Human impact overwhelms long-term climate control of weathering and erosion in southwest China

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ABSTRACT

During the Holocene there has been a gradual increase in the influence of humans on Earth systems. High-resolution sedimentary records can help us to assess how erosion and weathering have evolved in response to recent climatic and anthropogenic disturbances. Here we present data from a high-resolution (~75 cm/k.y.) sedimentary archive from the South China Sea. Provenance data indicate that the sediment was derived from the Red River, and can be used to reconstruct the erosion and/or weathering history in this river basin. Accelerator mass spectrometry (AMS) 14C dating provides direct age control and reveals coherent variations in clay mineralogy, geochemistry, and terrigenous flux, indicative of strong chemical weathering and physical erosion during the mid-Holocene warm period (6400–4000 cal [calibrated] yr B.P.), followed by weakening from ca. 4000–1800 cal yr B.P., and renewed intensification since 1800 cal yr B.P. Comparison with climatic records from China indicates that precipitation and temperature controlled both physical erosion and chemical weathering intensity before 1800 cal yr B.P. However, weathering proxies in the offshore sediment indicate recent increased soil erosion. We suggest that enhanced human activity (deforestation, cultivation, and mining) represents the most recent interglacial interval, with enhanced human activity. However, lake catchments are often local and delta sediment may be disturbed by reworking (Stanley and Hait, 2000). In contrast, continental slope settings can have relatively stable depositional environments and high sedimentation rates (Bayon et al., 2012). Here we report on the first continuous, high-resolution record of Red River (southwest China) discharge and investigate the interplay between Holocene climate variability, human activity, and erosion and weathering processes in southwest China.

INTRODUCTION

Continental erosion and weathering are the key processes that shape Earth’s landscape, regulate atmospheric CO2, and control the delivery of sediments and solutes to the ocean, affecting global climate over geological time scales (Raymo and Ruddiman, 1992). Temperature, precipitation, and physical erosion are critical factors influencing silicate weathering (Maher, 2011; West, 2012). Most studies of silicate weathering either focus on proxy records spanning thousands to millions of years (Colin et al., 2006; Lupker et al., 2013; Wan et al., 2012) or modern observations from soils or rivers (Liu et al., 2007; West, 2012). In contrast, high-resolution records spanning the Holocene are scarce (Bayon et al., 2012; Catalan et al., 2014; Hu et al., 2013); this time period is of particular interest for paleoclimate studies because it not only represents the most recent interglacial interval, but also one affected by anthropogenic processes (Bayon et al., 2012). Lake (Catalan et al., 2014; Shen et al., 2006) and deltaic cores (Hu et al., 2013; Li et al., 2009) have been used to reconstruct Holocene erosion and weathering rates to determine their relationship with climate and human activity. However, lake catchments are often local and delta sediment may be disturbed by reworking (Stanley and Hait, 2000). In contrast, continental slope settings can have relatively stable depositional environments and high sedimentation rates (Bayon et al., 2012). Here we report on the first continuous, high-resolution record of Red River (southwest China) discharge and investigate the interplay between Holocene climate variability, human activity, and erosion and weathering processes in southwest China.

MATERIALS AND METHODS

Core 337PC was retrieved from the Qiongdongnan Basin offshore of the Red River delta in 516 m water depth (Fig. 1). The area has largely been supplied by the Red River since the late Miocene (Wang et al., 2011) and derives sediment from southeastern Tibet. Core 337PC comprises homogeneous, hemipelagic clayey silt. Ten accelerator mass spectrometry (AMS) 14C dates from planktonic foraminifera reveal linear sedimentation rates of ~75 cm/k.y., providing a continuous, high-resolution record of continental conditions since ca. 6400 cal yr B.P. (Fig. 2A). Terrigenous grain size was analyzed for 478 samples by laser particle analyzer. Clay mineralogy was determined by routine X-ray diffraction (XRD) analysis (Wan et al., 2012). Major and trace element concentrations were determined from 48 bulk terrigenous samples and <2 μm clay separates of 116 samples by inductively coupled plasma–atomic emission spectrometry (ICP-AES) and ICP mass spectrometry (ICP-MS). Analytical uncertainties were <1% for major elements and 3% for trace elements. In order to constrain provenance, Sr and Nd isotopic compositions were determined on 12 samples, as well as on 4 muddy river sam-

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Figure 1. Locations of geographic features and terrestrial and marine records mentioned in the text. The global map inset shows other related cores in Redon Lake in western Europe (Catalan et al., 2014), offshore of Central Africa (Bayon et al., 2012), and in North America (Kurzweil et al., 2010).
PROVENANCE AND PROXIES

The Nd isotopic composition and to a lesser extent the silicate $^{87}\text{Sr}/^{86}\text{Sr}$ can be used as tracers of sediment provenance (Colin et al., 2006; Lupker et al., 2013). Figure 2B shows variations in $^{87}\text{Sr}/^{86}\text{Sr}$ values with potential sources, consistent with sediment delivery dominated by the Red River. Although Sr isotopes of detrital sediments show weak negative correlation ($R^2 = -0.18$) with the coarse grain-size fraction (Figs. DR1 and DR2 in the Data Repository), grain size does not exert a significant influence on provenance proxies because variations in $^{87}\text{Sr}/^{86}\text{Sr}$ values (0.722120–0.723993) are very small compared with those in possible source regions and are well within the range seen in the Red River (Fig. 2B). In contrast, Nd isotopes are not biased by grain size (Fig. DR2). Both Nd isotopes (Fig. 3A) and La/Th ratios (not shown) display no significant temporal trend during the Holocene, suggesting that there was no major change in source during that time. We conclude that this sequence effectively records the Holocene sediment discharge of the Red River, so it can be used to reconstruct environmental changes in this basin. The prevailing southward winter monsoon could possibly transport suspended materials from the river mouth to the study area, although the dominant sediment transport mechanism remains unclear.

We use kaolinite/illite and the chemical index of alteration (CIA; Nesbitt and Young, 1982) of the <2 μm clay fraction to reconstruct chemical weathering intensity through time, which gives a quantitative measure of chemical alteration by constraining the loss of labile Na, Ca, and K relative to stable Al. We define chemical weathering intensity here as the degree of chemical alteration of the soil products relative to host rocks in the drainage area caused by silicate weathering. Kaolinite is formed in soils developed in regions with warm humid climates and good drainage conditions, whereas illite is the product of physical erosion from bedrock or formed by weathering of feldspar and micas under moderate hydrolysis conditions (Chamley, 1989). With intensification of chemical weathering in the basin, further degradation of illite to kaolinite would result in a higher kaolinite/illite ratio (Liu et al., 2007; Wan et al., 2012). Terrigenous mass accumulation offshore delivered from rivers can also represent a proxy of accelerated soil erosion onshore (Clift et al., 2014; Wan et al., 2012).

In addition to chemical weathering and provenance changes, other factors may influence the sedimentary mineralogy and geochemistry, such as hydraulic sorting by oceanic currents, sea-level change, and postdepositional diagenesis. The absence of authigenic minerals observed by XRD or SEM indicates negligible diagenesis, consistent with the shallow burial and high sedimentation rates. Hydrologic sorting does not appear to have significant influ-

Figure 2. A: Depth-age profile. B: Sediment provenance discrimination diagram; 10 accelerator mass spectrometry (AMS) $^{14}$C dates of planktonic foraminifer samples are shown with an uncertainty of $2\sigma$. For comparison, Sr-Nd isotope data of sediments from the Pearl, Red, and Mekong Rivers (Liu et al., 2007), the Beibu Gulf (Wei et al., 2012), the Annamite Range (Schimanski, 2002), Taiwanese rivers (Lan et al., 2002), the Luzon River (Goldstein and Jacobsen, 1988), and the Hainan River (this study) are plotted.

Figure 3. Comparison of core 337PC records with other records since 6400 cal yr B.P. Vertical gray band indicates the time period dominated by human activity. A: Nd isotopic composition (red circle) with an uncertainty of $2\sigma$ and terrigenous mean grain size in core 337PC (raw data, gray line; 25 point running average, purple line). Black dots show 10 accelerator mass spectrometry $^{14}$C dates with an uncertainty of $2\sigma$. B: Temperature anomaly in southwest China (Hou and Fang, 2012) (orange line) with uncertainty (yellow band) and the summer monsoon proxy of stalagmite $^{18}$O at Dongge Cave (Wang et al., 2005) (raw data, blue line; 35 point average, black). PDB—Peedee belemnite. C: Chemical index of alteration (CIA) of clay fraction (magenta diamond) and kaolinite/illite (green circle) at core 337PC. D: Enrichment (enrich) factor of As (neon red diamonds) and terrigenous flux (brown circles) at core 337PC. E: Charcoal record of core VN in the Red River delta (Li et al., 2009) (black bars) and pollen record in Lake Erhai (Shen et al., 2006) (blue line). PRC—People’s Republic of China.
ence on either the kaolinite/illite ratio or the CIA of the <2 μm fraction (Fig. DR2). Because we have a single dominant source significant effects from mixed sources driven by changing currents can be excluded. No reversed 14C age or turbidite-like deposit was observed, suggesting insignificant reworking of sediments on the shelf. Sea level remained stable over the studied period (Siddall et al., 2003), so this is not expected to have had any influence on sediment composition in core 337PC. The lack of correlation between terrigenous grain size and sea level on one hand and terrigenous mass accumulation rate (MAR), kaolinite/illite, and CIA values on the other (Fig. 3; Fig. DR2) strongly suggest that these latter proxies do not reflect changes in transport processes, but instead can be used to reconstruct weathering and/or erosion onshore. Soil residence time in the river basin is crucial for the interpretation of weathering proxies in offshore sediments. Estimates for denudation rates in the Red River basin range from ~0.4 mm/yr to 0.7 mm/yr, based on sediment yield, rates in the Red River basin range from ~0.4 mm/yr to 0.7 mm/yr, based on sediment yield, and ~0.4–8 mm/yr, as calculated by 10Be data from the region (Henck et al., 2011). According to the relationship between denudation rate and soil time scale of von Blanckenburg (2005), we estimate ~200–1000 yr for soil residence time in the Red River basin. This means that the offshore weathering records could have a 200–1000 yr time lag between deposition and the initial chemical weathering.

CLIMATE VERSUS HUMAN CONTROL ON EROSION AND WEATHERING

The clay mineral and geochemical proxies reveal consistent variation since 6400 cal yr B.P. (Fig. 3C). In general, CIA and kaolinite/illite values show that the terrigenous alteration during the Holocene can be divided into three stages: stage 1 (6400–4000 cal yr B.P.), characterized by relatively strong weathering intensity during the mid-Holocene warm period; stage 2 (4000–1800 cal yr B.P.), with gradually weakening weathering intensity; and stage 3 (since 1800 cal yr B.P.), with evidence for a rapid strengthening of weathering. This trend is also supported by morphological examinations of >31 μm feldspar grains using SEM (Fig. DR3). Feldspar grains in sediments from stage 3 display higher weathering class (high) compared to those from stages 1 (medium high) and 2 (medium low). Similar variation is also found in the erosion record, as tracked by terrigenous MAR, with high values (~69 g/cm²/k.y.) during stage 1, very low values during stage 2 (~36 g/cm²/k.y.), and high values during stage 3 (~74 g/cm²/k.y.) (Fig. 3D).

In general, the long-term weathering and erosion trends during stages 1 and 2 track the temperature in southwest China (Hou and Fang, 2012). They also follow the decreased rainfall signal inferred from the Dongge Cave speleothem isotopic records (Fig. 3B) that is ultimately related to orbitally induced lowering of Northern Hemisphere summer solar insolation during this interval (Wang et al., 2005). Decreased physical erosion was driven by weakening precipitation during the time. Considering the much longer time span of the study period compared to the soil residence time and stable provenance, we are confident that the general weakening of chemical alteration during the mid-Holocene reflects an overall change of weathering conditions in the Red River basin.

Among the rivers that drain southeastern Tibet, the Red River has the highest physical erosion rate (1100 t/km²/yr) and far exceeds the supply limit condition (~100 t/km²/yr) (West, 2012). Under this weathering-limited regime, chemical weathering is incomplete, incongruent, and dependent on the kinetics of silicate mineral dissolution reactions, as regulated by temperature, runoff, and vegetation (Maheer, 2011; West, 2012). This mechanism is demonstrated by close coupling between continental silicate weathering, physical erosion, and climatic forcing during the middle Holocene in the Red River basin.

A similar decreased Holocene weathering trend is also found in the delta of the Pearl River in south China (Hu et al., 2013), and the Congo River in central Africa (Bayon et al., 2012), as well as Redon Lake in Spain (Catalan et al., 2014), and offshore North America (Kurzweil et al., 2010) (Fig. 1). The general, global-scale weakening of silicate weathering during the middle Holocene and consequent reduced CO₂ consumption correlates with rising atmospheric CO₂ levels (Lüthi et al., 2008). Although the sustained and slowly rising CO₂ has been ascribed to anthropogenic processes as long as 6000 yr ago (Ruddiman et al., 2011), climate change rather than human disturbance seems to have dominated continental silicate weathering, at least during the middle Holocene.

Some decoupling between climate and erosion and weathering records occurred during the late Holocene. Rapid intensification of both weathering intensity (Fig. 3C) and physical erosion (Fig. 3D) started after 1800 cal yr B.P. (stage 3), while both precipitation and temperature remained relatively stable between 1800 and 500 cal yr B.P. and slightly increased after 500 cal yr B.P. This suggests no direct relationship between weathering and erosion and precipitation and temperature at that time. Moreover, weathering proxies, including kaolinite/illite and CIA, reached maximum values after 500 cal yr B.P., rather than during the middle Holocene, despite the fact that precipitation and temperature were significantly lower at that time than before 4000 cal yr B.P. (Fig. 3). All the above suggest that climate alone cannot be solely responsible for the weathering and erosion changes observed since 1800 cal yr B.P. Because this interval is comparable to the soil residence time in the Red River basin, it is difficult to distinguish enhanced erosion of older soils from contemporaneous chemical weathering conditions. We suggest that both processes are related to stronger human activity and have contributed to the increased alteration observed in the core.

A striking feature of our results is that sulfur-related metal elements (i.e., As, Pb, Cu, Mo, and W) and corresponding element enrichment factors (Fig. 3D; Fig. DR4) strongly increased by 2–3× after 1800 cal yr B.P. Many of these elements occur together in polymetallic sulfide minerals in gold-bearing deposits. Gold mining in the Yunnan Province dates back to the Han Dynasty, ~2000 yr ago (Chen et al., 2001), and this activity could have released abundant sulfur-related metals into the river. In addition, smelting through burning of trees was crucial to gold extraction in ancient times. Moreover, strengthened weathering and erosion and sulfur-related metal element accumulation since 1800 cal yr B.P. coincide with evidence for intensified agriculture and early urbanization in the Red River basin (Li et al., 2009; Shen et al., 2006) (Figs. 1 and 3E). The large-scale human migration into the lower reaches of the Red River from south China occurred after ca. 2000 cal yr B.P. (Li et al., 2009). Regardless of the exact cause of the intensified deforestation since 1800 cal yr B.P., the higher demand for natural resources was probably the ultimate reason for the trends described here. Deforestation, cultivation, and mining-induced rock exposure stimulated stronger soil erosion and reworking of altered sediment from the existing weathering profile. Our data show that the human impact gradually superseded long-term climate control of erosion and weathering in the Red River basin, especially since 1800 cal yr B.P.

IMPLICATIONS

Our study provides evidence about when and how the Red River basin changed from a climate-dominated to a human-disturbed erosion and weathering pattern. One important implication of this finding is that millennium-scale changes in silicate weathering in regions with high denudation rates cannot be overlooked in the current context of global climate change and the carbon cycle. These regions may be particularly important in influencing the carbon cycle because of both high weathering flux and high sensitivity to long-term temperature-weathering feedbacks. Our study also highlights the importance of increased soil erosion, as tracked by weathering proxies in offshore sediments. This anthropogenic effect on the environment has exceeded the influence of natural climate change over the past 1.8 k.y., suggesting that the modern Red River cannot be used as a modern analog for understanding controls on erosion and weathering in the geologic past.
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Notes

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