

特提斯成矿域主要金属矿床类型与成矿过程^{*}

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摘 要 作为全球三大巨型成矿域之一的特提斯成矿域目前尚缺少系统的研究和总结。特提斯构造带是欧亚大陆南部一条全球性纬向展布的构造带,夹持于东欧、哈萨克、塔里木、华北、扬子、印度支那地块和印度、阿拉伯、非洲板块之间,由若干个小陆块,如 Anatolides、外高加索、Alborz、伊朗中部、鲁特、阿富汗、帕米尔、南羌塘、北羌塘、拉萨、保山、中缅马苏、西缅甸等,及陆块中间的造山带组成,是在晚古生代到新生代期间,古、新特提斯洋扩张与闭合过程中,历经两次大规模的板块俯冲、碰撞形成的。这一过程可主要概括为冈瓦纳大陆的裂解以及欧亚大陆的增生,其中欧亚主动大陆边缘和冈瓦纳被动大陆边缘起了主要的控制作用。特提斯成矿域复杂的地质演化过程注定了其成矿具多金属、多类型的特征,漫长的空间展布决定了其金属堆积的连续成带性,其中的一些重要成矿带全球著名。文章在特提斯成矿域中识别出了 6 种主要的成矿作用,分别形成斑岩型 Cu-Mo-Au、与岩浆热液有关的 Sn-W、岩浆型铬铁矿、VMS 型 Cu-Pb-Zn、浅成低温热液型 Au-Hg-Sb 及与沉积岩有关的 Pb-Zn 等矿床。这些矿床都是在洋盆扩张、洋陆俯冲、大陆碰撞等地球动力学背景中形成的。与环太平洋、古亚洲等增生型造山带相比,特提斯成矿域中也保存了众多与俯冲作用相关的矿产,如斑岩矿床、浅成低温矿床、VMS 矿床等。另外,特提斯成矿域中还有大量矿床的形成与碰撞环境密切相关,如东南亚锡多金属成矿带、Sahand-Bazman 铜矿带,以此区别于典型的增生型成矿域。

关键词 地质学 特提斯构造演化 成矿作用 成矿背景 地球动力学 特提斯成矿域

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Metallogenesis and geodynamics of Tethyan metallogenic domain: A review

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Abstract

Recent research on the geodynamic and ore genetic processes has aroused much interest among geologists all over the world. It is a regret that the Tethyan metallogenic domain (TMD), as an ideal case, is less documented and does not have systematical analysis and summary in comparison with other metallogenic domains such as the Circum-Pacific and the Central-Asia. The Tethys is a global latitudinal tectonic belt in the southern margin of Eurasia continent, located between Eastern European platform, Kazakhstan block, Tarim, North China, Yangtze, Indo-China, Arabian craton, Indian plate and African plate and composed of terrains of Anatolides, Transcaucasia, Alborz, Lut, Central Iran, Afghanistan, Pamirs, Northern Qiangtang, Southern Qiangtang, Lhasa, Baoshan, Sibumasu and Western Myanmar as well as the orogenic belts among these blocks. It was formed by two stage subduction and collision between these blocks which commenced in Late Palaeozoic and continued to Cenozoic, called Paleo- and Neo-Tethyan tectonic events.

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The Eurasian active margin and the Arabian passive margin played a major role in the geodynamic process of Tethys formation. The Tethyan metallogenic domain (TMD) has a very complex tectonic evolution process and wide spatial distribution, implying multiple types and extraordinary polymetallic concentration. In this metallogenic domain important gold, copper, base metals and tin ore belts comprising a large number of giant deposits are developed. Some metallogenic belts of TMD are famous in the world, such as the Sahand-Bazman porphyry copper belt, the Gangdese porphyry copper belt and the Southeast Asian tin belt. The main types of ore deposits include porphyry Cu-Mo-Au deposits, hydrothermal Sn-W mineralization related to granites, magmatic podiform chromite deposits formed in the ophiolite zone, VMS-type Cu-Pb-Zn deposits, epithermal Au-Hg-Sb deposits characterized by either low-sulfidation or high-sulfidation, and sediments-hosted Pb-Zn deposits. The distribution of ore deposits reflects the differences in structural and tectonic setting. Many of the ore deposits are spatially and temporally related to plate motion in the global geodynamic setting. The abundant mineral deposits in TMD were formed in major pulses, coincident with episodes of Tethys evolution. The Paleo-Tethyan oceans were closed in Late Triassic. As a branch ocean of Paleo-Tethyan oceans, the Garze-Litang oceanic plate subducted westwards, forming the Yidun island-arc. The Zhongdian porphyry Cu polymetallic belt which occurs in Zhongdian calc-alkaline volcano-magmatic complexes is located in the southern segment of Yidun island-arc, whereas the Gacun VMS deposit formed in the intra-arc rift zone is located in the northern segment. The Neo-Tethyan oceans were rifted and spread in Jurassic, causing the northern margin of Indian plate to become a passive margin. Cyprus type VMS deposits and chromites occur in the ocean middle ridge, and Pakistan Lasbela-Khuzdar SEDEX belt occurs in the passive margin. Many magmatic arcs containing porphyry deposits were formed during the subduction of the Neo-Tethyan ocean in Cretaceous, such as Bangonghu and Pontides. The latter also has epithermal deposits in the shallow-level of arc and Kuroko type VMS deposits in the backarc rift zone. Porphyry and related epithermal deposits have been formed in the collision belt since Eocene, such as Sanjiang and Gangdese in China and Sahand-Bazman in central Iran. The Mississippi Valley-type deposits (MVT) were formed in a distal environment by basin-wide fluid flow induced by collision effect. The collision and collage of the Indo-China terrain with Sibumasu, Western Myanmar and Indian plate along the suture of Inthanon, Shan Boundary and Woyla that commenced in Triassic and continued to Cretaceous resulted in the formation of southeast Asia mainland. The magmatic activity caused by prolonged collision led to the formation of the Southeast Asian tin belt. Orogenic gold deposits are obviously less related to Cordilleran-type metallogenic domain, such as the Circum-Pacific and the Central-Asia. Lots of ore deposits were formed during the collision process in TMD, which is noticeably different from things in Cordilleran-type metallogenic domain.

Key words: geology, tectonic evolution of Tethys, metallogenesis, metallogenic setting, geodynamics, the Tethyan metallogenic domain

特提斯成矿域是全球三大成矿域(环太平洋、特提斯、古亚洲)之一,该成矿域西起地中海西部,向东经阿尔卑斯、土耳其、伊朗中北部、巴基斯坦、阿富汗,经帕米尔延至喜马拉雅,再向南转向中南半岛,止于印尼苏门答腊(Sumatra)群岛,东西向延伸逾 10 000 km,赋存有东南亚锡矿带、玉龙铜矿带、冈底斯铜矿带、萨尔切什梅(Sar Cheshmeh)斑岩铜矿等世界级规模矿带(床),成矿规模和资源潜力足以与环太平洋和古亚洲成矿域相媲美。更难得的是,特提斯成矿域还完好记录了特提斯洋盆裂解→扩张→俯冲→碰撞的完整演化过程,增生造山与碰撞造山连续发育,成矿作用丰富多彩,显示了复合型成矿域特色,以此区别于环太平洋和古亚洲增生型成矿域,因此,对其进行研究和总结无疑具有重大的科学意义。

然而,限于地区研究程度的差异,现有的特提斯成矿域研究资料或是局限于特定地区(如 Sillitoe, 1978; Hou et al., 2007; Yigit, 2006; 2009),或是着眼于单个矿种(如 Jankovic, 1977; Vassileef et al., 1988; 张洪瑞等, 2009),对于整个成矿域缺少宏观把握。本文对特提斯成矿域中的主要成矿类型进行梳理总结,并结合构造演化来试述成矿过程,以期对特提斯成矿域的区域成矿规律有初步认识。

1 特提斯构造演化

Suess(1893)第一次提出“欧亚大陆上曾经横贯着一个大洋,沿喜马拉雅和阿尔卑斯山脉走向延伸”,并被命名为“Tethys”。此后,不同的学者对特提斯赋予了不同的含义。百余年来,特提斯的形成和演化等问题逐渐变得清晰明朗。现在人们认识到,特提斯成矿域是欧亚大陆南部一条全球性纬向展布的构造带(潘桂棠, 1994),夹持于东欧、哈萨克、塔里木、华北、扬子、印度支那地块和印度、阿拉伯、非洲板块之间,由若干个小陆块,如 Anatolides、外高加索(Transcaucasia)、Alborz、伊朗中部、鲁特、阿富汗、帕米尔、南羌塘、北羌塘、拉萨、保山、中缅马苏(Sibumasu)、西缅甸等,及陆块中间的造山带组成(图 1),是在晚古生代到新生代期间,古、新特提斯洋扩张与闭合的过程中,历经两次大规模的板块俯冲和碰撞形成的(如 Sengor, 1979; 1987)。

1.1 古特提斯洋盆演化

早古生代时,塔里木、华北等地块的古生物面貌仍与冈瓦纳大陆具有亲缘性,表明当时这些陆块在冈瓦纳大陆北缘,古特提斯洋盆尚未开启(Metcalf, 1996; 2002)。古地磁数据表

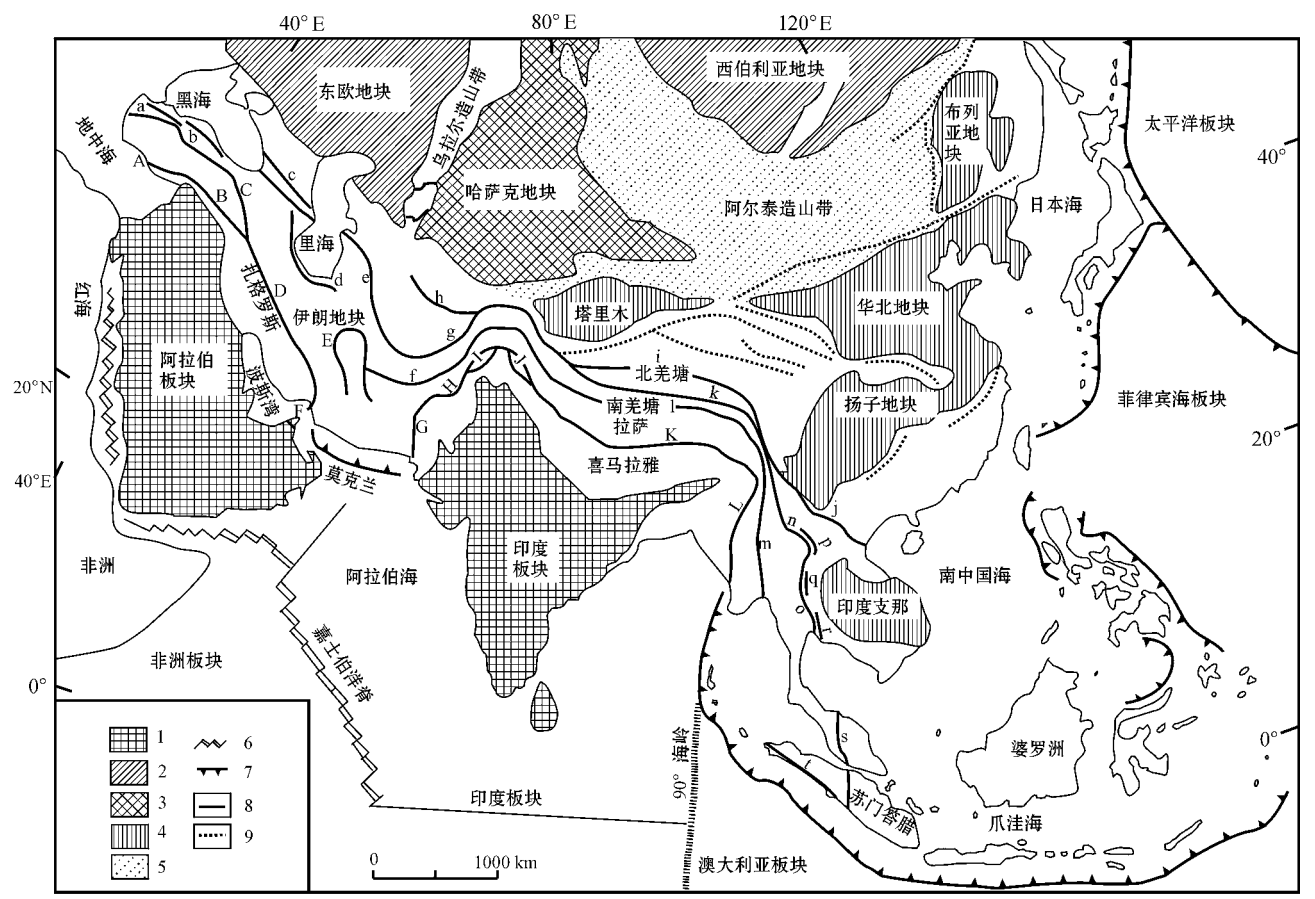


图 1 特提斯构造格架示意图(据 Sengor ,1987 Sengor et al. ,1996 Glennie 2000 ; Metcalfe ,1996 ;1998 2002 ; Robertson 2002 ;李才等 2006 Sorkhabi et al. 2008 等综合汇编)

古特提斯缝合带：a—北土耳其；b—卡拉卡亚；c—小高加索；d—Talesh-Mashhad；e—Kopet Dagh；f—Water (Farah-Rud)；g—北帕米尔；h—South Ghissar；i—金沙江 j—哀牢山；k—龙木错-双湖；l—班公湖-怒江；m—Shan Boundary；n—澜沧江；o—Inthanon；p—景洪；q—Nan-Uttaradit；r—Sra Kao；s—Raub-Bentong；t—Woyla。新特提斯缝合带：A—塞浦路斯；B—比特利斯；C—伊兹密尔；D—扎格罗斯；E—环伊朗中部；F—阿曼；G—Bela；H—Waziristan；I—Quetta；J—Ladakh；K—雅鲁藏布江；L—缅甸。1—前寒武纪冈瓦那地盾；2—前寒武纪劳亚地盾；3—哈萨克地块；4—晚古生代亚洲增生地块；5—阿尔泰造山带(古生代)；6—现代洋中脊；7—现代俯冲带；8—特提斯成矿域主要缝合带；9—特提斯构造域的其他缝合带

Fig.1 Tectonic framework of Tethyan metallogenic domain(modified after Sengor ,1987 Sengor et al. ,1996 ; Glennie 2000 ; Metcalfe ,1996 ;1998 ;2002 ;Robertson 2002 ;Li et al. 2006 ;Sorkhabi et al. 2008)

Palaeo-Tethyan sutures :a—North Turkey ;b—Karakaya ;c—Lesser Caucasus ;d—Talesh-Mashhad ;e—Kopet Dagh ;f—Water (Farah-Rud) ;g—North Pamir ;h—South Ghissar ;i—Jinshajiang ;j—Ailaoshan ;k—Longmucuo-Shuanghu ;l—Bangonghu-Nuijiang ;m—Shan Boundary ;n—Lancangjiang ;o—Inthanon ;p—Jinghong ;q—Nan-Uttaradit ;r—Sra Kao ;s—Raub-Bentong ;t—Woyla. **Neo-Tethyan sutures** :A—Cyprus ;B—Bitlis ;C—Izmir-Ankara-Erzincan ;D—Zagros ;E—Circum-Central Iran ;F—Oman ;G—Bela ;H—Waziristan ;I—Quetta ;J—Ladakh ;K—Indus-Yarlung-Zangbo ;L—Myanmar. 1—Precambrian cratons of Gondwana ;2—Precambrian cratons of Laurasia ;3—Kazakhstan block ;4—Continental blocks accreted to Asia(late Paleozoic) ;5—Altaids (Paleozoic) orogen ;6—Modern ridges ;7—Modern subduction zones ;8—Tethysides with major sutures including Paleo-Tethys and Neo-Tethys ;9—Tethysides with other sutures

明,大约在晚泥盆世—晚石炭世,胡安(Hun)陆块和扬子地块、华北地块陆续从冈瓦纳大陆向北漂移,古特提斯洋开始形成(Stampfli 2000)。古特提斯洋盆的裂解在扬子陆块上形成了晚泥盆世—早石炭世的巨大不整合(Metcalfe ,1996)。胡安陆块与北半球的东欧陆块、北美陆块碰撞组成劳亚大陆,而扬子地块、华北地块等则散布在古特提斯洋盆中(图 2)。

二叠纪左右,劳亚大陆与冈瓦纳大陆拼合形成潘吉亚(Pangea)超大陆,古特提斯洋盆呈向东打开的喇叭状,但东部海域并不是一望无际的广阔大洋,而是一个由多陆块、多洋盆和多岛弧相间排布而成的大洋体系(潘桂棠等 2001 2004)。

二叠世末,基梅里陆块群(包括外高加索、伊朗中部、南阿富汗、南帕米尔、羌塘、中缅马苏等一系列小陆块, Sengor ,

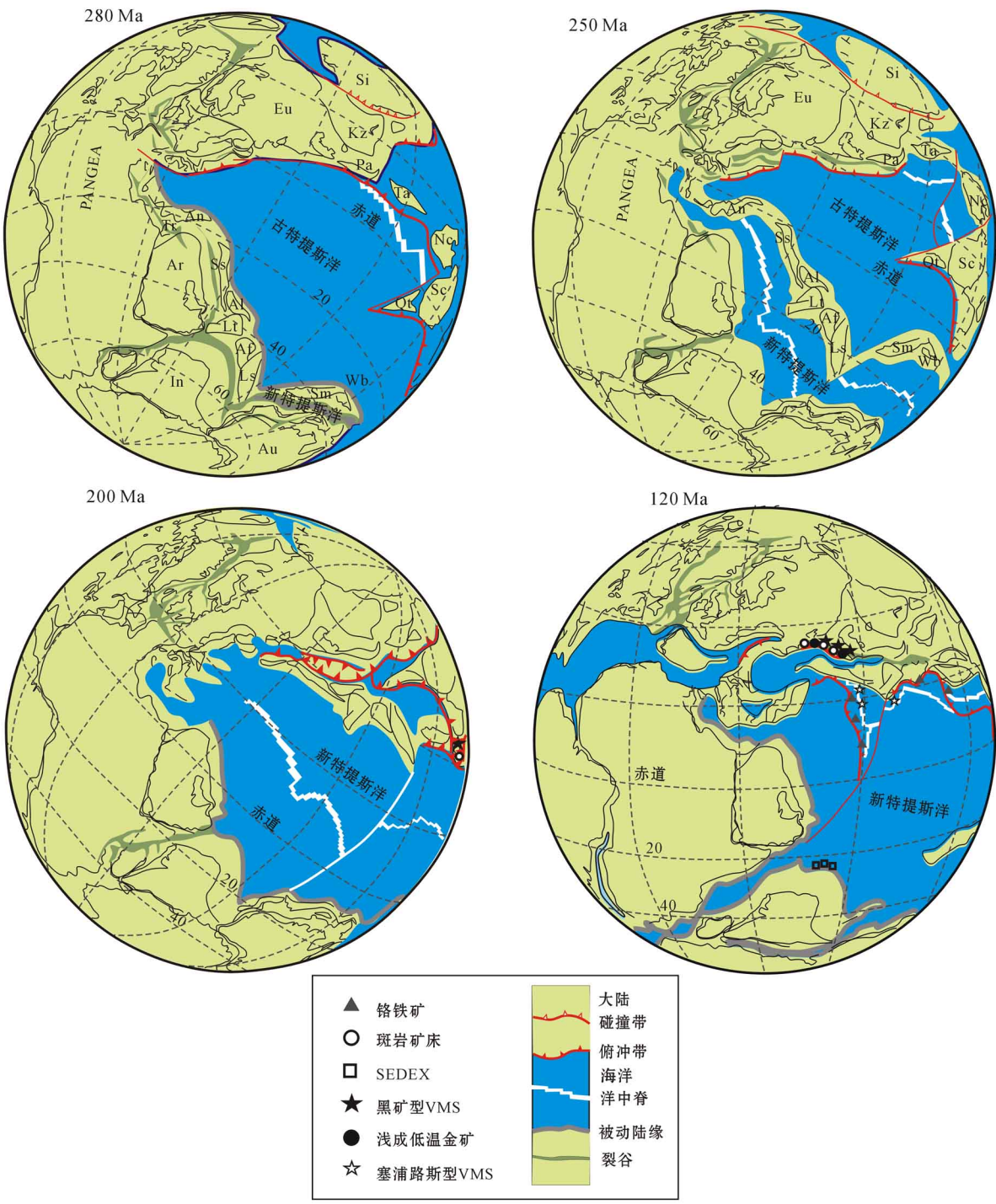


图 2 特提斯复原图及相关矿产(复原图引自 Stampfli et al. , 1991; 2000; 2002a; 2002b; Ferrari et al. , 2008)

Eu—东欧; Ar—阿拉伯; Au—澳大利亚; Si—西伯利亚; Kz—哈萨克斯坦; Ta—塔里木; Nc—华北; Sc—扬子; Sm—中缅马苏; Qt—羌塘; Ls—拉萨; Wb—西缅甸; Af—阿富汗; Lt—鲁特-伊朗中部; Al—Alborz; Ss—Sanandaj-Sirjan; An—Anatolides; Tr—外高加索; Pa—帕米尔

Fig. 2 Reconstruction of the Tethyan metallogenic domain and its related deposits(reconstruction map from Stampfli et al. , 1991; 2000; 2002a; 2002b; Ferrari et al. , 2008)

Eu—Eastern Europe; Ar—Arabia; Au—Australia; Si—Siberia; Kz—Kazakhstan; Ta—Tarim; Nc—North China; Sc—Yangtze; Sm—Sibu Ma-su; Qt—Qiangtang; Ls—Lhasa; Wb—Western Myanmar; Af—Afghanistan; Lt—Lut-Central Iran; Al—Alborz; Ss—Sanandaj-Sirjan; An—Anatolides; Tr—Transcaucasia; Pa—Pamirs

1987; Metcalfe, 1996; 1997; Ueno, 2003) 从冈瓦纳大陆北缘裂解 (Sengor, 1979) 打开了新特提斯洋。此次裂解事件使冈瓦纳大陆北侧的 Zagros 地区在二叠纪—三叠纪时期一直表现为裂谷环境 (Stocklin, 1974), 昌宁-孟连洋盆西侧的保山地区则发育以卧牛寺组为代表的大陆裂谷拉斑玄武岩 (从柏林等, 1993)。

随着新特提斯洋盆的扩张, 基梅里陆块群南北两侧发育成被动大陆边缘, 其岩石记录有阿曼的玄武岩, 澳大利亚西北缘的辉绿岩、流纹岩等双峰式岩石组合 (Veevers, 2004); 同时基梅里陆块群的向北漂移到古特提斯洋消减闭合提供了动力 (图 2, Metcalfe, 1996; 2002; Bortolotti et al., 2005), 劳亚大陆南缘发展成主动大陆边缘, 形成与之配套的沟-弧-盆体系。古特提斯洋盆在东部海域的分支——昌宁-孟连洋盆向印度支那板块俯冲, 在印度支那板块边缘形成 Sukhothai 岛弧岩浆系统 (Ueno et al., 2001), 弧内发育浅水沉积岩和二叠纪-三叠纪的 I 型花岗岩 (Rb-Sr 年龄 $280 \sim 210$ Ma), 弧后拉张形成景洪-Nan-Sra Kaeo 洋盆 (Sone et al., 2008), 金沙江-哀牢山洋盆向昌都-思茅地块俯冲并形成火山-岩岩浆弧 (吉义独埃达克质花岗岩闪长岩年龄 263 ± 6 Ma, Jian et al., 2008), 同时导致中咱地块从扬子地块西缘裂离, 其间发育成甘孜-理塘洋 (Hou, 1993; Mo et al., 1994; Hou et al., 2007)。二叠纪古特提斯板片俯冲回撤 (rollback) 使得 Anatolides 从亚欧大陆上裂离, 成为漂浮块体 (Moix et al., 2008)。

劳亚大陆南缘的沟-弧-盆体系一直持续到三叠纪, 甘孜-理塘洋盆向西俯冲生成义敦岛弧带 (Mo et al., 1994; 侯增谦等, 2004b)。长期的俯冲终于使得大量弧后洋盆萎缩关闭, 如景洪-Nan-Sra Kaeo 洋盆, 形成弧后杂岩带, 其基性片岩的阳起石 K-Ar 年龄为 262 Ma, 代表了仰冲就位年龄 (Sone et al., 2008), 昌都-思茅地块也重新拼合到扬子微大陆之上 (从柏林等, 1993), 进入前陆盆地演化阶段 (潘桂棠等, 1997)。

最终在三叠纪末原基梅里陆块群与劳亚大陆拼合, 古特提斯主洋盆闭合 (图 2)。其间经历了复杂的增生造山和弧-陆碰撞过程, 在劳亚大陆南缘留下多条缝合带, 如南羌塘地块与北羌塘地块之间的龙木错-双湖缝合带 (李才, 1987; 李才等, 2006), 北羌塘地块与扬子地块之间的金沙江-哀牢山缝合带 (潘桂棠等, 1997; Wang et al., 2000), 中缅马苏地块与印度支那板块间的澜沧江 (昌宁-孟连)-Inthanon-Raub-Bentong 缝合带 (Metcalfe, 2000; Sone et al., 2008); 伊朗中部地块、Alborz-阿富汗地块等 (Bagheri et al., 2008) 与北侧的东欧板块、Tulan 地块拼贴, 形成伊朗北部的小高加索 (Lesser Caucasus) 缝合带 (Guest et al., 2006, 2007; Hassanzadeh et al., 2008) 和土耳其北部的 Karakaya 缝合带 (Stampfli, 2000), 此后进入陆内演化阶段, 早侏罗纪 Shemshak 组陆相沉积不整合覆盖于蛇绿岩带之上 (Hassanzadeh et al., 2008)。

晚三叠世大量陆块拼合并没有改变特提斯东部海域的多岛洋格局, 此时, 拉萨地块、西缅甸地块等漂浮在新特提斯洋盆中。它们大约在侏罗纪末与欧亚大陆汇聚, 形成西藏地

区的班公湖-怒江缝合带 (Shi et al., 2008), 缅甸的 Shan Boundary 缝合带和印度尼西亚苏门答腊岛上的 Woyla 缝合带等 (Metcalfe, 1994; 1997; 1998, 2002)。

1.2 新特提斯洋盆闭合

侏罗纪初潘吉亚超大陆全面裂解 (Veevers, 2004), 印度板块和澳大利亚板块向北漂移, 造成了新特提斯洋盆的消减 (图 2), 洋盆沿已拼合到欧亚大陆上的 Pontides、外高加索和伊朗地块等南缘向北俯冲 (Spakman, 1986), 在伊朗中部地区形成 Sanandaj-Sirjan 钙碱性岩浆弧和 Siah Kuh 花岗岩基 (Shahabpour, 2005)。弧后拉张形成了一系列弧后洋盆, 如大高加索地区的古南里海 Izanca 洋盆 (Golonka, 2004), 土耳其地区的 Vardar 洋盆 (Stampfli et al., 2002a)。

白垩纪末, 伊朗 Sanandaj-Sirjan、小高加索、莫克兰等微板块在高加索-里海地区与伊朗-阿富汗板块拼贴 (Golonka et al., 2000)。与此同时, 这些微板块南缘也由被动陆缘演变为主动陆缘, 阿拉伯板块沿此边缘向北运动, 推动新特提斯洋的继续消减。这次洋盆消减生成了一系列火山岩岩浆弧: 在巴基斯坦东北部形成科西斯坦 (Kohistan) 岛弧带 (Pivnik et al., 1996); 在喜马拉雅地区生成南冈底斯岩浆弧 (潘桂棠等, 2006); 在土耳其地区, Vardar 洋盆向北俯冲, 形成 Pontides 造山带岛弧钙碱性火山岩浆系 (Moix et al., 2008), 森诺期火山弧岩浆活动布满全区, 该火山岩浆岩带向东一直延续到 Alborz 西部地区 (Alavi, 1996)。

古新世初, 非洲大陆的北移造就了新特提斯主体洋盆的闭合, 形成以 Izmir-Ankara-Erzincan 为代表的缝合带 (Moix et al., 2008)。个别残留洋盆和弧后扩张盆地, 如侏罗纪—白垩纪弧后系统、南里海盆地、Alborz Basin 和西南黑海盆地里的第三系洋盆等一直延续至今 (Golonka, 2004)。

1.3 大陆碰撞

新特提斯洋盆的闭合造成了印度、阿拉伯板块与欧亚大陆的碰撞, 这些碰撞是大陆内汇聚的典型代表, 形成单一的缝合带, 绵延数千公里, 从土耳其西部的塞浦路斯 (Cyprus) 向东到土耳其的比特利斯 (Bitlis), 沿伊朗的扎格罗斯 (Zagros) 向东南方向入阿曼湾, 在洋底以莫克兰 (Makran) 海沟的形式出现, 然后在巴基斯坦登陆, 在巴基斯坦境内为北东向 Bela-Waziristan-Quetta 缝合带, 经帕米尔 Karakoram 后与雅鲁藏布江缝合带 (IYS) 相接, 后者呈弧形在缅甸入印度洋 (图 1; Sengor, 1987; Sengor et al., 1996; Sorkhabi et al., 2008)。

印度与欧亚大陆大约在古新世发生碰撞, 强烈碰撞一直沿续至 41 Ma (侯增谦等, 2006a, 2006b)。伴随着大陆碰撞, IYS 以南的喜马拉雅地区发生强烈的逆冲褶皱, 形成前陆冲断带 (Searle, 1996; Yin et al., 2000); IYS 以北发育厚达 5 000 m 林子宗同碰撞火山岩和冈底斯花岗岩基 (莫宣学等, 2003), 形成青藏高原雏形。伴随印度与欧亚大陆的持续汇聚, 于始新世—渐新世进入晚碰撞阶段 (40~26 Ma), 在印度大陆的东、西两侧, 沿碰撞缝合带或早期岩石圈不连续带发生大规模走滑活动, 形成有金沙江、Chanman 大型走滑系统 (Sil-

litoe, 1978), 伴有部分块体逃逸, 从而调节了大陆碰撞引起的地壳缩短和应力应变(侯增谦, 2006a, 2006c)。渐新世开始青藏高原碰撞造山进入后碰撞阶段, 早期的下地壳流动与上地壳缩短作用(25~18 Ma)在藏南地区形成 EW 向延伸的藏南拆离系(STDs), 在拉萨地体发育 EW 向展布的逆冲断裂系; 晚期的地壳伸展与裂陷作用(< 18 Ma)形成一系列横切青藏高原的 NS 向正断层系统及其围陷的裂谷系和裂陷盆地(侯增谦, 2006a, 2006d)。

Zagros 地区主要构造单元的交切关系和沉积事件将阿拉伯板块与伊朗中部地块开始碰撞的时限限定为始新世-渐新世末(25~23 Ma, Agard et al., 2005)。这次碰撞是一个多阶段的、累积的过程, 至少造成了 2 个小洋盆的闭合(Glennie, 2000), 同时还伴有大规模岩体侵位, Sanandaj-Sirjan 地块向阿拉伯板块上逆冲, 形成 Zagros 逆冲推覆系统(Golonka, 2004); 早中新世—中中新世为晚碰撞阶段, 伊朗地块和 Anatolides 地块地壳缩短, 块体隆升, 走滑系统发育, 形成 Anatolian 大型走滑系统(Sengor, 1981), Anatolides 地块沿此向西逃逸(Gursoy et al., 2008); 晚中新世进入后碰撞阶段, 大量钙碱性、碱性小岩株遍布全区(Sengor et al., 2008)。

2 特提斯成矿域主要矿床类型

特提斯成矿域复杂的地质演化过程注定了其成矿具多金属、多类型的特征, 漫长的空间展布决定了其金属堆积的连续成带性, 其中一些成矿带全球著名。本文在特提斯成矿域中识别出了 6 种主要矿床类型, 分别有斑岩型 Cu-Mo-Au、与岩浆热液有关的 Sn-W、岩浆型铬铁矿、VMS 型 Cu-Pb-Zn、浅成低温热液型 Au-Hg-Sb 及与沉积岩有关的 Pb-Zn 等矿床。

2.1 斑岩型 Cu-Mo-Au 矿床

特提斯成矿域中的斑岩矿床储量丰富, 自土耳其境内, 沿着小高加索山经亚美尼亚到伊朗西北部, 经伊朗中部、南部到阿曼湾, 然后在巴基斯坦向东北, 通过我国的喜马拉雅, 一直到缅甸的蒙育瓦(Monywa)构成了一条世界级规模的巨型斑岩铜矿带。其中, 伊朗的萨尔切什梅(Sar Cheshmeh)、松贡(Sungun)、巴基斯坦的赛因德格(Saindak)和西藏的驱龙等都是世界级超大型斑岩矿床。

如此巨大的成矿带很早就引起了研究学者的关注(Jankovic, 1977; Vassileef et al., 1988), 但囿于基础资料的匮乏, 深入细致研究成为无根之木。根据斑岩铜矿床的特征、空间分布及其构造背景, 张洪瑞等(2009)将特提斯域中的斑岩矿床梳理出土耳其 Pontides、伊朗中部 Sahand-Bazman、巴基斯坦 Chagai、中国玉龙、中甸、班公湖、冈底斯 7 条斑岩矿床成矿带和中南半岛、土耳其 Anatolides 地块 2 个斑岩矿床成矿区(图 3)。

土耳其 Pontides 斑岩铜矿带(也称北土耳其成矿带, Yavuz et al., 1999)位于土耳其北部 Pontides 造山带中, 南部

以 Izmir-Ankara-Erzincan 缝合带与 Anatolides 造山带相隔, 西接 Balkanic 造山带, 东连高加索(Caucasus)造山带。Pontides 造山带在中生代一直位于活动大陆边缘, 广泛分布与弧相关的火山岩岩浆带(Moix et al., 2008)。斑岩铜矿即产于这条火山岩岩浆带中, 矿床类型为斑岩铜钼矿, 其西部 Rhodope-Strandja 区伴生 W(Ohta et al., 1988), 东部 Sakarya 区伴生 Au(Yigit, 2006)。成矿时代为晚白垩世到古新世(Yavuz et al., 1999)。斑岩铜矿带成矿年龄从西向东逐渐变小(Ohta et al., 1988; Yavuz et al., 1999; Strashimirov et al., 2002), 主要矿床有 Derekoy(76.7 ± 3) Ma, Ohta et al., 1988), Güzelyayla, Salikvan(64.5 ± 1.7) Ma, Moore et al., 1986; Yavuz et al., 1999)等。

伊朗中部 Sahand-Bazman 斑岩铜矿带位于伊朗中部地块西缘, 赋存在新生代 Sahand-Bazman 火山岩岩浆带中(Stocklin, 1974; Hezarkhani, 2006b)。古新世以来该带普遍发育始新世、中新世、第四纪等三期岩浆活动(Waterman et al., 1975; Hezarkhani et al., 1998; Zarasvandi et al., 2007), 与成矿有关的是中新世碰撞环境的埃达克质高 K 花岗闪长斑岩(Jankovic, 1984; Hezarkhani, 2006a, b; Shafiei et al., 2009)。含矿岩体空间上与区域走滑断裂密切共生(Zarasvandi et al., 2005; Jahangiri, 2007)。Sahand-Bazman 斑岩铜矿带与 Zagros 构造带平行, 从土耳其东部北西向延伸到伊朗南部, 长约 1700 km, 包括两个超大型(萨尔切什梅 Sar Cheshmeh, 松贡 Sungun)一个中型(Meiduk)以及众多小型铜矿床(Waterman et al., 1975; Singer et al., 2005; Cooke et al., 2005; Zarasvandi et al., 2005, 2007), 成矿年龄从北西(如松贡, 20 Ma)向南东(如萨尔切什梅, 12.2 Ma)逐渐变小(Samani, 1998; Mutschler, 1999)。

巴基斯坦 Chagai 斑岩铜矿位于伊朗-鲁特-阿富汗地块东南缘, 被认为是伊朗 Sahand-Bazman 斑岩铜矿带的延伸(Berberian et al., 1982; Jankovic et al., 1987; Bagheri et al., 2008)。北东向延伸不连续出露直至被 Chaman 走滑断层截断(Ahmad, 1992)。成矿类型为斑岩铜金矿, 含矿围岩为复杂杂岩体, 矿体赋存在花岗闪长斑岩、石英闪长斑岩中(Perello et al., 2008), 主要矿床有赛因德格(Saindak, 21 Ma, Sillitoe et al., 1977; Sillitoe, 1978; 1979)、雷科迪克(Reko Diq, Perello et al., 2008)、Koh-i-Dalik, Dasht-e-Kain 等。

玉龙斑岩铜矿带总体上处于昌都-思茅地块上, 夹持于金沙江缝合带和澜沧江缝合带之间, 北起青海南部, 经藏东江达-芒康, 南延至滇南哈播, 长超过 300 km, 宽 15~30 km, 由 20 多个斑岩体组成(Hou et al., 2003b; 2006f)。含矿岩体浅成侵位(1.5~3 km)于三叠纪地层中, 属于高 K 的钙碱质、钾玄质系列(Gu et al., 2003)。岩石类型为花岗斑岩-二长花岗斑岩-二长斑岩和少量正长斑岩, 类似埃达克岩(侯增谦等, 2004c)。地球化学特征表明岩浆来源于加厚地壳底部的壳-幔过渡带(Hou et al., 2007)。岩体就位受古新世以来印度与欧亚大陆碰撞形成的 NNW 向大规模走滑断裂的控制(Hou et al.,

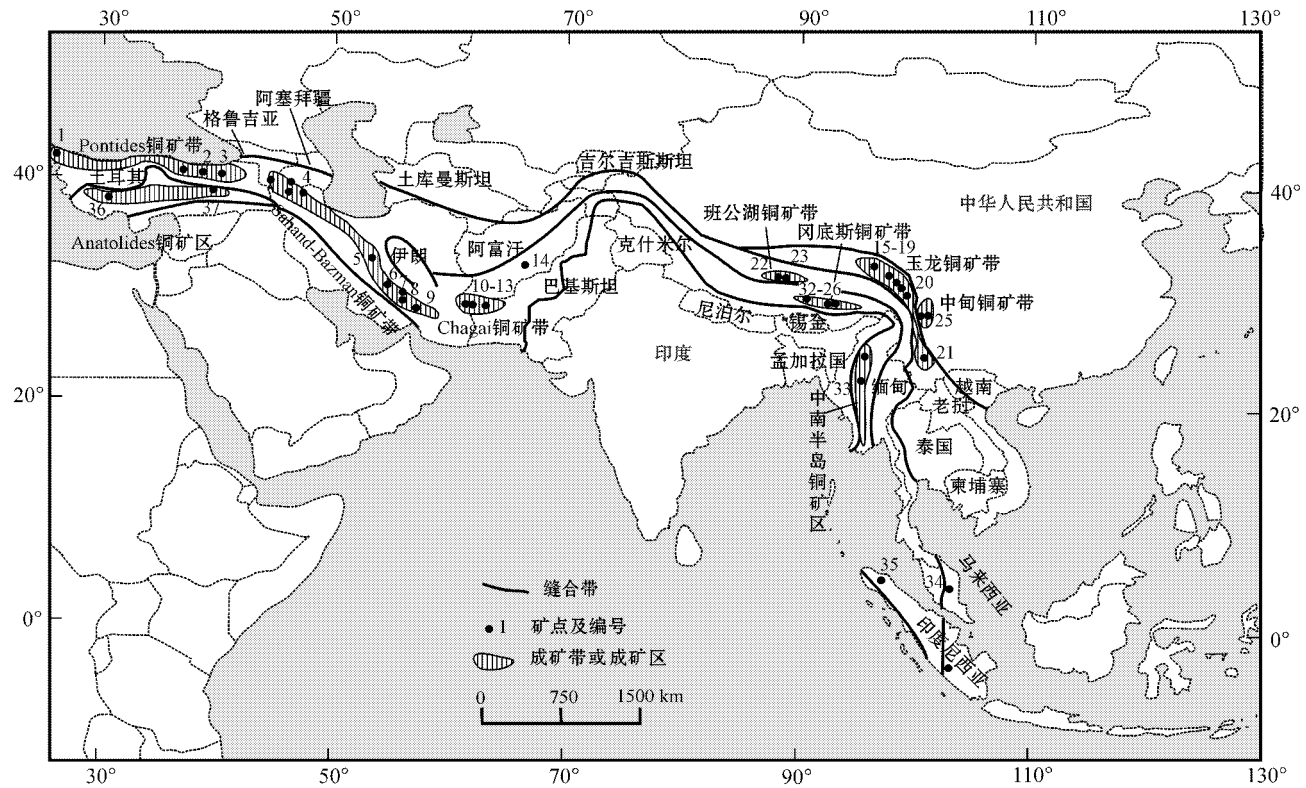


图 3 特提斯成矿域中斑岩矿床空间分布示意图(据 Singer et al. 2005 施俊法等 2006)

土耳其 Pontides 铜矿带:1—Derekoy;2—Guzelyayla;3—Salikvan;伊朗中部 Sahand-Bazman 铜矿带:4—松贡;5—Kale Kafi;6—Ali-Abad;7—Darrehzar;8—Meiduk;9—萨尔切什梅;10—赛因德格;巴基斯坦 Chagai 铜矿带:11—雷科迪克;12—Koh-i-Dalil;13—Dasht-e-Kain;14—Kundalyan;中国玉龙铜矿带:15—纳日贡玛;16—玉龙;17—扎那尔;18—莽宗;19—多霞松多;20—馬拉松多;21—马厂箐;中国班公湖铜矿带:22—多不杂;23—尕尔穷;中甸铜矿带:24—雪鸡坪;25—普朗;中国冈底斯铜矿带:26—甲马;27—驱龙;28—拉抗额;29—南木;30—厅宫;31—冲江;32—白容;中南半岛:33—蒙育瓦;34—Mengpur;35—Tangse;土耳其 Anatolides 地块:36—Kisladag;37—Copler

Fig. 3 Spatial distribution of porphyry copper deposits in the Tethyan metallogenic domain (modified after Singer et al. 2005 Shi et al. 2006)

Pontides porphyry copper belt in Turkey:1—Derekoy;2—Guzelyayla;3—Salikvan;Sahand-Bazman porphyry copper belt in central Iran:4—Sun Gun;5—Kale Kafi;6—Ali-Abad;7—Darrehzar;8—Meiduk;9—Sar-Cheshmeh;10—Saindak;Chagai porphyry copper belt in Pakistan:11—Reko Diq;12—Koh-i-Dalil;13—Dasht-e-Kain;14—Kundalyan;Yulong porphyry copper belt in China:15—Narigongma;16—Yulong;17—Zhanaga;18—Mangzong;19—Duoxiasongduo;20—Malasongduo;21—Machangqing;Bangonghu porphyry copper belt in China:22—Duobuza;23—Ganaqiong;Zhongdian porphyry copper belt in China:24—Xuejiping;25—Pulang;Gangdese porphyry copper belt in China:26—Jiama;27—Qulong;28—Lakang'e;29—Nanmu;30—Tingong;31—Chongjiang;32—Bairong;Indo-China area:33—Monywa;34—Mengpur;35—Tangse;Anatolides area in Turkey:36—Kisladag;37—Copler

2003b)成矿作用发生在晚碰撞期构造转化环境之压扭/张扭转换阶段(侯增谦等 2006a)。成矿年龄介于 40~30 Ma 之间(Wang et al. 2005;郭利果等 2006;曾普胜等 2006;Hou et al. 2006f)。

中甸铜矿带位于云南西北部,赋存于义敦岛弧带南部的中甸弧内,为晚三叠世甘孜-理塘洋向西俯冲形成(侯增谦等, 2004b)。含矿岩体为印支期浅成-超浅成相侵入体,岩石组合为闪长玢岩-石英闪长玢岩-二长斑岩-石英二长斑岩-花岗斑岩(Hou et al. 2007)。呈小岩株、岩瘤、岩墙状成群、成带产

出,可分为东、西 2 个斑岩带(曾普胜等 2003 2004)。

班公湖铜矿带位于班公湖-怒江缝合带北侧的多不杂构造岩浆弧中,已发现多不杂和尕尔穷 2 处斑岩矿床。尕尔穷矿区主要由斑岩与围岩接触带上的矽卡岩型铜矿体构成,为斑岩-矽卡岩型矿床(曲晓明等 2006a;芮宗瑶等 2006);多不杂矿区铜资源量达 200 余万吨,伴生金,为大型斑岩型铜金矿床,含矿斑岩为白垩纪中期侵位的石英闪长玢岩、花岗闪长斑岩,呈岩株状产出(曲晓明等 2006a;李光明等 2007)。

冈底斯斑岩铜矿带产于雅鲁藏布江缝合带北侧、拉萨地

块南缘的冈底斯构造-岩浆带中。西起尼木县冲江,东至工布江达县吹败子,东西长约 400 km,南北宽约 50 km,已发现 1 处超大型斑岩铜矿床(驱龙),3 处大型斑岩铜矿床(厅宫、冲江、甲马),4 处中-小型铜矿(白荣、南木、拉抗额、帮浦)及一系列矿点和矿化点(侯增谦等,2001b;Qu et al.,2004;Hou et al.,2009)。这些矿床和矿点整体上东西成带,南北成串(侯增谦等,2006d),含矿斑岩规模一般小于 1 km²,零星孤立分布,侵位于古新世-渐新世末同碰撞花岗岩基中。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,属钾玄岩至高钾钙碱性岩系。地球化学显示出埃达克岩浆亲和性(侯增谦等,2001b;2004a),岩浆来自加厚的新生下地壳的部分熔融(Hou et al.,2004d;侯增谦等,2004a;2005a;2005b)。岩浆活动发生在 11.2~19.7 Ma,成矿年龄为 13.8~16.0 Ma(侯增谦等,2003a;曲晓明等,2006b;Hou et al.,2009)。

中南半岛属于环太平洋成矿域和特提斯成矿域的交汇部位,斑岩铜矿床数量、储量都异常丰富,但大都是与现代洋壳俯冲有关的(Hutchison et al.,1978),而与特提斯成矿域相关的矿床,目前报道有缅甸蒙育瓦(Monywa)铜矿(Jankovic,2001),马来西亚 Mengpur 铜矿床和印度尼西亚苏门答腊岛上的 Tangse 矿床(Van Leeuwen et al.,1987;Van Leeuwen,1994)。

Anatolides 造山带位于土耳其中部,大地构造上夹持于欧亚大陆、阿拉伯板块和非洲板块之间。所含斑岩矿床数量不多,星点状散布,成矿时代变化较大,无法划分出带,多为含 Mo 高的斑岩金矿。典型矿床有 Kisladağ(Sillitoe,2002),Cöpler 等(Yigit,2006)。

2.2 与岩浆热液有关的 Sn-W 矿床

东南亚锡多金属成矿带北起缅甸东部,向南经泰国进入马来西亚,止于印尼的邦加(Bangka),勿里洞岛,3 800 km 长、800 km 宽,含 9.6 Mt 的锡,占世界总储量的 54%,是世界上锡资源最丰富、产锡量最大的矿带(Schwartz et al.,1995),成矿带上矿化分布不均匀,其中 7 个主要成矿中心占了矿石储量的 80%。锡多金属成矿带位于中缅马苏地块上,大地构造位置上沿澜沧江-Raub-Bentong 缝合带走向,在其两侧发育,但被严格限定在 Shan Boundary 断裂以东。锡矿化与 P-T 主要是在印度尼西亚、马来西亚或 K-H 尤其是在缅甸和泰国)的花岗岩有关(Cobbing et al.,1986),矿脉发育在燕山期花岗岩和石炭纪—二叠纪变质泥质沉积岩的接触带附近,有浸染型、接触交代型、热液脉型、伟晶岩型。矿体个体较小,在接触带上大量出现(Hutchison et al.,1978)。

通过大量含矿、不含矿岩体资料的积累,东南亚 W-Sn 矿床成矿模式被建立起来(Heinrich,1990),挥发分流体加入到正在冷凝的中酸性岩体中,与早期结晶的黑云母、白云母花岗岩反应,持续增大的流体压力导致伸展性的水压破裂,从而形成更大规模的热液循环,在张性劈裂带内形成云英岩脉。岩浆持续分异结晶致使 W、Sn 等不相容元素在残留熔体中逐步

富集,它们有可能沉淀于云英岩的云母中,也有可能以氯化物或络合物的形式存在于岩浆流体中,最后使岩浆流体变为富 Sn 的成矿流体(Groves et al.,1978),流体包裹体研究表明成矿流体中还含一定量的 NaCl 和 CO₂。CO₂ 沸腾挥发导致成矿流体温压降低,接下来在与赋矿岩石反应时 pH 值升高,W、Sn 等在石英或石英-电气石脉体中沉淀成矿(Yokarta et al.,2003)。由此形成的含 W-Sn 矿的花岗岩具有高 Rb,低 Ba、Sr 等特征。

2.3 与沉积岩有关的 Pb-Zn(-Ag)矿床

特提斯成矿域中与沉积岩有关的 Pb-Zn 矿床分布广泛、延伸稳定,从土耳其的西南部沿 Taurus 带向东经伊朗的铅锌矿带,过巴基斯坦,从青藏高原东部向南至中南半岛泰国等地(图 4)。这条铅锌矿带中包含有不同成因类型、不同成矿背景的众多矿床,显示出特提斯演化的复杂性和成矿的多样性。

在巴基斯坦和印度地段主要表现为伸展成矿,具同生层控的特点,赋存有巴基斯坦 Lasbela-Khuzdar 喷流-沉积型(SEDEX)Pb-Zn 矿带。大地构造上属印度古老陆块西北缘,在侏罗纪新特提斯洋盆扩张时,该区为新特提斯洋盆南部的被动陆缘,沉积有 Surmai、Gunga、Dhungei、Duddar 等矿床,构成著名的巴基斯坦 Lasbela-Khuzdar 铅锌矿带(Sillitoe,1978;Turner,1992;Jankovic,2001;Leach et al.,2005b)。

在土耳其、伊朗、中国、泰国等地皆为挤压驱动流体、后生成矿模式,但含矿建造时代、矿体赋存方式等也不尽相同。现有资料表明,伊朗、土耳其、泰国等地的 Pb-Zn 矿床都属 MVT 系白垩纪末—中新世受大陆碰撞挤压的影响,流体大规模运移形成。代表矿床有土耳其的 Taurus 成矿带、伊朗 Zagros 造山带中的 Kuh-e-Surmeh 矿床、Sanandaj-Sirjan 构造带中的 Irankuh 矿床(Ghazban et al.,1994),Anjireh-Vejin 矿床(Basuki et al.,2002),泰国西部 Padaeng 矿床等。

Taurus 带位于土耳其南部,主要由碳酸盐岩组成,广泛分布 Pb-Zn 矿。该带向西与地中海 MVT 矿带相连(Gokce et al.,2007),在其东部 Aladağ 地区 Yahyali 东部(又称 Zamanti Province)已发现有 9 个 Pb-Zn 矿床,其中 Goynuk 和 Celaldagi Desandre 是赋存在围岩中,其他几个与断裂有关(Koptagel et al.,2005,2007)。Goynuk 矿体赋存于晚二叠世—早三叠世的碳酸盐岩接触带上,或似层状、透镜状,或在碳酸盐岩的喀斯特溶洞中。矿区缺失岩浆活动,矿体与围岩没有明显的物质交换,共生矿石组合简单,矿石矿物肉眼只见方铅矿,显微镜下有方铅矿、闪锌矿、黄铁矿和白铁矿,少量菱锌矿、白铅矿、硫酸铅矿、针铁矿等,脉石矿物为方解石、白云石、石英等。白铁矿等矿物的出现证明成矿作用为低温环境(Koptagel et al.,2005)。方铅矿 $\delta^{34}\text{S}$ 值显示矿石中的硫来源于海水,Pb 同位素显示成矿金属源于造山带或者海水。矿石流体包裹体测得成矿温度为 50~162℃,盐度 $\omega(\text{NaCl}_{\text{eq}})$ 为 14%~28%,显示低温高盐度的热卤水特征(Hanilci et al.,2005)。

伊朗的 Kuh-e-Surmeh 矿床是赋存于碳酸盐岩中的 Pb-Zn 矿,位于伊朗西南部 Zagros 造山带 Simply 前陆褶皱冲断带

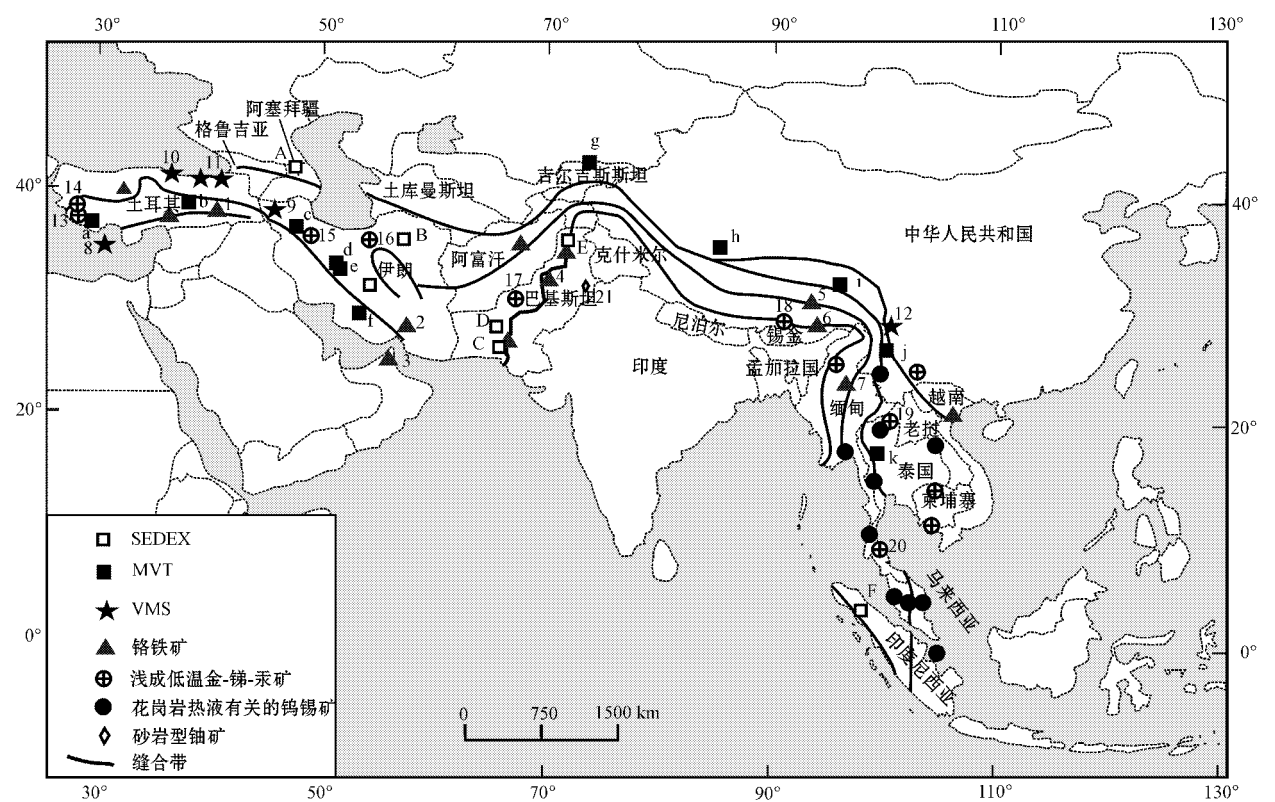


图 4 特提斯成矿域中部分矿床空间分布示意图(据 Sillitoe, 1978; Turner, 1992; Jankovic, 2001; Bradley et al., 2003; Leach et al., 2005a; Singer et al., 2005; Aftabi et al., 2006; Goodfellow et al., 2007 等综合汇编)

SEDEX: A—Filizchai; B—Mehdiabad; C—Duddar; D—Gunga; E—Lahore; F—Dairi (Sopokomil)。MVT: a—Bayindir; b—Yahyali; c—Emarat; d—Anjireh-Vejin; e—Irankuh; f—Kuh-e-Surmeh; g—Sumsar; h—卡兰古; i—东莫扎抓; j—金顶; k—Padaeng。铬铁矿: 1—土耳其古勒曼; 2—伊朗法里亚; 3—阿曼 Semail; 4—穆斯林巴赫; 5—中国东巧; 6—中国罗布莎; 7—缅甸太公当。VMS: 8—塞浦路斯 Troodos; 9—Zurabad; 10—马登科伊; 11—穆尔吉尔; 12—呷村。浅成低温金矿: 13—土耳其 Kursunlu; 14—土耳其 Ovacik; 15—伊朗 Sari Guna; 16—伊朗 Gandy; 17—巴基斯坦 Qila Abdullah; 18—藏南拆离系 Sb-Au-Hg 成矿带; 19—泰国 Mae Thae; 20—Huai Nai Khao; 21—巴基斯坦 Siwalik 砂岩型 U 矿

Fig. 4 Spatial distribution of some ore deposits in the Tethyan metallogenic domain (after Sillitoe, 1978; Turner, 1992; Jankovic, 2001; Bradley et al., 2003; Leach et al., 2005a; Singer et al., 2005; Aftabi et al., 2006; Goodfellow et al., 2007)

SEDEX: A—Filizchai; B—Mehdiabad; C—Duddar; D—Gunga; E—Lahore; F—Dairi (Sopokomil)。MVT: a—Bayindir; b—Yahyali; c—Emarat; d—Anjireh-Vejin; e—Irankuh; f—Kuh-e-Surmeh; g—Sumsar; h—Kagulan; i—Dongmozhashua; j—Jinding; k—Padaeng。Chromites: 1—Guleman in Turkey; 2—Faryah in Iran; 3—Semail in Oman; 4—Muslimbagh in Pakistan; 5—Dongqiao in China; 6—Luobusha in China; 7—Tagaung Taung in Myanmar。VMS: 8—Troodos; 9—Zurabad; 10—Madenkoy; 11—Murgul; 12—Gacun。Epithermal deposits: 13—Kursunlu; 14—Ovacik; 15—Sari Guna; 16—Gandy; 17—Qila Abdullah; 18—Sb-Au mineralization related to the South Tibetan detachment system; 19—Mae Thae; 20—Huai Nai Khao; 21—Siwalik sandstone-type uranium deposit in Pakistan

中,拥有可采矿石 990 000 t,平均含 Zn 12%,Pb 5.4%,是与造山有关的 MVT 矿床。矿体赋存于晚二叠世层状灰岩、白云岩中。矿化出现在 Kuh-e-Surmeh 背斜的两翼,主要是开放空间条件下充填于角砾碳酸盐岩中,偶尔也有晶形良好的矿石沉积在碳酸盐岩层间(Liaghat et al., 2000)。矿石矿物主要为闪锌矿、方铅矿以及少量黄铁矿、白铅矿、铅矾,脉石矿物有白云石、重晶石、石膏和方解石。重晶石、方解石包裹体均一温度为 50~150℃,显示了低温成矿的特点(Liaghat et al., 2000)。

MVT Pb-Zn 矿床向南延续至中南半岛,有泰国的 Padaeng 矿床,由于处在赤道附近,多雨潮湿,MVT 矿床多已氧化成为非硫化物型 Pb-Zn 矿(Reynolds et al., 2003)。

青藏高原东部沉积盆地内发育一套受逆冲推覆构造控制的 Pb-Zn 矿床,包括金顶、河西-三山、富隆厂、东莫扎抓等,它们形成于晚碰撞的构造转换阶段,主体赋存于第三纪前陆盆地中,其形成虽然与盆地沉积演化和流体活动有关,但明显受大型逆冲推覆构造和走滑拉分构造控制,称造山型 Pb-Zn-Ag-Cu 矿床(侯增谦等,2008)。

2.4 岩浆型铬铁矿

铬铁矿床常分为两大类型,一类是产在具有韵律性层理的超镁铁质-镁铁质岩侵入体内的层状铬矿床,另一类是产在蛇绿岩的超镁铁质构造岩建造内的豆荚状铬矿床。特提斯成矿域中的铬铁矿多为豆荚状,产在中、新生代形成的规模巨大的古、新特提斯蛇绿岩带中,近东西向绵延数千公里,从阿尔卑斯、西亚、喜马拉雅到中南半岛都有发育(图2、图4)。

西亚地区铬铁矿发育较连续,从西到东沿新特提斯缝合带上依次有塞浦路斯的特罗多斯(Troodos)矿床,土耳其的古勒曼矿床,伊朗的法尔亚(Faryah)矿床,巴基斯坦的穆斯林巴赫(Muslimbagh) Bela 矿床(Zaigham et al., 2000)等,这些矿床多为豆荚状铬铁矿,其超基性-基性杂岩体都是在晚白垩世—古新世就位(Misra 2000; Arif et al., 2006)。伊朗铬铁矿多为豆荚状,矿体在构造上极为不连续(Yaghubpur et al., 2006)。印度板块北缘的中央褶皱带中保存有一系列沿 Indus 缝合带近南北向展布的蛇绿岩,按 $Cr^{\#}$ 值的高低($Cr^{\#} = 100 \times Cr/(Cr + Al)$)可分为3组,高 Cr ($Cr^{\#} > 60$)、低 Cr ($Cr^{\#} < 60$)及 Cr 含量变化较大($Cr^{\#}$ 值在 15~90 间)。前两者分别形成于岛弧带和地幔底辟导致的弧内张裂部位, Cr 变化较大者赋含铬铁矿,如穆斯林巴赫和 Bela 蛇绿岩,矿体产于蛇纹石化的纯橄岩中,其构造环境应该是岛弧和洋中脊过渡地区的边缘海和仰冲带等(Arif et al., 2006)。

喜马拉雅地区沿雅鲁藏布江缝合带发育有罗布莎铬铁矿,罗布莎铬铁矿位于拉萨市东南 200 km,产于雅鲁藏布江蛇绿岩带中。该蛇绿岩体面积约 70 km²,形成于侏罗纪(177 Ma, Zhou et al., 2002),于 90~80 Ma 逆冲就位于北侧的冈底斯花岗岩基之上(Malpas et al., 2003),是一个半解体的蛇绿岩套,由地幔橄辉岩和堆晶岩共同组成完整剖面,其上部层序各单元已经解体,仅有零星的火山岩和硅质岩块作为混杂体出露在堆晶岩的北侧(王希斌等, 1987)。铬铁矿床主要产于距堆晶杂岩底部接触带 100~600 m 范围内的纯橄岩-斜辉辉橄岩杂岩带中,矿体常被很薄的纯橄岩外壳包裹,多呈似板状、透镜状以及其他不规则等形态(王希斌等, 1987)。班公湖-怒江缝合带上有东巧铬铁矿,赋存在东巧蛇绿岩中,形成于早侏罗世,于晚侏罗世班公湖洋盆闭合时就位。

中南半岛地区目前只在缅甸 Shan Boundary 缝合带附近发现太公当红土型镍矿,伴生有铬铁矿,产于蛇绿岩中,围岩是角砾蛇纹岩,含脉状、网格状镍矿脉(Hutchison et al., 1978)。

2.5 VMS 型 Cu-Pb-Zn 矿床

在特提斯成矿域中成规模的 VMS 矿床主要有 2 类:塞浦路斯型和黑矿型。Franklin 等(2005)将其分别称之为镁铁质、双峰质。塞浦路斯型主要沿新特提斯缝合带断续出露,从塞浦路斯 Troodos、土耳其 Kedak、伊朗 Zurabad 到阿曼 Byda,长达 2 000 km(图4)。这些矿床大都赋存在蛇绿岩套中的玄武岩、辉长岩中,成矿金属组合为 Cu-(Au-Ag),都是作为蛇绿岩残片的一部分仰冲到活动大陆边缘之上。伊朗 Zurabad 矿床位于伊朗 Khoy 市北西 40 km,赋存在 Khoy 蛇绿岩的玄武

岩中,系晚白垩世形成的 VMS 型 Fe-Cu 矿床。矿石矿物主要为黄铁矿、黄铜矿,含少量闪锌矿、磁黄铁矿。受后期仰冲作用影响 Zurabad 矿床的围岩及矿体都已发生了绿片岩相变质(Aftabi et al., 2006)。

黑矿型矿床主要形成于 2 个时期,晚三叠世和晚白垩世,分别与古特提斯、新特提斯洋盆的闭合高峰期相对应。代表矿床有呷村、穆尔吉尔(Murgul)、马登科伊(Madenkoy)、Cayeli。这些矿床都是产在汇聚边缘的伸展环境,尤其是弧后地区。赋矿岩石为酸性流纹岩、流纹质凝灰岩(Yigit 2006, 2009)。

呷村为特大型 Zn-Pb-Cu-Ag 矿床, $Zn + Pb + Cu$ 储量 4 Mt, Ag 3 800 t, 赋存在双峰式火山岩(由拉斑玄武岩系列的镁铁质火山岩和钙碱性系列的长英质火山岩构成)中。矿区热液蚀变具有明显不对称性,主要发育在脉状-网脉状矿带及含矿火山岩系,而块状矿带上部蚀变微弱,具有“层状矿席+层控网脉状矿带式”矿床结构特征(Hou et al., 2003b)。块状硫化物矿石 Re-Os 等时线年龄为 217 Ma(Hou et al., 2003b),与义敦弧间裂谷发育时限相当(图4)。

穆尔吉尔(Murgul)矿床是土耳其境内最大的 VMS 矿床,位于 Pontides 岛弧带后侧的弧后开裂部位(图2、图4)。主要金属组合为 Cu-Au, 矿体赋存在流纹质火山岩中,平面上呈卵形,纵向延伸为漏斗状,主要由网脉状黄铁矿-黄铜矿和少量层状硫化物组成(Yigit 2009)。

2.6 浅成低温热液型 Au-Ag-Hg-Sb 矿床

浅成低温热液矿床是地壳上部几公里金矿资源的主要来源(Simmons et al., 2005),主要形成在地壳浅部 < 2 km, 温度不超过 300℃ 处,其形成过程主要是地壳浅部地温升高,岩浆和流体进入近地壳环境,热液对流循环而成(Kerrick et al., 2000a, 2000b)。可分为高硫化型、低硫化型两种类型,与构造背景并没有严格的对应关系,可以形成在岛弧生长期间或碰撞后与地壳增厚和区域抬升有关的挤压变形高峰期(Kerrick et al., 2005)。

特提斯成矿域中浅成低温热液矿床数目众多,规模可观。高硫化型矿床多与第三纪以来的火山活动有关。它们分布广泛,延伸不远,在土耳其主要集中在西北部 and 东北部,西北部有 Agi Dagı, Kirazlı 等矿床,与晚中新世中酸性火山活动有关(Yigit 2006, 2009),而东北部的浅成低温热液矿床都赋存在 Pontides 造山带的晚白垩世—始新世钙碱性火山岩中(Yigit, 2006, 2009)。向东在伊朗境内零散分布有 Alborz 造山带中与始新世流纹岩有关的 Gandy 矿床(Shamanian et al., 2004; Fard et al., 2006)。另外,在东南亚分布有众多与花岗岩有关的浅成低温 Sb-Au 矿床(Hutchison et al., 1978)。

Gandy 矿床位于伊朗北部 Alborz 造山带中,成矿元素有 Au-Ag-Pb-Zn-Cu 等。矿化主要与中中新世火山活动有关,主要有角砾岩、裂隙充填和皮壳状生长 3 种形式,系岩浆释放的卤水上升与地下水混合而成(Fard et al., 2006)。赋矿围岩或为凝灰质火山角砾岩,或为安山岩,都属高 K 钙碱性(Shamanian et al., 2004)。

东南亚段 Sb-Au 矿带在空间上被局限于一狭小的长条带内,其东界是马来半岛的 the Main Range 断裂,西界是高变质岩带。围岩种类多样,为二叠纪—三叠纪的沉积岩、火山岩。矿脉是石灰质页岩中的石英-方解石脉,含黄铁矿、辉锑矿、白钨矿、毒砂和金等。矿化与下伏的花岗岩体有关,区域空间上与锡矿带重叠,但两者无成因联系(Hutchison et al. ,1978)。成矿时代跨度很大,从早中生代变化到新近纪,成矿组合逐渐从 Sb-W 变化至 Sb-Au(Dill ,2008)。典型矿床有泰国 Huai Nai Khao 中低温含 W 脉状 Sb 矿床。

Huai Nai Khao Sb 矿床位于泰国西部,澜沧江断裂东侧,属思茅成矿区,赋存于碳酸盐岩中,伴生 W 矿,成矿温度 45 ~200℃。Sb 矿床在空间上与石灰岩有密切关系。矿体发育在张性破碎带或剪切带中,含矿角砾岩分散于红土型覆盖层中(Dill ,2008)。

低硫化型矿床大多形成于中新世,与大陆碰撞引起的断层活动密切相关,成矿流体以天水为主,其金属淀积的主要机制是流体混合和沸腾作用(Simmones et al. ,2005)。主要分布在碰撞活动影响强烈地区,如土耳其西部、巴基斯坦中部和中国藏南地区等(图 4)。典型矿床有土耳其西部的 Ovacik、Narlica 矿床(Yilmaz,2002 ;Yilmaz et al. ,2007),Kursunlu、Emirli 矿床(Yigit ,2006),伊朗 Sanandaj-Sirjan 带上的 Sari Gunay 矿床(Richards et al. ,2006),巴基斯坦 Qila Abdullah 地区 Chaman 转换断层附近大型走滑作用驱动流体的 Sb 矿带(Sil-litoe ,1978),中国藏南拆离系中的 Sb-Au-Hg 成矿带(杜光树等 ,1993 ;杨竹森等 ,2006)等。

Ovacik 金矿床位于土耳其西部 Izmir 市北 100 km 处,是土耳其第二大浅成低温金矿床,赋存在早中新世安山质斑岩中,矿化与北东向 Bergama 地堑密切相关,金以皮壳状石英+冰长石脉和石英角砾岩胶结物的形式产出(Yilmaz et al. ,2007)。冰长石 Ar-Ar 定年显示成矿年龄为(18.2 ± 0.2) Ma ,为低硫化型浅成低温金矿床(Yigit ,2009)。

Sari Gunay 浅成低温金矿床位于伊朗 Sanandaj-Sirjan 带

上,赋存在中新世 Takab 带碱性粗安岩、粗面岩中。含矿岩体侵位年龄 11 Ma 稍晚于附近的 Sahand-Bazman 斑岩铜矿带,其岩石与斑岩带相比更富碱及不相容元素。与早期矿化有关的绢云母年龄为 10.7 Ma 稍晚于火山岩,碱性岩体及矿体的发育都受北西向走滑断层控制(Richards et al. ,2006)。

相对而言,喜马拉雅地区浅成低温热液 Sb-Au 矿床发育较好,构成了一条呈 EW 向展布长达 600 km 的 Sb-Au 成矿带。该成矿带夹持于藏南拆离系 STDs 与 IYS 缝合带之间,受藏南伸展拆离系控制,集中沿变质核杂岩带分布(聂凤军等 ,2005)并显示以变质核杂岩为中心的环状矿化分带特征,中部以 Au 为主,向外过渡到以 Sb 为主。矿体受拆离断层、层间断裂和 NS 向张性断裂的控制(侯增谦等 ,2003a)。Sb-Au 成矿作用主要是变质核杂岩构造剥蚀隆升,驱动浅层流体的对流循环,循环的地热流体从流经的岩石内萃取成矿物质,并搬运至构造扩容的有利场所沉淀成矿(杨竹森等 ,2006 ; Yang et al. ,2009)。矿化年龄为 20 ~ 8 Ma(侯增谦等 ,2006c)处于后碰撞阶段。

3 特提斯成矿域主要成矿过程

对应于特提斯的构造演化,其主要矿床的形成经历了古特提斯洋盆俯冲、新特提斯洋盆扩张、新特提斯洋盆消减和随后的大陆碰撞等 4 个过程(图 5)。

3.1 古特提斯洋盆俯冲与成矿

三叠纪末古特提斯洋闭合高峰期,其分支洋盆——甘孜-理塘洋盆向西俯冲,产生义敦岛弧,该岛弧北部张性弧的弧间裂谷盆地发育呷村特大型 Zn-Pb-Cu 矿床(Hou ,1993 ;Hou et al. ,2001c ;侯增谦等 ,2001a)。南部压性弧中赋存中甸斑岩铜矿带。

3.2 新特提斯洋盆扩张与成矿

基梅里陆块群从冈瓦纳大陆裂离,向北漂移造成新特提斯洋盆的扩张。当时的冈瓦纳大陆北缘在拉张应力下减薄,

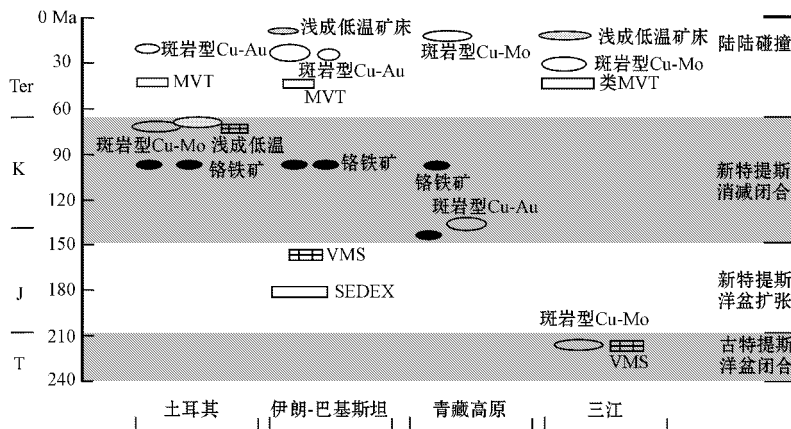


图 5 特提斯成矿域构造事件与成矿作用

Fig. 5 Major tectono-mineralization events in the Tethyan metallogenic domain

大幅度沉降形成被动大陆边缘。被动陆缘的同沉积断裂及黑色有机质页岩层 (Miall, 1990) 为来自盆地深部的含金属流体运移、沉淀提供了基础 (Leach et al., 2005a)。对流循环的中温 (220~290℃) 中低盐度 (3%~13%) 流体 (Basuki et al., 2002) 发生喷流-沉积, 形成巴基斯坦 Lasbela-Khuzdar SEDEX 型铅锌矿带 (Sillitoe, 1978; Sangster, 1990; Large et al., 2005)。

侏罗纪—白垩纪新特提斯洋盆规模达到极盛, 洋中脊近东西向带状分布, 岩浆驱动的海底热水的对流循环, 形成塞浦路斯型 VMS 矿床 (Lydon, 1988; Franklin et al., 2005)。洋盆闭合后 VMS 矿床沿新特提斯缝合带断续出露, 从塞浦路斯 Troodos、土耳其 Kedak、伊朗 Zurabad 到阿曼 Byda, 长达 2 000 km。

3.3 新特提斯洋盆俯冲与成矿

新特提斯洋盆洋内俯冲初始阶段, 俯冲带上盘常因洋壳拉伸形成一些伸展性小洋盆, 这些小洋盆存在短暂, 未来得及发育成成熟大洋, 就卷入随后的挤压事件而就位形成蛇绿岩, 称“SSZ 型”, 如班公湖、雅鲁藏布江等蛇绿岩 (史仁灯, 2007b), 其形成年龄代表了初始俯冲的时代。“SSZ 型”蛇绿岩岩浆的形成多有流体的加入 (Dilek et al., 2007; Zhang et al., 2008; Robinson et al., 2008), 受俯冲洋壳脱水交代的地幔楔熔融出富水的玄武质熔浆, 后者分解, 含铬铁矿的流体泡从中出溶, 上浮, 到达岩浆房顶部。当铬铁矿颗粒足够多时形成多晶集合体, 此时密度增加, 下沉到富橄榄石的硅酸盐熔体中, 在 7 km 深度、0.2 GPa 压力的条件下形成豆荚状矿体 (Edwards et al., 2000; Cawthorn et al., 2005)。侏罗纪班公湖—怒江古特提斯洋盆闭合, 洋壳仰冲到大陆壳上, 其蛇绿岩构造残片中赋存东巧铬铁矿床 (Shi et al., 2007); 白垩纪—始新世新特提斯洋盆闭合, 沿缝合带连续分布有古勒曼、法尔亚 (Kananian et al., 2001; Yaghubpur et al., 2006), Scnai (Auge, 1987; Misra, 2000), 穆斯林巴赫 (Sillitoe, 1978; Arif et al., 2006), 罗布莎 (李德威, 1995; Shi et al., 2007a) 等铬铁矿床。

新特提斯洋盆俯冲消减形成了大量火山岩岩浆弧。白垩纪中期, 班公湖—怒江洋盆在多不杂地区形成了多不杂火山岩岩浆弧, 该岩浆弧赋存有班公湖斑岩铜金矿带 (曲晓明等, 2006a)。白垩纪末—古新世初, 新特提斯洋盆的分支——Vardar 洋北向俯冲, 在土耳其东北部 Pontides 造山带生成岛弧型钙碱性火山岩岩浆系, 赋存多处大型斑岩铜矿床, 称 Pontides 斑岩铜矿带 (Nakov et al., 2002; Moix et al., 2008)。斑岩矿床的上部系统伴生有高硫型浅成低温热液 Cu-Au-Ag 矿床 (Yigit, 2006; 2009)。在岛弧带的后侧开裂断陷地段东西向带状发育穆尔吉尔 (Murgul), 马登科伊 (Madenkoy) 等十余处大型黑矿型 Cu-Zn-Pb 矿床 (Ozgur, 1993; Yigit, 2009)。

3.4 大陆碰撞与成矿

当新特提斯洋盆主体闭合, 构造演化进入大陆碰撞阶段。由于碰撞过程的岩浆类型、热液组成、温压条件等复杂多变, 其成矿类型亦多种多样, 既有空间上的分带性, 又有时间演化

上的阶段性。印度、阿拉伯板块与欧亚大陆的碰撞过程都显示了三阶段性, 即主碰撞陆-陆汇聚、晚碰撞构造转换和后碰撞地壳伸展。不同的演化阶段对应不同的成矿系统。

主碰撞陆-陆汇聚阶段, 碰撞带岩石圈加厚, 地壳深熔, 形成中央轴部碰撞岩浆带, 有林子宗火山岩和冈底斯花岗岩基 (莫宣学等, 2003)。Sanandaj-Sirjan 带上的始新世火成岩, 此时主要是地壳加厚重熔形成的壳源花岗岩, 多为 S 型, 部分为 S 与 I 混合型。青藏高原的壳源岩浆在充分的结晶分异晚期, 分凝出富含金属的正岩浆流体 (侯增谦等, 2006a), 形成来利山大型 Sn 矿 (刘增乾等, 1993), 腾冲百花脑稀有金属矿床 (吕伯西等, 1993)。

另外, 东南亚锡多金属带也是形成在这种环境, 只不过其时间跨度更为漫长。从三叠纪到侏罗纪再到白垩纪, 中緬马苏、西缅甸、印度板块分别沿 Inthanon、Shan Boundary、Woyla 缝合带拼合到印度支那板块上 (Metcalf, 2006), 长期的弧-弧碰撞、弧-陆碰撞和陆-陆碰撞过程持续引发了岩浆活动, 形成东南亚锡多金属成矿带。成矿时代跨度很大, 从早中生代变化到新近纪 (Dill, 2008), 总体有自东向西变年轻的趋势, 与构造演化过程相符。

陆-陆汇聚阶段还伴有大规模强烈逆冲和褶皱作用 (Yin et al., 2000)。如巴基斯坦及相邻地区和喜马拉雅地区的冲断带、Zagros 逆冲推覆系统 (Golonka, 2004; Ramsey et al., 2008), 碰撞带两侧的陆块发生挠曲变形形成前陆盆地。大量 MVT 铅锌矿床就此形成 (Bradley et al., 2003; Leach et al., 2005a)。如晚白垩世, 阿拉伯板块与土耳其 Anatolides 地块碰撞, 向北挤压, 驱动流体在土耳其 Taurus 地区沉淀成矿 (Hanilci et al., 2005; 2008; Koptagel et al., 2005, 2007); 与伊朗地块碰撞, 区域构造挤压造成 Zard-Kuh 盆地的脱水, 被排出的盆地流体沿断裂进入到高度疏松多孔的、角砾岩化的地层中, 金属在低温 (<200℃) 高盐度 ($\alpha(\text{NaCl}_{\text{eq}}) \approx 15\%$) 的盆地卤水中沉淀成矿 (Liaghat et al., 2000)。

晚碰撞构造转换阶段, 分别在印度、阿拉伯大陆的东、西两侧, 沿碰撞缝合带或早期岩石圈不连续带发生大规模走滑活动, 形成有金沙江、Chanman、扎格罗斯、Anatolian 等大型走滑系统, 伴有部分块体逃逸。岩浆系统主要是以幔源和壳幔混源为主的钾质岩浆 (Chung et al., 1998; Wang et al., 2001; Hou et al., 2003b; 2006f; Guo et al., 2005; Jiang et al., 2006)。这些岩浆分凝出成矿的岩浆流体, 发育成斑岩岩浆-热液成矿系统 (Hou et al., 2003b; 2007)。如受走滑断层及其拉分盆地控制的中国玉龙铜矿带 (侯增谦等, 2006c); 沿扎格罗斯走滑缝合带发育的伊朗中部 Sahand-Bazman 铜矿带。另外, Chaman 走滑断层还伴生有浅成低温热液 Sb 矿床 (Sillitoe, 1978)。

后碰撞地壳伸展阶段, 碰撞带附近的块体大都发生伸展、拆离, 壳源或壳幔混源钾质岩浆活动遍布碰撞全区。相关矿产为与斑岩铜矿、岩浆热液有关的浅成低温 Au-Sb 矿床。

4 讨 论

从特提斯构造演化可以看出,特提斯域内的陆块漂移推动了古、新特提斯洋盆的闭合,构造演化与成矿过程表明域内的陆块及其周缘的增生造山带是特提斯研究的载体,记录了裂解-俯冲-碰撞等地质过程,赋存有斑岩型 Cu-Mo-Au、与岩浆热液有关的 Sn-W、岩型铬铁矿、VMS 型 Cu-Pb-Zn、浅成低温热液型 Au-Hg-Sb 及与沉积岩有关的 Pb-Zn 等 6 种主要矿床类型。初步归纳显示,上述 6 种矿床类型主要形成于 3 类成矿背景中:洋盆扩张时的洋壳和相邻被动陆缘、洋盆消减过程中的俯冲带及洋盆闭合后的碰撞带。印度、阿拉伯板块与欧亚大陆的碰撞奠定了现今特提斯构造格局,碰撞活动引起的强烈挤压使不同的地质体堆叠并置,从而各种背景下的不同类型矿床都集中在狭窄长条的碰撞带中,造就了特提斯的复合型成矿域特色。

特提斯成矿域在洋盆扩张时主要是形成土耳其、伊朗等地的塞浦路斯型 VMS 矿床,但扩张洋脊的矿床一般不容易保存。现在能见到的都是洋盆闭合后仰冲到大陆壳上的蛇绿岩构造残片。另外,初始俯冲时洋壳拉伸形成的铬铁矿也与洋壳残片一起,仰冲到大陆壳上。仰冲作用使这些矿床在经受了绿片岩相变质后得以保存,碰撞时的挤压作用使矿体呈狭窄带状沿缝合带延伸;与碰撞相关的走滑作用造成矿体的不连续发育。最终以强烈改造的形式出现在汇聚板块边缘,尤其是碰撞缝合带中。

相对而言,俯冲带上的弧后洋盆宽度一般小于大陆岩石圈的厚度(Dogliani et al., 2007),洋壳岩石圈年轻,具有正浮力,在汇聚过程中更容易仰冲而保留。弧后洋盆中的 VMS 矿床和岩浆弧中的斑岩矿床、浅成低温矿床一起作为大陆增生边缘成矿系统在碰撞造山带中得以保存。特提斯成矿域中保存了呷村 VMS 矿床、Pontides 斑岩铜矿带等一系列与俯冲作用相关的矿产,这一点与环太平洋、古亚洲等增生型造山带相类似。

另外,特提斯成矿域中还有大量矿床的形成与碰撞环境密切相关,如东南亚锡多金属成矿带、Sahand-Bazman 铜矿带,以此区别于典型的增生型成矿域。相对而言,目前的特提斯地质演化定格在了碰撞过程,故碰撞成因的矿床在特提斯成矿域中大量出现。

5 结 论

特提斯成矿域是在晚古生代到新生代期间,古、新特提斯洋扩张与闭合的过程中,历经了两次大规模的板块俯冲、碰撞而形成的。这一过程中,欧亚主动大陆边缘和冈瓦纳被动大陆边缘起了主要的控制作用。而特提斯域内的陆块推动了古、新特提斯洋盆的闭合,陆块内部及其周缘增生形成的造山带记录了裂解-俯冲-碰撞等地质过程。复杂的地质演化过程

注定了其成矿具多金属、多类型的特征。本文在特提斯成矿域中识别出斑岩型 Cu-Mo-Au、与岩浆热液有关的 Sn-W、岩型铬铁矿、VMS 型 Cu-Pb-Zn、浅成低温热液型 Au-Hg-Sb 及与沉积岩有关的 Pb-Zn 等 6 种矿床类型。上述不同类型形成于 3 种成矿背景:洋盆扩张时的洋壳和相邻被动陆缘、洋盆消减过程中的俯冲带及洋盆闭合后的碰撞带。不同构造背景下的矿床集中在狭窄长条状的碰撞带附近,显示出特提斯的复合型成矿域特色。

志 谢 谨将此文献给翟裕生院士,并向翟先生 80 华诞表示热烈祝贺。衷心感谢翟先生长期以来对笔者及其研究团队的悉心指导,亲切关怀和帮助支持。感谢审稿专家对本文的建设性意见。特提斯成矿域蔚为壮观,宏伟巨大,本文难免挂一漏万,尝试性总结该域成矿规律,以期对同行有所参考。作者对文中的任何错误和曲解负责。

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