Miocene to recent eolian dust record from the Southwest Pacific Ocean at 40° S latitude

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Abstract

A 14-meter long pelagic clay core recovered at Marlin Rise (40°00.531′S, 154°2.601′W; 4775 m water depth) in the Southwest Pacific Basin contains a record of eolian dust deposited since the early Miocene. Downcore analysis of detrital minerals reveals a dominantly eolian signature with relatively constant proportions of quartz, feldspar and illite and trace amounts of chlorite, kaolinite and smectite, consistent with a continental (loess-like) source region. Fish tooth Sr isotope stratigraphy reveals the base of the core to be 17.5 Ma, with low sedimentation rates (<0.5 mm/kyr LSR) indicated for the interval 17.5 to 10 Ma; several hiatuses in deposition appear to be present upcore, but are beyond the age resolution of the fish teeth stratigraphy. These intervals are revealed as apparent discontinuities in the Sr isotope record, accompanied by pulses of anomalously rapid sedimentation at ~10 Ma, 6.7 Ma and 4.1 Ma. Bulk mass accumulation rates (MAR) are calculated at ~10 mg/cm²/kyr over the last 4 Myr, consistent with previously estimated Quaternary eolian flux rates to this part of the Pacific. Nd, Pb and Sr radiogenic isotopic compositions of the detrital mineral extract (<38 µm) show no trends with age, while ⁴⁰Ar/³⁹Ar ages show an upcore younging trend (~180 Ma to ~150 Ma), in concert with a slight coarsening of eolian grain-size distributions. These ages likely reflect mixing of Mesozoic illite-dominated clay from at least two continental source areas: southeastern Australia (Murray–Darling Basin/Lake Eyre Basin) and New Zealand (South Island). The data indicate remarkable constancy of continental eolian sources exposed to weathering and dispersal at this latitude during the Neogene.

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1. Introduction

Long-term records of Cenozoic eolian dust accumulation for the remote South Pacific Ocean are essentially lacking (Rea, 1994). At present, most of the South Pacific is thought to be characterized by minimal dust input (<10 mg/cm²/kyr; Rea, 1994), except for areas directly downwind of eastern Australia and New Zealand. Quaternary ice-core dust records from Antarctica have more recently been used to suggest wider dispersal and circulation of dust from these sources to remote parts of the Southern Hemisphere (Delmonte et al., 2004; Grouset and Biscaye, 2005; Revel-Rolland et al., 2006). Radiogenic isotope data have fingerprinted Patagonia as an important source of dust in Antarctic ice cores delivered during South American glacial episodes (Grouset et al., 1992; Basile et al., 1997), while recent work by Revel-Rolland et al. (2006) has identified Australia as a primary dust source during interglacial times. While very little dust from South America travels west with the tradewinds into the South Pacific, Rea (1994) noted that southeastern Australia contributes a moderate amount of dust to the western South Pacific in quantities of up to 200 mg/cm²/kyr. The extent of the Australian influence has not been tracked beyond this region in detail (Leinen et al., 1986). Hesse (1994) suggested a 2 to 9-fold increase in dust flux to the Tasman Sea from southeastern Australian sources during glacial maximum events, increasing near 40°S latitude. Kohfeld and Harrison (2001) also modeled large increases in
South Pacific dust accumulation rates during glacial intervals within the 35°–40°S latitude band. Tanaka and Chiba (2006) concluded that Australia currently dominates Southern Hemisphere dust production, although Mahowald et al. (1999) have cautioned that modern dust production rates are commonly overestimated. Few data currently exist for estimating contributions of the New Zealand (South Island) loess fields to the eolian flux in the South Pacific region (Rea, 1994).

A detailed study of Cenozoic dust deposition was carried out at DSDP Site 596 (24°S, 170°W; Fig. 1) in the northern South Pacific, where Zhou and Kyte (1992) identified a rapid increase in the eolian flux starting at ~3 Ma, concurrent with the late Pliocene increases in eolian flux observed for many North Pacific cores (Janecek and Rea, 1983; Rea, 1994). Stein and Robert (1985) examined sediment cores on the Lord Howe Rise (Tasman Sea) along a transect between 26°–36°S, 160°E, finding some evidence for increasing dust flux over the last 4 Myr. They also observed an upcore change in clay mineralogy during the Miocene, from illite–smectite dominated clays to kaolinite–illite dominated clays, a transition linked to aridification of Australia beginning ~15 Myr ago (Stein and Robert, 1985). Rea and Bloomstine (1986) and Bloomstein and Rea (1986) examined the pelagic clay record from ODP Leg 92 in the South Pacific along the west flank of the East Pacific Rise (19°S, 135°W–125°W), finding variation in eolian grain size that suggested a more energetic atmospheric circulation starting at ~10 Ma; however, they identified no significant change in late Cenozoic eolian flux rates. Others have concluded that there was an increase in late Cenozoic dust flux rates in the South Pacific, though not of the same magnitude as that observed by Zhou and Kyte (1992) for the northern South Pacific, or for the North Pacific (e.g., Kyte et al., 1993). In general, an increase in Southern Hemisphere dust production starting in the Miocene has been thought to be consistent with aridification of Australia as this landmass moved northward into the desert latitudes and the climate cooled (concurrent with the buildup of Antarctic ice sheets); increased grain size is also consistent with stronger winds associated with southern hemisphere cooling (Rea, 1994).

The core reported on here is from a remote region of the South Pacific that promises to help fill some key gaps in our understanding of late Cenozoic eolian flux and Southern Hemisphere dust production. In February 2005, the R/V Melville (drill site survey cruise TUIM-03) recovered a large-diameter jumbo piston core (MV0502-01JC) containing 14 m of pelagic red clay from Marlin Rise in the South Central Pacific, 2400 km east of New Zealand (Site SP-15; Rea et al., 2006). Core MV0502-01JC was recovered at 40°00.531′S, 154°2.601′W in 4775 m water depth (Fig. 1). This site is situated near the southwestern edge of the South Pacific bare zone, an area of the SW Pacific Basin that records little or no Cenozoic sediment accumulation (Rea et al., 2006; Stancin et al., in press). Site SP-15 exhibits a classic pelagic sediment drape atop 79 Ma basement (Fig. 2), with sediment thicknesses estimated at ~90 m (SPLAT site survey report, unpublished; M. Lyle, personal communication). A prominent acoustic reflector at ~20 mbsf (meters below sea floor — Fig. 2) was not penetrated by the 14 m piston core. This paper reports on the age, provenance and likely origin of the eolian component in the pelagic clay from this site, which was studied using chemical extraction procedures documented by Rea and Janecek (1981), Hovan (1995) and Stancin et al. (2006). The core material (light brown to dark brown zeolitic clay plus red-brown semi-opaque oxides) is barren of microfossils, except for ubiquitous fish teeth. It was therefore necessary to employ the technique of strontium isotope fish teeth dating in order to construct an accurate stratigraphic record (Gleason et al., 2002, 2004a,b). Mineralogic and radiogenic isotopic analysis was performed on the extracted terrigenous component of the core to help constrain its provenance, resulting in a long-term eolian source record spanning early Miocene to recent time. This record is apparently unique thus far for the Southwestern Pacific Basin, and its implications are discussed below.

Fig. 1. Location of Marlin Rise, Site SP-15 and piston core MV0502-01JC (40°00.531′S, 154°2.601′W; 4775 m water depth) in the SW Pacific Basin. DSDP Sites 596 (Zhou and Kyte, 1992) and 598 are discussed in the text, along with potential dust sources in SE Australia and New Zealand. The 17.5 Ma backtrack paleoposition for site SP-15 was calculated using a spreadsheet of pole rotations from Gripp and Gordon (1990). Bathymetric base map modified from Rea et al. (2006).
2. Methods

Fish teeth from twenty-one intervals of MV0502-01JC were picked, cleaned and dated at Michigan by Sr isotope stratigraphy using the methods of Gleason et al. (2002). Strontium isotope ratios were analyzed on a Finnigan MAT 262 TIMS at the University of Michigan (Gleason et al., 2002, 2004a,b), and ages were assigned to each interval by comparing the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the fish teeth with the seawater Sr isotope curve (LOWESS) of McArthur et al. (2001). The $^{87}\text{Sr}/^{86}\text{Sr}$ value of the NBS 987 Sr isotopic standard measured at Michigan was $0.710246\pm0.000012 (n=29)$ over the course of this study, requiring no adjustment to data. From this information, an age model, sedimentation rates and eolian flux rate estimates for the core were derived.

The red clay mineral extract for seventeen intervals was isolated at the Indiana University of Pennsylvania following the procedures of Rea and Janecek (1981), Hovan (1995) and Stancin et al. (2006). The sediment was first sieved at 63 µm to remove any microfossils or coarse ash. The sub-63 µm sediment was then subjected to acetic acid treatment to remove any carbonate. Hydrogenous Fe–Mn oxides were then removed with sodium citrate and sodium dithionate. Opal and organics were removed with a hot sodium hydroxide solution. The remaining material was then rinsed and freeze dried. At the University of Michigan, the samples were further cleaned in ammonium acetate, sieved at 38 µm, and freeze dried.

Mineral grain-size distribution on the <38 µm extracted fraction was determined at the University of Michigan on a Beckman Coulter Multisizer 3 with a 50 µm aperture diameter using the procedure of Hovan (1995). The samples were taken after extraction and suspended in a 5 g/l calgon/distilled water solution to prevent flocculation. Each sample was sonicated, agitated and diluted to a 5–7% concentration before beginning the measurements. Samples from each interval were analyzed three times and the results averaged, with standard deviations of 0.03–0.05 phi (<0.2 µm).

Mineral composition was determined at the Indiana University of Pennsylvania and University of Michigan using conventional X-ray diffraction techniques. Bulk (<38 µm) extracted sediments were lightly ground in acetone using an agate mortar and pestle, packed in shallow, non-diffraacting trays, and analyzed using a Bruker D8 ADVANCE powder diffraction system. Peak areas were measured using MacDiff 4.2.5 (Petschick, 2001) relative to background counts. Peak area data were obtained on the following mineral peaks: quartz (3.34 Å), feldspar-001 (3.18 Å), illite-001 (10 Å), kaolinite (3.58 Å), chlorite (3.54 Å), and smectite group after expansion with ethylene glycol (17 Å). The overlapping peak areas for kaolinite and chlorite were resolved using curve-fitting software routines provided by MacDiff (Petschick et al., 1996; Petschick, 2001).

Nd–Sr–Pb isotopic analysis of the <38 µm detrital extract followed the procedures of Stancin et al. (2006). Approximately 50 mg of sample was weighed out for acid digestion followed by conventional chemical separation procedures (Stancin et al., 2006). Strontium and neodymium isotopic ratios were determined on a Finnigan MAT 262 TIMS at the University of Michigan, and the isotopic composition of lead was measured.
on a Nu Plasma multi-collector ICP-MS at the University of Michigan following the procedures of Stancin et al. (2006).

The $^{40}\text{Ar}/^{39}\text{Ar}$ ages were determined in duplicate on the same <38 µm detrital extracts at the University of Michigan using standard $^{40}\text{Ar}/^{39}\text{Ar}$ irradiation techniques. The vacuum encapsulation method described by Dong et al. (1995), Hall et al. (1997) and Pettke et al. (2000) for this lab was not employed, and thus the total gas ages reported here are equivalent to the argon retention ages in the above studies. The samples were irradiated at McMaster University Nuclear Reactor in pure Al foil packets along with packets of the laboratory standard MMHb-1 (520.4 Ma) (Samson and Alexander, 1987). Following irradiation, samples were incrementally heated and degassed with a defocused beam of visible light from a Coherent Innova® model 70 Ar ion laser. Argon isotopic composition was measured with a VG 1200S mass spectrometer at the University of Michigan (Hall et al., 1997). Step analyses were analyzed with a Daly detector in analog mode. Mass discrimination was monitored daily by measuring the $^{40}\text{Ar}/^{36}\text{Ar}$ of air. System blanks were subtracted from the samples, and blanks were constantly monitored, typically every five fractions.

3. Results

3.1. Age model and sedimentation rates

Results of the fish teeth $^{87}\text{Sr}/^{86}\text{Sr}$ dating of piston core MV0502-01JC are reported in Table 1. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of fish teeth extracted from twenty-one intervals of the core are plotted vs. sediment depth below sea floor (cmbsf) in Fig. 3a. For each interval, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (Table 1) was compared to the global Sr isotope seawater curve (LOWESS) of McArthur et al. (2001), from which ages (and uncertainties) were derived (Fig. 3b). From this analysis, the base of the core was determined to have an age of 17.5 Ma. Mass Accumulation Rates (MAR) were calculated from an age model that incorporates a non-linear (exponential) fit from 10–17.5 Ma (1383 cm to 1141 cm), and near-linear interpolation between (and within) several younger intervals that are separated by apparent discontinuities, or hiatuses (Fig. 3b). These apparent discontinuities in the age model do not correspond to any obvious lithologic changes in the core itself (SPLAT site survey report, unpublished).

The Mass Accumulation Rate (MAR) was estimated from wet bulk density as measured on board the R/V Melville, assuming a grain density of 2.6 g/cm$^3$, and a seawater density of 1.026 g/cm$^3$:

$$\text{Porosity} = \frac{\text{GrainDensity}}{\text{WetBulkDensity}} - \frac{\text{GrainDensity}}{\text{SeaWaterDensity}};$$

$$\text{Dry Bulk Density} = \frac{1}{\text{Porosity}} - \frac{\text{GrainDensity}}{\text{C2}}.$$

Our preferred age model (Fig. 3b; Appendix A) shows decreasing sedimentation rates between 17.5 Ma and 10.5 Ma, and uniformly low sedimentation rates ($<0.5$ mm/kyr LSR; 12 mg/cm$^2$/kyr bulk MAR) over the last 4 Myr (120 cm to core top). When adjusted for the % eolian component recovered by the chemical extraction process (Appendix A), a late Cenozoic eolian MAR of ~7 mg/cm$^2$/kyr is computed, consistent with prior
overall increase in the average grain size from the bottom of the core to the top. An average grain-size maxima is recorded at about the 460 cmbsf interval followed by a decrease in median grain size between 460 and 260 cmbsf, then increasing again to the top of the core (Fig. 4a). These intervals do not correspond to obvious changes in flux rates, as determined from the age–depth model, although each of the ‘pulses’ recorded at 4.1, 6.7 and 10 Ma appears to register a slight upcore increase in average grain size (Fig. 4a). The interval 460–260 cmbsf (6.7 to 4.1 Ma) does not fit the overall trend towards increasing grain-size upcore, and also displays greater variance (Fig. 4a). Sedimentation rates over this interval are also higher than calculated for the core top (0–120 cm mbsf; 4.1 Ma to present), while the base estimates of Pleistocene eolian flux to this part of the ocean (Rea, 1994). Intervals registering pulses of anomalously rapid sedimentation at ~10 Ma (1140–760 cm), 6.7 Ma (760–460 cm) and 4.1 Ma (760–460 cm) appear to be bounded by hiatuses, or interruptions in deposition, that cannot be precisely resolved by the fish teeth Sr stratigraphy. The resulting large uncertainties in MAR estimates must also account for the ±1 Myr error in fish tooth ages, errors in the estimated shipboard DBD, as well as any potential errors in the extraction procedure (% eolian component), and must be considered rough estimates only. Nonetheless, the apparent discontinuities in this core, as revealed by the Sr isotope stratigraphy, appear to be real, though lacking in explanation at this time.

3.2. Grain size and mineralogy

Median grain size on the <38 µm detrital fraction of the core was determined every 20 cm for 63 samples (Fig. 4a). A moving average was fit to the data to reduce the effect of short-term variation on the long-term trend. Median grain size varies between 2.6 and 3.4 µm, showing a statistically significant increase in the average grain size from the bottom of the core to the top. An average grain-size maxima is recorded at about the 460 cmbsf interval followed by a decrease in median grain size between 460 and 260 cmbsf, then increasing again to the top of the core (Fig. 4a). These intervals do not correspond to obvious changes in flux rates, as determined from the age–depth model, although each of the ‘pulses’ recorded at 4.1, 6.7 and 10 Ma appears to register a slight upcore increase in average grain size (Fig. 4a). The interval 460–260 cmbsf (6.7 to 4.1 Ma) does not fit the overall trend towards increasing grain-size upcore, and also displays greater variance (Fig. 4a). Sedimentation rates over this interval are also higher than calculated for the core top (0–120 cm mbsf; 4.1 Ma to present), while the base estimates of Pleistocene eolian flux to this part of the ocean (Rea, 1994). Intervals registering pulses of anomalously rapid sedimentation at ~10 Ma (1140–760 cm), 6.7 Ma (760–460 cm) and 4.1 Ma (760–460 cm) appear to be bounded by hiatuses, or interruptions in deposition, that cannot be precisely resolved by the fish teeth Sr stratigraphy. The resulting large uncertainties in MAR estimates must also account for the ±1 Myr error in fish tooth ages, errors in the estimated shipboard DBD, as well as any potential errors in the extraction procedure (% eolian component), and must be considered rough estimates only. Nonetheless, the apparent discontinuities in this core, as revealed by the Sr isotope stratigraphy, appear to be real, though lacking in explanation at this time.

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of the core (1140–1380 mbsf; 10.5 to 17.5 Ma) displays both the least variance and minimum average grain size despite decreasing sedimentation rates (Figs. 3b, 4a). Fig. 4b and c show typical downcore grain-size distributions, with the volume % maximum grain size at ~2–3 µm indicative of eolian sedimentation (Rea and Hovan, 1995) throughout the core.

Qualitative XRD analysis shows that quartz and feldspar compose the majority of the <38 µm detrital fraction, with illite contributing most of the remainder (Fig. 5a,b). It should be noted that quantitative (standardized) XRD analysis performed on the sub-2 µm clay fraction would be more directly comparable to other datasets, though it is likely that the <2 µm fraction for core MV0502-01JC is dominated by illite (see also discussion of Ar–Ar data below). SEM imaging shows dominantly fine-grained (sub-5 µm) particles, with sparse larger (<38 µm) mineral grains of quartz and plagioclase in the splits that we studied. Most intervals also contained some chlorite (Table 2). Smectite peak areas suggest relatively greater abundance at intervals near 603, 843, 1203 and 1383 cmbsf; however, the significance of this result requires more detailed quantitative analysis. Kaolinite was also identified at interval 1323 cmbsf in the core. The dominantly quartzo-feldspathic composition reveals little downcore variation; illite abundances also remain nearly constant throughout the core (Fig. 5b).

3.3. Nd–Sr–Pb radiogenic isotopic composition of the detrital extract

The Nd–Sr–Pb isotopic signature of the <38 µm extracted detrital fraction for sixteen intervals in MV0502-01JC (Table 3) shows little downcore variation. 87Sr/86Sr ratios (n = 16) have the greatest range (±0.15%), from 0.7115 to 0.7139 (average 0.7127), but show no obvious downcore trends (Table 3). εNd values (n = 16) vary between −3.7 to −5.1 (average = −4.3), also with no downcore trend (Table 3). Lead isotope ratios (206Pb/204Pb = 18.9176–19.0611; 207Pb/204Pb = 15.6404–15.6623; 208Pb/204Pb = 38.8893–39.0581; 207Pb/206Pb = 0.8217–0.8276; 208Pb/206Pb = 2.0491–2.0592) are highly correlated but show no down core trends (Table 3). These values are consistent with an isotopically homogeneous supply of eolian dust being supplied to this site since the early Miocene from older continental sources (estimated Nd model ages are ~1.0 Ga). The larger variation in 87Sr/86Sr may be partly a function of grain-size fractionation in the natural environment.
samples (Pettke et al., 2000; C. Hall, unpublished data). Being released from the illite-dominated K-rich sites in these samples.

The younger 40Ar/39Ar ages recorded at the top of the core (Fig. 6; Table 4). Since few 40Ar/39Ar age data are published for marine pelagic clays (e.g., Pettke et al., 2000), we reference this pattern to the trend in 40Ar/39Ar age data for the late Cenozoic that is positively correlated with Recent MAR increase peaking at 40 mg/cm2/kyr (Zhou and Kyte, 1992), based on the constant cobalt accumulation age model employed for that study.

4. Discussion

4.1. Flux rates, mineralogy and regional constraints on dust sources

The relatively low sediment accumulation rate calculated for the uppermost part of the core is consistent with low dust fluxes thought to characterize much of the Quaternary South Pacific (Schmitz et al., 1986; Rea, 1994). The age resolution is not high enough to reveal potentially higher-flux glacial intervals (e.g., Kohfeld and Harrison, 2001). We note that the terrigenous component at DSDP Site 596 (23°51.20′S, 169°39.27′W), ~2300 km to the northwest of SP-15, shows an abrupt increase in MAR starting at approximately 6 Ma, with the late Pliocene to Recent MAR increase peaking at 40 mg/cm2/kyr (Zhou and Kyte, 1992), based on the constant cobalt accumulation age model employed for that study.

Table 2

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(a.g., Asahara et al., 1995), although no correspondence is noted between 87Sr/86Sr values and median grain size measured in the samples.

3.4. 40Ar/39Ar ages of the detrital extract

40 Ar/39 Ar ages of the <38 µm extracted detrital fraction for ten intervals show a systematic trend from base (~180 Ma) to top (~150 Ma) of the core (Fig. 6; Table 4). Since few 40Ar/39Ar Ar age data are published for marine pelagic clays (e.g., Pettke et al., 2000), we reference this pattern to the trend in 40Ar/39Ar Ar ages determined on the eolian extract for the central North Pacific giant piston core LL44-GPC3 (Gleason et al., 2004a; C. Hall, unpublished data), which shows an upcore increase in 40Ar/39Ar Ar ages for the late Cenozoic that is positively correlated with MAR. 40Ar/39Ar age spectra for Quaternary dust extracted from LL44-GPC3 are dominated by a ~200–220 Ma illite component that is distinctive of the Asian dust source region that supplies the central North Pacific pelagic clay province (Gleason et al., 2004a; Hall, unpublished data; Pettke et al., 2000). The younger 40Ar/39Ar Ar ages recorded at the top of MV0502-01JC are distinct from the North Pacific eolian signature (Pettke et al., 2000), and are suggestive of mixing between Mesozoic-age illite-dominated clays from Southern Hemisphere dust source regions (see discussion). We note that the youngest 40Ar/39Ar Ar age (150 Ma) falls off the MV0602-01JC age–depth trend; this corresponds to interval 200 cmbsf, having an assigned stratigraphic age of 4.1 Ma. This interval also corresponds to an apparent, albeit transient, decrease in average grain size (Fig. 5). 40Ar/39Ar step heating release spectra (Fig. 7) and derived Ca/K ratios are consistent with Ar being released from the illite-dominated K-rich sites in these samples (Pettke et al., 2000; C. Hall, unpublished data).

4. Discussion

4.1. Flux rates, mineralogy and regional constraints on dust sources

The relatively low sediment accumulation rate calculated for the uppermost part of the core is consistent with low dust fluxes thought to characterize much of the Quaternary South Pacific (Schmitz et al., 1986; Rea, 1994). The age resolution is not high enough to reveal potentially higher-flux glacial intervals (e.g., Kohfeld and Harrison, 2001). We note that the terrigenous component at DSDP Site 596 (23°51.20′S, 169°39.27′W), ~2300 km to the northwest of SP-15, shows an abrupt increase in MAR starting at approximately 6 Ma, with the late Pliocene to Recent MAR increase peaking at 40 mg/cm2/kyr (Zhou and Kyte, 1992), based on the constant cobalt accumulation age model employed for that study. This pattern is actually more typical of the central North Pacific, which responded to the inception of Northern Hemisphere glaciation with a 10-fold increase in dust accumulation rate during the Pliocene (Rea, 1994). Another MAR spike in the DSDP Site 596 detrital record, at about 11 Ma (Zhou and Kyte, 1992), appears to correspond to a time interval of extremely low sediment flux in MV0502-01JC (<5 mg/cm2/kyr) that immediately precedes a large flux increase at ~10 Ma; however, this ~10 Ma flux increase may in fact be closely coincident in time with the accelerated drying of the Australian continent (Stein and Robert, 1985). Carter et al. (2004) found interruptions in sedimentation at ODP site 1124, a drift deposit located west of Marlin Rise, which records hiatuses lasting from 11–14 Ma and 16.5–15 Ma, concurrent with cooling climate, East Antarctic ice sheet growth, and strengthening of the deep western boundary current in the Pacific (Carter et al., 2004). These patterns are similar to those identified in
Table 3
Sr–Nd–Pb isotopic composition of the terrigenous extract of MV0502-01JC (Site SP-15), NZ Loess, and DSDP Site 598

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Age (Ma)</th>
<th>δ13Corg</th>
<th>Sr</th>
<th>Sm</th>
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<th>Error</th>
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<th>206Pb/204Pb</th>
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<td>0</td>
<td>0</td>
<td>0.713277</td>
<td>0.000015</td>
<td>0.512881</td>
<td>0.00009</td>
<td>0.512418</td>
<td>-4.29</td>
<td>38.8693</td>
<td>0.0010</td>
<td>15.6404</td>
<td>0.0004</td>
<td>19.9274</td>
<td>0.0005</td>
<td>2.0546</td>
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External reproducibility of Pb isotope ratios by MC-ICPMS using Ti internal correction and standard-sample bracketing (Stancin et al., 2006), based on repeat runs of Pb standard NBS-981 and duplicate digests, is estimated as follows:

206Pb/204Pb = ±0.013%, 207Pb/204Pb = ±0.008%, 208Pb/204Pb = ±0.010%, 207Pb/206Pb = ±0.004%, 208Pb/206Pb = ±0.006%.

The La Jolla Nd isotopic standard measured by TIMS at Michigan during this period was 143Nd/144Nd = 0.511813 ± 0.000008 (N = 20), compared to the old Michigan value of 143Nd/144Nd = 0.511850, requiring a correction to the data of 0.007%. Data are normalized online to 146Nd/144Nd = 0.7219 to correct for instrumental mass bias.

εNd = 10[(143Nd/144Nd)sample / (143Nd/144Nd)chur] - 1, where 143Nd/144Ndchur = 0.512346.
MV0502-01JC. The late Miocene interval coincides with Australia migrating north into a more arid climatic zone (Stein and Robert, 1985), simultaneous with the climatic cool-down following the mid-Miocene optimum (Stein and Robert, 1985). It is therefore expected that more dust would have been available to enter the atmosphere as late Miocene aridification intensified in Australia (Rea, 1994). This matches with Rea and Bloomstine’s (1986) findings for the South Pacific, that suggest a more energetic atmospheric circulation commencing at about 10 Ma, coincident with ice buildup on Antarctica and a subsequent decrease in sea level (Rea and Bloomstine, 1986). Patagonia also began to become more arid at about 10 Ma, due to the Andean orogeny and its position within the rain shadow of the Andes (Zarate, 2003); thus, cooling and drying conditions were a hemispherical phenomenon at this time — although Patagonia would not have been favorably positioned for transport of dust by westerlies into the remote South Pacific region. Southeastern Australia is currently the largest source of dust to the southern hemisphere, accounting for ~6% of the world’s dust, and dominates the South Pacific eolian flux, particularly in the zonal westerlies (Tanaka and Chiba, 2006). It is a much more likely source for at least some of the post ~11 Ma dust component in MV0502-01JC, being at approximately the same paleolatitude (40°–43°S; Fig. 1) as site SP-15 during this time interval.

Tectonic events could also have been, at least in part, responsible for the increased dust flux observed in MV0502-01JC at ~6.7 Ma. The rising Alps on New Zealand’s South Island resulted in increased deposition in the offshore Canterbury Basin at about this time (Carter et al., 2004; Lu et al., 2005). There is some disagreement in the estimated time of initiation of alpine uplift, varying from 7 Ma (Lebrun et al., 2003) to 6.4 Ma (Sutherland et al., 2000; Carter et al., 2004), to 5 Ma (Chamberlain et al., 2005) to the majority of the uplift

![Fig. 6. 39Ar–40Ar age vs. depth and depositional age for MV0502-01JC.](image)

![Fig. 7. 40Ar/39Ar total gas age spectrum for one of the detrital extracts (<38 µm) in MV0502-01JC.](image)
occurring after 2.5 Ma (Williams, 1991). New Zealand is home to some of the largest loess deposits in the southern hemisphere (second only to Argentina; Berger et al., 2002), covering about 10% of its land area (Eden and Hammond, 2003), thus making it a potentially important source for the detrital component in MV0502-01JC (Harrison et al., 1990; Wandres et al., 2004; Marx and McGowan, 2005). Lewis and Eckale (1991) defined the South Island loess mineralogically as 40% quartz, 20% illite, 20% feldspar, 15% kaolinite, and 5% smectite, which is qualitatively similar to the abundances we report for core MV0502-01JC. North Island loess is volcanic, consisting of reworked andesitic tephra (Eden and Hammond, 2003), though it contains quartz dust deposits from deflation of the exposed continental shelf and coastal sediments during glaciations (Alloway et al., 1992). New Zealand has the second most extensive Pleistocene loess–paleosol deposits in the southern hemisphere, with sequences on the South Island up to 18 m thick (Berger et al., 2002). Most of the loess is found on the dry eastern side of the South Island (Berger et al., 2002), which makes it an ideal source of dust to the SW Pacific Basin. Little is known about pre-Pleistocene loess deposits on New Zealand’s South Island, but Stein and Robert (1985) suggested that late Cenozoic cooling was responsible for increased illite from New Zealand being deposited on the Lord Howe Rise starting approximately 9 Ma. Clay mineralogy by itself is generally not enough to establish provenance, since similar latitude and climate beget similar mineralogy (Grousset and Biscaye, 2005). The red clay at Marlin Rise (<38 mm) consists primarily of quartz, feldspar, illite and chlorite, with trace amounts of smectite and kaolinite (Table 2). Mechanical weathering tends to produce more illite and chlorite, while kaolinite is formed under humid conditions when chemical weathering dominates (Singer, 1984; Kohfeld and Harrison, 2001; Net et al., 2002). Chlorite and illite production are associated with high altitude or high elevation; however, they are also found near desert areas where there is little chemical weathering (Singer, 1984). In general, lack of smectite suggests minimal volcanic ash components, and high illite/kaolinite suggests more mechanically weathered sources dominating over chemically weathered or humid source areas (Singer, 1984).

Though Australia is generally not considered a major dust source in terms of the global flux, it nonetheless spawns frequent dust storm events. These are usually associated with strong cold fronts embedded in the zonal westerly circulation at this latitude (Knight et al., 1995; McGowan et al., 2005; McTainsh et al., 2005). Australia is one of the most arid continents on earth, second only to Antarctica (Hesse and McTainsh, 2003; Revel-Rolland et al., 2006), and serves as the source of two modern atmospheric dust dispersal pathways. The southern path removes dust from the Lake Eyre and Murray Darling Basins, which are the primary sources of dust for Australia (McTainsh, 1989; Hesse, 1994; Chen et al., 2002; Hesse and McTainsh, 2003) and carries it towards the South Pacific. On average, this region, which is part of New South Wales, has 5 dust storms per year (McTainsh et al., 2005; Tate et al., 2007). Australia as a whole can have upwards of 100 dust storms in a drought year (McTainsh et al., 2005). It requires 1.5 to 2 days for dust to travel from Australia to New Zealand (McGowan et al., 2005), where it is sometimes deposited on the Southern Alps. In one recent dust storm, between 1.7 and 3.0 million tons of Australian dust was transported towards New Zealand and the South Pacific (Knight et al., 1995). The northern dust path carries dust west to the Indian Ocean and thus does not apply (McTainsh, 1989) to the Marlin Rise region. McGowan et al. (2005) determined geochemically that 65% of the dust deposited in the New Zealand Alps during one storm event was from Australia, specifically 20% from western New South Wales, and 45% from the eastern Eyre Peninsula in South Australia, with 35% being locally derived. Hesse (1997) traced dust derived from Victoria, New South Wales and South Australia to at least the Tasman Sea and to New Zealand. Thiede (1979) and Leinen et al. (1986) mapped out quartz distributions in marine surface sediments, indicating modern transport of eolian material from southeastern Australia and New Zealand over the SW Pacific towards the Marlin Rise area. Thus, modern wind patterns are capable of delivering significant volumes of dust to site SP-15, and may have done so over much of the late Cenozoic.

While illite is a major clay mineral found in southeastern Australian dust source regions, there is also considerable kaolinite found in fluvial settings of the Murray–Darling and Lake Eyre Basins (Kiefert and McTainsh, 1995). Stein and Robert (1985) found the snowfields of SE Australia to be dominated by both illite and kaolinite, while Eyre Peninsula clays are ~35% kaolinite (McTainsh, 1989). Kiefert and McTainsh (1995) noted that suspended dust particles frequently differ from the composition of their source clays, with smectite and kaolinite typically forming aggregates that do not travel as far as single illite clay particles. The kaolinite/illite ratio decreases with increasing latitude as well as with distance from source (Kiefert and McTainsh, 1995), which may in part explain possible discrepancies with the proportions of clay inferred from the Marlin Rise data set. Quantitative XRD analysis of clays in core MV0502-01JC is required for a more direct comparison with other data sets. For example, Stein and Robert (1985) found a mid-Miocene increase in illite directly east of Australia at Lord Howe Rise (DSDP Site 588; ~30°S paleolatitude) that may be linked to increasing desertification of northern Australia. Their data show illite dominating the record at 3 sites spanning 30 to 40°S paleolatitude from late Miocene time to the present. It is, however, difficult to characterize Australian dust sources in detail due to the large regional variation within the continent (Chen et al., 2002). At the present time, the internal drainage basins of Lake Eyre and Murray Darling Basin appear to be supplying the majority of the Australian dust (McTainsh, 1989), with illite and kaolinite as the primary clays (Stein and Robert, 1985). The Murray–Darling Basin mineralogy (<2 mm river muds) varies with location, but includes smectite, illite, kaolinite and some chlorite (Gingele et al., 2004; Gingele and De Deckker, 2004; Forbes and Bestland, in press), and quartz/illite ratios of ~5–15; illite/smectite is high in the Murray Basin, while the reverse holds for the Darling Basin (Gingele and De Dekker, 2004). Both New Zealand and Australia could therefore be major suppliers of illite-dominated dust to site SP-15 at Marlin Rise in the SW
Pacific during the Neogene, though more rigorous regional comparisons await further characterization of clay mineralogy in core MV0502-01JC.

4.2. Grain-size constraints on transport of the eolian component

The mean grain size in MV0502-01JC increases slightly though significantly upcore, possibly reflecting an increase in the average strength of Southern Hemisphere late Cenozoic atmospheric circulation intensity (Rea, 1994). Such an increase is thought to be tied to global cooling and development of stable, permanent ice sheets in Antarctica during the middle Miocene (Stein and Robert, 1985). The apparent increase in grain size at ~10 Ma corresponds in age to a coarsening in grain size noted by Rea and Bloomstine (1986) at DSDP Site 598. Both cases suggest intensifying atmospheric circulation (trade winds at DSDP Site 598; westerlies at Marlin Rise). The reduction in mean grain size at ~4 Ma may correspond to a decrease in wind strength after these parameters peaked ~6.7 Ma. The peak at 6.7 Ma corresponds to increased Antarctic ice sheet buildup (Kennett, 1977; Stein and Robert, 1985; Kennett and von der Borch, 1985). Increased ice buildup would suggest a larger latitudinal thermal gradient and stronger winds, allowing for larger particles to be carried (Rea, 1994); coarsening of the average grain-size upcore indicates intensification of zonal winds for the younger portion of the record. The combination of increasing flux and grain size at 6.7 Ma in MV0502-01JC therefore suggests both increased availability of dust and increasing zonal wind strength during this interval. Increasing flux is consistent with drying climate conditions, but possibly also greater proximity to dust sources (Rea, 1994), as tectonic migration carried the Pacific plate westward towards Australia and New Zealand.

Fig. 8. $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\varepsilon_{\text{Nd}}$ for southern hemispheric continental eolian materials, craton values, and core MV0502-01JC (<38 µm detrital fraction). Despite considerable overlap, Australia appears to be the best match for the detrital component in MV0502-01JC. Data fields from Smith et al. (2003), Delmonte et al. (2004), Revel-Rolland et al. (2006), Walter et al. (2000), and Gallet et al. (1998). E. Antarctic craton value ($^{87}\text{Sr}/^{86}\text{Sr}=0.7380; \varepsilon_{\text{Nd}}=−18.9$) from high MAR Kerguelen Drift sediment (Joseph et al., 2002). Note that Tasman Sea marine sediment is nearly identical (Revel-Rolland et al., 2006), and would be most likely to contain the SE Australian signature plus a New Zealand detrital component (Hesse, 1994).
4.3. Radiogenic isotopic constraints on dust provenance

The use of geochemical and isotopic tracers to determine the provenance of eolian dust has become a commonly applied technique. For this to be effective, a factor that is both distinctive of its source area and conservative must be found (Grousset and Biscaye, 2005). Strontium, neodymium and lead isotopes are often used as tracers of dust source (Nakai et al., 1993; Jones et al., 1994; Ashara et al., 1995; Basile et al., 1997; Pettke et al., 2000; Jones et al., 2000; Delmonte et al., 2004; Grousset and Biscaye, 2005; Revel-Rolland et al., 2006; Stancin et al., 2006). Radiogenic isotope data from core MV0502-01JC (<38 µm extract) are compared here with data from Delmonte et al. (2004) and Revel-Rolland et al. (2006) for Antarctic ice-core dust and Australian dust sources (Fig. 8). While these authors examined only the sub-5 µm particle size, the vast majority (>90%) of particles in the samples examined for our study are also sub-5 µm, as confirmed by grain size and SEM analysis. Nonetheless, it should be noted that \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratios in particular have been shown to vary as a function of grain size analyzed (Smith et al., 2003; Delmonte et al., 2004; Grousset and Biscaye, 2005), with fine-grained (<2 µm) splits typically more radiogenic than coarser dust fractions extracted from marine pelagic clays. With these caveats in mind, Marlin Rise dust is nonetheless very similar in composition to New Zealand loess deposits in Nd–Sr isotopic space (Fig. 8), overlapping Antarctic dry valley samples and dust storm fallout from southeastern Australia as well (Delmonte et al., 2004). In detail, the isotopic signature of New Zealand South Island loess (\( 87\text{Sr}/^{86}\text{Sr} = -1.2 \) to \(-7.2 \); average=-5.4) is more similar to Marlin Rise than loess deposits on the volcanic North Island (\( 87\text{Sr}/^{86}\text{Sr} = 0 \) to \(-2.4 \); average=-0.8; Delmonte et al., 2004). Loess-like deposits in eastern Australia (New South Wales) appear to have \( 87\text{Sr}/^{86}\text{Sr} \) that is more radiogenic (0.717–0.719) and \( ^{143} \text{Nd}/^{144} \text{Nd} \) that is more negative (\(-8.7 \) to \(-9.4 \)) compared to Marlin Rise, while the Lake Eyre region of southeastern Australia shows the reverse pattern (\( 87\text{Sr}/^{86}\text{Sr} \approx 0.709–0.710; \) \( ^{143} \text{Nd}/^{144} \text{Nd} \approx -2.9 \) to \(-4 \); Revel-Rolland et al., 2006). An average of these sources closely overlaps the Marlin Rise Nd–Sr field (Fig. 8).

Very little Pb isotopic data exist for southern hemisphere dust, loess and other sediment for comparison with our dataset. In the study by Hemming and McLennan (2001), turbidites from most of the ocean basins were analyzed, showing a much larger range in Pb isotopic compositions than the Marlin Rise data. In fact, Marlin Rise is very similar to average upper crustal Pb (approximately 19.32±0.28, 15.76±0.09 and 39.33±0.39 for \(^{206}\text{Pb}/^{204}\text{Pb}, \) \(^{207}\text{Pb}/^{204}\text{Pb} \) and \(^{208}\text{Pb}/^{204}\text{Pb} \), respectively; Hemming and McLennan, 2001). Marlin Rise Pb is also isotopically similar to Asian loess and the eolian component in late Cenozoic central North Pacific pelagic clay (18.97±0.06, 15.67±0.02, and 39.19±0.11 for \(^{206}\text{Pb}/^{204}\text{Pb}, \) \(^{207}\text{Pb}/^{204}\text{Pb} \) and \(^{208}\text{Pb}/^{204}\text{Pb} \), respectively; Pettke et al., 2000). This similarity in no way suggests the presence of an Asian dust component in the remote South Pacific, but it demonstrates how similar worldwide the Pb isotopic composition of loess and loess-derived dust is to an average Upper Continental Crust lead value (Hemming and McLennan, 2001). More informative are the

Antarctic ice cores, which are one of the few specific sources of lead isotopic data for the southern hemisphere dust reservoir. Vallelonga et al. (2002) examined \(^{206}\text{Pb}/^{207}\text{Pb}, \) \(^{208}\text{Pb}/^{207}\text{Pb} \) and \(^{206}\text{Pb}/^{204}\text{Pb} \) isotopic ratios at Law Dome (66.6°S, 113°E) back to 4500 BC. In contrast to the Northern Hemisphere, where anthropogenic lead is first seen in Greenland ice cores over 2000 years ago (Hong et al., 1994), the Law Dome site has remained pristine up until the 1880s (Vallelonga et al., 2002). Pre-anthropogenic lead levels at Law Dome averaged 0.8130 for \(^{207}\text{Pb}/^{206}\text{Pb} \), 2.4849 for \(^{208}\text{Pb}/^{206}\text{Pb} \) and 19.1267 for \(^{208}\text{Pb}/^{204}\text{Pb} \) (Fig. 9), while Planchon et al. (2003) found that pre-anthropogenic ice-core dust (1840–1880 AD) near Coats Land, Antarctica (77°34'S, 25°22'W) averaged 0.8437 for \(^{207}\text{Pb}/^{206}\text{Pb} \), 2.4564 for \(^{208}\text{Pb}/^{207}\text{Pb} \) and 18.3314 for \(^{208}\text{Pb}/^{204}\text{Pb} \) (Fig. 9). The detrital extract at Marlin Rise plots closely with Law Dome values, with averages of 0.8256 for \(^{207}\text{Pb}/^{206}\text{Pb} \), 18.963 for \(^{208}\text{Pb}/^{207}\text{Pb} \), and \(^{208}\text{Pb}/^{204}\text{Pb} = 2.4893 \) (Fig. 9). Significantly, the Law Dome site is located directly south of Australia, while Coats Land is southeast of and closer to South America. For this study, a sample of New Zealand loess from the Canterbury Plains region of the South Island, as well as pelagic material from DSDP site 598, was also analyzed for Pb isotopic composition (Table 3). Both Marlin Rise and Law Dome lead data are very similar to loess (<38 µm fraction) from the Canterbury Plains, South Island (Table 3, Fig. 9), while DSDP Site 598 Pb plots closer to Coats Land Pb; this suggests that Marlin Rise dust and Law Dome ice-core dust share a Pb isotopic reservoir similar to that of New Zealand loess as well as SE Australian dust sources, while DSDP Site 598 and Coats Land dust share sources more characteristic of South America.

As previously discussed, the two main wind patterns that affect dispersal of Australian dust to the ocean are distinctive of specific continental source regions. Dust from the Murray–Darling and Lake Eyre region are likely carried downwind by westerlies to the Marlin Rise area. One of the few comparison
datasets (dated at <18.8 ka) that matches both $^{87}$Sr/$^{86}$Sr and $\varepsilon$Nd at Marlin Rise is marine sediment (interpreted to be a mixture of Australian-derived eolian and New Zealand-derived hemipelagic material) from the Tasman Sea (40°17′S, 168°20′E) (Hesse, 1994; Revel-Rolland et al., 2006). Hesse (1997) found that most of the Australian dust that travels over the Tasman Sea is from Victoria, New South Wales and South Australia (including the Murray–Darling and Lake Eyre Basins). In Fig. 10, a Sr–Nd isotope mixing line between average Lake Eyre Basin and Murray–Darling Basin end members, and North and South Island (New Zealand) end members, trends through all of the Australian Basins and all of New Zealand data with approximately the same slope (Fig. 10). It is evident that Marlin Rise data plot very close to this line, though shifted slightly toward more radiogenic strontium values. This offset could be partly explained by considering that natural $^{87}$Sr/$^{86}$Sr fractionation occurs as a function of grain size (Asahara et al., 1995), with the more radiogenic component being concentrated in finer-grained dust fractions. This effect is observed in the Sr isotopic data of the N. Pacific pelagic clay province (Asahara et al., 1995; Stancin et al., 2006), and would be compatible with Australia and New Zealand as primary dust sources for Marlin Rise (Graham et al., 1997). This point is made with the additional caveat that the pure $<2$ µm clay fraction from the Marlin Rise samples would likely be shifted even further towards more radiogenic Sr isotopic values.

4.4. $^{40}$Ar/$^{39}$Ar retention ages and sources of the illite-dominated clay component

Because the $^{40}$Ar/$^{39}$Ar ages of the sub-38 µm detrital extract in MV0502-01JC (Table 4) integrate all the steps in the incremental
heating profile without the $^{39}$Ar recoil component, they are analogous to a $^{40}$Ar/$^{39}$Ar bulk melting age (retention ages of Pettke et al., 2000). The $^{40}$Ar/$^{39}$Ar ages are clearly dominated by the release from the illite clay component based on the characteristic hump-shaped profile of the age spectra (Fig. 7), as observed in previous studies of marine pelagic clay (e.g. Dong et al., 1995; Pettke et al., 2000). The $^{40}$Ar/$^{39}$Ar that we measured suggests a highly Ar-retentive illite component with an average crystallization age that is Mesozoic. $^{40}$Ar/$^{39}$Ar essentially captures the average illite crystallization age of the sample (Dong et al., 1995; Pettke et al., 2000), and has thus found some utility as a provenance tool. Pettke et al. (2000) were able to demonstrate that the Chinese loess component of eolian sediment in central North Pacific pelagic clays is consistently ~200–220 Ma, which probably reflects the average age of illite crystallization associated with Mesozoic basin formation in the regions that supplied Quaternary silts and clays to the Asian Loess plateau — the primary dust source to the central North Pacific pelagic clay province (Guo et al., 2002; Rea et al., 1998). Few studies exist, however, for direct comparison of the illite $^{40}$Ar/$^{39}$Ar crystallization ages recorded in the pelagic material at Marlin Rise with potential Southern Hemisphere continental dust sources.

Eden and Hammond (2003) found that New Zealand loess is largely derived from uplifted and deformed Mesozoic turbidites (Torlesse Sequence), or from Neogene marine sediments derived from these same sources, possibly providing an isotopic match for the Marlin Rise dataset (Taylor and McLennan, 1985; Adams and Graham, 1996; Graham et al., 1997). Metamorphic, hydrothermal and burial diagenetic processes may all play a role in illite formation (essentially fine-grained muscovite, or sericite) within the ultimate dust source regions (e.g., Pettke et al., 2000). Other potential sources of Mesozoic-age illite include dust from the Great Artesian Basin in East Australia (Jurassic and Cretaceous sediments) and Queensland (including the Clarence Moreton Basin, the Gympie Province, and the Bowen Basin, all of which are primarily Permian to Mesozoic in age; Kamber et al., 2005). Further south, the Murray Basin (in New South Wales) is filled with Tertiary-age sediment (Ollier, 1995), and could also have contributed a younger illite component to the Marlin Rise site. As Australia moved north, younger Tertiary sediments may have become an increasingly larger component of the dust flux delivered to the Marlin Rise area, making the trend in Fig. 6 a potential record of Australia’s journey north into more arid latitudes. Alternatively, an increasingly dominant New Zealand-derived illite component upcore could have also produced the same “younging” trend observed in the MV0502-01JC Ar isotope record. Such interpretations must remain speculative, however, until more data can be gathered on the fine-grained clay components in these potential dust source regions.

5. Conclusions

Large diameter piston core MV0502-01JC records 17.5 Myr of eolian deposition at Marlin Rise in the remote South Pacific Basin (40°S latitude), 2400 km east of New Zealand. Mineralogy is consistent with a loess-like source area, consisting dominantly of quartz, feldspar and illite, while Nd–Sr–Pb–Ar isotopic compositions at this site are consistent with a homogeneous supply of eolian material being delivered from continental sources in Southeastern Australia and New Zealand. This source reservoir closely resembles the isotopic composition of Quaternary ice-core dust deposited at the Law Dome site in Antarctica. Calculated MAR varies over an order of magnitude, indicating variable late Cenozoic (Neogene) flux rates, but averaging ~10 mg/cm²/kyr over the past 4 Myr. Grain-size analysis indicates that the average strength of westerly winds delivering this material remained fairly constant or increased only slightly over the time interval being studied.

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Appendix A. Supplementary data


References


