



Re-Os dating, and Pb-H-O isotope characteristics, of the Abra Cu-Ag-Pb-Au polymetallic deposit in Western Australia

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Abstract The Abra deposit, a large lead-silver-copper-gold polymetallic deposit in Western Australia, is located at the eastern of the metallogenic belt of the Jilawarra basin in the Bangemall basin. The 4th to the 6th rock section of the Irrigully Group of Edmund Series are the principal ore-host strata, composed mainly of sandstone and fine sandstone. The orebody in Abra can be classified into two types as upper layer-like lead-silver and lower veins or netvein copper-gold. The metal minerals are mainly galena, chalcopyrite, and pyrite, while the gangue minerals are mainly quartz, dolomite, and barite. Both Re-Os isotopic age of the pyrite (1329.5 ± 98 Ma) with the initial ($^{187}\text{Os}/^{188}\text{Os}$) = 5.0 ± 3.8 and Pb isotopic compositions ($^{206}\text{Pb}/^{204}\text{Pb} = 15.914\text{--}15.967$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.425\text{--}15.454$, $^{208}\text{Pb}/^{204}\text{Pb} = 35.584\text{--}35.667$) suggests that the metal minerals were sourced from the wall-rocks. $\delta\text{D}_{\text{V-SMOW}}$ values of quartz range from -35% to -17% whereas $\delta^{18}\text{O}_{\text{V-SMOW}}$ value range from 12% to 16% which indicates that the ore-forming fluids of Abra were medium-

low temperature and medium-low salinity, and were mainly metamorphic water and secondary atmospheric precipitation. When the medium-low temperature ore-forming fluids are mixed with oxidizing reducing fluids carrying a large number of metal substances, a large number of ore-forming substances will be precipitated when the physical and chemical conditions change, thus it can be considered that the Abra deposit is a medium-low temperature hydrothermal polymetallic deposit.

Keywords Re-os isotope · Pb-H-O isotope · Abra cu-ag-pb-au polymetallic deposit · Australia

1 Introduction

The Abra gold polymetallic deposit (Abra deposit) is located at the eastern of the metallogenic belt of Jilawarra basin of the Bangemall basin in Western Australia, about 870 km NNE of Perth (Fig. 1). Its coordinate is $24^{\circ}39'\text{S}$, $118^{\circ}36'\text{E}$ (Boddington 1990). It was found by air magnetic survey in 1976 and displayed as a concealed ore body by gravity measurement. In 1982, it was confirmed through the core drilling, and subsequent geological explorations were started.

The Abra mineralization was published by Vogt and Stumpfl (1987); Boddington (1990); Collins and McDonald (1994); Vogt (1995); Cooper et al. (1998); and Austen (2007). Work on mineralogy, chronology, fluid inclusions, and isotopic geochemistry have been carried out in the Abra deposit, and the mineralization age and genesis of the deposit have been discussed, but are still controversial (Johnson et al. 2011; Cutten et al. 2015; Franco et al. 2015; Heta et al. 2019; Zi et al. 2015).

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In recent years, there are several studies on the isotope chronology of the Abra deposit, but the reported ages are not consistent with each other. Through the U–Pb isotope dating (Carr 1995), Commonwealth's Scientific and Industria Research Organisation (CSIRO) obtained a conclusion about 1640 Ma, but the later verification was quite different from the actual situation, and the obtained age value was wrong; Curtin University and Geological Survey of Western Australia (GSWA) carried out SHRIMP dating research on monazite (Rasmussen et al. 2010), yielding 1385 ± 20 Ma, which represents the age of one phase fluid flow.

Due to lack of direct mineralization age and systematic fluid characteristic data, the current genetic understanding of the Abra deposit is highly controversial, and the following three viewpoints are mainly summarized as follows: (1) Iron oxide type (IOCG type) copper and gold deposit (Vogt 1995); (2) SEDEX deposit (Boddington 1990); (3) the Abra deposit can be compared to Spain's Iberian Pyrite Belt (IBP) analogy (Pirajno et al. 2009). Due to the unclear of the Abra deposit mineralization period,

the exploration activities of the deposit have been brought to a halt without significant progress. At the same time, the mineralization age of the Abra deposit is not clear, which has seriously affected the understanding and summary of regional metallogenesis. In addition, sources of the ore-forming metals and fluid are controversial. Boddington (1990) believed that the Pb and Cu in the Abra Deposit mainly derived from concealed igneous rocks in the basin. While Pirajno (2004) thought that the metallogenic material in the Abra Deposit originated from the bottom strata through hydrothermal cycling extraction and precipitation enrichment. Thus, the work conducts systematic Re-Os isotope chronology, galena Pb isotope and quartz, H, O isotope to constrain the metallogenic epochs, sources of the ore-forming metals, and ore-forming fluid, trying to preliminarily build a metallogenic model, which might help further guide the prospecting work.

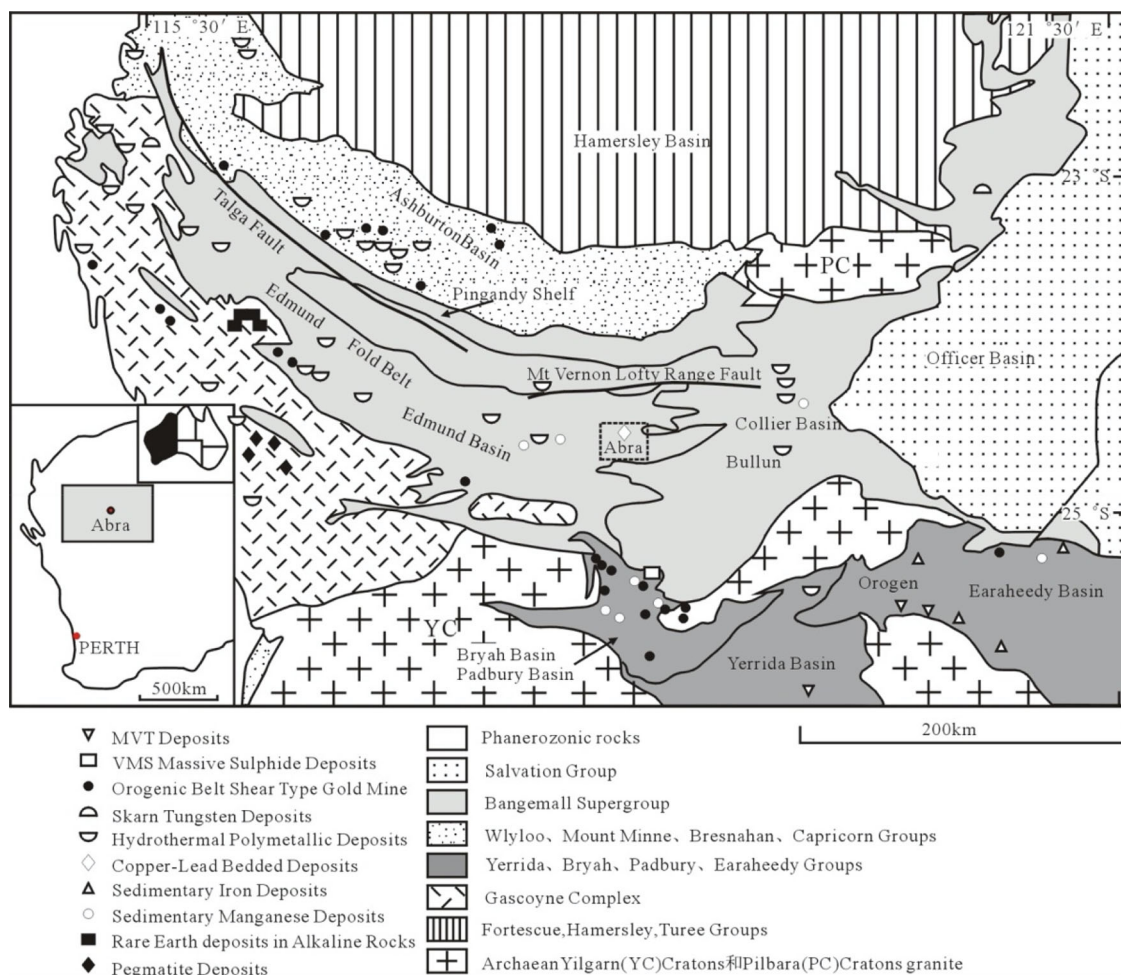
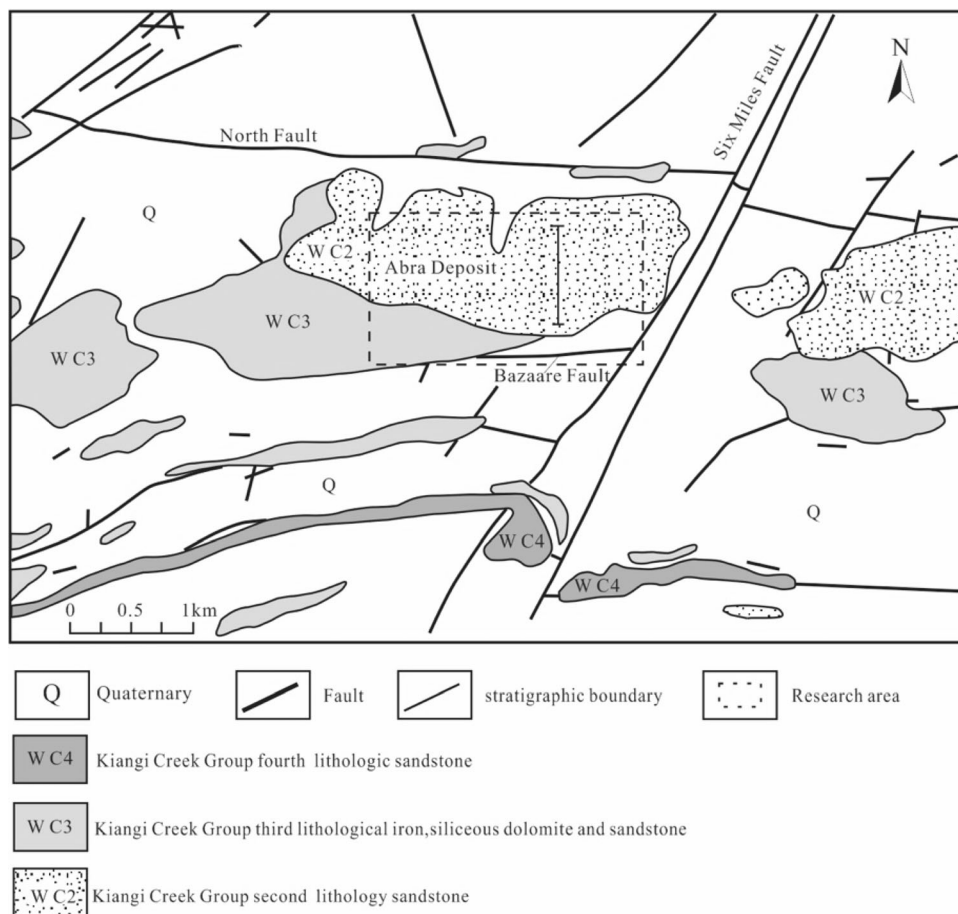


Fig.1 Simplified geological map of the Bangemall Basin showing mineral occurrences (Pirajno 2004)

Fig. 2 Sketch geological map of Abra deposit (Li et al. 2014)



2 Regional geologic background

Geotectonic position of the Abra deposit is located in the clastic rock and carbonate formation of the eastern end of the Jilawarra basin which is the secondary basin of the Bangemall basin belonging to the south of the Proterozoic Capricorn orogenic belt. It's eastern intersects the Collier basin hydrothermal polymetallic metallogenic belt, and western is the Edmund basin hydrothermal polymetallic metallogenic belt.

Structure in the Abra deposit is simple (Fig. 2). Its north is a nearly east–west normal fault. Its tendency is north, with 40° inclination and 150 m slip. This fault cuts off the orebody. In the southern, there is a near east–west hidden rupture—the Bazaare fault. Due to the low degree of research, the nature of the fracture is unknown. In the eastern, there is six miles fault (north to east). In the case of core drilling, the Abra deposit outputs in the south wing of a nearly E-W towards rolling anticline. The stratum angle is about 30° .

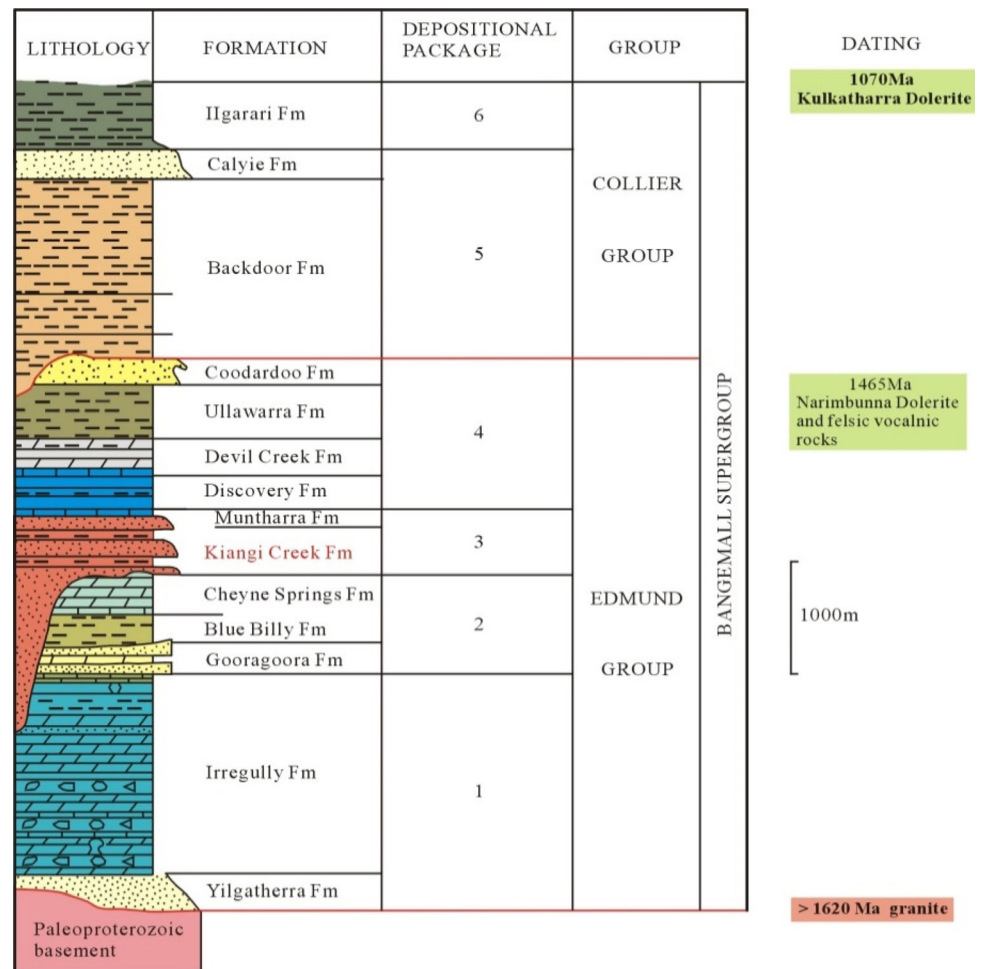
The Bangemall basin is mainly composed of the Bangemall Supergroup-shallow metamorphic sedimentary rocks (Fig. 3). The Bangemall Supergroup includes the Edmund Group at the lower and Collier Group at the upper.

The exposed lithology in the mining area is mainly sandstone, siltstone, and mudstone of the Kiangi Creek formation of the Collier Group, with a thickness of about 300 m. The 4th to 6th lithology section of the lower Edmund Group and Irrigully Group is a set of sandstone and fine sandstone with a thickness of over 600 m. The 1st to 3rd lithology section of the Irrigully group are mudstone, mudstone, and chlorite with un-defined thickness. There is a gradual transition relationship between the 3rd and 4th lithological sections.

According to the lithological characteristics, the 4th to 6th section of the Irrigully Group could be divided into the following five sub-sections:

1. Red Banded Zone (RBZ), located at the top of the Irrigully Group and bounded by a layer of mudstone above the Kiangi Creek formation. RBZ contains a large amount of hematite, a small number of veinlets of magnetite interspersing hematite, and some large-grained, well-crystallized barite. The mineralization is weak, with occasional lead ore veinlets. The thickness of RBZ is about 50–80 m (Fig. 5A);
2. Dolomite Banded Zone (DBZ), mainly distributed in the center of the ore deposit, the dome shape and

Fig. 3 Summary of Bangemall supergroup stratigraphy (Rasmussen et al. 2010)



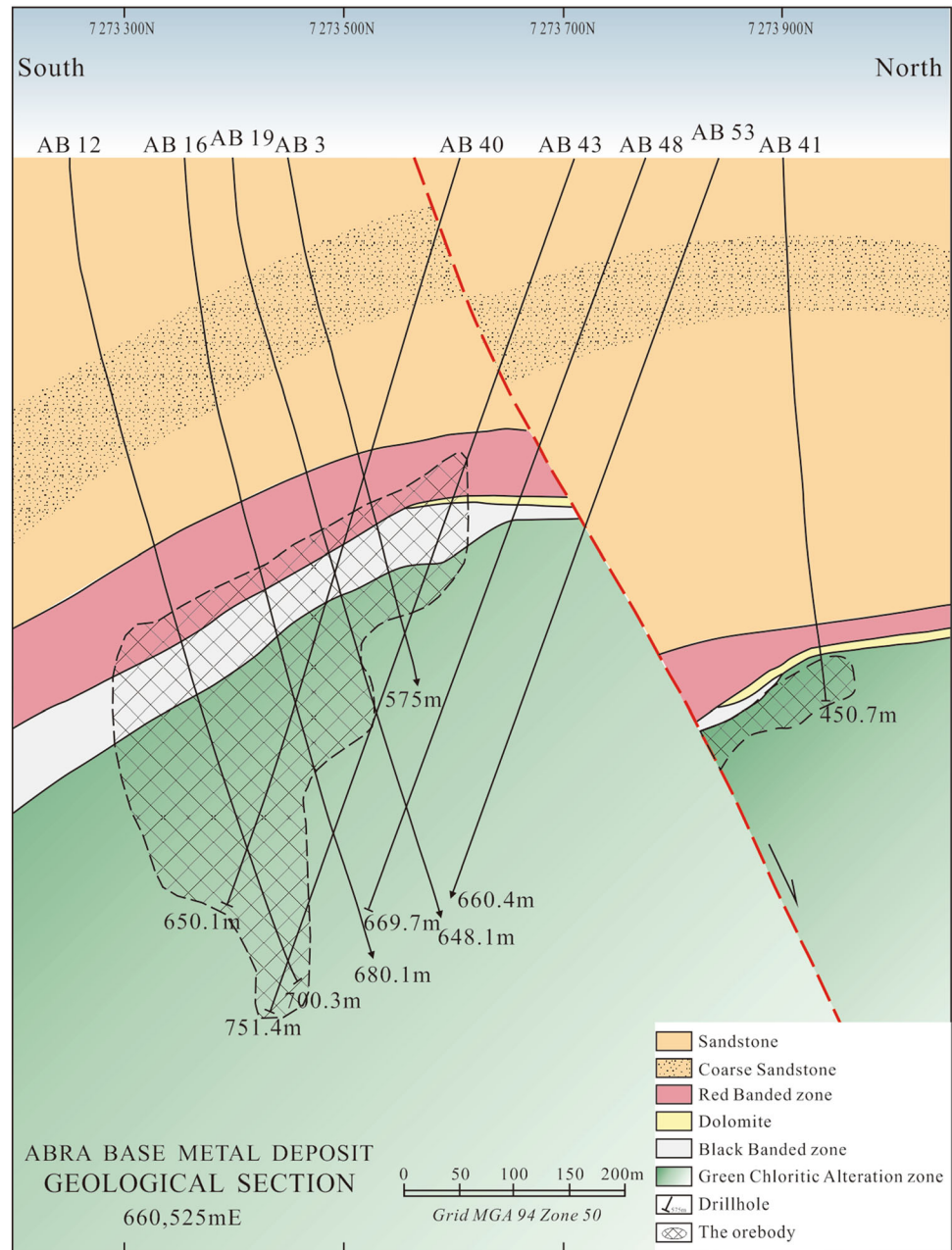
characterized by dolomite, contents of hematite and barite are less than the RBZ but relatively more abundant magnetite. The mineralization is weak, with some galena in veins. The thickness of the section is about 10–20 m;

3. Black Banded Zone (BBZ), characterized by mass development of magnetite, the contents of hematite and barite are greatly reduced, and barely containing dolomite and occasional quartz vein. The mineralization is intense, with mainly stratified lead mineralization. The content of pyrite increases. The thickness of BBZ is about 80–100 m (Fig. 5B);
4. Alteration Banded Zone (ABZ), variegated and gray. The fracture is large and well-developed, filled with quartz, and highly silicified. Hematite, magnetite, and barite are not developed, about could be found locally. The mineralization is characterized by veins and nets. The lead ore mineralization becomes less intense but chalcopyrite is more abundant. The thickness of ABZ about 80–120 m (Fig. 5C, 5E);
5. Chlorite Banded Zone (CBZ), light green and celadon. Magnetite, and barite, etc. only occasionally saw in the

fissure vein and the net pulse. The mineralization is controlled by fractures, which form large vein and veinlets mineralization. Ore minerals are dominated by chalcopyrite. It is found that the keratinite can be combined well, and the fractures are filled with chalcopyrite and pyrite. The thickness exceeds 100 m. Breccia has good join ability and the cracks are filled with chalcopyrite and pyrite (Fig. 5D, F).

3 Deposit geological characteristic

There are two types of ore bodies of the Abra deposit, lead-silver ore body and copper-gold ore body. The upper part is a stratiform-like lead-silver ore body, and the lower part is a large vein and net vein copper-gold ore body (Fig. 4). Ore bodies orientation is NW with the south-facing, dip angle is about 40° to 60°. The thickness of the upper ore body is about 200–250 m, and that of the lower ore body is about 100 m. This ore deposit is a large hidden polymetallic deposit, the main ore body mainly occurs within

Fig. 4 Geological section of Abra deposit (660,525 mE)

the scope of the 250 to 800 m. By the end of 2011, it has a proven resource of 107 million t, including the amount of Pb-Ag 93 million t (the average grade Pb 4.1%, Ag 10g/t) and Cu-Au resources of 14 million t (average grade Cu 0.6%, Au 0.5 g/t) (Fig. 4).

The mineralization types in the Abra deposit can be divided into layers of mineralization (upper) and veins (lower), and net mineralization according to their occurrences. The outputs of stratiform-like mineralization mainly in the red, dolomite, and black segments characterized by the development of the formation of the galena, and particles are smaller (Fig. 5G). The development of gig

net vein and vein mineralization mainly in the alteration and chlorite, variations of vein width are significant (from 0.5 cm to more than 10 cm), characterized by the vein filling of galena, chalcopyrite, and quartz (Fig. 5H).

The mineral assemblages in the Abra deposit are simple. Metallic minerals are mainly galena, chalcopyrite and pyrite, and a small amount of sphalerite. The gangue minerals are mainly quartz, barite, dolomite et ac. Galena grains are 0.5–2 mm in the upper layer stratiform-like ore block, occasionally more than 2 mm (Fig. 5I, J), but in the lower part of alteration and net vein mineralization, the majority of galena are larger than 2 mm. Chalcopyrite is

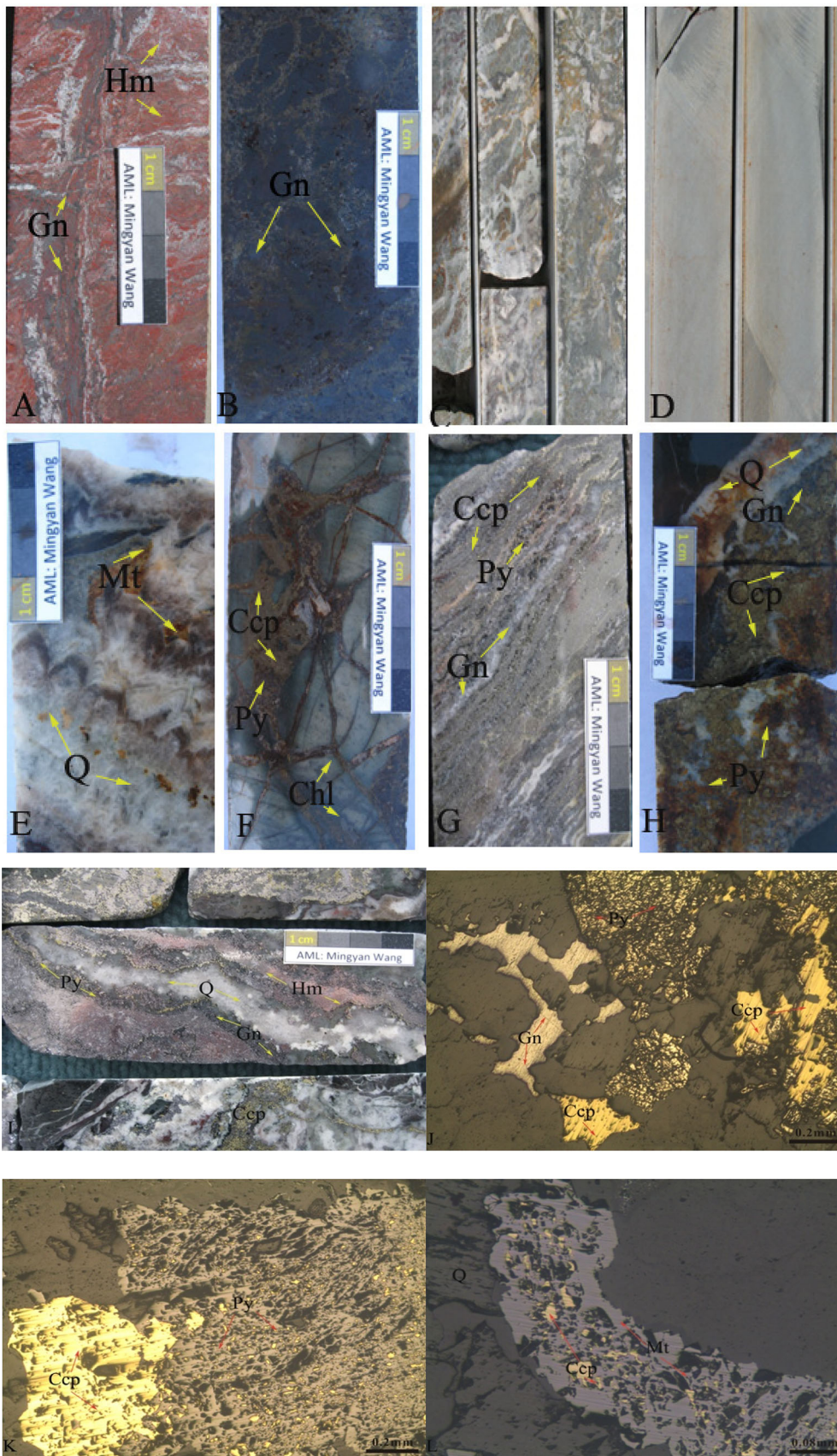


Fig. 5 Photos and microphotographs of Abra deposit A-Red banded zone; B-Black banded zone; C-Alteration zone; D-Chlorite zone; E-Multistage quartz vein; F-Hydraulic fracture; G-Layered mineralization; H-Vein mineralization; I-Lead and copper ore; J- Galena, chalcopyrite, pyrite symbiotic relationship; K- Chalcopyrite and pyrite symbiotic relationship; L- Quartz, chalcopyrite, magnetite symbiotic relationship; Q-Quartz; Gn-Galena; Hm-Hematite; Mt-Magnetite; Ccp-Chalcopyrite; Py-Pyrite; Chl-Chlorite

mainly the lower part of the deposit, most of which is an infestation, and closely symbiotic with pyrite (Fig. 5K). Pyrite is mostly xenomorphic-hypidiomorphic granule with the size of 0.2 mm, symbiosis with chalcopyrite and galena (Fig. 5J). Quartz is a xenomorphic granule with the size of 0.1–0.5 mm, and the carbonate minerals are distributed in the barite granules and fissures (Fig. 5L).

4 Sampling and analytical methods

4.1 Samples

Seven representative samples from AB56 and AB59 drilling cores were selected in the main layers of RBZ, BBZ, AB, Z, and CBZ (Table 1). We chose pyrites from the upper layered ore body and the lower vein ore body for Re-Os dating of the ore-forming ages.

In 2009, Abra company carried out studies on Pb, H, O isotope compositions and fluid inclusions from typical samples of RBZ, BBZ, ABZ, and CBZ. The samples are taken from AB24 and AB31 drilling cores. These samples are closely related to Pb-Cu mineralization, which can represent fluid characteristics of metallogenic stages.

4.2 Analytical methods

The pyrite separates for Re-Os isotopic dating are in close association with galena, chalcopyrite, and can represent the metallogenic stage (Fig. 5J, K).

The Re-Os isotope analysis was conducted in the Curtin University of Technology by Svetlana G Tessalina, Re and Os abundance and $^{187}\text{Os}/^{188}\text{Os}$ ratios were measured by inductively coupled plasma mass spectrometer LA-MC-ICP-MS (Fletcher et al. 2004). Seven samples of the pyrite Re-Os isotope were detected. $^{187}\text{Os}^*$ is the total ^{187}Os content. The analysis process of the study was listed in the literature (Du et al. 2012).

Pb isotope analysis was completed by Commonwealth's Scientific and Industria Research Organisation (CSIRO) on MAT-262 (Finnigan). O, H isotopes were measured in Europa GEO 20–2 at Queens University, Canada. The standard material is V-SMOW. O, H isotope analysis precisions were 0.1×10^{-3} and 1×10^{-3} , respectively.

5 Results

5.1 Pyrite Re-Os dating

Because of the extremely low contents of Re and Os isotopes in pyrite, the blank level in the analysis process is vital for data quality. In this analysis, the blank of Re is less than 0.5% (0.005×10^{-9} g), and the blank level of Os is less than 0.2%. Using the formula $t = 1/\lambda[\ln(1 + ^{187}\text{Os}/^{187}\text{Re})]$ to calculate model age, where $\lambda(^{187}\text{Re}$ decay constant) = $1.666 \times 10^{-11} \text{ yr}^{-1}$ (Smoliar et al. 1996).

The results of seven pyrite Re-Os isotopes are given in Table 2. The contents of Re in pyrite are 0.96 to 2.80 ppb, the total contents of Os range are 19.68 to 46.90 ppm, model age was 1286.6–1142.0 Ma. Using the data in Table 2 to regression calculation by ISOPLOT 3 software (Ludwig 2003). We obtained the isochron age is 1329 ± 98 Ma, MSWD = 1.2, $n = 7$ (Fig. 6), the initial value $(^{187}\text{Os}/^{188}\text{Os})_0 = 5.0 \pm 3.8$.

5.2 Pb isotope

The Pb isotope compositions of galena are given in Table 3. $^{206}\text{Pb}/^{204}\text{Pb}$ variation from 15.914 to 15.967, with

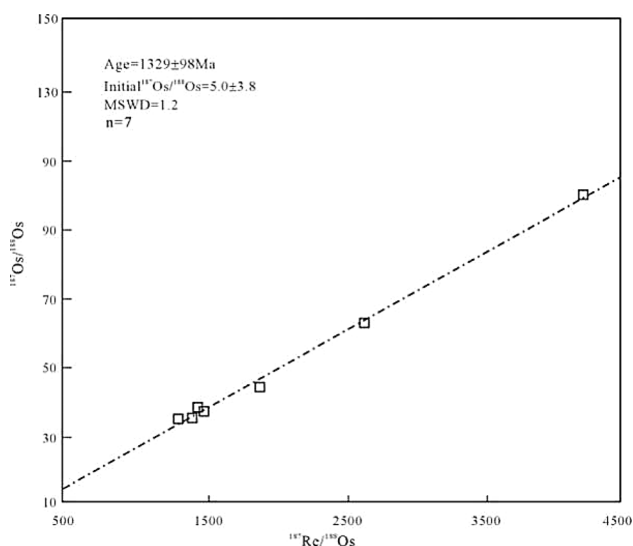
Table 1 The characteristics of samples in Abra deposit

Sample number	Depth (m)	Sample characteristics
AB56-1	415.5	Red banded zone, layered galena and pyrite, mineralization is weak
AB56-2	529.8	Dolomite banded zone, layered galena and pyrite, mineralization weak
AB56-3	537.5	Black banded zone, Veined galena, chalcopyrite, and pyrite mineralization
AB56-4	726.0	Net vein zone, chalcopyrite and pyrite, strong mineralization
AB59-2	694.4	Alteration banded zone, disseminated and veined galena, pyrite, and chalcopyrite
AB59-3	724.6	Net vein zone, chalcopyrite and pyrite, strong mineralization
AB59-4	729.3	Net vein zone, chalcopyrite and pyrite, strong mineralization

Table 2 Analysis result of Re-Os isotopes with pyrite samples in Abra deposit

Sample number	Weight (g)	Re ($\times 10^{-9}$)	$\pm 2\sigma$	^{187}Re ($\times 10^{-9}$)	Total Os ($\times 10^{-6}$)	$\pm 2\sigma$	$^{187}\text{Os}^*$ ($\times 10^{-9}$)	$^{187}\text{Re}/^{188}\text{Os}$	$\pm 2\sigma$	$^{187}/^{188}\text{Os}$	$\pm 2\sigma$	Age (Ma)
AB56-1	0.86	2.80	0.01	1.766	46.90	11	0.037	2612.72	506	62.84	12.1	1244.6
AB56-2	1.02	2.73	0.01	1.718	46.46	8.8	0.033	1873.52	287	44.07	6.77	1142.0
AB56-3	0.94	2.33	0.01	1.470	37.22	25	0.031	4195.84	217	99.79	51.8	1252.7
AB56-4	1.30	0.96	0.00	0.600	19.18	6	0.013	1421.20	8	38.66	0	1286.6
AB59-2	1.17	1.02	0.00	0.640	19.71	5.8	0.013	1375.44	358	35.67	9.74	1207.0
AB59-3	0.73	1.05	0.01	0.656	21.38	3.9	0.014	1289.20	226	35.07	5.99	1267.5
AB59-4	0.91	1.24	0.01	0.770	23.58	9.2	0.016	1458.16	467	37.53	12.70	1267.5
AB59-4	0.91	1.24	0	0.770	23.58	6.9	0.016	1458.16	351	37.53	9.04	1234.5

Dr. Svetlana G.Tessalina Analysis time: August 2011

**Fig. 6** Re-Os isochron of pyrite from Abra deposit

an average of 15.929 and variation of 0.3%; $^{207}\text{Pb}/^{204}\text{Pb}$ range from 15.425 to 15.454, with an average of 15.438 and variation of 0.2%; $^{208}\text{Pb}/^{204}\text{Pb}$ range from 35.584 to 35.667, with an average of 35.625 and variation of 0.2%. Variations of Pb isotope are. The value of μ was 9.69–9.73, ω was 37.05–37.47, both of which are higher than normal lead μ value (8.686–9.238) and normal lead ω value (35.55 + 0.59) respectively, Th/U value was 3.70–3.73, and the model age $t = 1728$ –1711 Ma.

5.3 H–O isotope

The results of the H–O isotope compositions of 7 quartz samples are shown in Table 4. The range of $\delta\text{D}_{\text{V-SMOW}}$ was -35‰ to -17‰ with an average of -23‰ . The range of $\delta^{18}\text{O}_{\text{V-SMOW}}$ was 12.386‰ to 16.161‰ with an average of 13.874‰. the range of $\delta^{18}\text{O}_{\text{fluid}}$ was 5.1‰ ~ 11.9‰ computed through the formula $1000 \ln \alpha_{\text{quartz}}$.

Table 3 Pb isotopic compositions of Abra deposit

Hole number	Depth (m)	Lithology	Mineral	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	μ	ω	Th/U	t(Ma)
AB31	392.3	Red banded zone	Galena	15.923	15.438	35.626	9.71	37.38	3.73	1727
AB24	376.05	Black banded zone	Galena	15.919	15.436	35.621	9.71	37.36	3.72	1728
AB24	444.75	Alteration zone	Galena	15.914	15.429	35.599	9.7	37.19	3.71	1725
AB24	452.63	Alteration zone	Galena	15.915	15.425	35.584	9.69	37.05	3.7	1721
AB24	461.67	Net vein zone	Galena	15.934	15.441	35.638	9.72	37.39	3.72	1722
AB24	600.18	Net vein zone	Galena	15.967	15.454	35.667	9.73	37.44	3.72	1711
AB31	642.7	Net vein zone	Galena	15.93	15.444	35.64	9.73	37.47	3.73	1727

Table 4 H and O isotopic compositions of the Abra deposit

Hole number	Depth (m)	Lithology	Mineral	$\delta^{18}\text{O}_{\text{V-SMOW}}$ (‰)	$\delta\text{D}_{\text{V-SMOW}}$ (‰)
AB24	297.90	Red banded zone	Quartz	14.680	– 19
AB31	423.50	Red banded zone/Black banded zone	Quartz	16.161	– 23
AB24	343.48	Black banded zone	Quartz	14.885	– 23
AB31	480.64	Black banded zone	Quartz	13.570	– 30
AB24	618.13	Net vein zone	Quartz	12.478	– 17
AB24	649.95	Net vein zone	Quartz	12.386	– 19
AB24	671.24	Net vein zone	Quartz	12.956	– 35

$\text{water} = 3.38 \times 10^{-6}/T^2 - 3.40$ (Clayton et al. 1972). Projecting the data of the $\delta\text{D}_{\text{V-SMOW}}$ and $\delta^{18}\text{O}_{\text{V-SMOW}}$ onto the hydrogen and oxygen isotope diagram, most of the samples fall within the scope of the metamorphic water, while a few were projected in the range of meteoric precipitation. The hydrogen and oxygen isotopic compositions of the ore deposit show that the ore-forming fluid was the mixture of metamorphic water and meteoric fluids, but mainly metamorphic water.

6 Discussion

6.1 Timing of mineralization

The main ore minerals of the Abra deposit are galena, chalcopyrite, and pyrite. Pyrite is in close association with chalcopyrite and galena (Fig. 5J, K), thus the pyrite formation time could be regarded as representative of lead and copper deposits metallogenic epoch. However, the galena Pb isotope model age $t = 1728\text{--}1711$ Ma is earlier than the pyrite Re-Os isotopic age value. This is probably because the galena Pb isotope μ and ω value are higher than normal lead (8.686 ~ 9.238) and (35.55 ± 0.59), indicating that the lead in this ore deposit is not a single stage normal lead, but radioactive anomaly lead. Therefore, the obtained model age is not the deposit metallogenic age. In this study, the time lineage obtained by fitting was 1329 ± 98 Ma (MSWD = 1.2) with low blank value and high confidence, it could be the ore-forming age of the ore deposit.

According to Western Australia Bureau (Fig. 3), the formation age of the Edmund group is 1620 ~ 1465 Ma, but the Abra deposit pyrite formation age is 1329 ± 98 Ma, suggesting that mineralization time is later than the Edmund group. It should belong to epigenetic instead of diagenetic. But from the formation sedimentary sequence the ore deposit should be formed through diagenetic processes, as evidence from the upper stratiform-like lead and silver mineralization body in the spatial distribution in the 4th to 6th lithology section of the upper Edmund Irrigully

group, and in the overlying Gooragoora group without mineralization.

How to explain the inconsistent phenomena of geological phenomenon and age data. There are two possibilities. One explanation is that 1329 ± 98 Ma represents the Abra deposit main metallogenic period. The layer control may be due to the overlying strata Gooragoora group contact area has a set of mudstone and shale rock with low permeability, ore-forming fluid did not travel through the horizon, so there was no mineralization in this stratum. The other explanation is that the Abra deposit is syngeneic, but at the same time there may be multiple metallogenic fluid activities, and 1329 ± 98 Ma is only the time of one primary mineralization.

Rasmussen et al. (2010) carried out in situ monazite dating of RBZ and BBZ sandstone to obtain isochronous age of 1385 Ma and argue that it is an important metallogenic fluid activity time. This is because in low temperature (100–550 °C) hydrothermal activities, monazite can dissolve and precipitation and growth, thus, serving as a good dating mineral (Rasmussen et al. 2001, 2005, 2007; Harrison et al. 2002). If there are multi-phase fluid activities, monazite will have a multiple ring structure or early monazite dissolved by the later fluid. And each zone represents a thermal activity, which revealed that fluid activity was not earlier than 1385 Ma.

Combining previous research results and this work, we support the first explain. Because the current age data were later than 1465 Ma, mainly between 1320 ~ 1385 Ma and these values were obtained from different mineral samples, which can eliminate the uncertainties caused by using a certain mineral. Moreover, these age values not only have the age values of Re-Os isotope, but also have the age values of monazite and U–Pb, and obtained from different laboratories, which can also eliminate the uncertainties caused by a single dating.

In conclusion, the pyrite Re-Os isotopes and monazite U–Pb dating support each other. Thus, the age data of 1329 ± 98 Ma can represent the main metallogenic age of the Abra deposit.

6.2 Sources of ore metals

Vogt and Stumpfl (1987) considered that the metallogenic material of the Abra deposit is derived from the red and sandstone layers with abundant metallogenic elements in the lower part of the basin, which is similar to the source of copper in the central African copper belt. Boddington (1990) considered that the origin of metallogenic metallic materials is from the deeply buried rocks, which is a SEDEX type deposit. Pirajno (2004) suggests that the Abra deposit may belong to the SEDEX type, which is derived from the base stratum. Re-Os isotope system can trace the metallogenic material source and the degree of precise instructions were mixed with crustal material (Foster et al. 1996); the crust is enriched Re, the involvement of crustal materials causes the radioactive ^{187}Os content increasing leading to the increasing of the initial value (Saal et al. 1998). The initial value of ($^{187}\text{Os}/^{188}\text{Os}$) = 5.0 ± 3.8 in this deposit is higher than the original mantle value (0.125), indicating that metallogenic materials originate from the crust.

Pb isotope composition is one of the most direct and effective methods for tracing mineralization, and it has been widely used in the study of various ore deposits (Sun et al. 2016; Wang et al. 2016). Franco Pirajno et al. (2015) has carried out a study of a suite of Galena separates from four different samples from the Abra deposit. He concluded that a crustal source and is compatible with sourcing lead in the Abra deposit from the Edmund Basin. The variations of Pb isotopes are the same as that got by Franco Pirajno et al. (2015) ($^{206}\text{Pb}/^{204}\text{Pb}$ variation from 15.918 to 15.959; $^{207}\text{Pb}/^{204}\text{Pb}$ range from 15.426 to 15.448; $^{208}\text{Pb}/^{204}\text{Pb}$ range from 35.584 to 35.659). And the variations of Pb isotopes of the seven galena are limited, indicating that the lead sources in the RBZ, BBZ, ABZ, and CBZ are probably a single reservoir. In the Zartman lead construction schematic diagram (Fig. 7), 7 samples almost all falling near the upper crust evolution line, which displays the sources of ore-forming materials lead is the crust. According to the study of sulfur and strontium isotope (Li 2014; He 2013), the metallogenic material Pb, Ag, Cu, Au mainly came from the surrounding rocks. In combination with the Re-Os isotope and Pb isotope characteristics of this deposit, the metallic substance is mainly derived from sedimentary strata such as the red layer and gravel layer at the bottom, which is carried into the favorable space and deposited into ores.

6.3 Nature and origin of the ore-forming fluids

We carried out a study on Fluid inclusion in RBZ, BBZ, ABZ, and CBZ. The results showed that (1) fluid inclusions in quartz vein are mainly primary, particle size range 4–8

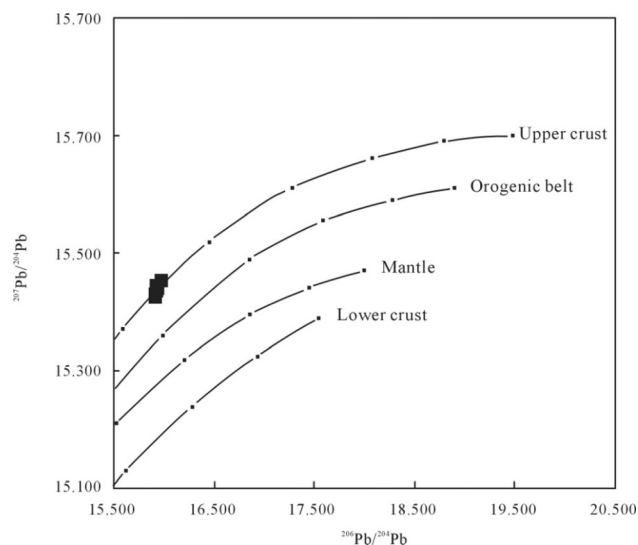


Fig. 7 The piumbotectonic model of the Abra deposit (Zartman and Doe 1981)

μm , generally less than $10 \mu\text{m}$; (2) the RBZ and BBZ are mainly pure liquid inclusions, while the ABZ and the CBZ are about 5% of the gas–liquid two-phase inclusions, and the gas phase and liquid phase ratio are generally 5%–10%; (3) Quantity of inclusions in ABZ and CBZ increased obviously, and some are greater than $20 \mu\text{m}$; and (4) the average temperature range and salinity of RBZ, BBZ, ABZ, and CBZ are respectively $162\text{--}195 \text{ }^\circ\text{C}$ and 6.9%–13.0%, $167\text{--}190 \text{ }^\circ\text{C}$ and 6.5%–11.2%, $173\text{--}251 \text{ }^\circ\text{C}$ and 7.0%–19.8%, having the ore-forming fluid characteristics of low temperature and low salinity. According to Li (2014); He (2013), there are mainly two-phase H_2O inclusions, inclusions containing CO_2 and CH_4 , and three-phase inclusions containing mineral, with the size of 2– $20 \mu\text{m}$. Their form is a more irregular shape, elliptical and rectangular, homogenization temperature and salinity range display characteristics for the low temperature and low salinity.

In the $\delta\text{D}_{\text{V-SMOW}}$ and $\delta^{18}\text{O}_{\text{V-SMOW}}$ hydrogen and oxygen isotope diagram (Fig. 8), the composition of quartz H–O isotopes show that the metallogenic fluid is a mixture of metamorphic water and atmospheric precipitation, and dominated by metamorphic water. In conclusion, the ore-forming fluid is the low temperature, and low salinity fluid, and is the mixed source dominated by metamorphic water and followed by meteoric water.

6.4 Metallogenic model

Due to the increase of overlying rocks and the deepening of burial depth, the bottommost sediments were gradually compacted and dehydrated, and the salinity of pore water kept increasing in the sedimentary basin. As the sediments

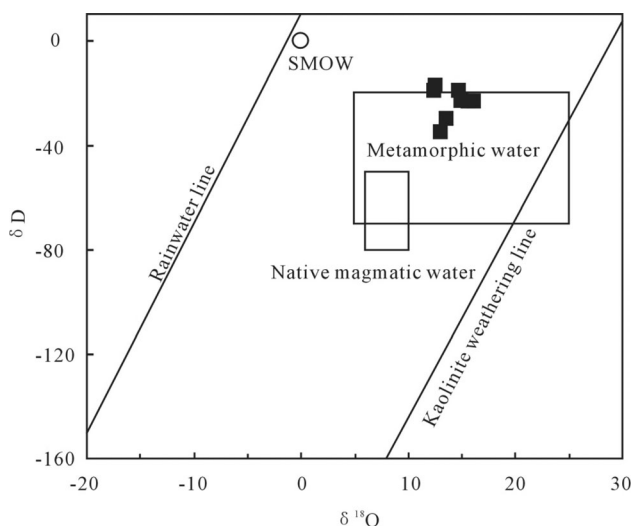


Fig. 8 The $\delta D_{V-SMOW}-\delta^{18}O_{V-SMOW}$ plot of ore-forming fluid in Abra deposit (Taylor 1974)

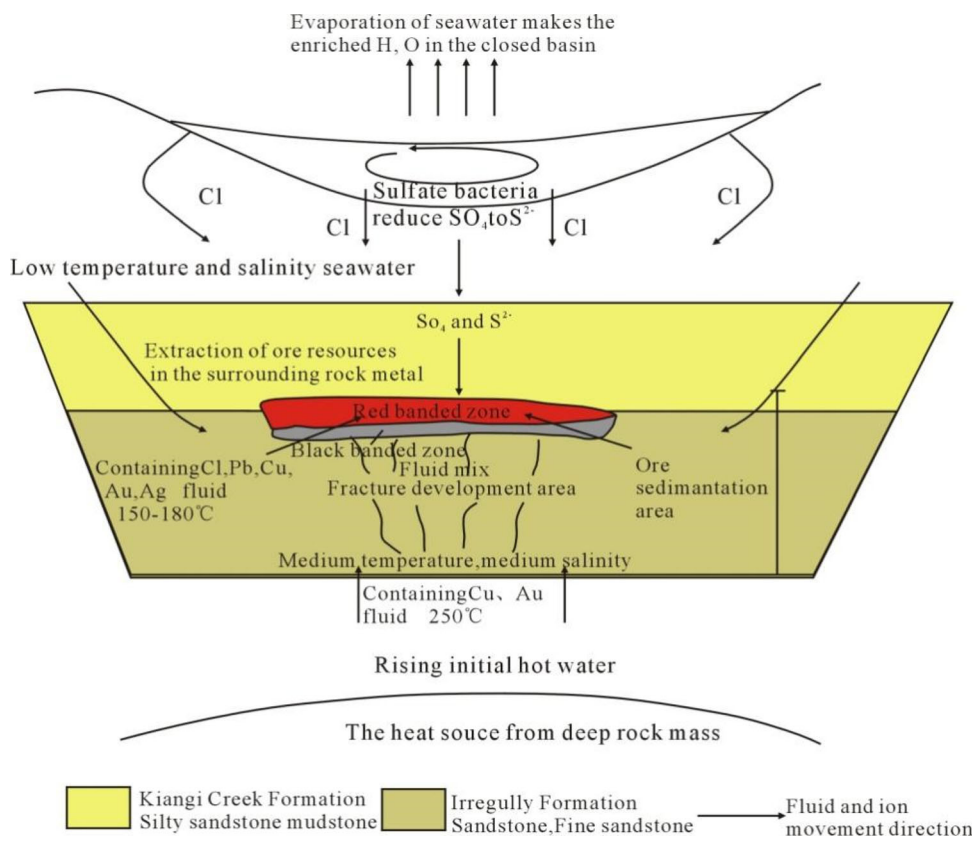
continued to be compacted under the influence of geothermal gradients, the expandable clay was transformed into non-expandable clay, and metallic materials were to be extracted from the minerals through fluid effect and entered syngenetic water. While sediments were further dehydrated by increasing pressure, on one hand, a large amount of

syngenetic water was discharged, and on the other hand, more metals were activated by fluid extraction and entered the syngenetic fluid to form the initial ore-bearing hydrothermal fluid and ore-forming fluid.

West Australia craton underwent long-term, large-scale magmatic activity since 1.43–1.07 Ga. Peregrine dike, dolerite, and rhyolite were well developed in the region. Pirajno (2004) suggests that due to the mantle plume, during this period, the abnormally high geothermal gradient increased fluid activity, strengthened the ability of fluid extraction ore-forming elements, activities, and frequency, and provide the heat source for mineralization.

Above all, in the process of metal material forming orebody, the reductive high-temperature ore-forming fluid-carrying metal ions such as Fe, Pb, Ag, Cu, Au et al. and S^{2-} ion moves from down to up along the fracture and mix with oxidizing fluid from in situ, or top-down migration. Then when the temperature, pressure, and pH changed, it generated metal minerals and formed ore bodies in favor of spatial precipitation (Fig. 9). The Abra deposit should be a low-medium temperature hydrothermal stratabound type deposit.

Fig. 9 Metallogenic model of the Abra deposit



7 Conclusion

1. The Abra deposit is located at the eastern of the metallogenic belt of the Jilawarra basin in the Bangemall basin in western Australia. The metallogenic belt is an important polymetallic mineral producing area in Western Australia. Abra deposit is mainly composed of upper layer lead-silver ore body and lower net vein copper–gold ore body, the main metal mineral is galena, chalcopyrite and pyrite, main gangue mineral is quartz, dolomite, barite.
2. The pyrite Re-Os isotopic age of the Abra deposit is 1329 ± 98 Ma, the initial value ($^{187}\text{Os}/^{188}\text{Os}$) = 5.0 ± 3.8 . The galena Pb isotopic compositions ($^{206}\text{Pb}/^{204}\text{Pb}$ range of 15.914 to 15.914, $^{207}\text{Pb}/^{204}\text{Pb}$ range of 15.425 to 15.454, $^{208}\text{Pb}/^{204}\text{Pb}$ range of 35.584 to 35.584) show that metallogenic metals mainly come from the host rock. Based on the previous fluid inclusions results and the quartz H–O isotope $\delta\text{D}_{\text{V-SMOW}}$ (–35‰–17‰), and the $\delta^{18}\text{O}_{\text{V-SMOW}}$ (12.386‰–16.161‰) indicating that the Abra deposit ore-forming fluid belongs to low temperature and low salinity fluid, the source of which is mainly for metamorphic water and mixed with atmospheric precipitation followed.
3. Reductive low-temperature ore-forming fluid-carrying metal ions such as Fe, Pb, Ag, Cu, Au et al., and S^{2-} ion mix with an oxidizing fluid. Then when physical and chemical conditions change, it generated metal minerals and form ore bodies. The Abra deposit should be a low- medium temperature hydrothermal strata-bound type deposit.

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