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Mechanism for enhanced eolian dust flux recorded in North Pacific Ocean sediments since 4.0 Ma: Aridity or humidity at dust source areas in the Asian interior?

Qiang Zhang[1,2], Qingsong Liu[3]*, Andrew P. Roberts[4], Juan C. Larrasoaña[5,6], Xuefa Shi[7] and Chunsheng Jin[1]

[1]State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, 100029 Beijing, China
[2]University of Chinese Academy of Sciences, 100049 Beijing, China
[3]Centre for Marine Magnetism (CM[2]), Department of Ocean Science and Engineering, Southern University of Science and Technology, 518055 Shenzhen, China
[4]Research School of Earth Sciences, Australian National University, Canberra, ACT 2601, Australia
[5]Instituto Geológico y Minero de España (IGME), Unidad del IGME en Zaragoza, C/ Manuel Lasala 44 9°B, 50006 Zaragoza, Spain
[6]Institute of Earth Sciences Jaume Almera (ICTJA)–Consejo Superior de Investigaciones Científicas (CSIC), C/ Solé i Sabarís s/n, 08028 Barcelona, Spain
[7]Key Laboratory of Marine Sedimentology and Environmental Geology, First Institute of Oceanography, Ministry of Natural Resources (MNR), 266061 Qingdao, China

ABSTRACT

Eolian material within pelagic North Pacific Ocean (NPO) sediments contains considerable information about paleoclimate evolution in Asian dust source areas. Eolian signals preserved in NPO sediments have been used as indices for enhanced Asian interior aridity. We here report a detailed eolian dust record, with chemical index of alteration (CIA) and Rb/Sr variations, for NPO sediments from Ocean Drilling Program Hole 885A over the past 4.0 m.y. CIA and Rb/Sr co-vary with the dust signal carried by combined eolian hematite and goethite concentrations. Changes in CIA around the intensification of Northern Hemisphere glaciation (iNHG) event at ca. 2.75 Ma indicate that dust production in source areas was associated mostly with physical and chemical weathering before and after the iNHG event, respectively. We here attribute the eolian flux increase into the NPO across the iNHG event mainly to increased availability of wind-erodible sediment in dust source areas derived from snow and glacial meltwater runoff, which resulted from glacial expansion and enhanced snowfall in the mountains surrounding the Tarim region in response to global cooling. Our results provide a deeper understanding of Asian interior environmental changes in response to global paleoclimate changes, where dust source areas became intermittently moister rather than more arid in response to global cooling.

INTRODUCTION

Asian interior dust source areas provide large quantities of eolian dust that is carried by westerlies to the North Pacific Ocean (NPO; Maher, 2011; Prospero et al., 2002; Ziegler and Murray, 2007). Eolian dust archived in pelagic NPO sediments provides valuable insights into paleoclimate changes over different time scales (Rea, 1994). It has been suggested that eolian flux to NPO sediments is related directly to the intensity of aridity in Asian dust sources (Hovan et al., 1989; Rea et al., 1998). However, dust production may be controlled by many factors, including the hydrologic and geomorphic environments in source areas (Prospero et al., 2002). Furthermore, increased moisture can potentially enhance erosion and weathering, releasing fine particles from parent rocks for eolian transportation (Kocurek and Lancaster, 1999; Nie et al., 2015, 2018). Hence, eolian records may not have a simple correlative relationship with source aridity.

Ocean Drilling Program (ODP) Hole 885A is located downwind of Asia and is sufficiently far from the continent to preclude riverine inputs and ice-rafted debris influences (Snoeckx et al., 1995). Sediments from this hole are sourced from the Tarim Basin and adjacent deserts (Pettke et al., 2000). Increased eolian flux in Hole 885A across the intensification of Northern Hemisphere glaciation (iNHG) event at ca. 2.75 Ma has been speculated to indicate enhanced aridity in Asian dust source areas (Rea et al., 1998; Snoeckx et al., 1995). However, interpretation of eolian proxies remains controversial (Pye, 1989; Prospero et al., 2002), and it is necessary to assess how eolian materials are produced within dust source areas in response to paleoclimate changes.

We present here a detailed eolian dust record from ODP Hole 885A since 4.0 Ma using a method proposed by Zhang et al. (2018), along with chemical index of alteration (CIA) and Rb/Sr records. By comparing eolian proxy variations with the CIA and Rb/Sr data, we provide new insights for interpretation of paleoclimatic variations in Asian interior dust source areas.

MATERIALS AND METHODS

In this study, 237 discrete sediment samples were taken at ~6 cm stratigraphic intervals from sections 1H-1W to 3H-4W of ODP Hole 885A (44°41′N, 168°16′W; water depth = 5708.5 m; Fig. 1) between depths of 0.13 and 16.54 m below seafloor (mbsf). These samples are

*E-mail: qsliu@sustech.edu.cn

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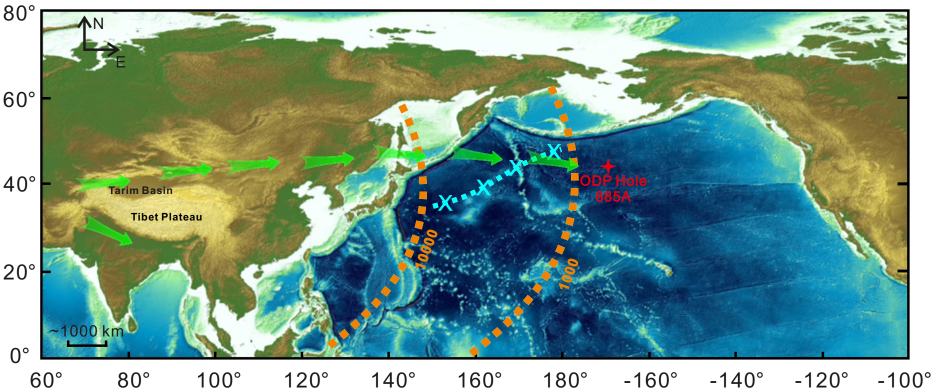

Figure 1. Location map of Ocean Drilling Program (ODP) Hole 885A, with green arrows denoting westerly wind trajectories from Merrill et al. (1989). "X" with dashed light blue line indicates the southern limit of ice-rafted debris (Bigg et al., 2008). Dashed orange lines indicate mineral aerosol fluxes to the North Pacific Ocean (NPO; in mg cm^{-2} k.y.$^{-1}$; from Duce et al., 1991).

predominantly composed of reddish brown and brown clay (Rea et al., 1993). An age model for this hole was obtained by linear interpolation between magnetic polarity reversals (Dickens et al., 1995) based on the geomagnetic polarity time scale (GPTS) of Gradstein et al. (2012). The age-depth relationship is presented in Part 1 of the GSA Data Repository[1]. Volcanic ash layers represent instantaneous accumulation layers (Part 2 of Data Repository material; Rea et al., 1993), so they were removed for age/linear sedimentation rate (LSR) determinations. The remaining pelagic sediments were not significantly affected by volcanic ash (see Part 5 of the Data Repository, La-Th-Sc ternary diagram).

Diffuse reflectance spectroscopy (DRS) was measured for these samples to obtain records of the combined relative concentration of hematite and goethite (Rel_{Hm+Gt}; Zhang et al., 2018) in the studied sediments and Rel_{Hm+Gt} flux. Dust from continental sources contains abundant hematite (Hm) and goethite (Gt; Larrasoaña et al., 2015; Oldfield et al., 2014). Rel_{Hm+Gt} is presented per unit mass of dry sediment by combining the measured DRS intensity for both Hm and Gt. Major and trace elements were also measured for 77 approximately equispaced samples to calculate CIA and the Rb/Sr ratio (details of above experimental procedures are presented in the Data Repository, Parts 3 and 4).

RESULTS

Diffuse Reflectance Spectroscopy

Downcore variations of Rel_{Hm+Gt}, Rel_{Hm+Gt} flux, the percentage content of operationally defined eolian dust (ODED; Snoeckx et al., 1995), and ODED flux are shown in Figure 2. Rel_{Hm+Gt} (Fig. 2E) and ODED content (Fig. 2F) variations have strong similarities, especially around the iNHG event, where they increase synchronously at 2.75 Ma and subsequently enter a high-eolian-input period, which further confirms that Rel_{Hm+Gt} is a reliable eolian proxy. Fluxes of Rel_{Hm+Gt} (Fig. 2G) and ODED (Fig. 2H) from ODP Hole 885A both increase progressively due to increasing contributions from hematite and goethite (Rel_{Hm+Gt}, Fig. 2E) and ODED minerals (Fig. 2F).

Chemical Index of Alteration (CIA) and Rb/Sr

CIA variations with time (Fig. 2D) are similar to the eolian records (Figs. 2E–2H) and increase abruptly at ca. 2.75 Ma across the iNHG event. All data from this hole nearly parallel the A–CN trend in an A–CN–K (Al_2O_3–CaO^*+Na_2O–K_2O) ternary diagram (Fig. 3). Pre-iNHG data (before 2.75 Ma) lie below the threshold for chemical weathering, and corresponding CIA values are less than that of the upper continental crust (UCC; Taylor and McLennan, 1985), which indicates that eolian materials are physical weathering products with no significant chemical alteration before 2.75 Ma. Post-iNHG data are distributed mainly in the weak chemical weathering region, which reflects incipient chemical weathering of source materials after the iNHG event (Fedo et al., 1995). Rb/Sr is also a chemical weathering indicator (Dasch, 1969) in terrestrial (Chen et al., 1999) and marine sediments (Wan et al., 2010). Rb/Sr (Fig. 2C) replicates CIA and other eolian variations, with increases at the iNHG event. Considering the relationship between weathering indicators (CIA and Rb/Sr) and eolian proxies, the enhanced eolian flux to Hole 885A was clearly associated with increased chemical weathering in source areas, where the transition from weak physical to enhanced chemical weathering provided more fine particles for eolian transportation to the NPO in response to the iNHG event.

DISCUSSION

Controls on CIA and Implications of Eolian Flux Changes

CIA is the most accepted among weathering indices for reconstructing source climate conditions (Nesbitt and Young, 1982, 1984). Higher CIA values suggest enhanced chemical weathering in moister source areas (Fedo et al., 1995), and lower CIA values may indicate the dominance of physical over chemical weathering processes (Nesbitt and Young, 1982; Young, 2001). In addition to climatic conditions, chemical weathering can be influenced by provenance, diagenesis, and sorting during transportation (Bahlburg and Dobrzinski, 2011). Sediments in Hole 885A were mainly derived from Asian interior dust sources, such as the Tarim Basin, over the past 12.0 m.y. without significant provenance variations (Pettke et al., 2000). The CIA data distribution nearly parallels the A–CN trend, which suggests that K-metasomatism during weathering was weak and that diagenetic influences were negligible (Fedo et al., 1995; Bahlburg and Dobrzinski, 2011). Sorting may enrich finer clay mineral components with higher CIA values (Nesbitt et al., 1997). During eolian transportation from source to sink, only finer particles (<8–10 µm) are carried long distances by wind to produce a homogeneous size distribution that reflects the intensity of the transporting wind (Gillette, 1981). Over the past 4.0 m.y., the eolian grain-size fraction has an increasing trend at Hole 885A (Fig. 2B; Rea et al., 1998). If grain-size variations dominated CIA changes, CIA should decrease in response to increased grain size, which is not observed. In summary, provenance, diagenesis, and sorting appear to have little effect on our record, so that CIA variations can be used to probe changing climatic conditions in the dust source region.

Under a background of global cooling since the late Cenozoic (Zachos et al., 2001), temperatures declined dramatically in the Asian interior during the iNHG (Haug et al., 2005; Maslin et al., 1995; Sigman et al., 2004). Hence, a moisture increase in Asian interior dust source areas is likely the dominant climatic factor for the transition from weak physical weathering to enhanced chemical weathering across the iNHG event. Co-variation among CIA, Rb/Sr, and eolian records suggests that the eolian input increase implies moister conditions in the dust source area.

Mechanism for Moisture Increase

The Tarim Basin is the largest dust source in East Asia; it is bounded by the Tibetan Plateau to the south, the Hindu Kush to the west, and the Tian Shan to the north. The basin is occupied mainly by the Taklimakan Desert,

[1]GSA Data Repository item 2020029, experimental procedures and supplementary interpretation, including age-depth relationships, depth-parameter relationships, details of experimental procedures and the CIA calculation, a La-Th-Sc diagram, and a land-ocean comparison, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

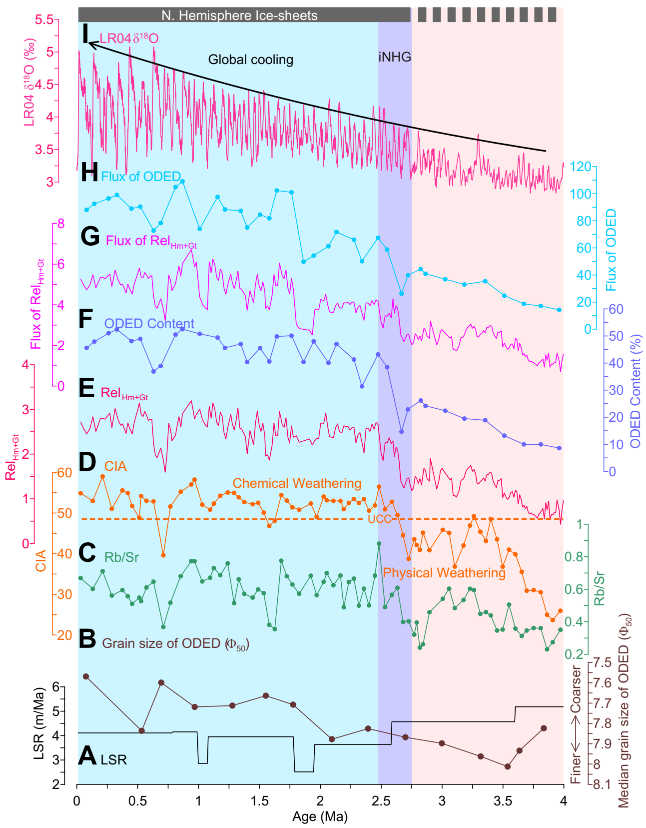

Figure 2. Chemical weathering and eolian records for Ocean Drilling Program (ODP) Hole 885A in the North Pacific Ocean. (A) Linear sedimentation rate (LSR). (B) Median grain size of operationally defined eolian dust (ODED; Rea et al., 1998). (C) Rb/Sr. (D) Chemical index of alteration (CIA). (E) Relative concentration of hematite and goethite (Rel_{Hm+Gt}). (F) ODED percentage content (Snoeckx et al., 1995). (G) Flux of Rel_{Hm+Gt}. (H) Flux of ODED (Snoeckx et al., 1995). (I) Benthic LR04 $\delta^{18}O$ stack (Lisiecki and Raymo, 2005). Vertical light pink, purple, and blue bands indicate pre-iNHG (intensification of Northern Hemisphere glaciation), iNHG, and post-iNHG periods, respectively. Orange dashed line in D indicates CIA value of the upper continental crust (UCC; Taylor and McLennan, 1985); values above this line indicate chemical weathering, while values below this line indicate physical weathering. Black bars at the top of the figure indicate development of Northern Hemisphere ice sheets (Zachos et al., 2001). Fluxes of Rel_{Hm+Gt} and ODED (Snoeckx et al., 1995) were recalculated using newly refined age model in this study.

which receives little rainfall (~10 mm/yr; Prospero et al., 2002). With such low rainfall, snow/glacial meltwater runoff from surrounding high mountains provides an important water source to the basin (Farinotti et al., 2015; Bolch, 2017; Chen et al., 2019). Snowmelt and glacial outwash from the surrounding mountains into the Tarim Basin also deliver alluvial/fluvial material that has led to deposition of hundreds of meters of Quaternary sediment (Prospero et al., 2002). Pye (1989) concluded that fluvial and chemical weathering efficiently produce small particles (i.e., grain size <10 µm) that can be carried easily by wind. After some degree of weathering involving water, such sedimentary deposits provide abundant fine-grained material that can be deflated by wind (Pye, 1989) and transported long-distance into the NPO (Prospero et al., 2002). Thus, increased snow/glacial meltwater runoff in response to global cooling likely played a key role in fueling eolian dust delivery from the Asian interior.

Eolian inputs into the NPO before the iNHG event were relatively low. This may have resulted from limited deposition of deflatable alluvial/fluvial material within Asian source areas, and insufficient snow/glacial meltwater to replenish runoff under relatively warmer conditions. Furthermore, chemical weathering would also have been limited by lower available moisture (Fig. 4A). With rapid development of Northern Hemisphere ice sheets (ca. 2.75 Ma), temperatures declined dramatically in the Asian interior during the iNHG (Haug et al., 2005; Sigman et al., 2004), which resulted in growth of large mid- to high-latitude Northern Hemisphere glaciers (Maslin et al., 1995). Glacier expansion and enhanced snowfall in the mountains surrounding the Tarim region in response to colder climates after the iNHG event provide a sound mechanism to explain the increased snow and glacial meltwater runoff into Tarim Basin, which provided a renewable source of dust for eolian transportation to the NPO, as discussed above (Fig. 4B). Thus, for the post-iNHG period, higher eolian fluxes at Hole 885A likely reflect greater snow/glacial meltwater supply of deflatable sediment rather than enhanced source area aridity. Eolian records from the Chinese Loess Plateau (CLP) have been affected by a complex interaction between Asian winter and summer monsoon systems, shifts in source areas, and considerable postdepositional alteration, and therefore they do not provide a straightforward comparison with NPO sediments (see the Data Repository, Part 6).

In addition to producing increased snow/glacial meltwater, the balance between moisture input and evaporation will also likely affect eolian dust generation (Mason et al., 2008, 2009). Increased effective moisture availability associated with an evaporation decline induced by decreased temperatures in response to the iNHG may have also facilitated eolian dust production from, and incipient chemical weathering within, alluvial/fluvial fans at the base of mountains around the Tarim region. While westerlies can deliver moisture to Central Asia (Aizen et al., 1996; Caves et al., 2015), strengthened westerlies across the iNHG event (ca. 2.75 Ma; Rea et al., 1998) are unlikely to have contributed much to the source area moisture increase, based on the small modern rainfall in the Tarim region (~10 mm/yr; Prospero et al., 2002).

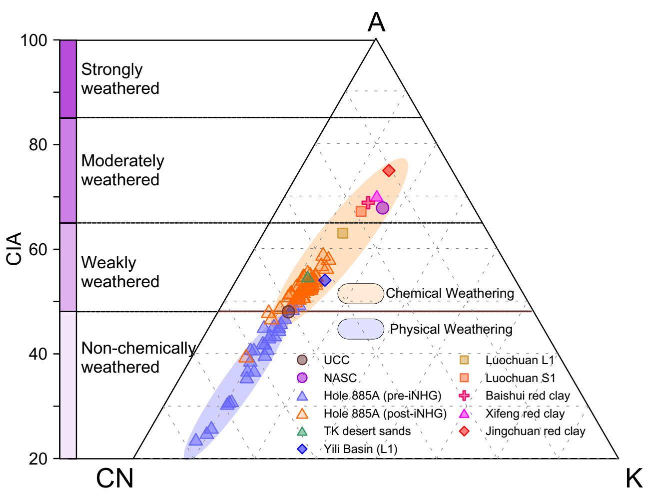

Figure 3. A–CN–K (Al_2O_3–CaO^*+Na_2O–K_2O) diagram (Nesbitt and Young, 1984, 1989), where upper continental crust (UCC) data are from Taylor and McLennan (1985); North American shale composite (NASC) data are from Gromet et al. (1984); loess (S1) and paleosol (L1) data from the Luochuan profile (Chinese Loess Plateau), are from Chen et al. (2001a); modern Yili Basin loess (L1) data are from Zhang et al. (2013); pre-Quaternary Xifeng red clay data are from Chen et al. (2001b); Baishui red clay data (mean value of chemical index of alteration [CIA] from pre-Quaternary samples) are from Xiong et al. (2010); Jingchuan red clay data (mean value of CIA from pre-Quaternary samples) are from Sun and Zhu (2010); and modern Taklimakan (TK) Desert data (surface samples) are from Honda and Shimizu (1998). Pre-iNHG (intensification of Northern Hemisphere glaciation) and post-iNHG data from Ocean Drilling Program Hole 885A are indicated with different colors.

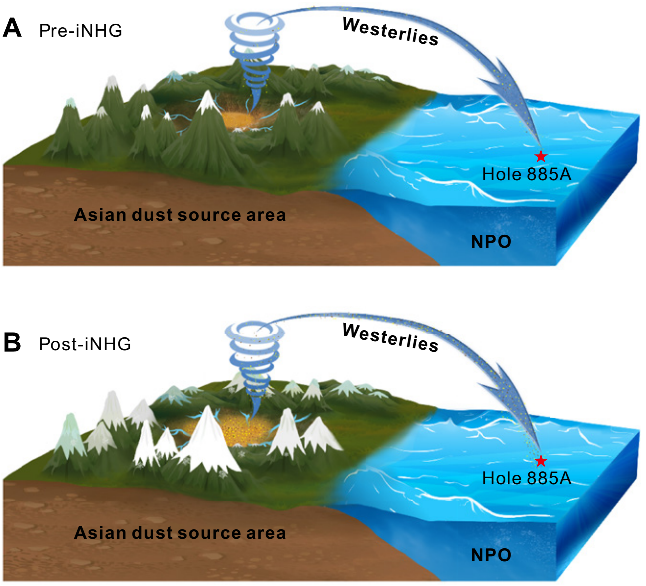

Figure 4. Cartoon illustration of "source-to-sink" pathway for Asian eolian dust. (A) In the pre-iNHG (intensification of Northern Hemisphere glaciation) period, there was insufficient snowmelt and glacial runoff into the Tarim Basin, which limited formation and deposition of fine-grained alluvial/fluvial sediment in basin floors and limited eolian dust contributions. (B) In the post-iNHG period, increased snow and glacial meltwater triggered by glacier expansion and enhanced snowfall in the mountains surrounding the Tarim region in response to colder climates transported more fine sediments into Tarim Basin. This sediment could then be deflated by wind and transported long distances to the North Pacific Ocean (NPO). Blue lines represent rivers that flow from surrounding mountains.

Among the mechanisms discussed, we suggest that snow/glacial meltwater runoff from surrounding mountains was the crucial factor in triggering enhanced eolian dust production in source areas, although effective moisture changes are also possible. The Asian interior has become increasingly arid through the Cenozoic as a result of paleo-Tethys Ocean retreat (Ramstein et al., 1997) and Tibetan uplift (An et al., 2001; Broccoli and Manabe, 1992). However, aridification alone is insufficient to produce dust sources from which long-term, long-distance dust transportation can occur. Dust is only likely to have been generated from restricted areas within the arid Asian interior in which renewable fine-grained sediment sources are available, such as the base of mountains and basin floors around the Tarim region, where alluvial/fluvial sediments derived from surrounding mountains are deposited (Prospero et al., 2002). Our results provide a new perspective to reexamine the paleoclimatic significance of NPO eolian records.

CONCLUSIONS

We have reconstructed a new eolian dust record from ODP Hole 885A for the past 4.0 m.y. We interpret increased eolian fluxes into the NPO as reflecting increased availability of wind-erodible sediment delivered by snow/glacial meltwater runoff into the Tarim region triggered by glacier expansion and enhanced snowfall in the mountains surrounding the Tarim region in response to colder climates, especially across the iNHG event. Increased snow/glacial meltwater runoff and intensified chemical weathering produced an intermittently renewable source of fine particles to the basin floor that were available for wind erosion and long-distance transport to the NPO. Our evidence suggests that moisture availability is critical and that the eolian record of NPO sediments should not be treated simply as an Asian dust source region aridity indicator.

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