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Magnetic properties of the road dusts from two parks in Wuhan city, China: implications for mapping urban environment

Tao Yang · Qingli Zeng · Zhifeng Liu · Qingsheng Liu

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Abstract Magnetic parameters and heavy metal concentrations of road dusts collected from two parks with distance about 16 km in Wuhan city, China, were measured. The Guishan Park is circled by main roads with heavy traffic, and the Moshan Park is located on the downwind hills of steelworks and a power plant. Mean values of magnetic susceptibility (χ) and saturation magnetization (M_s) of the dusts from the Moshan Park are 1.31 and 1.57 times those from the Guishan Park, respectively. Their magnetic mineralogy is dominated by pseudo-single domain magnetite; however, minor hematite was also identified in those from the Guishan Park. The dominant sources of non-natural magnetic particles and heavy metals were inferred as windblown emissions from the steelworks and the power plant for the Moshan Park, and road/railway traffics for the Guishan Park, respectively. Spatial variation in magnetic properties of road dust in the two parks and their different magnetic behavior propose that the magnetic measurements are sensitive to the different pollutant origins, as well as the urban environment, and that magnetic techniques have a high efficiency in mapping urban environment. Correlation between magnetic parameters and heavy metal concentrations is strongly site-specific: strong correlations were observed in the Moshan Park with correlation coefficients generally higher than 0.800, whereas correlations are poor in the Guishan Park. Therefore, it is strongly recommended that these relationships should be examined thoroughly before magnetic mapping.

Keywords Environmental magnetism · Heavy metal · Atmospheric pollution · Road dust · Wuhan city

T. Yang
Institute of Geophysics,
China Earthquake Administration,
Beijing 100081, China

Q. Zeng · Q. Liu (✉)
Department of Geophysics,
China University of Geosciences,
Wuhan 430074, China
e-mail: lqs321@cug.edu.cn

Z. Liu
Paleomagnetism and Geochronology Laboratory,
State Key Laboratory of Lithosphere Evolution,
Institute of Geology and Geophysics,
Chinese Academy of Sciences,
Beijing 100029, China

Introduction

Road dust that is dangerous to human health has been recognized as an important target for studying polluted environment related to urbanization processes. The potential anthropogenic input of road dust consists of a variety of mobile or/and stationary sources, such as vehicles (including tire dust, brake dust, body rust, and exhaust, etc.), industrial plants, power plants, residential oil burning, waste incineration, construction (including asphalt, concrete, and road paint, etc.), and demolition activities with re-suspension of surrounding contaminated soils, while natural components are primarily derived from soils and weathered rocks (Harrison and Yin 2000; Xie et al. 1999, 2001; Lecoanet et al. 2001; Sagnotti et al. 2006; McIntosh et al. 2007).

It is well known that many anthropogenic impacts on the environment (e.g., effluents from power plants, combustion of fossil fuel, metallurgical industries, smelters, road traffic, etc.) are accompanied by significant emissions of ferrimagnetic components. In particular, these magnetic components often have a causal link with heavy metals (Strzyszcz 1993), such as Cu, Pb, Zn, Cd, and Cr. Their deposition thus may be associated with the enhancement of both magnetization and concentration of pollutants in environmental matters (e.g., topsoils, sediments, fly ashes, and road dusts, etc.; Petrovský and Ellwood 1999; Ng et al. 2003; Lu and Bai 2006; Magiera and Zawadzki 2007; Hanesch et al. 2007; Sharma and Tripathi 2008; Lu et al. 2009; Liu et al. 2009; Yang et al. 2007a, 2009; Bućkol et al. 2010). Xie et al. (1999)'s study on the street dusts from Liverpool, UK, suggested that organic matter contents significantly correlate with some magnetic concentration-related parameters, and that the main magnetic carriers are a multi-domain (MD) ferrimagnetic phase with a small contribution of single-domain (SD) and antiferromagnetic grains. Large magnetite-like spherules with complex internal structure, as well as the melt-like particles and irregular-shaped grains containing heavy metals were found in the road dust from the industrial zone of Visakhapatnam city (India; Goddu et al. 2004). A 2-year magnetic monitoring of roadside dust in Seoul, Korea, revealed that the major magnetic phase is a magnetite-like material, with magnetic concentrations and particle sizes systematically fluctuating seasonally (high and large in winter versus low and small in summer) due to the seasonal influx variation of anthropogenic magnetic materials (Kim et al. 2007). Magnetic studies of roadside dust from Seoul, Korea, throughout a 13-month period, demonstrated that seasonal mapping using a mean apparent magnetic concentration (ACM) could be highly informative on the investigation of spatio-temporal pollution characteristics in urban areas (Kim et al. 2009). These works have demonstrated that magnetic methods can be employed not only for identification of sources of contaminants, but also as a complementary tool for the routinely employed geochemical methods, which are known to be more time consuming, tedious, and expensive (Hoffmann et al. 1999; Xie et al. 1999, 2001; Ng et al. 2003; Spiteri et al. 2005; Prajapati et al. 2006; Magiera and Zawadzki 2007; Hanesch et al. 2007; Sharma and Tripathi 2008; Blaha et al. 2008; Lu et al. 2009; Yang et al. 2007a, 2009; Kim et al. 2007, 2009).

Generally, the close relationship between magnetic parameters and concentration of pollutants is a fundamental prerequisite for magnetic mapping. In order to examine the efficiency of magnetic technique for mapping urban environment in Wuhan, China, magnetic measurements and chemical analyses were performed on the road dusts collected from two parks with different environmental settings, establishing links between anthropogenic magnetic particles and heavy metals with well-determined pollution sources, and exploring their implications for magnetic mapping.

Materials and methods

Study areas

Wuhan city, located in the middle reaches of the Yangtze River, is the capital of Hubei Province and the largest city in central China. Its population is approximately 8.18 million (end of 2006), approximately 4.3 million of them residing in nine urban core districts within an area of 201 km^2. The climate of the area is humid sub-tropical with an average annual temperature of 15.8–17.5°C and an annual rainfall of 1,269 mm. The prevailing wind direction through the year is from the north and northeast, with the average wind speed ranging 1.6–2.8 m/s. The whole city is divided into three parts (so-called three towns of Wuhan) by the Yangtze River and the Han River (Fig. 1a).

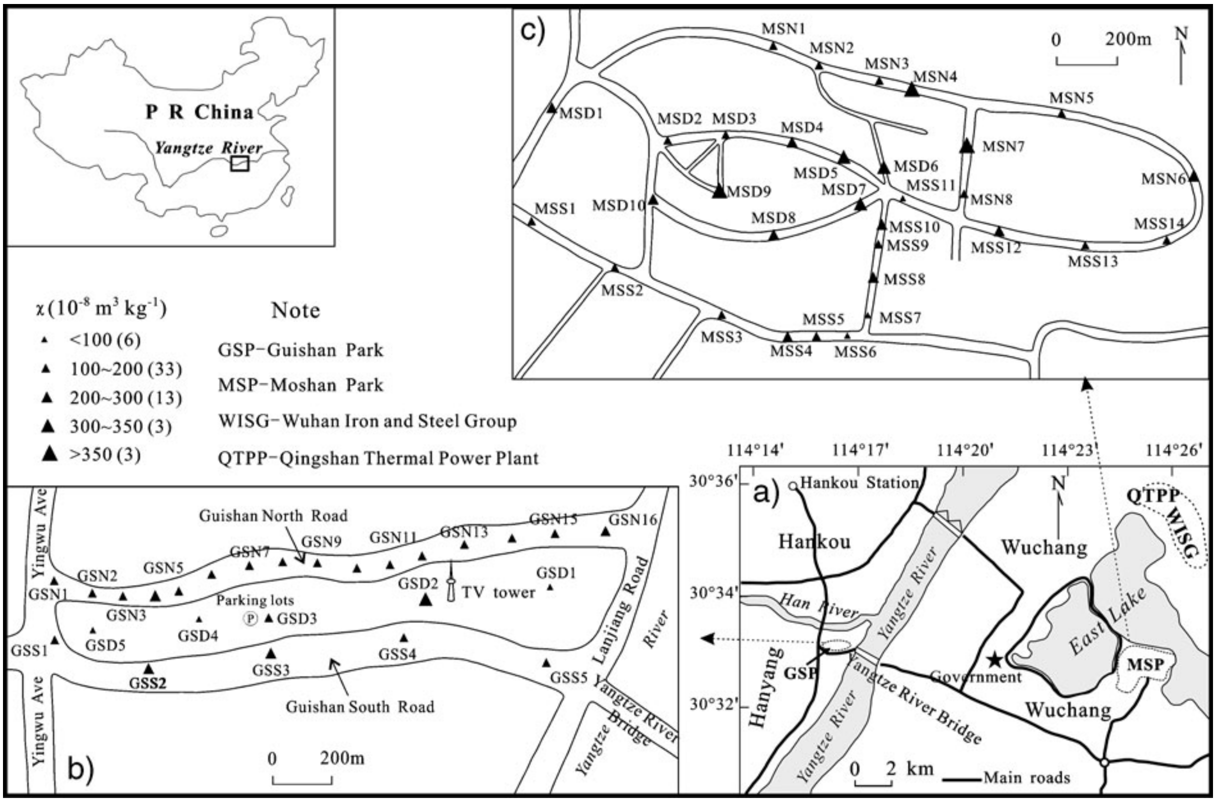


Fig. 1 Sketch map of the study area and sampling sites (*triangle symbols*) of road dust samples. The sizes of *symbols* mark the susceptibility values. The values in the *parentheses* are the number of samples within the corresponding range

Hankou, the commercial center and largest of the three, occupies the northwestern quadrant, lying west of the Yangtze and north of the Han River. Hanyang, the smallest of the three and a manufacturing section, lies west of the Yangtze and south of the Han River. Wuchang, the administrative and educational center, is on the eastern bank of the Yangtze.

The Guishan Park (GSP) located in Hanyang area, is surrounded by Lanjiang Road, Guishan North Road, Yingwu Ave, and Guishan South Road connected with the Yangtze River Bridge (Fig. 1a, b). There is heavy traffic (ca.100–120 vehicles per minute) on the Guishan South Road and Yingwu Ave, whereas the traffic load is relatively low on the Guishan North Road. A railway connecting two sections of the Jinggguang (Beijing-Guangzhou) railway (a major artery railway in China) runs along the Guishan South Road (Fig. 1a), and there are ca. 120 trains everyday (both electric and diesel trains, though the electric trains predominate). Some small foundries, dyehouses, and cotton spinning mills are distributed along the Guishan North Road. A television tower and parking lots are situated on the hilltop of the park.

The Moshan Park (MSP) is situated on the Moshan Hill in the southeast of Wuchang area, and is surrounded by the East Lake at the east, west, and north (Fig. 1a). The Moshan Hill is much higher in the north than in the south. The Wuhan Iron and Steel Group (WISG), the third largest iron and steel consortium in China, and the Qingshan Thermal Power Plant (QTPP) are situated northeast of the park (Fig. 1a). The QTPP is a coal-burning plant and has a total installed capacity of 986,000 kW. Small outcrops of granite were found in some sites on the hilltops of the park. The direct distance between the Guishan and Moshan Parks is about 16 km.

Samples collection

The sampling campaign was carried out over a 7-day dry weather period in September 2002. In total 26 samples were collected from the Guishan Park, including the Guishan North Road (GSN, $n = 16$), the hilltops of the Guishan Park (GSD, $n = 5$), and the Guishan South Road (GSS, $n = 5$; Fig. 1b). In total 32 samples were collected from the Moshan Park (Fig. 1c); sampling sites are mainly distributed at the southern hillside (MSS, $n = 14$), the top of park (MSD, $n = 10$), and the northern hillside (MSN, $n = 8$). At each sampling site, dust was collected by ground sweeping with a small paint brush from a square of 1–2 m^2 on the roads, and transferred to clean, self-seal polyethylene bags. In the laboratory, all samples were air-dried and passed through a 1-mm sieve to remove refuses and small stones.

Magnetic measurements and heavy metal analysis

Mass specific magnetic susceptibility (χ) was measured using a WSLA magnetic susceptibility meter (Aerogeophysical Survey China) with sensitivity of 1×10^{-5} SI. Magnetic hysteresis loops were measured using a Princeton Alternating Gradient Force Magnetometer (Model 2900 AGM); the maximum applied field was 1.0 T. Hysteresis parameters, saturation magnetization (M_s), saturation remanence (M_{rs}), and coercive force (B_c) were calculated after paramagnetic correction. Remanence coervcivity (B_{cr}) was determined by backfield measurements after reaching 1.0 T. In order to determine magnetic mineral phases, temperature dependence of magnetic susceptibility between room temperature and 700°C was measured using an AGICO KLY-3 Kappabridge equipped with a CS-3 high-temperature furnace in an argon atmosphere.

Total contents of heavy metals (Cu, Cr, Fe, Pb, Ni, and Zn, etc.) of 22 samples were determined using a Siemens SRS303 X-ray fluorescence spectrometer equipped with a Rh-anode X-ray tube and the Siemens SPECTRA AT evaluation software. About 3 g of road dust mixed with low-pressure polyethylene powder was pressed into powder pellets with a diameter of 34 mm. The relative error of parallel samples was determined as less than 5%.

Results and discussion

Magnetic properties of the road dusts

Magnetic parameters are summarized in Table 1 and shown by box-plots in Fig. 2. The spatial distributions of χ are also shown in Fig. 1 where the size of triangle symbol indicates qualitatively the magnitude of magnetic susceptibility. Magnetic concentration-dependent parameters of the road dusts in the Moshan Park are generally higher than those in the Guishan Park, i.e., the mean values of χ (Figs. 1 and 2a) and M_s (Fig. 2b) for the Moshan Park are 1.31 and 1.57 times those for the Guishan Park, respectively (Table 1). Both B_c and B_{cr}/B_c for the Moshan Park are lower than those for the Guishan Park (Fig. 2d, e).

As M_{rs}/M_s and B_c show (Table 1 and Fig. 2), magnetic minerals in the road dusts are dominated by low coercivity ferrimagnetic

Table 1 Statistics of the magnetic parameters and apparent magnetite concentration (AMC) for the road dust samples

	χ (10^{-8} m^3 kg^{-1})	M_s ($10^{-3}$$Am^2$ kg^{-1})	M_{rs}/M_s	B_c (mT)	B_{cr}/B_c	AMC (% by mass)
Guishan Park ($n = 26$)						
Range	42.2–315.5	210.3–1,237.5	0.06–0.11	5.17–10.70	1.34–3.60	0.23–1.34
Mean	160.0	744.1	0.09	7.04	2.52	0.81
SD	55.3	336.1	0.01	1.77	0.83	0.36
Moshan Park ($n = 32$)						
Range	99.2–484.5	407.2–3,088.0	0.06–0.09	3.53–7.60	1.14–4.12	0.44–3.36
Mean	209.0	1,167.7	0.07	5.26	1.94	1.27
SD	99.1	835.2	0.01	1.21	1.01	0.91

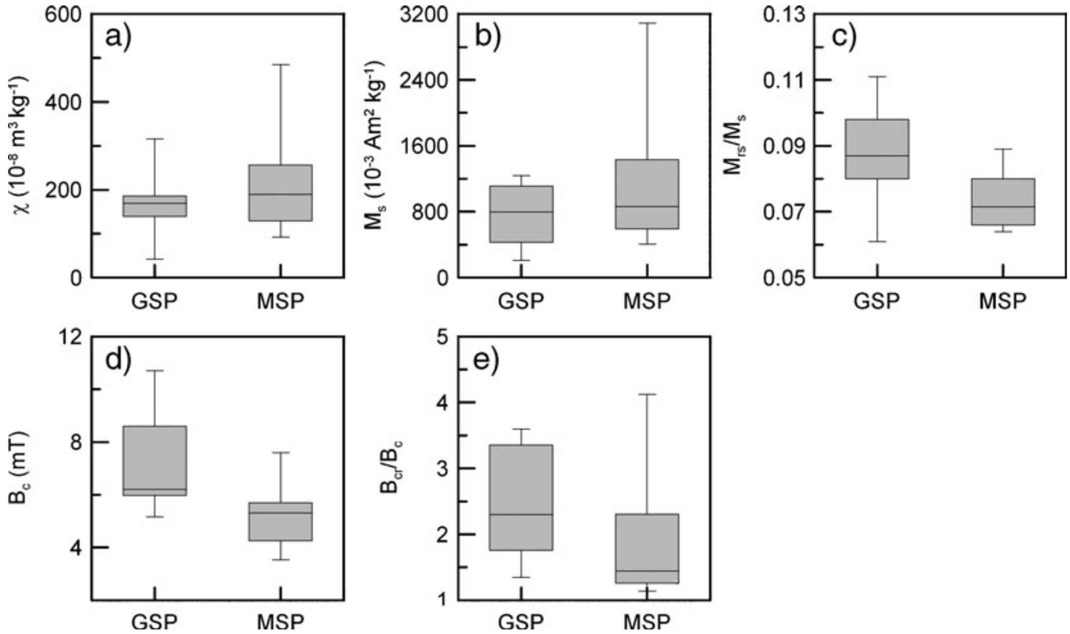
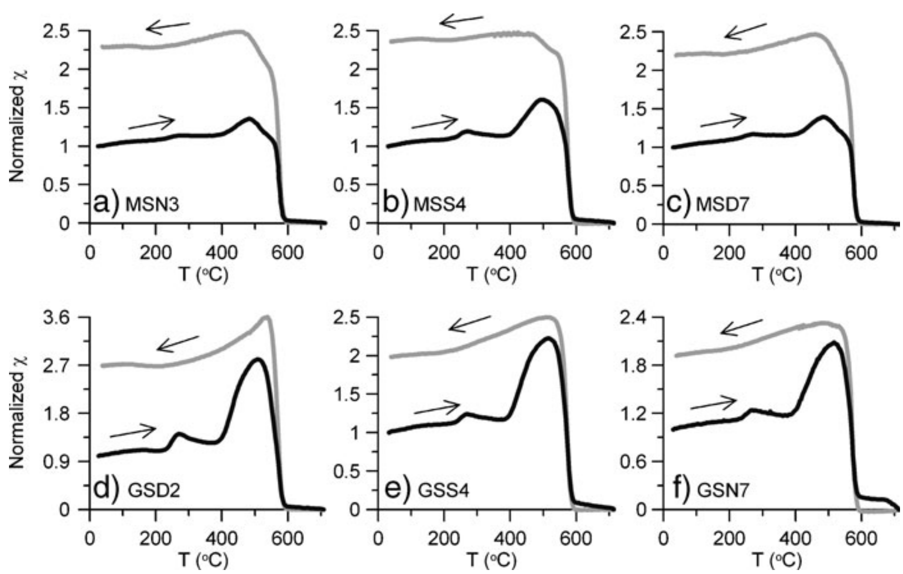


Fig. 2 *Box-plots* of **a** magnetic susceptibility (χ), **b** saturation magnetization (M_s), **c** ratios between saturation remanence (M_{rs}) and M_s, **d** coercive force (B_c), and **e** ratios between remanence coercivity (B_{cr}) and B_c of the road dusts from the Guishan Park (*GSP*) and Moshan Park (*MSP*)

phases. This finding can be confirmed by the χ–T curves (Fig. 3). The thermomagnetic behavior for all samples is dominated by a Curie temperature T_c of about 580°C, revealing the presence of a magnetite-like phase as the dominant magnetic carrier (Dunlop and Özdemir 1997). The increase at ca. 500°C in the heating runs is likely attributed to neoformation of magnetite as a result of

Fig. 3 Temperature-dependent magnetic susceptibility curves for selected samples. Each curve was normalized with its corresponding magnetic susceptibility at room temperature. The *black* and *grey lines* denote heating and cooling runs, respectively



thermal alteration of Fe-rich clay-minerals (Hoffmann et al. 1999). These alterations could be confirmed by cooling runs, ending at room temperature χ values more than twofold of the initial ones. A kink at 250–300°C is most noticeable in the Guishan Park (Fig. 3d–f), and may be attributed to the transition of SD particles into a superparamagnetic state (Liu et al. 2005) or to thermal break-down of some un-identified sulfides. Moreover, the presence of minor hematite in the Guishan Park is indicated by the distinct χ decrease at 670–680°C in the heating runs (Fig. 3e, f), which is similar to the T_c of hematite (Dunlop and Özdemir 1997). It is also interesting to note that the peaks at ca. 500°C in the heating runs for the dust from the Guishan Park (Fig. 3d–f) are much higher than those in the Moshan Park (Fig. 3a–c), it suggests that there are more neo-formation of magnetite during the thermal alteration for road dust in the Guishan Park (Hoffmann et al. 1999). Overall, the dominating magnetic carrier in the road dust from both parks is magnetite, while minor hematite was also present in the road dust from the Guishan Park.

The hysteresis properties for the representative samples are summarized in a Day plot (Fig. 4, Day et al. 1977). It is seen that most of the data points occupy the pseudo-single domain

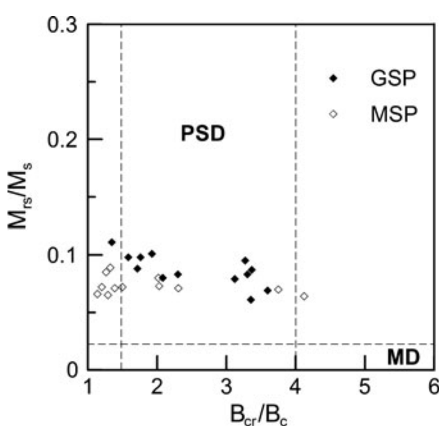


Fig. 4 Day plot of the ratios M_{rs}/M_s and B_{cr}/B_c for the road dust from the Moshan Park (*MSP*) and Guishan Park (*GSP*). Pseudo-single domain (*PSD*) and multi-domain (*MD*) boundaries are after Day et al. (1977)

(PSD) area, however, magnetic particles in dusts from the Guishan Park show slightly higher coercive properties, which could be a consequence of hematite revealed by thermomagnetic analysis (Fig. 3e, f).

M_s is independent of grain-size and proportional to the magnetic concentration, and often used to estimate the apparent concentration of magnetite in a sample ferrimagnetically predominated by magnetite. Stoichiometric magnetite has an M_s of 92 $Am^2\ kg^{-1}$ (Dunlop and Özdemir 1997). Given that the dominant magnetic carrier in road dusts has been identified as magnetite, the mass-specific ACM can be estimated in the order of 0.23–1.34% (mean 0.81%) and 0.44–3.36% (mean 1.27%) in the Guishan and Moshan Park, respectively (Table 1).

Heavy metal concentrations and their association with magnetic properties

Concentrations of the heavy metals in the road dusts are depicted in Table 2. The concentration of Fe in the Moshan Park is significantly higher than in the Guishan Park, which coincides with the estimated ACM (Table 1), but contrary patterns can be observed for Zn and Cu. The mean concentrations of Pb, Mn, and Cr are comparable in both parks, respectively.

Table 3 lists the Pearson's correlation coefficients between the element concentrations and magnetic parameters. The correlation matrix indicates that χ and M_s have generally a strong linear correlation with element concentrations in the Moshan Park; the correlation coefficients are generally higher than 0.800 (at a significance level of 0.01). In contrast, poor correlations are observed in the Guishan Park (Table 3), which is possibly due to the dependence of magnetic concentration-related parameters on mineral phases and magnetic domain state, and/or to the intermixture of elements from complex sources and their association with different magnetic minerals.

Furthermore, the Tomlinson pollution load index (PLI; Angulo 1996) was used to assess the overall heavy metal toxicity of the dusts. The PLI index is defined as the *n*-th root of the product of concentration factors (CF_{HM}), where CF_{HM} is the ratio between the concentrations of each

Table 2 Statistics of the heavy metal content in the road dust (unit: mg/kg except for Fe with unit of %)

	Fe	Zn	Pb	Ni	Mn	Cr	Cu	Co	PLI
Guishan Park ($n = 12$)									
Range	2.13–5.65	213–1,098	48.2–136	14.7–33.3	386–896	46.4–79	41.5–106	5.4–19.1	1.2–2.5
Mean	3.78	391.7	84.7	24.6	596.7	61.6	64.8	11.1	1.6
SD	0.91	252.6	33.4	6.1	149.6	9.4	17.4	3.6	0.36
Moshan Park ($n = 10$)									
Range	2.76–16	80.3–494	34.3–312	18.3–47.3	470–959	43–182	28.9–114	8.6–34.3	1.0–4.2
Mean	6.248	235.0	86.3	27.0	644	66.6	52.0	15.6	1.9
SD	3.7	125.9	82.2	9.0	165.3	41.6	23.7	7.4	0.93

heavy metal (C_{HM}) to its corresponding background value ($C_{background}$) or the lowest concentration value detected for each heavy metal (C_{lowest}). In the present study, the lowest concentration value for each element (C_{lowest}) in each of the two parks was used to calculate the PLI index:

$$CF_{HM} = C_{HM}/C_{lowest} \quad (1)$$

$$PLI = \sqrt[n]{CF_{HM1} \times CF_{HM2} \times \ldots \times CF_{HMn}} \quad (2)$$

The mean values of the PLI are 1.6 and 1.9 for the Guishan and Moshan Parks, respectively, indicating that the dusts exceed significantly the concentrations of heavy metals for natural environment (Angulo 1996), and that heavy metal pollution is more serious in the Moshan Park. It is worth noting that χ generally correlate more prominently with the PLI than with individual elements in the Moshan Park (Table 3), which suggests that χ values are more proportional to the concentration of collective heavy metals rather than each individual concentration. Similar results were also reported by Kim et al. (2007).

Sources of the magnetic particles and heavy metals

Principal component analysis (PCA) was applied to assist the identification of sources of pollutants. By extracting eigenvalues and eigenvectors from correlation matrix, the number of significant factors and the percentage of variance explained by each of them were calculated by using the Statistical Package for the Social Science package.

The Guishan Park has three factors with eigenvalues >1, accounting for 89.32% of the total variance. Plots of PCA loadings are presented in Fig. 5a, b, and the relationships between the heavy metals and magnetic parameters are presented. The first factor explains 44.76% of the total variance and loads heavily on Fe, Ti, Ni, Mn, Cr, and Co, and B_c (Fig. 5a). Ti, Mn, and Ni are largely soil-derived elements, while Fe is a mixed element of soil and urban origins (Xie et al. 2001); they are closely correlated with B_c that is sensitive to the fine magnetic particles often derived from pedogenesis (Thompson and Oldfield 1986). Therefore, this factor should be inferred as natural source, such as the erosion of the hill

Table 3 Correlation coefficients between the concentrations of heavy metals and magnetic properties

	Fe	Zn	Ti	Pb	Ni	Mn	Cr	Cu	Co	PLI
Guishan Park ($n = 12$)										
χ	0.085	0.160	−0.082	0.105	−0.467	−0.294	−0.338	0.369	−0.075	−0.027
M_s	0.486	0.411	0.223	0.098	−0.105	0.026	−0.055	0.479	0.329	0.334
B_c	0.318	0.162	0.362	−0.152	0.825*	0.698**	0.656**	0.002	0.500	0.470
Moshan Park ($n = 10$)										
χ	0.892*	0.846*	0.281	0.870*	0.844*	0.673**	0.870*	0.897*	0.872*	0.892*
M_s	0.977*	0.884*	0.265	0.972*	0.904*	0.691**	0.971*	0.964*	0.959*	0.968*
B_c	0.349	0.606	0.911*	0.245	0.553	0.734**	0.204	0.334	0.423	0.409

*$p = 0.01$, correlation is significant (two-tailed)
**$p = 0.05$, correlation is significant (two-tailed)

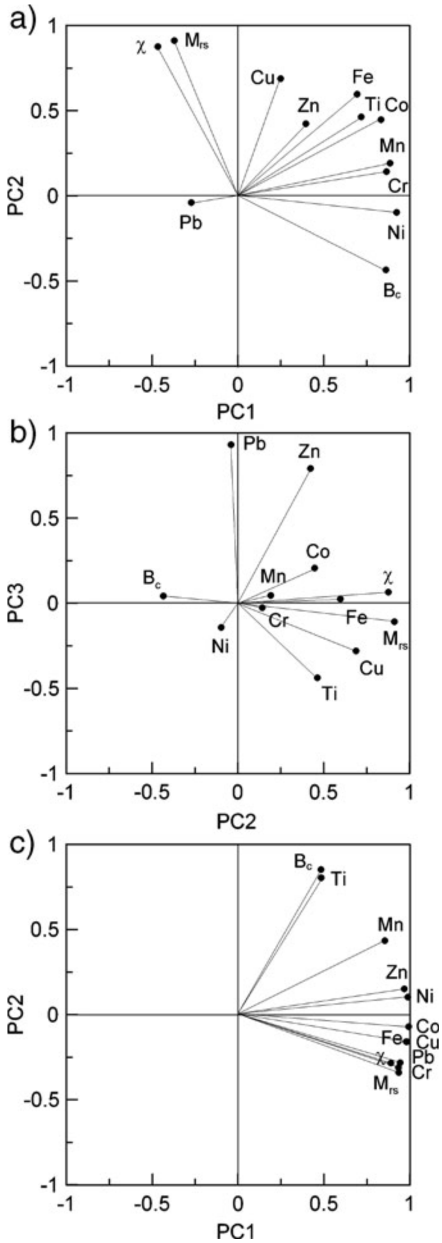


Fig. 5 Principal component analysis factor plots of **a**, **b** the Guishan Park and **c** Moshan Park in component space

body, roadside topsoil, and exotic soils brought by the vehicles, etc. Factor 2 represents 30.63% of the total variance, and is controlled primarily by Fe, Cu, χ, and M_{rs} (Fig. 5a). The Guishan Park is circled by the main roads, especially the Yingwu Ave and Guishan South Road (Fig. 1b) with high traffic density of more than 120 vehicles per minute. Road dusts suffer directly the inputs of vehicle emissions which often contain a great amount of magnetite-like particles with abundant Cu, Fe, Pb, and Zn (Hoffmann et al. 1999; Lu et al. 2005; Lu and Bai 2006; Prajapati et al. 2006; McIntosh et al. 2007). Due to the railway running along the Guishan South Road, railway debris may be also expected to contribute fine magnetic particles to road dust (Moreno et al. 2003; Urbat et al. 2004). Consequently, this factor may be explained by road/railway traffic, which is evident from the presence of high content of Cu with a mean value of 64.8 mg/kg and Fe with a mean content of 3.78% in the dusts. Lu et al. (2005) reported that the average concentrations of Cu and Fe in vehicle emission particulates are up to 95.83 mg/kg and 3.47%, respectively. Factor 3 contributes 13.93% of the total variance (Fig. 5b), and there are strongly correlations between Zn and Pb that are dominated by non-natural sources (Xie et al. 2001). Therefore, the source for this factor is industrial, likely involving the dyehouses and cotton spinning mills at the north of the park. Apparently, the sources for magnetic particles and heavy metals in the road dusts from the Guishan Park is relatively complex, which could be one of the possible reasons for the poor correlations between the magnetic concentration related parameters and heavy metal contents. In addition, the elevated magnetic susceptibility of the samples GSD2 and GSD3 (Fig. 1b) could be attributed to a certain extent to the television tower and tourism parking lots, respectively.

The PCA factor plot of the heavy metals and magnetic parameters for the Moshan Park is shown in Fig. 5c. The first two components account for 95.92% of the total variance. The first one exhibits the highest loading (ca. 75.18%) of Fe, Zn, Pb, Ni, Mn, Cr, Co, χ, and M_{rs}, this factor should be industrial. Factor 2 is loaded primarily by Ti and B_c, accounting for 20.74% of the total variance. The source for this factor should be from natural sources, such as the soils and the erosion/weathering products of outcropping granites. The elevated concentration of Fe, Zn, Pb, Ni, Mn, Cr, and Co in the dusts in the Moshan Park (Table 2) can be attributed to windblown emission and fly ashes from the WISG and QTPP. A great number of magnetic particles are formed both during the combustion of fossil fuels for power generation and the process of metallurgical and smelting industry (Petrovský et al. 2001; Kapička et al. 2001; Kapička et al. 2003). During fly ash formation, heavy metals are adsorbed on the surface of iron oxides (mainly magnetite) in a preferential order of Pb, Zn, Cu, Cr, and Cd (Georgeaud et al. 1997) or substituted in spinels of $Fe_{3-x}M_xO_4$ (Hunt et al. 1984), or they are dispersed with magnetic particles following the pattern of "same source–same distribution pathway" (Spiteri et al. 2005). The deposition of these particles on the ground contribute significantly to the magnetic and heavy metal concentrations of the road dusts from the Moshan Park situated in the downwind areas of the WISG and QTPP. This finding can also be supported by the presence of abundant coarse grained Fe-rich spherules with industrial origins in the sediments from the East Lake (Yang et al. 2007b, 2009).

Implications for magnetic mapping of urban environment

Spatial variation of χ of the road dust is characterized by position-specific distinctions (Fig. 6). For the Guishan Park, χ peaks in the Guishan South Road connected with the Yangtze River Bridge (GSS, with a mean value of 176.5×10^{-8} m^3 kg^{-1}), which is comparable with that in the Guishan North Road (with a mean value of 162.7×10^{-8} m^3 kg^{-1}), and followed by the lowest value at the hilltop of Guishan Park (with a mean value of 134.8×10^{-8} m^3 kg^{-1}). The highest magnetization in GSS could be attributed to the vehicle emission and railway debris released by the heavy traffic (>120 vehicles per minute) and the nearby busy railway. The traffic density is relatively lower in the Guishan North Road, but there are some small foundries, dyehouses, and cotton spinning mills. The different influx of vehicle traffic and industrial emissions can hence be associated with the variation in magnetic susceptibility. For the Moshan Park, the relative higher χ values are mainly restricted to the top of the Moshan Park (with a mean value of 266.2×10^{-8} m^3 kg^{-1}), followed by the northern hillside (with a mean value of 236.4×10^{-8} m^3 kg^{-1}), while the southern side (with a mean value of 152.5×10^{-8} m^3 kg^{-1}) shows the lowest values. The WISG and QTPP lie to the northeast of the Moshan Park, and the prevailing wind direction is north and northeast during the entire year in Wuhan. Samples MSS are situated in the typical back slope of the hill, where the wind-blown industrial emissions released by WISG and QTPP were intercepted by the hill. The top and northern side of the hill suffers directly deposition of these emissions. Consequently, it is suggested that spatial variation of magnetic susceptibility can delineate the spatial distribution of pollution. However, distribution of magnetic particles is not only influenced by the emission sources, but also by other complex factors, such as climate (e.g., wind direction, wind speed, and vertical turbulence) and geographical conditions (e.g., location and height).

Both parks are located within different settings in the same city with direct distance of about 16 km. However, as discussed above, magnetization of the road dusts from the Moshan Park is generally higher than that of the Guishan Park. PSD magnetite is the major magnetic phase in

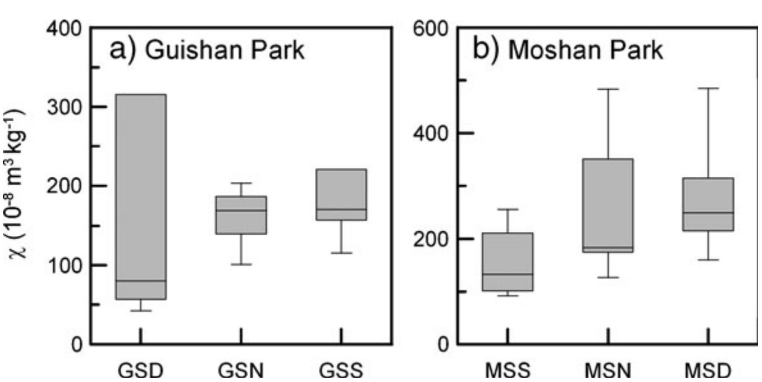


Fig. 6 *Box-plots* of magnetic susceptibility for road dust from different sampling sites. *GSN* Guishan North Road, *GSD* the top of the Guishan Park, *GSS* Guishan South Road, *MSS* the southern hillside of the Moshan, *MSD* the top of the Moshan Park, *MSN* the north hillside of the Moshan

both parks, however, minor hematite was also found in those from the Guishan Park (Figs. 3 and 4). Differences in the contents of heavy metals are also observed such as the mean contents of Fe are 6.25% and 3.78% in the dusts from the Moshan Park and Guishan Park (Table 2), respectively. Moreover, the magnetic concentration-related parameters significantly correlate with heavy metal concentrations in the Moshan Park, but exhibit poor correlations in the Guishan Park (Table 3). All these results reveal the differences in the sources of magnetic particles and heavy metals. The predominant source of non-natural magnetic particles and heavy metals in the road dusts was inferred to be due to vehicles emissions for the Guishan Park, and windblown industrial emissions from the QTPP power plant and the WISG steelworks for the Moshan Park, respectively. The spatial variations of magnetic susceptibility also reveal the different anthropogenic influx from different sources in these two parks. These results propose that the magnetic properties are sensitive to the different pollutant origins, hence having high potential for identifying and mapping polluted urban environments, even for contiguous areas in the same city. Therefore, it is suggested that rock magnetic techniques can be used as an efficient complementary tool in environmental evaluation.

Conclusions

Magnetic measurements and heavy metal analysis were performed on road dusts collected from two parks with different environmental settings in Wuhan city, China: the Guishan Park circled by main roads with heavy traffic, and the Moshan Park located in the downwind hill of steelworks and a power plant. The mean value of χ for the dusts from the Moshan Park is 1.31 times that from the Guishan Park. The dominant magnetic mineral is PSD magnetite in both parks; however, a minor amount of hematite was also present in the dust from the Guishan Park. The relationships between heavy metal concentrations and magnetic parameters of the dusts from the two parks are significantly different; correlation coefficients for heavy metal contents and magnetic concentration parameters χ and M_s in the Moshan Park are generally higher than 0.800, whereas poor correlations between them are observed in the Guishan Park. The dominant sources for non-natural magnetic particles and heavy metals in the dusts were inferred as windblown emission from the steelworks and the QTPP power plant for the Moshan Park, and vehicle traffic and to a certain extent also railway emissions for the Guishan Park.

In short, these obvious differences in magnetic properties and their correlations with the heavy metal concentrations indicate that magnetic properties are sensitive to the urban environment, and can be used as an alternative and complementary indicator for the heavy metal pollution. However, this should be attempted with caution, as the close relationships between magnetic parameters and heavy metal content are not necessarily “universal”. As suggested by the present study, the relationship is expected to be site dependent. Consequently, it is recommended that the nature of the relationships between magnetic properties and heavy metal contents should be first examined thoroughly when using magnetic measurements as a proxy tool for mapping heavy metal pollution.

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