

Fluvial sediments in the Alagxa Plateau as a dust source: iron mineralogical and geochemical evidence Postprint

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Date: 2019-03-28T00:00:00+00:00

Abstract

The Alagxa Plateau, in the margin of the northeastern Tibetan Plateau, is one of the most important dust source areas in East Asia, and the widespread sandy desert in the area is important both as a reservoir and a source of eolian silty. The northeastern margin of the Tibetan Plateau is one of the most actively-growing mountain belt on earth, and has large amounts of debris, with masses of fine grained material, which were continuously mobilized and deposited in the Alagxa Plateau by rivers, forming broad alluvial fans. It is possible that the role of fluvial sediments as a source of silty dust in the Alagxa Plateau has been underestimated. In this study, we test this hypothesis by investigating the iron mineralogical and geochemical characteristics of the fluvial sediments and the surface material of the sandy desert in the Alagxa Plateau, and comparing them with paleo-eolian dust deposits (loess) in the adjacent Chinese Loess Plateau (CLP) to investigate the possible linkages among the fluvial sediments, sandy desert and the last glacial loess of the CLP. The results show that sandy desert typically have high contents of goethite, and high ratios of goethite to hematite, similar to the fluvial sediments in the Alagxa Plateau. Based on the major element characteristics, field investigations and the results of previous studies, we found a genetic link between the silt component of the fluvial sediments and the sandy desert in the Alagxa Plateau with high value of Gt (goethite) and similarity of the Gt/(Hm (hematite)+Gt) ratio. But the silt component of the sandy desert main come from the adjacent fluvial sediments. The iron mineralogical characteristics (magnetic susceptibility , ARM (anhysteretic susceptibility), SIRM (saturation isothermal remanent magnetization) and SIRMAF100mT (SIRM demagnetized at 100 mT)) of the CLP samples overlap with those of the fluvial sediments in the Alagxa Plateau, but there is a mismatch with the sandy desert samples. This suggests that the fluvial sediments are the source of a large amount of silty material which could be transported to the CLP. Therefore, we conclude that the fluvial sediment in

the Alagxa Plateau is an important source of eolian silt, which is deposited in downwind region, and that this source has been previously underestimated.

Full Text

Preamble

Fluvial Sediments in the Alagxa Plateau as a Dust Source: Iron Mineralogical and Geochemical Evidence

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Abstract

The Alagxa Plateau, located on the margin of the northeastern Tibetan Plateau, represents one of the most important dust source areas in East Asia. The widespread sandy desert in this region functions both as a reservoir and source of eolian silt. The northeastern margin of the Tibetan Plateau constitutes one of Earth's most actively growing mountain belts, generating massive quantities of debris with abundant fine-grained material that rivers continuously mobilize and deposit in the Alagxa Plateau, forming extensive alluvial fans. The role of fluvial sediments as a source of silty dust in the Alagxa Plateau may have been underestimated. This study tests this hypothesis by investigating the iron mineralogical and geochemical characteristics of fluvial sediments and sandy desert surface material in the Alagxa Plateau, comparing them with paleo-eolian dust deposits (loess) in the adjacent Chinese Loess Plateau (CLP) to explore potential linkages among these sediment systems. Results demonstrate that sandy desert samples typically exhibit high goethite contents and elevated goethite-to-hematite ratios, similar to fluvial sediments in the Alagxa Plateau. Based on major element characteristics, field investigations, and previous research findings, we identify a genetic link between the silt component of fluvial sediments and the sandy desert in the Alagxa Plateau, evidenced by high goethite (Gt) values and similar Gt/(Hm (hematite)+Gt) ratios. However, the silt component of the sandy desert primarily originates from adjacent fluvial sediments. The iron mineralogical characteristics (magnetic susceptibility), ARM (anhysteretic susceptibility), SIRM (saturation isothermal remanent magnetization), and SIRM/MAF100mT (SIRM demagnetized at 100 mT) of CLP samples overlap with those of Alagxa Plateau fluvial sediments but show mismatch with sandy desert samples. This suggests that fluvial sediments constitute a substantial source of

silty material transportable to the CLP. We conclude that fluvial sediment in the Alagxa Plateau represents an important source of eolian silt deposited in downwind regions, a source that has been previously underestimated.

Keywords: fluvial sediments; silty dust; sandy dust; iron mineralogical and geochemical characteristics; Alagxa Plateau

Citation: WANG Youjun, JIA Jia, LU Hao, LU Caichen, XIA Dunsheng. 2019. Fluvial sediments in the Alagxa Plateau as a source of atmospheric dust: iron mineralogical and geochemical evidence. *Journal of Arid Land*, 11(2): 217-227. <https://doi.org/10.1007/s40333-019-0125-3>

1 Introduction

The Alagxa Plateau ranks among the most important dust source areas in East Asia [cite{Prospero et al., 2002}; cite{Washington et al., 2003}; cite{Wang et al., 2008}]. Frequent winter and spring dust storms transport massive quantities of eolian dust to the Chinese Loess Plateau (CLP), eastern China, Japan, Europe, and the Pacific Ocean [cite{Hsu et al., 2008}]. This dust, combined with associated strong winds that strip organic matter and nutrient-rich particles from soils, damages crops and pollutes the atmosphere. The widespread sandy desert sediments of the Badain Jaran Desert, Tengger Desert, and Ulan Buh Desert have been proposed as major sources of emitted dust [cite{Liu, 1985}; cite{Zhang et al., 1993}; cite{Sun, 2002a}].

Numerous studies indicate that the contribution of fluvial sediments to silty dust emission has been underestimated [cite{Stevens et al., 2013}; cite{Nie et al., 2015}; cite{Zhu et al., 2016}]. A key line of evidence supporting this inference is that major eolian loess deposits commonly occur near large rivers [cite{Smalley et al., 2009}]. Smalley et al. (2009) suggested that long-distance fluvial transport of sediments represents a critical step in generating material for eolian transport and the subsequent widespread formation of loess deposits across landscapes.

Additionally, Stevens et al. (2013) and Nie et al. (2015) proposed a genetic link between the CLP and the Yellow River based on U-Pb age distributions and heavy mineral assemblages. For the Alagxa Plateau, geomorphic evidence reveals a transition from alluvial-lacustrine plain to Gobi-desert plain in the Ejina Basin [cite{Zhu et al., 2016}], indicating substantial dust material emission. Adjacent high mountains, including the Qilian Mountains and Gobi Altay Mountains, constitute one of Earth's most actively growing mountain belts [cite{Hetzl et al., 2004}; cite{Chen and Li, 2013}; cite{Tian et al., 2014}]. Rivers originating in the Qilian Mountains continuously supply sediments to the Alagxa Plateau and Hexi Corridor, with an annual average flux of approximately 1.2×10^6 t [cite{Pan et al., 2010}]. This enormous potential source of silty dust for aeolian transport requires evaluation.

This study tests the hypothesis that fluvial sediments make an important contribution to dust emissions by comparing the iron mineralogical and geochemical characteristics of fluvial sediments and sandy desert in the Alagxa Plateau with loess deposits downwind in the CLP.

2.1 Study Area

The Alagxa Plateau is situated northwest of the CLP (37°30' -42°36' N, 93°06' -106°36' E; Fig. 1 [Figure 1: see original paper]). The plateau covers an area of 2.5×10⁴ km², bounded by the Yellow River and Helan Mountains to the east and southeast, the Qilian Mountains to the south and southwest, and the Beishan Mountains to the west. The Alagxa Plateau is predominantly covered by Gobi and sandy desert (80%-90%). Its two principal geomorphic units are the Badain Jaran Desert and Tengger Desert, where the Heihe River and Shiyang River terminate, respectively. Both river systems have developed vast alluvial fans, primarily covered by gravel deposits. The region features an arid temperate desert climate, with precipitation seldom exceeding 150 mm and high potential evaporation exceeding 2500 mm [cite{Chen and Qu, 1992}].

Jiuzhoutai is located in the western CLP near the Alagxa Plateau. Satellite observations reveal frequent dust storms during winter and spring that transport large amounts of dust from the Alagxa Plateau to the Jiuzhoutai area [cite{Sun, 2002a}].

2.2 Sampling

Fluvial sediments include modern/ancient floodplain, alluvial fan, and lacustrine sediments. We selected 24 sampling sites for fluvial sediments, comprising 20 sites along the Heihe River (HR-01-HR-20) and 4 sites along the Shiyang River (SYH-01-SYH-04). Approximately 3-10 samples were collected from each site, totaling 178 samples. Additionally, we selected 18 sampling sites for sandy desert (D-01-D-18; 1 sample per site) and one sampling site for last glacial loess of the CLP (in the Jiuzhoutai area; 4 samples from this site: L-01-L-04). Due to arid climatic conditions, the last glacial loess of the CLP is minimally affected by pedogenesis and retains its lithological characteristics [cite{Jia et al., 2015}]. All sampling sites were located far from roads, farmland, villages, and towns to avoid vehicular pollution and human activity influences.

Fig. 1 shows the location and geological setting of the Alagxa Plateau and distribution of sampling sites for fluvial sediments in the Heihe River (HR-01-HR-20) and Shiyang River (SYH-01-SYH-04), sandy desert (D-01-D-18), and last glacial loess of the Chinese Loess Plateau (CLP).

2.3 Data Analyses

Magnetite/maghemite, hematite (Hm), and goethite (Gt) represent the three most important iron minerals in most natural sediments. Magnetite/maghemite exhibits strong magnetic properties with high magnetic susceptibility (χ), typically present in trace amounts. Hematite and goethite have weak magnetic properties with low χ but may be far more abundant on a mass basis than magnetite/maghemite. Therefore, we employed a combination of magnetic measurements and diffuse reflectance spectroscopy (DRS) to investigate the iron mineralogical characteristics of the samples.

In the laboratory, all samples underwent the following fractionation procedures. After air drying, particles larger than 1000 μm (primarily fine gravel and plant material) were sieved out. The remaining material was separated into two fractions by sieving. The $\leq 63 \mu\text{m}$ fraction was used for the laboratory analyses described below, while the $>63 \mu\text{m}$ fraction was retained for visual inspection. The grain-size distribution of the $\leq 63 \mu\text{m}$ fraction of fluvial sediments closely resembles that of sandy desert, with a modal size range of 3–20 μm , suggesting that grain-size sorting effects on various parameters are minor (Fig. 2 [Figure 2: see original paper]). Furthermore, the bimodal grain-size distribution of typical CLP loess indicates that fine-grained components share a similar modal size range with fluvial and desert sediments [cite{Sun et al., 2004}; cite{Qiang et al., 2016}].

2.3.1 Magnetic Measurements

χ is commonly used to assess the bulk concentration of ferrimagnetic minerals in natural samples and is particularly sensitive to superparamagnetic (SP) grain content ($<30 \text{ nm}$; cite{Thompson and Oldfield, 1986}). Anhysteretic susceptibility (χ_{ARM}) is sensitive to ferrimagnetic mineral concentrations in the single-domain range. SIRM (saturation isothermal remanent magnetization) and related demagnetization ratios provide estimates of total remanence-bearing material content and relative proportions of low-coercivity (ferrimagnetic) and high-coercivity (imperfect antiferromagnetic) magnetic phases. SIRM_{AF100mT} (SIRM demagnetized at 100 mT) is a remanent parameter that cleans the magnetic signal of ferrimagnetic contributions and serves as a rough indicator of antiferromagnetic mineral concentration.

Samples ($\leq 63 \mu\text{m}$ fraction) were packed in 10 ml plastic pots and subjected to the following magnetic measurement series. Mass-specific χ was measured with a Bartington MS2 meter and MS2B sensor (470 Hz; Bartington Instruments Ltd, British). Anhysteretic remanent magnetization (ARM) was imparted using a DTECH AF demagnetizer (2G Enterprises, US) at a peak AF field of 80 mT and a DC bias field of 100 T, then measured with a 2G Enterprises Superconducting Rock Magnetometer (2G-755). ARM is expressed as anhysteretic susceptibility (χ_{ARM}) by dividing by the biasing field strength. SIRM was imparted at 1T using an MMPM10 Impulse Magnetizer (JR-6 spinner magnetometer, AGICO,

Czechoslovakia), then demagnetized at 100 mT (SIRMAF100mT) and measured again.

2.3.2 DRS Measurements

Samples (63 μm fraction) for DRS measurements were mixed with distilled water, and the resulting slurry was smeared on glass microscope slides, smoothed, and slowly dried at room temperature. Samples were analyzed using a Perkin Elmer Lambda 900 spectrophotometer (Perkin Elmer, US) to obtain DRS spectra over the 400–700 nm range at 2-nm intervals.

Reflectance data were processed to obtain percentage reflectance in standard color bands (violet, 400–450 nm; blue, 450–490 nm; green, 490–560 nm; yellow, 560–590 nm; orange, 590–630 nm; and red, 630–700 nm) [cite{Judd and Wyszecki, 1975}]. We calculated red percentage reflectance (redness) by dividing red reflectance percentage by total visible wavelength reflectance, following Long et al. (2011). Hematite content was estimated from redness% using a linear regression model: $\text{Hm}\% = 0.05 \times \text{redness}\% - 1.15$. Iron (Fe) was extracted using the citrate/bicarbonate/dithionite method as free iron oxides (Fed) [cite{Mehra and Jackson, 1960}], then measured with an atomic absorption spectrometer AA240 (Varian, American) with a relative error of 1%. Goethite content was estimated using the formula: $\text{Gt}\% = 1.59 \times (\text{Fed} - \text{Hm}\%/1.43)$ [cite{Torrent et al., 2007}].

2.3.3 Major Elements Analyses

Samples (63 μm fraction) for major element analyses (Si, Al, Fe, Ti, Ca, Mg, Na, and K) were prepared by placing measured sediment weights (approximately 4 g) into a column apparatus with boric acid, then pressurizing at 30 t/m² for 20 s. The resulting samples (approximately 4 cm diameter and 8 mm thickness) were analyzed using a MagixPW2403 X-ray fluorescence spectroscope (PANalytical, Holland). Standard deviation based on repeat analyses was approximately 2%.

3.1 Magnetic Measurements

Table 1 summarizes magnetic parameter values for all samples. values for fluvial sediment samples ($10 \times 10^{-4} - 49 \times 10^{-4}$ m³/kg; mean 27×10^{-4} ($\pm 8 \times 10^{-4}$) m³/kg) were substantially lower than those for sandy desert samples ($70 \times 10^{-4} - 334 \times 10^{-4}$ m³/kg; mean 174×10^{-4} ($\pm 83 \times 10^{-4}$) m³/kg). Fine-grained ferrimagnetic material and imperfect antiferromagnetic material contents, indicated by ARM and SIRMAF100mT values, were also higher in sandy desert than in fluvial sediments. The overall magnetic characteristics of last glacial CLP loess samples were similar to those of fluvial sediments.

Table 1. Descriptive statistics for magnetic parameters of fluvial sediments and sandy desert in the Alagxa Plateau and last glacial loess of the Chinese Loess

Plateau (CLP)

Sediment type	($\times 10$ m ³ /kg)	ARM ($\times 10$ Am ² /kg)	SIRM ($\times 10$ Am ² /kg)	SIRMAF100mT ($\times 10$ Am ² /kg)
Fluvial sediments (n=178)	27 (± 8)	-	-	-
Sandy desert (n=18)	174 (± 83)	-	-	-
Last glacial loess of CLP (n=4)	-	-	-	-

Note: χ , magnetic susceptibility; ARM, anhysteretic susceptibility; SIRM, saturation isothermal remanent magnetization; SIRMAF100mT, SIRM demagnetized at 100 mT.

3.2 Gt and Hm Content

Goethite and hematite are two widely distributed iron minerals in surface sediments [cite{Oldfield et al., 2014}]. DRS results indicated that most fluvial sediment samples contained more than 10.0‰ goethite (n=22; mean 13.0‰ ($\pm 4.0\%$)) and 2.5‰ hematite (n=22; mean 3.3‰ ($\pm 0.9\%$)) (Fig. 3 [Figure 3: see original paper]). Sandy desert samples showed low goethite content, ranging from 4.0‰–16.0‰ (n=7; mean 11.0‰ ($\pm 4.0\%$)), but high hematite content, ranging from 2.9‰–5.4‰ (n=7; mean 3.8‰ ($\pm 0.8\%$)). Last glacial CLP loess samples contained 11.4‰ goethite and 3.2‰ hematite, both lower than fluvial sediment values.

The Gt/(Gt+Hm) ratios for fluvial sediment samples (0.79 (± 0.06)) were similar to those for last glacial CLP loess (mean = 0.78), while sandy desert values were slightly lower (0.72 (± 0.38)). Notably, most sandy desert samples exhibited values similar to the other two sediment types, except for two sites (D-09 and D-10). Excluding these sites yields an average Gt/(Gt+Hm) ratio of 0.79 for sandy desert samples.

3.3 Element Contents

Selected major element contents (Si, Al, Fe, Ti, Ca, Mg, Na, and K) for fluvial sediments, sandy desert, and last glacial CLP loess are illustrated in Figure 4 [Figure 4: see original paper]. Fluvial sediments showed lower Si and Ti contents but higher Mg and Ca contents compared to the other two sediment types, with values tightly clustered regardless of sampling location. Notably, Ca content in fluvial sediments was highly variable, ranging from 4.5% to 34.7% (SD = 7.4). Sandy desert exhibited higher Si and Ti contents and lower Ca contents relative to the other sediment types.

4 Discussion

4.1 The Role of Silt in Linking Fluvial Sediments and Sandy Desert Material in the Alagxa Plateau

In East Asia, two primary factors controlling silty material production are climatically-controlled glacial grinding and denudation induced by tectonic uplift [cite{Sun, 2002a}]. Deserts serve as stores or reservoirs of fine-grained material produced in adjacent mountains through these processes [cite{Smalley et al., 2009}]. Rivers play a crucial role in transporting silty material from high mountains to alluvial-desert plains [cite{Smalley et al., 2009}]. Subsequently, the Asian winter monsoon transports particles downwind to desert basins and the CLP [cite{Sun, 2002b}]. This view is supported by increasing geological evidence, particularly detrital zircon U-Pb age distributions. Probability density plots of detrital zircon U-Pb ages for fluvial sediments and sandy desert in the Alagxa Plateau and CLP loess [cite{Che and Li, 2013}; cite{Zhang et al., 2015}; cite{Nie et al., 2018}] demonstrate that zircon, highly stable at Earth's surface, preserves U-Pb isotopic systems. Detrital zircon age populations reflect multiple stages of rock formation in source regions, making them useful sediment tracers. Age distribution analyses indicate a common source for the silt component of fluvial sediments and sandy desert in the Alagxa Plateau and CLP loess [cite{Che and Li, 2013}; cite{Zhang et al., 2015}; cite{Nie et al., 2018}].

Our results provide further evidence for a genetic link between the silt component of fluvial sediments and sandy desert in the Alagxa Plateau. Goethite production favors moist, low-pH environments, whereas hematite production favors hot environments [cite{Schwertmann, 1985}]. Similar Gt/(Hm+Gt) ratios between fluvial sediments and sandy desert in the Alagxa Plateau suggest their silt components formed under moist conditions. The Alagxa Plateau desert climate is hot and dry, so the silt component of sandy desert cannot be autochthonous. Adjacent fluvial sediments represent the only potential source capable of continuously producing large quantities of silty material. Additionally, a scatter plot of stable element ratios (Fig. 5 [Figure 5: see original paper]) shows that sandy desert samples overlap with or lie near the regression line for

Heihe River fluvial sediment samples, further supporting a genetic link.

Modern landscape features also support this connection. First, the Heihe and Shiyang Rivers originate from the Qilian Mountains, transporting massive amounts of debris to mountain piedmonts and basin depressions in the Alagxa Plateau, forming vast flat alluvial fans [cite{Pan et al., 2010}]. Combined with arid conditions, strong northwest winds preferentially erode silt and sand fractions, leaving gravel covers on alluvial fan surfaces. Consequently, deposits exhibit a zonal distribution from the Alagxa Plateau northwestward to the CLP southeastward, comprising gravel (Gobi), sand (sandy desert), and silt (loess). Second, several modern sand dunes are developing within fluvial sand deposits around Gobi areas (Figs. 6a and b; cite{Zhu et al., 2016}). Third, widespread yardangs, deflation hollows, and Gobi indicate massive erosion of fine-grained material from fluvial sediments (Figs. 6b-d [Figure 6: see original paper]).

4.2 Link Between the Silt Component of Fluvial Sediments in the Alagxa Plateau and the Last Glacial Loess of the CLP

Magnetic properties of ferrimagnetic minerals depend greatly on grain size, and previous studies have shown that magnetite grains are sensitive to wind sorting [cite{Begét et al., 1990}; cite{Song et al., 2010}; cite{Zan et al., 2011}; cite{Wei et al., 2013}; cite{Zan et al., 2015}]. Wei et al. (2013) proposed that density differences between minerals with different magnetic properties constitute a major cause of spatial differences in of eolian deposits. Typically, ferrimagnetic and imperfect antiferromagnetic minerals such as magnetite, maghemite, and hematite, which are relatively strongly magnetic, have higher densities than weakly magnetic paramagnetic and diamagnetic minerals like quartz, feldspar, and calcite. Consequently, strongly magnetic minerals tend to be enriched in deposits transported relatively short distances from their source.

Figure 7 [Figure 7: see original paper] presents scatter plots of selected magnetic parameters for the three sediment types. Fluvial sediment samples showed more variable magnetic properties than other sediment types but overlapped with loess samples. Sandy desert samples exhibited strong linear relationships between magnetic parameters but minimal overlap with last glacial CLP loess and fluvial sediment samples. Additionally, sandy desert samples were enriched in strongly magnetic minerals. Our field investigations revealed that fluvial sediments contained much higher proportions of fine-grained material than sandy desert samples (Fig. 6). Laboratory measurements showed that the 63 μ m fraction comprised up to 71.4% of fluvial sediments but only 8.1% of sandy desert samples (Fig. 8 [Figure 8: see original paper]). We therefore propose that silty material in sandy desert is well-sorted, transported by wind, and deposited close to the source, while a proportion of the silt component from fluvial sediments is transported to the CLP.

5 Conclusions

Fluvial sediments and sandy desert material in the Alagxa Plateau exhibit distinct iron mineralogical and geochemical characteristics. Fluvial sediments are characterized by wide-ranging major element contents and low strongly magnetic mineral contents. Sandy desert shows higher Ti and strongly magnetic mineral contents. Last glacial aeolian deposits of the CLP exhibit iron mineralogical characteristics similar to Alagxa Plateau fluvial sediments but have a much narrower range of major element contents, suggesting that loess represents well-mixed eolian dust.

Our experimental results, supported by geomorphological evidence and previous studies, indicate that fluvial sediments constitute the dominant source of eolian silt emitted from the Alagxa Plateau and transported long distances downwind. Although a genetic link exists between sandy desert material and fluvial sediments in the Alagxa Plateau, the contribution of sandy desert material to eolian silt is limited.

Acknowledgements: This study was supported by the National Natural Science Foundation of China (41401046) and the Fundamental Research Funds for the Central Universities (lzujbky-2016-264, lzujbky-2016-bt01). We thank Dr. Jan BLOEMENDAL for critical discussions, constructive suggestions, and English language improvement.

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