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Weathering and erosion in central Vietnam over the Holocene and Younger Dryas: Clay mineralogy and elemental geochemistry from the Vietnam Shelf, western South China Sea

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ABSTRACT

Clay mineralogy and elemental geochemistry of Core SO18401 on the Vietnam Shelf are used to reconstruct the history of weathering and erosion in central Vietnam over the past 13.2 ka. The variability of the clay species across the 13.2 ka BP together with the age model allows a subdivision into four temporal stages. Provenance analysis based on clay mineralogy indicates that small mountainous rivers in southern-central Vietnam are the major sources of terrigenous sediments on the central Vietnam Shelf. Smectite and kaolinite originated from the chemical weathering of Mesozoic and Neogene-Quaternary basaltic rocks and Paleo-Mesozoic felsic intrusive rocks, respectively, under warm and humid climate conditions; whereas illite and chlorite were mainly derived from physical weathering of Paleo-Mesozoic felsic intrusive rocks and Precambrian metamorphic rocks in central Vietnam. Accordingly, smectite/(illite + chlorite) ratio, together with elemental ratios of Al₂O₃/K₂O, TiO₂/Al₂O₃, and SiO₂/Al₂O₃, can be utilized to reflect the relative importance between chemical weathering and physical weathering/erosion of the parent rocks in southern-central Vietnam. Higher smectite/(illite + chlorite) and Al₂O₃/K₂O ratios indicate a more important role of chemical weathering, and higher TiO₂/Al₂O₃ and SiO₂/Al₂O₃ ratios suggest enhanced contribution of physical weathering and erosion. A combination of these mineralogical and elemental proxies allows the distinction of four stages of weathering and erosion evolution in southern-central Vietnam over the Holocene and Younger Dryas periods. Enhanced physical weathering and erosion took place during the periods ∼13.2–11.0 ka BP (Stage I) and ∼3.9–2.0 ka BP (Stage III), associated with relatively arid conditions. By contrast, strengthened chemical weathering occurred during the periods ∼11.0–3.9 ka BP (Stage II) and 2.0 ka BP to present (Stage IV), corresponding to more warm and humid climatic conditions. Our study suggests that the weathering and erosion history of southern-central Vietnam over the Holocene is mainly controlled by the East Asian monsoon climate.

1. Introduction

Central Vietnam is located in the eastern Indochina Peninsula (Fig. 1). The highlands of central Vietnam form a series of contiguous volcanic plateaus with an elevation ranging from 500 to 1500 m covered by significant amounts of soils. Central Vietnam’s drainage systems are characterized by short and steep mountainous rivers that drain small areas. Central Vietnam’s climate is influenced by the tropical East Asian monsoon, causing distinct rainy and dry seasons. The annual rainfall is high in the rainy season (75%) arriving during September to December and low in the dry season, with an average annual rainfall of 1,300 mm, along with stable average monthly temperature of 26 °C throughout the year (www.worldclimate.com). The basement of central Vietnam mainly consists of Paleo-Mesozoic felsic intrusive rocks (i.e., granite, granodiorite, and diorite), Mesozoic extrusive rocks (i.e., rhyolite, dacite, andesite, and felsite), and Neogene-Quaternary basaltic rocks, with minor Precambrian metamorphic rocks and Neogene sedimentary rocks (Luong and Bao, 1988; Hoang and Flower, 1998; Carter et al., 2000; Nam et al., 2001; Lepvrier et al., 2008; Hoang et al., 2013; Fig. 2). Quaternary sediments are distributed along river channels and coastal areas.

The Vietnam Shelf is located at the western margin of the South China Sea (SCS), with a total area of 700,000 km² (Schimanski and Stattegger, 2005; Fig. 1). The northern region off the Red River mouth
and the southern region off the Mekong River mouth of the shelf are wide in extension and low in gradient. The central region, however, is very narrow with an average slope inclination of 0.2° and up to 2.3° in the inner part (Szczuciński et al., 2008). The coastal areas of central Vietnam are characterized by rocky/sandy beaches and shallow (∼10–20 m in depth) bays (e.g., Nha Trang Bay) (Szczuciński et al., 2008). Several studies have been carried out on the circulation, sea-level change, sediment source, and seismic stratigraphy evolution on the Vietnam Shelf (e.g. Schimanski and Stattegger, 2005; Szczuciński et al., 2008; Barthel et al., 2009; Hanebuth et al., 2011; Bui et al., 2014; Tan et al., 2014; Koukina et al., 2017). Among them, the central Vietnam Shelf is shown to contain large amounts of detrital sediment that are mostly from central Vietnam, with usually very high sedimentation rates (up to 50–100 cm/ka) during the Holocene (Schimanski and Stattegger, 2005; Szczuciński et al., 2008). In addition, the climate and surface-water circulation in the SCS are largely controlled by the East Asian monsoon system, which is represented by seasonal wind patterns, blowing southwestward in winter and northeastward in summer (Wang et al., 1999; Fig. 1). The East Asian monsoon is thought to not only affect the precipitation and associated river runoff over the adjacent landmasses around the SCS but also influence the characteristics of vegetation cover (Webster, 1994). This implies that weathering processes in central Vietnam are strongly linked to East Asian monsoon evolution. Variations in monsoon rainfall intensity (dry and cool during Younger Dryas, wet and warm during Early and Middle Holocene) are derived from speleothem records at the Dongge Cave in Southwest China (Dykoski et al., 2005; Wang et al., 2005) and Puerta Princesa Cave, Palawan (Partin et al., 2015). For the central Vietnam region the relationship between climate conditions and weathering processes over the Holocene and Younger Dryas time scale has not been investigated so far. Taken together, the central Vietnam Shelf is an ideal area to study the silicate weathering processes in central Vietnam with respect to the interdependence of variations in the East Asian monsoon climate.

In this study, clay mineralogy and major-element geochemistry of sediments on the central Vietnam Shelf are investigated, in order to (1) elucidate provenance, and particularly (2) reconstruct physical/chemical weathering and erosion in the source regions, as well as (3) explore the relationship between weathering process and the East Asian monsoon over the past 13.2 ka.
Three new AMS 14C datings were measured on mixed species of foraminiferal tests \cite{Schimanski2005} and foraminiferal tests \cite{AMS14C} by utilizingAMS 14C years to calendar years \cite{Stuiver1993} by utilizing the calibration program Calib Rev 7.0.4 was used to calibrate the outer Vietnam Shelf was used for this study \cite{Fig. 1}. The core collected during the research cruise SO-140 of R/V Sonne in April–May 1999 is 707 cm long. The sediments consist of olive gray homogenous clay with rare sandy patches/lenses below 230 cm core depth and a sand-rich interval from 577 to 598 cm \cite{Fig. 3}. A total of 178 samples were taken at depth intervals of 4 cm for carbonate content, clay mineralogy, and major-element geochemistry analyses, which were done at the State Key Laboratory of Marine Geology, Tongji University.

Fig. 2. Geological map of central Vietnam modified from Luong and Bao \cite{1988}. 1. Quaternary deposits; 2. Neogene-Quaternary basalts; 3. Miocene sedimentary rocks; 4. Mesozoic extrusive rocks; 5. Paleo-Mesozoic felsic intrusive rocks; 6. Precambrian metamorphic rocks. Average clay mineral assemblages of surface river samples \cite{for explanation see Fig. 1} represented by pie charts \cite{n = number of samples} are shown for northern-central Vietnam \cite{C1}, southern-central Vietnam \cite{C2}, the Ba River \cite{B1} \cite{Liu2016; Sang2018}, and of Holocene samples of Core SO18401 \cite{S}.

2. Materials and methods

Core SO18401 \cite{(12°12.90′N, 109°32.09′E, 134 m water depth)} on the outer Vietnam Shelf was used for this study \cite{Fig. 1}. The core collected during the research cruise SO-140 of R/V Sonne in April–May 1999 is 707 cm long. The sediments consist of olive gray homogenous clay with rare sandy patches/lenses below 230 cm core depth and a sand-rich interval from 577 to 598 cm \cite{Fig. 3}. A total of 178 samples were taken at depth intervals of 4 cm for carbonate content, clay mineralogy, and major-element geochemistry analyses, which were done at the State Key Laboratory of Marine Geology, Tongji University.

Three new AMS 14C datings were measured on mixed species of planktonic and benthic foraminifera at the Beta Analytic Radiocarbon Dating Laboratory in Miami (USA). Intact foraminiferal tests \cite{(~ 10 mg)} were carefully hand-picked to avoid contamination by reworked materials. Together with two previous AMS 14C datings on gastropod materials \cite{Schimanski2005; Table 1}, the calibration program Calib Rev 7.0.4 was used to calibrate AMS 14C years to calendar years \cite{Stuiver1993} by utilizing the updated marine calibration data set of Marine13 \cite{Reimer2013}. A local reservoir correction \cite{(ΔR) of 30 ± 30.5 years} was used based on the reservoir age from the Hon Tre Island in the western SCS \cite{Bolton2016}.

Carbonate content was analyzed by a pressure calcimeter \cite{Liu2004}. This instrument determines the bulk carbonate content, based on the partial pressure of the resultant carbon dioxide \cite{(CO2)} from the reaction of calcium carbonate \cite{(CaCO3)} with the concentrated hydrochloric acid \cite{(HCl)}. Samples were dried at 50 °C for 24 h, and finely ground with an agate mortar and pestle. About 0.1 ± 0.005 g of ground samples was reacted with a sufficient amount of HCl inside the calcimeter. In-house standards and replicates \cite{(for every 10 samples)} were performed for uncertainty control. This method has a long-term instrumental error of less than 2%.

Clay minerals were identified using the PANalytical X’Pert PRO X-ray Diffraction (XRD) on oriented mounts of non-calcareous clay-sized \cite{( < 2 µm) particles} \cite{Holtzapfel1985}. Bulk sediment samples were treated with 0.2 N HCl to remove carbonate. This study used the methods described in \cite{Liu2004} to prepare the oriented mounts. Three XRD runs were carried out following air drying, ethylene-glycol solvation for 24 h, and heating at 490 °C for two hours. The position of the (0 0 1) series of basal reflections on the three XRD diagrams were used to identify clay minerals. Based on the glycolated curve, semi-quantitative estimates of peak areas of the basal reflections for the main clay mineral groups of smectite including mixed layer minerals \cite{(15–17 Å)}, illite \cite{(10 Å)}, and kaolinite/chlorite \cite{(7 Å)} \cite{Holtzapfel1985} were determined using the MacDiff software \cite{Petschick2000}. The ratios of the 3.57/3.54 Å peak areas were used to determine relative proportions of kaolinite and chlorite. Additionally, the ratio of the 5 Å and 10 Å illite peak areas in glycol-saturated samples was used to calculate illite chemistry index \cite{Esquevin1969}. Illite crystallinity was estimated with full width at half maximum of illite 10 Å peak. Illite chemistry index and illite crystallinity are usually utilized to determine source regions and transport paths \cite{Petschick1996; Gingelev2001; Liu2008}.

Major elements were measured by a PANalytical AXIOSmAX wavelength dispersive XRF spectrometer. Samples were dried and crushed to fine powder by using an agate mortar and pestle. Each sample was then coned and quartered to ensure that the powdered sample was well mixed, and subsequently compressed with boric acid powder \cite{(H3BO3)} into a disc for analysis. Boric acid was used as cover for the sediment samples. Chinese rock and sediment standards GSR06 and GSD15 were used to monitor the analytical precision and accuracy. The data were reported as major-element oxides \cite{(i.e., SiO2, Al2O3, Fe2O3, MgO, CaO, K2O, Na2O, P2O5, TiO2, and MnO)}.

3. Results

3.1. Age model

The chronology of Core SO18401 is established by five AMS 14C dates combined with the carbonate content variation \cite{Fig. 3; Table 1}. The result shows that the core covers a continuous sedimentary succession over the last 13.2 ka BP, including the complete Younger Dryas period \cite{( ~12.9–11.6 ka BP)}. Ages for the depth intervals from 0 to 26 cm and from 686 to 707 cm were obtained by linear extrapolation. Sedimentation rates show the highest values during the Late Holocene \cite{(average 113 cm/ka)} and the lowest values during the Middle Holocene \cite{(average 26 cm/ka) \cite{Fig. 3}. Since the core was sub-sampled at 4 cm interval, the record has an overall high resolution \cite{(average 75 years)} because of the high sedimentation rate. In addition, the carbonate contents are relatively high \cite{(average 7%) during the Holocene and low \cite{(average 3%) during the Younger Dryas period.}

3.2. Clay minerals

The clay minerals at Core SO18401 are composed mainly of smectite \cite{(33–56%)} followed by illite \cite{(16–32%)} and kaolinite \cite{(14–19%)} and chlorite \cite{(14–18%) \cite{Fig. 4}. In general, the patterns of relative...
abundance for illite and chlorite are similar, while that of smectite is inversely correlated with these two clay species. The variability of the clay species across the 13.2 ka BP allows a subdivision of four temporal stages (Fig. 4) together with the age model. In Stage I (13.2–11.0 ka BP), smectite content shows the lowest values, while illite and chlorite exhibit the highest values. At 11.0 ka BP, the relative abundance of smectite increases abruptly, while the relative abundances of both illite and chlorite decrease sharply. In Stage II (11.0–3.9 ka BP), the relative abundance of smectite shows high values with little variability, while illite and chlorite have low relative abundances. Stage III (3.9–2.0 ka BP) is characterized by slight decrease in both illite and chlorite contents, and a slight increase in smectite content. Lastly, the relative abundance of smectite decreases accompanied by increases in both illite and chlorite in Stage IV (< 2.0 ka BP). Kaolinite, on the other hand, displays a different pattern from the other three clay minerals since 13.2 ka BP. During Stages I and II, kaolinite content shows a similar pattern to smectite content, having low values in Stage I, and high values in Stage II. However, during Stages III and IV, kaolinite content exhibits a similar pattern to illite and chlorite. The illite crystallinity has high values during Stage I, decreases sharply at the beginning of Stage II, increases again during the most period of Stage II and shows large short-term fluctuations during Stages II and I with highest positive excursions in Stage II and lowest negative excursions in Stage I. Illite chemistry index shows no visible trend but lowest negative excursions during Stage II.

### Table 1
AMS 14C datings and calendar ages of Core SO18401.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Depth (cm)</th>
<th>Foraminifera species</th>
<th>14C age (years BP)</th>
<th>Calibrated age (years BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26 (24–28)</td>
<td>Cassidulina laevigata</td>
<td>810 ± 30</td>
<td>402</td>
</tr>
<tr>
<td>2*</td>
<td>226</td>
<td>Gastropod</td>
<td>2590 ± 40</td>
<td>2220</td>
</tr>
<tr>
<td>3</td>
<td>406 (404–408)</td>
<td>Rotalia ecuadorensis, R beccariiformis</td>
<td>3840 ± 30</td>
<td>3753</td>
</tr>
<tr>
<td>4*</td>
<td>590</td>
<td>Rotalia sp</td>
<td>9910 ± 50</td>
<td>10,844</td>
</tr>
<tr>
<td>5</td>
<td>686 (684–688)</td>
<td>Globorotalia kuenhi, Globorotalia menardi, R ecuadorensis, R beccariiformis</td>
<td>11,310 ± 40</td>
<td>12,760</td>
</tr>
</tbody>
</table>

*Note: AMS-14C ages were corrected by using a local reservoir correction (ΔR) of 30 ± 30.5 years from the Hon Tre island in the western SCS (Bolton et al., 2016).*  
*Data from Schimanski and Stattegger (2005).*
3.3. Major elements

Sediments of Core SO18401 consist mainly of SiO₂, Al₂O₃, CaO, and Fe₂O₃ (in total about 81%), with low concentrations of K₂O, MgO, Na₂O, TiO₂, MnO, and P₂O₅ (in total about 8%) (Fig. 5). Variations in SiO₂, Al₂O₃, Fe₂O₃, K₂O, and TiO₂ concentrations display an inverse correlation to CaO and CaCO₃ fluctuations. The same four stages of variations are observed in major element compositions. SiO₂, Al₂O₃, Fe₂O₃, K₂O, MnO, and TiO₂ contents present the highest values in Stage I, a sharp decrease at the beginning of Stage II with lowest values between 11.0 and 10.5 ka BP, and thereafter a slightly increasing trend with little variability. On the other hand, CaO and CaCO₃ show the lowest values in Stage I, a sharp increase at the beginning of Stage II with highest values between 11.0 and 10.5 ka BP, and thereafter a slightly decreasing trend in CaO but a slightly increasing trend in CaCO₃ in Stages II and III. Nevertheless, MgO decreases in Stage IV, while P₂O₅ increases. Lastly, Na₂O shows low values in Stage I, higher values in Stage II, some positive excursions in Stage II, and a decrease during Stage IV.

4. Discussion

4.1. Sediment sources

The paleoclimatic interpretation of clay minerals in marine sediments requires detailed knowledge of the potential source areas as well as their individual transport processes (Diekmann et al., 1996; Gingele et al., 1998; Liu et al., 2008, 2010). Variations in clay mineral composition of Core SO18401 may result from ways of transportation, weathering processes in source areas, and sea level change. Potential transportation pathways of the sediments are from the Mekong River in the south, the Red River in the north, and small mountainous rivers in central Vietnam (Fig. 1). The Mekong and Red rivers are among the largest rivers in the world in terms of sediment discharge, and they deliver 160 × 10⁶ t and 103 × 10⁶ t suspended sediments respectively.
to the SCS annually (Milliman and Meade, 1983). For the Mekong and Red rivers, clay mineral assemblages are characterized by high illite contents with average values of 35% and 43%, respectively (Liu et al., 2007a). Chlorite and kaolinite have similar average values of 24–28%, while the relative abundance of smectite is ≤10%. The small mountainous rivers in central Vietnam deliver less than 14 × 10^{6} t suspended sediments annually to the SCS (Milliman and Farnsworth, 2011). Smectite at this studied area, these rivers are far from the core location, and more importantly their sediments have low smectite contents (< 10%) (Liu et al., 2007a; Fig. 1). Consequently, smectite at this studied area can be mostly transported by the small mountainous rivers in southern-central Vietnam. The smectite abundance at Core SO18401 shows relatively low values (33–46%) during the Younger Dryas and high values (43–56%) during the Holocene, implying that smectite may be a useful indicator chemical weathering in central Vietnam.

Illite and chlorite are products of physical weathering, which relates largely to the weak hydrolysis and/or strong erosion of parent rocks under cold and arid climatic conditions (Chamley, 1989). Illite and chlorite can be generated by the weathering of non-layer silicate (e.g., feldspar from granitic rocks) under moderate hydrolysis conditions, and by the degradation of micas. Central Vietnam is underlain by abundant Paleo-Mesozoic felsic intrusive rocks with minor Precambrian metamorphic rocks (Fig. 2), which can be main sources of illite and chlorite. However, the tectonic stability, the tropical climate conditions, and the morphology of central Vietnam together may have reduced the magnitude of physical weathering and erosion due to the relatively low contents of illite and chlorite in weathering products. Accordingly, Core SO18401 contains moderate contents of illite and chlorite (Fig. 4) implying that the small mountainous rivers in both northern- and southern-central Vietnam could supply sufficiently illite and chlorite for this area. In addition, the Mekong and Red rivers, although far away could be considered as sedimentary sources of illite and chlorite in the southwestern and northwestern (Gulf of Tonkin) SCS (Liu et al., 2004, 2007b, 2016). However, illite in Core SO18401 sediments is mostly well correlated to rivers from both northern- and southern-central Vietnam including the Ba River due to the relatively low illite chemistry index and illite crystallinity values, distinct from the higher values from both the Mekong and Red rivers (Fig. 7). Among the rivers in the central Vietnam, the relatively wide range of illite crystallinity of southern-central Vietnam rivers has good correlation to the Holocene sediments of Core SO18401, while both southern- and northern-central Vietnam rivers have relatively good correlation to the Younger Dryas sediments of Core SO18401 (Fig. 7). Downcore variations of illite and chlorite contents show similar patterns (Fig. 4), suggesting similar provenance and weathering conditions. These findings indicate that the small mountainous rivers in northern-central Vietnam contributed the majority of illite and chlorite during the Younger Dryas period, while both northern- and southern-central Vietnam mountainous rivers have delivered significant amounts of illite and chlorite during the Holocene for this area.

Kaolinite is usually produced by monosialitization of parent rocks
enriched in alkali and alkaline earth elements (e.g., granite, granodiorite, and intermediate-acid volcanic rocks), referring to the intense hydrolysis under warm and humid climate. In central Vietnam, Paleozoic-Mesozoic felsic intrusive rocks are preferred to be weathered to kaolinite due to tropical warm and humid climatic conditions, tectonic stability, and the geomorphology. Rivers draining the areas that are thought to have high amounts of kaolinite (Fig. 2). Kaolinite usually settles almost immediately as it enters the sea, due to its relatively large size (0.5–8.0 µm in average diameter), and its enhanced flocculation in alkaline seawater (Patchineelam and Figueiredo, 2000). In the SCS, kaolinite has high abundances in sediments from surrounding fluvial systems (e.g., South China, most parts of Vietnam), and low abundances in distal seafloor sediments (Liu et al., 2016) due to the effect of differential setting mentioned before. Kaolinite from Core SO18401 is interpreted to be transported in high amounts via the small mountainous rivers draining southern-central Vietnam and depleted during marine transport to the core site. The small northern-central Vietnam Rivers, despite their high kaolinite content, are significantly distant from the core site. On the other hand, Mekong and Red river sediments are significantly more enriched in illite than kaolinite, and recent investigations (Liu et al., 2007a) suggest that these rivers are insignificant sources of illite on the central Vietnam Shelf. Therefore, kaolinite from Core SO18401 was mainly provided by the small mountainous rivers in southern-central Vietnam.

4.2. Effect of sea level change

Global sea level change can affect coastline configuration, such as location of river-mouth system and offshore sediment transport in relation to river power and marine forcing, which may cause variations in terrigenous sediment delivery to the open shelf (Steinke et al., 2003, 2008; Wang et al., 2012a,b; Chang et al., 2015). Sea level rose almost linearly after the meltwater pulse 1A (14.6–14.3 ka BP) until 9.0 ka BP followed by a phase of rapid sea-level rise between 9.0 and 8.2 ka BP (MWP-1C) and the last moderate phase of deglacial sea-level rise until the mid-Holocene sea-level highstand (6.7–5.0 ka BP) (Hanebuth et al., 2000; Bird et al., 2010; Stattegger et al., 2013; Tjallingii et al., 2014; Fig. 8). However, the coastline retrograded only by 50 km at maximum since 13.2 ka BP when the water depth at the core site was ~65 m (Hanebuth et al., 2011; Tjallingii et al., 2014). This is strongly related to the high-gradient and narrow shelf-slope morphology as well as to the deglacial and Holocene sedimentary architecture of the central Vietnam Shelf (Bui et al., 2014). Consequently, sea level change may not have significantly affected the variations in terrigenous sediments of our studied core from the outer shelf since the Younger Dryas since the high sediment discharge by the small mountainous rivers of central Vietnam continued due to the high relief in the hinterland. This is demonstrated by the major-element data and TiO2/Al2O3 ratios of Core SO18401 that have not changed significantly during the last major sea-level rise between 9.0 and 8.2 ka BP (Figs. 5 and 8). Ti is enriched in coarse fractions of marine sediment (Schütz and Rahn, 1982), while Al is mostly found in fine-particle clay minerals (Biscaye, 1965). Concerning clay minerals, smectite increases while kaolinite and chlorite decrease between 9.0 and 8.2 ka BP, but only change in a very small range compared to other major changes throughout the core, e.g. increase in smectite after Younger Dryas, fluctuations in kaolinite after Younger Dryas and during Stage III, fluctuations in chlorite during Stage IV. These changes after Younger Dryas and in the mid- and late Holocene cannot be assigned to sea-level rise but are attributed to changes in the weathering regime (see below) (Fig. 4).

4.3. Chemical weathering and East Asian monsoon evolution

Given that the main sources of terrigenous sediments of Core SO18401 are small mountainous rivers in southern-central Vietnam, clay minerals and major elements from this core can be used to reconstruct the history of physical versus chemical weathering and erosion in southern-central Vietnam since the Younger Dryas. In Core
mountainous rivers of central Vietnam. In Core SO18401, variations in these two ratios together can be useful in characterizing the degree of sediments (silt and sand) versus... (Partin et al., 2015). Our 2005; Wang et al., 2005; Ma et al., 2012; Fig. 8) and from the Puerta ratios, and enhanced physical erosion indicated by the relatively high... of the chemical weathering intensity indicated by signification. During Stage IV (< 2.0 ka BP) that corresponds to younger part... the declination of Champa Empire and succeeding continuous southward expansion by Vietnamese (Taylor, 1983).

The highest sedimentation rates (around 113 cm/ka) in Core SO18401 are observed during Stages III and IV. This is related to the variable weathering and erosion behavior during weakened monsoon intensity conditions relative to the Early and Middle Holocene. Erosion could have been enhanced in the lower parts of southern-central Vietnam due to the relative abundance of smectite as the weathering product of the widespread volcanic source rocks, and slightly high values of SiO2/Al2O3 and TiO2/Al2O3 ratios (Figs. 4 and 8). Enhanced erosion during Stage III may have easily removed the weathered products from rock surfaces, preventing formation of kaolinite. Therefore, kaolinite, illite, and chlorite decrease during Stage III while increase during Stage IV together with a decrease in smectite.

For Core SO18401, the mineralogical proxy for chemical weathering...
characterization (smectite/(illite + chlorite)), as well as the geochemical proxies for chemical weathering (Al2O3/K2O) and physical weathering and erosion (SiO2/Al2O3 and TiO2/Al2O3) are useful indicators of monsoon-controlled weathering processes over southern-central Vietnam (Fig. 8). Generally, long-term weathering and erosion trends correspond to the Younger Dryas and the Holocene paleoclimatic stadlagmite 818O records at the Dongge Cave (Dykoski et al., 2005; Wang et al., 2005), and the palynological records from the Red River delta (Li et al., 2006). The sharp excursions of the different weathering proxies at 11.0 ka BP may be related to the shift in the intensity of East Asian monsoon at the end of the Younger Dryas (e.g., Li et al., 2006; Nagumo et al., 2013). The Younger Dryas cool and dry climatic conditions correspond to a decrease in soil formation and development, and an increase in production of primary clay minerals as weathering products (i.e., illite and chlorite). On the contrary, the Holocene is characterized by warm and humid climatic conditions, causing enhanced chemical weathering and thus secondary clay mineral formation (i.e., smectite and kaolinite). Seasonal variations of the intertropical convergence zone (ITCZ) and interannual changes of the El Niño-Southern Oscillation (ENSO), usually coupled with Asian monsoon system, also affect regional precipitation patterns of the tropical western Pacific (Yan et al., 2011), and can influence the chemical weathering of East Asia at various timescales (Yu et al., 2016). Stages II and IV of clay mineralogical and chemical records of Core SO18401 indicate strengthened chemical weathering intensity in southern-central Vietnam, potentially affected by coupled strengthened East Asian monsoon and northward movement of ITCZ variations as both, changes in the global and regional monsoon precipitation domains are closely linked to the movement of the ITCZ (Wang et al., 2012a,b, 2017).

5. Conclusions

Clay mineralogy and major-element geochemistry of the sediments from Core SO18401 were used to study the major sediment provenance as well as the history of physical erosion versus chemical weathering in central Vietnam over the past 13.2 ka. Through this study, the following conclusions are drawn:

(1) The small mountainous rivers in southern-central Vietnam are the major sediment sources of Core SO18401 on the Vietnam Shelf in the western SCS since the Younger Dryas period. The clay mineral assemblage consists mainly of smectite (average 47%), followed by moderate contents of illite (average 21%), kaolinite (average 16%), and chlorite (average 15%). Smectite is mainly produced by chemical weathering of Mesozoic extrusive rocks and Neogene-Quaternary basaltic. Illite and chlorite are derived mainly from physical weathering of Paleo-Mesozoic felsic intrusive rocks and Precambrian metamorphic rocks. Kaolinite is formed principally from chemical weathering of Paleo-Mesozoic felsic intrusive rocks under warm and humid climatic conditions.

(2) Smectite/(illite + chlorite), Al2O3/K2O, SiO2/Al2O3, and TiO2/Al2O3 ratios are utilized as weathering proxies for reconstructing the history of physical/chemical weathering and erosion in southern-central Vietnam. Increased smectite/(illite + chlorite) and Al2O3/K2O ratios suggest enhanced chemical weathering, while increased SiO2/Al2O3 and TiO2/Al2O3 ratios indicate enhanced physical weathering and erosion. Our results show enhanced physical weathering and erosion during the Younger Dryas period and during 3.9–2.0 ka BP interval, while strengthened chemical weathering prevails during 11.0–3.9 ka BP and from 2.0 ka BP to present in southern-central Vietnam.

(3) The weathering and erosion history of southern-central Vietnam over the Holocene and Younger Dryas periods is mainly controlled by the East Asian monsoon climate. Four stages of weathering and erosion evolution could be identified. Stage I (11.0–11.1 ka BP) and Stage III (~3.9–2.0 ka BP) are characterized by enhanced physical weathering and erosion, associated with relatively arid conditions. By contrast, Stage II (~11.0–3.9 ka BP) and Stage IV (2.0 ka BP to present) exhibit strengthened chemical weathering, corresponding to more warm and humid climatic conditions.

Conflict of interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

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