Mechanism of the migration of gold in desert regolith cover over a concealed gold deposit

Rong Ye1*, Bimin Zhang1,2 & Yong Wang3

1 China University of Geosciences, Beijing, 100083, China
2 Institute of Geophysical and Geochemical Exploration, Langfang, Hebei 065000, China
3 Beijing Research Institute of Uranium Geology, Beijing, 100029, China

*Correspondence: yerong@cugb.edu.cn

Abstract: The mechanisms in transferring metals associated with mineralization upwards through transported cover are poorly understood. Geogas is thought to be an important medium in the process of vertical migration of elements. In this paper, metal particles in gases and soils overlying a concealed gold ore body at the Jinwozi gold field, Xinjiang, northwestern China were collected and observed using transmission electron microscopy (TEM) to study gold occurrences. In addition, Geogas and soil surveys were conducted along traverse lines across the ‘210’ gold deposit concealed by several to tens of meters of regolith cover. Soils were collected in a regolith profile to further study the horizontal and vertical distribution of gold. Geochemical analyses using ‘Geogas’ and soil methods show Au, Ag and Hg anomalies occur over the ‘210’ gold ore body. A drilled profile revealed a ‘C-shaped’ distribution pattern of mobile gold in the regolith. Gold-copper and copper-bismuth nanoparticles were detected by TEM in the Geogas and soil samples. The results indicated that nanoparticles sourced from the underlying concealed ore bodies are likely to have been the cause of the surface geochemical anomalies. The particles could travel upwards to the surface, during which the Geogas and soil anomalies are developed in pore space and in soil, which has a large surface area. At the surface, some of the particles are retained in the Geogas, while others are captured by soil constituents such as clays, iron and manganese oxides, which create the ‘C-shaped’ distribution patterns of the mobile gold in vertical profiles.

Keywords: regolith, concealed gold deposit, Geogas, mobile elements, nanoscale metal particles, nanoparticles

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Geochemistry is one tool applied to search for buried mineral deposits, using a variety of approaches, including selective leaching of soils and the measurement of Geogas (Cameron et al. 2004). Geogas is considered to be an ascending gas flow released from the interior to the earth’s surface containing N2, O2, CO2, CH4 and inert gases (Malmqvist & Kristiansson 1984). Geogas prospecting is a relatively new technique in exploration for concealed and deep-seated mineral deposits that was jointly developed in the 1980s by Kristiansson & Malmqvist (1980, 1982, 1987), and has been applied on a trial basis in Sweden (Kristiansson & Malmqvist 1982, 1987; Malmqvist et al. 1999), Germany (Hirner 1998), Canada (Cameron 2001), USA (Cameron 2001), Australia (Wang et al. 1999), Uzbekistan (Wang et al. 1997) and China (Wang et al. 1997; Tong & Li 1999; Wang et al. 2006). The results showed that the measured elemental compositions in Geogas across geological formations reveal much about the bedrock composition and the possible presence of concealed mineralization and ore bodies (Malmqvist et al. 1999). Geogas prospecting uses the principle that metallic nanoparticles associated with ore bodies can be adsorbed onto the surfaces of gas bubbles and can be transported to the Earth’s surface by ascending gas flows. More speculatively, nanoscience demonstrates that nanometer-scale metal particles have gas-like characteristics (Wu 1998). If this conclusion was universal in nature, nanoparticles (c. 1–100 nm) could migrate like gases, i.e. it would not be necessary for them to be transported by other gases (Wang et al. 2007). However, previous researchers focused mainly on the element concentrations of the Geogas materials captured by polyurethane foam or liquid absorbents (Tong et al. 1992; Wang et al. 1995; Wang et al. 1997). Some studies have verified the existence of nanoparticles in Geogas and soils (Cao et al. 2010; Wang & Ye 2011; Wang et al. 2012; Ye et al. 2012), which can help the development of the Geogas prospecting technique, and provide more direct evidence for the research into migration mechanisms of elements.

Wang (2005, 2007) found that gold and associated elements showed C-shaped distribution patterns in the vertical profile, i.e. elements tend to be enriched in the lower and upper parts of the regolith profile over the ‘210’ ore body at the Jinwozi gold field, Xinjiang, northwestern China. The possible model of migration that was proposed was mainly based on the migration of Geogas-carried nanoparticles through the cover. However, gold nanoparticles were not directly observed in Geogas and soils six years ago in the study by Wang et al. (2007). In this paper, metals in gases and soils overlying a concealed gold ore body were collected and observed using transmission electron microscopy (TEM) to study gold occurrences. In addition, Geogas and soil surveys were conducted along traverse lines across the 210 gold deposit and soils were collected in the regolith profile to further study the horizontal and vertical distribution of gold.

Geological Setting

The Jinwozi gold field is located 200 km north of Dunhuang city on the boundary of Xinjiang and Gansu provinces in northwestern China (Fig. 1). The Upper Devonian Jinwozi Formation widely outcrops in this area, which is composed of tuffaceous sandstone, carbonate and calcareous sandstone, with minor carbonates and basic to acid volcanics. The strata in this region are dip to 310–340°NW with an angle of 40–45°.
There are two mineralized belts in the Jinwozi gold field (Fig. 2). In the northern belt, ore bodies are associated with quartz veins, occurring at the contact between porphyry and Devonian sequences. The southern belt, the 210 gold belt, is situated 2–2.5 km south of the Jinwozi gold belt, and is covered by the Quaternary Gobi desert with a depth of a few to c. 10 m, in which the gold deposit occurs as a concealed ore body. The sequence of regolith materials from bottom to top is: weathered rocks, sands with interbedded gravels, a strongly cemented gypsum horizon, a sandy clay-rich horizon and desert crust, with black gravels at the surface (Wang et al. 2007).

In the 210 gold deposit, the ore body occurs as structurally altered quartz veins developing in a NE-trending ductile alteration fault, and classified as a shear zone gold deposit. The ore body is situated in mylonitized carbonaceous tuff and tuff breccias of the Jinwozi Formation of the Upper Devonian as large quartz-sulfide veins. The ore-controlling structure is a 65° NE-trending ductile fracture, consistent with the main direction of the regional structure lines. Six industrial lodes have been identified, in which the average Au grade of No.1 and No.2 lodes is 4.9 and 17.6 g/t, respectively. The proven total Au reserve is 10 t (Wang et al. 2012; Ye et al. 2004).

The ores of the 210 gold deposit are mainly composed of pyrite, galena and chalcopyrite. The pyrite in ores is the primary Au-bearing mineral, in which native Au and electrum occur as inter-particle and fissure Au. The main gangue mineral is quartz, with minor calcite, sericite and chlorite.

**Sample Collection and Analysis**

**Sample collection**

Three collectors were placed in the field for 10 months in order to collect the TEM samples in Geogas. The gases enter the collector through a 0.45-μm millipore filter and metal particles are captured by the carriers made by a Ge grid (passive adsorption method) (Fig. 3). In addition, the soil samples for separating nanoparticles were collected at a depth of 40–60 cm above the ore body and background area. Samples were dried at room temperature. The samples were sieved to <38 μm and then scattered using an electromagnetic oscillation micrometer sieve which is connected to a trap device and an air extractor. During the scattering process, the rising nanoparticles are captured by carriers (Ge grids) (Fig. 4). An overburden sampling drill was used to sample a single regolith profile above the 210 gold ore body (Fig. 2). Samples were collected continuously every meter from ground surface to bedrock. The final drilling depth was 24 m. The zoning structure and mineral composition of the regolith cover is illustrated in Figure 5.

At the same time, Geogas surveys were conducted along four traverse lines across the 210 ore body. Four lines are named L2, L1, L3, and L4, respectively, from the east to the west. The interval between the traverse lines is c. 250 m. Each line has 15–20 sampling points with a spacing interval of 50–100 m (Fig. 2). Seventy-six sampling points have been established in this survey area. Two kinds of medium (liquid absorbents and polyurethane foam) were used at each sampling point to capture metals in the Geogas collection process in our study (Wang et al. 1995; Liu et al. 2003). Dilute aqua regia solution (5%) was used as the liquid absorbent, which was purified at an ultrapure laboratory of the China University of Geosciences, while the polyurethane foam was pretreated using 10% aqua regia and immersed in 5% aqua regia after washing with super-purity water (18.2 MΩ·cm). Six holes were drilled using a steel chisel to 0.5–0.8 m in depth at every sampling point for each medium. The spacing of holes at every sampling point was 1 m. Three holes were designated for aqua regia (5%) to collect Geogas samples and the other three holes were for polyurethane foam to collect Geogas samples. The screwed sampler was pinched into the holes (Fig. 6). The holes were connected by silicone tubes with a filter equipped with a Millipore filter membrane (0.45 μm, nitrocellulose) and trapping sets. For the aqua regia (5%) medium, 3 litres of gas were extracted by the air extraction pump (developed by the Institute of Geophysical and Geochemical Exploration, IGGE) in each hole, and trapped by U-shaped bottles. The volume of aqua regia in the U-shaped bottle at each sampling point was set at 20 ml. For the polyurethane foam medium, the air sampler would extract the gas for 2 min at each hole, during which the gas flow rate was controlled as 1.5 l/min.

![Fig. 1. Location of the Jinwozi gold deposit (after Wang 2007).](image1)

![Fig. 2. Geological map of the Jinwozi-210 gold field (after Wang 2012).](image2)
In addition, the L4 line was selected to conduct the soil survey using the same sampling sites as the Geogas survey. The soil samples were collected from the sandy clay-rich horizon at a depth of 15–30 cm and sieved to <120 μm in the field.

**Tem analysis**

The observation of nanoparticles was carried out at Beijing University using an H9000NAR TEM produced by Hitachi. The point resolution, lattice resolution and minimal spot radius of this instrument are 0.18 nm, 0.1 nm, and 0.8 nm, respectively. The TEM is equipped with an X-ray Energy Dispersive Spectroscopy (EDS) which can detect elements with atomic numbers between 5 and 92. The accelerating voltage was set at 300 kV. The composition of the particles was determined using the EDS without reference material in our studies, and hence we cannot obtain the exact mass percent of the component. During the observations, the spot radius is set at < 0.2 μm.

**Chemical analysis**

The soil samples from drilling were sieved to <150 μm and divided into two parallel streams: one was used for sequential extraction of the mobile metals (Wang 1998), and the other for four-acid, near-total digestion. The various Au ‘forms’ were categorized as ‘water-extractable’ Au, clay-associated Au, Au associated with Fe and Mn oxides, and residual Au (Wang 1998). The soil samples from the L4 line were also digested using the four-acid digestion. All the soil samples were ground in the laboratory to < 200-mesh (75 μm). Reference materials (GAU9aGSS1, GAU10aGSS2, GAU11GSS3, GAU12GSD1a) and duplicate samples were used to monitor the analytical quality of total Au measurement (Table 1). There are no reference materials to control the method of sequential extraction, and therefore the use of duplicate samples provided quality control. Gold was determined by graphite furnace atomic absorption spectrometry (GF-AAS). The detection limit of the total Au determination is 0.2 ng/g and 0.05 ng/g by sequential extraction.

The Geogas samples in the dilute aqua regia medium were analysed directly using high resolution ICP-MS at the laboratory of the IGGE for the determination of Au, Ag, Cu, Zn, and Hg.
Results

Vertical distribution of gold in the profile

The results from the profile samples are shown in Table 4 and Figure 7. The average Au contents in the different forms are as follows: residual Au, the principal form, at 7.19 ng/g, water-extractable Au at 0.63 ng/g, Au associated with Fe and Mn oxides at 0.48 ng/g, and Au associated with clays at 0.28 ng/g.

<table>
<thead>
<tr>
<th>Table 2. Results of duplicate samples using the Geogas collector with polyurethane foam, in ng</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au (ng/g)</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Gau1aGS1</td>
</tr>
<tr>
<td>Result 1</td>
</tr>
<tr>
<td>Result 2</td>
</tr>
<tr>
<td>GAU10aGS12</td>
</tr>
<tr>
<td>Result 1</td>
</tr>
<tr>
<td>Result 2</td>
</tr>
<tr>
<td>GAU11aGS13</td>
</tr>
<tr>
<td>Result 1</td>
</tr>
<tr>
<td>Result 2</td>
</tr>
<tr>
<td>GAU12GD1a</td>
</tr>
<tr>
<td>Result 1</td>
</tr>
<tr>
<td>Result 2</td>
</tr>
<tr>
<td>Duplicate samples</td>
</tr>
<tr>
<td>RE (%)</td>
</tr>
<tr>
<td>RD (%)</td>
</tr>
</tbody>
</table>

Geogas samples in the polyurethane foam medium were ashed and dissolved in aqua regia before determination. Duplicate samples (5% of the total number of samples) were used to monitor the analytical quality of the data (Tables 2 and 3). Analyses were considered acceptable if the percent relative standard deviation (RSD) was < 40%.

Results

Gold distribution in Geogas and soils across the 210 gold deposit

The results of Au in Geogas, adsorbed by two different media, are shown in Tables 5 and 6 and Figure 8. The Au anomalies in the polyurethane foam medium are distributed on the vertical projection of the contact site between the ore body and the regolith, and the dipping direction (NW) of the ore body, although a number of other sites show elevated concentrations. In the aqua regia medium, the Au anomalies are mainly distributed on the near-surface and middle sections, the variation is not large.

Gold distribution in Geogas and soils across the 210 gold deposit

The data and distribution pattern obtained by analysis of the fine fraction of the soils along Line 4 are shown in Figure 9. There are two obvious anomalous points for Hg and single points for Au and Ag anomalies above the ore body.

Metal particles observed using TEM

Complex nanoscale metal particles composed of Au and other elements were observed in carriers (Ge grids) which captured nanoparticles from Geogas and soils above the ore body, as shown in Figures 10 and 11. The characteristics of the nanoparticles in Geogas and soils are as follows: (1) the radius of metal particles...
Vertical distribution of gold in the profile

Wang (2005, 2007) first found the C-shaped distribution patterns in the vertical profile over the 210 orebody at the Jinwozi gold field and reached the conclusion that: (1) high concentrations of Au in lower parts of the regolith profile were inherited from weathering of the mineralization; (2) high concentrations of Au in the upper parts of the regolith profile were enriched by soil geochemical barriers such as clays, oxides and colloids when Au had vertically migrated to the near-surface; and (3) the lower concentrations of Au in the middle parts of the profiles were due to the lack of geochemical barriers because the materials are composed of relatively coarse sand with low adsorption capacity. The ‘C-shaped’ pattern also occurs in the regolith of other landscapes, over the orebodies in the Yilgarn craton of Australia for example (Gray et al. 2008). This pattern was thought to be the depletion of elements in the middle of the regolith due to saline groundwater under an arid climate. In our study area, the groundwater table is below 200 m and the rain water, with an annual rainfall of <25 mm, does not extend down 20 cm from the soil surface (since the beginning of the Quaternary), and thus it is impossible for the elements to be depleted by saline groundwater in this very young wind-blown soil regolith terrain.

Gold distribution in Geogas and soils across the 210 gold deposit

In the position of the structurally altered zone, Au anomalies occur in Geogas and fine-grained soil samples which suggests that Geogas and soil surveys are effective for exploring for gold deposits in the landscape of desert regolith cover. More important for this study, it also shows that there must be some metals related to the orebody in Geogas which can be captured by our methods. Although there is only one obvious anomalous point for Au and Ag above the ore body in the results of fine-grained soil prospecting which may be related to the larger sampling interval and the whole sample analysis method, there is no doubt that fine-grained soil prospecting is effective to delineate the ore bodies.

Metal particles observed using TEM

The cogenetic comparative studies of the nanoparticles in Geogas and soils with respect to component, structure and micro-morphology revealed that the nanoparticles in both media are similar, suggesting that the nanoparticles have the same origin. One important observation is that there are no obvious targets or pathfinder metal particles found in Geogas and soil samples collected from the background area which further indicates that the nanoparticles are from the underlying concealed ore body. More speculatively, the nanoparticles are transported by an ascending Geogas stream and then physically adsorbed by the soil particles and captured by the geochemical barriers during their upward transportation. The nanoparticles can cause the Geogas anomaly in the soil pore space, and the mobile element anomaly in the soil medium. Due to their strong geochemical activities, the nanoparticles can be desorbed from the soil particle surface and migrate upwards, causing the near-surface mobile element anomalies.

Table 5. Contents of Au and mineralization elements by the Geogas collector with polyurethane foam (ng), n=76

<table>
<thead>
<tr>
<th></th>
<th>Au</th>
<th>Ag</th>
<th>Cu</th>
<th>Zn</th>
<th>Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>5.67</td>
<td>0.88</td>
<td>576</td>
<td>1215</td>
<td>0.64</td>
</tr>
<tr>
<td>Max.</td>
<td>61.05</td>
<td>20.86</td>
<td>13076</td>
<td>4276</td>
<td>2.11</td>
</tr>
<tr>
<td>Min.</td>
<td>1.61</td>
<td>0.20</td>
<td>110</td>
<td>666</td>
<td>0.36</td>
</tr>
<tr>
<td>Blank</td>
<td>1.75</td>
<td>0.25</td>
<td>186</td>
<td>920</td>
<td>0.44</td>
</tr>
<tr>
<td>RD (%)</td>
<td>22.8</td>
<td>26.3</td>
<td>25.6</td>
<td>26.9</td>
<td>15.1</td>
</tr>
</tbody>
</table>

RD, relative standard deviation.

Table 6. Contents of Au and mineralization elements using the Geogas collector with liquid absorbent, in ng/ml, n=76

<table>
<thead>
<tr>
<th></th>
<th>Au</th>
<th>Ag</th>
<th>Cu</th>
<th>Zn</th>
<th>Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.003</td>
<td>0.36</td>
<td>103</td>
<td>1207</td>
<td>0.08</td>
</tr>
<tr>
<td>Max.</td>
<td>0.007</td>
<td>3.15</td>
<td>3581</td>
<td>15237</td>
<td>0.57</td>
</tr>
<tr>
<td>Min.</td>
<td>0.001</td>
<td>0.01</td>
<td>1</td>
<td>89</td>
<td>0.01</td>
</tr>
<tr>
<td>Blank</td>
<td>0.001</td>
<td>0.01</td>
<td>0.23</td>
<td>0.49</td>
<td>0.02</td>
</tr>
<tr>
<td>RD (%)</td>
<td>22.2</td>
<td>7.3</td>
<td>8.2</td>
<td>5.6</td>
<td>10.3</td>
</tr>
</tbody>
</table>

RD, relative standard deviation.
Fig. 8. Contents of gold in the Geogas survey. (A) adsorbed by polyurethane foam medium and (B) adsorbed by the aqua regia medium.
Because a millipore filter (0.45 μm) was used in the process of particle collection, micro-particles were not observed by TEM. Considering the gravity of particles, it is unlikely the Geogas stream can carry micron-scale particles to the surface.

Conclusions

The results of the Geogas and fine-grained soil prospecting survey indicate that anomalies do exist directly over the underlying concealed gold ore body beneath the regolith cover. Hence, Geogas and fine-grained soil can be selected as geochemical sample media for concealed deposit exploration in the arid-desert area of China, especially fine-grain soils which have simple sampling and pretreatment processes (using the four-acid digestion). Fine-grain soils have greater clay contents that are considered important for trapping the nanoparticles of gold migrated from the concealed ore bodies.

Nanoparticles were observed in the Geogas and soils in the regolith cover above the ore body. The nanoparticles can be adsorbed onto bubbles and migrate upwards with the Geogas stream to the surface, due to their large surficial area; or they have characteristics similar to gases, which can ascend by themselves through the regolith cover. On the surface, we believe some of these nanoparticles prefer to remain in the Geogas phase, whereas others are trapped by the geochemical barriers in surface soils such as clay, iron and manganese oxides and lead to enrichment at surface and the formation of surface geochemical anomalies. This mechanism also leads to the formation of the 'C-shape' distribution patterns of the anomalies in the vertical profile, although this study was limited to a single profile.

![Fig. 9. Contents of Au, Ag, and Hg in fine-grained soils along Line 4.](image)
Fig. 10. Nanoscale particles in Geogas above the 210 gold ore body, Xinjiang. (A) Au-Cu nanoscale particles. (B) Cu-Bi nanoscale particles. (C) Hg-Cu nanoscale particles. (D) Fe-Co-V nanoscale particles.
Fig. 11. Nanoscale particles in soils above the 210 gold ore body, Xinjiang. (A) Au-Zn nanoscale particles. (B) Au-Cu-Ti nanoscale particles. (C) K-, Na-, and Si-bearing Cu-Fe-Co nanoscale particles. (D) Cu-Fe nanoscale particles.
Further studies are needed to have a better understanding of the origin and migration process of nanoparticles. Nanoparticles in ores have been observed in some studies (Palenik et al. 2004; Reich et al. 2006; Hough et al. 2011). Comparative studies can be done between nanoparticles in ores, soils and Geogas. New high-resolution techniques such as ‘nanoSIMS’ should allow detection of isotopic compositions of the particles to confirm the proposed origin of nanoparticles observed in this study.

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