL) dating has been used to date quartz and feldspar grains in cave sediments (e.g., Sheffer et al., 2003; Federici and Pappalardo, 2006; Ayliffe et al., 2008). Thermoluminescence (TL) has been applied to date volcanic sediments and burnt chert (e.g., Fattahi and Stokes, 2003). Electron spin resonance (ESR) has been used to dateapatite veins in a cave (Rink et al., 2003). These dating methods yield valuable temporal information. However, most are limited in their applicable time range to ≤106 yr, and, in many cases, magnetostratigraphy is the only dating tool that provides age constraints for Pliocene to Pleistocene continental sedimentary sequences lacking volcanic materials, which can be dated using radiometric methods (Opdyke and Channel, 1996). However, interpretation of magnetostratigraphic sequences is nonunique, unless the sequence can be anchored by one or more absolute ages.

Cosmogenic two-isotope burial dating fills the chronological hiatus in the dating techniques mentioned here, since it can be used to date very old (>106 yr) sediments inside caves. Granger et al. (1997) were the first to explicitly date sediments buried in caves using cosmogenic isotopes. They analyzed 26Al and 39Ar in alluvial sediments trapped in caves and determined burial ages of up to ca. 1.5 Ma in the New River, Virginia, and ca. 3.3 Ma in the Green River, Kentucky. Cosmogenic isotopes were later used in other locations (e.g., Stock...
et al., 2004; Haeuselmann et al., 2007) to date buried sediments in cave and infer rates of incision and mountain uplift. Several studies have demonstrated the applicability of cosmogenic two-isotope burial dating to successfully date buried cave sediments containing archaeological remains (e.g., Boaretto et al., 2000; Partridge et al., 2003), but few investigations have applied both cosmogenic burial age dating and magnetostratigraphy (e.g., Carbonell et al., 2008; Chazan et al., 2008; Shen et al., 2009; Kong et al., 2009). The combination of cosmogenic burial age dating and magnetostratigraphy can provide absolute, and sometime more reliable, ages for sedimentary sequences because they constrain each other and highlight sedimentary processes.

In South Africa, long records (>10^6 yr) of Quaternary sediments, although limited both in terms of number and spatial coverage, do exist. These include, for example, the Pretoria Salt Pan, spanning back to 220 ka (Partridge et al., 1997), and the Mamatwan manganese mine at Hotazel in the SW Kalahari (Bateman et al., 2003). However, the chronological framework provided by these records is limited by the range of the dating methods that have been used (OSL, U/Th, 14C), and it does not go beyond 250 ka. The discussion concerning older sediments, processes, and environmental conditions is generally tentative and lacks a framework of absolute dates. The tufa-based record from the southern part of the Ghaap Escarpment, in which Wonderwerk Cave is located (Fig. 1), may span more than 4 m.y. (Butzer et al., 1978). However, absolute dating of the Ghaap Escarpment sediments using ^14C is restricted to 32 ka. The ages of older sediments are provided by correlations with alluvial sediments from the lower Vaal River, which contain mammalian remains and archaeological artifacts (Butzer et al., 1973). Nevertheless, Butzer et al. (1978) proposed that late Pliocene to early Pleistocene sediments (phases II and III in Butzer et al., 1978), which correspond in time to the sediments we have dated in Wonderwerk Cave, represent periods of intense cold weather and perhaps increased precipitation.

The sedimentary sequence of Wonderwerk Cave provides a unique archive of early Quaternary environmental information. However, Bateman et al. (2003) and Chase (2009) have demonstrated that a direct and simple correlation between eolian activity and periods of lower rainfall and/or higher wind velocity is not as straightforward as previously suggested (e.g., Stokes et al., 1997). However, geomorphic processes operative in the Kalahari and its surroundings have shifted in response to environmental change (e.g., Thomas and Shaw, 2002; Bateman et al., 2003). Thus, sedimentary sequences throughout the Kalahari and its margins may provide a long and detailed record of Quaternary changes.

In this paper, we apply both cosmogenic isotope burial dating and magnetostratigraphy to elucidate the history of the sedimentary sequence of Wonderwerk Cave, South Africa. We then compare grain-size analysis results of the buried sediments with those preformed on sandy samples along a transect from the southern boundary of the Kalahari sand dunes to the vicinity of Wonderwerk Cave. The unique data set obtained in this current study has implications for environmental conditions in the southern Kalahari between the late Pliocene and early Pleistocene. Our results suggest that the environmental conditions that persisted during the late Pliocene and early Pleistocene while sand was deposited in the Wonderwerk Cave may have been similar to the present ones in the southern Kalahari, the Kuruman Hills, and the western Ghaap Plain.

**WONDERWERK CAVE**

Wonderwerk Cave (27°50′44.7″S, 023°33′12.3″E) is a phreatic tube that formed along the eastern flank of the Kuruman Hills in the semi-arid Northern Cape Province, South Africa (Fig. 1). The cave, which lies at the base of a hill, formed in dolomites of the Late Archean–Early Proterozoic Ghaap Group, immediately below the contact with the overlying Banded Iron Formation (Eriksson et al., 2003). The cave extends over 140 m into the hillside; its roof is 3–5.5 m high and forms a shallow dome, while the walls (ranging from 11 to 26 m

Figure 1. (A) Southern part of the African continent. Black circle denotes location of Wonderwerk Cave. Namib and Kalahari sands are characterized by smooth gray patches. Northwest prevailing winds transport quartz sand from the Kalahari Desert to the area of the Wonderwerk Cave. White circle denotes Hotazel. Image source: Google Earth. (B) Close-up image of the Hotazel–Wonderwerk Cave area. White dots indicate locations and names of samples for sand grain-size distribution. The word “Sand” was omitted from the name of each sample to avoid overcrowding of the figure. The southern boundary of the Kalahari linear dunes is apparent at the upper-left corner of the image. Digital elevation model source: USGS, 2006, 3 arc-second scene, filled finished B, Global Land Cover Facility, University of Maryland, College Park, Maryland.
in width) are smooth and roughly perpendicular (Fig. 2). It appears to have only a single entrance, 26 m wide (Rüther et al., 2009), from which there is an unimpeded view of the Ghaap Plain below.

During the early 1940s, archaeological remains and fossil bones were recovered in the cave, resulting in several archaeological investigations (Malan and Cooke, 1941; Malan and Wells, 1943; Camp, 1948; Butzer, 1984a, 1984b). Extensive excavations, however, were carried out only from the 1970s and lasted through to the late 1990s (Beaumont, 1982, 1990, 2004; Beaumont and Vogel, 2006; Humphreys and Thack-eray, 1983). These excavations yielded rich and varied lithic assemblages, and faunal and botanical remains spanning the Earlier (ESA), Middle (MSA), and Later (LSA) Stone Ages, i.e., from the middle Pleistocene through the late Holocene (Thackeray et al., 1981; Thackeray, 1984; Beaumont, 1982, 1990, 2004; Beaumont and Vogel, 2006; Chazan et al., 2008). Butzer (1984a, 1984b), who first studied the cave sediments, identified them as consisting of a sequence of fine sands and silts that were transported into the cave by natural fluvial and eolian processes.

East of the cave, the Ghaap Plain extends for hundreds of kilometers. It is overlain by fine sandy sediment, making them flat and wide (Fig. 2). The contact between the valley sediments and the bedrock slopes is generally sharp. The fine sand and silt both on the Ghaap Plain to the east of the cave and in the intermontane valleys is composed mostly of quartz grains coated by iron oxide.

Two localities within the cave were investigated: excavation 1, ~15 m from the present cave entrance, and excavation 6 at the back of the cave, ~140 m from the cave entrance (Fig. 2). For each excavation area, results of cosmogenic isotope dating and magnetostratigraphy are presented, as well as the results of grain-size distribution analysis. We emphasize that the derived ages in this study relate to the timing of initial entry of sediments into the cave and the acquisition time of a stable magnetic signal. The relation of these ages to archaeological and paleo-organic material is not discussed in this paper.

METHODS
Field Description and Grain-Size Distribution

Sedimentary sections in excavations 1 and 6 are briefly described based on visual observations of texture, structure, composition, color, and grain size. To determine the mode of transport of fine quartz sand from the Kalahari dunes and the possible distance of the source dunes from the Wonderwerk Cave during the time of sand deposition in the cave, seven samples from excavation 1 and six samples from excavation 6 were analyzed for particle size distribution. The results of these particle size distribution analyses were compared with analyses conducted on a series of modern sand samples, which were collected along a transect from Hotazel, at the southern edge of the Kalahari Desert dune field, to the cave (Figs. 1 and 3).

Malvern MS-2000 laser diffraction was used for particle size distribution analysis over the particle size range of 0.02–2000 μm. Measurement procedure included: sieving (<2 mm), removal of carbonates and iron oxides using 1 N HCl acid, dispersion using sodium hexametaphosphate solution, stirring for 5 min, and ultrasonication for 30 s. Three to six replicate samples of each sand sample were then subjected to three consecutive 5 s runs at a pump speed of 1800 revolutions per minute (rpm). The laser diffraction raw values were transformed into particle size distribution using the Mie scattering model, with optical parameters of RI = 1.52 and A = 0.1 (RI—refractive index; A—absorption index).

Cosmogenic Isotopes

If dosed quartz grains are buried and shielded from cosmic radiation, radioactive decay becomes the main factor that controls isotope concentrations, and their \( \frac{26}{10}Al/Be \) ratio will decrease at an exponential rate, since \( \frac{26}{10}Al \) decays about twice as fast as \( ^{10}Be \). Thus, the \( \frac{26}{10}Al/Be \) ratio is indicative of the time passed since burial of the sampled sediment. An estimation of burial time can be obtained, provided: (1) the sediment had a sufficient initial dose of cosmogenic isotopes, (2) the sediment was buried quickly relative to its total burial history, and (3) the sediment has remained buried deep enough to eliminate additional exposure to cosmic radiation, mainly deep-penetrating muons. The cosmogenic nuclide concentration in a buried quartz grain depends on the inherited concentration \( N_{26,\text{inh}} \) and \( N_{26,\text{postburial}} \) as well as a postburial component due primarily to muon reactions at depth.

\[
N_{26} = N_{26,\text{inh}}e^{-\tau/126} + \int P_{26,\text{postburial}}(t)e^{-\tau/126}dt, \quad (1A)
\]

Figure 2. (A) Photo of the slope above Wonderwerk Cave. Black arrow indicates cave mouth. (B) Typical landscape around the cave. (C) Measured cross section of the cave. Excavations 1 and 6 are marked by numbers. Rock overburden is 15 and 60 m above excavations 1 and 6, respectively.
where $N_{26}$ and $N_{10}$ are the concentrations of $^{26}$Al and $^{10}$Be, $t$ is the time since burial, and $\tau_{26}$ and $\tau_{10}$ are the mean lives in years of $^{26}$Al = 1.02 $\times$ 10$^6$ $\pm$ 0.09 (half-life 1.39 m.y.) and $^{10}$Be = 2.005 $\times$ 10$^8$ $\pm$ 0.09 (half-life 1.39 m.y.). If the postburial component is small, then the $^{26}$Al/$^{10}$Be ratio can be used straightforwardly. If the postburial component is not negligible with respect to the total concentrations, it must be estimated.

Eq. 2 can be expressed by the simple form:

$$R = \frac{N_{26}}{N_{10}} = \frac{N_{26}}{N_{10}} \rho \left(\frac{1}{\tau_{26}} - \frac{1}{\tau_{10}}\right) \int_0^t \rho \left(\frac{1}{\tau_{26}} - \frac{1}{\tau_{10}}\right) dt e^{-\frac{t}{\tau_{10}}},$$

where $t_{\text{burial}}$ is the time since burial.

Equation 2 can be written as:

$$R = N_{26}/N_{10} = R_{\text{ini}} e^{-t/\tau_{10}},$$

where $\tau_{\text{ini}} = 1/(1/\tau_{26} - 1/\tau_{10})$, and $R_{\text{ini}}$ is the initial ratio at the time of burial. In most geological settings, where erosion is faster than 1 mm k.y.$^{-1}$, the initial ratio of $^{26}$Al to $^{10}$Be in a sample is controlled by their production ratio, which is $~6.75$ (Balco and Rovey, 2008). The ratio of production rates is not influenced by the production rate itself (Granger, 2006).

Good examples of geological samples that were exposed and then buried are alluvial or eolian sediments trapped in caves. Any sand grain presently buried in the Wonderwerk Cave was dosed during eolian transport and then during storage on the Kuruman Hills until being transported and buried in the cave. Recently, several studies have shown that sand sediment transported by eolian processes experience a complex burial-exposure history that results in a $^{26}$Al/$^{10}$Be ratio in exposed sand that is lower than the production ratio (Vermeesch et al., 2010; Fugioka et al., 2009). Since the sandy sediments in Wonderwerk Cave have been transported by eolian processes to the vicinity of the cave, we considered the possibility of a low initial $^{26}$Al/$^{10}$Be ratio and tested exposed modern sand samples outside of the cave, ~3 km from its entrance (Table 1).

For cosiogenic burial dating, 13 sediment samples were collected from different lithostratigraphic units: seven samples from the east and north sections in excavation 1, and six from the stepped south section and north wall of the recess in excavation 6 (Figs. 4 and 5; Table 1). Not all units in each section were sampled. Where they overlapped, samples were taken in the vicinity of the paleomagnetic samples (see following).

The total shielding thickness in front of the cave above excavation 1 is 15 m of rock ($\rho = 2.7$), and it is 60 m of rock ($\rho = 2.7$) at the back of the cave above excavation 6. Rock shielding in the cave was estimated using simple trigonometric calculations and later confirmed from detailed light detection and ranging (LiDAR) mapping of the cave and its surroundings (Fig. 2; Rüther et al., 2009). All samples were sieved, and the 0.066–0.25 mm fraction was analyzed for cosiogenic nuclide concentration. Cosiogenic samples were processed following the method modified from Bierman and Caffee (2001) at The Hebrew University Cosmic Isotope Laboratory. The $^{10}$Be and $^{26}$Al values were measured at the Center for Accelerator Mass Spectrometry (AMS) at Lawrence Livermore National Laboratory. The $^{10}$Be concentrations were calculated against the AMS standard 07KNSTD3110, which has a value of 2.85 $\times$ 10$^{-12}$. The $^{26}$Al concentrations were calculated against the AMS standard KNSTD9919, which has a value of 9.919 $\times$ 10$^{-12}$.

To better appreciate the calculated preburial $^{10}$Be concentrations of samples collected in Wonderwerk Cave, these were compared with $^{10}$Be concentrations measured in a single modern sediment sample (COS-SUR) collected from the surface ~3 km from Wonderwerk Cave, and two modern sand samples (WD2b and WD2t) that were collected from active dunes in the eastern Sahara Desert, Egypt. Such a comparison helps to evaluate surface residence time and landscape stability.

### Magnetostatigraphy

The Earth’s magnetic field has undergone frequent changes of polarity (Cande and Kent, 1992). These have been observed and docu-
Sediment burial ages in Wonderwerk Cave

Figure 4. (A) Stratigraphic cross section of excavation 1. Archeological units 12–9 are marked by black numbers on left side of the column. Lithostratigraphic units 9–1 are marked by black italic numbers inside units. General locations of paleomagnetic polarity transitions are marked by dashed lines. Locations of samples for cosmogenic isotopes are marked with triangles and sample name. Paleomagnetic polarities are marked with white (reverse) and black (normal) circles followed by the number (n = ) of paleomagnetic samples. The white and black circles do not represent the sampling location of any individual sample. Cosmogenic samples WWD1 and COS1 were collected from the same horizon 2 yr apart. The upper part of lithostratigraphic unit 1 is exposed in a step not seen in this figure. Two paleomagnetic interpretations are given (left and right of the cross section). The interpretation to the right of the stratigraphic column considers an initial 26Al/10Be ratio of 6.75 and, thus, maximum cosmogenic burial ages. The interpretation to the left of the stratigraphic column considers an initial 26Al/10Be ratio of 4.03 and, thus, minimum cosmogenic burial ages. See text for further discussion. The normal polarity paleomagnetic samples in lithostratigraphic unit 1 most likely represent the Brunhes normal chron because they are located above the major unconformity between lithostratigraphic units 1 and 2. (B) Photo of northern section in excavation 1. Samples for cosmogenic isotope analyses are marked with white triangles and names. The age of the Cobb Mountain normal subchron is from Channell et al. (2002). The age of the Brunhes-Matuyama boundary is from Singer (2007). All other ages are from Opdyke and Channell (1996). Height of wall is ~2 m.

At Wonderwerk Cave, 87 oriented samples were collected from the freshly cleaned north and east stratigraphic sections in excavation 1 at 2–15 cm intervals. In excavation 6 at the back of the cave, 16 samples were collected from the stepped south wall and north wall of the recess. The samples were collected by carving a cubic pedestal with a stainless-steel knife, and then placing a nonmagnetic plastic capsule or quartz
Figure 5. (A) Stratigraphic cross section of excavation 6. Locations of samples for cosmogenic isotopes are marked with open triangles and sample name. Locations of individual paleomagnetic samples are marked with white (reverse) and black (normal) circles. Only the eight reliable paleomagnetic samples are shown. The sections are placed in their proper stratigraphic relations (i.e., sample COS 9 is correlated to sample COS 21). (B) Photo of the three south steps at the back of the cave indicating the locations of cosmogenic isotope samples. (C) The recess indicating the locations of cosmogenic isotope samples on the north wall. The U-Th minimum age (187 ka) is from Beaufort and Vogel (2006). All scale bars are 2 m high.

Cylinder over the pedestal. The orientation was carefully measured before the sample was removed from the excavation section.

Remanent magnetization of all samples was measured at the Paleomagnetic Laboratory of the Institute of Earth Sciences, The Hebrew University of Jerusalem, using a shielded three-axis superconducting 2G 750 SRM™ magnetometer with integrated alternating field (AF) coils. The natural remanent magnetization (NRM) was measured following stepwise demagnetization by AF with increasing intensity starting with 5 milliTesla (mT) increments, going up to 70 mT, or in some cases up to 160 mT. This procedure removed 50% to 90% of the NRM intensity. NRM of selected samples was also thermally demagnetized, in 100 °C to 25 °C intervals. Analysis of demagnetization procedures includes Zijderveld diagrams (Zijderveld, 1967).

Curie temperature (Tc) was determined for six samples from excavation 1 at the Paleol and Rock Magnetism Laboratory, Geoforschungszentrum (GFZ) Pots dam, Germany. The procedure used a fully computer-controlled variable field translation balance (VFTB) to obtain thermomagnetic curves between room temperature and 621 °C. The VFTB combines the principles of classical horizontal Curie balance and an alternating gradient force magnetometer. All samples yielded reversible heating and cooling curves.

Hysteresis parameters were measured for the same six samples using a Princeton Measurements Alternating Gradient Force Magnetometer (Micromag™) at GFZ Potsdam. The maximum magnetic field for the hysteresis loops was set to ±1 Tesla. The hysteresis parameters, saturation of remanence (Ms), saturation magnetization (Ms), and coercive force (Bc) were corrected for the high-field slope of the magnetization curves. Remanence coercivity (Bcr) was determined by a backfield measurement with 1 Tesla saturation field in increments of 3.5 mT during reversed field of up to 70 mT. The Micromag™ was also used for automated isothermal remanance magnetization (IRM) acquisition using 60 steps from 0 to 2 Tesla on logarithmic axis.

RESULTS

Field Description

Excavation 1

The sediments from excavation 1, closest to the cave mouth, were first described by Butzer (1984a, 1984b), who noted that they mainly included silty sands composed mostly of quartz, partly calcified, and roof spall. Chazan et al. (2008) provided a more detailed description of nine lithostratigraphic units (units 1−9 from top to bottom; Fig. 4) they identified in the north stratigraphic section in excavation 1. The lithic industry described in Chazan et al. (2008) consists of a small flake and core industry in the basal stratum with an Acheulian industry in the overlying strata. Faunal remains, which occur throughout the sequence, exhibit carnivore and porcupine damage. Generally, the sediments consist of soft, powdery, reddish, bedded silt, aggregates, and sand. Field observations indicate that water played an active role in the deposition and modification of lithostratigraphic units 2−9 in excavation 1. This is evident in the erosional contacts and the presence of fine laminations. There is no evidence for high-energy water transport that would have been strong enough to carry stone artifacts or large bones into the cave. Unit 1 in excavation 1 (from the top of unit 2 to the top of the sequence) contains mostly pan-derived silts, and the amount of quartz grain is significantly lower than in the lower units.

Excavation 6

Two sedimentary sections were described in excavation 6 at the rear of the cave: a stepped south section and the north wall of a recess that leads off from it toward the cave wall (Fig. 5). The top of the north wall of the recess correlates with the bottom of the lowest south step (Fig. 5). The base of the recess in the north wall consists of ~40–45 cm of interbedded, compact red sand and silt with very little evidence of bioturbation. This lower unit is over lain, with an irregular erosional contact, by a crumbly, poorly cemented and sorted sand unit with abundant fauna, manganese staining, and large blocks of roof fall, which are very weathered. Its thickness reaches up to 80 cm.

The top of the recess section is composed of 28–30 cm of very compact and poorly sorted
sand with abundant fauna and weathered dolomite blocks. The stepped south section includes three steps (Fig. 5). The bottom step is composed of fine-grained sand and exhibits fine laminations. At the top of this step, the sediments are truncated and eroded, with pockets rich in fauna, attesting to intensive raptor activity. The sediment in the middle step is generally compact, although slightly crumbly, and consists of poorly sorted sand with clay present in some pockets. This unit, 30–40 cm thick, includes abundant fauna remains. No bedding is apparent, and bedrock clasts are totally weathered. The topmost step consists of very soft, poorly sorted microconglomerate with millimeter-size pebbles, abundant fauna, and fresh, angular rockfall. The weakly bedded layers dip toward the back of the chamber. Localized fauna concentrations are also found. Throughout the section, there is evidence of silt pooling in the form of stacked weakly bedded layers. At the base of the uppermost step (Sand 9 to Sand 12, Sand 1), there is an average age of 172 ± 22 μm. This value is similar to other Kalahari grain-size measurements (Lancaster, 1986; Livingstone et al., 1999). Samples collected in the vicinity of the cave (Sand 4 to Sand 6 and Sand 16 to Sand 21) have an average age of 113 ± 16 μm. This average is somewhat larger, although similar within 1σ, than the typical grain size of sand that entered Wonderwerk Cave.

**Cosmogenic Isotopes**

The ratio of 26Al to 10Be is generally presented as a function of the measured 10Be concentration (scaled to sea level and high latitude) (Fig. 6). The exposure/burial history of a sample can be evaluated from its position in the graph. The most straightforward interpretation for samples that plot below the steady-state region indicates initial dosing, which depends on the exposure time or erosion rate of the source bedrock and subsequent partial or total shielding from cosmic radiation (e.g., by snow, sediment, glaciers, water). All samples collected from the buried sediments in Wonderwerk Cave yielded 26Al/10Be ratios that range between 2.82 ± 0.15 and 1.69 ± 0.15. Samples collected from outside the cave yielded 26Al/10Be ratios of 3.98 ± 0.24 and 4.08 ± 0.22. Measured 10Be concentrations in sand samples collected from active dunes in the Western Desert of Egypt are an order of magnitude lower than those measured in the Kalahari sand samples and range between 0.27 ± 0.008 × 106 and 0.20 ± 0.007 × 106 atoms g–1 quartz.

A straightforward interpretation of the measured concentrations and ratios in the buried samples implies burial periods that range between 2.63 ± 0.17 Ma and 1.56 ± 0.10 Ma, following initial exposure of 310–620 k.y. (Fig. 6; Table 3). Burial ages in excavation 1 range between 2.44 ± 0.13 Ma and 1.76 ± 0.11 Ma. Taking into account an initial 26Al/10Be ratio of ~4 (as indicated by the exposed surface samples), reduced ages range between 1.66 ± 0.20 Ma and 0.98 ± 0.19 Ma. Ages appear in stratigraphic order with one exception, where the mean age of sample COS 3 is slightly younger than that of the overlying COS 4. Nevertheless, the ages of these two samples easily overlap within 1σ. Repeat samples COS 1 and WWD 1, which were collected from the same location at the bottom of the section but several years apart, yielded isotopic ratios and burial ages that overlap within 1σ. In excavation 6, simple burial ages range between 2.63 ± 0.17 Ma and 1.56 ± 0.10 Ma. Similar to excavation 1, taking into account an initial 26Al/10Be ratio of 4 results in reduced ages that range between 1.85 ± 0.23 Ma and 0.78 ± 0.18 Ma.

**Paleomagnetic Results**

The NRM intensity of all samples is in the order of 10–3 A/m, i.e., six orders of magnitude stronger than the sample holder. The median destructive field (MDF) of the single-component samples is in the range of 30–70 mT, indicating medium-coercivity NRM. Both AF and thermal demagnetization behaviors were used to set rejection criteria in order to select the appropriate samples for further paleomagnetic analysis. The samples were divided into three groups: (1) samples that showed a clear stable vector (Fig. 7), (2) samples for which the secondary overprint could not be removed, and (3) samples that showed erratic, unstable behavior. Group 1

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**TABLE 2. GRAIN-SIZE DISTRIBUTION OF SAND SAMPLES FROM WONDERWERK CAVE AND THE MODERN TRANSECT**

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Mode (μm)</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Excavation 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COS 6</td>
<td>105.4</td>
<td>0.838</td>
<td>0.141</td>
<td>North wall</td>
</tr>
<tr>
<td>COS 5</td>
<td>89.5</td>
<td>1.346</td>
<td>1.376</td>
<td>East wall</td>
</tr>
<tr>
<td>COS 4</td>
<td>91.7</td>
<td>0.974</td>
<td>0.437</td>
<td>North wall</td>
</tr>
<tr>
<td>COS 3</td>
<td>108.8</td>
<td>0.841</td>
<td>0.064</td>
<td>North wall</td>
</tr>
<tr>
<td>COS 2</td>
<td>90.2</td>
<td>1.126</td>
<td>0.75</td>
<td>North wall</td>
</tr>
<tr>
<td>COS 1</td>
<td>92.2</td>
<td>0.448</td>
<td>0.214</td>
<td>North Wall</td>
</tr>
<tr>
<td><strong>Excavation 6</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COS 10</td>
<td>41.4</td>
<td>1.286</td>
<td>1.686</td>
<td>South wall (upper step)</td>
</tr>
<tr>
<td>COS 22</td>
<td>92.4</td>
<td>2.677</td>
<td>10.35</td>
<td>South wall (middle step)</td>
</tr>
<tr>
<td>COS 21</td>
<td>63.4</td>
<td>2.484</td>
<td>10.058</td>
<td>South Wall (lower step)</td>
</tr>
<tr>
<td>COS 9</td>
<td>79.0</td>
<td>1.512</td>
<td>4.824</td>
<td>Top of recess north wall</td>
</tr>
<tr>
<td>COS 8</td>
<td>79.1</td>
<td>0.988</td>
<td>0.448</td>
<td>Middle of recess north wall</td>
</tr>
<tr>
<td>COS 7 (rep)</td>
<td>99.8</td>
<td>0.495</td>
<td>–0.4</td>
<td>Bottom of recess north wall</td>
</tr>
</tbody>
</table>

**Transact from Hotazel to Wonderwerk Cave**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mode (μm)</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Location</th>
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<td>Sand 1</td>
<td>167.0</td>
<td>0.782</td>
<td>0.645</td>
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</tr>
<tr>
<td>Sand 2</td>
<td>111.9</td>
<td>1.772</td>
<td>5.361</td>
<td>27°36′05.2″S, 022°57′13.1″E</td>
</tr>
<tr>
<td>Sand 3</td>
<td>108.7</td>
<td>0.642</td>
<td>–2.932</td>
<td>28°12′02.0″S, 023°07′43.8″E</td>
</tr>
<tr>
<td>Sand 4</td>
<td>128.9</td>
<td>0.904</td>
<td>0.168</td>
<td>27°55′56.6″S, 023°37′37.2″E</td>
</tr>
<tr>
<td>Sand 5</td>
<td>78.7</td>
<td>0.696</td>
<td>0.063</td>
<td>27°50′35.5″S, 023°32′48.0″E</td>
</tr>
<tr>
<td>Sand 6</td>
<td>104.7</td>
<td>0.422</td>
<td>–0.289</td>
<td>27°50′09.7″S, 023°33′15.2″E</td>
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<tr>
<td>Sand 7</td>
<td>124.0</td>
<td>0.543</td>
<td>–0.203</td>
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</tr>
<tr>
<td>Sand 8</td>
<td>136.5</td>
<td>2.54</td>
<td>5.671</td>
<td>27°33′49.5″S, 023°14′61.4″E</td>
</tr>
<tr>
<td>Sand 9</td>
<td>157.7</td>
<td>2.158</td>
<td>6.201</td>
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<tr>
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<td>1.925</td>
<td>5.987</td>
<td>27°12′89.6″S, 022°54′18.4″E</td>
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<tr>
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<td>3.465</td>
<td>18.732</td>
<td>27°06′46.8″S, 022°39′30.0″E</td>
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<tr>
<td>Sand 12</td>
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<td>12.49</td>
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<tr>
<td>Sand 13</td>
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<td>35.061</td>
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<td>9.945</td>
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</tr>
<tr>
<td>Sand 15</td>
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<td>18.732</td>
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<td>Sand 16</td>
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<tr>
<td>Sand 17</td>
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<td>39.539</td>
<td>27°51′42.7″S, 023°32′38.0″E</td>
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<tr>
<td>Sand 18</td>
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<td>5.396</td>
<td>33.442</td>
<td>27°51′34.3″S, 023°32′66.6″E</td>
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<tr>
<td>Sand 19</td>
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<td>17.812</td>
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</tr>
<tr>
<td>Sand 20</td>
<td>121.8</td>
<td>0.344</td>
<td>–0.322</td>
<td>27°50′65.8″S, 023°33′20.3″E</td>
</tr>
<tr>
<td>Sand 21</td>
<td>131.6</td>
<td>0.46</td>
<td>–0.244</td>
<td>27°49′76.2″S, 023°34′28.3″E</td>
</tr>
</tbody>
</table>
showed a stable single or dual vector. The first vector to be removed was the secondary overprint, and the second was the stable primary characteristic remanent magnetization (ChRM), which probably resided in a higher-coercivity magnetic phase. The behavior of samples from group B, for which the secondary overprint could not be completely removed and the primary component could not be isolated (samples W32 and W33), is probably the result of very high coercive magnetic particles, probably magnetite, as suggested by the Tc and hysteresis properties (see Figs. DR1 and DR2). Careful examination of the texture of group C samples suggested that bioturbation (mainly activity of small insects) was probably the cause of the magnetic instability.

The facts that 50%–90% of the magnetization was removed in all samples by AF up to ~100 mT and that vectors project toward the origin (Fig. 7) imply that the remanent magnetism is carried by a cubic mineral phase, most likely detritus Ti-magnetite and not hematite or goethite. This conclusion is also supported by the thermal demagnetization experiments and the VFTB Curie temperature experiments (Fig. DR1 [see footnote 1]).

Six samples, which represent the full range of sediment colors and cover the entire sequence (W01, W20, and W50 are red silt, and samples W32, W33, and W36 are silt cemented by calcium carbonate), were measured and analyzed to obtain thermomagnetic curves and Curie temperatures. Five samples show reversible parallel heating curves in which intensity decayed to zero at ~560 °C. One sample exhibited unparallel curves (Fig. DR1 [see footnote 1]). The results support the thermal and AF experiments, which show that the magnetic carrier is a medium-coercivity magnetite (Fig. 7). Thus, we conclude that magnetization has not been affected by chemical alteration or remagnetization during digenesis and it is of a detritus remanent magnetization (DRM) origin.

Hysteresis loops (Fig. DR2 [see footnote 1] and parameters (Fig. DR3 [see footnote 1]) indicate a dominancy of pseudo–single-domain magnetic grains with a small contribution of paramagnetic materials. These, together with the saturation of isothermal remanent acquisition curve (SIRM) measurements, further corroborate the AF and VFTB findings. They demonstrate that the saturation field of the sediments is ~0.3 Tesla, which is typical for magnetite and much lower than that of hematite.

Based on successful and reliable demagnetization results for 65 samples (out of the 87 that were collected), the paleomagnetic results from excavation 1 yielded the following polarity sequence: N > R > N. The uppermost reversal was identified in only two

Figure 6. Buried sediment samples from Wonderwerk Cave. Initial exposure isochrons are indicated with plain numbers. Burial isochrons are indicated with bold numbers. Marked error includes uncertainty in 26Al/27Al, stable Al, and 10Be/9Be measurements. Samples indicate a simple burial period that ranges between 2.6 and 1.6 Ma. Initial dosing suggests exposure of 310 k.y. to almost 620 k.y. or equivalent erosion rates that range between 0.9 and 2.3 m m.y.–1. Exposed surface sample yielded ratios equivalent to ca. 0.78 Ma of apparent burial. When this initial burial signal is considered, the burial ages of the buried sediments in the cave range between 1.85 ± 0.23 Ma and 0.78 ± 0.18 Ma. SLHL—Sea Level High Latitude.

GSA Data Repository item 2011319, 3 figures and a table: Figure DR1 presents Curie plots of thermally demagnetized selected samples; Figure DR2 presents hysteresis curves of selected samples; Figure DR3 presents a Day plot of selected samples; the table presents the raw paleomagnetic data, is available at http://www.geosociety.org/pubs/ft2011.htm or by request to editing@geosociety.org.
samples, and intensive efforts to replicate this observation were unsuccessful, leading us to omit it from the sequence. Of the 16 samples collected at excavation 6, eight yielded reliable results. The polarity sequence in this locality is R > N.

**DISCUSSION**

**Sand Source and Transport**

The landscape surrounding Wonderwerk Cave is mostly underlain by Archean dolomite. In contrast, the sediment in the cave mainly includes fine quartz sand, aggregates of silty clay, and silt. Therefore, the source for sediments deposited in the cave must be external and possibly distant. The Kalahari dunes, their southern boundary presently situated some 100 km to the north and northwest of the cave, are the most likely ultimate source for the fine quartz sand. These sands are commonly transported by the NW prevailing winds and are typically coated by iron oxide (Thomas and Shaw, 1991). Similar to the Kalahari sands, the sandy lithostratigraphic units of the cave in excavations 1 and 6 are also coated with iron oxides and appear red or pink. The red, sandy and silty sediment in excavation 1 (lithostratigraphic units 9–2) and in the surrounding Kuruman Hills (Fig. 2) and that overlies the adjacent Ghaap Plain.

In order to test the hypothesis that the source for the quartz sand in the cave is the Kalahari dunes, we compared particle size distribution (PSD) analysis of buried sediments from the cave with sandy samples collected along a 100 km transect from the southern boundary of the Kalahari sand dune up to Wonderwerk Cave. The underlying hypothesis is that the grain-size distribution of windborne dune sand should reduce as its distance from the source increases. The process by which sand abrades to fine-sand size and then accumulates along the perimeters of dune fields has recently been shown to be

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**TABLE 3A. RAW DATA FOR WONDERWERK CAVE AND SURFACE SEDIMENT SAMPLES**

<table>
<thead>
<tr>
<th>Name</th>
<th>Sample size (g)</th>
<th>Be spike (g)**</th>
<th>26Al/10Be</th>
<th>10Be/9Be</th>
<th>26Al/27Al</th>
<th>Stable Al (x10^{-6} atoms g⁻¹ quartz)</th>
<th>26Al/10Be (x10^{12})</th>
<th>26Al (x10^{12} atoms g⁻¹ quartz)</th>
<th>26Al/26Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COS 6</td>
<td>35.1</td>
<td>0.312</td>
<td>4.59 ± 0.05</td>
<td>2.73 ± 0.06</td>
<td>4.73</td>
<td>1.45 ± 0.05</td>
<td>6.84 ± 0.35</td>
<td>2.51 ± 0.14</td>
<td></td>
</tr>
<tr>
<td>COS 5</td>
<td>35.2</td>
<td>0.297</td>
<td>4.55 ± 0.05</td>
<td>2.57 ± 0.06</td>
<td>5.14</td>
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<td>6.49 ± 0.32</td>
<td>2.53 ± 0.14</td>
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</tr>
<tr>
<td>COS 4</td>
<td>35.2</td>
<td>0.306</td>
<td>3.77 ± 0.07</td>
<td>2.19 ± 0.05</td>
<td>4.52</td>
<td>1.07 ± 0.04</td>
<td>4.83 ± 0.25</td>
<td>2.20 ± 0.12</td>
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</tr>
<tr>
<td>COS 3</td>
<td>34.9</td>
<td>0.323</td>
<td>4.17 ± 0.09</td>
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<td>4.38</td>
<td>1.33 ± 0.05</td>
<td>5.84 ± 0.31</td>
<td>2.27 ± 0.14</td>
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</tr>
<tr>
<td>COS 2</td>
<td>35.1</td>
<td>0.308</td>
<td>3.13 ± 0.04</td>
<td>1.84 ± 0.04</td>
<td>4.19</td>
<td>0.92 ± 0.03</td>
<td>3.84 ± 0.20</td>
<td>2.09 ± 0.12</td>
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</tr>
<tr>
<td>COS 1</td>
<td>35.2</td>
<td>0.316</td>
<td>1.81 ± 0.03</td>
<td>1.09 ± 0.03</td>
<td>4.38</td>
<td>0.48 ± 0.02</td>
<td>2.07 ± 0.13</td>
<td>1.91 ± 0.13</td>
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</tr>
<tr>
<td>WWD 1</td>
<td>28.6</td>
<td>0.293</td>
<td>1.51 ± 0.05</td>
<td>1.08 ± 0.04</td>
<td>3.39</td>
<td>0.64 ± 0.02</td>
<td>2.15 ± 0.12</td>
<td>1.99 ± 0.13</td>
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**Excavation 6**

<table>
<thead>
<tr>
<th>Name</th>
<th>Sample size (g)</th>
<th>Be spike (g)**</th>
<th>10Be/9Be</th>
<th>26Al/27Al</th>
<th>Stable Al (x10^{-6} atoms quartz)</th>
<th>26Al/10Be (x10^{12})</th>
<th>26Al (x10^{12} atoms g⁻¹ quartz)</th>
<th>26Al/26Be</th>
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<tbody>
<tr>
<td>COS 10</td>
<td>35.0</td>
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<td>3.60 ± 0.07</td>
<td>2.38 ± 0.07</td>
<td>20.47</td>
<td>0.29 ± 0.01</td>
<td>6.63 ± 0.38</td>
<td>2.79 ± 0.18</td>
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<tr>
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<td>0.206</td>
<td>5.69 ± 0.09</td>
<td>2.61 ± 0.06</td>
<td>1.76</td>
<td>1.25 ± 0.04</td>
<td>7.35 ± 0.36</td>
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<tr>
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<td>0.204</td>
<td>5.51 ± 0.07</td>
<td>2.50 ± 0.06</td>
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<td>6.37 ± 0.35</td>
<td>2.54 ± 0.15</td>
</tr>
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<td>35.0</td>
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<td>3.70 ± 0.06</td>
<td>2.17 ± 0.06</td>
<td>4.97</td>
<td>1.15 ± 0.03</td>
<td>5.71 ± 0.27</td>
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<td>COS 8</td>
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<td>2.61 ± 0.06</td>
<td>1.53 ± 0.05</td>
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<td>0.39 ± 0.01</td>
<td>2.94 ± 0.15</td>
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<tr>
<td>COS 7</td>
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<td>0.35 ± 0.03</td>
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**Surface samples**

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<th>Name</th>
<th>Sample size (g)</th>
<th>Be spike (g)**</th>
<th>10Be/9Be</th>
<th>26Al/27Al</th>
<th>Stable Al (x10^{-6} atoms quartz)</th>
<th>26Al/10Be (x10^{12})</th>
<th>26Al (x10^{12} atoms g⁻¹ quartz)</th>
<th>26Al/26Be</th>
</tr>
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<tr>
<td>29COS-SUR</td>
<td>25.10</td>
<td>0.307</td>
<td>5.72 ± 0.07</td>
<td>4.68 ± 0.11</td>
<td>5.65</td>
<td>3.30 ± 0.13</td>
<td>18.6 ± 1.0</td>
<td>3.98 ± 0.24</td>
</tr>
<tr>
<td>36COS-SUR</td>
<td>25.02</td>
<td>0.305</td>
<td>5.57 ± 0.1</td>
<td>4.53 ± 0.12</td>
<td>5.01</td>
<td>3.69 ± 0.09</td>
<td>18.5 ± 0.9</td>
<td>4.08 ± 0.22</td>
</tr>
<tr>
<td>WD2t**</td>
<td>30.0</td>
<td>0.307</td>
<td>5.36 ± 0.09</td>
<td>2.87 ± 0.08</td>
<td>2.70</td>
<td>0.27 ± 0.00</td>
<td>1.92 ± 0.12</td>
<td>1.92 ± 0.12</td>
</tr>
</tbody>
</table>

*Be spike concentration—974 ppm.

**Notes:**

- Measured Be ratios are normalized to Be standard 07KNSTD3110 with a value of 2.85 × 10^{-12}. Measured Al ratios are normalized to Al standard KNSTD9919 with a value of 9.919 × 10^{-12}.
- Samples 29COS-SUR and 36COS-SUR are replicates of a sand sample collected from the surface outside the Wonderwerk Cave at 27°55.93′ S, 023°37.62′ E, elevation 1565 m above sea level (masl).
- Samples WD2b and WD2t are sand samples collected from the base and top of a dune, respectively, in the Western Desert, Egypt (25°23.800′ N, 027°08.064′ E, elevation 515 masl).
Figure 7. Representative Zijderveld (left) and normalized intensity diagrams (right) of alternating field (AF) and thermal demagnetization experiments of samples from group A. Open squares are plotted on a vertical plane, and solid circles are plotted on a horizontally oriented plane. Samples W38, W74, W7-80t, and W7-85t are silt cemented by calcium carbonate, and samples W20, W53, W93, and W7-97 are red silt.
a common process (Crouvi et al., 2008, 2010; Amit et al., 2011a, 2011b). A similarity in the particle size distribution of sand that was transported from the Kalahari and deposited inside the cave and the particle size distribution of sand that was recently transported to the vicinity of the cave may indicate the distance, during the late Pliocene and early Pleistocene, between Wonderwerk Cave and the sand source was similar to that at present. Furthermore, it may also indicate that late Pliocene and early Pleistocene wind directions and intensities were similar to the present ones. Nonsimilar particle size distributions may indicate different conditions, such as greater or lesser aridity, which caused the dunes to be closer or farther away from the cave, and stronger or weaker winds.

The grain-size range of quartz sand collected along the route of sand transport from the southern edge of the Kalahari to the vicinity of the cave shows an expected size decrease from the Kalahari toward the cave (Crouvi et al., 2008, 2010). The sandy sediment now exposed at the surface in the vicinity of the cave consists of grains with a size range of 70–100 μm. All but one sandy sample collected in the cave, which are composed of Kalahari-derived red fine-sand sediment, show a grain size range of 70–100 μm, similar to that found in the sediment presently exposed on the surface outside the cave (Table 2). Thus, we can reasonably assume that late Pliocene to early Pleistocene Kalahari sand was abraded and blown by wind to the Kuruman Hills where Wonderwerk Cave is located. We do not, however, propose that sand entered deep into the cave by wind action, as most of the cave is currently protected from wind.

We therefore suggest a scenario that includes three stages of sediment transport into the cave: (1) eolian transport of Kalahari sand and deposition throughout the Kuruman Hills; (2) slope wash of the eolian sediment and its accumulation in the intermontane valleys; and (3) fluvial transport of sediments, which included both Kalahari sand and local clasts (<5 mm in size), from the intermontane valleys through the drainage system adjacent to the cave and its deposition in the cave, generally close to the entrance. The sandy sediment consisted of grains originally >170 μm (Lancaster, 1986; Livingstone et al., 1999) that were abraded during transport to a size of 70–100 μm and deposited throughout the Kuruman Hills. The second stage is evident in the sharp transition between the cave and the colluvial-alluvial deposits in the intermontane valleys (Fig. 2). Reworking of rock slopes in the Kuruman Hills and the confluence of the Kuruman and Tshagab Rivers is attested to by rounded clasts and aggregates within the entrance sediments. The transport of sediment within the cave and its final deposition are most likely the result of low-energy water activity such as sheet wash. Once in the cave, the cosmogenic burial “clock” started ticking, although sediment continued to be transported within the cave toward the back by low-energy water flow. Sediment transport time within the cave may have been in the order of >10^5 yr. This stage is evident in the fine lamination and cross-bedding structures observed in the red sediment in excavation 6. This observation rules out the possibility that a significant portion of the sediment now buried in the Wonderwerk Cave was introduced into the cave by wind action. The present transport regime supports this observation and conclusion. Although abundant in the environs of the cave, quartz fine sand is scarcely blown into the cave and definitely does not reach the back.

**Comparison of Cosmogenic Burial Ages and Magnetostratigraphy**

In many settings, magnetostratigraphy has been the only method that enabled the estimation of sedimentary depositional ages. The development of the cosmogenic two-isotope burial dating method has facilitated more accurate dating of buried sediments of great antiquity. It is thus natural that cosmogenic burial ages have been, and still are, compared with paleomagnetic chronology (e.g., Carbonell et al., 2008; Chazan et al., 2008; Gibbon et al., 2009; Kong et al., 2009; Shen et al., 2009). However, this comparison is not always straightforward. In many cases, each of the methods dates a different stage in the history of the buried sediment, and complications may arise from differences in the nature and scale of uncertainties inherent in each method (Muzikar and Granger, 2006). Sometimes, as will be shown in the following, the comparison between magnetostratigraphy and cosmogenic two-isotope burial dating is ambiguous.

Ideally, cosmogenic burial dating indicates the time since the sediment was shielded from cosmic radiation and production of cosmogenic isotopes ceased (Granger, 2006). Wonderwerk Cave provides such a case for cosmogenic burial dating. After a prolonged exposure-burial history of several hundreds of thousands of years in the eolian-fluvial system (Fig. 6), sediments entered the cave and were instantaneously shielded from cosmic radiation by many meters of dense rock comprising the cave roof.

At this point, it is crucial to consider the initial 26Al/10Be ratio of the buried sediments. The simplest calculated burial age assumes that the initial ratio is identical (or similar) to the 26Al/10Be production ratio of 6.75 (Balco and Rovey, 2008). Any other ratio lower than the production ratio, if not considered, will result in the overestimation of the burial age. Although the initial ratio cannot be measured directly, it can be estimated by measuring the 26Al/10Be ratio in modern sediment, which may serve as an analog for the sediment prior to burial. The sand sample collected at the surface outside the cave (COS-SUR), and measured twice, yielded an average 26Al/10Be ratio of 4.03 ± 0.16. This ratio is equivalent to an apparent burial age of 0.78 ± 0.15 Ma. The 26Al/10Be ratios in quartz sand grains transported by eolian processes in the Namib Sand Sea have been recently reported to yield values that range between 2.8 and 4.8. These ratios are equivalent to apparent burial ages that range between 0.8 and 1.1 Ma (Vermesch et al., 2010). Similarly, Fujikoa et al. (2009) reported ratios that range between 2.3 and 4.8 in Australian sands. Our measurements and the two other examples show that quartz grains transported by wind experience a complex burial-exposure history that is reflected in their relatively low 26Al/10Be ratio, even when the sand is presently exposed at the surface.

Although the 26Al/10Be ratio (and the apparent burial age) in the surface sample collected outside the Wonderwerk Cave may represent the initial ratio of the buried samples in the cave, our field observations suggest a fundamental difference between the exposure-burial history of the buried cave sediments and the modern analog. The 26Al and 10Be concentrations and ratio in the modern sand sample delivered to the vicinity of the cave from the Kalahari Desert indeed reflect the exposure-burial complexities caused by eolian transport. However, the sediments presently in the cave experienced a colluvial-alluvial transport phase after eolian transport ceased and before entering the cave. While shielding thickness in dunes may reach many meters, the sandy colluvial mantle could not be that thick. Therefore, while on the slopes of the Kuruman Hills, the sandy sediments experienced partial (and possibly even full) production of cosmogenic isotopes, and the low 26Al/10Be ratios caused by eolian transport probably increased and may have approached production rate ratios during storage on the slopes. Only tens of thousands to approximately 100 k.y. of residence time of these sands at or near the surface on the slopes of the Kuruman Hills could erase a burial signal of 0.5–1 Ma. Therefore, we hypothesize that the initial 26Al/10Be ratios in the sands that entered the cave during the late Pliocene to early Pleistocene were higher than those measured in the modern sands outside the cave, although they may have been lower than the production rate ratio. Nevertheless, we consider both extreme age values (Table 3B): maximum ages calculated by considering an initial ratio of 6.75...
In addition to the uncertainty in the initial $^{26}\text{Al}/^{10}\text{Be}$ ratios, analytical uncertainties associated with the measurements of $^{26}\text{Al}$ and $^{10}\text{Be}$ generate an age uncertainty generally $>$10$^5$ yr (Granger and Muzikar, 2001). It should be noted, however, that the cosmogenic burial ages provided in this study do not represent the time sediment was buried in its final depositional location in the cave, as transport time in the cave may have been long ($>$10$^5$ yr).

Magnetostratigraphy is subject to two major problems:

1. There is a possible time gap between sediment deposition and acquisition of a stable NRM (natural remanent magnetization). The stable ChRM (characteristic remanant magnetization) of the buried sediment may be acquired long after deposition, and consequently the age of the sediments will be older than the age of the magnetization. Furthermore, even after acquisition, the original magnetic vector of sediments can be overprinted or even totally erased by epigenetic processes. Therefore, the age of magnetization) and/or VRM (viscous remanant magnetization). Thus, a measured magnetic signal in buried sediments may be one that stabilized a long time after deposition. If a polarity transition occurred between the time of deposition and the time of final magnetic signal stabilization, this transition will not be recorded, and the paleomagnetic pattern will not represent the time of actual deposition.

2. The magnetic pattern is subject to temporal interpretation. The interpretation of a magnetostatigraphic sequence, which includes polarity transitions, is not unique. Thus, any interpretation should be anchored to at least one independent datum line.

These points imply that even if there is an apparent agreement between cosmogenic two-isotope burial ages and the paleomagnetic sequence, we cannot rule out the possibilities that:

1. The paleomagnetic sequence lags by hundreds of thousands of years behind the cosmogenic ages, and (2) significant unconformities may be included in the paleomagnetic sequence. In spite of the complexities associated with the comparison of cosmogenic burial dating and paleomagnetic stratigraphy, they have been compared several times, and in many cases, a good agreement was shown (e.g., Partridge et al., 2003; Gibbon et al., 2009; Carbonell et al., 2008; Chazan et al., 2008). In cases where such an agreement was not achieved, it was demonstrated that the sediment experienced chemical and/or physical processes that changed the original magnetic vector (e.g., Kong et al., 2009). Our paleomagnetic and rock magnetic experiments and sample selection criteria employed in this study indicate that the ChRM in the Wonderwerk Cave excavation 1 samples is indeed the primary NRM, which is DRM (detrital remanent magnetization) in nature, and that it has not been affected by later chemical and physical process. Therefore, the age of magnetization approximates the age of the sediment deposition in excavation 1. In contrast, sedimentary structures and the distance between the mouth and the back of the cave suggest a more complicated depositional history for excavation 6. Although diagenetic and epigenetic processes did not affect the original stable magnetic signal of the excavation 1 sediments, transport time of sediment inside the cave determines the possible difference between the cosmogenic burial ages, which records the entering of sediment into the cave, and the paleomagnetic age, which was acquired after deposition. Thus, short in-cave transport time would yield concordant paleomagnetic and cosmogenic ages, while slow transport over extended periods would result in a significant time lag between the cosmogenic burial ages and the paleomagnetic ones.

Several independent observations limit the maximum possible age of the basal sediment in the Wonderwerk Cave, which yielded a normal polarity: (1) The appearance of lithic artifacts, dominated by a small flake and core industry, in the basal layers of the sequence supports the maximum age as no older than 2.6 Ma (late Pliocene), based on comparison with the earliest artifacts from East Africa and Sterkfontein Member 5 (Semaw, 2000; Kuman and Clark, 2000; Chazan et al., 2008). (2) The red, quartz-rich basal sediment in the cave's entrance was derived from Kalahari quartz sand, a source which is probably no older than the late Pliocene (Thomas and Shaw, 1991). (3) The deposition of sand in the cave obviously requires that the cave entrance was open. Conceptually, the opening of any subsurface karstic cavity to the atmosphere is the consequence of geomorphic processes such as slope retreat and drainage system incision and the general lowering of the landscape. If we assume incision rates of ~10 m m.y.$^{-1}$ (a reasonable assumption considering the semiarid environment), 2.5–3 m.y. ago the valley floor would have been 25–30 m higher than it is today, and the cave entrance would have been at the subsurface. Thus, the dolomite phreatic cavity that is Wonderwerk Cave could not have been open before the middle to late Pliocene, at which time the surface of the landscape outside was higher than the level of the cave mouth. We therefore suggest that the lowest normal polarity interval in the paleomagnetic sequence measured in excavation 1 in Wonderwerk Cave (N > R > NIN) cannot be older than the top of the Gauss normal chron (2.58 Ma).

We first consider the correlation of the paleomagnetic sequence with the maximum calculated range of burial ages (Fig. 4). The overall range of burial ages suggests that the lowest normal interval in the paleomagnetic sequence measured in excavation 1 in Wonderwerk Cave (N > R > NIN) may be the top of the Gauss normal chron (2.58 Ma). However, the actual burial time may have been shorter, as implied by the low initial $^{26}\text{Al}/^{10}\text{Be}$ ratio, and the lowest normal interval in the paleomagnetic sequence is more likely to be the Reunion normal subchron (2.11–2.15 Ma). This correlation implies that the reverse polarity interval above the basal normal interval represents an early reverse period of the Matuyama chron, and the normal polarity above it represents the Olduvai subchron. The major unconformity between lithostratigraphic units 1 and 2 (in the middle of archeological unit 9) raises the possibility that the uppermost normal polarity samples may represent the Jararnillo normal subchron or even the Brunhes normal chron. Cosmogenic burial dating of sediment above this major unconformity was unsuccessful due to the very low quartz content. Due to the vertical spacing between individual paleomagnetic samples (2–15 cm), the exact location of any polarity transitions in the sedimentary sequence of excavation 1 is uncertain. For example, the location of the polarity transition between the lowermost normal and the reverse interval above it may be positioned either below or above cosmogenic burial sample COS 2. Therefore, this sample may be correlated to either the normal Reunion subchron or the early reverse period of the Matuyama chron. Similarly, sample COS 4 may be correlated with the early reverse period of the Matuyama chron or with the Olduvai normal subchron.

We now consider the correlation between the paleomagnetic sequence and the minimum calculated range of burial ages (Fig. 4). In this case, the overall minimum range of the cosmogenic burial ages suggests that the lowest normal interval in the paleomagnetic sequence measured in excavation 1 in Wonderwerk Cave (N > R > NIN) may represent the Olduvai normal subchron (1.96–1.78 Ma). This correlation implies that the reverse polarity interval above the basal normal interval represents the middle reverse period of the Matuyama chron, and the normal polarity above it represents the Jararnillo normal subchron. The major unconformity between lithostratigraphic units 1 and 2 (in the middle of archeological unit 9) raises the possibility that the uppermost normal polarity samples...
may represent the Brunhes normal chron. The aforementioned uncertainty in the location of the polarity transitions leads to some ambiguities. Sample COS 2 may be correlated to either the normal Olduvai subchron or the middle reverse period of the Matuyama chron. Similarly, sample COS 4 may be correlated with the middle reverse period of the Matuyama chron or with the Jaramillo normal subchron. We suggest that in both interpretations, the Cobb Mountain normal subchron is unlikely to be represented because of its short duration (Channell et al., 2002). Both interpretations, based on maximum and minimum cosmogenic age ranges, provide a higher resolution and a better temporal interpretation compared to that previously given by Chazan et al. (2008) thanks to the larger number of cosmogenic burial and paleomagnetic samples. Archeological considerations tend to favor an age range for the sedimentary sequence in excavation 1 closer to the younger age range as presented here.

The interpretation of the R > N magnetic pattern from excavation 6 is more difficult because it includes only one polarity transition and appears to have major unconformities within it. Given the great distance between the cave entrance and excavation 6 located in the back of the cave, currently ~140 m, it is most likely that the final deposition and the stabilization of the magnetic signal occurred a long time after the initial shielding of the sediment when it entered the cave and after diagenetic and epigenetic processes no longer affected the sediment. In contrast, the cosmogenic burial clock was set when the sediments initially entered the cave mouth. Furthermore, when the sediments entered the cave, the distance to the entrance was greater than the present one, since the cave mouth must have retreated since the Early Pleistocene. The transport of sediment through the cave by low-energy water flow and the pooling of water at the back of the cave, as indicated by the fine laminar structure of the sediment, suggest a long time gap between the initial introduction of sediment into the cave (and the setting of the cosmogenic burial clock) and the acquisition of a stable magnetic signal by buried sediments at the back. Thus, the R > N magnetic pattern measured in excavation 6 cannot be correlated with the cosmogenic burial ages, and the transition may represent any R > N transition that occurred since the Late Pliocene. A single U/Th date from near the top of the section in excavation 6 (Fig. 5) yielded a minimum age of 187,000 ± 8 ka (Beaumont and Vogel, 2006), suggesting the occurrence of relatively late chemical processes that affected the sediment. The U/Th age, the archaeological artifacts, and the magnetostratigraphy suggest a time range of between 0.780 and 0.187 Ma for the hominin occupation in this part of the cave (Beaumont and Vogel, 2006; Chazan and Horwitz, 2009).

The concordance between the cosmogenic burial ages and the paleomagnetic polarities (N and R) suggests that in the setting of excavation 1 in Wonderwerk Cave, cosmogenic burial ages and the stabilization of magnetic vectors were not significantly affected by chemical and physical processes. The general agreement implies that: (1) postburial production of cosmogenic isotopes was insignificant, which was expected since the shielding overburden is significant; and (2) postburial physical and chemical processes generally did not erase the primary ChRM magnetic vectors, which stabilized soon after deposition. These points cannot be applied to the sediments in excavation 6. Obviously, the discordance of results derived from the two methods in excavation 6 highlights the need for caution when cosmogenic burial ages and paleomagnetic sequences are compared.

Implication of Initial Dosing to Kalahari Sand Stability

All sediment samples collected in the Wonderwerk Cave yielded relatively high 10Be concentrations that range between (1.09 ± 0.03) × 10^6 atoms g⁻¹ quartz and (2.73 ± 0.06) × 10^6 atoms g⁻¹ quartz. These high concentrations, especially when considering the long burial time of the sediments, imply extensive dosing of the sediment prior to burial in the cave. The simple scenario of initial exposure and one long burial period implies initial preburial 10Be concentrations that range between 3.6 × 10^6 atoms g⁻¹ quartz and 6.6 × 10^6 atoms g⁻¹ quartz. When scaled to sea level and high latitude (scaling factor of 2.73), these concentrations range between 1.3 × 10^6 atoms g⁻¹ quartz and 2.4 × 10^6 atoms g⁻¹ quartz. Given that the primary source of most of the sediment in the cave is the dune fields of the Southern Kalahari and not the erosion products of well-lithified bedrock, it is more appropriate to consider the preburial concentrations in terms of their corresponding exposure ages. These ages range between 310 ± 10 k.y. and 620 ± 40 k.y. We realize that the quartz grains sampled in the cave were not continuously exposed for these durations at the surface before burial but rather were most likely buried (totally or partially) and reexposed periodically. Nevertheless, the high concentrations do imply long residence time at, or very close to, the surface. The long residence time could be explained by relative stability of the dune fields situated to the north.

The relative stability of the Kalahari dune fields during certain periods between the late Pliocene and the early Pleistocene may be assessed by comparing the calculated preburial 10Be concentrations in the cave sediments with those measured: (1) in sediments transported from the Kalahari and presently exposed at the surface in the vicinity of the cave, and (2) in active dunes. The 10Be concentrations in surface sediment are indicative of residence time at (or near) the surface similar to the calculated preburial 10Be concentrations in buried sediments. The 10Be concentration measured in the sandy sediment collected at the surface ~3 km from the cave entrance (sample COS-SUR) yielded a 10Be concentration of (4.68 ± 0.11) × 10^6 atoms g⁻¹ quartz (Table 3). When scaled to sea level and high latitude (scaling factor of 2.73), a concentration of 1.7 × 10^6 atoms g⁻¹ quartz is given. This concentration is similar to the calculated preburial 10Be concentration in the sediments now buried in the cave. The relatively high concentration indicates long surface exposure. For comparison, 10Be concentrations measured in active dunes in the hyperarid Western Desert of Egypt (scaling factor of 0.85), scaled to sea level and high latitude, are an order of magnitude lower and range between 0.32 × 10^6 atoms g⁻¹ quartz and 0.24 × 10^6 atoms g⁻¹ quartz (Table 3).

Presently, the southern part of the Kalahari receives an average annual precipitation of ~200 mm (http://www.saexplorer.co.za/south-africa/climate/hotazel_climate.asp), and the dunes are relatively stable and mostly covered by vegetation (Stokes et al., 1997). These are the conditions that enable the significant accumulation of 10Be in windblown sediment as measured in sample COS-SUR. The relative stability of the Kalahari dunes, the long exposure of the sediment, and the vegetation cover are the result of the present semiarid conditions. Because the calculated preburial 10Be concentrations in the Wonderwerk Cave samples are similar to those measured in the sandy sediment that was transported from the Kalahari dunes and is presently exposed at the surface around the cave, we suggest that vegetation cover and dune stability during deposition of these samples may have been similar to those of today, implying semiarid conditions along the southern boundary of the Kalahari during the late Pliocene to early Pleistocene. On a finer scale, however, one can observe a systematic decrease in apparent exposure age at burial with burial age, which would suggest that sand surface residence times have increased, although still in the 10⁵ yr range, through the Pleistocene. Such an increase would imply a gradual increase in the stability of the Kalahari dunes.

Our cosmogenic nuclide and grain-size data suggest that the environmental conditions that persisted during sand deposition in Wonderwerk Cave and the resultant rates of geomorphic
processes that controlled $^{10}$Be concentrations in the sediment along the southern margin of the Kalahari during the late Pliocene and early Pleistocene, as well as their grain-size distributions, were similar to the present ones in the southern Kalahari, the Kuruman Hills, and the western Ghaap Plains. As our data set cannot provide a detailed high-resolution record, we do not propose that the entire period of ~1 m.y., in which sand was deposited in the cave, retained the same climatic conditions. The duration in which sands in transport accumulated their cosmogenic-nuclide concentrations and entered the cave (~$10^6$ yr) is long relative to the frequency of climate variability. Thus, the nuclide concentrations are well buffered against short-time-scale variability, and although the sand transport system may well have changed back and forth a lot over that period, the average conditions have been more or less the same for the last couple of million years. No prolonged change in climate that would result in significantly different rates of geomorphic processes or cosmogenic nuclide dosing occurred. It is most probable that during these million years, periods of greater or lesser aridity prevailed.

CONCLUSIONS

The earliest sediments deposited in Wonderwerk Cave, South Africa, which contain rich archaeological remains, were dated between 1.56 ± 0.10 Ma and 2.63 ± 0.17 using the two-isotope cosmogenic burial dating method. These ages are reduced to a range between 1.85 ± 0.23 and 0.78 ± 0.18 Ma when a preburial $^{26}$Al/$^{10}$Be ratio of 4.03 ± 0.16 is considered. Calculations of preburial $^{10}$Be concentrations suggest that the sediments buried in the cave and those transported presently to the cave’s surrounding. This similarity suggests that the environmental conditions that persisted during late Pliocene and early Pleistocene and the resultant rates of geomorphic processes were similar to the present ones in the southern Kalahari, the Kuruman Hills, and the western Ghaap Plains, and that these conditions favored the transport of fine-grained quartz sand to the vicinity of the cave. However, currently, the cave entrance is not connected to the adjacent drainage system, and thus very little quartz sand is transported into the cave.

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