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Dating Pliocene lacustrine sediments in the central Jordan Valley, Israel — Implications for cosmogenic burial dating

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ABSTRACT

Cosmogenic burial dating of sediments is usually used at sites with relatively simple or known exposure–burial histories, such as in caves. In an attempt to extend the applicability of the method to other common geological settings (i.e. the dating of late Neogene sedimentary formations), where much less is known about the exposure–burial history, we apply the cosmogenic burial method on Pliocene–early Pleistocene (1.5–4.5 Ma) lacustrine sediments in the central Jordan Valley, Israel. ^{26}Al, ^{10}Be, and ^{21}Ne concentrations in quartz were obtained from a 170 m tectonically-tilted section. Assuming fast burial and no post-burial production we obtained burial ages which range between 3.5 and 5.3 Ma. Integrating simple geological reasoning and the cosmogenic nuclide data, post burial production is found to be insignificant. We also found that the samples contain two distinct populations of grains (chert and quartz) from two different sources which experienced different pre-burial exposure histories. The cosmogenic nuclide concentrations in the samples are in accordance with those expected for the mixing of two sources, and the burial ages computed for both end members agree. Theoretical calculations of two-source mixing show that initial ^{26}Al/^{10}Be ratios are depressed relative to the expected surface ratios and may result in burial ages overestimated by as much as 500 ka. Using ages derived from cosmogenic nuclides, independent age constraints, and magnetostratigraphy we correlate the bottom of the section to the Cochiti Normal magnetic subchron (4.19–4.30 Ma) within the Reverse Gilbert chron, and the top of the section to the Reverse subchron at the top of the Gilbert chron (3.60–4.19 Ma).

1. Introduction

Absolute dating of Plio-Pleistocene continental sedimentary deposits in the age range of 0.5–5 Ma is difficult due to the limited range of radiocarbon (^{14}C), U-series, luminescence (OSL and TL), and Electron Spin Resonance (ESR) dating methods, especially when appropriate material for Ar/Ar dating is not present. This poses a problem in the research of hominid evolution, geomorphology, neotectonics, and late Neogene geology. Stratigraphic relationships and paleontological data usually yield limited results and in many cases, magnetostratigraphic inference has been the only dating tool that provided age constraints to many Plio-Pleistocene continental sedimentary sequences (Opdyk and Channell, 1996). However, interpretation of magnetostratigraphic sequences is often non-unique, unless the sequence can be anchored to one or more absolute age data points. Over the past two decades in-situ produced cosmogenic nuclides have been used in many studies to date burial ages of sediments (0.5–5 Ma) (Granger, 2006). This dating method relies on the in-situ production of cosmogenic nuclides (^{10}Be, ^{26}Al, and stable ^{21}Ne) in quartz initially exposed at the earth's surface and their differential decay during subsequent burial to depths where complete shielding prevents further production. Klein et al. (1986) compared measured ^{26}Al/^{10}Be ratios in Libyan Desert glass to that predicted in non-buried surface rocks to conclude a complex cyclic history of burial and re-exposure of the glass within Libyan sand dunes. In principle, the appearance of ^{26}Al/^{10}Be ratios below the value determined by their surface production rate ratio suggests a period of either complete or partial burial, for example by ice or sediment (e.g. Bierman et al., 1999; Matmon et al., 2003). Numerous geomorphic studies of both surface and buried sediments have demonstrated the wide applicability of the technique. Caves containing fluvial sediments are readily amenable to burial dating since they provide an ideal setting where repeated burial episodes, variation in shielding depth and final re-exposure are absent (Granger et al., 1997, 2001; Haeuselmann et al., 2007; Stock et al., 2004). These studies provide long-term river incision rates by the burial dating of stream deposits in abandoned caves above the modern channel. Burial dating of gravels in cave deposits associated with hominid sites has recently become a powerful chronological tool (Carbonell et al., 2008; Chazan et al., 2008; Gibbon et al., 2009; Partridge et al., 2003; Shen et al.,

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2009). However, in more common sub-aerial sedimentary formations, such as exposed alluvial fans and abandoned river terraces (Anderson et al., 1996; Granger and Smith, 2000; Matmon et al., 2005; Repka et al., 1997; Wolkowinsky and Granger, 2004) , paleosols covered by glacial till (Balco et al., 2005a,b,c), and lacustrine sediments (Kong et al., 2009) the burial and initial exposure history and the source of the sediment are not always well-constrained and offer an added degree of complexity. Some of these studies use ^{10}Be and ^{26}Al depth profiles to deal with post burial production. Few studies deal with sub-aerial units and compare results with independent ages (Balco et al., 2005a; Granger et al., 2006). In this study we present the use of the cosmogenic burial dating method using ^{10}Be, ^{26}Al and ^{21}Ne on the Erk-el-Ahmar (EEA) formation — an intra-rift lacustrine section exposed in the central Jordan Valley, Israel. The results of the cosmogenic nuclide-based age model are interpreted in light of known stratigraphic, paleomagnetic, paleontological, and independent radiometric dating constraints on the age of the EEA section. The validity of our assumptions regarding initial cosmogenic nuclide concentrations prior to burial, burial history, and post burial production are discussed. We also present an analysis of the ^{26}Al and ^{10}Be data based on the identification and characterization of two populations of mineral grains — chert and quartz — that originate from different sources and discuss the influence of such mixing on a simple burial age model.

1.1. Theory of cosmogenic burial dating

The most updated and detailed description of the cosmogenic burial dating method has been recently provided by Granger (2006). The method considers the concentration ratio of two cosmogenic nuclides, generally ^{26}Al and ^{10}Be (^{10}Be half life — 1.39 Ma and ^{26}Al half life — 0.705 Ma) in sedimentary quartz grains that were initially exposed and dosed, and then shielded from cosmic radiation. The ^{26}Al/^{10}Be ratio during burial is a function of the initial ratio and the burial time. For most cases, the initial ^{26}Al/^{10}Be ratio is simply a function of the production rate ratio which is not influenced by changes in production rate itself and is generally not affected by changes in latitude, altitude, and pre-burial dosing time (Brown et al., 1992; Nishiizumi et al., 1989). Once buried and shielded from cosmic radiation, the ^{26}Al/^{10}Be ratio will decrease exponentially due the different half lives of the two isotopes (Granger et al., 1997):

$$\frac{N_{26}}{N_{10}} = \left(\frac{N_{26}}{N_{10}}\right)_0 e^{-t_{burial}\left(\frac{1}{\tau_{26}} - \frac{1}{\tau_{10}}\right)} \qquad (1)$$

where N_{26} and N_{10} are the concentrations of ^{26}Al and ^{10}Be in atoms per gram quartz, $(N_{26}/N_{10})_0$ is the initial ^{26}Al/^{10}Be ratio at burial, t_{burial} is the time since burial, and τ_{26} and τ_{10} are the mean lives in years of ^{26}Al ($1.02\times10^6 \pm 0.04\times10^6$ yr) (Nishiizumi, 2004) and ^{10}Be ($2.00\times10^6 \pm 0.02\times10^6$ yr) (Chmeleff et al., 2010; Korschinek et al., 2010). The initial concentrations of cosmogenic nuclides in the sediment prior to its burial can be represented as a function of the erosion rate of the source rock:

$$N_0 = P / (1 / \tau + E\rho / \Lambda) \qquad (2)$$

where P is the local production rate of the cosmogenic nuclide at the surface (atoms/yr per gram quartz), E is the erosion rate (cm/yr), ρ is the density (g/cm^3), Λ is the attenuation length (g/cm^2), and τ is the mean life (yr). Eqs. (1) and (2) can be solved iteratively to yield the burial age and the source erosion rate (and initial ^{10}Be concentration) (Granger et al., 1997). A good estimate of the burial age can be obtained provided: a) the burial duration is sufficiently long to create a measurable difference (outside analytical errors) in the concentration ratio compared to the ratio for non-buried sediment (this sets a minimum burial age of about 0.2–0.3 Ma), b) the sediment had a sufficient initial dose of cosmogenic isotopes such that the residual cosmogenic nuclide concentration is larger than the sensitivity limit of Accelerator Mass Spectrometry measurement technique (this sets the maximum burial age to about 5–6 Ma) and c) that it was buried quickly (relatively to its total burial history). An additional, but not essential, requirement is that the sample has remained buried deep enough to eliminate exposure to cosmic radiation. Post burial production via spallation by fast neutrons or by muon capture can be estimated and used to correct for the true burial time if the shielding depth has remained constant (Granger and Muzikar, 2001). For old sediments ($>10^6$ yr), even at depths greater than 10 m of rock overburden, production via muons may be significant. Calculating burial ages without including post-burial muon production leads to an underestimation of the true burial age.

The use of a third nuclide in the quartz system can provide additional insight into the processes that affected the burial-exposure history of the investigated sediment (e.g. Vermeesch et al., 2010). The analytical methods and identification of the stable cosmogenic nuclide ^{21}Ne in quartz have been developed by Niedermann (2000), Niedermann et al. (1997), and Niedermann et al. (1994) and the production ratios of ^{21}Ne/^{26}Al and ^{21}Ne/^{10}Be have been determined giving a sea-level high latitude (SLHL) reference production rate for ^{21}Ne ranging between 18.3 and 19.9 atoms/g/yr (Balco and Shuster, 2009a; Goethals et al., 2009; Niedermann, 2000; Niedermann et al., 1994). In recent studies, the concentrations of ^{21}Ne in sediments were measured and have reinforced ^{26}Al/^{10}Be ages (Balco and Shuster, 2009b; Placzek et al., 2010).

1.2. The Erk-el-Ahmar study site

The Erk-el-Ahmar (EEA) formation (Horowitz, 1979) is an intra-rift lacustrine unit exposed in the central Jordan Valley, Israel (Fig. 1). The formation consists of clay, silt, very fine sand layers, and a rich assemblage of fresh water mollusks abundant with Melanopsis and Unio species (Schütt and Ortal, 1993; Tchernov, 1975). Coarser fragments, such as coarse sand grains, pebbles, and boulders are rare. The lack of a coarse sediment component may suggest minor relief along the shores of the lake that deposited the sediments of the EEA formation. The quartz in the sediments is derived both from aeolian deposition on the drainage basin and from erosion of chert outcrops (further detailed in the Results and Discussion sections). The studied type section is exposed along the western bank of the Jordan River, ~10 km south of the Sea of Galilee, and is tectonically tilted to the east (10°–25°). The base of EEA is not exposed and horizontal lacustrine sediments of Lake Lisan deposited during the last glacial period overlie the formation on a truncated surface (Picard, 1965). In several areas these sediments have been eroded after the retreat of Lake Lisan. The thickness of the exposed section of the EEA formation is estimated to be at least 200 m. In the vicinity of the study site there are several other isolated outcrops attributed to the EEA formation, which contain mammalian remains and hand tools (e.g. Braun et al., 1991). However, no exposed stratigraphic relation between these EEA outcrops and the sampled EEA section is currently available and significant unconformities may exist. Thus, the correlation between these outcrops remains undetermined.

The age of the EEA formation is constrained by two other well-studied formations. Although there is no exposed contact between the formations, their relative ages and their relation to the EEA formation are firmly based on fauna assemblages, borehole data, and seismic profile data. The Ubeidiya formation which has been studied extensively and contains hominid remains, tools, and rich fauna (e.g. Bar-Yosef and Goren-Inbar, 1993; Belmaker et al., 2002; Tchernov et al., 1986), has been dated to ca. 1.5 Ma (Martinez-Navarro et al., 2009; Tchernov, 1987). Its proto type is exposed ~5 km north of the study site and based on marked differences in mollusk assemblages, the EEA formation is considered to be older than the Ubeidiya formation (Tchernov, 1975). Additionally, the Zihor Lake site in southern Israel, which was dated to ~1.6 Ma (Guralnik et al., 2010),