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中亚成矿域斑岩铜金成矿的地质环境问题*

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Abstract The well-known Central Asian Metallogenic Domain (CAMD) holds numerous giant and world-class porphyry Cu-Au deposits, e. g., Oyu Tolgoi, Almalyk, Andash-Taldy Bulak, Aktogai and Kounrad that occur in Mongolia, Uzbekistan, Kyrgyzstan and Kazakhstan. The continous and great discovery of porphyry Cu-Au deposits in northern Xinjiang, China, is waiting in much hope. What's the geodynamic setting for porphyry Cu-Au deposit formation in CAMD? How about the potential to find important industrial porphyry Cu-Au deposits continually in northern Xinjiang, especially in Tianshan, China? All of these are the key geological and exploration issues that unsolved. Based on extensive investigation on previous studies, together with our own works on regional geology of the Central Asia, it is suggested that porphyry Cu-Au deposits in the CAMD have ever formed in the all settings of oceanic subduction, continent-continent collision and post-collision, however, the island-arc setting caused by subduction of the Paleo-Asian ocean undoubted represent the most important one, and large-scale porphyry deposits appear to have been formed in elder arc setting during the lasted evolution stage of the ocean. It is an important geological problem why the large-scale porphyry Cu-Au mineralizations in CAMD took place in the elder arc. The island-arc systems in norethern Xinjiang, especially in Tianshan, China, are well developed, and arc-related magmatism lasted for a relatively long time, large and super-large porphyry Cu-Au deposits are hoped to find in this region.

Key words Porphyry Cu-Au mineralization; Elder arc; Metallogenic environment; Central Asia Metallogenic Domain

摘 要 中亚成矿域在蒙古、乌兹别克斯坦、吉尔吉斯斯坦和哈萨克斯坦产有 Oyu Tolgoi、Almalyk、Andash-Taldy Bulak、Aktogai、Kounrad 等众多巨型和世界级斑岩铜金矿床,中国新疆北部斑岩铜金找矿持续重大突破令人期待。中亚成矿域大规模斑岩铜金成矿于什么地质环境?新疆北部、尤其天山斑岩铜金地质找矿持续突破的前景怎样?都是颇受关注的重大地质和找矿问题。通过广泛深入文献调研和重要矿集区实地调查研究表明,中亚构造成矿域在古亚洲洋壳俯冲增生、陆陆碰撞和后碰撞伸展等不同时期地质环境中,虽然均有斑岩铜金成矿作用发生,但古亚洲洋俯冲形成不同时期的增生岛弧是中亚斑岩铜金最为重要的成矿地质环境,大规模斑岩铜金成矿出现在洋盆演化末期、或即将关闭时的成熟岛弧环境。为什么中亚重要斑岩铜金矿床多形成于年长的成熟岛弧是值得探索的重要科学问题。新疆北部、尤其天山不同时期的岛弧发育完整,岛弧岩浆作用强烈而漫长,斑岩铜金成矿条件优越,大型-超大型铜金矿地质找矿潜力巨大,有望持续发现重要斑岩铜金矿床。

关键词 斑岩铜金成矿;成熟岛弧;成矿环境;中亚成矿域

中图法分类号 P612; P618.41; P618.51

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1 引言

矿床是特定地质环境中成矿作用的产物,成矿地质环境厘定是找矿勘查和矿床学研究的基础(薛春纪等, 2007)。矿床越来越不易寻找和发现,而矿床形成的地质环境却相对容易识别。因而,成矿地质环境研究颇受关注。斑岩铜金成矿系统(包括斑岩型及与之密切相关的矽卡岩型、低硫-高硫浅成低温热液型等铜金矿床)提供了世界近75%的铜,50%的钼和20%的金(Sillitoe, 2010),经济意义巨大。环太平洋成矿域是巨型和世界级斑岩铜金矿床分布最为密集的区域,经典斑岩铜成矿理论从这里发祥(Lowell and Guilbert, 1970),大规模斑岩铜金成矿主要形成于西南太平洋年轻岛弧或中安第斯陆缘弧环境(Cooke *et al.*, 2005; Sillitoe, 1997, 2010; Singer *et al.*, 2005),而分布于特提斯-喜马拉雅成矿域的斑岩铜(金)矿床通常被认为形成于陆陆碰撞/后碰撞伸展环境(Hou *et al.*, 2006, 2009, 2011; Hou and Cook, 2009)。

斑岩型是中亚成矿域铜金矿床最为重要的成矿类型,发育 Oyu Tolgoi(Cu 43Mt, Au 1850t; Perelló *et al.*, 2011)、Kalmakyr(Cu 13Mt, Au 1400t; Cooke *et al.*, 2005)、Dal'neye (Cu 13Mt, Au 400t; Golovanov *et al.*, 2005)、Aktogai(Cu 5.8Mt, Au 68t; Seltmann and Porter, 2005)、Kounrad(Cu 5Mt, Au 600t; Seltmann and Porter, 2005)、Bozshakol(Cu 4.1Mt, Au 163t; Seltmann *et al.*, 2014)、Nurkazgan(Cu 1.8Mt, Au 76t; Seltmann *et al.*, 2014)、Taldy Bulak(Cu 0.7Mt, Au 196t; Seltmann *et al.*, 2014)、土屋(Cu 2.1Mt, Au 44t; 芮宗瑶等, 2002)等众多世界级和大型-超大型铜金矿床(表1),呈现巨大成矿和找矿潜力(薛春纪等, 2015)。前人研究(Mao *et al.*, 2014; Seltmann and Porter, 2005; Seltmann *et al.*, 2014; Yakubchuk, 2004, 2005, 2012; 申萍等, 2015)认为,中亚斑岩铜金矿床形成于古亚洲洋演化过程中不同时期的岛弧、陆缘弧及岛弧向陆缘弧过渡的地质环境。然而,相对于环太平洋俯冲型和特提斯-喜马拉雅碰撞型构造成矿域,中亚增生型构造成矿域经历了更为长期而复杂的区域地壳演化。中亚重要斑岩铜金矿床形成的地质环境与环太平洋地区究竟有何区别与联系?中亚成矿域是否发育陆陆碰撞环境下斑岩铜金矿床?

本文通过对前人相关研究成果的系统搜集和分析疏理,结合部分大型矿集区野外调查和成矿环境研究,试图揭示中亚成矿域斑岩铜金成矿的地质环境问题,并作初步讨论,以抛砖引玉,服务新疆天山、尤其西天山斑岩铜金地质找矿和相关研究工作。

2 中亚区域背景和斑岩铜金矿床

中亚地处亚欧大陆中部,西起俄罗斯乌拉尔山脉,向东经哈萨克斯坦、乌兹别克斯坦、吉尔吉斯斯坦、塔吉克斯坦、中国西北部、蒙古、中国东北部至太平洋西北岸(图1)。复杂多样的区域地壳演化作用造就了中亚多块体镶嵌、多缝合带连接、盆山耦合的大型构造格局和丰富的矿产资源,形成全球最大的增生型造山带(Şengör *et al.*, 1993; Şengör and Natal'In, 1996; Wilhem *et al.*, 2012; Windley *et al.*, 2007; Xiao *et al.*, 2009, 2010; Yakubchuk *et al.*, 2001),并蕴育出世人瞩目的中亚金铜多金属成矿域(Goldfarb *et al.*, 2014; Seltmann *et al.*, 2014; Yakubchuk *et al.*, 2001, 2012; 涂光炽, 1999; 朱永峰等, 2007; 朱永峰, 2009, 2014; 薛春纪等, 2014a, b, 2015; 图1)。

在区域板块构造中,中亚成矿域是夹持于东欧、西伯利亚、塔里木-卡拉库姆和华北克拉通之间的复合增生型造山带(图1),是新元古-晚古生代末期古亚洲多岛洋形成、演化、消亡及其之后改造的综合产物(Lomize *et al.*, 1997; Xiao *et al.*, 2010; Wilhem *et al.*, 2012; 高俊等, 2009; 薛春纪等, 2014a, b),经历了多陆块拼贴、多洋盆俯冲消减、多类型陆壳增生(Biske and Seltmann, 2010; Windley *et al.*, 2007)等地质过程,总体呈现一系列古生代造山带环绕众多微陆块近东西向展布格局(Alexeiev *et al.*, 2011; Kröner *et al.*, 2007, 2013, 2014)。新元古代-早古生代早期,中亚成矿域基本构造格局受古亚洲洋体系中 Kipchak、Tuva-Mongol 和 Urals-Zharma 三个近平行的南北向岛弧带及与之相关的弧后盆地控制(Yakubchuk *et al.*, 2001; Yakubchuk, 2004);晚奥陶世开始,西伯利亚板块和劳伦古陆之间的裂解过程诱发西伯利亚板块相对于东欧板块发生顺时针持续旋转并最终于二叠纪形成著名的"哈萨克斯坦山弯构造"(Yakubchuk *et al.*, 2001; Wang *et al.*, 2007; Xiao *et al.*, 2010)。与这一地质过程紧密相关,在中亚成矿域演化出 Beltau-Kurama 和 Kazakh-Mongol 两个重要的晚古生代岩浆弧并伴随大规模斑岩铜金成矿作用(Yakubchuk *et al.*, 2001; Yakubchuk, 2004),尤其 Kazakh-Mongol 志留-石炭纪岛弧是由哈萨克斯坦 Taldykurgan、中国新疆博罗霍洛和大南湖-头苏泉及蒙古 Gurvansayhan 等多个规模不等、持续时间不同的岛弧带构成,规模巨大,斑岩铜金成矿显著(Goldfarb *et al.*, 2014; Seltmann *et al.*, 2014; Wainwright *et al.*, 2011; Yakubchuk, 2004; 薛春纪等, 2015)。中亚成矿域区域地壳演化过程中出现的性质有别、规模各异的不同时期增生岛弧带与 Junggar-Balkhash、Turkestan、Terskey 等古亚洲洋的海底扩张和俯冲增生过程密切相关(Yakubchuk, 2004; Seltmann *et al.*, 2014; Xiao *et al.*, 2010; 薛春纪等, 2014a, b, 2015);伴随古亚洲大洋/洋盆晚古生代末期相继关闭,这些岛弧带及它们的增生楔最终在晚二叠世拼贴融合并伴随着大规模的逆冲推覆、剪切走滑和同/后碰撞岩浆过程(Windley *et al.*, 2007; Yakubchuk *et al.*, 2001; Yakubchuk, 2004)。

中亚成矿域重要斑岩铜金矿床及相关浅成低温热液和矽卡岩型金铜矿床主要分布巴尔喀什湖南北、Kurama 山脉和南蒙古(图1),集中产于早奥陶-晚石炭世不同时期、不同

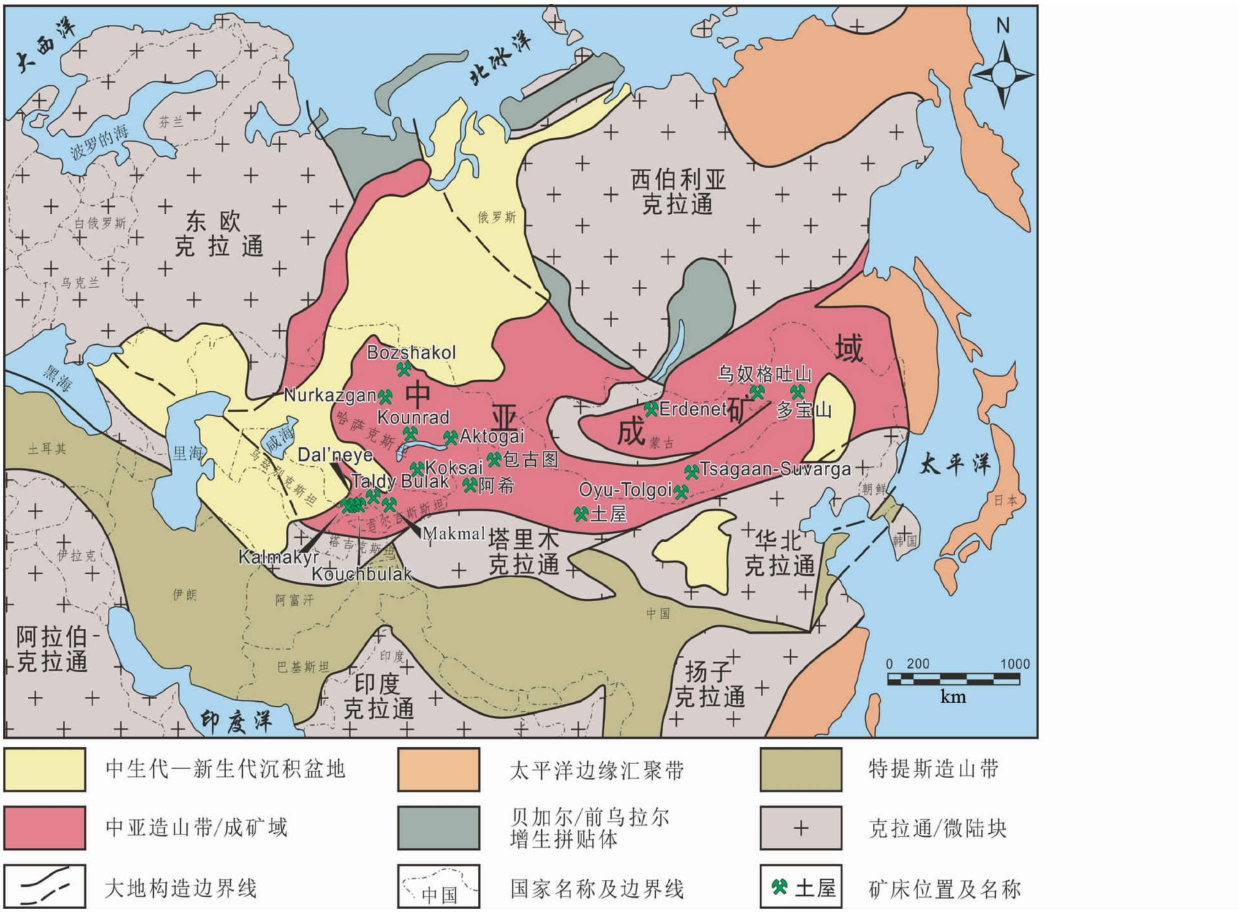

图 1　中亚成矿域构造位置和重要斑岩铜金矿床分布(据 Seltmann and Porter, 2005 修编)

Fig. 1　Simplified tectonic location of the Central Asia Metallogenic Domain showing the distribution of major porphyry Cu-Au deposits (modified after Seltmann and Porter, 2005)

位置的岛弧带上(表 1)。Kipchak 寒武-奥陶纪岛弧发育哈萨克斯坦 Bozshakol 斑岩铜金矿床(~481Ma; Kudryavtsev, 1996)、吉尔吉斯斯坦 Andash 和 Taldybulak 斑岩铜金矿床(475 ~455Ma; Yakubchuk *et al.*, 2010);Beltau-Kurama 泥盆-石炭纪岛弧产出 Kalmakyr-Dal'neye(315 ~308Ma; Seltmann *et al.*, 2011)、Sari-Cheku(~317Ma; 薛春纪等, 2013a)等斑岩铜金矿床和 Kochbulak(~301Ma; Seltmann *et al.*, 2011)、Kairagach(~290Ma; Chernyshev *et al.*, 2011)等浅成低温热液金矿床等构成的乌兹比克斯坦 Almalyk 石炭纪世界级铜金矿集区(薛春纪等, 2014a, b, 2015); Taldykurgan 石炭纪岛弧产有哈萨克斯坦 Aktogai (336 ~ 328Ma; Chen *et al.*, 2014)、Kounrad (327 ~ 308Ma; Chen *et al.*, 2014)、Koksai (~330Ma; Seltmann and Porter, 2005)和中国新疆包古图(314 ~309Ma; Shen *et al.*, 2012)等大型-超大型斑岩铜金矿床;中国新疆西部博罗霍洛泥盆-石炭纪岛弧发育阿希和京希-伊尔曼德等构成的吐拉苏浅成低温热液型金矿集区(~323Ma; Zhao *et al.*, 2014a, b; 赵晓波等, 2014);中国新疆东部大南湖-头苏泉泥盆-石炭纪岛弧产出土屋-延东新疆最大斑岩铜矿床(325 ~318Ma; Shen *et al.*, 2014a, b; Wang *et al.*, 2015a, b);蒙古南部 Gurvansayhan 泥盆纪岛弧产有 Oyu Tolgoi 亚洲最大斑岩铜金矿床(372 ~366Ma; Wainwright *et al.*, 2011)。

3　中亚斑岩铜金成矿地质环境

蒙古 Oyu Tolgoi 矿床探明铜储量 42.76Mt(平均铜品位 0.67%)、金储量 1850t(平均金品位 0.29g/t)(表 1),在全球 25 个规模最大的斑岩铜金矿床中,金储量排第 3 位、铜储量排第 5 位(Sillitoe, 2012)。Oyu Tolgoi 矿床产在 Junggar-Balkhash 大洋向南向蒙古 Gurvansayhan 地体之下俯冲形成的晚泥盆世岛弧带(Porter, 2015; Wainwright *et al.*, 2011),斑岩型金铜矿体产于晚泥盆世石英二长闪长岩岩株内,并伴随强烈的钾硅酸盐化蚀变(钾长石-黑云母-磁铁矿)、石英-绢云母化、中级-高级泥化和青磐岩化蚀变作用(Khashgerel *et al.*, 2006; 聂凤军等, 2004),含矿石英二长闪长岩(373 ± 1Ma ~366.7 ±2.6Ma, U-Pb 法; Wainwright *et al.*, 2011)与辉钼矿 Re-Os 法测得成矿时代(373 ±1Ma; Kirwin *et al.*,

表1 中亚成矿域斑岩-矽卡岩-浅成低温热液铜金矿床基本地质特征

Table 1 Geological characteristics of major porphyry-skarn-epithermal copper-gold deposits in the Central Asian Metallogenic Domain

矿床名称	储量	品位	构造环境	洋盆及存在时间	成矿时代	参考文献
Oyutolgoi	Cu 42.76Mt, Au 1850t	Cu 0.67%, Au 0.29g/t	Gurvansayhan 泥盆纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	372~366Ma	Porter (2015)
Aktogai	Cu 5.8Mt, Au 68t	Cu 0.34%, Au 0.04g/t	Taldykurgan 石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	336~328Ma	Chen *et al.* (2014)
Aidarly	Cu 5.8Mt, Au 15t	Cu 0.38%, Au 0.01g/t	Taldykurgan 石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	336~328Ma	Seltmann *et al.* (2014)
Koround	Cu 5Mt, Au 600t	Cu 0.62%, Au 0.76g/t	Taldykurgan 石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	327~308Ma	Chen *et al.* (2014)
Nurkazgan	Cu 1.8Mt, Au 76t	Cu 0.89%, Au 0.38g/t	Taldykurgan 石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	~410Ma	Seltmann *et al.* (2014)
Koksai	Cu 1.6Mt, Au 37t	Cu 0.52%, Au 0.12g/t	Taldykurgan 石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	~330Ma	Seltmann and Porter (2005)
Benqala	Cu 1.3Mt, Au 21t	Cu 0.42%, Au 0.07g/t	Taldykurgan 石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	~320Ma	Seltmann *et al.* (2014)
包古图	Cu 0.6Mt, Au 14t	Cu 0.28%, Au 0.14g/t	Taldykurgan 石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	314~305Ma	Shen *et al.* (2012)
阿希	Au 70t	Au 3~8g/t	博罗霍洛泥盆-石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	363~330Ma	Zhao *et al.* (2014a)
京希-伊尔曼德	Au 50t	Au 0.9~4.5g/t	博罗霍洛泥盆-石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	363~330Ma	Zhao *et al.* (2014a)
土屋	Cu 2.1Mt, Au 44t	Cu 0.75%, Au 0.16g/t	大南湖-头苏泉泥盆-石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	~322Ma	Han *et al.* (2006)
延东	Cu 2.1Mt, Au 22t	Cu 0.58%, Au 0.06g/t	大南湖-头苏泉泥盆-石炭纪岛弧	Junggar-Balkhash 洋、新元古代-晚石炭世	~323Ma	芮宗瑶等(2002)
Kalmakyr	Cu 13Mt, Au 1400t	Cu 0.4%, Au 0.5g/t	Beltau-Kurama 石炭纪岛弧	Turkerstan 洋、新元古代-晚石炭世	315~308Ma	Seltmann *et al.* (2011)
Dal'neye	Cu 13Mt, Au 400t	Cu 0.3%, Au 0.5g/t	Beltau-Kurama 石炭纪岛弧	Turkerstan 洋、新元古代-晚石炭世	315~308Ma	Golovanov *et al.* (2005)
Sari-Cheku	Cu 1.3Mt	Cu 0.8%	Beltau-Kurama 石炭纪岛弧	Turkerstan 洋、新元古代-晚石炭世	~317Ma	薛春纪等(2013a)
Kouchbulak	Au 600t	Au 13.4g/t	Beltau-Kurama 石炭纪岛弧	Turkerstan 洋、新元古代-晚石炭世	~301Ma	薛春纪等(2014a)
Kyzylarmasai	Au 470t	Au 6.7g/t	Beltau-Kurama 石炭纪岛弧	Turkerstan 洋、新元古代-晚石炭世	~301Ma	薛春纪等(2014a)
Kauldy	Au 400t	Au 5.4g/t	Beltau-Kurama 石炭纪岛弧	Turkerstan 洋、新元古代-晚石炭世	~301Ma	薛春纪等(2014a)
Makmal	Au 90t	Au 6~7g/t	Beltau-Kurama 石炭纪岛弧	Turkerstan 洋、新元古代-晚石炭世	~286Ma	Seltmann *et al.* (2011)
Bozshakol	Cu 4.1Mt, Au 163t	Cu 0.35%, Au 0.14g/t	Kipchak 寒武-奥陶纪岛弧	Terskey 洋、新元古代-中奥陶世	~481Ma	Seltmann *et al.* (2014)
Andash	Cu 0.6Mt, Au 21t	Cu 0.4%, Au 1.1g/t	Kipchak 寒武-奥陶纪岛弧	Terskey 洋、新元古代-中奥陶世	475~455Ma	Yakubchuk *et al.* (2010)
Taldy Bulak	Cu 0.7Mt, Au 196t	Cu 0.17%, Au 0.46g/t	Kipchak 寒武-奥陶纪岛弧	Terskey 洋、新元古代-中奥陶世	475~455Ma	Yakubchuk *et al.* (2010)

2005）一致；Junggar-Balkhash 大洋大致在新元古代打开，发育一系列洋盆持续扩张不同阶段和位置的相应洋壳岩石和地球物理记录（Biske and Seltmann, 2010; Windley *et al.*, 2007; Xiao *et al.*, 2004, 2009, 2010），并于泥盆-石炭纪形成了 Kazakh-Mongol 巨型岛弧带（Seltmann and Porter, 2005; Yakubchuk *et al.*, 2001; Yakubchuk, 2004）；而该大洋演化最终于晚石炭世末期关闭（Windley *et al.*, 2007; Yakubchuk, 2001; Yakubchuk, 2004; Xiao *et al.*, 2010），Oyu Tolgoi 矿床构造位置和晚泥盆世成矿的地质事实反映斑岩型铜金矿化应形成于 Junggar-Balkhash 大洋长期演化到中晚期出现的较成熟的增生岛弧环境。

世界著名的哈萨克斯坦环 Balkhash 斑岩铜成矿省主体产在 Junggar-Balkhash 大洋向南向哈萨克斯坦-伊犁陆块之下俯冲形成的 Taldykurgan 石炭纪增生岛弧带；Kounrad 铜金矿床位于 Balkhash 湖西北部，探明铜储量 5Mt（平均铜品位 0.62%）、金储量 600t（平均金品位 0.76g/t）（表 1），斑岩型铜金矿化呈细网脉状产于强烈钾硅酸盐化和石英-电气石化蚀变的晚石炭世花岗闪长岩杂岩体内并普遍被后期高硫化酸性蚀变（如石英-明矾石化、硬水铝石化等）叠加（Seltmann *et al.*, 2014），含矿斑状二长花岗岩形成时代为晚石炭世（年龄为 327.3 ± 2.1Ma, U-Pb 法；Chen *et al.*, 2014）；Aktogai 斑岩铜金矿床产在 Balkhash 湖东北部，拥有铜储量 5.8Mt（平均铜品位 0.34%）、金储量 68t（平均金品位 0.04g/t）（表 1），矿化呈浸染状和网脉状产在晚石炭世二长花岗岩-花岗闪长斑岩体内，与岩体内石英-黑云母化和石英-绢云母化蚀变关系密切（Seltmann and Porter, 2005），锆石 U-Pb 法测得含矿花岗闪长斑岩和斑状二长花岗岩年龄分别为 327.5 ± 1.9Ma 和 327.3 ± 2.1Ma（Chen *et al.*, 2014）；Koksai 矿床位于 Balkhash 湖东南部，探明铜储量 1.6Mt（平均铜品位 0.52%）、金储量 37t（平均金品位 0.12g/t）（表 1），斑岩铜金矿体呈透镜状产于 Koksai 环形断裂与花岗闪长岩、黑云母斜长花岗岩接触带，热液蚀变从侵入体中心向外依次出现石英-绢云母-黄铁矿带、石英-绢云母-辉钼矿-黄铜矿带、石英-绿泥石-绢云母带和石英-碳酸盐-绿泥石带（薛春纪等，2014a），含矿花岗闪长岩形成于晚石炭世（~330Ma; Seltmann and Porter, 2005）；同处于 Taldykurgan 石炭纪增生岛弧带，在中国新疆西准噶尔产有包古图斑岩铜金矿床，铜储量 0.6Mt（平均铜品位 0.28%）、金储量 14t（平均金品位 0.14g/t）（表 1），铜金矿化呈浸染状和脉状主体产于早期闪长岩岩株内，部分产在晚期闪长玢岩岩脉中，与钾硅酸盐化和绢英岩化蚀变密切相关（Shen *et al.*, 2010），矿区闪长岩和闪长玢岩锆石 U-Pb 年龄分别为 313.0 ± 2.2Ma 和 312.3 ± 2.2Ma，与辉钼矿 Re-Os 法获得的成矿时代（312.4 ± 1.8Ma）和新生黑云母 $^{40}Ar/^{39}Ar$ 反映的热液事件年龄（308.3 ± 1.9Ma 和 305.7 ± 1.8Ma）一致（Shen *et al.*, 2012），反映包古图斑岩铜金矿床岩浆-热液作用发生在晚石炭世。上述地质事实表明，环 Balkhash 成矿省重要斑岩铜金矿床均形成于晚石炭世，是 Junggar-Balkhash 洋（Pt_3-C_3）演化末期即将关闭前夕出现的成熟岛弧环境中岩浆-热液活动产物。

中国新疆西天山吐拉苏浅成低温热液金矿集区是 Junggar-Balkhash 洋向哈萨克斯坦-伊犁陆块俯冲在其东北缘形成的泥盆-石炭纪博罗霍洛岛弧带岩浆-热液活动产物（An *et al.*, 2013; Wang *et al.*, 2007; Zhao *et al.*, 2014a, b; 薛春纪等,2013b; 赵晓波等, 2014）。吐拉苏矿集区在前寒武系结晶基底之上，先后堆积了下古生界碎屑岩-碳酸盐岩夹少量火山岩和上古生界安山岩-安山质碎屑岩-碳酸盐岩建造，早古生代主体为次稳定大陆边缘性质，晚古生代为活动陆缘岛弧环境（赵晓波等, 2012）。矿集区探明阿希和京希-伊尔曼德两个大型金矿床，发现塔乌尔别克、恰布坎卓它、宽沟等中小型金矿床。阿希金矿拥有金储量 70t（金品位 3 ~ 8g/t）（表 1），金矿化呈网脉状和浸染状产在强烈硅化和绢云母化的晚泥盆-早石炭世安山岩中，金矿石角砾状、皮壳状构造发育，冰长石呈包裹体形式出现在含金石英脉中，主成矿期石英脉中流体包裹体均一温度 120 ~ 240℃，盐度 0.7% ~ 3.1% NaCleqv，成矿流体 δD_{H_2O} = −116‰ ~ −62‰、$\delta^{18}O_{H_2O}$ = −7.4‰ ~ 0.4‰（Zhai *et al.*, 2009），反映低硫型浅成低温热液矿床基本特征；京希-伊尔曼德金矿探明金储量 50t（平均金品位 0.9 ~ 4.5g/t）（表 1），金矿化呈角砾状和浸染状赋存在晚泥盆-早石炭世安山质、英安质凝灰岩中，发育多孔状石英和酸性硫酸盐矿物组合构成的高级泥化蚀变带，多孔状石英中流体包裹体均一温度 198 ~ 275℃，盐度 0.7% ~ 5.0% NaC1eqv，成矿流体 δD_{H_2O} = −93‰ ~ −68‰、$\delta^{18}O_{H_2O}$ = 4.1‰ ~ 5.8‰（Zhai *et al.*, 2009），属于典型高硫型浅成低温热液金矿床。阿希矿床金矿化安山岩和京希-伊尔曼德金矿床英安岩锆石 U-Pb 法测年分别获得 363 ± 6Ma（翟伟等, 2006）和 386.4 ± 9.3Ma（安芳和朱永峰, 2008）的成岩年龄，对与阿希金矿床相邻、矿化特点一致的塔乌尔别克低硫型浅成低温热液金矿床载金黄铁矿开展 Re-Os 法测年获得 323 ± 11Ma（赵晓波等, 2014），指示吐拉苏矿集区大规模金成矿作用应发生在晚石炭世，Junggar-Balkhash 洋（Pt_3-C_3）经过长时期演化，此时的博罗霍洛岛弧发育已经相当成熟，吐拉苏矿集区低硫-高硫型浅成低温热液金成矿应发生在 Junggar-Balkhash 洋演化末期出现的成熟岛弧环境。

土屋-延东是中国新疆最大的的斑岩铜金矿集区，探明铜储量 4.2Mt（平均铜品位 0.67%）、金储量 66t（平均金品位 0.11g/t）（表 1），产在 Junggar-Balkhash 洋向哈萨克斯坦-伊犁板块俯冲形成的大南湖-头苏泉岛弧带（Han *et al.*, 2006; Qin *et al.*, 2011; Wang *et al.*, 2015a, b; Zhang *et al.*, 2006; 芮宗瑶等, 2002）。斑岩铜金成矿与早石炭世英云闪长斑岩侵位及其内部广泛发育的绢英岩化和绿泥石-绢云母化蚀变作用有关（Shen *et al.*, 2014a, b）；延东矿床含矿英云闪长斑岩和花岗闪长斑岩锆石 U-Pb 年龄分别为 332.2 ± 2.3Ma（Shen *et al.*, 2014a）和 333 ± 2Ma（刘德全等, 2003），土屋矿床含矿英云闪长斑岩锆石 U-Pb 法测年获得 332.8 ± 2.5Ma

(*Shen et al.*, 2014b)和332.3±5.9Ma(Wang *et al.*, 2015a),显示中石炭世侵位,而辉钼矿Re-Os法测年证实土屋-延东矿集区成矿时代为晚石炭世(322.7±3.0Ma, Han *et al.*, 2006; 323.0±2.3Ma, 芮宗瑶等, 2002)。斑岩铜金成矿无疑形成于Junggar-Balkhash洋(Pt_3-C_3)演化末期的晚石炭世大南湖-头苏泉成熟岛弧环境。

乌兹别克斯坦东南部Almalyk金铜矿集区位于Turkestan洋向北向中天山陆块之下俯冲形成的Beltau-Kurama岛弧带东段(Golovanov *et al.*, 2005; Seltmann and Porter, 2005; 薛春纪等, 2014a, b)。Almalyk矿集区35km×30km范围内,以泥盆-石炭纪斑岩为主岩形成Kalmakyr、Sari-Cheku、Dal'neye等5个大型-超大型斑岩铜金矿床,在斑岩体和泥盆系碳酸盐岩接触带形成Kurgashigan大型矽卡岩型铅锌矿床,以石炭系安山岩和相关火山碎屑岩为主岩形成Kochbulak、Kauldy等20余个大型浅成低温热液金矿床,构成晚古生代巨型斑岩铜金成矿系统(Seltmann and Porter, 2005; 薛春纪等, 2014a, b, 2015)。Kalmakyr矿床探明铜储量13Mt(平均铜品位0.4%)、金储量1400t(平均金品位0.5g/t)(表1)、并伴生17t钯(平均钯品位0.06g/t)和1.7t铂(平均铂品位0.006g/t)(Pašava *et al.*, 2010)。Kalmakyr矿床斑岩型金铜矿体呈巨大的网脉状和椭球状产在中-晚石炭世二长闪长岩和花岗闪长岩中,由岩体中心向外侧依次出现石英-钾长石-黑云母化、石英-绢云母-绿泥石化、石英-伊利石-绿泥石-绿帘石化构成的热液分带,锆石U-Pb测年获得Kalmakyr矿床含矿花岗闪长斑岩和二长岩年龄分别为315±1Ma和308±1Ma(Seltmann *et al.*, 2011),而Sari-Cheku矿床(铜储量1.3Mt;表1)辉钼矿Re-Os年龄为317.6±2.5Ma(薛春纪等, 2013a);Kochbulak金矿床拥有金储量600t(平均金品位13.4g/t)(表1),金矿化主要产于晚石炭世安山岩和英安岩中,受破火山口环状、放射状断裂-裂隙构造控制,成矿作用伴随强烈硅化、明矾石化蚀变和富集F^--Cl^--Te^{2-}酸性流体周期性沸腾(Bonev *et al.*, 2005),属于典型高硫型浅成低温热液矿床(薛春纪等, 2014a),金矿化安山岩锆石U-Pb年龄为301±4Ma(Seltmann *et al.*, 2011)。Turkestan洋新元古代(~757Ma)打开,经古生代长期演化形成宽广大洋(Mirkamalov *et al.*, 2012),晚泥盆世在乌兹别克斯坦中天山南缘演化出Beltau-Kurama增生岛弧带(Goldfarb *et al.*, 2014; Golovanov *et al.*, 2005; Seltmann and Porter, 2005; Seltmann *et al.*, 2014; 薛春纪等, 2014a, 2014b);Turkestan洋最终于石炭纪末期关闭(McCann *et al.*, 2013; Nurtaev *et al.*, 2013; Windley *et al.*, 2007)。Almalyk矿集区斑岩铜金矿床和浅成低温热液金矿床均为形成于晚石炭世,显然是该大洋演化末期Beltau-Kurama成熟岛弧环境中岩浆-热液作用的产物。

吉尔吉斯斯坦Makmal金矿床拥有金储量90t(平均金品位6~7g/t)(表1),是中亚最大的矽卡岩型金矿床,与Almalyk矿集区同处于中天山南缘的Beltau-Kurama岛弧带(Jenchuraeva *et al.*, 2001; 薛春纪等, 2014a)。金矿体近东西向产在晚石炭世Chartash淡色花岗岩与早石炭世碳酸盐岩接触带,由接触带向两侧矽卡岩化显示出由石榴石-方柱石矽卡岩、石榴石-硅灰石矽卡岩、硅灰石矽卡岩、硅灰石化灰岩、大理岩、灰岩的明显分带(Jenchuraeva *et al.*, 2001),发育磁铁矿-矽卡岩型、块状硫化物型、含锡云英岩型和含金硫化物型等多种矿石类型。含矿淡色花岗岩锆石U-Pb年龄为286±5Ma(Seltmann *et al.*, 2011),指示Makmal矿床矽卡岩型金矿化同样应形成于Turkestan洋(Pt_3-C_3)演化末期的Beltau-Kurama晚石炭世成熟岛弧环境。

Taldy Bulak(铜储量0.7Mt、金储量196t;表1)和Andash(铜储量0.6Mt、金储量21t;表1)矿床是产在吉尔吉斯斯坦北天山南缘Kipchak奥陶纪岛弧带南部同一矿集区的2个超大型斑岩铜金矿床(薛春纪等, 2014a)。矿集区在前寒武系变质基底(千枚岩和板岩)之上,寒武-奥陶纪为安山岩-玄武安山岩-安山质凝灰岩建造并广泛被中奥陶世闪长玢岩侵入,金铜矿化成细脉浸染状和网脉状产于闪长玢岩(约75%)及其中的安山质捕掳体(约25%)中。金铜矿体呈巨大网脉状集合体和透镜状受东西向断裂-裂隙系统控制,热液蚀变由闪长玢岩中心向外依次出现钾化-硅化、绢英岩化和青磐岩化并构成明显分带(Jenchuraeva, 1997)。Taldy Bulak矿床矿化闪长玢岩时代为475~455Ma(Yakubchuk *et al.*, 2010),形成于Terskey洋向北向哈萨克斯坦-伊犁陆块之下俯冲形成的增生岛弧环境(Kipchak岛弧带;Seltmann *et al.*, 2014; 薛春纪等, 2014a, b)。Terskey洋大致在新元古代打开(Bazhenov *et al.*, 2003; Qian *et al.*, 2009),该洋盆向北向哈萨克斯坦-伊犁陆块俯冲在寒武纪演化出Kipchak增生岛弧带(Lomize *et al.*, 1997; Yakubchuk *et al.*, 2001; 薛春纪等, 2014a, b),向南向中天山俯冲形成吉尔吉斯斯坦中天山向东延伸到中国新疆夏特的479~460Ma钙碱性花岗岩(Gao *et al.*, 2009; Long *et al.*, 2011; Konopelko *et al.*, 2008, 2012);Terskey洋盆演化最终于中奥陶世关闭(Gao *et al.*, 2009; Mikolaichuk *et al.*, 1997; 高俊等, 2009)。Taldy Bulak-Andash矿集区成矿时代为中奥陶世,此时Kipchak岛弧带发育已经十分成熟,斑岩铜金成矿是Terskey洋演化末期成熟岛弧环境岩浆-热液活动的产物。

4 讨论

4.1 增生岛弧环境:年轻岛弧VS成熟岛弧

环太平洋成矿域斑岩铜矿床集中分布在南美安第斯、北美科迪勒拉和西南太平洋三个成矿省(Cooke *et al.*, 2005)。安第斯成矿省沿南美洲西缘广泛产有钙碱性陆缘弧安山岩并形成El Teniente、Chuquicamata和Río Blanco-Los Bronces等世界级斑岩铜矿床(成矿时代66~5Ma; Deckart *et al.*, 2014);科迪勒拉成矿省以北美大陆内部盛产晚白垩-早新生代巨型斑岩铜钼矿床(如美国科罗拉多洲Climax、Hendson

等)为基本特征(Leveille and Stegen, 2012)；与东太平洋的安第斯和科迪勒拉成矿省不同,西南太平洋地区发育由辉长-闪长质岛弧杂岩构成的年轻洋壳岛弧链,成矿作用以大量形成新生代富金斑岩铜矿(即斑岩铜金矿)为特色且往往在一个矿集区伴生相关的矽卡岩和高硫-低硫型浅成低温热液铜金矿床,构成典型的岛弧斑岩铜金成矿系统(Cooke *et al.*, 2011；Hedenquist *et al.*, 1998；Sillitoe, 2010；Waters *et al.*, 2011)；这些巨型和超大型斑岩铜金成矿系统被认为与年轻炙热的俯冲洋壳脱水熔融形成的埃达克岩熔体关系密切,是年轻岛弧环境构造-岩浆-热液作用的产物(Foley *et al.*, 2002；Oyarzun *et al.*, 2001；Sun *et al.*, 2010, 2011)。

中亚地区重要斑岩铜金矿床主体形成于古亚洲洋俯冲演化形成的增生岛弧环境(表1),这与环太平洋(尤其西南太平洋)地区斑岩铜金矿床形成环境相似。类似于西南太平洋地区岛弧斑岩铜金成矿系统在中亚成矿域也有明显表现,但中亚成矿域斑岩铜金成矿系统明显形成于大洋演化晚期或末期即将关闭出现的成熟岛弧环境(薛春纪等, 2015)。乌兹别克斯坦中天山南缘 Almalyk 矿集区即发育由5个世界级和大型斑岩铜金矿床、1个大型矽卡岩铅锌矿床和20余个高硫-低硫浅成低温热液金矿床,构成斑岩铜金多金属成矿系统(薛春纪等, 2014a, b, 2015),矿集区处在 Turkerstan 洋(Pt_3-C_3)向北向中天山之下俯冲形成的石炭纪 Beltau-Kurama 岛弧带(图2),成岩成矿年代学研究反映 Almalyk 矿集区铜金矿床均为晚石炭世(表1),形成于 Turkerstan 洋演化末期(~C_3)成熟岛弧环境。晚石炭世末期 Beltau-Kurama 成熟岛弧在吉尔吉斯斯坦中天山南缘形成 Makmal 超大型矽卡岩金矿床(~286Ma;表1、图2)。

Terskey 大洋寒武纪开始北向哈萨克斯坦-伊犁陆块俯冲,早奥陶世演化出 Kipchak 成熟岛弧带,伴随岛弧岩浆-热液过程形成吉尔吉斯斯坦 Taldy Bulak-Andash 大型斑岩铜金矿集区(475~455Ma；表1)和哈萨克斯坦 Bozshakol 超大型斑岩铜金矿床(~481Ma；表1)(图2)。Junggar-Balkhash 大洋(Pt_3-C_3)早古生代开始向南向哈萨克斯坦-伊犁、阿尔泰等陆块之下俯冲形成从哈萨克斯坦 Taldykurgan、向东经中国新疆博罗霍洛和大南湖-头苏泉到南蒙古 Gurvansayhan 十分壮观的志留-石炭纪增生岛弧带(即 Kazakh-Mongol 巨型岛弧带；Seltmann and Porter, 2005；Wainwright *et al.*, 2011；Yakubchuk, 2004),沿 Kazakh-Mongol 岛弧带发育 Aktogai(336~328Ma)、Kounrad(327~308Ma)、Koksai(~330Ma)、包古图(314~309Ma)、土屋-延东(323~322Ma)等众多大型-超大型斑岩铜金矿床和阿希、京希-伊尔曼德(图2)等构成的吐拉苏大型浅成低温热液金矿集区(~323Ma),这些重要矿床均为中-晚石炭世成矿,无疑是 Junggar-Balkhash 大洋演化末期成熟岛弧环境构造-岩浆-热液作用的产物。蒙古 Oyu Tolgoi 世界级斑岩铜金矿床也产在 Kazakh-Mongol 巨型岛弧带,但铜金成矿发生在晚泥盆世(372~366Ma；Wainwright *et al.*, 2011),此时岛弧成熟度明显较大规模铜金成矿的晚石炭世要低；哈萨克斯坦 Nurkazgan 斑岩铜金矿床(Cu 1.8Mt、Au 76t；表1)也处在 Junggar-Balkhash 大洋向南俯冲增生形成的 Kazakh-Mongol 岛弧带(Yakubchuk *et al.*, 2012；Seltmann *et al.*, 2014；图2),含矿花岗闪长斑岩和石英闪长斑岩形成于440~437Ma(Shen *et al.*, 2016),而早志留世 Kazakh-Mongol 岛弧刚刚开始发育,Nurkazgan 斑岩铜金矿床应形成于较 Oyu Tolgoi 矿床年轻的新生岛弧环境。可见,中亚成矿域斑岩铜金矿床在古亚洲洋演化形成不同时期、不同成熟度的增生岛弧带都有发育,但成熟岛弧环境无疑是中亚斑岩铜金成矿最为强烈最为重要的地质环境。

4.2 陆陆碰撞/后碰撞环境斑岩铜金成矿

大陆碰撞造山带斑岩铜金成矿潜力近年得到广泛关注(Hou and Cook, 2009；Hou *et al.*, 2009；Richards, 2009),特提斯-喜马拉雅成矿域在青藏高原东部玉龙成矿带和高原腹地的冈底斯成矿带是这类矿床的典型代表,形成于陆陆碰撞或后碰撞陆内伸展动力学背景(Hou *et al.*, 2009；Yang *et al.*, 2009),斑岩铜金成矿被认为与残留的古老洋壳或俯冲板片重熔并交代陆下岩石圈或下地壳有关(Richards, 2009, 2011；Shafiei *et al.*, 2009；Sillitoe, 2012)。中亚成矿域产于这种地质环境的斑岩铜金矿床鲜见报道。祁世军等(2015)认为中亚成矿域环 Balkhash 成矿省晚石炭世-早二叠世斑岩铜金矿床可能是后碰撞伸展阶段受挤压、拉伸和构造活化作用产物,尽管 Junggar-Balkhash 大洋最终关闭的确切时代尚存争议,但多数学者都一致同意该大洋在晚古生代末期已经关闭(Biske and Seltmann, 2010；Han *et al.*, 2010；Yakubchuk *et al.*, 2001；Yakubchuk, 2004),而与 Junggar-Balkhash 大洋俯冲增生有关的 Kazakh-Mongol 岛弧带经过从志留纪到晚石炭世-早二叠世演化发育,已经十分成熟。因此,我们认为环 Balkhash 成矿省336~309Ma 的斑岩铜金矿床(表1)仍然是 Junggar-Balkhash 大洋演化末期的成熟岛弧环境岛弧岩浆-热液活动的产物。

最近,在中国新疆阿尔泰东南缘哈腊苏矿床,研究揭示出从洋陆俯冲增生到陆陆碰撞、后碰撞不同时期多期岩浆-热液叠加斑岩铜矿金成矿作用(Xue *et al.*, 2015)。哈腊苏铜矿床处在 Junggar-Balkhash 大洋俯冲形成的 Kazakh-Mongol 岛弧带中部(图2),铜金矿体呈透镜状和不规则状产在含铜蚀变斑岩体(花岗闪长斑岩、斑状花岗岩、石英二长斑岩和石英闪长斑岩)中,热液蚀变从岩体向外呈现出钾硅酸盐化、黑云母绿泥石化、青磐岩化的分带趋势,铜金矿化以细脉浸染状产出的黄铁矿+黄铜矿+辉钼矿为主并常被后期石英+黄铜矿+黄铁矿脉体叠加形成脉状叠加型矿石。锆石 U-Pb 法测年在哈腊苏矿区揭示出从中泥盆世(斑状花岗岩、381.6±2.5Ma;花岗闪长斑岩、371.8±9.6Ma)到早二叠世(石英二长斑岩、265.6±3.7Ma)和晚三叠世(石英闪长斑岩、215.8±4.6Ma)多期含铜蚀变斑岩体,金铜矿石辉钼矿 Re-Os 法和钾长石$^{40}Ar/^{39}Ar$测得与斑岩体多期幕式侵位相对应的矿化

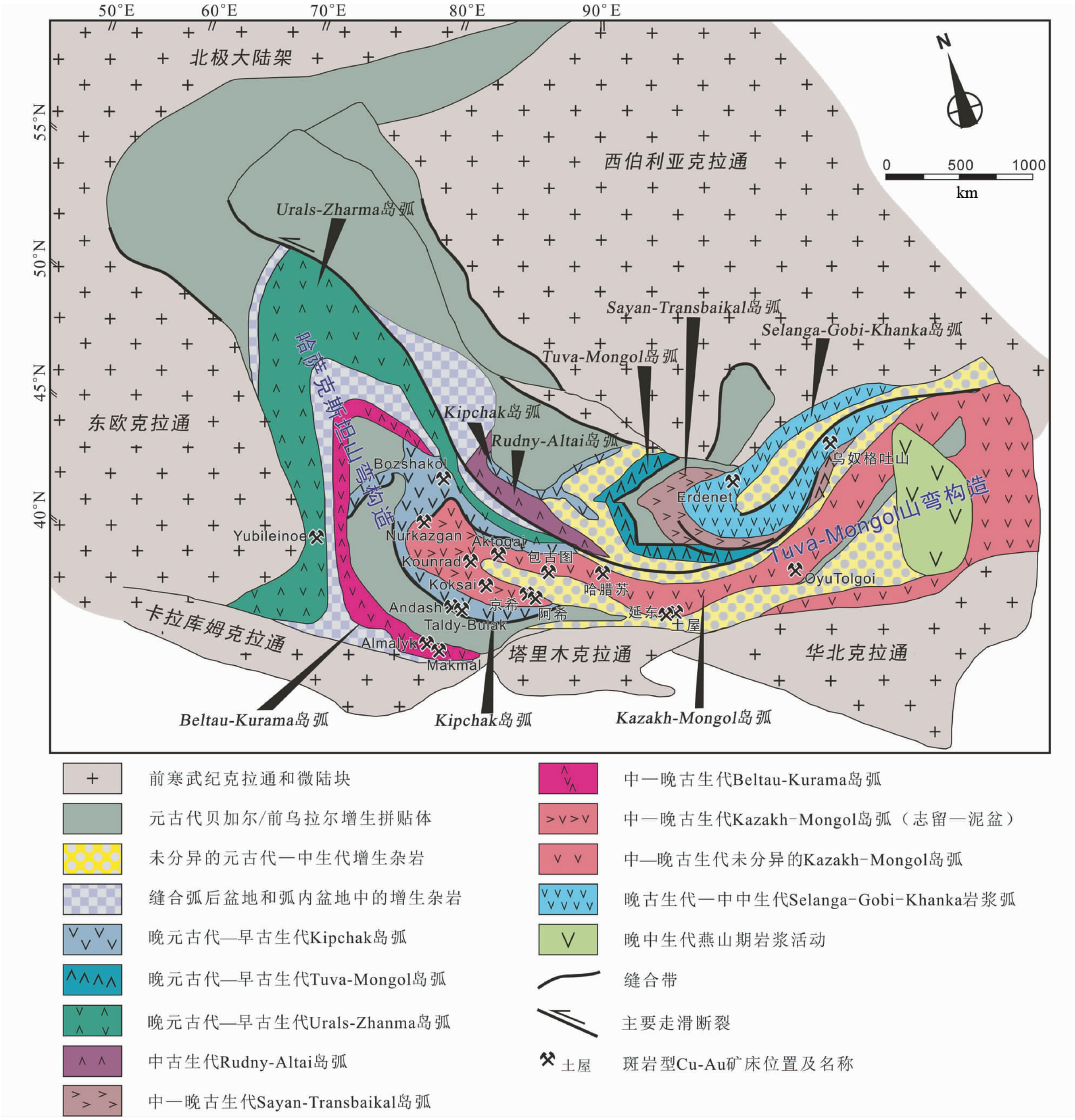

图2 中亚成矿域古生代构造古地理图及斑岩铜金矿床和岛弧带分布(据 Yakubchuk, 2005; Seltmann *et al.*, 2014 修编)

Fig. 2 Schematic map-view diagram showing the distribution of major porphyry Cu-Au deposits and island-arcs of the Central Asia Metallogenic Domain in the context of tectonics (modified after Yakubchuk, 2005; Seltmann *et al.*, 2014)

蚀变年龄,分别为 376.9 ± 2.2Ma、269.2 ± 3.2Ma 和 198.4 ± 2.3Ma(Xue *et al.*, 2015),哈腊苏斑岩铜矿床多期构造-岩浆-热液矿化蚀变跨越了洋陆俯冲增生、陆陆碰撞和后碰撞等不同构造时期,在时间上跨越了大约 160 ~ 180Ma,显示中亚成矿域斑岩铜金成矿多期叠加多阶段复合成矿的特色,也暗示陆陆碰撞/后碰撞伸展环境斑岩铜金找矿在中亚地区值得重视。

4.3 问题和前景

与环太平洋成矿域俯冲型和特提斯-喜马拉雅碰撞型造山不同,中亚成矿域是典型的增生型造山,经历了增生和碰撞不同时期和不同性质的造山过程(Şengör *et al.*, 1993; Windley *et al.*, 2007; Xiao *et al.*, 2009, 2010; 薛春纪等, 2014a),与这一漫长地质演化过程对应,中亚成矿域在俯冲增生、陆陆碰撞/后碰撞伸展等不同地质环境均发生了斑岩

铜金成矿，但古亚洲洋增生演化末期出现的成熟岛弧环境在中亚地区斑岩铜金成矿作用中尤为显著。中亚大型-超大型斑岩铜金成矿为何在成熟岛弧环境大量产出还不清楚，重要斑岩铜金矿床是否与某些特殊的构造机制有关还需深入研究。环太平洋成矿域的研究认为大洋板块俯冲的角度对斑岩铜金矿床形成具有明显控制作用(Mitchell, 1973)，许多巨型斑岩铜金矿床形成都与无震洋脊、洋隆和海底高原的低角度平坦俯冲有关(Cooke *et al.*, 2005)，而新近纪以来的大规模斑岩铜金成矿作用被认为与洋壳高浮力块体俯冲有关(Thorkelson, 1996; 陈华勇和肖兵, 2014)，很多巨型和超大型斑岩铜金矿床都与正在俯冲的洋中脊在构造位置上吻合(Sun *et al.*, 2010)。中亚成矿域很多地区都发现可能是洋中脊俯冲产物的埃达克富 Nb 岛弧火山岩、高 Mg 安山岩、玄武岩等洋壳岩石组合，如中国新疆西准噶尔(Tang *et al.*, 2010)、新疆天山北部(Niu *et al.*, 2006; 王强等, 2006)，但这些地区已发现的斑岩铜金矿床是否与这些可能的洋中脊构造有关还不明确。

美国地质调查局最近发布了《中亚西部斑岩铜矿床评估》，在中亚西段的乌兹别克斯坦、吉尔吉斯斯坦、塔吉克斯坦、哈萨克斯坦等国预测出 25 处隐伏的巨型和超大型斑岩铜金矿床，潜在铜资源量约 9500 万吨，是该区域当前已发现斑岩铜矿总储量的 1.8 倍(5400 万吨)(Berger *et al.*, 2014)，找矿潜力巨大。中亚成矿域在境外西天山、南蒙古、中国新疆西准、东准和东天山都有重要斑岩铜金矿床发现，而中国新疆西天山至今未发现大型斑岩铜金矿床。西天山区域地壳结构、古生代增生岛弧形成及演化、构造带的延伸和成矿带展布在境内外均具有可对接性和可对比性(薛春纪等, 2014a, b, 2015)，新疆西天山斑岩铜金找矿重大突破令人期待。中亚斑岩铜金矿床主体形成于古亚洲洋演化形成的增生岛弧环境，新疆西天山不同时期、不同位置发育的古岛弧区(北天山北缘博罗霍洛早泥盆-晚石炭世岛弧、北天山南缘伊什基里克晚泥盆-晚石炭世岛弧、中天山南缘巴音布鲁克奥陶-志留纪岛弧)斑岩铜金找矿值得高度关注；类似于 Beltau-Kurama 成熟岛弧环境产出的乌兹别克斯坦 Almalyk 斑岩铜成矿系统在新疆博罗霍洛岛弧带西段吐拉苏地区也有明显表现(表 1; Zhao *et al.*, 2014a, b;薛春纪等,2013b)，吐拉苏是值得高度重视的斑岩铜金找矿靶区；新疆中天山南缘巴音布鲁克岛弧带广泛出露富铜中基性岛弧火山建造和中酸性浅成-超浅成侵入的岩脉及相关脉状铜矿化(薛春纪等, 2014a, b, 2015)，反映出良好的斑岩铜金找矿潜力。新疆阿尔泰哈腊苏斑岩铜金矿床多期叠加多阶段复合成矿特征也提示人们，在增生岛弧环境应重视碰撞/后碰撞环境斑岩铜金矿床，而碰撞/后碰撞伸展环境、先期形成的增生岛弧环境中斑岩铜金找矿值得重视(Xue *et al.*, 2015)。

5 初步认识

中亚成矿域在俯冲增生、陆陆碰撞/后碰撞伸展等不同地质环境均可形成斑岩铜金矿床，但是，古亚洲演化不同时期的增生岛弧是中亚斑岩铜金最为重要的成矿环境，大规模斑岩铜金成矿出现在洋盆演化末期的成熟岛弧环境。

在成矿环境方面，中亚斑岩铜金成矿为何更多在成熟岛弧是值得深入研究的科学问题。新疆北部、尤其天山斑岩铜金成矿条件优越，成矿和找矿潜力巨大，有望持续发现重要斑岩铜金矿床。

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References

Alexeiev DV, Ryazantsev AV, Kröner A, Tretyakov AA, Xia X and Liu DY. 2011. Geochemical data and zircon ages for rocks in a high-pressure belt of Chu-Yili Mountains, southern Kazakhstan: Implications for the earliest stages of accretion in Kazakhstan and the Tianshan. Journal of Asian Earth Sciences, 42(5): 805 – 820

An F and Zhu YF. 2008. Study on trace elements geochemistry and SHRIMP chronology of volcanic rocks in Tulasu Basin, Northwest Tianshan. Acta Petrologica Sinica, 24(12): 2741 – 2748 (in Chinese with English abstract)

An F, Zhu YF, Wei SN and Lai SC. 2013. An Early Devonian to Early Carboniferous volcanic arc in North Tianshan, NW China: Geochronological and geochemical evidence from volcanic rocks. Journal of Asian Earth Sciences, 78: 100 – 113

Bazhenov ML, Collins AQ, Degtyarev KE, Levashova NM, Mikolaichuk AV, Pavlov VE and Van der Voo R. 2003. Paleozoic northward drift of the North Tien Shan (Central Asia) as revealed by Ordovician and Carboniferous paleomagnetism. Tectonophysics, 366(1 – 2): 113 – 141

Berger BR, Mars JC, Denning PD, Phillips JD, Hammarstrom JM, Zientek ML, Dicken CL and Drew LJ. 2014. Porphyry copper assessment of western Central Asia: U. S. Geological Survey Scientific Investigations Report 2010-5090-N, 8 Plates, and Spatial Data. 219, http://dx.doi.org/10.3133/sir20105090N

Biske YS and Seltmann R. 2010. Paleozoic Tian-Shan as a transitional region between the Rheic and Urals-Turkestan oceans. Gondwana Research, 17(2 – 3): 602 – 613

Bonev IK, Petrunov R, Cook NJ and Ciobanu CL. 2005. Kostovite and its argentian varieties: Deposits and mineral associations. Geochemistry, Mineralogy and Petrology, 42: 1 – 22

Chen HY and Xiao B. 2014. Metallogenesis of subduction zone: The progress and future. Earth Science Frontiers, 21(5): 13 – 22 (in Chinese with English abstract)

Chen XH, Seitmuratova E, Wang ZH, Chen ZL, Han SQ, Li Y, Yang Y, Ye BY and Shi W. 2014. SHRIMP U-Pb and Ar-Ar geochronology of major porphyry and skarn Cu deposits in the Balkhash Metallogenic Belt, Central Asia, and geological implications. Journal of Asian Earth Sciences, 79(Part B): 723 – 740

Chernyshev IV, Kovalenker VA, Goltsman YV, Plotinskaya OY, Bairova ED and Oleinikova TI. 2011. Rb-Sr isochron dating of late paleozoic epithermal ore-forming processes: A case study of the Kairagach gold deposit, Kurama ore district, Central Tien Shan. Geochemistry International, 49(2): 107 – 119

Cooke DR, Hollings P and Walshe JL. 2005. Giant porphyry deposits: Characteristics, distribution, and tectonic controls. Economic Geology, 100(5): 801 – 818

Cooke DR, Hollings P and Chang Z. 2011. Philippine porphyry and epithermal deposits: An introduction. Economic Geology, 106(8): 1253 – 1256

Deckart K, Silva W, Spröhnle C and Vela I. 2014. Timing and duration of hydrothermal activity at the Los Bronces porphyry cluster: An update. Mineralium Deposita, 49(5): 535 – 546

Foley S, Tiepolo M and Vannucci R. 2002. Growth of early continental crust controlled by melting of amphibolite in subduction zones. Nature, 417(6891): 837 – 840

Gao J, Long LL, Klemd R, Qian Q, Liu DY, Xiong XM, Su W, Liu W, Wang YT and Yang FQ. 2009. Tectonic evolution of the South Tianshan orogen and adjacent regions, NW China: Geochemical and age constraints of granitoid rocks. International Journal of Earth Sciences, 98(6): 1221 – 1238

Gao J, Qian Q, Long LL, Zhang X, Li JL and Su W. 2009. Accretionary orogenic process of Western Tianshan, China. Geological Bulletin of China, 28(12): 1804 – 1816 (in Chinese with English abstract)

Goldfarb RJ, Taylor RD, Collins GS, Goryachev NA and Orlandini OF. 2014. Phanerozoic continental growth and gold metallogeny of Asia. Gondwana Research, 25(1): 48 – 102

Golovanov I, Seltmann R, Kremenetsky A and Porter T. 2005. The porphyry Cu-Au/Mo deposits of Central Eurasia: 2. The Almalyk (Kal'makyr-Dalnee) and Saukbulak Cu-Au porphyry systems, Uzbekistan. In: Porter TM (ed.). Super Porphyry Copper and Gold deposit: A Golobal Prospective. Adelaide: PGC Publlishing, Vol. 2: 513 – 523

Han BF, Guo ZJ, Zhang ZC, Zhang L, Chen JF and Song B. 2010. Age, geochemistry, and tectonic implications of a Late Paleozoic stitching pluton in the North Tian Shan suture zone, western China. Geological Society of American Bulletin, 122(3 – 4): 627 – 640

Han CM, Xiao WJ, Zhao GC, Mao JW, Yang JM, Wang ZL, Yan Z and Mao QG. 2006. Geological characteristics and genesis of the Tuwu porphyry copper deposit, Hami, Xinjiang, Central Asia. Ore Geology Reviews, 29(1): 77 – 94

Hedenquist JW, Arribas A and Reynolds TJ. 1998. Evolution of an intrusion-centered hydrothermal system: Far Southeast-Lepanto porphyry and epithermal Cu-Au deposits, Philippines. Economic Geology, 93(4): 373 – 404

Hou ZQ, Zeng PS, Gao YF, Du AD and Fu DM. 2006. Himalayan Cu-Mo-Au mineralization in the eastern Indo-Asian collision zone: Constraints from Re-Os dating of molybdenite. Mineralium Deposita, 41(1): 33 – 45

Hou ZQ and Cook NJ. 2009. Metallogenesis of the Tibetan collisional orogen: A review and introduction to the special issue. Ore Geology Reviews, 36(1 – 3): 2 – 24

Hou ZQ, Yang ZM, Qu XM, Meng XJ, Li ZQ, Beaudoin G, Rui ZY, Gao YF and Zaw K. 2009. The Miocene Gangdese porphyry copper belt generated during post-collisional extension in the Tibetan Orogen. Ore Geology Reviews, 36(1 – 3): 25 – 51

Hou ZQ, Zhang HR, Pan XF and Yang ZM. 2011. Porphyry Cu (-Mo-Au) deposits related to melting of thickened mafic lower crust: Examples from the eastern Tethyan metallogenic domain. Ore Geology Reviews, 39(1 – 2): 21 – 45

Jenchuraeva RJ. 1997. Tectonic settings of porphyry-type mineralization and hydrothermal alteration in Paleozoic island arcs and active continental margins, Kyrghyz Range, (Tien Shan) Kyrghyzstan. Mineralium Deposita, 32(5): 434 – 440

Jenchuraeva RJ, Pak NT and Usmanov IA. 2001. The Makmal gold deposit. In: Seltmann R and Jenchuraeva RJ (eds.). Paleozoic Geodynamics and Gold Deposits in the Kyrgyz Tien Shan. IGCP-373 Excursion Guidebook. London: International Association on the Genesis of Ore Deposits, 82 – 96

Khashgerel BE, Rye RO, Hedenquist JW and Kavalieris I. 2006. Geology and reconnaissance stable isotope study of the Oyu Tolgoi porphyry Cu-Au system, South Gobi, Mongolia. Economic Geology, 101(3): 503 – 522

Kirwin DJ, Forster CN, Kavalieris I, Crane D, Orssich C, Panther C, Garamjav D, Munkhbat TO and Niislelkhuu G. 2005. The Oyu Tolgoi copper-gold porphyry deposits, South Gobi, Mongolia. In: Seltmann R, Gerel O and Kirwin DJ (eds.). Geodynamics and Metallogeny of Mongolia with a Special Emphasis on Copper and Gold Deposits. London: International Association on the Genesis of Ore Deposits, 155 – 168

Konopelko D, Biske G, Seltmann R, Kiseleva M, Matukov D and Sergeev S. 2008. Deciphering Caledonian events: Timing and geochemistry of the Caledonian magmatic arc in the Kyrgyz Tien Shan. Journal of Asian Earth Sciences, 32(2 – 4): 131 – 141

Konopelko D, Kullerud K, Apayarov F, Sakiev K, Baruleva O, Ravna E and Lepekhina E. 2012. SHRIMP zircon chronology of HP-UHP rocks of the Makbal metamorphic complex in the Northern Tien Shan, Kyrgyzstan. Gondwana Research, 22(1): 300 – 309

Kröner A, Windley BF, Badarch G, Tomurtogoo O, Hegner E, Jahn B, Gruschka S, Khain E, Demoux A and Wingate MTD. 2007. Accretionary growth and crust formation in the Central Asian Orogenic Belt and comparison with the Arabian-Nubian shield. Geological Society of America Memoirs, 200: 181 – 209

Kröner A, Alexeiev DV, Rojas-Agramonte Y, Hegner E, Wong J, Xia X, Belousova E, Mikolaichuk AV, Seltmann R, Liu D and Kiselev VV. 2013. Mesoproterozoic (Grenville-age) terranes in the Kyrgyz North Tianshan: Zircon ages and Nd-Hf isotopic constraints on the origin and evolution of basement blocks in the southern Central Asian Orogen. Gondwana Research, 23(1): 272 – 295

Kröner A, Kovach V, Belousova E, Hegner E, Armstrong R, Dolgopolova A, Seltmann R, Alexeiev DV, Hoffmann JE, Wong J, Sun M, Cai K, Wang T, Tong Y, Wilde SA, Degtyarev KE and Rytsk E. 2014. Reassessment of continental growth during the accretionary history of the Central Asian Orogenic Belt. Gondwana Research, 25(1): 103 – 125

Kudryavtsev YK. 1996. The Cu-Mo deposits of Central Kazakhstan. In: Shatov V, Seltmann R, Kremenetsky A, Lehmann B, Popov V and Ermolov P (eds.). Granite-Related Ore Deposits of Central Kazakhstan and Adjacent Areas. St. Petersburg: Global Publishing House, 119 – 144

Leveille RA and Stegen RJ. 2012. The southwestern North America porphyry copper province. In: Hedenquist JW, Harris M and Camus F (eds.). Geology and Genesis of Major Copper Deposits and Districts of the World: A Tribute to Richard H. Sillitoe. Littleton, CO: Society of Economic Geologists, 16: 361 – 401

Liu DQ, Chen YC, Wang DH, Tang YL, Zhou RH, Wang JL, Li HQ and Chen FW. 2003. A discussion on problems related to mineralization of Tuwu-Yandong Cu-Mo orefield in Hami, Xinjiang. Mineral Deposits, 22(4): 334 – 344 (in Chinese with English abstract)

Lomize MG, Demina LI and Zarshchikov AA. 1997. The Kyrgyz-Terskei Paleoceanic Basin, Tien Shan. Geotectonics, 31(6): 463 – 482

Long LL, Gao J, Klemd R, Beier C, Qian Q, Zhang X, Wang JB and Jiang T. 2011. Geochemical and geochronological studies of granitoid rocks from the Western Tianshan Orogen: Implications for continental growth in the southwestern Central Asian Orogenic Belt. Lithos, 126(3 – 4): 321 – 340

Lowell JD and Guilbert JM. 1970. Lateral and vertical alteration-mineralization zoning in porphyry ore deposits. Economic Geology, 65(4): 373 – 408

Mao JW, Pirajno F, Lehmann B, Luo MC and Berzina A. 2014. Distribution of porphyry deposits in the Eurasian continent and their corresponding tectonic settings. Journal of Asian Earth Sciences, 79: 576 – 584

McCann T, Nurtaev B, Kharin V and Valdivia-Manchego M. 2013. Ordovician-Carboniferous tectono-sedimentary evolution of the North Nuratau region, Uzbekistan (Westernmost Tien Shan). Tectonophysics, 590: 196 – 213

Mikolaichuk AV, Kurenkov SA, Degtyarev KE and Rubtsov VI. 1997. Northern Tien Shan: Main stages of geodynamic evolution in the Late Precambrian-Early Paleozoic. Geotectonics, 31(6): 445 – 462

Mirkamalov RK, Isokov MU, Chirikin VV, Kharin VG and Khan RS. 2012. New results of U-Pb (SHRIMP) dating of grannitoid and metamorphic complexes of Tien Shan folded belt. In: Akbarov KA and Nurtaev BS (eds.). Geosciences in Uzbekistan (Special volume for ICG34): 115－125

Mitchell AHG. 1973. Metallogenic belts and angle of dip of Benioff zones. Nature, 245(143): 49－52

Nie FJ, Jiang SH, Zhang Y, Liu Y and Hu P. 2004. Geological features and origin of porphyry copper deposits in China-Mongolia border region and its neighboring areas. Mineral Deposits, 23(2): 176－189 (in Chinese with English abstract)

Niu HC, Sato H, Zhang HX, Ito JI, Yu XY, Nagao T, Terada K and Zhang Q. 2006. Juxtaposition of adakite, boninite, high-TiO_2 and low-TiO_2 basalts in the Devonian southern Altay, Xinjiang, NW China. Journal of Asian Earth Sciences, 28(4－6): 439－456

Nurtaev B, Kharin V, McCann T and Valdivia-Manchego M. 2013. The north Nuratau fault zone, Uzbekistan-structure and evolution of a Palaeozoic suture zone. Journal of Geodynamics, 64: 1－14

Oyarzun R, Márquez A, Lillo J, López I and Rivera S. 2001. Giant versus small porphyry copper deposits of Cenozoic age in northern Chile: Adakitic versus normal calc-alkaline magmatism. Mineralium Deposita, 36(8): 794－798

Pašava J, Vymazalová A, Košler J, Koneev RI, Jukov AV and Khalmatov RA. 2010. Platinum-group elements in ores from the Kalmakyr porphyry Cu-Au-Mo deposit, Uzbekistan: Bulk geochemical and laser ablation ICP-MS data. Mineralium Deposita, 45(5): 411－418

Perelló J, Cox D, Garamjav D, Sanjdorj S, Diakov S, Schissel D, Munkhbat TO and Oyun G. 2001. Oyu Tolgoi, Mongolia: Siluro-Devonian porphyry Cu-Au-(Mo) and high-sulfidation Cu mineralization with a Cretaceous chalcocite blanket. Economic Geology, 96(6): 1407－1428

Porter TM. 2015. The geology, structure and mineralisation of the Oyu Tolgoi porphyry copper-gold-molybdenum deposits, Mongolia: A review. Geoscience Frontiers, doi:10.1016/j.gsf.2015.08.003

Qi SJ, Cheng SD, Gao P, Wang DL, Huang QF, Huang C, Song ZQ, Fang QX and Qiu RZ. 2015. Comparison of Metallogenic Conditions of the Balkhash-Junggar Porphyry Copper Belt, China-Kazakhstan. Beijing: Geological Publishing House, 1－237 (in Chinese)

Qian Q, Gao J, Klemd R, He GQ, Song B, Liu DY and Xu RH. 2009. Early Paleozoic tectonic evolution of the Chinese South Tianshan Orogen: Constraints from SHRIMP zircon U-Pb geochronology and geochemistry of basaltic and dioritic rocks from Xiate, NW China. International Journal of Earth Sciences, 98(3): 551－569

Qin KZ, Su BX, Sakyi PA, Tang DM, Li XH, Sun H, Xiao QH and Liu PP. 2011. SIMS zircon U-Pb geochronology and Sr-Nd isotopes of Ni-Cu-bearing mafic-ultramafic intrusions in eastern Tianshan and Beishan in correlation with flood basalts in Tarim Basin (NW China): Constraints on a ca. 280Ma mantle plume. American Journal of Science, 311(3): 237－260

Richards JP. 2009. Postsubduction porphyry Cu-Au and epithermal Au deposits: Products of remelting of subduction-modified lithosphere. Geology, 37(3): 247－250

Richards JP. 2011. Magmatic to hydrothermal metal fluxes in convergent and collided margins. Ore Geology Reviews, 40(1): 1－26

Rui ZY, Wang LS, Wang YT and Liu YL. 2002. Discussion on metallogenic epoch of Tuwu and Yandong porphyry copper deposits in Eastern Tianshan Mountains, Xinjiang. Mineral Deposits, 21(1): 16－22 (in Chinese with English abstract)

Seltmann R and Porter TM. 2005. The porphyry Cu-Au/Mo deposits of Central Eurasia: 1. Tectonic, geologic, and metallogenic setting and significant deposits. In: Porter TM (ed.). Super Porphyry Copper and Gold Deposit: A Global Perspective. Adelaide: PGC Publishing, 2: 467－512

Seltmann R, Konopelko D, Biske G, Divaev F and Sergeev S. 2011. Hercynian post-collisional magmatism in the context of Paleozoic magmatic evolution of the Tien Shan orogenic belt. Journal of Asian Earth Sciences, 42(5): 821－838

Seltmann R, Porter TM and Pirajno F. 2014. Geodynamics and metallogeny of the central Eurasian porphyry and related epithermal mineral systems: A review. Journal of Asian Earth Sciences, 79: 810－841

Şengör AMC, Natal'In BA and Burtman VS. 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. Nature, 364(6435): 299－307

Şengör AMC and Natal'In BA. 1996. Paleotectonics of Asia: Fragments of a synthesis. In: Yin A and Harrison TM (eds.). The Tectonic Evolution of Asia. Cambridge: Cambridge University Press, 486－640

Shafiei B, Haschke M and Shahabpour J. 2009. Recycling of orogenic arc crust triggers porphyry Cu mineralization in Kerman Cenozoic arc rocks, southeastern Iran. Mineralium Deposita, 44(3): 265－283

Shen P, Shen YC, Pan HD, Wang JB, Zhang R and Zhang YX. 2010. Baogutu porphyry Cu-Mo-Au deposit, West Junggar, Northwest China: Petrology, alteration, and mineralization. Economic Geology, 105(5): 947－970

Shen P, Shen YC, Pan HD, Li XH, Dong LH, Wang JB, Zhu HP, Dai HW and Guan WN. 2012. Geochronology and isotope geochemistry of the Baogutu porphyry copper deposit in the West Junggar region, Xinjiang, China. Journal of Asian Earth Sciences, 49: 99－115

Shen P, Pan HD and Dong LH. 2014a. Yandong porphyry Cu deposit, Xinjiang, China-Geology, geochemistry and SIMS U-Pb zircon geochronology of host porphyries and associated alteration and mineralization. Journal of Asian Earth Sciences, 80: 197－217

Shen P, Pan HD, Zhou TF and Wang JB. 2014b. Petrography, geochemistry and geochronology of the host porphyries and associated alteration at the Tuwu Cu deposit, NW China: A case for increased depositional efficiency by reaction with mafic host rock? Mineralium Deposita, 49(6): 709－731

Shen P, Pan HD and Seitmuratova E. 2015. Characteristics of the porphyry Cu deposits in the Central Asia Metallogenic Domain. Acta Petrologica Sinica, 31(2): 315－332 (in Chinese with English abstract)

Shen P, Pan HD, Seitmuratova E and Jakupova S. 2016. U-Pb zircon, geochemical and Sr-Nd-Hf-O isotopic constraints on age and origin of the ore-bearing intrusions from the Nurkazgan porphyry Cu-Au deposit in Kazakhstan. Journal of Asian Earth Sciences, 116: 232－248

Sillitoe RH. 1997. Characteristics and controls of the largest porphyry copper-gold and epithermal gold deposits in the circum-Pacific region. Australian Journal of Earth Sciences, 44(3): 373－388

Sillitoe RH. 2010. Porphyry copper systems. Economic Geology, 105(1): 3－41

Sillitoe RH. 2012. Copper province. In: Hedenquist JW, Harris M and Camus F (eds.). Geology and Genesis of Major Copper Deposits and Districts of the World: A Tribute to Richard H. Sillitoe. Littleton, CO: Society of Economic Geologists, 1－18

Singer DA, Berger VI and Moring BC. 2005. Porphyry copper deposits of the world: Database, map, and grade and tonnage models. Open-File Report 2005－1060. Menlo Park, Calif. USA: US Geological Survey

Sun WD, Ling MX, Yang XY, Fan WM, Ding X and Liang HY. 2010. Ridge subduction and porphyry copper-gold mineralization: An overview. Science China (Earth Sciences), 53(4): 475－484

Sun WD, Zhang H, Ling MX, Ding X, Chung SL, Zhou JB, Yang XY and Fan WM. 2011. The genetic association of adakites and Cu-Au ore deposits. International Geology Review, 53(5－6): 691－703

Tang GJ, Wang Q, Wyman DA, Li ZX, Zhao ZH, Jia XH and Jiang ZQ. 2010. Ridge subduction and crustal growth in the Central Asian Orogenic Belt: Evidence from Late Carboniferous adakites and high-Mg diorites in the western Junggar region, northern Xinjiang (west China). Chemical Geology, 277(3－4): 281－300

Thorkelson DJ. 1996. Subduction of diverging plates and the principles of slab window formation. Tectonophysics, 255(1－2): 47－63

Tu GC. 1999. On the Central Asia metallogenic province. Scientia Geologica Sinica, 34(4): 397－404 (in Chinese with English abstract)

Wainwright AJ, Tosdal RM, Wooden JL, Mazdab FK and Friedman RM.

2011. U-Pb (zircon) and geochemical constraints on the age, origin, and evolution of Paleozoic arc magmas in the Oyu Tolgoi porphyry Cu-Au district, southern Mongolia. Gondwana Research, 19(3): 764-787

Wang B, Shu LS, Cluzel D, Faure M and Charvet J. 2007. Geochemical constraints on Carboniferous volcanic rocks of the Yili Block (Xinjiang, NW China): Implication for the tectonic evolution of Western Tianshan. Journal of Asian Earth Sciences, 29(1): 148-159

Wang Q, Zhao ZH, Xu JF, Wyman DA, Xiong XL, Zi F and Bai ZH. 2006. Carboniferous adakite-high-Mg and andesite-Nb-enriched basaltic rock suites in the Northern Tianshan area: Implications for Phanerozoic crustal growth in the Central Asia orogenic belt and Cu-Au mineralization. Acta Petrologica Sinica, 22(1): 11-30 (in Chinese with English abstract)

Wang YH, Xue CJ, Liu JJ, Wang JP, Yang JT, Zhang FF, Zhao ZN, Zhao YJ and Liu B. 2015a. Early Carboniferous adakitic rocks in the area of the Tuwu deposit, eastern Tianshan, NW China: Slab melting and implications for porphyry copper mineralization. Journal of Asian Earth Sciences, 103: 332-349

Wang YH, Xue CJ, Wang JP, Peng RM, Yang JT, Zhang FF, Zhao ZN and Zhao YJ. 2015b. Petrogenesis of magmatism in the Yandong region of Eastern Tianshan, Xinjiang: Geochemical, geochronological and Hf isotope Constraints. International Geology Review, 57(9-10): 1130-1151

Waters PJ, Cooke DR, Gonzales RI and Phillips D. 2011. Porphyry and epithermal deposits and $^{40}Ar/^{39}Ar$ geochronology of the Baguio district, Philippines. Economic Geology, 106(8): 1335-1363

Wilhem C, Windley BF and Stampfli GM. 2012. The Altaids of Central Asia: A tectonic and evolutionary innovative review. Earth-Science Reviews, 113(3-4): 303-341

Windley BF, Alexeiev D, Xiao WJ, Kröner A and Badarch G. 2007. Tectonic models for accretion of the Central Asian Orogenic Belt. Journal of the Geological Society, 164(1): 31-47

Xiao WJ, Zhang LC, Qin KZ, Sun S and Li JL. 2004. Paleozoic accretionary and collisional tectonics of the Eastern Tianshan (China): Implications for the continental growth of Central Asia. American Journal of Science, 304(4): 370-395

Xiao WJ, Kröner A and Windley B. 2009. Geodynamic evolution of Central Asia in the Paleozoic and Mesozoic. International Journal of Earth Sciences, 98(6): 1185-1188

Xiao WJ, Huang BC, Han CM, Sun S and Li JL. 2010. A review of the western part of the Altaids: A key to understanding the architecture of accretionary orogens. Gondwana Research, 18(2-3): 253-273

Xue CJ, Qi SJ and Kui HM. 2007. Essentials of Mineral Deposits. Beijing: Geological Publishing House, 1-230 (in Chinese)

Xue CJ, Duan SG, Chai FM, Muhetaer MMT, Туресебеков AX and Qu WJ. 2013a. Metallogenetic epoch of the Almalyk porphyry copper ore field, Uzbekistan, and its geological significance. Earth Science Frontiers, 20(2): 197-204 (in Chinese with English abstract)

Xue CJ, Wang HG, Zhao XB and Chen LY. 2013b. Kexiaxi cluster of small intrusions in the Tulasu gold mineralization district, Western Tianshan, Xinjiang and its copper exploration prospect. Earth Science Frontiers, 20(6): 180-194 (in Chinese with English abstract)

Xue CJ, Zhao XB, Mo XX, Chen YC, Dong LH, Gu XX, Zhang ZC, Nurtaev B, Pak N, Li ZD, Wang XL, Zhang GZ, Yalikun Y, Feng B, Zu B and Liu JY. 2014a. Tectonic-metallogenic evolution of western Tianshan giant Au-Cu-Zn-Pb metallogenic belt and prospecting orietation. Acta Geologica Sinica, 88(12): 2490-2531 (in Chinese with English abstract)

Xue CJ, Zhao XB, Mo XX, Dong LH, Gu XX, Nurtaev B, Pak N, Zhang ZC, Wang XL, Zu B, Zhang GZ, Feng B and Liu JY. 2014b. Asian Gold Belt in western Tianshan and its dynamic setting, metallogenic control and exploration. Earth Science Frontiers, 21(5): 128-155 (in Chinese with English abstract)

Xue CJ, Chi GX, Zhao XB, Wu GG, Zhao ZF and Dong LH. 2015. Multiple and prolonged porphyry Cu-Au mineralization and alteration events in the Halasu deposit, Chinese Altai, Xinjiang, northwestern China. Geoscience Frontiers, doi: 10.1016/j.gsf.2015.10.008

Xue CJ, Zhao XB, Zhang GZ, Mo XX, Gu XX, Dong LH, Zhao SM, Mi DJ, Nurtaev B, Pak N, Li ZD, Wang XL, Zu B, Yalikun Y and Feng B. 2015. Metallogenic Environments, ore-forming types and prospecting potential of Au-Cu-Zn-Pb resources in Western Tian Shan Mountains. Geology in China, 42(3): 381-410 (in Chinese with English abstract)

Yakubchuk A, Seltmann R, Shatov V and Cole A. 2001. The Altaids: Tectonic evolution and metallogeny. Soc. Econ. Geol. Newsl., 46: 6-14

Yakubchuk A. 2004. Architecture and mineral deposit settings of the Altaid orogenic collage: A revised model. Journal of Asian Earth Sciences, 23(5): 761-779

Yakubchuk A. 2005. Geodynamic evolution of accreted terranes of Mongolia against the background of the Altaid and Transbaikal-Mongolian collages. In: Seltmann RG, Gerel O and Kirwin DJ (eds.). Geodynamics and Metallogeny of Mongolia with Special Emphasis on Copper and Gold Deposits. Guidebook Series 11. London: Centre for Russian and Central EurAsian Mineral Studies, 13-24

Yakubchuk A, Schloderer J, Woodcock J and Wurst A. 2010. Taldybulak Au-Cu-Mo deposit: A new >5 Moz Au (11.7 Moz Au eq) Ordovician porphyry hosted gold system in Kyrgyzstan, Central Asia. Applied Earth Science, Transactions of the Institute of Mining and Metallurgy, Section B, 119(2): 84

Yakubchuk A, Degtyarev K, Maslennikov V, Wurst A, Stekhin A and Lobanov KV. 2012. Tectonomagmatic settings, architecture, and metallogeny of the Central Asian Copper Province. In: Hedenquist JW, Harris M and Camus F (eds.). Geology and Genesis of Major Copper Deposits and Districts of the World: A Tribute to Richard H. Sillitoe. Society of Economic Geologists, Inc. Special Publication, 16: 403-432

Yang ZM, Hou ZQ, White NC, Chang ZS, Li ZQ and Song YC. 2009. Geology of the post-collisional porphyry copper-molybdenum deposit at Qulong, Tibet. Ore Geology Reviews, 36(1-3): 133-159

Zhai W, Sun XM, Gao J, He XP, Liang JL, Miao LC and Wu YL. 2006. SHRIMP dating of zircons from volcanic host rocks of Dahalajunshan Formation in Axi gold deposit, Xinjiang, China, and its geological implications. Acta Petrologica Sinica, 22(5): 1399-1404 (in Chinese with English abstract)

Zhai W, Sun XM, Sun WD, Su LW, He XP and Wu YL. 2009. Geology, geochemistry, and genesis of Axi: A Paleozoic low-sulfidation type epithermal gold deposit in Xinjiang, China. Ore Geology Reviews, 36(4): 265-281

Zhang LC, Xiao WJ, Qin KZ and Zhang Q. 2006. The adakite connection of the Tuwu-Yandong copper porphyry belt, eastern Tianshan, NW China: Trace element and Sr-Nd-Pb isotope geochemistry. Mineralium Deposita, 41(2): 188-200

Zhao XB, Xue CJ, Zhang ZC, Wang HG, Li XZ and Mi DJ. 2012. Rock enclaves discovered in andesite in the Tulasu Basin, Western Tian Shan, and its geological prospecting significance. Acta Geologica Sinica, 86(11): 1781-1791 (in Chinese with English abstract)

Zhao XB, Xue CJ, Chi GX, Wang HG and Qi TJ. 2014a. Epithermal Au and polymetallic mineralization in the Tulasu Basin, western Tianshan, NW China: Potential for the discovery of porphyry Cu-Au deposits. Ore Geology Reviews, 60: 76-96

Zhao XB, Xue CJ, Symons DTA, Zhang ZC and Wang HG. 2014b. Microgranular enclaves in island-arc andesites: A possible link between known epithermal Au and potential porphyry Cu-Au deposits in the Tulasu ore cluster, western Tianshan, Xinjiang, China. Journal of Asian Earth Sciences, 85: 210-223

Zhao XB, Xue CJ, Men QH, Yan YH, Wang HG, Zu B, Mi DJ and Li XZ. 2014. Origin and metallogenesis of the Tawuerbieke gold deposit, Western Tianshan: Insight from Re-Os geochronology and S-Pb isotopic compositions. Earth Science Frontiers, 21(5): 176-186 (in Chinese with English abstract)

Zhu YF, He GQ and An F. 2007. Geological evolution and metallogeny in the core part of the Central Asian metallogenic domain. Geological Bulletin of China, 26(9): 1167 - 1177 (in Chinese with English abstract)

Zhu YF. 2009. Some important issues for the studies on the Central Asian Metallogeny Domain. Acta Petrologica Sinica, 25(6): 1297 - 1302 (in Chinese with English abstract)

Zhu YF. 2014. Geological evolution and division of giant metallogenic belts in core part of Central Asian Metallogenic Region. Mineral Deposits, 33(3): 471 - 485 (in Chinese with English abstract)

附中文参考文献

安芳，朱永峰. 2008. 西北天山吐拉苏盆地火山岩SHRIMP年代学和微量元素地球化学研究. 岩石学报，24(12)：2741 - 2748

陈华勇，肖兵. 2014. 俯冲边界成矿作用研究进展及若干问题. 地学前缘，21(5)：13 - 22

高俊，钱青，龙灵利，张喜，李继磊，苏文. 2009. 西天山的增生造山过程. 地质通报，28(12)：1804 - 1816

刘德全，陈毓川，王登红，唐延龄，周汝洪，王金良，李华芹，陈富文. 2003. 土屋-延东铜钼矿田与成矿有关问题的讨论. 矿床地质，22(4)：334 - 344

聂凤军，江思宏，张义，刘妍，胡朋. 2004. 中蒙边境及邻区斑岩型铜矿床地质特征及成因. 矿床地质，23(2)：176 - 189

祁世军，成守德，高鹏，王德林，黄启峰，黄诚，宋志奇，方庆新，邱瑞照. 2015. 中哈合作巴尔喀什-准噶尔斑岩铜矿成矿条件对比研究. 北京：地质出版社，1 - 237

芮宗瑶，王龙生，王义天，刘玉琳. 2002. 东天山土屋和延东斑岩铜矿床时代讨论. 矿床地质，21(1)：16 - 22

申萍，潘鸿迪，Seitmuratova E. 2015. 中亚成矿域斑岩铜矿床基本特征. 岩石学报，31(2)：315 - 332

涂光炽. 1999. 初议中亚成矿域. 地质科学，34(4)：397 - 404

王强，赵振华，许继峰，Wyman DA，熊小林，资峰，白正华. 2006. 天山北部石炭纪埃达克岩-高镁安山岩-富Nb岛弧玄武质岩：对中亚造山带显生宙地壳增生与铜金成矿的意义. 岩石学报，22(1)：11 - 30

薛春纪，祁思敬，隗合明. 2007. 基础矿床学. 北京：地质出版社，1 - 230

薛春纪，段士刚，柴凤梅，木合塔尔·买买提，Туресебеков АХ，屈文俊. 2013a. 乌兹别克斯坦Almalyk斑岩铜矿田成矿时代及其地质意义. 地学前缘，20(2)：197 - 204

薛春纪，王洪刚，赵晓波，陈黎昀. 2013b. 新疆西天山吐拉苏金矿集区克峡希小岩体群及其铜矿找矿前景. 地学前缘，20(6)：180 - 194

薛春纪，赵晓波，莫宣学，陈毓川，董连慧，顾雪祥，张招崇，Nurtaev B，Pak N，李志丹，王新利，张国震，亚夏尔亚力坤，冯博，俎波，刘家瑛. 2014a. 西天山巨型金铜铅锌成矿带构造成矿演化和找矿方向. 地质学报，88(12)：2490 - 2531

薛春纪，赵晓波，莫宣学，董连慧，顾雪祥，Nurtaev B，Pak N，张招崇，王新利，俎波，张国震，冯博，刘家瑛. 2014b. 西天山“亚洲金腰带”及其动力背景和成矿控制与找矿. 地学前缘，21(5)：128 - 155

薛春纪，赵晓波，张国震，莫宣学，顾雪祥，董连慧，赵树铭，米登江，Nurtaev B，Pak N，李志丹，王新利，俎波，亚夏尔亚力坤，冯博. 2015. 西天山金铜多金属重要成矿类型、成矿环境及找矿潜力. 中国地质，42(3)：381 - 410

翟伟，孙晓明，高俊，贺小平，梁金龙，苗来成，吴有良. 2006. 新疆阿希金矿床赋矿围岩——大哈拉军山组火山岩SHRIMP锆石年龄及其地质意义. 岩石学报，22(5)：1399 - 1404

赵晓波，薛春纪，张招崇，王洪刚，李晓钟，米登江. 2012. 西天山吐拉苏盆地安山岩中发现岩石包体及地质找矿意义. 地质学报，86(11)：1781 - 1791

赵晓波，薛春纪，门启浩，闫永红，王洪刚，俎波，米登江，李晓忠. 2014. 西天山塔乌尔别克金矿成矿作用：Re-Os年龄和S-Pb同位素示踪. 地学前缘，21(5)：176 - 186

朱永峰，何国琦，安芳. 2007. 中亚成矿域核心地区地质演化与成矿规律. 地质通报，26(9)：1167 - 1177

朱永峰. 2009. 中亚成矿域地质矿产研究的若干重要问题. 岩石学报，25(6)：1297 - 1302

朱永峰. 2014. 中亚成矿域核心区地质演化和巨型成矿带划分. 矿床地质，33(3)：471 - 485