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Asian dust from land to sea: processes, history and effect from modern observation to geological records

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Preface

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Abstract

Production, transport and deposition of aeolian dust from land to sea closely interact with regional environment and global climate. This Special Issue addresses transport of aeolian dust from the Asian inland to the Loess Plateau and North Pacific Ocean and their possible links to oceanic ecosystem, global climate and even human activity, over various timescales. The papers in this volume are multidisciplinary in nature and include sedimentology, mineralogy, geochemistry, environmental magnetism and climate modelling on multi-timescales from interannual, glacial–interglacial to tectonic timescales. Based on modern observation, geological records and modelling, this Special Issue offers new insights especially into aeolian provenance, dynamics controls on dust production, a novel marine aeolian proxy, as well as long-term aeolian input to the marginal basins of NE Asia and its influence on oceanic productivity. This issue provides a good example for future comprehensive studies of source-to-sink processes of Asian dust from land to sea.

1. Introduction

Aeolian dust, defined as terrestrial materials transported by atmospheric circulation, is a major erosional product of arid land and a significant component of deep-sea sediments (Liu, 1985; Rea, 1994). Understanding how aeolian dust cycle interacts with the climate system has been a frontier research topic in Earth science in recent years (Jickells *et al.* 2005; Martínez-Garcia *et al.* 2011; Jacobel *et al.* 2019). Modern observations, model simulations and sediment records demonstrate that the production, emission and deposition of aeolian dust are closely linked to Earth's climate state (Ding *et al.* 1994; Shao *et al.* 2011; An, 2014; Sun *et al.* 2019 and references therein). A dustier Earth during glacial periods is usually associated with greater aridity in source regions, less vegetation and stronger winds (Lambert *et al.* 2008; Winckler *et al.* 2008; Muhs, 2013). On the other hand, dust can influence climate directly, by the reflecting and absorption of solar radiation, or indirectly, by modifying cloud properties (Forster *et al.* 2007; Maher *et al.* 2010). Dust transported to the oceans can also affect climate via ocean fertilization, as mineral dust containing iron can modulate the uptake of carbon in marine ecosystems and thus potentially influence the atmospheric CO_2 concentration and thus global climate (Martin, 1990; Jickells *et al.* 2005; Boyd *et al.* 2007; Murray *et al.* 2012; Tagliabue *et al.* 2017). The global distribution of monthly mean total iron concentration is closely correlated to the dust flux to the world oceans (Fig.1a, b), suggesting a dominant control over iron release to the deep sea by dust inputs.

Asia is the second largest dust source region in the world, with ~600 Mt and ~70 Mt annual dust emissions to the atmosphere and ocean, respectively (Fig. 1a) (Shao *et al.* 2011). Observational evidence implies that aeolian dust originating from Asia has a significant influence over the marine and continental environment, as well as global climate (Rea, 1994; Tanaka & Chiba, 2006; Uno *et al.* 2009). With the aid of atmospheric circulation (i.e. East Asian winter monsoon and westerlies) (Fig. 1b), aeolian dust from the Asian desert regions has been transported eastward to the Chinese Loess Plateau (Liu*et al.* 1985), wide areas of the Pacific Ocean (Duce *et al.* 1991; Rea, 1994; Nagashima *et al.* 2007; Winckler *et al.* 2008; Wan *et al.* 2012) and has reached North America (McKendry *et al.* 2001) and even Greenland (Biscaye *et al.* 1997; Uno *et al.* 2009). While our knowledge of the Asian aeolian sources, transport and deposition has greatly advanced in the last 30 years (An, 2014; Sun *et al.* 2020), large uncertainties and knowledge gaps, especially about the impacts and interactions of aeolian dust with the regional- and global-scale biogeochemical cycles, still exist

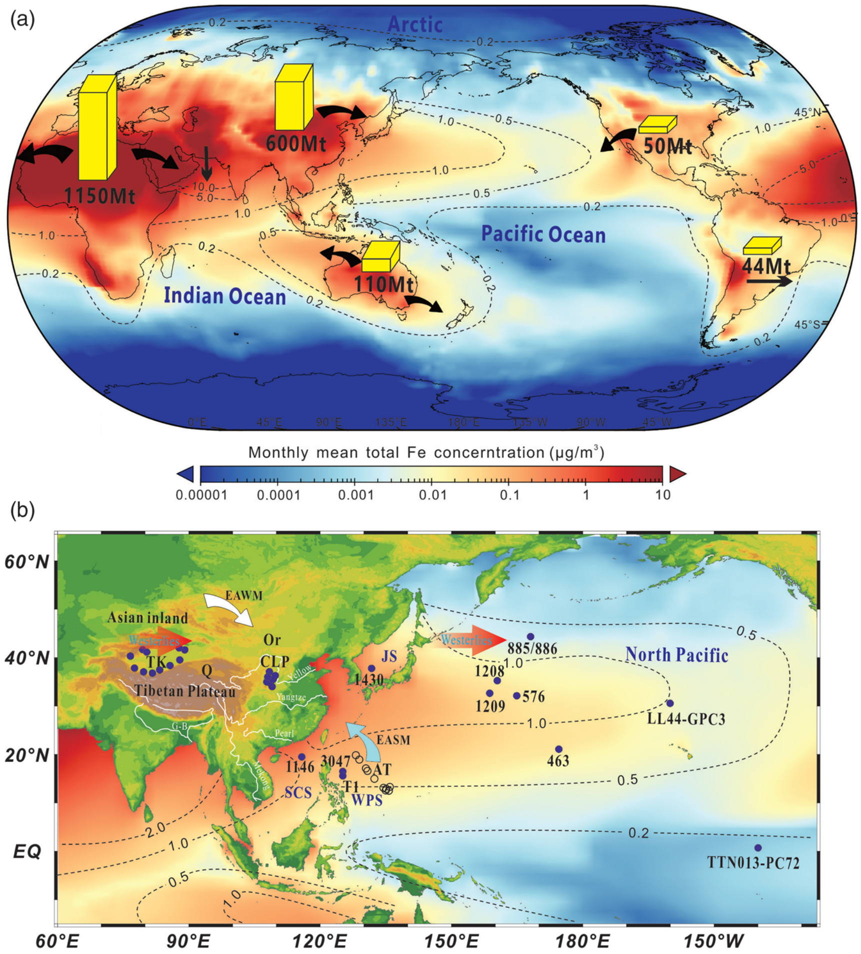

Fig 1. (a) Global distribution of the world's major deserts and dust emissions. The magnitudes of dust emission from different regions are given in Mt and indicated by bars (Tanaka & Chiba, 2006; Shao *et al.* 2011). The main routes of dust transport are indicated by black arrows. The global distribution of monthly mean total iron concentration (μg m^{-3}) (colour spectrum) and the dust flux (g cm^{-2} a^{-1}) (dotted line) to the world oceans are from Hamilton *et al.* (2019) and Jickells *et al.* (2005), respectively. Note the major contribution of Asian dust to the North Pacific. (b) Location map showing major geography of Asia-Pacific and the studied sites in this issue. The sediment sites and aerosol dust sites are indicated by blue dots and open black circles, respectively. Some important sites mentioned in this issue are also shown. The legends of iron concentration and dust flux are the same as in (a). Abbreviations: TK, Taklimakan Desert; Q, Qaidam basin; Or, Ordos Desert; CLP, Chinese Loess Plateau; JS, Japan Sea; SCS, South China Sea; WPS, West Philippine Sea; EAWM, East Asian winter monsoon; EASM, East Asian summer monsoon. The red, white and blue arrows indicate general wind directions of westerlies, EAWM and EASM, respectively.

(Tagliabue *et al.* 2017; Jacobel *et al.* 2019), partly because of a lack of comprehensive studies on source-to-sink processes of Asian dust from land to sea.

Asian topography has dramatically changed during the Cenozoic, with the progressive uplift of the Himalaya and Tibetan Plateau and the westward retreat of Paratethys (Prell & Kutzbach, 1992; Ramstein *et al.* 1997; Wang, 2004). At the same time global climate gradually cooled after the Eocene (Zachos *et al.* 2001). Driven by both tectonic uplift and global cooling, Asian inland areas experienced a long-term drying, eventually resulting in development of deserts and extensive deposition of loess in Central Asia during the Oligocene to Miocene (Guo *et al.* 2002; Zheng *et al.* 2015; Shen *et al.* 2017). This general geological background determines the production, emission, transport and deposition of Asian dust from land to sea from the geological past to present (Fig. 2). The huge dust inputs from Asia to the North Pacific supply large amounts of macronutrients (N, P and Si) and micronutrients (e.g. Fe, Mn and Cd) that are essential for phytoplankton growth (Jickells *et al.* 2005). The influence of Asian dust on oceanic biogeochemical processes, global carbon cycle and climate change is potentially significant (Fig. 2) (Han *et al.* 2011), but not well understood, which was the initial motivation for this Special Issue we have organized.

Great spatial (Asian interior to the Pacific) and temporal (modern to the Miocene) span is the main feature of this Special Issue (Fig. 1b). Ten papers address the transport processes and sedimentary records of Asian aeolian dust from the arid interior (Taklimakan Desert) to the Chinese Loess Plateau, marginal basins of NE Asia, the west Philippine Sea and the North Pacific, as well as their possible links to oceanic ecosystem, global climate and even human activity. This issue involves studies over multiple timescales (from interannual, glacial–interglacial to tectonic timescales) of Asian aeolian dust transportation from land to sea. New insights and the significant details from these contributions are outlined below in order of timescale.

2. Modern Asian dust from land to sea

In their contribution Yuko *et al.* (2020) study the origin of aeolian dust emitted from the Tarim Basin, which is considered to be one of the main sources of fine-grained dust in the northern hemisphere. However, it is unclear whether the source of dust emitted from the Tarim Basin is the Taklimakan or the Gobi Desert and mountain rivers around the basin, as the Gobi and fluvial sources produce more fine-grained detritus than the Taklimakan Desert. They analyse the electron spin resonance (ESR) signal intensity and Crystallinity Index (CI) of quartz from sediment samples of the potential sources surrounding the Tarim Basin. The converged values of the ESR intensity (7.2 ± 5.5) and CI (8.8 ± 0.2) of the fine silt of sediments from the rivers draining the Kunlun and Altyn mountains are similar to those of the aeolian dust emitted from the Tarim Basin, confirming their major contribution to that depocentre. This study highlights the importance of repeated cycling by fluvial and wind processes within the basin to produce homogeneous aeolian dust, which can be further transported to the Loess Plateau and North Pacific.

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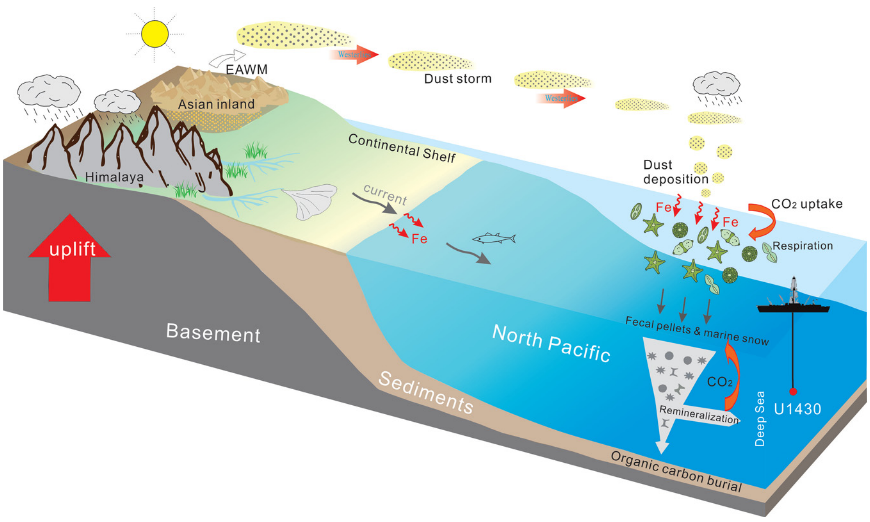

Fig. 2. Schematic representation of processes and effects of aeolian dust from Asian land to the North Pacific in the context of Cenozoic uplift of Himalaya and Tibetan Plateau and general drying of the Asian interior. The possible influence of dust iron on oceanic biogeochemical cycle is modified from Martínez-García & Winckler (2014). Note the significant role of iron fertilization in the carbon cycle through stimulating oceanic primary productivity, CO_2 uptake and burial of organic carbon in deep-sea sediments.

The west Philippine Sea has been suggested as one of the important sinks of dust transported from the Asian interior by winds. This is largely based on provenance analysis of mixed sediments (i.e. dust, volcanic and authigenic materials) deposited in the deep sea (e.g. Kolla *et al.* 1980; Wan *et al.* 2012; Xu *et al.* 2015), rather than pure dust collected in the air and/or water column by sediment traps, although the latter provides more reliable information on dust. Wang *et al.* (2020, this issue) investigate the microscopic mineralogy, trace elements and Sr–Nd isotopic compositions of modern dust samples collected in the air and seawater of the west Philippine Sea in 2014–15. The detrital minerals quartz, feldspar and gypsum show similar microscopic characteristics indicative of wind erosion (subangular to sub-round). Provenance analysis based on trace element and Sr–Nd isotopic compositions demonstrates that the modern aeolian dust deposited in the Philippine Sea mainly originates from the Ordos Desert (>80%), with minor supply from the Taklimakan Desert (<20%). Wind back-trajectories suggest that the dust was transported by the East Asian winter monsoon to the sea in 1 week. This result improves our understanding of modern Asian dust source-to-sink processes from land to sea.

Asian dust aerosols carried during some severe spring dust storms can be transported over long distances, even around the globe in a few days (Uno *et al.* 2009). However, the dominant factors that lead to abrupt changes of dust storm frequency on decadal timescale are not fully understood. Shang & Liu (2020, this issue) examine the spatial and temporal variations of East Asian dust storm frequency and Arctic sea-ice concentration during 1961–2015 and their possible links. Their results show that the spring dust storm frequency is highly correlated with the preceding winter Arctic sea-ice concentration and both of them experienced a remarkable fluctuating decrease in the past half-century. They further propose a mechanism whereby the Arctic sea-ice loss generates the hemispherical-scale atmospheric teleconnection pattern, including regional-scale circulation anomalies over East Asia and thus results in a reduction in dust storm frequency. This study provides an excellent example how high-latitude climate strongly influences the emission of modern Asian dust.

As an essential micronutrient for marine photosynthetic organisms, iron (Fe) transport to the open ocean primarily originates from terrestrial mineral dust derived from arid regions (Jickells *et al.* 2005; Murray *et al.* 2012). Due to increased human activity, however, pyrogenic Fe-containing aerosols are another possible source of dissolved iron (DFe) to open ocean (Mahowald *et al.* 2009). Ito *et al.* (2020, this issue) use one atmospheric chemistry transport model and two ocean biogeochemistry models to investigate the effects of atmospheric deposition of DFe from mineral dust and combustion aerosols on ocean biogeochemistry. The results show a higher sensitivity of net primary production in the North Pacific and North Atlantic to the change in combustion-generated aerosols than to mineral dust, regardless of the relative sedimentary source inputs. This study highlights the influence of the underestimated anthropogenic Fe-containing aerosols on the marine ecosystem in the context of increasing human perturbations.

3. Glacial–interglacial cycles of Asian dust from land to sea

Aeolian flux is widely accepted as a quantitative proxy for assessing the aridity of the dust source region (Rea *et al.* 1998; Winckler *et al.* 2008; An, 2014). However, the reconstruction of temporal–spatial dust flux variability across the Chinese Loess Plateau on glacial–interglacial timescales is rare because of poor constraints on loess age model and bulk density. Liu *et al.* (2020, this issue) are the first to present aeolian flux variations from eight loess–palaeosol sequences dating from 150 ka along two N–S-aligned transects on the Chinese Loess Plateau, based on a uniform age model of high-resolution optically stimulated luminescence (OSL) dating and pedostratigraphic correlation and reliable bulk density data. The aeolian flux results show consistent fluctuations, with higher and more variable values during glacial compared to interglacial periods. There is also a clear spatial increase from the southeastern Chinese Loess Plateau to its northwestern part. The high-resolution stacked aeolian flux records of the Loess Plateau since the Last Glacial Maximum (LGM) not only confirm the dominant control of global ice volume on dust production on glacial–interglacial timescales, but also provide a key curve for refining other dust flux datasets and improve models of past dust–climate interactions.

Sr–Nd isotopes, as robust indicators of sedimentary provenance, have been extensively used to constrain the signal of dust contribution to North Pacific sediments (Ziegler *et al.* 2007; Shen *et al.* 2017). Due to high cost and the time-consuming character of

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the analyses however, there are few high-resolution Sr–Nd isotopes records that can reveal how dust input to the deep sea on orbital timescales covaried with global climate. Zhang *et al.* (2020b, this issue) analyse Sr–Nd isotopes, trace elements and the grain-size of the silicate fraction extracted from sediments at high resolution from Ocean Drilling Program (ODP) Site 1209 in the North Pacific since 500 ka. The results show that a two-end-member mixing model between aeolian dust and dispersed volcanic ash accounts for the provenance. Variations of Nd isotopes mimic global deep-sea oxygen isotopes (LR04 stack) over the past five glacial–interglacial cycles, with lower (higher) ϵNd values during cooling (warm) periods. They propose that the relative contributions of Asian dust to volcanic ash during the glacial–interglacial cycles are the dominant factor controlling the sawtooth patterns of Nd and Sr isotopes. This study provides a potentially useful chronostratigraphy tool by analysing Nd isotope variations in detrital sediment in the North Pacific, especially for deep-sea sediments deposited below the lysocline (~3000 m) with no or limited amounts of calcareous microfossils.

Geological records from land to sea indicate that dust fluxes during glacial stages were globally two to five times higher than during interglacials (Maher *et al.* 2010). However, the relative contributions of different forcing factors (i.e. ice volume, sea level, CO_2, orbital parameters and underlying surface character) on the dust cycle are not well quantified. Li *et al.* (2020, this issue) conducted a series of sensitivity experiments with an Earth system model to evaluate the effects of various factors on Asian dust emission during the LGM. The simulation results show that the high-latitude ice-sheet extent and abnormal surface erosion in the dust source region were the two main forcing factors, which can cause Asian dust emissions to increase 3.77-fold and 1.25-fold compared to those of the present day, respectively. In contrast, the greenhouse gas content and orbital parameters were relatively weak. This study emphasizes the importance of accurate reconstructions of abnormal surface erosion in addition to considering ice-sheet extent during glacial–interglacial cycles.

4. Tectonic timescale Asian dust input to the Pacific

Effective extraction of an aeolian signal from marine sediment is crucial for further aeolian study. In addition to the conventional mineralogical and geochemical proxies, magnetic parameters (i.e. magnetic susceptibility, hard isothermal remanent magnetization (HIRM)) were also commonly used as indicators of long-term aeolian input to deep-sea sediment (Doh *et al.* 1988; Rea, 1994). However, these proxies usually comprise mixed information derived from all the magnetic particles, including dust, volcanic and biogenic components. Zhang *et al.* (2020a, this issue) review the study progress on mineral magnetism-related aeolian dust deposition in the North Pacific. They summarize the various magnetic minerals (iron sulphides, ferrimagnetic and antiferromagnetic minerals) with different origins in marine sediments and recommend a novel parameter Rel_{Hm+Gt} to infer the relative concentration of hematite and goethite, both of which have aeolian origin. The consistent variation of this new magnetic proxy with the chemically extracted aeolian content of sediments at ODP Site 885 in the North Pacific since 2.8 Ma confirm its reliability as a discriminator of aeolian provenance.

Long-term evolution of Asian aeolian dust input to the North Pacific has been investigated for nearly half a century (Rea *et al.* 1998 and references therein). However, there are very few similar studies from the marginal basins of NE Asia, which are major sediment sinks on the transport path for Asian dust from land to the North Pacific (Shen *et al.* 2017) (Fig. 1). Benefiting from samples recovered by Integrated Ocean Drilling Program (IODP) Expedition 346 with good age controls, Anderson *et al.* (2020, this issue) analyse the major and trace element contents of sediments from IODP Site U1430 located on the southern upper slope of the eastern Korean Plateau (Fig. 1) to reconstruct variations in aeolian flux since ~13 Ma. Multivariate partitioning analysis indicates that the Taklimakan Desert was the major sediment source of aeolian dust to the marginal basin, especially before the late Miocene (~12–8 Ma), while the contribution and flux from the Chinese Loess Plateau and Gobi Desert rapidly increased in the Plio-Pleistocene (since ~3 Ma). The provenance and flux trend at Site U1430 broadly agree with records elsewhere in the North Pacific. This study suggests that variation in dust source regions appears to track step-wise Asian aridification influenced by Cenozoic global cooling and periods of Tibetan uplift.

Both modern observations and glacial–interglacial-scale deep-sea records have demonstrated the significant influence of aeolian dust on oceanic biogeochemical cycles (Boyd *et al.* 2007; Murray *et al.* 2012). However, how this mechanism might operate on million-years timescales and how it would respond to climate change remains unclear (Martínez-Garcia *et al.* 2011). Zhai *et al.* (2020, this issue) examine the evolution of palaeoproductity in the marginal basins of NE Asia and its possible links to Asian dust input using bulk elements geochemistry and the total organic carbon (TOC) content of sediments at IODP Site U1430 (Fig. 1) since 4 Ma, during which the Earth experienced dramatic Northern Hemisphere Glaciation and global cooling. The results show that palaeoproductivity in the basin was greatly enhanced, especially at 3–2 Ma, consistent with rapidly increasing aeolian iron input from the Asian interior to the basin and growth of high-latitude ice sheets. Thus, in turn they propose that the enhanced efficiency of organic carbon burial in the marginal basin might contribute to the coeval decrease of atmospheric pCO_2 level and global cooling in the late Pliocene.

5. Conclusion

This Special Issue provides new insights about aeolian provenance, dynamic controls on dust production, novel marine aeolian proxies, as well as long-term aeolian inputs to the marginal seas of NE Asia and its influence on oceanic productivity. In the future, it is suggested that continuous *in situ* observations of aeolian dust transport and deposition processes from land to sea should be conducted, in order to quantitatively reconstruct long-term evolution of aeolian dust to the West Pacific, and to address any biogeochemical links to the carbon cycle and global Cenozoic cooling. Further data–model comparison would provide robust assessment of dust–climate interactions at different timescales.

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Conflict of interest. None.

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