Relationship between magnetic anomalies and hydrocarbon microseepage above the Jingbian gas field, Ordos basin, China

Qingsheng Liu, Lungsang Chan, Qingsong Liu, Haixia Li, Fang Wang, Shuangxi Zhang, Xianghua Xia, and Tongjin Cheng

ABSTRACT

In this study, soil magnetic measurements (susceptibility and hysteresis parameters) and soil hydrocarbon analyses were conducted on samples from three profiles (profiles I and II run across, and profile III runs parallel to the trend of the Jingbian gas field in the Ordos basin, central China) to determine the relationship between the magnetic anomalies (e.g., volume-specific magnetic susceptibility $k$) and the hydrocarbon seepage environments. The results document a strong correlation between magnetic susceptibility and soil-gas hydrocarbon concentration. Furthermore, the spatial distribution of $k$ and hydrocarbon anomalies correlate with those of the gas field. In addition, magnetic minerals in the soils with higher susceptibility are predominantly magnetite, with little or no substitution of titanium compared to that of samples with lower susceptibility ($< 7 \times 10^{-5}$ SI [International Unit of susceptibility]). These results provide strong evidences for the formation of highly magnetic minerals in close association with hydrocarbon seepage. Recognition of such seepage-induced magnetic anomalies can be used to facilitate the exploration for oil and gas in China and elsewhere.

INTRODUCTION

Magnetic susceptibility measurements of soil and well cuttings document that magnetic anomalies (including aeromagnetic, borehole, and ground magnetic surveys) are generally associated with oil and gas fields (Saunders et al., 1991; Foote, 1996; Berger et al., 2002;
SHUANGXI ZHANG ~ Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong, China

Shuangxi Zhang received a B.S. degree (1983) and an M.S. degree (1986) in applied geophysics from the China University of Geosciences (Wuhan) and a Ph.D. (2003) in earth sciences from the University of Hong Kong. His research interests are in seismic prospecting and its application to the geophysics of engineering and petroleum.

XIANGHUA XIA ~ Institute of Petroleum Geochemistry, China National Petroleum and Chemical Corporation (SINOPEC), Hefei 220023, China

Xianghua Xia is a researcher at the Hefei Institute of Petroleum Geochemical Exploration, SINOPEC. He obtained his B.S. degree (1986) in geochemistry at the China University of Geosciences (Wuhan) and a Ph.D. (2003) in petroleum geology at the Chengdu University of Technology. His research interest is oil and gas geochemical exploration.

TONGJIN CHENG ~ Institute of Petroleum Geochemistry, China National Petroleum and Chemical Corporation (SINOPEC), Hefei 220023, China

Tongjin Cheng received a B.S. degree (1978) in petroleum geology from Chengdu University of Technology. He is a professor at the Institute of Petroleum Geochemical Exploration, Hefei, SINOPEC. His specialization is in oil/gas migration and geochemical exploration.

ACKNOWLEDGEMENTS

The authors are grateful to the National Natural Science Foundation of China (No. 49874026) for support of this study and thank Deet Schumacher, Peter J. Hatgelakas, and Donald F. Saunders for the very helpful comments to improve this manuscript.

LeSchack and Van Altinie, 2002; Wollenben and Greenlee, 2002). Thus, these magnetic anomalies possess high potential for gas and oil exploration to complement conventional geologic and seismic methods.

Donovan et al. (1979) showed that abundant secondary magnetites relate to hydrocarbon microseepage (i.e., diagenetic magnetite) and possibly contribute high-frequency and low-amplitude magnetic anomalies above the Cement oil field in Oklahoma, United States. Since then, similar findings from other oil fields have also been reported (Cai, 1986; Foote, 1987, 1988, 1996; Li, 1987; Saunders et al., 1989; Reynolds et al., 1990a; Tompkins, 1990).

To confirm the genetic links between these magnetic anomalies and hydrocarbon seepage environments, the corresponding geochemical processes involving the seepage-induced alteration have been widely studied (Yeremin et al., 1986; Ellwood and Burkart, 1996; Schumacher, 1996; Saunders et al., 1999). Donovan et al. (1979) suggested that geochemical effects associated with hydrocarbon microseepage could extend to the surface above oil fields. Such hydrocarbon-induced alteration of soils and sediments is also known to produce microbiological anomalies, mineralogical changes, bleaching of red beds, clay mineral alteration, and electrochemical changes (Schumacher, 1996). Therefore, the chemical alteration of near-surface sediments by carbon dioxide and hydrogen sulfide produced by microbial degradation of hydrocarbons could account for the observed geomorphic, seismic, magnetic, and radiometric anomalies over petroleum deposits (Saunders et al., 1999).

Despite these previous efforts, uncertainties still exist as to the precise relationship between the magnetic anomalies and the corresponding hydrocarbon seepage environment. The main barriers are the inherent complexity of the hydrocarbon-produced magnetic anomalies and difficulties in determining the origin of the corresponding magnetic particles (Elmore et al., 1987; Sassen et al., 1989; Elmore and Crawford, 1990; Reynolds et al., 1990b; Elmore et al., 1993). Machel and Burton (1991) provided conceptual models for the causes and spatial distribution of magnetic anomalies in hydrocarbon seepage environments. They suggested that magnetic minerals (e.g., magnetite, pyrrhotite, and hematite) could be either produced or destroyed under the influence of hydrocarbons, resulting in both positive and negative magnetic anomalies. In addition, magnetic surveys are also affected easily by cultural noise or natural disturbances of the magnetic field (Reynolds et al., 1990a; Gay and Hawley, 1991; Gay, 1992).

To understand these problems better, we have, for the past 20 yr, extensively investigated the relationship between soil magnetic susceptibility and some major oil fields in Song-Liao, Tarim, Subei, and Qiangtang basins in China. Our studies documented that the soils above or adjacent to most oil/gas fields are characterized by high magnetic susceptibility anomalies. Further mineralogical analysis reveals that the enhanced magnetic susceptibility relating to the oil/gas fields are caused by secondary magnetite and the subsequent low-temperature oxidation products (maghemite)
To extend and confirm our previous results, in this study, we conducted parallel measurements of both soil magnetic properties (susceptibility and saturation isothermal remanent magnetization [SIRM]) and geochemical properties (e.g., total hydrocarbon, \(C_t\)) along three intersecting profiles across the Jingbian gas field in the Ordos basin, a well-studied field and basin in central China.

In this study, our first objective is to determine the correlation between the magnetic anomalies and the corresponding hydrocarbon anomalies. Second, we aim to determine whether the spatial distribution of the magnetic anomalies is controlled by the oil/gas field. Finally, by combining both the bulk information and detailed studies on magnetic extract of characteristic samples, we will further determine the origin of the magnetic particles responsible for the magnetic enhancements relating to hydrocarbon seepage.

### GEOLOGICAL BACKGROUND AND SAMPLING

The Ordos basin is a large sedimentary basin located near the western margin of North China craton in central China. The major sedimentary strata in the basin are of Carboniferous through Jurassic age. The basement consists of continental and shallow-marine sedimentary rocks of lower-middle Proterozoic age, overlain by fluvial-lacustrine facies of late Proterozoic age. The formation of the basin was controlled by the regional structure. The basin, including the Jingbian gas field and seismic nose structure situated north of Haotan, is a highly prospective region for oil and gas (Figure 1).

The sedimentary formations in the basin contain seven sets of oil- and gas-generating units (source rocks) that formed during the Sinian (late Precambrian) through Jurassic times (Yang et al., 1992). In recent years, large portions of the basin have been explored using a variety of surface geochemical methods, and some of these results have contributed to the development of the Jingbian gas field (Wang et al., 1992).

The three profiles examined in the current study are located in the northern part of the central uplift in the basin. Profiles I and II are oriented in an east-west direction, and profile III is oriented in a north-south direction, intersecting profiles I and II (Figure 1). Each of these profiles is more than 100 km (62 mi) long, and soil samples were collected at approximately 1-km (0.62-mi) intervals. A total of 413 samples were collected from these three profiles. For each sample, about 800 g of soil were collected at depth 1.5–2 m (5–6.5 ft) below the surface to avoid man-made contamination. Soil samples collected from the northern part of the basin consist primarily of sand and silt (profiles I, II, and the north half of profile III). The lithologies in the southern half of profile III are mainly sand and loess (Figure 1).

Profile I is approximately 187 km (116 mi) and crosses the town of Henshan (Figure 1). Profile II is a 116-km (72-mi)-long west-east traverse and passes over the central part of the Jingbian gas field (Figure 1). Profile III (110 km [68 mi] long) runs in a north-south direction and intersects with profiles I and II (Figure 1). To facilitate comparing the spatial distribution of magnetic anomalies of profiles I and II, the first point (west) of profile I is set as the reference point of zero (distance). Therefore, the initial point (west) of profile II is 24 km (15 mi). However, for profile III, its first point (north) is set as the reference point of zero (distance).

### METHODS

Magnetic susceptibility \(k\) measurements were measured using a WSL-A magnetic susceptibility meter, with a sensitivity of approximately \(10^{-5}\) SI units. Hysteresis loop measurements were conducted using an LDJ-9500 Vibration Magnetometer (LDJ-9500 VM) with a maximum applied field of 0.8 T. Hysteresis parameters without high field correction include saturation magnetization \(J_s\), SIRM \(J_{SIRM}\), and intrinsic coercivity \(B_I\). Ratio of \(J_{SIRM}/J_s\) is used to detect the grain-size variations of magnetic minerals in samples.

To distinguish the magnetic minerals in samples with normal \(k\) and enhanced \(k\), both iron and trace elements of the corresponding magnetic extracts, e.g., TiO\(_2\), CoO, NiO, Cr\(_2\)O\(_3\), and V\(_2\)O\(_5\) contents were quantified with electron probe microscopic analysis using a JCXA-733 electron probe.

To determine the background of susceptibility, first, we calculate the mean and standard deviation of \(k\) for all samples based on the method proposed by Saunders et al. (1989, 1991). Then, values that deviated from the mean by more than one standard deviation were eliminated, and the new mean and standard deviation values were calculated for the remaining data. The procedure was repeated, until the mean and standard deviations did not show significant changes in
consecutive steps. Commonly, the anomaly strengths are expressed in terms of the number of standard deviations above or below the background mean. The greater the number of standard deviations that a value differs from the background mean, the smaller the probability that the value is caused by random background variations. For a single value equal to the background plus one (two) standard deviation, the probability that it is a valid anomaly is about 84% (99.7%).

The composition and concentration of light hydrocarbons in soil were measured using the gas chromatography method (Yang et al., 1995; Sun et al., 1997). The analytical precision of the AUT-XL type gas chromatograph used in the current study is less than 3%. Two geochemical parameters were measured: (1) total hydrocarbons defined by $\sum C_1 \sim C_5 (C_t)$, and (2) heavy hydrocarbons defined as $\sum C_2 \sim C_5 (C_h)$ for this study. These two geochemical parameters have...

**Figure 1.** Location of profiles of the Jingbian gas field in the Ordos basin. The two horizontal lines and an intersecting vertical line mark the location of the profiles I, II, and III.
been shown to be reliable indicators of hydrocarbon microseepage from oil and gas reservoirs (Duchscherer, 1984, 1986; Horvitz, 1985; Klusman, 1993).

**RESULTS**

Figure 2 illustrates the spatial variations in $k$ (three-point smoothing method) and the corresponding geochemical parameters for these three profiles. Generally, $k$ is less than $12 \times 10^{-5}$ SI (International Unit of susceptibility), and the background means for all data is about $7.2 \pm 2.6 \times 10^{-5}$ obtained by the iterative method. In the following discussion, if several $k$ peaks are separated only by short-wavelength $k$ lows only several kilometers wide, to be convenient, we will name them as a broad $k$ peak, for example, the broad $k$ peak at sample site greater than 116 km (72 mi) for profile I, 28–84 km (17–52 mi) for profile II, and greater than 30 km (>19 mi) for profile III.

For profile I, there are four significant $k$ anomalies located at about 10–20, about 30, about 54–88, and greater than 116 km (~6.2–12, ~19, ~34–55, and >72 mi), respectively, with $k$ values larger than $7 \times 10^{-5}$ SI. The broad $k$ anomaly (>116 km >72 mi) coincides with a portion of the gas field. The distributions of geochemical anomalies of profile I share most features of that $k$. The ranges of variation are 1.61–490.60 μL/kg for total hydrocarbon content, and 0–34.26 μL/kg for heavy hydrocarbon. Profile II is shorter than profile I and includes only two $k$ anomalies, located between 24 and 88 and between 104 and 125 km (65 and 78 mi), respectively. Again, we found that these two $k$ anomalies correlate with elevated hydrocarbon concentration. However, the maximum total hydrocarbon ($C_t$) of the profile (~1000 μL/kg) is almost double compared to that of profile I (~500 μL/kg).
Table 1. Trace-Element Contents of Magnetite Grain from Representative Samples (wt.%)  

<table>
<thead>
<tr>
<th>Site</th>
<th>Number</th>
<th>Fe total*</th>
<th>MnO</th>
<th>NiO</th>
<th>Al₂O₃</th>
<th>Cr₂O₃</th>
<th>V₂O₅</th>
<th>MgO</th>
<th>TiO₂</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile I</td>
<td>87</td>
<td>93.251</td>
<td>0</td>
<td>0</td>
<td>0.238</td>
<td>0.207</td>
<td>0</td>
<td>0</td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>92.468</td>
<td>0.097</td>
<td>0.421</td>
<td>0</td>
<td>0.411</td>
<td>0</td>
<td>0.133</td>
<td>0.163</td>
<td></td>
</tr>
<tr>
<td></td>
<td>138</td>
<td>90.766</td>
<td>0.01</td>
<td>0.151</td>
<td>0.124</td>
<td>1.685</td>
<td>0</td>
<td>0.035</td>
<td>0.049</td>
<td>gas field</td>
</tr>
<tr>
<td>Profile II</td>
<td>82</td>
<td>91.432</td>
<td>0.046</td>
<td>0.188</td>
<td>0.077</td>
<td>0.273</td>
<td>0.519</td>
<td>0.015</td>
<td>0.187</td>
<td></td>
</tr>
<tr>
<td></td>
<td>101</td>
<td>92.870</td>
<td>0</td>
<td>0</td>
<td>0.026</td>
<td>0.225</td>
<td>0.201</td>
<td>0.032</td>
<td>0.278</td>
<td></td>
</tr>
<tr>
<td></td>
<td>112</td>
<td>92.725</td>
<td>0.313</td>
<td>0</td>
<td>0</td>
<td>0.069</td>
<td>0.466</td>
<td>0.094</td>
<td>0</td>
<td>gas field</td>
</tr>
<tr>
<td></td>
<td>119</td>
<td>91.786</td>
<td>0.062</td>
<td>0.112</td>
<td>0.191</td>
<td>0</td>
<td>0.029</td>
<td>0.049</td>
<td>gas field</td>
<td></td>
</tr>
<tr>
<td></td>
<td>124</td>
<td>92.163</td>
<td>0</td>
<td>0.235</td>
<td>0</td>
<td>0.140</td>
<td>0.430</td>
<td>0</td>
<td>0</td>
<td>gas field</td>
</tr>
<tr>
<td></td>
<td>134</td>
<td>91.545</td>
<td>0.148</td>
<td>0</td>
<td>0.230</td>
<td>0.639</td>
<td>0.447</td>
<td>0</td>
<td>0.247</td>
<td></td>
</tr>
<tr>
<td></td>
<td>141</td>
<td>91.271</td>
<td>0</td>
<td>0.140</td>
<td>0.071</td>
<td>0.931</td>
<td>0.263</td>
<td>0.085</td>
<td>0.257</td>
<td></td>
</tr>
<tr>
<td>Profile III</td>
<td>4</td>
<td>91.246</td>
<td>0</td>
<td>0.182</td>
<td>0.102</td>
<td>0.191</td>
<td>0</td>
<td>0.029</td>
<td>0.348</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>91.807</td>
<td>0.028</td>
<td>0.169</td>
<td>0.072</td>
<td>0.245</td>
<td>0</td>
<td>0.056</td>
<td>0.374</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95</td>
<td>92.481</td>
<td>0.430</td>
<td>0.341</td>
<td>0</td>
<td>0.491</td>
<td>0</td>
<td>0.728</td>
<td>0</td>
<td>near the oil field</td>
</tr>
</tbody>
</table>

*Fe total* = total iron content.

Profile III parallels to the long-axis direction of the Jingbian gas field (Figure 1). The whole profile is characterized by high $k$ and high hydrocarbon concentrations, except for samples between about 8 and 40 km (5 and 25 mi).

Figure 1 also provides the location of both the distribution of the gas field and the exact location of gas/oil wells along the profiles. The field outline is determined by the integrated geological and geophysical surveys, including exploration wells during the past several decades. Although the exact field margin needs further constraints, the north-northeast–south-southwest long-axis distribution of the field is believed to be well determined.

By connecting the $k$ highs and lows of the profiles I and II, we find that the directions of spatial distribution of these major $k$ anomalies parallel to the long-axis direction of the gas field.

To probe further the origin of the magnetic particles in samples with high susceptibility ($>7 	imes 10^{-5}$ SI), the iron and the trace-element (especially TiO₂) concentrations (wt. %) of the magnetic extracts for characteristic samples for these three profiles are listed in Table 1 and also shown in Figures 1 and 2. The total Fe (FeO + Fe₂O₃) contents for all selected samples are higher than 90 wt. %. The trace elements are sensitive indicators for the nature of the magnetic particles. In this study, we mainly focus on Titanium content. The working hypothesis is that magnetic particles with high Ti are of primary origin, and particles with low Ti substitutions represent in-situ secondary magnetic products from the hydrocarbon seepage environments (see details in the Discussion). It is evident that the magnetic particles in samples with high $k$ correspond to low (<0.05 wt. %) or zero Ti content, whereas the magnetic particles in samples with lower $k$ are characterized by high Ti content (0.163–0.374) (Table 1).

Figure 3 shows the crossplots of $J_s \sim k$ (Figure 3a, d) and $k \sim C_t$ (Figure 3e, m) for all measurements (column 1 in Figure 3) for these three profiles and the correlation for individual profile (columns 2–4 in Figure 3). On the whole, $J_s$ and $k$ are linearly correlated ($R^2 = 0.57$) (Figure 3a). When $J_s$ approaches zero, the $k$ corresponding values are about $3 \times 10^{-5}$ SI, corresponding to the susceptibility background caused by silicates (silicates do not carry remanences) in samples. Compared to the average $k$ background ($7 \times 10^{-5}$ SI) obtained from the iterative approach, the additional $k$ ($4 \times 10^{-5}$ SI) may be carried by the primary magnetic particles. Unlike profiles I and III, profile II shows that when $k$ is almost zero, the sample still carries a weak remanence (~10 A/m).

The parameters $k$ and $C_t$ are also positively correlated but not in a linear pattern. We used a power equation $\ln k = 0.212 \times \ln C_t + 1.143$ ($R^2 = 0.58$) fitting to the total measurements (Figure 3e). When $C_t$ is zero, samples without alteration by hydrocarbon have $k$ values between about 2 and $7 \times 10^{-5}$ SI. This confirms that the background value of $k$ ($7 \times 10^{-5}$ SI) obtained from the iterative method is reasonable. Therefore, we conclude that we may regard $k$ values significantly larger than $7 \times 10^{-5}$ SI (e.g., above $10 \times 10^{-5}$ SI) in this region as an indicator of a significant $k$ anomaly.
With increasing $C_t$ (<100 µL/kg, Figure 3e, m), $k$ is almost linearly correlated with $C_t$, indicating a strong relationship between the enhancement of $k$ and the hydrocarbon concentration. It seems that when $C_t$ is higher than 200 µL/kg, $k$ will be independent on variations in $C_t$ (Figure 3f, h). It is noted that samples with $C_t$ between 200 and 400 µL/kg have $k$ values relatively lower than the adjacent samples, with $C_t$ just smaller than 200 and higher than 400 µL/kg.

Hysteretic parameters ($J_{rs}$, $J_s$, $J_{rs}/J_s$, and $B_c$) for these three profiles are shown in Figure 4. The correlation between $J_s$ and $k$ is shown in Figure 3a, d. Apparently, both $J_{rs}$ and $J_s$ share most features of $k$ but with some local discrepancies. The background coercivity $B_c$ is about 15 mT (Figure 4). It is noted that samples with lower $k$ and $C_t$ (especially when $C_t$ is almost zero) have higher coercivities, e.g., samples between 110 and 120 km (68 and 75 mi) for profile I.

The ratio of $J_{rs}/J_s$ is dependent on grain size. Theoretically, single-domain (SD, 50–100 nm) magnetic grains have $J_{rs}/J_s$ higher than 0.5. In contrast, multidomain (MD, >30 µm) and superparamagnetic (SP, <40 nm) particles have ratios lower than 0.05–0.1. The exact threshold $J_{rs}/J_s$ value for pseudo-SD (PSD)/(MD + SP) have been assigned as 0.05 (Day et al., 1977) and 0.1 (Dunlop, 2002), respectively, because of their different approaches. Therefore, we do not intend to accurately estimate the exact grain sizes of the magnetic particles based on this ratio, but for qualitatively detecting the relative variations in the magnetic grain size. Figure 4 shows that samples with enhanced $k$ have lower $J_{rs}/J_s$ ratios of around 0.1, located at the PSD/(MD + SP) grain-size boundary. One noticeable feature for profile I is that samples around 110 km (68 mi) have fairly higher ratios of almost 0.5.

Figure 3. Correlations between $J_s$ and $k$ (a–d), between $k$ and $C_t$ (e–h), and the corresponding truncated figures (j–m) for all measurements (the first column), and profiles I (second column), II (third column), and III (fourth column).
Figure 4. Distance plots of $k$ and hysteretic parameters and ratios. The meanings of the dashed lines and gray bars are defined in Figure 2. Statistically, the grain sizes of magnetic particles in samples with higher $k$ are finer than in those with lower $k$. 
DISCUSSION

Correlation Between $k$ and $C_t$

To link tightly the magnetic anomalies (in this study, mainly referred to $k$) with the corresponding hydrocarbon seepage environments (represented mainly by $C_t$), we provide the following three lines of evidence: (1) positive correlation between $k$ and $C_t$, (2) consistency of the spatial distribution of $k$ anomalies and the distribution of the previously known gas field (long axis in Figure 1), and (3) the relationship between the Ti content of magnetic particles (the magnetic extract, not the bulk samples).

Surely, the elevated hydrocarbon concentrations in this region originate from the upward seepage of oil and gas. Ellwood and Burkart (1996) and Schumacher (1996) suggested that the presence of hydrocarbon gases could significantly change the chemical and physical properties of soils in the hydrocarbon seepage environment. Therefore, we expect certain correlation between magnetic properties (e.g., $k$) and the absolute concentration of hydrocarbon (e.g., $C_t$). Although the correlation may be positive or negative because of the complexities of the soil magnetism (Machel and Burton, 1991), for a specific region, we believe that the correlation between $k$ and $C_t$ at this region must be consistent, either positive or negative.

Figures 2 and 3 clearly exhibit a strong and consistent positive correlation between $k$ and $C_t$. When $C_t$ is zero, the $k$ values ($2-7 \times 10^{-5}$ SI) are believed to be caused by the silicates and the primary strongly antiferrimagnetic minerals prior to the alteration of hydrocarbon. The contributions of the weakly magnetic hematite and goethite are believed to be less important compared to these strongly magnetic minerals. Therefore, the $k$ enhancement (e.g., $k > 10-12 \times 10^{-5}$ SI) of samples must be directly related to the chemical alteration because of hydrocarbon seepage. However, this correlation is not always linear as revealed by Figure 3. The $k$ values are positively correlated with $C_t$ when $C_t$ is only less than 100 µL/kg. Above that, it seems that $k$ is independent of $C_t$.

The second evidence rests on the fact that the ground projection of the upward seepage of hydrocarbon must be controlled by the gas and oil accumulation. Hydrocarbon microseepage is predominantly vertical because the driving force is buoyancy. In addition, the rate of gas microseepage ranges from less than 1 m/day to tens of meters per day, which is at least an order of magnitude greater than the lateral movement of ground water (Klusman and Saeed, 1996). Dipping faults can also carry hydrocarbons to the surface and form narrow, linear anomalies that approximate the fault trend, but this is a different pattern than the anomaly (broad) formed by microseepage from an accumulation.

Therefore, for the elongated distribution of the oil and gas fields, the spatial distribution of $k$ and $C_t$ anomalies must agree with (or correlate with) the long axis of the projection of the corresponding geochemical plumes on the ground. In this study, the Ordos Jingbian gas field provides an ideal natural laboratory for testing this model. Figures 1 and 2 clearly show that the directions of lines connecting the associated $k$ anomalies for profiles I and II are parallel to the long axis of the gas field.

The third evidence is the different origin of the magnetic particles in samples with apparently low and high $k$. The origin of the iron-bearing minerals in soils is very complex. However, the variations in the concentration of the trace elements (especially Ti) of the magnetic particles can be used to qualitatively distinguish its origin. Generally, magnetic minerals with high TiO$_2$ content form generally under high-temperature conditions, such as volcanic rock and man-made materials (Wang, 1989). In contrast, the more pure (single-phase) magnetite, with minor or no Ti substitution, is produced by pedogenesis and/or products of hydrocarbon alteration.

Table 1 shows that magnetic particles in samples with lower $k$ have a higher Ti content than samples with higher $k$. We confidently conclude that the newly formed magnetite/maghemite particles with less or no Ti substitution are produced by the alteration of hydrocarbon probably on silicates and reduction of hematite and goethite.

By combining these three evidences, we believe that the enhanced $k$ is caused by the newly formed magnetite/maghemite with minor Ti substitution in the hydrocarbon seepage environment.

Future Work

The main objective of this study is to provide more documentation for linking the magnetic anomalies with the hydrocarbon seepage environments. However, the exact mechanism for formation of strongly magnetic particles in this seepage environment is not yet fully understood. We believe that more field and laboratory studies are necessary to unravel this problem.
First, we need to investigate more parallel profiles, crossing the gas field to further determine the relationship of the spatial distribution of $k$ anomalies and the gas field. Second, we could quantify the variations in the concentration of hematite/goethite and further compare them with variations in magnetite/hematite to check whether the newly formed magnetite/maghemite particles are reduced from hematite/goethite. Third, more detailed hysteric parameters (including remanent coercivity $B_{r}$) and scanning electron microscopy and transmission electron microscopy observations are also important for quantifying the grain sizes and structure of the primary and secondary magnetic particles. Finally, we have observed that the $k$ and $C_{1}$ anomalies are not always consistent with each other. We deduce that the migration of hydrocarbons is more dynamic than the formation and preservation of the hydrocarbon-related magnetic particles. In addition, the geochemical plumes associated with the hydrocarbon seepage may not always be vertical, resulting in shifts of the center of $k$ and $C_{1}$ anomalies compared to the projection of gas field. Therefore, knowledge of the detailed geological structure under the ground at this region is essential to understand the migration pathways of hydrocarbon.

In this study, we used the Ti content to specify the origin of the secondary magnetic particles in samples with high $k$. However, there are alternative means besides the TiO$_{2}$ measurements that could be used to determine whether the magnetite is of truly authigenic origin. These measurements may include petrographic studies and grain-size estimations by the Day et al. (1977) plot. We believe that the secondary authigenic magnetic particles will have a totally different grain-size distribution from the primary magnetic minerals.

**CONCLUSIONS**

Based on the foregoing discussion, we document a positive correlation between the enhanced $k$ and the concentration of hydrocarbon (e.g., $C_{1}$) at this study area. High magnetic susceptibility anomalies are generally present in soils above/near the Henshan and the Jingbian gas fields in the Ordos basin. This genetic relationship is further supported by the consistency of the spatial distribution of the gas field with the $k$ anomalies. Constrained by the trace-element analysis of the magnetic extracts from samples with characteristic low and high $k$ anomalies, we determined that the secondary strongly magnetic particles are single phase, with minor or no Ti substitution, apparently different from the primary magnetic particles characterized by high Ti substitution.

Although the use of soil magnetic susceptibility mapping could be a useful supplemental means of gas and oil exploration, we have to note that multiple high $k$ and $C_{1}$ anomalies may be caused by a single gas field because of the horizontal shift of the geochemical plumes. At the current stage of our knowledge, we may use the $k$ mapping to identify prospective exploration targets and trends and not to determine the location of specific gas and oil wells.

**REFERENCES CITED**


