Magnetic properties of sediments from major rivers, aeolian dust, loess soil and desert in China

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A B S T R A C T

The continent of China delivers huge terrigenous sediments to the East Asian marginal seas and northwest Pacific Ocean by riverine and aeolian inputs, which exerts a great impact on marine sedimentation, primary productivity and biogeochemical cycle. In this study, magnetic properties of the sediments from the Changjiang and Huanghe river systems were investigated, in order to provide potential provenance tracers. Besides, the top soil from the Loess Plateau, Taklimakan desert sand and dust storm particles were comparatively studied to reveal the controls of magnetic properties in various depositional environments.

The Changjiang sediment is characterized by the highest concentration of magnetic minerals and the largest variations for most magnetic parameters, while the Huanghe sediment has much lower content of magnetic minerals. The loess soil sediment yields the highest frequency-dependent susceptibility χfd%, while the aeolian dust has similar magnetic susceptibility but higher saturation isothermal remnant magnetization and lower anhysteretic remnant magnetization Zan. The desert sand has the lowest values of all magnetic parameters, indicating the lowest ferrimagnetic mineral concentration with coarser grain size. The magnetic properties of the Changjiang sediments are primarily determined by the diversity of lithology in its large drainage basin, while the sediment grain size basically accounts for the variation of magnetic parameters in the Huanghe sediment. The gradual increase of χfd% towards the lower reaches suggests it may potentially indicate grain size fractionation in the catchments. Although some magnetic parameters can apparently discriminate the origins of fluvial and aeolian sediments, reliable magnetic proxy for distinguishing sediment origins in marine environment can only be established if hydrodynamic differentiation and post-depositional diagenetic alteration of magnetic minerals are fully understood.

1. Introduction

The land–ocean interactions and relating earth surface processes are being conceived worldwide. Owing to the unique topography and monsoon climate, the East Asian continent delivers a huge amount of terrigenous material primarily through riverine and aeolian transport to the East Asian marginal seas and northwest Pacific Ocean, which exerts a great impact on marine sedimentation, primary productivity and biogeochemical cycle (Milliman and Meade, 1983; Duce et al., 1980; Jickells et al., 2005; Maher et al., 2010). The Changjiang (Yangtze River) and the Huanghe (Yellow River) are the two largest rivers in China (Fig. 1), transporting about 1.5 × 109 tons of sediment in total annually to the estuarine and shelf areas, which accounts for about 10% of the global sediment discharge (Milliman and Meade, 1983). Nevertheless, the sediment loads of the Changjiang and Huanghe decrease significantly over the last two decades primarily due to the constructions of numerous reservoirs in both drainage basins such as the world's largest dam, the Three Gorges Dam (Yang et al., 2006, 2007). The tremendous material from the Changjiang and Huanghe dominates the sedimentation in the East Asian marginal seas such as the Bohai, Yellow Sea and East China Sea. However, major part of the fluvial sediments is trapped in the deltaic, coastal and continental shelf due to the mild gradient, estuarine process and littoral currents (Chen et al., 1985), and thereby the fine-grained terrigenous material to the open ocean is mostly delivered by atmospheric dust (Duce et al., 1980; Jickells et al., 2005; Maher et al., 2010).

The global dust flux is estimated to range from 1000 to 2150 Tg/yr (Andreae and Rosenfeld, 2008), of which 8% is from central China (Tanaka and Chiba, 2006). Compared to the river input, nutrients and trace elements transported by aeolian dust are more significant in the open ocean (Jickells et al., 2005). Dust acts as one...
main source of iron to the open ocean where the availability of iron may limit primary productivity (Martin, 1990; Jickells et al., 2005). Boye et al. (2003) found that the dust from both the Mongolian and Taklimakan deserts could be recognized in ice cores from Greenland, and more recent study suggests that the finest particles from Taklimakan dust even had circled the globe more than once (Uno et al., 2009). Overall, Sandy desert, Gobi desert, Loess Plateau and the mixed barren soil in Northern China and Mongolia, are the main sources of Asian dust (Duce et al., 1980; Jickells et al., 2005; Engelbrecht and Derbyshire, 2010; Maher et al., 2010).

Although the Changjiang, Huanghe and aeolian dust are considered to be the main sources of terrigenous input to the west Pacific marginal seas, the discrimination method of these different sediment sources are still not well established (Yang et al., 2003). Traditional studies on provenance discrimination of the Changjiang and Huanghe sediments were primarily based on geochemical and mineralogical methods, while magnetic properties of these two river sediments have only been investigated until recent years (Niu et al., 2008; Zhang et al., 2008; Wang et al., 2009; Liu et al., 2010b), with a main aim to identify the sediment origins in marine environments. As a fast, low-cost and sensitive analysis of sediment character, environmental magnetism has been developed about 30 years ago (Thompson and Oldfield, 1986), and widely applied in paleoenvironmental study (Heller and Liu, 1986; Kukla and An, 1989; Maher and Thompson, 1991; Zheng et al., 1991; Liu et al., 2007a; Roberts, 2007), agrology (Thompson and Oldfield, 1986; Taylor et al., 1987), and heavy metal contamination indication (Scoullos et al., 1979; Hunt et al., 1984; Zhang et al., 2001; Li et al., 2011). Previous studies on magnetic property of the Changjiang and Huanghe sediments primarily gave emphasis to the estuarine and inner shelf areas (Liu et al., 2003, 2010b; Zhang and Yu, 2003; Zhang et al., 2008; Wang et al., 2004, 2009, 2010; Niu et al., 2008; Zheng et al., 2010; Horng and Huh, 2011), while the whole drainage basins, especially the upper and middle reaches, and the major tributaries have rarely been investigated. Compared to the fluvial sediments, environmental magnetism of the loess–paleosol profile and aeolian dust has been more widely applied to decipher the Quaternary paleoenvironmental changes (Liu, 1985; Heller and Liu, 1986; Kukla and An, 1989; Maher and Thompson, 1991; Zheng et al., 1991; Liu et al., 2007a; Sun et al., 2010; Zhao and Roberts, 2010). But detailed comparative study on environmental magnetism of the sediments from river, loess–paleosol and aeolian dust, however, has seldom been carried out yet. Furthermore, whether magnetic proxy can be established to identify the sediment origins in marine environments remain enigmatic (Liu et al., 2010a; Wang et al., 2010; Zheng et al., 2010; Horng and Huh, 2011).

The present study attempts to compare magnetic properties of the river sediment, aeolian dust, loess–paleosol, and desert sand. Meantime, systematic sediment samples taken from the major tributaries and mainstream of the Changjiang and Huanghe were also investigated, aiming to provide a better understanding of magnetic properties in the large rivers. Furthermore, this paper discusses the possibility of using magnetic properties to discriminate the sediment origins of East China marginal seas.

2. Geological settings

The Changjiang is the longest river in Asia, which flows about 6300 km from the glaciers on the Tibetan Plateau, with elevation above 4000 m and finally empties into the East China Sea. The river course of the Changjiang is traditionally divided into three sections. The mountainous upper reaches ranges from the headwater in western Tibetan Plateau to the city of Yichang. Particularly, the section from confluence with the Batang River, near Yushu, to Yibin is named Jinshajiang River. The middle reaches flows through a flat plain from Yichang to Hukou, and the lower reaches stretches from Hukou to the estuary in Shanghai before finally entering the East China Sea. The Changjiang drains one-fifth of China’s land area and its watershed feeds one-third of China’s population. The water discharge and sediment load of the Changjiang are about 900 km$^3$/yr and $4.78 \times 10^7$ t/yr, respectively, based on the long term hydrological observation (Milliman and Meade, 1983; Yang et al., 2004). The Changjiang catchment is primarily located in the temperate climate zone, with an annual precipitation of 1100 mm. Framed by the Mesozoic Yenshanian orogenic belt and mostly situated in the Yangtze Craton, the Changjiang river basin is characterized by complex geological settings. The upper basin comprises widely

Fig. 1. A sketch map showing the drainage basins of the Changjiang and Huanghe rivers, and sampling locations of all the studied samples. The distributions of the Loess Plateau and Taklimakan are modified from Liu (1985) and Honda and Shimizu (1998).
distributed Paleozoic carbonate rock, Jurassic red sandstone and Mesozoic igneous rocks, while the middle–lower valley mostly consists of Paleozoic and Quaternary sedimentary rocks, together with intermediate to felsic igneous rocks (China Geological Survey, 2004; Yang et al., 2004).

The Huanghe is the second largest river in China, with the drainage basin of 0.77 × 10^6 km². The vigorous upper reaches of the Huanghe starts from the headwater to Hekouzhen in Inner Mongolia. The middle reaches ends at Taohuayu in Zhengzhou City, and the lower reaches ranges from Taohuayu to the delta on the Bohai Sea. Though both sourced from the Tibetan Plateau, the Huanghe has significantly different geographic, hydrological and geological characteristics from the Changjiang. The Huanghe is featured by its low water discharge but tremendous amount of suspended sediment, about 1.08 × 10^3 t/yr, after it drains the Loess Plateau (Milliman and Meade, 1983; Ren and Shi, 1986). In addition, silty samples from the Taklimakan Desert are also taken (Heller and Liu, 1986), and is highly subject to erosion because of sparse vegetation, heavy precipitation in summer, and extensive gullying.

In addition, silty samples from the Taklimakan Desert are also studied in this paper in order to make a detailed comparison with those fluvial sediments and loess–paleosol samples. The Taklimakan Desert in the Tarim Basin of Central Asia with an area of 3.37 × 10^6 km², is the world’s 17th largest desert and the second largest shifting sand desert (Zhu et al., 1980). It is bounded by the Kunlun Mountains to the south, and the Pamir and Tian Shan Mountains to the west and north respectively.

3. Materials and methods

3.1. Sample sources

A total of 48 samples were collected from diverse environments including river, loess, desert and aeolian dust. For those river sediments, 24 floodplain and suspended sediments were collected from the mainstream and major tributaries of the Changjiang in April, 2003 and August, 2004. The floodplain sediments of each about 500 g were taken using a pre-cleaned spoon from the subsurface at 5 cm depth of the floodplains, and the sampling locations covered the whole river system from the upper Jinshajiang downstream to the river mouth (Yang et al., 2009; Fig. 1; Table 1). The suspended particulate matter (SPM) was filtered in situ by 0.45 μm pre-cleaned membrane filter. A total of ten SPM samples in April, 2009 and five floodplain sediments were taken from the Huanghe mainstream and tributaries in September, 2009. For comparison, two top soil samples were taken from the loess–paleosol profiles in Mangshan and Xi’an respectively. Mangshan is located near the most southeastern margin of the Loess Plateau. It is separated by the Huanghe and represents the transition from aeolian loess landforms in the northwest to fluvial terrains in the east (Jiang et al., 2007). Cutting through this Mangshan plateau, the Huanghe drains the North China Plain with a mild gradient before finally entering into the Bohai Sea. Another soil sample was taken from a loess–paleosol profile near Xi’an City, which is located about 350 km west of the Mangshan site. In addition, four desert samples were collected from the Taklimakan Desert, and three dust samples from a dust storm happened in Beijing on April 17–18, 2006 (Zeng and Zhang, 2008). All of these sampling locations are shown in Fig. 1 and Table 1.

3.2. Measurement of magnetic properties

Major magnetic parameters used in environmental magnetism study include specific magnetic susceptibility (χ), Anhysteretic Remnant Magnetization (ARM), and Saturation Isothermal Remanent Magnetization (SIRM). Low (0.47 kHz) and high (4.7 kHz)
frequency susceptibilities ($\chi_{lf}$ and $\chi_{hf}$, respectively) were measured with a Bartington MS2B meter. Frequency-dependent susceptibility was termed in percentage form

$$\chi_{lf} = \frac{\chi_{lf}}{\chi_{hf}} \times 100\%$$

The hard IRM (HIRM) was calculated as

$$\text{HIRM} = 0.5 \times \frac{(\text{SIRM} + 300\text{mT})}{\text{SIRM} \times 100 \times 100\%}$$

where SIRM was defined as $0.5 \times (\text{SIRM} - \text{IRM}_{100\text{mT}})$, i.e. remnant magnetization, was obtained by first saturating the sample in a 1 T field, and then applying a backfield of ~300 mT to reverse the SIRM contributed by magnetite or maghemite (Liu et al., 2007b). Susceptibility of ARM ($\chi_{ARM}$) was obtained in a 0.04 mT DC field superimposed on a peak AF demagnetization field of 100 mT. The L-ratio was proposed by Liu et al. (2007b) and calculated as

$$\text{L-ratio} = \frac{\chi_{ARM}}{\chi_{IRM}}$$

where $\chi_{IRM}$ is the magnetic susceptibility measured in a field of 300 mT. The $\chi_{ARM}$ $\times$ SIRM $\times$ 100 $\times$ 100$\%$ was proportional to ferrimagnetic minerals (e.g. magnetite and maghemite) versus high coercivity magnetic minerals (e.g. hematite and goethite), and S-ratio $\times$ 1 generally suggests low coercivity ferrimagnetic mineral (Evans and Heller, 2003). However, the indication of some magnetic parameters is still controversial, e.g., HIRM can reflect concentration of hematite and/or goethite only when the L-ratio is relatively constant (Liu et al., 2007b). More detailed interpretations of these magnetic variations are critical.

In general, $\chi$ and SIRM primarily reflect the concentration of magnetic grains in sediments, but SIRM is irrelevant to the diamagnetic, paramagnetic super-paramagnetic domain (SP). The susceptibility of ARM ($\chi_{ARM}$) is roughly proportional to ferrimagnetic grains in the fine-grained stable single domain (SSD) (Maher, 1988), and HIRM varies with concentration of high coercivity minerals. Frequency-dependent susceptibility ($\chi_{hf}$) $\times$ IRM $\times$ 100$\%$ indicates contribution of fine viscous grains at the SSD/SP border to the total ferromagnetic assemblage (Thompson and Oldfield, 1986; Maher and Taylor, 1988; Evans and Heller, 2003). S-ratio is indicative of relative contribution of low coercivity minerals (e.g. magnetite and maghemite) versus high coercivity magnetic minerals (e.g. hematite and goethite), and S-ratio $\times$ 1 generally suggests low coercivity ferrimagnetic mineral (Evans and Heller, 2003). However, the indication of some magnetic parameters is still controversial, e.g., HIRM can reflect concentration of hematite and/or goethite only when the L-ratio is relatively constant (Liu et al., 2007b). More detailed interpretations of these magnetic variations are critical.

Note: ‘‘–’’ means no determination.

<table>
<thead>
<tr>
<th>Samples</th>
<th>$\chi$ (10^-3 m^3/kg)</th>
<th>$\chi_{lf}$</th>
<th>$\chi_{ARM}$ (10^-3 m^3/kg)</th>
<th>SIRM (10^-3 Am^2/kg)</th>
<th>HIRM (10^-3 Am^2/kg)</th>
<th>S_100 (%)</th>
<th>S_300 (%)</th>
<th>$\Phi$ (Mz)</th>
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4. Results

The magnetic properties of the measured samples from the rivers, loess soil, desert and aeolian dust are given in Table 2. Different magnetic parameters exhibit large variations between the samples from different environments and even within the same environment such as those from the Changjiang (Table 2; Fig. 2). The Changjiang sediments have the most variable magnetic compositions among all the samples, while the Taklimakan desert samples are on the contrary (Table 2). The Changjiang sediment has the highest mean $\chi$ values, followed by the loess soil and aeolian dust samples, while the Huanghe and desert samples have the lowest $\chi$ values (Fig. 2), suggesting the lowest contents of magnetic minerals in these samples. The top soil samples from the loess profiles are characterized by much higher $\chi_{50\%}$ and $Z_{ARM}$, indicating abundant fine-grained SSD magnetite and/or ultra-fined SP grains, while the aeolian dust shows the highest mean $S_{700}$ value. A positive correlation exists between $\chi$ and SIRM ($R^2 = 0.81$) among all the samples, together with the high (>90%) average $S_{300}$ values, suggesting the dominance of ferromagnetic minerals in these samples (Fig. 3), which has also been found in the Changjiang and the Huanghe estuarine sediments (Zhang et al., 2008; Wang et al., 2009). It is noteworthy that the magnetic properties between the Huanghe sediment and the loess soil samples are highly correlated, and much different from those of the Changjiang sediment that exhibits significantly scattered distributions (Fig. 3).

The magnetic parameters of the Changjiang sediments overall display large variations from upstream to downstream and between the mainstream and tributaries (Fig. 4). For example, the highest $\chi$ ($352 \times 10^{-8} \text{ m}^3/\text{kg}$) is observed in the Yalongjiang sediment (CJ-FP-2) and the lowest ($10 \times 10^{-8} \text{ m}^3/\text{kg}$) in the Fujiang (CJ-FP-9), with a mean $\chi$ of $114 \times 10^{-8} \text{ m}^3/\text{kg}$ in all the Changjiang sediments. Apart from the Yalongjiang, all the other tributaries have very low values of $\chi$ and SIRM. Generally, $\chi$ and SIRM show similar variations in the whole catchment. Both parameters are extraordinarily low in the upper Jinshajiang reaches, and increase abruptly until Yalongjiang (CJ-FP-2), reaching the maximum $\chi$ and SIRM in all the samples. Downstream the confluence of the Yalongjiang and Jinshajiang, both $\chi$ and SIRM decrease gradually. The $\chi_{50\%}$ displays a stepwise increase towards the lower reaches and reaches the maximum at Nantong, while the $Z_{ARM}$ and $S_{300}$ show serrated variations in the whole Changjiang sediments, without a clear trend.

Fig. 2. Comparison of magnetic susceptibility ($\chi$) in different samples. The numbers of the samples are indicated in each bracket. Note: CJ = Changjiang River; HH = Huanghe River.

Fig. 3. Comparisons of magnetic parameters between different sediment samples: (a): linear regression line is indicated in solid line for all the samples; (b–d): linear regression line is indicated in dashed line for the Huanghe sediment and loess soil samples only.
Compared to the Changjiang sediment, the Huanghe sediment reveals smaller difference between the mainstream and the tributaries (Fig. 5). All magnetic parameters in the Huanghe sediments show similar trends, i.e. relatively stable in the middle reaches (from HH-SPM-1 to HH-SPM-6, apart from HH-FP-1), and then serrated varying towards the river mouth (from HH-SPM-7 to HH-FP-4).

5. Discussion

5.1. Controls of magnetic properties in the fluvial, loess, desert and aeolian sediments

As introduced above, different magnetic parameters bear various implications, such as composition, concentration, and granulometrics of magnetic mineral grains in sediments. The abundance of magnetic minerals in sediments is thus primarily determined by sediment provenance, weathering condition, particle grain size, hydrodynamic differentiation during sediment transport and deposition, and post-depositional alteration as well (Thompson and Oldfield, 1986; Lovley et al., 1987; Maher, 1988; Oldfield and Yu, 1994; Roberts, 1995). Among these constraints, sediment provenance may play a dominant role and is basically, constrained by lithology in the source area.

The higher values and larger variations of bulk \( \chi \), SIRM and HIRM are clearly observed in the Changjiang sediments than in the samples from the Huanghe, loess soil, desert and aeolian dust (Table 2). The distinct magnetic properties among these various sediments are primarily controlled by their different provenance lithology. The Changjiang river basin drains about one-fifth of
China’s land area, and comprises complicated landscape, tributary system, provenance geology and weathering regimes. In particular, the well-developed tributaries of the Changjiang possess a variety of bedrock types, including carbonates, igneous, siliciclastic and metamorphic rocks (China Geological Survey, 2004; Yang et al., 2004, 2009); which determines the various sources of magnetic minerals in the riverine sediments. Primary magnetic minerals in the Changjiang sediments largely come from Mesozoic basic, intermediate-acid intrusive and volcanic rocks, which contain metamorphic iron deposits of the Mesozoic Yenshanian phase in the upper and middle Changjiang valley (Wang et al., 1990, 1992; Yang et al., 2004, 2009). Besides, the major part of the Changjiang catchment is located in a humid subtropical zone subject to a typical Asian monsoon climate, which induces a strong chemical weathering. Ferrallitic weathering widely observed in the Sichuan Basin and surrounding area leads to the accumulation of iron oxide (presumably magnetite, hematite and goethite) in soil, which consequently results in a high abundance of magnetic minerals in the upper Changjiang sediments (Yang et al., 2009).

Compared to the Changjiang sediment, the Huanghe sediment is characterized by lower values and smaller variations of magnetic parameters (Table 2; Figs. 2 and 5), which are consistent with the observations by Zhang et al. (2008) and Wang et al. (2009) on the estuarine sediments. Given that the Huanghe sediment is overwhelmingly sourced from the Loess Plateau in northwest China (Ren and Shi, 1986), it may inherit the magnetic characteristics from the loess–paleosol deposits. The high linear correlations of most magnetic parameters between the Huanghe and loess soil samples reveal the inheritance of magnetic property despite the difference in absolute values of 

\[
\chi, \chi_{\text{ARM}}, \chi_{\text{SIRM}} \text{ and } \text{SIRM} (\text{Fig. 3}).
\]

The loess soil samples from the loess profiles are characterized by extremely high susceptibility of the dust is more attributed to coarser magnetic grains, rather than the SP and SSD grains. The dust samples were collected in Beijing after a dust storm on April 17–18, 2006. Strong anthropologic activities, especially the burning of fossil fuels, may cause a heavy atmospheric pollution, which contains abundant secondary magnetite grains (Dearing, 1999). Hence, we infer that the dust samples are more dominated by ferrimagnetic grains larger than SP size.

Compared to the loess soil and dust samples, the Taklimakan desert samples have low values of all magnetic parameters (Table 2). The 

\[
\chi \text{ value in the desert sample is } 20 \times 10^{-8} \text{ m}^3/\text{kg, and the } \chi_{\text{ARM}} \text{ is only 1.5%, suggesting few SP grains present (Dearing, 1999).}
\]

Although having similar \( \chi \) with the loess soil, the aeolian dust has much higher SIRM. Generally, both \( \chi \) and SIRM reflect the abundance of ferrimagnetic grains, but the SIRM is irrespective of SP grain. Together with the low \( \chi_{\text{ARM}} \) (~2.5%) and \( \chi_{\text{SIRM}} \) (~215 \times 10^{-8} \text{ m}^3/\text{kg}) in the dust sample, it is referred that the susceptibility of the dust is more attributed to coarser magnetic grains, rather than the SP and SSD grains. The dust samples were collected in Beijing after a dust storm on April 17–18, 2006. Strong anthropologic activities, especially the burning of fossil fuels, may cause a heavy atmospheric pollution, which contains abundant secondary magnetite grains (Dearing, 1999). Hence, we infer that the dust samples are more dominated by ferrimagnetic grains larger than SP size.

Compared to the loess soil and dust samples, the Taklimakan desert samples have low values of all magnetic parameters (Table 2). The 

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\]

The consistently low susceptibility in the desert samples probably indicates a small portion of detrital (lithogenic) magnetite (~0.05 wt.%). In this study, we cannot make a detailed interpretation of magnetic property in the desert sand due to the lack of mineralogical and chemical data. The Fe2O3 content (total iron) in the desert sands is generally very low, e.g. only 2.1–3.8% (Honda and Shimizu, 1998; Rudnick and Gao, 2003). Isotopic and elemental analyses demonstrated that the Taklimakan desert sand is not far-traveled and mostly derived from surrounding source rocks (Chang et al., 2000; Nishikawa et al., 2000; Hattori et al., 2003), which determines the difference in its magnetic property from those relatively well-mixed loess and aeolian dust samples.
5.2. Spatial variations of magnetic property in the drainage basins

The magnetic properties of the Changjiang and Huanghe estuarine sediments have been revealed by previous studies (Niu et al., 2008; Zhang et al., 2008; Wang et al., 2004, 2009), which suggests that sediment provenance and grain size are two dominant constraints for the variation of magnetic properties. However, as the two largest rivers in China, the Changjiang and Huanghe watersheds cover different geologic settings, which result in complicated variations of magnetic property from upstream to downstream (Figs. 4 and 5). Therefore, the spatial variations of magnetic property in the whole Changjiang and Huanghe basins remain to be clarified.

The extremely low \( V \) and SIRM in Shigu (CJ-SPM-1) may represent the source rock composition from the widely distributed carbonates in the upper Jinshajiang catchment (Fig. 4). After draining through the Panzhihua region where multi-metal ore deposits are well developed, the \( V \) and SIRM increase rapidly in the river sediments. The Panzhihua Fe–Ti–V oxide mine that has been explored since 1960s is broadly distributed in the Yalongjiang valley and part of the Jinshajiang catchments. Magnetite and other magnetic mineral grains are widely observed in the provenance rocks and accompanied ore deposits in these river basins (Wang et al., 1990, 1992), which induces the extraordinarily concentrated magnetic minerals in the fluvial sediments (China Geological Survey, 2004; Yang et al., 2009). As a result, the rapid increase of \( V \) and SIRM in the samples taken in the Jinshajiang (CJ-FP1, CJ-SPM-2, CJ-FP-3) and the Yalongjiang (CJ-FP-2) are closely related to the high abundance of magnetic mineral grains in the provenance rocks. Downstream the confluence of the Yalongjiang and Jinshajiang, the Changjiang mainstream drains into the Sichuan Basin where is mostly covered by siliciclastic rocks. The tributary samples (CJ-FP-4, CJ-SPM-3, CJ-FP-6, CJ-FP-9, CJ-FP-10 and CJ-FP-11) collected in and around the Sichuan basin are characterized by low \( V \) and SIRM, probably suggesting the dilution of the fluvial sediments produced in these tributary basins with low abundance of magnetic minerals. On the other side, the effect of grain size on magnetic properties is also taken into account, and most magnetic parameters show poor correlations with mean grain size (Fig. 6). Therefore, it is inferred that the large variation of magnetic properties in the Changjiang sediments is basically controlled by sediment provenance, and thus can be termed as provenance-dominated.

For the Huanghe sediment (Fig. 5), all magnetic parameters exhibit a stable distribution in the middle Huanghe reaches (from HH-SPM-1 to HH-SPM-6), but fluctuate in the lower reaches (below HH-FP-2), which is probably due to the strong anthropogenic activities in the lower reaches, e.g. contamination of several large steel works in there. The apparent abnormity of HH-FP-1 is attributed to its coarser mean grain size than the neighboring SPM samples. Because of the simple tributary system and the dominant sediment provenance (the Loess Plateau), grain size plays a more significant role in determining the spatial variation of magnetic property in the Huanghe sediments (Fig. 6). Good correlations between mean grain size and magnetic properties (except \( \chi_{SPM} \% \)) in the Huanghe sediment reveal the control of sediment grain size on magnetic composition (Fig. 6). Correspondingly, the Huanghe sediment can be defined as size-dominated regardless of provenance.

It is notable that the \( \chi_{SPM} \% \) in both rivers shows much similar trends irrespective of the other magnetic parameters and grain size, which gradually increases from upstream to downstream (Figs. 4–6b). The enrichment of SP grain, formed by strong weathering condition in paleosol, is regarded as the reason for higher susceptibility in paleosol layer than in loess layer (Zhou et al., 1990; Zheng et al., 1991). Nevertheless, the reason of the \( \chi_{SPM} \% \) variability along the river course awaits more investigations.

5.3. Magnetic tracer for sediment provenance discrimination

Magnetic approach has been well applied to identify different marine sediment provenances (Oldfield, 1994; Walden et al., 1997). Recently, environmental magnetic investigations are also widely carried out in the East Asian marginal seas, such as the Yellow Sea, the East China Sea, and the South China Sea, with a main aim to trace different sediment sources (Kissel et al., 2003; Liu...
et al., 2003; Niu et al., 2008; Zhang et al., 2008; Wang et al., 2009, 2010; Liu et al., 2010a,b). Nevertheless, magnetic properties of potential sediment end-members such as the Changjiang and the Huanghe, in particular the aeolian dust, are insufficient, which makes it dissatisfactory to quantitatively and reliably discriminate different sediment provenances in the East Asian marginal seas. This study has offered elementary data of magnetic property for these potential sediment provenances, and thereby makes the first attempt to compare the estuarine sediment and aeolian dust in marginal seas in terms of magnetic characters.

The Changjiang and Huanghe estuarine sediment has been well studied by previous researches, and some magnetic parameters have been approved to be effective to indicate their difference. This study re-examines these magnetic proxies (Liu et al., 2007b; Zhang et al., 2008; Wang et al., 2010), and make a fully comparison of magnetic compositions between riverine and estuarine sediments and aeolian dust.

The discrimination plot of SIRM vs. $S_{\text{top}}$ has been well applied to differentiate the Changjiang from Huanghe estuarine sediment (Zhang et al., 2008). This paper re-examines this method by combining more sediment samples from the catchment and marine environment (Fig. 7a). The fluvial and estuarine sediments of the Changjiang and Huanghe display quite different clusters, despite considerably scattered Changjiang samples. The aeolian dust shows similar magnetic characters with the Changjiang estuarine sediment, but much different from the Huanghe estuarine sediment.

On another discrimination plot of SIRM vs. $S_{\text{top}}$, the discrimination of the Changjiang and Huanghe estuarine sediment has been well applied to differentiate the Changjiang from Huanghe estuarine sediment (Zhang et al., 2008). This paper re-examines this method by combining more sediment samples from the catchment and marine environment (Fig. 7a). The fluvial and estuarine sediments of the Changjiang and Huanghe display quite different clusters, despite considerably scattered Changjiang samples. The aeolian dust shows similar magnetic characters with the Changjiang estuarine sediment, but much different from the Huanghe estuarine sediment.

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sediments is not clear (Fig. 7b). The Huanghe and Changjiang estuarine sediments (Wang et al., 2004, 2009) are largely mixed and overlapped in this discrimination plot (Wang et al., 2004; Niu et al., 2008; this study), which makes it impossible to reliably discriminate both sediments into the sea. This uncertainty may arise from sample inhomogeneity (e.g. grain size differentiation) and/or different analytical conditions, which is beyond the scope of this research. Overall, the aeolian dust exhibits closer magnetic compositions with the Changjiang sediments in these two discrimination plots (Fig. 7a and b).

The L-ratio is supposed to be sensitive for tracing hematite/goethite (Liu et al., 2007b). In the plot of L-ratio vs. HIRM (Fig. 7c), the Huanghe sediment and Taklimakan desert sand are closely clustered, mid-lower Changjiang mainstream sediments and aeolian dust samples clustered, while the upper Changjiang mainstream sediments display a clearly different group with the other sediments. In comparison, the sediments from the tributaries of the Changjiang show much scattered variations in this plot, probably suggesting complex controls of various source rocks on magnetic property in the tributary sediments. Nevertheless, the good linear correlation between L-ratio and HIRM in the mainstream sediments indicates that the HIRM is basically controlled by the coercivity rather than by antiferromagnetic mineral concentration (Liu et al., 2007b). Thereby, the samples that show different linear correlations may have different hematite/goethite compositions, diagnostic of variable sediment sources. In other words, the plot of L-ratio vs. HIRM can be considered to distinctly discriminate the sediments from different rivers and from different reaches within one river.

As discussed above, the fluvial sediments (e.g. Yalongjiang and Tuojiang rivers) from Panzhihua region where multi-metal (Fe-Ti-V oxides) ore deposits are well developed, overall control the magnetic composition of the upper Changjiang mainstream sediment. The good linear correlation of L-ratio with HIRM (Fig. 7c) between the upper Changjiang mainstream and the Yalongjiang and Tuojiang tributary sediments further confirms the significant contribution of Panzhihua iron ore deposits to the magnetic property of the Changjiang sediments.

Overall, despite the feasibility of discriminating the Changjiang sediment, Huanghe sediment and aeolian dust based on their distinct magnetic properties, all comparisons and discriminations proposed above are only based on the samples taken on land. While using these discrimination approaches to identify the aeolian dust and fluvial sediments in the East Asian marginal seas, we have to assume that these terrigenous sediments undergo weak or no alteration during and after entering into the sea. Nevertheless, depositional and post-depositional diagenetic alterations can form pyrite, pyrrhotite or greigite due to magnetite reduction process in marine environments (Lovley et al., 1987). Significant partitioning and dissolution of specific magnetic minerals under marine environments in the East China Sea have been reported previously (Roberts, 1995; Liu et al., 2004; Zheng et al., 2010). Therefore, a better understanding of the influence of hydrodynamic sorting, diagenetic process and redox reaction on depositional magnetic minerals appear to be a prerequisite for more reliably identifying the origins of these terrigenous sediments in the marginal seas.

6. Conclusions

Typical magnetic properties of the sediment samples from diverse environments including the rivers, top soil from the loess profile, desert and aeolian dust were investigated in this contribution. In particular, the suspended and floodplain sediments from the mainstream and main tributaries of the Changjiang and Huanghe rivers were comparatively studied to examine the spatial variation of magnetic compositions and their constraints. The Changjiang sediment is characterized by the highest magnetic mineral concentration and the largest variations for most magnetic parameters, while the Huanghe sediment has much lower contents of magnetic minerals. The loess soil has the highest %XARM, indicative of the enrichment of finer SP grains. The aeolian dust displays similar X with the soil sample, but is higher in SIRM and lower in %ARM, possibly indicating dominance by coarser ferrimagnetic grains larger than SP and SSD size. The desert sample has the lowest values of each magnetic parameter.

The rapid increase of χ and SIRM in some Jinshajiang and Yalongjiang samples is primarily caused by high abundance of magnetic minerals in their provenance rocks. Downstream the confluence of the Jinshajiang and Yalongjiang, the gradual decrease of χ and SIRM in the river sediments is probably due to the dilution by many tributaries with low abundance of magnetic minerals. Comparatively, most magnetic parameters in the Huanghe sediments are relatively stable in the middle reaches but show large fluctuations in the lower reaches, probably resulting from grain size variation between the samples and strong anthropogenic activities in the lower basin. Overall, magnetic property in the Changjiang sediment is mainly constrained by its diverse lithology in the basin (provenance-dominated), while magnetic property in the Huanghe sediment is highly related to sediment grain size because of the simple sediment provenance (size-dominated). It is interesting to note that %ARM may indicate grain size fractionation in a river basin.

Based upon the discrimination plot of SIRM vs. S.L, the Changjiang sediment, Huanghe sediment and aeolian dust can be clearly discriminated, and the plot of L-ratio vs. HIRM is sensitive for differentiating the mainstream sediments from different reaches of the Changjiang. Overall, magnetic method sheds a new light on the possibility of identifying the sediment origins in East China marginal seas, with great caution of hydrodynamic differentiation and diagenetic alterations of terrigenous magnetic minerals in marine environment.

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References


