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评 述 中国科学院学部 科学与技术前沿论坛 板块俯冲带

大陆碰撞带成矿作用: 年轻碰撞造山带对比研究

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摘要 新特提斯俯冲带之上的年轻碰撞造山带是进行大陆碰撞成矿研究的天然实验室和理想对象. 本文以比利牛斯、阿尔卑斯、扎格罗斯、喜马拉雅四个地球上最年轻的大陆碰撞造山带为例, 通过对这些造山带结构组成、演化过程和成矿系统等方面的概述, 划分碰撞造山带类型, 探讨不同类型碰撞带成矿同异性及缘由. 对比研究表明, 四个碰撞造山带可划分成简单碰撞和复合碰撞两种类型. 前者以比利牛斯和阿尔卑斯为代表, 表现为狭窄线状造山带和对称式造山带结构, 缺乏弧岩浆活动, 发育以中上地壳物质活动为主的成矿系统(密西西比河谷型铅锌矿床和造山型金矿床). 后者以扎格罗斯-伊朗高原和喜马拉雅-青藏高原为代表, 在欧亚大陆南缘表现为宽阔的造山高原和不对称式造山带结构, 大陆边缘弧岩浆活动显著, 产有大规模成矿系统(岩浆碳酸岩型稀土矿床、碰撞型斑岩铜矿床、造山型金矿床、密西西比河谷型铅锌矿床和伸展构造有关的锑金多金属矿床). 尽管在简单碰撞带形成之前也有新特提斯洋壳的俯冲, 但是没有形成大陆弧. 而复合碰撞带在大陆俯冲之前有大陆边缘弧的形成, 大陆碰撞引起增生造山带再活化, 其中新特提斯洋壳俯冲作用为随后大陆碰撞带成矿提供了金属预富集.

关键词 比利牛斯, 阿尔卑斯, 扎格罗斯, 喜马拉雅, 碰撞造山带, 增生造山带, 碰撞成矿作用

1 引言

大陆碰撞造山带是地球表面最为雄伟壮观的地质构造单元之一. 在全球尺度上可以明显识别出的碰撞造山系主要有欧亚大陆南缘的比利牛斯-阿尔卑斯-扎格罗斯-喜马拉雅山链, 分隔欧亚大陆的乌拉尔山、欧洲西部的加里东和华力西山系, 以及美洲东部的阿巴拉契亚山(图1). 早在板块构造提出之前, 对阿尔卑斯地区的研究表明, 某些构造单元可以发生长距离的水平运动, 由此发展出推覆构造理论(Heritsch, 1929), 丰富了构造地质学内容, 对当时广泛受"固定论"影响的地质学界带来了认知上的冲击. 板块构造提出以来,

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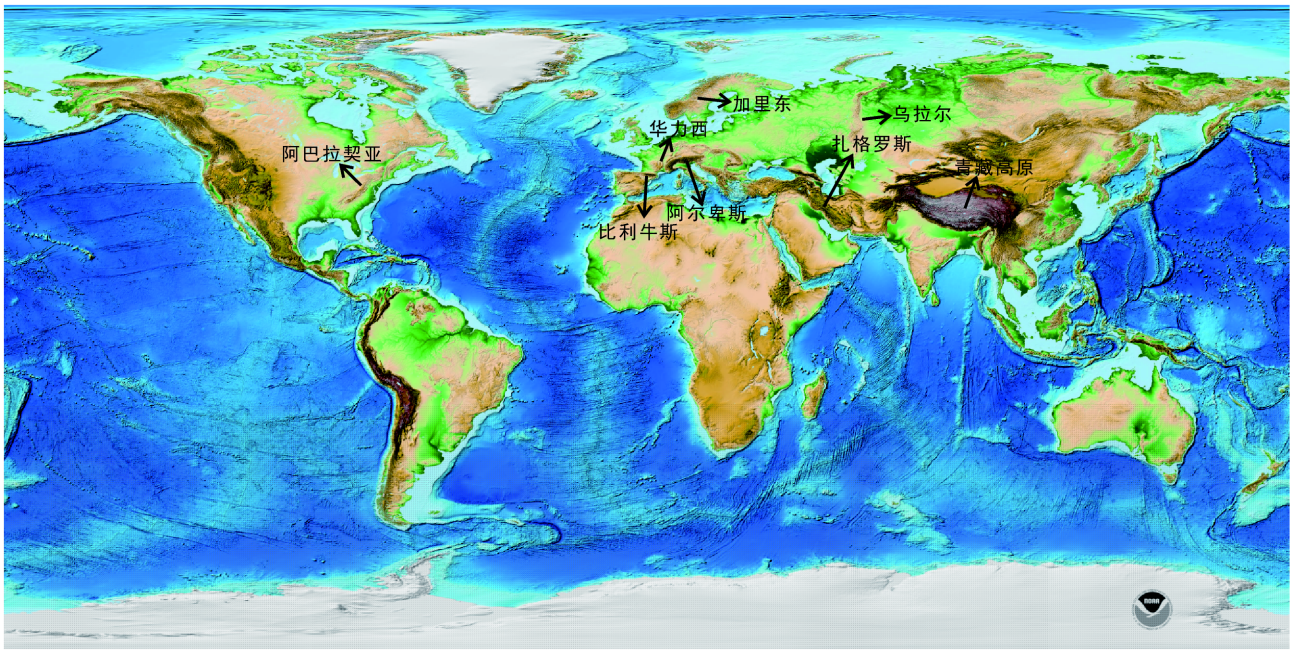

图 1　全球主要碰撞造山带分布图(底图据www.ngdc.noaa.gov)

大陆碰撞造山带成为检验板块构造“登陆”的关键场所，大陆碰撞过程与成矿研究内容成为地球科学前沿(郑永飞等, 2015). 事实上，大陆碰撞是以大洋俯冲为先导，大洋和大陆俯冲带在结构和演化上既有不同点也有相似点(Zheng和Chen, 2016). 近年来，大陆碰撞被赋予了新的内涵，认为它是超大陆形成的最重要和最有效机制(Spencer等, 2017).

相对于碰撞造山的过程和机制等热点(Zheng, 2012; Zheng等, 2012)，针对碰撞造山带成矿的过程和机制研究明显不足. 其原因主要包括: (1) 受传统板块构造和简单威尔逊旋回等观念影响，学术界主流观点认为，大陆碰撞仅表现为干的冷的陆块简单拼合对接，这一过程中没有新生地壳形成(Zheng, 2012; Zheng等, 2018)，也匮乏成矿流体活动，因此大陆碰撞作用本身很难成矿(Kerrich等, 2005; Groves和Bierlein, 2007); (2) 对少数几个古老碰撞造山带实例解剖显示，这些碰撞带很少产出矿床. 在华力西造山带识别出几种与大陆碰撞过程有关的矿床，如钨、锡、铀等(Seltmann和Faragher, 1994)，无论是规模还是潜力，均远逊于大洋俯冲作用形成的矿产(Bierlein等, 2009). 因此，大多学者都在采用俯冲模式来解释碰撞带矿床成因，如伊朗扎格罗斯造山带的克尔曼铜矿带等(Cooke等, 2005; Hezarkhani, 2006).

本世纪以来，随着青藏高原碰撞成矿理论雏形的建立和重大找矿突破的实现，传统的碰撞不成矿观念受到了质疑(侯增谦, 2010; Hou和Cook, 2009). 对藏南冈底斯和藏东玉龙新生代成矿作用的深入研究实践表明，大陆碰撞可以引起先期大陆边缘弧岩石圈再活化，从而发生大规模成矿作用. 碰撞成矿的规模和潜力足以同大洋俯冲作用形成的安第斯铜矿带等相媲美(张洪瑞等, 2009, 2010; Hou和Zhang, 2015). 由此引发的思考: 为什么碰撞成矿作用在加里东、华力西等造山带寥若晨星，而在青藏高原却异彩纷呈? 一种可能的解释是，加里东、华力西等属于古生代碰撞造山带，其赋存矿床容易被后期演化过程改造或剥蚀; 而青藏高原则为新生代碰撞造山带，其地质记录都尽可能完整地被保存下来. 本文暂且不讨论这种解释是否合理. 不容否定的是, 相对于古老的古生代造山带而言, 年轻的新生代造山带形态、大小、板块边界以及地表相对运动都可以被直接观测. 另外, 年轻造山带的地壳结构分层、重力分布等信息也可以被地球物理方法约束. 很显然，年轻碰撞造山带是进行碰撞成矿研究的天然实验室和理想对象. 开展年轻碰撞造山带成矿作用对比研究，将有助于从更宏观的角度审视地球动力学过

程与成矿过程之关联, 理解大陆碰撞成矿作用机制, 进而达到认识碰撞造山带成矿规律之目的.

欧亚大陆南缘分布有比利牛斯-阿尔卑斯-扎格罗斯-喜马拉雅山链, 它们是在新特提斯洋闭合后发生大陆碰撞而形成, 属于年轻的新生代碰撞造山带. 已有研究表明, 比利牛斯、阿尔卑斯、扎格罗斯和喜马拉雅四个造山带碰撞造山式样、演化阶段和成矿系统不尽相同(如张洪瑞和侯增谦, 2015). 本文以这四个年轻碰撞造山带为研究对象, 通过造山带结构组成、演化过程和成矿系统等方面的概述, 划分碰撞造山带类型, 探讨不同类型碰撞带成矿同异性及缘由, 以期从更广范围更深层次来理解大陆碰撞成矿作用.

2 比利牛斯

2.1 比利牛斯造山带结构及演化

比利牛斯造山带整体呈狭窄线状横亘于伊比利亚半岛北缘. 该带由伊比利亚板块与欧亚大陆碰撞形成, 为一典型对称式造山带(Vergés和Fernàndez, 2012)(图2), 即以中央轴部带为核, 两侧分别发育褶皱逆冲带和前陆盆地. 其主要构造单元自南向北依次为: Ebro前陆盆地、南比利牛斯逆冲系统、中央轴部带、北比利牛斯褶皱逆冲系统和Aquitaine前陆盆地(Munoz等, 1986; Roure等, 1989; Vergés等, 1995, 2002).

地球物理资料揭示出比利牛斯造山带的深部结构(图2剖面; Teixell等, 2018): 造山带北侧的褶皱逆冲系统并没有向深部垂向延伸, 而是被欧亚大陆截切, 后者向南部的伊比利亚陆块楔入. 伊比利亚陆块下地壳与中上地壳解耦, 中上地壳被欧亚大陆阻隔, 而下地壳则向下俯冲至地幔.

比利牛斯造山带主要经历了中生代裂解和新生代碰撞两阶段演化历程. 中生代之前伊比利亚板块与欧亚大陆为一个整体. 三叠纪时, 受大西洋打开的影响, 伊比利亚开始与欧亚大陆裂离(Lagabrielle和Bodinier, 2008). 裂解主要集中在晚侏罗世-早白垩世和白垩纪中期两个时段(Sibuet等, 2004), 造成地壳极端减薄和二辉橄榄岩等地幔岩的出露(Lagabrielle等, 2010), 伊比利亚成为一个独立的微陆块. 但伊比利亚与欧亚大陆之间的白垩纪洋盆规模存在较大争议. 古地磁资料认为, 该洋盆可达320km(Vissers和Meijer, 2012; Vissers等, 2016); 而地质资料却表明, 两大陆之间都是浅水碳酸盐岩沉积(Vergés等, 2002), 很可能没有洋壳形成(Wortmann等, 2001). 另外, 比利牛斯地区也没有洋盆俯冲相关的弧岩浆岩、增生杂岩等构造单元.

晚白垩世伊比利亚与欧亚大陆重新汇聚, 发展成比利牛斯碰撞造山带(Choukroune, 1992). 该造山带缺乏与碰撞有关的岩浆活动, 主要表现为大规模地壳缩短. 大陆碰撞推动伊比利亚陆块向欧亚大陆之下俯冲至少80km, 同时造成地表约165km的缩短量, 形成南、北比利牛斯褶皱逆冲系统(Beaumont等, 2000). 强烈挤压作用主要发生在始新世-渐新世(图6a)(Fitzgerald等, 1999; Lacombe和Jolivet, 2005). 中渐新世开始, 受Valencia Trough打开的影响, 比利牛斯地区转为伸展背景(Roca等, 1999; Vergés等, 2002), 大陆汇聚停止, 碰撞造山作用结束.

与阿尔卑斯和喜马拉雅等成熟碰撞造山带相比, 比利牛斯造山带只发育碰撞造山作用初期的褶皱逆冲系统, 还未出现碰撞造山中后期普遍发育的大规模逆冲推覆系统、走滑剪切系统和同挤压伸展系统, 其碰撞造山过程被区域伸展事件中断. 现今两陆块的汇聚速率<0.2mm/a(Nocquet, 2012), 基本处于停滞状态. 因此, 比利牛斯属于即将夭折的碰撞造山带(张洪瑞和侯增谦, 2015).

2.2 比利牛斯成矿系统及发育特征

比利牛斯碰撞造山带发育众多铅锌矿床(图2, 7a), 矿床主要分布在造山带两侧的前陆盆地中, 如造山带北侧Causses盆地中的Cevennes矿集区(Leach等, 2006)、造山带西南侧Basque-Cantabrian盆地中的Reocin铅锌矿床(Velasco等, 2003)和东南侧Maestrat盆地边缘的Avecilla矿床(Bradley和Leach, 2003)等. 这些矿床中, 矿体有的呈似层状、条带状赋存在侏罗系-白垩系台地相碳酸盐岩中(Reocin铅锌矿床, Velasco等, 2003; Cevennes矿集区, Leach等, 2006), 有的呈不规则状沿溶蚀垮塌构造或断裂带分布(Picos de Europa矿床, Pašava等, 2014). 矿石结构构造都显示出开放空间充填、后生构造控制的特征. 矿石矿物组成简单, 主要为方铅矿和闪锌矿. 成矿流体为低温的盆地卤水(80~150℃, Leach等, 2006). Pb同位素示踪表明, 金属来自于造山带基底或上覆沉积物(Velasco等, 2003). 矿石淀积与有机热还原(Piqué等, 2009)或流体混合(Pašava等, 2014)有关. 这些特征表明, 比利牛斯带铅锌矿床

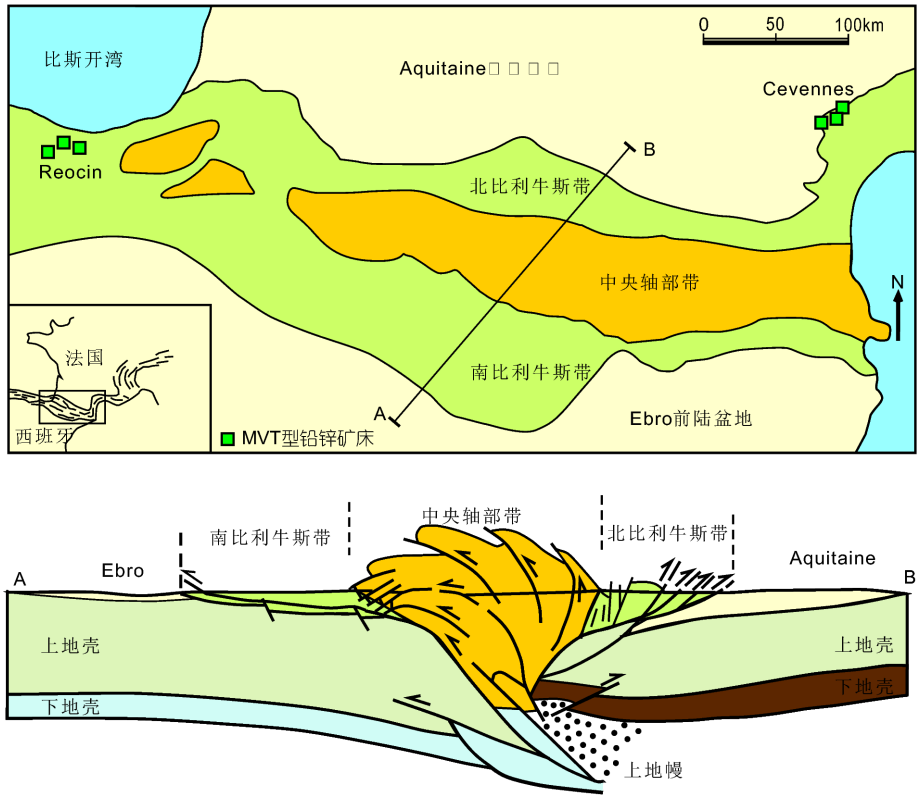

图 2　比利牛斯碰撞造山带构造框架、矿床分布及剖面结构

据Vergés等 (2002)修改

属于典型的密西西比河谷型(MVT型)矿床(Leach等, 2010).

MVT型铅锌矿床由于成矿温度低, 缺少适合定年的矿物. 其成矿年代历来是矿床学研究的难题. 近年来, 随着闪锌矿Rb-Sr、含矿方解石Sm-Nd、磷灰石裂变径迹和古地磁法等定年技术的发展(Grandia等, 2000; Leach等, 2001; Li和Song, 2006; Symons等, 2009), 这一难题得以缓解. 方解石U-Pb等时线法获得Avecilla矿床成矿年龄为(62.6±0.7)Ma(Grandia等, 2000). 另外, 地质研究表明, 比利牛斯造山带铅锌矿床成矿主要发生在古新世-渐新世, 是伊比利亚板块与欧亚大陆碰撞作用的产物(Leach等, 2001).

3　阿尔卑斯

3.1　阿尔卑斯造山带结构及演化

阿尔卑斯造山带整体呈弧形近东西向坐落在欧洲南部亚平宁地区(图3), 是欧亚大陆向亚德里亚(Adriatic)板块俯冲碰撞的产物(Coward和Dietrich, 1989). 与比利牛斯相似, 阿尔卑斯造山带也是一个典型的对称式造山带(Dal Piaz等, 2003). 不同之处在于, 其中央轴部带的组成更为复杂, 可以划分出三套不同构造单元(Schmid等, 2004): (1) Austroalpine带, 由中生代被动陆缘沉积和蛇绿岩残片组成, 含有晚白垩世绿片岩-榴辉岩和始新世榴辉岩; (2) Penninic带, 由从欧洲大陆被动陆缘和洋壳岩石圈上刮削下来的一系列变质推覆体组成, 局部含有始新世榴辉岩; (3) Helvetic带, 由基底残片和晚石炭世-古新世盖层推覆体组成, 这些盖层是欧洲大陆边缘的远端沉积系统.

最新的地震层析成像研究揭示, 在阿尔卑斯造山带, 一条高速带从地表向岩石圈地幔深部连续延伸(Zhao等, 2015, 2016). 该高速带被解释为俯冲的欧亚大陆地壳相连的古大洋板片, 从而认为欧洲下地壳俯冲到亚德里亚岩石圈地幔深度. 该俯冲陆壳带与地表出露的高压超高压变质岩带相连, 从而为高压超高压变质岩的大陆深俯冲成因模式提供了直接证据.

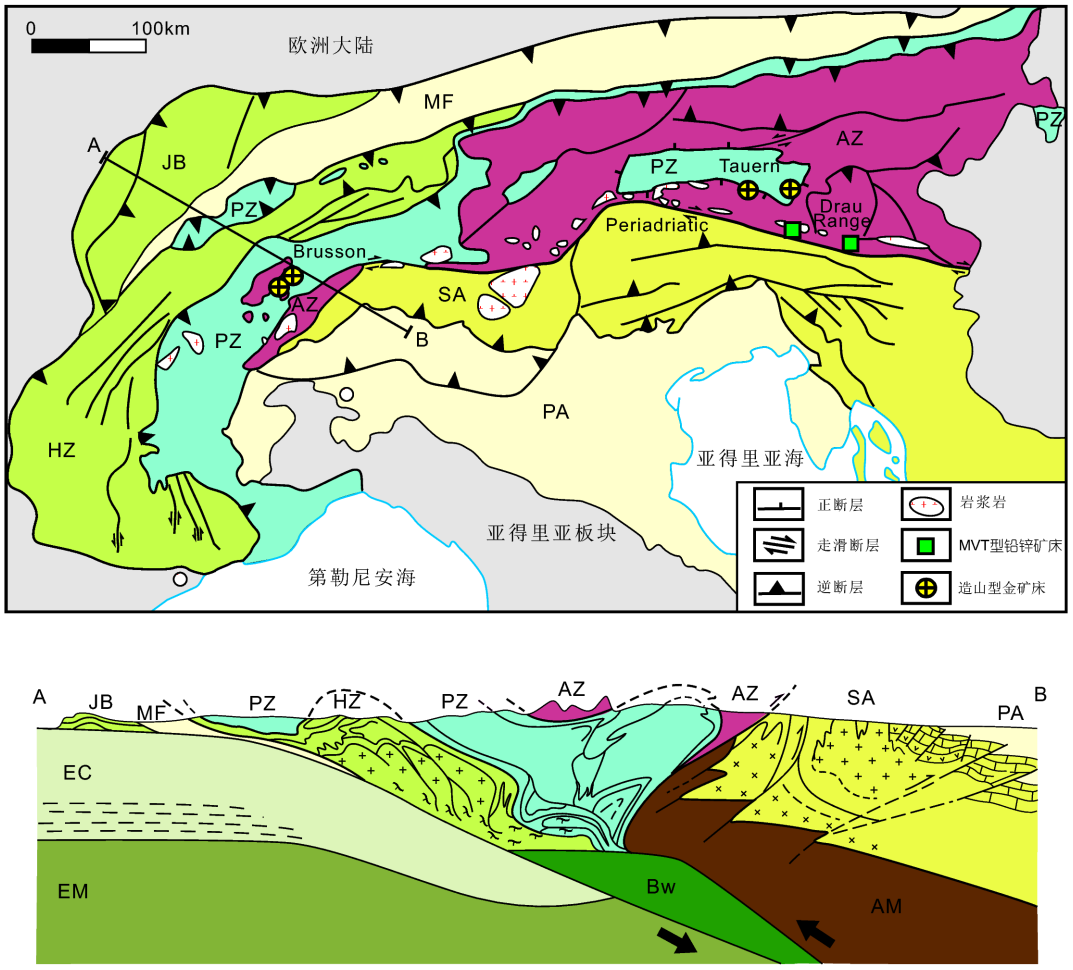

图 3　阿尔卑斯碰撞造山带构造框架、矿床分布及剖面结构

据Dal Piaz等(2003)修改. JB-Jura带; MF-Molasse前陆盆地; PZ-Penninic带; HZ-Helvetic带; AZ-Austroalpine带; SA-南阿尔卑斯(亚德里亚板块); PA-Padane-Adriatic前陆盆地; EC-欧洲大陆地壳; EM-欧洲大陆地幔; Bw-高压变质岩; AM-亚德里亚地幔

与比利牛斯造山带类似, 阿尔卑斯造山带也经历了中生代裂解和新生代碰撞两阶段过程. 初始裂解发生在三叠纪, 亚德里亚板块与欧亚大陆之间逐渐发展出特提斯小洋盆(Golonka, 2004). 白垩纪时洋盆消减, 但规模非常有限, 难觅与之相关的弧岩浆岩记录(Carminati等, 2010). 晚白垩世(Neubauer等, 2000; Dilek, 2006)或始新世(Beltrando等, 2010; Handy等, 2010)亚德里亚板块与欧亚大陆碰撞, 形成阿尔卑斯碰撞造山带. 具体碰撞造山过程可划分为三个主要阶段:

(1) 始新世(55~35Ma), 以大规模逆冲推覆构造(Carminati等, 2012)和高压超高压变质作用(Reddy等, 1999)为特征(图6b). 逆冲推覆作用表现为碰撞带核部的Austroalpine带、Penninic带和Helvetic带卷入变形, 形成叠瓦状构造(Carminati等, 2012). 高压超高压变质岩主要出露于Austroalpine带和Penninic带中(Reddy等, 1999), 变质年龄集中在45~36Ma, 记录了陆壳深俯冲并快速折返的过程(Rubatto和Hermann, 2001). 另外, Austroalpine带内还存在一期晚白垩世高压变质岩, 被认为是洋壳俯冲的产物(Dal Piaz等, 2003). 始新世还发育有同碰撞岩浆岩, 出露在南阿尔卑斯Adamello地区, 岩性主要为英云闪长岩、奥长花岗岩和花岗闪长岩, 岩浆活动年龄集中在42~38Ma(Tiepolo等, 2011).

(2) 始新世末-中新世初(35~20Ma), 以东阿尔卑斯向东逃逸和不同来源岩浆活动为特征(Stipp等, 2004; Lustrino等, 2011). 东阿尔卑斯地区发育Periadriatic大型走滑断层, 表现为一系列东西向右行走滑断层系, 走

滑活动发生在35~20Ma(Mancktelow等, 2001; Michard等, 2002). 与走滑活动近同时, 大量岩浆岩沿Periadriatic断层系统就位(Rosenberg, 2004). 该期岩浆岩具有岩体规模小但成分复杂的特点. 同一个岩体可由多成分岩性共同组成, 包括辉长岩、闪长岩, 正长岩和花岗岩等(Lustrino等, 2011). 另外, 岩体还被大量同期或稍晚期岩墙侵位(Rosenberg, 2004). 岩体以钙碱性、高钾钙碱性为主, 伴生有少量钾质超钾质岩石(Lustrino等, 2011), 岩浆活动峰期年龄集中在32~28Ma(von Blanckenburg和Davies, 1995; Carminati等, 2010).

(3) 中新世至今(20Ma~), 以低角度拆离断层为特征. 断层主要发育在东阿尔卑斯地区的Austroalpine带和Penninic带内, 为一系列近东西走向的低角度拆离断层(Ratschbacher等, 1989, 1991). 拆离伸展作用造成东阿尔卑斯地区Tauern天窗的出露(Schmid等, 1996; Neubauer等, 1999; Frisch等, 2000; Viola等, 2001). 此外, 少量岩浆活动喷发在东阿尔卑斯地区, 形成钙碱性、高钾钙碱性火山岩和钾质、超钾质岩(Carminati等, 2010).

3.2 阿尔卑斯成矿系统及发育特征

阿尔卑斯造山带碰撞有关矿床主要发育造山型金矿床和MVT型铅锌矿床(图3, 7b). 造山型金矿床主要集中在西部Monte Rosa (Pettke等, 2000)和东部Hohe Tauern (Horner等, 1997)两个地区, 为一系列中小型矿床(矿化点). 矿化式样主要为含金石英脉, 以金、银为主, 还包括铅、锌、铜、砷等. 矿体受走滑或拆离断裂控制, Monte Rosa地区主要发育在Periadriatic大型走滑断层附近, Hohe Tauern地区则与Tauern变质核杂岩密切相关(Neubauer, 2002). 流体包裹体研究指示, 成矿均一温度在400~200℃之间(Horner等, 1997). 成矿作用发生在20~16Ma, 与变质核杂岩剥蚀和区域性隆升年龄一致(Amann等, 2002).

MVT型铅锌矿床则主要分布在造山带中东部Drau Range地区, 为上百个中小型矿床(点), 总体呈南西西向串珠状分布, 走向与Periadriatic断裂系统相平行(Henjes-Kunst等, 2017). 矿体似层状出现在三叠纪碳酸盐岩中, 闪锌矿具有典型的皮壳状结构, 显示开放空间充填的特征. 成矿作用为富金属流体和富还原硫流体的混合沉淀的结果(Henjes-Kunst等, 2017).

4 扎格罗斯

4.1 扎格罗斯-伊朗高原结构及演化

扎格罗斯造山带位于伊朗西南部, 由阿拉伯板块与欧亚大陆碰撞而成, 但是碰撞影响范围可扩展至伊朗全境, 形成伊朗高原. 扎格罗斯-伊朗高原主要由数条北西-南东向条带状构造单元组成(图4; Agard等, 2011), 自南西向北东依次为: (1) 扎格罗斯褶皱逆冲带(ZFTB), (2) 萨南达杰-锡尔詹中生代岩浆变质带(SSZ), (3) 乌兹密尔-杜克塔尔新生代火山岩浆带(UDMA), 和(4) 中部伊朗地体. SSZ和UDMA等碰撞带上盘不发育明显的褶皱冲断带和前陆盆地, 而是大面积的构造岩浆带, 使得扎格罗斯-伊朗高原整体显示为不对称式结构.

地球物理资料揭示, 在扎格罗斯造山带深部, 阿拉伯板块地壳已经俯冲至欧亚大陆之下, 在东南部Neyriz-Kerman剖面上已经越过SSZ带, 在西北部Hamadan-Tehran剖面上甚至穿过SSZ和UDMA带, 俯冲至中部伊朗地体之下(Paul等, 2010; Motaghi等, 2015).

扎格罗斯-伊朗高原发育多条蛇绿岩带, 其中东北部地区出露有古特提斯洋壳残片(Alavi, 1991), 是二叠-三叠纪中部伊朗地体与欧亚大陆拼合的记录(Zanchi等, 2016); 东部和西南部为新特提斯洋壳残片(Moghadam和Stern, 2015), 包括锡斯坦(Sistan)、纳因-巴福特(Nain-Baft)和克尔曼沙阿-内里兹(Kermanshan-Neyriz)等, 它们记录了白垩纪中部伊朗地体周缘洋盆扩张的过程.

扎格罗斯地区在侏罗-白垩纪发生过大规模洋壳俯冲作用(Ghasemi和Talbot, 2006), 相关弧岩浆岩主要分布在SSZ带上. 侏罗纪主要为深成岩体, 岩性包括辉长岩、闪长岩和花岗岩等, 呈北西-南东向断续出露在SSZ带南缘, 侵位年龄为183~145Ma(Hassanzadeh和Wernicke, 2016; Zhang等, 2018). 白垩纪岩浆岩分布在SSZ西北部和中部纳因地区, 主要为中基性火山岩, 包括玄武岩、安山岩和熔结凝灰岩等.

关于阿拉伯板块与欧亚大陆的初始碰撞时限, 目前存在从晚白垩世至中新世等不同观点(Okay等, 2010及所引文献). 本文采用大多数学者的观点, 即36~25Ma, 位于始新世末-渐新世(Allen和Armstrong, 2008; Agard等, 2011; Mouthereau等, 2012). 碰撞过程可分为两个阶段(图6c): (1) 始新世末-中中新世(35~

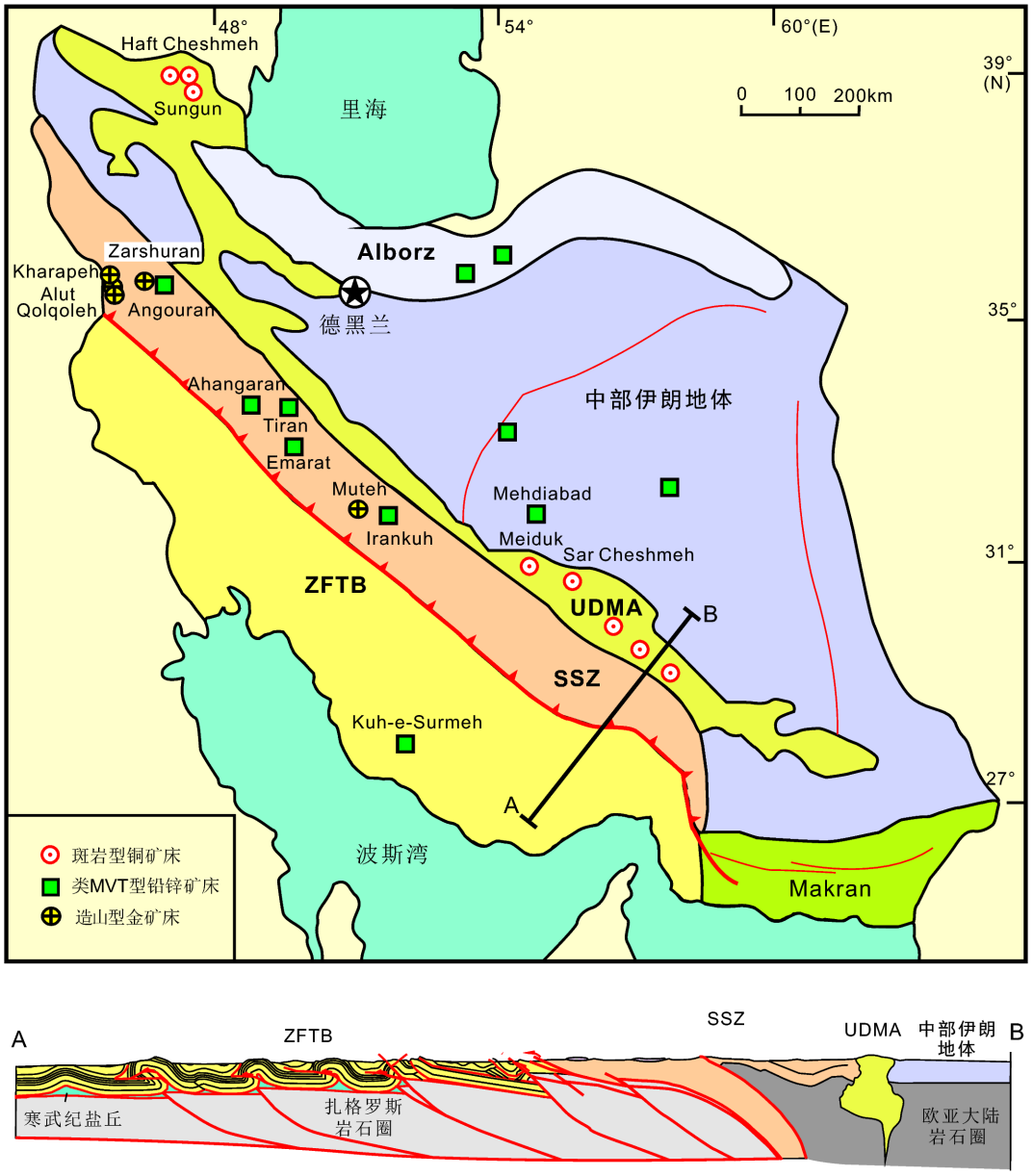

图 4　扎格罗斯-伊朗高原构造框架、矿床分布及剖面结构

据Agard等(2011)修改. ZFTB, 扎格罗斯褶皱逆冲带; SSZ, 萨南达杰-锡尔詹变质岩浆带; UDMA, 乌兹密尔-杜克塔尔岩浆带

10Ma): ZFTB和SSZ带发生大规模褶皱逆冲作用(Agard等, 2005, 2006; Sarkarinejad等, 2008), 在28~25Ma伴随有显著隆升剥蚀(Homke等, 2010; Agard等, 2011). 同时, UDMA带上侵位有大量埃达克质斑岩体(Jahangiri, 2007; Shafiei等, 2009; Chiu等, 2013); (2) 中中新世以来(10Ma~): 大规模挤压活动开始向阿拉伯板块方向扩展, 形成扎格罗斯山前大断裂(MFF) (Homke等, 2004). 同时, 碰撞挤压还形成了南北向走滑断层, 这些断层主要见于ZFTB东部和中部伊朗地体内部, 为一系列近平行的右行断层, 是调节碰撞挤压应变和块体刚性旋转的产物(Authemayou等, 2009; Babaahmadi等, 2010; Regard等, 2010; Smit等, 2010; Allen等, 2011). 本阶段岩浆岩主要为钙碱性埃达克岩(Ghadami等, 2008)和碱性熔岩(Mirnejad等, 2010).

4.2 扎格罗斯-伊朗高原成矿系统及发育特征

扎格罗斯-伊朗高原金属矿产资源丰富, 成矿类型多样, 与大陆碰撞作用相关的矿床类型主要有: 斑岩型铜钼金矿床、类MVT型铅锌矿床和造山型金矿床等(图7c). 其主要成矿带包括: 阿塞拜疆-克尔曼(Arasbar-an-Kerman)铜矿带、塔卡卜-亚兹德(Takab-Yazd)铅锌矿带和Piranshahr-Saqez-Sardasht造山型金矿集区等(Hou和Zhang, 2015).

阿塞拜疆-克尔曼铜矿带又称Sahand-Bazman铜矿带(Hou等, 2011), 位于伊朗UDMA带内, 可分为西北部和东南部两部分. 西北部矿床集中在阿塞拜疆省内, 包括Sungun、Haft Cheshmeh等若干铜矿床(Hezarkhani和Williams-Jones, 1998; Hezarkhani, 2006). 金属组合以Cu-Mo为主, 成矿年龄在20Ma左右(Aghazadeh等, 2015). 东南部矿床包括Sar Cheshmeh、Meiduk等十余座, 金属组合以Cu-Au为主, 成矿年龄集中在12Ma左右(Richards等, 2012; Aghazadeh等, 2015). 该铜矿带含矿岩体多为高钾花岗闪长斑岩, 普遍具埃达克质岩石地球化学特征, 即高Sr/Y和La/Yb比值, 无Eu异常, 指示岩浆起源于加厚大陆下地壳的部分熔融(Shafiei等, 2009; Richards等, 2012).

塔卡卜-亚兹德(Takab-Yazd)铅锌矿带位于SSZ带内及附近, 主要矿床包括: Angouran、Ahangaran、Ravanj、Emarat、Tiran、Iran Kouh和Mehdi Abad等. 这些矿床都赋存在上白垩统碳酸盐岩中, 具有盆地流体、构造控制、开放空间充填成矿等特征, 与MVT型铅锌矿床相似(Ghazban等, 1994; Ehya等, 2010). 不同之处在于, 该套矿床发育在褶皱逆冲带而不是在前陆盆地中. 另外, 大多数矿床中富含热液石英, 这在经典MVT矿床中很罕见. 本文称之为类MVT型矿床. 韩朝辉等(2015)认为, 该类矿床中热液石英的大量出现是由于热的盆地卤水与较冷围岩发生相互作用、温度快速下降所致.

Mehdi Abad矿床为该带上唯一的超大型矿床, 矿石储量为218Mt(Rajabi等, 2013), 矿体受半地堑式伸展断层控制(Goodfellow和Lydon, 2007). Angouran是伊朗目前正在开采的最大铅锌矿床, 可分为硫化物型、硫化物-碳酸盐混合型和碳酸盐型三种矿化类型(Daliran等, 2013), 矿体呈筒状产于新元古界-寒武系大理岩和片岩建造内(庄亮亮等, 2015); 其他矿床多为中小型, 矿体受与逆断层相关的次级断层、岩性分界面等控制(刘英超等, 2015); 成矿发生在新生代, 与阿拉伯地块与欧亚大陆碰撞密切相关(Gilg等, 2006; Hou和Zhang, 2015).

Piranshahr-Saqez-Sardasht造山型金矿集区位于SSZ带西北部, 由Qolqoleh、Kharapeh和Alut等若干金矿床(点)组成(Aliyari等, 2012). 矿体赋存在晚白垩世绿片岩相变质的火山沉积岩中. 矿区范围内大面积发育黄铁矿化、硅化和绢云母化. 金矿化或以浸染状出现在糜棱岩中, 或以脉状、不规则状出现在蚀变岩中(Aliyari等, 2007, 2009). 成矿被认为与扎格罗斯碰撞造山引起的挤压作用密切相关(Niroomand等, 2011). 该矿集区向东延伸, 在SSZ带中北部和中部分别发育Zarshuran和Muteh两个大型金矿床. Zarshuran金矿矿区地层主要有前寒武纪变质岩、寒武纪-奥陶纪灰岩、白云岩和渐新世-中新世火山沉积岩组成. 矿体主要见于前寒武纪碳酸盐岩和黑色页岩中, 主要蚀变类型有脱钙作用、硅化、泥化和白云石化(Asadi等, 2000). 金主要出现在沿北西向断层侵位的热液石英脉中, 或以浸染状出现在炭质、硅质和钙质黑色页岩中(Asadi等, 1999). 对热液泥化带的K-Ar法和Ar/Ar法定年揭示, 成矿作用发生在14~13Ma(Mehrabi等, 1999). Muteh金矿矿体赋存在变质流纹岩、黑云斜长片麻岩和石英绢云片岩中(Mehrabi等, 2012). 蚀变类型有硅化、绢云岩化、绿泥石化、碳酸盐化和少量高岭土化. 金矿体由若干条北西-南东向含金石英脉组成(Moritz等, 2006). 白云母Ar/Ar年龄表明, 矿化作用发生在始新世(Moritz等, 2006), 与扎格罗斯碰撞过程形成的右行压扭断层活动有关(Kouhestani等, 2014).

5 喜马拉雅

5.1 喜马拉雅-青藏高原结构及演化

喜马拉雅造山带由印度板块与亚洲大陆碰撞而形成, 碰撞影响范围可扩展至整个中国西部, 形成青藏高原(图5). 碰撞带上盘是拉萨地块, 向北是南羌塘地块、北羌塘地块、昆仑造山带、柴达木盆地、祁连造山带, 主体为上千公里宽的构造岩浆带, 含有早中生代、晚古生代和早古生代榴辉岩(Yin和Harrison, 2000; Zheng等, 2012). 从这个角度来看, 喜马拉雅-青藏高原是一系列复合的增生-碰撞造山带(Zheng等,

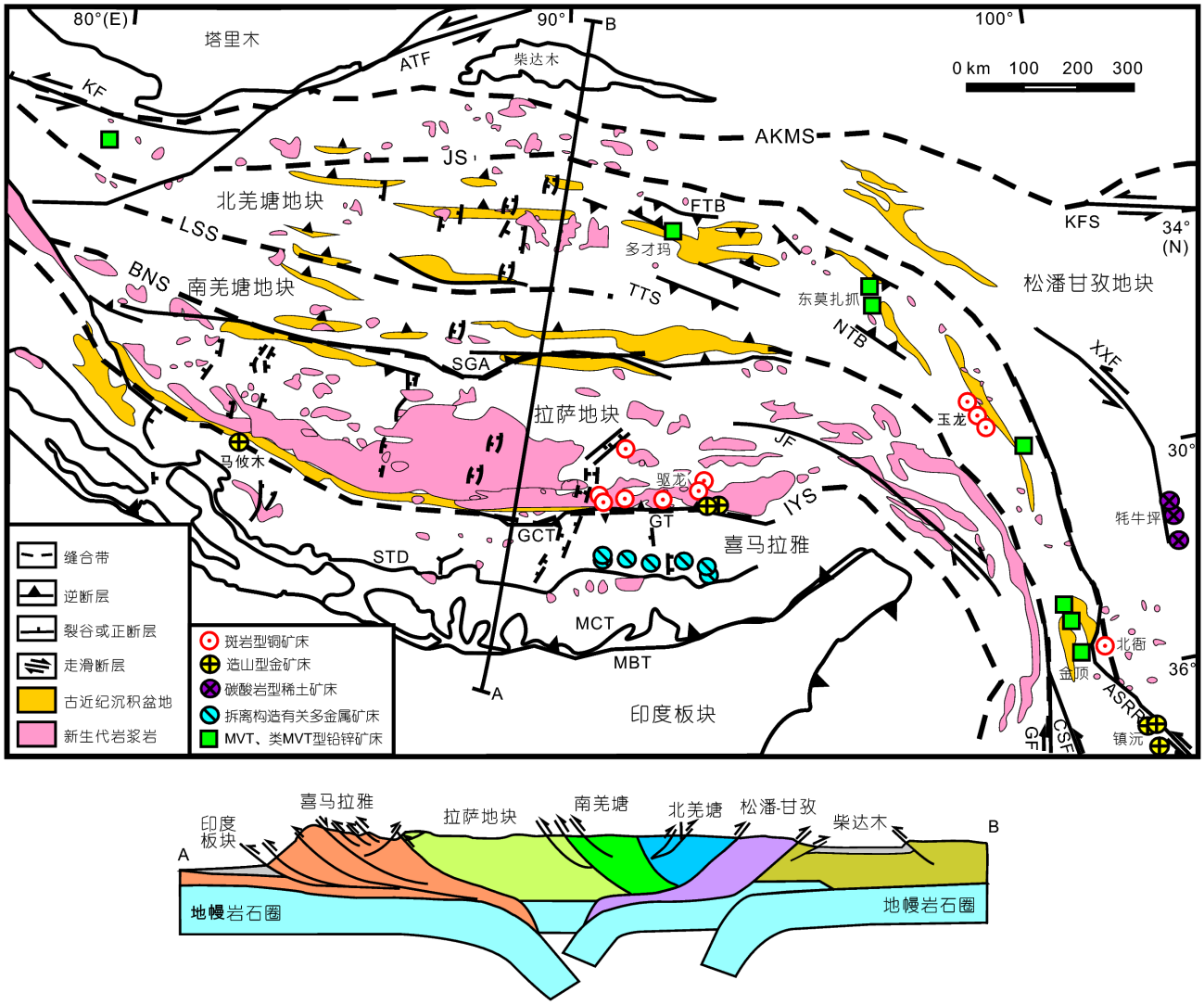

图 5　喜马拉雅-青藏高原构造框架、矿床分布及剖面结构

据Chung等(2005)、侯增谦(2010)、Li等(2015)、张洪瑞和侯增谦(2015)修改. AKMS-阿尼玛卿-昆仑缝合带; JS-金沙江缝合带; LSS-龙木错-双湖缝合带; BNS-班公湖-怒江缝合带; IYS-雅鲁藏布江缝合带; MBT-主边界断层; MCT-主逆冲断层; STD-藏南拆离系; GCT-大反冲断层; GT-冈底斯逆断层; SGA-狮泉河-改则-安多逆冲系统; TTS-唐古拉逆冲系统; FTB-风火山褶皱逆冲带; NTB-囊谦褶皱逆冲带; KFS-昆仑山断裂系统; ATF-阿尔金断裂; KF-喀喇昆仑断裂; JF-嘉黎断裂; XXF-鲜水河-小江断裂; GF-高黎贡断裂; CSF-崇山断裂; ASRR-哀牢山-红河剪切带

2013；肖文交等, 2017), 剖面上显示为明显的不对称式结构(张洪瑞和侯增谦, 2015). 地球物理资料显示, 俯冲的印度大陆在不同地区表现不尽相同, 在西部叠瓦状堆垛在缝合带附近(Gao等, 2016), 在中部以低角度下插至亚洲大陆岩石圈之下(Shi等, 2016), 在东部以高角度俯冲至亚洲大陆岩石圈之下(Liang等, 2016). 这种俯冲角度变化的几何结构注定了俯冲板片的撕裂(Chen等, 2015; Liang等, 2016). 除东西向撕裂外, 俯冲板片在垂向上存在不连续的现象(Replumaz等, 2004, 2010), 被认为是板片断离的结果(Zhao等, 2017).

青藏高原由众多的小陆块及陆间缝合带组成, 具体自东北向西南分别有阿尼玛卿缝合带、松潘-甘孜地块、金沙江缝合带、北羌塘地块、龙木错-双湖缝合带、南羌塘地块、班公湖-怒江缝合带、拉萨地块和雅鲁藏布江缝合带等(Yin和Harrison, 2000; Zhu等, 2013). 这些陆块大多是在早古生代(南羌塘地块及其以北地块)或中生代(拉萨地块)从冈瓦纳大陆上裂解出来的小陆块(Li等, 2016), 经历了复杂演化过程后于白

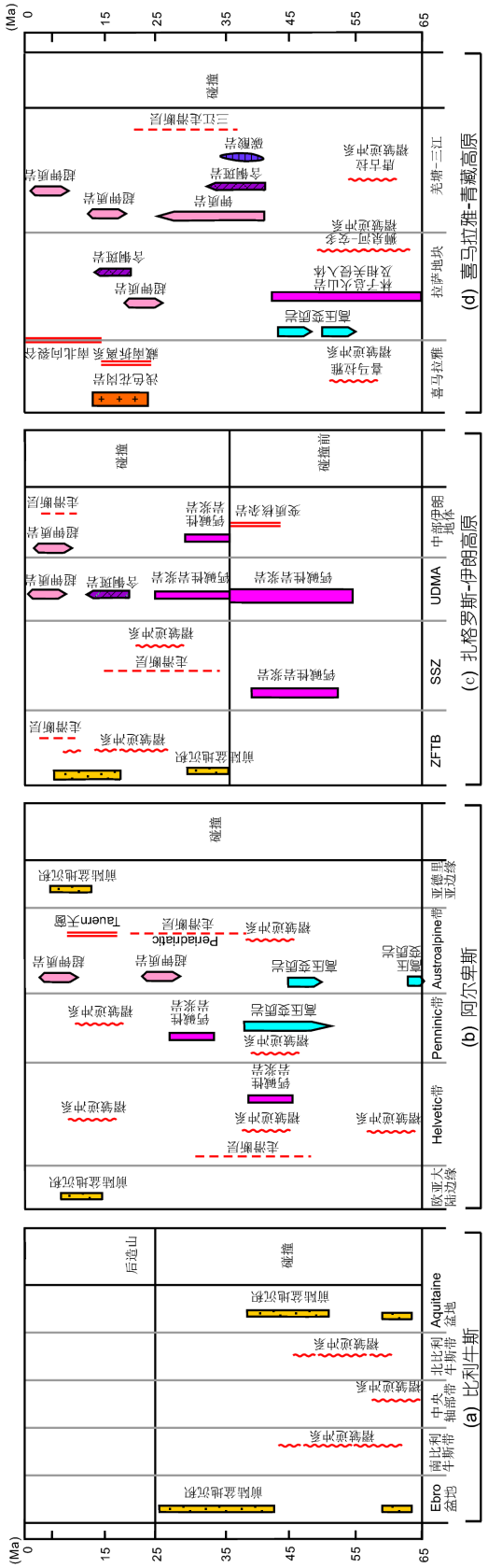

图 6 比利牛斯、阿尔卑斯、扎格罗斯-伊朗高原和喜马拉雅-青藏高原四个碰撞带主要构造岩浆作用

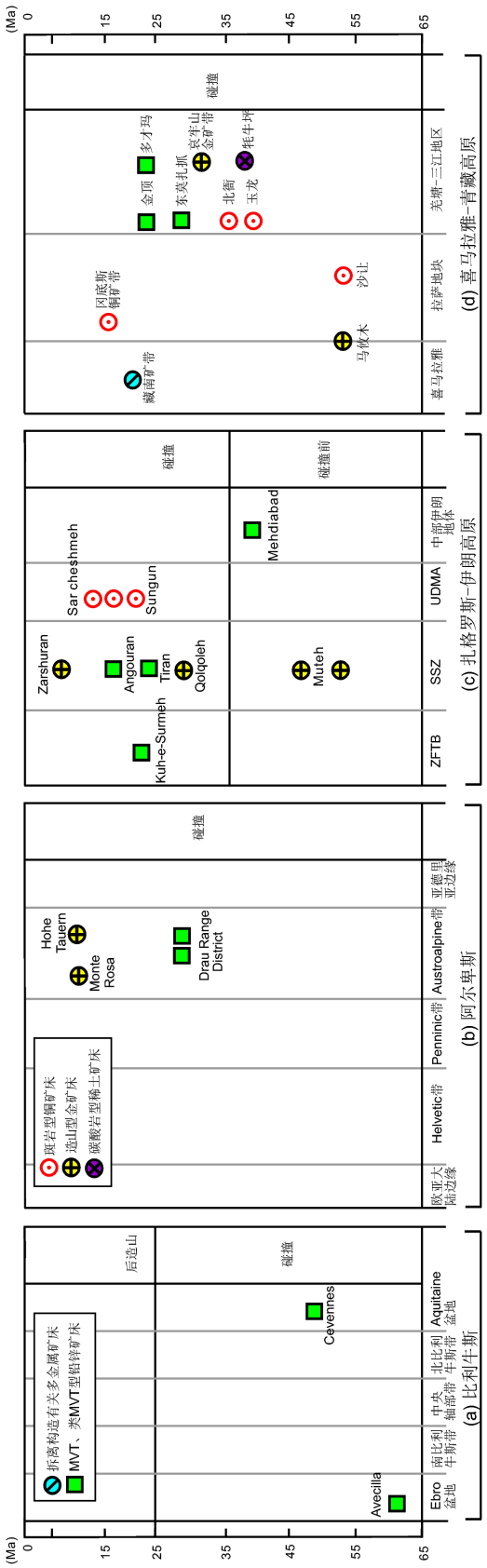

图 7 比利牛斯、阿尔卑斯、扎格罗斯-伊朗高原和喜马拉雅-青藏高原四个碰撞带主要矿床类型

垩纪或之前碰撞拼贴到欧亚大陆之上, 与欧亚大陆连为一体(Yin和Harrison, 2000; Yang等, 2011, 2012, 2014; Pan等, 2012; Zhu等, 2013; Zhang等, 2016, 2017a).

新生代以来, 印度大陆与欧亚大陆碰撞, 拉萨地块及周缘经历了三个阶段的改造作用(图6d): (1) 65~41Ma: 以岩浆大规模底侵、岩石圈缩短加厚、地壳垂向增生及峰期变质作用为特征, 发育林子宗火山岩(Mo等, 2007, 2008; Lee等, 2009; Zhu等, 2015)和大型挤压构造, 如唐古拉山逆冲断裂带、囊谦断裂系和风火山断裂系(Kapp等, 2005, 2007; Spurlin等, 2005; DeCelles等, 2007; Li等, 2015); (2) 40~26Ma: 以发育大规模剪切系统、褶皱逆冲系统和旋转构造为特征, 形成哀牢山-红河、崇山等多条大型剪切带(Wang等, 2006; Searle等, 2011; Cao等, 2011). 壳幔物质侧向流动诱发深部大规模壳/幔钾质岩浆活动(Chung等, 1998; Wang等, 2001; 赵志丹等, 2008; Wang等, 2008; Xu等, 2008; Zhang H等, 2015); (3) 25~0Ma: 发育多种类型岩浆活动, 如钾质-超钾质火山岩(拉萨地块)、富钾埃达克质岩(冈底斯)和淡色花岗岩(喜马拉雅)(Miller等, 1999; Turner等, 1996; Chung等, 2003, 2005; Wang等, 2005; Zhao等, 2009). 同时发育地壳伸展, 主要表现为喜马拉雅造山带东西向延伸的藏南拆离系(STD)(Burchfiel等, 1992)和喜马拉雅-拉萨地块上的一系列南北向正断层及裂谷系(14~10Ma)(Blisniuk等, 2001; Hintersberger等, 2010).

5.2 喜马拉雅-青藏高原成矿系统及发育特征

伴随着印度大陆与亚洲大陆的强烈碰撞, 青藏高原内发育了一系列大型-超大型金属矿床, 形成了世界级规模的巨型成矿带(图5), 如冈底斯和玉龙斑岩型铜矿带(Hou等, 2006, 2009a, 2015a, 2015b; Yang等, 2009a)、三江类MVT型铅锌矿带(侯增谦等, 2008; He等, 2009; 张洪瑞等, 2011, 2013)、哀牢山造山型金矿带(胡云中等, 1995; Sun等, 2009; Deng等, 2014)、川西岩浆碳酸岩型稀土矿带(Hou等, 2009b, 2015c)和藏南大型拆离构造有关的锑金多金属矿带(聂凤军等, 2005; 杨竹森等, 2006; Yang等, 2009b; Zhai等, 2014)等(图7d).

(1) 冈底斯和玉龙斑岩铜矿带. 冈底斯斑岩铜矿床主要集中于冈底斯中段, 斑岩结晶年龄介于20~12Ma, 侵位高峰期在(16±1)Ma左右; 成矿年龄介于20.7~13.5Ma, 集中于(15±1)Ma左右(Hou等, 2009a; 侯增谦等, 2012). 玉龙铜矿带成矿年龄介于40~30 Ma 之间(Hou等, 2006). 相对于大陆碰撞时间的(55±10)Ma(Hu等, 2016; 胡修棉等, 2017; 朱弟成等, 2017), 两条铜矿带明显是碰撞造山作用之后造山带再活化的产物.

冈底斯斑岩铜矿带空间分布与南拉萨大陆边缘弧新生地壳相对应, 含铜岩浆主要源自有新生下地壳部分熔融(Hou等, 2013). 锆石Hf同位素研究表明, 这一对成矿有重要贡献的新生下地壳很可能与侏罗纪大陆弧岩浆底垫有关(Hou等, 2015b). 玉龙铜矿带发育在碰撞带东缘, 该区在碰撞之前构造位置属于扬子地块西缘, 在新元古代早期Rodinia超大陆聚合之时遭受过古洋壳的俯冲改造. 在新生代时, 受印度-亚洲大陆碰撞的影响, 该区发育强烈岩浆活动(Wang等, 2001), 形成有玉龙、北衙等众多大、中、小型斑岩矿床. 其中, 北衙矿床研究显示, 铜金等金属来自新元古代底垫弧岩浆(Hou等, 2017).

已有研究表明, 早期洋壳俯冲作用与晚期碰撞后阶段的斑岩型铜成矿作用可能有成因联系: 弧岩浆在相对封闭环境下保持高fO_2,导致金属Cu、Au逐渐集聚于演化岩浆中, 形成俯冲型斑岩铜矿. 相反, 弧岩浆在开放环境与地壳相互作用, 岩浆fO_2降低, 将导致岩浆硫化物在新生下地壳堆积. 在碰撞后期过程中, 富含金属硫化物的新生下地壳发生部分熔融, 金属Cu向岩浆系统释放, 形成碰撞型斑岩铜矿(Hou等, 2015b).

除上述两条主要成矿带外, 近年来冈底斯岩基北侧新发现了一期成矿在52Ma的斑岩型钼矿床(沙让钼矿)(Zhao等, 2014), 成矿作用与大陆碰撞同期, 属于大陆碰撞阶段成矿作用产物.

(2) 三江类MVT型铅锌矿带. 新生代印度-亚洲大陆碰撞引发地壳大规模缩短, 形成一系列大型挤压构造, 如高原腹地的唐古拉山逆冲断裂带、囊谦-风火山断裂系和兰坪-思茅褶皱逆冲带. 这些褶皱逆冲带内发育有金顶、白秧坪、东莫扎抓、莫海拉亨、多才玛等一系列铅锌矿床, 构成一条上千公里长的铅锌矿带(侯增谦等, 2008; 宋玉财等, 2011). 该套矿床可分为金顶式、河西-三山式、东莫扎抓式、多才玛式4种不同的矿床式(He等, 2009; Zhang等, 2017b). 矿体受控于古岩溶构造(茶曲帕查, 张洪瑞等, 2011, 2012)、褶皱逆冲作用有关的断裂系统(白秧坪, 胡茂德等, 2015)、挤压

有关的盐底辟构造(金顶; Leach等, 2017)以及大型断裂构造上盘的裂隙空间(东莫扎抓; 张洪瑞等, 2013). 定年研究表明, 铅锌成矿年龄在白秧坪矿床是30Ma(王晓虎等, 2011), 在东莫扎抓矿床是35Ma(田世洪等, 2011a), 在多才玛矿床是23Ma(张洪瑞等, 2011), 在金顶矿床是23Ma(Yalikun等, 2018), 总体上晚于大陆碰撞年龄(55±10)Ma(Hu等, 2016; 胡修棉等, 2017; 朱弟成等, 2017), 因此成矿作用属于大陆碰撞之后造山带再活化作用的产物.

该带上的矿床赋存于沉积岩, 尤其是碳酸盐岩中; 成矿具典型后生构造控制特征, 与岩浆活动无关(Song等, 2015). 这些特征与密西西比河谷型(MVT型)铅锌矿床相类似. 与典型MVT型矿床相比, 该套矿床发育在褶皱逆冲带而不是在前陆盆地中(侯增谦等, 2008); 金属来源于二叠纪、三叠纪陆缘弧而非被动陆缘(田世洪等, 2011b; 郝宏达等, 2017); 流体系统受构造挤压驱动而非重力作用. 本文称之为类MVT型矿床, 其具体成矿过程可概括为: 大陆碰撞产生的褶皱逆冲系统, 在深部形成拆离滑脱构造, 在前锋产生圈闭构造(Liu等, 2011, 2015, 2017); 碰撞后伸展作用使含金属流体得以沿拆离滑脱构造向圈闭构造运移. 应力快速松弛诱发含矿流体快速排泄, 有利于金属硫化物淀积成矿(宋玉财等, 2011).

(3) 哀牢山造山型金矿带. 滇西哀牢山金矿带产于青藏高原东缘东缘哀牢山-红河剪切带附近(Sun等, 2009). 该剪切带左行走滑起始于约40Ma, 在27Ma左右达到活动高峰(Searle等, 2011). 金成矿作用伴随大规模走滑活动而发生, 矿带整体赋存在剪切带的绿片岩相和角闪岩相变质带内, 矿体就位于哀牢山-红河剪切带的二级或次级构造上(Deng等, 2014). 主要矿化类型包括含金石英脉型和含金构造蚀变岩型. 成矿流体盐度高低不一, 但都以高CO_2含量为特征; 矿物流体包裹体He和Ar同位素组成表明, 成矿是富含地壳放射成因氦的饱和空气雨水与富含幔源氦的深源流体两端元混合的结果(胡瑞忠等, 1999).

除哀牢山地区外, 藏南地区雅鲁藏布江缝合带附近也发育少量金矿床(化), 如加查、折木郎和马攸木等. 这些矿床成矿发生在古新世, 与大陆碰撞同期, 成矿作用可与与大陆地壳俯冲产生的变质流体活动有关(侯增谦, 2010; Jiang等, 2009; Zhai等, 2014).

(4) 川西岩浆碳酸岩型稀土矿床. 青藏高原东缘川西地区发育李庄、牦牛坪、大陆槽等若干稀土矿床. 这些矿床都赋存在冕宁-德昌岩浆碳酸岩-碱性岩杂岩带内, 受鲜水河-小江走滑断裂控制. 碳酸岩-正长岩杂岩体成岩年龄与其相应的成矿年龄基本一致, 主要集中在27~22Ma和11Ma(Tian等, 2015; Liu和Hou, 2017). 含矿岩浆碳酸岩具有高放射性Sr同位素特征, EMII型Sr-Nd同位素特征, 这种岩石圈地幔的富集很可能与新元古代以来俯冲沉积物衍生流体的加入有关(Hou等, 2015c). 新生代时大型走滑断裂切穿地壳, 诱发岩石圈地幔减压熔融, 形成富稀土的岩浆碳酸岩(Hou等, 2009b). 岩浆上侵过程中, 不混溶过程导致稀土元素进一步集聚于碳酸岩熔体中. 碳酸岩熔体再出溶出富稀土的成矿流体(750~650℃), 强烈沸腾作用导致稀土矿物的大量沉淀(450~210℃; Xie等, 2015).

(5) 藏南大型拆离构造有关锑金多金属矿带. 藏南喜马拉雅地区发育一条长达600km的锑金多金属矿带. 该成矿带受藏南伸展拆离系控制, 显示以变质核杂岩为中心的环状矿化分带特征, 中部以铅锌为主, 向外过渡到以金、锑为主(聂凤军等, 2005). 成矿发生在20~8Ma, 锑金成矿与变质核杂岩剥蚀隆升导致的流体对流循环有关(杨竹森等, 2006; Yang等, 2009b). 最近研究发现, 变质穹隆核部侵入的淡色花岗岩体还伴有铌钽锂铍锡钨等矿化(李光明等, 2017; 王汝成等, 2017; 吴福元等, 2017).

6 对比讨论

6.1 碰撞造山带类型

关于碰撞造山带的类型, 前人有多种划分方案. 有以造山带名称来代表的, 如阿尔卑斯型、喜马拉雅型(Sengor, 1990; Beaumont等, 1996); 有以造山单元来划分的, 如弧弧碰撞、弧陆碰撞和陆陆碰撞(李继亮等, 1999; Brown和Huang, 2009; Glen和Meffre, 2009; 郑永飞等, 2015); 有以结构来划分的, 如对称式、背驼式(许志琴等, 1996; 车自成等, 2002; 侯增谦, 2010); 有以板块相对运动划分的, 正向带和斜向带(Authemayou等, 2006; 张洪瑞和侯增谦, 2015). 这些划分方案是人们从不同角度来认识碰撞造山带的阶段性成果. 本文以比利牛斯、阿尔卑斯、扎格罗斯-伊朗高原、喜马拉雅-青藏高原四个碰撞造山带为研究实例, 来讨论这个问题. 需要指出的是, 我们的下述认识不一定有普遍

意义, 但是也能反映出一定的规律性.

对比发现, 四个大陆碰撞造山带可分为两类: 一类为简单碰撞带, 表现为狭窄线状造山带、没有或者有限规模的碰撞岩浆活动和以中上地壳物质活动为主的成矿系统(MVT型铅锌矿床和造山型金矿床), 实例来自比利牛斯和阿尔卑斯. 另一类为复合碰撞带, 表现为宽阔的造山高原大规模碰撞岩浆活动和壳幔物质活动有关的成矿系统(岩浆碳酸岩型稀土矿床、碰撞型斑岩铜矿床、造山型金矿床、类MVT型铅锌矿床和伸展构造有关的锑金多金属矿床), 实例来自扎格罗斯-伊朗高原和喜马拉雅-青藏高原中东部.

简单碰撞带发育对称式造山带结构(图8a), 表现为中央轴部带及两侧的褶皱逆冲带和前陆盆地. 复合碰撞带则为不对称式造山带结构(图8b). 在扎格罗斯造山带, 碰撞影响范围扩展至SSZ、UDMA甚至中部伊朗地体, 形成伊朗高原. 而这些受碰撞影响的块体中, SSZ和UDMA属于新特提斯洋壳俯冲形成的大陆边缘弧, 而中部伊朗地体属于古特提斯俯冲带的上盘大陆岩石圈. 在喜马拉雅造山带, 碰撞影响范围可扩展至拉萨、南羌塘、北羌塘等不同地块, 形成青藏高原. 其中, 拉萨地块南缘发育新特提斯洋壳俯冲形成的大陆边缘弧, 而拉萨、南羌塘、北羌塘等地块则是在古生代-中生代期间多次增生-碰撞作用而形成的大陆岩石圈.

6.2 不同碰撞带成矿对比

不同类型碰撞造山带成矿系统存在一些相同的特点. 四个碰撞造山带都发育沉积岩容矿铅锌矿床(此处指MVT和类MVT型矿床)(图7). 该类矿床与中低温盆地流体的循环沉淀密切相关(Leach等, 2010). 碰撞造山过程很容易形成盆地流体, 并驱动流体对流循环, 因此MVT和类MVT型矿床成为碰撞造山带的特征性矿床. 其中, 简单碰撞带发育的MVT型矿床是碰撞造山带在拉张垮塌条件下中央核部带明显隆升的背景中, 盆地流体受重力驱动迁移上千公里, 从基底岩石中萃取金属, 到前陆盆地中沉淀成矿(Leach等, 2010). 复合碰撞带发育的类MVT型矿床也是在碰撞造山带拉张垮塌的过程中, 盆地流体受构造底辟作用, 萃取弧岩浆岩或弧后碳酸盐岩中的金属, 就近沉淀在褶皱逆冲带中(如扎格罗斯带SSZ和青藏高原三江地区).

除了比利牛斯外, 其他三个造山带都发育少量造山型金矿床. 该类矿床常见于增生型造山带中, 是变质流体从围岩地层中淋滤金, 沿大型断裂带向上运移, 在有利构造部位卸载而形成(Goldfarb等, 2005). 大陆碰撞过程中, 虽然俯冲板片脱水能产生变质流体, 沿缝合带、大型剪切带等深断裂也可为流体迁移提供通道, 但是由于大陆俯冲带具有冷的物理化学性质(郑永飞等, 2016), 难以溶解地幔楔中的成矿元素, 因此难以构成有利成矿条件. 对于比利牛斯造山带来说, 其碰撞过程还未进行到大规模剪切构造出现就发生夭折. 因此, 可能是碰撞夭折扼杀了该区造山型金矿的形成.

不同类型碰撞造山带成矿系统也存在若干差异性. 简单碰撞造山带相对缺乏火山弧, 普遍不发育与岩浆作用相关的矿床类型, 包括岩石圈之下地幔减压熔融有关的碳酸岩型稀土矿床、加厚下地壳部分熔融有关的斑岩型铜钼金矿床和中上地壳部分熔融有关的稀有金属矿床. 相反, 大陆边缘弧在复合碰撞造山带明显发育, 这些矿床也蔚为壮观. 显然, 复合碰撞更有利于大陆弧下部壳幔物质活化迁移, 并在地壳浅层沉淀成矿.

6.3 不同碰撞带发育机制

上一节分析了不同碰撞带成矿系统发育的异同性及其原因. 沿着碰撞成矿主控因素的思路继续思考, 在更宏观的尺度上, 有哪些是控制一个造山带成为简单或者复合碰撞带的根本性因素? 简单或者复合碰撞带发育机制是什么?

(1) 洋壳俯冲阶段形成的大陆弧. 构造演化资料表明, 四个碰撞造山带都是新特提斯洋盆闭合后的产物(图9). 其中, 两个简单碰撞带的大陆俯冲都是由新近从欧洲大陆裂解分离出来的陆块(如比利牛斯的伊比利亚板块、阿尔卑斯的亚德里亚板块)重新与欧洲大陆拼合. 相比而言, 比利牛斯地区是否存在早期洋壳俯冲还存在较大争议(Teixell等, 2018); 阿尔卑斯造山带在白垩纪特提斯洋壳俯冲时地温梯度为5~6℃/km (Malusà等, 2011, 2015), 虽然俯冲板片经受过加热脱水, 但是在冷的俯冲带地幔楔中的交代岩难以发生部分熔融(郑永飞等, 2016). 无论是何种原因, 两个汇聚陆块之间缺乏大陆边缘弧(Carminati等, 2010).

复合碰撞带在大陆碰撞之前一般经历了复杂的洋壳俯冲到大陆边缘弧增生过程(潘桂棠等, 2004; Zheng等, 2013), 形成有喜马拉雅造山带北侧的冈底斯岩浆

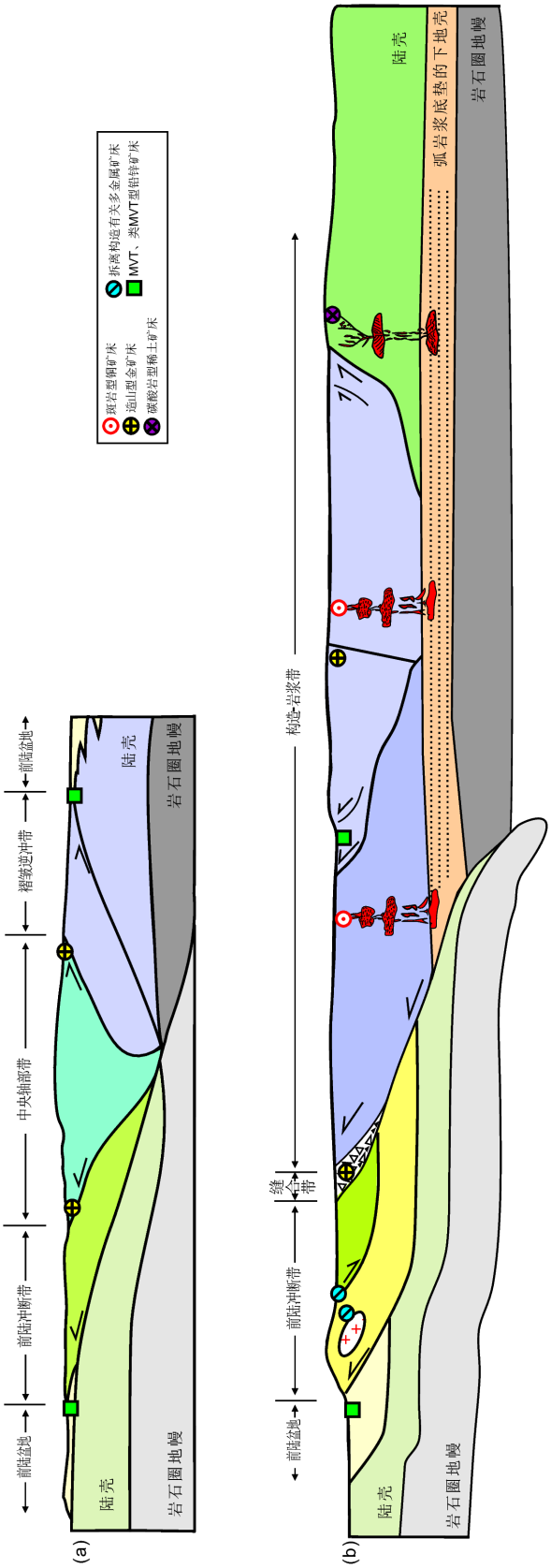

图 8　简单(a)、复合(b)碰撞造山带结构及主要矿床类型示意图
未按比例尺绘制

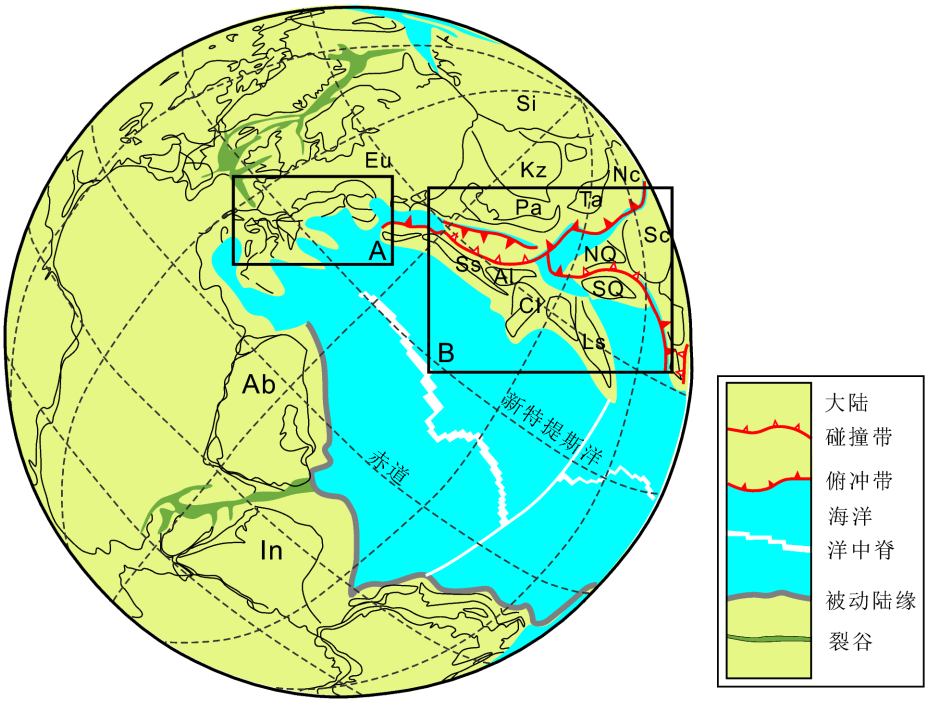

图 9　三叠纪特提斯构造复原图(修改自Stampfli, 2000)

图中A区为从欧亚大陆裂离的陆块与其重新汇聚, 大陆碰撞表现为简单碰撞; B区为多陆块复合造山, 随后大陆碰撞表现为复合碰撞. 陆块名称: Eu, 东欧; Ab, 阿拉伯; Si, 西伯利亚; Kz, 哈萨克斯坦; Ta, 塔里木; Nc, 华北; Sc, 扬子; SQ, 南羌塘; NQ, 北羌塘; Ls, 拉萨; CI, 中部伊朗地体; Al, Alborz; Ss, 萨南达杰-锡尔詹; In, 印度; Pa, 帕米尔

弧和扎格罗斯造山带的萨南达杰-锡尔詹中生代岩浆变质带(SSZ). 因此, 大陆边缘弧的存在与否成为不同碰撞造山带类型发育的关键. 另外, 来自喜马拉雅-青藏高原冈底斯带和玉龙带北衙矿床的研究表明, 含矿岩浆的源区是由早期洋壳俯冲形成的. 这种弧岩浆携带大量金铜硫化物底垫在下地壳, 在碰撞过程中硫化物活化, 被携带搬运至上地壳(Hou等, 2015a, 2017). 可见, 在大陆弧形成阶段金属初步富集对碰撞型斑岩铜矿床成矿至关重要.

我们注意到, 无论是冈底斯弧还是SSZ带, 都位于碰撞缝合带附近有限的狭窄区域. 而两个复合碰撞带, 喜马拉雅-青藏高原和扎格罗斯-伊朗高原, 都是造山高原, 扩展范围甚广, 远不只碰撞缝合带附近. 所以, 除大陆边缘弧外, 还有其他因素控制复合碰撞带的发育.

(2) 早期陆块拼贴形成的岩石圈薄弱带. 比利牛斯和阿尔卑斯是两个简单碰撞带, 分别由伊比利亚板块、亚德里亚板块与欧洲大陆碰撞而形成. 这几个卷入碰撞的板块都是相对稳定的陆块. 相对而言, 扎格罗斯-伊朗高原和喜马拉雅-青藏高原碰撞带上盘亚洲大陆南部是由多个小陆块新近拼合在一起的, 其内部可能不是稳定的"铁板一块"(张洪瑞和侯增谦, 2015). 在扎格罗斯-伊朗高原, 碰撞岩浆活动已经延伸至北部Alborz和东部Sistan地区. 这两个地区分别是古特提斯和新特提斯板块焊接处(Alavi, 1991; Zanchi等, 2016). 在喜马拉雅-青藏高原, 碰撞有关褶皱逆冲带主要沿古缝合带分布. 在小比例尺地质图上, 与碰撞有关的岩浆岩分布与造山带尺度的古构造线相一致, 如三江地区富碱斑岩带与金沙江古构造带. 另外, 早期俯冲碰撞等陆块拼合过程往往形成厚岩石圈, 在后期容易失稳. 因此, 早期拼贴在一起的陆块常具有不稳定的岩石圈结构, 受到碰撞造山影响而再活化. 我们目前不确定这种活化的深部机制是陆内俯冲(邓万明和黄萱, 1998)、岩石圈拆沉(Bird, 1979)、地幔对流减薄(e.g., Williams等, 2004), 还是碰撞加厚造山带减薄之后软流圈上涌引起的再活化(Zheng和Chen, 2017). 但是, 岩石圈结构不稳定是这些地区碰撞后再活化的先决条件.

6.4 碰撞型与增生型造山带成矿对比

除碰撞型造山带以外, 汇聚板块边缘还发育另外一种类型的造山系统——增生型造山带(Cawood等, 2009; Xiao等, 2015). 研究表明, 增生型造山带不同构造部位赋存不同成矿系统, 如弧前增生楔伴生造山型金矿、岛弧陆缘弧发育斑岩型铜矿床和浅成低温热液金矿床、弧间裂谷弧后盆地产有VMS型铜铅锌矿床等(Groves和Bierlein, 2007; Bierlein等, 2009). 其中斑岩型矿床产出规模、吨位储量首屈一指, 备受研究者关注. 其成矿过程可概述为: 俯冲大洋板片析出的流体交代地幔楔, 地幔楔发生部分熔融产生钙碱性弧岩浆, 该岩浆经过结晶分异(Richards, 2003), 演化成含铜岩浆系统(Kelley和Cottrell, 2009; Richards, 2009). 过去通常认为铜来源于地幔楔(McInnes等, 1999; Griffin等, 2013), 在部分熔融过程中被带入到岩浆系统. 但是也有研究指示, 有些弧下岩石圈地幔中不存在铜富集源区(Lee等, 2012). 铜富集主要是岩浆在加厚下地壳内分异出铜硫化物堆积导致(Nadeau等, 2010; Chiaradia, 2014).

相比而言, 碰撞带成矿系统也赋存在不同构造部位或单元内, 如前陆盆地和褶皱逆冲带内产有MVT、类MVT型铅锌矿床, 板块缝合带和大型剪切带附近产有造山型金矿床, 碰撞岩浆岩赋存斑岩型铜钼金矿床、碳酸岩型稀土矿床等. 这其中, 无论是岩浆作用有关的斑岩型铜钼金矿床、碳酸岩型稀土矿床, 还是沉积岩有关的MVT、类MVT型铅锌矿床, 其金属来源都与早期洋壳俯冲作用有关, 体现了碰撞成矿对早期俯冲作用的继承和发展.

与大洋板片俯冲类似, 在大陆碰撞造山带, 大陆板片俯冲到高压超高压深度时也会脱水, 释放出流体交代陆下岩石圈地幔和下地壳(Zheng等, 2011; Zheng, 2012). 然而, 大陆俯冲带上盘岩石圈处于较低的温度, 受到流体交代的地幔楔难以发生部分熔融形成大陆弧岩浆作用(郑永飞等, 2016), 这一过程对同碰撞岩浆作用和成矿事件的贡献不显著, 这种碰撞造山带以阿尔卑斯和比利牛斯为代表. 如果大陆俯冲带上盘岩石圈处于较高的温度, 则会造就大量同碰撞岩浆岩的形成, 如藏南冈底斯65~40Ma岩浆岩(林子宗火山岩和同期的冈底斯岩基)和伊朗扎格罗斯始新世-渐新世岩浆岩. 在碰撞后阶段, 俯冲带之上岩石圈受拆沉/减薄、造山带垮塌等作用影响就可以发生伸展构造背景下的部分熔融和裂熔造山(Zheng和Chen, 2017; Zheng等, 2018), 这个构造过程也就有可能引起下地壳成矿组分再活化形成斑岩型矿床. Yang等(2016)用其来解释冈底斯含铜埃达克质岩的成因, 认为印度陆壳的脱水对于加厚下地壳的熔融至关重要. 这一认识不同于Guo等(2007)的超钾质岩石提供热源和Liu等(2016)的印度地壳物质直接参与部分熔融等模型.

与大洋俯冲环境斑岩铜矿床相比, 大陆碰撞环境斑岩铜矿床的金属起源是一致的, 都来自于俯冲带流体交代地幔楔引起的成矿元素富集以及地幔楔部分熔融衍生岩浆分异造成的硫化物堆积. 不同之处在于, 前者形成在洋壳俯冲时期, 堆积的硫化物熔体直接被高氧逸度的岩浆运移至上地壳进而成矿; 而后者于洋壳俯冲时期在下地壳形成硫化物堆积体, 直至后期大陆碰撞过程或者之后重熔再活化成矿(Hou等, 2015a).

7 结语

经典的矿床学研究专注于矿床类型和成矿过程, 聚焦于孤立的矿点或成矿区域, 以*Economic Geology*杂志上发表的众多典型矿床解剖文章为代表, 此为矿床学发展的第一个阶段. 板块构造提出以来, 矿床学家开始在区域构造演化框架下来理解成矿作用(Groves等, 1998, 2005; Kerrich等, 2005), 认识到成矿作用是俯冲带演化过程中的有机组成部分, 其研究应该与该区构造岩浆过程结合起来(Blundell, 2002; Blundell等, 2005; Groves等, 2005), 矿床学研究进入第二个阶段. 西方学者通过解剖环太平洋(Sillitoe和Perello, 2005; Garwin等, 2005)、古亚洲成矿域(Yakubchuk等, 2005)等增生型造山带, 提出大洋俯冲作用与成矿作用之间的时空关系, 阐释了增生造山带成矿机制(Groves和Bierlein, 2007; Bierlein等, 2009). 我国学者通过研究喜马拉雅-青藏高原, 初步提出了大陆碰撞成矿理论框架(侯增谦, 2010; Hou和Cook, 2009; Hou和Zhang, 2015), 为矿床学发展作出了重要贡献. 本文即是在这一背景下, 对碰撞造山带成矿作用的尝试性对比总结, 发现大陆弧的存在与否是碰撞造山带成矿的关键.

本文所列四个碰撞造山带都是新特提斯洋盆闭合的产物, 是新生代欧亚大陆南缘陆块汇聚的结果. 从全

球尺度构造演化角度审视, 这四个年轻造山带与前言所提到的加里东、华力西、乌拉尔山等古老碰撞造山带, 甚至包括古亚洲增生造山带, 都形成在欧(劳)亚大陆聚合的背景下. 该大陆很可能会继续聚合澳洲大陆和美洲大陆, 形成一个世界级超大陆. 因此, 无论是年轻造山带还是古老造山带, 无论是碰撞造山带还是增生造山带, 它们在超大陆聚合背景下都具有一定的相关性和演化连续性. 大陆碰撞对增生造山带的改造可能是其中成矿组分再活化的重要因素.

从造山循回的角度来看, 大陆碰撞往往紧随大洋俯冲而发生, 增生造山和碰撞造山是板块汇聚的两种主要类型, 它们是介于大陆生长和陆内再造的重要环节. 碰撞造山带成矿作用对比研究表明, 早期大洋俯冲作用形成的增生造山带对随后的大陆碰撞带成矿具有重要控制作用. 由此引发了一系列思考: 早期增生造山作用在后期大陆碰撞和陆内再造中扮演何种角色? 基于碰撞带研究而建立的成矿理论是否适用于陆内造山带及其他构造环境? 不同构造背景下成矿作用的关键控制要素是什么? 基于这些问题, 我们认为, 加强不同构造背景成矿作用对比研究, 从根本上理解矿床形成机制和造山带成矿规律, 有可能推动矿床学研究走向新的发展阶段.

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