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Geological and geochemical characteristics of the Baimazhai Ni-Cu-(PGE) sulphide deposit in Yunnan, China

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Abstract The sulphide ores of the Baimazhai deposit, although typically orthomagmatic, locally exhibit peculiar textural features and are intimately associated with hydrothermal minerals, such as biotite, amphibole and chlorite. This association suggests that the magmatic sulphide ores were subjected to hydrothermal alteration and subsequent redistribution, resulting in the observed textural features. Geochemically, the Baimazhai sulphide ores are enriched in Cu, Pd and Au, which，according to previous studies, reflects the action of hydrothermal fluids. Interestingly, Ar-Ar dating yielded the plateau ages of about 160–170 Ma, which are at odds with the established Permian age of the Emeishan large igneous province. We interpreted these younger ages as due to thermal resetting during post-Permian tectonothermal events. We have proposed a model in which tectonic movements and hydrothermal fluids related to these events modified the pre-existing magmatic sulphides. Given the degree of overprint, we suggested two possible scenarios: 1) the sulphide disseminations that surround the massive magmatic ores are the result of deformation and hydrothermal alteration; and 2) there were both magmatic massive and disseminated sulphides, in which case the scale and relocation of remobilization would have been smaller, but still detectable.

Key words Baimazhai; Ni-Cu-(PGE) mineralization; Emeishan flood basalt; geochemistry; sulphide hydrothermal remobilization

1 Introduction

The Baimazhai Ni-Cu deposit is located in the Jinping area, on the SW margin of the Yangtze Craton, and within the Jinping-Song Da rift, in Southeast Yunnan Province (Fig. 1). Only limited previous geological research has been done on the characteristics of the deposit prospecting for nickel. Guan Tao et al. (2003, 2004) did some research on the geochemistry of the REE and trace elements of lamprophyres in the Baimazhai nickel deposit, and they concluded that the lamprophyres in the Baimazhai nickel deposit were derived from a metasomatism-enrichment mantle; Wang Christa Yan et al. (2004) held that the Baimazhai sulphide deposit was formed by emplacement of olivine crystals much abundant in sulphide melts based on the geochemistry of the ores and intrusions; Xu Ping et al. (1999) and Zhang Xueshu et al. (2005) carried out geochemical research on the mafic-ultramafic sill swarms in the Baimazhai and Jiangjiaping areas respectively, they both concluded that the source reservoir of the sill swarms in the Jinping area may be at the terminal of the mantle plume. On a regional scale, Zhang Xueshu et al. (2004) and Xiao Long et al. (2003a, b) both carried out geochemical studies on the Permian basalts and held that the Permian basalts in the Jinping area were derived from mantle plume, and Zhang Xueshu et al. (2004) also made a detail discussion over the genetic relations between Permian flood basalts and nickel-copper deposits in the Jinping area, and concluded that the geochemical evidence showed that there would be genetic relations among the Permian basalts and mafic-ultramafic intrusions and their associated nickel-copper deposits in the Jinping area. Guan Tao et al. (2005) did a study on the REE geochemistry of lamprophyres in the Baimazhai nickel deposit, and concluded that the lamprophyres were derived from a metasomatism-enrichment-type mantle.

Reported in this paper are the results of field observation and the petrography and geochemistry data on the Baimazhai Ni-Cu-(PGE) deposit. This deposit has such unusual features that the host mafic and ultramafic rocks have experienced extensive hydrothermal alteration, which, as we suggested, resulted in substantial modification of the sulphide ores. The available Ar-Ar age data support our model, as is explained as follows.

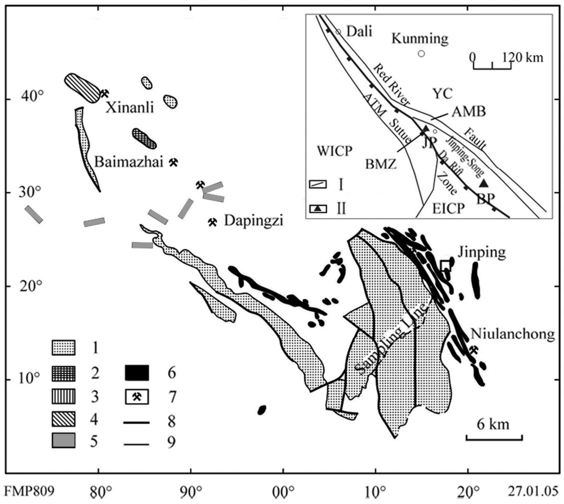

Fig. 1. Geological sketch map of the Permian flood basalts and the selected Ni-Cu-(PGE) deposits in the Jinping area. The inset shows the position of the Baimazhai nickel deposit and its regional context. YC. Yangtze Craton; ATM. Ailaoshan-Tengtiaohe-Song Ma suture zone; BMZ. Baimazhai; BP. Ban Phuc; WICP. West Indo-China plate; EICP. East Indo-China plate; AMB. Ailaoshan metamorphic belt; JP. Jinping. I. Deeply situated fault; II. mafic-ultramafic swarm and nickel sulfide deposit. 1. Permian basalt; 2. gabbro; 3. pyroxenite; 4. diabase; 5. lamprophyre dyke; 6. mafic and ultramafic intrusions; 7. Ni-Cu-(PGE); 8. fault; 9. geological boundary.

2 Geological setting

In SW China, magmatic Ni-Cu-(PGE) deposits are genetically and spatially associated with continental flood basalts of the Late Permian Emeishan large igneous province (ELIP). One typical example is the Baimazhai Ni-Cu-(PGE) deposit, which constitutes the topic of this contribution. About 35 km SE of Baimazhai is the Niulanchong Ni prospect, hosted by a gabbro sill associated with the Emeishan basaltic lavas (Fig. 1).

In the ELIP, apart from Baimazhai, other magmatic ore deposits include the Ni-Cu-(PGE) sulphides at Yangliuping and Limahe (Song Xieyan et al., 2003; Zhou Meifu et al., 2002a), the PGE-dominated Lufangqing, Bading and Dayanzi (Yao Yong et al., 2001), the Hongge Fe-V-Ti oxide ores (Zhong Hong et al., 2002, 2003) and the Panzihua and Xinjie V-Ti-Fe-PGE ores (Yao Yong et al., 2001). Fragments of the ELIP are present in NW Vietnam, where a komatiite-basalt complex hosts the Ban Phuc Ni-Cu-PGE deposit (Glotov et al., 2001).

The ELIP covers an area of at least 250 000 km^2 [Chung Sunglin et al., 1998; Chung Sunglin and Jahn, 1995; but according to Xiao Long et al. (2003a), this is a conservative estimate] in SW China (Yunnan, Sichuan and Guizhou provinces), and in NW Vietnam (south of the Jinping-Song Da rift, see Fig. 1). The ELIP consists of a succession of predominant tholeiites, with minor picritic and rhyolitic lava flows. In addition to lava flows, mafic-ultramafic layered complexes, dykes and sills, syenite and other alkaline intrusions, constitute part of the ELIP (Xu Yigang and Chung Sunglin, 2001; Boven et al., 2002; Zhang Xueshu et al., 2004; Xiao Long et al., 2004a, b).

SHRIMP zircon U-Pb dating of mafic and ultramafic intrusions in the ELIP yielded ages ranging from 259±3 Ma to 262±3 Ma (Zhou Meifu et al., 2002a, 2004; Guo Zhengfu et al., 2005). Lo Chinghua et al. (2002) reported high-precision $^{40}Ar/^{39}Ar$ dates between 251.2±1 Ma and 252.1±1.4 Ma, whereas Boven et al. (2002), also using the $^{40}Ar/^{39}Ar$ method, reported an age of 246±4 Ma for the Panzhihua layered complex and an age of 254±5 Ma from a pyroxenite. Additional $^{40}Ar/^{39}Ar$ dating (Ali et al., 2004) yielded younger ages, ranging from 147 to 42 Ma, which were attributed to thermal resetting due to tectonic events that affected the western Yangtze Craton between the Jurassic-Cretaceous (Yanshanian orogeny) and the Eocene (Himalayan-Alpine orogeny). This has important implications for the Baimazhai deposit, because one or more of these thermal events may have affected and modified the host rocks and sulphide ores both at Baimazhai and at the Niulanchong Ni prospect.

The emplacement age of the ELIP indicates that it is coeval with the Siberian large igneous province (Siberian Traps; Sharma, 1997), which as already mentioned, hosts the large Noril'sk Cu-Ni-(PGE) deposits. These massive outpourings of lavas at the Permo-Triassic boundary prompted several investigations into the possible role of flood volcanism for mass extinction (Chung Sunglin et al., 1998; Lo Chinghua et al., 2002; Ali et al., 2002; Zhou Meifu et al., 2002b; Kamo et al., 2003). The contemporaneity of the Emeishan and Siberian events also led to proposals of a possible Ni-Cu-PGE-enriched superplume activity (Yakubchuk and Nikishin, 2004).

In the Jinping area, the maximum thickness of the lava flows is estimated at about 4536 m, in going westwards it tends to decrease to less than about 1200 m (Zhang Xueshu et al., 2004, 2005), besides the lava flows, there exist lots of mafic-ultramafic intrusion swarms and associated nickel-copper deposits that are both genetically related to the Permian basalts in the Jinping area, which constitute fragments and parts of the ELIP (Zhang Xueshu et al., 2004, 2005; Xiao Long et al., 2003b).

3 Geology of the deposit

The area around Jinping is underlain by Lower Ordovician clastic sedimentary rocks, Silurian and Devonian siltstones, shales and limestones. These sedimentary rocks are intruded by a series of NW-trending mafic and ultramafic layered sill-like bodies extending along a belt about 20 km long. To the east of this mafic-ultramafic sill zone separated by a NW-trending fault, is a thick (about 4.5 km) succession of flood basalts. Syenite porphyry and lamprophyre dykes crosscut both the sedimentary, volcanic rocks and sills. To the east of the zone of sills are developed elongated bodies of biotite granite, quartz monzonite and nepheline-acmite syenite. The ages of these syenitic, granitic and lamprophyre intrusions in this area are unknown, but similar rocks elsewhere and along the Ailaoshan fault have isotopic ages ranging from 181 to 30 Ma (Hou Zengqian et al., 2002, 2003; Wang Yuejun et al., 2002; Hu Ruizhong et al., 2004; Guo Zhengfu et al., 2005).

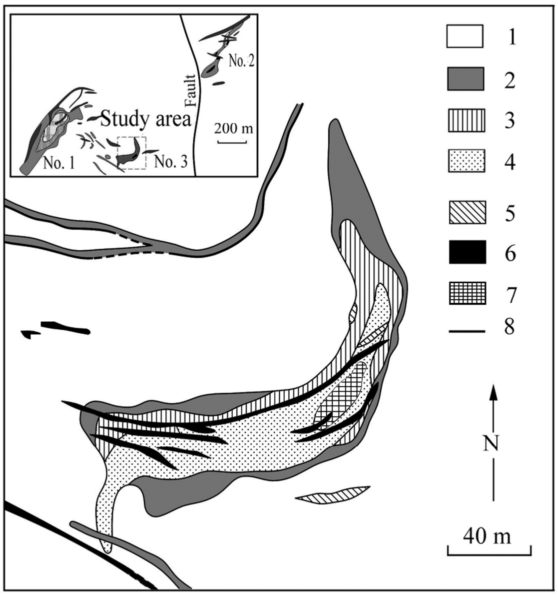

Fig. 2. Geological map of the No. 3 intrusion in the Baimazhai area. 1. Sedimentary rock; 2. gabbro; 3. pyroxenite; 4. olivine pyroxenite and peridotite; 5. diabase; 6. lamprophyre; 7. gossan (sulphide); 8. fault.

The Baimazhai Ni-Cu ore deposit is hosted by three mafic-ultramafic intrusions (named Nos. 1, 2, 3; Fig. 2) emplaced into sedimentary rocks of the Xiangyang Formation of the Lower Ordovician. The intrusions and ore-bodies are both cut by lamprophyre dykes. The Nos. 2 and 3 intrusions contain massive sulphides, but only No. 3 is economically valuable in grade (Ni and Cu up to 4.5% and 2.3%, respectively). The deposit in the No. 3 intrusion has reserves of 50000 t Ni, with a total resource of about 100000 t Ni (unpublished data obtained from the mine staff). The No. 3 intrusion is banana-shaped with a mafic shell enclosing a core of ultramafic rocks, which hosts massive sulphides (Fig. 3). From the rim to the core, the rock types are: gabbro, pyroxenite, olivine-pyroxenite, and peridotite. These rock types all show nearly pervasive to pervasive alteration characteristics and possess the mineral assemblages of amphibole, chlorite, quartz, talc and carbonate in varying amounts.

3.1 Mineralization

There are three principal styles of mineralisation:

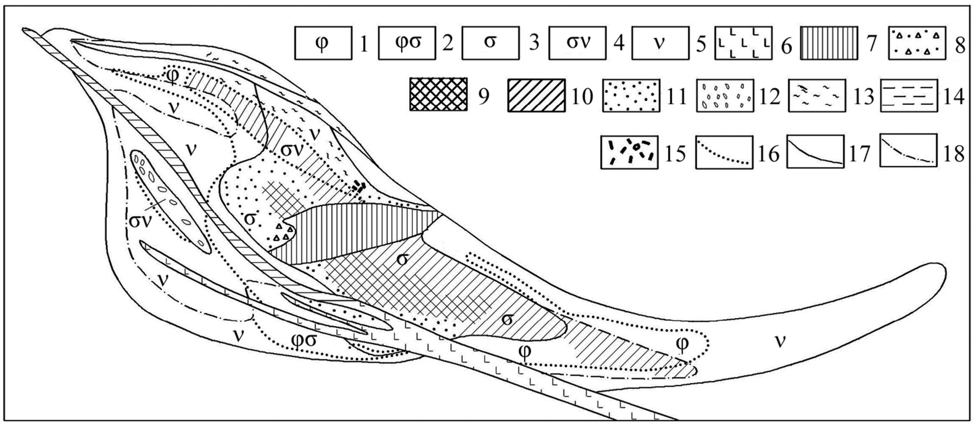

Fig. 3. Sketch map showing the ore-types in the Baimazhai Ni sulphide deposit. 1. Peridotite; 2. olivine pyroxenite; 3. pyroxenite; 4. pyroxenite dyke; 5. gabbro; 6. lamprophyre; 7. massive ore; 8. brecciated ore; 9. sideronitic ore; 10. metasomatic disseminated ore; 11. fine-grained disseminated ore; 12. patched ore; 13. veinlet disseminated ore; 14. flaky ore; 15. mottled ore; 16. rock boundary; 17. economic ore limit; 18. sub-economic ore boundary.

disseminated, alteration-modified disseminated and massive ores (Figs. 2 and 3). Disseminated ores are hosted in gabbro and pyroxenite and are generally distributed around the margins of the massive sulphide ore-bodies, effectively forming a shell. Sulphides, 0.5–3.5 mm across, are unevenly disseminated among silicate grains and have a volume percentage of between 6% and 12%. The ore minerals include pyrrhotite, pentlandite, chalcopyrite and violarite with trace amounts of magnetite, ilmenite and chrome spinel. In the gabbro host the sulphides are finer-grained than those in the pyroxenite host. The ratio of pyrrhotite:pentlandite:chalcopyrite is 53:2:1.

The distribution of alteration-modified disseminated ores is shown in Fig. 4. These alteration-modified disseminated ores form tabular bodies within the zones of disseminated sulphides. Here the sulphide contents range from 15vol.% to 30vol.% and the sulphides are irregular or ovoid in shape (Fig. 4a, b), with abundant sulphide veinlets developed locally. Ore minerals include pyrrhotite, pentlandite, chalcopyrite, magnetite, chrome spinel and ilmenite with trace amounts of galena, Ni-cobaltite and parkerite $Ni_3(Bi,Pb)_2S_2$. The ratio of pyrrhotite:pentlandite:chalcopyrite is 14:1.4:1. Characteristically, these sulphides are associated with brown biotite (possibly phlogopitic), actinolite- tremolite and chlorite, which not only form the host groundmass, but also tend to be intergrown with the margins of sulphide grains, exhibiting a peculiar texture (Fig. 4a–d).

Massive sulphides form flat, tabular bodies in the

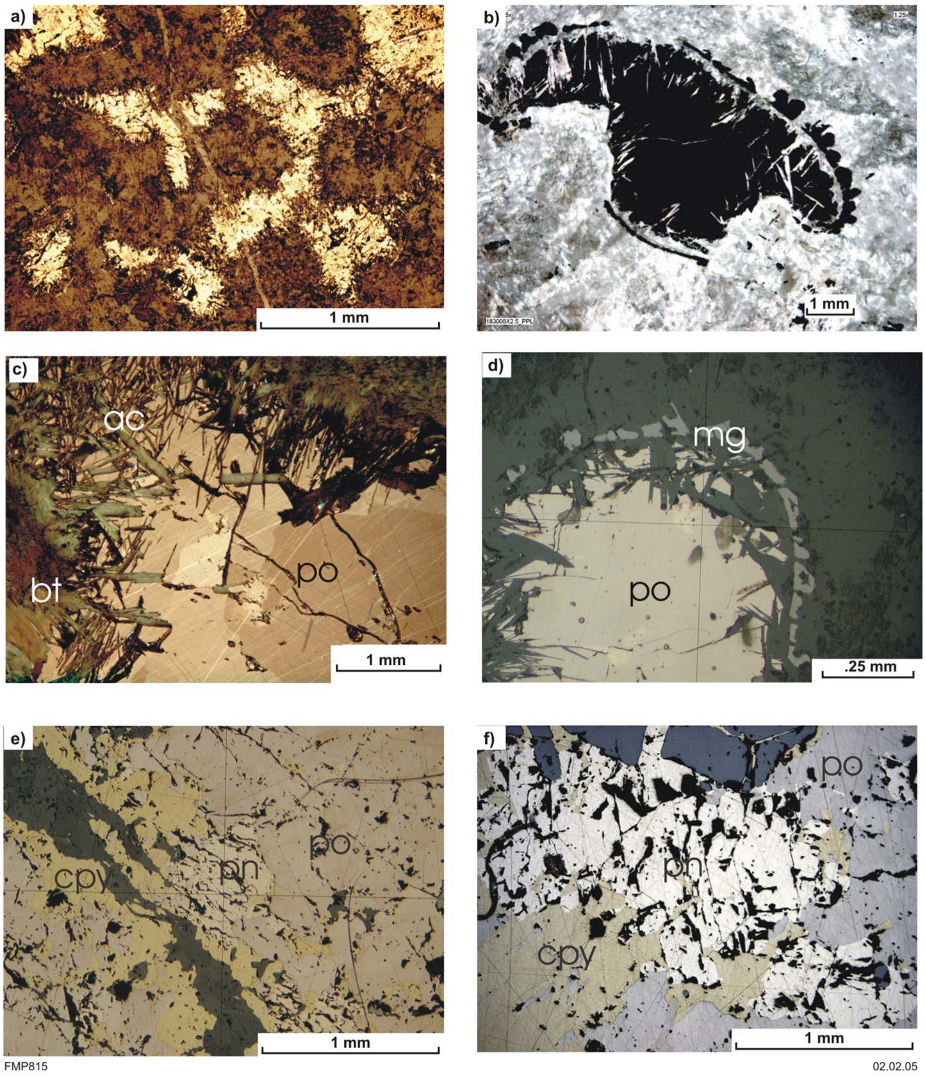

Fig. 4. Reflected light photomicrographs showing (a, b) alteration-modified disseminated pyrrhotite, the host matrix is pervasively altered to an assemblage that consists of actinolite, biotite and chlorite; (d) the margins of pyrrhotite (po) are intergrown with biotite (bt) and actinolite (ac) and are commonly rimmed by a ring of magnetite (c); reflected light photomicrographs (e) and (f) showing the association of chalcopyrite (cpy), pyrrhotite (po) and pentlandite (pn) in the massive sulphide ores.

centre of the host rock and are locally transgressive across the igneous layers (Figs. 2 and 3). The transgressive structure could be either an original feature that resulted from the emplacement of sulphide liquid, or due to later tectonic deformation. The ore minerals include pyrrhotite, pentlandite, chalcopyrite (Fig. 4e, f) and magnetite with minor galena, parkerite, argentopentlandite, Ni-colbaltite, mackinawite, altaite and electrum. The ratio of pyrrhotite: pentlandite:chalcopyrite is 12 :1.7:1.

In addition to disseminated, alteration-modified disseminated and massive ores there are also brecciated and "mottled" (locally called irregular patches of pyrrhotite and chalcopyrite aggregates) ores. Breccias are present in sandstone and gabbro, where the component clasts are cemented by sulphides. Breccia ores contain the same sulphides as in the massive ores but with relatively high contents of chalcopyrite. The ore minerals include pyrrhotite, pentlandite and chalcopyrite. The grains are about 0.1 to 0.3 mm across. The "mottled" ore is hosted by gabbro, with the sulphides forming pisolitic aggregates ranging in grain size from 5 to 15 mm across.

3.2 Rare-earth element geochemistry

Samples of ores and host rocks were analyzed for their rare-earth elements (REE) at the Yichang Institute of Geology and Mineral Resources of the Chinese Geological Survey in Yichang, Hubei Province, by ICP-MS (inductively coupled plasma mass spectrometry). The REE data for ore-hosting rocks and ores in the Baimazhai nickel deposit are given in Table 1.

The chondrite-normalized REE patterns are shown in Fig. 5A and B. Shown in Fig. 5A are comparisons of the Baimazhai ores with the Kalangtoke and Yangliuyping (Song Xieyan et al., 2003) ores. The Baimazhai ores are slightly LREE-enriched, with $(La/Yb)_N$=8.28 for disseminated ore, 14 for massive ore, and 7.42 for alteration-modified ore. All the ores show weak negative Eu anomalies (δEu=0.77 for disseminated ore, 0.731 for massive ore and 0.87 for alteration-modified ore). The chondrite-normalized REE patterns in disseminated, alteration-modified ores and weakly mineralized gabbro, together with disseminated and massive ores from Kalangtoke and Yangliuping, are coherent, their δEu values are about 10–50 times the chondrite values, and the ores mentioned above are considerably REE-enriched as compared to the Baimazhai massive ores.

Presented in the second REE plot (Fig. 5B) is a comparison of the chondrite-normalized Baimazhai ore-hosting rocks with those of the Jinchuan Ni-Cu deposit, Yangliuping and Hongge intrusions (data from Song Xieyan et al., 2003 and Zhong Hong et al., 2002, respectively). The Baimazhai rocks (peridotite) are LREE-enriched (20–300 times chondrite values;

Table 1. Rare-earth analyses of ore-hosting intrusions and sulphide ores (unit: 10^{-6})

Sample No.	BMZ02	BMZ11	BMZ06	BMZ03	BMZ04	BMZ07	BMZ01	BMZ09	BMZ10	BMZ average	Jinping basalt avg (*n*=10)
Rock	DO	DO	MO	MO	AMO	AMO	MG	Peridotite	Pyroxenite		
La	6.5	6.63	0.35	1.03	4.04	4.75	23.4	102	5.44	93.95	26.78
Ce	7.98	11.2	0.52	1.01	3.94	8.14	38.4	174	13.9	6.27	52.34
Pr	1.4	1.28	0.066	0.12	0.77	1.18	4.5	11.5	1.04	26.805	5.345
Nd	5.34	5.41	0.3	0.42	3.06	4.02	19.5	48.6	5.01	5.69	21.65
Sm	1.25	1.25	0.081	0.097	0.68	1.04	4.21	9.91	1.47	1.435	5.03
Eu	0.53	0.13	0.017	0.024	0.33	0.18	1.02	2.55	0.32	5.32	1.808
Gd	1.34	1.45	0.064	0.11	0.74	1.16	3.66	8.8	1.84	0.785	5.922
Tb	0.19	0.19	0.01	0.017	0.14	0.16	0.63	1.29	0.28	3.305	0.91
Dy	1.41	1.32	0.06	0.1	0.82	1.21	3.79	5.23	1.38	0.62	5.474
Ho	0.24	0.2	0.013	0.023	0.15	0.17	0.7	0.9	0.34	1.415	1.031
Er	0.65	0.68	0.032	0.071	0.46	0.56	1.55	2.07	0.76	0.275	2.786
Tm	0.056	0.082	0.01	0.01	0.059	0.064	0.2	0.39	0.16	1.55	0.419
Yb	0.45	0.58	0.016	0.051	0.33	0.45	1.34	2.14	0.96	0.285	2.534
Lu	0.069	0.1	0.01	0.01	0.055	0.08	0.15	0.36	0.21	22.8	0.396
Y	4.95	5.04	0.12	0.46	3.65	4.43	12.5	34.1	11.5	22.8	29.93

Note: DO. disseminated ore; MO. massive ore; AMO. alteration-modified ore; MG. mineralized gabbro; *n*. number of samples.

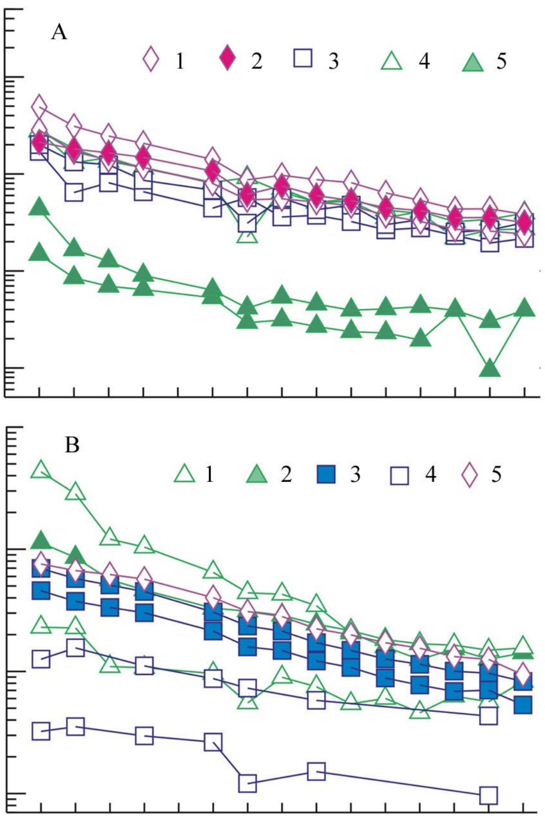

Fig. 5. Chondrite-normalised REE patterns of A) Baimazhai massive, disseminated, and alteration-modified ores, compared to those of the ores from Kalangtoke and Yangliuping (data sources cited in the text): 1. Kalangatoke; 2. Yangliuping; 3. Baimazhai hydrothermal-modified; 4. Baimazhai disseminated; 5. Baimazhai massive; B) Baimazhai host rocks, compared to those from Jinchuan, Yangliuping and Hongge (data sources cited in the text): 1. Baimazhai ultramafic rock; 2. Jinping basaltic lava; 3. Yangliuping basalt; 4. Jinchuan ultramafic rock; 5. Hongge intrusion. Normalizing factors from Sun Shensu and McDonough (1989).

$(La/Yb)_N$ is 31.43 for olivine pyroxenite, 3.73 for peridotite), except the Jinping basalts which have approximately the same pattern as the Jinchuan peridotite (approximately 10 times the chondrite values). The Yangliuping basalts, Hongge intrusions and Jinping basalts all show similar REE patterns.

4 Age constraints for the Baimazhai mineralization

An attempt was made to constrain the age of mineralization by using the ^{40}Ar/^{39}Ar method on the selected whole rocks (peridotite, pyroxenite and gabbro). These age determinations were carried out by Guiling Mineral Resources Institute, Guiling City, Guangxi. The details for the dating are described as follows.

4.1 Sampling

Based on detailed microscopic examination, 3 rock samples (peridotite, pyroxenite and gabbro) with weak alteration and mineralization out of 10 samples from the underground in the Baimazhai nickel deposit have been selected to constrain the age of mineralization by using the ^{40}Ar/^{39}Ar method.

4.2 ^{40}Ar/^{39}Ar dating method

Ar-Ar dating was done on a Micromass M-1200 Type isotope mass spectrometer, equipped with a Faraday electron multiplier detector. The blank values for ^{40}Ar were 10^{-14} mol, and 10^{-16} mol for ^{36}Ar, ^{37}Ar, ^{38}Ar and ^{39}Ar. The sample for dating was irradiated with fast neutrons (the total influx of the exposure is 1.3×10^{18} n/cm^2), and then put into the stainless vacuum furnace for extraction and purification. The vacuum pressure in the furnace was 1.33×10^{-6} Pa, and the heating and temperature were controlled by an electron-bombardment furnace. The extracted gas in each heating step was purified by titanium sponges, and transferred to the mass spectrometer, to undertake the static analysis of the Ar isotopes. The relevant parameters used in the dating are present below: J=0.0109655, the standard sample, with an age of 132.8±1.2 Ma, used in dating is biotite granite from the Fangshan area in Beijing.

Table 2. Results of whole-rock Ar^{39}-Ar^{40} dating

Sample No.	Rock type	Type	Age (Ma)
BMZ 01	Gabbro	Tp	167.96 ±1.8
		Tiso	170.02 ±3.4
		Tf	167.97±3
BMZ10	Pyroxenite	Tp	164.17±2.5
		Tiso	160.48±3.32
		Tf	164.16±3.8
BMZ 11	Peridotite	Tp	166.78±1.8
		Tiso	164.51±3.29
		Tf	166.97±3

Note: Tp. Age calculated at the turning point of the heating curve; Tiso. isochron time; Tf. age for melted samples. For details, see the text.

4.3 Results of the dating

The results are presented in Table 2 and shown in Fig. 6. As listed in Table 2 and shown in Fig. 6, the calculated ages range from 170.02±3.4 Ma to 160.48±3.32 Ma (Middle Jurassic). These ages are in marked contrast to the Permo-Triassic boundary age of the ELIP (SHRIMP zircon U-Pb: 259±3 Ma to 262±3 Ma; ^{40}Ar/^{39}Ar: 246±4 Ma to 254±5 Ma as previously mentioned). The 170–160 Ma age range

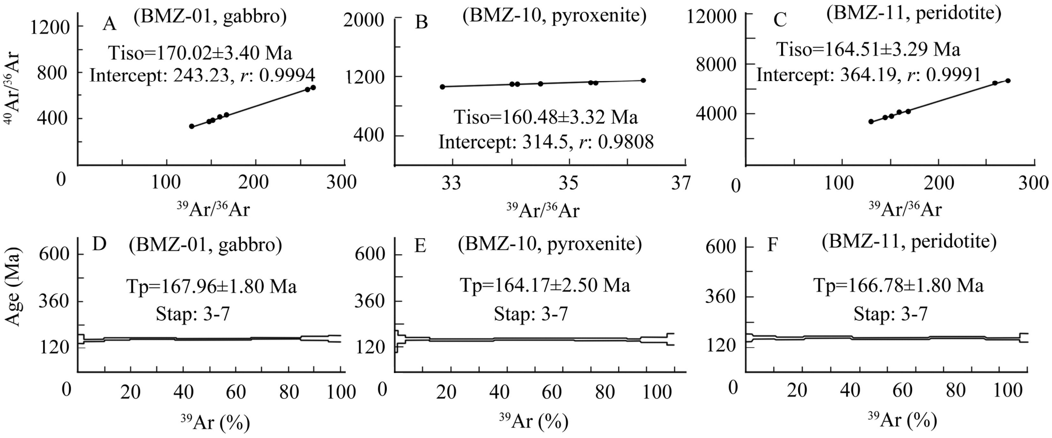

Fig. 6. Whole-rock ^{39}Ar-^{40}Ar dating results showing the isochron (A, B, C) and the plateau ages (D, E, F).

obtained in this work is consistent with the ^{40}Ar/^{39}Ar age clusters (±175 Ma) reported by Ali et al. (2004) and ascribed to resetting due to a 177–135 Ma collision event (Ali et al., 2004; Hou Zengqian et al., 2002), which brought together the Lhasa Block and the Qiantang-Indochina Block. This tectonic event, which was accompanied by the intrusion of granodiorite plutons (Wang Yuejun et al., 2002), falls within the age range of the Yanshanian orogeny (190–90 Ma).

The Baimazhai Ni-Cu sulphides and hydrothermally altered host rocks are crosscut by unaltered lamprophyre dykes. While the age of these dykes in the Jinping area is unknown, a belt of alkaline rocks, including lamprophyres and syenites, is developed along the Ailaoshan fault system with ages ranging from 40 Ma to 30 Ma (Wang Jianghai et al., 2001; Hu Ruizhong et al., 2004; Guo Zhengfu et al., 2005). The age of the Baimazhai intrusive is likely to be that of the Emeishan flood basalts with which the mafic-ultramafic rocks hosting the deposit are intimately associated. Alternatively, the intrusive rocks hosting the deposit are post-Emeishan in age and related to a later thermal event. Post-Permian tectonothermal events in China (see Zhou Meifu et al., 2002b for an overview) are: the Indosinian orogeny (260–208 Ma), the Yanshanian orogeny (190–90 Ma) and the Himalayan orogeny (65–0 Ma). If it is assumed that the lamprophyre dykes at Baimazhai are Himalayan in age (40–30 Ma), then the hydrothermal event at Baimazhai is intermediate between the Indosinian and Yanshanian orogenies (260–90 Ma).

The resetting of ^{40}Ar/^{39}Ar ages, hydrothermal alteration and associated modification of disseminated sulphide ores suggested that the Baimazhai Ni-Cu-(PGE) sulphide deposit would have interacted with hydrothermal fluids, which are most likely to be related with a tectonothermal event that affected the region in the Jurassic (Hou Zengqian et al., 2002; Wang Yuejun et al., 2002). The precise nature of the interaction between hydrothermal fluids and magmatic sulphides is not known even up to now, and more work is needed in this aspect.

The tectonic history of the region began with Proterozoic oceanic crust subduction beneath the western margin of the Yangzte Craton (Xu De'en and Chen Youliang, 1995). This was followed by rifting between the Yangzte Craton and the Indo-China Block, which became separated by a branch of the Paleaotethys Sea (Lancang Ocean; Wang Xiaofeng et al., 2000). A major suture with ophiolitic rocks now marks the line of closure of the Lancang Ocean (Yang Kaihui, 1998; Wang Xiaofeng et al., 2000). Subduction during Permo-Triassic times led to the formation of a calc-alkaline volcanic arc, partly exposed east of the Lancang suture. This was followed by back-arc extension and rifting between the Yangtze Craton and the Indo-China Block (Wang Xiaofeng et al., 2000), resulting in the Jinsha Ocean, now also represented by a suture. The Emeishan flood basalts were erupted at about 250 Ma marking the impingement of a mantle plume beneath the western margin of the Yangtze Craton (Xiao Long et al., 2003a). The closure of the Palaeotethys Sea leading to the collision of the Indo-China Block and the Yangtze Craton took place in Middle Triassic times, forming the major ASRR fault zone and giving rise to the final amalgamation of the Indo-China terranes with the Yangtze Craton and South China Block. The ASRR and adjacent sutures were reactivated during the 55–50 Ma collision of the Indian plate with the Eurasian plate. This reactivation of the ASRR is estimated to have occurred at about 300 km of left-lateral strike slip movement (Tapponier et al., 1990). The movement along the ASRR was coincident with regional progressive metamorphism (up to amphibolite facies) and a predominantly alkaline magmatic activity during the Eocene-Oligocene (Qian

Xianggui, 1999; Guo Zhengfu et al., 2005).

As previously mentioned, Ali et al. (2004) used the Ar-Ar dating method to chronologically define the post-Permian tectonothermal events which took place in the Indo-China-western Yangtze region, affected by Emeishan flood volcanism. These events cluster at ca 175, 142, 98 and 42 Ma, which Ali et al. (2004) ascribed to strike-slip and collision tectonic movements along the complex major sutures that separate the Indian Bock in the west from the Indo-China and South China blocks to the east and the Songpan-Ganze Basin to the northwest. It is suggested that the ca Ar-Ar age of 170 Ma reported in this study is most likely to indicate a thermal resetting in the Middle Jurassic, whereas Ali et al. (2004) attributed their ca 175-Ma age to a resetting caused by strike-slip movements along the Qinling-Dabie suture that separates the North China Block from the South China Block. While neither of the possibilities is ruled out, it is also possible that the hydrothermal modification of the Baimazhai sulphide system was the result of tectonic movements along the ASRR fault zone during phases of the Himalayan orogeny, which also resulted in the emplacement of alkaline igneous rocks (lamprophyre and syenites) in the zone. The age of this magmatic event in SE Tibet and Yunnan Province is constrained by Ar-Ar dating at between 32 Ma and 34 Ma (Guo Zhengfu et al., 2005). If this is correct , then the whole-rock Ar isotopic ages for the Baimazhai deposit may represent a composite reworked mineralization event which occurred between the eruption of Emeishan flood basalts (260 Ma) and the Himalayan tectonothermal event (65–0 Ma).

Perhaps Cu-rich nickeliferous ores in the mafic-ultramafic systems can be explained by using the hydrothermal model, in consideration of the possibility that Cu (and Pd) enrichement may be related to post-magmatic modification of sulphide ores by interaction with late hydrothermal fluids. Our study is preliminary, however, we try to further conduct deep-going research in terms of trace elements and isotope geochemistry. At the same time, we have invited other geoscientists engaged in research on mafic-ultramafic mineralized systems to evaluate and attest our model.

5 Discussion and conclusions

Thin section and ore microscopic studies of the disseminated sulphide ores suggested that the sulphide assemblages were modified during the processes of post-magmatic sulphide remobilisation or relocalization. This is especially evident in the altered-disseminated ores. Remobilisation of the sulphide ores is not uncommon and is usually linked with regional high-grade metamorphism (Marshall et al., 2000). The specific effects of hydrothermal alteration on sulphide ores is less known, but as pointed out by Tomkins et al. (2004), dehydration reactions during progressive metamorphism would have produced hydrothermal fluids that had the capacity to dissolve sulphides, remobilize their constituents, resulting in both textural and mineralogical changes. The presence of biotite and chlorite, which are alteration minerals in this case, is indicative of halogen volatile activity (e.g. Cl). The halogen activity is considered by several authors to have resulted in the remobilisation of PGE-bearing and PGM phases (McCallum et al., 1976; McCandless and Ruiz, 1991; Boudreau and McCallum, 1992). The occurrence of biotite, chlorite and amphibole inter-grown with sulphides is additional evidence of volatile activity (Farrow and Watksinson, 1999). Post-crystallisation alteration of primary Ni-Cu sulphides led to the formation of Cu-rich ores, accompanied by exotic phases such as Pt- and Pd-rich arsenides, tellurides and Bi-bearing minerals (Watkinson and Melling, 1992; Farrow and Watkinson, 1999). These minerals are also associated with hydrous silicates (e.g. chlorite and sericite) and, more importantly, they are enriched in Au and Ag, as in fact observed at Baimazhai. Therefore, these modified ores tend to be enriched in Cu, Au and Pd.

Hydrothermal remobilisation at Baimazhai is probably linked to post-magmatic tectonothermal events in the region. These events are responsible for the production of hydrothermal fluids that were concentrated into suitable structures and the same fluids also would modify the existing mafic-ultramafic sulphide systems. No detailed structural data are available from the Baimazhai region, but limited field structural observations showed that mylonites are present in the ASRR fault zone and an overturned anticline affects the sedimentary rocks that are in intrusive relation with the Baimazhai intrusions. At Baimazhai, there is convincing evidence of hydrothermal alteration of the intrusive rocks, during which the silicate minerals were pervasively replaced by hydrous phases. The hydrothermal fluids may not have modified the entire body of massive sulphides, but it is possible that tectonic movements have affected its margins, forming zones of disrupted or brecciated sulphides. This would have facilitated the introduction of hydrothermal fluids resulting in the formation of disseminated and interstitial sulphide ores. The “alteration-modified” sulphides (Fig. 4) are interpreted as an example of this tectonic and hydrothermal activity. This is also indicated by the presence of sulphide phases, other than the normal pyrrhotite-pentlandite-chalcopyrite assemblage, in which redistribution of certain trace elements such as

Bi and Pb occurred, as a result, exotic sulphides (e.g. parkerite) were precipitated.

Based on previous evidence, it is envisaged that there are two possibilities for the ways leading to the formation of the alteration-modified ores: 1) a massive sulphide body was deformed and its marginal zones were disrupted and brecciated, hence allowing access of hydrothermal fluids, which modified the sulphides and their host rock; and 2) alternatively, a magmatic massive sulphide body was originally overlain by a zone of magmatic disseminated sulphides; upon deformation of the massive-disseminated sulphide system, hydrothermal fluids penetrated the most permeable zones as represented by the disseminated zone. In both cases the contact between sulphides and wall rocks is a zone of the highest geochemical gradient as well as a favourable structural locus and the fluids are expected to be concentrated within this zone.

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