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# Deep-penetrating geochemistry for sandstone-type uranium deposits in the Turpan–Hami basin, north-western China

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# ABSTRACT

The Turpan-Hami basin, covering an area of approximately 50,000 km<sup>2</sup> in NW China, contains concealed sandstone-type U deposits in a Jurassic sequence of sandstone, mudstone and coal beds. Sampling of soil profiles over the Shihongtan concealed U deposit in this basin shows that fine-grained soil collected from the clay-rich horizon contains U concentrations three times higher than similar soils at background areas. Selective leaching studies of these soils show that U is mainly associated with clay minerals, which comprise from 17.9% to 40% (average 30.4%) of the total mineral content. This may indicate that U is converted to uranyl ions  $[UO_2]^{2+}$  under oxidizing conditions and is sorbed on clay minerals to accumulate in anomalous concentrations. Fine-grained soil (<120 mesh, <0.125 mm) from the clay-rich horizon, generally occurring at a depth of 0-40 cm, is shown to be an effective sampling medium for deep-penetrating geochemical surveys. A wide-spaced geochemical survey at a density of approximately 1 site per 100  $\text{km}^2$ was carried out throughout the whole basin using this sampling medium. Samples were analyzed for 30 elements by ICP-MS following a 4-acid extraction. Three large-scale geochemical anomalies of U and Mo were delineated over the whole basin. One of the anomalies is consistent with the known U deposit at Shihongtan in the western part of the basin. A new potential target in the eastern part of the basin was selected for a follow-up survey at a density of 1 sample per 4 km<sup>2</sup>. A drilling exploration programme at the center of the geochemical anomaly delineated by this follow-up survey discovered a new U deposit. © 2011 Elsevier Ltd. All rights reserved.

# 1. Introduction

Traditional exploration for U deposits depended on ore-genetic models and radiometric methods (Morse, 1969; Harshman, 1970; Rubin, 1970). However, these methods are not effective for locating sandstone-type U deposits occurring at depths of hundreds of meters in sedimentary basins (Riese et al., 1978). Radioactivity detectors are ineffective in regions where there is even a relatively thin inactive overburden (Bowie et al., 1970). Geochemical sampling of soil and stream sediment in exploration for concealed sedimenthosted U may be ineffective due to geochemical dispersion and concealment by the sedimentary cover (Pirlo and Giblin, 2004). Geochemical surveys, as a part of the Regional Geochemistry-National Reconnaissance (RGNR) project (Xie et al., 1997), based on sampling of coarse-grained soil and stream sediment (>20 mesh, >0.84 mm) to avoid dilution of element concentrations by windblown sand failed to delineate U geochemical anomalies in sedimentary basins of NW China.

Sandstone-type U deposits in the Turpan–Hami basin of NW China were discovered in the 1990s (Quan and Li, 2002), and geochemical exploration interest was renewed. Since 1999, a number of geochemical surveys have been conducted in an attempt to penetrate the cover and to discover concealed sandstone-type deposits in the Turpan–Hami basin (Wang, 2001; Wang et al., 2007a,b; Liu and Wang, 2005). This paper describes the results of deeppenetrating geochemistry studies over the U deposit at Shihongtan and the application of the results for the location of new sandstone-type U deposits.

# 2. Geological setting

The Turpan–Hami basin covers an area of approximately 50,000 km<sup>2</sup> in Xinjiang, NW China (Fig. 1). Its western part, near the city of Turpan, is the lowest area in mainland China, with an elevation of 154 m below mean sea level. The region is extremely arid with an average annual rainfall of less than 15 mm.

The region is almost completely covered by regolith sediments, which conceal prospective bedrock sequences. The regolith sediments include windblown sand, alluvial gravel, and caliche horizons. Commonly, the vertical profile of the regolith sediments



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Fig. 1. Simplified geological map of the study area. The area within the square border at Dananhu shows the location of the follow-up study,

consist of loose windblown sand underlain by weakly cemented sand and compacted caliche-cemented sediment with gypsum.

Miocene sandstone overlying Jurassic sedimentary rocks occurs in the Turpan-Hami basin. Sandstone-type U deposits are hosted in the Jurassic sandstone (Quan and Li, 2002).

# 3. Concentrations and variation of elements and minerals above known U mineralization

# 3.1. Methods

Soil samples were taken from a vertical soil profile directly overlying the Shihongtan U deposit (Fig. 1) to investigate element variation from weathered bed rocks to the soil surface. The samples from top to bottom were: desert crust (0-10 cm), sandy clay-rich horizon (10-30 cm), sand with salts (30-50 cm), and another three samples at 20-cm intervals to a depth of 110 cm. Samples from the sandy clay-rich horizon (10-30 cm) were sieved in the field into five fractions: 4-20 mesh (4.75-0.841 mm), 20-60 mesh (0.841-0.25 mm), 60-100 mesh (0.25-0.149 mm), 100-160 mesh (0.149-0.0965 mm) and <160 mesh (<0.0965 mm). Samples from other depths were only sieved to <120 mesh (<0.125 mm) in the field. After sieving, each sample weighed approximately 500 g. Subsequently, the samples were ground to <200 mesh (<0.074 mm) in a high-alumina ceramic mill for total analysis.

In addition, 50 samples were collected at 100-m spacing from the sandy clay-rich horizon at a depth of 10-30 cm along a 5-km traverse across the mineralized zone to an area considered to be representative of geochemical background. Each sample was sieved to <120 mesh (<0.125 mm) in the field.

All the samples for total analysis were ground to <200 mesh. Total trace element concentrations were determined by ICP-MS after the soil samples were digested in a hot 4-acid mixture. Major element concentrations were determined by XRF. Table 1 shows the elements determined and methods used. Reference materials and duplicate samples were used to control analytical quality. Four standard reference materials of the GSS series (Xie et al., 1989) were inserted blindly into each batch of 50 samples and analyzed simultaneously with the samples. The percent relative standard deviation (RSD) was then calculated to monitor the between-batch bias as follows:

$$%$$
RSD =  $(C_d - C_r)/C_r * 100$ 

where  $C_d$  is the determined concentration and  $C_s$  is the reference concentration.

Analyses were considered acceptable if the RSD was <17% for those samples with concentrations less than 3-times the detection limit and <10% for those samples with concentrations more than 3times the detection limit. Duplicate samples, equaling 5% of the to-

### Table 1

Methods used

elements)

XRF (33 elements)

ICP-MS (27

Elements determined and analytical methods used. Elem

Mn.

Elements determined	Sample preparation
Ba, Be, Bi, Cd, Co, Cr, Cs, Cu, Ga, Hf, In, Li, Mo, Nb, Ni, Pb, Rb, Sb, Sc,	0.250 g sample dissolved by HF + HNO <sub>3</sub> + HClO <sub>4</sub> + aqua regia 25 mL solution
Sr, Ta, Th, Tl, U, V, W, Zn	in 5% aqua regia Pipette 1 mL clear solution Dilute to 10 mL with 2% HNO3
Al <sub>2</sub> O <sub>3</sub> , As, Ba, Br, CaO, Ce, Cl, Co, Cr, Cu, Fe <sub>2</sub> O <sub>3</sub> ,Ga, Hf, K <sub>2</sub> O, La, MgO,	4.0 g sample pressed pellets
Mn. Na <sub>2</sub> O. Nb. Nd. Ni. P. Pb. Rb. Sc. SiO <sub>2</sub> , Sr. Th. Ti. V. Y. Zn. Zr	

tal number of samples, were inserted randomly to evaluate the precision of the analyses. The percent relative deviation (RD) was calculated as follows:

$$\%$$
RD = [( $A_1 - A_2$ )/(( $A_1 + A_2$ )/2)] \* 100

where  $A_1$  is the first determination and  $A_2$  is the second determination.

Analyses were considered acceptable if the RD was <40%.

# 3.2. Concentrations and variations

The average concentration of U was 3.5 ppm (maximum 29.6 ppm) in soil samples from a depth of 10–30 cm in the profile above the U mineralization, whereas the average concentration of U along the traverse away from the mineralization at the background area was 1.6 ppm. Fig. 2 shows that concentrations of U and associated elements Mo, La, Ce, Au, and Th, tend to increase in the finer soil fractions. Uranium concentrations increase from 2.0 ppm in the <20 + 60 mesh fraction to 3.6 ppm in the <160 mesh fraction. The highest element concentrations associated with the U deposits are in the <160 mesh fraction.

Fig. 3 shows the vertical variation of elements and clay content in <120-mesh soils in the soil profile over the deposit. The concentrations of these elements in the profile can be divided into three zones: (i) surface and near surface zone (<30 cm depth) where there is a strong enrichment in U, V, Sb, Th, Sr, Ti, Mn, CaO, MgO, Fe<sub>2</sub>O<sub>3</sub> and clay, (ii) middle zone (30–50 cm) where concentrations of all elements, except Na<sub>2</sub>O and La, are depleted, and (iii) bottom zone (>50 cm) where concentrations of most elements vary about their respective average values.

Fig. 4 shows the distribution of U and Mo along the traverse across the mineralized zone at the Shihongtan deposit into background areas. The greatest concentrations of these elements occur over the U ore body and demonstrate that the fine-grained fraction of soils from the clay-rich horizon can give very a good indication of U mineralization to at least a depth of 300 m.

### 3.3. Mineralogy

The samples from the vertical profile over the mineralized zone at the Shihongtan deposit were ground to <300 mesh to make the pressed pellets for mineral analysis by X-ray diffraction (XRD). Rigaku Corporation X-ray diffraction instruments and software were used to provide the estimates of mineral percentages. Quantification is based on reference intensity ratios (RIR values) and on the scale factors of the mineral phases. Results are considered to be 'semi-quantitative'.

Table 2 shows the approximate percentage of selected minerals from the soil profile above the U deposit at Shihongtan as determined by XRD. The clay minerals (kaolinite, illite and chlorite) make up 35% of the total mineral content in surface samples, with the proportion decreasing with depth. Fig. 5 shows that clay minerals tend to increase in the finer soil fractions. The <120mesh fraction of soils from a depth of 10–30 cm contains the highest percentage of clay minerals (40%). This observation, coupled with the finding that U is preferentially enriched in the finer-grained fractions of soil from a depth of 10–30 cm over the Shihongtan deposit (Fig. 2), indicates that U is easily adsorbed by clay minerals.

### 3.4. Sequential extractions

Near-surface samples (0–30 cm) contain a higher percentage of clays than deeper samples (30–50 cm). To further investigate uranium accumulation on clays, samples from these two depths were collected from two sites over the deposit. The samples were sieved to <100 mesh in the field. The mineralogical host of U in these samples was investigated in the laboratory using a 4-stage sequential selective leaching procedure that determined: (i) water extractable metals (WEM), (ii) adsorbed and exchangeable metals (AEM) on clays, (iii) metals in carbonate minerals (OCM) and (iv) adsorbed metals on coatings of Fe–Mn oxides (FMM) (Wang, 1998). The sequential selective leaching procedure is summarized as follows:



Fig. 2. Bar graphs showing the concentrations of various elements in different size fractions of soil from a depth of 10–30 cm over the Shihongtan sandstone-type uranium deposit.



Fig. 3. Element variations in <100 mesh soil in a representative vertical profile over the Shihongtan sandstone-type U deposit. Explation of vertical axis: 0: 0–10 cm; 1: 10–30 cm; 2: 30–50 cm; 3: 50–70 cm; 4: 70–90 cm; 5: 90–110 cm.

- (i) water extractable metals (WEU):
  - (1) Ten gram of sample is placed in a 250 mL flask, and 100 mL deionized water is added.
  - (2) The mixture is shaken and allowed to stand overnight.
  - (3) The liquid is filtered through a 0.45 μm Millipore filter into a labeled polypropylene bottle.
  - (4) Ten milliliter of the liquid is put into a test-tube and immediately stabilized with 1 mL ultrapure HNO<sub>3</sub>.
- (ii) adsorbed and exchangeable metals on clays (AEM):
- (5) To the residue from step 3, 100 mL of 5% ammonium citrate is added, and steps (2) through (4) are repeated.(iii) metals in carbonate minerals (OCM):
  - (6) To the residue from step 5, 100 mL of 4 mol/l glacial acetic acid are added, and steps (2) through (4) are repeated.
- (iv) adsorbed metals on coatings of Fe–Mn oxides (FMM):
  (7) To the residue from step 6, 100 mL of 0.3 M ammonium citrate +0.1 M hydroxylamine hydrochloride at pH 7 are added, and steps (2) through (4) are repeated.



Fig. 4. U and Mo anomalies over the Shihongtan U deposit.

# Table 2Mineral concentrations, estimated by X-ray diffraction, in soils from different depths of a profile above the Shihongtan U deposit.

Depth (cm)	Sample no.	Clay minerals			Quartz	Feldspar	Calcite	Amphibole	Salts
		Kaolinite	Illite	Chlorite					
<10	0	10	15	10	35	20	<5	<5	
10-30	1		13	5	40	30	5	5	
30-50	2		5	<5	50	15		<5	20
50-70	3	<5%	5		60	25	<3	<2	
>70	4		5	<5	20	20	5	5	40



Fig. 5. Percentage proportion of clay minerals in different soil fractions.

Results from the sequential selective leaching show that U is largely present in adsorbed forms on clays, making up approximately 40% of the total U content, and in carbonate minerals, making up approximately 15% of the total U content in the near-surface clay-rich horizon (Table 3, SHT34P0 and SHT32P0).

The association of U with clay minerals is consistent with previous investigations (Bradshaw and Lett, 1980; Terner et al., 1996; Rose and Wright, 1980; Puigdomenech, 2004). The fine-grained fraction of soils from the clay-rich horizon at a depth of 0–30 cm is likely to be the natural "trap" for U and, thus, is concluded to be an effective sampling medium for deep-penetrating geochemical exploration.

#### Table 3

Concentration of U as determined by sequential selective extraction and the fraction of U contained in each in operationally defined mineralogical host.

Samples	U concent	U concentration (ppb)					Fraction (%) of total U			
	WEU	ACU	CU	FMU	Т	WEU/T	ACU/T	CU/T	FMU/T	
SHT34P0	53.8	954.6	381.3	35.5	2392.5	2.3	39.9	15.9	1.5	
SHT34P1	26.7	407.9	228.4	26.4	1712.2	1.6	23.8	13.3	1.5	
SHT32P0	57.8	976.9	378.2	47.7	2444.3	2.4	40.0	15.5	1.9	
SHT32P1	22.2	331.7	203.4	28.3	1856.8	1.2	17.9	10.9	1.5	
Average	40.1	667.8	297.8	34.5	2101.5	1.9	30.4	13.9	1.6	

WEU – water extractable U; ACU – U adsorbed onto clay minerals; CU – U contained in carbonate minerals; FMU – U adsorbed onto Fe–Mn oxide coatings; T – total U. POsurafce soil (0–30 cm), P1-subsurface soil (30–50).

# 4. Regional geochemical surveys

# 4.1. Methods

Based on the studies conducted on soils above the Shihongtan U deposit, the <120-mesh fraction of soils collected from the near-surface clay-rich horizon was selected as the sampling medium for regional geochemical surveys at a scale of 1:1000,000 and 1:250,000. Samples were collected at a density of one sample per 7.5' (longitude) by 5.0' (latitude) (ca. 100 km<sup>2</sup>) resulting in a total of 1580 soil samples and 86 field duplicate samples over an area of approximately 160,000 km<sup>2</sup>. In total, 351 of these sampling sites are located in the Turpan–Hami basin, covering an area of approximately 35,000 km<sup>2</sup>. These low-density surveys delineated an extensive U anomaly in the vicinity of Dananhu, Hami (Fig. 1).

### Table 4

Statistical parameters of the regional and follow-up geochemical surveys (all values in ppm).

Elements	Sampling density	No. of samples	Concentration range	Average values	Background	Standard deviation
U	1/100 km <sup>2</sup>	351	0.92–12.84	2.5	1.7	0.36
	1/4 km <sup>2</sup>	1690	0.87–29.6	2.6	1.8	0.40
Мо	1/100 km <sup>2</sup>	351	0.43–17.6	1.5	0.9	0.22
	1/4 km <sup>2</sup>	1690	0.27–17.2	1.3	0.9	0.23



Fig. 6. Dendrogram showing correlation between elements by R-mode cluster analysis: (left) 1:1000,000 scale regional geochemical survey and (right) 1:250,000 scale follow-up survey).



Fig. 7. Geochemical anomalies of U and Mo delineated by wide-spaced sampling of 1 site per 100 km<sup>2</sup>.

A follow-up survey at a scale of 1:250,000 was conducted over this anomaly. The sampling density was 1 sample per 1.5' (longitude) by 1.2' (latitude) (ca. 5 km<sup>2</sup>). In total, 1690 samples were collected over an area of 6400 km<sup>2</sup>.

Sample sites were located at the lowest point within each sampling cell of ca.  $100 \text{ km}^2$  for the wide-spaced sampling and at ca.  $5 \text{ km}^2$  for follow-up sampling, and their coordinates recorded by GPS. Samples were collected from the sandy clay-rich horizon at depths generally between 0 and 40 cm, and each sample was sieved to <120 mesh (<0.125 mm) in the field. After sieving, each sample weighed approximately 500 g.

The samples were subsequently ground to <200 mesh (<0.074 mm) in a high-alumina ceramic mill and analyzed by ICP-MS following a 4-acid digestion as described earlier.

# 4.2. Data analysis

Table 4 shows a statistical summary for U and Mo. The background values were calculated after removal of values two standard deviations above the mean. The threshold was subsequently obtained by using the background values plus two standard deviations. The average and background values of the regional and follow-up surveys appear to be very robust, although the samples were taken in different years. The correlation between elements by cluster analysis is shown in Fig. 6. The dendrogram shows that U and Mo are highly correlated and always fall into one group based on a 0.6 correlation coefficient, although a different number of groups is defined for each survey conducted at a different scale.

### 4.3. Geochemical patterns

Three geochemical provinces, based on thresholds of 2.8 ppm for U and 1.5 ppm for Mo, were delineated by the 1:1000,000 scale survey in the Turpan–Hami basin (Fig. 7). The westernmost anomaly is over the large Shihongtan sandstone-type U deposit. Whereas, the eastern anomaly occurs in an area of no known U mineralization and warrants a follow-up survey.

Figs. 8 and 9 show U and Mo anomalies, respectively, delineated by the follow-up survey at a density of 1 sample per approximately 5 km<sup>2</sup> at Dananhu, Hami. The results show that (1) geochemically anomalous concentrations are consistent with the first-stage, lower-density, survey, although the follow-up survey mapped the geochemical patterns in more detail, and (2) U and Mo anomalies are apparently very robust.

Subsequent to the follow-up geochemical survey, sandstonetype U mineralization was discovered at a depth of 300 m by a preliminary drilling programme. Therefore, a more detailed drilling



Fig. 8. U anomalies delineated by follow-up sampling of 1 site per 5 km<sup>2</sup> at Dananhu, Hami.



Fig. 9. Mo anomalies delineated by sampling of 1 site per 5 km<sup>2</sup> at Dananhu, Hami.

program was planned to delimit the size and grade of U mineralization. This drilling program is ongoing.

### 5. Conclusions

The formation of large-scale regional U anomalies in soils is a complicated process involving mobilizing U from the U-bearing phase of the mineralized parent material (bedrock), transporting the mobile aqueous phase (likely uranyl ion or a uranyl-carbonate complex) vertically through the soil column, and incorporating the U within soil minerals probably by adsorption on clay minerals. Studies of element and mineral distribution in soils above the Shihongtan sandstone-type U deposit showed that clay-rich soil at a depth of approximately 0-30 cm was enriched in U and provided an excellent sample medium for identifying buried U deposits in the arid environment of the Turpan-Hami basin in NW China. A regional-scale geochemical survey using this sample medium identified an area of anomalous U and Mo in a region where U mineralization was unknown. Follow-up, higher density geochemical surveys using a similar sample medium defined a target area where a U deposit was found at a depth of 300 m by a subsequent drilling programme. The utilization of clay-rich horizons in soils from other desert regions of the world may prove useful in the search for U resources.

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