Late Quaternary climatic control on erosion and weathering in the eastern Tibetan Plateau and the Mekong Basin

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Abstract

High-resolution siliciclastic grain size and bulk mineralogy combined with clay mineralogy, rubidium, strontium, and neodymium isotopes of Core MD01-2393 collected off the Mekong River estuary in the southwestern South China Sea reveals a monsoon-controlled chemical weathering and physical erosion history during the last 190,000 yr in the eastern Tibetan Plateau and the Mekong Basin. The ranges of isotopic composition are limited throughout sedimentary records: $^{87}\text{Sr}/^{86}\text{Sr} = 0.7206–0.7240$ and $\varepsilon_{\text{Nd}}(0) = -11.1$ to $-12.1$. These values match well to those of Mekong River sediments and they are considered to reflect this source region. Smectites/(illite + chlorite) and smectites/kaolinite ratios are used as indices of chemical weathering rates, whereas the bulk kaolinite/quartz ratio is used as an index of physical erosion rates in the eastern Tibetan Plateau and the Mekong Basin. Furthermore, the 2.5–6.5 $\mu$m/15–55 $\mu$m siliciclastic grain size population ratio represents the intensity of sediment discharge of the Mekong River and, in turn, the East Asian summer monsoon intensity. Strengthened chemical weathering corresponds to increased sediment discharge and weakened physical erosion during interglacial periods. In contrast, weakened chemical weathering associated with reduced sediment discharge and intensified physical erosion during glacial periods. Such strong glacial–interglacial correlations between chemical weathering/erosion and sediment discharge imply the monsoon-controlled weathering and erosion.

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Keywords: Erosion; Chemical weathering; Grain size; Clay minerals; Neodymium isotope; Fourier Transform Infra-Red (FTIR) spectroscopy; East Asian monsoon; Tibetan Plateau; Mekong River; South China Sea

Introduction

Temporal changes in continental erosion and weathering reflect tectonic uplift (Raymo et al., 1988) and/or climate changes (Molnar and England, 1990), but the importance of each effect still remains uncertain. For the million-year scale since the Miocene, tectonically controlled climate change was expressed by an evolution of Asian monsoons in phase with the uplift of the Himalaya and the Tibetan Plateau (An et al., 2001; Kutzbach et al., 1993).

Much of the sediment derived from erosion of the Himalayas is well preserved, especially in the Arabian Sea and the Bay of Bengal, providing an opportunity to examine how clastic sediments record erosion and weathering processes (Curray, 1994; Derry and France-Lanord, 1997). Results from sediments stored in the Bay of Bengal indicate that the strength of summer monsoon rainfall is an important factor driving weathering and erosion of the Himalayas (Bouquillon et al., 1990; Derry and France-Lanord, 1996). Over the last two glacial/interglacial cycles, smectite/(illite + chlorite) and kaolinite/quartz ratios combined with a chemical index of alteration for sediments from Andaman Sea and Bay of Bengal indicate that the weathering intensity of the Himalayan and Burman ranges...
is mainly controlled by the summer monsoon rainfall intensity (Colin et al., 1999, 2001). Therefore, similar monsoon-controlled weathering and erosion would be expected to occur over the eastern Tibetan Plateau and the Mekong Basin, where the relation of erosion and climate remains poorly understood (Schäfer et al., 2002).

The upper reach of the Mekong River on the eastern Tibetan Plateau consists mainly of Mesozoic sedimentary rocks (meta-sandstone, shale, slate, and phyllite), with minor Precambrian metamorphic and extrusive igneous rocks (Fig. 1). The plateau zone allows physical weathering processes and forms lithosols containing illite and chlorite (Liu et al., 2003a). The middle reach is covered mainly by Paleozoic–Mesozoic sedimentary rocks (meta-sandstone, shale, and slate) and intrusive igneous rocks (mainly granites) to produce bissialitic and ferrallitic soils. The lower reach is characterized by Mesozoic sedimentary rocks (mainly sandstone and mudstone) with some extrusive igneous rocks (basalts) and a broad alluvial plain mainly with bissialitic soils (Ségalen, 1995). Liu et al. (2004) suggested a late Quaternary chemical weathering history based on clay mineralogy and element geochem-

Figure 1. Schematic geological map of the SE Asia continent and location of the studied core. Modified after Commission for the Geological Map of the World (1975).
istry of sediments off the Mekong River mouth in the southwestern South China Sea. But no physical erosion and monsoon rainfall information have been revealed from previous studies for this region.

This paper presents a high-resolution study of siliciclastic grain size and bulk mineralogy combined with clay mineralogy, rubidium, strontium, and neodymium isotopes reported for an International Marine Past Global Change Study (IMAGES) of Core MD01-2393 located off the Mekong River in the southwestern South China Sea (Bassinot and Baltzer, 2002) (Fig. 1). Sediments retrieved from the core were analyzed in the present study in order to reconstruct the erosional and weathering history of the eastern Tibetan Plateau and the Mekong Basin during the late Quaternary (the last 190,000 yr). No major changes in tectonic activity occurred during this short time period, allowing us (i) to establish a relationship between past changes in the intensity of the East Asian monsoon rainfall and in the intensity of chemical and physical weathering in the eastern Tibetan Plateau and the Mekong Basin, and (ii) to assess the effect of sea-level changes induced by glacial–interglacial changes on the transport of sediments to the southern margin of the South China Sea. The results indicate that strengthened chemical weathering corresponds to increased sediment discharge and weakened physical erosion during interglacial periods and that weakened chemical weathering is associated with reduced sediment discharge and intensified physical erosion during glacial periods, implying the monsoon-controlled weathering and erosion.

Materials and methods

Core MD01-2393 (10°30.15′N, 110°03.68′E, 1230 m water depth), located on the continental slope 400 km from the mouth of the Mekong River, was collected during the IMAGES cruise VII-WEPAMA in 2001 (Bassinot and Baltzer, 2002) (Figs. 1 and 2). The lithology is homogeneous, dominated by olive gray foraminifer-rich or diatom-bearing nannofossil ooze with terrigenous clay. Binocular investigation indicates that biogenic silica (e.g., diatom and radiolarian) comprises around 5–10% in volume of particles >63 μm. Samples were collected at 10- to 20-cm intervals for the last 74,000 yr and 20- to 40-cm intervals for the older part to analyze siliciclastic grain size, bulk, and clay mineralogy with average temporal resolutions of 300–600 yr for the younger part and a lesser resolution of 1000–2000 yr for the older part. Additionally, 15 samples were selected for Rb, Sr, and Nd isotopic measurements according to clay mineralogy variations.

Grain size distribution measurements of carbonate- and biogenic silica-free sediments were carried out on a Laser Particle Size Analyzer LS130 at the Orsayterre Laboratory, University of Paris XI. Bulk sediments were first decarbonated via reaction with 0.2 N HCl, followed by successive washing with distilled water. Sediments were then treated with 1 N Na2CO3 solution to remove biogenic silica, which mainly presents as opal. The reaction was performed in a water bath at a temperature of 85°C for 4 h. The Na2CO3 solution was then neutralized by a series of distilled water rinsing steps followed by centrifugation. Binocular observation of selected samples shows that biogenic silica can be removed completely.

The kaolinite, quartz, and calcite contents of the bulk fraction were determined by Fourier Transform Infra-Red (FTIR) spectroscopy (Pichard and Fröhlich, 1986) at the IRD (Bondy, France) following the procedure described by Colin et al. (1999). Bulk samples were ground in acetone to a particle size of <2 μm with small agate balls in an agate vial and kept at 4°C to prevent heating and structural changes. The powder was then mixed with KBr in an agate mortar with a dilution factor of 0.25%. A 300-mg pellet, 13 mm in diameter,
was pressed into a vacuum die with up to $8 \times 10^7$ Pa. For each sample, an infrared spectrum averaging 50 scans in the 4000- to 250-cm$^{-1}$ energy range with a 2-cm$^{-1}$ resolution was recorded.

Rb, Sr, and Nd isotopic measurements were performed on the carbonate-free fraction using static multicollection on a Finnigan MAT-262 at the Laboratoire des Sciences du Climat et de l’Environnement (CEA-CNRS, Gif/Yvette) following the procedure described by Colin et al. (1999). Samples were decarbonated and then dissolved in HF–HClO$_4$ and HNO$_3$–HCl mixtures. Sr and Rb were eluted with 2 N HCl and the light rare-earth elements with 2.5 N HNO$_3$. Nd was isolated by reverse-phase chromatography on HDEHP-coated Teflon powder. $^{87}$Sr/$^{86}$Sr ratios have been corrected from mass fractionation using normalization to an $^{88}$Sr/$^{86}$Sr ratio = 0.1194. Similarly, $^{144}$Nd/$^{146}$Nd ratios have been corrected from mass fractionation using a normalization to the natural $^{143}$Nd/$^{144}$Nd ratio = 0.7219. Nd results are expressed as $\varepsilon_{\text{Nd}}(0) = \left[ \frac{\left( \frac{^{143}\text{Nd}}{^{144}\text{Nd}}_{\text{meas}} \right)}{0.512638} - 1 \right] \times 1000$, using the CHUR value given by Jacobsen and Wasserburg (1980).

### Chronological framework

The chronology of Core MD01-2393 has been established by correlating the marine oxygen isotope record for the planktonic foraminifera Globigerinoides ruber (white) $\delta^{18}$O with Core MD97-2151 (8°43.73’N, 109°52.17’E, 1550-m water depth, Fig. 1). The chronology for the latter core is constrained by twelve AMS $^{14}$C dates (Lee et al., 1999) over the last 18,000 yr (Fig. 3). For the older period, chronology was established using the SPECMAP oxygen isotope stratigraphy (Martinson et al., 1987) (Fig. 3). High-resolution calcium carbonate stratigraphy, the occurrence of the Youngest Toba Tuff dated at 74,000 ± 2000 yr (Ninkovich et al., 1978), and the last occurrence of G. ruber (pink) dated at 120,000 yr (Thompson et al., 1979) were also used to constrain the age scale model for Core MD01-2393 (Liu et al., 2004).

The core provides a continuous sedimentary record extending to early marine oxygen isotope stage (MIS) 6 (~190,000 yr ago) with a higher average sedimentation rate of 37.1 cm/10$^3$ yr for the Holocene, and of ~23 cm/10$^3$ yr for
glacial MIS 3, 4, and 6, and a lower sedimentation rate of 14.0 cm/10^3 yr for interglacial MIS 5 (Fig. 4).

Results

Siliciclastic grain size

Mean grain size of siliciclast of the core shows large variations between 6 and 30 μm (Fig. 5). For the last 60,000 yr, the sediment is coarser with an average mean grain size of 13 μm, while between 60,000 and 190,000 yr the sediment is finer with a mean grain size of 8 μm. Besides, long-term variations in mean grain size values are characterized by glacial–interglacial changes with higher values in Holocene and MIS 2, 3, 4, and 6, and lower values in MIS 5 (Fig. 5).

The classification of grain size variations was suggested previously on the basis of South China Sea sediments in two classes: clay (<6.3 μm) and silt (6.3–63 μm), considering that the clay content was defined as the percentage of the acid-insoluble grain size fraction smaller than 6.3 μm (Wang et al., 1999). Here, we prefer to define the most sensitive grain size class using the method of the highest standard deviation (Boulay et al., 2003), which provides easy identification of the grain size intervals. For each 72 grain size classes probed by the Laser Particle Size Analyzer, standard deviations of each class grain size were calculated for all samples. Standard deviation values vs. grain size classes are displayed in Figure 6. Two peaks with larger standard deviations are observed in the 2.5–6.5 μm and 15–55 μm grain size intervals. Both size classes represent the populations of grains with the highest variability through time. On the contrary, other intervals, such as the intermediate 8–12 μm size class, are characterized by low standard-deviation values, implying no important change of the proportion of this grain size population in the siliciclastic fraction through time. This different behavior is well expressed by the variations of the 2.5–6.5 μm, 8–12 μm, and 15–55 μm size class contents through time (Fig. 5). Both the 2.5–6.5 μm and 15–55 μm grain size populations vary significantly with glacial–interglacial changes. No significant variation can be observed in the 8–12 μm grain size population, and long-term fluctuations of the 2.5–6.5 μm size class distribution are inversely correlated to those of the 15–55 μm size class. Interglacial stages are characterized by high proportions (32–35%) of the 2.5–6.5 μm and low proportions (5–12%) of 15–55 μm size intervals, while glacial stages present low proportions (15–25%) of the 2.5–6.5 μm and high proportions (17–35%) of 15–55 μm size intervals (Fig. 5).

Bulk and clay mineralogy

Kaolinite, quartz, and calcite contents of bulk samples were determined using FTIR spectroscopy for the core. As dolomite and aragonite are absent in our FTIR results, kaolinite and quartz proportions were corrected from carbonate dilution using the following relationship:

\[ \% \text{ Mineral cor}_{\text{bulk}} = \% \text{ Mineral mes}_{\text{bulk}} / (100 - \% \text{ CaCO}_3_{\text{mes}_{\text{bulk}}}) \times 100 \]

Carbonate contents vary between 5% and 22%, with higher values during interglacial periods. Bulk kaolinite proportions are 6–18% in detrital minerals and vary generally with climate changes (Fig. 7). MIS 4, late MIS 5, and early MIS 6 are characterized by lower values than MIS 1, 2, 3, early MIS 5, and late MIS 6. Bulk quartz contents vary between 11% and 24%, with an average of 16%. Except for MIS 4, when values of quartz contents were higher, their variations do not follow the glacial–interglacial fluctuations (Fig. 7). This relationship between glacial–interglacial changes and bulk kaolinite and quartz content variations is also observed in results obtained by Liu et al. (2004) in the <2-μm size fraction. Smectites (22–58%) and illite (21–40%) are the dominant clay minerals in the <2-μm size fraction; kaolinite (11–25%) and chlorite (10–25%) are less abundant (Fig. 7). Globally, illite, chlorite, and kaolinite distributions are similar and inversely correlate to the smectite distribution. Kaolinite content in the clay fraction presents a general trend similar to those obtained by IRTF on the bulk sample, suggesting their same sedimentary source. Glacial MIS 2, 3, 4, and 6 are characterized by higher contents of illite, chlorite, and
Figure 5. Variations of mean grain size and proportions of grain size classes 2.5–6.5, 8–12, and 15–55 µm of the siliciclastic fraction of Core MD01-2393. Distance of the core from the Mekong River mouth and global sea level change through the past 190,000 yr indicate the sea level change-controlled variations of the 15–55-µm grain size population. Dashed areas highlight glacial stages.
kaolinite, and by lower contents of smectites than interglacial MIS 1 and 5.

**Rb, Sr, and Nd isotopic results**

Rb, Sr, and Nd concentrations and isotopic ratios measured on carbonate-free fraction are listed in Table 1. The Sr and Nd concentrations vary between 96–110 ppm and 28.9–33.6 ppm, respectively. The 87Sr/86Sr ratio presents a narrow range between 0.7206 and 0.7240 and the ɛNd(0) between /C011.1 and /C012.1 (Fig. 7). These values are consistent with the previously published South China Sea data (Wei et al., 2000) and do not present any significant changes with the glacial/interglacial oscillations, suggesting no significant changes in the sedimentary source during the last 140,000 yr.

**Discussion**

**Sediment sources**

Considering the clay mineral assemblage of Core MD01-2393 and mineralogical components of soils in the Mekong Basin, Liu et al. (2004) suggested that the Mekong River basin could be the major detrital source for the core. However, other sources are possible, such as eolian dust, the Sunda shelf, the Indonesian Islands, and the Red River. We will now examine each of these sources. 87Sr/86Sr vs. Rb/Sr and ɛNd(0) versus 87Sr/86Sr measured at the core sediments are presented in Figures 8a and b with a compilation of previously published data from potential sedimentary sources: the Mekong River, the Red River, the Pearl River (J. Gaillardet, personal communication, 2003), the Java-Sumatra volcanic arcs (Whitford, 1975), and Chinese Loess deposits (Jahn et al., 2001). 87Sr/86Sr ratios and ɛNd(0) values of Core MD01-2393 sediments (Fig. 8) are similar from one Mekong River sample (87Sr/86Sr = 0.72354; ɛNd(0) = −11.2) (J. Gaillardet, personal communication, 2003), confirming that the Mekong River is the major source of sediments to the margin close to the Mekong River mouth. Chinese loess isotopic compositions are different from those of the core sediments (Fig. 8), suggesting a limited contribution of eolian input to the core. During the Plio-Pleistocene, the eolian contribution was reported as 15–30% of the total sediment accumulation for the northern South China Sea (Wang et al., 1999; Wehausen and Brumsack, 2002). In contrast, the southern South China Sea seems to be dominated strongly by fluvial input (Tamburini et al., 2003). An estimated aerosol flux (at maximum, accounting for 12% of the total sediment accumulation) and carbonate-free TiO2/Al2O3 contents during the Pliocene defined at ODP Site 1143 in the southern South China Sea suggest a minor eolian contribution to the terrigenous accumulation (Wehausen et al., 2003). For Core MD01-2393, considering an average sedimentation rate of 40.7 cm/103 yr, carbonate content of 16%, and an average dry density of 0.592 g/cm3 (reported from similar carbonate content sediments of ODP Site 1143 in the southern South China Sea; Shipboard Scientific Party, 2000), Liu et al. (2004) estimated the maximum eolian sediment flux may only account for about 2.5% of the total terrigenous accumulation, in agreement with a negligible eolian contribution for the core.

The Sunda shelf and the Indonesian Islands produce sediments with not only high concentration of smectites (25–40%), but also high concentration of kaolinite (30–40%) (Gingele et al., 2001). These minerals could feed the South China Sea through the Borneo Strait following...
Figure 7. Bulk quartz and kaolinite contents (corrected from carbonate dilution), clay mineral proportions (%) on the $<2 \mu$m size fraction (Liu et al., 2004), $\delta^{18}$O (‰ PDB) G. ruber, and $\varepsilon$Nd(0) values vs. age ($10^3$ yr) for Core MD01-2393.
northeasterly sea surface currents, which are driven by the East Asian summer monsoon. However, in Core MD01-2393, the increase in smectite is not associated with lower Sr radiogenic ratios (Fig. 7) and there is no suggestion of mixing of the Mekong River sediments with a potential end-member such as volcanic rocks from Java and Sumatra (Whitford, 1975) (Fig. 8). This implies that smectite could not be derived from weathering of volcanic rocks from the Indonesian Islands.

This leads us to conclude that the terrigenous source for Core MD01-2393 is the Mekong River. We, therefore, can constrain the origin of the different clay minerals:

(1) Illite and chlorite derived mainly from the eastern Tibetan Plateau, where physical erosion of metamorphic and granitic parent rocks is dominant. Both illite and chlorite may derive either from the degradation of micas of metamorphic and igneous formations or from the erosion of sedimentary rocks. Consequently, illite and chlorite can be considered as mainly primary minerals, deriving from physical erosion or moderate chemical weathering and glacial scour such as those mainly present in the highland of the Mekong Basin.

(2) Smectite could be produced by chemical weathering of parent aluminosilicate and ferromagnesian silicates under warm and humid conditions in the middle to lower reaches of the Mekong River, where bisalitic soils are well developed. But the weathering of extrusive basalt of the lower part of the Mekong Basin (Fig. 1) has a potential significant contribution of smectite to the core sedimentation. Because $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\varepsilon_{\text{Nd}}(0)$ values do not show any relationship with the smectite content variability and there is a low volume of such volcanic rocks in the huge Mekong Basin, we exclude smectite derived from weathering of volcanic material.

(3) Generally, in tropical conditions, kaolinite is mainly considered to be derived from ferrallitic soils which are well developed in a plain environment where hydrolysis processes are very active. In Core MD01-2393, bulk and clay fraction (<2 μm) kaolinite contents indicate a similar pattern to those of illite and chlorite with higher content during glacial periods (Fig. 7), suggesting that most of the kaolinite could also derive from active erosion of inherited clays from reworked sediments in the middle reach of the Mekong River.

### Table 1

Rb, Sr, and Nd isotope data of Core MD01-2393

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Age (10^3 yr)</th>
<th>MIS</th>
<th>Sr (ppm)</th>
<th>Rb (ppm)</th>
<th>Nd (ppm)</th>
<th>Rb/Sr</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
<th>$^{143}\text{Nd}/^{144}\text{Nd}$</th>
<th>$\varepsilon_{\text{Nd}}(0)$</th>
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<td>98.8</td>
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<td>1.89</td>
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<td>0.512051</td>
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<td>2.71</td>
<td>1</td>
<td>107.0</td>
<td>176.5</td>
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<td>1.65</td>
<td>0.72065</td>
<td>0.512049</td>
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</tr>
<tr>
<td>270</td>
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<td>1.99</td>
<td>0.72272</td>
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a The age uncertainty is estimated as ±90 14C yr over the last 18,000 yr (Lee et al., 1999) and ±5000 yr before 18,000 yr (Martinson et al., 1987).

b MIS: marine oxygen isotope stage.

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**Significance of grain size and mineralogical changes**

The siliciclastic grain size measurement (Fig. 5) displays a definite correlation between the variation of the 15–55 μm size fraction and the mean grain size curves, indicating that the silt population, 15–55 μm, is the main factor controlling mean grain size variations for this period. These fluctuations are generally reversely correlated with the distance from the Mekong River and global sea-level change, as is also visible in Figure 5.

The scanning electron microscopy (SEM) investigation on the silt population 15–55 μm size fraction from selected samples reveals that detrital minerals mainly include quartz, mica, and rock fragments with minor feldspar in different sizes and shapes. Generally, quartz is angular with irregular recesses on its surface; feldspar is also angular but with flat and cleaved surface; mica is always rounded and sheet-shaped. All those characteristics suggest a fluvial origin for the silt fraction. When sea level dropped during glacial periods, the position of Core MD01-2393 was closer to the paleo-Mekong River mouth (Fig. 5) and thus could easily be reached by more silt-size sediments mainly from the exposed continental shelf (Fig. 2). The more silt-sized sediments could also reflect a reworking of the coarse detrital material deposited on the continental shelf during...
Figure 8. $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Rb/Sr (a) and $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $\varepsilon_{\text{Nd}(0)}$ (b) diagrams indicating the isotopic distribution of both interglacial and glacial samples from Core MD01-2393. Data of the Red River, the Pearl River, the Mekong River (J. Gaillardet, personal communication, 2003), the Chinese Loess (Jahn et al., 2001), and volcanic rocks of Java and Sumatra (Whitford, 1975) are presented for comparison.
periods of low sea level. Therefore, the proportion of the silt fraction could be controlled mainly by the sea-level change. We find that the mean grain size distribution during interglacial Holocene is similar to those for MIS 2–3 and is different from MIS 5 (Fig. 5). Its silt fraction, however, is much closer to the interglacial MIS 5. This could imply that other grain size distributions (e.g., 8–12 μm) could contribute the coarser size during Holocene, and the fundamental change may need further investigation.

On the other hand, the grain size in the clay population (2.5–6.5 μm) has an inverse distribution compared to that of the silt population (Fig. 5). According to various studies on similar sediments (Liu et al., 2003b; Wehausen and Brumsack, 2002), clay minerals are preferably transported by rivers into the South China Sea. The 2.5–6.5-μm grain size population could represent the intensity of the sediment discharge of the Mekong River.

Therefore, we adopt the grain size ratio of 2.5–6.5 μm/15–55 μm to represent the sediment discharge of the Mekong River. The Mekong’s discharge is derived mainly from the East Asian summer monsoon rainfall between May and October and partly from the summer snowmelt in the eastern Tibetan Plateau (Gupta et al., 2002). This ratio indicates a higher sediment discharge during MIS 5 and, in turn, a stronger summer monsoon rainfall for that period with lower discharge levels during MIS 1, 2, 3, 4, and 6 (Fig. 9).

Kaolinite seems to be derived mainly from active erosion of inherited clays from reworked sediments in the middle part of the Mekong Basin. The reworked kaolinitic paleoweathering materials in the landscapes may seriously alter the paleoclimatic signal of kaolinite in the sedimentary record (Thiry, 2000). Therefore, the kaolinite contents reflect the erosion level that occurred in the Mekong Basin, instead of reflecting contemporary climates. Quartz is a common mineral present in sedimentary and igneous rocks in the Mekong Basin and also on continental shelves. Therefore, the values of quartz contents do not follow the glacial–interglacial fluctuations (Fig. 7). Thus, the quartz-normalized bulk kaolinite, i.e., the bulk kaolinite/quartz ratio, is used to indicate the intensity of physical erosion that occurred in the eastern Tibetan Plateau and the Mekong Basin to avoid the dilution of individual component. The result suggests that the physical erosion was strong during late MIS 6 and early MIS 5 (115,000–135,000 yr ago) and MIS 1, 2, and late MIS 3 (0–45,000 yr ago) (Fig. 9). The physical erosion suggests a stepwise strengthening during MIS 6 and MIS 1, 2, and 3, respectively, with a negative correlation to the sediment discharge indicator of the 2.5–6.5 μm/15–55 μm grain size ratio (Fig. 9).

Figure 9. Comparison of grain size population (2.5–6.5 μm)/(15–55 μm), bulk kaolinite/quartz, clay-size fraction smectites/(illite + chlorite), and smectites/kaolinite ratios with planktonic foraminifera G. ruber (white) δ¹⁸O record of Core MD01-2393.
Besides kaolinite in clay minerals, illite and chlorite were derived mainly from the eastern Tibetan Plateau, where physical erosion of metamorphic and granite parent rocks was dominant, and they are also representative of the physical erosion ability. However, smectites originated mainly through chemical weathering of parent aluminosilicate and ferromagnesian silicate under warm and humid conditions that are dominant in the middle to lower reach of the Mekong River. Therefore, we adopt ratios of smectites/(illite + chlorite) and smectites/kaolinite as clay mineralogical indicators to reconstruct history of the chemical weathering vs. physical erosion as it occurred in the eastern Tibetan Plateau and the Mekong Basin (Liu et al., 2004). In the core, variations in smectites/(illite + chlorite) and smectites/kaolinite ratios show similar variations during the last 70,000 yr (Fig. 9). The relatively higher ratios, observed during interglacial periods throughout the past 190,000 yr, suggest a strengthened chemical weathering and weak physical erosion; by contrast, the lower ratios corresponding to glacial periods indicate intensified physical erosion and weakened chemical weathering (Fig. 9).

Along with the chemical weathering history obtained by Liu et al. (2004), our results indicate that the sediment discharge (revealed by the 2.5–6.5 $\mu$m/15–55 $\mu$m grain size ratio) is well correlated with the chemical weathering (revealed by the smectites/(illite + chlorite) and smectites/kaolinite ratios) during the late Quaternary (the last 190,000 yr), with the exception of the Holocene (Fig. 9). This demonstrates that enhanced summer monsoon precipitation, i.e., increased chemical weathering and runoff, causes the increase in the sediment discharge. Similarly, variations in the physical erosion (revealed by the bulk kaolinite/quartz ratio) have an inverse correlation with those of the chemical weathering, with the exceptions of the Holocene (Fig. 9). This would then imply intensified physical erosion coincides with weak summer monsoon rainfall. Our results provide strong evidence of monsoon-controlled erosion and weathering processes in the eastern Tibetan Plateau and the Mekong Basin over the past 190,000 yr.

However, the Holocene is an exception for some proxies of erosion and weathering processes (Fig. 9). The clay mineral assemblages indicate the same pattern of illite and chlorite variations but an inverse behavior of smectites and kaolinite fluctuations (Figs. 7 and 9). These could be the effect of differential settling of smectites, which could be transported more easily over a greater distance from the Mekong River mouth. The relative increase in smectites will result in the relative decrease in kaolinite. It is the same reason for the increase in bulk kaolinite during the Holocene for the core (Fig. 7). Additionally, the fine silt proportion 8–12 $\mu$m size fraction increased abruptly in the middle of Holocene (Fig. 5). This could be relative to the fast drop of local sea level, which started to decrease around 5000 yr ago (Ta et al., 2002). Both differential settling of clay minerals and local sea level changes may contribute inverse behaviors for our proxies of monsoon-controlled erosion and weathering history and need to be examined further.

Summary and conclusions

High-resolution siliciclastic grain size and bulk mineralogy combined with clay mineralogy, rubidium, strontium, and neodymium isotopes of Core MD01-2393 were analyzed to establish a relationship between past changes in erosion and chemical weathering with East Asian monsoon rainfall during the late Quaternary (the last 190,000 yr) in the eastern Tibetan Plateau and the Mekong Basin.

(1) Source analysis indicates that the Mekong River has provided most of the siliciclastic materials found in the core, appearing to be ideally suited for the study of the interaction of climate change with erosion and weathering processes. The silt fractions of siliciclasts were derived mainly from the exposed continental shelf during the glacial low sea-level stands.

(2) Smectites/(illite + chlorite) and smectites/kaolinite ratios reveal a history of chemical weathering rates relative to physical weathering rates, whereas bulk kaolinite/quartz ratio reflects the physical erosion history. Furthermore, siliciclastic 2.5–6.5 $\mu$m/15–55 $\mu$m grain size ratio suggests the intensity of sediment discharge of the Mekong River and, in turn, the East Asian summer monsoon intensity.

(3) Strengthened chemical weathering corresponds to increased sediment discharge and weakened physical erosion during interglacial periods. In contrast, weakened chemical weathering associated with reduced sediment discharge and intensified physical erosion during glacial periods. Such strong correlations between chemical weathering and sediment discharge imply the monsoon-controlled weathering and erosion occurred in the eastern Tibetan Plateau and the Mekong Basin.

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References


Lee, M.-Y., Wei, K.-Y., Chen, Y.-G., 1999. High resolution oxygen isotope stratigraphy for the last 150,000 years in the southern South China Sea: core MD972151. Tao 10, 239–254.


