History of Asian eolian input to the West Philippine Sea over the last one million years

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Abstract

The eolian component in Pacific Ocean sediments has been recognized as providing a direct link between the continental loess and marine δ18O climate records over orbital timescales since 500 ka. Here we extend this eolian record over the past one million years. We constructed high-resolution clay mineral stratigraphies based on δ18O chronology in sediments from the International Marine Past Global Change (IMAGES) Core MD06-3050 from the West Philippine Sea in order to trace the sources of clay minerals and reconstruct proxy records of past changes in the Asian eolian input to the basin since 1.0 Ma. The clay mineral assemblage in Core MD06-3050 mainly consists of smectite (~65%) and illite (~25%), with minor kaolinite (~5%) and chlorite (~5%). Provenance analysis suggests that smectite was derived mainly from the weathering of volcanic rocks on Luzon island, whereas illite, chlorite and kaolinite were mainly transported as eolian dust by the East Asian winter monsoon from central Asia. Illite/smectite values in Core MD06-3050 are generally higher in high-latitude glaciation, East Asian winter monsoon intensity and eolian input to the West Philippine Sea at eccentricity (100 ka), obliquity (41 ka) and precession (23 ka) bands since 1.0 Ma.

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1. Introduction

Eolian dust, which is terrestrial material transported by atmospheric circulation, is a significant component of many deep-sea sediments (Rea, 1994). Each year, an estimated 2000 million tons of eolian dust is emitted into the atmosphere, 75% of which is deposited on the land and 25% in the ocean (Shao et al., 2011). The emitted and deposited dust participates in a range of physical, chemical and biological processes, during which it profoundly affects the energy balance of the Earth system (Park et al., 2010). The iron in eolian dust is vital to ocean productivity and ocean–atmosphere CO2 exchange (Cassar et al., 2007). Despite this importance the controls on eolian dust emissions are not well defined. Asia is one of the most important dust source regions in the world. Observational evidence implies that dust originating from Asia has significant influence on marine sedimentation and climate on a global scale (Rea, 1994; Tanaka and Chiba, 2006). Asian dust has been transported to wide areas of the Pacific Ocean (Duce et al., 1980; Rea, 1994; Husar et al., 2001), and has reached North America (McKendry et al., 2001) and even Greenland (Biscaye et al., 1997).

Because of the reliability and uniformity of dating techniques using δ18O chronology in marine sediments, eolian dust preserved in the Pacific Ocean can be used as a high-resolution climatic archive for the source region. Marine dust records can also be directly linked to the loess–soil sequence in the Chinese Loess Plateau and to the δ18O timescale since at least 500 ka (Hovan et al., 1989). However, dust records for Asia are scarce compared with the long-term (million year scale) and high-resolution (2–3 ka timescale) records for Africa derived from the tropical Atlantic (Tiedemann et al., 1994), as well as in the Arabian (deMenocal, 1995), and Mediterranean Seas (Trauth et al., 2009). Lack of long-term Asian eolian dust records in the deep-sea prevents us from testing for links between Asian continental and marine records on orbital-timescales.

In this study we present the first high-resolution Asian eolian record from the West Philippine Sea spanning over one million years. The West Philippine Sea is an ideal location to reconstruct the history of Asian eolian deposition because it is located downwind of the East Asian winter monsoon that carries Asian dust to the southeast (Zhang et al., 1993; Tsai et al., 2009; Shao et al., 2011). More importantly, the West Philippine Sea is largely shielded from the influence of suspended materials from the East Asian rivers by the island of Luzon (Fig. 1). Moreover, the very different mineral assemblages found in sediment eroded from the...
Asian continent and from the Luzon volcanic arc make it possible to isolate the signal of Asian eolian dust in the sediments. Previous sedimentological and mineralogical studies from Cores WP1 (Qin et al., 1995; Shi et al., 1995), Ph-03, and Ph-04 (Chi et al., 2009) located just south of the study site in the West Philippine Sea suggest significant influx of eolian dust from the Asian mainland into this area. Unfortunately, there were no chronostratigraphic constraints to date the sediments in those earlier cores, which prevented them from being interpreted in the context of a time series.

Here we conducted a high-resolution analysis of the evolving clay mineral assemblages based on δ¹⁸O chronology (Sun et al., 2011) from Core MD06-3050 taken in the West Philippine Sea (Fig. 1) by the International Marine Past Global Change Study (IMAGES) in order to (1) constrain the clay mineral source to the study core and find a suitable proxy for tracing eolian dust input to this region; (2) to reconstruct the evolving eolian deposition over orbital timescales since 1 Ma and thus test for any link between the Chinese loess and marine climatic records.

2. Materials and methods

Piston core MD06-3050 is located at a water depth of 2967 m on the Benham Rise of the West Philippine Sea (15°57.09′ N, 124°46.77′ E) (Fig. 1). The Benham Rise is an oceanic plateau that formed along the Central Basin Ridge at 45–50 Ma (Hilde and Lee, 1984). The core site is located about 240 km east of Luzon. The continental shelves along eastern Luzon are very narrow (average less than 10 km) and the core is relatively far from the shelf (about 230 km), so that the effects of sea-level variation on fluvial input from Luzon to the study core are expected to be negligible. The region of Luzon is dominated by a sub-tropical East Asian monsoonal climate, with a heavy annual rainfall of 1900–2100 mm, of which nearly 85–90% arrives during the summer season between May and October. Temperature varies between 23° and 34 °C in both winter and summer, with a maximum of 34 °C in middle April (Liu et al., 2009).

For this study, a total of 400 samples were taken regularly at 4-cm intervals from the upper 16.40 meters of the core. The core mostly comprises brown-gray clayey sediments, rich in nannofossils, as well as intercalated volcanic ash layers that mainly consist of glass shards (Fig. 2). The volcanic ash layers were identified by color and structural changes in the sediment sequence as observed on the surface of the split core. No turbidite-like deposit was observed during sampling. In any case sediment transport by turbidity currents is unlikely because the area of deposition is situated on a plateau that sits high above the abyssal seafloor and is separated from Luzon by the...
East Luzon Trough and Philippine Trench, which would tend to trap turbidity flows. A chronostratigraphic framework for Core MD06-3050 was developed by correlating the planktonic foraminifera G. rubber δ¹⁸O record of the core (Sun et al., 2011) (Fig. 2) to the LR04 δ¹⁸O stack (Lisiecki and Raymo, 2005). According to this chronology, the average linear sedimentation rate (LSR) varies over the range of 1.0–4.0 cm/k.y., with higher values generally appearing during glacial stages 28, 26, 24, 22, 20, 14, 12, 8, 4, and interglacial stages 11, 9, 1. The overall studied sediment sequences span approximately the last 1.02 Ma, with a sample resolution of about 2.5 k.y. In addition eleven loess samples were collected from the Lanzhou Malan Loess section (Fig. 1), which was deposited during the Last Glaciation Maximum (LGM). These samples were used to characterize the clay mineralogy of this potential source area.

Clay mineral studies were carried out on the <2 μm fraction, which was separated based on the Stoke’s settling velocity principle after the removal of carbonate and organic matter (Wan et al., 2007; Wan et al., 2010b) by treating with acetic acid (15%) and hydrogen peroxide (10%), respectively. Clay minerals were identified by X-ray diffraction (XRD) using a D8 ADVANCE diffractometer with CuKα (alpha) radiation (40 kV, 40 mA) in the Laboratory of the Institute of Oceanology, Chinese Academy of Sciences (IOCAS). Each sample was measured three times: (1) after drying at room temperature (scanning from 3° to 30° 2θ, step size of 0.02°); (2) after ethylene-glycol solvation over the range 3°–30° 2θ at 0.02° steps; and (3) at high resolution between 24° and 26° 2θ (0.01° steps) in order to identify the 3.54/3.58 Å kaolinite/chlorite double peak. In addition, several samples were heated at 490°C for two hours in order to test for the presence of kaolinite, smectite and its mixed-layered variations. Identification of clay minerals was made according to the position of the (001) series of basal reflections on the three XRD diagrams (Moore and Reynolds, 1997). Semi-quantitative estimates of peak areas of the basal reflection for the main clay mineral groups (smectite − 17 Å, illite − 10 Å, and kaolinite/chlorite − 7 Å) were carried out on the glycolated samples using Topas 2P software with the empirical factors of Biscaye (1965). Relative clay mineral abundances are given in percent. Replicate analysis of the same sample produced results with a relative error margin of ±5%. Mixed layer clays are mainly smectite–illite mixed layers. The proportion of mixed-layer clay minerals in Core MD06-3050 is very low (<2%) and therefore has been included as being part of the “smectite” group. In addition, all the clay mineralogical results cited in this study have been recalculated using the approach of Biscaye (1965) so that the results can be directly compared.

The illite chemical composition was estimated using the ratio of the peak areas for 5 Å and 10 Å illite in the ethylene-glycolated samples (Esquevin-Index; Esquevin, 1969). Ratios above 0.4 indicate Al-rich illites, which are formed under strong hydrolysis. In contrast, ratios below 0.4 represent Fe-Mg-rich illites (e.g., biotites, micas) that are characteristic products of physical erosion. Illite crystallinity was calculated as the full width at half maximum height (FWHM) of the illite 10 Å peak. Generally, high FWHM values indicate poor crystallinities (highly degraded), whereas low values indicate good crystallinities (relatively unaltered). The two parameters are usually used to track source regions and transport paths (Esquevin, 1969; Ehrmann, 1998; Liu et al., 2010; Wan et al., 2010a).

We used “AnalySeries 2.0.2.4” (Paillard et al., 1996) to perform Blackman–Tukey power spectral analyses and cross-spectral analyses on our sediment records in time domains.

3. Results

The clay mineral assemblage from Core MD06-3050 mainly consists of smectite (~65%) and illite (~25%). Kaolinite (~5%) and chlorite (~5%) are present in lesser amounts (Figs. 2 and 3A). Over the last one million years, smectite is present in relatively higher percentages between marine isotope stages (MIS) 21 to 11 (about 866–374 ka) and lower for MIS 27 to 22 (about 1000–866 ka), as well as during MIS 10 to 1 (since 374 ka). By contrast, illite reveals the opposite long-term trend. On the glacial (tens of thousands of years) timescale, the clay mineral percentages exhibit clear glacial–interglacial cycles since
with an average value of 0.36 (Fig. 2), indicating that illite is typically
higher during glacial periods when illite reaches ~30%, chlorite ~6% and kaolinite ~6% but lower during interglacial periods. In contrast, smectite displays an opposing trend with decreased
chlorite ~6% and kaolinite ~6% but lower during interglacial periods.

The low-temperature alteration of submarine basalts may be
primary source of smectite. However, smectite produced by in-situ alteration of submarine basalt is unlikely to be transported to the study core in the absence of deep-water bottom currents in the study area (Kawabe and Fujio, 2010). Crucially, because these volcanic rocks are submarine they are not strongly eroded as is the case with subaerial sources, meaning that their alteration products tend to stay where they are formed. Moreover, the rate of low-temperature (0–3 °C) alteration of submarine basalt in the alkaline seawater is far lower than weathering on land at high temperature (23–34 °C) in the presence of carbonic, acid-rich groundwater (Aumento et al., 1976). Furthermore, the crystallinity and percent of smectite in sediments from Core MD06-3050 display a set of strong periodicities at 150 ka, 100 ka, 41 ka, 30 ka and 23 ka (Fig. 4), suggesting a climatic control on the formation of smectite. The 23 ka-long cycle (precession) is also recognized as the dominant periodicity of the East Asian summer monsoon (Wang et al., 2008) and the 30 ka band has been interpreted to reflect the influence of long-term ENSO-like forcing, as well as glacial-interglacial cyclicity on the East Asian summer monsoon (Beaufort et al., 2003). Both these cycles are muted in records of bottom water temperature in the Pacific Ocean (Waelbroeck et al., 2002). Therefore, we exclude alteration of submarine basalts as a primary contributor of smectite to the core site.

We further conclude that the alteration of submarine tephra is also not a significant source of smectite to the study core because volcanic eruptions in Luzon are intermittent, as revealed by tephrostratigraphic records from Cores MD97-2142 and MD97-2143 from the west and east side of Luzon island (Fig. 1) (Ku et al., 2009). The volumetrically limited, intercalated tephra layers (Fig. 2) cannot supply the high volumes of smectite (~65%) found through the core. The fact that the ash and surrounding layers in the core are not characterized by increased smectite further argues that these cannot be the primary source of smectite.

However, erosion from Luzon cannot explain the high content of illite (average 25% in Core MD06-3050 (Fig. 3a)) because the sediment of the major rivers in the west and central Luzon presently has only 2% illite (Liu et al., 2008). Even under colder, drier climatic conditions during glacial periods the bedrock geology of Luzon does not favor the generation of illite as an erosion product. Clay mineral
segregation usually results in an increasing smectite percent relative to illite with distance offshore a given river mouth because smectite is finer grained than other clay minerals (Gibbs, 1977). As a result, the main source of illite in the sediments at the study core cannot be Luzon. Previous investigation of clay mineral distribution in the surface sediments of the Philippine Sea suggested that the illite-and chlorite-rich sediments are derived from eastern China or Taiwan, or even from the Loess Plateau (Kolla et al., 1980). Moreover, a detailed mineralogical study (Qin et al., 1995) of Core WP1 that is located nearby Core MD06-3050 (Fig. 1) emphasized the significant eolian contribution to the area from continental Asia during glacials in the late Quaternary. This conclusion was based on the clay mineralogy and occurrence of detrital carbonate and gypsum, both of which are characteristic minerals of arid environments, i.e. Chinese loess (Qin et al., 1995).

A ternary diagram of smectite-(illite+chlorite)-kaolinite (Fig. 3a) also supports the hypothesis that the clay minerals at Core MD06-3050 are largely Luzon-derived, but with a secondary contribution from continental Asia. In order to further constrain the source of clay minerals of the Philippine Sea suggested that the illite-and chlorite-rich sediments are derived from eastern China or Taiwan, or even from the Loess Plateau (Kolla et al., 1980). Moreover, a detailed mineralogical study (Qin et al., 1995) of Core WP1 that is located nearby Core MD06-3050 (Fig. 1) emphasized the significant eolian contribution to the area from continental Asia during glacials in the late Quaternary. This conclusion was based on the clay mineralogy and occurrence of detrital carbonate and gypsum, both of which are characteristic minerals of arid environments, i.e. Chinese loess (Qin et al., 1995).

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and the intensity of the East Asian winter monsoon, respectively. The aridity of central Asia is closely coupled with the development of the East Asian winter monsoon (Guo et al., 2004). The higher and more variable dust fluxes and grain sizes found during glacials compared to interglacial periods suggest that both Asian continental aridity and East Asian winter monsoon intensity strengthened when the global climate was colder (Sun and An, 2005; Sun et al., 2006). Eolian dust from continental Asia is transported as far into the North Pacific (Hovan et al., 1989) and even the western and central equatorial Pacific (Patterson et al., 1999; Winckler et al., 2008). The eolian records in the north (Hovan et al., 1989) and equatorial (Patterson et al., 1999; Winckler et al., 2008) Pacific generally mirror the temporal variability in dust MAR and mean quartz grain-size in the Loess Plateau (Sun and An, 2005; Sun et al., 2006)(Fig. 5). Because the regional climate around Luzon and the West Philippine Sea is controlled by both the East Asian summer and winter monsoons (Compo et al., 1999; Wang et al., 2000), we anticipate that the winter monsoon circulation could have carried eolian dust from central Asia to the basin, as previously suggested (Qin et al., 1995). The study core lies approximately 1300 km downwind of mainland China and 2600 km from the important dust sources in central Asia (Fig. 1) but this is within the transport limits already known from the North Pacific.

Here, we use the ratio of illite/smectite in Core MD06-3050 to trace the changing strength of Asian eolian input to the West Philippine Sea over the last one million years. It is expected that the stronger East Asian winter monsoons active during glacial periods would transport more illite to the study core relative to fluvial-derived smectite. In contrast, if the illite was primarily derived from eastern Taiwan and then transported by Luzon Undercurrent, two possible factors (source and current) should be considered when interpreting the changing abundances. Illite is the most abundant clay mineral in Taiwanese river sediments (average 71%)(Liu et al., 2008) and erosion rates were higher in Taiwan during interglacial periods compared to glacials, as inferred from river incision rates (Schaller et al., 2005). Thus weakened East Asian summer monsoon precipitation (Sun et al., 2006) and dampened erosion in Taiwan during glacial periods should supply less illite to the margin at those times. Although, changes in the intensity of the Luzon Undercurrent itself could also have influenced the southward transport of illite, little is known concerning the glacial–interglacial variations of that current in the West Philippine Sea and we do not consider this to be the dominant control on clay mineralogy at the study site.

In any case, as shown in Fig. 5, variations in illite/smectite at Core MD06-3050 over the last 1.0 Ma match variations in mean quartz grain-size and loess MAR in Loess Plateau. Because loess forms in semi-arid conditions during times of glaciation (Sun and An, 2005) high eolian input, as traced by higher illite/smectite, should coincide with late Pleistocene glaciations if the illite is truly derived from central Asia. The pattern found in Core MD06-3050 is very similar to the eolian record in Core V21-146 in the North Pacific (Hovan et al., 1989)(Fig. 5). The ratio shows not only generally higher values during glacials and lower during interglacials, but also many spikes during the glacials, which correspond to periods of rapid variable and strengthened East Asian winter monsoon and increased aridity in continental Asia during glacial periods (Sun et al., 2006)(Fig. 5). The correlation suggests that the illite was much more likely transported by wind rather than by the Luzon Undercurrent from Taiwan, which is in any case counteracted by transport in the opposite direction by the Kuroshio Current. This in turn confirms the previous suggestions of significant Asian eolian input to the basin (Qin et al., 1995). The changing clay mineral ratios suggest that eolian input into the West Philippine Sea generally co-varied with East Asian winter monsoon intensity and with Asian aridity over the last one million years.

Fig. 5. Comparison between illite/smectite from Core MD06-3050 in the West Philippine Sea (this study), mean grain-size of loess quartz (Sun et al., 2006) and MAR in the Chinese Loess Plateau (Sun and An, 2005), eolian flux at Core V21-146 in the North Pacific (Hovan et al., 1989), eolian $^4$He flux at ODP Site 806 in the west Equatorial Pacific (Patterson et al., 1999). The planktonic foraminifera G. ruber $\delta^{18}O$ stratigraphy in Core MD06-3050 (Sun et al., 2011) is shown for comparison. The shaded bars and numbers indicate marine isotope interglacial stages.
We also consider alternative mechanisms for causing the temporal change in the relative abundance of illite versus smectite. Smectite contents could have changed through time without any major changes of illite. Input of smectite from Luzon to the West Philippine Sea could be modified by several processes, such as changes of the monsoon rainfall on the Luzon and accompanying changes of the intensity of the physical erosion and chemical weathering of the rocks on the island (Liu et al., 2009). For example, MIS 13 (533–478 ka) is shown to be an unusual period with the lowest ratios of illite/smectite (Fig. 5), suggesting the weakest eolian input and/or the strongest fluvial supply since 1.0 Ma. The low illite/smectite is consistent with a weakened East Asian winter monsoon inferred from the loess grain-size (Sun et al., 2006), but contrasts with the stable or slightly increased aridity of central Asia, as reflected by faster eolian MAR in the Loess Plateau (Sun and An, 2005) and the North Pacific (Hovan et al., 1989; Patterson et al., 1999) (Fig. 5). Moreover, it is noteworthy that the smectite percentage and crystallinity also display abnormally high values during this interglacial MIS 13 (Fig. 2), suggestive of more chemical weathering at that time. Because the smectite mainly originated from the weathering of volcanic rocks in Luzon, as discussed above, and because a moderate linear correlation between the chemical index of alteration (CIA) and smectite crystallinity was observed for clay-fraction sediments in Luzon rivers (Liu et al., 2009), more and higher crystallinity smectite in MIS 13 sediments may indicate an exceptionally strengthened East Asian summer monsoon at that time. This inference is consistent with the loess Fe record in northern China (Yin and Guo, 2008), which argues for an unusually warm and wet climate from low to middle latitude in East Asia during MIS 13.

4.3. Spectral analysis

In order to better understand the dynamic link between the changes in eolian input on orbital timescales and those of high-latitude ice-sheet variations and East Asian winter monsoon intensity, we performed a Blackman–Tukey spectral analysis and cross-spectrum analysis on the proxy records since 1.0 Ma (Fig. 4). Spectral analysis shows that illite percent and illite/smectite ratios have a set of strong periodicities corresponding to the orbital eccentricity (100 ka), obliquity (41 ka) and precession (23 ka) bands over the last 1.0 Ma (Fig. 4). This observation is consistent with the dominant periodicity identified in East Asian winter monsoon proxy records during the Pleistocene (Ding and Liu, 1998; Sun et al., 2006). Cross-spectral analysis between illite/smectite and loess grain-size, as well as illite/smectite and δ18O in Core MD06-3050 shows very high non-zero coherences (>80%) between the three parameters at eccentricity (100 ka), obliquity (41 ka) and precession (23 ka) bands (Fig. 4), further revealing the close link between high-latitude climate change, East Asian winter monsoon intensity and eolian input to the West Philippine Sea since 1.0 Ma. It should be emphasized that illite/smectite essentially reflects the contribution of eolian illite relative to fluvial suspended smectite into the study area, rather than absolute flux. Further work is needed to quantify the flux of eolian dust, fluvial suspended materials, and intermittent volcanic ash to the study core, but this does not affect the main conclusions of this study and the links between eolian flux and the strength of the East Asian winter monsoon.

5. Conclusions

In order to trace the source of clay minerals to Core MD06-3050 in the West Philippine Sea and thus reconstruct the orbital-scale variations of Asian eolian deposition in the basin, we analyzed clay mineral assemblages at high-resolution based on a δ18O chronology. We draw the following conclusions from this work:

(1) The clay mineral assemblage at Core MD06-3050 mainly consists of smectite (~65%) and illite (~25%), with minor kaolinite (~5%) and chlorite (~5%). Clay mineral analysis combined with comparison to other eolian proxy records in the Loess Plateau and North Pacific Ocean suggests that smectite was derived mainly from the weathering of volcanic rocks on the island of Luzon, whereas illite, chlorite and kaolinite were primarily transported as eolian dust from central Asia by the East Asian winter monsoon. The Kuroshio Current cannot have transported the illite-rich sediments from the East China Sea continental shelf or Taiwan to the study area as previously suggested.

(2) The ratio of illite/smectite in sediments taken from Core MD06-3050 was applied to trace the strength of Asian eolian input into the West Philippine Sea. The ratio was generally higher and more variable during glacial and lower during interglacials, suggesting that the eolian input to the West Philippine Sea has generally covaried with East Asian winter monsoon intensity and the aridity of central Asia since 1.0 Ma. Eolian input was much weakened and accompanied by more and higher crystallinity smectite during the unusually warm and wet MIS 13 (533–478 ka). Cross-spectral analysis further reveals the close link between high-latitude climate change, East Asian winter monsoon intensity and eolian input to the West Philippine Sea at major orbital periods since 1.0 Ma.

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