特提斯成矿域中新世斑岩铜矿岩石成因、源区、构造演化及其成矿作用过程

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内容提要：作为全球三大成矿域之一，特提斯成矿域发育众多的世界级成矿带（矿床），例如，旁地德斯、萨汉德-巴兹曼、贾盖、玉龙、冈底斯成矿带等。为了进一步了解特提斯成矿域中新世斑岩铜矿的成因及成矿作用，本文对萨汉德-巴兹曼、贾盖和冈底斯铜矿带典型矿床的地质、地球化学、Sr-Nd-Pb数据进行对比分析，探讨含矿斑岩岩石成因、源区特征和构造环境，归纳其构造演化与其成矿作用过程。地球化学数据显示，这三个铜矿带中新世斑岩体总体显示钙碱性I型花岗岩的特征，具有埃达克岩亲和性。与冈底斯铜矿带相比较，萨汉德-巴兹曼铜矿带和贾盖铜矿带斑岩体显示出弧岩浆岩与埃达克岩过渡的地球化学特征，暗示其岩浆源区MORB质角闪榴辉岩或榴辉岩可能发生的较大程度的部分熔融。Sr-Nd-Pb同位素数据显示，这些含矿斑岩主要来源于受岩浆作用控制的壳幔混合物质，显示DUPAL异常。综合研究分析，认为这些含矿斑岩可能形成于岛弧造山带演化过程中，是洋壳俯冲消减和大陆碰撞过程中增厚下地壳部分熔融的结果。

关键词：斑岩铜矿；中新世；岩石成因；源区；构造演化；成矿作用；特提斯

作为全球三大成矿域（环太平洋成矿域、特提斯成矿域、古亚洲成矿域）之一，特提斯成矿域位于欧亚大陆与冈瓦纳大陆的交接部位，被认为是欧亚大陆南部一条全球性东西展布的构造带，也是地球上最年轻的造山褶皱带（Pan Guitang，1994；Zhang Hongrui et al.，2010）。它是在晚古生代到新生代期间，历经古、新特提斯洋的扩张、沉积和闭合过程，由两次大规模的板块俯冲和碰撞作用形成的，以中生代、新生代地质演化为主（Sengör，1979，1987；Zhang Hongrui et al.，2009）。

特提斯成矿域不但具有巨大的成矿规模和资源潜力，而且还完整地记录了特提斯洋盆裂解→扩张→俯冲→碰撞的演化过程（Dixon et al.，1974；Sengör，1979，1987；Pan Guitang，1994；Zhang Hongrui et al.，2010；Hou et al.，2015）。因此，Dixon等早在1974年就试图将特提斯地区的成矿作用与板块构造结合起来（Dixon et al.，1974），随后众多国内外学者不断对特提斯成矿域构造背景（Jankovic，1977；Sengör，1987；Shahabpour，2005；Qu Xiaoming et al.，2006；Lü Pengrui et al.，2017a）、成矿作用过程（Jankovic，1984；Sillitoe，1978；Hassanzadeh，1993；Hou et al.，2007a，2009a；Zhang Hongrui et al.，2010；Lü Pengrui et al.，2015a，2016a）、成矿物质来源及成矿时代（Shahabpour et al.，1987；Miller et al.，1999；Qu Xiaoming et al.，2002，2006；Hou Zengqian et al.，2003a；Wang Liangliang et al.，2006；Zarasvandi et al.，2007；Cheng Wenbin et al.；2010；Lü Pengrui et al.，2015b；Hu et al.，2017；Deng et al.，2018；Golestani et al.，2018）、岩石地球化学特征（Hou Zengqian et al.，2004；Hezarkhani，2006；Barzegar，2007；Jahangiri，2007；Siddiqui et al.，2007；Nicholson et al.，2010）等方面进行了研究。复杂的地质演化过程赋予特提斯成矿域独特的成矿条件和

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Lü Pengrui，Yao Wenguang，Zhang Huishan，Zhang Haidi，Hong Jun，Liu Shengrong. 2020. Petrogenesis，source，tectonic evolution and mineralization process of the Miocene porphyry Cu deposits in the Tethyan metallogenic domain. Acta Geologica Sinica，94(8)：2291～2310.

多样的成矿作用，形成了斑岩型 Cu-Mo-Au 矿床、与岩浆热液有关的 W-Sn 矿床、岩浆型铬铁矿、VMS 型 Cu-Pb-Zn 矿床、浅成低温热液型 Au-Hg-Sb 矿床及沉积岩有关的 Pb-Zn 矿床，其中不乏一些世界级规模矿带，如东南亚锡矿带、冈底斯铜矿带、玉龙铜矿带、巴基斯坦贾盖(Chagai)铜矿带、伊朗萨汉德-巴兹曼(Sahand-Bazman)铜矿带。

特提斯成矿域发育众多的斑岩型铜矿床，其中不乏一些世界级的斑岩型铜矿床，如萨尔切什梅(Sar Cheshmeh)铜金矿床(伊朗)、松贡(Sungun)铜钼矿床(伊朗)、萨因达克(Saindak)铜金矿床(巴基斯坦)、雷克迪克(Reko Diq)铜金矿床(巴基斯坦)、蒙育瓦铜金矿床(缅甸)、唐塞(Tangse)铜钼矿床(印度尼西亚)、德列科(Derekoy)铜钼钨矿(土耳其)等(Zhang Hongrui et al.，2009)。早在 1988 年，Vassileef et al. (1988)就认识到特提斯成矿域钙碱性火山岩浆带及其赋含的斑岩铜矿的重要性。随着特提斯成矿域青藏高原段大量斑岩铜矿的不断发现，前人对特提斯成矿域斑岩铜矿的研究逐步深入(Zhou Yiji，1980；Hou Zengqian et al.，2001；Qu Xiaoming et al.，2001，2006；Hou et al.，2011；Lü Pengrui et al. 2015a；Hu et al.，2017；Deng et al.，2018；Golestani et al.，2018)。众多学者分别从控矿因素及成因(Zhou Yiji，1980；Hou et al.，2011；Lü Pengrui et al.，2017b)、时空分布特征(Kirkham et al.，2000；Cooke et al.，2005；Shafiei et al.，2008；Zhang Hongrui et al.，2009)、地质特征及动力学背景(Qu Xiaoming et al.，2001；Hou Zengqian et al.，2001；Taghipour et al.，2008；Lü Pengrui et al.，2016b)、成矿物质来源及成矿时代(Shahabpour et al.，1987；Miller et al.，1999；Qu Xiaoming et al.，2006；Hou Zengqian et al.，2003a；Wang Liangliang et al.，2006；Zarasvandi et al.，2007；Cheng Wenbin et al.；2010；Lü Pengrui et al.，2015b，2016c；Deng et al.，2018)、矿产资源潜力(Doebrich et al.，2007；Lü Pengrui et al.，2015a)等方面对这些斑岩铜矿床进行探讨和剖析。近年来才逐渐有人对特提斯成矿域斑岩矿床的分布特征、成因类型、成矿规律等方面进行归纳、总结(Zhang Hongrui et al.，2010；Hou et al.，2011；Ji Xiangyong，2013；Deng et al.，2018)。但由于研究程度的差异和基础资料的匮乏，一定程度影响了对该成矿域斑岩铜矿床的理解及其潜力分析，随着"一带一路"倡议的实施，境内外信息的交流和地质工作的不断深入，为开展境内外斑岩铜矿对比研究提供了需求和创造了条件。本文在前人研究基础上，以中国冈底斯铜矿带、巴基斯坦贾盖铜矿带、伊朗萨汉德-巴兹曼铜矿带为研究对象，对这些中新世斑岩铜矿带的区域地质背景、地质特征、岩石地球化学特征、Sr-Nd-Pb 同位素特征进行总结分析，探讨含矿斑岩岩石成因、源区特征和构造环境，归纳总结其构造演化及其成矿作用过程。

1 地质背景

随着新特提斯洋的闭合，印度板块、阿拉伯板块与欧亚大陆不断碰撞(Zhang Hongrui et al.，2010)，特提斯成矿域进入碰撞造山阶段，先后经历了主碰撞期(65～41Ma)、晚碰撞转换(40～26Ma)和后碰撞伸展(25～0Ma)等 3 个碰撞造山过程(Hou Zengqian et al.，2008；Zhang Hongrui et al.，2009)，与此同时形成了众多的金属矿床，如斑岩型 Cu-Mo-Au 矿床、岩浆型铬铁矿、VMS 型 Cu-Pb-Zn 矿床、浅成低温热液型 Au-Hg-Sb 矿床等(Zhang Hongrui et al.，2009；Hou et al.，2014，2015)。

Zhang Hongrui et al. (2010)按斑岩铜矿床的特征、空间分布及其构造背景，将特提斯成矿域中的斑岩矿床分为土耳其旁地德斯铜矿带、伊朗萨汉德-巴兹曼铜矿带、巴基斯坦贾盖铜矿带、中国班公湖铜矿带、冈底斯铜矿带、玉龙铜矿带、中甸铜矿带等 7 条铜矿带，以及 2 个铜矿区：土耳其安纳托利德斯铜矿区和中南半岛铜矿区(图 1)。其中，萨汉德-巴兹曼、贾盖、冈底斯 3 个铜矿带的大多数斑岩铜矿床与中新世斑岩铜矿化作用密切相关。

晚白垩世，阿拉伯板块的洋壳向北俯冲到欧亚板块之下。渐新世-早中新世开始，阿拉伯板块与中伊朗板块沿着主扎格罗斯断裂发生持续的碰撞挤压(Wen Lei et al.，2015)。萨汉德-巴兹曼斑岩铜矿带是在阿拉伯板块俯冲到中伊朗板块之下的后碰撞环境中形成的，主要发育始新世-渐新世、中-晚渐新世(Berberian，1976；Berberian et al.，1981；Pourhosseini，1982)、中-晚中新世(Hassanzadeh，1993；Kirkham et al.，2000；Ahmadian et al.，2008) 3 期岩浆活动和铜矿化作用。其中，大多数斑岩铜矿化作用与中-晚中新世花岗岩的侵位作用同期或略晚(Shafiel et al.，2009)，含矿围岩主要为闪长玢岩、花岗闪长斑岩和石英二长斑岩。

巴基斯坦及邻区在始新世初开始受到印度板块与欧亚大陆碰撞的强烈影响(Zhang Hongrui et

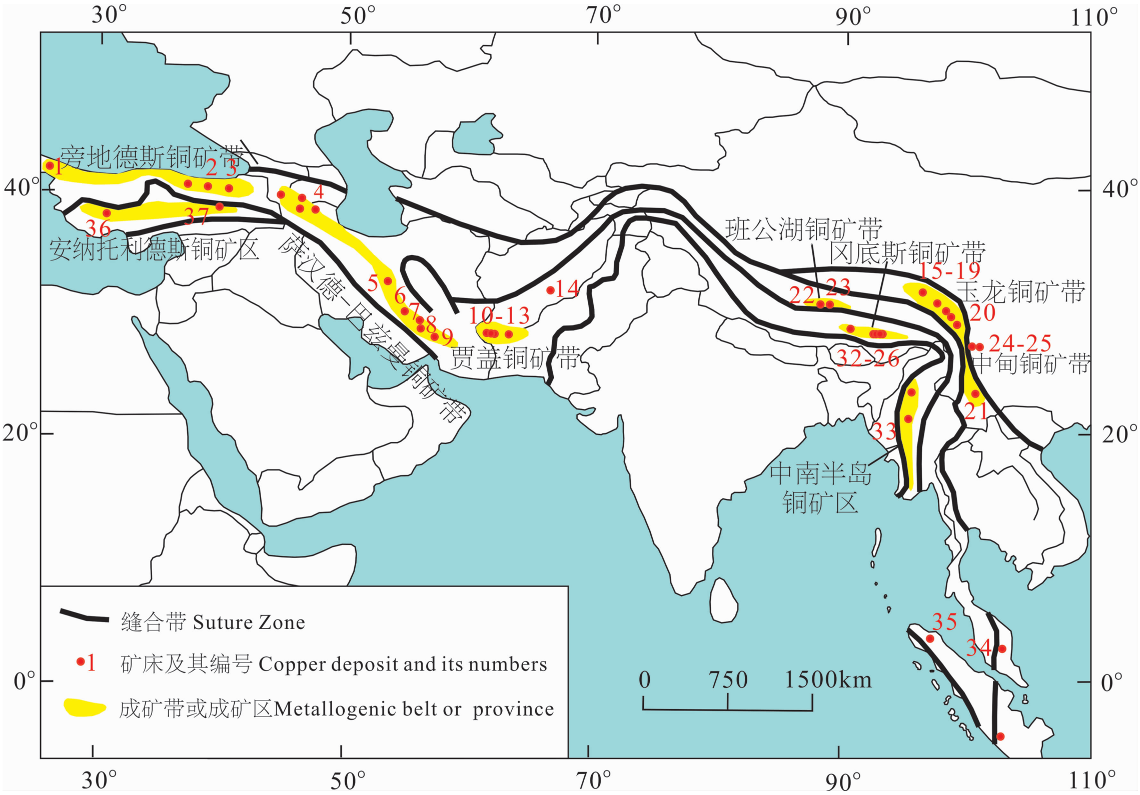

图 1　特提斯成矿域斑岩铜矿分布图(据 Zhang Hongrui et al. ,2009,2010;Lü Pengrui et al. ,2015a 修改)

Fig. 1　Spatial distribution of porphyry copper deposits in Tethyan metallogenic domain (after Zhang Hongrui et al. , 2009, 2010 and Lü Pengrui et al. , 2015a)

土耳其旁地德斯铜矿带:1—德列科;2—古则尔亚伊拉;3—苏里文;伊朗萨汉德-巴兹曼铜矿带:4—松贡;5—卡莱·卡菲;6—阿里·阿巴德;7—达雷查尔;8—梅杜克;9—萨尔切什梅;巴基斯坦贾盖铜矿带:10—萨因达克;11—雷克迪克;12—科·伊·达利尔;13—达斯特·伊·凯恩;14—昆达尔延(阿富汗);中国玉龙铜矿带:15—纳日贡玛;16—玉龙;17-扎那尕;18—莽宗;19—多霞松多;20—马拉松多;21—马厂箐;中国班公湖铜矿带:22—多不杂;23—尕尔穷;中国中甸铜矿带:24—雪鸡坪;25—普郎;中国冈底斯铜矿带:26—甲玛;27—驱龙;28—拉抗俄;29—南木;30—厅宫;31—冲江;32—白容;中南半岛铜矿区:33—蒙育瓦(缅甸);34—门格普尔(马来西亚);35—唐塞(印度尼西亚);土耳其安纳托利德斯铜矿区:36—基斯拉达格;37—科普利尔

Pontides Cooper Belt in Turkey: 1—Derekoy; 2—Güzelyayla; 3—Salikvan; Sahand-Bazman Cooper Belt in Iran: 4—Sungun; 5—Kale Kafi; 6—Ali-Abad; 7—Darrehzar; 8—Meiduk; 9—Sar Cheshmeh; Chagai Cooper Belt in Pakistan: 10—Saindak; 11—Reko Diq; 12—Koh-i-Dalil; 13—Dasht-e-Kain; 14—Kundalyan (Afghanistan); Yulong Cooper Belt in China: 15—Narigongma; 16—Yulong; 17—Zhanaga; 18—Mangzong; 19—Duoxiasongduo; 20—Malasongduo; 21—Machangqing; Bangong Lake Cooper Belt in China: 22—Duobuza; 23—Gaerqiong; Zhongdian Cooper Belt in China: 24—Xuejiping; 25—Pulang; Gangdese Cooper Belt in China: 26—Jiama; 27—Qulong; 28—Lakang'e; 29—Nanmu; 30—Tinggong; 31—Chongjiang; 32—Bairong; Copper Mine Area in Indo-China Peninsula: 33—Monywa (Myanmar); 34—Mengpur (Malaysia); 35—Tangse (Indonesia); Anatolides Cooper Mine Area in Turkey: 36—Kisladag; 37—Copler

al. ,2009),随着印度板块与欧亚板块的碰撞,贾盖斑岩铜矿带先后经历四次大规模的岩浆作用和成矿作用形成的(Perellŏ et al. ,2008,Lü Pengrui et al. ,2015a)。斑岩铜矿化受控于后碰撞区域性事件,其中,大多数斑岩型铜矿床形成于早中新世和中中新世,含矿围岩主要为石英闪长斑岩和花岗闪长斑岩。

冈底斯斑岩铜矿带是在中新世随着俯冲洋壳板片的断离(Miller et al. , 1999;Maheo et al. ,2002),冈底斯-念青唐古拉地块发生东西向伸展运动的过程中形成的(Cheng Wenbin et al. ,2010)。大多数斑岩铜矿床主要与中中新世后碰撞岩浆作用密切相关,含矿围岩主要为二长花岗斑岩、石英二长斑岩,少数为花岗闪长斑岩、花岗斑岩等(Zhang Hongrui et al. ,2009,2010;Hou et al. ,2011)。

2　特提斯成矿域中新世斑岩铜矿带地质特征

2.1　伊朗萨汉德-巴兹曼斑岩铜矿带

伊朗萨汉德-巴兹曼斑岩铜矿带位于中伊朗微板块南缘,赋存于 NW 向中新世萨汉德-巴兹曼火

山岩浆带内，又称中伊朗火山岩浆带（Jankovic，1984；Zarasvandi et al.，2005；Shahabpour，2005），或乌尔米耶-达克塔尔（Urumieh-Dokhtiar）火山岩浆带（Agard et al.，2005），属于阿尔卑斯-喜马拉雅碰撞造山带的一部分（Shafiei et al.，2009）。

萨汉德-巴兹曼斑岩铜矿带是在阿尔卑斯造山运动时期阿拉伯板块俯冲到中伊朗板块之下形成的（Berberian，1976；Berberian et al.，1981；Pourhosseini，1982），发育三期主要的岩浆活动和铜矿化作用：始新世-渐新世（Ahmadian et al.，2008）、中-晚渐新世（Kirkham et al.，2000）、中-晚中新世（Shahabpour et al.，1987；Hassanzadeh，1993；Kirkham et al.，2000；McInnes et al.，2005a；Razique et al.，2007）。其中，大多数斑岩铜矿化作用与中-晚中新世花岗岩的侵位作用密切相关（Shafiel et al.，2009），部分含矿岩体受 NE 向褶皱逆冲带、走滑断裂及其派生构造控制（Zarasvandi et al.，2005，2007；Jahangiri，2007）。该铜矿带主要由碱性、钙碱性火山岩及相关侵入岩组成，斑岩铜矿主要与中新世-第四纪碱性斑岩体有关（Jankovic，1984；Hezarkhani，2006），含矿围岩主要为闪长玢岩、花岗闪长斑岩和石英二长斑岩（表 1）。

萨汉德-巴兹曼斑岩铜矿带向东与巴基斯坦贾盖斑岩铜矿带相连，向西延伸到土耳其旁地德斯斑岩铜矿带，平行于伊朗扎格罗斯造山带，从伊朗阿塞拜疆省呈 NW 向延伸到东南部，长约 1700km，宽约 100km，发育有大量的斑岩铜矿床（图 1；表 1），包括 2 个超大型铜矿（萨尔切什梅矿床，1200Mt，铜品位 0.7%，钼品位 0.03%，金品位 0.06%；松贡矿床，650Mt，铜品位 0.76%，钼品位 0.01%；Mutschler，1999；Cooke et al.，2005；Shafiei et al.，2008），2 个大型铜矿（Kale Kafi 矿床，245Mt，铜品位 0.26%，钼品位 0.026%；梅杜克矿床，170Mt，铜品位 0.86%，钼品位 0.007%；Singer et al.，2005；Taghipour et al.，2008）、至少 3 个中型铜矿（Zarnab Exploration Consulting Company，2009；Li et al.，2011；Sori，2012），以及众多小型铜矿（McInnes et al.，2005b；Taghipour，2007；Shafiei et al.，2009；Zarasvandi et al.，2011）。

2.2 巴基斯坦贾盖斑岩铜矿带

巴基斯坦贾盖斑岩铜矿带位于伊朗-鲁特-阿富汗地块东南缘（Zhang Hongrui et al.，2010），赋存于贾盖钙碱性火山岩浆带（又称被北贾盖岩浆弧；Hunting Survey Corp.，1960）或莫克兰（Makran）岩浆弧（Doebrich et al.，2007）中，其东部的斑岩铜矿床受早白垩世辛贾拉尼（Sinjrani）群火山岩和贾盖侵入体控制，主要分布在贾盖侵入体的边缘或与围岩接触带的几公里范围内；西部的铜矿床受古新世和更年轻的碎屑岩和火山岩控制，主要分布在索尔科（Sor Koh）侵入体的岩株中（Perelló et al.，2008）。

贾盖斑岩铜矿带在随着印度板块与欧亚板块的开始碰撞之后的安第斯型构造背景中形成，先后经历了中-晚始新世（43～37Ma）、早中新世（24～22Ma 和 18～16Ma）、中中新世（13～10Ma）和晚中新世-早上新世（6～4Ma）4 次岩浆作用和成矿作用（Perelló et al.，2008）。其中，大多数斑岩型铜矿床形成于早中新世（24～22Ma 和 18～16Ma）和中中新世（13～10Ma），成矿类型为斑岩铜金矿，矿体赋存于石英闪长斑岩和花岗闪长斑岩中，含矿围岩为复杂的杂岩体，主要产于陡倾的多相斑状侵入体中（Perelló et al.，2008），蚀变分带明显，自岩体中心向外分为钾化、石英-绢云母化、泥化和青磐岩化，其中高级泥化发育（表 1）。

贾盖斑岩铜矿带位于巴基斯坦俾路支省西部 Saindak 和 Dasht-e-Kain 之间，其西部与伊朗萨汉德-巴兹曼斑岩铜矿带相接（Berberian et al.，1982；Jankovic et al.，1987；Bagheri et al.，2008），中间部分被莫克兰磨拉石截断（Jankovic et al.，1987；Bagheri et al.，2008），北东向延伸，不连续出露晚白垩世-第三纪的安山质和花岗闪长质小岩株，直至被杰曼（Chaman）走滑断层截断（Ahmad，1992）。贾盖斑岩铜矿带沿贾盖山脉，临近巴基斯坦西部俾路支高原，呈 EW 走向展布，延伸长达 300km，斑岩铜矿分布着 48 个斑岩矿床（点）（图 1；表 1），包括萨因达克铜金矿床（440Mt，铜品位 0.41%，金品位 0.5g/t；Sillitoe et al.，1977；Sillitoe，1978，1979；Ahmad，1992）、雷克迪克铜金矿床（855Mt，铜品位 0.65%，金品位 0.33g/t；Cooke et al.，2005；Perelló et al.，2008）、达斯特伊凯恩铜矿床（350Mt，铜品位 0.3%；Ahmad，1992；Singer et al.，2005）、科伊达利尔铜金矿床（Ahmad，1992）、Tanjeel 铜矿床、Missi 铜矿床、Ziarat Pir Sultan 铜矿床（Siddiqui et al.，2007）等。

2.3 中国冈底斯斑岩铜矿带

中国冈底斯斑岩铜矿带位于雅鲁藏布江缝合带北侧、拉萨地体南缘，赋存于中新世冈底斯构造-岩浆带中（Zhang Hongrui et al.，2009），大地构造位

表 1 特提斯成矿域主要中新世斑岩铜矿床地质特征(据 Zhang Hongrui et al. ,2009;Lü Pengrui et al. ,2015a 修改)

Table 1 Geological features of main Miocene porphyry copper deposits in Tethyan metallogenic domain (after Zhang Hongrui et al. , 2009; Lü Pengrui et al. , 2015a)

序号	矿床名称	金属组合	构造背景	母岩	围岩	蚀变	年龄(Ma)	资料来源
1	松贡(Sungun)	Cu-Mo	伊朗萨汉德-巴兹曼中新世火山岩浆带	早期的二长岩、石英二长岩和晚期的闪长岩、花岗闪长岩	白垩纪石灰岩、始新世安山质凝灰岩、集块岩	早期主要为钾化和青磐岩化,晚期为绢云母化、硅化和泥化	19.28±0.33～21.13±0.23	Mutschler,1999; Cooke et al. ,2005; Aghazadeh et al. ,2015
2	阿里阿巴德(Ali-Abad)	Cu-Mo-Ag	伊朗萨汉德-巴兹曼中新世火山岩浆带	碱性花岗岩、花岗闪长岩、石英二长闪长岩	始新世英安质-流纹质凝灰岩	从内到外依次为绢云母化、泥化、青磐岩化	16.5±0.5	Zarasvandi et al. , 2005,2007; Aghazadeh et al. ,2015
3	达雷查尔(Darrehzar)	Cu-Mo-Au-Ag	伊朗萨汉德-巴兹曼中新世火山岩浆带	石英闪长岩、石英二长岩、英云闪长岩和花岗岩	始新世凝灰岩、白垩纪灰岩	从内到外依次为钾化、绢云母化、泥化、青磐岩化	15.8±0.3～16.40±0.22	Zarasvandi et al. , 2005,2007; Aghazadeh et al. ,2015
4	梅杜克(Meiduk)	Cu	伊朗萨汉德-巴兹曼中新世火山岩浆带	石英闪长岩、花岗闪长岩、闪长岩	始新世火山岩和火山碎屑岩	钾化、绢云母化、泥化、青磐岩化、硅化	11.3±0.5～12.5±0.1	Hassanzadeh,1993; Tangestani et al. ,2002; McInnes et al. ,2003; Singer et al. ,2005; Alirezaei et al. ,2017
5	萨尔切什梅(Sar-Cheshmeh)	Cu-Mo-Au-Ag	伊朗萨汉德-巴兹曼中新世火山岩浆带	闪长岩至花岗闪长岩,英安岩及相关斑岩,安山岩及相关岩墙	早第三纪火山沉积岩,包括安山岩、凝灰岩、熔结凝灰岩和集块岩	早期为中心钾化,外围青磐岩化,后期叠加绢云母化	8.7±0.5～13.6±0.1	Waterman et al. ,1975; Samani,1998; Cooke et al. ,2005; Aghazadeh et al. ,2015
6	萨因达克(Saindak)	Cu-Au	巴基斯坦贾盖钙碱性火山岩浆带	英云闪长斑岩体、石英闪长斑岩岩株	北部为始新世火山集块岩、凝灰岩,南部为渐新世粉砂岩、砂岩、凝灰岩	从内到外依次为钾化、绢云母化、青磐岩化	22.18±0.2～22.4±0.4	Perelló et al. ,2008; Fu et al. ,2006
7	雷克迪克(Redo Diq)	Cu-Au	巴基斯坦贾盖钙碱性火山岩浆带	石英闪长岩、花岗岩闪长岩	晚渐新世-早中新世安山质火山岩、碎屑沉积压	从内向外依次为钾化、绢云母化-黏土-绿泥石化、绢云母化、青磐岩化	10.5±0.2～23.75 ±0.19	Perelló et al. ,2008; Fu et al. ,2006; Razique,2013
8	科伊达利尔(Koh-i-Dalil)	Cu-Au	巴基斯坦贾盖钙碱性火山岩浆带	石英闪长岩、二长岩、花岗闪长岩、英安斑岩	中新世火山集块岩、熔岩	从内向外:钾化、绢云母化、青磐岩化	10.1±0.2 18.4±2.5	Ahmad,1992; Perellő et al. ,2008
9	达斯特伊凯恩(Dasht-e-Kain)	Cu-Au	巴基斯坦贾盖钙碱性火山岩浆带	渐新世闪长岩体	晚白垩世辛贾拉尼群火山集块岩、凝灰岩	从内向外:钾化、绢云母化、泥化、青磐岩化	21	Ahmad,1992; Singer et al. ,2005
10	甲马	Pb-Zn-Cu-Au	中国冈底斯火山岩浆弧	二长花岗岩	早白垩世-中侏罗世砂岩、板岩、灰岩	钾化、石英绢云母化、青磐岩化、矽卡岩化	15.18±0.98	Hou et al. , 2009b
11	驱龙	Cu-Mo	中国冈底斯火山岩浆弧	二长花岗岩、花岗岩	中侏罗世火山凝灰岩、流纹岩、灰岩、板岩	钾化、石英绢云母化、青磐岩化	15.99±0.32	Yang Zhiming et al. ,2008; Hou et al. ,2009b
12	拉抗额	Cu-Mo	中国冈底斯火山岩浆弧	花岗闪长岩、二长花岗岩	早白垩世火山碎屑岩、灰岩、花岗岩	钾化、石英绢云母化、青磐岩化	13.6±0.1	Hou et al. ,2009b
13	南木	Cu-Mo	中国冈底斯火山岩浆弧	花岗闪长岩、二长花岗岩	古新世碰撞花岗岩	钾化、石英绢云母化、青磐岩化	14.76±0.60	Hou et al. ,2009b
14	厅宫	Cu-Mo	中国冈底斯火山岩浆弧	石英二长花岗岩、花岗岩	古新世碰撞花岗岩	钾化、石英绢云母化、青磐岩化、泥化	15.49±0.36	Hou et al. ,2009b
15	冲江	Cu-Mo	中国冈底斯火山岩浆弧	二长花岗岩	古新世碰撞花岗岩	钾化、石英绢云母化、青磐岩化、泥化	14.00±0.43	Hou et al. ,2009b
16	白容	Cu-Mo	中国冈底斯火山岩浆弧	二长花岗岩、英安斑岩	古新世碰撞花岗岩	钾化、绢云母化、泥化、青磐岩化	12.01±0.29～14.73±0.13	Hou et al. , 2009b; Zhou Weide et al. ,2014

置位于冈底斯-念青唐古拉板片次级构造单元冈底斯陆缘火山- 岩浆弧东段，介于雅鲁藏布江缝合带和班公湖-怒江缝合带之间，分别与三江构造带和帕米尔-喀喇昆仑构造带相连(Zheng Youye et al.，2007)。

冈底斯斑岩铜矿带是在中新世随着俯冲洋壳板片的断离(Miller et al.，1999；Maheo et al.，2002)，冈底斯-念青唐古拉地块发生东西向伸展运动的过程中(Cheng Wenbin et al.，2010)，由长英质岩浆侵位与中新世钾质-超钾质火山活动相伴发育形成的，主要产于冈底斯花岗岩基及其围岩二叠纪—白垩纪地层中(Hou Zengqian et al.，2001，2003b；Qu Xiaoming，2001)，发育 3 套钾质钙碱性熔岩和数量众多的花岗质斑岩体(Coulon et al.，1986；Qu Xiaoming et al.，2002)。这些斑岩带中的矿床和矿(化)点整体上东西向成带分布，平行于冈底斯逆冲带，局部南北向成串(Hou Zengqian et al.，2006a)，沿近 SN 向正断层分布，常常受近 EW 向逆冲断裂带和近 SN 向正断层交汇点控制(Hou Zengqian et al.，2005，2006a)。含矿斑岩规模一般较小，零星孤立分布，侵位于古新世-渐新世末同碰撞花岗岩基之中，岩性主要为二长花岗斑岩、石英二长斑岩，少数为花岗闪长斑岩、花岗斑岩等(表 1；Zhang Hongrui et al.，2009，2010)。

西藏冈底斯斑岩铜矿带位于雅鲁藏布江北岸，西起尼木县冲江，东至工布江达县，东西长约 400 km，南北宽 50 km，目前已发现 1 处超大型斑岩铜矿床(驱龙)、6 处大型斑岩铜矿床(厅宫、冲江、甲马、朱诺、吉如、得明顶)、4 处中-小型斑岩铜矿床(白荣、南木、拉抗俄、帮浦、吹败子、象背山)，以及一系列斑岩矿(化)点(德曲、懂师布、勒宗、生浦、夏工普、加尔西、汤不拉、则多拉、松多握、普下、巴拉)(图 1；Hou Zengqian et al.，2001；Qu et al.，2004；Zheng Youye et al.，2007；Hou et al.，2009a)。

3 讨论

本文主要以萨汉德-巴兹曼铜矿带的萨尔切什梅、松贡、梅杜克斑岩铜矿，贾盖铜矿带的萨因达克、雷克迪克斑岩铜金矿，以及冈底斯铜矿带的驱龙铜矿、冲江、拉抗俄、南木、厅宫、甲玛等斑岩铜矿为例，对这些矿床含矿斑岩的地球化学数据和 Pb、Sr、Nd 同位素数据进行系统梳理和分析对比，在此基础上探讨其岩石成因类型、岩浆源区、构造演化及其成矿作用过程。

3.1 岩石成因类型

总结归纳前人研究数据发现，特提斯成矿域中新世斑岩型铜矿床大多数含矿斑岩样品的 A/CNK 指数小于 1.10，里特曼指数小于 3.3，个别介于 3.3～9.0 之间，总体显示钙碱性 I 型花岗岩的特征。该成矿域 3 个铜矿带含矿斑岩均具有较高的 SiO_2、Al_2O_3 含量和 Sr/Y 比值(绝大多数＞35)，亏损 HREE 和 Y，轻、重稀土强烈分馏，无明显的 Eu 异常等特征(图 2)，显示其具有埃达克岩的亲合性。通过岩石地球化学特征对比发现，特提斯成矿域中新世含矿斑岩与典型埃达克岩具有十分相似的地球化学特征(表 2)。

特提斯成矿域 3 个中新世斑岩铜矿带含矿斑岩的稀土分配模式均为右倾斜的 LREE 富集型，LREE 与 HREE 强烈分异，均没有明显的 Eu 异常，表明其岩浆源区无斜长石，或残留相无斜长石(图 2；Hou Zengqian et al.，2004)，此外岩体相对富集 Sr，说明岩浆不是幔源玄武质原生岩浆分离结晶斜长石后的残余岩浆。这些铜矿带 Yb 均强烈亏损，轻、重稀土强烈分馏，指示角闪榴辉岩或石榴石角闪岩发生了大约 10%～25%的部分熔融，以满足埃达克岩的形成(Defant et al.，1990)。该成矿域中新世斑岩总体明显富集 LILE(Ba、Rb、Sr)，强烈亏损 HFSE(Nb、Ta、Ti)，说明其起源于含水地幔楔的部分熔融，或者反映了一种相对富水而角闪石和金红石在部分熔融过程中得以残留的岩浆源区特征(图 2；Hou Zengqian et al.，2012；Xu et al.，2017；Zhang Zeming et al.，2019)。含矿斑岩均有较高的 Sr/Y、La/Yb 比值，显示轻稀土富集配分型式，缺乏明显的负 Eu 异常，类似于新生代铁镁质加厚下地壳来源的埃达克岩(Hou Zengqian et al.，2012)，而具高 Sr/Y(＞40)、La/Yb 比值的弧岩浆(残留相矿物以含有石榴子石，无长石为标志)富水、氧逸度(f_{O_2})高和富 S，有利于岩浆-热液系统的形成(Richards，2011；Wang Cuiyun et al.，2012)。Nb、Ta 的负异常，显示大陆地壳的特征(Rollinson，1993)。含矿斑岩总体具有较高的 $Mg^{\#}$ 值，大多数样品的 $Mg^{\#}$ 值大于 45，也可能指示存在地幔物质的混染，源岩中地幔物质参与量的不同，导致不同岩体 $Mg^{\#}$ 值的变化(Rapp et al.，1999)。

在 Y-Sr/Y 图解(图 3a)与 Yb_N-$(La/Yb)_N$ 图解(图 3b)中，特提斯成矿域 3 个铜矿带中新世斑岩绝大多数样品也落入埃达克岩的区域。洋壳板片俯冲至一定深度，大洋玄武岩(MORB)发生变质作用，斜

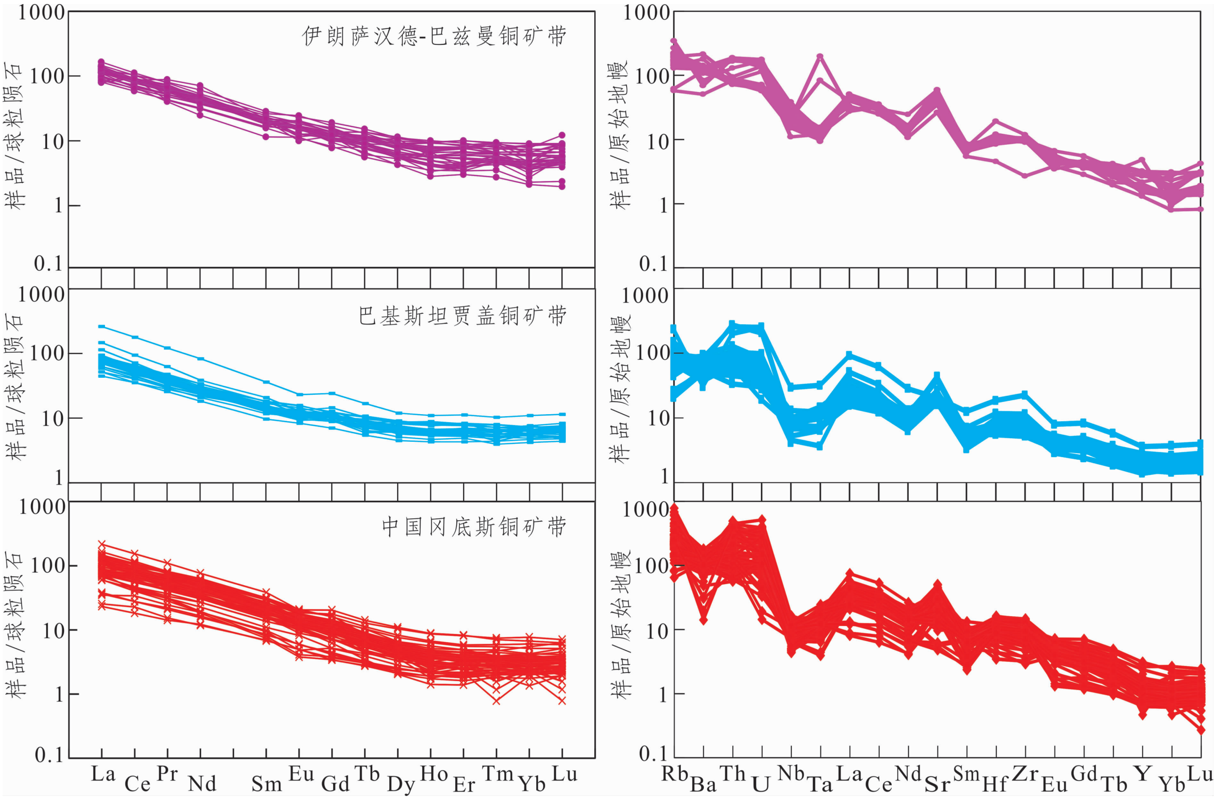

图 2　特提斯成矿域中新世含矿斑岩稀土元素配分图与微量元素蛛网图(标准化值据 Sun et al.，1989)

Fig. 2　REE distribution patterns and spider diagram of Miocene ore-bearing porphyries in Tethyan metallogenic domain (the normalized values sourced from Sun et al.，1989)

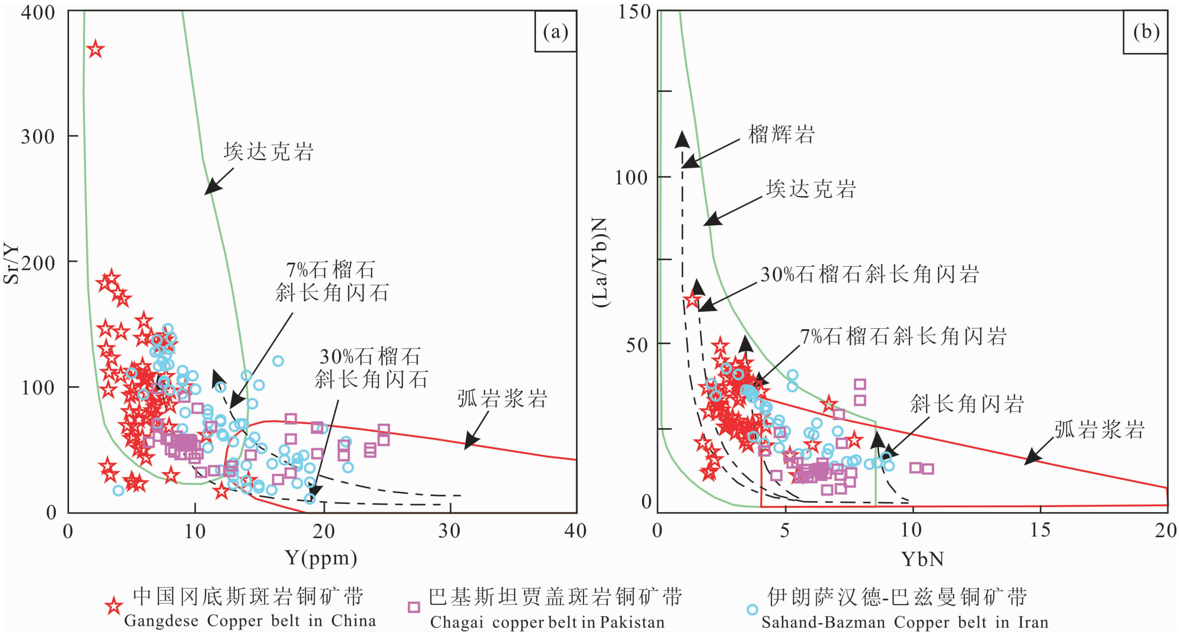

图 3　特提斯成矿域中新世含矿斑岩 Y-Sr/Y 图解与 Yb_N-$(La/Yb)_N$ 图解

(底图据 Martin，1986；Defant et al.，1990；Drummond et al.，1990；Petford et al.，1996)

Fig. 3　Y-Sr/Y and Yb_N-$(La/Yb)_N$ diagrams of Miocene ore-bearing porphyries in Tethyan metallogenic domain (Basemaps sourced from Martin，1986；Defant et al.，1990；Drummond et al.，1990；Petford et al.，1996)

表 2 特提斯成矿域中新世含矿斑岩与埃达克岩的岩石地球化学特征对比表

Table 2 Geochemistry comparison between Miocene ore-bearing porphyries in Tethyan metallogenic domain and adakites

	埃达克	O 型 埃达克岩(29)	C 型 埃达克岩(14)	萨汉德-巴兹曼 铜矿带	贾盖 铜矿带	冈底斯 铜矿带
SiO_2	≥56%	≥56%	≥56%	62.47% (73)	58.57% (47)	68.65% (70)
Al_2O_3	≥15%	≥15%	≥15%	16.22% (73)	15.57% (47)	14.84% (70)
MgO	<3%	<3%	<3%	2.32% (73)	3.13% (47)	1.05% (70)
Sr($\times10^{-6}$)	>400	298~1500	490~2573	788 (73)	695 (47)	503 (67)
Y($\times10^{-6}$)	≤18	8~31	2~12	12 (73)	12.44 (47)	5.84 (67)
Yb($\times10^{-6}$)	≤1.9	0.4~3.5	0.37~1.29	0.90 (41)	1.12 (39)	0.52 (67)
Sr/Y	>20~40	12.29~150	54.44~448.5	72.20 (73)	56.00 (44)	92.64 (67)
La/Yb	>20	3.59~94	15.26~78.79	36.19 (41)	20.49 (39)	44.20 (67)
Eu 异常	正异常	正异常	正异常	弱异常	无/弱异常	弱异常
Sr 异常	正异常	正异常	正异常	正异常	正异常	正异常

注:埃达克岩数据据 Drummond et al. (1990),表格中的值为平均值,括号内为样品个数。萨汉德-巴兹曼铜矿带数据来源于 Hezarkhani (2006)、Richards et al. (2006)、Barzegar(2007)、Taghipour(2007)、Shafiel et al. (2009)、Zarnab Exploration Consulting Co. (2009)、Mohammadi (2010)、Soltani(2011)、Sori(2012)、Taghinejad(2012)、Asadi et al. (2014);贾盖铜矿带数据来源于 Siddiqui et al. (2007)、Nichiolson et al. (2010)、Richards et al. (2012)、Razique,2013;冈底斯铜矿带数据来源于 Qu Xiaoming et al. (2001,2002)、Gao Yongfeng et al. (2003)、Meng Xiangjin(2004)、Wang Liangliang et al. (2006)、Li Bing et al. (2007)、Gao Cheng et al. (2014)。

长石、角闪石矿物依次分解,释放大量的水,形成角闪岩、榴辉岩,成为埃达克岩的理想岩浆源区;在角闪岩、榴辉岩部分熔融过程中,石榴子石和金红石等作为残留相出现(Hou Zengqian et al.,2003b)。与冈底斯铜矿带相比较,萨汉德-巴兹曼和贾盖铜矿带含矿斑岩样品明显向右偏移(图 3),暗示其岩浆源区 MORB 质角闪榴辉岩或榴辉岩可能发生的较大程度的部分熔融(Defant et al.,1990),显示出弧岩浆岩与埃达克岩过渡的地球化学特征。

3.2 岩浆源区

特提斯成矿域 3 个中新世斑岩铜矿带含矿斑岩的$^{206}Pb/^{204}Pb$ 比值介于 18.289~18.765 之间,$^{207}Pb/^{204}Pb$ 比值范围为 15.502~15.733,$^{208}Pb/^{204}Pb$比值介于 38.389~39.153 之间,类似于陆缘弧火山岩的铅同位素组成,反映了火山岩源区有陆壳组分的加入(Wei Qirong et al.,2003),前人认为这些含矿斑岩是特提斯洋岩石圈俯冲消减有关的岩浆作用的产物(Zhao Zhidan et al.,2007)。μ 值介于 9.28~9.70 之间(表 3),均高于原始地幔铅 μ 值(8.92),接近上地壳铅(9.58),明显不同于下地壳或上地幔铅的低 μ 值特征(Stacey et al.,1975;Doe et al.,1979;Kamona et al.,1999;Wu Kaixing et al.,2002);ω 值变化范围为 35.63~39.60(表 3),大多高于地壳平均 ω 值(36.84);Th/U 比值介于 3.72~3.95 之间(表 3),均高于地幔 Th/U 比值(3.45),表明铅主要来源于壳幔混合物质,更多的来源于富含 U、Th 的上地壳物质。大多数样品均有高正△7/4Pb(简记为△7/4)和低正△8/4Pb(简记为△8/4)比值(表 3),反映了长期的高 μ 值源区作用的结果(Ren Kangxu et al.,2006)。贾盖铜矿带与冈底斯铜矿带的部分 H-H 模式年龄出现了负值(表 3),明显不符合单阶段铅演化模式,表明该样品的铅并非普通铅,可能是在高 μ 值背景下经历了多阶段演化后(Ren Kangxu et al.,2006),混入了放射性成因铅(Faure et al.,2005)。$^{87}Sr/^{86}Sr$ 比值介于 0.70491~0.70792 之间(表 3),大多高于地幔的锶同位素比值(0.704;Faure,1986)和原始地幔现代值(0.7045,DePaolo et al.,1979),明显低于大陆地壳$^{87}Sr/^{86}Sr$ 平均值(0.719;Sun Shengli,2001;Xiao Qinghui et al.,2002);$^{143}Nd/^{144}Nd$ 比值介于 0.51228~0.51292 之间(表 3),略高于原始地幔现代值(0.512638,Jacobson et al.,1980),表明含矿斑岩属于壳幔混合来源。

在铅同位素构造环境演化图解中(图 4a、4b),大多数样品落在造山带演化曲线附近,显示壳幔混合来源的特征。所有样品点均位于北半球参照线之上、地球等时线之下,前人将这种铅同位素特征解释为岩浆作用过程中卷入了大陆物质(Hegner et al.,1992;Van Bergen et al.,1993;Vroon et al.,1993)。在铅同位素物质源区判别图解中(图 4c、4d),大多数样品落在成熟弧的区域,接近深海沉积物,显示其源岩与岛弧物质相近,可能与俯冲的岛弧或洋壳有关,与前文所述的壳幔混合物源观点相吻合。

铅同位素 Δβ-Δγ 成因分类图(图 5a)显示,特提斯成矿域中新世含矿斑岩铅同位素具有地幔和上地壳(或俯冲沉积物)的混合特征,来源于受岩浆作用

表 3　特提斯成矿域中新世含矿斑岩 Pb-Sr-Nd 同位素组成及其特征值

Table 3　Pb-Sr-Nd isotopic compositions and their characteristic parameters of Miocene ore-bearing porphyries in Tethyan metallogenic domain

	萨汉德-巴兹曼铜矿带	贾盖铜矿带	冈底斯铜矿带
Pb^{206}/Pb^{204}	18.521～18.608 (7)	18.627～18.772 (9)	18.289～18.765 (26)
Pb^{207}/Pb^{204}	15.583～15.648 (7)	15.637～15.647 (9)	15.502～15.733 (26)
Pb^{208}/Pb^{204}	38.547～38.804 (7)	38.796～38.993 (9)	38.389～39.153 (26)
t(Ma)	28.0～98.7 (7)	－41.1～57.3 (9)	－66.3～232.6 (26)
μ	9.42～9.54 (7)	9.51～9.52 (9)	9.28～9.70 (26)
ω	36.21～37.42 (7)	37.10～37.21 (9)	35.63～39.60 (26)
Th/U	3.72～3.80 (7)	3.77～3.78 (9)	3.72～3.95 (26)
V1	59.98～69.99 (7)	68.03～72.44 (9)	52.90～85.95 (26)
V2	53.32～56.99 (7)	56.51～59.00 (9)	46.22～60.29 (26)
$\triangle\alpha$	71.99～78.47 (7)	77.43～81.66 (9)	63.81～86.69 (26)
$\triangle\beta$	16.50～20.84 (7)	19.76～20.44 (9)	11.25～26.81 (26)
$\triangle\gamma$	31.48～39.44 (7)	37.70～40.61 (9)	27.60～53.19 (26)
△7/4	8.43～14.08 (7)	11.65～12.97 (9)	1.98～22.48 (26)
△8/4	52.81～68.96 (7)	64.38～66.99 (9)	55.39～102.87 (26)
$^{87}Sr/^{86}Sr$	0.70425～0.70470 (6)	0.70512～0.70537 (9)	0.70491～0.70792 (42)
$^{143}Nd/^{144}Nd$	0.51265～0.51283 (6)	0.51269～0.51273 (9)	0.51228～0.51292 (42)
ε_{Sr}	75.29～81.72 (6)	87.71～91.20 (9)	84.65～127.76 (42)
△Sr	42.53～47.02 (6)	51.21～53.65 (9)	49.07～79.20 (42)
ε_{Nd}	0.29～3.39 (6)	0.99～1.79 (9)	－7.02～5.50 (42)

注:括号内为样品个数。萨汉德-巴兹曼铜矿带数据来源于 Shafiel et al. (2009)、Golestani et al. (2018);贾盖铜矿带数据来源于 Razique (2013);冈底斯铜矿带数据来源于 Qu Xiaoming et al. (2002,2004)、Meng Xiangjin et al. (2006)、Hou et al. (2004)、Li et al. (2011)、Hu et al. (2015,2017),$\triangle 7/4=[(^{207}Pb/^{204}Pb)-0.1084\times(^{206}Pb/^{204}Pb)-13.491]\times 100$(Hart,1984);$\triangle 8/4=[(^{208}Pb/^{204}Pb)-1.209\times(^{206}Pb/^{204}Pb)-15.627]\times 100$(Hart,1984);$\triangle Sr=[(^{87}Sr/^{86}Sr)-0.7]\times 10000$(Hart,1984);$\varepsilon_{Nd}=10000\times[(^{143}Nd/^{144}Nd)\div(^{143}Nd/^{144}Nd)_{CHUR}-1]$,$(^{143}Nd/^{144}Nd)_{CHUR}=0.512638$(Lai Shaocong et al.,2007);$\varepsilon_{Sr}=10000\times[(^{87}Sr/^{86}Sr)\div(^{87}Sr/^{86}Sr)_{UR}-1]$,$(^{87}Sr/^{86}Sr)_{UR}=0.698990$(Lai Shaocong et al.,2007)。

控制的壳幔混合物质。在△7/4-△8/4 图解中,所有数据点均落在了 EMII 与 DM 地幔端元之间,EMII 通常被认为是俯冲的或再循环的陆壳物质(Xing Guangfu,1997),也从侧面证实了壳幔混合来源的观点。

在$^{143}Nd/^{144}Nd$-$^{87}Sr/^{86}Sr$ 图解中,所有样品落在了下地壳与亏损地幔混合线附近(图 6a),显示了壳幔混合来源的特征,相比而言,贾盖铜矿带和冈底斯铜矿带的数据略向上地壳方向偏移,说明有一定量的上地壳物质参与,以异常铅的形式表现出来;大多数样品位于地幔演化线延伸方向上(图 6b),显示了区域岩浆混合作用特征;所有样品落在下地壳源埃达克岩的区域内(图 6a),大多数样品落入了林子宗火山岩的区域,被认为是新特提斯洋地幔端元(以雅鲁藏布江 MORB 为代表)或一个新亏损地幔端元的控制的亲特提斯洋型岩浆作用,是新特提斯洋岩石圈俯冲及再循环或幔源岩浆注入地壳的结果(Mo Xuanxue et al.,2006;Zhao Zhidan et al.,2007),这也进一步支持了壳幔混合来源的观点。

特提斯成矿域 3 个中新世斑岩铜矿带含矿斑岩△7/4 比值均大于 3,△8/4 比值均大于 10,△Sr 值均大于 40,满足 DUPAL 异常的边界条件(Hart,1984),特别是大多数样品的△8/4 比值大于 60,△Sr 值均大于 50,符合典型 DUPAL 异常的特征。此外,所有样品数据在构造环境演化图解中(图 4a、4b)位于北半球参照线之上,地球等时线右侧,与 Hart 所定义的 DUPAL 异常 Pb 同位素特征一致。在$^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$、△7/4-△8/4、$^{87}Sr/^{86}Sr$-$^{206}Pb/^{204}Pb$、$^{143}Nd/^{144}Nd$-$^{206}Pb/^{204}Pb$,以及$^{143}Nd/^{144}Nd$-$^{87}Sr/^{86}Sr$ 图解中(图 4a、图 5b、图 6),所有数据点均落在了 EMII 与 DM 地幔端元之间,与候青叶所讨论的特提斯地幔组成特征一致(Hou Qingye,2005),体现了两端元混合的特征,表明特提斯成矿域中新世含矿斑岩 DUPAL 异常可能直接产生于 EMII 与 DM 的混合源区,反映为可能有俯冲的或再循环的陆壳物质加入。

综合分析特提斯成矿域中新世含矿斑岩 Pb 同位素比值和 μ、ω、Th/U 等特征值,Sr、Nd 同位素比值,以及 Pb、Sr、Nd 同位素的各类判别图解(图 4、图 5、图 6),可以得知,特提斯成矿域中新世含矿斑

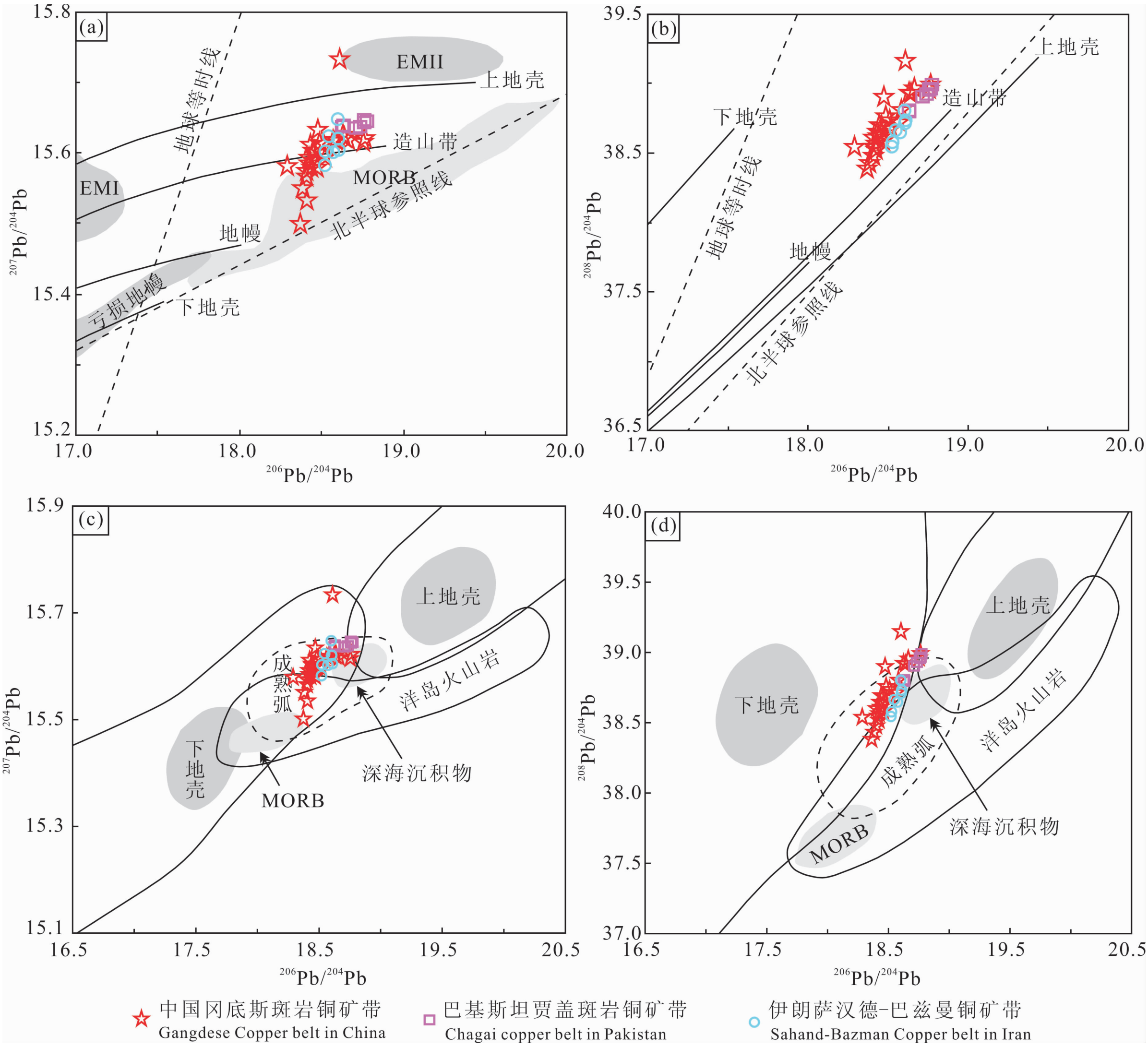

图 4 特提斯成矿域中新世含矿斑岩 Pb 同位素构造演化图解与源区判别图解(底图据 Zartman et al.,1981;Doe et al.,1979)

Fig. 4 Tectonic setting evolution and source divisional diagrams of lead isotope from Miocene ore-bearing porphyries in Tethyan metallogenic domain (base maps from Zartman et al., 1981; Doe et al., 1979)

岩主要来源于受岩浆作用控制的壳幔混合物质,是新特提斯洋岩石圈俯冲及再循环或幔源岩浆注入地壳的产物。其中,异常铅(放射性铅)来源于富含 U、Th 的上地壳物质,表现为 DUPAL 异常。相比而言,贾盖铜矿带和冈底斯铜矿带的数据略向上地壳方向偏移,说明有一定量的上地壳物质参与。

3.3 构造演化及其成矿作用过程

在新特提斯洋板块向北俯冲、阿拉伯板块-欧亚大陆碰撞及印度-亚洲大陆碰撞过程中,以雅鲁藏布江蛇绿岩为代表的新特提斯洋地幔域被大量消减,新特提斯洋岩石圈在俯冲和碰撞过程中以不同方式参与到了弧岩浆作用和某些碰撞后岩浆作用的源区中(Zhao et al.,2001;Hou et al.,2004;Mo et al.,2005;Mo Xuanxue et al.,2006)。始新世初,巴基斯坦及邻区开始受到印度板块与欧亚大陆碰撞的强烈影响(Zhang Hongrui et al.,2009)。渐新世,碰撞过程导致的变质作用和地壳缩短在巴基斯坦北部地区达到顶峰,随后向南逐渐扩展(Searle,1996),贾盖火山岩浆带则是在中伊朗微陆块与阿富汗微陆块拼合期间及之后伴随着特提斯构造域的演化而形成的(Siddiqui et al.,2007;Perelló et al.,2008)。喜马拉雅地区形成了同碰撞的林子宗火山岩和冈底斯花岗岩基(Mo Xuanxue et al.,2003),同时碰撞带附近发生了强烈的逆冲和褶皱作用(Yin et al.,2000)。始新世末-渐新世,阿拉伯板块开始与欧亚大陆碰撞(Agard et al.,2011)。渐新世以来,阿拉伯板块与欧亚大陆全面碰撞,在欧亚大陆南缘形成萨汉德-巴兹曼火山岩浆带(Shafiei et al.,2009;

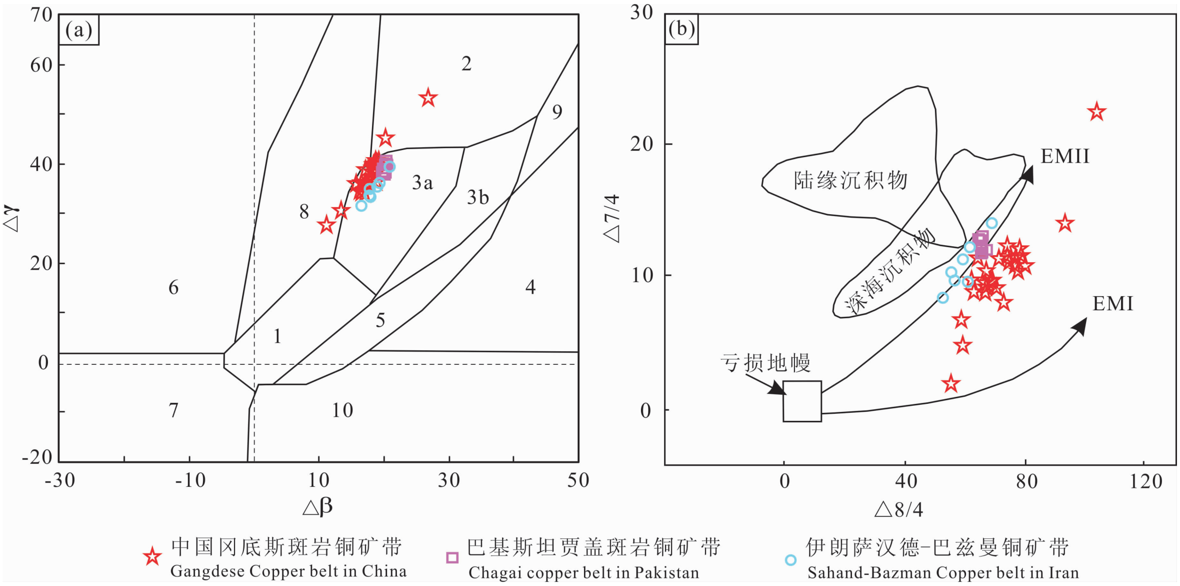

图 5　特提斯成矿域中新世含矿斑岩 Δβ-Δγ 图解和△7/4-△8/4 图解(底图 Zhu Bingquan，1998；Zhong Lifeng et al.，2006)

Fig. 5　Δβ-Δγ and △7/4-△8/4 diagrams of Miocene ore-bearing porphyries in Tethyan metallogenic domain (base maps from Zhu Bingquan, 1998 and Zhong Lifeng et al., 2006)

1—地幔源铅；2—上地壳源铅；3—上地壳与地幔混合的俯冲带铅(3a—岩浆作用；3b—沉积作用)；4—化学沉积型铅；5—海底热水作用铅；6—中深变质作用铅；7—深变质下地壳铅；8—造山带铅；9—古老页岩上地壳铅；10—退变质

1—mantle lead; 2—supracrustal lead; 3—subducted lead from the supracrustal-mantle mixed substances (3a—magmatism; 3b—sedimentation); 4—chemical deposit lead; 5—submarine hydrothermal lead; 6—medium to deep metamorphic lead; 7—deep metamorphic supracrustal lead; 8—orogenic belt lead; 9—ancient shale subcrustal lead; 10—retrograde metamorphic lead

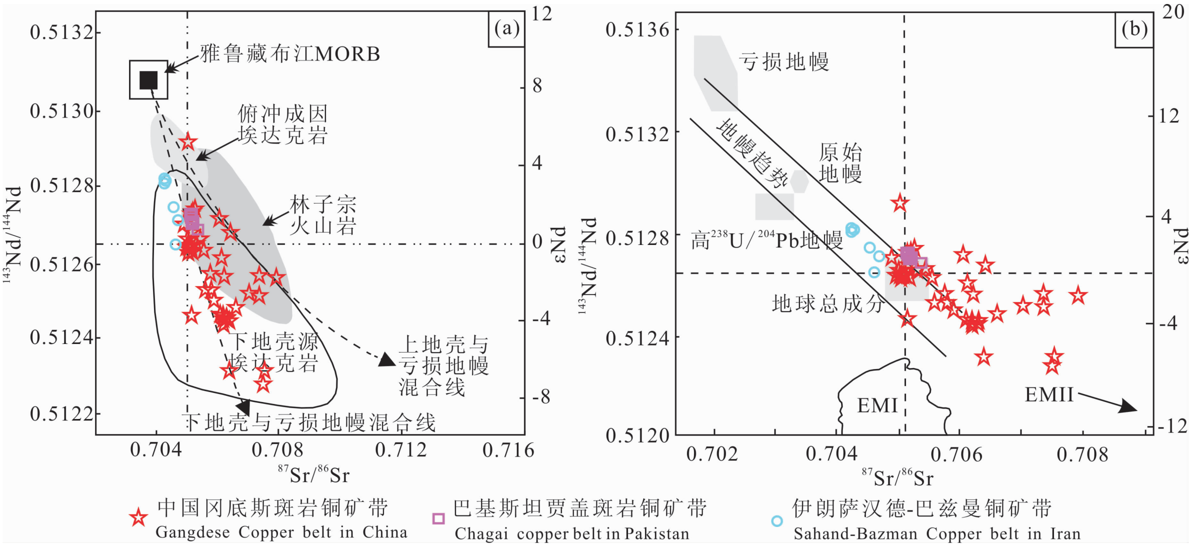

图 6　特提斯成矿域中新世含矿斑岩 ^{143}Nd/^{144}Nd-^{87}Sr/^{86}Sr 图解(底图据 Zindler et al.，1986；Guan et al.，2012)

Fig. 6　^{143}Nd/^{144}Nd-^{87}Sr/^{86}Sr diagrams of Miocene ore-bearing porphyries in Tethyan metallogenic domain (base maps from Zindler et al., 1986 and Guan et al., 2012)

Zhang Hongrui et al.，2015)。铅同位素构造环境演化图解(图 4a、4b)显示，铅主要来源于壳幔混合物质。Δβ-Δγ 成因分类图(图 5a)表明岩浆受到板块俯冲作用的影响。

Mo et al. (2007)研究发现，幔源物质的加入是大陆碰撞之后导致地壳增生加厚的重要因素。特提斯洋俯冲消减作用和亏损地幔物质的加入对原有大陆基底产生大规模的改造作用，导致地壳增生加厚和高原隆升，在俯冲消亡的前缘地区形成大量岛弧型火山岩，记录了大规模的壳幔相互作用和高原岩

石圈演化与隆升过程的信息(Mo Xuanxue et al.,2006;Zhao Zhidan et al.,2007)。前人研究发现,萨汉德-巴兹曼、贾盖、冈底斯斑岩铜矿带的大多数斑岩铜矿产于后碰撞环境中,与中新世岩浆作用密切相关(Zarasvandi et al.,2007;Perelló et al.,2008;Hou et al.,2009a,2015)。微量元素构造环境判别图显示(图 7),表明这些斑岩铜矿形成于后碰撞环境的火山弧中,与下地壳源埃达克岩的主要构造环境(地壳增厚的火山弧或火山弧晚期)一致(Zhu Dicheng et al.,2002)。铅同位素物质源区判别图解显示(图 4c、4d),这些含矿斑岩可能与俯冲的岛弧或洋壳有关,其形成环境为成熟岛弧。

依据 Ryan et al.(1995)指出的岛弧碰撞造山带演化过程可以推测,随着阿拉伯板块、印度板块与欧亚板块的不断碰撞,由于阿拉伯板块和印度板块的北向俯冲作用,俯冲板块脱水降低了地幔楔的初熔温度,诱发了岛弧岩浆作用,而俯冲流体交代软流圈地幔诱发其部分熔融形成高钾钙碱性岩浆,表现为新生地壳的长期生长。伴随着板块的不断俯冲,大陆碰撞导致的地壳挤压缩短和火山弧钙碱性岩浆的底侵作用与增生,导致了明显的地壳加厚与生长(Richards,2009;Zhang Zeming et al.,2019)。在初始的镁铁质下地壳或下地壳源角闪岩堆晶的熔融过程中,上涌的软流圈通过板块断离窗(slab broken window)诱发硫化物的分解,并为含水的高氧逸度(high-f_{O_2})钙碱性长英质岩浆提供金属铜,形成具有埃达克岩特征的高钾钙碱性后碰撞岩浆及相应的斑岩型铜矿床(Hou et al.,2009a,2011,Richards,2009)。Hou et al.(2011,2015)等认为,特提斯成矿域斑岩铜矿与高钾钙碱性岩浆和钾玄质岩浆相关,这些斑岩铜矿既可以产于晚碰撞转换环境和后碰撞伸展环境中,也可以产于陆内伸展环境中。前人研究发现,后碰撞型斑岩铜矿通常产于构造岩浆带中,经历早期俯冲作用和晚期碰撞作用等复杂的演化过程,具有高钾钙碱性特征和埃达克岩地球化学特征,被认为是初始的镁铁质下地壳熔融的产物(Hou et al.,2004,2009a;Shafiei et al.,2009)。特提斯构造域这 3 个铜矿带斑岩体具有高钾、钙碱性的特征,显示典型的埃达克岩的亲和性;同位素特征也显示这些斑岩铜矿来源于壳幔混合物质。结合这三个斑岩铜矿带的区域地质背景、地质特征、地球化学特征、Sr-Nd-Pb 同位素特征,对特提斯成矿域萨汉德-巴兹曼、贾盖、冈底斯斑岩铜矿带的构造演化与斑岩成矿过程做了大致总结归纳。

阿拉伯板块在始新世-渐新世陆续向欧亚大陆汇聚(Agard et al.,2005),阿拉伯板块南侧扎格罗斯被动陆缘沿着萨南达季-锡尔詹(Sanandaj-Sirjan)边缘俯冲(Alavi,1994;Ramsey et al.,2008),导致特提斯洋残留的品都斯洋(Pindos)不断消减,最终形成伊朗扎格罗斯缝合带(Golonka,2004)。中中新世以来,非洲大陆和印度大陆继续俯冲碰撞欧亚大陆,促使品都斯洋最终闭合,萨南达季-锡尔詹板块向阿拉伯板块逆冲,形成扎格罗斯逆冲推覆系统(Golonka,2004;Ramsey et al.,2008)以及与之相关的萨汉德-巴兹曼岩浆带(Shafiei et al.,2009;Hou et al.,2011),该区域出现南北向走滑断层,发

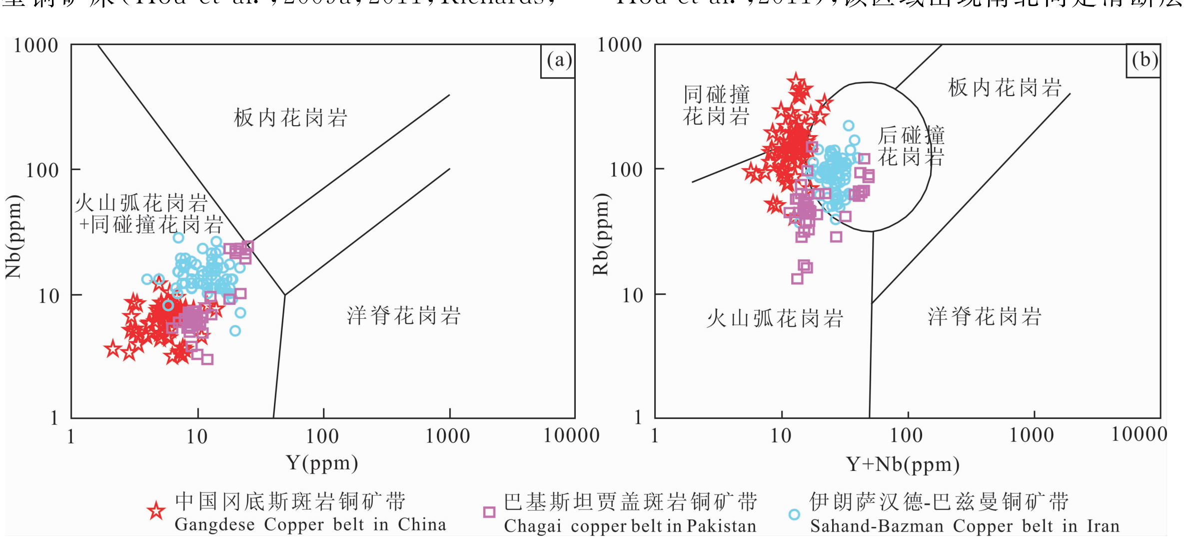

图 7 特提斯成矿域中新世含矿斑岩构造环境判别图图解(底图据 Pearce et al.,1984)

Fig. 7 Discrimination diagrams for the tectonic environment of Miocene ore-bearing porphyries in Tethyan metallogenic domain (base map sourced from Pearce et al., 1984)

育钾质、超钾质和碱性岩石,表明进入后碰撞阶段(Ghadami et al.,2008;Kheirkhah et al.,2009;Mirnejad et al.,2010;Chiu et al.,2013;Zhang Hongrui et al.,2015)。在阿拉伯板块向中伊朗板块之下俯冲的过程中,萨汉德-巴兹曼地区发育NE向褶皱逆冲带、走滑断裂及其派生构造控制(Zarasvandi et al.,2005,2007;Jahangiri,2007),为岩浆的侵位和流体的运移提供了通道,早期俯冲阶段的弧岩浆在下地壳底垫,导致上地壳的加厚(Zhang Hongrui et al.,2015)。被弧岩浆底垫加厚的下地壳部分熔融,形成含铜埃达克质岩浆,含铜岩浆向上运移时,Mo和部分S等壳源物质不断加入,受挤压环境影响,在上地壳沉淀冷凝成富含矿斑岩体以及相应的斑岩型Cu-Mo矿床(Shafiei et al.,2009;Zhang Hongrui et al.,2015)。

巴基斯坦及邻区在始新世初开始受到印度板块与欧亚大陆碰撞的强烈影响(Zhang Hongrui et al.,2009)。渐新世以来,随着碰撞过程的不断进行,巴基斯坦持续遭受变质作用和地壳缩短的影响(Searle,1996),巴基斯坦贾盖地区在安第斯型构造背景中经历早中新世、中中新世和晚中新世-早上新世岩浆作用和斑岩铜矿化,大面积出露新近世火山岩、始新世-渐新世贾盖侵入体和中新世索尔科侵入岩(Perelló et al.,2008;Lü Pengrui et al.,2015a)。晚渐新世-中新世,随着新特提斯洋的闭合,阿拉伯板块、印度板块与欧亚板块的不断碰撞,在持续的挤压条件下,贾盖火山岩浆岩带发生了一系列的构造形变,发育了大量的逆冲断裂系统和背斜,不仅控制了含矿斑岩的侵位,还提供了有利的导矿/容矿场所(Lü Pengrui et al.,2015a)。在俯冲消减和大陆碰撞过程中,增厚下地壳熔融形成富含Cu-Au的埃达克质岩浆,并在石英闪长斑岩和花岗闪长斑岩中产出斑岩型Cu-Au矿床。

青藏高原碰撞造山伴随着印度大陆与欧亚大陆持续汇聚,在始新世-渐新世进入晚碰撞阶段,形成陆内俯冲、大规模逆冲推覆、走滑断裂系统,导致藏东富碱斑岩、碳酸岩-正长岩,藏北钾质-超钾质火山岩的大规模产出(Hou Zengqian et al.,2006b,2006c)。渐新世开始,青藏高原碰撞造山进入后碰撞阶段,下地壳流动与上地壳缩短形成了EW向延伸的藏南拆离系,地壳伸展与裂陷作用造成了一系列NS向正断层系统及其围限的裂谷系和裂谷盆地(Hou Zengqian et al.,2006b,2006d)。在冈底斯快速隆升的后碰撞伸展环境中,该区域长英质岩浆侵位与中新世钾质-超钾质火山活动相伴发育,形成钾质钙碱性熔岩和数量众多的花岗质斑岩体(Coulon et al.,1986;Qu Xiaoming et al.,2002),由增厚下地壳熔融产物形成的埃达克岩沿着近SN向正断层系统,侵位于古新世-渐新世末同碰撞花岗岩基之中,形成冈底斯铜矿带的斑岩Cu-Au矿床。

4　结论

(1)特提斯成矿域中新世斑岩铜矿总体显示钙碱性I型花岗岩的特征,具有埃达克岩的亲合性。与冈底斯铜矿带相比较,萨汉德-巴兹曼铜矿带和贾盖铜矿带含矿斑岩显示出弧岩浆岩与埃达克岩过渡的地球化学特征,其岩浆源区MORB质角闪榴辉岩或榴辉岩可能发生的较大程度的部分熔融。

(2)特提斯成矿域中新世含矿斑岩属于下地壳源埃达克岩,主要来源于受岩浆作用控制的壳幔混合物质,是新特提斯洋岩石圈俯冲及再循环或幔源岩浆注入地壳的结果。其中,异常铅(放射性铅)来源于富含U、Th的上地壳物质,表现为DUPAL异常。与萨汉德-巴兹曼铜矿带相比较,贾盖铜矿带和冈底斯铜矿带有更多的上地壳物质参与。

(3)特提斯成矿域中新世斑岩铜矿可能是在岛弧碰撞造山带演化过程中,伴随着特提斯构造域的演化而形成的,是洋壳俯冲消减和大陆碰撞过程中增厚下地壳部分熔融的结果。

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Petrogenesis, source, tectonic evolution and mineralization process of the Miocene porphyry Cu deposits in the Tethyan metallogenic domain

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Abstract

Several world class ore-forming belts (deposits) such as the Pontides, the Sahand-Bazman, the Chagai, the Yulong and the Gangdeseoccur in the Tethyanmetallogenic domain, referred to as one of the three giant metallogenic domains. In order to further understand the genesis and mineralization of Miocene porphyry copper deposits in the Tethyan domain, the geological, geochemical and Sr-Nd-Pb isotopic data of ore-bearing porphyries from typical porphyry Cu deposits in the Sahand-Bazman, the Chagai and the Gangdese belts have been analyzed and compared, their petrogenesis, source and tectonic environment have been discussed, and their tectonic evolution and metallogenic process have been deduced and summarized in this paper. The geochemical results suggest that the Miocene porphyries in these three belts show the characteristics of calc-alkaline I-type granite, with adakite magmatic affinity. Compared with the lithogeochemical features of porphyries in the Gangdese belt, the ones in the Sahand-Bazman and the Chagai belts show the transitioning characteristics from arc magmatic suites to adakites, which might be caused by the partial melting of MORB-derived amphibole eclogite or eclogite occurred in the magma source with a greater degree. The Sr-Nd-Pb isotopic data suggests that these ore-bearing porphyries might have been sourced from a mixture of crust and mantle controlled by magma, showing DUPAL anomaly. After comprehensively analyzing the geological, geochemical and isotopic characteristics of these porphyry deposits, it is believed that these ore-bearing porphyries were formed in the island arc setting of collision-orogenic belt, serving as the partial melting products of thickened lower crust during the subduction of oceanic crust and the continental collision.

Key words: porphyry Cu deposits; Miocene; petrogenesis; source; tectonic evolution; mineralization; Tethyan