Geochemical and magnetic characteristics of aeolian transported materials under different near-surface wind fields: An experimental study

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By combining ﬁeld investigations, ﬁeld sampling, wind-tunnel experiments, and laboratory measurements, the relationships between near-surface winds and the geochemical and magnetic characteristics of wind-transported materials were statistically analyzed. Our study was conducted using bulk surface samples from a major potential dust source area in Central Asia (the Ala Shan Plateau). Under near-surface wind velocities ranging from 8 to 22 m/s, the coefﬁcients of variation ranged between 1.6% and 14.9% for χf, 1.4% and 11.0% for χARM, and 0.7% and 12.3% for SIRM of the transported materials. For the 26 elements and oxides investigated, the coefﬁcients of variation of Ti, Cr, As, Zr, Ce, Pb, and Cu in the samples were greater than 10%. No consistent patterns were found between magnetic characteristics and elemental and iron oxide concentrations as a function of variations in near-surface wind velocities. In potential dust source areas under near-surface wind velocities, there are variations in the relationships between magnetic and geochemical characteristics in the ﬁne fractions of transported materials with different particle sizes. Given the wide variation in magnetic and geochemical characteristics of aeolian-transported materials under different near-surface winds, their use as proxies for past climate reconstruction must be carefully appraised.

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1. Introduction

Ancient aeolian deposits derived from the transportation and deposition of atmospheric mineral dust can record the mechanisms and rates of emission from source areas and potential transport routes, as well as the effects of post-depositional weathering, pedogenesis and other processes strongly linked with regional environmental change (Kukla et al., 1988; Harrison et al., 2001; Larrasoña et al., 2003; Maher, 2011). Analysis of data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Total Ozone Mapping Spectrometer (TOMS), as well as of dust storm frequency over the past half-century at a global scale, suggests that the Gobi and other sandy deserts of Central Asia (Prospero et al., 2002), particularly those in arid western China and southern Mongolia (Natsagdorj et al., 2003; Wang et al., 2006, 2008), are major potential sources of modern aeolian dust.

Throughout the Quaternary, dust emissions from these regions, which include the Tarim Basin, the northeastern Qinghai-Tibetan Plateau (Honda et al., 2004; Stevens et al., 2010; Pullen et al., 2011), the Ala Shan Plateau, and the Southern Gobi Desert of Mongolia (Sun et al., 2000, 2002a, b), have been the source of the material transported to form vast accumulations of dust such as those on the Chinese Loess Plateau (Liu, 1985). Transported materials provide evidence concerning atmospheric circulation patterns as well as dust traces in ice cores in Arctic regions (Bory et al., 2002, 2003), and have been used as proxies for past climate changes (Hao and Guo, 2005; Bloemendal et al., 2008; Sun et al., 2008, 2010) in depositional areas. In East Asia, the effects of post-depositional weathering and other processes on the particle size, geochemistry, and magnetic properties of aeolian deposits have been used as proxies for variations in the intensity of the Asian monsoons (Chen et al., 2007; Chavagnac et al., 2008; Rao et al., 2009), regional precipitation (Maher and Thompson, 1991; Balsam et al., 2011), pressure gradients and resultant wind velocities (Yancheva et al., 2007; Sugden et al., 2009), and aeolian processes and chemical weathering (Jeong et al., 2011).

Transportation of materials by aeolian processes is a prerequisite for the emission, transportation, and deposition of ﬁne particles such as dust aerosols far from the source regions. Because of the signiﬁcance of this dust for regional climate and environmental change, post-depositional processes affecting their geochemical and magnetic characteristics have been discussed in detail. For example, Oldﬁeld et al. (2009) suggested that, in a wide range of depositional environments, there is a strong link between particle size classes and magnetic properties. In addition, long-distance transportation and variations in transportation paths may change the magnetic characteristics of aeolian dust (Baker and Croft, 2010). Furthermore, over timescales of a few
hundred years (typical durations for soil formation), regional temperature and rainfall variations (Maher, 1998; Maher et al., 2003) and changes in the contributions of magnetotactic bacteria (e.g., Bloemendal et al., 1988) and cosmogenic and volcanic spherules (Maher, 2011) have led to significant variations in pedogenic magnetic susceptibility (Maher and Thompson, 1992; Liu et al., 2012), even though their major ingredients

Fig. 1. (A) Aeolian geomorphology of Central Asia and (B) location of sampling sites.

Fig. 2. Schematic diagram of (A) surface samples and (B) the wind tunnel and sample arrangement during the wind-tunnel experiments.
are aeolian-transported materials. With reference to the magnetic and geochemical characteristics of these sediments, parameters such as the magnetic susceptibility ($\chi$), frequency-dependent susceptibility ($\chi_f$), hard isothermal remanent magnetization (HIRM), susceptibility of anhysteretic remanent magnetization ($\chi_{ARM}$), saturation isothermal remanent magnetization (SIRM), S-ratio (the ratio of the remanence remaining after DC demagnetization of the SIRM to the original SIRM), $\chi_{ARM}/\chi_{SIRM}$, SIRM/$\chi_f$ and the ratios of the contents of various elements and iron oxides (e.g., the Rb/Sr ratio) have been used as indicators of palaeo-environmental changes.

During each aeolian event, variations in near-surface wind field strength may change the composition of transported materials, and, consequently, create variations in the dust fractions within these materials; this can lead to differences in the geochemical and magnetic properties of the transported materials, and their inter-relationships, at depositional sites. In contrast to descriptions of aeolian deposits that have been subject to post-depositional change, there have been few studies of the magnetic and geochemical characteristics of modern dust (Maher, 2011), and their response to changes in the near-surface wind field remains poorly understood.

Poor understanding of the geochemical and magnetic characteristics of wind-transported materials has hindered our ability to identify the sources of materials that form aeolian deposits and describe more precisely the post-depositional weathering and other processes that alter the materials once they become incorporated within aeolian deposits. This has made it difficult to use the geochemical and magnetic characteristics of these materials to reconstruct past environmental changes. To deepen our understanding of these processes, we obtained bulk (unaltered) surface samples from potential dust source areas in Central Asia, and used wind-tunnel experiments and laboratory analysis to simulate the effects of near-surface winds on the geochemical and magnetic characteristics of the transported materials. The aims of our study were to enhance our understanding of the effects of aeolian processes on the geochemical and magnetic characteristics of the transported materials, thereby improving our understanding of the degree of variation in the magnetic and geochemical characteristics of sediments in potential source areas, and to facilitate the interpretation of post-depositional changes in aeolian sediments sourced from Central Asia.

### 2. Regional environment and sampling criteria

#### 2.1. Sampling location and criteria

Sampling sites were selected in the Ala Shan Gobi, an extremely arid area of western Inner Mongolia that lies adjacent to southern Mongolia (Fig. 1). As an area with one of the highest dust-emission frequencies in China (e.g., Zhou and Zhang, 2003; Wang et al., 2008), this region also produces one of the highest emissions of dust aerosols (i.e., particulate matter (PM) fractions <10 $\mu$m in diameter; henceforth, PM10; e.g., Zhang et al., 2003) and is one of the most important potential dust source areas in Central Asia (e.g., Washington et al., 2003). The
regional environment and surface characteristics have been described by Wang et al. (2005).

From 9 to 13 June 2010, we obtained 15 bulk surface samples at three sites (Fig. 1) using 120 × 30 × 30 cm sample boxes (Fig. 2A). These sites were selected because they were representative of the Gobi surfaces in this area and, therefore, captured key characteristics of the region. Details of our sampling criteria and collection procedures are described in Wang et al. (2012a). Bulk samples were obtained by placing a sample box on the surface, removing the soil around the box, and then excavating about 80 cm down so that the box could be lowered around the sampled soil without disturbing the surface or sides of the sample. A wooden sheet was inserted horizontally below the box to serve as its bottom. The box was covered, and steel wires were used to wrap the box to ensure that its contents did not change during transportation. As we could not detect compositional differences in the surface sediments in the field, we collected five samples separated by 50 to 200 m at each site to increase the likelihood of capturing the full range of variation at each site. Each sample had similar characteristics: no vegetation cover, a flat surface, no surface cracks, no biological or physical crusts, no evidence of human disturbance, and a similar degree of gravel coverage. However, during the wind-tunnel experiments, tiny cracks were found in the surfaces of 2 of the 15 samples. To avoid introducing errors caused by these cracks, we excluded the data from the 2 damaged samples, and only the remaining 13 were analyzed.

2.2. Wind-tunnel experiments

Wind-tunnel experiments were carried out at the Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. Details are described in Wang et al. (2012b). The blow-type non-circulating wind tunnel has a total length of 37.8 m, with a 16.2-m long test section. The cross-sectional area of the test section is 0.6 × 1.0 m. The free-stream wind velocity in the wind tunnel can be adjusted from 1 to 40 m/s. Additional details of the apparatus have been described in several papers (e.g., Dong et al., 2004). The design of the experimental apparatus is illustrated in Fig. 2B. To summarize, each sample was positioned in the working section of the wind tunnel with the surface at the same level as the bottom of the wind tunnel, and then fixed in place. At a distance of 30 cm downwind from the sample, we installed a dust collection sampler that was 30 cm wide (i.e., the same width as the surface samples) by 30 cm tall to collect windblown materials. Based on previous analysis in the wind tunnel by its designers, the dust sampler can collect more than 95% of the transported materials under the conditions used in our wind-tunnel experiments (Wang et al., 2012a, b).

To simulate the variations in near-surface wind velocity that occur in the field near our sampling sites, the experiments were started with a free-stream wind velocity of 8 m/s, and then progressively increased.
the velocity to 22 m/s, which represents the maximum wind velocity recorded in meteorological records from the study area. For each run, sampling was stopped when no more particle motion was observed. From our experiments, under a wind velocity of 8 m/s sediment transport ceased within 360 s, and within 60 s under a wind velocity of 22 m/s.

3. Sample treatment and analytical methods

After the experiment at each wind velocity was completed, the transported materials collected in the dust trap were removed for analysis. Particle size analysis was carried out using a Mastersizer 2000 (Malvern Co. Ltd., Malvern, UK; sample range: between 0.02 and 2000 μm in diameter). For the magnetic analysis, we packed known weights of the samples (6.2–7.2 g, with an average of 6.9 g) into plastic pots. We then measured the low-frequency (0.47 kHz) and high-frequency (4.7 kHz) magnetic susceptibilities (\(\chi_{lf}\) and \(\chi_{hf}\), respectively) using a Bartington Instruments MS2 magnetic susceptibility sensor. The difference between the low-frequency susceptibility and the high-frequency susceptibility (\(\chi_{lf} - \chi_{hf}\)) was expressed as a mass-specific term (\(\chi_{ms}\)) and as the frequency-dependent susceptibility (\(\chi_{fd}\)). Anhysteretic remanent magnetization (ARM) was measured using a DTECH alternating field (AF) demagnetizer with a peak AF of 100 mT and a DC bias field of 0.04 mT. Measurements were expressed as the ARM susceptibility (\(\chi_{ARM}\)) by dividing the remanence by the steady field. SIRM at 1 T was determined using an MMPM10 pulse magnetizer. All remanence measurements were performed using a Minispin magnetometer. SIRM is expressed on a mass-specific basis. IRMs in the reverse fields (−20 mT, −100 mT, and −300 mT) were expressed as percentages of the reverse saturation of the SIRM (\(S_{-20}\), \(S_{-100}\), and \(S_{-300}\)). The S-ratio is expressed as the ratio of IRM to SIRM. All magnetic parameters were measured at the Key Laboratory of West China’s Environmental Systems, Lanzhou University.

Concentrations of 26 elements and oxides were determined at the Key Laboratory of Desert and Desertification, Chinese Academy of Sciences, namely, P, Ti, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, As, Rb, Sr, Y, Zr, Nb, Ba, Ce, Pb, SiO2, Al2O3, Fe2O3, MgO, CaO, Na2O, and K2O. Element concentrations were measured on a fully automated sequential

| Fraction | \(\chi_{lf}\) | \(\chi_{hf}\) | ARM | SIRM | ARM/SIRM | SIRM/\(\chi_{lf}\) | S-ratio |
|----------|---------------|---------------|-----|------|----------|----------------|---------|
| Fraction 2.0 μm in diameter | −0.175 | 0.186* | 0.259* | −0.042 | 0.414* | 0.464* | 0.351* |
| Fraction 5.0 μm in diameter | 0.464* | −0.155 | −0.086 | 0.363* | −0.640* | −0.611* | 0.078 |
| Fraction 10 μm in diameter | −0.533* | 0.116 | −0.010 | −0.448* | 0.669* | 0.632* | −0.262* |
| Mean particle size | −0.499* | 0.257* | −0.134 | −0.370* | 0.465* | 0.604* | 0.124 |

* Correlation is significant at the 0.05 level (one-tailed).

Fig. 4. XRD patterns for transported materials as a function of near-surface wind velocity and comparison with the patterns for surface sediments.
wavelength-dispersive X-ray fluorescence (XRF) spectrometer (AXIOS, PANalytical B.V.) equipped with a Super Sharp Tube for the Rh-anode, with the following settings: 40 kW, 60 kV, 160 mA, and a 75 μm UHT Be end-window. SuperQ software version 5 was used for the XRF analysis. Samples were prepared as follows: after drying the samples at 105 °C, 1 g samples were compressed (at 30-ton stress) into a 32 mm-diameter pellet and then stored in desiccators. After the XRF analysis was completed, the elemental concentrations were calibrated using the Chinese National Standards for rock (GBW07103 and GBW07114 (GSR01 and GSR12), GBW07120 and GBW07122 (GSR13 and GSR15)), for soil (GBW07401 and GBW07408 (GSS01 and GSS8)), GBW0743 and GBW07430 (GSS9 and GSS16), and for water-laden sediments (GBW07301a and GBW07318 (GSD01 and GSD14)). The equipment was calibrated following the manufacturer's instructions, and it was found that the analytical uncertainties (relative standard deviations) were less than ±5% for most of the elements and oxides, except Co, Cr, V, and Pb. The uncertainties of all measured elements and oxides can be found in Wang et al. (2012c).

Semi-quantitative mineralogical analysis (with relative errors of about 10%), as well as magnetic and elemental analysis, was performed using an XPert Pro Multi-Purpose X-ray Diffractometer (XRD; PANalytical) that scanned with Co Kα1 radiation at 45 kV and 50 mA, at scan angles ranging from 0° to 167° (2θ), a precision of 0.0025°, and a resolution of 0.037°.

In addition, because a stronger wind will transport not only the material actually transported at that wind velocity but also all the materials that would have been transported at lower wind velocities during previous stages of the experiment; all values for a given wind velocity are expressed as the mean cumulative values for the materials collected at that wind velocity and all previous velocities. Although this approach inevitably affects the precision of the results, it reflects more closely the effects of aeolian processes in the field. In addition, because of the limited amount of sediment collected under some conditions, results for only 94 samples are presented.

4. Results and discussion

4.1. Rock magnetism

Rock magnetic parameters for the 94 samples collected from the 13 bulk samples under wind velocities of 8 to 22 m/s are summarized in Table 1. There is considerable variation (coefficient of variation, CV) under the observed range of wind velocities for some magnetic parameters such as $X_{m}$, $X_{arm}$, and SIRM/$X_{arm}$ (Table 1). For instance, the coefficients of variation for $X_{m}$ ranged between 1.6 and 14.9%; for $X_{arm}$, it ranged between 1.4 and 11.0%, and for SIRM it ranged between 0.7
and 12.3%. In contrast, the coefficient of variation ranged up to 29.6% for $Z_{d3}$. The coefficient of variation was smaller for $X_{ARM}$/SIRM, SIRM/$X_{AR}$, and the S-ratio, ranging from 0.2 to 6.1%. There is also considerable variation in the magnetic characteristics of samples from the same site (i.e., within sites 1, 2, and 3), even though each bulk sample was collected using the same approach. In addition, in different sites some magnetic parameters are positively correlated with wind speed, some are negatively correlated, and some have no significant correlation (Table 2). These results suggest that there are no consistent patterns between the near-surface wind field and the magnetic properties of the transported materials in the potential dust source areas.

4.2. Geochemical characteristics

Statistical data for the elements and oxides are summarized in Table S1 (Supplemental materials). For all bulk samples, the CV values of Ti, Cr, As, Zr, Ce, Pb, and Cu are more than 10%, compared with values of less than 1% for the other elements and oxides. Sample E from Site 1 has a particularly high CV, even though we obtained this sample and measured its contents using the same methods as for all other samples. As pedogenesis is very weak in this extremely arid area (e.g., Sun et al., 2011), it is assumed that pedogenetic processes have not significantly affected the geochemical characteristics of the transported materials. The mechanisms responsible for the observed variability in the source materials are therefore unclear. In addition, principal-component analysis (PCA) reveals four principal components (PCs) with eigenvalues >1 (Table S2). These PCs explain 90.4% of the total variance. If we consider only loadings with magnitudes greater than 0.80 (i.e., the elements or oxides that positively contributed most strongly to each PC, Table S3), PC1 (which explains 47.0% of the variance) included Ti, Fe, P, V, Cr, Mn, Co, Ni, Rh, Y, Zr, Nb, Ce, and Al$_2$O$_3$, which suggests that these elements and oxides may have the same source (i.e., they may come from the same or similar minerals). PC2 (which explains 24.1% of the variance) includes Ga, As, Al$_2$O$_3$, MgO, Na$_2$O, and K$_2$O. PC3 (which explains 10.4% of the variance) includes Zn, Pb, and Cu, some of which may come from the metal pollution brought by upwind from the study area. PC4 (which explains 8.8% of the variance) contained no loadings greater than 0.60, suggesting that their sources are complicated. In addition, for all 94 samples, no significant correlations were found between the concentration of most elements or oxides and wind velocity (Table 3). For Ti, Rh, Sr and Fe$_2$O$_3$, results show that there are no consistent patterns between their concentrations with increasing wind velocity (Fig. 3). This suggests that there are no clear relationships between the near-surface wind velocity and elemental and oxide concentrations in transported materials from the potential dust source areas.

4.3. Relationships between fine fractions with different particle sizes and geochemical and magnetic characteristics

Gobi deserts of the Ala Shan Plateau are major potential sources of modern aeolian dust (Wang et al., 2006, 2008). In this region, under aeolian processes these fine fractions in the transported materials are deposited at a considerable distance from the source regions, and are more sensitive to post-depositional weathering and other processes, but their magnetic properties, geochemical characteristics, and particle size characteristics have been used to provide a quantitative basis for describing interactions between dust aerosols and climate (e.g., Maher, 2011); as such, they have been used as proxies for variations in precipitation (Maher et al., 1994; Porter et al., 2001; Maher and Possolo, 2013) and winter monsoon strength (Yancheva et al., 2007). However, there are large heterogeneities in the fine-grained surface sediments (i.e., those <38 μm or <63 μm in diameter; e.g., Maher et al., 2009; Wang et al., 2012c), and large variations in the magnetic and geochemical characteristics of transported materials under a range of near-surface wind velocities have been demonstrated here. In addition, the composition of the transported materials also appears to differ from that of the surface sediments from which they were derived, which are also identified in the XRD patterns of the surface sediments (Fig. 4). These results suggest that under different near-surface wind velocities, although the transported materials had mineral assemblages similar to those of the surface sediments there are nonetheless differences in the mineral assemblages of the transported materials at a given wind speed.

In addition, for a wide range of depositional environments, a strong link has been demonstrated between fine particles (i.e., <2 or 5 μm) and magnetic properties (e.g., Oldfield et al., 2009). In natural materials such as lake sediments, some magnetic properties appear to be particularly sensitive to the fine magnetite fraction, while others are more sensitive to the coarse fraction (e.g., King et al., 1982; Oldfield, 1994). In the potential dust source areas considered here, under different near-surface wind velocities, we find that there are variations in the relationships between fine fractions with different particle sizes and magnetic parameters. For instance, the $\chi_{fd}$ and SIRM have significant positive correlations with fractions <5.0 μm in diameter, while $X_{ARM}$ has significant positive correlation with fractions <2.0 μm in diameter (Table 4). These results indicate that even in potential dust source areas the variations in grain size within the fine fractions play an important role in determining the magnetic characteristics of transported sediments.

In potential dust source areas and under near-surface wind velocities, there are also different relationships between the different grain sizes of the fine fraction of transported materials and their geochemical characteristics (Table 5). Partial correlation analysis results indicate that although most elements and oxides measured were significantly and positively correlated with the contents of fraction <2.0 μm, Cr and Cu are more closely associated with the fraction <5.0 μm, and Sr usually has significant positive correlations with the coarser fine fraction (i.e., <10 μm). In addition, different inter-relationships between the magnetic properties and the element and oxide concentrations of the transported fine fraction are observed. For instance, although all the magnetic parameters exhibit significant positive correlations with the fine fractions (i.e., <2.0 μm), the correlation coefficients between the magnetic parameters such as $X_{fd}$, $X_{ARM}$, SIRM, ARM/SIRM and SIRM/$X_{fd}$ and the element and oxide concentrations decrease with increasing proportions of the coarser fine fractions (i.e., <5.0 or 10 μm) (Table S4a–c). For the combined transported materials, the $X_{fd}$ exhibits significant positive correlations with Ti, Fe, P, V, Cr, Co, Ni, Y, Zr, Nb, Ce, and Cu, and $X_{ARM}$ has significant positive correlations with Mn and Ba (Table 6). These statistical results show that magnetic property variations appear to be mostly controlled by the geochemical characteristics and the particle sizes of transported materials. There variations in the relationships between the geochemical and magnetic characteristics of the transported materials with different particle sizes mean that their use as proxies for past climate reconstruction must be carefully appraised.

5. Conclusions

The geochemical and magnetic characteristics of materials transported by wind from potential dust source areas in Central Asia vary due to differences in the source materials. Under a range of near-surface wind velocities, we found CV values ranging from 1.6% to 29.6% for $X_{d3}$. The coefficient of variation was smaller for $X_{ARM}$/SIRM, SIRM/$X_{AR}$, and the S-ratio, ranging from 0.2 to 6.1%. There is also considerable variation in the magnetic characteristics of samples from the same site (i.e., within sites 1, 2, and 3), even though each bulk sample was collected using the same approach. In addition, in different sites some magnetic parameters are positively correlated with wind speed, some are negatively correlated, and some have no significant correlation (Table 2). These results suggest that there are no consistent patterns between the near-surface wind field and the magnetic properties of the transported materials in the potential dust source areas.
of aeolian-transported materials and their utility as indicators of past climate change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.geomorph.2015.03.017.

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