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增生型造山带结构解析与时空制约

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摘要： 增生型造山带记录复杂的板块汇聚过程，增生造山作用演化历史漫长，发育多期次造山作用.就增生型造山带的特征与复杂性进行简要总结与评述，并讨论增生造山作用时空分析思路.增生造山作用是多种性质（汇聚、转换和离散）的板块边缘，沿一个核心大陆边缘最终发生复杂相互作用动力学过程的总和.弧前发育增生杂岩和各种混杂岩或者构造岩片，上叠有以弧前盆地为代表的各类沉积盆地，共同制约增生过程的时空演化特征.增生型造山带多发育多岛海复杂古地理格局，增生造山作用具有多组分、多岛海、多盆地类型、多种性质的岩浆活动、宽阔的增生杂岩、多俯冲极性、多地体拼贴、长期演化与面状增生等特性.以古地磁、古地理、古生物与古气候等资料为基本依据，划分一级大地构造单元界线.以构造地质解析和关键地区详细的地质填图，结合物质成分和年代学分析，进行二级大地构造单元及其相互关系的详细解剖.卷入增生造山事件中最年轻的地质体或者组分，提供了该期增生事件时限的下限；卷入增生造山事件中最年轻的角度不整合，以及最年轻的高压－低温变质事件，可能提供了最晚增生事件时限的下限；而未卷入增生造山事件中最老的区域性角度不整合，则可能提供了最晚增生事件时限的上限.

关键词： 增生型造山带；增生杂岩；造山带结构；复式增生造山作用；增生造山作用时限；大地构造学.

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Structural Analyses and Spatio-Temporal Constraints of Accretionary Orogens

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Abstract: Accretionary orogens record complicated geological processes during plate convergence, and are characterized by long evolutionary history with multi-stage orogenesis. This paper presents a brief summary and review on the characteristics and complexity of accretionary orogens, and also discusses the methods of analyzing the spatio-temporal evolution of accretionary orogeny. Accretionary orogeny is here defined as a collection of interactions between various types (convergent, transform and divergent) of plate boundaries along a host continental margin with multiple orogenic phases. The forearc region of an accretionary orogen includes accretionary complexes with overlying sedimentary basins such as forearc basin and wedge-top basin, which together constrain the spatio-temporal evolution of accretionary processes. Accretionary orogens are characterized by complicated archipelagic paleogeographic patterns with the development of different types of basins, diverse magmatism, wide accretionary complexes, multiple subduction polarity, multiple terrane accretion, secular evolution and planar accretion. By using the paleomagnetic, paleogeographic, paleontological and paleoclimate data, first-order tectonic units can be deciphered.

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Based on structural analysis and detailed geological mapping, in combination with material and geochronological analysis, second-order tectonic units can be divided. The lower time limit of accretionary events can be discriminated by defining the youngest components, unconformities, and high-pressure metamorphic events involved in the accretion; while the upper time limit relies on the oldest unconformities which are not involved in the accretion.

Key words: accretionary orogenic belt; accretionary complex; orogenic architecture; multiple accretionary orogenesis; time limit of accretion; tectonics.

0　引言

造山作用与大陆生长一直是地球动力学经久不衰的研究主题(Dewey and Bird, 1970; Coward and Butler, 1985; Dewey *et al*., 1989; Yin and Nie, 1996; 张国伟等,2001; Chen and Jahn, 2002, 2004; Aoya *et al*., 2003; Aoya and Wallis, 2003; Chen and Arakawa, 2005; Ding *et al*., 2005; Canil *et al*.,2006; 许志琴等,2006; Castillo, 2008; Yin, 2010).根据板块构造理论,威尔逊旋回实际上强调用大陆之间大洋张开和闭合来诠释大陆造山带的地球动力学过程(Wilson, 1966).因此,20世纪60—90年代,特提斯—喜马拉雅(碰撞)型和环太平洋(俯冲)型造山作用是国际地质学界关注的热点(Dickinson, 1973; Dickinson and Seeley, 1977; Ben-Avraham *et al*., 1981; Crawford *et al*., 1981; Coward and Butler, 1985; Coleman, 1989; Dewey *et al*., 1989; Stern, 1994; Ding *et al*., 2005; Wu *et al*., 2007; 任纪舜等,2016; 肖庆辉等,2016).然而,地球科学家认识到许多大陆造山带具有更复杂的特征,经历了复杂的裂解、俯冲、增生和焊接过程,产出多条蛇绿岩、增生楔杂岩、韧性剪切带、花岗岩、火山岩和高压变质岩带(李继亮,2004).经典的造山作用理论尚不能全面概括其结构、组成、过程和造山机制.这类特殊造山带被称为“增生型造山带”或者“突厥型造山带”(Şengör and Okurogullari, 1991; Şengör *et al*., 1993; 马文璞,1999).

增生型造山带以其独特的侧向增生和垂向增生过程为主要特征(Han *et al*., 1997; Gao *et al*., 1998; Jahn *et al*., 2000; Yuan *et al*., 2003, 2005, 2007),对大陆岩石圈的生长具有显著的重要贡献(Şengör *et al*., 1993; Jahn *et al*., 2000; Li *et al*., 2003; Xiao *et al*., 2004, 2008; Li, 2006;肖文交等,2006, 2008),并导致了矿产和能源资源的巨量富集(Rui *et al*., 2002; Seltmann *et al*., 2003; Yakubchuk, 2004; Seltmann and Porter, 2005).

增生型造山带包括前寒武纪绿岩带(如西非的Birimian带、芬兰和瑞典的Svecofennian带、阿拉伯的Arabian-Nubian带以及北美Superior和澳大利亚Yilgarn Provinces),新元古代—中生代中亚造山带,以及新元古—新生代环太平洋—加勒比造山带等(Windley, 1995; Cawood and Buchan, 2007; Dickinson, 2008).

增生造山作用与超大陆旋回在全球尺度上存在一定耦合关系(Cawood and Buchan, 2007).当小陆块聚合逐步形成超大陆时,在超大陆的外围将会开始增生造山作用(Cawood and Buchan, 2007).

20世纪90年代初,随着世界各地造山带研究的不断深入,增生造山作用研究已经迅速成为国际地球动力学研究前沿与热点(Bohlen, 1991; Brown, 1993; Baker and Stolper, 1994; Isozaki and Blake, 1994; Kusky *et al*., 1997; Hall, 2002; Buckman and Aitchison, 2004; Cawood and Buchan, 2007; Windley *et al*., 2007).针对此类主题,国际地质对比计划和国际岩石圈计划都实施一系列的研究计划(如IGCP 420, 473, 480以及国际岩石圈计划“全球增生系统”).

本文试图阐述增生型造山带的基本特征,特别是讨论其结构组成及其时空制约,以探讨大陆造山带的形成过程和动力学机制.

1　增生型造山带的基本特征

增生型造山带被定义为碰撞型造山带的一种新类型(Şengör and Okurogullari, 1991; Şengör *et al*., 1993; 李继亮,2004).然而,这些复杂造山带与以大陆岩石圈发生深俯冲为主要特征的特提斯碰撞型造山带确实存在巨大的差异.因此,造山带被分为增生型造山带与碰撞型造山带(Windley, 1995).实质上,增生造山作用是多种性质(汇聚型、转换型和离散型)的板块边缘,沿一个或者多个大陆边缘最终发生复杂相互作用的大地构造过程的总和.增生型造山带以各种不同性质的岩石圈板块及其边界发生复杂相互作用为基本特征.

从结构上来讲,增生造山作用指由一个核心大

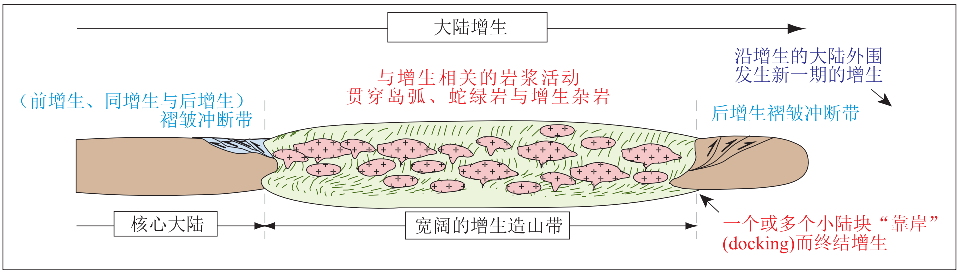

图 1　核心大陆通过增生造山带与小陆块拼贴而发生显著增生示意

Fig.1　Schematic diagram of growing processes by means of accretionary orogenesis

修改自Şengör and Natal'in(1996)

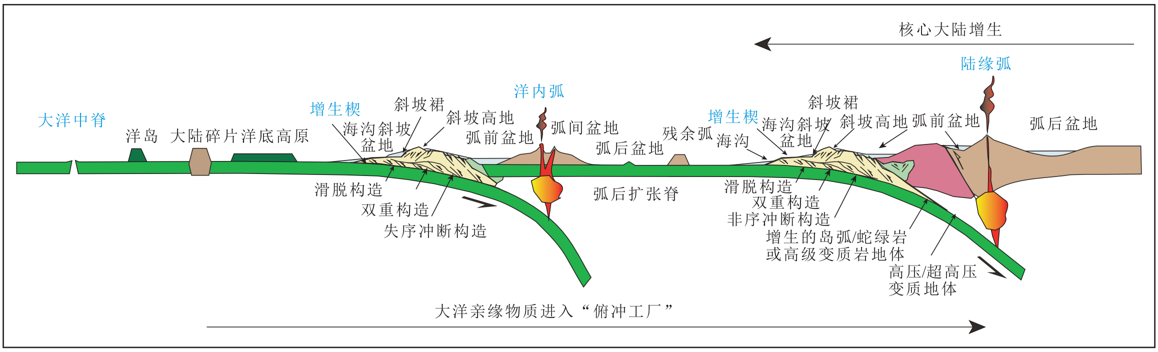

图 2　基于活动大陆边缘增生造山作用简图

Fig.2　Accretionary orogenesis along an active margin

陆(host continent)往外通过复杂的拼贴和增生作用而逐步增生,包括弧前连续增生和小型陆块拼贴或者“靠岸”(docking)(Cloos, 1993),直到有较大尺度的大陆块体与之发生碰撞造山作用才终结的大地构造过程(图 1).

概括而言,增生造山作用具有多组分、多岛海、多盆地类型、多种性质的岩浆活动、宽阔的增生杂岩、多俯冲极性、多地体拼贴、长期演化的特征.因此,与特提斯造山带典型的线状分布特征不一样,增生造山带具有面状增生等特性(Şengör and Okurogullari, 1991; Şengör *et al.*, 1993; Encarnación, 2004; 李继亮,2004; Xiao *et al.*, 2008).

增生型造山带在组成上有来自洋中脊、转换断层、大洋裂隙带、海山、洋底高原、大洋岛屿、微陆块、大洋岛弧与海沟等大洋组分,也有来自增生楔(杂岩)、弧前盆地组合、弧前蛇绿岩或者早期变质基底、岛弧(狭义)、弧间盆地组合、弧后盆地组合、残余岛弧与陆缘弧等活动大陆边缘组分(Falloon and Crawford, 1991; Şengör *et al.*, 1993; Dickinson, 1995; Sacks *et al.*, 2000; Taira, 2001; Suyehiro *et al.*, 2003; Niitsuma, 2004; Escuder Viruete *et al.*, 2006;王强等,2006;Long *et al.*, 2007;Sun *et al.*, 2008),甚至有被动大陆边缘沉积组合的贡献(Westbrook *et al.*, 1988).在演化过程中这些多组分进入俯冲带或者活动陆缘,经“俯冲工厂”加工或者地体拼贴增生在核心大陆边缘(图 2).

2　增生杂岩与混杂过程

除常规的岛弧组合(弧相关盆地、岛弧)外,增生楔(杂岩)是解剖增生型造山带结构与演化过程的关键(Moore and Sliver, 1987).增生楔(杂岩)(accretionary prism/wedge/complex, subduction/accretion-subduction complex),又称为第一弧或者消减杂岩,包括沉积混杂岩、构造混杂岩、蛇绿岩与蛇绿混杂岩等.

这些相关的岩石组合可以追索到最早出现在威尔士北部 Anglesey 地区的关于 mélange 的文献中(Greenly, 1919; Barber and Max, 1979).在美国西海岸进行构造填图时,弗朗西斯科杂岩(Franciscan Complex)被定义为经典的具有“岩块－基质”混杂特点的构造－岩石组合(Hsü, 1968; 1971; Cowan, 1974, 1978).20 世纪 70 年代以来,增生楔(杂岩)在世界许多俯冲带被系统地识别并进行了详细

的研究(Karig, 1974; Karig and Sharman, 1975; Dewey, 1977; Dickinson and Seely, 1977).

增生杂岩是指俯冲带上经铲刮、褶皱、断层、碎裂、沉积与混杂等复杂过程形成的岩石—构造单元,主要包括蛇绿岩碎片(超基性岩、基性岩、硅质岩、深海灰岩与软泥等)、蛇绿混杂岩与滑混堆积以及巨厚的复理石等连续单元.

在增生型造山带中发育了大量的蛇绿岩残片或者构造岩片,它们是增生杂岩中的主要组分.蛇绿岩通常被认为是消失的大洋岩石圈残片(Moores, 1970; Dewey, 1977).蛇绿岩曾是寻找缝合带的关键岩石构造组合,赋予了大陆发生碰撞、其间洋盆闭合的关键角色(Dewey, 1977).在实际研究工作中,蛇绿岩出露地点往往被当成缝合带位置.然而,在世界许多增生型造山带中,产出有数量巨大的蛇绿岩残片或者蛇绿混杂岩,它们大小不一,从上百公里到厘米级尺度均有发育,并且在许多情况下,无法简单地连成“缝合带”.大量系统的研究工作表明,保存在造山带中的许多蛇绿岩实质上是蛇绿混杂岩(Şengör and Natal'in, 2004).

此外,蛇绿混杂岩的大地构造背景十分复杂,有来自经典的弧前俯冲带铲刮下来的大洋岩石圈板块残余(Hsü, 1968, 1971; Cowan, 1974),弧前—弧后盆地(Huang *et al.*, 2000; Xiao *et al.*, 2002),以及转换断层(Saleeby, 1984).这些不同性质的蛇绿混杂岩构造就位在增生楔或者其他岛弧相关的大地构造单元中(Stern, 1994, 2004; Şengör and Natal'in, 2004).

正常大洋岩石圈在俯冲过程中被刮削就位到弧前位置的蛇绿混杂岩理论上具有彭罗斯会议定义的经典蛇绿岩的结构和物质组成,包括地幔橄榄岩、辉长岩、席状岩墙、基性熔岩及深海硅泥岩.但它们就位到增生楔的过程中往往发生构造肢解导致某些组分的缺失.这种蛇绿混杂岩的基性岩通常具有洋中脊玄武岩(MORB)的地球化学特征.如我国东北地区佳木斯地块东缘的跃进山增生杂岩中的蛇绿岩,其玄武岩具有正常洋中脊玄武岩(N-MORB)地球化学属性,该蛇绿岩被认为是古太平洋板块向东亚大陆俯冲过程中被刮削就位的大洋岩石圈残片(James,1971; Kamenetsky *et al.*, 1997; Harper, 2003; Zhou *et al.*, 2014).弧前—弧后盆地蛇绿岩形成于俯冲带上盘的强烈伸展环境,称为俯冲带之上(suprasubduction-zone, SSZ)蛇绿岩,其基性岩具有显著的弧岩浆的地球化学特征(Pearce *et al.*, 1984).环太平洋俯冲—增生杂岩中的蛇绿混杂岩大多属于这种类型,如北美加州海岸山脉蛇绿岩(Coast Range ophiolite; Wakabayashi *et al.*, 2010).经典的塞浦路斯 Troodos 蛇绿岩和阿曼 Semail 蛇绿岩也被认为属于 SSZ 型蛇绿岩(Pearce *et al.*, 1984; Dilek and Furnes, 2009).我国天山造山带、北山造山带和兴蒙造山带中的蛇绿混杂岩也大多属于俯冲带之上蛇绿岩(Wang *et al.*, 2006, 2007, 2011; Xiao *et al.*, 2010; Ao *et al.*, 2011; Song *et al.*, 2015b).

除蛇绿混杂岩外,基性岩(主要为枕状和块状玄武岩)与硅质岩也是增生楔中的特征岩石组合.在野外露头研究中,枕状熔岩以其鲜明的枕状构造成为良好的识别标志,硅质岩也以其独特的褶皱冲断变形或者平整的层状产出成为特征识别标志.在日本岛弧增生楔分析中,枕状熔岩与硅质岩扮演了十分重要的角色,特别是放射虫时代分析很好地厘定了原本难以识别的冲断成因的“巨厚出露”的硅质岩(Matsuoka, 1995; Taira, 2001).许多古老的增生造山带结构和演化过程的解析也得益于枕状熔岩与硅质岩的系统分析.

在青藏高原,通过对雅鲁藏布蛇绿岩中放射虫硅质岩的研究及其与西太平洋相关放射虫的对比,对重建该地区的古地理格局起到重要作用(Wu, 1993; Matsuoka *et al.*, 2005).Graymer and Jones (1994)通过对北美西海岸内华达山麓放射虫的系统分析,区分出晚二叠世、晚三叠世、早侏罗世、中侏罗世和中侏罗世晚期5个时期的放射虫硅质岩,据此把 Placerville 带划分了5个地体.Danelian and Robertson(2001)根据希腊东部增生楔中放射虫生物地层学分析重建了该地区新特提斯洋的演化过程.

浊积岩是由浊流沉积作用形成的半深海至深海沉积产物,以特征的鲍马序列为标志;复理石也属于半深海、深海相沉积,其特征是具有多次重复性韵律层理,单个韵律层厚度不大,但总厚度巨大.巨厚的复理石或浊积岩等连续单元不太容易识别,特别是在混杂岩出露较少或者不太发育的造山带中,这些连续沉积单元是否属于增生楔则更加难以厘定.然而,复理石或浊积岩在许多造山带中的增生楔十分发育,如澳大利亚拉克兰造山带(Lachlan Orogen)的中西部区域主要由强烈褶皱变形的砂岩和页岩构成的浊积岩组成(Glen, 1992; Glen *et al.*, 2007; Foster *et al.*, 1999; Foster and Gary, 2000; Spaggiari *et al.*, 2004).在北美阿拉斯加地区,中生代

Chugach terrane 增生杂岩中的上白垩统 Valdez 群就是由岩屑砂岩和泥质板岩组成的海底扇复理石连续沉积单元，其物源主要来自中生代岩浆弧和海岸山脉岩基（Defant and Drummond，1990，1993 ；Defant *et al*.，1992；Kepezhinskas *et al*.，1996；Defant and Kepezhinskas，2001；Kochelek *et al*.，2011）.复理石和（或）浊积岩是中亚造山带内大部分增生楔的主要组成单元，如阿尔泰地区额尔齐斯增生楔发育厚层的由变沉积岩构成的复理石（Long *et al*.，2010；Xiao *et al*.，2015），西准噶尔克拉玛依－白碱滩泥盆纪－石炭纪增生楔发育浊积岩（Zhang *et al*.，2011），北山南部的二叠纪柳园增生杂岩，发育大量枕状熔岩和由砂岩、泥岩组成的浊积岩（Guo *et al*.，2012）.

远洋碎屑沉积物和碳酸岩也可以作为主要组分出现在增生楔中.在有洋中脊、海山或者洋底高原卷入增生楔的情况下，由于它们的顶部可能发育浅水碳酸盐岩，则在增生楔中可不同程度发育浅水灰岩或者大理岩（Robertson，1994；Danelian and Robertson，2001；Taira，2001）.日本中部美浓地体（Mino terrane）中生代增生杂岩就是由于海山就位到弧前位置，导致弧前发生构造破碎、混杂形成大规模混杂岩，同时组成海山的玄武岩和生物礁灰岩也保存在混杂带内（Okamura，1991）.在哥斯达黎加西海岸，洋底高原和海山在汇聚板块边缘的增生使弧前增生楔中出现大量的玄武岩、远洋灰岩和硅质岩（Buchs *et al*.，2009）.

增生楔除了经典的基质－岩块相互剪切构造关系外，在构造样式上表现为多重逆冲叠瓦扇（imbrication fan）和双重构造（duplex）的组合等特征（von Huene *et al*.，1980，1994；Sacks *et al*.，2000；Taira，2001；Suyehiro *et al*.，2003；Niitsuma，2004）.逆冲叠瓦扇构造与双重构造由相互叠置且倾向相同的一系列冲断层和褶皱构造组成，而背形堆叠则形成复杂的褶皱冲断带组合.这些构造样式可出现在不同的构造层次，形成不同尺度的皱褶冲断带（图 3）.

增生楔组分呈堆叠或者叠瓦构造，是与混杂岩具有多种端元特征密切相关的.在经典的分析中（Raymond，1984），混杂岩有 4 种情况：混杂端元、连续端元、破断单元、肢解单元（图 4）.实质上，该理念强调沉积－构造作用对混杂岩形成的意义与贡献.在弱变形域或者其他有利条件下，岩层可以保持原有的层序或者层序基本完整，形成连续端元；而在强变形域或者始终处于强烈变形的条件下，岩层层序全部被打乱，则形成混杂端元，出现岩块－基质的经典混杂岩面貌.如果在过渡情况下，如岩层受到构造变形而导致部分层序被扰乱，但整体上层序仍可追索，则形成破断单元；如构造变形进一步加强，则形成局部可见部分层序的肢解单元.

在一个增生楔中，往往这 4 种不同变形程度的单元以不同的比例混杂在一起，并且随着板块汇聚过程的发展它们的比例也发生变化.连续端元常见于增生楔中的复理石或浊积岩单元，因变形微弱，其韵律层理或鲍马序列很好地保存了下来.破断单元中常见逆冲断层和褶皱等变形特征，而原始的沉积构造仍可识别.肢解单元由于强烈的剪切变形形成构造透镜体、构造岩片，常见布丁构造和 S-C 组构.而混杂端元则可以明显地区分出经过强烈剪切变形的“基质”和大小不等的“岩块”，岩块存在多种岩性和来源，如 Franciscan Complex 的蓝片岩、绿片岩和杂砂岩等岩块与剪切页岩基质构成的混杂岩

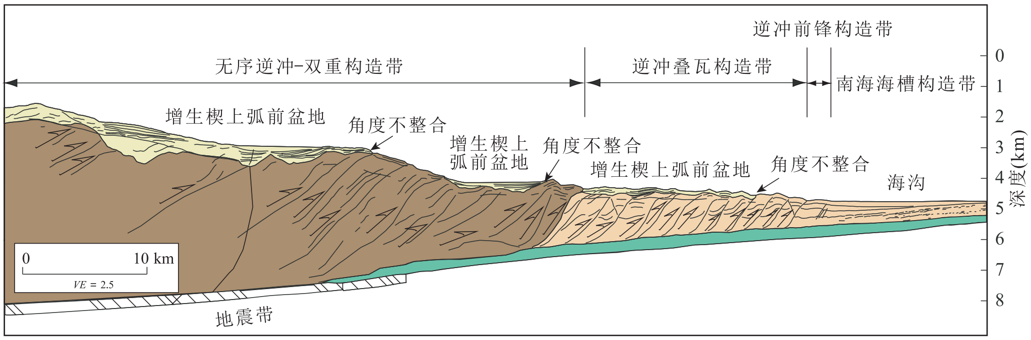

图 3　日本岛弧增生楔的基本组成与构造

Fig.3　Structure and basins of the accretionary complex of the Japan Islands

修改自 von Huene *et al*.（1980，1994）；Sacks *et al*.（2000）；Taira（2001）；Suyehiro *et al*.（2003）；Niitsuma（2004）

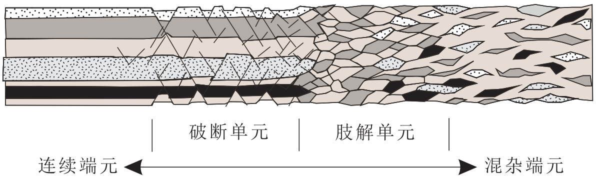

图4　混杂岩基本组成端元

Fig.4　End-member of mélanges

修改自Raymond(1984)

(Wakabayashi，2015).

此外，在伊朗至巴基斯坦南部沿海的莫克兰增生造山带与地中海以及科迪勒拉增生造山带中，许多早期拼贴的块体或者增生杂岩可以形成晚期增生楔的组成部分(Dickinson，1973，1995，2008；Berberian *et al*.，1982；McCall and Kidd，1982；Khain *et al*.，2002；Hosseini-Barzi1 and Talbot，2003；Ghazi *et al*.，2004；Khan *et al*.，2007).

增生楔的发展遵循库仑楔理论(Cameron *et al*.，1979；Davis *et al*.，1983；Platt，1986，1993；Dahlen，1990；Willett *et al*.，1993；Del Castello *et al*.，2004).增生楔可能因为库仑楔夹角调整而在上部出现引张构造组合，而在深部或者底部出现多重逆冲叠瓦扇、双冲构造和背形堆叠构造等挤压构造组合.

弧前或者大洋岛弧上还可能发育有变质核杂岩构造(Davies and Warren，1988).特别是洋中脊随迁移的三联点与活动大陆边缘发生复杂相互作用时(Marshak and Karig，1977；Thorkelson，1996；Maruyama *et al*.，1997；Bradley *et al*.，2003；Sisson *et al*.，2003；Aguillón-Robles *et al*.，2001；Thorkelson and Breitsprecher，2005；Wessel *et al*.，2005；Díaz Azpiroz *et al*.，2006；Madsen *et al*.，2006；Fletcher *et al*.，2007)，大型的走滑构造与伸展构造会在弧前同时并存，往往还呈现规律性的迁移(图5和图6).

在特殊情况下，比如在经历洋中脊或者大洋破碎带俯冲的情况下(图5)，增生楔与弧前(forearc)其下深部可发育板片窗而导致软流圈物质上涌，可能因此发生高温低压变质并伴随伸展作用(Ernst，1977，1988；Thorkelson，1996；Maruyama *et al*.，1997；Bebout and Barton，2002；李强与张立飞，2004；Zhang *et al*.，2005，2007；Fletcher *et al*.，2007).洋中脊俯冲及其引起的特殊地质效应在环太平洋造山带得到了深入研究，如北美科迪勒拉造山带(Sisson *et al*.，2003)、南美安第斯造山带(Anma and Orihashi，2013)和日本造山带(Kodaira *et al*.，2003).随着研究的深入，古老造山带中洋中脊俯冲现象也被大量识别出来，如中亚造山带(Windley and Xiao，2018)、泛非造山带(Meneghini *et al*.，

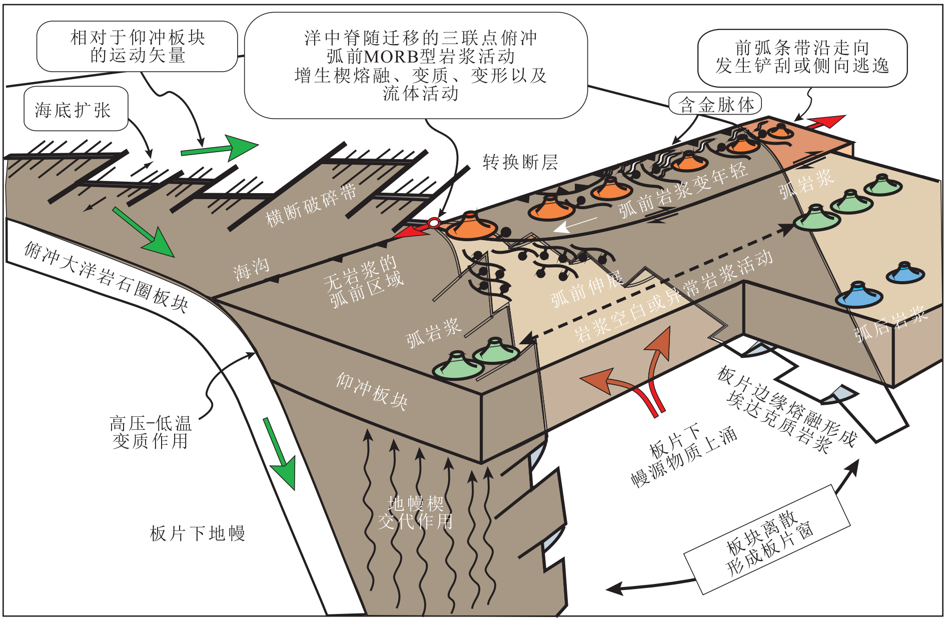

图5　洋中脊随迁移的三联点与活动大陆边缘发生复杂相互作用示意

Fig.5　A schematic diagram showing complex interaction between an oceanic ridge along with a migrating triple junction and an active continental margin

修改自Thorkelson(1996)；Bradley *et al*.(2003)；Sisson *et al*.(2003)

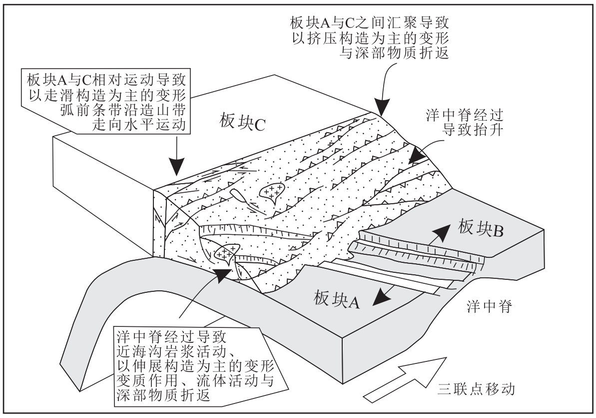

图 6　基于大洋中脊俯冲的板块移动及其大地构造过程

Fig. 6 Interactions between different plates during ridge subduction

修改自 Kusky *et al*.（1997）；Bradley *et al*.（2003）

2014）和阿巴拉契亚造山带（Schoonmaker and Kidd，2006）.

洋中脊俯冲引发的地幔上涌将使弧前增生杂岩发生高级变质作用、深熔作用、岩体侵入和玄武岩底垫作用.在阿拉斯加，Kula-Farallon 洋中脊向北美大陆的俯冲引发的板片窗地幔上涌使增生楔中的浊积岩发生绿片岩至角闪岩相变质，形成了 Chugach 变质杂岩（Scharman *et al*.，2012）.在中国阿尔泰造山带，泥盆纪洋中脊俯冲引发的区域高温变质作用形成了广泛分布的角闪岩相变质杂岩（Jiang *et al*.，2010）.洋中脊俯冲引发的板片窗及其伸展作用还将在弧前形成 A 型花岗岩和 OIB 型玄武岩等具有“板内”地球化学属性的岩浆作用，而正常的弧岩浆作用将暂时停止，如智利 Patagonia 上新世洋中脊俯冲作用形成的“板内”岩浆作用（Esponoza *et al*.，2008）.此外，洋中脊俯冲还可能导致弧前物质发生侵蚀，其侵蚀速率比正常的板块俯冲造成的侵蚀速率高得多（Bourgois *et al*.，1996）.

随着世界各地造山带研究的深入，洋中脊俯冲逐渐被发现是大洋俯冲和增生造山带演化过程中的普遍地质过程（Windley and Xiao，2018）.

3　弧前盆地与沉积作用

增生楔的沉积作用除了经典的海沟斜坡盆地外，弧前盆地是主要的沉积物堆积场所.弧前盆地是指位于岛弧和增生楔之间或者上叠于增生楔的沉积盆地，其盆地边缘将随着增生楔向大洋方向的生长而发生向洋的迁移（Dickinson，1995）.弧前盆地这一概念最早起源于 20 世纪 70 年代（Dickinson，1973；Karig and Sharman，1975）.弧前盆地大多以蛇绿岩、增生楔或早期增生的变质地体为基底，因而其沉积物源也来自岛弧、增生楔（杂岩）、弧前蛇绿岩或者早期变质岩基底.在少数特殊情况下，如巴巴多斯增生楔中，还有其南面巴西克拉通被动大陆边缘沉积为其提供物源（Westbrook *et al*.，1988）.值得注意的是，弧前盆地也可能出现陆相沉积物（Dickinson，1995；Kimbrough *et al*.，2001）.

由于增生楔具有由深部到浅部生长的特性（Davis *et al*.，1983；Platt，1986，1993；Dahlen，1990），弧前盆地的沉积物堆积可以与下伏的增生楔新物质的添加是同时或者更早.也就是说，弧前盆地沉积物并不总是比位于角度不整合面之下的增生楔所有组分都年轻.因此，在增生造山过程中，可以发育不同性质的沉积盆地，并且造山作用与沉积作用可以同时进行，形成特殊的多级角度不整合面.在海沟附近，同时代的地层可能出现不整合接触关系，如日本中部晚中新世—上新世增生杂岩与上覆上新世海沟斜坡盆地之间存在角度不整合接触.

由于持续的增生作用，许多沉积盆地，如弧前盆地，往往被构造挤压破碎，成为增生楔或者混杂岩的一部分.如我国台湾造山带中混杂岩中就有搓碎变形的早期弧前盆地（Huang *et al*.，2000）.重要的是，这些含有早期弧前盆地的增生楔又被更年轻的上叠弧前盆地角度不整合覆盖.如地震学研究显示，日本 Nankai 增生楔在其向大洋方向发展过程中，不同时代的增生楔分别被不同时代的更年轻弧前盆地或楔顶盆地不整合覆盖（图 3）（Strasser *et al*.，2009）.

增生楔呈现由岛弧向大洋方向总体逐渐变年轻的趋势，相关的弧前盆地与增生楔上叠盆地也会随增生楔主体发生向大洋方向总体逐渐变年轻（Taira，2001）.在日本岛弧增生楔的解剖中，靠岛弧一侧是古生代岩石和侏罗纪的增生楔，向大洋方向依次出现白垩纪、第三纪和现代增生楔（Taira，2001）.当然，在这种向大洋逐渐变年轻的总体趋势中，还存在局部或者短时间的向大陆方向的迁移（Dickinson，1973，1995，2008）.如安第斯造山带北部哥伦比亚汇聚带，中新世期间随着增生楔的生长，弧前盆地的沉降中心持续向大陆方向发生迁移（Mountney and Westbrook，1997）.

传统上认为弧前盆地的发育总是与增生楔的生长具有紧密联系（Dickinson，1973，1995）.需要指出的是，根据深海钻探计划对现今太平洋俯冲带的

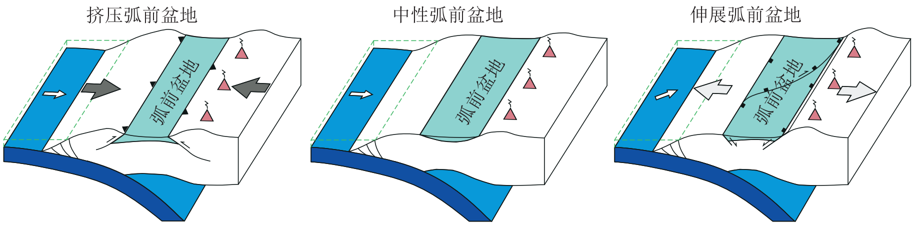

图 7 基于所处构造应力状态的弧前盆地分类

Fig.7 The classification of forearc basins based on the mode of deformation they subjected

修改自 Horton(2018)

研究，弧前盆地不仅发育在增生型大陆边缘如阿拉斯加、阿留申、苏门答腊－爪哇等俯冲带，在不发育增生楔的侵蚀型俯冲带同样可以形成弧前盆地沉积，如马里亚纳俯冲带、中美洲墨西哥和南美洲厄瓜多尔和秘鲁俯冲带(Stern，2002).根据弧前盆地所处的应力状态和盆地沉降中心的迁移方向，弧前盆地可以分为挤压型、伸展型和中性弧前盆地 3 个端元类型(图 7；Noda，2016；Horton，2018).挤压型弧前盆地形成于弧前位置受挤压应力控制的环境，常发育逆冲断层和褶皱变形，同时盆地的沉降中心向大陆方向迁移，如阿拉斯加弧前盆地(von Huene and Klaeschen，1999)；伸展型弧前盆地形成于弧前相对伸展的应力背景，发育正断层，同时盆地的沉降中心向大洋方向迁移，一般与俯冲板块回卷后撤有关，如现今南美智利南部地区的弧前盆地(Polonia *et al.*，2007)；中性弧前盆地则变形微弱，如阿留申弧前盆地(Ryan，2012).随着俯冲大洋岩石圈年龄的变化，同一个弧前盆地在其长期的演化过程中，则可能经历挤压、伸展、走滑等不同变形样式的影响(Horton，2018).如下加利福尼亚半岛(Baja California Peninsula)俯冲带在其中生代演化过程中经历了从高度伸展到中度伸展，再到挤压变形的转变(Busby，2004).

弧前盆地及其沉积作用保存了汇聚板块边缘俯冲板块与上覆板块之间复杂相互作用引发的岩浆作用、山脉隆升、构造侵蚀等地质过程信息，是增生造山演化时空过程的重要“档案”，很多增生造山带的时空解剖都得益于对弧前盆地沉积物的详细研究(Kimbrough *et al.*，2001；Stevens Goddard *et al.*，2018).特别是随着现代同位素分析技术的发展，通过弧前盆地沉积物碎屑锆石 U-Pb 年代学和低温热年代学(如锆石或磷灰石裂变径迹)的研究，重建大洋俯冲动力学过程.如基于阿拉斯加中南部 Cook Inlet 弧前盆地新生代沉积物碎屑锆石 U-Pb 和裂变径迹年龄的同时测定，有效地识别了洋中脊俯冲和平板俯冲等地质过程对弧前盆地物源的影响(Enkelmann *et al.*，2019).

4 高级变质地体属性

由片岩、片麻岩等组成的高级变质地体存在于全球各类造山带中，是构成增生造山带的重要地质单元.由于这些变质地体通常发育强烈的变质和变形构造，它们往往被当成造山带中的前造山结晶基底或“微陆块”.然而，太平洋俯冲－增生造山带的演化表明，有些高级变质地体可以形成于俯冲背景下弧前增生楔的环境，如中－新生代阿拉斯加 Chugach 增生楔有大量高角闪岩相变质岩组成(Scharman *et al.*，2012；Bruand *et al.*，2014).青藏高原北缘和中亚造山带存在大量高级变质地体，这些地体曾被认为前寒武纪古老陆块.随着精细野外构造解析和高精度年代学工作的开展，这些造山带中的很多高级变质地体被证明形成于古生代甚至中生代，众多变质地体被解体为大洋俯冲过程形成的弧前增生楔残片或岛弧根带组分(Xiao *et al.*，2005；Sun *et al.*，2008；Song *et al.*，2013，2016).

例如西昆仑库地高级变质地体主要由片麻岩和片岩组成，传统上被认为是前寒武纪微陆块.高精度年代学研究表明这些片麻岩中存在原岩为泥盆纪的副变质岩，与区域上火山岩和辉长岩的年龄相匹配.其逆冲叠瓦构造样式和形成时代表明这些片麻岩是大洋俯冲过程形成的弧前增生楔的一部分(Xiao *et al.*，2005).

阿尔泰地区存在大量高级变质杂岩，其中以哈巴河群最具代表性，出露于阿勒泰－清河一带，主要岩性组成为片麻岩、混合岩、角闪片岩、糜棱岩、混合岩化花岗岩及片麻状花岗岩等.根据大理岩中微古化石资料和片麻岩中获得的元古代 Sm-Nd 等时线年龄，李会军等(2006)认为存在阿尔泰前寒武纪微

陆块.然而，最近一系列对片麻岩的高精度定年显示这些变质岩实际上形成于寒武纪至泥盆纪，阿尔泰属于古亚洲洋向西伯利亚板块俯冲形成的活动大陆边缘（Long *et al*., 2007; Sun *et al*., 2008）.根据高温变质作用时代和 Hf 同位素变异特征，Sun *et al*.(2009)和 Jiang *et al*.(2010)进一步指出泥盆纪高级变质杂岩形成于洋中脊俯冲环境.

位于天山和阿拉善之间的北山地区存在大量以片麻岩—片岩组成的变质地体，统称为“北山杂岩”或者“敦煌岩群”，主要岩性包括花岗片麻岩、黑云斜长片麻岩、变粒岩、石英岩、石榴云母片岩、大理岩等.前人根据区域地质对比以及在这些片麻岩中获得的 Sm-Nd 等时线年龄和锆石 U-Pb 上交点年龄，认为北山地区存在大量太古代至古元古代变质基底，并据此认为北山存在明水—旱山微陆块、马鬃山微陆块和柳园—穿山驯古陆（左国朝和李茂松，1996；魏学平等，2000；左国朝等，2003；孙新春等，2005）.详细的野外地质解析和高精度年代学研究表明北山地区绝大部分高级变质杂岩的原岩形成于古生代（Song *et al*., 2013, 2014, 2016），并不是前人认为的前寒武纪结晶基底.此外，还有一些变质杂岩岩性组成非常复杂，如北山中部勒巴泉变质杂岩，不仅包括长英质片麻岩和云母石英片岩，还存在变质硅质岩、变质基性岩、大理岩等原岩来自俯冲大洋板片的岩石.变质硅质岩和大理岩等以构造岩块的形式位于强烈剪切变形的云母石英片岩基质之中，构成“岩块”—“基质”构造混杂特征.同时该变质杂岩发育多种形态的褶皱构造（包括紧闭褶皱、不对称褶皱、宽缓褶皱）及韧性剪切变形等多期次构造叠加，这些变质杂岩与大洋俯冲形成的增生杂岩具有相似的岩石组成和构造变形样式（Song *et al*., 2014）.根据云母石英片岩碎屑锆石年代学和穿切变质杂岩的未变形中性岩脉，限定其变形发生于～424～280 Ma，属于古生代弧前增生杂岩（Song *et al*., 2014）.

在兴蒙造山带，存在以锡林浩特群为代表的锡林郭勒杂岩，包括变质沉积岩、变质基性—超基性岩和长英质变质岩，变质程度达到角闪岩相.该变质杂岩长期以来被认为是组成锡林郭勒微陆块的前寒武纪基底岩系（邵济安，1991；Dalziel, 1992, 1997; Dalziel *et al*., 2000；张臣和吴泰然，2001）.然而，后来的研究相继在这些变质杂岩中获得了古生代的锆石 U-Pb 年龄，证明锡林郭勒杂岩至少部分形成于古生代造山过程.详细的年代学研究表明锡林郭勒杂岩的原岩是新元古代沉积于西伯利亚南缘的活动大陆边缘组分，其混合岩化和变质作用发生于452±5 Ma，是古亚洲洋向北俯冲形成的岩浆弧的组成部分，记录了中亚造山带长期增生过程（Li *et al*., 2011）.

由此可见，增生造山带中的高级变质地体具有多种成因.有些变质地体可能是古大陆裂解形成的微陆块条带（continental ribbon）或大陆碎片，如吉尔吉斯天山和图瓦—蒙古构造带存在一些中元古代甚至更老的变质杂岩（Levashova *et al*., 2011; Kröner *et al*., 2017），它们往往作为更年轻的岛弧的基底，并为增生楔和弧前盆地提供物源.有些变质地体可能是由于洋中脊俯冲导致的异常热形成的高温变质作用的产物，如阿拉斯加 Chugach 变质地体（Scharman *et al*., 2012）.还有些变质地体属于弧前增生杂岩深部物质或岛弧根带的组成，如北山造山带大部分变质杂岩属于古生代增生造山的产物（Song *et al*., 2013, 2014, 2016）.对这些高级变质地体的形成时代、构造变形和大地构造属性的正确厘定是解剖增生造山带结构和增生造山机制的基础.

5　增生方式与增生构造古地理

在时空格架上，增生型造山带往往具有向大洋方向侧向迁移的特征（Taira, 2001）.除增生楔呈现由岛弧向大洋方向逐渐变年轻以外，岩浆前锋（magmatic front）与壳幔相互作用的产物也具有（向洋）侧向迁移的特征（Xu *et al*., 2006, 2009）.增生造山作用过程中一个或者多个不同性质的连续块体在核心大陆边缘发生靠岸（docking），则靠外侧新一轮增生过程又将启动（图 1）.

与增生楔连续增生过程不同，地体拼贴或者不同性质块体“靠岸”（docking）也是增生造山带重要的增生过程.地体拼贴增生（terrane accretion）是指不同性质的连续单元，即由断层分割的、不同地质历史的地质体（Coney *et al*., 1980; Ben-Avraham *et al*., 1981; Schermer *et al*., 1984）拼贴到一个核心大陆边缘（host continent）.地体分析概念（Terranology）强调相邻地质体不同的地质历史，并有系统的沉积—构造分析流程（Ben-Avraham *et al*., 1981; Schermer *et al*., 1984; Nokleberg *et al*., 2000）.

虽然地体分析对地质体尺度上没有严格的定义，在弧前增生楔的发育过程中，确实会卷入尺度较大、密度较轻的连续地质体（buoyant objects），如洋底高原、大洋岛弧、大洋岛屿、海山或者其他性质的

块体（Cloos，1993）．

这些连续地质体卷入增生楔会改变组成及变形－变质条件，形成新的沉积－构造－岩浆－变质组合．如果这些连续地质体卷入增生楔后被肢解，可能形成大规模的混杂岩或者成为增生楔的一部分，增生楔持续发展．如果难以肢解，则可能会暂时阻塞（chock）俯冲作用，并进一步导致俯冲带向洋跳跃迁移，但不影响整体增生过程的持续发展．

增生型造山带在其演化过程中多具有多岛海古地理格局（Hamilton，1979；Sun *et al*．，1991；Hall，2002；Xiao *et al*．，2003，2004，2005），在增生造山过程中发生大规模山弯构造（oroclinal bending）（Şengör *et al*．，1993；Şengör and Natal'in，1996；van der Voo，2004；van der Voo *et al*．，2006；Xiao *et al*．，2015，2018）．

现今欧亚大陆东南缘是欧亚板块、印度－澳大利亚板块以及太平洋－菲律宾海板块等发生复杂相互作用形成的增生型造山带，形成了典型的多岛海增生格局（Hall，2009）．其现今构造格局是太平洋和印度洋在中－新生代向巽他古陆（Sundaland continent）发生持续俯冲的结果，多板块相互作用引起的走滑、挤压、拉伸形成了多海沟俯冲带、多岛弧和多盆地构成的复杂沟－弧－盆系统．同时，俯冲板块的后撤形成了大型山弯构造如班达弧（Banda arc）山弯构造（Spakman and Hall，2010）．

澳大利亚东部的西南太平洋俯冲－增生造山系统则是由西太平洋板块向印度－澳大利亚板块俯冲形成的多岛海增生造山系统（图 8）．太平洋板块向东幕式后撤导致俯冲带上盘发生大规模伸展形成一系列弧后盆地．在～82～52 Ma 期间，太平洋板块向东后撤了大约 1 200 km，促使了 New Caledonia、South Loyalty、Coral Sea 和 Pocklington 等弧后盆地的打开；第 2 个阶段的大洋后撤发生于渐新世至早中新世，形成了 South Fiji Basin 和 Norfolk Basin 等弧后盆地；晚中新世以来太平洋板块向东的后撤导致了 Lau Basin 弧后盆地的打开（图 8）（Schellart *et al*．，2006）．

地中海地区是另一典型的多岛海增生造山系统（Civile *et al*．，2015），多个俯冲带的共同作用形成了东地中海弧、中地中海系统和西地中海弧（Royden and Faccenna，2018）．亚德里亚板块（Adria Plate）向欧洲板块的挤入及俯冲板块的后撤和撕裂共同导致了大量山弯构造的形成，包括 Gibraltar Orocline、Calabrian Orocline、Aegean Orocline、Cyprus Orocline 等（Rosenbaum，2014；van Hinsbergen *et al*．，2014）．

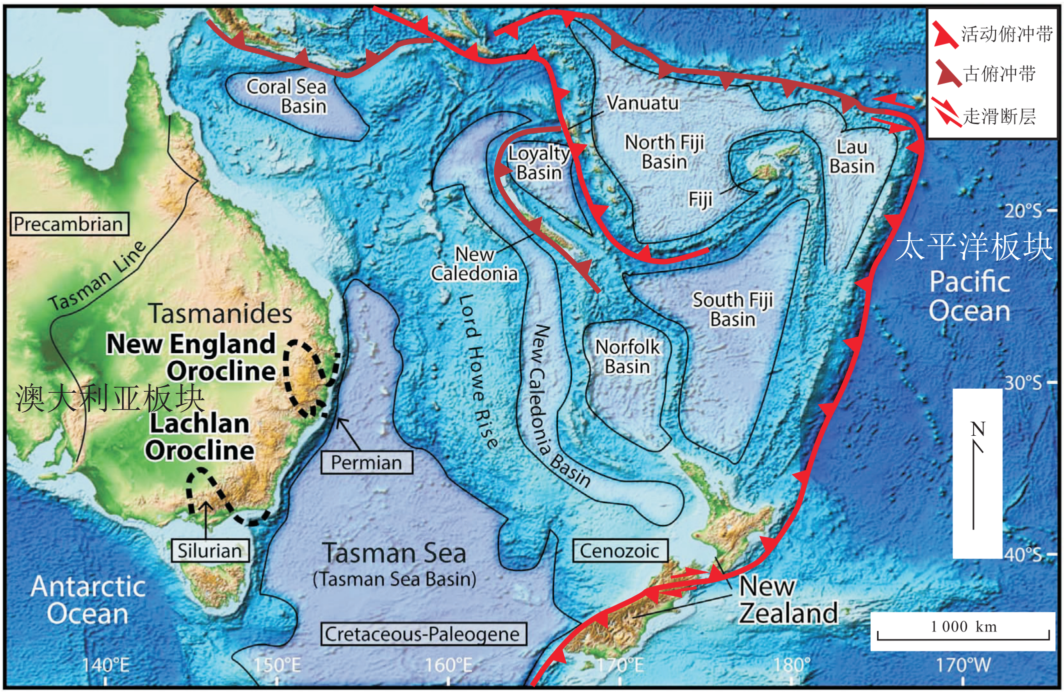

图 8　澳大利亚东部西南太平洋多岛海增生造山系统

Fig.8　The southwestern Pacific archipelagic accretionary system to the east of Australia

修改自 Schellart *et al*．（2006）；Xiao *et al*．（2018）

古地磁和古生物资料显示，中亚造山带的演化过程中存在与现今东南亚俯冲－增生系统类似的多岛海构造格局(Windley *et al*., 2007; Xiao *et al*., 2015)，同时形成了哈萨克斯坦和图瓦－蒙古两大山弯构造(Şengör and Natal'in, 1996; Xiao *et al*., 2015).增生型造山带演化过程中的多岛海古地理格局和山弯构造的形成往往与俯冲板块向大洋方向的后撤导致的弧后伸展裂解有直接关系(Faccenna *et al*., 2004; Schellart *et al*., 2006; Xiao *et al*., 2018).

6　增生型造山带大地构造单元解剖

增生造山作用具有长期演化的复杂历史，经后期构造作用改造和叠加后出现更为复杂的图式.已有的研究工作表明，增生造山作用以其独特的侧向增生和垂向增生过程为主要特征，动态地发育弧前增生、弧后扩张与增生弧－增生楔拼贴等复杂造山作用(Xiao *et al*., 2002, 2003, 2008; 肖文交等, 2006, 2008)，是威尔逊旋回早期阶段在时空的叠加，对大陆生长具有显著的重要贡献(Cawood and Buchan, 2007).因此，对增生型造山带的构造解析与时空分析必须针对增生型造山带的复杂性与独特性，形成适合于增生型造山带的解剖思路与方法论.

在解剖增生造山带时，“地体分析”不失为一种可行的构造解析方法，特别是在研究基础比较薄弱的地区.但是，简单地把地体之间的界线等同为划分一级大地构造单元的界线的做法有时候就会导致片面的看法.由于增生造山作用往往具有多岛海古地理特征，单一的俯冲带分析难免带来片面认识，从而难以在大区域和大尺度上把握一级大地构造单元分区.因此，构造－古生物地理区划和古地磁分析数据是划分一级大地构造单元界线的关键.

以古地磁、古地理、古生物与古气候等资料为依据，古地理－古生物区划应该成为一级大地构造单元划分界线.只有厘定了一级大地构造单元划分界线后，才能正确地分析核心大陆的主要增生区域，从而成功地解剖沿核心大陆边缘的长期复杂的增生造山作用.Wallace line(Metcalfe, 2006)就是分割东南亚多岛海中不同古地理分区的主要界线.

在中亚造山带的大地构造解剖中，古生物地理区划发挥了重要作用.如志留纪图瓦贝化石广泛分布于西伯利亚克拉通南缘及其周边的蒙古、哈萨克斯坦东部和中国西部地区，但这些地区以南则不存在图瓦贝，从而沿着中国阿尔泰－东准噶尔有一条古地理分界线分割了含有图瓦贝的蒙古－鄂霍茨克动物省和不含图瓦贝的中国－澳大利亚动物省(Rong *et al*., 1995; Xiao *et al*., 2015).石炭－二叠纪期间，东欧克拉通以欧美植物群(Euramerian flora)为特征，西伯利亚克拉通和哈萨克斯坦地体具有共同的安加拉植物群(Angaran flora)，而塔里木克拉通含华夏和欧美植物群(Cathaysian and Euramerian floras)(Guo, 2010)，表明二叠纪时期东欧克拉通已经和天山造山带南缘及塔里木克拉通基本连接在一起.而华北克拉通在石炭－二叠纪时期只含有华夏植物群(Guo, 2010)，表明其与西伯利亚－哈萨克斯坦增生地体相距很远的距离.根据二叠纪安加拉植物群和华夏植物群的分隔和混生特征，Xiao *et al*.(2015)将中亚造山带划分了三大主要造山拼贴体，即北部的蒙古拼贴体，南部塔里木－华北拼贴体及西部哈萨克斯坦拼贴体，这三大增生拼贴体直到中三叠世才最终拼贴在一起形成中亚造山带.

在划分一级大地构造单元界线的基础上，再进行二级大地构造单元及其相互关系的详细解剖.二级大地构造单元及其相互关系的详细解剖有很多方法，包括“地体分析”、“大地构造相分析”与“大洋板块地层学”.

“地体分析”与“大地构造相分析”都是不同的构造分析流派(Robertson, 1994)，实际上都是借助现代海洋板块主要的大地构造背景下形成的主要岩石－构造组合分析，来“将今论古”地分析过去地质历史中的造山作用.但是，无论是“地体分析”，还是“大地构造相分析”，都对不同单元中间的相互关系重视不够，特别是缺乏系统的构造样式解析.

流行于日本岛弧与东南亚多岛海地区的“大洋板块地层学”(Ocean Plate Stratigraphy)(Isozaki *et al*., 1990; Maruyama *et al*., 1997)在解剖俯冲带的结构和演化方面取得了重要成果.但是对平行造山带大规模走滑构造不够重视.平行造山带大规模走滑构造，可以导致大地构造单元的肢解与叠覆，出现复杂多解性.应对造山带中的大规模走滑构造进行详细解剖，从时空特征上排除或者评估它们对构造古地理恢复的贡献与作用.由于增生型造山带的独特演化过程，几乎卷入增生造山作用的各种组分都已经呈现“无序”或者“混杂”状态，特别是宽阔增生楔的广泛发育，单纯的“大洋地层学分析”可能产生误导.

但是，“地体分析”、“大地构造相分析”与“大洋板块地层学”包含了分析二级大地构造单元及其相互关系的良好学术思想和方法论.在结合这些方法

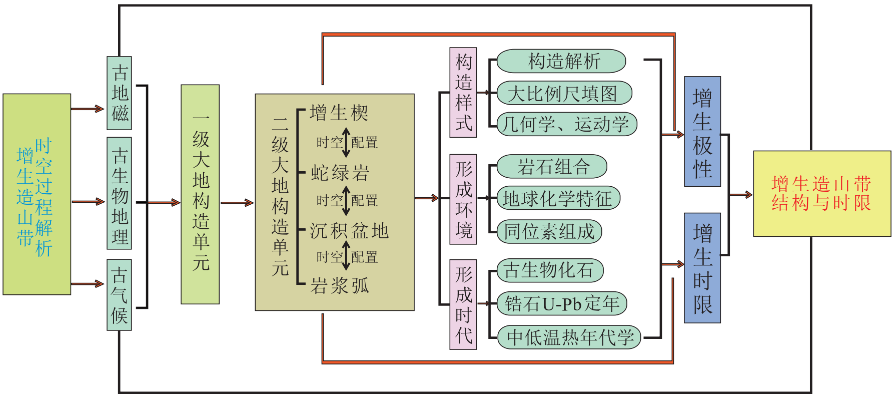

图 9　增生型造山带时空解析思路示意

Fig.9　A sketch diagram illustrating the tectonic analytic methods of an accretionary orogen

论的基础上，增生型造山带解析重点应该通过构造地质解析和关键地区详细的地质填图，结合物质成分和年代学分析，查明增生型造山带中增生杂岩的几何学、运动学及其时代，厘定增生楔的精细结构、构造样式和形成时限，确定增生造山作用的最终拼贴时限，并筛分后期构造作用的叠加与改造.增生型造山带时空解析的主体思路可概略体现于图 9 中.

如在西准噶尔增生过程的解剖中，Zhang *et al*.(2011)通过大比例尺岩性－构造地质填图结合地球化学分析，详细解析了克拉玛依－白碱滩增生楔的物质组成、构造样式和形成时代，据此建立了西准噶尔泥盆纪－石炭纪的增生构造演化过程.通过关键地区详细的地质填图和构造解析，Song *et al*.(2014)在北山中部识别出由云母石英片岩、片麻岩、变质硅质岩、变质基性岩和大理岩等组成的复杂变质杂岩，存在岩块－基质混杂现象，发育褶皱变形和韧性剪切构造，据此厘定勒巴泉杂岩为经历角闪岩相变质的弧前增生杂岩.根据岩浆弧、增生杂岩及蛇绿岩等大地构造相的时空配置关系，Song *et al*.(2015a)进一步建立了北山古生代增生构造演化模式，认为北山存在日本型俯冲－增生系统.

7　增生型造山作用时限分析

关于造山作用时限在国际学术界仍存在很大的争议.目前广泛接受的关于特提斯型大陆碰撞造山带的时限分析，主要依赖于俯冲被动陆缘的前陆盆地、沉积环境由海相向陆相变迁、角度不整合和蛇绿岩或者弧岩浆活动记录(Aitchison *et al*., 2007).而关于环太平洋型俯冲造山带的时限分析，可以由岛弧钙碱性岩浆系列和俯冲－增生杂岩来确定造山作用的时空特征(Robertson, 1994).

然而，与这些造山作用过程解析模型不同，增生造山作用具有前述的特殊性.单纯依赖于前陆磨拉石沉积和蛇绿岩或者弧岩浆活动记录来限定造山作用时限，往往不能全面反映增生造山作用的特征.因此，必须开展增生型造山带时限分析讨论.

在增生型造山带的形成过程中多发育小洋盆，呈现多岛海古地理特征.同时，蛇绿岩的来源非常复杂(Dilek and Furnes, 2011).因此，增生造山作用所产生的蛇绿岩，可能仅仅代表了某一阶段，或者某一局部的洋盆或者岛弧，甚至可能代表大洋岛弧或者弧前盆地的基底.并非所有的蛇绿岩都如经典的碰撞造山模型中所阐述的“两陆夹一洋”的线状展布的蛇绿岩那样，代表了最后消失的大洋盆.所以，蛇绿岩或者蛇绿混杂岩只是增生造山作用的一个组成部分，必须是最年轻的蛇绿岩才有参考意义，而且只能提供一个增生造山作用时限的下限依据.

如北山地区由北向南存在红石山、石板井－小黄山、红柳河－牛圈子－洗肠井、柳园等多条近平行展布的蛇绿混杂岩带，其时代分别为二叠纪、石炭纪、寒武－奥陶纪、二叠纪(Xiao *et al*., 2010; Ao *et al*., 2011).最年轻的蛇绿岩为北山北部的红石山蛇绿岩和南部的柳园蛇绿岩，其形成时代均为二叠纪，因此北山增生造山作用至少持续到二叠纪.在兴蒙造山带，Song *et al*.(2015b)通过总结蛇绿岩的形成年龄，认为该地区洋盆经历了两个阶段的扩张或俯冲过程：400～410 Ma 和 360～220 Ma，据此认为增生造山最终结束于 220 Ma 之后.

弧岩浆活动记录在追踪大洋岩石圈板块俯冲过程的分析中扮演了重要角色.但是，在长期的增生造山过程中，板块之间的相互作用非常复杂.除了以大

洋岩石圈板块俯冲为主导机制外，转换边界、地体斜向拼贴以及俯冲跳跃（反转）等不发育大洋岩石圈板块俯冲的阶段也占有重要地位.在存在俯冲的情况下，地体拼贴以及俯冲跳跃（反转）可能阻塞俯冲作用.同时，大洋岩石圈板块动力学重组（reorganization）也会导致非俯冲的活动型大陆边缘等复杂过程.即便是在以大洋岩石圈板块俯冲为主导机制的情况下，虽然弧岩浆活动记录仍然可以追踪大洋岩石圈板块的俯冲过程，但是存在大洋岩石圈板块低角度或者平缓俯冲作用，特别是可能周期性地发生大规模的洋中脊俯冲作用，在这几种情况下都可能不出现正常岛弧岩浆活动或者出现异常岩浆活动.所以，与蛇绿岩的时限意义类似，弧岩浆活动记录也只是增生造山作用的一个组成部分，必须是最年轻的弧岩浆活动才有参考意义，而且只能提供增生造山作用时限的下限依据.

对科迪勒拉造山带弧岩浆形成时代的统计表明，尽管大洋板块一直持续俯冲，弧岩浆作用表现出显著的幕式发育的特征，晚三叠世、中侏罗世和白垩纪表现为强烈的弧岩浆作用，而早侏罗世和晚侏罗世则出现岩浆平静期（Paterson and Ducea，2015）.显然，早侏罗世和晚侏罗世的弧岩浆平静期并不代表增生造山作用结束或接近停止.

前陆盆地、沉积环境由海相向陆相变迁或者角度不整合曾在经典的阿尔卑斯等碰撞型造山带分析中承担了独特的角色，十分有效地限定了碰撞造山作用时限.然而，在增生造山带中并不发育周缘前陆盆地，而是发育以构造、沉积、变质以及岩浆活动都可能同时或者相互穿时进行的弧前盆地、弧间盆地、弧后盆地、或者弧前上叠盆地.如果仅仅以这些特殊的沉积盆地沉积环境由海向陆变迁或者角度不整合来限定造山作用，则只是得到十分局部的特征.由于增生造山带具有多重俯冲极性，这些复杂的弧前盆地或者弧前上叠盆地是多级、多方位发育.前已提及，在这些复杂盆地中可能出现陆相沉积物，发育多级角度不整合面，并参与增生造山作用（Dickinson，1995）.如果增生造山作用被一个或者多个不同性质的连续块体的靠岸而暂时终结，则靠外侧新一轮增生又将启动（图 1），上述过程将很快重复出现，而新一轮增生又将叠加和改造前期的组合，直到最终不断往外长大的核心大陆与另一个次大陆级别的块体发生碰撞造山作用.因此，与传统的周缘前陆盆地或者磨拉石盆地不同，这些沉积环境由海向陆变迁或者角度不整合不可以单一地用来限定增生事件.同样，必须是卷入增生造山事件中最年轻的角度不整合才有参考意义，而且只能提供一个增生造山作用时限的下限依据.

如现今的南美安第斯造山带，位于秘鲁的 Moquegua 弧前盆地在～50～40 Ma 时候是接近海平面但与大洋分隔的盐湖相沉积，在～35～25 Ma 由于地壳加厚和地表隆起而接受河流相沉积（Decou *et al.*，2011），虽然它们均属于陆相沉积，但显然我们无法根据这些陆相沉积来判定安第斯造山作用在渐新世就已经结束，因为太平洋板块向南美大陆的俯冲现在正在持续进行.类似的例子在现今环太平洋造山带广泛存在.在北美科迪勒拉造山带，亚利桑那地区的 Bisbee 弧间盆地发育碎屑岩、火山岩和火山碎屑岩的互层，并且晚侏罗统至下白垩统砾岩等粗碎屑沉积覆盖在早中侏罗统火山岩之上，该盆地中存在 8 个角度不整合面（Bassett and Busby，2005）.而在墨西哥中西部的弧间盆地，存在晚中新世至第四纪的湖泊相和河流相沉积（Israde-Alcantara and Garduño-Monroy，1999）.这些形成于俯冲带之上的沉积盆地沉积相的演变对我们解剖古老造山带类似的地质过程具有重要启示意义.

在传统的造山作用分析中，伸展与走滑构造、A 型花岗岩以及地幔柱、拆沉等深部动力学过程多被厘定为“造山后”（post-orogenic），这些构造或者动力学记录的发育时间被广泛应用于“造山后”的时限厘定.这些组合的出现，有些情况确实有可能是“造山后”环境.然而，这些组合并非“造山后”环境所特有.例如，在弧前俯冲环境中，由于板块重组或三联点相互作用，挤压、伸展与走滑构造可以同时存在或者发生沿造山带走向迁移的现象（Noda，2016）.如现今东南亚增生造山系统中存在大量挤压、伸展和走滑变形，形成一系列拉分盆地和弧后盆地（Schellart *et al.*，2006；Hall，2009）.白垩纪期间，安第斯造山带则发育挤压和伸展构造的交替现象（Zapata *et al.*，2019）.现今的地中海俯冲造山体系，同样存在大量的走滑、伸展和挤压变形（Royden and Faccenna，2018）.

A 型花岗岩的形成往往与拉张背景有关，可以产生于不同的大地构造环境（Whalen，1987）.研究表明，在增生造山带的演化过程中，一些“特殊”的俯冲带地质过程可以在俯冲带上盘形成 A 型花岗岩.这些“特殊”地质过程包括洋中脊俯冲、俯冲板块后撤引起的弧后裂解过程.例如，华南早白垩世 A 型花岗岩被认为是古太平洋洋脊俯冲的产物（Li *et* *al*.，2012).新西兰泥盆纪 A 型花岗岩是大洋向冈瓦纳大陆东南缘发生俯冲后撤形成的伸展构造的产物（Turnbull *et al*.，2016).拉克兰造山带也存在弧后伸展过程形成的 A 型花岗岩（Collins *et al*.，1982).

研究表明，地幔柱可以非定向选择大陆岩石圈、大洋岩石圈板块或者增生造山带，分别可形成大陆溢流玄武岩、大洋高原（热点）或者阿拉斯加型基性－超基性杂岩组合（Taylor，1967；James，1971；Taylor *et al*.，1994).同时，拆沉、板片断离等深部动力学过程如今正在环太平洋地区广泛发育.但是，它们并非碰撞后的专属产物.例如在俄罗斯远东及我国黑龙江省地区，环状阿拉斯加型超基性杂岩及基性－超基性岩墙侵入到侏罗纪增生杂岩中.在新疆北山存在二叠纪的阿拉斯加型杂岩体，其地球化学属性显示具有岛弧岩浆的演化趋势（陈毓川等，2004；艾永亮等，2005；Ao *et al*.，2010).而太平洋－法拉隆洋脊与北美大陆边缘相互作用的过程中导致了俯冲板片断离形成了与海沟平行展布的板片窗（Michaud *et al*.，2006).

显而易见，在增生造山带中伸展与走滑构造可以贯穿整个造山过程，地幔柱、拆沉等深部动力学过程并不排斥增生造山作用；它们并非具有“造山后”的标志性意义.如果把伸展与走滑构造、A 型花岗岩以及地幔柱、拆沉等深部动力学过程简单地等同于“后造山”环境，则可能会导致片面认识甚至相反的结论.

总之，在分析增生造山作用的时限时，必须全面分析所有可能找到的时限证据.根据增生造山作用长期演化的复杂特征，在一级大地构造单元的古地理分区的总体限定下，应注意寻找卷入增生事件中最老的组分来限定增生造山作用开始的时限.如大洋岩石圈俯冲过程中形成的最老的高压变质岩，最老的弧岩浆作用年龄，及卷入增生造山作用最老的角度不整合面等，这些判别标志可能提供或者略晚于增生造山作用开始的时限（表 1).

关于增生造山作用的结束时限，应注意寻找卷入增生事件中最年轻的地质体或者组分，它们提供了该期增生事件时限的下限.卷入增生造山事件中最年轻的角度不整合，以及最年轻的高压－低温变质事件，可能提供了最晚增生事件时限的下限；而未卷入增生造山事件中最老的角度不整合和褶皱冲断带中最晚的沉积物时代则可能提供了最晚增生事件时限的上限（表 2).

表 1　增生造山作用开始时限的识别标志

Table 1　Discrimination criteria of the start of accretionary orogenesis

上限或准同时
1.大洋岩石圈消减过程中形成的最老的高压变质年龄
2.大洋岩石圈消减过程中形成的最老的高温变质年龄
3.岩浆弧活动时期最老的火山岩的年龄或地层时代
4.岩浆弧活动时期最老的花岗岩的生成年龄
5.增生弧中弧火山岩和花岗岩的最老年龄
6.与弧相关盆地中大洋岩石圈岩石的最老年龄
7.大型剪切带中最老的新生矿物的年龄
8.卷入增生造山作用最老角度不整合面

表 2　增生造山作用结束时限的识别标志

Table 2　Discrimination criteria of the end of accretionary orogenesis

下限	上限
1.混杂带中大洋岩石圈火成岩块的最小年龄	1.未卷入增生造山作用最老的角度不整合面
2.混杂带中深海沉积物的最年轻的生物时代	2.褶皱冲断带中最晚的沉积物时代
3.混杂带中最年轻的岩块年龄	
4.混杂带中基质最小时代	
5.大洋岩石圈消减过程中形成的最小的高压变质年龄	
6.大洋岩石圈消减过程中形成的最小的高温变质年龄	
7.岩浆弧活动时期最晚的火山岩的年龄或地层时代	
8.岩浆弧活动时期最晚的花岗岩的生成年龄	
9.增生弧中弧火山岩和花岗岩的最小年龄	
10.与弧相关盆地中大洋岩石圈岩石的最小年龄	
11.大型剪切带中最年轻的新生矿物的年龄	
12.卷入增生造山作用最年轻角度不整合面	

8　结语

由于增生造山作用长期演化的复杂特征，本文所阐述的关于增生造山作用及其时限研究思路与标志难免挂一漏万.特别是增生造山作用结束时限一直是国际造山带研究颇具争议的问题，仍需大量的研究工作成果来充实提高.随着全球关于增生造山带研究的不断积累，一定会出现更加完善的研究思路与标志体系.

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