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俯冲侵蚀的研究历史、现状与展望*

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Abstract　Subduction erosion refers to the tectonic process where the subducting plate removes material from the overlying plate and transports it into the deep mantle. Previous research has indicated that subduction erosion is a widespread and important geodynamic process in the Cenozoic circum-Pacific subduction zones, and it also play an important role in the deformation of active continental margins, the generation of magmatic arcs, metallogenesis, crust-mantle material recycling, and the growth and evolution of continental crust. Basing on reviewing the previous research history, this paper succinctly delineates the fundamental model and controlling factors of subduction erosion and systematically summarizes the geological effects induced by subduction erosion, as well as the criteria for its identification. Then we analyzed and discussed the connection between subduction erosion, metallogenesis, and the evolution of continental crust. Moreover, we introduced the research progress on subduction erosion within China, and we analyzed two research examples identifying the Late Mesozoic subduction erosion processes along the Bangong-Nujiang Suture Zone and the Yarlung Zangbo Suture Zone in the Tibetan Plateau, which unveil that the southern margin of the Eurasian continent was an erosive-type convergence boundary during the Late Mesozoic. Finally, we proposed our thoughts and prospects on subdction erosion researches in the future.

Key words　Convergent margin; Subdction zone; Subduction erosion; Magmatism; Metal mineralization; Continental destruction

摘　要　俯冲侵蚀是指在板块俯冲过程中,俯冲板块通过构造作用移走俯冲上盘的物质并将其带到深部地幔的过程。前人研究表明,俯冲侵蚀在新生代环太平洋俯冲带是一种十分普遍且非常重要的地质过程,同时对活动陆缘的构造变形、岩浆弧的形成、金属成矿、壳-幔物质循环以及大陆地壳的生长与演化均具有重要的影响。本文在回顾前人研究历史的基础上,简要介绍了俯冲侵蚀的基本模型和控制因素,系统总结了俯冲侵蚀引起的地质效应以及识别依据,分析探讨了俯冲侵蚀与金属成矿、大陆地壳演化的关系。此外,本文还介绍了俯冲侵蚀在国内的研究现状,并分析了青藏高原的班公湖-怒江缝合带和雅鲁藏布江缝合带晚中生代俯冲侵蚀识别的研究实例,揭示了欧亚大陆南缘在晚中生代是一个侵蚀型的板块汇聚边界。最后对我国今后开展相关研究提出了一些思考和展望。

关键词　汇聚边界;俯冲带;俯冲侵蚀;岩浆作用;金属成矿;陆壳破坏

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俯冲侵蚀(subduction erosion)是指在板块俯冲过程中，俯冲的下伏板块通过构造作用移走俯冲上盘的物质并将其带到深部地幔的过程(Clift and Vannucchi, 2004; von Huene *et al.*, 2004)。俯冲侵蚀是现代板块汇聚边界十分普遍且非常重要的地质过程，并且与俯冲带的深源地震和海啸地震的发生密切相关(Wells *et al.*, 2003; Bilek, 2010; Cubas, 2017)。目前对于俯冲侵蚀的研究主要集中在新生代的洋-陆俯冲带(如:环太平洋的中-南美洲和日本等地区)(Stern, 2011, 2020; Straub *et al.*, 2020)，并且强调遭受侵蚀的必须是上覆陆壳(或弧前地壳)的物质，包括陆壳基底(或弧前基底)以及陆源斜坡沉积物(von Huene and Scholl, 1991)。同时也有一些学者的研究涉及洋-洋俯冲(Miura *et al.*, 2004; Tonarini *et al.*, 2011)以及陆-陆俯冲碰撞过程中的构造侵蚀过程(Yin *et al.*, 2007; 郑永飞, 2008; Lu *et al.*, 2018)，并特别指出侵蚀的物质主要来自于上覆板片。板块构造理论提出以来，俯冲侵蚀的研究在近几十年受到了广泛的关注，并成为当前国际地质研究的热点之一。本文系统总结了国内外关于俯冲侵蚀的研究历史和现状，并介绍了作者近年来关于青藏高原中南部晚中生代俯冲侵蚀识别的研究实例，最后提出存在的前沿科学问题和研究展望。

1 早期研究历史

对俯冲侵蚀所引起的地质现象的描述和记录最早可以追溯到20世纪60年代，那时海底扩张理论刚提出不久，普遍认为洋壳扩张并俯冲至大陆地壳之下时，洋壳之上的沉积物会被铲刮下来，继而堆积在海沟处，并且随着洋壳持续俯冲，这些海沟沉积物会经历不同程度的挤压变形。然而在秘鲁-智利俯冲带，3条近东西向剖面的地震波反射数据显示，北部剖面缺失海沟沉积物，南部两条剖面的海沟沉积物没有预期中的变形，并保持着近水平的层理(Scholl *et al.*, 1968)。Scholl *et al.* (1968)将上述的异常现象解释为:(1)海沟沉积物沉积过程中洋壳停止扩张;(2)洋壳并不是在海沟的位置俯冲，而是在海沟之前的某个未知的位置向下俯冲，或者洋壳的横向移动在到达海沟前被洋壳自身的变形所吸收，因此洋壳扩张并没有影响海沟沉积物使其变形;(3)南美洲大陆沿着洋壳扩张的方向向东漂移。这是最早关于俯冲侵蚀现象的文献记录，随后的一些学者也相继发现海沟沉积物缺失或洋壳扩张过程中海沟沉积物未发生变形的现象(Lomnitz, 1969; Seyfert, 1969; Scholl *et al.*, 1970)，但由于时代的局限性，他们并没有给出合理的解释。

直到70年代初，Rutland (1971)发现智利中北部紧靠海岸线分布着一条中生代的岩浆弧，自中生代开始岩浆活动逐渐向东迁移，目前最年轻的岩浆弧位于安第斯山脉，大约距离现今海岸线220km，距离海沟325km，中生代以来海沟和海岸线的位置向大陆一侧后退了近200km，这期间伴随着大量的陆壳消失。因此，Rutland (1971)首次提出大陆边缘陆壳俯冲(subduction of marginal continental crust)这个概念，并将洋壳扩张过程中海沟不发育沉积物或者沉积物未发生变形的现象解释为海沟靠大陆一侧的快速剥蚀，这是俯冲侵蚀理论的雏形。几乎同时，Miller (1970a, b)和Murauchi (1971)分别发现智利中部陆壳东西向的缩短以及日本本州岛北部古老大陆基底的缩短，并暗示上述现象与陆壳的侵蚀有关。整个70年代，陆续有学者提出证据证明活动陆缘的缩短、沉降以及陆壳物质的消失(Hussong *et al.*, 1976; Scholl *et al.*, 1977)。直至1980年，Scholl *et al.* (1980)正式提出俯冲侵蚀(subduction erosion)的概念，将其定义为构造侵蚀(tectonic erosion)的一种，指示在洋壳俯冲的驱动下，上盘的陆缘物质经历剥蚀垮塌，机械搬运，并最终表现为俯冲边界的减薄以及海沟向陆的后退(Scholl *et al.*, 1980)。整个80年代，随着深海钻探计划的开展，多通道地震反射数据采集和处理技术的进步，人们对汇聚板块边界有了更直观的认识，俯冲侵蚀理论得到了进一步的发展。来自环太平洋(秘鲁、智利以及日本等地)的钻探岩芯均揭示了这些地区的活动陆缘曾经历了不同程度的沉降，陆壳经历了规模不一的减薄(Hussong and Uyeda, 1982; von Huene *et al.*, 1982; von Huene and Suess, 1988)。尽管少数人认为活动大陆边缘的沉降可能涉及俯冲侵蚀之外的构造过程(Karig *et al.*, 1976; Langseth *et al.*, 1981)，但是绝大多数学者认为数千米甚至更大规模的沉降是由侵蚀作用引起的。至此，俯冲侵蚀过程才被研究地球科学的学者们广泛接受(Scholl *et al.*, 1980; Hussong and Uyeda, 1982; von Huene *et al.*, 1982; von Huene and Suess, 1988; Scholl, 1987; Cloos and Shreve, 1988a, b)。20世纪90年代以来，地球物理技术的快速发展可以直接观测正在发生的俯冲侵蚀作用(von Huene and Lallemand, 1990; Ranero and von Huene, 2000; von Huene *et al.*, 2004)。同时，越来越多的岩石学家也开始关注俯冲侵蚀与弧岩浆之间的关系(Stern, 1990, 1991; Kay *et al.*, 1991, 2005, 2013; Guivel *et al.*, 1999; Kay and Mpodozis, 2002; Kay, 2003, 2006; Clift *et al.*, 2005; Goss and Kay, 2006, 2009; Stern *et al.*, 2010; Tonarini *et al.*, 2011; Goss *et al.*, 2013; Holm *et al.*, 2014; Straub *et al.*, 2014, 2015, 2020; Jicha and Kay, 2018; 王强等, 2020b; Yang *et al.*, 2021; Huang *et al.*, 2022)，以及俯冲侵蚀对俯冲带成矿作用的影响(Stern *et al.*, 2010, 2011, 2019; Cawood and Hawkesworth, 2015; Spencer *et al.*, 2017; 王强等, 2020b)。

回顾早期研究历史，人们对汇聚板块边界的认识逐渐系统和完善。早期认为汇聚板块边界是沉积物增生的主要场所的观点也被逐渐抛弃，越来越多的研究表明沉积物增生并不是汇聚板块边界的普遍特征，并将汇聚板块边界划分为增生型和侵蚀型两种类型(图1, von Huene and Scholl, 1991; Clift and Vannucchi, 2004)。早期的观点将增生型边界定义为发育厚层的增生楔，而侵蚀型边界的增生楔规模很小甚至不具有增生楔(von Huene and Scholl, 1991)。后来也有学者

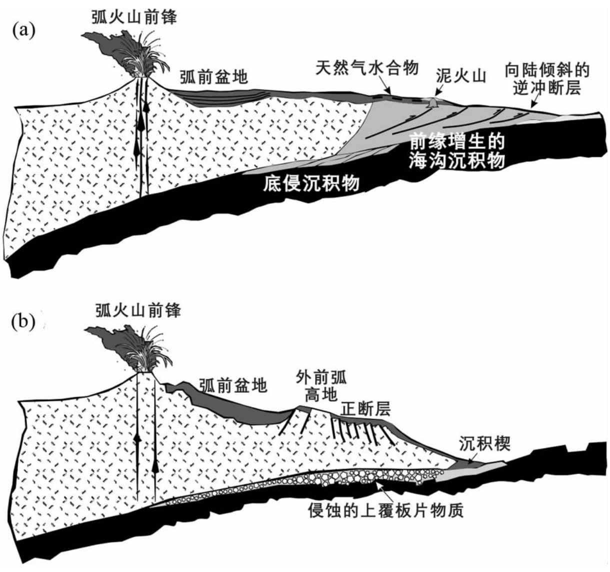

图 1 活动陆缘的两种基本类型——增生型(a)和侵蚀型(b)(据 Clift and Vannucchi, 2004 修改)

Fig. 1 Schematic cartoons showing the two basic types of active margin: Accretionary (a) and erosive (b) (modified after Clift and Vannucchi, 2004)

提出,如果考虑俯冲带的整个弧前区域(包括海沟),汇聚板块边界的类型则取决于一段时间内弧前区域物质的净增生量(Clift and Vannucchi, 2004)。同时指出增生型边界不一定发育增生楔,俯冲的沉积物可以通过底辟或底侵作用增生在上覆板片的底部,关键在于上覆板片有物质的净增生;而侵蚀型边界也可以发育海沟沉积(增生楔),上覆板片的基底可以被侵蚀从而造成净负增生(Clift and Vannucchi, 2004)。俯冲侵蚀作用可以出现在全球几乎所有的俯冲带中(Stern, 2011),即使是典型的增生型边界(例如日本的 Nankai 海槽),海山的俯冲也能引起弧前增生楔的侵蚀(Bangs *et al.*, 2006)。对于现今的俯冲带而言,增生型和侵蚀型边界的划分通常依据距今 5 ~ 10 个百万年内弧前物质净增生量累积的平均结果。最新的定量化分析结果显示,目前全球超过 60% 以上的汇聚板块边界具有侵蚀性质,而不具有增生性质(Clift and Vannucchi, 2004; Clift *et al.*, 2009; Straub *et al.*, 2020)(图 2)。

2 俯冲侵蚀的基本模型与控制因素

俯冲侵蚀既可以出现在弧前楔的最前端,也可以发生在弧前楔的底部,前者称为前缘侵蚀(frontal erosion),后者称为基底侵蚀(basal erosion)(von Huene and Lallemand, 1990; von Huene and Scholl, 1991)。早期的观点认为俯冲侵蚀的发生受控于两种机制:(1)板块间在高应力条件下的物理磨蚀作用(physical abrasion);(2)低应力下的流体辅助磨蚀作用(fluid-assisted abrasion)。前者是指俯冲的大洋岩石圈板块在下潜进入海沟前,在转折端的位置发生弯曲和断裂,形成一系列的地堑与地垒,这些洋壳表面锯齿状的构造在进入俯冲带后会增加与上覆板片底部的摩擦力,引发基底侵蚀(Hilde, 1983)。后者则认为进入俯冲隧道的沉积物和岩石碎片富含孔隙流体,随着俯冲深度的增加,流体大量且快速排出并向上迁移至上覆板片的底部,一旦流体压力超过岩石的静岩压力,岩石就会破碎,引发顶蚀作用(stoping)和水裂作用(hydrofracturing)(Murauchi and Ludwig, 1980; Pichon *et al.*, 1993),这也属于基底侵蚀的一种。结合前人的观点,von Huene *et al.* (2004)提出了俯冲侵蚀的基本模型(图 3):持续的俯冲作用使得海沟处不发育以大洋沉积物为主的增生楔,取而代之的是以弧前斜坡沉积物为主的前缘柱(frontal prism)以及由解体的上覆板块基底组成的后挡板(backstop)。前缘柱的存在有利于海沟沉积物更有效地进入俯冲隧道,同时减小板片间的物理磨蚀。沿着板块界面发育活动逆冲断裂并发生剧烈的水裂作用,上盘板片的基底物质以脱落的碎片形式被带入俯冲隧道,结果导致板块界面的活动逆冲断裂不断向上迁移,上覆板块的减薄以及中间斜坡的沉降。

洋壳表面异常的高地形是引起俯冲侵蚀另一个主要的原因。地球物理观测以及实验模拟的结果均表明,海山的俯冲能同时引起前缘侵蚀和基底侵蚀(von Huene and Lallemand, 1990; Dominguez *et al.*, 1998, 2000; Ranero and von Huene, 2000; von Huene *et al.*, 2004; Kukowski and Oncken, 2006)。海山的俯冲会破坏前缘柱,持续向下俯冲还会侵蚀上覆板块的基底,陆缘斜坡发生强烈的沉降(图 4),垮塌至海沟的物质以及破碎的基底岩石一并沿俯冲隧道向下俯冲。海山的俯冲还会加宽俯冲通道,从而加快海沟物质的俯冲速率和基底岩石的侵蚀速率(Stern, 2011)。单个海山或相对独立的数个海山引起的俯冲侵蚀是局部且短期的,而数百千米长的海山链、洋中脊、无震海岭甚至是数千平方千米的洋底高原发生俯冲,可以导致大规模的俯冲侵蚀,并且这个过程持续的时间更长。从全球尺度来看,几乎所有的侵蚀型边界都与海山链和无震海岭(或洋中脊)的俯冲密切相关(图 2)。例如中美洲与 Cocos Ridge、Coiba Rigde 和 Quepos Plateau;秘鲁与 Carnegie Rigde,智利与 Nazca Ridge、Iquique Ridge、Juan Fernandez Ridge 和 Chile Ridge;日本西南部与 Kyushu-Palau Ridge;Izu-Bonin 弧与 Ogasawara Plateau;Mariana 弧与西太平洋海山群;西南太平洋与 Ontong-Java Plateau;汤加海沟与 Louisville Ridge(Ballance *et al.*, 1989; Lallemand, 1998; Clift and MacLeod, 1999);堪察加半岛与皇帝海岭(Geist and Scholl, 1994; Klaeschen *et al.*, 1994; Wells *et al.*, 2003)。即使是在一些增生型边界,海山或无震海岭的俯冲也能引起一定规模的侵蚀作用,例如爪哇海沟与 90 度海岭和 Roo Rise(Kopp *et al.*, 2006);阿拉斯加湾与 Kodiak-Bowie seamount chain (Smoot, 1985; Harris and Chapman, 1994);小安德列斯与 Barracuda Ridge 和 Tiburon

图2 环太平洋域增生型与侵蚀型汇聚板块边界的分布(据 Straub *et al.*, 2020;孙卫东等, 2010 修改)

Fig. 2 Map showing the distribution of accretionary margins versus erosive margins around the Pacific Rim (modified after Straub *et al.*, 2020; Sun *et al.*, 2010)

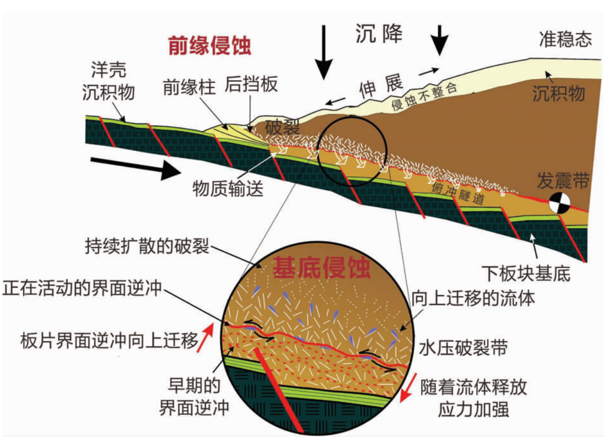

图3 俯冲侵蚀的基本模型(据 von Huene *et al.*, 2004 修改)

Fig. 3 Subduction-erosion model (modified after von Huene *et al.*, 2004)

Ridge(Bouysse and Westercamp, 1990)等。

俯冲侵蚀的发生还与上覆板片的抗破碎强度、板片的汇聚速率以及俯冲角度密切相关。数值模拟的结果显示,减小俯冲角度或者增加板块间的汇聚速率,会增加上覆板片的剪切牵引力,有利于俯冲侵蚀的发生(Keppie *et al.*, 2009; van Dinther *et al.*, 2012)。从全球统计结果来看,目前侵蚀型边界的板块汇聚速率一般大于 6±0.1cm/yr,增生型边界均小于 7.6cm/yr(Clift and Vannucchi, 2004)。俯冲角度会影响侵蚀作用的类型(Frisch *et al.*, 2011),小角度俯冲或者平俯冲会导致弧前挤压,板片间的强烈耦合引起前缘侵蚀(例如南美洲俯冲带);而高角度向下俯冲的大洋板片在转折端会形成大型的堑垒构造,与正常角度俯冲所形成堑垒构造相比规模更大,产生的摩擦阻力更强,会触发有效的基底侵蚀(例如马里亚纳俯冲带)。

3 俯冲侵蚀的地质效应与识别

俯冲带的增生和侵蚀是两个相对的过程,前者有明确的物质记录,可以发育大型的增生楔,后者则很难直接观测和量化,通常只能通过俯冲侵蚀引起的二次效应进行推断和识别。总结前人的研究成果可以发现,俯冲侵蚀会普遍导致弧前地壳的构造变形与沉降,大规模的侵蚀会引起弧地壳的截切,海沟和海岸线向陆一侧后退、年轻的火山弧朝着大陆内

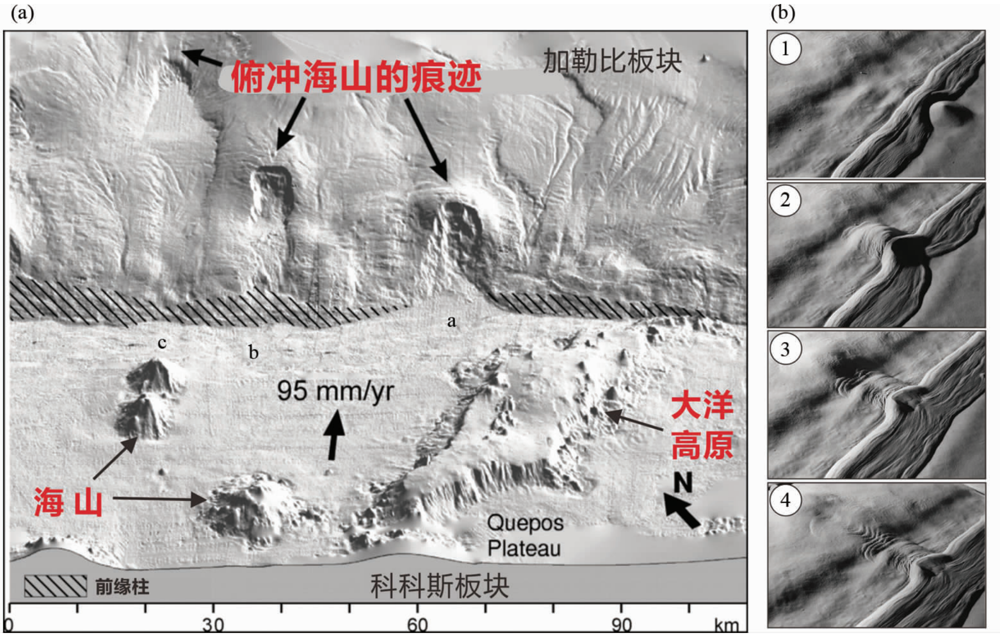

图 4　海山的俯冲对弧前地形地貌的影响(据 von Huene *et al.*, 2004;Dominguez *et al.*, 1998 修改)

(a)多波束测深观察到哥斯达黎加地区海山的俯冲:a-俯冲的海山破坏了前缘柱;b-斜坡沉积物的填充使得前缘柱的缺口逐渐愈合;c-已经愈合的前缘柱即将被第二次的海山俯冲所破坏;(b)沙箱实验模拟的海山俯冲:过程①~②对应 a;过程③对应 b;过程④对应 c

Fig. 4　The subduction of seamounts and its impact on forearc topography (modified after von Huene *et al.*, 2004; Dominguez *et al.*, 1998)

(a) perspective of multibeam bathymetry off central Costa Rica showing the subducting seamounts: a-subducting seamount has breached prism; b-breach is healing; c-healed prism is modified by secondary seafloor features; (b) seamount subduction seamount modeled by sandbox experiments: Processes ①~② correspond to a; Process ③ corresponds to b; Process ④ corresponds to c

部迁移甚至引起古老的岩浆弧“消失”。侵蚀的物质向深部俯冲,还会进入弧岩浆源区,参与弧岩浆的形成。

3.1　弧前地壳的变形与沉降

俯冲侵蚀通常发生在板块间强烈耦合的区域,一般会引起弧前区域剧烈的构造变形。海山的俯冲通常会破坏弧前斜坡的地形地貌,斜坡中上部首先会经历短暂的挤压和抬升,周围的物质(以斜坡沉积物为主)垮塌进入海沟,填补早先形成的前缘柱缺口,随着海山持续向前俯冲,基底岩石开始遭受侵蚀,原先隆起的部位发生沉降(图 4)(Ranero and von Huene, 2000; von Huene *et al.*, 2004),这是俯冲侵蚀导致弧前地壳变薄的结果。地球物理和构造地质学的证据表明,基底侵蚀会导致陆缘斜坡的垮塌,并在俯冲上盘的弧前地区形成大量的正断层(von Huene and Ranero, 2003; Sage *et al.*, 2006)。例如智利西海岸的安托法加斯塔地区,伊基克海岭的俯冲会在弧前形成两种类型的正断层。一种是向陆倾斜的正断层,与基底岩石被侵蚀有关;另一种是向海倾斜的高角度正断层,可能与重力垮塌作用有关(von Huene and Ranero, 2003)。

长期的俯冲侵蚀作用会导致弧前区域的持续沉降,从而引起弧前盆地沉积的连续更新(图 5)。尤其是海洋钻探计划 DSDP(Deep Sea Drilling Program)、ODP(Ocean Drilling

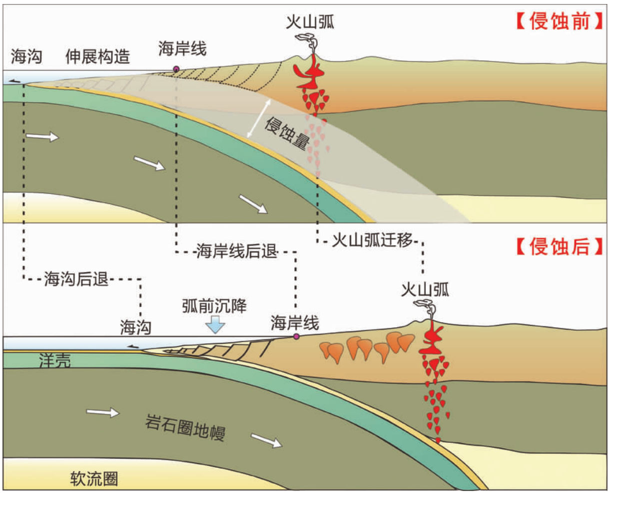

图 5　俯冲侵蚀引起的弧前沉降、海沟和海岸线的后退以及火山弧的迁移(据 Frisch *et al.*, 2011 修改)

Fig. 5　Forearc subsidence, retreat of coastline and trench are caused by subduction erosion (modified after Frisch *et al.*, 2011)

Program)和 IODP(Integrated Ocean Drilling Program)的钻井岩芯所获得的古水深标志(底栖有孔虫地层学和其他沉积相标志),显示了一些板块汇聚边缘弧前区域的大尺度沉降,这些

地区的沉降历史可以很好地反演曾经发生的俯冲侵蚀过程。沿着日本东北部的陆缘斜坡,DSDP 438/439 号钻井揭示渐新统海滨沉积不整合于晚白垩世增生杂岩之上,岩芯中的地层年龄递减而沉积深度却不断增加,目前不整合面位于海平面以下 2750m(von Huene *et al.*, 1982),通过重建新近纪早期日本东北部活动陆缘的形态,可以计算出过去 20Ma 陆壳的侵蚀速率约为 $50km^3/km/Myr$(von Huene and Lallemand, 1990)。ODP 112 航次的钻探结果反演了秘鲁弧前区域新近纪以来的两次沉降事件,并夹带着一期短暂的抬升(von Huene and Suess, 1988; Suess and von Huene, 1988)。区域上来看,后一期的沉降与 Nazca Ridge 的俯冲时间吻合,而且短期的抬升事件很可能是 Nazca Ridge 的初始俯冲引起的。陆缘重建计算结果表明,Nazca Ridge 未俯冲之前,20~8Ma 间的侵蚀速率约为 $20km^3/km/Myr$,而 8Ma 以来的侵蚀速率增加至 $46km^3/km/Myr$(von Huene and Suess, 1988; von Huene and Lallemand, 1990; von Huene and Scholl, 1991),可见无震海岭的俯冲明显加快了俯冲侵蚀的速率。海洋钻探所揭示的弧前沉降现象普遍出现在中美洲的哥斯达黎加和危地马拉、汤加以及马里亚纳等地区(Hussong and Uyeda, 1982; Kimura *et al.*, 1997; Clift and MacLeod, 1999; Meschede *et al.*, 1999, 2002; Vannucchi *et al.*, 2004; Schindlbeck *et al.*, 2016)。尤其是哥斯达黎加的西海岸自中新世(17Ma)以来经历了数次复杂的沉降历史(Vannucchi *et al.*, 2001, 2003, 2013)。晚中新世之后弧前地区发生了连续沉积,6.5 个百万年间超过 $750km^3$ 的上盘物质被侵蚀,侵蚀速率超过 $115km^3/km/Myr$(Vannucchi *et al.*, 2003)。靠近 Osa 半岛的陆缘斜坡,IODP"U1379"号钻孔揭示了其 3Ma 来复杂的沉降历史:(1)2.5~2.3Ma,早期形成的弧前盆地从近 800m 深的半深海环境快速抬升至到近岸环境;(2)2.3~2Ma,快速沉降至海平面之下约 1200m;(3)约 1.9Ma 至今,又相对隆升约 1000m,短时期内快速的沉降与隆升与 Cocos Ridge 的俯冲密切相关(Vannucchi *et al.*, 2013)。

近年来,高分辨率地震反射层析成像更直观地反映上述现象。例如日本东北部地区的弧前沉降主要集中在斜坡的中段和上段,浅部沉积的地层甚至朝大陆倾斜,并且发育切穿地层(甚至基底)的高角度正断层(Arai *et al.*, 2014; Boston *et al.*, 2017)。智利中北部大陆斜坡的下段与中段之间存在地震波速不连续界面就是前缘侵蚀导致斜坡最前端大规模沉降引起的(Contreras-Reyes *et al.*, 2014)。

3.2 弧地壳的截切

俯冲侵蚀会引起大规模弧前地壳的缺失,从结果上看主要表现为弧地壳的截切。例如智利南部 Taitao Peninsula 半岛的海岸线附近出露的一套石英闪长岩-花岗闪长岩体(CRP),研究表明其起源于俯冲板片熔融,形成深度 >35km,而目前岩体与下部俯冲洋壳的竖直距离不足 14km(Bourgois *et al.*, 1996);另一英安岩岩体与上述岩体成因相似,岩浆起源深度为 25~45km,而目前却出露于海沟附近(Guivel *et al.*, 2003)。这是上覆板块遭受侵蚀导致弧前地壳缩短的结果(图 6a, b),而俯冲侵蚀的发生与智利扩张脊的俯冲密切相关(Bourgois *et al.*, 1996; Guivel *et al.*, 2003)。类似的现象还出现在 Izu-Bonin 弧,位于弧前斜坡的 Hahajima Seamount 本是一个起源于弧下地幔楔的蛇纹岩海山,而现在却是一个"无根"的飞地,这是因为太平洋板块上的 Ogasawara Plateau(一个比正常洋壳厚 2~3km 的大海山)俯冲期间,被"削"去了山根(图 6c)(Miura *et al.*, 2004)。

伴随着弧前地壳被截切,海沟和海岸线的位置相对于俯冲侵蚀前发生明显的向陆一侧后退(图 5),这种现象在全球典型的侵蚀型板块汇聚边界十分普遍。统计前人对海沟后退速率的定量计算结果可以发现(表 1),不同俯冲带的海沟后退速率具有明显的差异,这可能与俯冲侵蚀的类型有关。即使是同一条俯冲带,在不同的地质历史时期具有不同的海沟后退速率。例如智利中部不同区域海沟后退速率的差异与 Juan Fernandez Ridge 的俯冲位置有关(Kay *et al.*, 2005),秘鲁 10Ma 前后海沟后退速率的差异与 Nazca Ridge 的俯冲密切相关(Clift *et al.*, 2003)。

大量的弧前地壳被截切,导致古老的岩浆弧结晶基底暴露在现今的海岸线以及近海的区域,这种现象很早就被发现并被认为与俯冲侵蚀作用有关。例如智利西海岸的中北部(Rutland, 1971; Ziegler *et al.*, 1981; Stern, 1991; Peterson, 1999)、日本本州岛北部(Murauchi, 1971)以及墨西哥的西南部(Schaaf *et al.*, 1995; Morán-Zenteno *et al.*, 2018)。持续的俯冲侵蚀甚至可以截切整个古老的弧地壳,导致弧的"消失",表现为一些古老的俯冲带缺失某一段(或几段)时期弧岩浆岩的记录。例如日本弧缺失早古生代和早中生代岩浆岩的记录并不是岩浆间歇引起的,上三叠统和更老的沉积岩中发现了大量 520~400Ma 的碎屑锆石,而下侏罗统及之后的沉积岩中却未见早古生代的碎屑锆石。因此 Isozaki *et al.* (2010)提出早古生代的岩浆弧因为俯冲侵蚀而"消失",并且侵蚀作用发生在晚三叠世-早侏罗世期间。同理也可以推断早中生代岩浆弧的侵蚀大致发生在晚白垩世(Isozaki *et al.*, 2010; Aoki *et al.*, 2012)。类似的现象还出现在我国西藏的南羌塘地块,与班公湖-怒江特提斯洋俯冲相关的弧岩浆在 170~145Ma 期间广泛发育,但明显缺失早-中侏罗世(170Ma 以前的晚中生代)弧岩浆岩(Yang *et al.*, 2021)。南羌塘靠近缝合带的侏罗纪沉积岩中的碎屑锆石显示 ~175Ma 和 ~154Ma 两个主要年龄峰,而白垩纪沉积物中这些物质占比却低于 5%。这反映了至少部分的早-中侏罗世岩浆弧可能被俯冲侵蚀作用截切而破坏,使得其在白垩纪时期不再作为主要沉积碎屑物源提供者(Yang *et al.*, 2021)。碎屑锆石年代学证据同样揭示了北美西南部以及阿拉斯加州南部的俯冲侵蚀过程(Grove *et al.*, 2008; Amato and Pavlis, 2010; Jacobson *et al.*, 2011; Chapman *et al.*, 2016)。

表 1　全球不同地区俯冲带海沟后退速率以及俯冲侵蚀速率统计

Table 1　Trench retreat rate and subduction erosion rate statistics in different subduction zone globally

地区	距今(Ma)	海沟后退速率(km/Myr)	俯冲侵蚀速率(km^3/km/Myr)	备注	参考文献
哥斯达黎加	17~0	3		Cocos Ridge 俯冲	Clift and Vannucchi, 2004
墨西哥		1			Clift and Vannucchi, 2004
危地马拉		0.9			Clift and Vannucchi, 2004
秘鲁	47~11	1.5~3.1	35.2		Clift *et al.*, 2003
	11~0	4.6~9.1	320	Nazca Ridge 俯冲	Clift *et al.*, 2003
	20~0	2.5	24~31		von Huene and Lallemand, 1990
	8~0	3.5	36~46	Nazca Ridge 俯冲	von Huene and Lallemand, 1990
	20~0		90		Scholl and von Huene, 2007, 2009
智利中部	10~0	3	96~128	Juan Fernandez Ridge 俯冲	Laursen *et al.*, 2002; Kukowski and Oncken, 2006
智利南部	19~16	8.8			Kay *et al.*, 2005
	7~3	10		Juan Fernandez Ridge 俯冲	Kay *et al.*, 2005
	4.2~1.5	8.5	231~443		Bourgois *et al.*, 1996
	0.3~1.12	16		智利扩张脊俯冲	Guivel *et al.*, 2003
日本东北部	20~0	3	40~55		von Huene and Lallemand, 1990
汤加	35~0	3.9			Clift and Vannucchi, 2004
		<1.5			Clift and MacLeod, 1999
		4~10		Louisville Ridge 俯冲	Lallemand, 1998
伊豆-小笠原	5.5~0	9		Ogasawara Plateau 俯冲	Miura *et al.*, 2004
		2			Clift and Vannucchi, 2004
马里亚纳		1			Clift and Vannucchi, 2004
South Sandwich Island	15~0	3.1~4.7	31~47		Vanneste and Larter, 2002

3.3　俯冲侵蚀与弧岩浆作用

3.3.1　岩浆弧的迁移

绝大多数的岩浆弧呈线状并且平行于海沟分布，一般位于俯冲板片之上 100~125km(Stern, 2002; Grove *et al.*, 2012)，而弧岩浆形成的深度是由软流圈地幔楔在含水条件下的固相线所决定(Hacker *et al.*, 2003; Gaetani and Grove, 1998)。随着上覆板片的物质不断被侵蚀，海沟持续后退以及俯冲板片的位置不断向前移动，软流圈地幔楔的熔融区域同时沿俯冲方向前进，这就造成新的岩浆弧向着大陆内部的方向迁移(图 5)。智利中北部新生代的岩浆弧相对于侏罗纪的岩浆弧向东迁移超过 250km(Rutland, 1971; Ziegler *et al.*, 1981; Stern, 1991; Peterson, 1999)，并且北部地区渐新世以来的火山弧前锋向东迁移了近 50km(Goss *et al.*, 2013)，中部地区 19Ma 以来经历了两次迁移，迁移距离分别为 35km 和 50km，后一期的迁移事件是 Juan Fernandez Ridge 俯冲引起的(Kay *et al.*, 2005)。日本西南部早中新世的岩浆弧相对晚白垩世的岩基向西迁移了近 150km(Isozaki *et al.*, 2010)。始新世晚期以来，阿留申群岛中部的火山前锋向北移动了 30~60km(Jicha and Kay, 2018)。岩浆间歇期与火山弧的迁移时间密切相关，而且不同时期的迁移速率存在变化。始新世晚期到中新世中期迁移速率较小(约 0.6~1.2km/Myr)，但随后迁移速率开始加快，在 5Ma 达到峰值(2~5km/Myr)并迁移到如今的位置，迁移速率的突然增加可能与中新世末期库拉脊的俯冲有关(Jicha and Kay, 2018)。

3.3.2　特征的弧岩浆岩

除了洋壳和大洋沉积物，通过俯冲侵蚀进入俯冲带的物质(包括上覆陆壳物质和陆源沉积物)可能通过两种方式参与弧岩浆的形成(Stern, 2011)：(1)脱水/部分熔融产生的富水流体/熔体交代上覆地幔楔；(2)部分熔融产生埃达克质岩浆，该岩浆在上升过程中可能混合其他幔源岩浆或与地幔楔橄榄岩反应。

中-南美洲西海岸是俯冲侵蚀研究的典型地区，Rogers and Hawkesworth (1989)最早发现智利北部侏罗纪至第四纪的岩浆弧向东迁移，且伴随着弧岩浆岩的 $^{87}Sr/^{86}Sr$ 比值和 Sr 含量逐渐升高以及 $\varepsilon_{Nd}(t)$ 值逐渐降低，起初认为这种现象是靠近大陆内部古老的元古代岩石圈地幔的活化引起的(Rogers and Hawkesworth, 1989)。进一步的研究表明，除了安第斯地区的 CVZ(Central Volcanic Zone)火山带，包括整个 SVZ(Southern Volcanic Zone)普遍存在俯冲侵蚀引起的构造活动-岩浆作用耦合现象(图 7)，因此一些学者提出这是俯冲侵蚀的陆壳物质混染弧下地幔源区的结果(Stern, 1990, 1991; Kay *et al.*, 1991)。尤其是在智利中部，仅从渐新世至今，区域上弧岩浆(特别是基性岩浆)的 Sr、Nd、Pb 同位素组成随着年龄的降低逐渐变得富集(图 7c)，并且同一时期的酸性-基性岩石具有大致相同的同位素组成(Kay *et al.*, 2005; Stern *et al.*, 2010, 2011)。Holm *et al.* (2014)对 SVZ

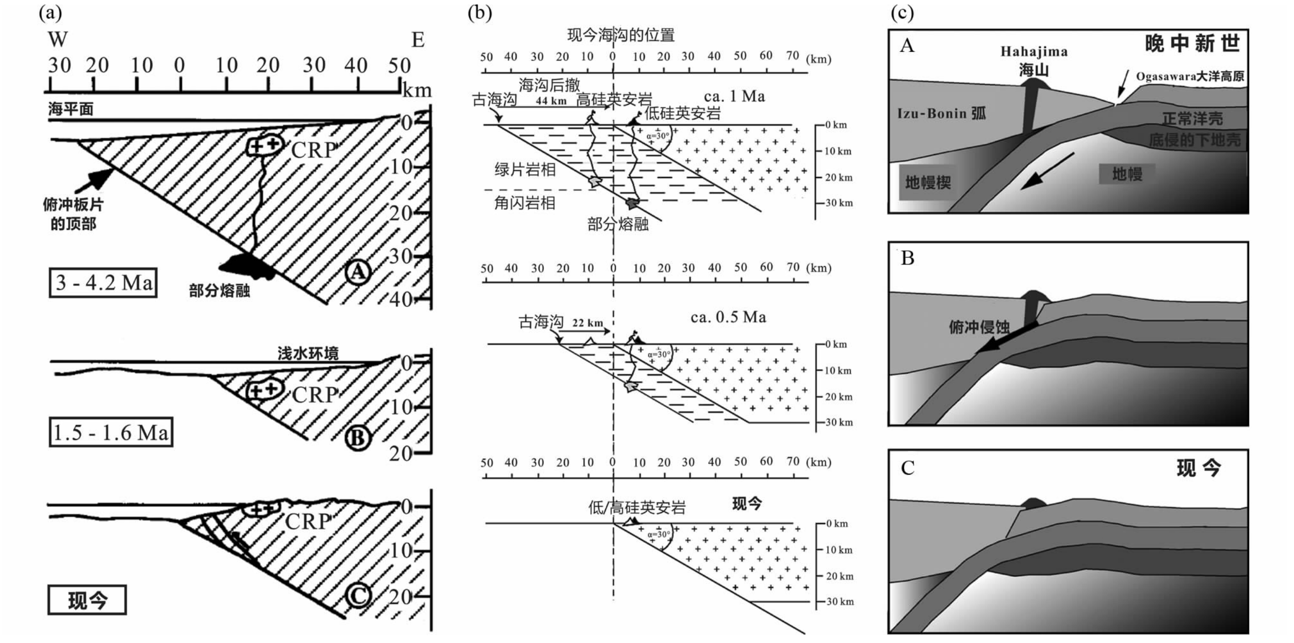

图6 俯冲侵蚀引起弧地壳截切的实例

(a、b)智利南部弧前地壳的截切(据 Bourgois *et al.*, 1996; Guivel *et al.*, 2003 修改);(c)西太平洋 Izu-Bonin 弧前地壳的截切(据 Miura *et al.*, 2004 修改). CRP(Cabo Raper pluton):石英闪长岩-花岗闪长岩体

Fig. 6 The truncation of forearc crust by subduction erosion

(a, b) the truncation of forearc crust in southern Chile (modified after Bourgois *et al.*, 1996 and Guivel *et al.*, 2003); (c) the truncation of forearc crust on the southern Izu-Bonin forearc (modified after Miura *et al.*, 2004). CRP: Cabo Raper pluton

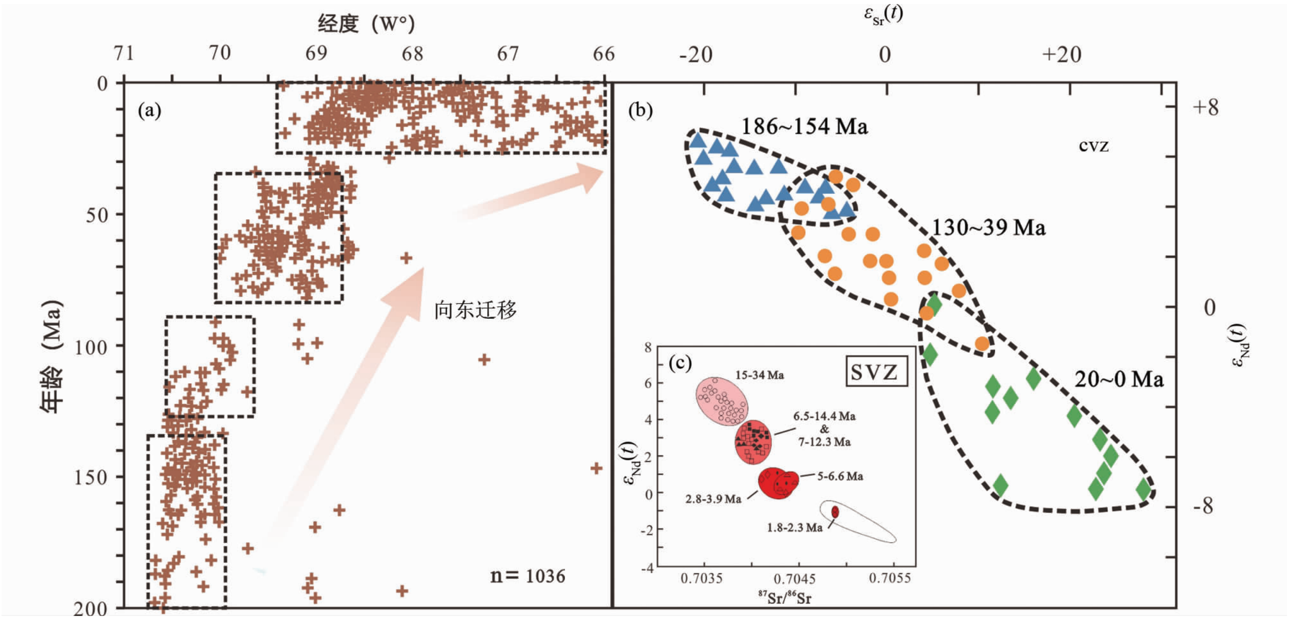

图7 安第斯地区俯冲侵蚀引起的弧岩浆迁移与弧岩浆源区富集相耦合

(a)中生代以来弧岩浆逐渐向东迁移(据 Haschke *et al.*, 2002 修改);(b)安第斯 CVZ 带弧岩浆岩 Sr-Nd 同位素随时间的变化趋势(据 Stern, 1990 修改);(c)安第斯 SVZ 带渐新世以来的幔源岩浆 Sr-Nd 同位素变化趋势,其中晚中新世以来的岩浆与 El Teniente 铜钼矿密切伴生(据 Stern *et al.*, 2010 修改)

Fig. 7 A coupling of magmatic arc migration toward the continent interior with a marked incompatible enrichment of sub-arc mantle magma sources in the Andean area

(a) eastern migration of the magmatic arc front during the Mesozoic (modified after Haschke *et al.*, 2002); (b) the Sr-Nd isotopic variation for arc magmatic rocks of different ages from the CVZ (Central Volcanic Zone) in the Andes (modified after Stern, 1990); (c) the Sr-Nd isotopic variation of mantle-derived magma of Andean Southern Volcanic Zone (SVZ) since the Oligocene, with magmatism closely associated with the El Teniente Cu-Mo deposit since the Late Miocene (modified after Stern *et al.*, 2010)

带的第四纪中基性火山岩进行了详细的地球化学分析，结果显示这些火山岩所代表的中北部弧下地幔源区受到不同程度（2% ～5%）的熔体混染，该熔体具有大陆上地壳的地球化学特征并且明显区别于海沟沉积物。早期认为墨西哥TMVB（Trans-Mexican Volcanic Belt）的火山熔岩（玄武岩-流纹岩系列）是幔源岩浆结晶分异和地壳混染的产物（Márquez *et al.*，1999；Verma，1999；Agustín-Flores *et al.*，2011）。最近的研究发现这些火山岩中普遍存在原始岩浆早期结晶的高 Ni 橄榄石斑晶，橄榄石具有类似地幔的高的$^{3}He/^{4}He$ 比值（$^{3}He/^{4}He=7\sim8Ra$）且不随 SiO_2 的含量变化。并且通过橄榄石斑晶氧同位素推算得到的平衡熔体的 $\delta^{18}O_{melt}$ 值很高（$\delta^{18}O_{melt}=+6.3‰\sim+8.5‰$），暗示这些橄榄石的寄主岩浆接近原始岩浆，但是地幔源区受到了地壳物质的混染。俯冲侵蚀进入地幔源区的弧前花岗闪长岩控制着弧岩浆高-中度不相容元素的含量，Nd-Hf 同位素组成，Nd/Hf 比值，以及混合模拟计算表明循环的地壳端元主要是弧前花岗闪长岩基而非海沟沉积物（Straub *et al.*，2014，2015）。TMVB 东部全新世火山熔岩的锆石核部具有古元古代到中新世的年龄，同样揭示了古老的弧前地壳物质经历埋藏、侵蚀、俯冲以及底辟上升穿过热的地幔楔，最终作为锆石捕虏晶重新出现在弧岩浆中的整个过程（Gómez-Tuena *et al.*，2018）。

弧岩浆中的埃达克岩并不及岛弧玄武岩（IAB）常见，但它们的出现往往可以反映一些短暂的特殊事件（Gutscher *et al.*，2000a；王强等，2020a）。在侵蚀型板块边界常出现具有埃达克质特征的弧岩浆，并且这些岩石在时空上与岩浆弧迁移、海山或无震海岭的俯冲相吻合（王强等，2020b）。智利北部中新世晚期（7～3Ma）的安山岩被认为是俯冲侵蚀的弧前陆壳部分熔融的产物（Goss and Kay，2009；Goss *et al.*，2013；Kay *et al.*，2013）。这些安山岩与区域内的其他火山岩相比具有明显的埃达克质特征（高 Sr 和高 Sr/Yb 比值）和富集的同位素组成，其高的 $Mg^{\#}$（50～61）、Cr（$100\times10^{-6}\sim350\times10^{-6}$）、Ni（$40\times10^{-6}\sim70\times10^{-6}$）是熔体上升过程中与地幔橄榄岩反应造成的（Goss *et al.*，2013）。哥斯达黎加南部和巴拿马中部的埃达克岩（～4Ma）被认为是俯冲侵蚀的弧前蛇绿混杂岩部分熔融的产物（Goss and Kay，2006）。日本西南部埃达克质高镁安山岩（15～13Ma）的地球化学特征与陆源海沟沉积物吻合，可能是俯冲的陆源沉积物熔体在上升过程中与地幔橄榄岩反应所形成（Shimoda *et al.*，1998）。阿留申群岛的埃达克岩通常认为是俯冲的玄武质洋壳在榴辉岩相条件下部分熔融的产物（Kay，1978；Yogodzinski *et al.*，1995，2015），然而最近一些学者提出用俯冲侵蚀的弧前地壳物质部分熔融来解释这些埃达克岩的成因（Kay，2003，2006；Jicha and Kay，2018）。

从全球尺度来看，弧岩浆的放射成因同位素比值（$^{87}Sr/^{86}Sr$、$^{207}Pb/^{204}Pb$、$^{206}Pb/^{204}Pb$、$^{143}Nd/^{144}Nd$ 和$^{176}Hf/^{177}Hf$）通常在亏损的上地幔和富集的大陆地壳之间变化（Plank and Langmuir，1993）。因此，有学者用原始弧岩浆的 $\varepsilon_{Nd}(t)$ 值来

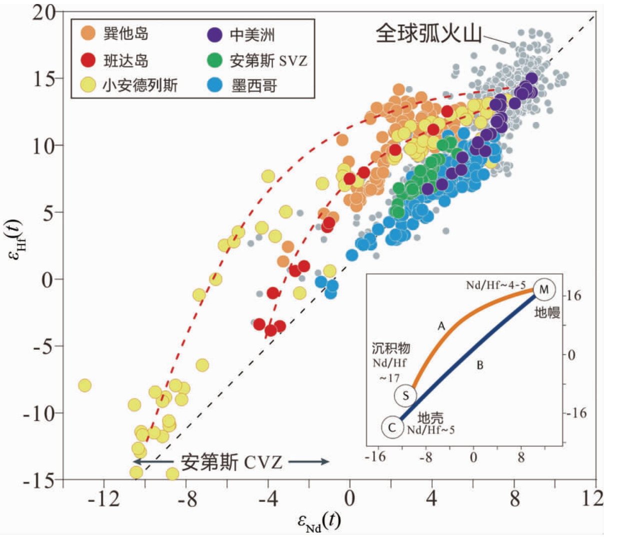

图 8　全球一些典型弧火山岩的 Nd-Hf 同位素变化趋势（据 Straub *et al.*，2020 修改）

插图中曲线 A 代表地幔和海沟沉积物的二元模拟混合线，直线 B 代表地幔和地壳的二元模拟混合线

Fig. 8　Nd-Hf isotopic variations of global arcs（modified after Straub *et al.*，2020）

Insert figure: Curved（A）trends resulting from mixing of endmember between mantle and trench sediment, straight（B）trends resulting from mixing of endmember between mantle and crust

简单刻画弧岩浆中再循环大陆地壳物质（侵蚀的陆壳为主＋少量海沟沉积物）参与的比例，低 $\varepsilon_{Nd}(t)$ 值的弧岩浆暗示其源区可能包含更多侵蚀的再循环地壳物质（Clift *et al.*，2009）。在 Nd-Hf 同位素体系中，如果仅考虑亏损地幔和弧前地壳、海沟沉积物两个端元（地幔与地壳的 Nd/Hf 比值：～5；富黏土的海沟沉积物 Nd/Hf 比值：～17），全球大多数弧岩浆落在亏损地幔和侵蚀地壳的混合线上，仅有少量的弧岩浆（例如巽他弧、班达群岛和小安德列斯群岛）落在亏损地幔和海沟沉积物的混合线上（图 8）。即使考虑到弧岩浆在上升过程中经历轻微的地壳混染，侵蚀的地壳物质对弧岩浆源区的交代作用依然占据主导（Straub *et al.*，2020）。

4　俯冲侵蚀的研究意义

4.1　俯冲侵蚀与金属成矿

环太平洋地区是世界上探明的大型-超大型斑岩铜金矿聚集的地区，尤其是在中-南美洲的西海岸，一些新生代铜金矿化与无震海岭的俯冲、俯冲侵蚀作用具有密切的时空联系（图 2），如：（1）Cocos Ridge 向中美洲哥斯达黎加-巴拿马弧俯冲，形成了 Cerro Colorado 铜金矿床（Cooke *et al.*，2005）；（2）Carngie Ridge 向厄瓜多尔岛弧俯冲，形成了 Chaucha 铜钼矿床（Cooke *et al.*，2005）；（3）Iquique ridge 向智利北部俯冲，形成 Chuquicamata（0.66 亿 t）和 Radomiro Tomic（0.2 亿 t）

两个世界级矿床(曹明坚等, 2011);(4)Juan Fernandez Ridge向智利中部之下俯冲,同时伴随 El Teniente(0.94 亿 t)、Rio Blanco(0.57 亿 t)、Los Pelambres(0.27 亿 t)等超大型铜矿床的形成(Cooke *et al.*, 2005; Rosenbaum *et al.*, 2005),它们分别是位居世界上第 1、第 3、第 9 位的铜矿床,探明铜金属总储量超过 1.5 亿 t(孙卫东等, 2010)。

南美洲安第斯斑岩矿床根据时间跨度可划分为白垩纪到上新世 5 个成矿带,并呈现出南北向平行展布、由西向东迁移的趋势,而这些地区正好对应 Juan Fernandez Ridge 和 Iquique Ridge 的俯冲(Camus and Dilles, 2001; 曹明坚等, 2011)。智利中部晚中新世(~14Ma)以来,由于 Juan Ferandez Ridge 的俯冲,减小了俯冲角度并且加快了俯冲侵蚀的速率(Kay *et al.*, 2005),与 El Teniente 铜钼矿密切伴生的幔源岩浆向东迁移且 Sr-Nd-Hf 同位素逐渐富集,表明俯冲侵蚀的陆壳物质对地幔源区的混染程度逐渐增加(图 7c)。因此一些学者提出俯冲侵蚀与大型-超大型斑岩矿床之间可能存在直接的成因联系(Stern *et al.*, 2010, 2011, 2019)。然而两者之间究竟存在怎样的内在联系目前还不清楚。通常认为挤压构造环境对形成斑岩矿床具有重要的意义(Sillitoe, 1998; Kerrich *et al.*, 2000; Cooke *et al.*, 2005),而俯冲侵蚀一般发生在低角度俯冲或平板俯冲的地区(以南美安第斯为典型代表),并可能出现弧火山作用的寂静期(Gutscher, 2002),因此未喷发至地表的浅部岩浆房在挤压背景下可以经历长时间的演化,有利于岩浆-热液矿床的形成(Sillitoe, 1998; 曹明坚等, 2011)。其次,一些学者提出俯冲侵蚀的物质可以引起弧下地幔的持续富水,并且具有高氧逸度的幔源富水岩浆(例如煌斑岩)可能与俯冲带铜、金矿床的成因密切相关(Stern *et al.*, 2010, 2011, 2019)。

4.2 俯冲侵蚀与大陆地壳

大陆地壳的形成与演化一直以来都是地球科学研究的核心问题,而俯冲带不仅是大陆地壳增生的主要场所,俯冲作用也是大陆地壳再循环进入地幔最重要的驱动机制之一。陆壳物质可以通过沉积于海沟的陆源沉积物的俯冲(Coats, 1962; von Huene and Scholl, 1991)、洋壳俯冲引起的构造侵蚀作用(Clift and Vannucchi, 2004; von Huene *et al.*, 2004; Clift *et al.*, 2009; Stern, 2011; Spencer *et al.*, 2017)、下地壳的拆沉(Kay and Mahlburg-Kay, 1991; Jagoutz and Behn, 2013; Lee, 2014)以及碰撞造山带的大陆深俯冲(Yin *et al.*, 2007; 郑永飞, 2008; Lu *et al.*, 2018)等方式进入地幔(图 9)。不同学者计算的长期的(距今 150 百万年以来)陆壳体积平均消亡速率大致为 4.9~5.25AU($1AU = 1km^3/yr$),其中俯冲侵蚀的速率为 1.3~1.7AU(Stern and Scholl, 2010; Clift *et al.*, 2009; Scholl and von Huene, 2009; Stern, 2011)。如果将陆缘海沟沉积物俯冲也定义为广义俯冲侵蚀的一种,那么俯冲侵蚀所占的比例最大从而成为引起大陆地壳破坏和消亡最主要的方式。俯冲侵蚀的大部分陆壳物质会进入

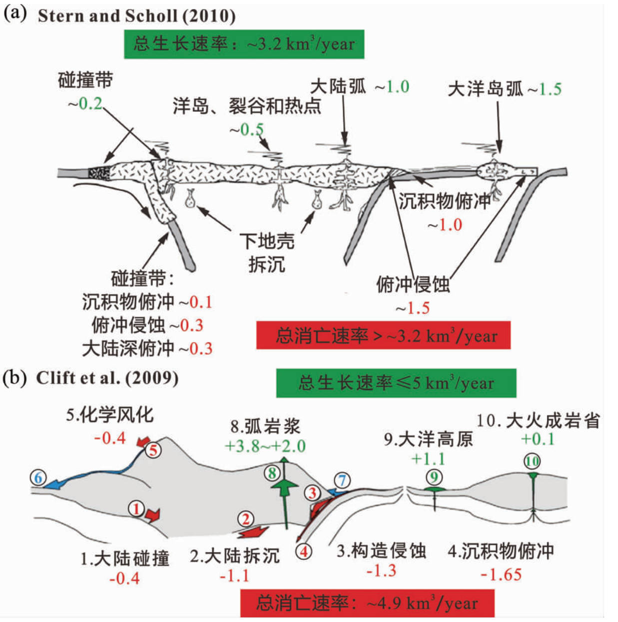

图 9 地壳增生和消亡的方式以及对地壳增生和消亡速率的估算(据 Stern and Scholl, 2010; Clift *et al.*, 2009 修改)

Fig. 9 Different estimates of global rates of crustal losses and additions (modified after Stern and Scholl, 2010; Clift *et al.*, 2009)

地幔深部,只有少部分会底侵(underplating)到弧前基地底部(Clift and Hartley, 2007; Grove *et al.*, 2008; Jacobson *et al.*, 2011; Chapman *et al.*, 2016)或者刮垫(relamination)到弧下地壳的底部(Hacker *et al.*, 2011, 2015; Jagoutz and kelemen, 2015; Kelemen and Behn, 2016)。前文提到侵蚀的陆壳物质和沉积物会通过弧岩浆的方式重新回到大陆地壳,除了少部分地区例如哥斯达黎加有超过 70% 的侵蚀物质转换成为弧岩浆,从全球尺度来看,这部分物质的比例不会超过 10%(Clift *et al.*, 2009; Scholl and von Huene, 2009; Stern, 2011)。以上三种方式都属于陆壳的自循环,不涉及陆壳的净生长。大量俯冲侵蚀的物质最终将停滞在地幔转换带或者核幔边界,形成地幔中的"陆壳储库"(Lay and Garnero, 2011; Kawai *et al.*, 2013; Zhao *et al.*, 2015; Ma *et al.*, 2016; Garnero *et al.*, 2016)。俯冲侵蚀的陆壳物质长期赋存于地幔中,会引起地幔的不均一性,体现在一些 OIB 所代表的富集地幔端元(EM Ⅰ 和 EM Ⅱ)(Willbold and Stracke, 2006; Jackson *et al.*, 2007; Workman *et al.*, 2008; White, 2010)。陆壳物质高度富集 K、U、Th 等放射性元素,对地幔柱或超级地幔柱的形成起到至关重要的作用(Senshu *et al.*, 2009; Stern, 2011)。

当大陆地壳的生长速率和破坏速率达到平衡,可以保持整体体积的相对稳定(Clift and Vannucchi, 2004; Clift *et al.*, 2009; Stern and Scholl, 2010; Spencer *et al.*, 2017)。定量计算表明墨西哥西部的俯冲带在距今 1 个百万年内达到了陆壳生长和破坏的平衡(Parolari *et al.*, 2018)。然而从地球长

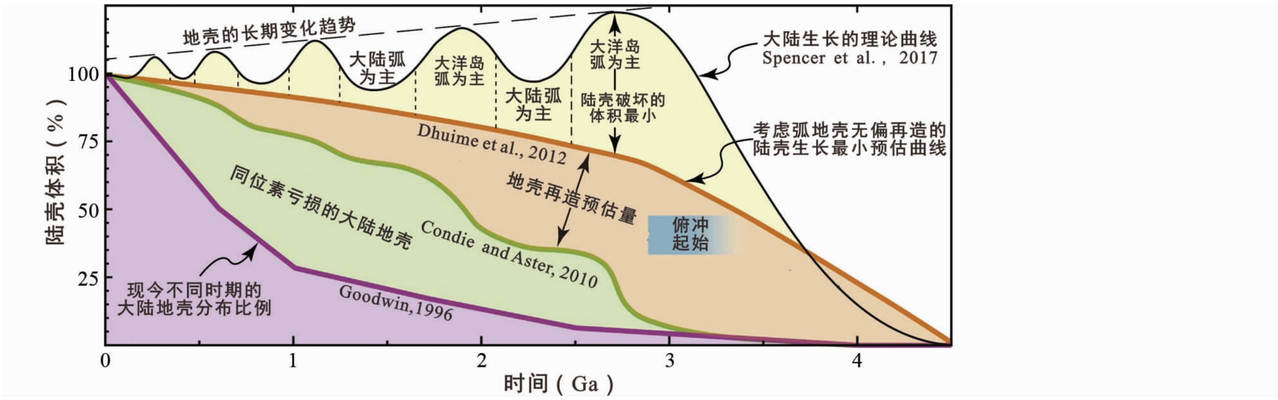

图 10 大陆地壳生长和循环的不同假说和模式(据 Spencer *et al.*, 2017 修改)

Fig. 10 Different hypotheses and models of continental crust growth and recycling (modified after Spencer *et al.*, 2017)

期的演化历史来看，大陆地壳的生长模式存在诸多模型和争议(图 10)。大陆地壳的生长和破坏可能并不保持长期的平衡，尤其是在超大陆循环的不同阶段：大陆地壳的消亡速率在超大陆聚合期间达到最大值，这是因为沿着汇聚板块边界发生广泛的俯冲侵蚀作用；而岩浆作用爆发使得大陆地壳的生长速率在超大陆裂解期间达到峰值(Stern and Scholl, 2010; Collins *et al.*, 2011; Gardiner *et al.*, 2016; Spencer *et al.*, 2017)。因此一些学者提出自板块构造启动以来，大陆地壳的体积虽然波动变化但整体表现为净负生长的趋势，即侵蚀的速率大于增生的速率(Stern and Scholl, 2010; Spencer *et al.*, 2017)。

大陆地壳整体具有安山质的平均成分(SiO_2 = 57% ~ 65%; $Mg^{\#}$ = 44 ~ 55)，而微量元素表现为现今弧岩浆的特征，因此被认为主要形成于与俯冲作用相关或相似的弧环境(Rudnick, 1995; Jagoutz and Kelemen, 2015)。对于安山质陆壳和玄武质弧岩浆之间的成分矛盾，早期用岩浆弧根的拆沉作用(delamination)来解释(Kay and Mahlburg-Kay, 1991; Jagoutz and Behn, 2013; Lee, 2014)。近些年来，一些学者提出俯冲侵蚀的上地壳物质通过刮垫作用(relamination)补充到弧地壳的底部，可以更好地解释整体大陆地壳的组成(Hacker *et al.*, 2011, 2015; Castro *et al.*, 2013; Kelemen and Behn, 2016)。此外，通过俯冲侵蚀进入俯冲隧道的陆壳物质可以与沉积物和少量地幔楔物质形成混杂岩，这些混杂岩具有富硅和低密度的特征，可以底辟上升至岩石圈地幔底部，随后发生熔融或者与地幔反应直接形成中性的弧岩浆，即“混杂岩底辟”(melange diapirs)模型(Marschall and Schumacher, 2012; Hao *et al.*, 2016; Nielsen and Marschall, 2017; Straub *et al.*, 2020; Parolari *et al.*, 2021)。

5 国内的研究现状与研究实例

5.1 国内研究现状

国内的学者对于俯冲侵蚀作用的研究起步相对较晚，相关研究最早出现在中文期刊可以追溯到 20 世纪 80 年代初。李永植(1982)用大陆岩石圈向大洋岩石圈仰冲过程中的“滚卷”来解释日本弧前的逆掩褶皱和断陷沉降。随后叶尚夫(1987)引入“俯冲侵蚀”这个概念，并认为我国台湾以东海域在中生代后期至新生代早期以俯冲侵蚀为主，导致褶皱造山带的下沉消失，大陆边缘后退到大南澳群变质岩带。在这之后国内很少有学者开展与俯冲侵蚀相关的研究，直到进入 21 世纪尤其是近几年来又重新引起了国内学者的关注。在苏鲁超高压变质带内部根据碎屑锆石研究发现了华北陆块来源的构造岩片(Zhou *et al.*, 2008)，说明在大陆碰撞过程中存在俯冲板片对仰冲陆块沉积盖层的前锋侵蚀(郑永飞, 2008)。在黑龙江杂岩带中的变沉积岩同样记录了晚中生代牡丹江洋向松辽板块之下俯冲时的构造侵蚀过程(Aouizerat *et al.*, 2020; Jing *et al.*, 2022)。在中国东部，中生代华北克拉通的破坏和大陆岩石圈的减薄可能与太平洋板块的低角度俯冲或洋脊俯冲引起的物理侵蚀有关(Zhang *et al.*, 2009; Zheng and Wu, 2009; Ling *et al.*, 2013; Luo *et al.*, 2018)。也有学者提出板块俯冲作用引起软流圈物质的扰动和上涌，是导致中国东部大陆岩石圈侵蚀和有效减薄的外在有利因素(郑建平, 2020)。除了变质岩石学方面的研究，国内的一些学者利用地球物理和地球化学的手段也相继识别出了南海东部马尼拉俯冲带和雅浦岛弧的俯冲侵蚀现象(Zhu *et al.*, 2013b; 张正一等, 2017; 朱俊江等, 2017; Zhang *et al.*, 2019; Liu *et al.*, 2023)。

青藏高原是横跨欧亚大陆的特提斯构造域的重要组成部分，它记录了一系列裂解自冈瓦纳大陆北缘的块体或者微陆块逐渐拼贴到欧亚大陆南缘的历史，同时也经历了与多阶段造山相关的洋盆扩张和大洋俯冲等动力学过程(Yin and Harrison, 2000; 许志琴等, 2006; Zhu *et al.*, 2013a; 吴福元等, 2020)。在青藏高原北部的柴北缘和北祁连地区相继发现了俯冲折返后剥露的高压-超高压变质岩石，并识别出了早古生代大陆俯冲和洋壳俯冲过程中对俯冲上盘的侵蚀作用(Zhang *et al.*, 2012; Lu *et al.*, 2018)。羌塘中部发现了

二叠纪低温高压变质岩,折返于大洋俯冲阶段,可能与洋岛或海山的俯冲及引发的俯冲侵蚀作用相关(Zhang *et al.*, 2017; 张修政等, 2018)。来自青藏高原中部的退变质榴辉岩揭示了安多微陆块向羌塘地块南缘拼贴过程中的俯冲侵蚀过程(Peng *et al.*, 2022)。最近一些学者在青藏高原北部发现了一条长约3000km的二叠纪-三叠纪榴辉岩带,并识别出同期的俯冲侵蚀作用(Wu *et al.*, 2023)。然而截止目前为止,从岩浆作用的角度探讨俯冲侵蚀作用的研究还比较少。接下来简单介绍本文作者近些年关于南羌塘和冈底斯带俯冲侵蚀识别的工作。

5.2　通过岩浆作用研究特提斯构造域俯冲侵蚀的实例

5.2.1　南羌塘俯冲侵蚀作用

羌塘地块位于青藏高原中北部的腹地内,其南缘以班公湖-怒江缝合带为界与拉萨地块接壤。最新的沉积、构造和古地磁等研究结果表明,班公湖-怒江缝合带所代表的洋盆闭合时间不早于早白垩世(Kapp *et al.*, 2007; Zhu *et al.*, 2016; Hao *et al.*, 2019)。尼玛县东部距离班公湖-怒江缝合带仅~20km康琼埃达克岩形成于~155Ma,为大洋板块俯冲阶段岩浆活动产物。这些岩石具有典型弧岩浆岩的微量元素特征,还具有高$Mg^{\#}$、富钠、高Sr/Y、弱-无显著Eu负异常的特征,类似于俯冲环境的埃达克质岩(Drummond *et al.*, 1996)。它们还具有富集的Sr-Nd同位素、正常幔源岩浆锆石O同位素和偏低的全岩Zr饱和温度(700~800℃)。详细的岩石成因讨论表明康琼埃达克岩不可能由俯冲玄武质洋壳直接熔融、也不是由加厚地壳熔融、岩浆分离结晶或岩浆混合作用形成。这些埃达克岩富Na、高Th/Ce和Th/La比值以及类似正常地幔的锆石O同位素也不支持沉积物熔融的成因模式。玄武质岩石脱水熔融所要求的温度显著高于其Zr饱和温度,指示玄武质岩石的水致熔融。富H_2O熔融时,斜长石不稳定而分解,使得形成的熔体具有弱的负Eu异常和高的Sr含量特征。此外,这些埃达克质岩的Pb同位素与南羌塘下地壳大致相似(Li *et al.*, 2016),这要求俯冲带上盘的物质被带入其源区参与岩浆形成。俯冲板片在弧前区域脱去其携带的绝大部分H_2O,这使得弧前区俯冲板片之上的上盘地壳被水化、甚至发生水压致裂作用。综上所述,康琼埃达克质岩的地球化学特征指示上覆板块(南羌塘)地壳组分被俯冲破碎,并被带入弧下地幔1.5~2.5GPa压力范围发生水致熔融(Yang *et al.*, 2021)。

区域上,更早时期的岩浆活动前锋具有随侵位年龄降低而发生向北侧迁移的规律,稍早时期的残留弧前碎屑沉积记录了快速的沉降事件。在现代活动俯冲带,即使在高角度俯冲环境下,弧岩浆与海沟之间的距离依然大于150km(Dzierma *et al.*, 2011)。构造与沉积资料显示(Kapp *et al.*, 2007),在康琼埃达克质岩侵位至今,板块碰撞导致的班怒带区域的地壳缩短量仅约90km,这都不足以解释该岩体与班公湖-怒江缝合带之间极短的空间距离,这更可能反映了部分弧前地壳被俯冲侵蚀截切。区域上约145~125Ma的岩浆间歇期也可能是因为板片以低角度俯冲,使得地幔楔逐渐减小而不能继续发生熔融形成弧岩浆岩。南羌塘靠近班怒带的侏罗纪地层中大量的~175Ma的碎屑锆石记录了强烈的同期岩浆活动,但它们在白垩纪地层中明显缺乏,且区域上出露极少的早-中侏罗世岩浆岩。这些现象指示,早-中侏罗世岩浆弧可能被俯冲侵蚀破坏,并被卷入俯冲带搬运至弧下地幔深度。研究还表明,班怒带侏罗纪以来至少存在两次大洋高原或无震海岭的俯冲(Zhang *et al.*, 2017; Hao *et al.*, 2019; Sun *et al.*, 2020),其与弧岩浆的迁移、岩浆间歇以及俯冲侵蚀密切相关(图11)。综合以上资料认为,羌塘南缘的康琼埃达克岩记录了侏罗纪时期的俯冲侵蚀,这为前新生代消亡俯冲带曾发生的俯冲侵蚀作用提供了首个岩石学证据(Yang *et al.*, 2021)。

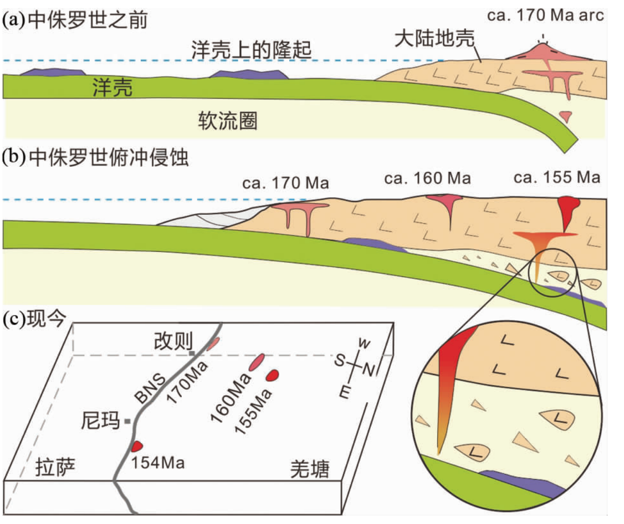

图11　南羌塘晚中生代俯冲侵蚀模式图(据Yang *et al.*, 2021修改)

(a)中侏罗世岩浆弧的形成,俯冲板片上的高地形隆起可能是引起后续俯冲侵蚀的主要原因;(b)弧前物质被侵蚀并参与弧岩浆的形成,伴随着弧前地壳的截切以及岩浆弧向内陆方向迁移;(c)目前观察到如此短的弧与缝合带的距离是俯冲侵蚀的结果. BNS:班公湖-怒江缝合带

Fig. 11　Cartoons of the subduction erosion model in the southern Qiangtang terrane during the Late Mesozoic (modified after Yang *et al.*, 2021)

(a) Generation of Middle Jurassic arc; positive topographic relief on the incoming slab could be a cause of later subduction erosion; (b) Forearc materials removed from the toe of the upper plate have been involved in arc source melting, which was accompanied by forearc crust truncation and frontal-arc migration toward the hinterland; (c) Observed short arc-suture distance could be a consequence of subduction erosion. BNS: Bangong-Nujiang suture

5.2.2　冈底斯俯冲侵蚀作用

青藏高原南部的冈底斯弧是新特提斯洋向欧亚大陆南缘俯冲形成的大陆边缘弧,其在规模以及性质上可以与美洲

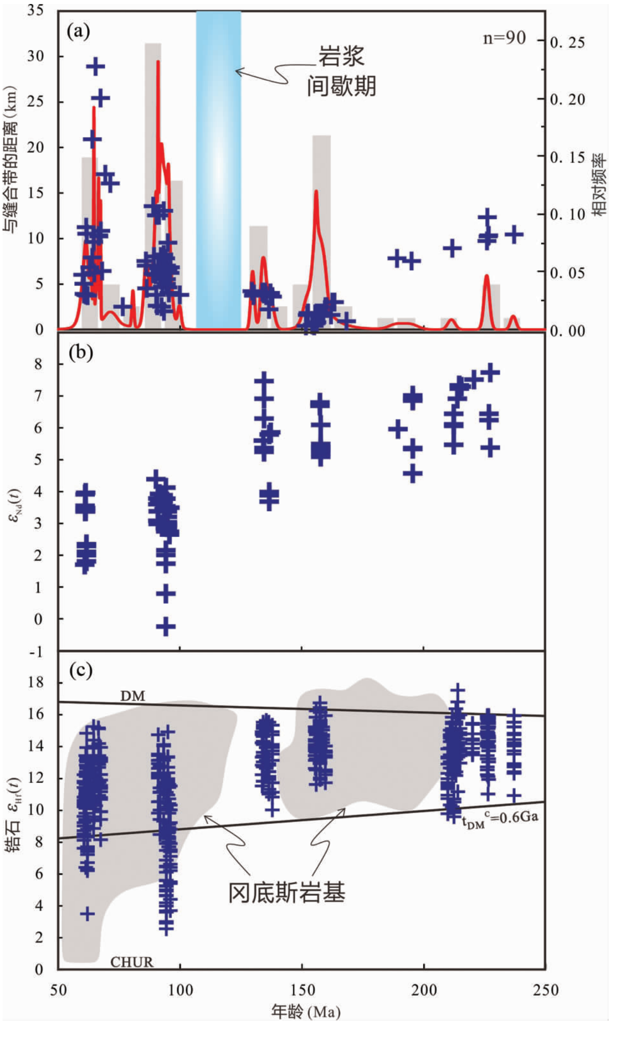

图 12 冈底斯弧晚中生代弧岩浆的迁移与弧下地幔源区富集相耦合

(a)定年样品与俯冲带的距离随年龄变化；(b)基性岩全岩 Nd 同位素值随年龄变化；(c)基性岩锆石 Hf 同位素值随年龄变化

Fig. 12 The spatial differences and temporal changes in the isotopic composition of Mesozoic Gangdese arc magmatism

(a) plot ofarc rock ages against the distance to the suture; (b) plot of mantle-derived magma ages against whole-rock Nd isotope; (c) plot of mantle-derived rock ages against zircon Hf isotope

的科迪勒拉弧和安第斯弧相媲美(纪伟强等, 2009)。前人的研究指出冈底斯中生代岩浆岩普遍具有亏损的 Nd-Hf 同位素组成，表明冈底斯弧在该时期经历了长期且显著的新生地壳的生长(Chu *et al.*, 2006; Ji *et al.*, 2009; Zhu *et al.*, 2011)。然而该时期欧亚大陆南缘的俯冲增生或侵蚀过程并没有得到很好的约束，同时也限制了冈底斯弧地壳净生长的定量计算。

冈底斯弧中东段中生代岩浆活动发育，尤其是在泽当地区，缝合带两侧的地质构造单元完整，从南到北依次包括特提斯喜马拉雅地层、泽当蛇绿混杂岩、泽当岩体以及北部的冈底斯岩基。与冈底斯西段的日喀则地区不同，泽当地区的蛇绿岩与弧岩浆之间并不存在弧前盆地，晚侏罗世岩浆弧(J_3)与南部的蛇绿岩(130～120Ma)直接断层接触在一起，缺失了增生楔和弧前杂岩。在考虑到印度-欧亚大陆碰撞缩短量与原始的日喀则弧前盆地的宽度的基础上，反演得到的晚中生代弧-沟距离(60～90km)远小于正常的弧-沟距离(>150km)(Zhu *et al.*, 2019)。因此弧前地壳的截切以及缩短的弧-沟距离最有可能是俯冲侵蚀引起的，而与新生代以来的陆-陆碰撞过程无关。两条近南北向的实测剖面以及统计的年龄数据显示，从晚侏罗世到白垩纪末期，随着弧岩浆年龄的逐渐年轻，岩浆活动向北迁移，并且伴随着基性岩所代表的幔源岩浆全岩 Nd 同位素和锆石 Hf 同位素的逐渐富集，三者具有很好的耦合关系(图 12)，这与中南美洲俯冲侵蚀引起的构造-岩浆耦合现象高度相似(Stern, 1991; Stern *et al.*, 2011; Parolari *et al.*, 2018)，是俯冲侵蚀的、较富集的弧前陆壳物质交代弧下地幔源区的结果。冈底斯中东部大量出露的晚白垩世(～90Ma)埃达克岩具有与俯冲板片相关的埃达克岩特征(高 $Mg^{\#}$值、Cr 和 Ni 含量)，与晚白垩世之前形成的板片熔体成因埃达克岩相比，前者具有更高的 K_2O 含量和 K_2O/Na_2O 比值、Th 含量和 Th/La 比值，以及更加富集的 Sr-Nd 同位素和锆石 Hf 同位素特征。同位素二元混合模拟显示绝大多数晚白垩世埃达克岩落在 MORB 与陆壳的混合线上而非 MORB 与沉积物的混合线，这表明其源区可能包括洋壳和俯冲侵蚀的陆壳物质，类似产出于新生代弧环境的一些和俯冲侵蚀相关的埃达克岩(Goss and Kay, 2006, 2009; Goss *et al.*, 2013)。

冈底斯中东部存在一个明显的岩浆间歇期(130～110Ma)并在之后发生了弧岩浆向内陆的迁移，该岩浆间歇期代表大规模俯冲侵蚀发生的时间，并且俯冲侵蚀的触发与新特提斯洋壳上的海山链、无震海岭、大洋高原甚至扩张洋脊的俯冲密切相关(图 13)(Huang *et al.*, 2022)。综合以上资料，作者首次提出中东部拉萨地块的南缘在晚中生代是一个典型的侵蚀型板块汇聚边界，该时期的冈底斯弧地壳不仅存在长期且明显的垂向生长，同时也有大量陆壳通过侧向侵蚀循环进入地幔，冈底斯弧在这期间可能并没有地壳的净生长(Huang *et al.*, 2022)。

与中东段不同的是，雅鲁藏布江缝合带西段的部分地区不仅具有弧前盆地，而且还保存了弧前的增生楔沉积。沉积学的研究发现增生楔中缺少从洋壳铲刮下来的海沟沉积，因此一些学者提出碰撞前的冈底斯弧南缘虽然发育小增生楔，但仍以侵蚀为主(An *et al.*, 2017)。东西段的差异不仅体现在构造单元组成的不同，Hf 同位素填图显示冈底斯中东段大部分地区中生代岩浆岩中的锆石具有较高的 $\varepsilon_{Hf}(t)$ 值(0～+14)，并且具有更加年轻的地壳 Hf 模式年龄(图 14)，表明这些地区主要由新生地壳组成且幔源物质的贡献多，而西段则具有相反的特征(Hou *et al.*, 2015)。这种现象可能暗示着中东段的俯冲侵蚀强烈，地壳(或岩石圈地幔)经历较高程度的改造和置换，而西段的古老地壳或岩石圈地幔则更多

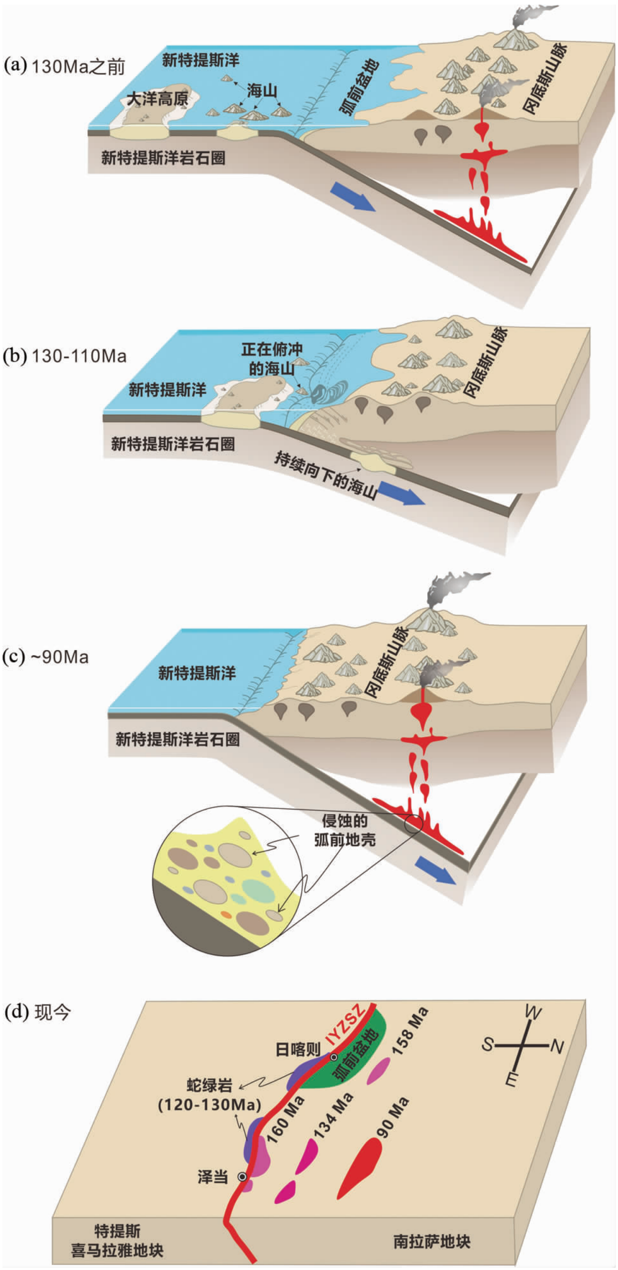

图 13 冈底斯弧晚中生代俯冲侵蚀模式图

(a)早白垩世以前,新特提斯壳正常俯冲形成冈底斯弧岩浆;(b)洋壳上的高地形(例如海山和大洋高原等)俯冲导致上盘的弧前地壳触发大规模的构造侵蚀,并导致弧岩浆活动暂时停止;(c)侵蚀的弧前陆壳物质参与弧岩浆的形成,并伴随弧前锋向内陆迁移;(d)现今观察到弧地壳的截切以及缝合带两侧构造单元的分布. IYZSZ:雅鲁藏布江缝合带

Fig. 13 Cartoons of the subduction erosion model in the Gangdese during the Late Mesozoic

(a) generation of pre-Early-Cretaceous arc; (b) positive topographic relief on the incoming slab triggered extensive subduction erosion, following a period of magmatic lull; (c) forearc materials removed from the upper plate have been involved in arc source melting, which was accompanied by forearc crust truncation and frontal-arc migration toward the hinterland; (d) the present distribution of geologic features on both sides of the Yarlung-Zangbo suture zone could be a consequence of subduction erosion. IYZSZ: Indus-Yarlung Zangbo Suture Zone

地被保留,然而造成这种差异的深层动力学机制还需要更加深入的研究,将是以后工作的方向。

6 科学问题与展望

6.1 俯冲侵蚀与平坦俯冲的关系

中-南美洲是俯冲侵蚀研究最早且研究程度最高的地区,同时也是研究平坦俯冲的典型区域(Gutscher *et al.*, 1999, 2000a, b)。通常认为异常厚的洋壳(大洋高原、无震海岭或者海山)是形成平坦俯冲的一种可能机制(曹明坚等, 2011),并且平坦俯冲同样会造成弧岩浆作用往大陆方向发生迁移,形成异常宽阔的岩浆弧带(Kay and Abbruzzi, 1996)。随着俯冲洋壳以低角度近水平的俯冲,最终导致俯冲平板之下软流圈地幔消失,造成弧岩浆寂静期(Gutscher, 2002; Kay and Mpodozis, 2002),这与俯冲侵蚀的特征和表现形式非常相似。最新的数值模拟研究表明平坦俯冲通常与弧前的俯冲侵蚀相伴生,并且平板俯冲能从上覆板片的底部铲刮 20 ~ 50km 厚的大陆岩石圈地幔(Axen *et al.*, 2018; Gutscher, 2018),这是一种更深尺度下的俯冲侵蚀作用。平坦俯冲通常会经历(1)正常俯冲阶段;(2)平坦俯冲转变与发展阶段以及(3)平坦俯冲岩浆寂静期三阶段演化过程(Gutscher *et al.*, 2000a),然而俯冲侵蚀出现在平坦俯冲的哪一阶段目前并不清楚,并且俯冲侵蚀与平坦俯冲之间存在怎样的成因联系还需要进行更加深入的研究。

6.2 前新生代俯冲侵蚀的识别

对于前新生代俯冲侵蚀的识别一直是个难点,特别是在洋盆已经闭合的俯冲带,这是因为相比于正在活动的俯冲系统,前新生代的俯冲带(或者缝合带)中进入俯冲带的俯冲板片年龄和俯冲板片的地形特征信息几乎是完全缺失的;另一方面,由俯冲侵蚀引起的弧前沉降、地壳的构造变形等现象会在长期的俯冲以及后续的闭合-碰撞过程中被破坏。目前变质岩石学方面的研究为我们识别缝合带中的俯冲侵蚀提供了很好的视角(Zhang *et al.*, 2012, 2017; Lu *et al.*, 2018),但是对于变质原岩的物源分析仍然是个难点。与俯冲侵蚀相关的岩浆活动记录在俯冲带闭合的过程中能够得以保留,但是利用弧岩浆作用反演俯冲侵蚀过程时通常要综合考虑区域上沉积学和构造地质学的证据(Yang *et al.*, 2021; Huang *et al.*, 2022)。近年来,随着地球化学分析测试技术的发展,一些非传统稳定同位素开始应用于俯冲带侵蚀作用的研究。例如 South Sandwich 岛弧火山岩异常重的 B 同位素组成($\delta^{11}B = +12‰ \sim +18‰$)揭示了俯冲侵蚀的弧前地幔楔蛇纹岩进入弧下深度并脱水,可以交代弧下地幔产生富 ^{11}B 的岩浆(Tonarini *et al.*, 2011)。吕宋岛具有重 Mo 同位素组成($\delta^{98/95}Mo$: $-0.18‰ \sim 0$)的埃达克岩指示了弧前的俯冲侵蚀作用(Liu *et al.*, 2023)。在未来的研究中,一些新的地球化学示踪剂对与俯冲侵蚀有关的弧岩浆可能有巨大

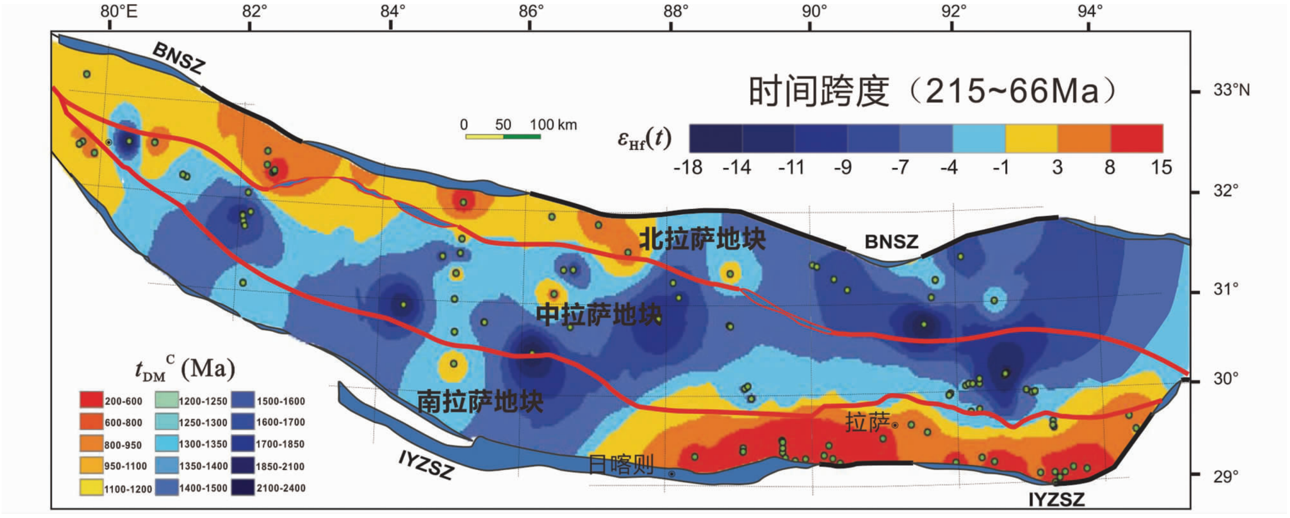

图 14 拉萨地块中生代岩浆岩锆石 $\varepsilon_{Hf}(t)$ 值的空间变化(据 Hou *et al.*, 2015 修改)

t_{DM}^{C}:地壳模式年龄;BNSZ:班公湖-怒江缝合带;IYZSZ:雅鲁藏布江缝合带

Fig. 14 Hf isotope contour map showing the spatial variation of zircon $\varepsilon_{Hf}(t)$ values for the Late Mesozoic magmatic rocks in the Lhasa terrane (modified after Hou *et al.*, 2015)

t_{DM}^{C}: crustal Hf model ages; BNSZ: Bangong-Nujiang suture zone; IYZSZ: Indus-Yarlung-Tsangpo suture zone

的研究潜力,例如$^{238}U/^{235}U$(Andersen *et al.*, 2015; Freymuth *et al.*, 2019)、$^{205}Tl/^{203}Tl$(Nielsen *et al.*, 2016)和$^{138}Ce/^{142}Ce$(Bellot *et al.*, 2015)等。研究过程中还需要充分考虑与俯冲作用有关的各端元储库组成,包括海沟沉积物、弧前和弧地壳、弧后岩浆以及弧下地幔楔。此外,俯冲侵蚀的弧前地壳物质参与弧岩浆作用的方式也值得进一步的关注。

6.3 俯冲侵蚀速率的定量计算

大陆地壳的生长速率是研究大陆地壳演化的关键并且至今仍有争论(Spencer *et al.*, 2017)。计算大陆地壳的生长速率(这里特指净生长),不仅要厘定陆壳增生的速率,还要弄清陆壳的侵蚀量以及侵蚀速率。目前对俯冲侵蚀速率的计算主要建立在对弧前地壳缺失体积大致估计的基础之上,通常需要考虑弧前地壳的厚度,弧前沉降程度和持续时间,以及海沟后退的速率(Vannucchi *et al.*, 2003; Clift and Vannucchi, 2004; Scholl and von Huene, 2007)。即使如此,对于同一个俯冲带同一时期内的俯冲侵蚀速率,不同学者的计算结果存在较大的差异(表 1)。基于越来越多地质数据的累积,目前最新的全球平均俯冲侵蚀速率的估算结果为 ~$66\pm34km^3/km/Myr$(Straub *et al.*, 2020),明显高于早期的估计(~$23km^3/km/Myr$)(von Huene and Scholl, 1991)。然而,精确计算俯冲侵蚀的速率仍然是一个极具挑战性的难题。俯冲侵蚀的速率与俯冲带环境的动态变化密切相关,例如板块汇聚速率的变化、洋壳俯冲角度以及俯冲隧道的宽度等。此外,侵蚀的陆壳物质并不会全部进入深部地幔,一部分会底侵到弧前基底底部或者刮垫到弧下地壳的底部,或者通过弧岩浆重新回到地壳。因此在定量化计算陆壳的侵蚀速率时需要充分考虑上述因素。

6.4 俯冲侵蚀与板块构造的启动

板块运动是什么时候开始的一直是地学界争论的热点问题(Korenaga, 2013)。现今地球上没有发现冥古宙的岩石而且也仅存在少量太古宙的岩石,在地球形成早期是否存在原始的大陆地壳一直存在争议。一些学者提出可能存在古老的原始大陆地壳,但是因为俯冲作用而消失,甚至提出地球形成早期就出现板块构造,并伴随出现早期的俯冲侵蚀作用(Ichikawa *et al.*, 2013, 2017; Azuma *et al.*, 2017)。4Ga 至今,累计循环进入地幔的陆壳物质约 $10^{10}km^3$,超过了现存大陆地壳的总体积(Ichikawa *et al.*, 2013),其中俯冲侵蚀可能是重要的机制之一(Azuma *et al.*, 2017)。其次,一些显生宙的岛弧钙碱性岩石的地球化学特征与太古宙 TTG 岩系十分相似(Kimbrough and Grove, 2006; Grove *et al.*, 2008),这些岩石可能由俯冲侵蚀的陆壳物质部分熔融形成。而在热梯度更高的太古代和元古代早期,俯冲侵蚀可能更普遍,弧岩浆主要以 TTG 的形式循环回到地壳(Stern, 2011)。很多学者认为太古宙甚至冥古宙就已经出现板块运动(Dhuime *et al.*, 2015; Turner *et al.*, 2020),并认为大陆地壳的快速生长与板块俯冲密切相关(Dhuime *et al.*, 2012)。而俯冲侵蚀会抑制大陆的快速生长,那么伴随着板块运动的开始是否有俯冲侵蚀的发生?如果有,与现今刚性的板块俯冲相比,早期的俯冲侵蚀是怎样的发生机制与表现形式?这是未来研究中值得思考的问题。

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