综 述

洋中脊或海岭俯冲与岩浆作用及金属成矿

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摘要 扩张洋中脊、无震海岭或大洋高原和残余弧脊是现代海洋的重要组成部分, 其面积超过当今世界海洋总面积的20~30%。它们均可以发生俯冲, 可称为脊或海岭俯冲, 这是现代大洋板块动力学系统中十分普遍且非常重要的一种地质过程, 并可能与岛弧岩浆作用的产生及物质循环、大陆地壳生长与演化、上覆板块变形以及金属成矿相关, 受到广泛关注。现代典型扩张洋中脊在正向或高角度俯冲时, 会形成板片窗, 并形成特殊的埃达克岩-高镁安山岩-富Nb玄武岩-洋岛玄武岩型或洋中脊玄武岩型玄武岩组合, 且与金成矿关系密切。无震海岭或大洋高原由于其厚的地壳(大于正常洋壳厚度6~7km)、高的地形, 传统上被认为很难发生俯冲或只能发生碰撞或平坦(低角度<10°)俯冲。但是, 新生代太平洋东西两岸的无震海岭或大洋高原发生了俯冲, 其中太平洋东岸无震海岭或大洋高原俯冲一般为平坦或相对小角度俯冲, 这时往往会形成岩浆间歇期, 但是在板片回卷或板片撕裂过程, 板片会发生熔融, 并形成一些埃达克岩或埃达克岩-高镁安山岩-埃达克质安山岩-富Nb玄武岩组合, 伴随俯冲作用的进行, 也会形成一些重要的铜金矿床; 在太平洋西岸, 无震海岭或大洋高原大多发生了较高角度(>30°)的俯冲, 且形成了较大规模的玄武岩-玄武安山岩-安山岩组合, 其与俯冲流体交代地幔楔熔融产生的岩浆经过分离结晶有关。日本西南部有残余弧脊发生了俯冲, 产生了玄武岩、高镁安山岩和埃达克岩, 同时有金矿伴生。除了岩浆作用和铜金成矿之外, 脊或海岭的俯冲也可能导致俯冲带俯冲侵蚀作用发生。需要进一步关注的前沿领域包括脊或海岭俯冲的形式及其动力学机制与物质循环过程、岩浆和金属作用产生的深部机制及影响因素、前新生代的脊或海岭俯冲作用的识别以及板块构造启动时间与太古代大陆地壳生长机制等。

关键词 扩张洋中脊, 无震海岭, 大洋高原, 残余弧脊, 俯冲, 岩浆作用, 金属成矿, 地壳生长

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1 引言

扩张洋中脊(spreading oceanic ridge)、无震海岭(aseismic ridge)或大洋高原(oceanic plateau)以及残余弧脊(inactive arc ridge)是现代海洋的重要组成部分,其面积超过当今世界海洋总面积的20~30%(Yesson等, 2011; Harris等, 2014)。“Ridge subduction”(脊或海岭俯冲)一般包括扩张洋中脊、无震海岭或大洋高原以及残余弧脊的俯冲(例如, Vogt, 1973; Thorkelson, 1996; Gorring和Kay, 2001; Rosenbaum等, 2005; Thorkelson和Breitsprecher, 2005; Madsen等, 2006; Rosenbaum和Mo, 2011; Cao等, 2014; Fan等, 2016; Baillard等, 2018)。这类俯冲不同于正常(具有6~7km地壳厚度)大洋板块的俯冲过程,是现代大洋板块动力学系统中很普遍且非常重要的一种地质过程,并可能与弧岩浆作用及物质循环、大陆地壳生长与演化、上覆板块变形以及金属成矿相关。脊或海岭俯冲已成为当前国际地质研究的热点之一,但是与其相关的很多问题仍旧存在争论。本文详细调研了近年来有关脊或海岭俯冲的研究进展,并讨论了存在的前沿科学问题。

2 现代大洋中的脊或海岭

2.1 扩张洋中脊

大洋中脊或中央海岭(middle oceanic ridge),又称扩张洋中脊(spreading oceanic ridge),是火山结构系统非常发育的全球大洋张性板块边界(图1)。现代的大洋中脊贯穿全球四大洋(大西洋、太平洋、印度洋和北

冰洋),也是世界上最长的山脉(图2),长达80000km,包括东太平洋海隆、大西洋中脊、印度洋中脊和北冰洋哈克尔(Gakkel)海岭(Michael等, 2003)等。除了上述贯穿四大洋的大洋中脊外,在一些小的洋盆中也有洋中脊出露,如西南太平洋所罗门海域中的伍德拉克(Woodlark)(Yoneshima等, 2005)、中美洲以西海域加拉帕戈斯(Galapagos)(Abratis和Wörner, 2001)、东南太平洋海域的智利(Bourgois等, 2016)、斯科舍海域的东斯科舍(East Scotia)(Livermore, 2003)等洋中脊。大洋中脊的脊部通常高出两侧洋盆底部1~3km,脊顶水深多为2~3km,少数山峰出露于海面形成岛屿,如大西洋中的冰岛、亚速尔群岛等在地表形成裂谷或地堑,冰岛同时也是洋中脊与地幔柱交汇的地方。大洋中脊是软流圈地幔对流上升形成的,上升的热软流圈地幔减压熔融产生玄武质岩浆,岩浆涌出后冷却形成新的大洋地壳(图1)。洋中脊是板块分离的部位,也是新洋壳开始生长的地方(图1),洋壳的年龄随着远离洋中脊而逐渐变老。

2.2 无震海岭与大洋高原

无震海岭(Aseismic ridge)一般是指出露于大洋盆地中由一系列热点或地幔柱作用在移动的大洋板块上形成的由火山构成的线性山状(或隆起)构造(图1),其重要特征是地震不发育,从而明显区别于地震发育的大洋中脊(Wilson, 1963; Morgan, 1971)。无震海岭地形一般起伏不大,顶面较平坦,两坡较陡,绵延700~5000km,宽150~400km,高出洋盆2000~4000m,局部露出水面成为洋岛(如夏威夷岛)。在现代海洋中,无震海岭非常发育(图2),典型的例子包括: (1) 太平洋东部

图1 大洋扩张、地幔柱或热点活动以及俯冲作用

图 2 全球扩张洋中脊、大洋高原或无震海岭分布

据NASA(<https://visibleearth.nasa.gov/view.php?id=88415>)、Kent(2014)、McCrory和Wilson(2009)的图修改

海域有胡安费尔南德兹(Juan Fernandez)、伊基克(Iquique)、纳斯卡(Nazca)、卡内基(Carnegie)和科库斯(Cocos)等无震海岭; (2) 太平洋北部海域有夏威夷-帝王(Hawaii-Emperor)、科迪亚克(Kodiak)和科布(Cobb)等无震海岭; (3) 太平洋西缘有小笠原(Ogasawara)、卡罗琳(Caroline)无震海岭; (4) 太平洋西南海域有德昂特勒卡斯托(D'Entrecasteaux)、忠诚(Loyalty)、路易维尔(louisville)等无震海岭; (5) 大西洋中有沃尔维斯海脊(Walvis)或鲸(Whale)、里奥格兰德(Rio Grande)等无震海岭; (6) 北冰洋有罗蒙诺索夫(Lomonosov)无震海岭和印度洋有90°E无震海岭等。

大洋高原或洋底高原是指出露于大洋盆地中比周围地形明显高(一般2~3km)且面积广大、相对平坦、由镁铁质-超镁铁质岩石组成的高地。一般认为, 大洋高原的形成可能与地幔柱或热点岩浆活动有关(Mann和Taira, 2004; Zhang等, 2014; 陆鹿等, 2016), 类似于无震海岭。无震海岭多数与大洋高原相连, 两者分别可能是地幔柱尾部和头部熔融的产物(Sleep, 1992; Campbell, 2007; 鄢全树和石学法, 2014)。大洋高原在太平洋和印度洋分布非常广泛(图2), 典型代表包括加勒比-哥伦比亚、翁通爪哇(Ontong Java)、沙斯基隆起(Shatsky Rise)、希库朗伊(Hikurangi)、西托里斯(West Torres)和印度洋中的凯尔盖朗(Kerguelen)大洋高原等。其中, 翁通爪哇大洋高原与路易维尔无震海岭被一些研究认为很可能分别是同一地幔柱的头部和尾部熔融的产物(Antretter等, 2004; Kerr和Tarney, 2005; Koppers等, 2011)。这里需要指出的是, 加勒比-哥伦比亚大洋高原西部、南部的局部已经成为拉丁美洲、南美大陆的一部分(Kerr和Tarney, 2005), 阿拉斯加亚库塔特(Yakutat)地块曾经为大洋高原, 但目前已经成为与北美大陆的一部分(Eberhart-Phillips等, 2006; Gulick等, 2007)。

2.3 残余弧脊

残余弧脊曾经是弧的一部分, 由于后期的地质作用(如弧后扩张)导致原来的弧被裂解或破坏而只留下一些残余痕迹在大洋盆地中, 如菲律宾海盆中的九州-帕劳(Kyushu-Palau)、奄美(Amami)、大东(Daito)、冲大东(Okai-Daito)(图3)(张洁等, 2012; Nishizawa等, 2014)以及劳海盆中的劳脊(图3)(Frisch等, 2011; 鄢全树和石学法, 2014)。在西菲律宾海盆中的残余弧脊的组成除了玄武岩外, 还有一些晚白垩世-始新世

(117~37Ma)英云闪长岩出露(Haraguchi等, 2003; Hickey-Vargas, 2005; 张洁等, 2012; Nishizawa等, 2014), 指示这些岩石主要形成在岛弧环境(Haraguchi等, 2003)。西菲律宾海盆很可能是在侏罗纪-早新生代的弧地体杂岩的基础上打开的, 盆地中的残余弧脊保留了原来弧的信息, 其中部分(如九州-帕劳(Kyushu-Palau)残余弧脊)也可能是从伊豆-小笠原-马里亚纳弧通过弧后伸展分离出来的(Haraguchi等, 2003; Hickey-Vargas, 2005; Ishizuka等, 2018)。劳海盆中的劳脊很可能是从汤加弧经过弧后扩张分离出来的, 已经成为不活动或残余弧脊(Frisch等, 2011)。

与正常的大洋地壳相比较, 无震海岭、大洋高原和残余弧脊的地壳密度相对小些, 但其地壳厚度比正常大洋地壳(6~7km)要厚, 一般为10~33km(Mann和Taira, 2004)。

3 扩张洋脊俯冲、岩浆作用与金属成矿

3.1 扩张洋脊俯冲

扩张洋脊俯冲是指扩张洋中脊与俯冲带交叉而随俯冲板片一起俯冲到地幔的一种现象, 所有的俯冲带最终都会与扩张洋中脊相互作用而结束(Thorkelson, 1996)。但是, 扩张洋中脊与俯冲带相交的角度不同, 会影响俯冲的动力学过程。如果扩张洋中脊只是小角度甚至平行于海沟俯冲时, 具有正地形的洋中脊与大陆边缘之间会发生碰撞导致蛇绿岩的构造侵位, 而具有负地形的洋中脊会俯冲到大陆边缘之下(Forsythe等, 1986; Zheng和Chen, 2016)。当扩张洋中脊处于正向或者大角度俯冲时, 俯冲的洋中脊由于俯冲增压导致洋中脊之下软流圈减压熔融停止, 从而使新的洋壳停止生长, 但洋中脊持续扩张作用将会使该洋中脊扩张中心轴线两侧的大洋板片之间、在上覆板块之下形成一个持续加宽的间隙, 这个间隙称为板片窗(slab window)——扩张洋中脊俯冲最核心特征(Thorkelson, 1996; Sisson等, 2003)(图4)。一般“正常的”大洋板块俯冲, 会在俯冲板片的上方形成地幔角流(corner flow); 而扩张洋中脊的俯冲, 除了有地幔角流外, 伴随扩张洋中脊俯冲过程中板片窗的打开, 会有来自板片之下的大量软流圈物质上涌。因此, 与“正常的”大洋板块俯冲触发的弧岩浆岩相比较, 扩张洋脊俯冲所形成的岩浆岩的类型更丰富、产出位置更多(Thorkelson,

图3 菲律宾海残余弧脊的分布
据Nishizawa等(2014)

1996; Sisson等, 2003). 这里需要说明的是, 一个不再处于活动阶段的洋中脊(fossil oceanic ridge)发生俯冲时, 即使是正向或者高角度俯冲, 也不会形成板片窗。

在环太平洋俯冲带, 有许多新生代扩张洋中脊正在发生俯冲作用, 典型的例子包括: (1) 伍德拉克扩张洋中脊沿东北向俯冲于所罗门弧之下(Weissel等, 1982; Yoneshima等, 2005; König等, 2007; Chadwick等, 2009; Taylor等, 2008; Schuth等, 2011; Holm等, 2016); (2) 智利扩张洋中脊沿东南向俯冲于南美大陆弧之下(Lagabrielle等, 1994, 2000; Gorrington和Kay, 2001; Gorrington等, 2003; Guivel等, 2006; Anma等, 2009; Bourgois等, 2016); (3) 加拉帕戈斯(Galapagos)扩张洋中脊向东俯冲于中美洲大陆弧之下(Johnston和Thorkelson, 1997; Abratis和Wörner, 2001; Hoernle等, 2008); (4) 胡安德富卡(Juan de Fuca)扩张洋中脊向东俯冲于北美大

陆之下(Rogers等, 1985; Cole和Basu, 1992; Madsen等, 2006; Cole和Stewart, 2009; Thorkelson等, 2011). 除了上述正在发生的扩张洋中脊的俯冲之外, 一些研究认为, 库拉(Kula)-法拉龙(Farallon)/复活(Resurrection)扩张洋中脊在古新世-始新世向阿拉斯加地块下面发生了俯冲(例如, Breitsprecher等, 2003; Haeussler等, 2003; Benowitz等, 2012; Scharman等, 2012), 以及早新生代(60~50Ma)伊佐奈岐-太平洋扩张洋中脊向东亚之下的俯冲(Whittaker等, 2007; Seton等, 2015). 一些证据显示, 南极板块和凤凰(Phoenix)板块之间的凤凰扩张洋中脊在中新世-上新世(20~3Ma)期间向南极大陆之下发生了俯冲(Eagles, 2004; Livermore等, 2004; Breitsprecher和Thorkelson, 2009).

确定扩张洋中脊俯冲作用最重要的工作就是证实板片窗的存在。地球物理资料揭示纳斯卡、南极两大

图4 扩张洋中脊俯冲与岩浆作用

据Thorkelson(1996)和Sisson等(2003)

洋板块的边界-智利扩张洋中脊发生俯冲之后, 纳斯卡、南极岩石圈之间的区域在地幔100~200km深处出现明显的P波和S波间断(gap)或板片窗, 即该区地幔波速明显低于周围地幔, 暗示有异常热的软流圈物质上涌, 这表明软流圈物质上涌进入到了板片窗中(Russo等, 2010a, 2010b). 另外, 火山岩的Pb同位素组成也揭示出, 所罗门海域中的伍德拉克扩张洋中脊向所罗门弧下俯冲, 已经在所罗门弧下形成了板片窗, 来自深部的俯冲太平洋板片组分已经通过板片窗进入到了所罗门岛弧的岩浆岩中(Chadwick等, 2009; Schuth等, 2011).

3.2 扩张洋中脊俯冲产生的岩浆岩组合

扩张洋中脊俯冲与正常大洋板块俯冲所产生的岩浆作用既有相似之处, 也有不同之处. 相似之处在于, 在扩张洋中脊俯冲的过程中, 在板片窗的两侧, 正常大洋板块俯冲也同时在进行, 板片脱水会发生, 会产生与正常大洋板块俯冲类似的岩浆岩组合(图4), 如玄武岩-玄武安山岩-安山岩-英安岩-流纹岩组合(例如, Benoit等, 2002; König等, 2007). 不同点在于, 由于扩张洋中脊俯冲导致了板片窗的打开, 软流圈上涌不仅带来了大量的热, 而且在俯冲带形成了伸展的环境, 在这样一个近似“板内伸展”的环境中, 会形成一套“特殊的”弧

岩浆岩组合, 包括: (1) 板片窗两侧年轻的洋壳发生熔融形成埃达克岩(例如, Kay等, 1993; Stern和Kilian, 1996; Aguillón-Robles等, 2001; Benoit等, 2002; Gorrington等, 2003; Guivel等, 2003); (2) 来自深部软流圈熔融产生的和与洋岛玄武岩(OIB)有类似微量元素、Sr-Nd同位素特征的(OIB型)玄武质岩石(例如, Gorrington等, 2003; Thorkelson等, 2011); (3) 深部软流圈沿着板片窗上升到浅处发生减压熔融产生的、与大洋中脊(MORB)有类似微量元素、Sr-Nd同位素特征的(MORB型)玄武岩(例如, Cole和Basu, 1992; Lytwyn等, 1997; Thorkelson等, 2011); (4) 被板片熔体(埃达克质岩浆)交代的上覆板块的弧下地幔熔融形成富Nb玄武岩(例如, Aguillón-Robles等, 2001; Benoit等, 2002); (5) 板片熔体(埃达克质岩浆)与上覆地幔的相互作用或被其交代的地幔低度熔融形成高镁安山岩(例如, Rogers等, 1985; Kay等, 1993; Stern和Kilian, 1996; Aguillón-Robles等, 2001; Benoit等, 2002; Osozawa等, 2012); (6) 板片窗之上热异常导致上覆板块的地幔高度熔融形成拉斑玄武岩(例如, Benoit等, 2002); (7) 板片窗之上热异常导致上地壳沉积岩或基底变沉积岩形成流纹岩和英安岩(Cole和Basu, 1992); (8) 在板片窗的高热条件下亏损地幔多次熔融形成玻安岩(例如, Osozawa等, 2012).

因此, 扩张洋中脊俯冲所产生的岩浆岩组合既包含了正常岛弧岩浆岩的组合, 也包含了类似“板内伸展”环境岩浆岩的组合; 岩浆岩的源区组成也非常复杂, 既有地幔楔橄榄岩, 也有俯冲洋壳、弧的中下地壳, 以及从板片窗上升的软流圈等. 特别需要指出的是, 在扩张洋脊俯冲产生的埃达克岩都展示了与蚀变洋中脊玄武岩熔融产生的熔体一致的微量元素、Sr-Nd-Pb同位素特征(例如, Aguilón-Robles等, 2001; Benoit等, 2002).

3.3 扩张洋中脊俯冲与金属成矿

扩张洋中脊俯冲会与金属成矿之间关联吸引了广泛的关注(Haessler等, 1995, 2003; Ling等, 2009; 孙卫东等, 2010). 新生代的典型例子是库拉-法拉龙/复活扩张洋中脊在65~50Ma向阿拉斯加之下俯冲, 俯冲的洋脊导致板片窗打开, 从板片窗上涌的软流圈加热弧前增生楔沉积物导致其发生高温低压变质作用, 并释放出流体, 导致石英脉型金矿的形成(图5)(Haessler等, 1995, 2003). 尽管南美安第斯山大陆弧和巴布亚新几内亚-所罗门岛弧新生代与俯冲相关的金属矿床非常发育(Solomon, 1990; Rosenbaum等, 2005), 但现代智利和伍德拉克扩张洋中脊的俯冲并没有产生相应的金属矿床. 因此, 扩张洋中脊俯冲导致金属成矿的潜力还需要进一步深入研究.

4 无震海岭俯冲、岩浆作用与金属成矿

4.1 无震海岭俯冲

一般地来说, 无震海岭或大洋高原相对于正常的

洋壳来说, 由于其密度小、厚度大而难以俯冲, 一般直接拼贴在岛弧或者大陆边缘弧上或与弧发生碰撞, 导致地壳侧向生长(Niu等, 2003; Kerr, 2014; Zhang等, 2014; Whattam和Stern, 2015; 牛耀龄等, 2015). 典型例子包括: (1) 在晚中生代, 中美洲白垩纪加勒比-哥伦比亚大洋高原(Kerr等, 1997; Kerr, 2014)、日本岛弧侏罗纪大洋高原(Kimura等, 1994; Ichiyama等, 2014)在大陆边缘或弧侧的增生; (2) 太平洋西岸卡罗琳(Caroline)无震海岭与雅浦(Yap)弧正在发生碰撞(Dong等, 2018). 但是, 有研究认为, 大约三分之二的无震海岭或大洋高原并没有发生碰撞或增生, 而是发生了俯冲(McGeary等, 1985).

大量的地球物理探测资料显示, 一些无震海岭正在发生俯冲(Gutscher和Peacock, 2003; Espurt等, 2008; Mason等, 2010; Morell等, 2012, 2013; Martinod等, 2013; Baillard等, 2018). 在太平洋东部海域, 胡安费尔南德兹、伊基克、纳斯卡、卡内基和科库斯等正在发生相对平坦的或较小角度(俯冲角度 $<30^\circ$)俯冲作用(图6)(Bourdon等, 2003; Hoernle等, 2008; Espurt等, 2008; Rosenbaum和Mo, 2011; Morell等, 2012, 2013). 太平洋北部的科迪亚克、科布无震海岭正在向阿拉斯加-阿留申弧发生平坦俯冲(Gutscher和Peacock, 2003; Eberhart-Phillips等, 2006; Fuis等, 2008; Worthington等, 2012). 在太平洋西缘和西南缘小笠原、德昂特勒卡斯托和路易维尔无震海岭则是发生陡倾(俯冲角度 $>50^\circ$)俯冲(Mason等, 2010; Martinod等, 2013; Baillard等, 2018).

地球物理探测资料也揭示出, 一些大洋高原也正

图5 阿拉斯加扩张洋中脊俯冲与变质作用、金成矿作用

据Haessler等(1995, 2003)

图6 纳斯卡-南美会聚系统的动力学背景

(a) 纳斯卡板块包含有许多地形异常(无震海岭或大洋高原(灰色区域)). 这些区域地壳异常厚有浮力的. 估计的这些异常区域在南美板块之下俯冲的长度用淡灰色区域表示. 红色三角形表示活动安山质岩浆作用. (b) 根据地震中心分布位置绘制的纳斯卡板块在南美板块之下的剖面形态. 据Espurt等(2008)

在发生俯冲(例如, Fuis等, 2008; Schuth等, 2011; Baillard等, 2018). 根据俯冲的特征和类型, 可以分成三类: (1) 陡倾俯冲: 西南太平洋西托里斯(West Torres)大洋高原向东往瓦努阿图岛弧之下陡倾俯冲(Baillard等, 2018); (2) 碰撞与平坦俯冲: 亚库塔特(Yakutat)大洋高原与北美板块发生碰撞, 然后向北美板块之下发生平坦(倾角 6°)俯冲, 且在最近10Ma已经俯冲了近500km(Eberhart-Phillips等, 2006; Gulick等, 2007; Fuis等, 2008; Worthington等, 2012); (3) 碰撞与

陡倾俯冲: 翁通爪哇大洋高原与所罗门岛弧发生碰撞, 高原上部物质(地壳最上部7km厚的玄武岩和沉积物)增生到所罗门前缘, 但高原下部物质(高原80%的地壳厚度)发生陡倾俯冲(Petterson等, 1997; Mann和Taira, 2004; Miura等, 2004; Schuth等, 2011); (4) 俯冲与撕裂: Meiji大洋高原向勘察加、阿留申岛弧之下的俯冲, 但发生了明显板片撕裂(slab tear)或灾难性板片丢失(catastrophic slab loss)(Yogodzinski等, 2001; Levin等, 2002, 2005).

4.2 无震海岭俯冲产生的岩浆岩组合

一般认为, 无震海岭或大洋高原的俯冲或与其与弧、大陆的碰撞常常被认为会导致岩浆间歇期出现或岩浆作用停止(例如, McGeary等, 1985), 最典型的例子就是太平洋西岸卡罗琳无震海岭与雅浦弧正在发生碰撞和纳斯卡无震海岭正在向南美大陆之下俯冲时没有产生第四纪的岛弧岩浆作用(McGeary等, 1985; Dong等, 2018; Rosenbaum和Mo, 2011). 但是一些正在发生无震海岭或大洋高原俯冲的弧区域岩浆作用也非常发育, 包括: (1) 与伊基克、卡内基和科库斯等无震海岭俯冲共生的南美安第斯弧和中美洲弧(Gutscher等, 2000; Beate等, 2001; Samaniego等, 2002, 2005; Bourdon等, 2003; Hoernle等, 2008; Rosenbaum和Mo, 2011; Ancellin等, 2017); (2) Meiji-夏威夷-帝王无震海岭或大洋高原俯冲密切相关的勘察加弧和阿留申弧西部(Yogodzinski等, 1994, 1995, 2001); (3) 与德昂特勒卡斯托无震海岭、西托里斯大洋高原俯冲密切相关的瓦努阿图岛弧(Beaumais等, 2013, 2016; Beier等, 2018). Rosenbaum等(2005)的板块构造重建显示, 一些正在发生无震海岭平坦俯冲的岛弧区虽然并没有同期的现代弧岩浆作用出现, 但是, 无震海岭从初始俯冲演化到当前的位置时, 可能曾经出现过与俯冲同期的弧岩浆作用.

无震海岭或大洋高原的俯冲, 会产生几类特殊的岩浆岩组合: (1) 埃达克岩-高镁安山岩-埃达克质安山岩-富Nb玄武岩组合(Gutscher等, 2000; Beate等, 2001; Samaniego等, 2002, 2005; Bourdon等, 2003; Bryant等, 2006; Yogodzinski等, 1994, 1995, 2001; Levin等, 2002). 典型例子是与卡内基无震海岭俯冲共生的厄瓜多尔岛弧(Gutscher等, 2000; Beate等, 2001; Samaniego等, 2002, 2005; Bourdon等, 2003; Bryant等, 2006): 埃达克岩由平坦俯冲的无震海岭板片熔融形成, 高镁安山岩由板片熔体与地幔反应形成; 板片熔体交代地幔形成富含韭闪石、金云母和石榴石的富集地幔, 该地幔中韭闪石在通过对流进入到对流地幔时候, 韭闪石首先不稳定, 导致富集地幔发生第一次熔融形成了埃达克质安山岩; 随着富集地幔进一步进入更深的位置, 金云母不稳定, 导致地幔第二次熔融形成富Nb玄武岩. (2) 埃达克岩与OIB型碱性玄武岩. 最典型的例子是与科库斯无震海岭俯冲共生的中美洲哥斯达黎加-巴拿马弧: 埃达克岩由俯冲的无震海岭熔融形成, OIB

型碱性玄武岩来自通过板片窗上升的软流圈地幔(Abratis和Wörner, 2001; Hoernle等, 2008; Gazel等, 2015). (3) “牙买加型”(Jamaica-type)埃达克岩(高硅、低镁、富钠, 相对高的La/Yb和低的Sr/Y比值)和高Nb玄武岩. 最典型的例子是加勒比大洋高原向牙买加弧下俯冲, 平坦俯冲的大洋高原在石榴石角闪岩相条件下熔融形成高硅低镁埃达克岩, 被板片熔体交代地幔楔物质减压熔融或地幔柱样(mantle plume-like)的源区熔融形成高Nb玄武岩(图7)(Hastie等, 2010a, 2010b, 2015). (4) 玄武岩-玄武安山岩-安山岩. 最典型的是西南太平洋托里斯大洋高原和德昂特勒卡斯托无震海岭向瓦努阿图新赫布里底岛弧俯冲形成的火山岩, 其由俯冲流体交代地幔楔熔融的岩浆经过分离结晶演化而形成(Beaumais等, 2013, 2016; Beier等, 2018).

4.3 无震海岭俯冲与金属成矿

在新生代, 一些无震海岭俯冲与铜金矿化密切共生, 主要表现在: (1) 南海中的Scarprugh无震海岭向吕宋(Luzon)岛弧之下的俯冲(Yang等, 1996), 形成Baguio、Lepanto-Far South East金矿和Guinaoang、Santo Tomas II 铜矿(Cooke等, 2005; 孙卫东等, 2010); (2) Euripik隆起(Rise)或大洋高原向巴布亚新几内亚岛弧之下俯冲(Gutscher等, 2000), 形成了著名的Grasberg、Frieda River、Ok Tedi和Porgera铜金矿(Cooke等, 2005); (3) Roo Rise大洋高原向东爪哇岛弧之下俯冲(Shulgin等, 2011), 形成了Batu Hijau铜金矿(Cooke等, 2005); (4) 科库斯无震海岭向中美洲哥斯达黎加-巴拿马弧俯冲(Abratis和Wörner, 2001; Hoernle等, 2008), 形成了Cerro Colorado铜金矿床(Cooke等, 2005); (5) 卡内基无震海岭向厄瓜多尔岛弧俯冲(Beate等, 2001; Bourdon等, 2003), 形成了Chaucha铜钼矿床(Cooke等, 2005); (6) 胡安费尔南德兹无震海岭向南美大陆之下俯冲(Rosenbaum等, 2005), 同时伴随的El Teniente、Rio Blanco、Los Pelambres等超大型铜矿床的形成(Cooke等, 2005; Rosenbaum等, 2005).

比较有争议的是, 纳斯卡无震海岭当前正在俯冲, 但其上盘的大陆弧中并没有金属矿床产出(Cooke等, 2005; 孙卫东等, 2010). Rosenbaum等(2005)的板块构造重建显示, 纳斯卡无震海岭在16~2Ma向南美大陆俯冲时, 在大陆弧上不仅有弧岩浆作用出现, 也有许多大型铜矿矿床产出.

图7 牙买加型埃达克岩-高Nb玄武岩形成的构造岩浆模式

COP, 加勒比大洋高原; DMM, 亏损的MORB型地幔源区。数字的含义: (1) 从30~50km深处, 俯冲的加勒比大洋高原经历了部分熔融产生牙买加型埃达克岩浆, 这些岩浆穿过薄的地幔楔而只与地幔楔进行了有限的反应; (2) Wagwater盆地伸展, 地幔物质上涌并经历减压熔融; (3) 地幔柱样(mantle plume-like)的源区在较深的位置发生熔融形成第一类高Nb玄武岩; (4) 被板片熔体交代地幔楔物质减压熔融第二类高Nb玄武岩。据Hastie等(2015)

5 残余弧脊的俯冲、岩浆作用与成矿

西菲律宾海盆中存在九州-帕劳、奄美、大东、冲大东等残余弧脊(Haraguchi等, 2003; Hickey-Vargas, 2005; 张洁等, 2012; Nishizawa等, 2014)。这些残余弧脊正在同西菲律宾洋盆一起向日本西南岛弧之下俯冲(Wallace等, 2009; Cao等, 2014)。九州-帕劳余弧脊俯冲在九州岛弧产生玄武岩、高镁安山岩和埃达克岩(Morris, 1995; Cao等, 2014), 同时, 产有Hishikari和Nansatsu金矿床(Hedenquist等, 1994; Cooke等, 2005)。

6 脊或海岭俯冲的共同效应

扩张洋中脊、无震海山或大洋高原以及残余弧脊俯冲是现代大洋板块动力学系统中十分普遍且非常重要的一种地质过程。脊或海岭的俯冲除了产生岩浆、金属成矿作用外, 还会导致上盘发生挤压或伸展变

形、地表沉降、地表抬升或高原隆升甚至陆内造山带的形成(例如, Livaccari等, 1981; Gutscher和Peacock, 2003; Madsen等, 2006; Taylor等, 2005; Espurt等, 2008; Guillaume等, 2009; Wallace等, 2009; Liu等, 2010; Rosenbaum和Mo, 2011; Benowitz等, 2012; Martinod等, 2013; Margirier等, 2015; Yonkee和Weil, 2015; Salze等, 2018), 同时伴随在俯冲上盘前缘或基底发生俯冲侵蚀作用(von Huene和Scholl, 1991; Ranero和von Huene, 2000; von Huene等, 2004; Bourgois等, 1996; Miura等, 2004)。俯冲侵蚀作用是在大洋板块俯冲过程中, 俯冲板块通过构造作用移走俯冲上盘的物质并将其带到地幔深部的过程, 是俯冲带的一种基本过程(图8)(von Huene等, 2004)。海山或海岭(包括无震海岭或大洋高原、扩张洋中脊和残余弧脊)俯冲最容易导致俯冲上盘发生俯冲侵蚀作用(例如, Bourgois等, 1996; von Huene等, 2004; Miura等, 2004; Bangs等, 2006; Ramírez de Arellano等, 2012; Vannucchi等, 2016)。相对

图 8 俯冲侵蚀模型

据 von Huene 等(2004)

于大洋俯冲过程中形成的增生型边界, 俯冲侵蚀会把俯冲前缘和俯冲上盘的物质带入地幔深处, 使得在会聚板块边界形成另外一种类型板块边界——侵蚀型边界(von Huene和Scholl, 1991; Clift和Vannucchi, 2004). 在新生代环太平洋俯冲带, 在南美和中美洲西部、西南日本-琉球岛弧和伊豆-小笠原-马里亚纳岛弧以及西南太平洋等出露有海山或海岭的区域, 大多形成了侵蚀型边界(图9). 俯冲侵蚀是俯冲板片将陆壳物质带入到地幔深处的一种重要机制(von Huene等, 2004; Clift和Vannucchi, 2004). 通过俯冲侵蚀进入到地幔深部的陆壳物质, 也会改变上覆地幔楔物质组成, 从而改变弧岩浆岩的地幔源区组成(Goss和Kay, 2006; Goss等, 2013).

7 科学问题与展望

7.1 俯冲形式与动力学机制

大洋板块具有极为复杂的形态、结构, 因此俯冲方向的不同将导致扩张洋中脊、无震海岭或大洋高原、残余弧脊与海沟所组成的空间几何形态多样, 这在一定程度上将会导致差异巨大的地质现象. Thorkel-

son(1996)从理论上详细讨论了不同俯冲角度的扩张洋脊与俯冲带的关系、板片窗的形成与形态及弧岩浆作用的演化等. 但要恢复扩张洋脊从开始俯冲到板片窗、弧岩浆作用的演化详细过程, 确实是一个非常具有挑战性的工作. 有研究显示, 扩张洋中脊只是小角度甚至平行于海沟俯冲时, 具有正地形的洋中脊会与大陆边缘碰撞, 而具有负地形的洋中脊会俯冲到大陆边缘之下(Forsythe等, 1986; Zheng和Chen, 2016). 另外, 大量研究表明, 大洋拆离断层系统在大洋中非常发育且重要, 且主要是在慢速、超慢速扩张系统中代替岩浆的增生来调整大洋板块的分离(Cann等, 1997; Dick等, 2003; Smith等, 2006; Escartin等, 2008; Liu等, 2014; 吴福元等, 2014; Maffione等, 2015; Gülcher等, 2019). 因此, 慢速、超慢速扩张洋脊系统中常常缺乏洋壳. 如果这样的系统受到挤压, 有可能存在两种情况: (1) 大洋拆离断层系统或慢速、超慢速扩张洋脊系统发生俯冲, 有可能形成板片窗; (2) 大洋拆离断层系统作为富含蛇纹石、滑石的断裂带, 是大洋岩石圈的薄弱带, 有可能成为调整挤压的应变带, 从而触发接近扩张脊的洋内初始俯冲作用(例如, Maffione等, 2015; Keenan等, 2016; Gülcher等, 2019; Zhang等,

图9 环太平洋域增生型与侵蚀型汇聚板块边界

据 von Huene 和 Scholl (1991) 和 Frisch 等 (2011)

2019). 因此, 扩张洋中脊的俯冲形式实质上非常复杂.

存在的另外一个重要问题是, 如果扩张洋中脊、无震海岭或大洋高原以及残余弧脊发生俯冲, 那么导致俯冲作用发生的驱动力是什么? 一般认为, 大洋板块俯冲的驱动力一般包括洋脊的推力、地幔对流、地幔柱、地壳增厚所产生的重力潜能、板块的拖曳力 (pull) 和板片的吸力 (suction) 等 (Stern, 2007; Faccenna 等, 2013). 其中, 板块的拖曳力和板片的吸力被认为是板块俯冲的最重要的驱动力, 占 90% (Stern, 2007). 同正常大洋板块的俯冲一样, 扩张洋中脊、无震海岭或大洋高原以及残余弧脊发生俯冲的驱动力也应该主要与板块的拖曳力和板片的吸力有关. 另外, 前面的论述已经提到, 太平洋东西两岸扩张洋中脊、无震海岭或大洋高原以及残余弧脊俯冲角度存在明显的差异, 一般东边相对平坦, 西边相对陡倾 (Rosenbaum 和 Mo, 2011). 那么, 制约上述板块俯冲角度的控制因素究竟是什么? 一些研究提出, 高的海底地形、地壳密度、板片厚度、板片年龄、板片的吸力、海沟的后退、上覆板块性质及运动特点、地幔楔的热状态及流变学性质等都有可能影响板块的俯冲角度 (Gerya 等, 2009; Martinod 等, 2013; Antonijevic 等, 2015; Zeumann 和 Hampel, 2016). 上述推断仍旧需要大量更深入的工作来进一步

的检验. 不管扩张洋中脊、无震海岭或大洋高原以及残余弧脊俯冲的角度如何, 这些板块最后都可能会发生撕裂、回卷乃至拆沉 (Levin 等, 2002, 2005; Guivel 等, 2006; Fuis 等, 2008; Sigloch 等, 2008; Liu 和 Stegman, 2012; Antonijevic 等, 2015; Portner 等, 2017; Zhao 等, 2017; Zhou 等, 2018; Zhou, 2018).

7.2 俯冲带物质循环

大洋岩石圈俯冲带是地球壳幔物质和能量交换、层圈相互作用以及物质循环的重要场所 (Stern, 2002; Tatsumi, 2005; 郑永飞等, 2015; Zheng 和 Chen, 2016; Zheng 和 Zhao, 2017), 被称为“俯冲工厂” (Tatsumi, 2005; Staudigel 等, 2010). 在经典的大洋岩石俯冲过程中, “俯冲工厂”加工大洋沉积物、洋壳以及地幔岩石圈和地幔楔等原始的材料, 制造岛弧岩浆和大陆地壳等产物, 同时工厂中产生的废弃物质或残留物质 (如化学上改变的板片组分 (洋壳、沉积物) 和拆沉的镁铁质下地壳) 被运移和储存在深部地幔作为与地幔柱或热点岩浆作用的源区 (Tatsumi, 2005). 但是, 在脊、海岭或海山俯冲的过程, 无震海岭、大洋高原和残余弧脊以及俯冲侵蚀带来的俯冲上盘的物质都有可能成为俯冲工厂的原始材料 (von Huene 等, 2004; Clift 和 Vannuc-

chi, 2004; Goss和Kay, 2006; Goss等, 2013; Staudigel等, 2010), 并且这些物质可能比正常的大洋地壳更富集K、Ba、La、Ce、U、Th、Pb、Rb和Cs等元素, 很可能在全球地幔的化学不均一性中发挥重要作用(Staudigel等, 2010). 最近的研究表明, 一些正在发生俯冲的无震海岭(如科克斯、路易斯维尔)的组分可能已经进入到俯冲带的地幔流中, 并通过岛弧岩浆而展示出来(Turner和Hawkesworth, 1997, 1998; Hoernle等, 2008; Timm等, 2013; Gazel等, 2015). 但存在的问题是, 如何准确区分岛弧岩浆中俯冲无震海岭、大洋高原和残余弧脊的组分(Beate等, 2001; Samaniego等, 2002, 2005; Bourdon等, 2003; Bryant等, 2006; Hoernle等, 2008; Gazel等, 2015)与俯冲侵蚀带来的俯冲上盘的物质(Goss和Kay, 2006; Goss等, 2013)的贡献, 仍然是俯冲带研究工作的一个难点.

7.3 岩浆作用产生的深部机制

前面提到, 当扩张洋中脊发生正向或高角度俯冲时会形成板片窗, 会有大量软流圈物质上涌, 带来大量热和物质, 这对大量岩浆的产生非常有利(Thorkelson, 1996; Thorkelson和Breitsprecher, 2005). 但是当扩张洋中脊只是低小度甚至平行于海沟俯冲时, 具有正地形的洋中脊与大陆边缘之间会发生碰撞, 这时并不会形成板片窗. 另外, 一个不再处于活动阶段的洋中脊(fossil oceanic ridge)即使是正向或者高角度俯冲, 也不会形成板片窗. 在这两种情况下, 没有板片窗, 就不能带来大量的热, 不利于产生岩浆作用. 无震海岭或大洋高原以及残余弧脊俯冲尽管被认为会产生岩浆停止或间歇期(例如, McGeary等, 1985), 但是实际上相当一部分新生代无震海岭或大洋高原以及残余弧脊俯冲也产生了岩浆作用(例如, Gutscher等, 2000; Beate等, 2001; Bourdon等, 2003; Beaumais等, 2013, 2016). 在岛弧或大陆弧区, 究竟是什么导致了岩浆作用产生了? 一般认为, 除了流体的加入之外, 俯冲板片之上软流圈地幔楔的加热(McGeary等, 1985; Gutscher等, 2000; Gerya等, 2009; Frisch等, 2011)、俯冲板片的回卷(rollback)触发软流圈在俯冲板片和地幔楔之间流动带来热(例如, 郑永飞等, 2016; Zheng和Chen, 2016; Zheng, 2019; Zheng等, 2020)和俯冲板片的撕裂导致板片之下软流圈上涌带来大量的热(Yogodzinski等, 2001; Rosenbaum等, 2008)对弧岩浆岩的产生有决定性的作用.

以板片回卷为例, 俯冲板片发生回卷, 这时软流圈地幔会加热回卷板片的表面, 使其发生部分熔融产生长英质(包括埃达克质)熔体, 这些熔体与地幔相互作用或交代地幔, 可以形成埃达克岩-高镁安山岩-富Nb玄武质岩石或OIB型玄武岩(例如, Bourdon等, 2003; Tang等, 2010; 郑永飞等, 2015, 2016; Zheng等, 2020; Zheng和Chen, 2016; Zheng, 2019; Hao等, 2019).

最近的地球物理探测或数字模拟显示, 扩张洋中脊俯冲会形成板片窗导致深部的软流圈物质上涌到俯冲板片之上(Russo等, 2010a, 2010b). 无震海岭或大洋高原以及残余弧脊俯冲会导致板片撕裂或拆沉(Levin等, 2002, 2005; Liu等, 2010; Liu和Stegman, 2012; Cao等, 2014; Antonijevic等, 2015; Portner等, 2017; Zhao等, 2017), 板片之下的软流圈物质上升到了俯冲板片之上(Portner等, 2017; Zhao等, 2017), 这些上升的热软流圈可能会给弧岩浆岩的产生提供重要的物质和热贡献(图10)(Yogodzinski等, 2001; Rosenbaum等, 2008; Manca等, 2013).

7.4 金属成矿作用的深部控制机制与影响因素

扩张洋中脊、无震海岭或大洋高原以及残余弧脊俯冲会导致金属矿床的形成(例如, Haeussler等, 1995, 2003; Ling等, 2009; Cooke等, 2005; Rosenbaum等, 2005; 孙卫东等, 2010; Tang等, 2010; 曹明坚等, 2011; Sun等, 2015; 詹美珍等, 2015). 尽管一部分研究认为, 俯冲洋壳的熔融产生的熔体及其与地幔的相互作用会带来金属成矿物质, 有可能对成矿有利(Mungall, 2002; Ling等, 2009; 孙卫东等, 2010), 但实际上成矿过程是非常复杂的(例如, Rosenbaum等, 2005). 为什么会形成金属矿床? 这可能受多种因素控制(例如, Rosenbaum等, 2005). 以南美新生代无震海岭俯冲为例, 有些金属矿床与同期俯冲的无震海岭(如胡安费尔南德兹、纳斯卡、卡内基和科库斯)共生且主要出现在岩浆间歇期或岩浆活动晚期(Cooke等, 2005; Rosenbaum等, 2005), 但有些金属矿床并没有与同期俯冲的无震海岭(如伊基克)的共生(Rosenbaum等, 2005). 一些研究指出, 与无震海岭平坦俯冲相关的地表挤压变形、地壳增厚过程、俯冲角度变化、岩浆演化过程、流体活动、岩浆的产出类型(火山喷发或岩浆侵入)或板片熔融等都可能对金属成矿产生重要影响(Kay和Mpodozis, 2001; Rosenbaum等, 2005). 因此, 扩张洋中脊、无

图 10 板片撕裂或断离的示意图

(a) 与岩石圈板片最后拆离的板片断离(一般出现在碰撞过程中); (b) 垂向扩展的撕裂; (c) 水平扩展的撕裂; (d) 分离两个俯冲的板片段(segment)的岩石圈撕裂断层的三维结构; (e) 两个撕裂断层(双箭头)连接一个俯冲系统中的三个俯冲板片段(具有不同回卷速度($V_{RB}(b) > V_{RB}(a) > V_{RB}(c)$)). 三角形暗示了俯冲的方向, 单一的箭头暗示了板片回卷的方向. 据Rosenbaum等(2008)

震海岭或大洋高原以及残余弧脊俯冲可能并不是与俯冲有关金属矿床形成的必要控制因素, 但是有可能导致了动力学环境的改变, 并可能创造了形成大型岩浆热液金属矿床形成的有利动力学条件(例如, Rosenbaum等, 2005). 此外, 在上述俯冲过程中, 岩浆源区、氧逸度和挥发份等对金属矿床形成的影响作用也被广泛关注(例如, Ling等, 2009; 孙卫东等, 2010; Sun等, 2013, 2015; Zhang等, 2013; 詹美珍等, 2015).

7.5 前新生代的脊或海岭俯冲作用的识别

新生代或正在发生的扩张洋中脊、无震海岭或大洋高原以及残余弧脊的俯冲可以通过地球物理方法确定(例如, Yogodzinski等, 2001; Levin等, 2002, 2005; Fuis等, 2008; Wallace等, 2009; Russo等, 2010a, 2010b; Gutscher等, 1999; Gutscher和Peacock, 2003; Schuth等, 2011; Cao等, 2014; Baillard等, 2018). 但是古老的或已经消亡的扩张洋中脊、无震海岭或大洋高原以及残余弧脊俯冲很难用地球物理方法确定. 因此, 如何示踪前新生代的扩张洋中脊、无震海岭或大洋高原以及残余弧脊俯冲作用, 是一个亟待解决的重要前沿科学问题. 近年来, 一些研究者已经从岩石组合的角度探索去揭示前新生代可能存在的扩张洋中脊俯冲作用(Geng等, 2009; Sun等, 2007, 2013; 孙敏等, 2009; Ling等, 2009, 2011, 2013; Cai等, 2010; Zhang等, 2010; Osozawa等,

2012; Tang等, 2010, 2012a, 2012b; Zhu等, 2013; Meneghini等, 2014; Schoonmaker等, 2014; Kuiper, 2016; Li等, 2014, 2016; Windley和Xiao, 2018). 通过厘定西准噶尔晚石炭世大洋中脊型(MORB)玄武岩-洋岛型(OIB)玄武岩-紫苏花岗岩-A型花岗岩-高镁闪长岩岩墙-埃达克岩组合, 并查明紫苏花岗岩-A型花岗岩-高镁闪长岩岩墙-埃达克岩都具有与洋中脊玄武岩类似的Sr-Nd-Pb同位素特征, 提出其形成于洋脊俯冲-板片窗的动力学环境(Tang等, 2010, 2012a, 2012b). 最近, 通过厘定南羌塘早白垩世晚期MORB型玄武岩-富Nb玄武安山岩-安山岩-英安岩-“牙买加型”埃达克质流纹岩, 并结合班公湖-怒江蛇绿岩带出现大量洋岛型玄武岩组成的大洋高原块体的资料, 早白垩世大洋高原俯冲被认为在班公湖-怒江俯冲带的演化中发挥了重要作用(Hao等, 2019). 这里需要指出的是, 尽管岩石组合及时空分布被广泛应用于揭示前新生代洋脊俯冲、无震海岭、大洋高原或残余弧脊的俯冲过程(例如, Morris, 1995; Gorrington等, 2003; Thorkelson等, 2011; Cao等, 2014), 但是一些岩石的成因可能是多解的. 例如, 一些OIB型玄武岩被认为是扩张洋脊发生俯冲后板片窗打开软流圈上涌的标志性岩石(例如, Gorrington等, 2003; Thorkelson等, 2011). 但是, 最近的一些研究显示, 这些 OIB型玄武岩可能是俯冲洋壳熔融(金红石发生了分解)产生的富集Nb和Ta熔体交代的地幔深部

源区熔融形成的(例如, 郑永飞等, 2015, 2016; Zheng等, 2020; Zheng和Chen, 2016; Zheng, 2019), 有的可能是沿古俯冲带发生的大陆裂断作用(rifting)引起的古俯冲洋壳的部分熔融(Zheng和Zhao, 2017). 因此, 识别洋脊俯冲、无震海岭、大洋高原或残余弧脊的俯冲的标志型岩石组合仍需要进一步深入研究. 另外, 如前面所述, 大洋板块具有极为复杂的形态、结构, 其发生俯冲可能导致复杂多样的俯冲形式出现及伴随的差异巨大的地质现象. 因此, 如何准确地识别前新生代的扩张洋中脊、无震海岭或大洋高原以及残余弧脊俯冲作用, 仍然是一个研究难点.

7.6 板块构造启动时间与太古代大陆地壳生长机制

板块构造启动的时间是当前国际地质研究的最热点地质问题之一. 相当一部分研究者认为板块构造活动在太古宙已经出现并且太古宙大陆地壳生长机制也与大洋板块的俯冲有关, 但是板块构造启动(即洋壳俯冲)的时间(3.0~2.5、3.5~2.5或>3.5Ga)存在激烈争议(Shirey和Hanson, 1984; Kerrich等, 1998; Smithies, 2000; Polat等, 2002; Polat和Kerrich, 2002; Smithies等, 2003, 2004; Martin等, 2005, 2014; Hastie等, 2010a, 2010b, 2015). 一部分研究者根据晚太古代(3.0~2.5Ga)出现了类似现代弧环境的玻安岩-高镁安山岩(赞岐

岩)-富Nb玄武岩-埃达克岩等组合, 提出类似现代板块构造(大洋俯冲)(图11)活动至少在晚太古代已经启动, 俯冲大洋板块的熔融及产生的熔体交代的地幔楔相互作用产生了上述岩石(Kerrich等, 1998; Polat等, 2002; Polat和Kerrich, 2002; Smithies等, 2004; Martin等, 2005, 2014). 但是一些研究者提出, 板块构造也有可能早在太古代已经启动(例如, Hastie等, 2010a, 2010b, 2015; Martin等, 2014), 并且可能的方式是“太古宙浅的平坦俯冲”, 即不包含有地幔楔(图12), 不同于新生代那种包含有地幔楔的大洋岩石圈或无震海岭的平坦俯冲(Smithies等, 2003). 有研究显示, 俯冲大洋高原地壳的熔融可能导致太古宙英云闪长岩-奥长花岗岩-花岗闪长岩(TTG)形成与地壳生长的重要机制(Hastie等, 2010a, 2010b, 2015; Martin等, 2014; Gazel等, 2015). 例如, 早太古代(>3.5Ga)的TTG与“牙买加型”埃达克岩类似, 后者为加勒比晚白垩世大洋高原于早新生代(~55Ma)向牙买加弧之下发生浅的平坦俯冲(不含或含有极薄的地幔楔)时在石榴石角闪岩相条件下熔融形成的(图7)(Hastie等, 2010a, 2010b, 2015). 这似乎说明在

图 11 现代方式的陡倾和低角度俯冲模式

显示了两种模式不同的岩浆岩源区, 但是两种模式中地幔楔仍旧存在, 并且板片来源的熔体与地幔发生了明显作用. 据Smithies等(2003)

图 12 早太古代地壳演化的可能模式

太古宙平坦俯冲, 当镁铁质地壳下部发生容熔融形成TTG, 残留物转变成榴辉岩. (a) 大洋地壳(板片①)俯冲在略微老的增厚镁铁质(大洋)地壳. 太古宙的平坦俯冲在下地壳薄弱带(板片②和③: 出现在厚的和热的地壳中), 据Smithies等(2003). (b) 榴辉岩发生拆沉, 并从侧面和上面被富TTG(“TTG-fertile”)大洋地壳所替代

早太古代以大洋高原为主的大洋板块的浅的平坦俯冲(即“太古代浅的平坦俯冲”)过程已经发生(Hastie等, 2010a, 2010b, 2015), 并很可能与早太古代普遍高地热梯度条件下地幔柱活动强烈、大洋高原发育有关(例如, Martin等, 2014)。但是, 数值模拟的资料显示, 在太古宙较高地热梯度的条件下, 俯冲板块强度太弱而不可能支持连续的平坦俯冲, 会导致频繁的板片断离和间歇性俯冲作用(van Hunen和Moyen, 2012)。van Hunen和Moyen(2012)认为应该放弃早太古代浅的平坦俯冲这种模式。因此, 早太古代板块构造在地球动力学机制上仍旧不清楚, 相应的早太古代主要岩石TTG的成因以及大陆地壳早期形成机制仍需要进一步深入研究。Zheng和Zhao(2020)提出, 在太古宙和元古宙出现的是古板块构造, 在这个时期既有韧性板块边缘为主导的暖俯冲, 也有软流圈地幔沿减薄的汇聚板块边缘上涌所产生的裂断作用。

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