



A growing sandstone type uranium district in South Yili Basin, NW China as a result of extension of Tien Shan Orogen: Evidences from geochronology and hydrology

Chuang Zhang*, Hongxu Liu

Beijing Research Institute of Uranium Geology, China National Nuclear Corporation, Beijing 100029, China

Key Lab of Uranium Resource Prospecting and Evaluating Technology, China National Nuclear Corporation, Beijing 100029, China

ARTICLE INFO

Article history:

Received 30 January 2019

Received in revised form

21 May 2019

Accepted 3 June 2019

Available online 30 July 2019

Handling Editor: F. Pirajno

Keywords:

U–Pb dating

Pitchblende

Sandstone type uranium deposit

Tien Shan

Yili Basin

ABSTRACT

The Mesozoic Yili Basin of NW China represents the largest known concentration of U deposits in China and contains five major deposits, namely (from west to east) the 512 (Kujie'ertai), 513, 511, 510 (Mengqiguer), and 509 deposits. Pre-mining resources within the explored sandstone-type uranium deposits in this area are reportedly as much as 20,000 t contained U. The mineralization is hosted by the Middle–Lower Jurassic Shuixigou Group, which (from base to top) is divided into the Badaowan, Sangonghe, and Xishanyao formations. The U–Pb isotopic analysis of ores from the Kujie'ertai and Mengqiguer deposits indicate that they contain high and variable amounts of initial (common) Pb, meaning that the only possible way to date these deposits is by using U–Pb isochrons. Two major stages of uranium mineralization have been identified by the U–Pb isotope dating of uranium ores in this region. The Kujie'ertai deposit apparently formed between 23.4 ± 3.3 and 20.18 ± 0.49 Ma, corresponding to a period of crustal thickening and uplift within the Tien Shan Orogen. This event (35–21 Ma) accommodated the majority of the strain generated by the northward collision of the Indian Plate with the Asian Plate. However, the dating of samples from the Mengqiguer deposit yielded much younger ages (between 0.61 ± 0.24 and 0.347 ± 0.0048 Ma). The western Tien Shan mountains expanded until the Pliocene as a result of the far-field influence of continuous penetration of the Indian Plate into the Asian Plate. This activated reverse faults and folds in the piedmont of the Tien Shan mountains and caused the continuous uplift of the southern flank of the Yili Basin. The uplift caused the erosion of anticline hinge zones, introducing significant amounts of oxidizing water into the Shuixigou Group, generating a second stage of uranium mineralization. Hydrological sampling also suggests that the Mengqiguer deposit continues to grow, indicating a possible third stage of uranium mineralization (~0 Ma). This also indicates that the U within these deposits is derived not only from U-bearing sediments but from the Tien Shan mountains as a result of groundwater cycling. The evolution of the U contents of groundwater that was initially derived from cold springs that flow into the mineralized units indicates that these cold springs have an essential role in mobilizing U from the Tien Shan mountains, with rivers flowing through areas of outcropping mineralized units acting as a source of mineralizing fluids during the formation of the Mengqiguer deposit.

© 2019 International Association for Gondwana Research. Published by Elsevier B.V. All rights reserved.

1. Introduction

Sandstone-type uranium mineralization was first formally defined by Finch and Davis (1985) as epigenetic concentrations of U minerals occurring as impregnations and replacements primarily in fluvial, lacustrine, and deltaic sandstone formations, and has been a major exploration target since the discovery of numerous deposits of this type within the Western Cordilleran region of North America. This style of mineralization hosts around 30% of world U resources but is

responsible for nearly half of world U production to date (Cuney and Kyser, 2008; Cuney, 2009; Zhang, 2012, 2016; Cai et al., 2015).

Over 50% of currently identified Chinese uranium resources occur in sandstone-hosted deposits, including roll-front deposits (e.g., the Shihongtan uranium deposit within the Turpan–Hami Basin and the Dongsheng uranium deposit within the Ordos Basin; Dahlkamp, 2009; Zhang et al., 2017b, 2018) and tabular-shaped deposits (e.g., the Nalinggou uranium deposit in the Ordos Basin and the Qianjiadian and Baxingtou deposits in the Songliao Basin; Bonnetti et al., 2017b; Zhang et al., 2017b, 2018) within Mesozoic sedimentary basins in north China (OECD-NEA/IAEA, 2014; Bonnetti et al., 2015; Hou et al., 2017). These sandstone-type U deposits

* Corresponding author at: No.10 Xiaoguandongli, Beijing 100029, China.

E-mail address: zhangc198506@126.com (C. Zhang).

are typically small to medium in size but can contain >10,000 t of contained U at grades of 0.03%–0.10% (Dahlkamp, 2009). The basement and the areas surrounding U-bearing basins always contain granite and felsic volcanics (Zhang et al., 2018).

The Southern Yili uranium district is located within the Yili Basin of NW China and is presently the largest U-producing district in China. The timing of formation of this uranium district remains controversial despite intensive research. For example, Zhou (2000) reported U–Pb ages of 24–19 Ma whereas Xia et al. (2002) obtained highly variable apparent ages of 29.8 to 0.8 Ma for these U deposits, although neither study considered the effect of the elevated concentrations of common Pb in these deposits, which hampers realistic age determinations. More recently, UPb isochrons determined for samples from the Kujiertai deposit indicate that this area records two episodes of carbonaceous mudstone- and sandstone-hosted uranium mineralization at 12 ± 4 and at 1 Ma, with high-U sandstone samples yielding further ages of 5 ± 1 and 2 Ma for the Tajistan deposit (Pan, 2000; Chen et al., 2002a, 2010; Xia et al., 2003; Han et al., 2004; Dahlkamp, 2009). This wide range of ages means the timing of mineralization in this area remains uncertain, and outlines the need for more U–Pb isotopic and geochronological analysis.

Sandstone-type U deposits are known to have formed across a wide range of geological time from the Paleozoic to the Tertiary and less commonly in the Proterozoic and Quaternary, but modern

analogues are seldom reported. This paper focuses on the timing of mineralization of the Kujiertai and Mengqiguer uranium deposits and the influence of groundwater on the latter deposit, providing an overview of the present-day U metallogeny that continues in this region and the tectonic influences on the formation of U deposits in the region. The Mesozoic Yili Basin represents the largest known concentration of U deposits in China, is located within an area that juxtaposes a major U district (the Ily Basin) in Kazakhstan (Dahlkamp, 2009), and contains a number of deposits including the Kujiertai (formerly referred to as Deposit 512), 513, Tajistan (511), Mengqiguer (510), and Daladi (509) deposits, all of which are located within the southern margin of the basin (Figs. 1, 2). The northern margin of the basin also includes several apparently less important U prospects. Original in situ resources of the known sandstone-type uranium deposits in this area included >20,000 t of contained U (Dahlkamp, 2009).

2. Tectonic background and regional geological setting

The Yili Basin is thought to represent a domain of the Yili microcontinental block, is underlain by Precambrian basement material, and has a triangular shape that widens westwards into Kazakhstan. It is bounded by units of the Tien Shan Orogen and separated which into northern and southern branches (Fig. 1; Enkin

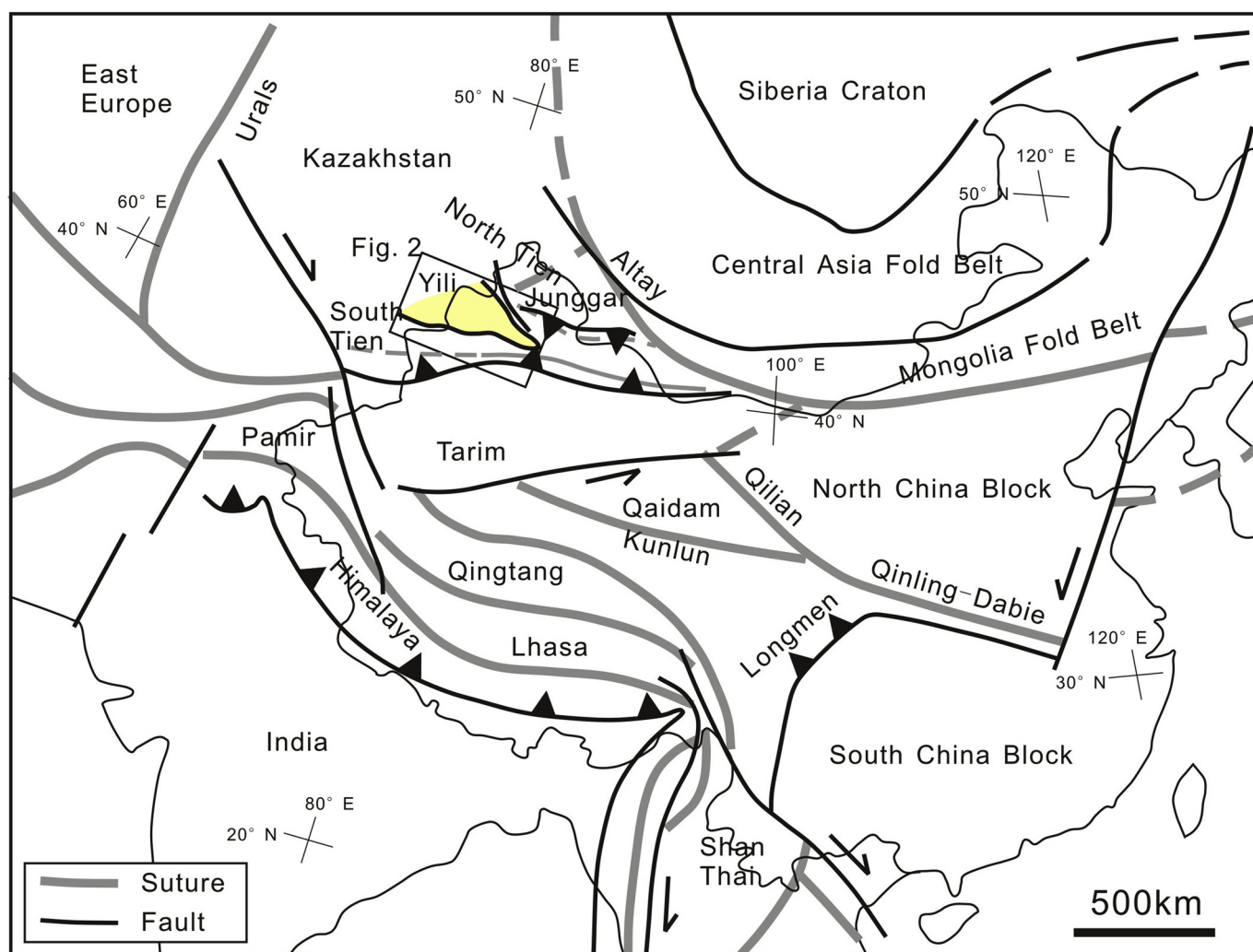


Fig. 1. Simplified map showing the location of the India–Asia collision zone and the geographical and geotectonic location of the Yili Basin and the Tien Shan orogenic belt (modified after Molnar and Tapponnier, 1975; Wang et al., 2007b).

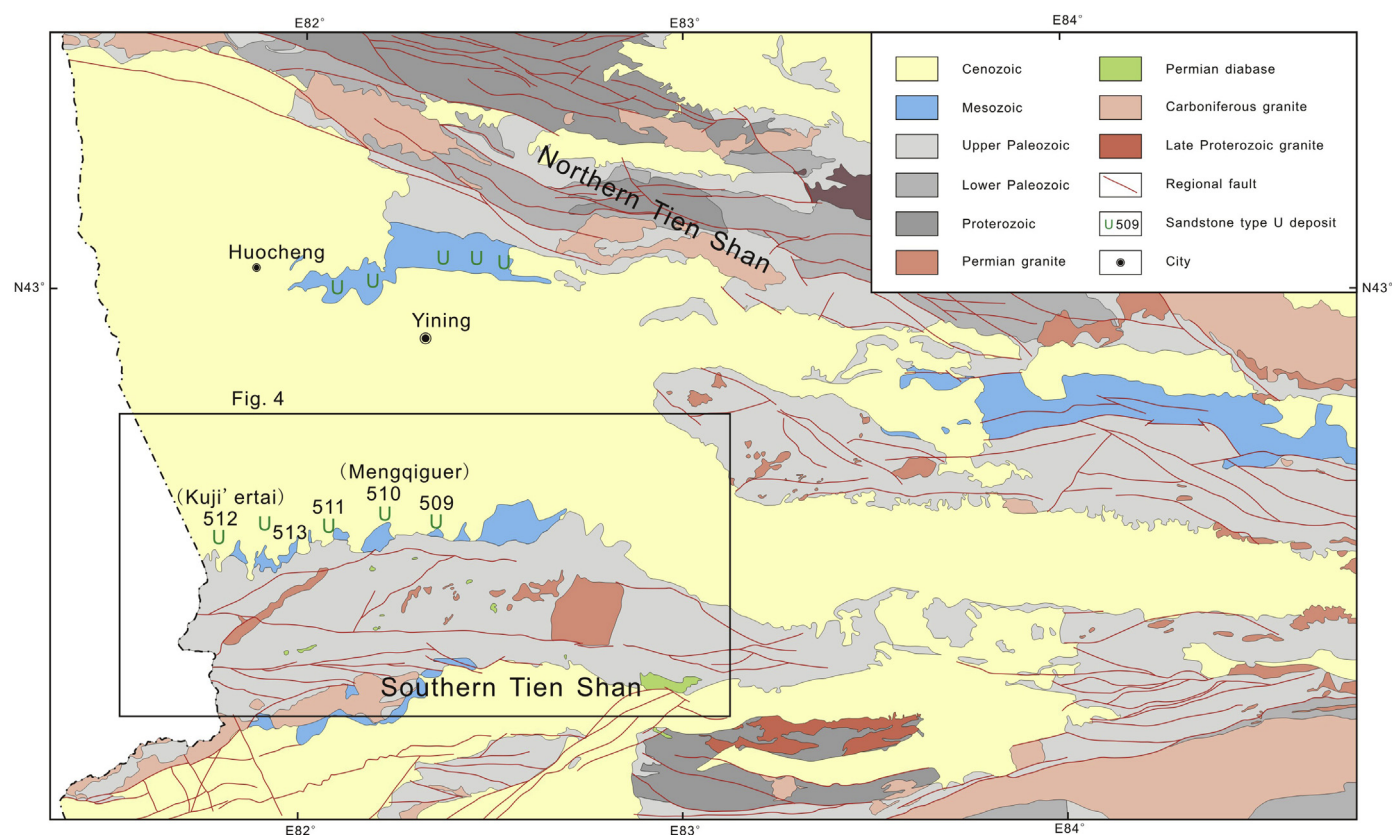


Fig. 2. Generalized geological map showing the location of sandstone-type uranium deposits and occurrences along the margin of the intermontane Yili Basin (modified from Chen and Huang, 1993).

et al., 1991; Allen et al., 1993; Chen et al., 1999a, 1999b; Wang et al., 2006b, 2007a, 2007b). The Tien Shan belt extends east–west for over 2500 km with a north–south width of 150–300 km and consists of a series of east–west trending and nearly parallel mountain ranges and intermontane basins (Konopelko et al., 2017; Dolgoplova et al., 2017). This region contains the Yili Basin as well as the Tarim Basin to the south and the Junggar Basin to the north (Fig. 1).

The Tien Shan orogenic belt records multiple phases of tectonism and differential uplift during its long evolutionary history (e.g., Chen et al., 1999a, 1999b; Gao et al., 2009; Wang et al., 2009b, 2015; Degtyarev et al., 2017; Pelsmaeker et al., 2018). The original Tien Shan belt was formed as a result of the convergence of a small number of continental fragments during the late Paleozoic (Burtman, 1975; Windley et al., 1990; Allen et al., 1993; Gao et al., 2006; Grave et al., 2013; Chen et al., 2015). The relatively stable Mesozoic regional geological setting allowed the peneplanation of the belt (Sobel and Amaud, 2000; Simonov et al., 2008) before the reactivation of the older Tien Shan basement began during the Cenozoic as a result of the distal effect of India–Asia collision (Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979).

The Yili Basin is an elongate, closed, stable continental basin that hosts several large oil and natural gas reservoirs as well as coal-fields (Min et al., 2005a). The southern margin of the basin, which also forms the northern piedmont of the Tien Shan mountains, contains outcropping basement rocks of Proterozoic metasedimentary, Carboniferous intermediate–acidic volcanic and volcanoclastic, and Permian granite units (Min et al., 2005a). Pre-Triassic units in this area, especially Permian granites and Carboniferous acidic volcanic and volcanoclastic rocks, contain relatively high

concentrations of uranium (>5 ppm; Konopelko et al., 2007; Wang et al., 2007a; Li et al., 2018).

The Yili Basin contains Middle–Upper Triassic Xiaoquangou Group sandstones and shales, Lower–Middle Jurassic Shuixigou Group conglomerate, sandstone, shale, and coal units, Cretaceous red conglomerate and sandstone units, Tertiary red conglomerate, sandstone, and shale units, and Quaternary gravels, sands, and clays. The U mineralization within the southern Yili Basin is hosted by the Middle–Lower Jurassic Shuixigou Group (Fig. 3), which is divided from base to top into the Badaowan (J_1b), Sangonghe (J_1s), and Xishanyao (J_2x) formations, each of which range in thickness from 220 to 450 m (Min et al., 2001). This group is thought to be the source of some of the U within the southern Yili U district, as these sediments contain relatively high concentrations of U (average of 9 ppm; NWIUG, 1997; Min et al., 2005a, 2005b). This group has been divided into eight sedimentary cycles named I to VIII from base to top (Tan, 1998), and four intercalated coal seams occur within the southern flank of the synclinal Yili Basin, where the sedimentary units dip at 3°–8° to the northeast (Min et al., 2001; Li et al., 2002a; Wang et al., 2005a, 2005b, 2006a, 2006c). In addition to the sandstone-type U mineralization that is hosted by cycles II, III, V, and VII, the lignite beds that separate cycles VI and VII also host U mineralization and are useful marker units (Fig. 3).

The sandstones within the Yili Basin formed in an alluvial fan–braided river setting. The outcropping of ore-hosting sandstone was >100 km long and up to 20 km wide, covering an area exceeding 1500 km² and trending E–W trend (Fig. 2). These sediments were most likely derived from Proterozoic metasediments, Carboniferous volcanic rocks, and late Paleozoic granites located on

Fig. 3. Stratigraphic column for Lower to Middle Jurassic sediments within the southern flank of the synclinal Yili Basin, outlining the main hosts of mineralization in this area (after Min et al., 2001; Li et al., 2002b).

Geochronology		Thickness (m)	Lithology		U
Cretaceous		530–560		Yellow-brown sandy (calcareous) conglomerate, massive bedding	
Lower–Middle Jurassic Shuixigou Group	Middle Jurassic Xishanyao Formation	VIII ~30		Variegated mudstone and sandstone, horizontal bedding	
				Medium to coarse-grained sandstone, massive bedding	
		VII >40		Mudstone, siltstone and (pebbly) sandstone, horizontal bedding	
	Lower Jurassic Sangonghe Formation	VI ~30		Pebbly sandstone, parallel bedding	
				Coal seam	
		V >80		Sandstone, siltstone	
				Pebbly sandstone, horizontal bedding	
		Lower		Fine grained sandstone with intercalations of siltstone and mudstone, horizontal bedding	
				Coal seam	
				Siltstone and mudstone, horizontal bedding	
Lower–Middle Jurassic Shuixigou Group	Upper	V >80		Pebbly sandstone, wedgelike bedding	
				Siltstone and muddy siltstone, wavy bedding	
	Lower Jurassic Badaowan Formation	IV ~60		Coal seam	
				Muddy siltstone, horizontal bedding	
		III ~25		Muddy siltstone	
				Sandy conglomerate and sandstone, massive bedding	
		II ~30		Coal seam	
				Muddy siltstone and fine-grained sandstone	
Lower–Middle Jurassic Shuixigou Group	I ~25	I ~25		Sandy conglomerate and coarse-grained sandstone, massive bedding	
				Muddy siltstone and fine-grained sandstone, horizontal bedding	
	Middle–Upper Trassic	440		Sandy conglomerate with intercalation of fine-grained sandstone, massive bedding	
				Siltstone, mudstone, and fine-grained sandstone with intercalation of sandy conglomerate	

the margin of the basement. The ore-hosting sandstone is dominantly medium- to coarse-grained and classified as lithic subarkosic sandstone (Min et al., 2001). There is no significant difference in sandstone mineralogy between mineralized and barren samples. The ore-hosting sandstones are dominated by detrital quartz (30% to 40%), feldspar (15% to 20%), carbonaceous debris (2% to 3%), and rock fragments (20% to 40%), with the latter consisting of tuff, andesite, granite, rhyolite, quartzite, sandstone, siltstone, and slate. These sandstones also contain minor amounts of detrital biotite, muscovite, tourmaline, hornblende, and heavy minerals (zircon, apatite, magnetite, allanite, monazite, titanite, ilmenite, and scarce brannerite) (Min et al., 2005a). The detrital grains are angular to subangular and poorly sorted, indicative of rapid deposition. The ore-hosting sandstones contain a matrix of clay, silt, and fine-grained sand (Min et al., 2005a).

3. River systems

Intense crustal shortening and tectonic uplift in the study area resulted in an average altitude of 3500 m and numerous glaciers (Avouac and Burov, 1996; Deng et al., 2000; Zhao et al., 2010). The southern margin of the Yili Basin contains a series of inland rivers that originate from glaciers within the middle- to higher-altitude areas of the range, transversely cut the foreland thrust fault–fold belts, and eventually flow into the Yili Basin (Fig. 4; Wu et al., 2018). These rivers are located in the northern piedmont area of the southern Tien Shan Orogen and generally trend N-S. The prevailing drought and low rainfall conditions in this area mean that flow in these rivers is strongly dependent on melt water and is seasonally variable (Chen and Li, 1997; Li et al., 2011). Some 70% of the discharge from these rivers is from melt water, with the remaining 30% derived from rainfall that generally occurs during the summer. The majority of these rivers flow out of the southern Tien Shan mountains and either flow into the Yili river, terminate in the desert, or are consumed by irrigation (Fig. 4; Lei et al., 2010; Wu et al., 2018).

The rivers in the study area generally have deeply incised valleys that frequently contain terrace sequences (Molnar et al., 1994; Deng, 2000; Deng et al., 2000; Lu et al., 2010; Yang et al., 2013; Gong et al., 2014). Seven main terraces that formed in a time span of ~540–1.8Ka have been identified within the northern piedmont of the southern Tien Shan mountains (Xu et al., 1992; Molnar et al., 1994; Shi et al., 2004; Lv et al., 2008a, 2008b). The formation of river terraces indicates that river erosion and aggradation have alternated or changed over time (Burbank and Anderson, 2012). The two main factors in this process are climatic fluctuations and tectonic movements (especially uplift), both of which can drive changes in erosion and aggradation (Wu et al., 2018). This means that terrace systems can quantitatively constrain the temporal evolution of climate and regional tectonics in an area. The Tien Shan region records climate changes caused by alternating interglacial and glacial periods that resulted in river downcutting and the generation of river terraces (Chatters and Hoover, 1992; Martin, 1992; Zhang et al., 1995; Starkel, 2003; Hu et al., 2013). However, areas of stable crust contain rivers dominated by lateral erosion, whereas rivers quickly downcut in areas of crustal uplift. The series of river terraces within the northern piedmont of the southern Tien Shan mountains therefore also formed as a result of intermittent uplift associated with active faulting and folding (Deng et al., 2000; Yang and Li, 2005; Li et al., 2012; Yang et al., 2013).

4. Ore deposit geology

4.1. Kuji'ertai uranium deposit

The Kuji'ertai uranium deposit is located 80 km SW of the Yining

deposit, close to the Kazakhstan border, and was discovered in the late 1950s. The deposit has U resources of 5000 to 20,000 t (OECD-NEA/IAEA, 2000; Zhou, 2000), making it one of the largest known uranium deposits in China. Exploitation by in situ leaching has been ongoing since 1993 (Dahlkamp, 2009).

The Kuji'ertai deposit contains four spatially separated inter-layer oxidation zones with redox fronts some 10 km long in an E–W direction (Fig. 5; Tan, 1998). These oxidation zones are well developed and show down-dip zoning from an intensely altered brown–yellow sandstone containing elevated concentrations of high hydrogoethite to a weakly altered yellow sandstone containing ~6.5% hydrogoethite and then into the redox front and related orebodies. These oxidation zones provide evidence of the inflow of oxygenated groundwater derived from U-bearing surficial water from the south, the leaching of uranium under oxidizing conditions, and the mobilization of U within alluvial/fluvial systems and in groundwater moving through the hosting sediments.

The orebodies in the deposit are generally roll-front subtypes although some tabular subtypes are also present. They crop out in an area 12 km long and 5 km wide. The roll-front orebodies are generally 50–150 m long, on average are 5 m thick, and are between 200 and 350 m wide, although locally up to 500 m. The deposit has grades between 0.01% and 0.20% U (average of 0.05% U), and this mineralization is generally hosted by cycles II and III of the Badaowan and Sangonghe formations and cycle VII of the Xishanyao Formation (Fig. 5). The hosting sandstones are generally sandwiched by coal seams or mudstones, both of which are laterally extensive and impermeable.

Mineralized sandstones are generally grey and have a clay mineral cement that forms ~20% of the rock. This cement consists of illite, kaolinite, montmorillonite, and chlorite, with minor calcite. The clay minerals have commonly replaced feldspar (Min et al., 2001). The principal epigenetic metallic minerals in the ores (listed in paragenetic sequence from oldest to youngest) are hematite, sphalerite, pyrite, and U-bearing minerals, including pitchblende, coffinite, and brannerite, with only minor uranium absorbed on altered volcanic detritus or carbonaceous material (Min et al., 2001). Pyrite is generally framboidal, with diameters of 0.01 to 0.04 mm, and is particularly associated with high-grade regions of the orebodies. Microscopic crystals of pyrite are also disseminated throughout the pelitic cement of the sandstones. Pitchblende and coffinite are common in those parts of ore zones that contain elevated concentrations of carbonaceous material and are generally located adjacent to carbonaceous material and pyrite (for details, see Min et al., 2001).

4.2. Mengqiguer uranium deposit

The Mengqiguer uranium deposit is located in the central part of the southern margin of the Yili Basin (Fig. 2) and was initially thought to be a coal-hosted U deposit when discovered in 1955. The deposit contains 500–1500 t U in resources with grades of 0.03%–0.10% U (Dahlkamp, 2009). Exploration since the 1980s has discovered significant sandstone-hosted U mineralization within dark clastic coal-bearing Jurassic sediments (Figs. 6, 7), with minor amounts of mineralization located in overlying Paleogene clastic sediments. The mineralized sandstone unit within the deposit formed in proximal braided stream, lacustrine, lakeshore delta, and alluvial fan environments (Zhang et al., 2010).

The mineralization within the Mengqiguer deposit is hosted by the 350–450 m thick Shuixigou Group. The uranium orebodies within this group are located within the II, III, V, and VII sedimentary cycles (Fig. 7) in quartzose sandstone, volcanic-debris-bearing feldspathic (kaolin altered) sandstone, and sandy conglomerate units. The mineralized sedimentary unit generally

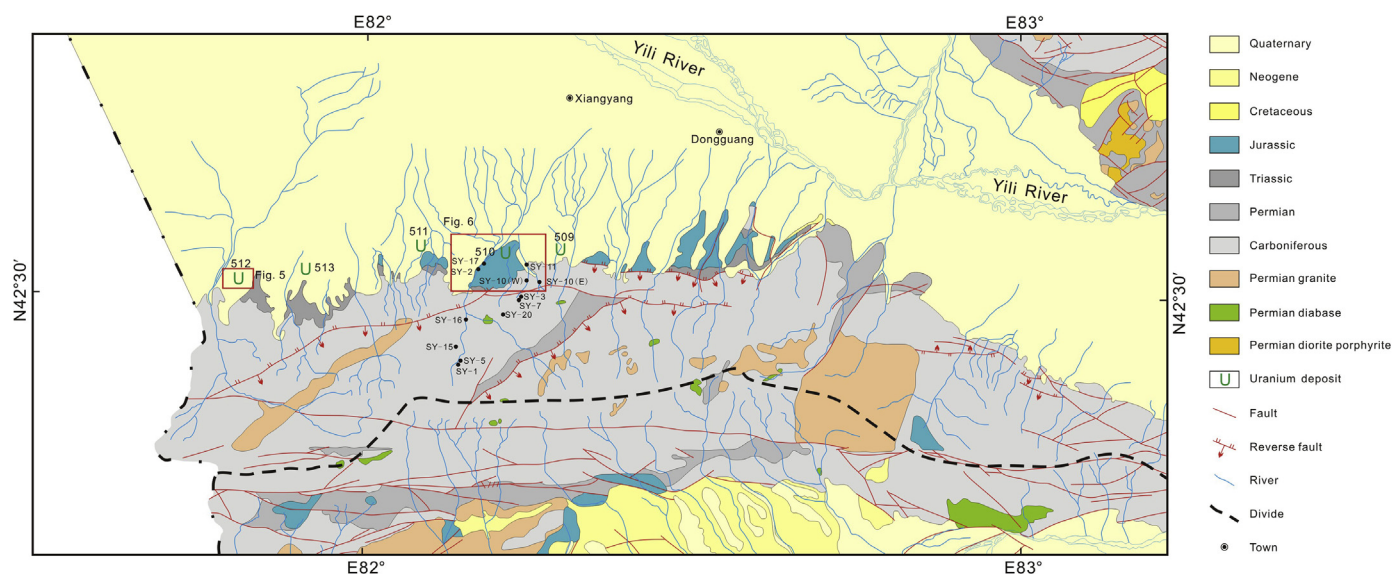


Fig. 4. Sketch maps showing the locations of river systems in the Southern Tien Shan orogen, including the generally N-S trending rivers to the north of the Southern Tien Shan that feed into the Yili Basin. The black circles indicate water sampling locations.

has a sand/mud ratio of 1–3 and contains 0.3%–3.0% organic carbon. The deformation of this group formed a gentle ENE–WNW striking anticline with limbs that host the majority of the orebodies of the deposit. Three major ENE–WNW striking reverse faults have also been identified during drilling, with these faults thought to control the location of uranium mineralization (Wang et al., 2006c). The F1 fault passes to the SE of the deposit and dips to the NW at 10°–15°. The F2 fault is located 1 km NW of F1 and has a similar orientation and dip, suggesting this is a secondary fault associated with the main F1 fault. The F3 fault occurs along the hinge zone of the gentle ENE–WNW striking anticline and dips to the NW at ~20°. The course of the Thajistan River roughly follows the F3 fault from SW to NE (Fig. 6; Wang et al., 2009a).

The groundwater associated with the Mengqiguer deposit is generally hosted by the Lower–Middle Jurassic Shuixigou Group (Fig. 6). These water are injected into exposed Jurassic sediments, with 68,976 m³/d of water injected from the Thajistan River to the southwest, and 289 and 151 m³/d on average for the Mengqiguer and Langka rivers to the south, respectively. The groundwater in this area flows to the NE, most likely as a result of the NE dip of the Jurassic units, with a flow rate of 0.01–0.11 m/d (Lin et al., 2017).

Two pairs of interlayer oxidation zones have been identified within the Mengqiguer deposit (Figs. 6, 7), reflecting the inflow direction of oxygenated groundwater. Pair I formed as a result of the inflow of oxygenated groundwater from the southern sources of the Mengqiguer and Langka rivers, forming a redox front >20 km long in an ENE direction. These oxidation zones are generally located within the Badaowan Formation. However, Pair II formed as a result of groundwater inflow from the Thajistan River, yielding a redox front about ~8 km long in a NW direction. This suggests that the Thajistan, Mengqiguer, and Langka rivers represent the sources of the ore-forming fluids that formed this deposit.

Major orebodies within the deposit generally have more or less irregularly shaped rolls or are tabular. These orebodies are usually hundreds of meters wide, can reach tens of kilometers long, and are 0.5 m to tens of meters thick. The ores are usually low to medium grade (<0.5% U) and are commonly grey, dark grey, or black in color as a result of the presence of U-minerals, Fe-sulfides, and carbonaceous debris. Clay minerals form a pervasive matrix that hosts the detrital grains (mostly quartz and feldspar, with a few heavy minerals) and

also replace the feldspar within the sediment (Fig. 8G, H). The ores are indurated and have moderate permeability although some ores are water saturated and are essentially unconsolidated. The highest-grade mineralization is commonly also enriched in Mo and V, and has sharp lithological contacts with surrounding barren but altered rock, although U grades gradually decrease across this boundary rather than dropping off sharply. Fossil carbonaceous material is moderately common within the unaltered sandstone and is often well preserved. Epigenetic alteration has changed the originally black sandstone to pink as a result of hematite alteration, yellow associated with limonite alteration, or white as a result of argillic alteration. The U within the deposit is generally present as pitchblende (Fig. 8A–D), but also minor coffinite (Fig. 8E) and brannerite, and adsorbed onto clay minerals (Fig. 8F), pyrite, and coal debris (for details, see Min et al., 2005b and Dahlkamp, 2009).

5. Sampling and analysis

The samples analyzed during this study are listed in Table 1. The intimate intergrowth of ore minerals and gangue within these samples means that whole-rock analysis was the primary approach used (Ludwig et al., 1985). The effects of small-scale U-daughter migration and variations in initial Pb isotopic composition were overcome by the use of relatively large samples (>1 kg). All samples are fresh and non-friable, with no visible secondary U minerals, and generally contain >300 ppm U. Pitchblende separates were also obtained from several samples, with >80% purity separates handpicked under a binocular stereo-microscope from material coarser than 20–40 mesh. The resulting separates were analyzed to compare with the results of previous U–Pb dating using pitchblende separates (Li et al., 1980; Li, 1982; Xia et al., 2003; Zhang, 2008; Luo et al., 2015).

Samples were obtained from roll-shaped orebodies within the Badaowan Formation in the Kuji'ertai deposit (Groups A, E, F, G; Fig. 5) and the Sangonghe Formation in the Mengqiguer deposit (Groups B–D; Fig. 7). Groups A and D represent the inner core parts of U orebodies, whereas Group B was collected from the wings of a roll-shaped U orebody, and Group C was taken from the head zone of a roll-shaped U orebody. Finally, Groups E–G are hand-picked pitchblende separates taken from inner core, wing, and head zones within roll-shaped orebodies, respectively. All of these samples are fresh and contain no visibly oxidized U minerals.

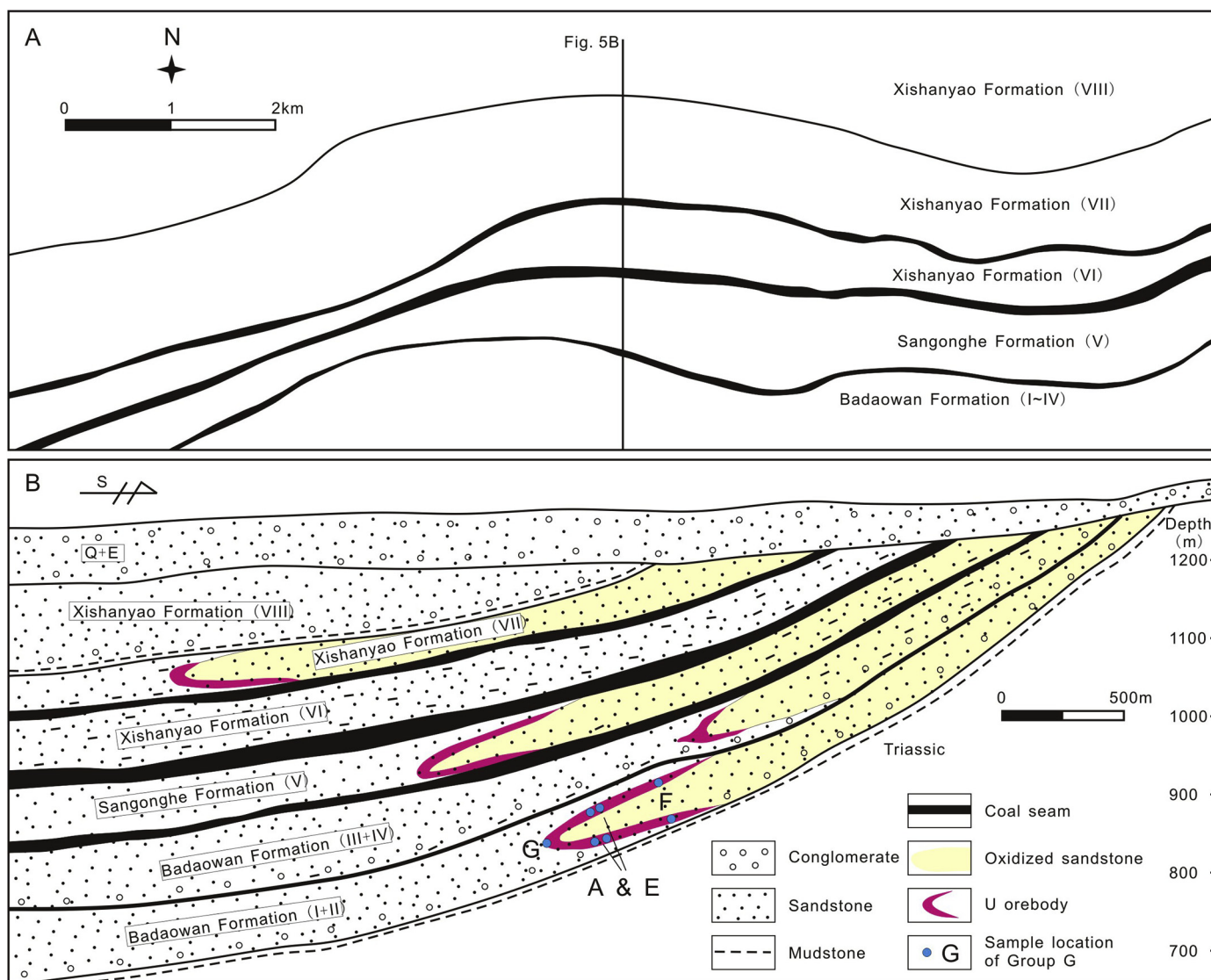


Fig. 5. A. Geological sketch map of the Kuji'ertai uranium deposit, showing the location of the cross-section in B. B. N-S cross-section through the central part of the Kuji'ertai uranium deposit, showing the locations of orebodies and mineralization-hosting sedimentary units (Qin et al., 1999; Wang and Geng, 2009).

The samples were crushed and milled to fine-grained sand before splitting with a microsplitter to yield representative 5 g fractions for dissolution. The approach of Ludwig et al. (1985) was used in that all samples were completely dissolved in hot HF–HNO₃–HClO₄ at 1 atm before small (2–20 µl) liquid aliquots of the 50 ml total solution were employed for U and Pb purification using conventional HBr (Pb) and HNO₃ (U) ion exchange column techniques. The U and Pb concentrations within the aliquots were determined by isotope dilution–mass spectrometry before isotopic compositions were determined using an ISOPROBE-T mass spectrometer. Pb isotope ratios are corrected for mass discrimination and laboratory blanks, and uncertainties vary somewhat from sample to sample but are on average 0.01% (on a 2σ basis) for Pb²⁰⁶/Pb²⁰⁴, Pb²⁰⁷/Pb²⁰⁴, and Pb²⁰⁸/Pb²⁰⁴, and ~0.15% for U²³⁸/Pb²⁰⁴ and U²³⁵/Pb²⁰⁴, as assessed by analysis of Chinese national pitchblende standards GBW 04220, NBS Pb 981 standard from the US National Institute for Standards and Testing, and Certified Reference Material (CRM) U-030. Uncertainties and error correlations for blank-corrected isotope ratios (all blank corrections were negligible) and the resulting concentrations were determined using the equations of Ludwig (1980, 1984). Measurements were performed at the Geological Analysis and Testing Center,

Beijing Research Institute of Uranium Geology, Beijing, China. All uncertainties are given at the 95% confidence level and ore isotopic ratios (²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²³⁵U) were used to estimate ages using ISOPLOT (v.4.15, Ludwig, 1993).

The U–Pb dating of samples from the Mengqiguer deposit suggest that this deposit is still forming; consequently, we undertook systematic sampling of groundwater around this deposit for chemical analysis. A total of 23 water samples were obtained during field trips in 2015 and 2016. The influence of rainfall was minimized by the collection of all samples during a single week that had no rainfall. Each sampling point involved the in situ measurement of temperature, pH, Eh (oxidation–reduction potential; ORP), total dissolved solids (TDS), electrical conductivity (CON), and dissolved oxygen (DO) values using a Hach sens-ION instrument). This approach used four specific electrodes (electrode 51910-00 for pH and temperature; electrode 51975-00 for electrical conductivity and TDS; electrode 51937-00 for Eh; and electrode 51970-03 for DO) and one standard electrical conductivity solution (CON, 1000 ± 10 µS/cm with a salinity of 491 mg/L NaCl and a TDS value of 500 ± 5 ppm).

A total of six samples were taken from cold springs located roughly to the south of the Mengqiguer deposit that flow into the

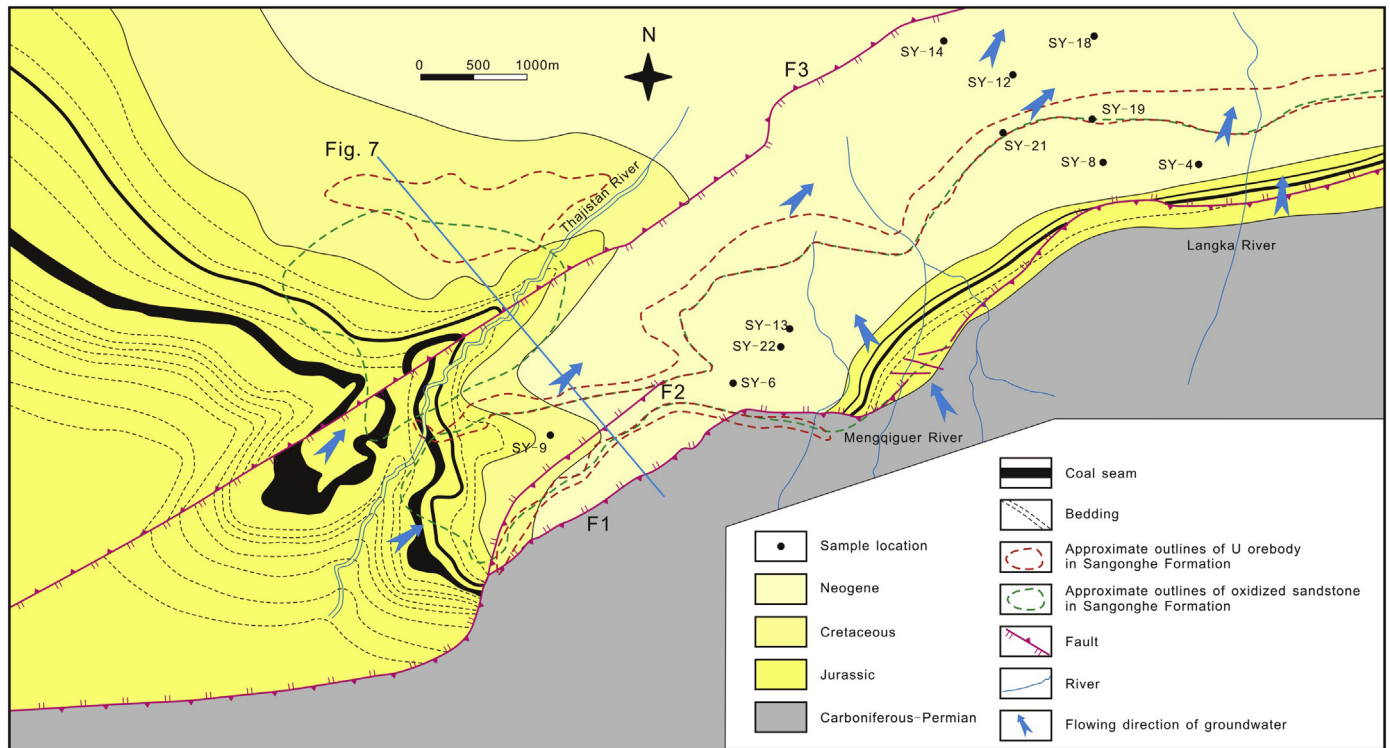


Fig. 6. Geological sketch map of the Mengqiguer uranium deposit, showing the direction of groundwater flow and the approximate locations of oxidized zones and uranium orebodies within the Sangonghe Formation (modified from Wang et al., 2009a; Kang and Wang, 2010; Li and Chen, 2010).

Mengqiguer or Thajistan rivers and a further six samples were taken from the upper and middle reaches of the Mengqiguer and Thajistan rivers (Figs. 4, 6; Appendix A). A further 11 underground samples

were taken from deep hydrological wells used to monitor water-level variations and open wells for household use (Fig. 6). The cold spring samples generally represent the composition of melt water

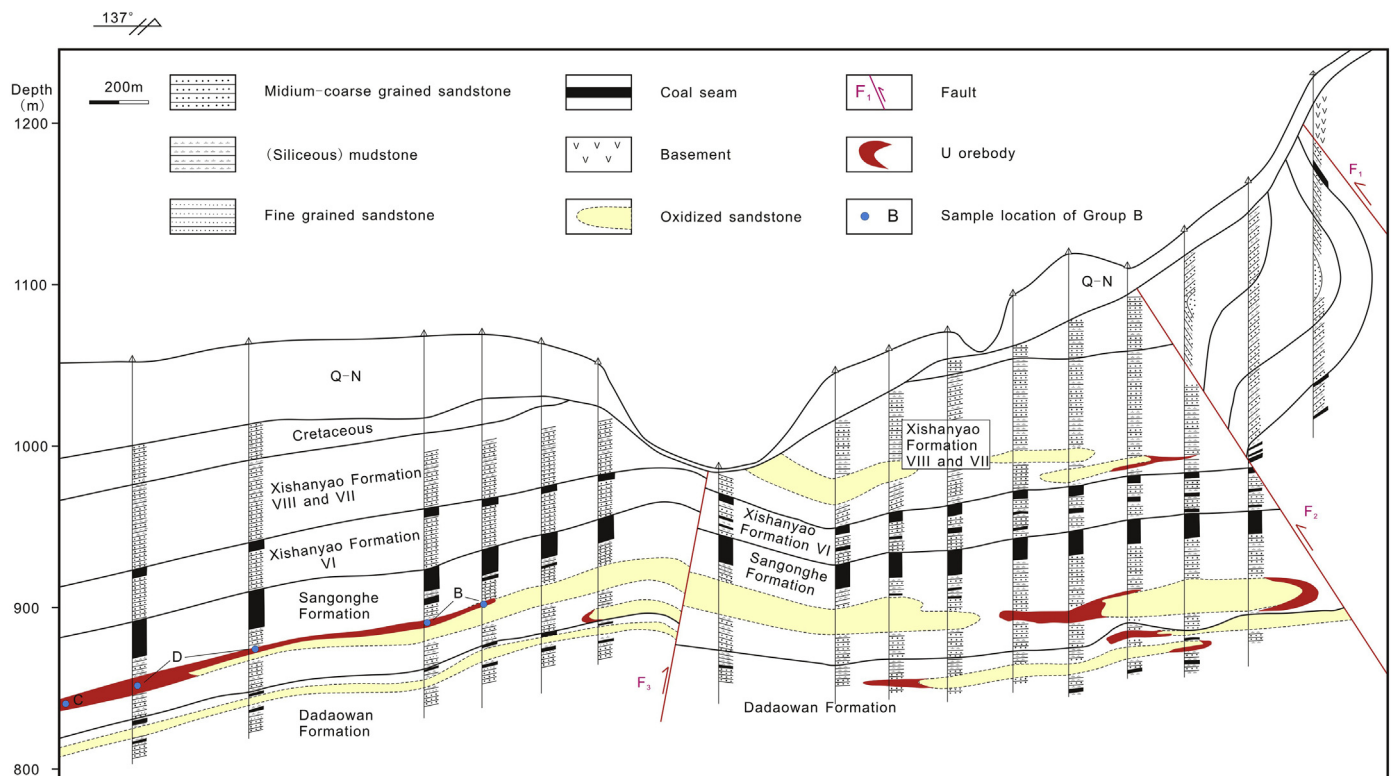
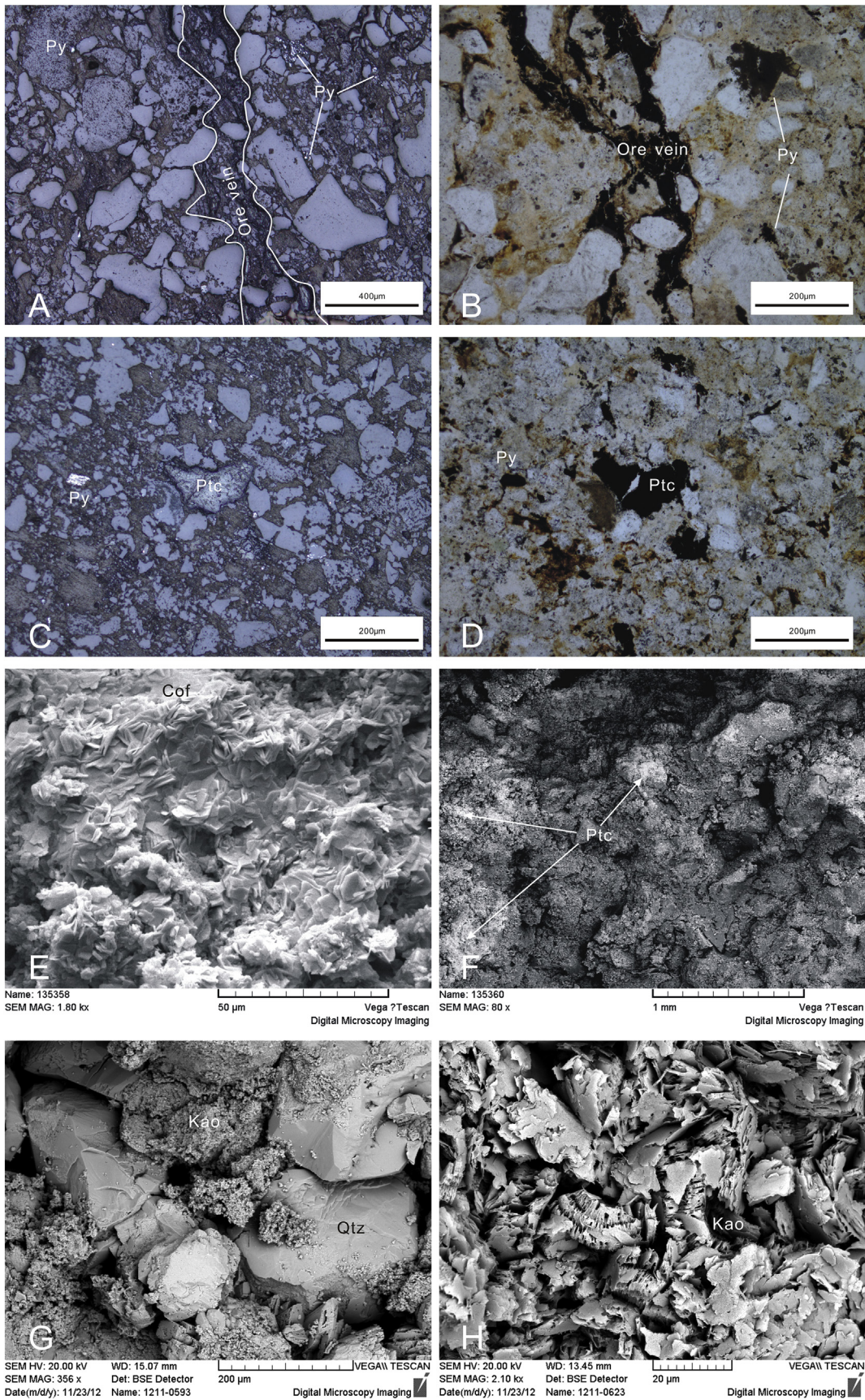


Fig. 7. NW–SE cross-section through the Mengqiguer uranium deposit, showing the location of the gentle anticline associated with the deposit, faults, oxidized zones, and uranium orebodies (modified from Geological Team No. 216, 2016).



that flows through fractures, with upstream river samples representing surficial melt waters combined with some water derived from cold springs and midstream river samples representing upstream river water combined with predominantly meteoric soil water. The underground samples are divided according to their location either within the oxidation zone (at least 200 m from the U orebody), close to the orebody, and within the reduced zone. The locations of the samples from the oxidation zone and close to the orebody represent river waters that have seeped into the mineralized sandstone, where these fluids have undergone water–rock interaction and associated oxidation. However, the samples from the reduced zone represent groundwater from the oxidation zone that has been reduced as a result of water–rock interaction.

Water was pumped using either installed submersible pumps or bailers depending on the situation at the sampling point, with water transported using PVC riser tubes. Mutual contamination was avoided by pumping of water for 30 min prior to sampling. All water samples were stored in two glass bottles that were airfreighted to the Geological Analysis and Testing Center of the Beijing Research Institute of Uranium Geology, Beijing, China. Bulk ion compositions of water samples were determined using ion chromatographic analysis (Bray et al., 1991; Channer and Spooner, 1991) employing a DIONEX-500 ion chromatography system, with analytical precision and accuracy are generally $\pm 2\%$. The concentrations of U, Fe, and Al within water samples were determined using high resolution–inductively coupled plasma–mass spectrometry (HR–ICP–MS) employing a Finnigan MAT Element I instrument, with analytical precision and accuracy are generally $\pm 1\%$. Commercial standard solutions were used for daily calibration and the limits of quantitation were determined by 10 point calibration as per the DIN 32645 standard. HCO_3^- and CO_3^{2-} concentrations were determined using a SCHOTT Titroline Alpha Plus automatic titration system employing a modified DIN 38409-H7-2 standard approach by evaluating titration curve shapes for the identification and quantitation of these species. Precision values were determined by the daily analysis of standards according to the DIN ISO 11352:2013–03 standard with accuracy values determined from proficiency testing results and the daily measurement of standard solutions.

6. Results

6.1. U and Pb contents

Before describing the U and Pb isotope data generated during this study, it is important to place these data in context by discussing the U and ^{204}Pb (representing initial Pb concentrations) contents of ores and pitchblende. These data provide insights into variations in U and Pb isotopic data that reflect either initial contents or the influence of small-scale migration. The data shown in Table 1 and Fig. 9 indicate that although samples within individual groups have variable U and ^{204}Pb compositions, indicating that these data would yield unreliable apparent ages, the ores have roughly constant ^{204}Pb contents (0.10–0.30 ppm). This is significantly different from the negative correlation between ^{204}Pb and U obtained from the analysis of pitchblende. Here, we use pitchblende analyses for comparison with our whole-rock data to assess the small-scale migration of radioactive uranium daughter products as well as variations in radiogenic Pb contents derived from hand-picking and the influence of both of these factors on U–Pb dating.

6.2. Pb isotope data

The U and ^{204}Pb contents of the ores indicate highly variable initial Pb contents but not highly variable initial Pb isotopic compositions, with the latter expected to be constant during the formation of the mineralization, at least on an orebody scale. The Pb isotopic compositions of whole-rock ore samples and pitchblende from the southern Yili uranium district are given in Table 1 and shown in Fig. 10. Prior to discussing the U–Pb dating of these samples it is important to assess their Pb isotopic compositions. This reflects the fact that these ores contain relatively high amounts of initial (common) Pb, meaning it is not possible to employ typical concordia diagram or straightforward U–Pb isochron approaches that assume negligible or isotopically constant initial Pb. Plotting these samples in a $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (Fig. 10) shows three trends, suggesting these samples should be subdivided into three clusters (I, II, and III) reflecting their properties and locations. Cluster I includes Groups B–D, all of which are from the Sangonghe Formation within the Mengqiguer deposit. In comparison, Clusters II and III represent ores and handpicked pitchblende, respectively, from the Kuji'ertai deposit. All three linear trends defined by these clusters are parallel, indicating that they do not have the same initial Pb isotope compositions. This is supported by their $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 1424 ± 310 Ma (Cluster I), 409 ± 190 Ma (Cluster II), and 876 ± 74 Ma (Cluster III), with associated initial $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of 16.30, 18.07, and 17.28, respectively, and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of 15.53, 15.35, and 14.12, respectively. The mineralization in the southern Yili district contains only trace amounts of Th (usually several ppm), meaning that the $^{208}\text{Pb}/^{204}\text{Pb}$ ratios have remained unchanged since their formation (as shown by Clusters I and II; Fig. 10B). This means that the $^{208}\text{Pb}/^{204}\text{Pb}$ ratios of these samples should reflect variations in initial Pb isotopes. Any U present in oxidized fluid can be extracted as U^{6+} complexes, enabling the easy release of associated radiogenic Pb. However, Th is inert and is unlikely to be mobilized, meaning that the resulting radiogenic ^{208}Pb is more immobile during mineralizing processes. The different geochemical properties of U and Th within the oxidized fluid therefore mean that initial $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values are more likely to be homogenous than $^{208}\text{Pb}/^{204}\text{Pb}$ values (Faure, 1977). This can explain the fact that although both Cluster II and III samples are from a roll-shaped U orebody within the Kuji'ertai deposit and define similar linear trends in a $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, the $^{208}\text{Pb}/^{204}\text{Pb}$ values of the Cluster III samples are much more variable than those of Cluster II samples, reflecting the influence of handpicking of the pitchblende samples (Fig. 10).

In conclusion, plotting samples from the study area on $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams suggests that the ores within the southern Yili U district have variable initial Pb isotopic compositions, although these are consistent on an orebody scale, enabling the selection of groups of consistent samples for U–Pb dating.

6.3. U–Pb isotope data

The mineralized sandstone in the study area is loosely consolidated and is dominated by moderately well sorted and rounded quartz and feldspar grains in a matrix of illite, calcite, and hematite,

Fig. 8. Photomicrographs of representative ore samples from the Mengqiguer deposit. A. Pitchblende veins hosted by quartz sandstone with a disseminated-pyrite-bearing matrix (reflected light, sample P3523). B. Pitchblende veins along the contact surface of detrital quartz within a disseminated-pyrite-bearing matrix (plane polarized light, sample P3523). C. Disseminated pitchblende within sandstone (reflected light, sample P5116). D. Disseminated pitchblende within sandstone (plane polarized light, sample P5116). E. Backscattered electron image of aggregated coffinite ore (sample P5358). F. Backscattered electron image of disseminated pitchblende (appearing bright white) ore (sample P5360). G. Semi-rounded quartz within sandstone with a kaolinite matrix, yielding a relatively high permeability (SEM image, sample P2056). H. Aggregated sheet-like kaolinite matrix in sandstone, yielding a relatively high permeability (SEM image, sample P2311).

Table 1

U–Pb isotopic data for samples from the southern Yili uranium district, Yili Basin.

Group	Sample no.	Lithology	U(ppm)	Pb (ppm)	$^{204}\text{Pb}(\text{ppm})$	$^{238}\text{U}/^{204}\text{Pb}$	$^{235}\text{U}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}(2\sigma)$	$^{207}\text{Pb}/^{204}\text{Pb}(2\sigma)$	$^{206}\text{Pb}/^{204}\text{Pb}(2\sigma)$
A	P824a	Coarse sandstone, grey	4058	16.8	0.123	28118.668	204.049	39.291(0.002)	18.411(0.001)	76.313(0.003)
A	P824b	Coarse sandstone, grey	471	11.2	0.135	2967.279	21.533	39.23(0.003)	16.123(0.001)	25.399(0.001)
A	P824d	Coarse sandstone, grey	3816	16.8	0.129	25186.576	182.771	39.246(0.002)	18.226(0.001)	70.387(0.004)
A	P824e	Coarse sandstone, grey	2409	20.4	0.188	10857.015	78.786	39.282(0.002)	17.114(0.001)	49.417(0.004)
A	P824f	Coarse sandstone, grey	2078	11.6	0.124	14352.403	104.150	39.228(0.002)	16.184(0.001)	36.143(0.003)
A	P824g	Coarse sandstone, grey	3699	18.8	0.115	27513.761	199.659	39.309(0.003)	20.095(0.001)	101.619(0.008)
A	P824h	Coarse sandstone, grey	3854	16.1	0.119	27,627.140	200.482	39.344(0.002)	18.348(0.001)	75.392(0.003)
A	P824i	Coarse sandstone, grey	1920	17.2	0.191	5434.251	39.435	39.301(0.002)	16.256(0.001)	32.178(0.003)
A	P824j	Coarse sandstone, grey	3655	16.9	0.088	35248.16	255.785	39.351(0.002)	21.559(0.001)	127.035(0.009)
A	P824k	Coarse sandstone, grey	2263	15.3	0.125	15356.38	111.437	39.284(0.003)	17.512(0.001)	62.778(0.001)
A	P824l	Coarse sandstone, grey	3990	19.7	0.119	28538.843	207.098	39.234(0.002)	19.892(0.001)	103.546(0.003)
B	02835-1a	Medium sandstone, grey	405	9.74	0.127	2702.923	19.614	39.181(0.001)	15.813(0.001)	19.300(0.001)
B	02835-1b	Medium sandstone, grey	337	16.3	0.210	1360.752	9.874	39.202(0.003)	15.863(0.001)	20.262(0.002)
B	02835-1c	Medium sandstone, grey	413	15.8	0.203	1733.233	12.577	39.253(0.002)	15.887(0.001)	20.367(0.001)
B	02835-1d	Medium sandstone, grey	385	9.82	0.128	2552.764	18.524	39.227(0.004)	15.82(0.002)	19.306(0.002)
C	02827-1f	Medium sandstone, grey	3646	24.4	0.309	10030.493	72.788	39.177(0.002)	16.024(0.001)	21.634(0.001)
D	02011-1a	Coarse sandstone, grey	1591	11.7	0.151	8922.667	64.749	39.262(0.002)	15.855(0.001)	19.951(0.001)
D	02011-1b	Coarse sandstone, grey	1748	10.8	0.140	10643.449	77.236	39.254(0.002)	15.859(0.001)	20.048(0.001)
D	02011-1c	Coarse sandstone, grey	1543	11.4	0.147	8917.887	64.714	39.299(0.001)	15.861(0.001)	19.951(0.001)
D	02011-1d	Coarse sandstone, grey	2128	19.1	0.248	7296.878	52.951	39.207(0.002)	15.847(0.001)	19.865(0.001)
D	02011-1e	Coarse sandstone, grey	937	15.6	0.203	3935.072	28.555	39.245(0.002)	15.838(0.001)	19.686(0.001)
D	02011-1f	Coarse sandstone, grey	732	23	0.299	2081.342	15.104	39.237(0.001)	15.822(0.001)	19.584(0.001)
E	P1316a	Pitchblende	399000	614	0.214	261259.6	1895.885	40.210(0.002)	36.093(0.009)	389.986(0.023)
E	P1316b	Pitchblende	628000	535	0.086	1173723.0	8517.364	38.907(0.001)	85.756(0.023)	1037.128(0.172)
E	P1316c	Pitchblende	562000	451	0.111	965477.2	7006.188	38.982(0.001)	69.387(0.009)	791.532(0.105)
F	CN11M-1	Pitchblende	692000	385	0.043	3593843	26079.480	42.070(0.002)	157.326(0.047)	2125.186(0.329)
F	CN11M-3	Pitchblende	740000	316	0.164	1228349	8913.769	42.030(0.003)	49.787(0.014)	516.939(0.050)
F	CN11M-4	Pitchblende	728000	733	0.156	547613.3	3973.871	39.205(0.003)	47.083(0.016)	553.737(0.047)
F	CN11M-6	Pitchblende	663000	3227	0.225	78571.52	570.171	42.338(0.003)	36.209(0.011)	364.902(0.041)
F	CN11M-7	Pitchblende	209000	1453	1.008	12318.85	89.394	39.230(0.003)	17.145(0.002)	41.831(0.001)
F	CN11M-9	Pitchblende	495000	743	0.693	82879.45	601.432	39.038(0.003)	19.801(0.002)	84.462(0.006)
F	CN11M-10	Pitchblende	19100	1425	0.564	2047.922	14.862	41.420(0.005)	20.959(0.002)	113.926(0.007)
F	CN11M-12	Pitchblende	354000	1237	0.398	61925.97	449.379	45.771(0.005)	24.656(0.004)	179.829(0.011)
G	K1607-7	Pitchblende	472000	48.7	0.566	1475492	10707.22	39.284(0.003)	22.035(0.005)	114.359(0.008)

Pb isotope ratios are corrected for mass discrimination and laboratory blanks, and uncertainties vary somewhat from sample to sample but are on average 0.01% (on a 2σ basis) for $\text{Pb}^{206}/\text{Pb}^{204}$, $\text{Pb}^{207}/\text{Pb}^{204}$, and $\text{Pb}^{208}/\text{Pb}^{204}$, and $\pm 0.15\%$ for $\text{U}^{238}/\text{Pb}^{204}$ and $\text{U}^{235}/\text{Pb}^{204}$.

meaning that the ores might have been influenced by post-mineralization fluid activity. The U–Ra coefficient of roll-shaped orebodies is generally in equilibrium ($K_p = 0.84\text{--}1.08$ where K_p equals the U–Ra equilibrium coefficient and calculated as $(\text{Ra molar concentration})/(\text{U molar concentration})$; Li et al., 2002b; Zhang et al., 2018). This suggests that the mineralization at the head of the redox front formed during oxidation and was unaffected by later processes. However, the oxidation zone is in disequilibrium ($K_p = 2.64\text{--}3.32$; Li et al., 2002b), meaning that these ores have undergone secondary oxidation and redistribution or re-enrichment of U or Pb (Rosholt et al., 1973; Faure, 1977; Li et al., 2002b). None of the clusters from the oxidation zone yield well-defined linear trends that correspond to meaningful $^{207}\text{Pb}/^{206}\text{Pb}$ ages. However, these isotopic data can be made more useful and meaningful by plotting $^{238}\text{U}/^{204}\text{Pb}$ and $^{235}\text{U}/^{204}\text{Pb}$ values against $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values, respectively (Fig. 11), suggesting that it is possible to date these samples using the U–Pb approach once erroneous data have been removed (Fig. 9). Plotting data from Clusters I–III in $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{238}\text{U}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{235}\text{U}/^{204}\text{Pb}$ diagrams indicates that Group B and C samples in Cluster I and samples CN11M-1, -3, -6, -7, -9, and K1607-7 in Cluster III should be excluded from U–Pb dating, as all of these samples have undergone U or Ra (Pb) loss or addition, meaning that they plot away from the linear trends defined by all the other samples (Faure, 1977; Ludwig, 1978, 1980; Ludwig et al., 1981, 1984, 1985; Holliger et al., 1989; Nikolay et al., 2009). In addition, Cluster II should be divided into two sub-clusters where sub-cluster II(A1) includes samples P824a, d, f, and h, and sub-cluster II(A2) includes all other samples in this cluster.

The remaining data were plotted on $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{238}\text{U}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{235}\text{U}/^{204}\text{Pb}$ diagrams. The

meaningful data in Cluster I yield a linear trend in a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{238}\text{U}/^{204}\text{Pb}$ isochron diagram that corresponds to an age of 0.347 ± 0.0048 Ma, whereas the same samples plotted on a $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{235}\text{U}/^{204}\text{Pb}$ diagram define a linear trend that yields an isochron age of 0.61 ± 0.24 Ma. These trends also yield initial $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values of 19.4725 ± 0.0056 and 15.817 ± 0.013 , respectively (Fig. 11A1–A4). The U–Pb dating of sub-cluster II(A1) yields a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{238}\text{U}/^{204}\text{Pb}$ age of 19.1 ± 3.7 Ma and a $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{235}\text{U}/^{204}\text{Pb}$ age of 22.9 ± 9.1 Ma, with initial $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values of -6 ± 14 and 13.9 ± 1.6 , respectively (Fig. 11B1–B6). Sub-cluster II(A2) yields similar $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{238}\text{U}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{235}\text{U}/^{204}\text{Pb}$ ages of 20.18 ± 0.49 and 23.4 ± 3.3 Ma, respectively, with initial $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios of 15.3 ± 1.6 and 15.32 ± 0.52 , respectively (Fig. 11B1–B6). Finally, the Cluster III samples (barring the excluded data discussed above) yield a $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{238}\text{U}/^{204}\text{Pb}$ age of 4.73 ± 0.78 Ma and a $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{235}\text{U}/^{204}\text{Pb}$ age of 7.38 ± 0.88 Ma, with initial $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values of 142 ± 81 and 20.8 ± 4.2 , respectively (Fig. 11C1–C4).

Finally, the high common Pb contents and variations in initial $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values indicate that $^{206}\text{Pb}/^{238}\text{U}$ versus $^{207}\text{Pb}/^{235}\text{U}$ concordia ages derived without considering common Pb and correcting initial Pb isotopes are erroneous. As such, $^{206}\text{Pb}/^{238}\text{U}$ versus $^{207}\text{Pb}/^{235}\text{U}$ concordia diagrams are not employed in this study.

6.4. Groundwater characteristics

The basic characteristics of groundwater include temperature, pH, Eh, CON, TDS, salinity, and DO, all of which are given in Appendix A along with sample descriptions including location

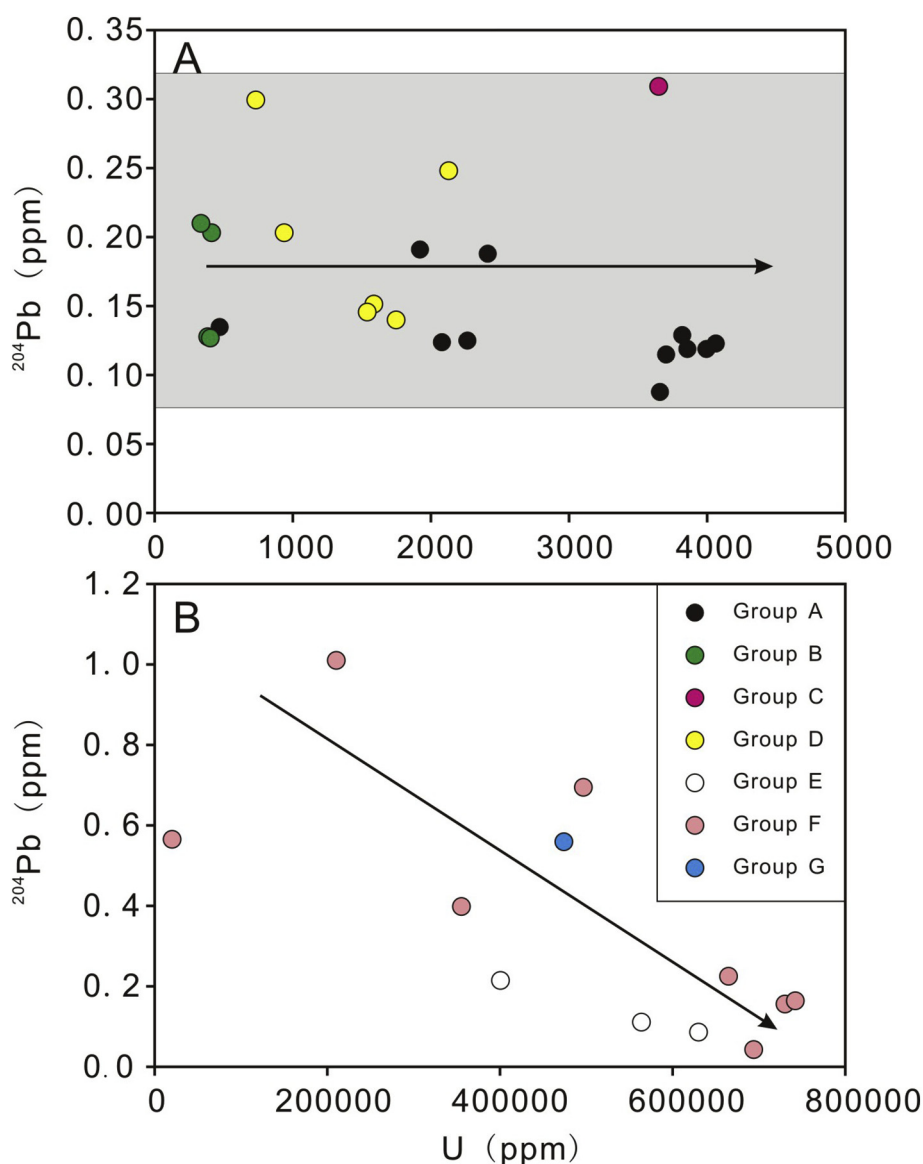


Fig. 9. U versus ^{204}Pb diagrams for ores (A) and handpicked pitchblende (B) within samples from the southern Yili uranium district.

descriptors such as cold spring, upstream and midstream river, groundwater from oxidation zone, redox zone (close to the ore-body), or reduced zones (Appendix A; Fig. 12).

The majority of these water samples have pH values of 6.89–9.57 that indicate they are generally alkaline waters, barring one sample with a pH of 11.06 that reflects the slightly alkaline property of the meteoric water in the Yili region (Appendix A; Wang et al., 2009a). The groundwater in this area yields TDS values that are controlled by sampling location, with a minimum TDS value of 132.9 ppm derived from a sample in the upstream part of the Thajistan river and close to a cold spring, reflecting dilution by surface flows of glacial meltwater. Surficial waters in the study area have TDS values of 132.9–666 ppm, whereas groundwaters have values of 610–1362 ppm. The higher TDS of groundwater probably reflects water–rock interaction between the groundwater and the hosting sandstone that contains soluble salts.

The surficial water and groundwater within and around the Mengqiguer deposit show characteristic Eh and DO variations. The Eh (ORP) values of the surficial waters are generally >100 mV, with DO values >8 ppm (Fig. 12). After this surficial water seeps into the

mineralized sandstone, the resulting groundwater undergoes a significant drop in Eh and DO values to less than –5 mV and <6 ppm, respectively, barring individual samples with values of 168.6 mV and 6.69 ppm. The lowest Eh and DO values are from the reduction zone, where samples yield values of –315.6 mV and 2.4 ppm, respectively.

6.5. Groundwater ion compositions

The groundwater Fe, Al, and U ion contents around the Mengqiguer deposit are listed in Appendix B based on location (Fig. 12). These groundwaters have anion contents dominated by HCO_3^{3-} and SO_4^{2-} species, and cation contents dominated by Na^+ and Ca^{2+} , with very low F^- and CO_3^{2-} contents. The flow path between the cold spring and the groundwater in the reduced zone yields variations in ion compositions that can be divided into three classes, namely Class I waters that contain F^- , CO_3^{2-} , K^+ , and HCO_3^- , Class II waters that only contain Fe, and Class III waters that contain all the other ion species listed in Appendix B.

The Class I fluids have generally consistent ion contents along

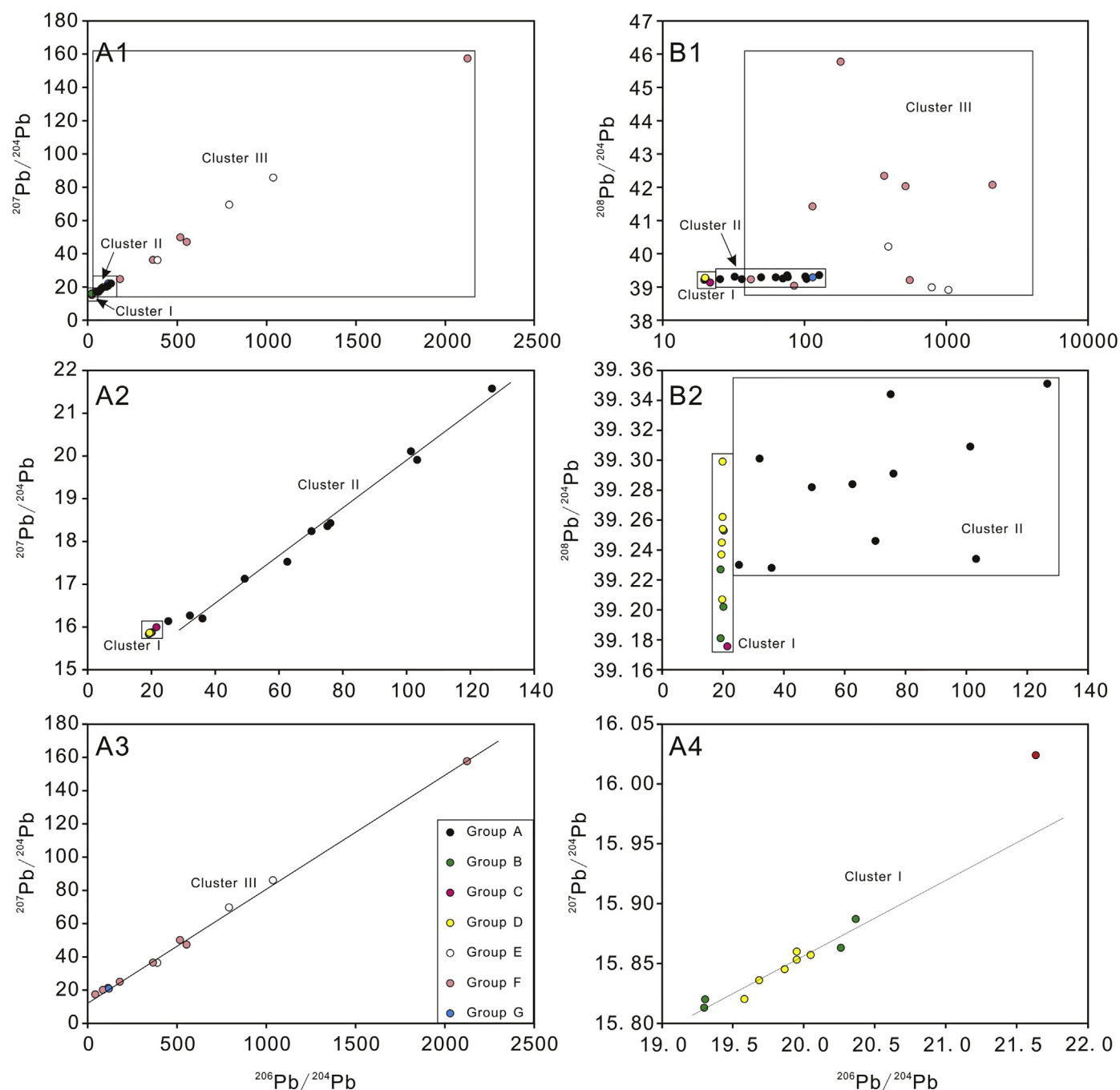


Fig. 10. $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams for ores and handpicked pitchblende samples from the study area. The data in the $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams are divided into three general clusters, where Cluster I includes Group B–D samples, Cluster II corresponds to Group A samples, and Cluster III contains Group E–G samples. Each of these clusters defines a linear trend. Clusters I and II have similarly constant $^{208}\text{Pb}/^{204}\text{Pb}$ ratios, whereas Cluster III has variable $^{208}\text{Pb}/^{204}\text{Pb}$ ratios.

their flow path, although these fluids contain low concentrations of F^- and CO_3^{2-} . The Class III fluids record variations (Fig. 12) that reflect three stages of evolution. Stage I represents a decrease in ion contents as a result of dilution of cold spring waters by river water that is derived mainly from glacial meltwater. In comparison, stage II records an increase as a result of water–rock interaction between groundwater and clastic rocks, whereas stage III records a decrease in ion contents as a result of flow through the redox zone containing the U orebodies. The Class II fluids can also be divided into three evolutionary stages, with stages II and III being similar to those recorded by Class III fluids, although the Class II fluids show a stage I involving an increase in Fe contents, the opposite to that

recorded in the Class III stage I fluids.

Fluid Cl^-/F^- ratios vary along the flow path from the cold spring (29.7–647.6), through the upstream (131.4) and midstream (2.3–12.1) parts of the rivers to the oxidation zone (16.3–118.6), the redox zone (close to the orebody; no data), and finally into the reduced zone (89.3). These different zones yield $\text{HCO}_3^-/(\text{NO}_3^- + \text{SO}_4^{2-})$ ratios of 0.8–5.5, 2.2, 3.6–25.1, 1.0–6.0, 0.3–0.9, and 2.1–7.1, respectively. In addition, the fluids in these areas have Na^+/K^+ ratios of 18.0–150.3, 54.5, 12.4–37.8, 16.4–150.4, 140.6–762.2, and 45.9–50.9, respectively. Finally, they have $\text{Ca}^{2+}/\text{Mg}^{2+}$ ratios of 0.9–6.0, 3.2, 3.7–4.6, 1.8–3.3, 1.6–2.5, and 2.9–4.0, respectively. Anion budgets can be represented by

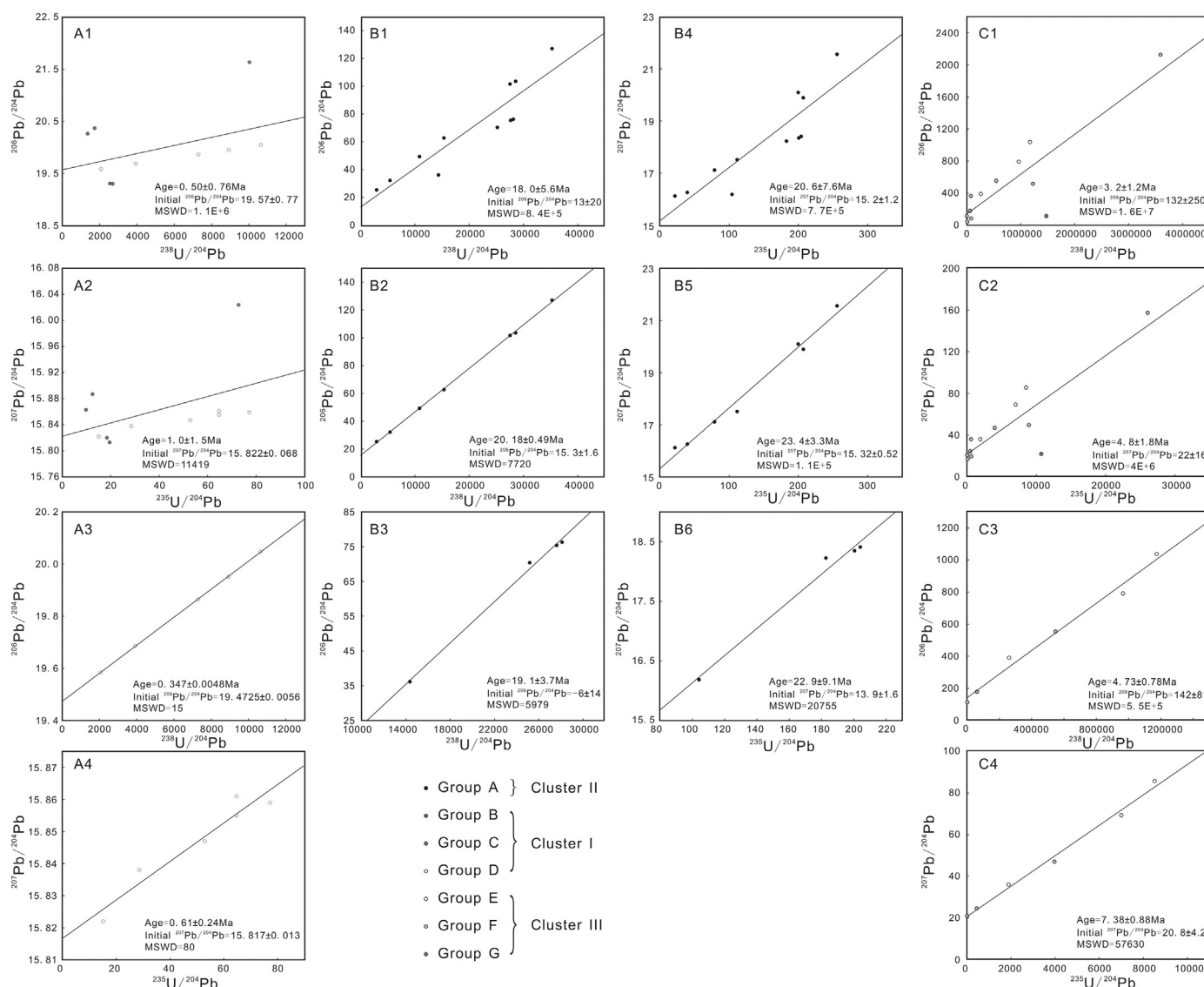


Fig. 11. $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{238}\text{U}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{235}\text{U}/^{204}\text{Pb}$ diagrams for Clusters I–III. A1–A4. Cluster I samples define linear trends that yield meaningful ages once invalid data are excluded (Groups B and C). B1–B6. This cluster (II) can be divided into two sub-clusters (here named Sub-clusters A1 and A2), each of which defines a linear trend and yields a meaningful age. C1–C4. This cluster (III) does not define a linear trend and yields variable ages once invalid data are excluded.

$\sum(\text{F}^- + \text{Cl}^- + \text{NO}_3^- + 2\text{SO}_4^{2-} + 2\text{CO}_3^{2-} + \text{HCO}_3^-)$ values, which for the zones outlined above are 5.5–16.5, 5.0, 2.9–5.5, 4.7–6.9, 14.2–32.2, and $3.7\text{--}6.0 \times 10^{-3}$ mol/L, respectively. Finally, cation budgets can be represented using $\sum(\text{Na}^+ + \text{K}^+ + 2\text{Mg}^{2+} + 2\text{Ca}^{2+})$ values, which for the zones outlined above are 8.1–26.2, 7.3, 3.5–5.6, 5.4–9.4, 18.7–48.8, and $4.2\text{--}7.6 \times 10^{-3}$ mol/L, respectively (Fig. 13; Table 2). (See Tables 3 and 4.)

7. Discussion

7.1. Timing of mineralization within the southern Yili uranium district and geological significance

The pitchblende and ores dated during this study contained significant amounts of common Pb during their formation, as evidenced by their non-radiogenic ^{204}Pb isotopic compositions (Fig. 9). This common Pb must be considered during $^{238}\text{U}/^{206}\text{Pb}$ and $^{235}\text{U}/^{207}\text{Pb}$ dating. As such, we analyzed mineralized samples to obtain isochrons, an approach that can yield age solutions for

simply disturbed systems without explicit knowledge of the common Pb isotope composition of the samples in question (Levchenkov and Shukolyukov, 1970; Neymark and Levchenkov, 1979; Wendt, 1984). The U-Pb isotopic data of the ores from the study area were obtained by whole-rock analysis, meaning these samples also contain detrital minerals such as quartz, feldspar, biotite, and clays, all of which means that the initial Pb ratios (i.e., common Pb) of these samples might not be homogeneous if these samples have only been weakly hydrothermally altered.

The dominant type of U mineralization is disseminated mineralization hosted by sandstones with a matrix containing permeable clay minerals and hematite. Scanning electron microscope (SEM) imaging indicates that the U minerals in these samples are either coffinite aggregates (~5 μm in diameter; Fig. 8) or uraninite spheres (~5–10 μm in diameter; Min et al., 2001), both of which are coated by highly permeable clay minerals and impermeable hematite (Fig. 8). Consequently, these ores have moderate permeabilities. In addition, the mineralized sandstones contain groundwater that flows at 0.01–0.11 m per day (Lin et al., 2017). These petrological

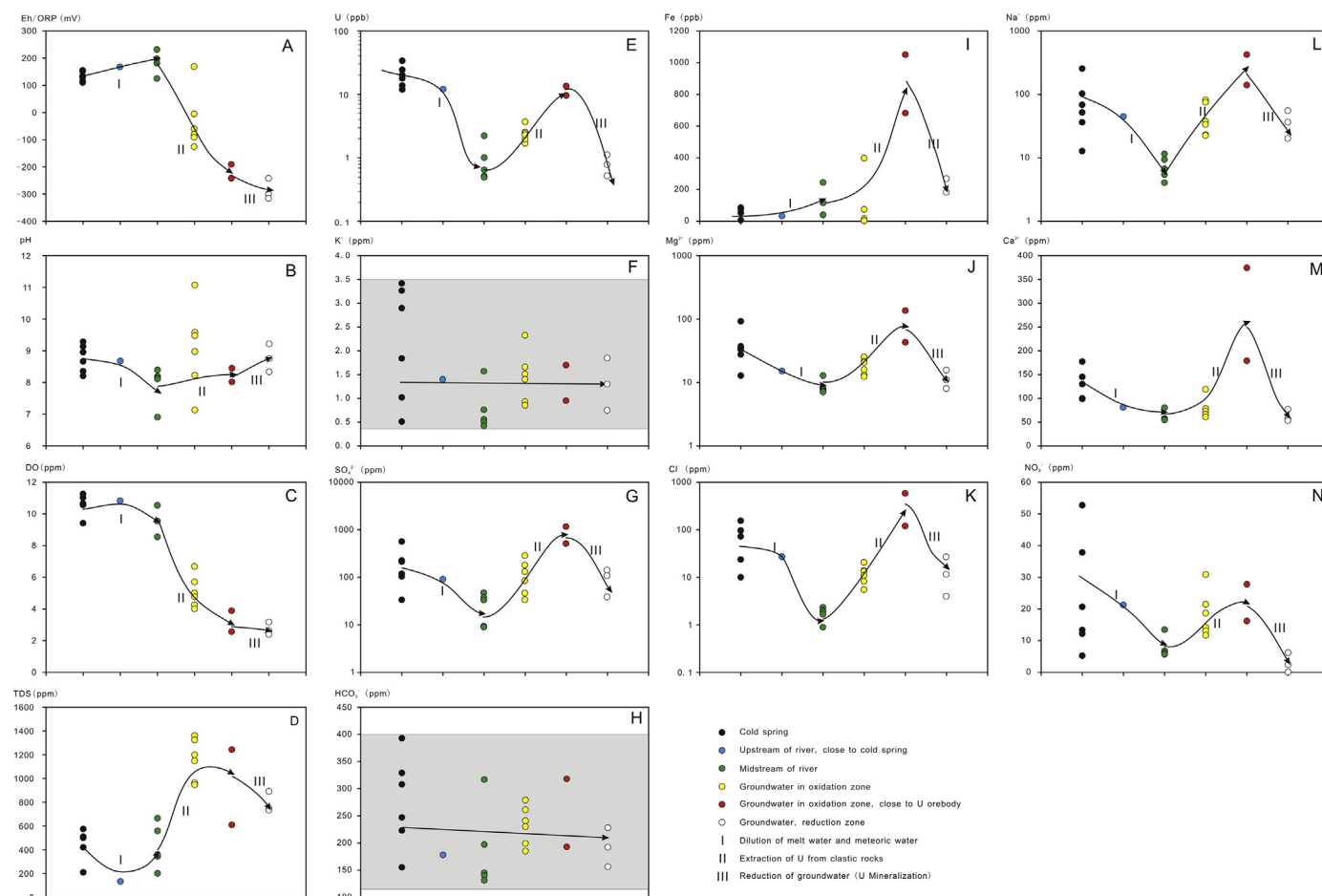


Fig. 12. Diagrams showing the basic characteristics, main ion species, and U and Fe concentrations within cold springs, river water, and groundwater within the Menggiquer deposit. A. Variations in Eh (shown as oxidation–reduction potential; ORP) in mV. B. Variations in pH. C. Variations in dissolved oxygen (DO) concentrations in ppm. D. Variations in total dissolved solid (TDS) concentrations in ppm. E. Variations in U concentrations in ppm. F. Variations in K^+ concentrations in ppm. G. Variations in SO_4^{2-} contents in ppm. H. Variations in HCO_3^- contents in ppm. I. Variations in Fe contents in ppb. J. Variations in Mg^{2+} contents in ppm. K. Variations in Cl^- contents in ppm. L. Variations in Na^+ contents in ppm. M. Variations in Ca^{2+} contents in ppm. N. Variations in NO_3^- contents in ppm.

and hydrological data indicate that the U minerals in this area (especially pitchblende) could have been affected after their formation by flowing groundwater, primarily as U^{6+} is highly soluble in oxidizing, carbonate-bearing groundwaters and low-temperature hydrothermal fluids. These processes can therefore either increase or decrease the U–Pb ages of these samples. In addition, the high permeability and loosely consolidated nature of the ore-bearing sandstones might have enabled the long-term continuous leakage of one or more of the radioactive daughters of ^{238}U (i.e., ^{222}Rn and ^{226}Ra), potentially forming a geochemical halo around the uranium deposits (e.g., Granger, 1963; Holliger et al., 1989). This would have lowered the U–Pb ages of these deposits even without significant U loss. This can explain the U–Pb isotopic data for hand-picked pitchblende obtained during this research; consequently, an in situ approach to pitchblende analysis was not used in the present study.

If young uranium ores (e.g., those within the Southern Yili Basin) have not undergone uranium migration, then any lead and/or radioactive daughters lost from the pitchblende might have been trapped by surrounding material, meaning that the whole-rock geochronological analysis of these samples is likely to yield meaningful results. The main requirement of this open-system type of dating is that the lead lost by the U minerals is similar to the lead gain by the surrounding materials (i.e., mass balance; Ludwig, 1978; Ludwig et al., 1980). As such, we selected ores that have undergone

little deformation, minimal loss of radiogenic daughter products, are high grade, and are surrounded by *syn*-ore calcite or hematite in order to minimize any loss of lead from the samples.

Sandstone-type uranium deposits form under relatively low-temperature conditions, meaning they contain submicroscopic uraninite that is finely intergrown with gangue minerals (i.e., galena, pyrite), yielding very high surface contact areas. The ores in the study area contain 0.1–0.3 ppm common ^{204}Pb , with these relatively uniform concentrations indicating a relatively stable abundance of common Pb. However, the handpicked pitchblende shows increasing U concentrations (representing increasingly successful removal of gangue minerals during handpicking) that negatively correlate with ^{204}Pb concentrations, suggesting the latter is hosted by the gangue minerals in the ores (Fig. 9). In addition, although the uraninites in these ores contain extremely low concentrations of common Pb, they cannot be used for in situ dating (Li et al., 2003, 2007, 2009a, 2009b, 2009c, 2010a, 2010b; Kazumasa et al., 2015; Liu et al., 2015; Lu et al., 2015; Matthew et al., 2015) because the extremely large contact area between the uraninite and the surrounding gangue means that the crystallographically incompatible daughter Pb (^{206}Pb and ^{207}Pb) within uraninite or even the ^{208}Pb within clastic minerals could have undergone continuous diffusion into the surrounding gangue material (Ludwig, 1978; Ludwig et al., 1980, 1984; Ludwig and Simmons, 1992). This means that purifying the uraninite in these samples

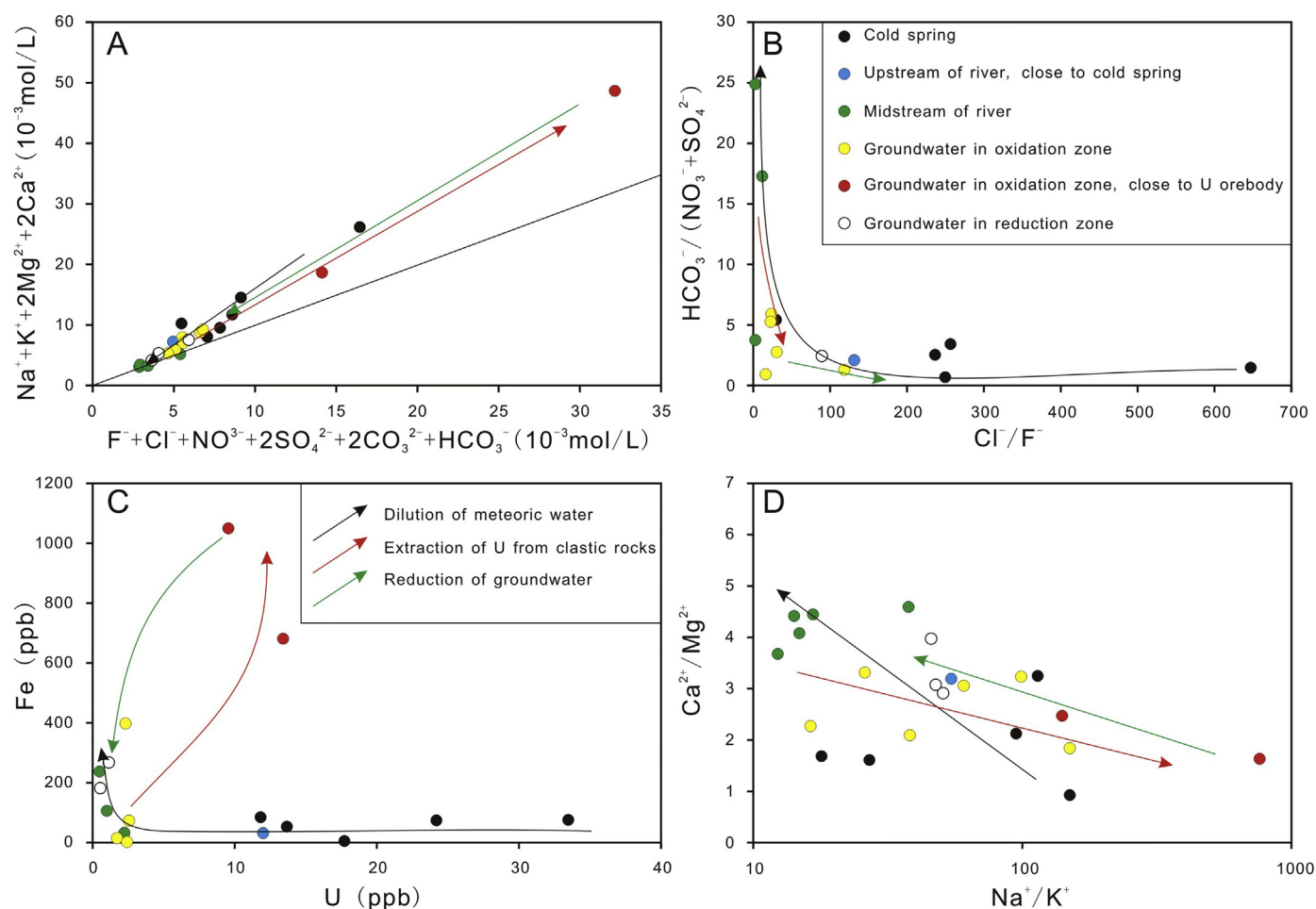


Fig. 13. Diagrams of groundwater $\sum(F^- + Cl^- + NO_3^- + 2SO_4^{2-} + 2CO_3^{2-} + HCO_3^-)$ versus $\sum(Na^+ + K^+ + 2Mg^{2+} + 2Ca^{2+})$, Cl^-/F^- versus $HCO_3^-/(NO_3^- + SO_4^{2-})$, U versus Fe, and Na^+/K^+ versus Ca^{2+}/Mg^{2+} , showing the geochemical evolution of groundwater along flow paths in the study area.

would also remove significant amounts of radiogenic Pb, as evidenced by the much lower U–Pb dates obtained from handpicked pitchblende samples relative to whole-rock analysis of ores

(Fig. 11). This is another reason why an in situ U–Pb dating approach was not used during this study. However, the handpicked pitchblende samples generally define the same linear trend in Pb

Table 2

Basic characteristics of surface and groundwater within and around the Mengqiguer uranium deposit.

Sample no.	Location	T (°C)	pH	Eh (ORP)	CON (μs/cm)	TDS (ppm)	DO (%)	DO (ppm)
SY-1	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	8.2	9.12	110.3	421	210	87.6	11.27
SY-3	Cold spring, south of Mengqiguer deposit, flow into Mengqiguer river	8.5	8.34	151.7	1013	506	80.4	10.57
SY-5	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	7.9	8.65	133.8	843	420	92.5	10.6
SY-7	Cold spring, SW of Mengqiguer deposit, flow into Mengqiguer river	8.3	8.19	114.6	996	500	88.6	9.42
SY-15	Cold spring, south of Mengqiguer deposit, flow into Mengqiguer river	8.5	9.27	155.2	1018	510	91.3	10.67
SY-20	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	8	8.94	129.4	1149	575	90.7	11.04
SY-16	Thajistan river, upstream, SW of Mengqiguer deposit, close to cold spring	12.2	8.66	167.6	265.7	132.9	93.5	10.84
SY-17	Thajistan river, midstream, SW of Mengqiguer deposit, seep into Jurassic sandstone	13.9	8.12	181.1	719	360	88.7	9.56
SY-2	Thajistan river, midstream, SW of Mengqiguer deposit, seep into Jurassic sandstone	14.9	8.38	125	404	202	85.8	8.56
SY-10 (E)	Mengqiguer river, upstream, close to cold spring	18.5	8.18	197.3	1332	666	94	9.54
SY-10 (W)	Mengqiguer river, upstream, close to cold spring	17.4	6.89	125.6		344	94.7	
SY-11	Mengqiguer river, midstream, south of Mengqiguer deposit, seep into Jurassic sandstone	16.5	8.09	231.5	1118	559	98.4	10.55
SY-4	Groundwater, oxidation zone	14	11.06	168.6	1897	948	35.6	4.01
SY-6	Groundwater, oxidation zone	16.8	7.11	–5	2563	1326	44.7	4.78
SY-8	Groundwater, oxidation zone	23	9.46	–90.8	2300	1151	66.8	6.69
SY-9	Groundwater, oxidation zone	17.9	8.21	–125.7	2409	1200	48.5	4.26
SY-13	Groundwater, oxidation zone	20.4	9.57	–60.4	1927	965	62.1	5.71
SY-22	Groundwater, oxidation zone	15.8	8.96	–80.1	2715	1362	53.4	5.02
SY-19	Groundwater, close to orebody	13.8	8.43	–190.5	1218	610	34.7	3.89
SY-21	Groundwater, close to orebody	23.6	8	–241.9	2481	1244	30.3	2.57
SY-12	Groundwater, reduction zone	15	8.32	–242.4	1791	892	31.4	2.65
SY-14	Groundwater, reduction zone	19	9.2	–300.4	1473	735	30.9	3.17
SY-18	Groundwater, reduction zone	17.6	8.74	–315.6	1502	749	28.6	2.4

Abbreviations are as follows: ORP = oxidation–reduction potential, CON = electrical conductivity, TDS = total dissolved solids, DO = dissolved oxygen.

Table 3

Ion and gas compositions of surface and groundwater within and around the Mengqiguer uranium deposit.

Sample no.	Location	F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	CO ₃ ²⁻	HCO ₃ ⁻	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Al	Fe	U
SY-1	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	0.163	72.09	37.85	33.6	—	155	52.2	3.27	36.5	98.5	16.2	85.0	11.82
SY-3	Cold spring, south of Mengqiguer deposit, flow into Mengqiguer river	0.330	154	52.8	568	—	329	257	2.90	93.0	145	10.3	74.7	24.2
SY-5	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	<0.05	23.65	20.7	213	14.4	223	12.8	0.51	12.9	129.9	5.89	—	19.48
SY-7	Cold spring, SW of Mengqiguer deposit, flow into Mengqiguer river	0.060	72.6	13.4	225	—	247	103	1.84	27.8	98.8	2.50	53.2	13.67
SY-15	Cold spring, south of Mengqiguer deposit, flow into Mengqiguer river	0.180	10.0	5.24	104	—	393	36.3	3.42	35.4	100	0.848	5.16	17.72
SY-20	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	0.200	96.0	12.2	119	—	308	68.7	1.02	32.7	177.4	—	76	33.48
SY-16	Thajistan river, upstream, SW of Mengqiguer deposit, close to cold spring	0.110	27	21.3	94	—	178	45	1.4	15.2	81	16.6	32	12
SY-17	Thajistan river, midstream, SW of Mengqiguer deposit, seep into Jurassic sandstone	<0.05	2.33	6.20	47.2	6.87	131	6.69	0.760	8.17	56.1	5.02	244	0.497
SY-2	Thajistan river, midstream, SW of Mengqiguer deposit, seep into Jurassic sandstone	0.206	0.889	13.5	33.2	5.83	140	4.04	0.480	7.33	54.6	18.7	—	0.650
SY-10 (E)	Mengqiguer river, upstream, close to cold spring	0.318	1.85	6.85	9.31	—	317	11.5	1.57	12.9	80.2	2.46	39.2	2.23
SY-10 (W)	Mengqiguer river, upstream	<0.05	1.66	6.03	37.5	7.18	145	5.43	0.550	7.66	57.5	2.72	—	0.519
SY-11	Mengqiguer river, midstream, south of Mengqiguer deposit, seep into Jurassic sandstone	0.090	2.03	5.62	8.96	—	197	9.37	0.420	7.10	55.0	2.78	115	1.01
SY-4	Groundwater, oxidization zone	0.125	5.51	14.2	46.5	—	261	33.3	0.930	13.1	66.9	3.72	—	3.69
SY-6	Groundwater, oxidization zone	0.060	13.3	18.7	181	—	185	81.9	1.40	12.5	67.5	2.24	—	1.98
SY-8	Groundwater, oxidization zone	0.190	8.21	21.5	33.9	—	230	22.5	2.33	16.0	60.8	3.77	2.13	2.42
SY-9	Groundwater, oxidization zone	0.190	10.9	30.9	85.0	—	241	37.5	1.66	20.8	72.8	0.266	73.3	2.55
SY-13	Groundwater, oxidization zone	0.450	13.7	11.7	287	—	199	75.4	0.850	25.5	78.5	—	14.7	1.70
SY-22	Groundwater, oxidization zone	<0.05	20.6	13.1	132	—	279	23.2	1.51	21.5	119	—	398	2.30
SY-19	Groundwater, close to orebody	<0.05	583	27.8	1170	—	193	427	0.950	137	375	—	1051	9.54
SY-21	Groundwater, close to orebody	<0.05	119	16.2	514	—	318	141	1.70	43.3	179	—	682	13.4
SY-12	Groundwater, reduction zone	0.160	26.7	0.070	141	—	228	55.5	1.85	15.8	76.9	0.159	182	0.524
SY-14	Groundwater, reduction zone	<0.05	3.98	2.44	38.7	—	192	20.3	0.750	8.05	53.4	—	—	0.787
SY-18	Groundwater, reduction zone	<0.05	11.5	6.21	108	—	156	36.6	1.30	11.1	57.0	—	268	1.12

Al, Fe, and U concentrations are in ppb, with all other concentrations in ppm.

isotopic space as the ores, suggesting that radiogenic ²⁰⁶Pb and ²⁰⁷Pb were removed in equal proportions and the ores have not undergone any long-term, continuous leakage of one or more of the radioactive daughters of uranium.

The half-lives of the radioactive daughters of ²³⁸U are orders of

Table 4

Compilation of Cl⁻/F⁻, HCO₃⁻/(NO₃⁻ + SO₄²⁻), Na⁺/K⁺, and Ca²⁺/Mg²⁺ ratios and $\sum \text{Na}^+ + \text{K}^+ + 2\text{Mg}^{2+} + 2\text{Ca}^{2+}$, $\sum \text{F}^- + \text{Cl}^- + \text{NO}_3^- + 2\text{SO}_4^{2-} + 2\text{CO}_3^{2-} + \text{HCO}_3^-$ values for waters within the southern Yili uranium district.

Sample no.	Cl ⁻ /F ⁻	HCO ₃ ⁻ /(NO ₃ ⁻ + SO ₄ ²⁻)	Na ⁺ /K ⁺	Ca ²⁺ /Mg ²⁺	F ⁻ + Cl ⁻ + NO ₃ ⁻ + 2SO ₄ ²⁻ + 2CO ₃ ²⁻ + HCO ₃ ⁻	Na ⁺ + K ⁺ + 2Mg ²⁺ + 2Ca ²⁺
SY-1	236.7	2.6	27.1	1.6	5.5	10.3
SY-3	249.8	0.8	150.3	0.9	16.5	26.2
SY-5	—	1.4	42.6	6.0	7.1	8.1
SY-7	647.6	1.6	94.9	2.1	8.7	11.8
SY-15	29.7	5.5	18.0	1.7	7.9	9.6
SY-20	256.9	3.5	114.2	3.3	9.2	14.6
SY-16	131.4	2.2	54.5	3.2	5.0	7.3
SY-17	—	3.6	14.9	4.1	2.9	3.8
SY-2	2.3	4.1	14.3	4.5	3.0	3.5
SY-10 (E)	3.1	25.1	12.4	3.7	5.5	5.6
SY-10 (W)	—	4.9	16.7	4.5	3.0	3.8
SY-11	12.1	17.6	37.8	4.6	3.5	3.8
SY-4	23.6	6.0	60.7	3.1	5.2	5.9
SY-6	118.6	1.4	99.2	3.2	5.6	8.0
SY-8	23.1	5.4	16.4	2.3	4.7	5.4
SY-9	30.7	2.9	38.3	2.1	5.7	7.0
SY-13	16.3	1.0	150.4	1.8	6.9	9.4
SY-22	—	2.9	26.1	3.3	6.7	8.8
SY-19	—	0.3	762.2	1.6	32.2	48.8
SY-21	—	0.9	140.6	2.5	14.2	18.7
SY-12	89.3	2.5	50.9	2.9	6.0	7.6
SY-14	—	7.1	45.9	4.0	3.7	4.2
SY-18	—	2.1	47.7	3.1	4.1	5.4

$\sum \text{F}^- + \text{Cl}^- + \text{NO}_3^- + 2\text{SO}_4^{2-} + 2\text{CO}_3^{2-} + \text{HCO}_3^-$ and $\sum \text{Na}^+ + \text{K}^+ + 2\text{Mg}^{2+} + 2\text{Ca}^{2+}$ values are in 10⁻³ mol/L; ratio calculations use values in mol/L.

magnitude greater than those of the daughter products of ²³⁵U decay, meaning that radioactive daughter leakage would preferentially lower ²³⁸U/²⁰⁶Pb ages relative to ²³⁵U/²⁰⁷Pb ages. As such, this study focuses on ²³⁵U/²⁰⁷Pb ages rather than ²³⁸U/²⁰⁶Pb ages, given the lesser potential effect on the latter relative to the former. Plotting the data for the three clusters on ²³⁸U/²⁰⁴Pb versus ²⁰⁶Pb/²⁰⁴Pb and ²³⁵U/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb diagrams yields seemingly meaningful ages with variable MSWD (mean standard weighted deviation) values (Fig. 11). The MSWD values for the ²³⁸U/²⁰⁴Pb versus ²⁰⁶Pb/²⁰⁴Pb diagrams are much smaller than those for the ²³⁵U/²⁰⁴Pb versus ²⁰⁷Pb/²⁰⁴Pb diagrams, suggesting the ²³⁸U-²⁰⁶Pb ages of these samples are more precise than their ²³⁵U-²⁰⁷Pb ages. However, the ²³⁸U/²⁰⁶Pb ages of the samples are younger than the ²³⁵U/²⁰⁷Pb ages, suggesting that the samples have lost more ²³⁸U radioactive daughter nuclides than ²³⁵U. In addition, the formation of the U mineralization within the sandstone might have spanned a period of time until the sealing of the porosity within the sandstone by calcite or hematite cementation changed the system from open to closed. However, the continuous leakage of one or more of the radioactive daughters of uranium (Granger, 1963) must have occurred prior to closure of the system, given the younger ²³⁸U/²⁰⁶Pb ages compared with the ²³⁵U/²⁰⁷Pb ages. As such, we suggest that the ²³⁸U/²⁰⁶Pb ages represent the final sealing of the system, and the ²³⁵U/²⁰⁷Pb ages represent the timing of deposit formation. The samples from the study area contain much less ²³⁵U than ²³⁸U as well as much less radiogenic ²⁰⁷Pb than radiogenic ²⁰⁶Pb. Therefore, the ²³⁵U/²⁰⁷Pb values might have become more variable than the ²³⁸U/²⁰⁶Pb values during later interaction with groundwater passing through the system, which could influence both MSWD values and the results of U-Pb dating. The small difference between the ²³⁵U/²⁰⁷Pb and ²³⁸U/²⁰⁶Pb ages suggests that the age span between these two ages reflects the time taken for the system to close.

After unreliable samples had been excluded from the dataset (as discussed in Section 6.3), the remaining samples yielded two meaningful ages from 23.4 ± 3.3 to 20.18 ± 0.49 and 0.61 ± 0.24 to

0.347 ± 0.0048 Ma. There are two explanations for the presence of two stages of U mineralization: (1) the Southern Yili uranium district hosts at least two stages of uranium mineralization, as represented by the ~ 24 – 20 Ma Kujiertai deposit and the ~ 0.6 – 0.3 Ma Mengqiguer deposit, although the latter deposit continues to form, suggesting a third stage of ongoing mineralization at ~ 0 Ma; or (2) a single mineralizing event from 23.4 ± 3.3 to 20.18 ± 0.49 Ma was overprinted by a remobilizing and isotopic resetting event from 0.61 ± 0.24 to 0.347 ± 0.0048 Ma that affected the earlier-formed primary U ores. The latter explanation also involves the ongoing present destruction or modification (~ 0 Ma) of the primary U ores by interaction with groundwater.

The second model outlined above is commonly proposed for sandstone-type uranium deposits such as the deposits within the Ambrosia lake uranium district (Ludwig et al., 1982; Turner-Peterson and Fishman, 1986) and the Dongsheng uranium district (Zhang et al., 2018). This model requires that both primary and secondary ores are hosted by the same sedimentary units. In addition, the secondary ores should have higher initial $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ isotopic ratios than the primary ores, as the former should at least partially inherit the radiogenic Pb from the primary ores as common Pb. For example, the secondary ores within the Dongsheng uranium district have initial $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ values of 82.4 ± 6.2 and 18.0 ± 1.9 , respectively, whereas the primary ores have values of 68.9 ± 7.3 and 12.0 ± 2.2 , respectively (Zhang et al., 2018). Two stages of uranium mineral formation can also sometimes be observed in roll-shaped orebodies, such as those within the Dongsheng uranium district (Zhang et al., 2018). In comparison, the 23.4 ± 3.3 to 20.18 ± 0.49 Ma Stage I ores from the Kujiertai deposit within the Southern Yili uranium district are located >50 km from the 0.61 ± 0.24 to 0.347 ± 0.0048 Ma Stage II ores within the Mengqiguer deposit. In addition, the Stage I ores are located within the monoclinical Shuixigou Group, whereas the Stage II ores are located within the limbs of an anticline. These long distances and differences in geological setting indicate that the second model outlined above is not applicable to the study area. In addition, these two stages of mineralization yield similar initial Pb isotopic compositions, with Stage I and II ores having initial $^{207}\text{Pb}/^{204}\text{Pb}$ values of 15.32 ± 0.52 and 15.817 ± 0.013 , respectively, again contrasting with the second model outlined above. The marked decrease in the U contents of the groundwater as it passes through the mineralized redox zone suggests that the third stage of uranium modification (~ 0 Ma, Stage III) is ongoing, although this process requires the destruction or modification of primary ore (Stage II) and most likely resulted in the isotopic resetting of the U–Pb isotopic system, as evidenced by Cluster I (Fig. 11). The Southern Yili uranium district also contains a series of interlayered red or yellow oxidation zones with redox fronts that trend roughly ENE–WNW for tens of kilometers, although no secondary interlayer oxidation zones have been reported close to the orebodies, again supporting the first model outlined above.

The continuous northward penetration of the Indian Plate into the Asian Plate has caused extensive shortening-related deformation in Central Asia, with a significant part of this crustal shortening accommodated by the Tien Shan orogenic belt. In addition to the shortening-related deformation and crustal thickening, strain related to India–Asia collision might also have been accommodated by eastward and southeastward extrusion of South China and Indochina block, respectively (Tapponnier et al., 1982; Lee and Lawver, 1995; Bullen et al., 2003; Zhang et al., 2004; Fig. 1). The shortening-related deformation, crustal thickening, and uplift of the Tien Shan belt is divided into four stages associated with India–Asia collision (Harrison et al., 1992; Coleman and Hodges, 1995; Wang et al., 2015). Stage I (45–35 Ma) began after the initiation of continental collision. This stage resulted in crustal

shortening and uplift, and the generation of the proto-Tibetan Plateau (i.e., the Lhasa and Qingtang terranes) although it did not significantly influence the Tien Shan Orogen. Stage II (35–21 Ma) involved the expansion of the Tien Shan mountains by folding and thrusting northward and southward, as evidenced by fission track dating (Liu et al., 2004; Guo et al., 2006; Buslov et al., 2008; Chen et al., 2008; Lv et al., 2008a, 2008b). The Tien Shan mountains underwent initial episodic uplift during this stage (Liu et al., 2004; Chen et al., 2008), leading to the development of numerous faults and folds within Jurassic units in the southern flank of the Yili Basin. This rapid uplift is also evidenced by Pliocene sediments that unconformably overlie Cretaceous sediments within the southern Yili Basin, indicating that rapid uplift began before the Miocene. Stage III occurred after the cessation of Indochina block extrusion, causing the Tien Shan mountains to undergo quasi-synchronous Miocene deformation and uplift (21–18 Ma, Harrison et al., 1992; 23–15 Ma, Wang et al., 2015). This stage also probably involved the initial collision between the Pamir and southwestern Tien Shan blocks (Liu et al., 2017). The Indian subcontinent has continued to move northwards since the late Miocene (Stage IV, 8–0 Ma, Wang et al., 2015; ~ 3 – 0 Ma, Liu et al., 2017), causing the extension of the proto-Tibetan Plateau into the present-day Himalaya and the Qilian Orogen, and leading to the final rapid uplift of the Tien Shan region. Present-day global positioning system (GPS) measurements indicate that approximately north–south shortening is still occurring across the entire Tien Shan region, although this shortening decreases gradually from west to east (Abdrakmatov et al., 1996; Larson et al., 1999; Holt et al., 2000; Reigber et al., 2001; Yang et al., 2008). The rate of shortening is as high as ~ 20 mm yr $^{-1}$ in the western Tien Shan, nearly half of the total shortening rate within the overall India–Asia collision zone (Abdrakmatov et al., 1996; Reigber et al., 2001; Yang et al., 2008). This shortening generated numerous Cenozoic thrust faults and folds along the southern and northern piedmonts of the mountain ranges (Avouac et al., 1993; Yin et al., 1998; Allen et al., 1999; Burchfiel et al., 1999; Lin et al., 2003). This last abrupt post-Pliocene episodic uplift event is evidenced by the coarse-grained Xiyu Formation sediments, growth-related sedimentary units within the southwest Tarim Basin (Chen et al., 2002b; Heermance et al., 2007; Liu et al., 2017), and fluvial river terraces within the piedmonts of the Tien Shan mountains (Xu et al., 1992; Molnar et al., 1994; Shi et al., 2004; Lv et al., 2008b). The fluvial-terrace abandonment ages for the northern piedmont of the Southern Tien Shan mountains indicate that the last episodic uplift of the Southern Yili Basin margin occurred in three sub-stages at ~ 600 (sub-Stage I), ~ 300 (sub-Stage II), and ~ 30 ka to the present day (sub-Stage III) (Xu et al., 1992; Molnar et al., 1994; Shi et al., 2004; Lv et al., 2008b). The current morphology of the western Tien Shan developed during this last stage of tectonism.

The tectonic uplift and exposure of basin margins allows the introduction of oxidizing groundwater to form roll-shaped U ore at or near oxidation fronts. This is the result of organic carbon and other minerals fixing the oxidation front as it progresses down-dip, with the resulting ore minerals and humate reducing the permeability of the sandstone (Hansley and Spirakis, 1992; Cuney and Kyser, 2008). The timing of mineralization within the Southern Yili district suggests that the U deposits in this area formed contemporaneously with uplift of the western Tien Shan mountains. The first stage of uranium mineralization within the Kujiertai deposit formed in the ENE-dipping Jurassic Shuixigou Group (Fig. 5), indicating that the U-bearing Shuixigou Group sediments must have been uplifted to be exposed within the northern foothills of the Tien Shan mountains before $\sim 23.4 \pm 3.3$ Ma (Fig. 11). In addition to the exposed southern margins of the Shuixigou Group, the considerable amount of U mineralization and associated oxidation zones present in this area require the introduction of significant volumes of oxidizing groundwater, suggesting that direct input of

meteoric water alone was insufficient to generate the mineralization. The uplift of the southern flank of the Yili Basin before the first stage of uranium mineralization suggests that the southern margin of the Shuixigou Group was exposed exactly at the northern base of the Tien Shan mountains. This allowed the relief of the Tien Shan mountains to channel meteoric water that was then introduced to the mineralized Shuixigou group. Two processes might have ended the first stage of uranium mineralization within the Kujiertai deposit: (I) continuous uplift resulted in migration of the southern margin of the Shuixigou Group away from the northern foot of the Tien Shan mountains, thereby ending the introduction of voluminous amounts of meteoric water; or (II) a marked drop in the permeability of the ore-bearing formation was caused by uranium mineralization, preventing the flow of U-bearing groundwater through the group as well as the injection of significant volumes of meteoric water. Li et al. (2002a) reported that the redox zone associated with the deposit contains more pyrite, organic matter, V-Se minerals, and hematite than oxidized zones in this area, suggesting that the introduction of this material caused a dramatic drop in permeability. This closure of the system also explains why the U-Pb ages for the ores are meaningful.

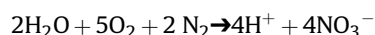
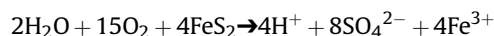
The western Tien Shan mountains expanded until the Pliocene as a result of the far-field influence of the continuous penetration of the Indian Plate into the Asian Plate, which activated reverse faults and folds within the piedmont of the Tien Shan mountains as well as causing the continuous uplift of the southern flank of the Yili Basin. The uranium mineralization within the Mengqiguer deposit is located within the limbs of an uplifted anticline and formed between 0.61 ± 0.24 and 0.347 ± 0.0048 Ma (Fig. 11). This suggests that the hinge zone of the fold and an associated reverse fault acted as a preferential conduit for the introduction of water (Figs. 6, 7), as evidenced by the distribution of oxidation zones. This second stage of mineralization occurred nearly 20 Myr after the first stage, suggesting that the uplift of the ore-controlling anticline occurred much later than the first stage of mineralization and was probably related to the post-Pliocene sub-stage I and II uplifts of the Tien Shan mountains. The Thajistan, Mengqiguer, and Langka rivers probably provided the oxidizing water involved in the genesis of the uranium mineralization at the Mengqiguer deposit, and supplied the fluids involved in the generation of the presently forming mineralization. >70% of this river water is derived from glacial meltwaters (Lin et al., 2017), meaning that the glaciers in the Tien Shan mountains represent the main source of ore-forming groundwater. This also indicates that alternating interglacial and glacial periods that result from climatic fluctuations are an important control on the genesis of the uranium mineralization within the Southern Yili district. The continuous injection of surface water into the mineralized Shuixigou Group was probably responsible for the U addition/loss and Ra (Pb) addition/loss within the Cluster I and II samples (Fig. 11; Cuney and Kyser, 2008).

7.2. Ongoing metallogenesis within the Southern Yili Uranium District and sources of U

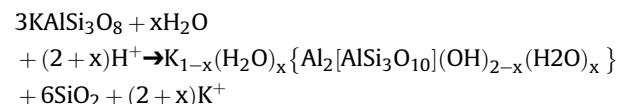
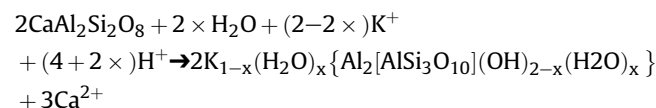
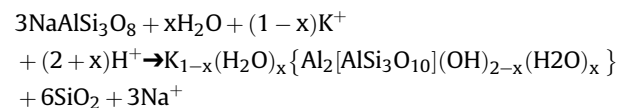
The cold springs derived from glaciers that contain 11.82–33.48 ppb U, much higher than the rivers in this area (Fig. 12; Appendix B). Cold springs in high-altitude mountains are generally derived from fractures that allow the flow of circulating glacial meltwater, suggesting that these meltwaters mobilized U from the basement rocks during circulation. Both Carboniferous–Permian

metamorphic volcanic rocks and Hercynian granites within the basement surrounding the southern Yili Basin are dominated by felsic rocks that are variably enriched in K, U, and Th (Barbarin, 1999; Konopelko et al., 2007; Li et al., 2009c, 2010b; Seltnmann et al., 2011). Bonnetti et al. (2017a) suggested that these igneous rocks represent a major source of uranium for the U deposits located within associated basins in northern China, as they contain U-bearing accessory minerals such as allanite and U-thorite that could release U during metamictization. Uranium mass balance calculations indicate that 1 km^3 of these U-rich igneous rocks could release more than ten thousand tonnes of U. The high U content within the cold springs supports this inference, as well as providing evidence of U transportation. Therefore, the basement material in the western Tien Shan could have contributed some of the U within the sandstone-type uranium mineralization in the southern Yili Basin.

The low U contents of the rivers in the study area suggest they dilute the higher U concentrations within the cold springs. This dilution reduces the concentrations of nearly all of the ions in these rivers (as well as U) except K^+ and HCO_3^- . This dilution also represents the addition of O_2 into the relatively reducing cold springs. However, this process negatively correlates with Fe concentrations (Fig. 12), probably reflecting the influence of suspended iron particles. The roughly constant HCO_3^- contents reflect the relatively high CO_2 contents of these waters, as the latter can react with H_2O to form H^+ and HCO_3^- . However, the constant K^+ concentrations probably reflect the extraction of these ions from the surrounding rocks, given the low K^+ content of meteoric water (Roy et al., 1999). This down-dip flowing section is characterized by an increase in the concentrations of nearly all of the ion species present, except K^+ and HCO_3^- (Fig. 12). This is also linked with the exhaustion of O_2 (Fig. 12), as evidenced by a decrease in Eh from 41.1 mV within the intensely oxidized zone to 18.9 mV within the redox zone (Li et al., 2002b). The coincident increases in SO_4^{2-} and NO_3^- contents suggest that the O_2 was transferred into acidic species during oxidation, as follows (Lowson, 1982; Pons et al., 1982):

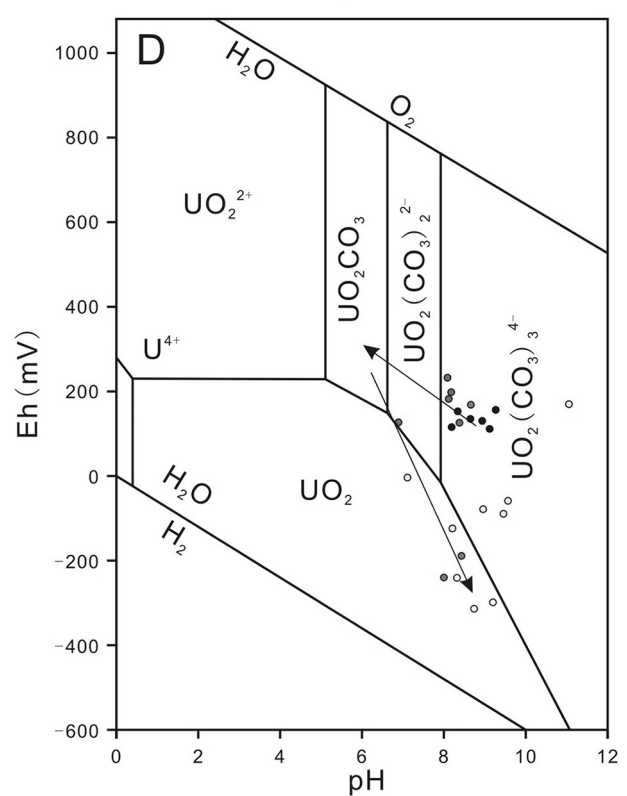
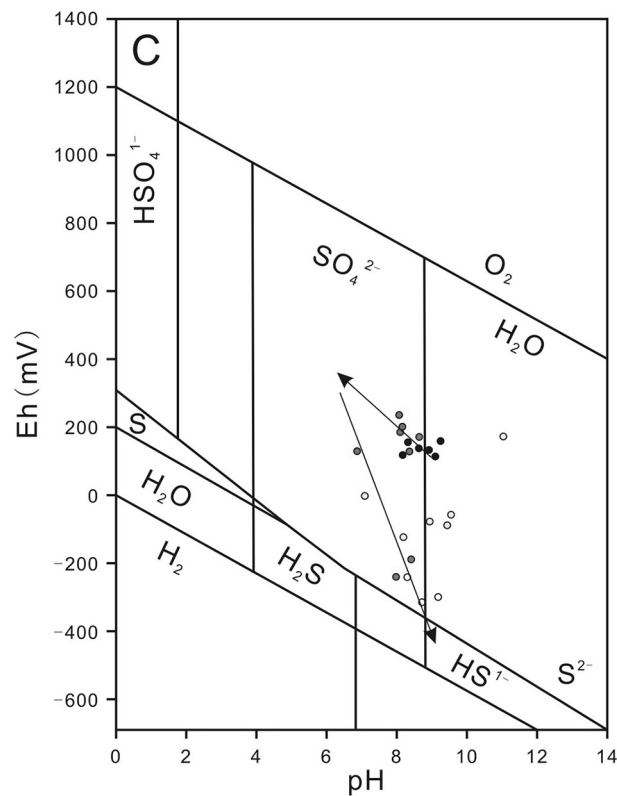
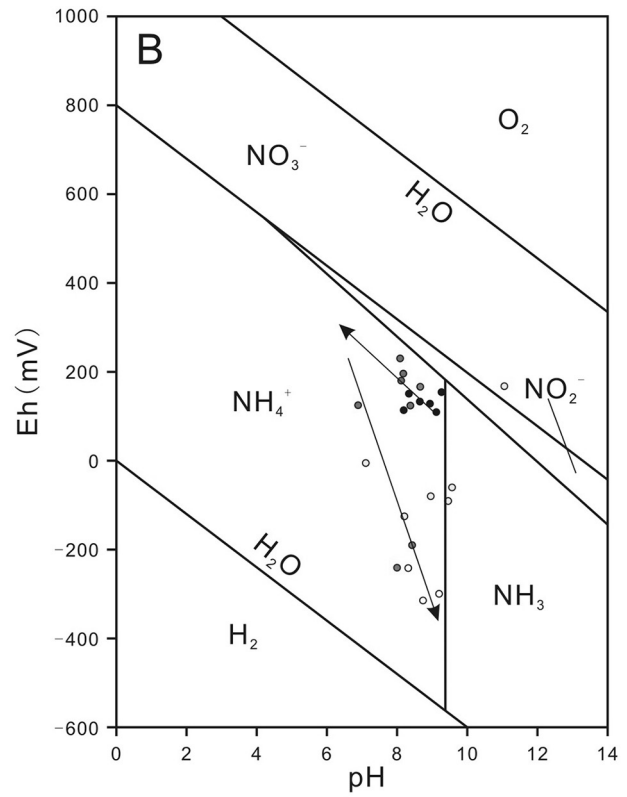
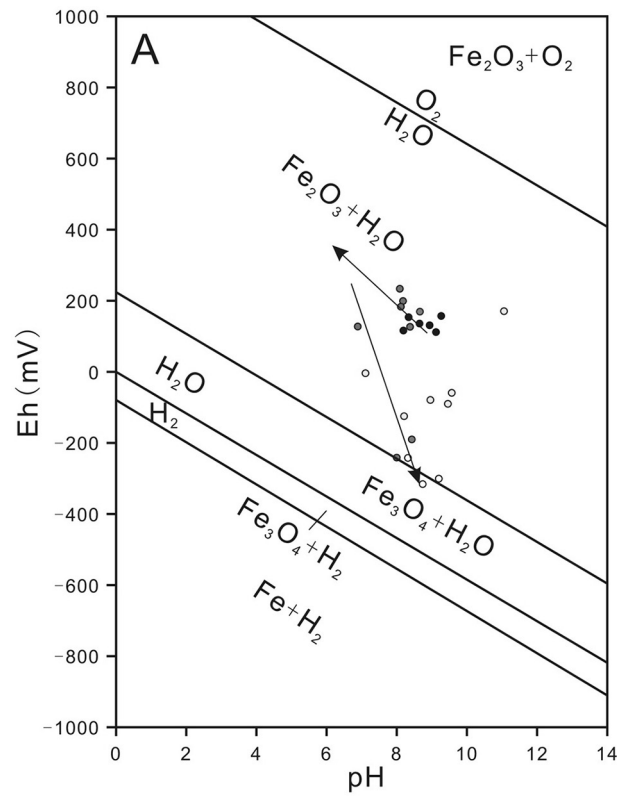


The resulting H^+ would then react with clastic plagioclase and minor K-feldspar, releasing Ca^{2+} , Na^+ , and K^+ into the groundwater as follows (Robb, 2005; Zhang et al., 2017a):



The hydrolysis of plagioclase would consume the K^+ present within the groundwater, although the hydrolysis of K-feldspar

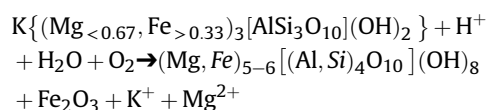
Fig. 14. pH versus Eh diagrams showing the transformation of major anion species and uranyl–carbonate species within groundwater flowing through the Mengqiguer deposit. A. The groundwater conditions within the Mengqiguer deposit mean that Fe_2O_3 is stable and some of the Fe^{3+} within the groundwater flowing into the redox and reduced zones changes to Fe^{2+} . B. The groundwater conditions within the Mengqiguer deposit mean that NO_3^- is not stable and changes to NH_4^+ . C. Some of the SO_4^{2-} within the groundwater moving into the redox and reduced zones becomes increasingly unstable and is converted into H_2S and HS^- . D. Groundwater flowing into the redox and reduced zones undergoes a conversion from unstable uranyl–carbonate complexes into UO_2 , which is subsequently deposited as pitchblende.



- Cold spring
- Upstream of river, close to cold spring
- ◐ Midstream of river
- Groundwater in oxidation zone
- Groundwater in oxidation zone, close to U orebody
- Groundwater in reduction zone

would conversely release K^+ . The roughly constant K^+ contents within the groundwater indicate the amount of K^+ consumed is roughly equal to the amount released. These hydrolysis processes would also increase the Ca^{2+} and Na^+ contents of the groundwater, as is evident in Fig. 12.

The increase in the Mg^{2+} content of the groundwater was the result of the oxidation of biotite, which produced chlorite and hematite within the oxidized sandstone as follows (Robb, 2005; Zhang et al., 2017a):



In addition, U was extracted from clastic minerals within the sandstone, as evidenced by the increase in U concentrations of the groundwater within the oxidation zone. This indicates that the sandstones through which the groundwater passed, prior to entering the mineralization-hosted redox zone, could have contributed significant U to the deposits. The movement of the U-enriched groundwater into the redox zone is associated with a dramatic decrease in U concentrations as well as a decrease in nearly all of the ion species present in the groundwater. This strongly suggests that the drop in U concentrations relates to the formation of U mineralization, indicating in turn that the Mengqiguer deposit is continuing to grow.

We assume that the groundwater prior to entering and after leaving the redox zone contained an average of 10 and 1 ppb U, respectively. A total of 50,000 t per day of groundwater is thought to flow through the Mengqiguer deposit, the majority of which would flow through the redox zone. This means that the deposit might be increasing in size by ~4.5 kg of U per day, suggesting that over 10,000 years the deposit could grow by an additional 15,000 t of U. Even if only 10% of this assumed growth actually occurs, this still represents rapid growth of the deposit, with around 15,000 t of U deposited over a period of 0.1 Myr. In addition, the measured U contents of surficial waters and groundwater in this area suggest that the U present within the river was derived from the basement of the Tien Shan. The increase in U contents of the groundwater before these waters entered the redox zone was the result of the mobilization of U from the ore-hosting sandstone. This result is important, as these data suggest that only ~10% of the U within the groundwater is derived from the Tien Shan basement (average U contents of midstream river/average U contents of groundwater close to the U orebody = 0.086), with the remaining 90% sourced from the ore-hosting sandstone. The initial $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ values of the ores also roughly indicate that the U in the deposit was derived from orogenic or upper crustal sources, even without a detailed analysis of the Tien Shan basement and the ore-hosting sandstone.

7.3. Uranyl complexes in groundwater and processes of mineralization

The Southern Yili uranium district contains groundwater with pH values of 6.89–9.57 (–6.90–8.40; Wang et al., 2009a) with the exception of a single sample with a pH value of 11.06. These data indicate the waters are weakly alkaline (Fig. 13A). The samples have cation total valences that are slightly higher than their total anion valences, suggesting the presence of OH^- to supplement the shortage of anions, as is typically the case for weakly alkaline waters. The low-temperature, weakly alkaline, and highly oxidizing nature of these fluids means that F^- , Cl^- , SO_4^{2-} , and NO_3^- anions will not form uranyl complexes, indicating in turn that the U in these fluids is transported as carbonate–uranyl complexes. This contrasts with the extremely

low CO_3^{2-} contents of the groundwater, seemingly ruling out the possibility of U transportation as carbonate–uranyl complexes. However, Long et al. (2015) reported that dissolved U(VI) species dominantly form carbonate–uranyl complexes in the presence of bicarbonate. These species are dominated by the uncharged calcium–uranyl tricarboxylate species $(Ca_2)UO_2(CO_3)_3^0$, which comprised some ~97% of the dissolved U, followed by $CaUO_2(CO_3)_3^{2-}$, $MgUO_2(CO_3)_3^{2-}$, and $UO_2(CO_3)_3^{4-}$ complexes (Fig. 14; Dong and Brooks, 2006; Stewart et al., 2007). This suggests that HCO_3^- plays an important role in the transportation of U within surficial waters in the southern Yili uranium district, as supported by the high concentrations of HCO_3^- within these waters. The groundwater within the southern Yili Basin is weakly alkaline, relatively reducing (Appendix A), and contains elevated concentrations of U that is most likely present as $Ca_2UO_2(CO_3)_3^0$ complexes, as the geochemical modelling of Tullborg et al. (2017) indicates that elevated concentrations of dissolved U can be stabilized as Ca–uranyl–carbonate complexes.

Min et al. (2001) identified the cell texture of fossil wood within the study area that contains pitchblende and coffinite, suggesting that the replacement of organic debris by primary uranium minerals may relate to the presence of a local reducing environment derived from the production of CH_4 , H_2S , or H_2SO_3 during decomposition, or as a result of biochemical reaction as evidenced by the presence of framboidal pyrite. Further research by Min et al. (2005a, 2005b) reported that the primary uraninite and coffinite within the high-grade ore samples were biogenically precipitated and occur as pseudomorphs after fungi and bacteria (Anderson et al., 2003; Williams et al., 2011). This again suggests that microorganisms played a key role in the generation of the uranium mineralization within the southern Yili uranium district. The presence of bicarbonate could have promoted the rate of microbial U(VI) reduction, induced by elevated concentrations of bicarbonate oxyanions (Abdelouas et al., 1998; Long et al., 2015).

Cai et al. (2007a) suggested that sulfate-reducing bacteria were likely to simultaneously reduce sulfates to sulfides during petroleum oxidization, indicating that this is a more important factor in the reduction of hexavalent uranium [U(VI)] to tetravalent uranium [U(IV)] than the preconcentration of U(VI) by adsorption and subsequent inorganic reduction (Caccavo Jr. et al., 1992; Lovley and Phillips, 1992; Francis et al., 1994; Tebo and Obratzsova, 1998; Wade and DiChristina, 2000; Cai et al., 2007b). However, the redox zones within the southern Yili uranium district contain more pervasive hematite development than pyrite, with the latter always being surrounded by the former. This records an ongoing change to more oxidizing conditions over time as a result of the injection of oxidized groundwater. This change mobilized massive amounts of Fe^{2+} from biotite and illite, with the Fe being oxidized to Fe^{3+} and deposited as Fe_2O_3 (Fig. 14A). The movement of the groundwater into the redox and reduction zones reduced some of the Fe^{3+} to Fe^{2+} , forming Fe_3O_4 or FeS_2 and resulting in lower Eh. The pH and Eh conditions of the groundwater within the Mengqiguer deposit indicate that SO_4^{2-} is stable, although the reduction of Eh values within the groundwater most likely transformed some SO_4^{2-} into HS^- (Fig. 14C). In addition, some of the NO_3^- within the groundwater was probably converted to NH_4^+ , as the pH and Eh conditions of the groundwater within the Mengqiguer deposit indicate that NO_3^- is not stable whereas NH_4^+ is stable (Fig. 14B). The uranyl–carbonate complexes ($UO_2(CO_3)_3^{4-}$, $UO_2(CO_3)_2^{2-}$, $UO_2CO_3^0$) within groundwater would also have been transformed into UO_2 and deposited as pitchblende that was finely intergrown with gangue minerals (Fig. 14D).

The O_2 contents of groundwater should be significantly reduced when uranyl-bearing fluids flow into ore-hosting sandstones, as the majority of the O_2 would be exhausted by aerobic bacteria and the

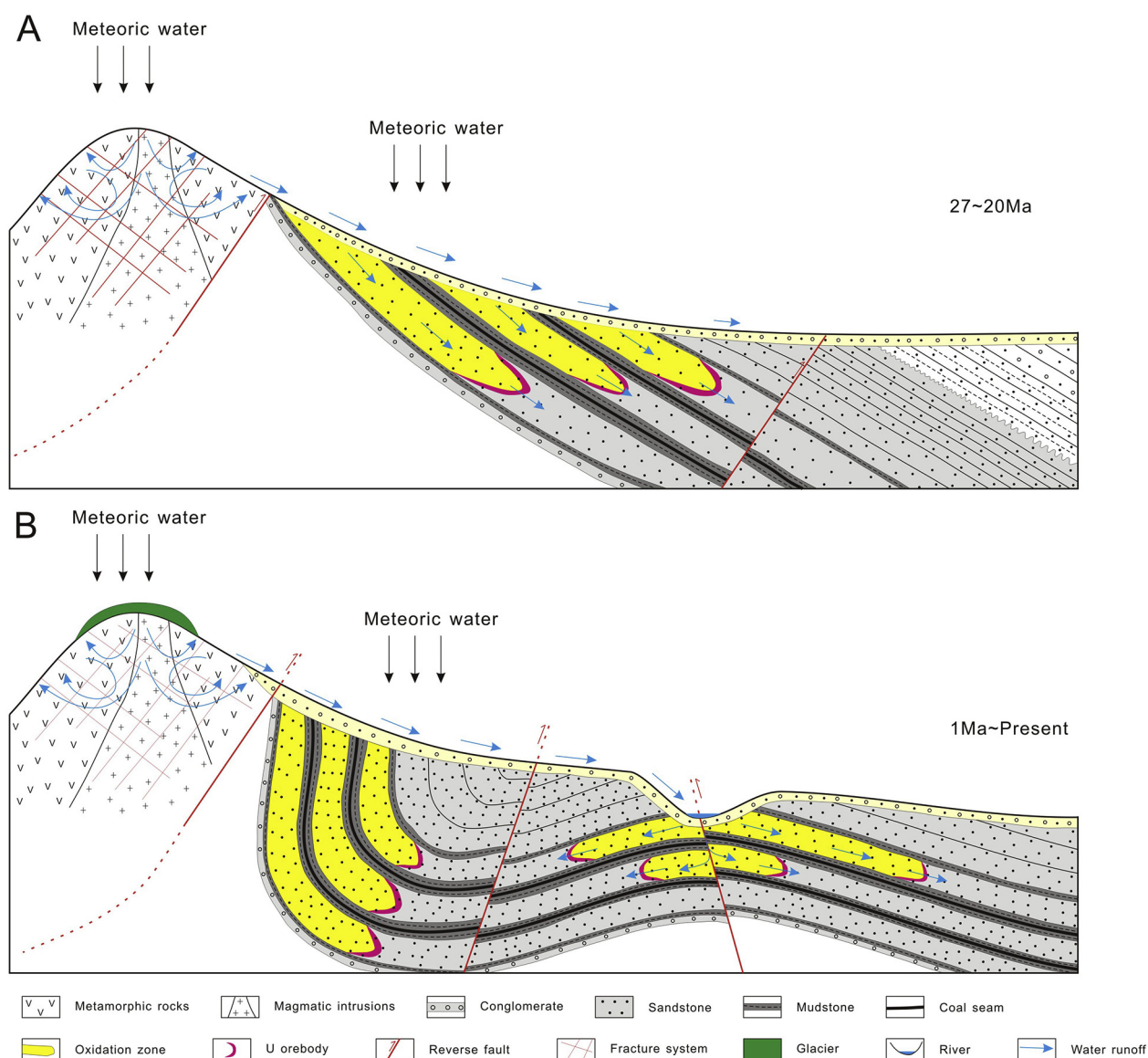
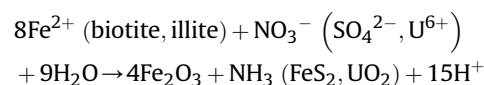


Fig. 15. Genetic model of mineralization within the southern Yili uranium district.

extraction of U from clastic rocks. These conditions would mean that the majority of the bacteria within the redox zones are anaerobic. Although Fe(II)-oxidizing bacteria are common in natural environments, the majority of these bacteria are aerobic. However, recent research has identified anaerobic Fe(II)-oxidizing bacteria (Kappler et al., 2005; Weber et al., 2006; Miot et al., 2009; Larese-Casanova et al., 2010; Konhauser et al., 2011; Carlson et al., 2012; Shelobolina et al., 2012a, 2012b; Melton et al., 2014), and significant progress has been made toward understanding the biogeochemical mechanisms of this process, which might represent a viable mechanism of uranium precipitation. This type of bacteria is present in various environments, including lakes, streams, hydrothermal vents, wetlands, and aquifer sediments (Weber et al., 2006), although they are often few in number relative to aerobic bacteria. The movement of such fluids into the ore-hosting sandstones would cause an increase in the abundance of anaerobic bacteria as a result of a decrease in O_2 concentrations, supported by the presence of plant debris. These bacteria can utilize the following reaction to provide energy to support their growth (Rackley, 1972; Reynolds et al., 1982; Weber et al., 2006), which also

reduces the concentrations of NO_3^- and SO_4^{2-} within groundwater:



This reaction allows the biological oxidation of both aqueous Fe^{2+} and structural Fe(II) within oxides (Chaudhuri et al., 2001; Weber et al., 2001, 2006; Kappler et al., 2005; Miot et al., 2009; Larese-Casanova et al., 2010). More recent research has demonstrated the biological oxidation of structural Fe(II) in phyllosilicates, including biotite (Shelobolina et al., 2012b), nontronite (Zhao et al., 2013, 2016), and illite–smectite mixed-layer clays (Shelobolina et al., 2012a). These reactions produce H^+ that is consumed by reactions with detrital feldspar, plagioclase, sericite, and illite to balance the pH of the fluid to near-neutral conditions (Robb, 2005). This microbe–Fe(II) interaction could have important implications for the processes involved in the generation of sandstone-type uranium deposits. The oxidation of aqueous Fe^{2+} and structural Fe(II) within phyllosilicates could be coupled with sulfate, nitrate, and uranyl reduction by the indigenous microbial community in

Appendix A. Basic characteristics of surface and groundwater within and around the Mengqiguer uranium deposit

Sample no.	Location	T (°C)	pH	Eh (ORP)	CON (μs/cm)	TDS (ppm)	DO (%)	DO (ppm)
SY-1	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	8.2	9.12	110.3	421	210	87.6	11.27
SY-3	Cold spring, south of Mengqiguer deposit, flow into Mengqiguer river	8.5	8.34	151.7	1013	506	80.4	10.57
SY-5	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	7.9	8.65	133.8	843	420	92.5	10.6
SY-7	Cold spring, SW of Mengqiguer deposit, flow into Mengqiguer river	8.3	8.19	114.6	996	500	88.6	9.42
SY-15	Cold spring, south of Mengqiguer deposit, flow into Mengqiguer river	8.5	9.27	155.2	1018	510	91.3	10.67
SY-20	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	8	8.94	129.4	1149	575	90.7	11.04
SY-16	Thajistan river, upstream, SW of Mengqiguer deposit, close to cold spring	12.2	8.66	167.6	265.7	132.9	93.5	10.84
SY-17	Thajistan river, midstream, SW of Mengqiguer deposit, seep into Jurassic sandstone	13.9	8.12	181.1	719	360	88.7	9.56
SY-2	Thajistan river, midstream, SW of Mengqiguer deposit, seep into Jurassic sandstone	14.9	8.38	125	404	202	85.8	8.56
SY-10 (E)	Mengqiguer river, upstream, close to cold spring	18.5	8.18	197.3	1332	666	94	9.54
SY-10 (W)	Mengqiguer river, upstream, close to cold spring	17.4	6.89	125.6		344	94.7	
SY-11	Mengqiguer river, midstream, south of Mengqiguer deposit, seep into Jurassic sandstone	16.5	8.09	231.5	1118	559	98.4	10.55
SY-4	Groundwater, oxidization zone	14	11.06	168.6	1897	948	35.6	4.01
SY-6	Groundwater, oxidization zone	16.8	7.11	-5	2563	1326	44.7	4.78
SY-8	Groundwater, oxidization zone	23	9.46	-90.8	2300	1151	66.8	6.69
SY-9	Groundwater, oxidization zone	17.9	8.21	-125.7	2409	1200	48.5	4.26
SY-13	Groundwater, oxidization zone	20.4	9.57	-60.4	1927	965	62.1	5.71
SY-22	Groundwater, oxidization zone	15.8	8.96	-80.1	2715	1362	53.4	5.02
SY-19	Groundwater, close to orebody	13.8	8.43	-190.5	1218	610	34.7	3.89
SY-21	Groundwater, close to orebody	23.6	8	-241.9	2481	1244	30.3	2.57
SY-12	Groundwater, reduction zone	15	8.32	-242.4	1791	892	31.4	2.65
SY-14	Groundwater, reduction zone	19	9.2	-300.4	1473	735	30.9	3.17
SY-18	Groundwater, reduction zone	17.6	8.74	-315.6	1502	749	28.6	2.4

Abbreviations are as follows: ORP = oxidation–reduction potential, CON = electrical conductivity, TDS = total dissolved solids, DO = dissolved oxygen

underground environments (Lovley et al., 1991; Zhao et al., 2013, 2017). In summary, anaerobic Fe(II)-oxidizing bacteria might also play a role in accelerating the reduction of uranyl(VI) into uranous(IV) and therefore could play an essential role in the generation of sandstone-type uranium deposits. Behrends and Cappellen (2005) undertook a series of competition experiments between the enzymatic and abiotic reduction of uranyl(VI) under iron-reducing conditions, and surprisingly found that hematite could increase the reduction rate of uranyl(VI) by Fe(II) if reducing bacteria were present. Therefore, the presence of hematite within the southern

Yili Basin might have been crucial for the generation of uranium mineralization in the study area.

8. Conclusions

- (1) U–Pb isotopic analysis of ores from the Kujie'ertai and Mengqiguer deposits record two major stages of uranium mineralization within the Southern Yili uranium district at 23.4 ± 3.3 to 20.18 ± 0.49 and 0.61 ± 0.24 to 0.347 ± 0.0048 Ma.

Appendix B. Ion and gas compositions of surface and groundwater within and around the Mengqiguer uranium deposit

Sample no.	Location	F ⁻	Cl ⁻	NO ₃ ⁻	SO ₄ ²⁻	CO ₃ ²⁻	HCO ₃ ⁻	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺	Al	Fe	U
SY-1	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	0.163	72.09	37.85	33.6	—	155	52.2	3.27	36.5	98.5	16.2	85.0	11.82
SY-3	Cold spring, south of Mengqiguer deposit, flow into Mengqiguer river	0.330	154	52.8	568	—	329	257	2.90	93.0	145	10.3	74.7	24.2
SY-5	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	<0.05	23.65	20.7	213	14.4	223	12.8	0.51	12.9	129.9	5.89	—	19.48
SY-7	Cold spring, SW of Mengqiguer deposit, flow into Mengqiguer river	0.060	72.6	13.4	225	—	247	103	1.84	27.8	98.8	2.50	53.2	13.67
SY-15	Cold spring, south of Mengqiguer deposit, flow into Mengqiguer river	0.180	10.0	5.24	104	—	393	36.3	3.42	35.4	100	0.848	5.16	17.72
SY-20	Cold spring, SW of Mengqiguer deposit, flow into Thajistan river	0.200	96.0	12.2	119	—	308	68.7	1.02	32.7	177.4	—	76	33.48
SY-16	Thajistan river, upstream, SW of Mengqiguer deposit, close to cold spring	0.110	27	21.3	94	—	178	45	1.4	15.2	81	16.6	32	12
SY-17	Thajistan river, midstream, SW of Mengqiguer deposit, seep into Jurassic sandstone	<0.05	2.33	6.20	47.2	6.87	131	6.69	0.760	8.17	56.1	5.02	244	0.497
SY-2	Thajistan river, midstream, SW of Mengqiguer deposit, seep into Jurassic sandstone	0.206	0.889	13.5	33.2	5.83	140	4.04	0.480	7.33	54.6	18.7	—	0.650
SY-10 (E)	Mengqiguer river, upstream, close to cold spring	0.318	1.85	6.85	9.31	—	317	11.5	1.57	12.9	80.2	2.46	39.2	2.23
SY-10 (W)	Mengqiguer river, upstream	<0.05	1.66	6.03	37.5	7.18	145	5.43	0.550	7.66	57.5	2.72	—	0.519
SY-11	Mengqiguer river, midstream, south of Mengqiguer deposit, seep into Jurassic sandstone	0.090	2.03	5.62	8.96	—	197	9.37	0.420	7.10	55.0	2.78	115	1.01
SY-4	Groundwater, oxidization zone	0.125	5.51	14.2	46.5	—	261	33.3	0.930	13.1	66.9	3.72	—	3.69
SY-6	Groundwater, oxidization zone	0.060	13.3	18.7	181	—	185	81.9	1.40	12.5	67.5	2.24	—	1.98
SY-8	Groundwater, oxidization zone	0.190	8.21	21.5	33.9	—	230	22.5	2.33	16.0	60.8	3.77	2.13	2.42
SY-9	Groundwater, oxidization zone	0.190	10.9	30.9	85.0	—	241	37.5	1.66	20.8	72.8	0.266	73.3	2.55
SY-13	Groundwater, oxidization zone	0.450	13.7	11.7	287	—	199	75.4	0.850	25.5	78.5	—	14.7	1.70
SY-22	Groundwater, oxidization zone	<0.05	20.6	13.1	132	—	279	23.2	1.51	21.5	119	—	398	2.30
SY-19	Groundwater, close to orebody	<0.05	583	27.8	1170	—	193	427	0.950	137	375	—	1051	9.54
SY-21	Groundwater, close to orebody	<0.05	119	16.2	514	—	318	141	1.70	43.3	179	—	682	13.4
SY-12	Groundwater, reduction zone	0.160	26.7	0.070	141	—	228	55.5	1.85	15.8	76.9	0.159	182	0.524
SY-14	Groundwater, reduction zone	<0.05	3.98	2.44	38.7	—	192	20.3	0.750	8.05	53.4	—	—	0.787
SY-18	Groundwater, reduction zone	<0.05	11.5	6.21	108	—	156	36.6	1.30	11.1	57.0	—	268	1.12

Al, Fe, and U concentrations are in ppb, with all other concentrations in ppm.

- (2) Hydrological data indicate that the Mengqiguer deposit is still growing, yielding a third uranium mineralization stage at ~0 Ma. This suggests that the U within these deposits is not only derived from U-bearing sediments but also from the Tien Shan mountains as a result of groundwater cycling.
- (3) The geological, geochronological, and hydrological data for the Southern Yili uranium district presented in this study indicate a four-stage genetic model comprising the extension and uplift of the Tien Shan mountains at 35–21 Ma, during the Pliocene, and recently. All of this reflects the far-field influence of the continuous penetration of the Indian Plate into the Asian Plate, as follows.
 - a. The 35 to 21 Ma reactivation and expansion of the western Tien Shan orogeny occurred as a far-field effect of India–Eurasia collision, causing the uplift of the southern flank of the Yili Basin. This resulted in the southern margin of the Jurassic Shuixigou Group being exposed up until 23.4 ± 3.3 Ma, which allowed meteoric water from the hillsides to the north to be gravitationally introduced to the sediments, generating the first stage of U mineralization (Fig. 15A).
 - b. This first stage of U mineralization was followed by a cessation of groundwater influx as a result of the presence of pyrite, organic matter, V–Se minerals, and hematite, all of which dramatically reduced the permeability of the sandstone. This was enhanced by continuous uplift that moved the exposed southern margin of the Shuixigou Group sediments away from the northern foot of the Tien Shan mountains, removing the access point for meteoric water into the groundwater system.
 - c. The western Tien Shan mountains expanded until the Pliocene as a result of the far-field influence of the continuous penetration of the Indian Plate into the Asian Plate, reactivating reverse faults and folds within the piedmont of the Tien Shan mountains and causing the continuous uplift of the southern flank of the Yili Basin. The uplift of anticlines in this area caused the erosion of their hinge zones, introducing a significant amount of oxidizing water into the Shuixigou Group and generating a second stage of uranium mineralization (0.61 ± 0.24 to 0.347 ± 0.0048 Ma).
 - d. The mineralization in the southern Yili uranium district continues to expand, as evidenced by the fall in U contents of groundwater passing through redox zones (Fig. 15B).
- (4) The ongoing growth of a second stage of uranium mineralization (0.61 ± 0.24 to 0.347 ± 0.0048 Ma) within the Southern Yili uranium district indicates that climate change related to alternating interglacial and glacial periods plays an important role in the genesis of uranium mineralization. This is especially true in the study area, as glacial melting accounts for nearly 70% of the water in the rivers within the northern piedmont of the Tien Shan mountains (Lei et al., 2010; Wu et al., 2018).

Acknowledgement

This research was jointly supported by the National “973” Program of China (2015CB453004) and the Centralized Research and Innovation Project of CNPC (Grant No. Geo-LCEQ-1). We are grateful to Prof. Larry Meinert, Prof. XiaoYong Yang, and the reviewer Eric Hiatt for their helpful and constructive opinions.

References

- Abdelouas, A., Lu, Y., Lutze, W., Nuttall, H.E., 1998. Reduction of U(IV) to U(III) by indigenous bacteria in contaminated ground water. *J. Contam. Hydrol.* 35, 217–233.
- Abdrakmatov, K.Y., Aldazhanov, S.A., Hager, B.H., Hamburger, M.W., Herring, T.A., Kalabaev, K.B., Makarov, V.I., Molnar, P., Panasyuk, S.V., Prilepin, M.T., Reilinger, R.E., Sadybakasov, I.S., Souder, B.J., Trapeznikov, Y.A., Tsurkov, V.Y., Zubovich, A.V., 1996. Relatively recent construction of the Tien Shan inferred from GPS measurements of present-day crustal deformation rates. *Nature* 384, 450–453.
- Allen, M.B., Windley, B.F., Zhang, C., 1993. Palaeozoic collisional tectonics and magmatism of the Chinese Tien Shan, Central Asia. *Tectonophysics* 220, 89–115.
- Allen, M.B., Vincent, S.J., Wheeler, P.J., 1999. Late Cenozoic tectonics of the Kepingtage thrust zone: interactions of the Tien Shan and the Tarim Basin, Northwest China. *Tectonics* v. 18, 639–654.
- Anderson, R.T., Vrionis, H.A., Ortiz-Bernad, I., Resch, C.T., Long, P.E., Dayvault, R., Karp, K., Marutzky, S., Metzler, D.R., Peacock, A., White, D.C., Lowe, M., Lovley, D.R., 2003. Stimulating the in situ activity of *Geobacter* species to remove uranium from the groundwater of a uranium-contaminated aquifer. *Appl. Environ. Microbiol.* 69, 5884–5891.
- Avouac, J.P., Burov, E.B., 1996. Erosion as a driving mechanism of intracontinental mountain growth. *J. Geophys. Res.* 101, 17747–17769.
- Avouac, J.P., Tapponnier, P., Bai, P., You, H., Wang, G., 1993. Active thrusting and folding along the northern Tien Shan, and late Cenozoic rotation of the Tarim relative to the Junggar and Kazakhstan. *J. Geophys. Res.* 98, 6755–6804.
- Barbarin, B., 1999. A review of the relationships between granitoid types, their origins and their geodynamic environments. *Lithos* 46, 605–626.
- Behrends, T., Cappellen, V.P., 2005. Competition between enzymatic and abiotic reduction of uranium under iron reducing conditions. *Chem. Geol.* 220, 315–327.
- Bonnetti, C., Cuney, M., Malartre, F., Michels, R., Liu, X.D., Peng, Y.B., 2015. The Nuheting Deposit, Erlan Basin, NE China: synsedimentary to diagenetic uranium mineralization. *Ore Geol. Rev.* 69, 118–139.
- Bonnetti, C., Cuney, M., Bourlange, S., Deloule, E., Poujol, M., Liu, X.D., Peng, Y.P., Yang, J.X., 2017. Primary uranium sources for sedimentary-hosted uranium deposits in NE China: insight from basement igneous rocks of the Erlan Basin. *Mineral. Deposita* 52, 297–315.
- Bonnetti, C., Liu, X.D., Yan, Z.B., Cuney, M., Michels, R., Malartre, F., Mercadier, J., Cai, J.F., 2017. Coupled uranium mineralisation and bacterial sulphate reduction for the genesis of the Baxingtu sandstone-hosted U deposit, SW Songliao Basin, NE China. *Ore Geol. Rev.* 82, 108–129.
- Bray, C.J., Spooner, E.T.C., Thomas, A.V., 1991. Fluid inclusion volatile analysis by heated crushing, on line gas chromatography; applications to Archean fluids. *J. Geochem. Explor.* 42, 167–193.
- Bullen, M.E., Burbank, D.W., Garver, J.I., 2003. Building the Northern Tien Shan: integrated thermal, structural, and topographic constraints. *J. Geol.* 111, 149–165.
- Burbank, D.W., Anderson, R.S., 2012. *Tectonic Geomorphology* (2nd Ed.). John Wiley, U. K., Chichester. 195–243.
- Burchfiel, B.C., Brown, E.T., Qidong, D., Li, J., Feng, X., Molnar, P., Shi, J., Wu, Z., You, H., 1999. Crustal shortening on the margins of the Tien Shan, Xinjiang, China. *International Geology Reviews* 41, 663–700.
- Burtman, V.S., 1975. Structural geology of Variscan Tien Shan, USSR. *Am. J. Sci.* 275, 157–186.
- Buslov, M.M., Kokh, D.A., Grave, J.D., 2008. Mesozoic–Cenozoic tectonics and geodynamics of Altai, Tien Shan, and Northern Kazakhstan, from apatite fission-track data. *Russ. Geol. Geophys.* 49, 648–654.
- Caccavo Jr., F., Blakemore, R.P., Lovley, D.R., 1992. A hydrogenoxidizing, iron(III)-reducing microorganism from the Great Bay estuary, New Hampshire. *Appl. Environ. Microbiol.* 58, 3211–3216.
- Cai, C.F., Dong, H.L., Li, H.T., Xiao, X.J., Ou, G.X., Zhang, C.M., 2007. Mineralogical and geochemical evidence for coupled bacterial uranium mineralization and hydrocarbon oxidation in the Shashagetai deposit, NW China. *Chem. Geol.* 236, 167–179.
- Cai, C.F., Li, H.T., Qin, M.K., Luo, X.R., Wang, F.Y., Ou, G.X., 2007. Biogenic and petroleum-related ore-forming processes in Dongsheng uranium deposit, NW China. *Ore Geol. Rev.* 32, 262–274.
- Cai, Y.Q., Zhang, J.D., Li, Z.Y., Guo, Q.Y., Song, J.Y., Fan, H.H., Liu, W.S., Qi, F.C., Zhang, M.L., 2015. Outline of uranium resources characteristics and metallogenetic regularity in China. *Acta Geol. Sin.* 89, 1051–1069 (in Chinese with English abstract).
- Carlson, H.K., Clark, I.C., Melnyk, R.A., Coates, J.D., 2012. Toward a mechanistic understanding of anaerobic nitrate-dependent iron oxidation: balancing electron uptake and detoxification. *Front. Microbiol.* 3–57, 1–6.
- Channer, D.M.DeR., Spooner, E.T.C., 1991. Multiple fluid inclusion generations in variably deformed quartz: Hollinger–McIntyre and Kerr Addison–Chesterville Archean Au-bearing vein systems. *Ontario Geological Survey Miscellaneous Paper* 156, 47–64.
- Chatters, J.C., Hoover, K.A., 1992. Response of the Columbia river fluvial system to Holocene climatic change. *Quat. Res.* 37, 42–59.
- Chaudhuri, S.K., Lack, J.G., Coates, J.D., 2001. Biogenic magnetite formation through anaerobic biooxidation of Fe(II). *Appl. Environ. Microbiol.* 67, 2844–2848.
- Chen, C.M., Lu, H.F., Jia, D., Cai, D.S., Wu, S.M., 1999. Closing history of the southern Tianshan oceanic basin, western China: an oblique collisional orogeny. *Tectonophysics* 302, 23–40.
- Chen, J., Burbank, D., Scharer, K., Sobel, E., Yin, J., Rubin, C., Zhao, R., 2002. Magnetochronology of the Upper Cenozoic strata in the Southwestern Chinese Tien Shan: rates of Pleistocene folding and thrusting. *Earth Planet. Sci. Lett.* 195, 113–130.
- Chen, K., Lin, W., Wang, Q.C., 2015. The Bogeda Shan uplifting: evidence from multiple phase of deformation. *Journal of Asian Earth Science* 99, 1–12.
- Chen, Y.B., Hu, A.Q., Zhang, G.X., Zhang, Q.F., 1999. Zircon U–Pb age and Nd–Sr

- isotopic composition of granitic gneiss and its geological implications from Precambrian window of western Tianshan, NW China. *Geochimica* 28, 515–520 (in Chinese with English abstract).
- Chen, Y.N., Li, W.H., 1997. The influence of precipitation to river water and sediment yield on northern slope of Tian Shan Mountain. *Mountain Research* 15, 47–52 (in Chinese with English abstract).
- Chen, Z.B., Li, S.X., Cai, Y.Q., Chen, D.S., 2002. Geologic evolution and uranium metallogenetic regularity in Yili Basin. *Mineral Deposits* 21 (S), 849–852 (in Chinese with English abstract).
- Chen, Z.L., Li, L., Liu, J., Gong, H.L., Jiang, R.B., Li, S.X., Zheng, E.J., Han, X.Z., Li, X.G., Wang, C., Wang, G.R., Wang, G., Lu, K.G., 2008. Preliminary study on the uplifting–exhumation process of the western Tianshan range, northwestern China. *Acta Geol. Sin.* 24, 625–636 (in Chinese with English abstract).
- Chen, Z.Y., Huang, S.J., 1993. In-Situ Leachable Sandstone Uranium Resources in Yili Basin, Xinjiang AR, China. NEA/IAEA Uranium Group meeting, Paris, 11 p.
- Chen, Z.Y., Chen, D.S., Gu, K.H., Wang, Y.J., 2010. The regional distribution regularities of ore–hosting horizon, deposit type and mineralization age of China's sandstone–hosted uranium deposits. *Uranium Geology* 26, 321–330 (in Chinese with English abstract).
- Coleman, M., Hodges, K., 1995. Evidence for Tibetan plateau uplift before 14 Myr ago from a new minimum age for east–west extension. *Nature* 374, 49–52.
- Cuney, M., 2009. The extreme diversity of uranium deposits. *Mineral. Deposita* 44, 3–9.
- Cuney, M., Kyser, K., 2008. Recent and not–so–recent developments in uranium deposits and implications for exploration. *Mineralogical Association of Canada Short Course series*. Quebec 39, 210–250.
- Dahlkamp, J.F., 2009. Uranium deposits of the world. Berlin Heidelberg, Springer–Verlag, pp. 1–30.
- Degtyarev, K., Yakubchuk, A., Tretyakov, A., Kotov, A., Kovach, V., 2017. Precambrian geology of the Kazakh Uplands and Tien Shan: an overview. *Gondwana Res.* 47, 44–75.
- Deng, Q.D., 2000. Seismotectonics of Tien Shan. *Seismological Press*, Beijing, pp. 1–75 (in Chinese).
- Deng, Q.D., Feng, X.Y., Zhang, P.Z., Xu, X.W., Yang, X.P., Peng, S.Z., Li, J., 2000. Active Tectonics of the Tian Shan Mountains. *Seismology Press*, Beijing (in Chinese).
- Dolgoplova, A., Seltmann, R., Konopelko, D., Biske, Y.S., Shatov, V., Armstrong, R., Belousova, E., Pankhurst, R., Koneev, R., Divaev, F., 2017. Geodynamic evolution of the western Tien Shan, Uzbekistan: Insights from U–Pb SHRIMP geochronology and Sr–Nd–Pb–Hf isotope mapping of granitoids. *Gondwana Res.* 47, 76–109.
- Dong, W., Brooks, S.C., 2006. Determination of the formation constants of ternary complexes of uranyl and carbonate with alkaline earth metals (Mg^{2+} , Ca^{2+} , Sr^{2+} , and Ba^{2+}) using anion exchange method. *Environ. Sci. Technol.* 40, 4689–4695.
- Enkin, R.J., Chen, Y., Courtillot, V., Besse, J., Xing, L., Zhang, Z., Zhuang, Z., Zhang, J., 1991. A lower cretaceous pole from South China and the Mesozoic hairpin turn of the Eurasian apparent polar wander path. *J. Geophys. Res.* 96, 4007–4028.
- Faure, G., 1977. *Principles of Isotope Geology*. John Wiley and Sons, New York, N.Y., pp. 146–209, 475.
- Finch, W.I., Davis, J.F., 1985. Sandstone–type uranium deposits—An introduction. In: *Geological environments of sandstone–type uranium deposits*, TECDOC–328. IAEA, Vienna, p. 11–20.
- Francis, A.J., Dodge, C.J., Lu, F., Halada, G.P., Clayton, C.R., 1994. XPS and XANES studies of uranium reduction by *Clostridium* sp. *Environ. Sci. Technol.* 28, 636–639.
- Gao, J., Long, L.L., Qian, Q., Huang, D.Z., Su, W., Klemd, R., 2006. South Tianshan: a late Paleozoic or a Triassic Orogen. *Acta Petrol. Sin.* 22, 1049–1061 (in Chinese with English abstract).
- Gao, J., Long, L.L., Klemd, R., Qian, Q., Liu, D.Y., Xiong, X.M., Su, W., Liu, W., Wang, Y.T., Yang, F.Q., 2009. Tectonic evolution of the South Tianshan Orogen and adjacent regions, NW China: geochemical and age constraints of granitoid rocks. *Int. J. Earth Sci.* 98, 1221–1238.
- Geological Team No. 216, 2016. Report of Specialized Mapping and Technological Application on the Sandstone Type Exploration District in Yili Basin. Xinjiang, Urumqi, 57 p. (in Chinese).
- Gong, Z.J., Li, S.H., Li, B., 2014. The evolution of a terrace sequence along the Manas River in the northern foreland basin of Tian Shan, China, as inferred from optical dating. *Geomorphology* 213, 201–212.
- Granger, H.C., 1963. Radium migration and its effect on the apparent age of uranium deposits at Ambrosia Lake, New Mexico. U. S. Geological Survey Professional Paper 745, (82 p).
- Grave, D.J., Glorie, S., Buslov, M.M., Stochli, F.D., McWilliams, O.M., Batalev, Y.V., Van den Haute, P., 2013. Thermo-tectonic history of the Issyk-Kul basement (Kyrgyz Northern Tien Shan, Central Asia). *Gondwana Res.* 23, 998–1020.
- Guo, Z.J., Zhang, Z.C., Wu, C.D., Fang, S.H., Zhang, R., 2006. The Mesozoic and Cenozoic exhumation history of Tianshan and comparative studies to the Junggar and Altai mountains. *Acta Geol. Sin.* 80, 1–15 (in Chinese with English abstract).
- Han, X.Z., Li, S.X., Zhen, E.J., Li, X.G., Cai, Y.Q., Chen, Z.L., 2004. Neotectonic activity characteristics of Yili Basin and its relationship to the formation of sandstone–type uranium deposits. *Xinjiang Geol.* 22, 378–281 (in Chinese with English abstract).
- Hansley, P.L., Spirakis, C.S., 1992. Organic matter diagenesis as the key to a unifying theory for the genesis of tabular uranium–vanadium deposits in the Morrison Formation, Colorado Plateau. *Econ. Geol.* 87, 352–365.
- Harrison, T.M., Copeland, P., Kidd, W.S.F., Yin, A., 1992. Raising Tibet. *Science* 255, 1663–1670.
- Heermance, R.V., Chen, J., Burbank, D.W., Wang, C., 2007. Chronology and tectonic controls of Late Tertiary deposition in the southwestern Tian Shan foreland, NW China. *Basin Res.* 19, 599–632.
- Holliger, P., Pagel, M., Pironon, J., 1989. A model for ^{238}U radioactive daughter loss from sediment–hosted pitchblende deposits and the Late Permian–Early Triassic depositional U–Pb age of the Mullenbach uranium ore (Baden–Württemberg, F.R.G.). *Chem. Geol. Isot. Geosci.* 80, 45–53.
- Holt, W.E., Chamot-Rooke, N., Le Pichon, X., Haines, A.J., Shen-Tu, B., Ren, J., 2000. Velocity field in Asia inferred from quaternary fault slip rates and global positioning system observations. *J. Geophys. Res.* 105, 19185–19209.
- Hou, B.H., Keeling, J., Li, Z.Y., 2017. Paleovalley-related Uranium Deposits in Australia and China: a review of geological and exploration models and methods. *Ore Geol. Rev.* 88, 201–234.
- Hu, X.F., Pan, B.T., Gao, H.S., Hu, Z.B., Cao, B., Li, Q.Y., Geng, H.P., 2013. Development of Holocene fluvial terraces in the eastern Qilianshan mountain and its relationship with climatic changes. *Quaternary Science* 33, 723–736 (in Chinese with English Abstract).
- Kang, Y., Wang, B., 2010. The more current supply of Menggiqu uranium ore deposit in southern margin of Yili Basin. *Xinjiang Geol.* 28, 316–318 (in Chinese with English abstract).
- Kappler, A., Schink, B., Newman, D.K., 2005. Fe(III) mineral formation and cell encrustation by the nitrate–dependent Fe(II) – oxidizer strain BoFeN1. *Geobiology* 3, 235–245.
- Kazumasa, A., Yukio, I., Atsushi, Y., Shuhei, S., Takafumi, H., 2015. Mid–Paleozoic arc granitoids in SW Japan with Neoproterozoic xenocrysts from South China: New zircon U–Pb ages by LA–ICP–MS. *Journal of Asian Earth Science* 97, 125–135.
- Konhauser, K.O., Kappler, A., Roden, E.E., 2011. Iron in microbial metabolisms. *Elements* 7, 89–93.
- Konopelko, D., Biske, G., Seltmann, R., Eklund, O., Belyatsky, B., 2007. Hercynian post-collisional A-type granites of the Kokshaal range, Southern Tien Shan, Kyrgyzstan. *Lithos* 97, 140–160.
- Konopelko, D., Seltmann, R., Yamadjanov, Y., Romer, R.L., Rojas-Agramonte, Y., Jeffries, T., Fidaev, D., Niyozov, A., 2017. A geotraverse across two paleo-subduction zones in Tien Shan, Tajikistan. *Gondwana Res.* 47, 110–130.
- Larese-Casanova, P., Haderlein, S.B., Kappler, A., 2010. Biomineralization of lepidocrocite and goethite by nitrate-reducing Fe(II)–oxidizing bacteria: effect of pH, bicarbonate, phosphate, and humic acids. *Geochim. Cosmochim. Acta* 74, 3721–3734.
- Larson, K.M., Bürgmann, R., Bilham, R., Freymueller, J., 1999. Kinematics of the India–Eurasia collision zone from GPS measurements. *J. Geophys. Res.* 104, 1077–1093.
- Lee, T.Y., Lawver, L.A., 1995. Cenozoic plate reconstruction of Southeast Asia. *Tectonophysics* 251, 85–138.
- Lei, X.N., Zhou, Y., Zhu, L.P., 2010. Suggestion for optimizing allocation of water resources of the Northern Tianshan Economic zone. *Arid Land Geography* 33, 968–970 (in Chinese with English abstract).
- Levchenkov, O.A., Shukolyukov, Y.A., 1970. A new method for calculating age and time of metamorphism of minerals and rocks without correction for ordinary lead. *Geochem. Int.* 1, 60–65.
- Li, B.X., Chen, Y.H., 2010. A study of genesis of the interlayer oxidized zone in the Menggiqu region, Ili Basin. *Geological Journal of Sichuan* 30, 395–398.
- Li, J.L., Su, W., Zhang, X., Liu, X., 2009. Zircon Cameca U–Pb dating and its significance for granulite–facies gneisses from the western Awulake Mountains, Western Tianshan, China. *Geological Bulletin of China* 28, 1852–1862 (in Chinese with English abstract).
- Li, J.L., Qian, Q., Gao, J., Su, W., Zhang, X., Liu, X., Jiang, T., 2010. Geochemistry, zircon U–Pb ages and tectonic settings of the Dahalajunshan volcanics and granitic intrusions from the Adengtao area in the Southeast Zhaozu, western Tianshan Mountains. *Acta Petrol. Sin.* 26, 2913–2924.
- Li, K.M., Li, Z.Q., Gao, W.Y., Wang, L., 2011. Recent glacial retreat and its effect on water resources in eastern Xinjiang. *Chin. Sci. Bull.* 56, 3596–3604 (in Chinese).
- Li, M.G., Zhou, W.B., Zhang, Z.S., Shi, X.P., 2002. Kerogen characteristics of Kujiertai uranium ore deposit. *Journal of East China Geological Institute* 25, 181–186 (in Chinese with English abstract).
- Li, P., Liu, H.X., Ding, B., Tian, M.M., 2018. The Zircon U–Pb geochronology and dynamics mechanism for the formation of monzonitic granite in the Qiongbola area, south of Yili Basin. *Geol. China* 45, 720–739 (in Chinese with English abstract).
- Li, S.X., Chen, D.S., Cai, Y.Q., 2002b. Geologic evolution and uranium metallogenetic regularity of Yili Basin. In: Bureau of Geology, CNNC (ed) *Sandstone–type uranium deposits in China: Geology and exploration techniques*. Atomic Energy Press, Beijing, pp. 53–64.
- Li, X.H., Li, Z.X., Zhou, H.W., Liu, Y., Liang, X.R., Li, W.X., 2003. SHRIMP U–Pb zircon age, geochemistry and Nd isotope of the Guandaoshan pluton in SW Sichuan: Petrogenesis and tectonic significance. *Science in China (Series D)* 46 (S), 73–83.
- Li, X.H., Li, Z.X., Li, W.X., Liu, Y., Yuan, C., Wei, G.J., Qi, C.S., 2007. U–Pb zircon, geochemical and Sr–Nd–Hf isotopic constraints on age and origin of Jurassic I– and A–type granites from Central Guangdong, SE China: a major igneous event in response to foundering of a subducted flat–slab. *Lithos* 96, 186–204.
- Li, X.H., Li, W.X., Li, Z.X., Lou, C.H., Wang, J., Ye, M.F., Fang, Y.H., 2009. Amalgamation between the Yangtze and Cathaysia Blocks in South China: constraints from SHRIMP U–Pb zircon ages, geochemistry and Nd–Hf isotopes of the Shuangxiwu volcanic rocks. *Precambrian Res.* 174, 117–128.
- Li, X.H., Li, W.X., Wang, X.C., Li, Q.L., Liu, Y., Tang, G.Q., 2009. Role of mantle–derived

- magma in genesis of early Yanshanian granites in the Nanling Range, South China: in situ zircon Hf–O isotopic constraints. *Science in China (Series D)* 52, 1262–1278.
- Li, X.H., Li, W.X., Wang, X.C., Liu, Y., Tang, G.Q., Gao, Y.Y., Wu, F.Y., 2010. SIMS U–Pb zircon geochronology of porphyry Cu–Au–(Mo) deposits in the Yangtze River metallogenic belt, eastern China: magmatic response to early cretaceous lithospheric extension. *Lithos* 119, 427–438.
- Li, Y.L., Si, S.P., Lu, S.H., Wang, Y.R., 2012. Tectonic and climatic controls on the development of the Kuitun River terraces in the northern piedmont of Tianshan Mountains. *Quaternary Science* 32, 880–890 (in Chinese with English Abstract).
- Li, Y.S., 1982. The discussion of mineralization ages and genesis of granite–type uranium deposits in South China. In: Du et al. (eds) *Galaxy of research achievements of granite type deposit*. Atomic Energy Press, Beijing, pp. 122–131 (in Chinese).
- Li, Y.S., Zhu, J.C., Li, X.B., Ying, J.L., 1980. The summarization of mineralization ages of hydrothermal type uranium deposits in China. *Radioactive Geology* 1, 1–8 (in Chinese).
- Lin, A.M., Fu, B.H., Kano, K.I., Maruyama, T., Guo, J.M., 2003. Late Quaternary dextral shearing of the active faults in Yanqi Basin. *Xinjiang Geol.* 21, 103–115 (in Chinese with English abstract).
- Lin, X.B., Liu, H.X., Wang, Z.M., Hao, W.L., 2017. Hydrogeochemical modelling study on Menggiguer uranium deposit in Yili Basin. *Uranium Geology* 33, 346–355 (in Chinese with English Abstract).
- Liu, D.L., Li, H.B., Sun, Z.M., Cao, Y., Wang, L.Z., Pan, J.W., Han, L., Ye, X.Z., 2017. Cenozoic episodic uplift and kinematic evolution between the Pamir and Southwestern Tien Shan. *Tectonophysics* 712–713, 438–454.
- Liu, Y., Zhang, R.Q., Zhang, Z.Y., Shi, G.H., Zhang, Q.C., Abuduwayiti, M., Liu, J.H., 2015. Mineral inclusion and SHRIMP U–Pb dating of zircons from the Alamas nephrite and granodiorite: Implications for the genesis of a magnesian skarn deposit. *Lithos* 212–215, 128–144.
- Liu, Y.Q., Wang, Z.X., Jin, X.C., Li, T., Li, Y., 2004. Evolution, chronology and depositional effect of uplifting in eastern sector of the Tianshan mountains. *Acta Geol. Sin.* 78, 319–331 (in Chinese with English abstract).
- Long, P.E., Williams, K.H., Davis, J.A., Fox, P.M., Wilkins, M.J., Yabusaki, S.B., Fang, Y.L., Waicher, S.R., Berman, E.S.F., Gupta, M., Chandler, D.P., Murray, C., Peacock, A.D., Giloteaux, L., Handley, K.M., Lovley, D.R., Banfield, J.F., 2015. Bicarbonate impact on U(VI) bioreduction in a shallow alluvial aquifer. *Geochim. Cosmochim. Acta* 150, 106–124.
- Lovley, D.R., Phillips, E.J.P., 1992. Reduction of uranium by *Desulfovibrio desulfuricans*. *Appl. Environ. Microbiol.* 58, 850–856.
- Lovley, D.R., Phillips, E.J.P., Gorby, Y.A., Landa, E.R., 1991. Microbial reduction of uranium. *Nature* 350, 413–416.
- Lowson, R.T., 1982. Aqueous oxidation of pyrite by molecular oxygen. *Chem. Rev.* 82, 461–497.
- Lu, H.H., Burbank, D.W., Li, Y.L., 2010. Alluvial sequence in the north piedmont of the Chinese Tianshan over the past 550 kyr and its relationship to climate change. *Paleogeography Paleoclimatology Paleoeology* 285, 343–353.
- Lu, J.S., Wang, G.D., Wang, H., Chen, H.X., Peng, T., Wu, C.M., 2015. Zircon SIMS U–Pb geochronology of the Lushan terrane: dating metamorphism of the southwestern terminal of the Paleoproterozoic Trans–North China Orogen. *Geol. Mag.* 152, 367–377.
- Ludwig, K.R., 1978. Uranium daughter migration and U/Pb isotope apparent ages of uranium ores, Shirley Basin, Wyoming. *Econ. Geol.* 73, 29–49.
- Ludwig, K.R., 1980. Calculation of uncertainty of U–Pb isotope data. *Earth Planet. Sci. Lett.* 46, 212–220.
- Ludwig, K.R., 1984. PBDAT—a program for reduction of Pb–U–Th isotope data, for use with HP–86/87 microcomputers. U.S. Geological Survey, Open–File Report 83–113, (54p).
- Ludwig, K.R., 1993. ISOPLOT: a plotting and regression program for radiogenic–isotope data. U.S. Geological Survey, Open File Report 91–445, 1–42.
- Ludwig, K.R., Simmons, K.R., 1992. U–Pb dating of uranium deposits in collapse breccia pipes of the Grand Canyon Region. *Econ. Geol.* 87, 1747–1765.
- Ludwig, K.R., Nash, J.T., Naeser, C.W., 1980. Age of uranium mineralization, U–Pb isotope systematics, and ore mineralogy of the Midnite mine, Washington. U.S. Geological Survey, Open File Report 80–236, (62p).
- Ludwig, K.R., Nash, J.T., Naeser, C.W., 1981. U–Pb isotope systematics and age of uranium mineralization, Midnite mine, Washington. *Econ. Geol.* 76, 89–110.
- Ludwig, K.R., Rubin, B., Fishman, N.S., Reynolds, R.L., 1982. U–Pb Ages of Uranium Ores in the Church Rock Uranium District, New Mexico. *Econ. Geol.* 77, 1942–1945.
- Ludwig, K.R., Simmons, K.R., Webster, J.D., 1984. U–Pb isotope systematics and apparent ages of uranium ores, Ambrosia Lake and Smith Lake districts, grants mineral belt, New Mexico. *Econ. Geol.* 79, 322–337.
- Ludwig, R.K., Wallace, R.A., Simmons, R.K., 1985. The Schwartzwalder uranium deposit, II: age of uranium mineralization and Lead isotope constraints on genesis. *Econ. Geol.* 80, 1858–1871.
- Luo, J.C., Hu, R.Z., Fayek, M., Li, C.S., Bi, X.W., Abdu, Y., Chen, Y.W., 2015. In–situ SIMS uraninite U–Pb dating and genesis of the Xianshi granite–hosted uranium deposit, South China. *Ore Geological Reviews* 65, 968–978.
- Lv, H.H., Li, Y.L., Liu, Y.M., Si, S.P., Zhao, H.Z., 2008. Sedimentary environment evolution since 8Ma B.P. in the Taxihe area, Xinjiang, Northwest China, and its tectonic significance. *Quaternary Science* 28, 243–252 (in Chinese with English abstract).
- Lv, H.H., Li, Y.L., Nan, F., Si, S.P., Liu, Y.M., Qian, M., Zhao, H.Z., 2008. Sequences and ages of fluvial terraces along the northern piedmont of the Tianshan mountains. *Acta Geograph. Sin.* 163, 65–74 (in Chinese with English Abstract).
- Martin, C., 1992. The response of fluvial systems to climate change: an example from the central Great plains. *Phys. Geogr.* 13, 101–114.
- Matthew, P.M., Amy, L.W., Andrea, F., Rufus, L.B., David, M.H., Stephen, S.F., 2015. U–Pb zircon tuff geochronology from the Karoo Basin, South Africa: implications of zircon recycling on stratigraphic age controls. *International Geology Reviews* 57, 393–410.
- Melton, E.D., Swanner, D.E., Behrens, S., Schmidt, C., Kappler, A., 2014. The interplay of microbially mediated and abiotic reactions in the biogeochemical Fe cycle. *Nat. Rev. Microbiol.* 12, 797–808.
- Min, M.Z., Luo, X.Z., Mao, S.L., Wang, Z.Q., Wang, R.C., Qin, L.F., Tan, X.L., 2001. An excellent fossil wood cell texture with primary uranium minerals at a sandstone hosted roll–type uranium deposit, NW China. *Ore Geol. Rev.* 17, 233–239.
- Min, M.Z., Chen, J., Wang, J.P., Wei, G.H., Fayek, M., 2005. Mineral paragenesis and textures associated with sandstone-hosted roll-front uranium deposits, NW China. *Ore Geol. Rev.* 26, 51–69.
- Min, M.Z., Xu, M.H., Chen, J., Fayek, M., 2005. Evidence of uranium biomineralization in sandstone-hosted roll-front uranium deposits, northwestern China. *Ore Geol. Rev.* 26, 198–206.
- Miot, J., Benzerara, K., Morin, G., Bernard, S., Beyssac, O., Larquet, E., Kappler, A., Guyot, F., 2009. Transformation of vivianite by anaerobic nitrate–reducing iron–oxidizing bacteria. *Geobiology* 7, 373–384.
- Molnar, P., Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. *Science* 189, 419–426.
- Molnar, P., Brown, E.T., Burchfiel, B.C., Deng, Q., Feng, X., Li, J., Raisbeck, G.M., Shi, J., Zhangming, W., Yiou, F., 1994. Quaternary climate change and the formation of river terraces across growing anticlines on the north flank of the Tien Shan, China. *J. Geol.* 102, 583–602.
- Neymark, L.A., Levchenkov, O.A., 1979. A method of age calculating for open U–Pb isotope systems. *Geochem. Int.* 5, 34–39.
- Nikolay, P.L., Vasily, I.V., Ai, F., Naotatsu, S., Alexey, P.A., Enver, E.A., Vyacheslav, N.G., Tatiana, L.K., Alexander, A.P., Igor, V.C., 2009. Uranium behavior in the process of primary Pitchblende ore alteration by the post–ore hydrothermal solutions: an application to assessment of uranium migration from underground spent nuclear fuel repositories. *Resour. Geol.* 59, 342–358.
- NWUIG (Northwest Institute of Uranium Geology), 1997. Geological report of the Shihongtan uranium deposit. Unpublished geological report. Xi'an 17–39 (in Chinese).
- OECD–NEA, IAEA, 2014. Uranium 2014: Resources, Production and Demand. OECD Nuclear Energy Agency, Paris.
- OECD–NEA, IAEA, 2000. Uranium: Resources, Production and Demand. Biannual publications.
- Pan, W., 2000. Discussion on space–time distribution of uranium mineralization in Yili Basin and prospecting strategy for interlayer oxidation zone sandstone–type uranium deposit. *Uranium Geology* 16, 19–25 (in Chinese with English abstract).
- Pelsmaeker, D.E., Jolivet, M., Laborde, A., Poujol, M., Robin, C., Zhimulev, I.F., Nachtergaele, S., Glorie, S., Clercq, D.S., Batalev, Y.V., Grave, D.J., 2018. Source-to-sink dynamics in the Kyrgyz Tien Shan from the Jurassic to the Paleogene: Insights from sedimentological and detrital zircon U–Pb analyses. *Gondwana Res.* 54, 180–204.
- Pons, L.J., Van Breeman, N., Driessen, P.M., 1982. Physiography of coastal sediments and development of potential soil acidity. In: Kittrick, J.A. (Ed.), *Acid Sulfate Weathering*, Soil Science Society of America, Special Publication, vol. 10, pp. 1–18.
- Qin, M.K., Zhao, R.Q., Wang, Z.B., 1999. Recognition model for in–situ leachable sandstone–type uranium deposit. *Uranium Geology* 15, 129–136 (in Chinese with English abstract).
- Rackley, R.L., 1972. Environment of Wyoming Tertiary uranium deposits. *AAPG Bull.* 56, 755–774.
- Reigber, C., Michel, G.W., Galas, R., Angermann, D., Klotz, J., Chen, J.Y., Papschev, A., Arslanov, R., Tzurkov, V.E., Ishanov, M.C., 2001. New space geodetic constraints on the distribution of deformation in Central Asia. *Earth Planetary Science Letters* 191, 157–165.
- Reynolds, R.L., Goldhaber, M.B., Carpenter, D.J., 1982. Biogenic and nonbiogenic ore–forming processes in the South Texas uranium district: evidence from the Panna Maria deposit. *Econ. Geol.* 77, 541–556.
- Robb, L.J., 2005. *Introduction to ore–forming processes*. Blackwell Publishing company, Oxford, pp. 166–168.
- Rosholt, J.N., Zartman, R.E., Nkomo, I.T., 1973. Lead isotope systematics and uranium depletion in the granite mountains. *Geol. Soc. Am. Bull.* 84, 989–1002.
- Roy, S., Gaillardet, J., Allegre, C.J., 1999. Geochemistry of dissolved and suspended loads of the Seine river, France. Anthropogenic impact, carbonate and silicate weathering. *Geochimica et Cosmochimica Acta* 63, 1277–1292.
- Seltmann, R., Konopelko, D., Biske, G., Divaev, F., Sergeev, S., 2011. Hercynian post–collisional magmatism in the context of Paleozoic magmatic evolution of the Tien Shan orogenic belt. *Journal of Asian Earth Science* 42, 821–838.
- Shelobolina, E., Konishi, H., Xu, H., Benzine, J., Xiong, M., Wu, T., Roden, E., 2012. Isolation of phyllosilicate–iron redox cycling micro–organisms from illite–smectite rich hydromorphic soil. *Front. Microbiol.* 3–143, 1–10.
- Shelobolina, E., Xu, H., Konishi, H., Kukkadapu, R., Wu, T., Blothe, M., Roden, E., 2012. Microbial lithotrophic oxidation of structural Fe(II) in biotite. *Appl. Environ. Microbiol.* 78, 5746–5752.
- Shi, X.M., Yang, J.C., Li, Y.L., Nan, F., 2004. Deformation of Manas River terraces and neotectonics in northern front of the Tianshan Mountains. *Acta Sci. Nat. Univ. Pekin.* 40, 971–978 (in Chinese with English Abstract).

- Simonov, V.A., Mikolaichuk, A.V., Rasskazov, S.V., Kovyazin, S.V., 2008. Cretaceous–Paleogene within–plate magmatism in Central Asia: data from the Tien Shan basalts. *Russ. Geol. Geophys.* 49, 520–533.
- Sobel, E.R., Amaud, N., 2000. Cretaceous–Paleogene basaltic rocks of the Tuyon Basin, NW China and the Kyrgyz Tien Shan: the trace of a small plume. *Lithos* 50, 191–215.
- Starkel, L., 2003. Climatically controlled terraces in uplifting mountain areas. *Quat. Sci. Rev.* 22, 2189–2198.
- Stewart, B.D., Neiss, J., Fendorf, S., 2007. Quantifying constraints imposed by calcium and iron on bacterial reduction of uranium(VI). *J. Environ. Qual.* 36, 363–372.
- Tan, L.Q., 1998. Geological and geochemical metallogenic conditions and prospecting significance of Kujie'ertai uranium deposit in Yili Basin. *Uranium Geology* 14, 150–157 (in Chinese with English abstract).
- Tapponnier, P., Molnar, P., 1979. Active faulting and Cenozoic tectonics of the Tien Shan, Mongolia, and Baykal regions. *J. Geophys. Res.* 84, 3425–3458.
- Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., Cobbold, P., 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. *Geology* 10, 611–616.
- Tebo, B.M., Obratzsova, A.Y., 1998. Sulfate-reducing bacterium grows with Cr(VI), U(VI), Mn(IV), and Fe(III) as electron acceptors. *FEMS Microbiol. Lett.* 162, 193–198.
- Tullborg, E.L., Suksi, J., Geipel, G., Krall, L., Auque, L., Gimeno, M., Puigdomenech, I., 2017. The occurrences of $\text{Ca}_2\text{UO}_2(\text{CO}_3)_3$ complex in Fe(II) containing deep groundwater at Forsmark, Eastern Sweden. *Procedia Earth and Planetary Science* 17, 440–443.
- Turner-Peterson, C.E., Fishman, N.S., 1986. Geologic Synthesis and Genetic Models for Uranium Mineralization in the Morrison Formation, Grants Uranium Region, New Mexico. In: Turner-Peterson, C.E., Santos, E.S., Fishman, N.S. (Eds.), *A Basin Analysis Case Study: The Morrison Formation, Grants Uranium Region, New Mexico*. AAPG Studies in Geology, vol. 22, pp. 357–388.
- Wade, R., DiChristina, T.J., 2000. Isolation of U(VI) reduction-deficient mutants of *Shewanella putrefaciens*. *FEMS Microbiol. Lett.* 184, 143–148.
- Wang, B., Faure, M., Cluzel, D., Shu, L.S., Charvet, J., Meffre, S., 2006. Late Paleozoic tectonic evolution of the northern West Tianshan, NW China. *Geodin. Acta* 19, 237–247.
- Wang, B., Shu, L.S., Cluzel, D., Faure, M., Charvet, J., 2007. Geochemical constraints on Carboniferous volcanic rocks of Yili Block (Xinjiang, NW China): implication on tectonic evolution of Western Tianshan. *Journal of Asian Earth Science* 29, 148–159.
- Wang, B., Chen, Y., Zhan, S., Shu, L.S., Faure, M., Cluzel, D., Charvet, J., Laurent-Charvet, S., 2007. Primary Carboniferous and Permian paleomagnetic results from the Yili Block (NW China) and their implications on the geodynamic evolution of Chinese Tianshan belt. *Earth and Planetary Letters* 263, 288–308.
- Wang, B., Kang, Y., Zhang, D.X., 2009. Hydrogeochemical characteristics and the relationship with uranium mineralization in Mengqiguer Area. *Xinjiang Geol.* 27, 364–367 (in Chinese with English abstract).
- Wang, B., Cluzel, D., Shu, L.S., Faure, M., Charvet, J., Chen, Y., Meffer, S., De Jong, K., 2009. Evolution of calc–alkaline to alkaline magmatism through Carboniferous convergence to Permian transcurrent tectonics, western Chinese Tianshan. *Int. J. Earth Sci.* 98, 1275–1298.
- Wang, J., Geng, S.F., 2009. Characteristics of the interlayer oxidation zone and the Kujie'ertai uranium deposit in Yili Basin. *Geology of China* 36, 705–713 (in Chinese with English abstract).
- Wang, J.P., Min, M.Z., Chen, Y.H., Peng, X.J., 2005. Study on the relationship between $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios and ore-bearing capacity in interstratified oxidized zone: exemplified by Kujie'ertai and Wukuerqi uranium deposit. *Geol. J. China Univ.* 11, 77–84 (in Chinese with English abstract).
- Wang, M., Zhang, J.J., Liu, K., 2015. Continuous denudation and pediplanation of the Chinese Western Tianshan orogeny during Triassic to Middle Jurassic: Integrated evidence from detrital zircon age and heavy mineral chemical data. *Journal of Asian Earth Science* 113, 310–324.
- Wang, Y., Chen, Z.L., Liu, J., Zheng, E.J., Wang, C., Li, S.X., Han, X.Z., 2006. Neotectonics in southern Yili Basin and its control of sandstone–type uranium deposits. *Geotecton. Metallog.* 30, 486–494 (in Chinese with English abstract).
- Wang, Z.Q., Cao, S.L., Pan, J.Y., Guan, T.Y., Zhang, G.Y., 2005. Trace element geochemistry of no. 511 uranium ore deposit in Xinjiang. *Mineral Deposits* 24, 409–415 (in Chinese with English abstract).
- Wang, Z.Q., Li, Z.Y., Guan, T.Y., Zhang, G.Y., 2006. Geological characteristics and metallogenic mechanism of no. 511 sandstone–type uranium ore deposit in Yili Basin, Xinjiang. *Mineral Deposits* 25, 302–311 (in Chinese with English abstract).
- Weber, K.A., Picardal, F.W., Roden, E., 2001. Microbially catalyzed nitrate–dependent oxidation of biogenic solid–phase Fe(II) compounds. *Environ. Sci. Technol.* 35, 1644–1650.
- Weber, K.A., Achenbach, L.A., Coates, J.D., 2006. Microorganisms pumping iron: anaerobic microbial iron oxidation and reduction. *Nat. Rev. Microbiol.* 4, 752–764.
- Wendt, I., 1984. A three–dimensional U–Pb Discordia plane to evaluate samples with common lead of unknown isotopic composition. *Chem. Geol.* 46, 1–12.
- Williams, K.H., Long, P.E., Davis, J.A., Steefel, C.I., Wilkins, M.J., N'Guessan, A.L., Yang, L., Newcomer, D., Spane, F.A., Kerkhof, L.J., McGuinness, L., Dayvault, R., Lovely, D.R., 2011. Acetate availability and its influence on sustainable bioremediation of uranium-contaminated groundwater. *Geomicrobiol. J.* 28, 519–539.
- Windley, B.F., Allen, M.B., Zhang, C., Zhao, Z.Y., Wang, G.R., 1990. Paleozoic accretion and Cenozoic redeformation of the Chinese Tien–Shan–Range, Central–Asia. *Geology* 18, 128–131.
- Wu, C.Y., Zheng, W.J., Zhang, Z.Q., Jia, Q.C., Yu, J.X., Zhang, H.P., Han, G.H., Yao, Y., 2018. Terrace sequence along the Yushangxi River in the southern piedmont of Tien Shan and its relationship to climate and tectonics in northwestern China. *Geomorphology* 313, 48–57.
- Xia, Y.L., Lin, J.R., Liu, H.B., Fan, G., Hou, Y.X., 2002. Research on geochronology of sandstone–hosted uranium ore–formation in major uranium–productive basins, Northern China. In: Bureau of Geology, CNNC (ed) *Sandstone–type uranium deposits in China: Geology and exploration techniques*. Atomic Energy Press, Beijing, pp. 166–177.
- Xia, Y.L., Lin, J.R., Liu, H.B., Fan, G., Hou, Y.X., 2003. Research on geochronology of sandstone–hosted uranium ore–formation major uranium productive basins, northern China. *Uranium Geology* 19, 129–136 (in Chinese with English abstract).
- Xu, X.W., Deng, Q.D., Zhang, P.Z., 1992. Deformation of river terraces across the Manas–Huoerguos reverse fault and fold zone and its Neotectonic implication in Xinjiang, northwestern China. *Research of Active Fault* 2, 117–126 (in Chinese with English Abstract).
- Yang, J.C., Li, Y.L., 2005. *Principle of Geomorphology*. Peking University Press, Beijing. (in Chinese).
- Yang, S., Li, J., Wang, Q., 2008. The deformation pattern and fault rate in the Tianshan Mountains inferred from GPS observations. *Science in China (Series D)* 51, 1064–1080.
- Yang, X.P., Li, A., Huang, W.L., 2013. Uplift differential of active fold zones during the late Quaternary, northern piedmonts of the Tianshan Mountains, China. *Science in China (Series D)* 56, 794–805.
- Yin, A., Nie, S., Craig, P., Harrison, T.M., Ryerson, F., Qian, X.L., Yang, G., 1998. Late Cenozoic tectonic evolution of the southern Chinese Tien Shan. *Tectonics* 17, 1–27.
- Zhang, C., Cai, Y.Q., Xu, H., Dong, Q., Liu, J.L., Hao, R.X., 2017. Mechanism of mineralization in the Changjiang uranium ore field, South China: evidence from fluid inclusions, hydrothermal alteration, and H–O isotopes. *Ore Geol. Rev.* 86, 225–253.
- Zhang, C., Yi, C., Dong, Q., Cai, Y.Q., Liu, H.X., 2018. Geological and geochronological evidence for the effect of Paleogene and Miocene uplift of the Northern Ordos Basin on the formation of the Dongsheng uranium district, China. *J. Geodyn.* 114, 1–18.
- Zhang, G.Q., 2008. *Geochemistry of hydrothermal uranium deposits in South China: A case study of the No. 302 uranium deposit*. Chinese Academy of Science, Ph.D. Dissertation, Guiyang, pp. 1–96 (in Chinese with English abstract).
- Zhang, J.D., 2012. Progress and outlook of uranium exploration in Meso–Cenozoic basins in North China. *Uranium Geology* 28, 193–198 (in Chinese with English abstract).
- Zhang, J.D., 2016. Innovation and development of metallogenic theory for sandstone type uranium deposit in China. *Uranium Geology* 32, 321–332 (in Chinese with English abstract).
- Zhang, L., Liu, C.Y., Fayek, M., Wu, B.L., Lei, K.Y., Cun, X.N., Sun, L., 2017. Hydrothermal mineralization in the sandstone–hosted Hangjinqi uranium deposit, North Ordos Basin, China. *Ore Geol. Rev.* 80, 103–115.
- Zhang, P.Z., Deng, Q.D., Yang, X.P., Feng, X.Y., Peng, S.Z., Zhao, R.B., 1995. Glaciofluvial fan and neotectonic movement along the north piedmont of Tien Shan Mountains. *Research of Active Fault* 4, 63–78 (in Chinese with English Abstract).
- Zhang, P.Z., Shen, Z., Wang, M., Gan, W.J., Bürgmann, R., Molnar, P., 2004. Continuous deformation of the Tibetan Plateau from global positioning system data. *Geology* 32, 809–812.
- Zhang, Z.F., Jiang, H., Wang, M.M., 2010. Metallogenic factors of the Mengqiguer uranium deposit and their significance in the uranium prospecting in Yili Basin. *Mineral Deposits* 29 (s), 165–166 (in Chinese).
- Zhao, J.D., Song, Y.G., King, J.W., Liu, S., Wang, J., Wu, M., 2010. Glacial geomorphology and glacial history of the Muzart River valley, Tianshan Range, China. *Quat. Sci. Rev.* 29, 1453–1463.
- Zhao, L., Dong, H., Kukkadapu, R., Agrawal, A., Liu, D., Zhang, J., Edelmann, R.E., 2013. Biological oxidation of Fe(II) in reduced nontronite coupled with nitrate reduction by *Pseudogulbenkiania* sp. Strain 2002. *Geochim. Cosmochim. Acta* 119, 231–247.
- Zhao, L., Dong, H., Kukkadapu, R.K., Zeng, Q., Edelmann, R.E., Pentra, M., Agrawal, A., 2016. Biological redox cycling of iron in nontronite and its potential application in nitrate removal. *Environ. Sci. Technol.* 49, 5493–5501.
- Zhao, L.D., Dong, H.L., Edelmann, R.E., Zeng, Q., Agrawal, A., 2017. Coupling of Fe (II) oxidation in illite with nitrite reduction and its role in clay mineral transformation. *Geochim. Cosmochim. Acta* 200, 353–366.
- Zhou, W.X., 2000. *Uranium provinces in China*. Manuscript for IAEA atlas/UDEPO, 18 p (unpublished).