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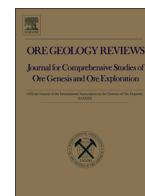
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Geology, geochemistry and genesis of the Cretaceous and Paleocene sandstone- and conglomerate-hosted Urogen Zn–Pb deposit, Xinjiang, China: A review



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ARTICLE INFO

Article history:

Received 30 March 2014

Received in revised form 2 June 2014

Accepted 3 June 2014

Available online 10 June 2014

Keywords:

Sandstone-hosted

Zn–Pb deposit

Urogen

Meso-Cenozoic

Continental basin

Kashi

Xinjiang

ABSTRACT

The Urogen Zn–Pb deposit in Wujia County, Xinjiang, China, is hosted in sandstones and conglomerates of the Lower Cretaceous Kezilesu Group and argillaceous dolomite of the Paleocene Aertashi Formation in the Kashi sag, northwestern Tarim basin. The deposit is characterized mainly by low grade (Zn + Pb ~ 3 wt.%) and large tonnage (~3 Mt metals in the southern ore zone, potentially 10 Mt metals for the whole deposit), with an average Zn/Pb ratio of about 5.8. The orebodies are tabular and stratiform, mainly distributed in a syncline. The ores are characterized by disseminated sulfides with minor massive, veinlet, patchy structures, and fine-grained, locally colloform and frambooidal, textures. The main primary metallic minerals are sphalerite, galena, pyrite and marcasite, and minor supergene minerals include smithsonite, hydrozincite, anglesite, calamine, jarosite, and limonite. The ore minerals mainly occur as replacement of cements, matrix and framework grains of the host rocks and as open space filling to a lesser extent. Based on the fact that orebodies straddle across a hiatus between the lower Cretaceous and Paleocene host rocks and on the replacement and open-space filling textures and structures, the mineralization is interpreted to be epigenetic. The tightly clustered Pb isotopic values of the main-stage ore minerals (²⁰⁶Pb/²⁰⁴Pb ranging from 18.608 to 18.663, ²⁰⁷Pb/²⁰⁴Pb from 15.619 to 15.669, ²⁰⁸Pb/²⁰⁴Pb from 38.677 to 38.839) suggest that a single source supplied the metals, whereas the wide range of S isotopes (δ³⁴S from −27.9‰ to 14.6‰ VCDT) indicates multiple sources of reduced sulfur including those from thermal sulfate reduction (TSR) and bacterial sulfate reduction (BSR). The organic matter in the ores is characterized by relatively low concentrations of saturated hydrocarbons, high concentrations of aromatic hydrocarbons, asphaltenes and non-hydrocarbons, and low maturity compared to that in the host rocks and equivalent strata away from mineralization. Both hydrocarbons in the ores and host rocks show little biodegradation. These characteristics of organic matter suggest that the site of mineralization was buried to significant depths and heated to above 80 °C before the charging of hydrocarbons (thus non-development of biodegradation), that some of the hydrocarbons were consumed in mineralization (thus decreased maturity), probably used as reducing agents for sulfate reduction in situ, and that bacteria-derived sulfur in the ores was not generated in situ. Mineralization probably resulted from mixing of a metal-rich fluid with multiple fluids carrying reduced sulfur from different sources (including some reduced sulfur from in situ TSR). However, it remains unclear whether the metal-carrying fluid was derived from a near-surface groundwater system and flowed downward to the site of mineralization at burial conditions, or was derived from deeper parts of the basin and flowed up to the site of mineralization as part of a hydrothermal system; the distinction of the two models requires a better understanding of the thermal profile across the deposit.

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1. Introduction

Zn–Pb deposits hosted in sedimentary rocks represent the most important resources of lead and zinc in the world, among which the

largest are of sedimentary exhalative (SEDEX) type and Mississippi Valley-type (MVT) (Leach et al., 2005). Compared to shale- and carbonate-hosted SEDEX and MVT deposits, only a few large Zn–Pb deposits have been found in sandstones (Bjorlykke and Sangster, 1981; Leach et al., 2005), including the Jinding Zn–Pb deposit in China (Kyle and Li, 2002; Xue et al., 2007) and the Laisvall Pb–Zn deposit in Sweden (Rickard et al., 1979). The Urogen deposit in Xinjiang, China,

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is hosted in lower Cretaceous and Paleocene sandstones and conglomerates, and it represents a new example of large, coarse clastic rocks-hosted Zn–Pb deposits. The large size of the Uragen deposit was not recognized although discovered in the 1950s until 2007 when reassessment exploration of the deposit indicated a resource of 980.9 Mt of ore grading 2.61% Zn and 0.45% Pb for the western part of the southern ore zone, with a potential resource of 10 Mt of metals for the whole deposit (Zhu et al., 2010). Large-scale production at Uragen started in 2010 from an open pit in its southern ore zone, and production from the northern zone is being planned. These newly-discovered, large-tonnage, low-grade ore zones provide a good opportunity to examine the formation mechanism of the class of sandstone- and conglomerate-hosted Zn–Pb deposits, which is much less understood for the genesis of this class than for SEDEX and MVT deposits.

A number of studies have been carried out on the Uragen deposit and published in the Chinese literature (Bai et al., 2008; Cai, 1993; Dong et al., 2013; Gao et al., 2002; He, 2007; Kang et al., 2009; Kong, 1984; Li et al., 2005, 2013; Peng, 1990; Xie et al., 2003; Ye et al., 1999; Zhang, 2010; Zhu et al., 2010). These studies have classified the deposit into various types, including syngenetic or SEDEX (Bai et al., 2008; Cai et al., 2002; Xie et al., 2003), reworked syngenetic (He, 2007; Li and Wang, 2006), epigenetic basinal-brine type (Gao et al., 2002; Kang et al., 2009; Li et al., 2005; Ye et al., 1999), and a sandstone-hosted variant of MVT (Zhang, 2010; Zhu et al., 2010). Sulfur isotope studies of sulfides have yielded a wide range of $\delta^{34}\text{S}$ (VCDT) values, from -27.9‰ to 14.6‰ (Cai et al., 2002; Zhang, 2010), whereas the Pb isotopes of sulfides fall in a fairly narrow range with $^{206}\text{Pb}/^{204}\text{Pb}$ from 18.618 to 18.629, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.632 to 15.640, and $^{208}\text{Pb}/^{204}\text{Pb}$ from 38.708 to 38.734 (Zhang, 2010). The presence of hydrocarbons at the site of mineralization and in surrounding areas has been noticed, and their potential roles have been discussed (e.g., Liu et al., 2010). However, many questions about the mineralization conditions and processes remain unanswered. The age of mineralization and its relative timing with the host rocks, the sources of the ore forming fluids, metals and sulfur, and the mechanisms of ore precipitation remain questions of debate. The present paper aims to provide an up-to-date summary of the geologic characteristics of the Uragen deposit, and to discuss its origin based on previous and new geologic and geochemical data, especially ore petrography, S and Pb isotopes, and geochemistry of organic matter.

2. Regional geological setting

The Uragen Zn–Pb deposit is located in the northwestern part of the Kashi sag on the western margin of the Tarim basin (Fig. 1). The Kashi sag is a Meso-Cenozoic intracontinental basin developed between the Southern Tianshan and Western Kunlun mountain orogens. Thus the structural framework is controlled by the east-northeast trending Southern Tianshan to the north, west-northwest trending Western Kunlun to the south, and the northwest trending Fergana dextral fault (Fig. 1; Wang et al., 2003; Zhou et al., 2005).

The Kashi sag is underlain by Paleozoic sedimentary rocks that rest on a Precambrian metamorphic basement. The lower Paleozoic sedimentary rocks were developed in passive margins associated with the Southern Tianshan ocean and the Western Kunlun ocean, whereas the upper Paleozoic strata were deposited in foreland basins following the closure of the oceans when the Kashi sag was connected to the rest of the Tarim basin in shallow-marine carbonate and clastic environments (Wang et al., 2003; Zhou et al., 2005). After a period of non-deposition during the Triassic, alluvial and lacustrine coal-bearing successions were deposited in the Jurassic, followed by widespread development of red-colored sandstone, conglomerate and mudstone in alluvial and braided river environments in the Early Cretaceous (Li and Wang, 2008; Li and Zeng, 2007; Wang et al., 2003). From Late Cretaceous to Paleogene, the Kashi sag was subject to a widespread marine transgression, forming a succession of transitional-marine and marine clastic

rocks, carbonates and evaporites. In the Neogene, as a result of the collision between the continents of India and Eurasia and the associated rapid uplift of the Southern Tianshan and Western Kunlun, the Kashi sag experienced rapid subsidence and received a thick accumulation of shales, siltstones, sandstones and evaporites, mainly in lacustrine and fluvial environments but partly also in marginal marine environments. The Quaternary sediments are characterized by conglomerates deposited in alluvial fans (Li and Wang, 2008; Li and Zeng, 2007; Wang et al., 2003; Zhou et al., 2005). Various mineral and energy resources are developed in the Kashi sag, including copper (J_3 and N_1), lead–zinc (K_1 and E_1), uranium (K_1), oil and gas (K_1), coal (J_1) and salts (K_1) (Li et al., 2011).

3. Geology of the Uragen Zn–Pb deposit

The strata occurring regionally around the Uragen Zn–Pb deposit include, from older to younger, the Proterozoic Akesu Group, Lower Jurassic Kangsu Formation, Middle Jurassic Yangye and Taerduo formations, Upper Jurassic Kuzigongsu Formation, Lower Cretaceous Kezilesu Group, Paleocene Artashi Formation, Paleocene–Eocene Qimugen Formation, Eocene Kalatar and Uragen formations, Eocene–Oligocene Bashibulake Formation, Oligocene–Miocene Keziluoyi Formation, Miocene Anjuan and Pakabulake formations, and Quaternary Xiyu Formation. The lithologies of these stratigraphic units are described in Table 1.

The orebodies are hosted mainly in the Lower Cretaceous Kezilesu Group and to a lesser extent in the Paleocene Artashi Formation. The Kezilesu Group is divided into five members, and their lithologies, from older to younger, are described as follows. The first member (lowermost) consists of brown-red (locally grey-green to grey-white) mudstone with intercalated sandstone and conglomerate, the second member of purple-grey to dark brown-red sandstone interbedded with mudstone with local gravelly sandstone, the third member of thick grey-white beds of gravelly sandstone and lithic sandstone with minor brown-red silty mudstone and local conglomerate, the fourth member of brown-red lithic sandstone and interbedded silty mudstone with intercalated gravelly sandstone and conglomerate, and the fifth member of grey-white, grey-brown and brown-yellow conglomerate, sandy conglomerate, gravelly sandstone, quartz sandstone and lithic sandstone with intercalated purple-red to brown-red mudstone and intercalated sandstone at the top. The Paleocene Artashi Formation consists of grey-white gypsum with intercalated grey, argillaceous dolomite that is topped by bioclastic limestone.

The lithologies in the Uragen area are controlled by an east–west trending syncline that plunges to the west (the Uragen syncline, Figs. 2 and 3). The southern limb dips to NNW at a dip angle of about 50° , whereas the northern limb dips to the south with dip angles from 65° to 80° (locally overturned). A NE-trending fault (the Heiziwei Fault, or F_1) is developed in the south limb of the fold, separating Jurassic and Proterozoic strata from the Miocene Pakabulake Formation to the southeast (Fig. 2). The E–W trending Wuheshalu Fault (F_2) is developed between the Artashi Formation and the Kezilesu Group in the northern limb of the Uragen syncline, and truncates the Cretaceous strata near the hinge of the fold (Fig. 2). The F_3 reverse fault located to the north truncates and offsets the Cretaceous and Jurassic strata (Fig. 2). A few NE- and ENE-trending reverse faults are also developed east of the hinge of the syncline (Fig. 2).

The orebodies are tabular and stratiform, distributed on both limbs of the Uragen syncline (Fig. 2) as well as in the hinge area (at depth, Fig. 3). The orebodies shown in Fig. 2 are those of economic value; they are transitional to low-grade ore in Fig. 3. The majority of the ore is hosted in grey-white sandy conglomerate of the fifth member of the Cretaceous Kezilesu Group, and a minor portion is hosted in grey, argillaceous dolomite of the Paleocene Artashi Formation (Figs. 2 and 3). The deposit is divided into the northern ore zone and the south zone that are located in the northern and southern limbs of the Uragen

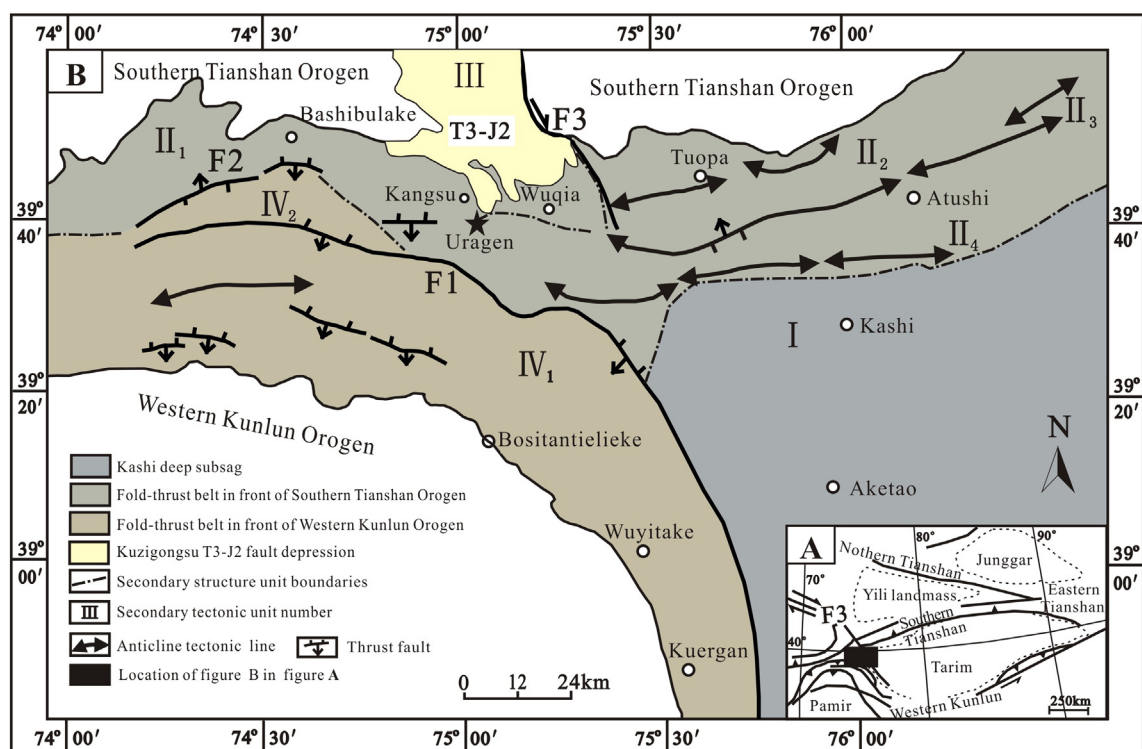


Fig. 1. Regional geologic map of the Kashi sag with the inset showing its location in the Tarim basin and relationships with Southern Tianshan and Western Kunlun orogens (modified after Gao et al., 2002; Ma and Yang, 2003; Zhou et al., 2005). I – Kashi deep subsag; II – Fold-thrust belt in front of the Southern Tianshan Orogen; II₁ – Bashibulak fold-thrust zone; II₂ – Tuopa–Tashipisake anticline; II₃ – Atushi anticline; II₄ – Kashi anticline; III – Kuzigongsu T₃–J₂ fault depression; IV – Fold-thrust belt in front of the Western Kunlun Orogen; IV₁ – Wupa thrusting zone; IV₂ – Xiaerbulak structure zone; IV₃ – Yingjiesha anticline; F₁ – Wuchibielike Mountain fault; F₂ – Wuqia fault; F₃ – Talas–Fergana large-scale strike-slip fault.

Table 1
Stratigraphic units and lithologies in the Uragen Zn–Pb deposit area.^a

Era	System	Formation/Group	Abbrev.	Lithologies
Cenozoic	Quaternary	Xiyu Fm	Q	Dark grey, grey-black conglomerate with local interbedded grey to grey-yellow sandstone
	Miocene	Pakabulake Fm	N _{1p}	Grey-brown calcareous mudstone and silty mudstone with interbeds of light-brown fine- to median-grained sandstones and intercalated light-grey and grey-green siltstone
		Anjuan Fm	N _{1a}	Grey-green (Cu-bearing) lithic quartz arenite with interbedded mudstone, light purple-red mudstone with interbedded grey-green lithic quartz arenite present in the uppermost part
		Keziluyi Fm	(E ₃ –N ₁)k	Upper part: light purple-red mudstone with sandstone interbeds
	Oligocene	Bashibulake Fm	E _{2-3b}	Lower part: light purple-red sandstone with minor mudstone and thin evaporite interbeds
				Upper part: purple-red mudstone with interbeds of sandstones
	Eocene	Uragen Fm	E _{2w}	Middle part: purple-red mudstone with interbeds of grey-green calcareous mudstone and shelly limestone
				Lower part: massive gypsum
				Grey-green calcareous mudstone with interbeds of shelly limestone
				Upper part: grey massive limestone and shelly limestone
Mesozoic	Paleocene	Qimugen Fm	E _{1-2q}	Lower part: grey to grey-green mudstone with interbeds of grey limestone, shelly limestone and argillaceous limestone and gypsum
				Upper part: brown-red evaporite-bearing mudstone
				Lower part: grey-green calcareous mudstone with interbeds of shelly limestone
				Grey-white massive gypsum with interbedded grey argillaceous dolomite with grey bioclastic limestone at the top
	Lower Cretaceous	Kuzigongsu Fm	J _{3k}	Purple-red sandstone with interbeds of grey-white sandstone, conglomerate and minor silty mudstone, with minor thin beds of grey-green fine-grained sandstone in the middle-upper part
				Dark-red and brown-red (grading laterally to grey or green) conglomerate with interbeds of sandstone and minor sandy mudstone
	Upper Jurassic	Taerduo Fm	J _{2t}	Grey-green mudstone with interbeds of grey-green massive sandstones and minor purple-red mudstone and thin beds of argillaceous limestone with a conglomerate bed at the base
				Grey to grey-black shale with thin interbeds of massive sandstone, carbonaceous shale, argillaceous limestone, coal seams and minor conglomerate
	Middle Jurassic	Yangye Fm	J _{2y}	Grey-green and grey-white fine-grained quartz sandstone interbedded with carbonaceous mudstone, conglomerate and coal beds
				Chlorite schist, biotite schist, chlorite-sericite schist with interbedded lenses of marble
Proterozoic	Changcheng	Akesu Gr	Chak	

^a Modified after XSCG, 1981; Cai et al., 2002; Wang et al., 2003.

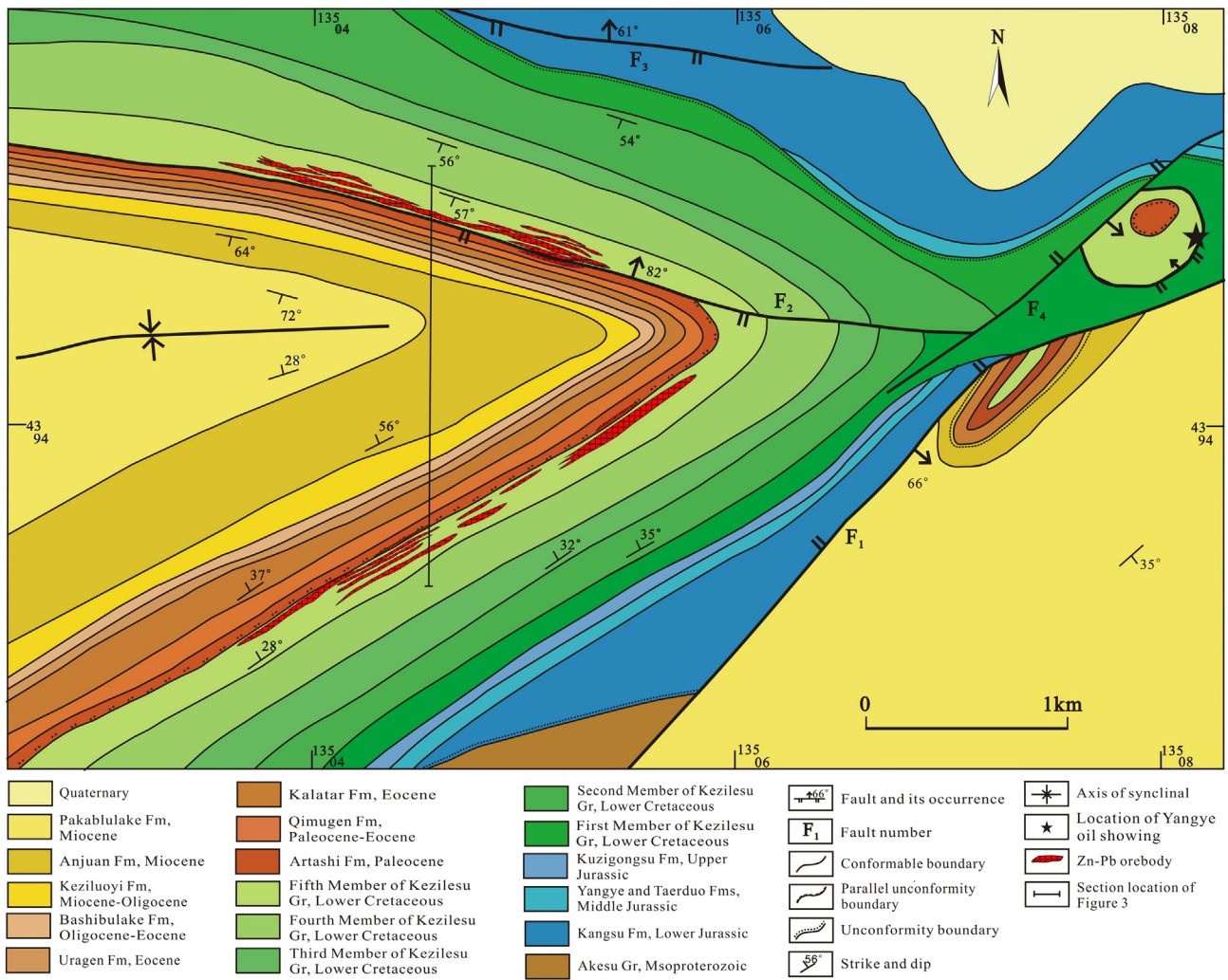


Fig. 2. Geologic map of the Uragen Zn-Pb deposit and surrounding area. Modified after Zhu et al. (2010).

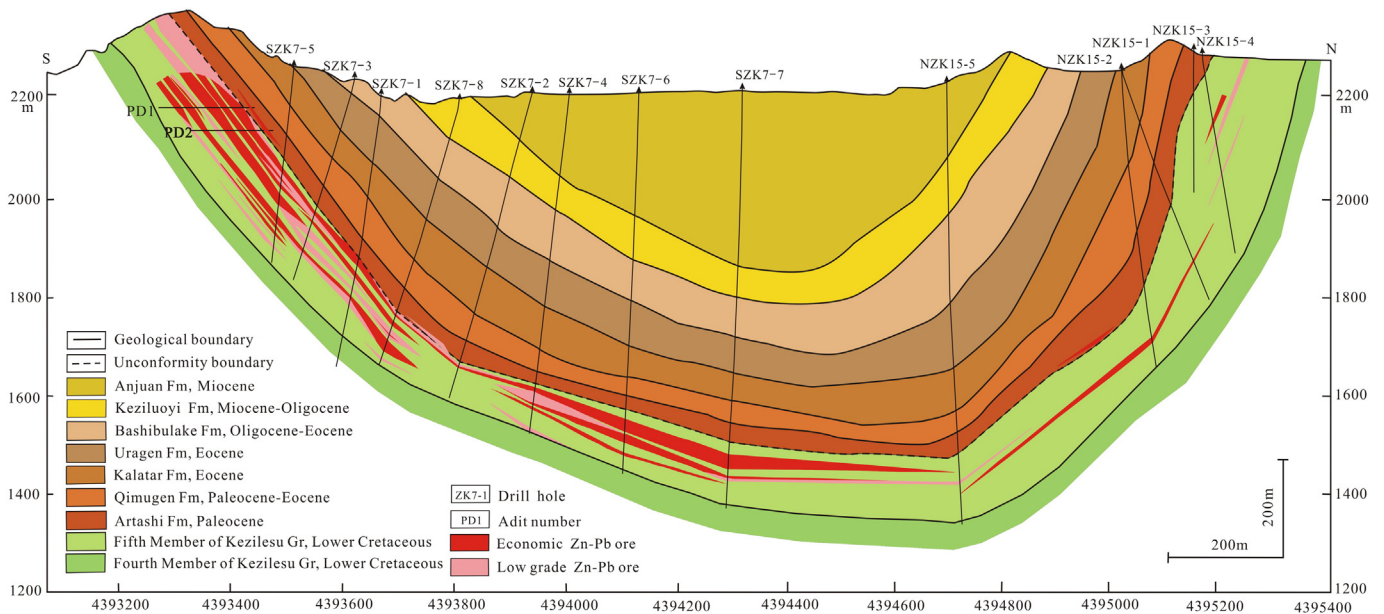


Fig. 3. A cross section of the Uragen Zn-Pb deposit (modified after Jinwang Mining Company). The location of the cross-section is shown in Fig. 2.

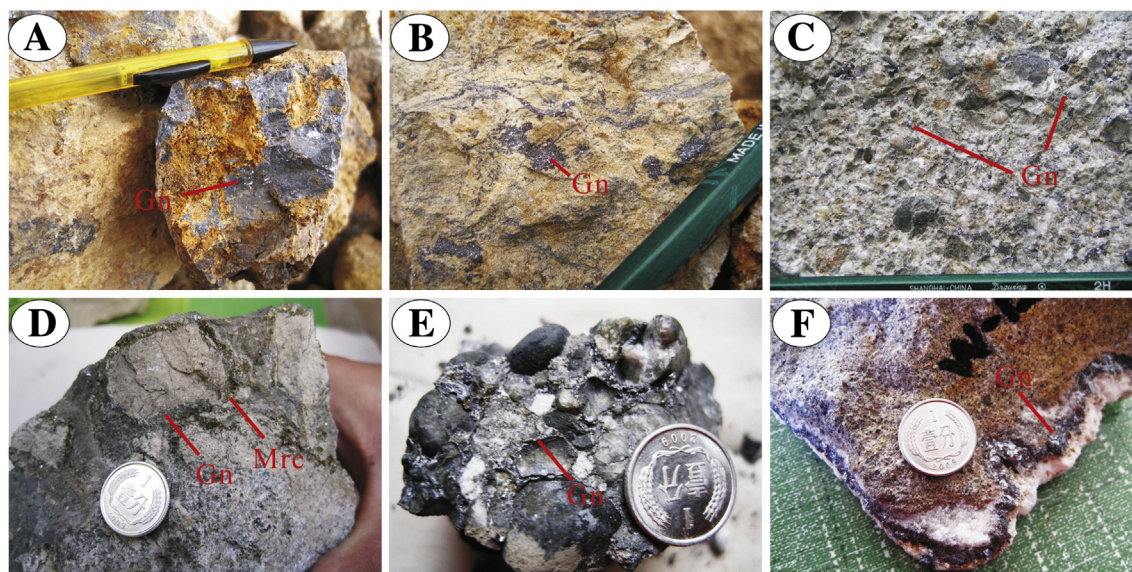


Fig. 4. Photographs of hand samples from the Uragen Zn–Pb deposit showing various occurrences of mineralization. A) massive ore composed of mainly fine-grained galena, hosted in dolomite of Paleocene Artashi Formation from northern ore zone; B) patches of fine-grained galena in sandstone from the southern ore zone; C) fine-grained sphalerite and galena disseminated in gravelly sandstone from the southern ore zone; D) fine-grained galena and marcasite disseminated in the matrix of conglomerate from the southern ore zone; E) fine-grained galena disseminated the matrix of a conglomerate from the southern ore zone; F) a galena–sphalerite–celestine vein from the northern ore zone. Gn—galena; Mrc—marcasite.

syncline, respectively (Fig. 2). The northern ore zone, mainly developed along the Wuheshalu fault (F₂, Fig. 2), has an average thickness of 100 m with Pb grades from 0.03 to 0.47 wt.% and Zn grades from 2.24 to 3.41 wt.%. The orebodies appear to have been controlled by the fault, but locally they are cut and offset by the latter. The southern ore zone has an average thickness of 150 m with Pb grades from 0.23 to 0.89 wt.% and Zn grades from 1.69 to 3.64 wt.%. A core drill in 2007 in the middle of the Uragen syncline intersected Zn–Pb mineralization at a depth of 700 m, suggesting that the two ore zones are connected at depth (Fig. 3). There is no significant supergene-enriched mineralization above the primary sulfide orebodies because of the arid climate. On-going exploration is aimed at delineating orebodies in the western part and the hinge area of the syncline.

The Zn–Pb mineralization in the Uragen deposit occurs as massive sulfides (Fig. 4A), patches and veinlets of sulfides in the host rocks (Fig. 4B), disseminations in the matrix and cements of sandstones (Fig. 4C) and conglomerates (Figs. 4D and E), and locally as veins of sulfides and celestine (Fig. 4F). The disseminated ore represents the dominant type of ore in the deposit, accounting for the largest percentage of contained metals, and some massive ore is locally developed in the northern ore zone.

The primary sulfide minerals in the ores are mainly sphalerite, galena, pyrite and marcasite, and the trace supergene minerals include smithsonite, hydrozincite, anglesite, calamine, jarosite, and limonite. Primary sulfide minerals mainly occur as fine crystals (0.001–0.01 mm in diameter) that infill interstitial space between framework grains in

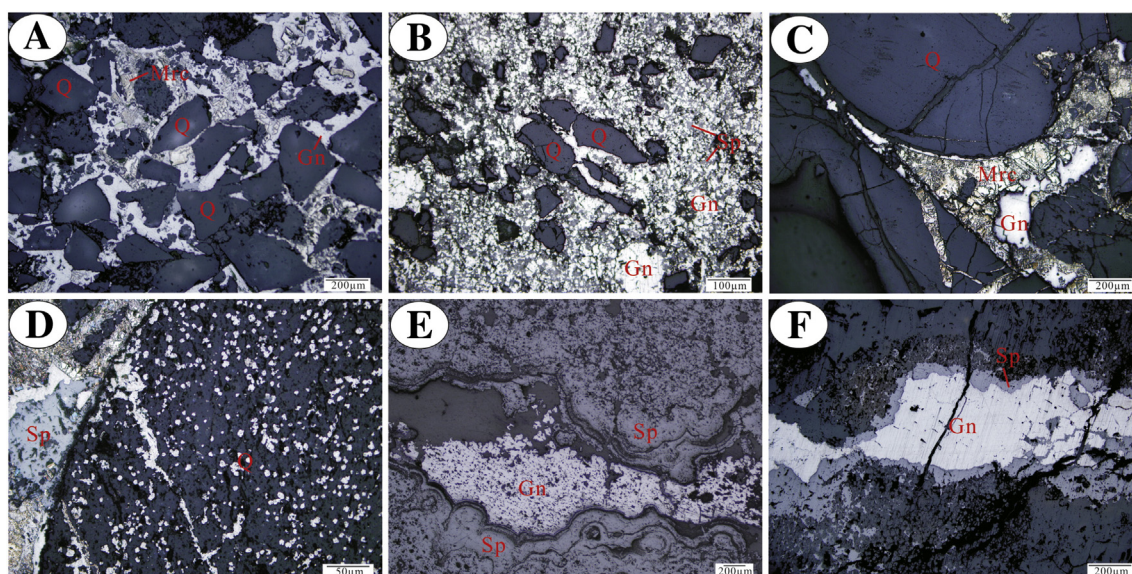


Fig. 5. Photomicrographs of ores from the Uragen Zn–Pb deposit showing various ore textures. A) fine-grained galena, sphalerite and marcasite disseminated in sandstone and replacing matrix, calcareous cements and framework grains from the southern ore zone; B) high-grade ore with fine-grained sphalerite and galena massively replacing the matrix and framework grains of sandstone from the southern ore zone; C) galena and marcasite disseminated in matrix of conglomerate from the southern ore zone; D) fine-grained sphalerite, galena and marcasite disseminated in the matrix and within a quartz pebble in conglomerate, locally forming veinlets with the pebble from the southern ore zone; E) colloform sphalerite followed by galena in the residual space of the massive ore from the northern ore zone; F) a veinlet of sphalerite and galena filling a fracture with galena postdating sphalerite from the northern ore zone. Gn—galena; Sp—sphalerite; Mrc—marcasite; Q—quartz.

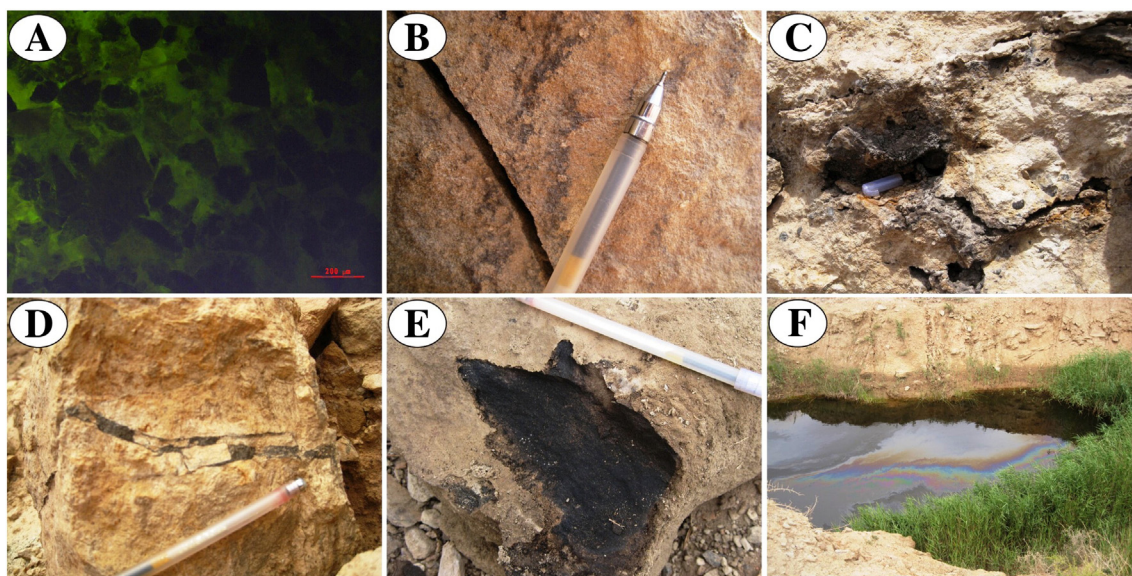


Fig. 6. Various occurrences of organic matter in the Uragen Zn–Pb deposit. Photomicrographs of: A) a sandstone-hosted ore under the ultraviolet light showing yellowish green fluorescence of organic matter from the northern ore zone; B) oil stains in sandstone of the fifth member of Kezilesu Group, Lower Cretaceous, southern ore zone; C) solid bitumen in cavities in conglomerate of the fifth member of Kezilesu Group, Lower Cretaceous, southern ore zone; D) a bitumen vein in gravelly sandstone of the fifth member of Kezilesu Group, Lower Cretaceous, northern ore zone; E) bitumen-saturated sandstone of the fifth member of Kezilesu Group, Lower Cretaceous, northern ore zone; F) liquid oil derived from the fifth member of Kezilesu Group, Lower Cretaceous, floating in a pond, Yangye oil show.

sandstones and conglomerates, and that replace matrix and calcareous cements as well as framework grains (Figs. 5A to D). Open-space filling textures are locally developed, including colloform sphalerite filling vugs, followed by galena (Fig. 5E), and sphalerite and galena filling fractures (Fig. 5F). The relative timing of the sulfides in the disseminated ores is difficult to determine, but locally a sequence from pyrite through sphalerite to galena was recognized (Figs. 5A and B). The minor, open space-filling sulfides post-date the disseminated sulfides with galena being generally later than sphalerite (Figs. 5E and F). Calcite, gypsum and celestine occur in the matrix and interstitial space in the sandstones and conglomerates, and as veins cutting across the mineralized host rocks. The former occurrence may have been formed in the sedimentary or early diagenetic stage, whereas the latter occurrence post-date mineralization. Gypsum and celestine are locally associated with Zn–Pb sulfides, but they do not appear to be co-precipitated (Fig. 4F). The overall paragenetic sequence is sedimentation of the host-rocks → formation of calcite, gypsum and celestine in the early diagenetic stage → disseminated mineralization (pyrite + marcasite + sphalerite + galena ± gypsum and celestine) → open space-filling mineralization (sphalerite + galena ± gypsum and celestine) → veins of calcite, gypsum and celestine.

Organic matter commonly occurs in the ores and host rocks of the Uragen deposit, as well as oil-sands in the Yangye oil-showing near Uragen (Fig. 2). The organic matter, including kerogen, heavy oil and bitumen, is disseminated in the ores and host rocks, and shows a yellowish green fluorescence under ultraviolet microscopy (Fig. 6A). Oil stains (Fig. 6B) and solid bitumen (Fig. 6C and D) are commonly seen in the host rocks. In the Yangye area near Uragen (Fig. 2), oil-sands (Fig. 6E) are locally developed in the Kezilesu Formation (K₁kz), and liquid oil occurs on the surface of some water ponds (Fig. 6F).

4. Methods and results

In recent years, field work has been carried along several lines in the Uragen region including measurements of geological sections, observations of open pit, adits and drill cores, sampling of ores, rocks and organic matters. Thin and polished sections were cut for petrographic and ore microscopy observations. The S- and Pb-isotopic compositions of sulfide

minerals in the ores and the geochemical compositions of organic matters in various samples have been analyzed.

4.1. S- and Pb-isotopic analyses

The sulfide minerals were separated from the ores and analyzed for S- and Pb-isotopes. A few sulfate samples and whole-rock samples from the host rocks were also analyzed for S- and Pb-isotopes, respectively.

Sulfide minerals were manually separated with a purity of >98%. Both sulfide and whole-rock samples were ground to powder (200 mesh) and analyzed at the Beijing Institute of Geology of the Ministry of Nuclear Industry. The sulfur in sulfides and sulfates was first converted to SO₂ through reaction with Cu₂O, and then analyzed with a Finnigan MAT-251 mass spectrometer; the accuracy of the S isotope analyses is better than ±0.2‰. The results of S isotope analyses are listed in Table 2. The lead in sulfides and whole-rock samples were extracted through reaction with HF + HClO₄ solutions, followed by ion exchange processes, and Pb isotopes were then analyzed with an ISOPROBE-T surface ionization mass spectrometer. The error of analysis for 1 μg Pb is <0.05‰ for ²⁰⁶Pb/²⁰⁴Pb and <0.005‰ for ²⁰⁸Pb/²⁰⁶Pb. The results of Pb isotope analyses are listed in Table 3.

δ³⁴S_{V-CDT} of sulfides vary widely from −27.9‰ to 14.6‰ (electronic supplementary materials (ESM)—Table 2, Fig. 7), whereas those of sulfates fall in a narrow range from 17.9‰ to 18.6‰. The δ³⁴S_{V-CDT} values are −27.9‰ to 14.6‰ (average −10.9‰) for galena, −16.3‰ to 1.1‰ (average −6.08‰) for sphalerite, and −8.6‰ to −4.4‰ (average −6.46‰) for pyrite. There is an apparent difference in δ³⁴S_{V-CDT} between the northern ore zone and the southern ore zone (Fig. 7) with those in the former ranging from −24.4‰ to −6.1‰ (average −15.2‰) and those in the latter from −27.9‰ to 14.6‰ (average −4.71‰).

The Pb isotopes of sulfides in the ores fall in a small range with ratios of ²⁰⁶Pb/²⁰⁴Pb from 18.528 to 18.663, ²⁰⁷Pb/²⁰⁴Pb from 15.611 to 15.669 and ²⁰⁸Pb/²⁰⁴Pb from 38.616 to 38.839 (ESM—Table 3, Fig. 8). If the few data points from the minor late-stage fracture-filling sulfides (samples W-081, W-088, W-077 and W-093, ESM—Table 3) are excluded, the Pb isotopic compositions of most ore sulfides are even more tightly clustered with ²⁰⁶Pb/²⁰⁴Pb from 18.608 to 18.663, ²⁰⁷Pb/²⁰⁴Pb from 15.619 to 15.669, and ²⁰⁸Pb/²⁰⁴Pb from 38.677 to 38.839. The Pb isotopes of

Table 2

S-isotopic compositions of sulfide and sulfate minerals from the Urogen Zn–Pb deposit.

Sample no.	Occurrences	Mineral	$\delta^{34}\text{S}_{\text{V-CDT}}\%$	Data source
<i>Northern ore zone</i>				
W-210	Pyrite-rich ore in conglomerate	Pyrite	−7.8	This study
W-227	Pyrite-rich ore in sandstone	Pyrite	−8.5	This study
W-40-5	Fine-grained massive ore in dolomite	Galena	−9.6	This study
W-40-10	Coarse-grained massive ore in dolomite	Galena	−20.9	This study
W-31	Coarse-grained massive ore in dolomite	Sphalerite	−7.2	This study
W-30	Coarse-grained massive ore in dolomite	Galena	−17.8	This study
W-30	Coarse-grained massive ore in dolomite	Sphalerite	−16.3	This study
W-231	Coarse-grained massive ore in dolomite	Galena	−22	This study
W-26	Disseminated ore in dolomite	Galena	−18.9	This study
WLG-60	Disseminated ore in dolomite	Pyrite	−6.1	Zhang, 2010
WLG-61	Disseminated ore in dolomite	Galena	−24.4	Zhang, 2010
WLG-22	Disseminated ore in dolomite	Galena	−13.2	Zhang, 2010
WLG-28-3	Massive ore in dolomite	Galena	−11.4	Zhang, 2010
WLG-28-1	Massive ore in dolomite	Galena	−24.4	Zhang, 2010
WLG-28-4	Massive ore in dolomite	Galena	−23.2	Zhang, 2010
KB410	Massive ore in dolomite	Galena	−14.4	Cai et al., 2002
KB413	Massive ore in dolomite	Galena	−17.7	Cai et al., 2002
W-10	Massive ore in dolomite	Galena	−10.5	Cai et al., 2002
W-27	Strata of Paleocene Artashi Formation	Celestine	18.1	This study
<i>Southern ore zone</i>				
W-196	Disseminated ore in sandstone	Galena	4.6	This study
W-215	Disseminated ore in gravelly sandstone	Galena	3.4	This study
W-215	Disseminated ore in gravelly sandstone	Sphalerite	−3.9	This study
W-225-3	Disseminated ore in sandstone	Sphalerite	1.1	This study
WLG-10	Disseminated ore in sandstone	Galena	−27.9	Zhang, 2010
WLG-16	Disseminated ore in sandstone	Galena	−24.5	Zhang, 2010
WLG-38	Disseminated ore in sandstone	Galena	1.1	Zhang, 2010
WLG-39	Disseminated ore in sandstone	Galena	0	Zhang, 2010
WLG-36	Disseminated ore in sandstone	Galena	0.8	Zhang, 2010
W-195	Disseminated ore in conglomerate (level 2190 m)	Galena	−6.7	This study
W-195	Disseminated ore in conglomerate (level 2190 m)	Sphalerite	−4.4	This study
W-245	Disseminated ore in conglomerate (level 2190 m)	Galena	2.2	This study
W-188	Disseminated ore in conglomerate (level 2190 m)	Galena	−12.4	This study
W-233	Disseminated ore in conglomerate (level 2190 m)	Sphalerite	−5.9	This study
W-81	Ore in a fracture zone (level 2190 m)	Sphalerite	−1.2	This study
W-73	Ore in a fracture zone (level 2190 m)	Pyrite	−8.6	This study
W-73	Ore in a fracture zone (level 2190 m)	Sphalerite	−3.9	This study
W-90	Ore in a fracture zone (level 2190 m)	Galena	−5.1	This study
W-90	Ore in a fracture zone (level 2190 m)	Sphalerite	−10	This study
W-88	Ore in a fracture zone (level 2190 m)	Pyrite	−4.4	This study
W-85	Ore in a fracture zone (level 2190 m)	Pyrite	−4.7	This study
W-77	Ore in a fracture zone (level 2190 m)	Galena	−15.1	This study
W-93	Ore in a fracture zone (level 2190 m)	Sphalerite	−9.1	This study
W-128	Massive ore in dolomite (open pit)	Galena	1.6	This study
W-123	Massive ore in dolomite (open pit)	Galena	−2.8	This study
W-130	Massive ore in dolomite (open pit)	Galena	−6.2	This study
W-234	Massive ore in dolomite (open pit)	Galena	−4.4	This study
W-12	Disseminated ore in sandstone	Galena	14.6	Cai et al., 2002
W-12	Disseminated ore in sandstone	Pyrite	−4.8	Cai et al., 2002
W-125	Strata of Paleocene Artashi Formation (open pit)	Gypsum	17.9	This study
W-126	Strata of Paleocene Artashi Formation (open pit)	Gypsum	17.9	This study
W-127	Strata of Paleocene Artashi Formation (open pit)	Gypsum	18.6	This study

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the host rocks fall in slightly wider ranges with $^{206}\text{Pb}/^{204}\text{Pb}$ from 18.362 to 18.629, $^{207}\text{Pb}/^{204}\text{Pb}$ from 15.594 to 15.662 and $^{208}\text{Pb}/^{204}\text{Pb}$ from 38.380 to 38.787 (ESM–Table 3, Fig. 8). In the $^{207}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (Fig. 8, left), both sulfide and host rock samples fall between the evolution curves for the upper crust and orogens (Zartman and Doe, 1981), and in the $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ diagram (Fig. 8, right), they are close to the evolution curve of orogens (Zartman and Doe, 1981).

4.2. Organic matter analyses

Organic matter is abundant in the ores and host rocks of the Urogen deposit. Samples of ores and host rocks, as well as oil sands from the Yangye oil showing near Urogen (Fig. 2), were crushed to 0.1 mm and then subjected to trichloromethane to extract chloroform bitumen “A”, which was then separated into saturated hydrocarbons, aromatic

hydrocarbons, asphaltenes, and non-hydrocarbons with column chromatography. The hydrocarbons were analyzed with a HP-7890GC gas chromatography and an Agilent 5973N gas chromatography–mass spectrometry at the Analytical Center of Petroleum Geology, Institute of Petroleum Exploration and Development of China in Beijing. For the analysis results of the organic matter in the host rocks, the Lower Cretaceous strata and the ore samples, the contents of chloroform bitumen “A” and its components are shown in ESM–Table 4 and Fig. 9, the distribution of n-alkanes is displayed in ESM–Table 5 and Fig. 10, the parameters of terpane biomarkers in ESM–Table 6 and sterane biomarkers in ESM–Table 7.

5. Discussion

The Urogen deposit has been classified into various deposit types by different authors with the main controversy being syngenetic versus

Table 3
Pb-isotopic compositions of ore sulfides and host rocks in the Urogen Zn–Pb deposit.

Sample no.	Occurrences and location	Mineral/rock	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	Data source
Ores						
W-195	Disseminated ore in conglomerate (southern ore zone)	Galena	18.663	15.669	38.839	This study
W-098	Disseminated ore in conglomerate (southern ore zone)	Galena	18.654	15.663	38.821	This study
W-233	Disseminated ore in conglomerate (southern ore zone)	Galena	18.651	15.658	38.813	This study
WLG-60	Disseminated ore in conglomerate (southern ore zone)	Pyrite	18.622	15.636	38.719	Zhang, 2010
WLG-60	Disseminated ore in conglomerate (southern ore zone)	Galena	18.618	15.632	38.708	Zhang, 2010
W-214	Disseminated ore in gravelly sandstone (southern ore zone)	Galena	18.651	15.652	38.785	This study
W-215	Disseminated ore in gravelly sandstone (southern ore zone)	Galena	18.653	15.656	38.795	This study
W-242	Disseminated ore in gravelly sandstone (southern ore zone)	Galena	18.618	15.619	38.677	This study
WLG-16	Disseminated ore in sandstone (southern ore zone)	Galena	18.625	15.639	38.729	Zhang, 2010
WLG-10	Disseminated ore in sandstone (southern ore zone)	Galena	18.629	15.635	38.724	Zhang, 2010
WLG-4	Disseminated ore in sandstone (southern ore zone)	Sphalerite	18.626	15.638	38.731	Zhang, 2010
WLG-4	Disseminated ore in sandstone (southern ore zone)	Pyrite	18.626	15.638	38.732	Zhang, 2010
W-081	Massive ore in fracture zone (southern ore zone, level 2190 m)	Pyrite	18.604	15.611	38.642	This study
W-088	Massive ore in fracture zone (southern ore zone, level 2190 m)	Pyrite	18.608	15.617	38.663	This study
W-077	Massive ore in fracture zone (southern ore zone, level 2190 m)	Galena	18.649	15.651	38.777	This study
W-093	Massive ore in fracture zone (southern ore zone, level 2190 m)	Pyrite	18.528	15.614	38.616	This study
W-40-10	Coarse massive ore in dolomite (northern ore zone)	Galena	18.621	15.626	38.696	This study
W-031	Fine massive ore in dolomite (northern ore zone)	Galena	18.619	15.627	38.703	This study
W-227	Fine massive ore in dolomite (northern ore zone)	Pyrite	18.608	15.623	38.678	This study
W-026	Disseminated ore in dolomite (northern ore zone)	Galena	18.638	15.651	38.772	This study
W-030	Disseminated ore in dolomite (northern ore zone)	Galena	18.612	15.624	38.694	This study
W-123	Massive ore in dolomite (southern ore zone)	Galena	18.636	15.635	38.732	This study
W-130	Massive ore in dolomite (southern ore zone)	Galena	18.637	15.631	38.718	This study
WLG-28-4	Massive ore in dolomite (northern ore zone)	Galena	18.623	15.637	38.725	Zhang, 2010
WLG-28-3	Massive ore in dolomite (northern ore zone)	Galena	18.628	15.641	38.734	Zhang, 2010
WLG-28-1	Massive ore in dolomite (northern ore zone)	Galena	18.623	15.636	38.721	Zhang, 2010
Host rocks						
W-103	Strata of fourth member of Kezilesu Group, Lower Cretaceous	Sandstone	18.362	15.594	38.381	This study
W-102	Strata of fourth member of Kezilesu Group, Lower Cretaceous	Sandstone	18.421	15.604	38.428	This study
W-066	Strata of fifth member of Kezilesu Group, Lower Cretaceous	Sandstone	18.584	15.631	38.674	This study
W-067	Strata of fifth member of Kezilesu Group, Lower Cretaceous	Sandstone	18.622	15.647	38.746	This study
W-068	Strata of fifth member of Kezilesu Group, Lower Cretaceous	Sandstone	18.629	15.662	38.787	This study
W-178	Strata of fifth member of Kezilesu Group, Lower Cretaceous	Sandstone	18.621	15.631	38.705	This study
W-233	Strata of fifth member of Kezilesu Group, Lower Cretaceous	Sandstone	18.568	15.646	38.711	This study

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epigenetic. An epigenetic origin is favored by the observation that the orebodies straddle across a hiatus in the host rocks (between Lower Cretaceous Kezilesu Group and Paleocene Artashi Formation) and by the development of replacement and open-space filling textures and structures in the ores. The stratiform shapes of the orebodies and the locally-developed banded ore structures, which were used to support a SEDEX origin for the deposit (Cai et al., 2002; He, 2007; Xie et al., 2003), can be formed by replacement and are not uncommon in epigenetic mineral systems. In this aspect, the Urogen deposit is strikingly similar to the Jinding Zn–Pb deposit that is also developed in Lower Cretaceous and Paleocene siliclastic rocks and mainly stratiform, and for which a SEDEX origin has been proposed (Wang et al., 1992), however, various studies including isotopic dating suggest that mineralization took place long after deposition of the host rocks, therefore supporting an epigenetic origin (Chi et al., 2007; Kyle and Li, 2002; Xue et al., 2007). Zhu et al. (2010) and Zhang (2010) classified the Urogen deposit as a sandstone-hosted variant of the MVT because the deposit was interpreted to be epigenetic but not hosted in carbonate rocks as are MVT deposits (Leach et al., 2005).

Two genetic models, both epigenetic in nature, have been proposed for sandstone-hosted lead–zinc deposits in general, as summarized by Bjorlykke and Sangster (1981). The groundwater transport model, described in detail by Samama (1969) for the Largentière Pb–Zn–Ag deposit in France and generalized by Bjorlykke and Sangster (1981) for the “sandstone lead deposits”, proposes that metals were extracted from basement rocks exposed on the surface through chemical weathering, transported by saline groundwater (related to evaporation) in a topography-driven fluid flow system, and precipitated through mixing

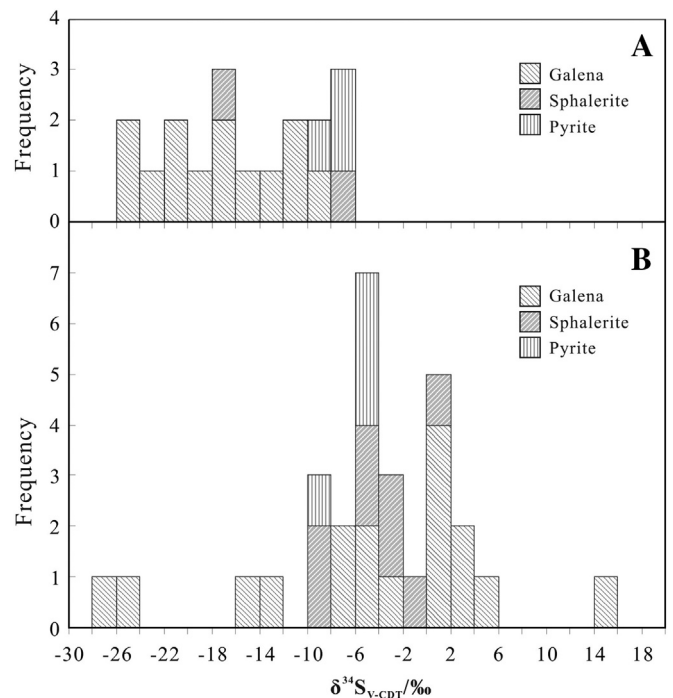


Fig. 7. Histogram of sulfur isotopic composition of sulfide minerals from the northern ore zone (A) and southern ore zone (B) of the Urogen Zn–Pb deposit.

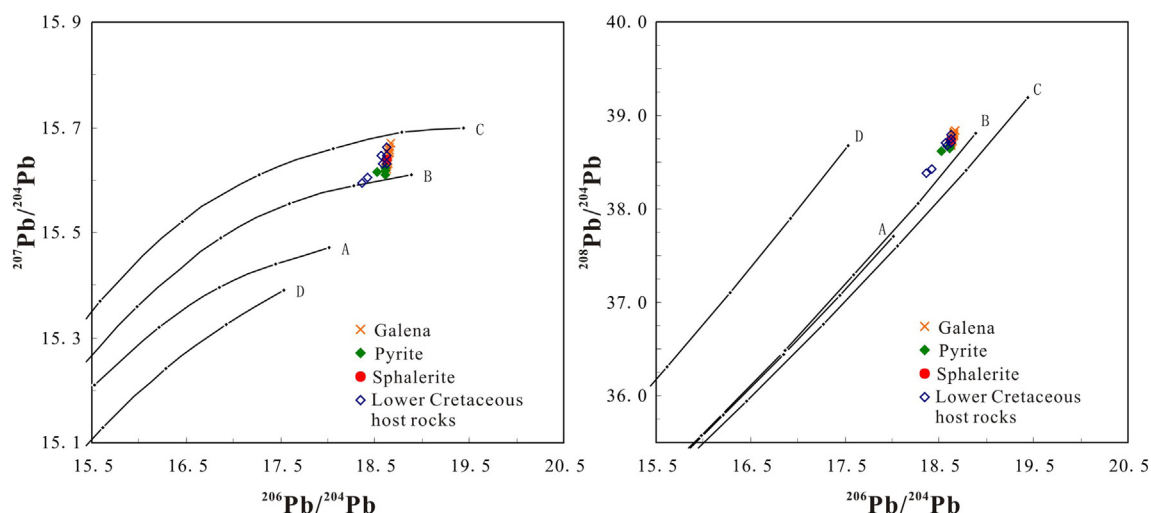


Fig. 8. Pb isotope compositions of sulfides and host rocks of the Fifth member, Kezilesu Formation, Lower Cretaceous, from the Uragen Zn–Pb deposit. The evolution lines for the mantle (A), orogens (B), upper crust (C), and lower crust (D) are from Zartman and Doe, 1981.

with a fluid containing reduced sulfur. In contrast, the hydrothermal (basin brine) model, favored by Rickard et al. (1979) for the Laisvall deposit, suggests that the mineralization was related to hot basinal brines that extracted metals from basin sediments and then flowed upward and toward the margins of the basins where they are cooled, met reduced sulfur or other reducing agents and precipitated metal sulfides. This process is similar to those proposed for the carbonate-hosted MVT deposits (see Leach et al., 2005). A key support for the hydrothermal model is the elevated homogenization temperatures and salinities of fluid inclusions that are comparable to those of MVT deposits, such as those found in the Laisvall deposit in Sweden (Rickard et al., 1979), the Largentière Pb–Zn–Ag deposit in France (Chi et al., 1997), and the Jinding deposit in China (Xue et al., 2007). In the Uragen deposit, a few fluid inclusion studies have been carried out (Kang et al., 2009; Li et al., 2005) that have reported homogenization temperatures for fluid inclusions in ore-stage gypsum ranging from 62 to 193 °C, and salinities from 7.2 to 20.3 wt.% NaCl equivalent. The large spread of homogenization temperatures would be related to the deformation overprinting because the orebody and the host strata were folded and faulted after the Zn–Pb mineralization and gypsum is a very soft mineral compared with quartz, dolomite, or even calcite, but the fluid inclusions measured in the ore-stage gypsum are all primary (Kang et al., 2009; Li et al., 2005). Although it cannot be completely ruled out that the elevated homogenization temperatures, compared with that in groundwater transport model, resulted from post-mineralization reworking or overprinting, as discussed by Bjorlykke and Sangster (1981), these fluid inclusion data are interpreted to indicate that the mineralization at Uragen was related to warm brines. It should be pointed out that the “warm brines” were not necessarily part of a hydrothermal system; they could be derived from descending groundwater (surface brines) if mineralization took place at significant depths approaching ~10 km, as have been proposed for some sandstone-hosted uranium deposits (Xue et al., 2010). In other words, the fluid inclusion data alone cannot distinguish between the modified groundwater transport model (at burial conditions) and the hydrothermal model.

The narrow ranges of Pb isotopes of ore minerals from the Uragen deposit (Fig. 7) suggest that the metals were from a single source. It is an open question whether this source is located in the deeper part of the basin (the hydrothermal model) or on the surface, such as lakes in piedmonts (the groundwater transport model) because both are compatible with continental or orogenic sources of lead (Fig. 8).

In contrast, the wide range in sulfur isotopes of the sulfides (Fig. 7) suggests that the sulfur involved in the mineralization may have been derived from multiple sources. Similar sulfur isotope characteristics

have been observed for sandstone-hosted copper deposits in the area (Li et al., 2011; Wang et al., 2011). The sulfides and sulfates were not co-precipitated in the same paragenetic stage, and their difference in sulfur isotopes cannot be simply attributed to isotope fractionation. The various sulfides analyzed, although mostly belonging to the main mineralization stage, do not show textural evidence of co-precipitation. Similarly their difference in $\delta^{34}\text{S}$ cannot be interpreted by isotope fractionation either. While the positive $\delta^{34}\text{S}$ values may possibly indicate thermal reduction of sulfates, the negative $\delta^{34}\text{S}$ values are likely related to bacteria participation in sulfate reduction (Greenwood et al., 2013; Navarro-Gonzalez et al., 2003; Southam and Saunders, 2005). The fluid inclusion data discussed above and the absence of biodegradation of hydrocarbons suggest that the mineralization site was too hot for bacteria to survive (Navarro-Gonzalez et al., 2003). Therefore, the bacteria-related reduced sulfur may not have been generated in situ probably, but rather produced elsewhere and migrated to the site of mineralization. On the other hand, the positive $\delta^{34}\text{S}$ values suggest that some reduced sulfur might have been produced by in situ thermal sulfate reduction (Greenwood et al., 2013; Southam and Saunders, 2005), which is consistent with the observation that the organic matter at the site of mineralization appears to have been altered by oxidation. Such a reduced sulfur production mechanism is likely considering the abundance of evaporites in the host rocks (e.g., in the Fifth Member of the Lower Cretaceous Kezilesu Formation, and the Paleocene Artashi Formation). Similar sulfur isotope characteristics have been found in other sediment-hosted Zn–Pb deposits where mineralization was interpreted to have resulted from hot basinal brines flowing into a hydrocarbon reservoir (Xue et al., 2007). The apparent difference in $\delta^{34}\text{S}$ between the northern and southern ore zones is probably due to sampling bias because most of our samples from the northern zone were collected from orebodies hosted by dolomite of Paleocene Artashi Formation, whereas those from the southern zone were from various types of host lithologies. However, we cannot rule out the possibility that the sources of sulfur are different for the northern and southern ore zones.

The organic matter in the host rocks of the Uragen deposit (including mineralized host rocks) is similar to that in the Lower Cretaceous strata (including the oil sands from Yangye) near the deposit in terms of hydrocarbon composition, characterized by the dominance of saturated hydrocarbons and the low contents of aromatic hydrocarbons (ESM–Table 4 and Fig. 9). The ore samples, however, are characterized by relatively low concentrations of saturated hydrocarbons and relatively high concentrations of aromatic hydrocarbons, asphaltenes and non-hydrocarbons (ESM–Table 4 and Fig. 9).

Table 4

Compositions of organic matter in ores and host rocks of the Urogen Zn–Pb deposit, as well as the Lower Cretaceous strata (including oil sands from the nearby Yangye oil show).

Sample no.	Lithology	Content of chloroform bitumen "A" %	Composition of chloroform bitumen "A" %				Asphaltene + Non-hydrocarbons%	Totalhydrocarbons%	Saturated/aromatic hydrocarbons
			Saturated hydrocarbons	Aromatic hydrocarbons	Asphaltene	Non-hydrocarbons			
W-89	Sandstone-hosted Zn–Pb ore	0.0021	10.69	9.02	16.6	63.69	80.29	19.71	1.19
W-176	Sandstone-hosted Zn–Pb ore	0.0022	39.51	11.98	10.25	38.26	48.51	51.49	3.3
W-189	Sandstone-hosted Zn–Pb ore	0.0014	34.49	10.34	8.6	46.57	55.17	44.83	3.33
W-23	Zn–Pb Mineralized host rock	0.5192	73.86	1.05	4.84	20.25	25.09	74.91	70.24
W-25	Zn–Pb Mineralized host rock	0.5051	78.37	0.69	2.62	18.32	20.94	79.06	113.58
W-32	Zn–Pb Mineralized host rock	0.4429	73.42	1.37	3.19	22.02	25.21	74.79	53.59
W-13	Host sandstone and conglomerate	0.0197	62.95	1.94	6.25	28.86	35.11	64.89	32.45
W-14	Host sandstone and conglomerate	0.0085	63.81	1.85	4.71	29.63	34.34	65.66	34.49
W-15	Host sandstone and conglomerate	0.0054	67.11	undetected	5.27	27.62	32.89	67.11	Undetected
W-18	Host sandstone and conglomerate	0.1656	59.01	0.89	6.54	33.56	40.1	59.9	66.3
W-19	Host sandstone and conglomerate	0.0785	72.96	0.63	2.41	24.01	26.41	73.59	115.81
W-202	Host sandstone and conglomerate	0.0101	45.55	2.77	12.11	39.57	51.68	48.32	16.44
W-203	Host sandstone and conglomerate	0.0095	60.86	undetected	4.89	34.25	39.14	60.86	Undetected
W-69	Host sandstone and conglomerate	0.0072	61.53	0.55	7.29	30.63	37.92	62.08	111.87
W-105	Host sandstone and conglomerate	0.0136	50.15	undetected	5.23	44.62	49.85	50.15	Undetected
W-106	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	2.217	75.61	1.84	7.21	15.34	22.55	77.45	41.09
W-107	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	3.8193	68.28	1.5	8.26	21.96	30.22	69.78	45.52
W-108	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	9.6948	66.84	1.09	16.11	15.96	32.07	67.93	61.32
W-109	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	4.7235	79.86	0.52	7.28	12.34	19.62	80.38	153.58
W-110	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	14.9461	80.99	0.36	3.68	14.97	18.65	81.35	224.97
W-111	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	8.0017	81.86	0.43	2.96	14.75	17.71	82.29	190.37
W-112	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	11.6427	61.64	0.96	20.9	16.5	37.4	62.6	64.21
W-113	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	0.5266	74.09	3.03	3.32	19.56	22.88	77.12	24.45

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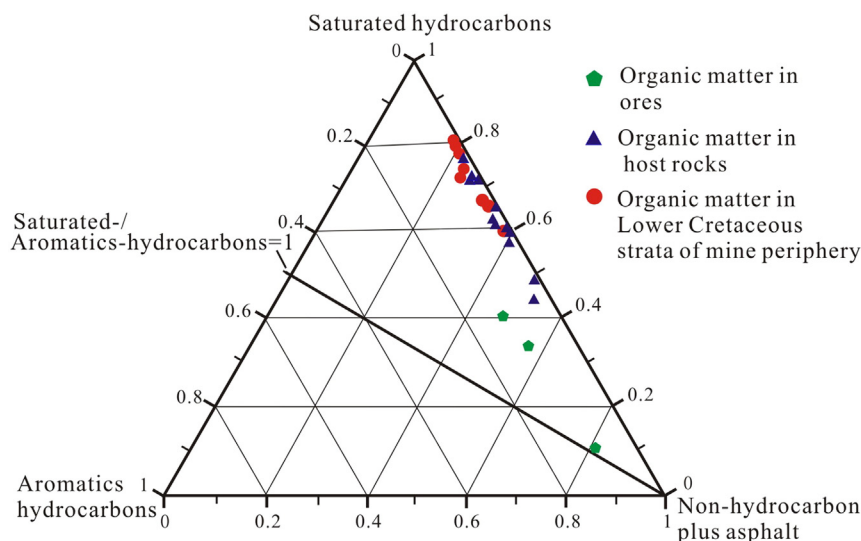


Fig. 9. Contents of chloroform bitumen "A" and its family components of organic matter in the Urogen Zn–Pb deposit and periphery area.

The distribution of n-alkanes is similar between the organic matter in the host rocks (including mineralized host rocks) and that in the Lower Cretaceous strata (including oil sands from Yangye) near the deposit with both characterized by a concentration between C_{12} and C_{37} and a single peak at C_{27} (ESM–Table 5 and Fig. 10). The ore sample is different from the other samples in that its n-alkanes are mainly from C_{14} to C_{31} , with a peak at C_{22} (ESM–Table 5 and Fig. 10). The ore sample also differs from the host rocks in various other parameters with the former having much higher $\Sigma C_{21-}/\Sigma C_{22+}$ (0.8), $C_{(21+22)}/C_{(28+29)}$ (20.75), Pr/nC_{17} (1.31), and Ph/nC_{18} (2.05) than the latter ($\Sigma C_{21-}/\Sigma C_{22+}$ from 0.03 to 0.12, $C_{(21+22)}/C_{(28+29)}$ from 0.11 to 0.34, Pr/nC_{17} from 0.41 to 1.06, Ph/nC_{18} from 0.27 to 1.00) (ESM–Table 5). The Pr/Ph and OEP values are lower for the ore sample (0.50 and 1.01) than the host rocks (0.68 to 1.06 and 1.10 to 1.15) (ESM–Table 5), where $OEP = (C_i + 6C_{i+2} + C_{i+4})/(4C_{i+1} + 4C_{i+3})$ for odd numbers of i , or $OEP = (4C_{i+1} + 4C_{i+3})/(C_i + 6C_{i+2} + C_{i+4})$ for even numbers of i .

Parameters of terpane biomarkers are similar between the organic matter in the host rocks (including mineralized host rocks) and that in the Lower Cretaceous strata (including oil sands from Yangye) near the deposit, while the ore sample shows systematic differences in all parameters (Table 6). For the host rocks, Ts/Tm is from 1.28 to 1.50 (with

one outlier at 0.66), $Ts/(Ts + Tm)$ from 0.40 to 0.60, gammacerane/ $\alpha\beta$ -hopanes from 0.07 to 0.18, $\beta\alpha$ -MO alkyl/ $\alpha\beta$ -hopanes from 0.13 to 0.17, hopanes $C_{32}S/R$ from 1.21 to 1.78, C_{31} homohopane $22S/(S + R)$ from 0.56 to 0.58, C_{29} hopane/ C_{30} hopane from 0.47 to 0.52, and $C_{30}^*/C_{29}Ts$ from 0.47 to 0.53. For the Lower Cretaceous strata (including oil sands from Yangye) near the deposit, Ts/Tm is from 1.34 to 1.51, $Ts/(Ts + Tm)$ from 0.57 to 0.60, gammacerane/ $\alpha\beta$ -hopanes from 0.09 to 0.12, $\beta\alpha$ -MO alkyl/ $\alpha\beta$ -hopanes is 0.14, hopanes $C_{32}S/R$ from 1.30 to 1.45, C_{31} homohopane $22S/(S + R)$ from 0.56 to 0.57, C_{29} hopane/ C_{30} hopane from 0.47 to 0.48, and $C_{30}^*/C_{29}Ts$ from 0.53 to 0.59. For the ore sample, Ts/Tm is 0.46, $Ts/(Ts + Tm)$ 0.32, gammacerane/ $\alpha\beta$ -hopanes 0.27, $\beta\alpha$ -MO alkyl/ $\alpha\beta$ -hopanes 0.21, hopanes $C_{32}S/R$ 1.31, C_{31} homohopane $22S/(S + R)$ 0.56, C_{29} hopane/ C_{30} hopane 0.36, and $C_{30}^*/C_{29}Ts$ 0.39 (Table 6).

Similar comparison between the host rocks, the Lower Cretaceous strata (including oil sands from Yangye) near the deposit and the ore sample can also be made for parameters related to sterane biomarkers (ESM–Table 7). For the host rock samples, $\alpha\alpha\alpha$ - C_{27} is from 21.05 to 40.44%, $\alpha\alpha\alpha$ - C_{28} from 25.19 to 41.48%, $\alpha\alpha\alpha$ - C_{29} from 32.20 to 38.58%, $\alpha\alpha\alpha$ - $C_{27}/\alpha\alpha\alpha$ - C_{29} from 0.56 to 1.25, diasteranes/regular steranes from 0.15 to 0.48, aaa - $C_{29}S/(S + R)$ from 0.45 to 0.54, $C_{29}(S + R) \beta\beta/(\beta\beta + \alpha\alpha)$ from 0.51 to 0.58, regular

Table 5
N-alkane and isoprenoid alkane compositions and parameters.

Sample no.	Lithology	Distribution	Main range	Peak	$\Sigma C_{21-}/\Sigma C_{22+}$	$C_{(21+22)}/C_{(28+29)}$	Pr/Ph	Pr/nC_{17}	Ph/nC_{18}	OEP*
W-176	Sandstone-hosted Zn–Pb ore	Single peak	C_{14} – C_{31}	C_{22}	0.8	20.75	0.5	1.31	2.05	1.01
W-25	Zn–Pb mineralized host rock	Single peak	C_{13} – C_{37}	C_{27}	0.05	0.19	0.73	0.41	0.37	1.13
W-32	Zn–Pb mineralized host rock	Single peak	C_{13} – C_{36}	C_{27}	0.04	0.19	0.76	0.52	0.44	1.13
W-13	Host sandstone and conglomerate	Single peak	C_{12} – C_{36}	C_{27}	0.05	0.17	0.74	0.45	0.48	1.13
W-14	Host sandstone and conglomerate	Single peak	C_{12} – C_{37}	C_{27}	0.12	0.34	0.78	0.87	1	1.12
W-19	Host sandstone and conglomerate	Single peak	C_{13} – C_{36}	C_{27}	0.03	0.17	0.84	0.51	0.44	1.14
W-105	Host sandstone and conglomerate	Single peak	C_{12} – C_{37}	C_{27}	0.1	0.28	0.73	0.45	0.47	1.15
W-202	Host sandstone and conglomerate	Single peak	C_{12} – C_{37}	C_{27}	0.08	0.25	0.68	0.43	0.49	1.13
W-106	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	Single peak	C_{13} – C_{37}	C_{27}	0.03	0.13	0.88	0.69	0.48	1.15
W-107	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	Single peak	C_{13} – C_{37}	C_{27}	0.03	0.12	0.88	0.74	0.56	1.15
W-109	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	Single peak	C_{13} – C_{38}	C_{27}	0.03	0.12	0.71	0.42	0.32	1.13
W-111	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	Single peak	C_{13} – C_{36}	C_{27}	0.03	0.11	0.74	0.31	0.27	1.13
W-113	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	Single peak	C_{13} – C_{37}	C_{27}	0.04	0.08	1.06	1.14	0.97	1.1

OEP = $(C_i + 6C_{i+2} + C_{i+4})/(4C_{i+1} + 4C_{i+3})$ for odd numbers of i , or OEP = $(4C_{i+1} + 4C_{i+3})/(C_i + 6C_{i+2} + C_{i+4})$ for even numbers of i . Analyzed in Analytical Center of Petroleum Geology, China Institute of Petroleum Exploration and Development, Beijing

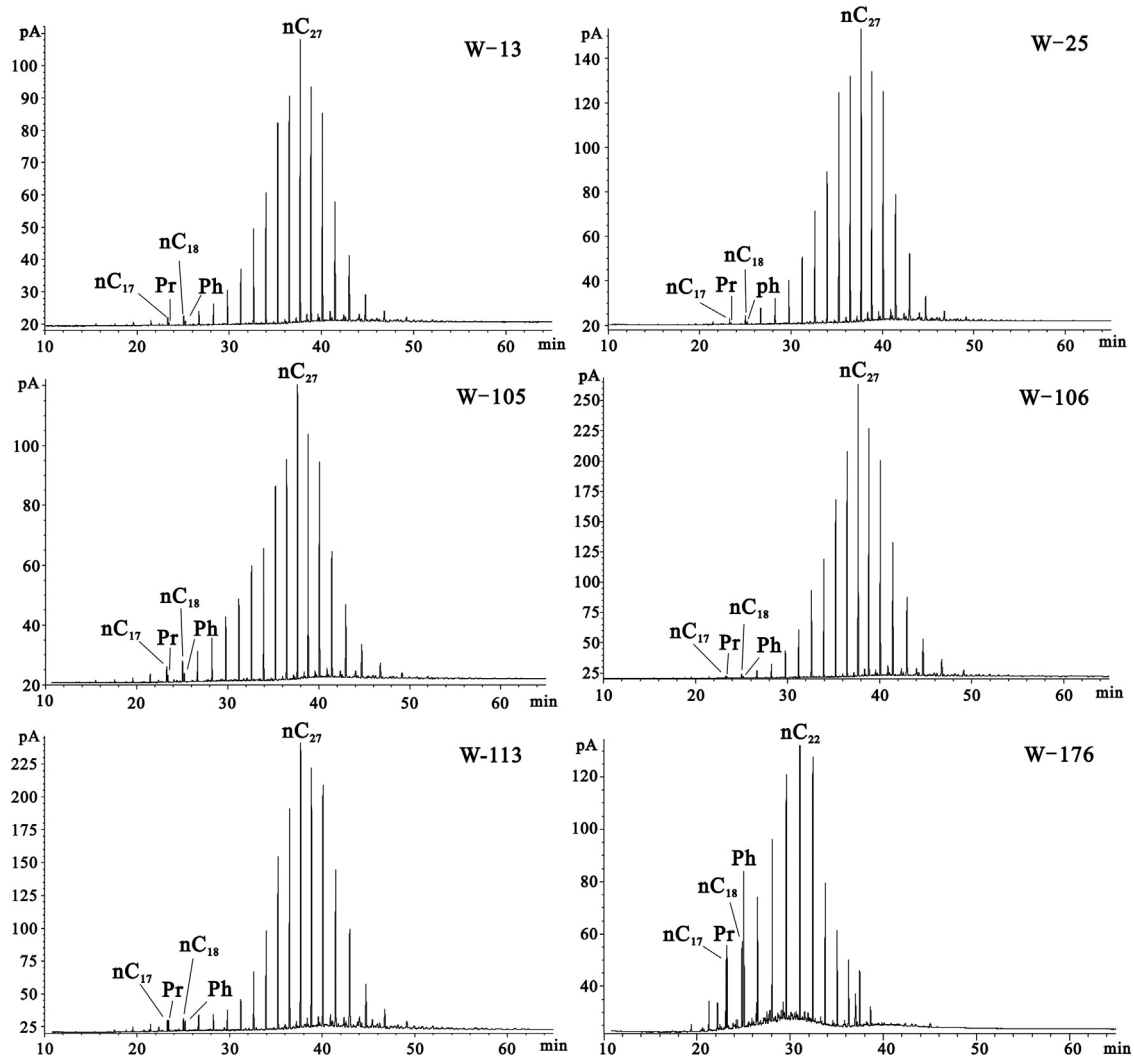


Fig. 10. Saturate fraction gas chromatograms of hydrocarbons from the Urogen Zn–Pb deposit and periphery area. Samples of W-13 and W-105 are host sandstones and conglomerates. Samples of W-113 and W-106 are strata K₁kz (including oil-bearing sandstones, Yangye oil show). Sample W-25 is Zn–Pb Mineralized host rock. Sample W-176 is sandstone-hosted Zn–Pb ore.

steranes/17 α (H) hopanes from 0.58 to 0.93. For the Lower Cretaceous strata (including oil sands, Yangye) of near deposit, $\alpha\alpha\alpha$ -C₂₇ from 35.07 to 40.35%, $\alpha\alpha\alpha$ -C₂₈ from 27.14 to 28.55%, $\alpha\alpha\alpha$ -C₂₉ from 32.11

to 36.69%, $\alpha\alpha\alpha$ -C₂₇/ $\alpha\alpha\alpha$ -C₂₉ from 0.96 to 1.26, diasteranes/regular steranes from 0.38 to 0.41, $\alpha\alpha\alpha$ -C₂₉ S/(S + R) from 0.41 to 0.49, C₂₉(S + R) $\beta\beta$ /($\beta\beta$ + $\alpha\alpha$) from 0.48 to 0.56, regular steranes/

Table 6

Terpane compositions and parameters.

Sample no.	Lithology	Ts/Tm	Ts/(Ts + Tm)	Gammacerane/ $\alpha\beta$ -hopanes	$\beta\alpha$ -MO alkyl/ $\alpha\beta$ -hopanes	HopanesC32S/R	C ₃₁ homohopane 22S/(S + R)	C ₂₉ hopane/C30 hopane	C ₃₀ */C ₂₉ Ts
W-176	Sandstone-hosted Zn–Pb ore	0.46	0.32	0.27	0.21	1.31	0.56	0.36	0.39
W-25	Zn–Pb Mineralized host rock	1.46	0.59	0.12	0.14	1.34	0.57	0.5	0.53
W-32	Zn–Pb Mineralized host rock	1.37	0.58	0.11	0.15	1.78	0.58	0.51	0.47
W-13	Host sandstone and conglomerate	1.34	0.57	0.13	0.14	1.41	0.57	0.47	0.56
W-14	Host sandstone and conglomerate	0.66	0.4	0.18	0.14	1.26	0.57	0.58	0.55
W-19	Host sandstone and conglomerate	1.5	0.6	0.07	0.15	1.21	0.58	0.5	0.56
W-105	Host sandstone and conglomerate	1.34	0.57	0.13	0.13	1.34	0.57	0.49	0.53
W-202	Host sandstone and conglomerate	1.28	0.56	0.11	0.17	1.35	0.56	0.52	0.48
W-106	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	1.51	0.6	0.11	0.14	1.3	0.57	0.47	0.59
W-107	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	1.43	0.59	0.11	0.14	1.34	0.57	0.48	0.58
W-109	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	1.41	0.59	0.09	0.14	1.32	0.56	0.47	0.53
W-111	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	1.4	0.58	0.11	0.14	1.34	0.57	0.48	0.55
W-113	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	1.34	0.57	0.12	0.14	1.45	0.57	0.48	0.58

Analyzed in Analytical Center of Petroleum Geology, China Institute of Petroleum Exploration and Development, Beijing

Table 7
Sterane compositions and parameters.

Sample no.	Lithology	Steranes composition (%)			$\alpha\alpha\alpha\text{-C}_{27}/\alpha\alpha\alpha\text{-C}_{29}$	Diasteranes/ regular steranes	aaa-C ₂₉ S/ (S + R)	C ₂₉ (S + R)ββ/ (ββ + αα)	Regular steranes/ 17α (H) hopanes
		$\alpha\alpha\alpha\text{-C}_{27}$	$\alpha\alpha\alpha\text{-C}_{28}$	$\alpha\alpha\alpha\text{-C}_{29}$					
W-176	Sandstone-hosted Zn–Pb ore	29.13	28.97	41.9	0.71	0.15	0.27	0.29	2.99
W-25	Zn–Pb Mineralized host rock	36.5	26.02	37.48	0.97	0.44	0.45	0.52	0.61
W-32	Zn–Pb Mineralized host rock	31.73	29.69	38.58	0.82	0.41	0.46	0.51	0.93
W-13	Host sandstone and conglomerate	35.93	28.65	35.42	1.01	0.39	0.45	0.52	0.81
W-14	Host sandstone and conglomerate	21.05	41.48	37.47	0.56	0.15	0.54	0.54	0.64
W-19	Host sandstone and conglomerate	40.21	27.59	32.21	1.25	0.42	0.47	0.53	0.8
W-105	Host sandstone and conglomerate	40.44	25.19	34.37	1.18	0.44	0.47	0.52	0.66
W-202	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	40.41	27.14	32.46	1.24	0.48	0.53	0.58	0.58
W-106	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	35.07	28.55	36.38	0.96	0.41	0.41	0.48	0.59
W-107	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	37.82	28.14	34.04	1.11	0.41	0.45	0.51	0.64
W-109	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	40.35	27.54	32.11	1.26	0.38	0.48	0.54	0.55
W-111	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	35.22	28.09	36.69	0.96	0.41	0.45	0.51	0.68
W-113	Strata of Lower Cretaceous Kezilesu Group (including oil-bearing sandstones, Yangye oil show)	38.01	27.14	32.46	1.18	0.4	0.49	0.56	0.74

Analyzed in Analytical Center of Petroleum Geology, China Institute of Petroleum Exploration and Development, Beijing

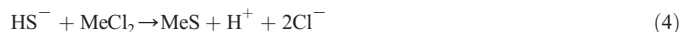
17α (H) hopanes from 0.55 to 0.68. For the ore sample, $\alpha\alpha\alpha\text{-C}_{27}$ is 29.13%, $\alpha\alpha\alpha\text{-C}_{28}$ 28.97%, $\alpha\alpha\alpha\text{-C}_{29}$ 41.90%, $\alpha\alpha\alpha\text{-C}_{27}/\alpha\alpha\alpha\text{-C}_{29}$ 0.7, diasteranes/regular steranes 0.15, aaa-C₂₉S/(S + R) 0.27, C₂₉(S + R)ββ/(ββ + αα) 0.29, and regular steranes/17α (H) hopanes 2.99 (Table 7). The difference in organic matter geochemistry between the ores and the host rocks is also reflected in their maturity. Steranes aaa-C₂₉S/(S + R) – hopanes C₃₂S/R and steranes C₂₉(S + R)ββ/(ββ + αα) – steranes aaa-C₂₉S/(S + R) diagrams (Fig. 11) indicate that the organic matter in the ores is clearly less mature than those in the host rocks.

As discussed above, organic matter is present in the ores and in the host rocks adjacent to and away from mineralization. The organic matter in the host rocks adjacent to mineralization is similar to the Lower Cretaceous strata (including oil sands from Yangye) near the deposit in terms of the compositions of chloroform bitumen “A”

(ESM–Table 4 and Fig. 9), n-alkanes (ESM–Table 5 and Fig. 10), terpanes (ESM–Table 6) and steranes (ESM–Table 7), whereas the ore sample is distinct in all these aspects with relative low concentrations of saturated hydrocarbons, high concentrations of aromatic hydrocarbons, n-alkanes peak at C₂₂, the low Pr/Ph and OEP etc. (Tables 4, 5, 6, 7 and Figs. 9, 10, 11). The similarity of organic matter in the host rocks and the Lower Cretaceous strata suggests that they were probably derived from the same sources and subject to similar thermal maturation. The difference of organic matter in the ores from host rocks is most likely caused by the alteration of organic matter by the mineralization fluids that were probably rich in SO₄^{2−} because of its forming or flowing within the Mesozoic and Cenozoic evaporation strata in the Kashi sag, suggesting that organic matter participated in the mineralization process. In the alteration process, the organic matter was possibly oxidized and the sulfide formed through following reaction schemes (1) and (2), such as in HYC deposit of the McArthur Basin, Australia (Chen et al., 2003; Greenwood et al., 2013), resulting in the decreasing of saturated hydrocarbons and other organic parameter-changes.



The reaction schemes (3) and (4) were also proposed to present the oxidation of organic matter to produce sulfides (Greenwood et al., 2013; Rieger et al., 2008).



It is remarkable that the maturity of organic matter in the ore is distinctly lower than that in the host rocks (Fig. 11). Such a phenomenon has been observed in several MVT deposits by Héroux et al. (1997) who noted that the reflectance values increased toward the sites of mineralization for organic matter within impermeable rocks, and decreased for those within permeable rocks (the orebodies and immediate host rocks of ores). They attributed the increase in the former to be caused by thermal effect related to the mineralization event, whereas they

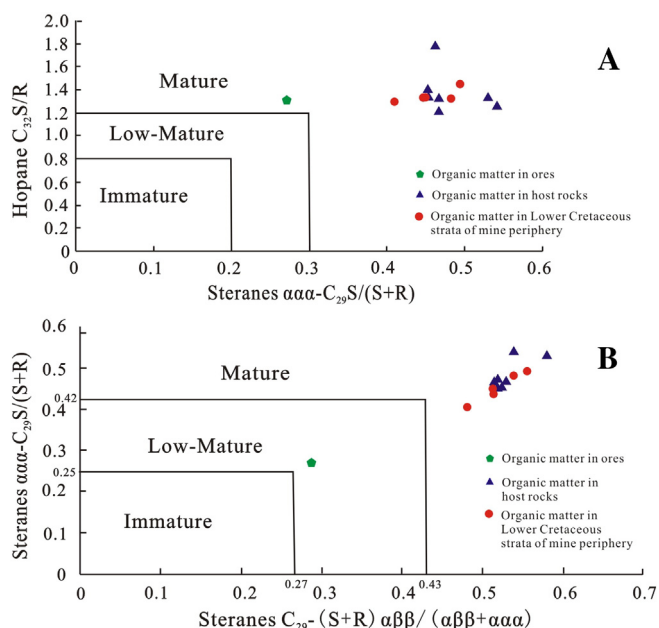


Fig. 11. Organic matter maturation as reflected by the chemical compositions: a) correlation between C₃₂S/R-hopane and aaa-C₂₉S/(S + R)-sterane (after Seifert and Moldowan, 1980); b) correlation between $\alpha\alpha\alpha\text{-C}_{29}\text{S}/(\text{S} + \text{R})$ and C₂₉(S + R)ββ/(ββ + αα) (after Peters and Moldowan, 1993).

attributed the latter to the consumption of hydrogen in hydrocarbons to produce H₂S during the mineralization (Héroux et al., 1997).

The n-alkane distribution patterns of the organic matter in the host rocks, with the peak at C₂₇ (Fig. 10), suggest that the hydrocarbons have not undergone any significant biodegradation (Greenwood et al., 2013). This is further supported by the $\alpha\alpha\alpha$ 20R peaks of C₂₇, C₂₈ and C₂₉ steranes and the relatively low contents of diasteranes (ESM–Table 7).

The chemical composition of the organic matter in the host rocks suggests that it was mainly derived from shales rather than carbonates, as indicated by the relatively high saturated/aromatic hydrocarbon ratios (16–224, ESM–Table 4), low Pr/Ph ratios (0.50–0.88, ESM–Table 5), and high Ph/nC₁₈ ratios (0.32–0.97, ESM–Table 5) (Connan, 1981; Moldowan et al., 1985; Palacas, 1984; Tissot and Welte, 1984). The characteristics of biomarkers suggest that the hydrocarbon-source rocks were mainly formed in continental environments, as reflected by regular steranes/17 α (H) hopane ratios (0.55–0.93, ESM–Table 7) (Tissot and Welte, 1984). Comparison with potential source rocks in the region in biomarkers suggests that the organic matter in the host rocks of the Urogen deposit was derived from Lower and Middle Jurassic lacustrine shales and coals in the northern part of the Kashi sag (Zhou et al., 2003).

6. Conclusion

The Urogen deposit represents a new example of a large-scale zinc–lead deposit hosted in sandstones and conglomerates. The deposit is epigenetic and was formed from hot brines, which may have been derived from deeper parts of the basin in a hydrothermal system, or have descended from a near-surface groundwater system and become hot at burial conditions. The narrow range in lead isotope composition of the ores suggests that the metals were derived from a single source, whereas the wide range of sulfur isotopes indicates multiple sources of sulfur, including those related to bacterial activities and thermal sulfate reduction. At least part of the sulfur may have been generated through *in situ* thermal sulfate reduction, with organic matter at the site of mineralization being the main reducing agent. The participation of organic matter in mineralization is reflected by its reduced maturity relative to the maturities in the host rocks away from mineralization.

Acknowledgments

This study is supported by NSFC–Xinjiang Union Foundation (U1303292) and China Science and Technology Support Plan (2011BAB06B02). We would like to thank Dr. Jingbin Wang and Dr. Zhaochong Zhang for their help during the field and laboratory work. The paper has benefited from constructive comments by two anonymous reviewers of Ore Geology Reviews and by the editor-in-chief, Dr. Franco Pirajno.

References

- Bai, H., Nian, W., Quman, G., 2008. Geologic characteristics and exploration model of the Urogen lead–zinc deposit in Wuqia County, Xinjiang. *Nonferrous Met. Xinjiang* 5, 1–4 (in Chinese with English abstract).
- Bjorlykke, A., Sangster, D.F., 1981. An overview of sandstone lead deposits and their relation to red-bed copper and carbonate-hosted lead–zinc deposits. *Economic Geology 75th Anniversary Volume*, pp. 178–213.
- Cai, T., 1993. *Stratigraphy of Xinjiang*. China University of Geosciences Publishing House, Wuhan, ((393 pp.) (in Chinese)).
- Cai, H., Deng, G., Zheng, Y., 2002. Genesis of the Urogen lead–zinc deposit in Xinjiang. *Min. Resour. Geol.* 16, 1–5 (in Chinese with English abstract).
- Chen, J.H., Walter, M.R., Logan, G.A., Hinman, M.C., Summons, R.E., 2003. The Paleoproterozoic McArthur River (HYC) Pb/Zn/Ag deposit of northern Australia: organic geochemistry and ore genesis. *Earth Planet. Sci. Lett.* 210, 467–479.
- Chi, G., Rhéau, P., Schrijver, K., 1997. The Largentière sandstone-hosted Pb–Zn–Ag deposit, Ardèche, France: Geological setting and microthermometry of fluid inclusions in sphalerite. *Econ. Geol.* 92, 108–113.
- Chi, G., Xue, C., Lai, J., Qing, H., 2007. Sand injection and liquefaction structures in the Jinding Zn–Pb deposit, Yunnan, China: indicators of an overpressured fluid system and implications for mineralization. *Econ. Geol.* 102, 739–743.
- Connan, J., 1981. Biological markers in crude oils. *Pet. Geol. China* 11, 48–70.
- Dong, X., Xue, C., Li, Z., Liu, Z., 2013. Characteristics and geological significances of the organic matter in the Urogen Zn–Pb deposit, Kashi sag, Xinjiang. *Earth Sci. Front.* 20, 129–145 (in Chinese with English abstract).
- Gao, Z., Liu, J., Shu, G., Kuang, W., Hu, J., 2002. Geologic conditions and genesis of lead–zinc deposits in Wuqia, Xinjiang. *J. Cent. South Univ. Technol.* 33, 116–120 (in Chinese with English abstract).
- Greenwood, P.F., Brocks, J.J., Grice, K., Schwark, L., Jaraula, C.M.B., Dick, J.M., Evans, K.A., 2013. Organic geochemistry and mineralogy. I. Characterisation of organic matter associated with metal deposits. *Ore Geol. Rev.* 50, 1–27.
- He, H., 2007. *Geologic Characteristics and Preliminary Genetic Analysis of the Urogen Lead–Zinc Deposit in Wuqia County, Xinjiang*. (M.Sc. thesis) Guilin Institute of Technology, Guilin, ((61 pp.) (in Chinese with English abstract)).
- Héroux, Y., Chagnon, A., Savard, M., 1997. Organic matter and clay anomalies associated with base-metal sulfide deposits. *Ore Geol. Rev.* 11, 157–173.
- Kang, Y., Ouyang, Y., Fan, J., Liu, W., 2009. Origin of the Urogen lead–zinc deposit from hydrothermal brines, Wuqia, Xinjiang. *Geol. J. Sichuan* 29, 400–405 (in Chinese with English abstract).
- Kong, X., 1984. The Urogen polymetallic deposit in western Tarim Basin. *Xinjiang Geol.* 2, 75–80 (in Chinese with English abstract).
- Kyle, J.R., Li, N., 2002. Jinding: A giant tertiary sandstone-hosted Zn–Pb deposit, Yunnan, China. *Soc. Econ. Geol. Newsl.* 50, 8–16.
- Leach, D.L., Sangster, D.F., Kelley, K.D., Large, R.R., Garven, G., Allen, C.R., Gutzmer, J., Walters, S., 2005. Sediment-hosted lead–zinc deposits: a global perspective. *Economic Geology 100th Anniversary Volume*, pp. 561–607.
- Li, B., Wang, J., 2006. *Lead–Zinc Deposits in Xinjiang*. Geological Publishing House, Beijing, ((55–63 pp.) (in Chinese with English abstract)).
- Li, S., Wang, G., 2008. Effects of Mesozoic and younger tectonic events on uranium mineralization in the Kashi sag. *World Nucl. Geosci.* 25, 7–12 (in Chinese with English abstract).
- Li, S., Zeng, Y., 2007. Tectonic evolution of the Kashi sag and its relationship with uranium mineralization. *Xinjiang Geol.* 25, 302–306 (in Chinese with English abstract).
- Li, F., Wang, W., Yang, J., 2005. Geologic and geochemical characteristics of the Urogen lead–zinc deposit and its genesis, Wuqia County, Xinjiang. *Miner. Resour. Geol.* 19, 335–340 (in Chinese with English abstract).
- Li, Z., Xue, C., Xin, J., Wang, S., Jia, Z., Shi, H., Dong, X., Shao, X., 2011. Geologic characteristics and sulfur and lead isotope geochemistry of the Sareke copper deposit in Xinjiang. *Geosciences* 25, 720–729 (in Chinese with English abstract).
- Li, Z., Xue, C., Dong, X., Liu, Z., Zhong, T., Qi, S., 2013. Ore geology, S- and Pb-isotopic compositions of the Urogen Zn–Pb deposit, Wuqia County, Xinjiang. *Earth Sci. Front.* 20, 40–54 (in Chinese with English abstract).
- Liu, Z., Chen, Z., Han, F., Chen, B., Zhou, Y., Cui, L., Jiang, B., Li, L., 2010. Traces of oil and gas in the mineralization in the Urogen lead–zinc deposit, Kashi, Xinjiang. *Miner. Deposits* 29, 1049–1050 (in Chinese with English abstract).
- Ma, H., Yang, Z., 2003. Evolution of Cenozoic basins in southwestern Tarim basin, Xinjiang. *Xinjiang Geol.* 21, 92–95 (in Chinese with English abstract).
- Moldowan, J.M., Serfert, W.K., Gallegos, E.J., 1985. Relationship between petroleum composition and depositional environment of petroleum source rocks. *AAPG Bull.* 69, 1255–1268.
- Navarro-Gonzalez, R., Rainey, F.A., Molina, P., Bagaley, D.R., Hollen, B.J., Rosa, J., Small, A.M., Quinn, R.C., Grunthaner, F.J., Caceres, L., Gomez-Silva, B., McKay, C.P., 2003. Mars-like soils in the Atacama Desert, Chile, and the dry limit of microbial life. *Science* 302, 1018–1021.
- Palacas, J.G., 1984. Carbonate rocks as sources of petroleum: geological and chemical characteristics and oil-source correlations. *Proceedings of the Eleventh World Petroleum Congress (1983 London)*, pp. 31–34.
- Peng, S., 1990. Geologic characteristics and genesis of major lead–zinc deposits in the Kashi district. *Nonferrous Met. Xinjiang* 2, 8–16 (in Chinese with English abstract).
- Peters, K.E., Moldowan, J.M., 1993. *The Biomarker Guide: Interpreting Molecular Fossils in Petroleum and Ancient Sediments*. Prentice Hall, Englewood Cliffs, New Jersey, (362 pp.).
- Rickard, D.T., Willden, M.Y., Marinder, N.E., Donnelly, T.H., 1979. Studies on the genesis of the Laisvall sandstone lead–zinc deposit, Sweden. *Econ. Geol.* 74, 1255–1285.
- Rieger, A., Schwark, L., Cisternas, M.E., Miller, H., 2008. Genesis and evolution of bitumen in Lower Cretaceous lavas and implications for strata-bound copper deposits, north Chile. *Econ. Geol.* 103, 387–404.
- Samama, J.C., 1969. Contribution à l'étude des gisements de type Red-beds: unpublished doctorate thesis, University of Nancy, Nancy (450 pp.).
- Seifert, W.K., Moldowan, J.M., 1980. The effect of thermal stress on source-rock quality as measured by hopane stereochemistry. *Phys. Chem. Earth* 12, 229–237.
- Southam, G., Saunders, J.A., 2005. The geomicrobiology of ore deposits. *Econ. Geol.* 100, 1067–1084.
- Tissot, B.P., Welte, D.H., 1984. *Petroleum Formation and Occurrences*. Springer-Verlag, New York, (699 pp.).
- Wang, J., Li, C., Chen, X., 1992. A new genetic model for the Jinding lead–zinc deposit. *Geol. Explor. Nonferrous Met.* 1, 200–206 (in Chinese with English abstract).
- Wang, Q., Hu, Y., Liu, S., 2003. Oil and gas geology in the northern outcropped area of the Kashi sag in the Tarim basin. *Petroleum Industry Publishing House, Beijing*, ((192 pp.) (in Chinese with English abstract)).
- Wang, S., Xue, C., Li, Z., 2011. Geologic and S–Pb isotopes characteristics of the Jiashi sandstone type copper deposits in Xinjiang. *Geosciences* 25, 219–227 (in Chinese with English abstract).

- Xie, S., Mo, J., Yang, J., Yang, J., 2003. A study of the SEDEX origin of the Cenozoic Urogen lead–zinc deposit in Wuqia County, Xinjiang. *Miner. Resour. Geol.* 17, 11–16 (in Chinese with English abstract).
- XSCG (Xinjiang Stratigraphy Compilation Group), 1981. *Stratigraphy of Northwest China – Xinjiang Division*. Geological Publishing House, Beijing, ((100 pp.) (in Chinese)).
- Xue, C., Zeng, R., Liu, S., Chi, G., Qing, H., Chen, Y., Yang, J., Wang, D., 2007. Geologic, fluid inclusion and isotopic characteristics of the Jinding Zn–Pb deposit, western Yunnan, South China: a review. *Ore Geol. Rev.* 31, 337–359.
- Xue, C., Chi, G., Xue, W., 2010. Interaction of two fluid systems in the formation of sandstone-hosted uranium deposits in the Ordos Basin: geochemical evidence and hydrodynamic modeling. *J. Geochem. Explor.* 106, 226–235.
- Ye, Q., Wu, Y., Fu, X., Chen, M., Ye, J., Zhuang, D., Yang, F., Bai, H., 1999. Mineralization Conditions and Prediction of Nonferrous Deposits in Southwestern Tianshan. Geological Publishing House, Beijing, ((129–140 pp.) (in Chinese with English abstract)).
- Zartman, R.E., Doe, B.R., 1981. Plumbotectonics — the model. *Tectonophysics* 75, 135–162.
- Zhang, S., 2010. *Geologic and Geochemical Characteristics and Genesis of Representative Lead–Zinc Deposits in Southern Tishan*. (M.Sc. thesis) China University of Geosciences, Beijing, ((90 pp.) (in Chinese with English abstract)).
- Zhou, X., Hu, Y., Liu, S., 2003. *Oil and Gas Geology of the Outcrops in the Northern Part of the Kashi sag, Tarim Basin*. Petroleum Industry Publishing House, Beijing, (192 pp.).
- Zhou, X., Luo, J., Mai, G., 2005. *Structural Characteristics and Oil and Gas Geology in the Kashi Sag and Surrounding Areas in the Tarim Basin*. Petroleum Industry Publishing House, Beijing, ((233 pp.) (in Chinese with English abstract)).
- Zhu, X., Wang, J., Liu, Z., Fang, T., 2010. Geologic characteristics and genesis of the Urogen lead–zinc deposit, Xinjiang. *Acta Geol. Sin.* 84, 695–702 (in Chinese with English abstract).