LETTERS

A late Miocene dust shower from the break-up of an asteroid in the main belt

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Throughout the history of the Solar System, Earth has been bombarded by interplanetary dust particles (IDPs), which are asteroid and comet fragments of diameter ~1–1,000 μm. The IDP flux is believed to be in quasi-steady state: particles created by episodic main belt collisions or cometary fragmentation replace those removed by comminution, dynamical ejection, and planetary or solar impact. Because IDPs are rich in ^{3}He, seafloor sediment ^{3}He concentrations provide a unique means of probing the major events that have affected the IDP flux and its source bodies over geological timescales[1–4]. Here we report that collisional disruption of the >150-km-diameter asteroid that created the Veritas family 8.3 ± 0.5 Myr ago[5] also produced a transient increase in the flux of interplanetary dust-derived ^{3}He. The increase began at 8.2 ± 0.1 Myr ago, reached a maximum of ~4 times pre-event levels, and dissipated over ~1.5 Myr. The terrestrial IDP accretion rate was overwhelmingly dominated by Veritas family fragments during the late Miocene. No other event of this magnitude over the past ~10^8 yr has been deduced from main belt asteroid orbits. One remarkably similar event is present in the ^{3}He record 35 Myr ago, but its origin by comet shower[1] or asteroid collision[6] remains uncertain.

After release from their comet or asteroid parent bodies, IDPs spiral towards the Sun under the effects of non-gravitational forces including Poynting-Robertson (P-R) and solar wind drags[7]. P-R drag occurs when dust grains revolving around the Sun absorb solar photons and then reradiate the energy in all directions. At the same time, implantation of solar wind ions enriches IDPs in ^{3}He. If these particles avoid intense frictional heating during atmospheric entry, they can reach the Earth's surface with their ^{3}He intact[8]. We have obtained ^{3}He data on sediments spanning the past 70 Myr (refs 1, 9, 10), with new data in the interval 3–38 Myr ago reported here. We analysed two pelagic carbonate cores: ODP Site 757 in the Indian Ocean over this entire interval, and Site 926 in the Atlantic Ocean in the late Miocene.

^{3}He measurements indicate the IDP flux is characterized by a somewhat bumpy continuum punctuated by sharp peaks at 8.2 and 35 Myr ago (Fig. 1). The older of these peaks, in the late Eocene, has been described from a different locality[1]. This peak is well above the average of the past 70 Myr and is coincident with the formation of the two largest terrestrial impact craters of the Cenozoic era: Popagai and Chesapeake Bay. The simultaneous increase in the dust and large body flux, and the match between the duration of the dust spike and that predicted for the ejection timescale of long period comets, were taken as evidence for a comet shower, perhaps produced by a close stellar encounter[1]. However the composition of impact melt at Popagai crater suggests an L-chondrite impactor[6], implying that asteroids rather than comets may produce the spikes in IDP flux. Although several other episodes of elevated flux have been hinted at, none have yet been confirmed. Possible connections between the late Miocene and Eocene events are further discussed in Supplementary Information.

To assess the distribution and temporal evolution of the late Miocene (8.2 Myr ago) peak, we studied the event at higher temporal resolution (Fig. 2) at Site 757 and also at Site 926. A ^{3}He flux peak beginning 8.2 Myr ago and with nearly identical relative magnitude (factor of ~4 above pre-event values) and duration (~1.5 Myr) is apparent at both sites. The only major distinction between the records is that the flux at Site 926 is about three times higher than at Site 757. This probably reflects the effects of sediment focusing, which is known to occur at Site 926 (ref 11). Given the similarity of the ^{3}He peak at these two sites, and the fact that the peak does not correspond to dramatic changes in sediment composition or sedimentation rate (Supplementary Information), it seems unlikely that it is a sedimentation artefact. Furthermore, at both sites the flux peak corresponds to peaks in ^{3}He concentration, ^{3}He/^{4}He ratio and ^{3}He/non-carbonate fraction (Supplementary Fig. S1). These observations indicate an increase in the IDP flux[9]. Thus we conclude that this ^{3}He peak, like that in the late Eocene, is a global signature of an IDP-producing astronomical event.

Although the late Miocene and late Eocene ^{3}He peaks are similar in duration and magnitude (Fig. 1), there is one important difference. Unlike the late Eocene with its two large impact craters that demand an increase in the large body flux coincident with the IDP spike, no late Miocene craters have yet been found. Apparently the late Miocene event was not accompanied by an asteroid or comet shower. This suggests the need for a mechanism capable of increasing the flux of IDPs striking Earth without affecting the flux of larger bodies. A likely candidate is the disruption of the diameter $D > 150$ km asteroid that produced the Veritas family, a cluster of fragments on similar orbits at 3.17 AU. The Veritas event was the largest asteroid disruption in the past 10^8 yr (refs 5, 12); resulting collisions still produce as much as 10% of all Solar System near-ecliptic dust[13–15]. The age of the family, 8.3 ± 0.5 Myr (ref. 5) was determined by tracking the orbits of Veritas family members backwards in time to their formation (for details, see Supplementary Fig. S4), and coincides with the onset of the late Miocene ^{3}He spike.

When the parent body of Veritas disrupted, it ejected almost half of its mass in the form of fragments ranging from micrometre-sized dust grains to multi-kilometre asteroids[5]. These bodies then experienced dynamical evolution according to size. The evolution of small fragments ($D = 1$–1,000 μm) was dominated by planetary perturbations and non-gravitational forces, which caused them to spiral inwards towards the Sun. In contrast, larger fragments ($D > 1,000$ μm) were trapped in the main belt unless they could reach a chaotic resonance capable of placing them onto a planet-crossing orbit. The nearest resonances capable of producing an

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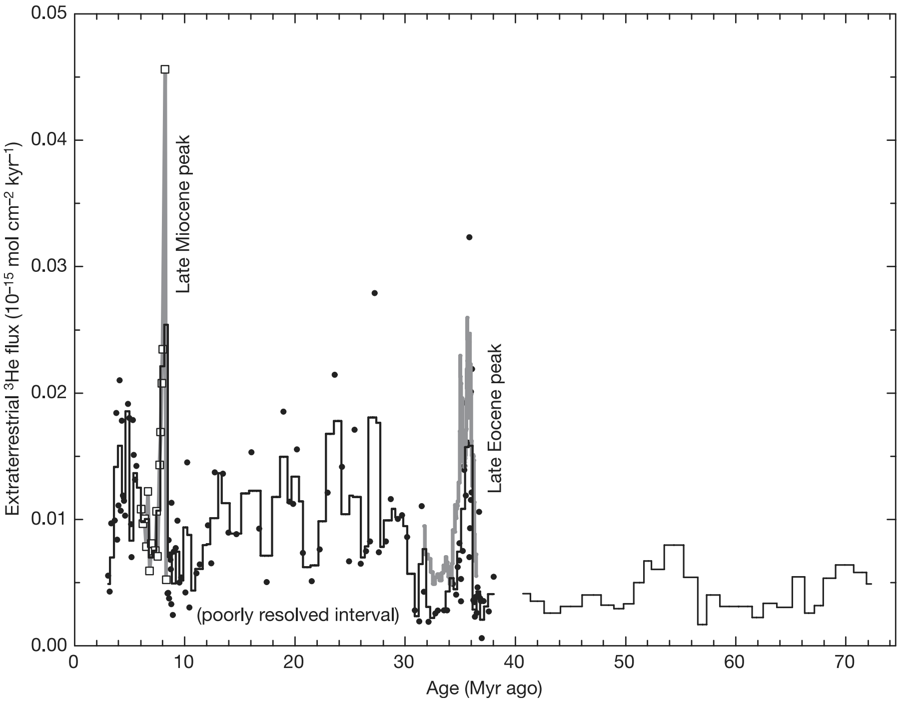

Figure 1 | Two periods of elevated ^{3}He flux, at ~35 Myr ago (late Eocene) and ~8 Myr ago (late Miocene), indicate intervals of enhanced accumulation rate of IDPs. Open and filled symbols are individual new ^{3}He measurements from ODP Site 757 (central Indian Ocean, 17° 01.458′ S, 88° 10.899′ E). Lines are 3-point running means through the data points, taken to minimize the effects of occasional sampling of large individual IDPs[10]. The grey segments of the running mean line indicate the late Miocene event (highlighted by open symbols), and the previously reported late Eocene peak from the Italian Apennines[1]. Cretaceous to mid-Tertiary running mean data are from ref. 10. Details of the new samples, analytical methods, data and age models are provided in Supplementary Information.

asteroid shower are ~0.1 AU from the Veritas family[16] (for example, the 9:4, 11:5 or 2:1 mean motion resonances with Jupiter). This distance would either require huge ejection velocities from Veritas (that are not observed) or extremely long drift times via Yarkovsky thermal forces (which would fail to produce a spike of impactors). (Yarkovsky drift occurs when small asteroids absorb solar photons, heat up and then reradiate the energy away in a non-isotropic manner after a short delay[7].) Moreover, these resonances are very unlikely to produce Earth impactors[17,18]. Thus, the event that formed the Veritas family almost certainly did not produce an asteroid shower on Earth, so the absence of craters of this age is not surprising.

To investigate under what conditions the Veritas collision might produce a dust spike similar to that defined by the ^{3}He record, we developed a statistical Monte Carlo model to track the collisional and dynamical evolution of particles formed by the disruption of Veritas. (Model details can be found in Supplementary Information). The results of our code were calibrated by modelling the evolution of dust in several latitudinal bands observed by the Infrared Astronomical Satellite (IRAS; see ref. 15 for details). To compare our model results with the ^{3}He data, we calculated the flux of $D = 10\,\mu$m particles reaching 1 AU. Particles of about this size can escape intense atmospheric entry heating and He loss, and currently dominate the ^{3}He flux to Earth[8]. Since we do not yet have a model of ^{3}He implantation in IDPs, or one for heating and helium retention during atmospheric entry of IDPs produced during the dust spike, here we simply compare our model 1 AU flux with the shape and duration of the ^{3}He peak.

Small particles from the Veritas family were assumed to reach Earth through P-R and solar wind drags. The production rate of the first-generation particles that were started at 3.17 AU was defined using a 'broken' cumulative power-law size frequency distribution (SFD) with two slopes, index α_1 at smaller sizes and α_2 at larger sizes. The SFD extends from $D = 10\,\mu$m to 1 cm. We assume the SFD decays exponentially with time from collisional evolution and radiation drag forces. This causes the diameter of the knee between α_1 and α_2 to increase with time. The rate of IDP disruptions was defined as a function of diameter D and heliocentric distance R (ref. 19). When a particle disrupts, we replace it with a swarm of fragments that follow a power-law SFD. We assumed that the mass of the largest fragment was half that of the parent particle. The power law index of the fragment size distribution was determined by mass conservation[20]. Thus, in our simulations, we follow several generations of particles produced by a collisional cascade; typical runs track the histories of 10^8–10^9 particles.

We find that $D = 10\,\mu$m IDPs from Veritas reach 1 AU in ~40 kyr, typically shorter than their collisional lifetime (20–200 kyr, depending on model assumptions[19]). This means the ^{3}He signal at Earth would be extremely brief unless these particles are continuously replenished in some fashion. The Veritas break-up, however, produced a SFD of fragments. We note that $D = 1$–5 mm particles have short collisional lifetimes[19] (<100 kyr), such that their fragments not only replenish the $D = 10\,\mu$m population but also create intermediate-size particles that also dynamically evolve and disrupt over time. This means that the ^{3}He signal was produced by fragments from a collisional cascade that was fed new material by disruption events occurring both near the Veritas source region and *en route* to Earth.

The late Miocene event allows us to glean insights into the SFD of particles produced by the break-up and how it changes with time. We found that the initial break-up of the Veritas family probably produced a swarm of IDPs that dominated the main belt population by at least an order of magnitude for ~1 Myr. Our best fit to the shape and the decay time of the ^{3}He peak comes from using $\alpha_1 = -2.5$ and $\alpha_2 = -3.3$ (Fig. 2). We found that α_2 values significantly shallower or steeper than our best fit value produce ^{3}He peaks that are longer or shorter, respectively, than those observed.

Today, collisions in the Veritas family produce one of the prominent dust bands observed by infrared telescopes, and also contribute at least 5×10^6 kg per year to the terrestrial IDP flux[15]. Our modelling suggests that the IDP flux from the Veritas family will continue to decay for several tens of Myr until it reaches a collisional steady state

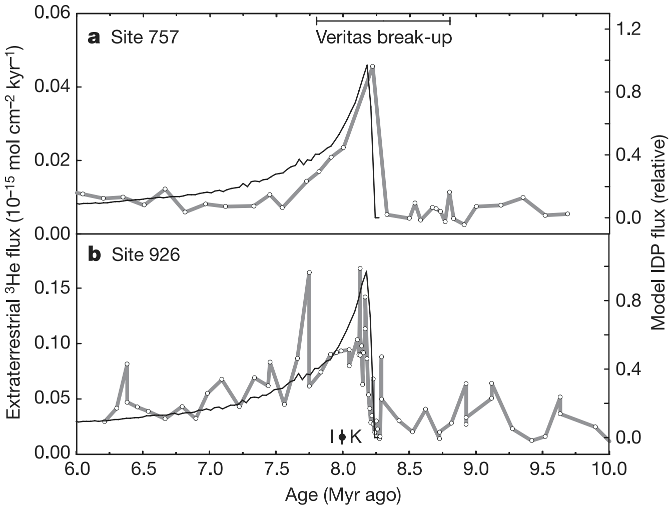

Figure 2 | Concordant ^{3}He data from two widely separated seafloor sites support a global increase in IDP flux at 8.2 Myr ago that can be attributed to the asteroid collision that produced the Veritas family. a, b, The extraterrestrial ^{3}He flux peak (grey line, with small symbols) through the Late Miocene event is similar at Site 757 (**a**) and Site 926 (**b**; western equatorial Atlantic; 3° 43.148′ N, 42° 54.507′ W). The modelled 10-μm IDP flux following the Veritas collision is shown by the black curves. The model dust spike was positioned at 8.25 Myr ago and scaled to align with the ^{3}He peak. The fast rise time and ~1.5 Myr decay time observed in the ^{3}He record at both sites are well matched by the model. The inferred time of Veritas break-up is indicated (see Supplementary Fig. S4 for details). The symbol at ~8 Myr ago indicates transition from illite (I) to kaolinite (K) clays at Site 926, a proxy for climate change.

and takes on the same approximate shape of the overall main belt size distribution for $D < 5$ km bodies[21].

The late Miocene event roughly coincides with cosmic ray exposure ages of 7–8 Myr on many H-chondrite meteorites[22]. The connection between these observations, however, is unclear. As described previously, the nearest powerful resonances are not only ~0.1 AU from Veritas family members, but they are also highly inefficient at producing Earth impactors. Moreover, mineralogical and spectroscopic differences between Veritas family members and the H-chondrites indicate that the latter almost certainly did not originate on the former[23]. We also find it highly unlikely that the projectile that produced the Veritas family was the source of the H-chondrites, partly for the reasons above, but also because the H-chondrites do not show evidence for significant shocks at 7–8 Myr ago[24]. If the two events are indeed linked, we postulate that Veritas family members disrupted a well-positioned fragment from the H-chondrite parent body shortly after the family-forming event took place.

Previous work has suggested a possible link between the IDP accretion rate and Earth's climate[25]. Correlations between extraterrestrial ^{3}He in sediments and global climate in the Quaternary period may support this suggestion[9] but also may be an artefact of climate-induced changes in sedimentation[26]. Modest global cooling and strengthening of the Asian monsoon occurred in the late Miocene[27]. At Site 926 there is a sharp transition from kaolinite-rich to illite-rich sediment[28], occurring within the ^{3}He peak but 200 kyr after its onset (Fig. 2). This transition may document a change from warm humid to cold dry continental weathering. Although the relative timing of these events is suggestive, we caution that a compelling link between the events cannot be established until a plausible mechanism is found by which IDPs can change climate.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions K.A.F. measured ^{3}He in the seafloor sediments. D.N. determined the age of the Veritas family using numerical integration methods. D.V., W.F.B. and D.N. constructed the Monte Carlo dust evolution code and analysed the results.

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Supplementary Material to

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Samples

Carbonate sediments were studied from two deep sea cores. A suite of samples spanning from the middle Eocene to ~3 Ma was obtained from Hole 757B in the central Indian Ocean, 17°01.458'S, 88°10.899'E, on the Ninety East Ridge. This hole was cored on Leg 121 of the Ocean Drilling Program and has been described in detail[1]. Over the studied time interval this site is thought to have subsided from a middle Eocene depth of ~1500 m to its present depth of 1650 m. Sediments from this site are extremely pure carbonate oozes (usually >95% $CaCO_3$) that have accumulated at a fairly slow average rate of 0.35 cm/kyr. The purpose of this suite was to identify any intervals worthy of more detailed study at sites with faster accumulation rates and hence higher temporal resolution. ~140 samples were analyzed at about 1 meter intervals from ~18 to ~ 135 mbsf, except in two areas of interest, in the Late Eocene and the Late Miocene, where sampling density was higher.

Based on elevated extraterrestrial ^3He concentrations in the late Miocene an additional suite of samples was obtained from amongst the best studied cores spanning this interval, from Hole 926B. This hole was drilled on the Ceara Rise, western equatorial Atlantic (3°43.148'N, 42°54.507'W, 3600 m water depth) on Leg 154 of the Ocean Drilling Program[2]. The Late Miocene interval is a clayey carbonate ooze (~65% $CaCO_3$) with a mean accumulation rate of ~1.7 cm/kyr. 73 samples were analyzed in the interval between 159 and 224 mbsf. The spacing of these samples is ~ 1.5 meters away from the ^3He peak to as close as a few cm at the peak.

Methods

Samples were analyzed for helium isotopes following removal of $CaCO_3$ using standard procedures at Caltech[3]. In all cases ^3He and ^4He blank levels were sufficiently low compared to sample signals that blank corrections were not required. Many samples were analyzed in duplicate to detect and eliminate anomalously high ^3He values arising from occasional over-sampling of large IDP grains[4]. When preparing the final ^3He and $^3He/^4He$ data set the following procedure was adopted for incorporating replicated analyses. If the duplicates agreed to within a factor of three, the average was used. If the difference exceeded a factor of three, the higher value was excluded. This led to exclusion of about 6% of the ^3He measurements. For ^4He and non-carbonate fraction data the replicates were simply averaged.

Age Models

Site 757

The age model for site 757 comes primarily from shipboard biostratigraphy. Event locations are from the shipboard report[1] with updated datum ages from Backman and Raffi[5]. To facilitate comparison with previous wok at the Massignano GSSP, biostratigraphic event ages for the Eocene were adopted[6]. Additional ages based on Sr isotope ratios[7] provide greater resolution through the Oligocene portion of the core. There is no magnetostratigraphy available for this core. Ages were assigned to samples by interpolating between tie points in the age model. Linear sedimentation rates (LSRs) were calculated between each tie point (Figure S1). Mass accumulation rates were computed by multiplying linear sedimentation rates interpolated for each depth by the dry bulk density from the Shipboard Report[1] interpolated for that same depth. Martin and Scher[7] have suggested the possibility of a hiatus in the lower Miocene portion of this core. Our observations provide no evidence for the existence of a hiatus, but the interval between about 20 and 15 Ma must be interpreted with caution. This is substantially lower in the core than the Late Miocene ^{3}He peak (Figure S1).

Site 926

At Site 757 the onset of the ^{3}He peak coincides with the first occurrence of the index fossil *D. quinqueramus* (a morphotype of *D. bergrenni*), which has an astronomically calibrated age of 8.2 Myr (ref 5). To test that the ^{3}He peak is global, we used this tie point to select coeval sediments from Site 926, located more than 10,000 km from Site 757. Detailed biostratigraphy[5] and orbitally-tuned cyclostratigraphy based on magnetic susceptibility[8] have been undertaken on the Miocene portion of Site 926 and provide a high resolution age model for this work. While both biostratigraphy and orbital tuning could be used to determine linear sedimentation rates, the orbitally-tuned model yields a seemingly unrealistic amount of high frequency variability in LSR (Figure S1). Instead the lower resolution biostratigraphic model was used to interpolate LSRs for each sample. These values were multiplied by a constant dry bulk density appropriate for this depth interval at Site 926 (1.28 g/cm^3 (ref 2) to obtain mass accumulation rates.

Results.

Measurements from the two sites are tabulated below and plotted against depth in supplementary Figures S2 and S3.

Leg 121
Hole 757B

Sample			MBSF Depth	Age	3He	3He/4He	ET3He flux	Non-Carbonate
Core	Segment	cm	Meters	(Ma)	(fmol/g)	(x10-6)	fmol/cm2/kyr	Fraction
3H	3	130	18.3	3.0571	0.0121	6.8222	0.0055	0.0131
3H	4	81	19.31	3.1971	0.0086	6.7438	0.0043	0.0112
3H	5	31	20.31	3.3357	0.0178	12.1688	0.0097	0.0116
3H	6	11	21.61	3.5158				0.0114
3H	6	111	22.61	3.6544	0.0155	7.9254	0.0099	0.0107
3H	7	61	23.61	3.7821	0.0273	16.6124	0.0184	0.0099
4H	1	95	24.55	3.8794	0.0122	7.1806	0.0084	0.0121
4H	2	45	25.55	3.9829	0.0156	9.1882	0.0111	0.0113
4H	2	144	26.54	4.0854	0.0288	19.6784	0.0210	0.0110

4H	3	94	27.54	4.1889	0.0143	8.3510	0.0107	0.0115
4H	4	44	28.54	4.2924	0.0232	16.1084	0.0178	0.0110
4H	4	144	29.54	4.3959	0.0151	11.6074	0.0119	0.0105
4H	5	94	30.54	4.4994	0.0142	14.8428	0.0115	0.0084
4H	6	44	31.54	4.6030	0.0125	11.5178	0.0103	0.0059
5H	1	88	34.08	4.8659	0.0218	24.7842	0.0191	0.0086
5H	2	38	35.08	4.9694	0.0200	23.6460	0.0180	0.0079
5H	2	138	36.08	5.1261	0.0105	14.4228	0.0096	0.0086
5H	3	87	37.07	5.1754	0.0075	11.7768	0.0070	0.0141
5H	4	37	38.07	5.2789	0.0186	17.2046	0.0179	0.0095
5H	4	138	39.08	5.3850	0.0154	24.3922	0.0151	0.0065
5H	5	88	40.08	5.5002	0.0137	21.8988	0.0131	0.0065
5H	6	38	41.08	5.6154	0.0151	20.8712	0.0142	0.0076
6H	2	20.5	44.505	6.0467	0.0123	17.7996	0.0108	0.0079
6H	2	120.5	45.505	6.2003	0.0112	11.2028	0.0097	0.0121
6H	3	67.5	46.475	6.3493	0.0119	15.9292	0.0101	0.0075
6H	4	20.5	47.505	6.5075	0.0095	12.2696	0.0079	0.0080
6H	4	122.5	48.525	6.6642	0.0152	19.4110	0.0122	0.0077
6H	5	69.5	49.495	6.8132	0.0075	11.4268	0.0059	0.0071
6H	6	20.5	50.505	6.9683	0.0106	12.1016	0.0081	0.0077
6H	6	118.5	51.485	7.1189	0.0100	14.2268	0.0075	0.0065
7H	1	36.5	52.865	7.3309	0.0105	24.2130	0.0075	0.0051
7H	1	140.5	53.905	7.4504	0.0143	21.9856	0.0106	0.0100
7H	2	90.5	54.905	7.5426	0.0089	14.1456	0.0071	0.0060
7H	3	140.5	56.905	7.7271	0.0158	21.6538	0.0143	0.0071
7H	4	90.5	57.905	7.8193	0.0176	24.3012	0.0169	0.0084
7H	5	40.5	58.905	7.9115	0.0204	36.3188	0.0208	0.0057
7H	5	140.5	59.905	8.0038	0.0219	28.8260	0.0235	0.0067
8H	1	5.5	62.255	8.2205	0.0378	54.9003	0.0456	0.0072
8H	1	100.5	63.205	8.3311	0.0043	6.1642	0.0052	0.0086
8H	2	50.5	64.205	8.4985	0.0036	4.4254	0.0042	0.0078
8H	2	75.5	64.455	8.5404	0.0073	14.8820	0.0084	0.0040
8H	2	100.5	64.705	8.5822	0.0033	10.1094	0.0037	0.0030
8H	3	3.5	65.235	8.6710	0.0066	11.5556	0.0072	0.0078
8H	3	20.5	65.405	8.6994	0.0063	6.4988	0.0068	0.0030
8H	3	40.5	65.605	8.7329	0.0056	9.8028	0.0061	0.0047
8H	3	60.5	65.805	8.7664	0.0031	8.1298	0.0033	0.0030
8H	3	80.5	66.005	8.7999	0.0107	22.6618	0.0113	0.0040
8H	3	100.5	66.205	8.4384	0.0040	5.8240	0.0041	0.0066
8H	3	145.5	66.655	8.9087	0.0024	4.6900	0.0024	0.0040
8H	4	50.5	67.205	9.0008	0.0076	13.0088	0.0074	0.0105
8H	5	10.5	68.305	9.1850	0.0085	12.7960	0.0077	0.0083
8H	5	110.5	69.305	9.3525	0.0116	20.6864	0.0099	0.0078
8H	6	60.5	70.305	9.5199	0.0063	11.5710	0.0050	0.0047
8H	7	10.5	71.305	9.6873	0.0075	13.6626	0.0054	0.0077
9H	1	78.5	72.585	10.0637	0.0062	11.9014	0.0042	0.0073
9H	2	38.5	73.685	10.4121	0.0046	9.0454	0.0030	0.0075
9H	2	140.5	74.705	10.2137	0.0229	28.7238	0.0145	0.0094
9H	3	91.5	75.715	11.0550	0.0094	12.0274	0.0057	0.0100
9H	4	38.5	76.685	11.3623	0.0110	17.4202	0.0064	0.0095

9H	5	120.5	79.005	12.0971	0.0182	33.7386	0.0095	0.0086
9H	6	68.5	79.985	12.4075	0.0131	23.4304	0.0065	0.0083
9H	7	20.5	81.005	12.7306	0.0291	50.8984	0.0137	0.0111
10H	2	29.5	83.295	13.4559	0.0332	34.6430	0.0136	0.0121
10H	2	129.5	84.295	13.9781	0.0233	22.6128	0.0090	0.0106
10H	3	82.5	85.325	14.6927	0.0246	21.0350	0.0088	0.0114
10H	4	129.5	87.295	16.0594	0.0492	48.7564	0.0153	0.0100
10H	5	80.5	88.305	16.7602	0.0324	13.5016	0.0093	0.0177
10H	6	28.5	89.285	17.4401	0.0194	11.9644	0.0050	0.0122
11H	1	28.5	91.485	18.9664	0.0906	41.4778	0.0185	0.0221
11H	1	128.5	92.485	19.5190	0.0489	16.2078	0.0114	0.0229
11H	2	80.5	93.505	19.8429	0.0317	16.1056	0.0112	0.0246
11H	3	30.5	94.505	20.1818	0.0398	25.4681	0.0155	0.0209
11H	3	130.5	95.505	20.7375	0.0268	18.7166	0.0073	0.0205
11H	4	82.5	96.525	21.5121	0.0334	17.3628	0.0051	0.0217
11H	5	30.5	97.505	22.2341	0.0414	20.3840	0.0076	0.0221
11H	5	132.5	98.525	22.9562	0.0637	37.1187	0.0121	0.0176
11H	6	82.5	99.525	23.6082	0.1058	33.3998	0.0214	0.0341
11H	7	30.5	100.505	24.2651	0.0684	17.1780	0.0141	0.0293
12H	1	85.5	101.655	24.9123	0.0298	24.8178	0.0067	0.0144
12H	2	34.5	102.645	25.4258	0.0651	40.4124	0.0171	0.0240
12H	2	135.5	103.655	25.9675	0.0244	11.3006	0.0065	0.0161
12H	3	85.5	104.655	26.4453	0.0259	19.2374	0.0075	0.0186
12H	4	15.5	105.455	26.8120	0.0269	20.7186	0.0082	0.0158
12H	4	115.5	106.455	27.2372	0.0849	38.0940	0.0279	0.0195
12H	5	65.5	107.455	27.6256	0.0201	7.1918	0.0074	0.0201
12H	6	45.5	108.755	28.2495	0.0408	16.1042	0.0083	0.0248
12H	6	145.5	109.755	28.6892	0.0364	12.9878	0.0116	0.0260
13H	1	76.5	111.265	29.3307	0.0220	9.1140	0.0100	0.0214
13H	2	25.5	112.255	29.7069	0.0252	10.9914	0.0103	0.0215
13H	2	125.5	113.255	30.1801	0.0260	12.7722	0.0086	0.0208
13H	3	76.5	114.265	30.8788	0.0143	5.3424	0.0028	0.0233
13H	4	25.5	115.255	31.2915	0.0088	3.9984	0.0019	0.0240
13H	4	75.5	115.755	31.5000	0.0478	10.1920	0.0110	0.0246
13H	4	125.5	116.255	31.7085	0.0176	6.1579	0.0043	0.0197
13H	5	75.5	117.255	32.1254	0.0071	2.6502	0.0019	0.0162
13H	6	75.5	118.755	32.7508	0.0084	4.6158	0.0026	0.0146
13H	6	125.5	119.255	32.9592	0.0088	4.8195	0.0028	0.0130
14H	1	50.5	120.605	33.5214	0.0080	2.6600	0.0028	0.0167
14H	2	1.5	121.615	33.7948	0.0069	2.1868	0.0028	0.0172
14H	2	100.5	122.605	34.0629	0.0124	2.6222	0.0058	0.0228
14H	3	50.5	123.605	34.3337	0.0093	1.6954	0.0049	0.0250
14H	4	0.5	124.605	34.6252	0.0075	2.7160	0.0040	0.0175
14H	4	51.5	125.115	34.7772	0.0116	4.2672	0.0062	0.0200
14H	4	100.5	125.605	34.9234	0.0127	3.5966	0.0068	0.0196
14H	4	101.5	125.615	34.9263	0.0153	3.7674	0.0081	0.0195
14H	5	0.5	126.105	35.0725	0.0067	1.7976	0.0035	0.0203
14H	5	1.5	126.115	35.0755	0.0101	1.6590	0.0053	0.0264
14H	5	50.5	126.605	35.2216	0.0143	2.2372	0.0075	0.0264
14H	5	100.5	127.105	35.3707	0.0272	7.3052	0.0142	0.0230

14H	5	102.5	127.125	35.3767	0.0267	4.8356	0.0139	0.0261
14H	6	0.5	127.605	35.5198	0.0229	6.7018	0.0119	0.0231
14H	6	0.5	127.605	35.5198	0.0371	4.6158	0.0192	0.0354
14H	6	51.5	128.115	35.6719	0.0312	6.2874	0.0161	0.0309
14H	6	75.5	128.355	35.7435	0.0439	8.6520	0.0225	0.0197
14H	6	100.5	128.605	35.8180	0.0631	8.2376	0.0323	0.0250
14H	6	101.5	128.615	35.8210	0.0138	2.5676	0.0070	0.0276
14H	6	125.5	128.855	35.8926	0.0183	2.3114	0.0093	0.0212
14H	7	0.5	129.105	35.9671	0.0395	6.1110	0.0201	0.0300
14H	7	0.5	129.105	35.9671	0.0228	3.3236	0.0115	0.0243
14H	7	19.5	129.295	36.0238	0.0240	2.4892	0.0121	0.0260
14H	7	37.5	129.475	36.0778	0.0433	6.9090	0.0219	0.0146
15H	1	2.5	129.825	36.1869	0.0073	1.0584	0.0036	0.0236
15H	1	25.5	130.055	36.2586	0.0070	0.8946	0.0034	0.0250
15H	1	50.5	130.305	36.3365	0.0046	1.0178	0.0023	0.0168
15H	1	75.5	130.555	36.4144	0.0078	1.3874	0.0039	0.0210
15H	1	100.5	130.805	36.4924	0.0052	1.2110	0.0026	0.0132
15H	1	125.5	131.055	36.5703	0.0093	1.9026	0.0046	0.0210
15H	2	2.5	131.325	36.6545	0.0081	1.1900	0.0040	0.0228
15H	2	25.5	131.555	36.7262	0.0212	3.8794	0.0106	0.0220
15H	2	50.5	131.805	36.8041	0.0076	1.1886	0.0037	0.0172
15H	2	75.5	132.055	36.8820	0.0071	1.5162	0.0035	0.0160
15H	2	100.5	132.305	36.9599	0.0012	0.7070	0.0006	0.0164
15H	3	2.5	132.825	37.1220	0.0072	1.2250	0.0035	0.0210
15H	4	2.5	134.325	37.5896	0.0056	1.2530	0.0027	0.0208
15H	5	2.5	135.825	38.0475	0.0110	1.6030	0.0055	0.0240

Leg 154
Hole 926 B

Sample Core	Segment	cm	Composite Depth Meters	Model Age (Ma)	3He (fmol/g)	3He/4He (x10-6)	ET3He flux fmol/cm2/kyr	Non-Carbonate Fraction
18H	1	77	179.69	6.21	0.0119	0.297	0.0298	0.27
18H	2	80	181.34	6.30	0.0171	0.291	0.0418	0.37
18H	3	78	182.82	6.38	0.0328	0.573	0.0815	0.36
18H	3	78	182.82	6.38	0.0194	0.363	0.0471	0.37
18H	4	81	184.35	6.46	0.0181	0.326	0.0427	0.35
18H	5	78	185.82	6.54	0.0167	0.381	0.0389	0.27
18H	6	80	187.34	6.67	0.0141	0.386	0.0321	0.23
19H	1	78	190.62	6.79	0.0196	0.533	0.0432	0.27
19H	2	78	192.12	6.90	0.0154	0.433	0.0325	0.33
19H	3	78	193.62	6.99	0.0267	0.543	0.0551	0.41
19H	4	81	195.15	7.09	0.0344	0.454	0.0677	0.51
19H	5	78	196.62	7.22	0.0217	0.617	0.0431	0.36
19H	6	78	198.12	7.34	0.0348	0.805	0.0693	0.35
20H	1	27	200.01	7.44	0.0315	0.570	0.0621	0.45
20H	1	48	200.29	7.45	0.0414	0.909	0.0831	0.37
20H	2	48	202.27	7.56	0.0220	0.683	0.0450	0.28
20H	3	48	204.17	7.66	0.0407	1.091	0.0867	0.38
20H	4	48	205.67	7.75	0.0752	1.537	0.1642	0.41
20H	4	48	205.67	7.75	0.0288	0.634	0.0616	0.41
20H	5	48	207.17	7.84	0.0337	0.867	0.0743	0.34
20H	6	48	208.67	7.91	0.0401	0.871	0.0902	0.26
20H	7	5	209.72	7.95	0.0405	0.745	0.0919	0.23
21H	1	48	210.57	7.99	0.0405	0.869	0.0933	0.36
21H	2	48	211.94	8.05	0.0408	0.591	0.0945	0.31
21H	2	48	211.94	8.05	0.0346	0.515	0.0798	0.31
21H	3	48	213.30	8.11	0.0433	1.007	0.1035	0.17
21H	3	82	213.61	8.12	0.0376	0.809	0.0899	0.21
21H	3	107	213.84	8.13	0.0692	1.533	0.1678	0.19
21H	3	107	213.84	8.13	0.0373	0.841	0.0895	0.28
21H	3	132	214.07	8.14	0.0407	0.861	0.0979	0.19
21H	3	147	214.20	8.15	0.0263	0.724	0.0630	0.15
21H	3	147	214.20	8.15	0.0381	1.026	0.0922	0.15
21H	4	14	214.36	8.15	0.0379	0.897	0.0917	0.17
21H	4	48	214.67	8.17	0.0464	1.259	0.1133	0.15
21H	4	48	214.67	8.17	0.0580	1.485	0.1420	0.16
21H	4	82	215.01	8.18	0.0356	0.736	0.0863	0.21
21H	4	108	215.27	8.19	0.0226	0.420	0.0538	0.23
21H	4	130	215.49	8.20	0.0178	0.279	0.0414	0.34
21H	4	145	215.64	8.21	0.0124	0.259	0.0287	0.21
21H	5	25	215.94	8.22	0.0149	0.316	0.0351	0.20
21H	5	48	216.17	8.23	0.0277	0.706	0.0680	0.37
21H	5	48	216.17	8.23	0.0117	0.287	0.0273	0.18
21H	5	82	216.51	8.24	0.0090	0.154	0.0198	0.25

21H	5	108	216.77	8.25	0.0128	0.269	0.0302	0.21
21H	5	132	217.01	8.26	0.0097	0.263	0.0228	0.16
21H	5	142	217.11	8.26	0.0076	0.140	0.0166	0.21
21H	6	21	217.40	8.28	0.0072	0.140	0.0157	0.21
21H	6	21	217.40	8.28	0.0064	0.144	0.0141	0.20
21H	6	25	217.44	8.28	0.0073	0.143	0.0160	0.20
21H	6	48	217.67	8.29	0.0355	0.591	0.0880	0.27
21H	6	48	217.67	8.29	0.0208	0.332	0.0499	0.27
22H	1	48	219.72	8.42	0.0138	0.263	0.0307	0.24
22H	2	48	221.27	8.52	0.0099	0.204	0.0204	0.19
22H	3	48	222.81	8.62	0.0196	0.402	0.0408	0.19
22H	4	48	224.34	8.73	0.0075	0.249	0.0142	0.22
22H	4	48	224.34	8.73	0.0108	0.192	0.0201	0.22
22H	5	48	225.84	8.82	0.0153	0.276	0.0282	0.22
22H	6	48	227.34	8.93	0.0333	0.777	0.0640	0.20
22H	6	48	227.34	8.93	0.0147	0.312	0.0270	0.19
22H	6	48	227.34	8.93	0.0178	0.385	0.0332	0.19
23H	1	48	230.11	9.12	0.0275	0.452	0.0508	0.23
23H	1	48	230.11	9.12	0.0344	0.598	0.0643	0.23
23H	2	48	232.42	9.27	0.0132	0.253	0.0231	0.23
23H	3	48	234.55	9.42	0.0072	0.242	0.0124	0.14
23H	4	48	236.05	9.52	0.0099	0.174	0.0162	0.23
23H	5	48	237.55	9.63	0.0295	0.475	0.0521	0.27
23H	5	48	237.55	9.63	0.0212	0.333	0.0366	0.25
24H	1	75	241.85	9.90	0.0129	0.220	0.0249	0.22
24H	2	74	243.76	10.02	0.0066	0.081	0.0098	0.29
24H	3	74	245.26	10.13	0.0156	0.267	0.0269	0.26
24H	4	74	246.76	10.26	0.0088	0.171	0.0136	0.23
24H	5	74	248.26	10.40	0.0089	0.155	0.0136	0.24
24H	6	74	249.76	10.50	0.0188	0.438	0.0333	0.22

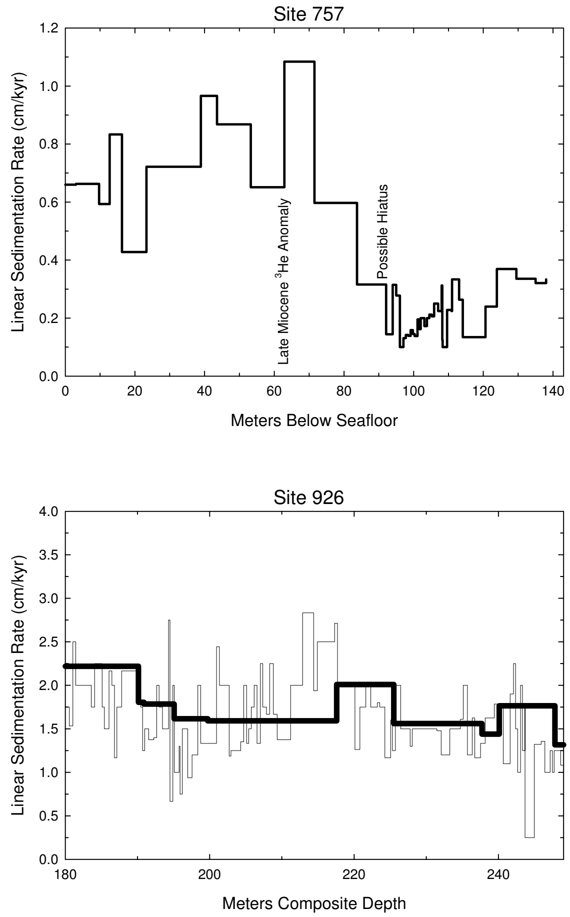

Figure S1. *Linear sedimentation rate models for the two studied ODP holes. In the upper panel (Site 757) the depths of the Late Miocene ^{3}He anomaly and a possible hiatus[7] are indicated. In the lower panel (Site 926) both the orbital-tuning derived sedimentation model (fine line) and the biostratigraphic model (bold line) are shown.*

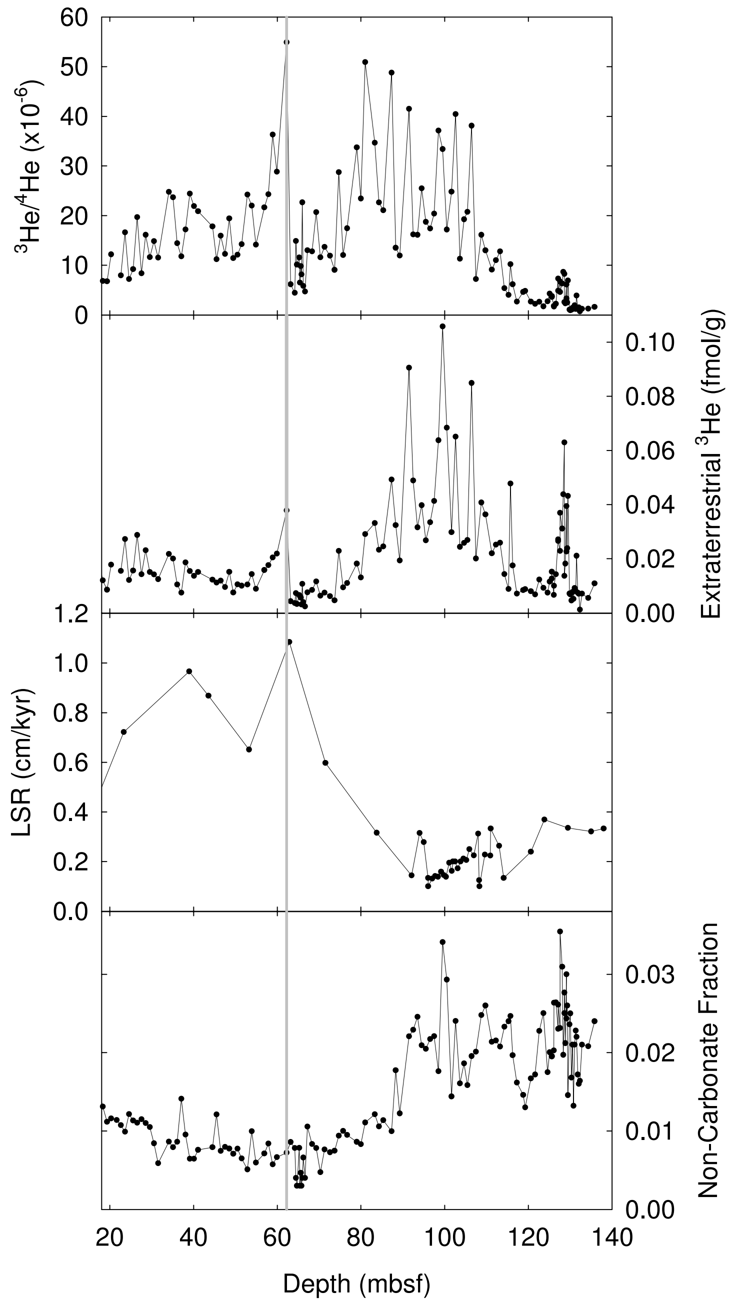

Figure S2. *Detailed comparison of $^3He/^4He$ ratio, extraterrestrial ^3He concentration, linear sedimentation rate (LSR) and non-carbonate fraction (residue after carbonate dissolution with 10% acetic acid) at Site 757. Vertical gray line indicates the onset of the late Miocene ^3He anomaly.*

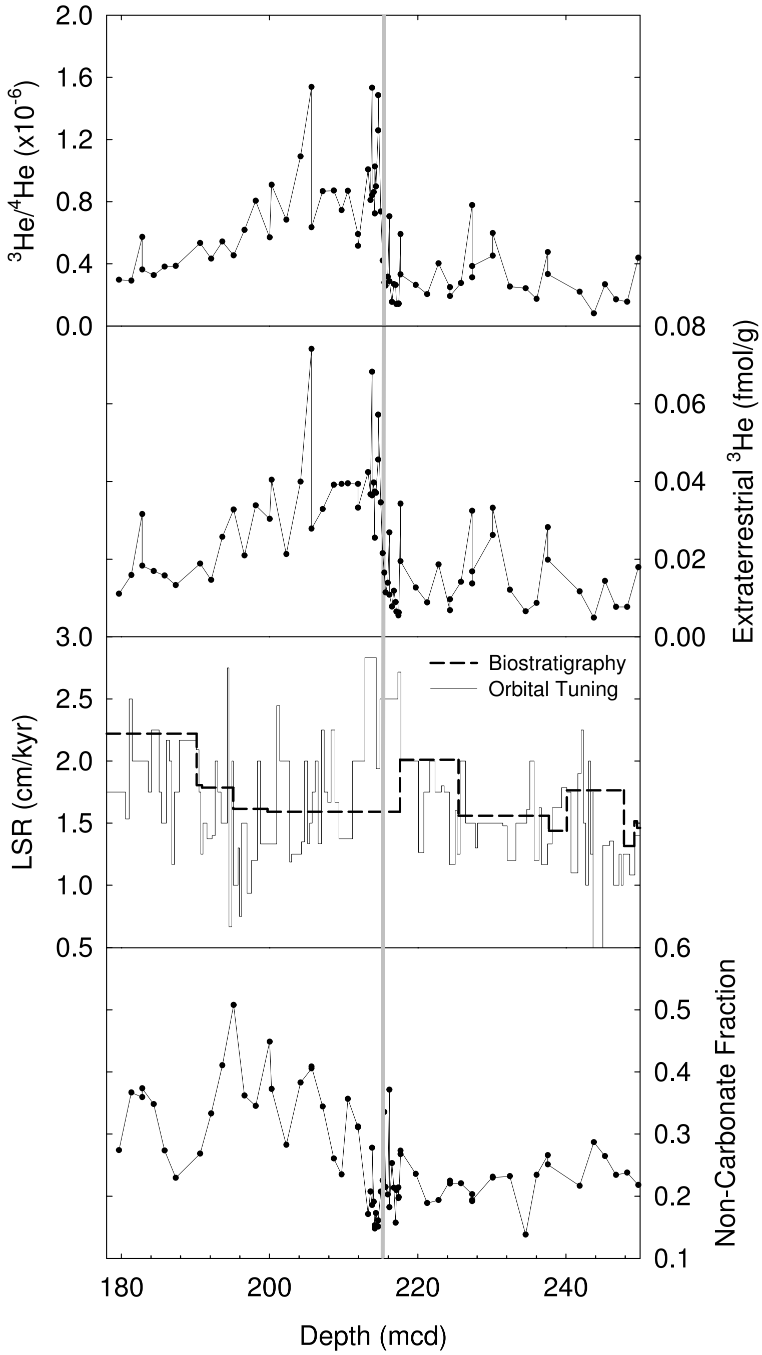

Figure S3. *Detailed comparison of $^3He/^4He$ ratio, extraterrestrial ^3He concentration, linear sedimentation rate (LSR) and non-carbonate fraction at Site 926. The similarity in ^3He and $^3He/^4He$ ratio and the lack of significant changes in sedimentation rate and non-carbonate fraction well-correlated with ^3He indicate a change in extraterrestrial ^3He flux, as discussed previously[3]. Vertical gray line indicates the onset of the late Miocene ^3He anomaly.*

Monte Carlo Dust Evolution Model

Small particles from the Veritas family were assumed to reach Earth through P-R and solar wind drags. We defined the production rate of first-generation Veritas particles as $P(D,t)$, where D is diameter and t is the elapsed time since the family formed. Motivated by results from main belt collisional evolution models[9], we assumed $P(D,t)$ has a segmented cumulative power-law size frequency distribution with index α_1 in the interval (D_{min}, D_{break}) and α_2 in the interval (D_{break}, D_{max}). We assumed that collisional and dynamical evolution causes $P(D,t)$ to vary such that D_{break}, the diameter at which the power-law slope changes, increases with time according to:

$$\log_{10}\left(\frac{D_{break}}{D_{\min}}\right) = \log_{10}\left(\frac{D_{\max}}{D_{\min}}\right)\left[1 - \exp(-t/\tau_{decay})\right]$$

with $D_{min} = 10$ µm, D_{max}=1 cm, and τ_{decay} a characteristic decay constant that is described below. The rate of IDP disruptions is defined by the collisional lifetime, $\tau_{col}(D,R)$ that was set to be a function of diameter D and heliocentric distance R (ref 10).

The particles were started at heliocentric distance 3.17 AU. Their orbital evolution were then tracked using P-R and solar drag equations[11] over time t with a timestep Δt = 1000 years. Each surviving particle was followed from heliocentric distance R_t to $R_{t+\Delta t}$ (both in AU) using:

$$R_{t+\Delta t}^2 - R_t^2 = 2.5 \times 10^{-3}\,\beta\,\Delta t$$

$$\beta = 1.15 / (\rho\, D)$$

where the density of the particle is $\rho = 1.5$ g cm^{-3} and D in microns. Each particle was followed until it disrupted (see below) or reached 1 AU.

At each timestep, we checked to see if the particle was disrupted. The probability of this event was $\Delta t / \tau_{col}(D,R)$. When a particle was found to disrupt, we replaced it with a swarm of fragments that follow a power-law size distribution. We assumed that for each breakup event, the mass of the largest fragment was half that of the parent particle. The power law index of the fragment size distribution is then set by mass conservation[12]. Thus, in our simulations, we follow several generations of particles produced by a collisional cascade; typical runs track the histories of 10^8-10^9 particles.

Using our model, we ran a number of trial cases to determine a reasonable range of input parameters. Our full production runs then used α_1=-2, -2.25, -2.5 and α_2 values between -3 and -4. The former values are shallower than the canonical value of -2.5 (ref 13) because P-R drag quickly removes small particles from the main belt, while the latter values are steeper because we need to link our size distribution to the observed members of the Veritas family while also conserving mass. We also tested values of τ_{decay} = 0.5, 0.75, and 1 Myr, where the timescales were drawn from collision code experiments[9].

We found that the initial breakup of the Veritas family likely produced an IDP population that dominated the main belt population by at least an order of magnitude for ~1 Myr. This would explain both the shape and the decay time of the ^{3}He peak. Our best fit comes from α_1 = -2.5, α_2 =-3.3 and τ_{decay} = 1 Myr (Figure 2 in main text). It is important to note, however, that the parameters α_2 and τ_{decay} are correlated, with a longer τ_{decay} timescale producing the same solution as a steeper α_2. Our results allow us to rule out (i) steep α_2 values and τ_{decay} < 0.5 Myr values that produce shorter ^{3}He peaks than those observed and (ii) shallow α_2 and τ_{decay} > 1.5 Myr values that create longer ^{3}He peaks than those observed.

Late Miocene vs. Late Eocene Event

Given the success of our model in matching the Veritas breakup to the Late Miocene ^{3}He event and the similarity in the ^{3}He patterns at ~35 and ~8.2 Myr ago, it is possible that an asteroid collision also produced the Late Eocene peak (Figure 1 in main text). However, we find no evidence for the disruption of an asteroid larger than ~100 km diameter in the main belt other than Veritas over the last ~100 Myr (ref 14). Moreover, because the Late Eocene event must also produce a short-lived but prominent asteroid shower to account for the two large craters, candidate families must inject numerous bodies into a resonant "escape hatch" that can quickly and with high efficiency move this material onto Earth-crossing orbits. It is unclear whether any recently-formed families are consistent with this criterion. For this reason, the Late Eocene event remains a mystery.

Other Putative Features in the ^{3}He Sediment Record

At least one other recent asteroid breakup event has a known age over the sampled interval shown in Figure 1 (main text), namely that of the Karin cluster. The Karin cluster was produced 5.75 ± 0.05 Myr ago from the disruption of a D = 33 km asteroid in the Koronis family[15,16]. This event, while far smaller than the Veritas breakup, has produced a dust band observed by infrared telescopes. In Figure 1 (main text), we find a moderate increase in the ^{3}He flux near that time, but no pronounced spike like that of the Late Miocene or Eocene events. We cannot yet say whether this increase is associated with the Karin breakup or is merely representative of the background flux from that epoch. A comprehensive study of this issue is left for future work.

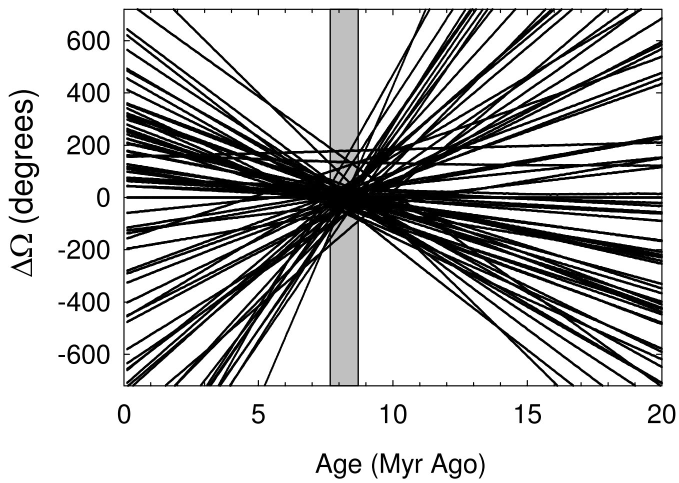

Figure S4. *Convergence of nodal longitudes suggests that the Veritas family formed by a catastrophic collision at 8.3 ± 0.5 Myr ago (see also ref 14 for an alternative way to plot the same data), gray band. Immediately after the disruption, the fragments all circled the Sun, as a group, in nearly identical orbits. Over time planetary perturbations forced their orbital orientations (specified by the longitude of the ascending node and argument of perihelion) to drift away from each other, eventually spreading out uniformly. By numerically integrating the present orbits of large asteroid members of the Veritas family back in time, we discovered a clustering of nodal longitudes. The figure shows orbital histories of nodal longitudes relative to that of large member asteroid (1086) Nata (ΔΩ). The mean ΔΩ is ~40^o at t ~ 8.3 Myr, much smaller than at other times, suggesting a strong statistical significance of the nodal alignment.*

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