文章编号: 0258-7106 (2022) 03-0449-20　　Doi: 10. 16111/j. 0258-7106. 2022. 03. 001

兴蒙造山带中与古亚洲洋演化有关的成矿系统初步研究*

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摘　要　古亚洲洋演化过程中在兴蒙造山带中形成了大量金属矿床。早古生代早期,古亚洲洋向北俯冲,形成了奥陶纪多宝山-铜山斑岩 Cu-Au 成矿系统;早古生代晚期,古亚洲洋向南俯冲并形成了晚奥陶世白乃庙 Cu-Mo-Au 成矿系统和志留纪别鲁乌图海底喷流块状硫化物成矿系统。古亚洲洋在晚古生代早期向北俯冲,形成了晚泥盆世欧玉陶勒盖 Cu-Au 成矿系统。基本同时,古亚洲洋向南俯冲,形成了晚泥盆世哈达门沟 Mo 成矿系统。早石炭世,研究区构造体制从岛弧环境逐渐转变为陆内伸展环境,并在此过程中形成了豆荚状铬铁矿成矿系统和小型斑岩 Mo-Cu 成矿系统。

关键词　地质学;古亚洲洋;兴蒙造山带;斑岩矿床;多金属矿床;成矿系统
中图分类号: P618.41; P618.51　　**文献标志码**: A

Study on ore-forming systems related with evolution of Paleo-Asian ocean in Xing-meng orogenic belt

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Abstract

Abundant metal deposits formed during the evolution of the Paleo-Asian ocean in the Xing-meng orogenic belt. The northward subductions of the Paleo-Asian ocean during the early Early Paleozoic formed the Ordovician Duobaoshan-Tongshan Cu-Au porphyry ore-forming system. The southward subductions of the Paleo-Asian ocean during the late Early Paleozoic formed the late Ordovician Bainaimiao Cu-Mo-Au ore-forming system and Silurian Bieluwutu VHMS ore-forming system. During the early Late Paleozoic, the northward subductions of the Paleo-Asian ocean formed the late Devonian Oyu Taolgoi porphyry Cu-Au ore-forming system. In the same period, the southward subductions of the Paleo-Asian ocean formed the late Devonian Hadamengou Mo ore-forming system. Tectonic pattern changed to extensional environment during Early Carboniferous periods, and formed podiform chromite and small porphyry Mo-Cu ore-forming systems.

Keywords: geology, Paleo-Asian ocean, Xing-meng orogenic belt, porphyry deposit, polymetallic deposit, ore-forming system

古亚洲洋东段兴蒙造山带在形成和演化过程中发育大量金属矿床(毛景文等, 2013; 许立权等, 2016;江思宏等, 2018; Boldbaatar et al., 2019; Hart-Madigan et al., 2020; Davaasuren et al., 2021; Deng et al., 2021; Wang L et al., 2021)。这些矿床包括斑岩型铜-金矿床(欧玉陶勒盖、多宝山、铜山、白乃庙、查

* 本文得到国家自然科学基金项目(编号:42072077)和国家重点研发计划(编号:2017YFC0601302)共同资助
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收稿日期　2021-11-03;改回日期　2022-04-14。张绮玲编辑。

干苏布尔加、苏廷)、斑岩型铜-钼矿床(准苏吉花、查干花、库里吐、八大关、锅盔顶子、比鲁甘干)、斑岩型钼矿床(车户沟、高岗山、元宝山、撒岱沟门)、矽卡岩型多金属矿床(白音诺尔、翠宏山)、岩浆型铜-镍-铬铁矿矿床(额尔布图、别力盖庙、红旗岭、贺根山)、海底喷流块状硫化物型(VHMS)多金属矿床(别鲁乌图、霍各乞、小坝梁)、热液脉-蚀变岩型多金属矿床(哈达门沟、后石花、朱拉扎嘎、东伙房、老羊壕、夏尔楚鲁)及造山型金矿床(图古日格、杨金沟、浩尧尔忽洞、孟德河)等(表1,图1)。与古生代相比,印支期的矿种和矿化类型相对丰富(见图1中的插图)。本文在分析研究典型矿床地质特征的基础上,初步总结了兴蒙造山带中与古亚洲洋演化相关的金属成矿系统。

1 矿床特征

兴蒙造山带中金属矿床的地质特征(表1)显示,与古亚洲洋演化有关的金属矿床成矿时间跨越整个古生代并延续到印支期末,主要成矿作用发生在泥盆纪、石炭纪、二叠纪和三叠纪。各类矿种资源量与产出年代的关系如图1b所示。古生代和中生代均产出Au、Ag、Cu、Mo、Pb-Zn等矿床,中生代特有的矿种为W、Fe、Co、Ni。铜矿和金矿在古生代与印支期均有产出,古生代单个斑岩矿床的金属资源量普遍大于印支期斑岩矿床的金属资源量。

斑岩型矿床在热液蚀变、容矿岩石组合以及矿石矿物组合等方面均显示出一致性。容矿岩石岩性以花岗斑岩、花岗闪长斑岩和石英二长闪长岩为主。主要矿石矿物组合为黄铁矿、黄铁矿、辉钼矿、方铅矿、闪锌矿、斑铜矿、黝铜矿。一些矿体呈脉状产出在斑岩与围岩的接触带中,具有斑岩型-热液脉型矿化的特点。矿化多与钾化、硅化、黄铁绢英岩化关系密切。大多数斑岩矿床含矿岩体的成岩年龄与矿化年龄接近,如多宝山含矿花岗闪长斑岩体的成岩年龄为(477.7±2.8)Ma,辉钼矿的年龄为(475.9±7.9)Ma(Zhao et al., 2018)。查干苏布尔加含矿二长花斑岩体的锆石U-Pb年龄为(365.7 ±3.6)Ma,辉钼矿的Re-Os年龄为(370.4±0.8)Ma(侯万荣等, 2010a; Tungalag et al., 2018)。矿化一般呈细脉状和浸染状分布在含矿斑岩体内,表明成岩与成矿过程是同一岩浆热液活动的产物。

欧玉陶勒盖斑岩矿床是该地区最大的铜矿和金矿矿集区,由5个独立的矿床组成,从北往南依次为Hugo Dummett北矿床、Hugo Dumnett矿床、欧玉陶勒盖中心矿床、欧玉陶勒盖东南矿床和欧玉陶勒盖南矿床。在该矿集区以南约4 km处,还发现了Heruga斑岩铜金矿。这些矿床均形成于Gurvansayhan岛弧中,与晚泥盆世石英二长闪长岩有关。矿化同期的石英二长闪长岩中锆石U-Pb年龄为(378 ±3)Ma和(371±1.2)Ma。矿石中辉钼矿的Re-Os年龄为370~373 Ma(Kirwin et al., 2005; Wainwright et al., 2011; Hart-Madigan et al., 2020)。成矿侵入体在成分上属于高钾钙碱性,有岛弧亲缘性。矿集区大面积分布英安质凝灰岩,其中的锆石U-Pb年龄为(365±4)Ma。斑岩矿床中的石英脉高度扭曲,单个矿脉常分叉裂开,这种结构说明矿脉形成于高温环境。强烈水解形成大面积高级黏土化带是最重要的找矿标志。高级黏土化蚀变带最接近铜-金矿化带。叶腊石是欧玉陶勒盖矿集区高级黏土化蚀变带中的主要成分,与高岭石共生。分布广泛的地开石脉是这类蚀变在野外的显著标志。在欧玉陶勒盖南矿床,岩浆岩的黑云母化蚀变呈环带向外,在铜金矿化核部约600 m外围形成一个绿帘石-绿泥石-伊利石-黄铁矿共生组合带。欧玉陶勒盖中心矿床是一个非典型斑岩矿床,以白云母蚀变密集的石英二长闪长岩为主。黄铁矿-铜蓝矿化呈圆锥体,延伸深度大于600 m。黄铁矿-铜蓝矿化与白云母有关,硫砷铜矿与明矾石、叶腊石、黄玉、氯黄晶、硬水铝石和高岭石-地开石蚀变有关。

Hugo Dummett是欧玉陶勒盖矿集区最大的单个矿床,是世界上最富铜的斑岩成矿系统之一,被英安岩(~369 Ma)不整合覆盖(Wainwright et al., 2017)。高品位(w(Cu)>2.5%)矿石以浸染状和裂隙充填型矿化为主,主要矿物为斑铜矿和黄铜矿。矿床中心为石英二长闪长岩中的密集石英脉为Hugo Dummett北矿床发育富金斑铜矿和钾化,富矿体宽400~600 m、深约800 m(Khashgerel et al., 2006),形成了一个横截面90 m宽、垂直延伸约600 m、走向长度>1500 m的透镜体。与白云母蚀变有关的斑铜矿石英脉出现在岩体边缘及上方数百米处。硫化物在大尺度上有一个整体向上、向外的环带模式:斑铜矿-黄铜矿、辉铜矿、黄铁矿-硫砷铜矿。高品位斑铜矿或斑铜矿-黄铜矿矿化与白云母化共生,在一些地方与绿泥石共生。早期蚀变通常以叶腊石、黄玉、氯黄晶、硬水铝石、高岭石、地开石为主,并伴随黄铁矿、硫砷铜矿

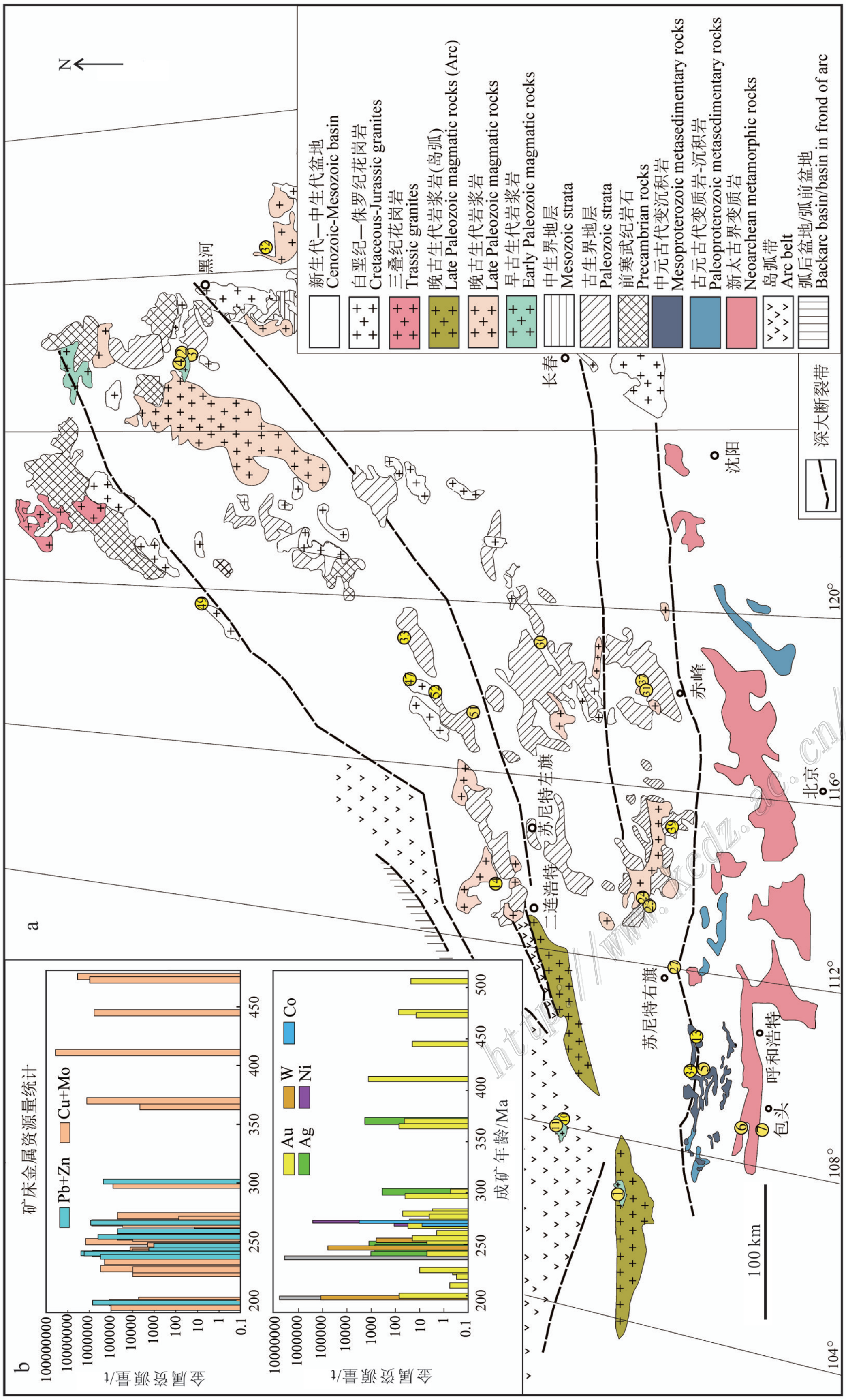

图1 兴蒙造山带中与古亚洲洋演化相关的金属矿床分布图(a)及矿床金属资源量统计-成矿年龄直方图(b)

矿床序号与表1对应，数据来自表1中参考文献

Fig. 1 Regional geology map showing the distribution of metal deposits related to the evolution of the Paleo-Asian ocean(a) and histogram of metal reserves versus ore-forming ages(b)

the number of deposits is identical to number in Table 1 and the data from references in Table 1

表1 兴蒙陆内造山带中与古亚洲洋演化有关的典型金属矿床地质特征简表

Table 1 Representative deposits and their major characteristics related with the evolution of the Paleozoic Asian ocean in the Xing-meng orogenic belt

序号	矿床名称	矿床类型	容矿岩石	成矿年龄/Ma(方法)	成岩年龄/Ma(方法)	矿物组合	蚀变特征	资料来源
1	欧玉陶勒盖	斑岩型	石英二长闪长岩、花岗闪长岩	373~370 (Re-Os)	367.9 (U-Pb)	黄铜矿、磁铁矿、斑铜矿、辉铜矿、辉钼矿、硫砷铜矿、砷黝铜矿、自然金	钾化、白云母-绿泥石化、黄玉-叶蜡石-地开石-冰长石化、高级黏土化	Khashgerel et al.,2006; Wainwright et al.,2011; 2017
2	多宝山	斑岩型	花岗闪长斑岩、粉砂岩、灰岩	475.9 ±7.9 (Re-Os)	475.8±2.8 (U-Pb)	黄铜矿、斑铜矿、辉钼矿	黄铁绢英岩化、青磐岩化、钾化	Cai et al., 2021; Liu et al., 2017; Zhao et al., 2018; Zeng et al., 2014
3	争光	热液脉-蚀变岩型	安山岩、凝灰岩、火山角砾岩	506 ±44 (Re-Os)	480.3±2.1 (U-Pb)	黄铜矿、闪锌矿、自然金	硅化、绿泥石化、黄铁绢英岩化、碳酸盐化	Wang L et al., 2018; 2021
4	铜山	斑岩型	英云闪长岩	470~477 (Re-Os)	471.5±1.3 (U-Pb)	黄铜矿、斑铜矿	黄铁绢英岩化、硅化	Hao et al.,2014; Liu et al.,2017; Wang RL et al.,2021
5	白乃庙	斑岩型	花岗闪长斑岩	433.9 ±3.1 (Re-Os)	445±3.4 (U-Pb)	黄铜矿、辉钼矿、闪锌矿、方铅矿、磁黄铁矿	硅化、黑云母化、黄铁绢英岩化	高旭等,2018; Li W B et al.,2015; Liu M et al., 2020
6	别鲁乌图	VHMS	板岩、凝灰岩、火山碎屑岩	430.2 ±2 (U-Pb)	435 ±2 (U-Pb)	黄铜矿、闪锌矿、磁黄铁矿	硅化、绿泥石化	Li W B et al., 2021
7	哈达门沟-柳坝沟	热液脉-蚀变岩型	片麻岩、片岩、石英脉	386.4±2.7 (Re-Os); 217.9±3.1 (Ar-Ar)		辉钼矿、磁铁矿、自然金、方铅矿、黄铜矿、闪锌矿、银金矿	钾化、硅化、黄铁矿化	Wang L et al.,2014; Zhang et al.,2017a; 章永梅等,2011; 侯万荣等,2014
8	乌拉山	热液型	片麻岩、片岩、磁铁石英岩、正长岩	297±4 (Ar-Ar)	333.8±1.3 (U-Pb)	黄铁矿、自然金	黄铁绢英岩化、绿泥石化	Nie et al., 2002
9	额尔布图	岩浆型	斜方辉石岩、橄榄斜辉岩	294.2±2.7 (U-Pb)	294.2±2.7 (U-Pb)	镍黄铁矿、黄铜矿、磁黄铁矿	蛇纹石化	Peng et al., 2013
10	查干苏布尔加	斑岩型	二长花岗斑岩、花岗闪长斑岩	370.4±0.8 (Re-Os)	365.7±3.6 (U-Pb)	黄铜矿、辉钼矿、方铅矿、闪锌矿、黝铜矿、磁黄铁矿	绢云母化、硅化、黄铁矿化	Watanabe et al., 2000; 侯万荣等, 2010a; 苗来成等, 2000
11	苏廷	斑岩型	花岗斑岩	333±5 (U-Pb)	321±9 (Rb-Sr)	黄铜矿、辉铜矿、斑铜矿、磁黄铁矿、辉钼矿	黄铁矿化、硅化、钾化	Batkhishig et al., 2010; 朱明帅等, 2015
12	1017高地	热液脉-蚀变岩型	黑云二长花岗岩	301.2±1.8 (Ar-Ar)	296.8±4.1 (U-Pb)	黄铁矿、方铅矿、闪锌矿、黄铜矿、磁黄铁矿	绿泥石化、绿帘石化	王治华等, 2013; 孙磊等, 2014
13	后石花	热液脉型	片麻岩、片岩、大理岩	281.9±1.8 (Re-Os)	301±5 (Ar-Ar)	黄铁矿、碲金矿、碲金银矿、叶碲矿	黄铁绢英岩化、碳酸盐化	王梁等, 2015; Nie et al., 2002
14	准苏吉花	斑岩型	似斑状花岗岩	298.2±3.6 (Re-Os)	298.9±2.8 (U-Pb)	辉钼矿、黄铁矿、黄铜矿、辉铜矿	硅化	Zhang et al., 2018; 刘翼飞等, 2012a; 刘聪等, 2020
15	朱拉扎嘎	热液脉-蚀变岩型	粉砂岩、石英砂岩	282.3±0.9 (Ar-Ar)	280±6 (U-Pb)	自然金、黄铁矿、黄铜矿、方铅矿、毒砂、磁黄铁矿	绿泥石化、硅化、孔雀石、蓝铜矿	江思宏等, 2001; 李俊建等, 2010; Ding et al., 2016
16	东伙房	热液脉-蚀变岩型	片麻岩、花岗岩、二长岩、正长岩	277±4 (Ar-Ar)	280-276 (Ar-Ar)	硅化、黄铁矿、自然金	黄铁绢英岩化、钾化、绿泥石化、碳酸盐化	Nie et al., 2002
17	十八倾壕	热液脉-蚀变岩型	角闪岩、片麻岩、片岩、混合岩、煌斑岩脉	264±3 (Ar-Ar)	265±4 (Ar-Ar)	黄铁矿、石英、自然金	黑云母、绢云母、绿泥石、绿帘石化	Nie et al., 2002
18	新兴	热液脉-蚀变岩型	花岗闪长岩	259±3 (Rb-Sr)	258 (Ar-Ar)	方铅矿、闪锌矿、黄铜矿	绿帘石化、碳酸盐化、黄铁矿化	Guo et al., 2018a; 杨群等, 2018
19	老羊壕	热液脉-蚀变岩型	角闪斜长片麻岩、绿泥石英片岩、变辉长岩	256±3 (Ar-Ar)	261.1±3.5 (U-Pb)	自然金、银金矿、黄铁矿、黄铜矿、赤铁矿	绢云母化、绿泥石化、绿帘石化、硅化	Nie et al., 2002
20	图古日格	造山型	花岗斑岩	305.6±4.5; 268±15 (Re-Os)	276±2 (U-Pb)	黄铁矿、黄铜矿、方铅矿、闪锌矿、自然金	黄铁绢英岩化、硅化、绢云母化	Ding et al., 2016; 李永等, 2019; 丁成武等, 2021; 张锋等, 2016

续表 1-1

Continued Table 1-1

序号	矿床名称	矿床类型	容矿岩石	成矿年龄/Ma(方法)	成岩年龄/Ma(方法)	矿物组合	蚀变特征	资料来源
21	老柞山	造山型	黑云母花岗岩	256±1.3 (Re-Os)	256±3.1 (U-Pb)	毒砂、磁黄铁矿、黄铜矿、黄铁矿	硅化、矽卡岩化	李明飞等, 2014
22	东风北山	斑岩型	花岗闪长岩、石英闪长岩、花岗岩	194±2.0 (Re-Os)	194.8±0.8 (U-Pb)	辉钼矿、黄铜矿、磁铁矿、磁黄铁矿、毒砂	硅化、钾化、黄铁绢英岩化	Guo et al.,2018b; 杨群等, 2015
23	哈达庙	斑岩型	花岗斑岩	271.8±3.3 (U-Pb)	272.9±2.4 (U-Pb)	自然金、银金矿、黄铜矿、磁铁矿、斑铜矿、铜蓝	硅化、电气石化、黄铁绢英岩化、孔雀石	Qiao et al., 2019; 郝百武等, 2010
24	毕力赫	斑岩型	花岗岩、花岗闪长斑岩、粉砂岩	268±1 (Re-Os)	271.5-259.4 (U-Pb)	黄铜矿、磁铁矿、斑铜矿、黝铜矿、辉钼矿、方铅矿、闪锌矿、磁黄铁矿	黄铁绢英岩化、电气石化、绿泥石化	Liu et al., 2015; Zhu et al.,2018; 朱雪峰等, 2018; Huang et al., 2020
25	别力盖庙	岩浆型	橄榄辉石岩、斜方辉石岩、辉长岩		269±2.1 (U-Pb)	镍黄铁矿、黄铜矿、磁黄铁矿	绿泥石化、蛇纹石化	Peng et al., 2017
26	五道沟	造山型	石英硫化物脉、蚀变岩	253±1.3 (U-Pb)	267.8±1.0 (U-Pb)	毒砂、黄铁矿、黄铜矿、闪锌矿	硅化、绢云母化、绢英岩化	Ren et al., 2016; 陈聪等, 2015; 方焱等, 2020
27	夏尔楚鲁	热液脉型	黑云母花岗岩	263.8±4.4; 261.7±1.5 (Re-Os)	271.1±3.7 (U-Pb)	针铁矿、辉钼矿、辉铋矿、黄铜矿、自然金	硅化、黄铁绢英岩化	Wang et al., 2016; 王佳新等, 2014
28	白土营子	斑岩型-热液脉型	黑云母二长花岗岩、二长花岗斑岩	248±10 (Re-Os)	248.2±0.64 (U-Pb)	辉钼矿、黄铜矿、斑铜矿、赤铁矿、磁铁矿	钾化、黄铁矿化	Sun et al., 2017a; 2017b; 2018; 孙燕等, 2013
29	白音诺尔	矽卡岩型	硅灰石-石榴石-辉石矽卡岩、花岗斑岩	242~244 (U-Pb)	243±1 (U-Pb)	闪锌矿、方铅矿、黄铜矿、磁黄铁矿	矽卡岩型蚀变带	Jiang et al., 2017; 于琪等, 2015
30	查干花	斑岩型	花岗闪长岩	242.7~243 (Re-Os)	253.8±3.7 (U-Pb)	磁黄铁矿、辉钼矿、黄铜矿	黄铁绢英岩化、硅化、钾化	刘翼飞等, 2012b
31	车户沟	斑岩型	花岗斑岩、正长斑岩	250.2±7.2 (Re-Os)	251.6±3.2 (U-Pb)	辉钼矿、黄铁矿、黄铜矿	硅化、绢云母化	Zeng et al., 2011; Wan et al., 2009; 孟树等, 2013
32	高岗山	斑岩型	花岗岩	247±6 (Re-Os)	259.9±2.0 (U-Pb)	黄铁矿、辉钼矿	硅化、钾化	Zhang et al., 2017b
33	阿尔哈达	热液脉型	砂岩、砂质板岩	256~272		方铅矿、闪锌矿、黄铁矿、自然银	硅化、碳酸盐化、萤石化	Ke et al., 2017
34	杨金沟	造山型	黑云二长花岗岩	241.57±1.2 (Ar-Ar)	262.3±1.3 (U-Pb)	辉钼矿、黄铜矿、自然金、毒砂	硅化、黄铁绢英岩化	Zhao et al., 2013; Ren et al., 2016
35	霍各乞	VHMS	云母绿泥石片岩、石英岩、碳质页岩、大理岩	239.8±3.4 (Ar-Ar)	271.4±29.5 (Ar-Ar)	黄铜矿、方铅矿、闪锌矿、磁黄铁矿	硅化、绿泥石化、钠长石化、黄铁矿化	Bao et al., 2021; Zhong et al., 2013; Pi et al., 2015; 钟日晨等, 2015
36	撒岱沟门	斑岩型	二长花岗岩、石英-正长斑岩、闪长玢岩	236.5±2.2 (Re-Os)	227.1±2.7 (U-Pb)	辉钼矿、磁铁矿、闪锌矿、黄铜矿、斑铜矿	硅化、黄铁绢英岩化	Jiang et al., 2014; 代军治等, 2007; 骆文娟等, 2010
37	元宝山	斑岩型	花岗岩、石英二长岩	248.0±2.6 (Re-Os)	269±3 (U-Pb)	辉钼矿、方铅矿、磁铁矿、自然金、银金矿	黄铁绢英岩化、萤石化、碳酸盐化、硅化	Liu J M et al., 2010
38	查干敖包	斑岩型	钾长花岗岩、二长花岗岩、花岗斑岩	239.2±5.8 (Re-Os)	253.5±3.3 (U-Pb)	磁黄铁矿、辉钼矿、黄铜矿	黄铁绢英岩化、钾化	张万益等, 2008; 梁帅等, 2015
39	沙子沟	热液脉型	云母石英片岩、混合岩	243.8±1.6 (Re-Os)	245 ±2.6; 270±2.4 (U-Pb)	辉钼矿、黑钨矿、方铅矿、闪锌矿、自然金	硅化	Li H et al., 2017
40	库里吐	斑岩型	二长花岗岩	236±3 (Re-Os)	229.4±4.3 (U-Pb)	辉钼矿、黄铜矿	黄铁绢英岩化、硅化、绿泥石化	Sun et al.,2018; 吴华英等, 2008
41	河坎子	斑岩型	钾长花岗岩、大理岩	222.8±3.2 (Re-Os)	235.3±1.0 (U-Pb)	黄铜矿、辉钼矿、辉铜矿、方铅矿、闪锌矿、磁铁矿	黄铁绢英岩化	刘勇等, 2012

续表 1-2

Continued Table 1-2

序号	矿床名称	矿床类型	容矿岩石	成矿年龄/Ma(方法)	成岩年龄/Ma(方法)	矿物组合	蚀变特征	资料来源
42	二道沟	热液脉型	角闪岩、石英闪长岩、花岗岩	230-219; 204 (Ar/Ar)	223±2 (U-Pb)	黄铜矿、方铅矿、闪锌矿、白钨矿、自然金、黄铁矿、辉银矿	黄铁绢英岩化、绿泥石化	Yang et al.,2021; Deng et al., 2014
43	小北沟	造山型	角闪岩、花岗片麻岩	230~219 (Ar/Ar)		黄铜矿、方铅矿、闪锌矿、磁铁矿、磁黄铁矿、黄铁矿、自然金	硅化、绢云母化	Li et al., 2016; 杨利亚等, 2013
44	红旗岭	岩浆型	角闪-黝帘石片麻岩、片麻状花岗岩、大理岩	208±21 (Re-Os)	220.6±2.0 (U-Pb)	磁黄铁矿、镍黄铁矿、黄铁矿、黄铜矿、紫硫镍铁矿		Lü et al., 2011; 郗爱华等, 2004; 冯光英等, 2011
45	大苏计	斑岩型	花岗岩、花岗斑岩、石英斑岩	222.8±3.2 (Re-Os)	224.1±3.2 (U-Pb)	辉钼矿、方铅矿、闪锌矿	黄铁绢英岩化、硅化	吴昊等, 2018; Wu et al., 2018; Chen et al., 2019; 2021
46	八家子	斑岩型	英云闪长片麻岩、角闪岩、正长斑岩	203.6 ±0.3 (Ar-Ar)	218±6 (U-Pb)	黄铜矿、方铅矿、闪锌矿、白钨矿、自然金	黄铁绢英岩化、碳酸盐化、硅化	Miao et al., 2005; 刘军等, 2018
47	查干敖包Fe-Zn	矽卡岩型	矽卡岩	237±6 (U-Pb)	237±6 (U-Pb)	磁铁矿、镜铁矿、赤铁矿、闪锌矿	矽卡岩化	张万益等, 2012
48	太平川	斑岩型	花岗闪长斑岩	200~201.6 (Re-Os)	202±5.7 (U-Pb)	黄铜矿、辉钼矿、斑铜矿、黝铜矿	黄铁绢英岩化、硅化	Zhang et al., 2014; 陈志广等, 2010
49	八大关	斑岩型	花岗闪长斑岩	226.7±2.4 (Re-Os)	237.8±3 (U-Pb)	辉钼矿、黄铜矿	黄铁绢英岩化、青磐岩化	Shi et al., 2021; Mi et al., 2017; 康永建等, 2016
50	翠宏山	矽卡岩型	碳酸盐岩、陆源碎屑岩	205-204 (Re-Os)	493±4 (U-Pb)	辉钼矿、白钨矿、方铅矿、闪锌矿、黄铜矿、磁铁矿	矽卡岩化	Chen et al., 2017; Fei et al., 2018; Hu et al., 2014; 郝宇杰等, 2013
51	贺根山	岩浆型	蛇绿岩		361~339 (U-Pb)	铬铁矿、高Al尖晶石、高Cr尖晶石	蛇纹石化、绿泥石化、碳酸盐化	陆国隆等, 2021; Jiang et al., 2020
52	小坝梁	VHMS	凝灰岩	326±3 (U-Pb)	326±3 (U-Pb)	黄铁矿、黄铜矿、方铅矿、闪锌矿	绿泥石化、碳酸盐化	Zhang et al., 2021
53	新地沟	造山型	变质火山岩	301±1.7 (独居石U-Th-Pb)		黄铁矿、黄铜矿、自然金	黄铁绢英岩化、碳酸盐化、硅化	Nie et al.,2002; Zhang et al., 2020
54	巴彦都兰	热液脉型	黑云母二长花岗岩	300.0±2.0; 300.2±2.2 (U-Pb)		黄铁矿、黄铜矿、闪锌矿	硅化	佘超等, 2017
55	额尔布图	岩浆型	辉石岩、方辉橄榄岩		294.2±2.7 (U-Pb)	镍黄铁矿、磁黄铁矿	蛇纹石化	Peng et al., 2013
56	哈拉图庙	岩浆型	二辉石岩、异剥橄榄岩		292.3±1.5 (U-Pb)	辉钼矿、黄铁矿、黄铜矿、闪锌矿、镍黄铁矿	钾化、硅化、绿泥石、方解石、萤石	Sun et al., 2021
57	浩尧尔忽洞	造山型	碳质板岩、变质砂岩	256 Ma (榍石U-Pb)		黄铁矿、白钨矿、磁黄铁矿、自然金	黑云母化、硅化、石墨化	Nie et al., 2002; 李楠等, 2021
58	锅盔顶子	斑岩型	花岗闪长斑岩	250.0±1.5 (Re-Os)	251.2±2.1 (U-Pb)	辉钼矿、黄铁矿、黄铜矿、毒砂	钾化、青磐岩化、绢英岩化	Yang et al., 2021
59	比鲁甘干	斑岩型	黑云母花岗斑岩、二长花岗斑岩	237.9±1.7; 238 ±1 (Re-Os)		辉钼矿、黄铁矿、黄铜矿、闪锌矿	钾化、硅化、绿泥石、方解石、萤石	Zhang et al., 2019; 李俊建等, 2016
60	阿扎哈达铜铋矿床	热液脉型	二长花岗岩、碱长花岗岩、花岗岩		313.9±1.7; 308.4 ±1.5 (U-Pb)	黄铁矿、黄铜矿、辉铜矿、辉铋矿、自然铋	石英、萤石、方解石	王银宏等, 2020; Wang Y H et al., 2021
61	撰山子金矿	热液脉型	花岗斑岩		237±1.4; 219±4.7 (U-Pb)	黄铁矿、黄铜矿、方铅矿、闪锌矿、自然金	石英、萤石、方解石、绿帘石	欧阳鑫等, 2021
62	孟德河	造山型	二长花岗岩、花岗岩	209.6±3.1 (Rb-Sr, 黄铁矿); 211.5 ±4.3(U-Pb)	245.9±2.1 (U-Pb)	自然金、黄铁矿、方铅矿、闪锌矿、黄铜矿、磁铁矿	硅化、绿泥石、绢云母化、碳酸盐化	Li C L et al., 2021

和砷黝铜矿沉淀。随后发生与白云母蚀变有关的高品位斑铜矿-黄铜矿矿化过程。高品位硫化物集合体的形成时间晚于高级黏土化过程。斑岩系统发育硫化物环带,从核部的斑铜矿-黄铜矿逐渐变化到黄铜矿、再到系统边部的黄铁矿-硫砷铜矿。岩浆流体向外运移并逐渐冷却,遇到发育高级黏土化的地带,高硫态的硫化物沉淀并伴随黄铁矿、砷黝铜矿和硫砷铜矿结晶。高品位斑铜矿-黄铜矿矿化与晚期白云母和绿泥石平衡的流体有关。

同位素地球化学数据显示,斑岩型矿床成矿流体的成分复杂,多数样品落在岩浆水区域附近,其他类型矿床的成矿流体具有混合来源。岩浆热液脉型和矽卡岩型矿床的成矿流体主要以岩浆水为主。与热液脉型矿床相比,造山型金矿的样品更接近大气降水线。热液脉型矿床和造山型金矿往往受断裂控制,矿石多呈脉状、网脉状、浸染状、条带状产出,金矿化多与石英-硫化物脉关系密切,常常具有多期次矿化的特征,部分矿床具有矿化形式多样的特征。

2　成矿地质环境

古亚洲洋在古生代时期的俯冲-碰撞造山过程中形成了大量与岛弧岩浆活动有关的矿床,如多宝山、铜山、白乃庙、欧玉陶勒盖、查干苏布尔加斑岩型矿床。二叠纪兴蒙造山带处于碰撞后陆内伸展构造环境,形成了毕力赫、哈达庙、浩尧尔忽洞、图古日格、夏尔楚鲁、后石花、准苏吉花等矿床。三叠纪岩石圈伸展减薄过程中形成了一系列与碱性-钙碱性花岗岩演化有关的矿床,包括大苏计、比鲁甘干、河坎子、库里吐、八大关等矿床。在构造环境判别图解上(图 2a~c),欧玉陶勒盖、查干苏布尔加、苏廷、白乃庙、图古日格、车户沟、多宝山、铜山等矿床主要落在岛弧区域;哈达庙、毕力赫、查干花、白土营子、查干敖包、准苏吉花、撒岱沟门等矿床的样品主要落在岛弧和同碰撞区域。需要特别说明的是,那些落在岛弧区域的样品并不一定说明相关矿床形成于岛弧环境,因为石炭纪之后,研究区的构造体制转化为陆内造山阶段(Zhu et al., 2001a; 2001b; 徐备等, 2018)。因此,不能仅仅依据微量元素图解判别矿床形成的大地构造环境。在与构造地质研究结论产生矛盾时,这些微量元素判别图的主要作用是显示相关岩石在化学组成上的区别。因此,晚古生代晚期形成

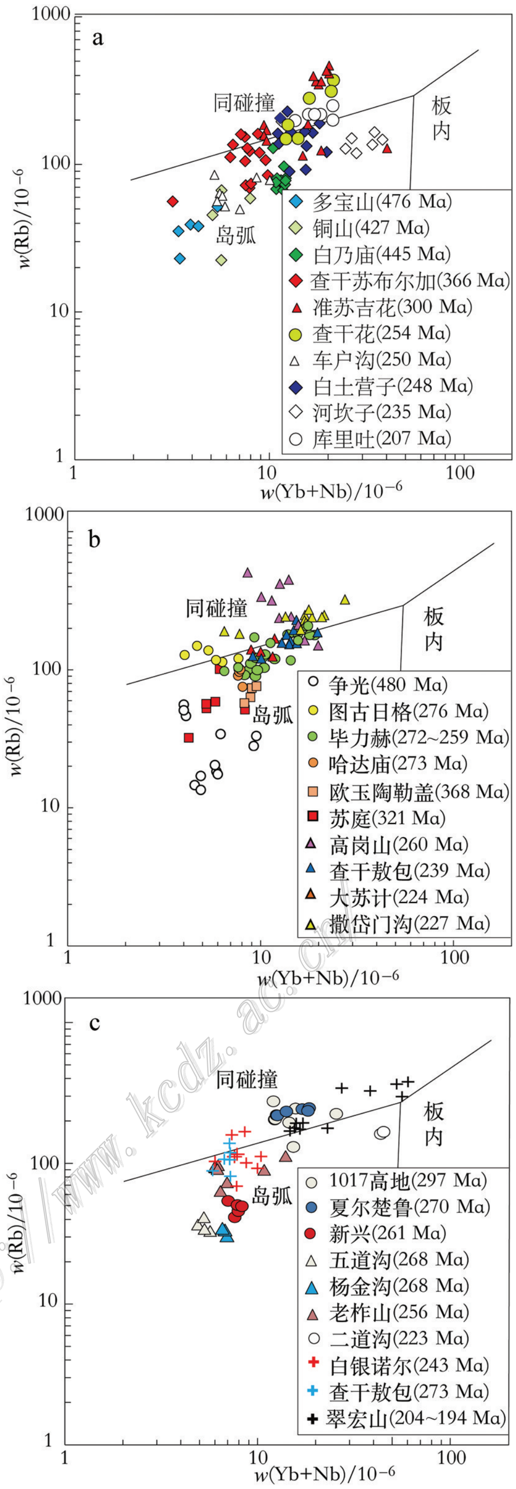

图 2　兴蒙造山带中与古亚洲洋演化相关矿床成矿岩石 Rb-Yb+Nb 构造环境图

图例显示矿床名称以及成矿年龄,数据来自表 1 的参考文献

Fig. 2　Rb-Yb+Nb plots showing magmatic rock samples hosting deposits related to the evolution of the Paleo-Asian ocean

the number of deposits is identical to number in Table 1 and the data from references in Table 1

的矿床，无论其落在微量元素判别图的哪个区域，都应该属于陆内造山环境。

3 古亚洲洋演化与成矿系统

中国东北及邻近蒙古国东南地区古生代以来向北和向南发生双向俯冲增生及碰撞造山，在此漫长而复杂的地质演化过程中发育了多期次成矿作用。古亚洲洋在早古生代期间分别向北和向南发生双向俯冲，并形成了典型的沟-弧-盆体系。早古生代早期，古亚洲洋向北俯冲，形成了奥陶纪多宝山-铜山斑岩Cu-Au成矿系统；早古生代晚期，古亚洲洋向南俯冲并形成了晚奥陶世—志留纪白乃庙岛弧以及赋存其中的白乃庙Cu-Mo-Au成矿系统和别鲁乌图VHMS成矿系统。

古亚洲洋地质演化早期形成了奥陶纪多宝山-铜山斑岩Cu-Au成矿系统。这个时期的古亚洲洋发生双向俯冲，在大陆边缘形成岛弧，并形成斑岩型矿床。这类矿床目前并不多见，可能原因是后期强烈的造山过程改造和破坏了先前形成的各类矿床，使早期矿床或者矿化体重新进入大陆地壳物质循环，此过程类似中亚成矿域中发生的成矿物质多阶段富集成矿机制（何国琦等, 2006; 朱永峰等, 2014; Zhu et al., 2016）。这种成矿物质循环富集过程为包括兴蒙造山带在内的中亚成矿域发育大规模晚古生代—中生代金属成矿作用奠定了物质基础。白乃庙Cu-Mo-Au矿床属于晚奥陶世斑岩成矿系统，但在中泥盆世经历了强烈的变形和变质改造并发生新的成矿过程。早期乳白色石英-硫化物脉遭受了角砾化破碎，并被烟灰色石英-硫化物所胶结。成矿带南端主成矿阶段的多金属硫化物未发生变形。北部矿带中，块状矿石主要产在花岗闪长斑岩与绿片岩的接触带中，矿体由厚层石英脉与薄板状石英硫化物构成，矿化受EW向断裂控制。矿体中Cu含量随深度递减，Mo含量随深度递增，黑云母化和硅化与铜矿化过程密切相关。成矿作用具有多期多阶段性。辉钼矿模式年龄为441~446 Ma，等时线年龄为（445.0 ±3.4）Ma（Li W B et al., 2012）。北矿带花岗闪长斑岩锆石U-Pb年龄为（445 ±6）Ma。南矿带矿体中黑云母$^{40}Ar/^{39}Ar$等时线年龄为（396±2）Ma。该地区广泛出露的白乃庙群主要由绿片岩和长英质片麻岩组成，被花岗岩、花岗闪长斑岩和石英闪长岩侵入。绿片岩中黑云母的坪年龄为（429±4）Ma和（422±3）Ma，等时线年龄为（429 ±4）Ma和（423 ±4）Ma（Li W B et al., 2015），代表绿片岩相变质作用的时间。产在白乃庙岛弧中的别鲁乌图VHMS型多金属矿床形成于早志留世（Li W B et al., 2021）。

泥盆纪时期，古亚洲洋向北俯冲形成Gurvansayhan岛弧，并在其中形成大型斑岩矿床（Watanabe et al., 2000; Crane et al., 2012; Boldbaatar et al., 2019），包括世界级规模的欧玉陶勒盖斑岩Cu-Au成矿系统和查干苏布尔加斑岩Cu-Au成矿系统。欧玉陶勒盖斑岩铜金成矿系统（图3）与晚泥盆世石英二长闪长岩的侵入有关。矿化同期的石英二长闪长岩的锆石U-Pb年龄为（378±3）Ma和（371±1.2）Ma。矿石中辉钼矿的Re-Os年龄为370~373 Ma（Kirwin et al., 2005; Wainwright et al., 2011）。蒙古国东南部地质演化和成矿作用显示多阶段性，分别发生在中泥盆世、石炭纪和早二叠世的岩浆活动导致了大规模成矿作用，并形成了包括欧玉陶勒盖、查干苏布尔、苏庭、Zogdor在内的大量斑岩矿床（Davaasuren et al., 2021）。

古亚洲洋在晚泥盆世向南俯冲，形成了哈达门沟Mo成矿系统（图3），其中，辉钼矿Re-Os模式年龄为374~390 Ma，等时线年龄（381.6 ± 4.3）Ma（Zhang et al., 2017a）。该地区的地质演化和成矿作用显示多阶段性。矿脉与蚀变岩之间断层泥中铬云母的最小年龄为（351.4±0.8）Ma（Hart et al., 2002），辉钼矿Re-Os年龄为（386.4 ±2.7）Ma（侯万荣等，2014）。哈达门沟地区大桦背岩体的锆石U-Pb年龄为（353±7）Ma（苗来成等，2001），矿区含金钾化蚀变岩和金矿石中的绢云母的$^{40}Ar/^{39}Ar$年龄为（322.58±3.24）Ma和（239.76±3.04）Ma（聂凤军等，2005）。

除了发育斑岩型钼成矿作用，该地区在印支期还形成了包括哈达门沟、柳坝沟金矿在内的一些重要金矿。哈达门沟金矿由90多条矿脉组成，这些矿脉中的大部分受控于近东西向断裂，局部被北东向断裂所切穿。金矿化主要与石英脉、浸染状黄铁矿、钾化蚀变和硅化岩石相关，石英脉通常在矿体中心出露，在石英脉两侧发育钾化和硅化。一般发育钾长石-石英-辉钼矿阶段、石英-黄铁矿-绿帘石/绿泥石阶段、石英-多金属硫化物-自然金阶段和碳酸盐-石英阶段。13号矿脉中绢云母^{40}Ar-^{39}Ar年龄为（239.8±3.0）Ma、矿石中钾长石^{40}Ar-^{39}Ar坪年龄为（217.9±3.1）Ma（章永梅等, 2011），这些年龄数据反映了陆内造山过程对泥盆纪

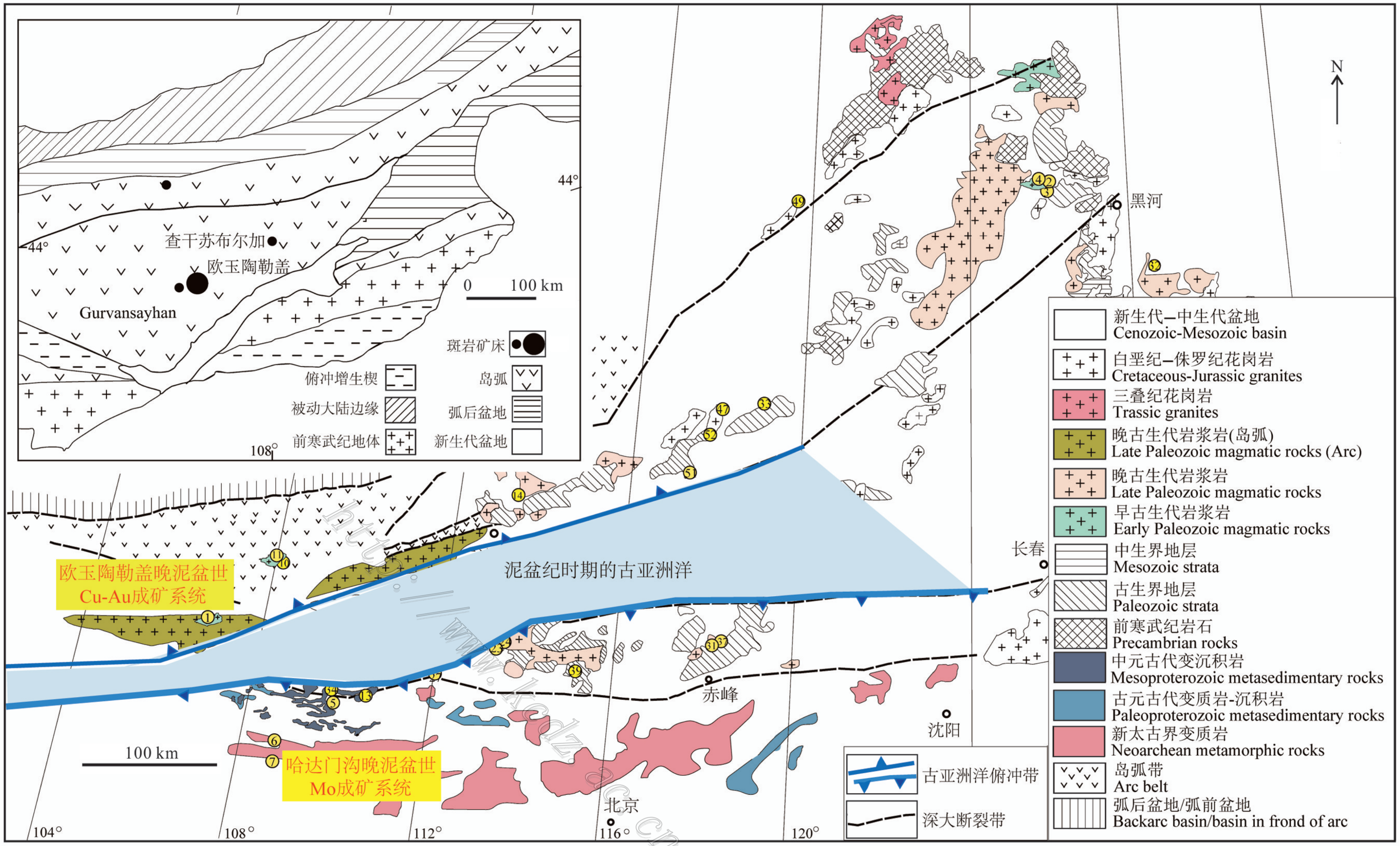

图3 兴蒙造山带泥盆纪时期的地质特征和成矿系统,图中显示产在Gurvansayhan岛弧中的晚泥盆世欧玉陶勒盖斑岩型Cu-Au成矿系统、白乃庙岛弧中的哈达门沟晚泥盆世斑岩型Mo成矿系统(矿床序号与表1对应)。插图为欧玉陶勒盖-查干苏布尔加地区地质图(引自Blight et al., 2010)

Fig. 3 Geological framework of the Xing-meng orogenic belt during late Devonian showing ore-forming systems related to the evolution of the Paleo-Asian ocean including the Oyu Tolgoi porphyry Cu-Au ore-forming system in the Gurvansayhan arc and the Hadamengou porphyry Mo ore-forming system in the Bainaimiao arc (the number of deposits is identical to number in Table 1). Insert shows geological map of the Oyu Tolgoi (after Blight et al., 2010)

岛弧中形成矿床的改造和再造作用时间。位于哈达门沟北部的西沙德盖钼矿的Re-Os等时线年龄为(226.4±3.3)Ma,含钼矿化花岗斑岩的锆石U-Pb年龄为(226.8±0.87)Ma(侯万荣等,2010b)。这些年龄资料记录了该地区复杂地质演化史以及相应的成矿事件。

晚泥盆世—早石炭世期间发育了贺根山裂谷带。对贺根山地区的超镁铁质岩石的成因有争议,主流观点认为它属于蛇绿岩带的组成部分,代表洋壳残余(Jiang et al., 2019),形成了豆荚状铬铁矿成矿系统(图4a~d)。矿区堆晶辉长岩和橄长岩亏损轻稀土元素,富集大离子亲石元素,其地球化学特征与受俯冲板片流体交代影响形成的类似MORB成分的熔体相似。铁镁质岩脉具有平缓或亏损轻稀土元素、亏损Nb、富集大离子亲石元素的地球化学特征,与岛弧拉斑玄武岩相似。贺根山蛇绿岩中出现不同亏损程度的地幔橄榄岩,显示不同程度全岩及单斜辉石亏损轻稀土元素、Sr和Ba正异常的特征。虽然贺根山豆荚状铬铁矿母岩浆的Al_2O_3及微量元素与洋中脊玄武岩相似,但是铬铁矿母岩浆的一些差异则反映了其与洋中脊玄武岩显著的差异(Jiang et al., 2019; 2020):铬铁矿母岩浆比典型洋中脊玄武岩更亏损Ti,高Al铬铁矿结晶时的$f(O_2)$高于典型洋中脊玄武岩。原始熔体在地幔上升过程中,与地幔橄榄岩围岩发生熔体-岩石反应。在岩石圈地幔顶部,地幔对流方向由垂直方向转为水平,熔体在岩浆通道中上升速度变慢,熔体与中等亏损程度的方辉橄榄岩反应程度达到最高。通过该反应,熔体中Cr_2O_3达到饱和。含水熔体-地幔橄榄岩反应还导致方辉橄榄岩围岩亏损程度升高,Ti以及部分含水熔体/流体迁移元素含量升高,并在反应程度较高的位置形成纯橄岩。次生高Si熔体与原始低Si熔体不均匀混合时,高Al铬铁矿在低Si熔体中不断富集。地幔橄榄岩中较高的熔体通量有利于熔体-地幔橄榄岩反应持续发生。持续的熔体-地幔橄榄岩反应保证岩浆通道中熔体的混合作用持续发生,并可以将混合后熔体的成分长时间锁定在铬铁矿稳定域内,有利于高Al铬铁矿持续结晶。在熔体-地幔橄榄岩反应程度较低的区域形成稠密浸染状和中度浸染状铬铁矿矿石,而在熔体-地幔橄榄岩反应程度较高的区域,形成稠密浸染状和块状铬铁矿矿石。母岩浆较高的水含量可能导致含水流体相出溶,最终形成块状铬铁矿矿石。

除了形成豆荚状铬铁矿外,早石炭世在该地区还形成了苏廷斑岩铜-金成矿系统和小坝梁VHMS型铜-金成矿系统(图4a~d)。小坝梁铜金矿床主要赋存于晚古生代凝灰岩地层中,矿区直接赋矿围岩为凝灰岩、细碧岩和火山角砾岩。小坝梁矿床可能形成于大陆裂谷有限洋盆环境,成矿物质Au可能来自于成矿早阶段海底富Au沉积物,Cu来自于成矿晚阶段岩浆的释气作用。赋矿围岩安山质凝灰岩是受交代的软流圈地幔部分熔融的产物,并经历了强烈的分离结晶作用(Zhang et al., 2021)。

晚石炭世—二叠纪时期形成大量热液-蚀变岩-斑岩型矿床,如准苏吉花、哈达庙、毕力赫、阿尔哈达、夏尔楚鲁、朱拉扎嘎、后石花等矿床。准苏吉花钼矿床的形成暗示该地区成矿环境发生了明显改变。由铜矿化转变到钼矿化,记录了该地区由俯冲增生体制向伸展构造体制的转变。这种转变也显示了二叠纪及其后高钾钙碱性高分异型花岗质岩浆活动与斑岩型钼矿化的成因联系。准苏吉花矿区出露的花岗闪长岩年龄为(300.0±2.0)Ma,花岗岩岩脉年龄为(299.3±2.0)Ma,锆石U-Pb年龄与辉钼矿Re-Os年龄一致,分别为(298.2±3.6)Ma和(298.1±3.6)Ma(刘翼飞等,2012a;2012b)。毕力赫-哈达庙金矿区出露晚石炭世—早二叠世海相沉积岩、早二叠世安山-流纹质凝灰岩-角砾岩夹杂砂岩和灰岩,并被中晚二叠世花岗闪长岩-石英闪长岩-花岗斑岩侵入。火山岩的锆石U-Pb年龄为274~270 Ma,石英闪长岩的年龄为(261±2)Ma和(259±3)Ma,花岗斑岩的锆石U-Pb年龄为(253±3)Ma(Liu et al., 2015)。

作为岩浆型矿床的代表,额尔布图Ni-Cu硫化物矿床产于超镁铁质岩体中。岩体由底部的方辉橄榄岩和顶部的辉石岩组成,二者之间渐变过渡。含矿岩体主要由方辉橄榄岩组成。轻稀土元素相对富集,显示Nb-Ta负异常和中等Hf正异常的地球化学特征。同位素地球化学研究表明,母岩浆类似于玻安质岩浆,在岩浆演化和成矿过程中均遭受地壳成分混染。高品位矿石产于辉石岩下部及方辉橄榄岩中。岩体下部常发生硫化物网状结构矿化,其中Ni品位(质量分数)高达2%(Peng et al., 2013)。

在印支期,岩石圈大规模伸展减薄,发生了叠加成矿作用。印支期形成了大量造山型金矿(Zhao et al., 2013; Zhang et al., 2020)和斑岩型铜钼矿(Zeng

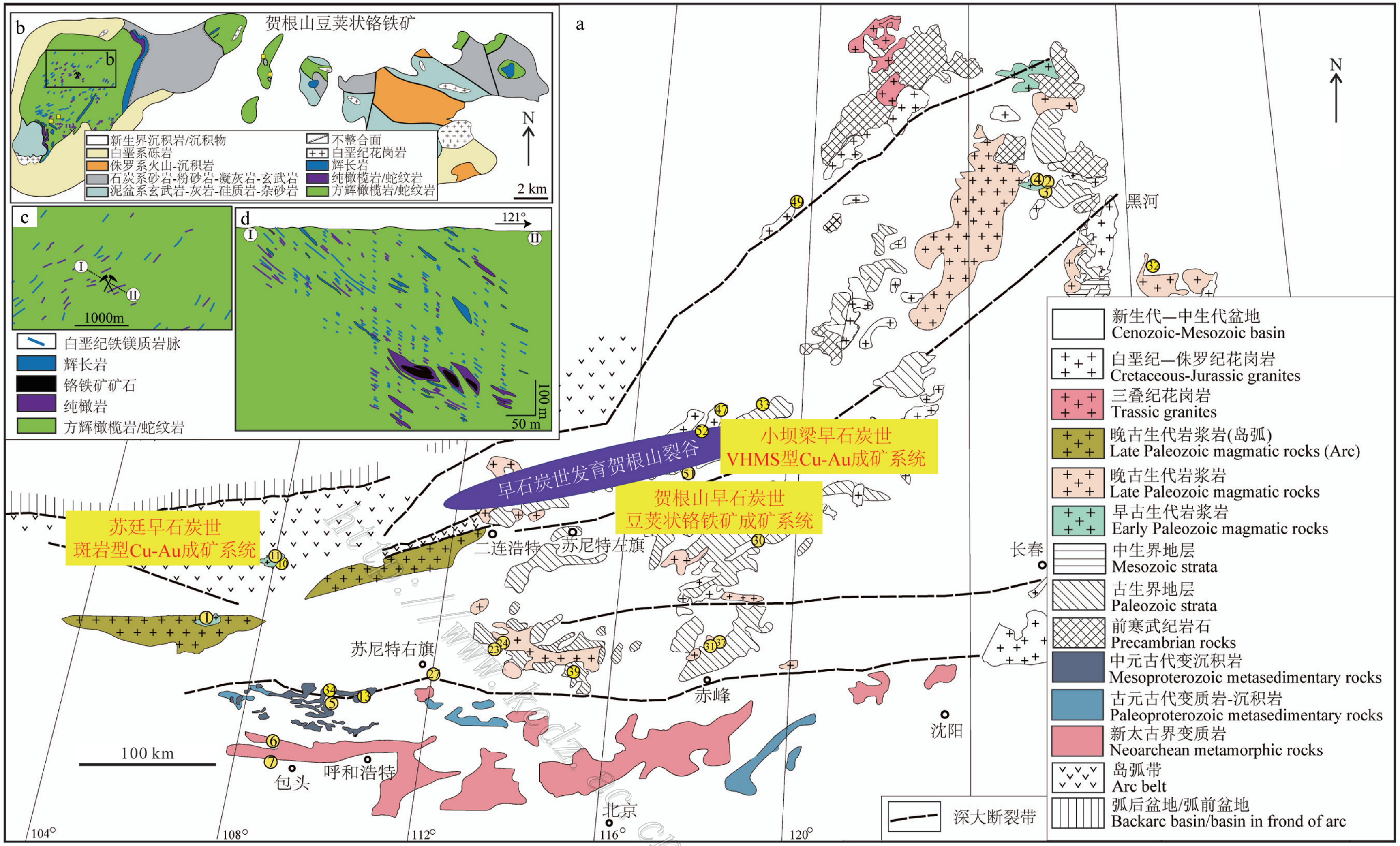

图 4　兴蒙造山带早石炭世时期地质特征和成矿系统(a)，图中显示贺根山豆荚状铬铁矿成矿系统、苏廷斑岩型 Cu-Au 成矿系统和小坝梁 VHMS 成矿系统(矿床序号与附表 1 对应)及贺根山豆荚状铬铁矿地质图(b)和矿床剖面图(c、d)(引自 Jiang et al., 2020)

Fig. 4　Geological framework of the Xing-meng orogenic belt during Early Carboniferous (a) showing ore-forming system related to the evolution of the Paleo-Asian ocean including the Hegenshan podiform chromitite, Suting porphyry Cu-Au and Xiaobaliang VHMS (the number of deposits is identical to number in Table 1)) and geological map (b) and cross sections (c, d) of the Hegenshan podiform chromitite (after Jiang et al., 2020) et al., 2011; Zhang Y M et al., 2017b; Zhang L L et al., 2019),例如巴嘎旗比鲁甘干斑岩钼矿的辉钼矿 Re-Os 同位素模式年龄变化范围为(236.9±3.7)Ma~(238.7±2.4)Ma,年龄加权平均值为(237.9±1.7)Ma(李俊建等,2016)。属于西拉沐伦斑岩矿床成矿带的锅盔顶子斑岩铜矿的辉钼矿 Re-Os 年龄为(250.0±1.5)Ma,含矿的蚀变花岗闪长岩的锆石 U-Pb 年龄为(251.2±2.1)Ma(Yang Q et al., 2021)。印支期形成的矿床应该是兴蒙造山带陆内地质演化的产物,古亚洲洋长期演化为造山带中形成大规模成矿作用奠定了物质基础,起到成矿物质预富集的作用。

4 结 论

古亚洲洋在古生代向北和向南发生双向俯冲增生、碰撞造山,并最终形成了兴蒙陆内造山带,在此过程中形成了大量斑岩矿床、矽卡岩矿床、岩浆型铜-镍-铬铁矿、VHMS 型多金属矿床、热液型及造山型金矿等。早古生代早期,古亚洲洋向北俯冲,形成了奥陶纪多宝山-铜山斑岩 Cu-Au 成矿系统;晚奥陶世—志留纪时期,古亚洲洋向南俯冲并形成了白乃庙 Cu-Mo-Au 成矿系统和别鲁乌图 VHMS 成矿系统。泥盆纪时期,古亚洲洋向北俯冲形成了欧玉陶勒盖晚泥盆世斑岩 Cu-Au 成矿系统,向南俯冲形成了晚泥盆世哈达门沟 Mo 成矿系统。晚泥盆世—石炭纪期间形成了贺根山豆荚状铬铁矿成矿系统、小型斑岩 Mo-Cu 成矿系统和 VHMS 型成矿系统。印支期矿床是兴蒙陆内造山带陆内地质演化的产物,古亚洲洋在古生代的长期演化为中生代大规模成矿作用奠定了丰富的物质基础。

致 谢 《矿床地质》审稿专家提供的具体修改意见和建议对完善本文有重要帮助,特此致谢。

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