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Extraterrestrial ^3He in Paleocene sediments from Shatsky Rise: Constraints on sedimentation rate variability

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ABSTRACT

We attempt to constrain the variability of the flux of extraterrestrial ^3He in the Paleocene by studying sediments from Shatsky Rise (Ocean Drilling Program, ODP Leg 198) that have tight orbital age control. ^3He concentrations in Shatsky Rise sediments vary periodically at high frequency by about a factor of 6 over the 800-ka record analyzed. Virtually all of the sedimentary ^3He (>99.98%) is of extraterrestrial origin. The total helium in the sediments can be explained as a binary mixture of terrestrial and extraterrestrial components. We calculate an average $^3He/^4He$ ratio for the extraterrestrial endmember of $2.41 \pm 0.29 \times 10^{-4}$, which is, remarkably, equal to that measured in present-day interplanetary dust particles. We determine a constant extraterrestrial ^3He flux of $5.9 \pm 0.9 \times 10^{-13}\,cm^3STP{\cdot}cm^{-2}\,ka^{-1}$ for our 800-ka Paleocene record at ~58 Ma. This value is identical within error to those for the late Paleocene in sediments from the northern Pacific and the Weddell Sea. Bulk sediment MARs (derived using a constant extraterrestrial ^3He flux) respond to climate-forced carbonate preservation cycles and changes in eolian flux over the late Paleocene. This is the first direct evidence for significant changes in dust accumulation in response to eccentricity forcing during a greenhouse climate interval.

1. Introduction

Constant-flux sedimentary proxies (CFPs), tracers with a known rate of supply, provide for a quantitative assessment of particle and mass fluxes to ocean sediments through time. Extraterrestrial ^3He in deep-sea sediments is a newly-developed CFP that has been used across a variety of timescales from the Holocene to the Cretaceous (e.g., Farley, 1995; Marcantonio et al., 1995, 1996; Mukhopadhyay et al., 2001a; Farley and Eltgroth, 2003; Winckler et al., 2005). If the flux of extraterrestrial ^3He, which is a proxy for the flux of interplanetary dust particles (IDPs) delivered to the Earth's surface, is known to be constant over a certain time period, sediment mass accumulation rates (MARs) can be calculated. Such MARs can be determined by simply dividing the known flux of extraterrestrial ^3He by the measured concentration of extraterrestrial ^3He in an interval of deep-sea sediment. The extraterrestrial ^3He signature, is preserved in marine sediments as old as 65 Ma (Farley, 1995; Mukhopadhyay et al., 2001a,b), and perhaps as old as 480 Ma (Patterson et al., 1998).

Although the flux of extraterrestrial helium varies by about an order of magnitude on long timescales such as the Cenozoic (Farley, 1995), such variability occurs at low frequency (~4 to 5 Ma). Over short intervals (~1 Ma or less), using various means of quantifying rates of sedimentation, the ^3He flux has been shown to be constant (Marcantonio et al., 1996, 2001a; Mukhopadhyay et al., 2001a,b; Farley and Eltgroth, 2003; Winckler et al., 2005, 2008). For late Quaternary and Holocene sediments, sedimentation rates have been quantified (and, hence, ^3He fluxes determined) using excess ^{230}Th as an independent CFP (Marcantonio et al., 1995, 1996, 2001b; Higgins et al., 2002). One must also assume that the effects of diagenesis on the retention of ^3He would be constant over a relatively short timescale in sediments of the same age. An advantage of MARs calculated using constant-flux proxies such as extraterrestrial ^3He is that they reflect "instantaneous" vertical rain rates of the sediment sample analyzed, and therefore, have a higher resolution than traditionally derived MARs which rely on linear interpolation between widely spaced biostratigraphic or magnetostratigraphic datums or astronomically-derived tie points. In addition, when there are independent constraints on sediment chronology, CFP-derived MARs reflect vertical rain rates and normalize for any lateral inputs due to sediment redistribution processes at the seafloor. Past changes in oceanic productivity, assessed from the accumulation rates of a variety of paleoproductivity proxies (e.g., opal, organic carbon, barite), and the accumulation rates of $CaCO_3$, which follow regular patterns in phase with the earth's changing climate, are examples of types of information obtained with the aid of CFPs. Such information contributes to our understanding of the ocean's role in regulating past changes in atmospheric CO_2 concentrations. Similarly, evaluating past changes in

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the flux of terrigenous material transported to the deep sea leads to an improved understanding of the variability of wind patterns and of continental aridity.

There is only one study in which extraterrestrial ^3He has been used as a CFP in order to determine sediment mass accumulation rates in the Paleocene (Farley and Eltgroth, 2003). If additional constraints can be placed on the variability of the flux of extraterrestrial ^3He in the Paleocene, we could significantly improve estimates of short-term mass accumulation rates of important sedimentary constituents. Here we test the hypothesis that during short periods of time (i.e., sub-Ma), extraterrestrial ^3He can function as a constant-flux proxy in Paleocene-age sediments. The sequence of Paleocene sediments from Shatsky Rise (Ocean Drilling Program, ODP Leg 198) provides an ideal framework to address this question because of newly established orbital age control (Westerhold et al., 2008). Cyclic variations in sediment lithology (indicated by shipboard magnetic susceptibility measurements and shore-based Fe content data) at Shatsky Rise ODP Site 1209 correlate to similar lithologic cycles in sediments deposited in the northwestern and southeastern Atlantic, and are confirmed records of 100-ka and 400-ka eccentricity forcing (Fig. 1, from Westerhold et al., 2008). The orbitally-forced changes in sediment lithology reflect a combination of changes in the delivery of terrigenous material and changes in the accumulation of biogenic carbonate. Of the locations with globally correlative lithologic cycles, Shatsky Rise is the most ideal for this study because it was located in the central tropical North Pacific during the Paleocene (~58 Ma) far from any shoreline. This paleogeography simplifies the depositional setting, as the only source of terrigenous material (which can complicate determinations of the extraterrestrial helium component of the sediment sample) to the seafloor was windblown dust. Changes in overall sediment accumulation therefore reflect some combination of carbonate production/preservation and dust delivery.

2. Methodology and sampling

For helium isotope analysis, we have sampled a set of eight consecutive short eccentricity (100 ka) cycles recorded in the sediments of Shatsky Rise (about 50 samples spanning a 4-m section at ~58 Ma). The sampling provides a resolution of 4 or 5 samples per eccentricity cycle. The well-accepted orbital origin of these cycles is based on periodic changes in the magnetic susceptibility or Fe content of early Paleogene deep-sea sediments on 100- and 400-kyr time scales and the fact that such cyclic sedimentary records can be correlated globally (e.g., Westerhold et al., 2008). In order to remove the biogenic, non-helium-containing fraction of the sediment (Marcantonio et al., 1995), approximately 2–4 g of discrete bulk sediment aliquots were leached with about 50 mL of 0.5 N acetic acid (mixture of trace metal grade acetic acid with distilled water). The 2- to 4-g sample size corresponds to an average area-time product (Farley et al., 1997) of about 0.3 $m^2\ a^{-1}$, which allows for reasonable estimates of the true extraterrestrial ^3He flux. The leaching step enables us to estimate the amount of helium in the detrital (mainly non-carbonate) fraction of the sediment that is insoluble in acid. Shatsky Rise sediments are composed almost entirely of $CaCO_3$ (~88–95%, Woodard et al., submitted). After leaching, the non-dissolvable detrital fraction was rinsed three times with distilled water and dried to a constant weight at 80 °C. Samples were placed in Al foil "boats," which were subsequently shaped into small balls for analysis. At the Lamont-Doherty Earth Observatory, helium was extracted from the sample "balls" by *in-vacuo* fusion at 1400 ºC in tantalum crucibles, and helium isotope ratios were measured on a MAP 215-50 noble gas mass spectrometer. Blank corrections were negligible for ^3He concentrations (<0.1% of measured values). For ^4He, all corrections were <1.4% for all but five samples, which have blank corrections ranging from 3.4 to 7.1%. $^3He/^4He$ ratios were normalized to the MM secondary standard (Yellowstone hotspot gas), which was run at least once for every 3 samples processed. Analytical errors average about 1.2%, 2.5%, and 2.1% for the ^4He concentration, ^3He concentration, and $^3He/^4He$ ratio, respectively. However, the external reproducibility, determined by replicate sample measurements, is larger than the analytical error. Replicate measurements (Table 1) of seven of the samples analyzed in this study suggest that ^3He and ^4He concentrations are reproducible to within about 15% (1σ), similar to the reproducibility reported by others (e.g., Marcantonio et al., 2001b; Higgins et al., 2002; Farley and Eltgroth, 2003; Winckler et al., 2005).

3. Results and discussion

The component of sedimentary ^3He that is derived from extraterrestrial sources is estimated assuming binary mixing between extraterrestrial (IDP) and terrestrial sources. There is a two- to four-order-of-magnitude difference between the helium isotope ratios of terrestrial (10^{-8} to 10^{-6} range; e.g., Marcantonio et al., 1998) versus extraterrestrial sources (10^{-4}; Nier and Schlutter, 1992). The high $^3He/^4He$ ratios of Shatsky Rise sediments (average $= 1.21 \times 10^{-4}$), indicates that virtually all of the sedimentary ^3He (>99.98%) in these Paleocene age sediments is of extraterrestrial origin. The small amount of continentally-derived detrital material delivered to this site, which plate reconstructions place in the central equatorial Pacific at 58 Ma (Bralower et al., 2002), is the reason measured ^4He concentrations are so low (average value of 8.5×10^{-9} cm^3STP g^{-1}). A significant portion of the ^4He content is derived from extraterrestrial (27–92%) rather than terrestrial (crustal) sources.

The extraterrestrial ^3He concentrations in Shatsky Rise sediments vary by about an order of magnitude from 0.28 to 2.43×10^{-9} cm^3STP g^{-1} (Fig. 2). Such extraterrestrial helium concentrations are very similar to those found in late Quaternary and Holocene carbonate-rich sediments of the central equatorial Pacific (e.g., Marcantonio et al., 1995, 1996, 2001b; Winckler et al., 2004, 2005). The extraterrestrial ^3He, the crustal ^4He, detrital and Fe concentrations all follow similar patterns of high-frequency variability (Fig. 2). Variations in the detrital concentrations are almost identical to those of the crustal ^4He concentrations (Fig. 2).

Marcantonio et al. (1995) showed that the acid-dissolvable, mainly biogenic, component of recent deep-sea sediment contains no helium. Indeed, it is thought that the majority of the helium signal in deep-sea sediments is derived from the detrital and extraterrestrial components. Shatsky Rise sediments provide further support for this idea. The linear correlation between the helium isotope ratio ($^4He/^3He$ in this instance) and the inverse helium concentration of the detrital fraction ($r^2 = 0.82$, Fig. 3) suggest that helium in the sediments from Shatsky Rise is derived from a binary mixture of extraterrestrial and terrestrial sources. Importantly, the high correlation coefficient suggests that there is little variability in either the terrestrial or extraterrestrial endmembers within the 800-ka record analyzed. The implication, therefore, is that the eolian and extraterrestrial dust being supplied to the Shatsky site each had unique sources that did not vary significantly over the 8 eccentricity cycles. Moreover, because virtually all of the ^3He is extraterrestrial in origin, we are able to tightly constrain the $^3He/^4He$ ratio of the extraterrestrial source of helium. As the inverse ^3He concentrations approach zero (i.e., very high extraterrestrial ^3He concentrations), an intercept is approached that approximates the helium isotope signature of the pure extraterrestrial component. The intercept on Fig. 3 ($^4He/^3He = 4.14 \pm 0.39 \times 10^3$) corresponds to an extraterrestrial $^3He/^4He$ value of $2.41 \pm 0.23 \times 10^{-4}$. The average $^4He/^3He$ isotope ratio measured in present-day individual stratospheric IDPs is about $4.17 \pm 0.50 \times 10^3$ ($^3He/^4He = 2.40 \pm 0.29 \times 10^{-4}$; Nier and Schlutter, 1992). A similar range in the $^3He/^4He$ ratios of individual stratospheric IDPs was found in more recent studies (Pepin et al., 2000, 2001). The average IDP $^4He/^3He$ (4.17×10^3) and $1/^3He$ concentration (3.3×10^4 g cm^{-3}STP) determined by Nier and Schlutter (1992) are also plotted in Fig. 3 (star). The coincidence between measured present-day IDP values and those

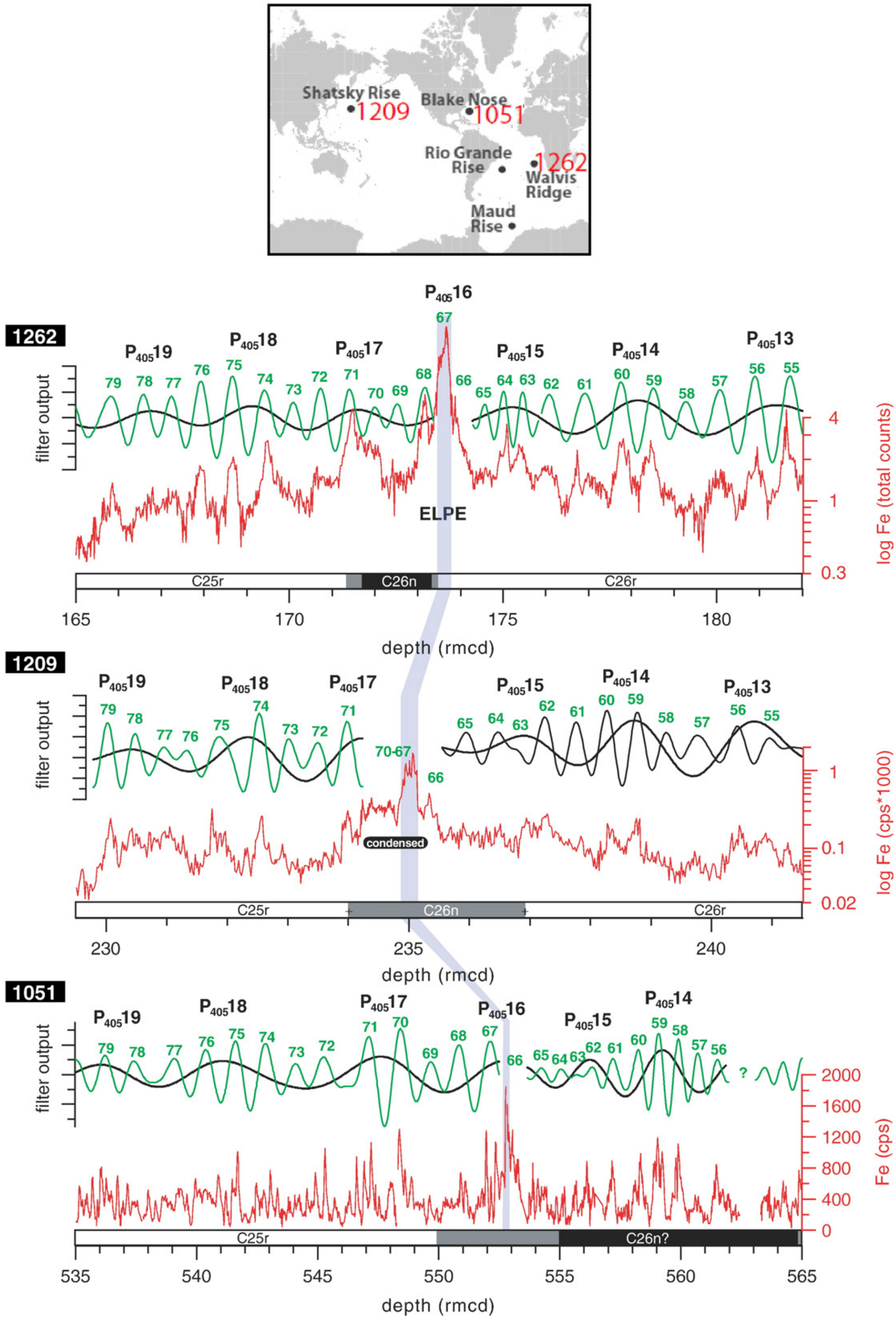

Fig. 1. Map of the present locations of Ocean Drilling Program sites with globally correlative lithologic cycles. Fe abundance data with 100-ka (green curve) and 400-ka (black curve) eccentricity cycles determined for ODP Sites 1262, 1209, and 1052 (Fig. 7 in Westerhold et al., 2008). This study spans 100-ka eccentricity peaks 71–79 at Shatsky Rise Site 1209.

obtained in this study for sediment deposited at 58 Ma is remarkable, and suggests that from the Paleocene to today there is a potentially unchanging source of extraterrestrial ^{3}He delivered to the Earth and that there is, therefore, little change in the mechanism which produces high ^{3}He IDPs. Lal and Jull (2005) argue that a major portion of the extraterrestrial ^{3}He in sediments is contained in >35-μm fragments of meteoroids that were broken up upon atmospheric entry and that, therefore, retain their ^{3}He which was produced in the original extraterrestrial matrix by interaction with galactic cosmic rays. Others (e.g., Ozima et al., 1984; Farley, 1995; Farley et al., 1997) argue that the high ^{3}He/^{4}He ratios in IDPs is a surface-implantation feature in which particles <35 μm retain their solar-wind-implanted helium because

Table 1
Helium isotope ratio data for sediments from Shatsky Rise (ODP Leg 198, Site 1209).

Depth (rcmd)	Detrital (non-dissolvable) fraction	^4He ($cm^3STP \cdot g^{-1}$)	^3He ($cm^3STP \cdot g^{-1}$)	$^3He/^4He$
229.93	0.989	8.58E−09	1.71E−12	2.00E−04
230.01	0.986	7.25E−09	8.03E−13	1.11E−04
230.07	0.979	1.34E−08	1.67E−12	1.25E−04
230.07	0.980	1.53E−08	1.67E−12	1.10E−04
230.16	0.989	5.09E−09	6.43E−13	1.27E−04
230.25	0.991	4.15E−09	4.42E−13	1.06E−04
230.34	0.986	8.13E−09	1.10E−12	1.35E−04
230.43	0.981	1.01E−08	1.31E−12	1.30E−04
230.43	0.981	1.43E−08	1.19E−12	8.24E−05
230.57	0.985	7.48E−09	7.87E−13	1.05E−04
230.72	0.983	9.57E−09	1.16E−12	1.21E−04
230.87	0.984	9.48E−09	1.56E−12	1.65E−04
231.01	0.978	1.93E−08	2.43E−12	1.26E−04
231.07	0.982	9.84E−09	1.31E−12	1.33E−04
231.07	0.982	1.02E−08	1.54E−12	1.51E−04
231.14	0.983	7.87E−09	1.06E−12	1.35E−04
231.21	0.988	6.86E−09	9.49E−13	1.38E−04
231.27	0.981	7.29E−09	8.56E−13	1.17E−04
231.27	0.981	7.11E−09	7.68E−13	1.08E−04
231.31	0.984	6.46E−09	7.03E−13	1.09E−04
231.39	0.992	5.85E−09	1.25E−12	2.15E−04
231.51	0.989	7.53E−09	1.38E−12	1.81E−04
231.63	0.988	5.03E−09	7.54E−13	1.49E−04
231.75	0.974	1.35E−08	1.40E−12	1.04E−04
231.95	0.983	6.91E−09	4.85E−13	7.02E−05
232.16	0.990	3.31E−09	4.31E−13	1.30E−04
232.38	0.984	5.28E−09	4.67E−13	8.83E−05
232.56	0.961	1.61E−08	1.55E−12	9.49E−05
232.56	0.961	1.41E−08	1.19E−12	8.43E−05
232.65	0.984	6.75E−09	8.34E−13	1.24E−04
232.73	0.987	5.69E−09	8.30E−13	1.46E−04
232.81	0.986	5.31E−09	6.20E−13	1.17E−04
232.82	0.988	4.63E−09	4.99E−13	1.08E−04
232.84	0.986	6.13E−09	8.27E−13	1.35E−04
232.91	0.983	7.86E−09	1.15E−12	1.47E−04
232.95	0.986	5.22E−09	4.99E−13	9.57E−05
232.95	0.986	5.41E−09	6.13E−13	1.13E−04
233.1	0.985	9.66E−09	1.95E−12	2.01E−04
233.24	0.988	4.29E−09	2.95E−13	6.89E−05
233.39	0.987	3.74E−09	2.81E−13	7.52E−05
233.42	0.987	3.92E−09	4.68E−13	1.19E−04
233.42	0.985	5.27E−09	7.60E−13	1.44E−04
233.6	0.986	5.34E−09	6.17E−13	1.16E−04
233.69	0.984	4.56E−09	3.57E−13	7.84E−05
233.8	0.982	6.73E−09	8.00E−13	1.19E−04
233.89	0.982	6.14E−09	3.89E−13	6.33E−05
233.99	0.949	2.30E−08	2.02E−12	8.79E−05
233.99	0.949	1.98E−08	1.57E−12	7.94E−05

they are small enough to withstand high frictional heating temperatures upon Earth entry. There is support for the latter hypothesis in a recent size fractionation study (Mukhopadhyay and Farley, 2006) that suggested that more than 60% of the ^3He resides in particles that are <37 μm.

The relationship of Fe cycles to eccentricity has been well established and is well accepted (e.g., Westerhold et al., 2008). Indeed, early Paleogene deep-sea sediments that contain orbital-scale lithologic cycles have been recovered from the northwest Atlantic Ocean (Blake Nose, ODP Leg 171B), the southwest Atlantic Ocean (Walvis Ridge, DSDP Leg 84 and ODP Leg 208), the southeast Atlantic Ocean (Rio Grande Rise, DSDP Legs 39 and 72), the Southern Ocean (Maud Rise, ODP Leg 113), and the northwest Pacific (Shatsky Rise, ODP Leg 198). The cyclic lithology can be correlated among all locations with sufficiently long and continuous records (e.g., Westerhold et al., 2008), implying a global-scale controlling mechanism, i.e., orbitally-forced changes in insolation. While the absolute age of any given sediment horizon will likely change as the time scale is refined, the relative ages (i.e., the fact that the peaks reflect 100- and 400-ka cycles) will remain constant. We feel confident, therefore, that we can determine the true flux of extraterrestrial ^3He, by using the independent orbitally-controlled age model of Westerhold et al. (2008) for Shatsky Rise. Still, there is the potential for circular reasoning if we are to use independent age models to determine ^3He fluxes and then use the latter flux to calculate mass accumulation rates. To overcome this potential limitation we have to critically address two phenomena that can act to lower or raise ^3He inventories (and, therefore, fluxes) at different sites: 1) ^3He could be lost during diagenesis or 2) ^3He could be lost or gained during sediment redistribution processes. Perhaps the best way to ascertain whether either sedimentary phenomenon affects the apparent ^3He flux is to empirically compare independently-derived ^3He fluxes from multiple sites as suggested by Farley and Eltgroth (2003). One would expect that if such processes are at work, they would produce apparent ^3He fluxes that are variable in magnitude across wide distances over the globe.

For Shatsky Rise, we can calculate an average extraterrestrial ^3He flux by multiplying the average MAR by the average extraterrestrial ^3He

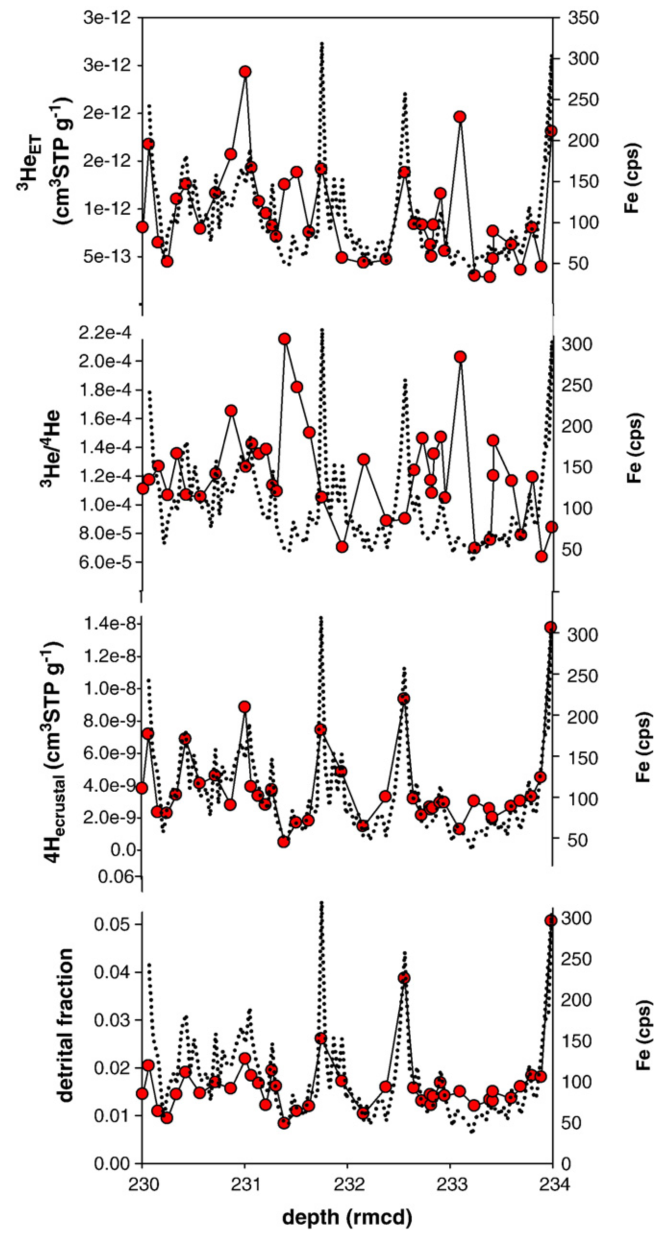

Fig. 2. In each panel the Fe abundance data (XRF counts per second data from Westerhold et al., 2008) is plotted against revised meters composite depth (rmcd), along with a) extraterrestrial ^3He content, b) $^3He/^4He$ isotope ratio, c) $^4He_{crustal}$ (terrestrially-derived ^4He) content, and d) detrital fraction (assumed to be the non-dissolvable fraction of the sediment).

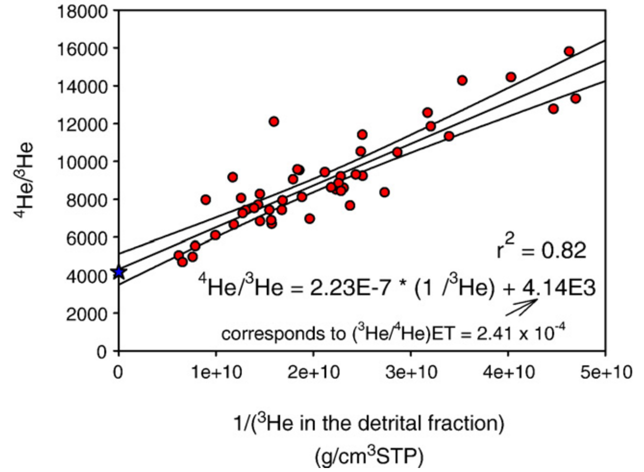

Fig. 3. ^{4}He/^{3}He isotope ratio plotted against 1/^{3}He(non-dissolvable). The data are linearly correlated ($r^2 = 0.82$; 1σ error regression envelope drawn around line). The intercept approximates the ^{4}He/^{3}He isotope ratio of the extraterrestrial IDP end-member. The blue star is the average helium isotope ratio and ^{3}He concentration values for modern-day IDPs measured by Nier and Schlutter (1992).

concentration (1.0×10^{-12} cm^{3}STP·g^{-1}). The average MAR can be calculated by multiplying the average linear sedimentation rate for the 392-cm record (0.48 cm·ka^{-1}, orbital age model from Westerhold et al., 2008) by the average measured dry bulk density of 1.23 g·cm^{-3} (modified γ-ray attenuation data, Bralower et al., 2002). We determine an extraterrestrial ^{3}He flux value of $5.9 \pm 0.9 \times 10^{-13}$ cm^{3}STP cm^{-2} ka^{-1}, which is identical to the values calculated for Paleocene sediments in the northern central Pacific (5×10^{-13} cm^{3}STP·cm^{-2}·ka^{-1}, no error given; Farley, 1995) and in the Weddell Sea ($6.9 \pm 1.0 \times 10^{-13}$ cm^{3}STP· cm^{-2}·ka^{-1}; Farley and Eltgroth, 2003). In the northern central Pacific work (Farley, 1995) sediments were sampled at low resolution across the entire Cenozoic (~10 samples over the entire Paleocene), while sediments in the Weddell Sea study were sampled at higher resolution (similar to ours) in the late Paleocene. A Paleocene extraterrestrial ^{3}He flux has also been measured in pelagic limestones of the Apennines (Mukhopadhyay et al., 2001a) and in Blake Nose sediments of the northwestern Atlantic (Farley and Eltgroth, 2003). However, at both of these locations the apparent ^{3}He flux is a factor of 3 (Blake Nose) to 7 (Apennines) times lower that those calculated in the Pacific and Southern Oceans. With respect to the Apennines, Mukhopadhyay et al. (2001a) speculate that the cause of the extremely low measured fluxes (throughout the Cretaceous and Paleogene) is subaerial degradation of the magnetic ^{3}He-containing extraterrestrial phase. Experimental data indicate that ^{3}He is up to three times more likely to diffuse out of IDPs in sediments exposed at the Earth's surface compared to those that lie at the seafloor (Mukhopadhyay and Farley, 2006). In the case of the Blake Nose, the lower values may be more likely due to the relative proximity to the continental margin and potential for sediment redistribution processes, which lower ^{3}He inventories and, thus, fluxes.

The constancy of the extraterrestrial fluxes at the geographically separated sites of Shatsky Rise, the Weddell Sea, and the North Pacific suggests empirically that the ^{3}He flux at these sites are not affected by diagenetic or sediment focusing processes and represents a true supply rate from space in the Paleocene. More data from diverse geographic locations are needed to confirm this finding. Using our determined extraterrestrial ^{3}He flux of $5.9 \pm 0.9 \times 10^{-13}$ cm^{3}STP·cm^{-2}·ka^{-1}, we can begin to address the variability in sediment and sediment component mass accumulation rates at Shatsky Rise. Interestingly, compared to the relatively constant modern (Holocene) and Last Glacial extraterrestrial ^{3}He fluxes measured in sediment and ice records from various latitudes (~8×10^{-13} cm^{3}STP·cm^{-2}·ka^{-1} e.g., Brook et al., 2000; Marcantonio et al., 2001a; Higgins et al., 2002; Winckler and Fischer, 2006), Paleocene extraterrestrial ^{3}He fluxes are only slightly lower.

Unlike tie-point-derived MAR models which provide average mass accumulation rates across large intervals of sediment, constant-flux proxies have the ability to provide "instantaneous snapshots" of sediment MARs that are limited only by bioturbation. Assuming a constant flux of extraterrestrial ^{3}He equal to 5.9×10^{-13} cm^{3}STPcm^{-2} ka^{-1}, we calculate bulk sediment MARs that range from about 0.5 to 2.0 g cm^{-2} ka^{-1} (Fig. 4), similar to those found in the central equatorial Pacific today. The pattern of high-frequency variability of ^{3}He-derived MARs is coincident with that observed in the high-resolution Fe record, within which orbital eccentricity cycles have been identified (Westerhold et al., 2008). For the most part, low MARs are coincident with the peaks in the eccentricity cycles, while high MARs are coincident with the lows in these cycles (scale for MARs is reversed in Fig. 4). Although there is some higher-frequency variability earlier in the record between 234 and 233 m, the most notable departure from the agreement between the interpreted eccentricity cycles and the ^{3}He-derived MARs is eccentricity peak 76. The inverse correlation between Fe counts (representative of the dust content) and bulk sediment MARs (Fig. 4) suggest that changes in sediment accumulation may be due to changes in carbonate production/preservation (i.e., dissolution), and/or dilution by terrigenous sediment supply.

The almost identical patterns of temporal variations of the detrital fraction, the Fe concentration, and the crustal ^{4}He concentrations provide strong support for using the ^{4}He content as a proxy for the eolian component in Shatsky Rise sediment. ^{4}He abundance in oceanic sediments is a function of previous U and Th decay in old continentally-derived zircons (Patterson et al., 1999). Young wind-blown volcanogenic dust contains negligible ^{4}He (Marcantonio et al., 1998; Patterson et al., 1999; Winckler et al., 2005; Mukhopadhyay and Kreycick, 2008), whereas older sources of continentally-derived dust contain up 3 orders of magnitude higher ^{4}He concentrations. In addition, the good correlation between ^{232}Th (a known proxy for the terrigenous component; Anderson et al., 2006; McGee et al., 2007) and ^{4}He in different oceanic basins (Marcantonio et al., 1999, 2001a; Winckler et al., 2008) suggests both proxies are most easily explained if they reflect eolian sources.

At Shatsky Rise there is a pattern of high-frequency variability in the ^{3}He-derived flux of $^4He_{crustal}$ (Fig. 5). The $^4He_{crustal}$ fluxes, which are a proxy for eolian fluxes, vary by over an order of magnitude in synchrony with, for the most part, the short 100-ka eccentricity cycles. The variability in the $^4He_{crustal}$ flux corroborates the findings of Woodard et al. (submitted) who found that, using traditional sedimentological methods, dust fluxes vary on an eccentricity basis (both the short and long eccentricity cycles). This is the first direct evidence for significant changes in dust accumulation in response to eccentricity forcing during a greenhouse climate interval. As with the traditionally-determined dust flux data based on fine fraction silicate mass accumulation, the

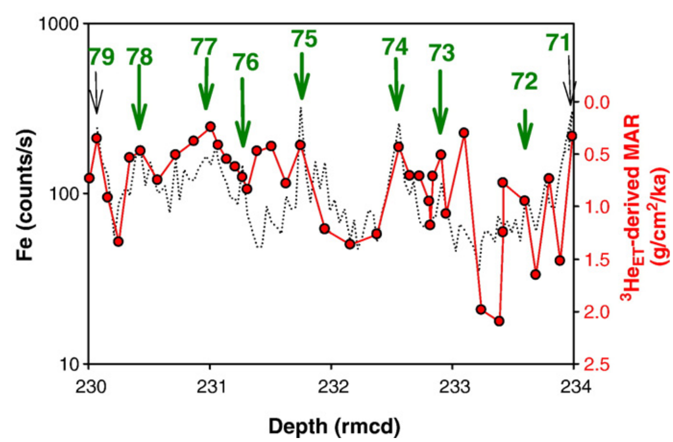

Fig. 4. Depth variations in Fe data and extraterrestrial ^{3}He-derived MARs (reverse scale). The variations in MARs generally follow the 100-kyr eccentricity peaks 71–79 (identified in Fig. 1). Lowest MARs are associated with peaks in eccentricity and vice versa.

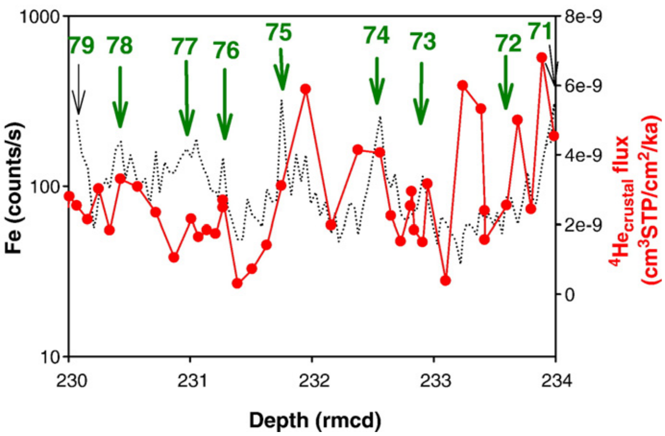

Fig. 5. Depth variations in the flux of $^4He_{crustal}$ derived using the ^3He-calculated MARs. The flux of $^4He_{crustal}$ is an estimate of the flux of windblown dust from the continents. For the most part, highest $^4He_{crustal}$ fluxes coincide with peaks in eccentricity.

highest dust fluxes based on the $^4He_{crustal}$ data coincide with peaks in eccentricity in all but two cases (Fig. 5). There are two exceptions to this relationship evident in the $^4He_{crustal}$ data—there is no increase in flux associated with peak 79 and there is a large increase in the dust flux between peaks 72 and 73. While peak eccentricity results in lower average annual solar insolation, the relationship between maxima in dust accumulation and maxima in orbital eccentricity is likely related to seasonality. Peak eccentricity leads to more extreme seasonal contrasts (in conjunction with orbital precession) likely creating more arid conditions in the dust source region on a seasonal basis (Woodard et al., submitted).

In contrast to the bulk sediment MARs which are lowest at times coincident with peak eccentricity, eolian fluxes are lowest during eccentricity lows suggesting an inverse correlation between carbonate (which usually makes up >90% of the sediment in these samples) and windblown dust MARs. In the central equatorial Pacific Ocean over the late Quaternary, the carbonate and eolian MARs vary in concert (i.e., both MARs are increased during glacials, e.g., Marcantonio et al., 2001b; Higgins et al., 2002; Anderson et al., 2006; McGee et al., 2007; Winckler et al., 2008), suggesting different lithological responses to orbital forcing mechanisms in icehouse versus greenhouse worlds. Specifically, although Paleocene eolian fluxes seem to be higher during peak eccentricity, Paleocene carbonate fluxes are higher during eccentricity lows. There are several possible explanations for the orbitally-forced changes in sediment accumulation. Carbonate dissolution likely played a role, and we are currently investigating whether this was due to wholesale changes in the lysocline, or a change in deep-water aging patterns. Changes in non-carbonate accumulation could be due to a dramatically different wind regime during the ice-free early Paleogene. It has long been speculated that an ice-free Antarctic continent would result in a global seasonal change in wind patterns (e.g., Hay et al., 2005) ostensibly creating a large scale monsoon. Seasonal wet/dry changes would become more pronounced during peak eccentricity, e.g., arid regions would be expected to yield more dust during more pronounced dry seasons. Ongoing work at other locations seeks to test this hypothesis.

4. Conclusions

We summarize our conclusions as follows:

1) The empirically determined ($^3He/^4He$) ratio of extraterrestrial dust particles in the late Paleocene is identical to that measured in present-day interplanetary dust particles and is equal to $2.41 \pm 0.23 \times 10^{-4}$.
2) Our best estimate of the flux of extraterrestrial ^3He during the late Paleocene is 5.9×10^{-13} cm^{3}STPcm^{-2}ka^{-1}, identical within error to those fluxes measured in sediments from the north central Pacific and Wedell Sea, and higher than that measured in sediments from the Blake Nose.
3) Bulk sediment MARs (derived using a constant $^3He_{ET}$ flux) respond to climate-forced changes in eolian supply from the continents and preservation of $CaCO_3$. Over this "greenhouse-world" time period, there are 10-fold changes in dust flux and 5-fold variations in carbonate fluxes that are anti-phased, and vary with the short 100-ka eccentricity cycles.

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