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# Clay mineral variations in Holocene terrestrial sediments from the Indus Basin

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A B S T R A C T

We employed X-ray diffraction methods to quantify clay mineral assemblages in the Indus Delta and flood plains since ~14 ka, spanning a period of strong climatic change. Assemblages are dominated by smectite and illite, with minor chlorite and kaolinite. Delta sediments integrate clays from across the basin and show increasing smectite input between 13 and 7.5 ka, indicating stronger chemical weathering as the summer monsoon intensified. Changes in clay mineralogy postdate changes in climate by 5–3 ka, reflecting the time needed for new clay minerals to form and be transported to the delta. Samples from the flood plains in Punjab show evidence for increased chemical weathering towards the top of the sections (6–<4 ka), counter to the trend in the delta, at a time of monsoon weakening. Clay mineral assemblages within sandy floodplain sediment have higher smectite/(illite + chlorite) values than interbedded mudstones, suggestive of either stronger weathering or more sediment reworking since the Mid Holocene. We show that marine records are not always good proxies for weathering across the entire flood plain. Nonetheless, the delta record likely represents the most reliable record of basin-wide weathering response to climate change.



## Introduction

Variations in climate are one of the most prominent drivers of change in continental environments. Reconstructing the response of landscape to climate change over long periods of geological time is often difficult because of fragmentary sedimentary records, and because of the paucity or even complete lack of age control in terrestrial sediments. As a result, marine sediments are often used to constrain evolving continental environments, based on the assumption that the sediments that accumulate on a continental margin at any given time are representative of the terrestrial drainage basins from which they are sourced and the processes occurring therein (Thiry, 2000). However, if the flux of sediment at the delta largely reflects reworking of older flood-plain deposits, or if the sediment transport times are long and punctuated, then this assumption may not be valid. In such circumstances marine sediments would not act as good proxies of continental weathering conditions.

In this study we assess the linkage between marine and terrestrial clay mineral records in a single major river system. To do this we present clay mineral data from across the flood plains and contemporaneous deltaic sediments from the Indus River basin in SW Asia (Fig. 1). We chart how clay mineral assemblages have changed onshore in response to evolving monsoon intensity since ~14 ka. We further compare those mineralogies deposited in the flood plains with those at the delta in order to establish if the marine record evolves coherently with the flood plain, or not. By studying both the potential source areas and the delta sink, we establish a better understanding of the constraints and the caveats on the use of clay mineral assemblages as proxies of continental environmental change, a perspective that is not available to most studies of marine sediments that are typically made without the onshore controls enjoyed here.

The purpose of the current study is to document temporal variations in the clay mineralogy of the terrestrial sediments of the Indus system during the Holocene and to determine how these might be linked to previously published reconstructions of climatic variations since the end of the Last Glacial Maximum (LGM: ~20 ka) (Overpeck et al., 1996; Fleitmann et al., 2003; Gupta et al., 2003). Here we report for the first time on how monsoon variations since 14 ka correlate with changing clay mineral compositions in a major river flood plain, feeding one of the world's largest delta systems. In so doing we provide a linked continental source to marine sink perspective on the interpretation of clay mineral records in terms of environmental evolution, a perspective that is rarely considered, or indeed available when older marine sequences are analyzed.

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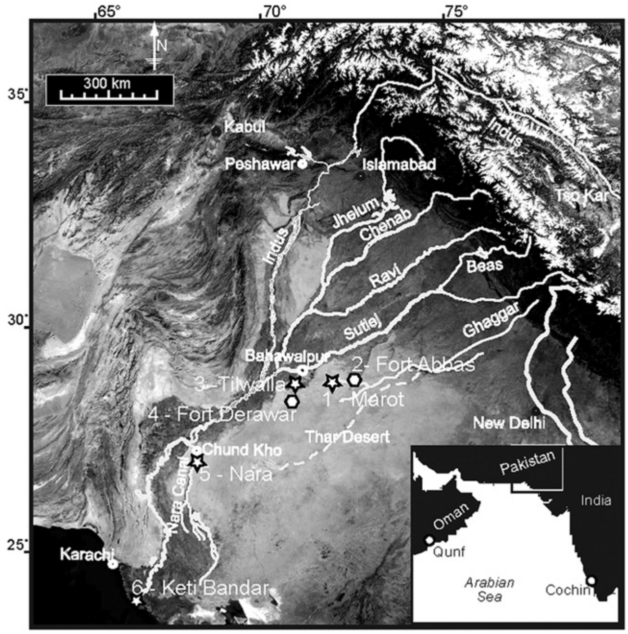


**Figure 1.** Study area showing four core sites (stars) and two trenches (hexagons) in the Indus River floodplain. Inset map provides regional overview, as well as the location of sites mentioned in the text outside the Indus basin.

## Clay mineral weathering proxies

There is general consensus among clay mineralogists that the neo-formation and transformation of clay minerals in soil profiles and regoliths is determined by an interaction between the geology, geomorphology (insofar as it controls drainage) and the climate of the source terrain (Morgan, 1973; Singer, 1984; Hillier, 1995; Wilson, 1999). Thus global-scale maps of mineral distribution on the deep-sea floor show that the general zonation of clay minerals mirrors contemporary climates on the continents (Biscaye, 1965; Griffin et al., 1968; Hamann et al., 2009). This implies that climatic conditions are a primary control on clay mineralogy, and that temporal changes in climate have the potential to cause changes in the clay mineralogy of the clastic component of the run-off (Singer, 1984; Chamley, 1989; Thiry, 2000). An outstanding question is how fast the response time of the weathering is to climate change and if marine clay mineralogy can record changes on millennial scales.

Before using clay mineral assemblages to interpret paleoclimate, however, a number of assumptions have to be made. One is that clay mineral formation is a direct response to climatic conditions (Thiry, 2000) and the time required to respond to changes in climate is shorter than the time interval being examined. This assumption may become less valid as shorter time periods are considered (<1000 yr), simply because the formation of new clays, or the transformation of existing clay minerals, are both dependent on weathering reactions with finite rate-determining steps (Fig. 2). Sediment-transport and residence times also may be an additional source of uncertainty, although this is likely to be less important on time scales $>10^6$ yr. Clay mineral records from the South China Sea show a good correspondence between clay assemblages and the intensity of the East Asian monsoon over periods $>10^6$ yr (Wan et al., 2007). Recently, it has also been suggested that changes in mineralogy linked to millennial-scale variations are recorded in sediments from other Asian continental margins (Boulay et al., 2007; Colin et al., 2010), implying that the clay minerals in a weathering system can respond and leave a record on these shorter time scales too. We further assume that inherited clay minerals give information about the environment from which they have been derived (Hillier, 1995) and that, once formed, clay minerals remain stable unless altered by diagenetic processes, i.e. post-sedimentary processes.

This study was designed to examine how clay mineralogy within the Indus basin might reflect the evolving Holocene climate, principally the intensity of the SW Asian summer monsoon. Does weathering respond rapidly to postglacial climate change? We use illite crystallinity to trace the intensity of weathering because this is commonly interpreted as an index of the hydrolyzing power of the (soil) environment from which the mineral is derived (Lamy et al., 1998). Higher temperatures and rainfall leads to leaching by strong hydrolyzation, resulting in low crystallinity (wider XRD peaks). Thus, relative changes in the crystallinity of detrital illite can potentially help to differentiate between more or less weathering and thus to cold-dry and warm-humid conditions. We employ this method to assess whether monsoon intensity affects weathering over time scales of ~1000 yr in the manner anticipated from longer-term studies, because a strong monsoon might be expected to favor strong hydrolyzation.

In addition to illite crystallinity, we ratio a variety of clays whose origins are believed to be different and which have been used in the past as indicators of weathering intensity. Illite and chlorite are generally considered to be the products of physical erosion of low-grade metamorphic rocks with little chemical weathering and alteration. Illite distributions in marine sediments are related to detrital rather than authigenic processes (Griffin et al., 1968; Rateev and Gorbunova, 1969). Similarly chlorite, frequently associated with illite, is notably more abundant in present-day high-latitude soils and sediments (Biscaye, 1965; Jacobs, 1970). A clay–mineral assemblage rich in chlorite and illite is therefore typical of soils and sediments produced in high latitudes or by cold-climate weathering because chemical weathering in such settings is weak (Bockheim, 1982; Campbell and Claridge, 1982).

In contrast, soil forms rapidly and to greater depths in tropical and subtropical environments, where chemical weathering is intensified by the process of leaching (Birkeland, 1984). As a result, kaolin-group minerals and gibbsite are frequently abundant in well-developed (meters thick) soils from regions of tropical climate with high rainfall, whereas warm, dry regions with less leaching dominantly produce smectite-rich soil. Chlorite and illite prevail at high latitudes where physical weathering dominates (Thiry, 2000). Soil formation in arid areas, both cold and warm, is insensitive to climatic conditions; hence, paleoclimate reconstruction in these regions is generally not feasible using soils (Thiry, 2000). The kaolinite/chlorite ratio in marine sediments constitutes a reliable indicator of chemical hydrolysis versus physical processes in continental weathering profiles (Chamley, 1989). Kaolinite/chlorite and kaolinite/illite are proxies of humidity and high values are indicative of enhanced humidity (Thamban et al., 2002; Thamban and Rao, 2005).

When a soil is eroded its clays may be transported to the continental margin. This explains why in recent deep-sea sediments of the North and South Atlantic the distribution of physically eroded chlorite has been observed to be nearly reciprocal to that of neo-formed, soil-derived kaolinite (Biscaye, 1965; Zimmermann, 1977). These patterns in the world oceans represent the signals of clay mineral change caused by large differences in climate. Over smaller regions, or with less extreme climate variation, the sedimentary record of weathering is likely to be manifested by more subtle changes in clay mineralogy. For example, changes in the relative abundances of clay minerals along a climatic gradient (280–720 mm average annual modern rainfall, mean annual temperature 9–13°C) across the Chinese Loess Plateau, related to variations in the Asian Monsoon, showed kaolinite increasing from around 2–3 to 5–6%, while expandable (smectitic) clays increased from ~30 to 60%, chlorite decreased from 7–8 to 0–3%, and illite (micas) decreased from 40–50% to 20–30% (Jeong et al., 2011). It is not clear if less dramatic changes would register as a clear paleoclimatic signal in sediments because