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论 文

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新特提斯单向俯冲的动力学机制

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摘要 新特提斯洋向北单向俯冲的机制涉及两个核心问题, 分别是南侧冈瓦纳被动大陆的不断裂解和拼贴到欧亚大陆南缘陆块诱发的俯冲起始. 本文统计了大火成岩省的分布规律, 发现200~80 Ma期间, 与地幔柱相关的大火成岩省主要分布于南半球, 暗示该时期南半球地幔温度高于北半球地幔温度. 在南北半球地幔温差和地幔柱/大火成岩省作用下, 引起上覆岩石圈抬升、破裂, 结合新特提斯洋的北向俯冲, 共同诱发冈瓦纳大陆的多期裂解. 由于南北半球地幔温差会造成地幔柱头岩浆向北扩散并与新特提斯洋中脊发生相互作用, 在特殊情况下, 会引发原来大洋中脊的堵塞和跃迁, 形成新的洋中脊, 促进了陆块不断向北漂移. 在古特提斯洋闭合后洋壳持续俯冲引发的应力作用下, 欧亚大陆南缘具有高含水特性的洋陆过渡带率先破裂并产生向北的俯冲起始. 驱动新特提斯大洋岩石圈持续向北俯冲的动力, 除俯冲板片的拖曳力/重力外, 还应该包含南半球高地幔温度和洋中脊产生的向北推力.

关键词 新特提斯洋, 单向俯冲, 俯冲起始, 南北半球地幔温差, 欧亚大陆南缘富水岩石圈

尽管地球表面大约173000 TW的能量主要来自太阳辐射[1], 但地球的构造运动则主要源于地球内热和物质分异的驱动, 如温度差和成分差异都能引起密度差异, 从而产生浮力差异, 这是造成不同尺度地幔对流的根源. 热对流需要存在较大温差的热边界层, 地球的岩石圈和核幔界面分别为地幔对流的冷热边界层, 冷边界层冷却地幔, 驱动了板块构造; 热边界层冷却地核, 驱动了地幔柱. 板块运动驱动力一直是地球科学研究的热点, 传统观点认为, 俯冲板片拖曳力是造成海底扩张和板块运动的主要动力, 比俯冲板片拖曳力小一个量级的洋中脊推力只在板块俯冲的特定阶段起重要作用. 尽管地幔柱可能诱发大陆裂解, 但难以驱使大陆持续漂移并维持洋盆不断扩张[2~6].

板块构造理论认为, 扩张脊和转换断层的形成是被动的过程, 汇聚边界(俯冲带)是主动的, 然而汇聚边界俯冲如何起始却是板块构造和威尔逊旋回理论的薄弱环节[7]. 俯冲起始是指俯冲带从无到有并发育为成熟俯冲体系之前的短暂过程, 它是洋盆消减的必要条件, 是威尔逊旋回必不可少的关键一环. 研究俯冲起始对理解新特提斯演化极为必要, 但由于俯冲起始非常短暂, 且本身是一个破坏过程, 目前我们对其成因及机制知之甚少. 一般认为, 俯冲起始可能发生在两个部位, 一是大洋内部的薄弱带(死亡的洋中脊、转换断层、破碎带等), 另一个是洋陆过渡带(被动陆缘). 无论是大洋内部, 还是被动陆缘的俯冲起始, 都既可能是自发的, 也可能是诱发的. 微陆块、洋底高原或火山弧到达海沟时会引起板内应力变化, 导致大洋岩石圈重力坍塌或俯冲带的变化甚至跃迁. 针对微陆块/海底高原与大

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陆碰撞诱发的俯冲带跃迁问题, 数值模拟研究揭示, 在应力集中的被动陆缘易发生俯冲起始或俯冲跃迁. 俯冲带跃迁滞后于碰撞拼合大约10 Ma时间尺度[8]. 潘吉亚(Pangea)超大陆与特提斯洋形成之后, 冈瓦纳大陆不断破裂, 先后形成新特提斯洋、印度洋等一系列大洋盆地, 依此向北俯冲、闭合、碰撞, 形成了特提斯造山带[5,9~13]并产生大量的岩浆岩和矿床[14~18]. 值得注意的是, 与现今太平洋两岸板块双向俯冲明显不同, 新特提斯洋主要是多陆块在不同时代向北单向俯冲[5,19]. 在新特提斯洋主大洋岩石圈向北俯冲的大背景下, 可能存在局部向南的俯冲. 例如, Zhu等人[20]认为班公-怒江洋向南俯冲并引发雅鲁藏布江洋的打开. 但这种局部向南的俯冲不影响特提斯岩石圈整体向北俯冲的格局. 本文重点从特提斯区域演化历史来探讨向北单向俯冲的动力学机制. 为便于特提斯构造域的东西向对比, 本文采用特提斯两分方案, 将基梅里陆块群南侧的特提斯洋定义为本文所界定的新特提斯洋.

1 冈瓦纳大陆不断裂解的原因

1.1 地幔柱对大火成岩省和冈瓦纳大陆裂解的作用

地幔柱是地球上最重要的垂向运动[21], 甚至在板块构造体制开始之前, 就是地球内部最主要的运动方式之一[22~24]. 地幔柱往往会形成直径>1000 km的大火成岩省[21,25,26], 自潘吉亚形成以来(~320 Ma), 位于太平洋和非洲下地幔底部的大型剪切波低速省(分别称之为Jason和Tuzo)就已经存在, 其位置基本保持稳定[27~29], 在地表观测到的80%大火成岩省主要由分布在Jason和Tuzo周缘的地幔柱产生. 在对潘吉亚超大陆期间地幔柱与下地幔下部大型剪切波低速省边缘存在对应关系研究的基础上, Torsvik等人[30,31]进一步论证了至少500 Ma以来, Jason和Tuzo在下地幔下部的位置一直保持不变, 在它们周缘对应的地表可识别出30个大火成岩省[31]. 其中, 200 Ma之前和80 Ma以来喷发的大火成岩省主要分布在北半球, 与此形成鲜明对比的是, 200~80 Ma之间喷发的大火成岩省则主要分布在南半球(图1). 在新特提斯洋主要演化阶段(200~80 Ma), 全球地幔柱主要分布在南半球(冈瓦纳大陆及南太平洋下方), 俯冲带则集中在欧亚大陆南缘, 中生代从冈瓦纳裂解的陆块运动轨迹呈逆时针螺旋状向北半球欧亚大陆南缘汇聚. 下地幔Jason和Tuzo两个大型剪切波低速省对应的上地幔温度比全球地幔平均温度要高, 非洲广泛分布的侏罗纪热点说明, 该时期冈瓦纳上地幔是异常热的, 其热量是由其下Tuzo提供的. 同时, 地震学和数值模拟证据均指示主体位于南半球的Jason和Tuzo大型剪切波低速省具有高的温度[35,36]. 侏罗纪-白垩纪(特别是200~80 Ma期间)是全球优质烃源岩最发育的时期, 探明可采油气储量占全球油气可采储量的48.1%. 值得注意的是, 侏罗纪-白垩纪, 北半球以石油为主, 而南半球以天然气为主. 这些证据都说明中生代南半球地幔温度高于北半球地幔温度[36].

在新特提斯洋的逐步扩张过程中, 由于Argo Margin地幔柱的作用(~155 Ma), 东冈瓦纳北缘分裂出西缅甸和印度尼西亚两个微陆块[37]; 大约在136和132 Ma, Gascoyne和Bunbury地幔柱分别上升到东冈瓦纳大陆岩石圈, 引发印度陆块从冈瓦纳大陆北缘裂解. 大约134 Ma, Tristan地幔柱上升到西冈瓦纳大陆岩石圈, 形成Paraná-Etendeka大火成岩省, 导致非洲-阿拉伯陆块与南美洲陆块分离. 随后, 冈瓦纳大陆进入快速裂解时期[38]. 地幔柱上涌可以导致上覆岩石圈受热膨胀, 密度降低[26]. 在大的地幔柱喷发前, 数以百万立方千米的岩浆聚集在岩石圈之下. 岩石圈地幔橄榄岩的密度约为3300 kg/m^3, 而玄武岩浆的密度约为2700 kg/m^3, 由于岩浆的密度比岩石圈地幔的密度低约20%, 对岩石圈产生强烈的顶托作用, 引发上覆岩石圈千米级的大幅度隆升, 这一现象在峨眉山大火成岩得到观察事实的支持[39,40]. 值得注意的是, 地幔柱作用的直接结果是导致上覆板块隆升, 并形成薄弱带, 甚至裂解, 但并非造成板块漂移. 板块的漂移需要在地幔柱形成薄弱带或裂谷的基础上由俯冲带的拖拽力驱动. 冈瓦纳大陆北缘不同时代裂解出的陆块在古/新特提斯洋壳俯冲拖拽下, 向北逐渐漂移. 新特提斯洋演化过程中正是这种地幔柱导致的冈瓦纳大陆裂解以及先存俯冲板片的拖拽, 使得裂解的陆块不断向北漂移, 新的洋壳不断生长, 新的洋中脊间歇性出现.

有必要指出的是, 冈瓦纳快速裂解的这一阶段, 其周缘也存在不同方向的俯冲带, 比如澳大利亚和南美分别被古太平洋的不同板块俯冲. 正是这些俯冲带的作用, 导致南美陆块向西漂移, 澳大利亚陆块向东漂移[41]. 从冈瓦纳裂解的其他陆块也是在新特提洋向北俯冲拖拽力的作用下, 持续向北漂移. 在此过程中还有一类特殊的现象, 即洋中脊的跃迁. 通常认为, 大洋扩张中心跃迁是由板块速度变化、先存的薄弱部位、弧后拉张等地质过程触发. 实际上, 在特定的地幔对流状

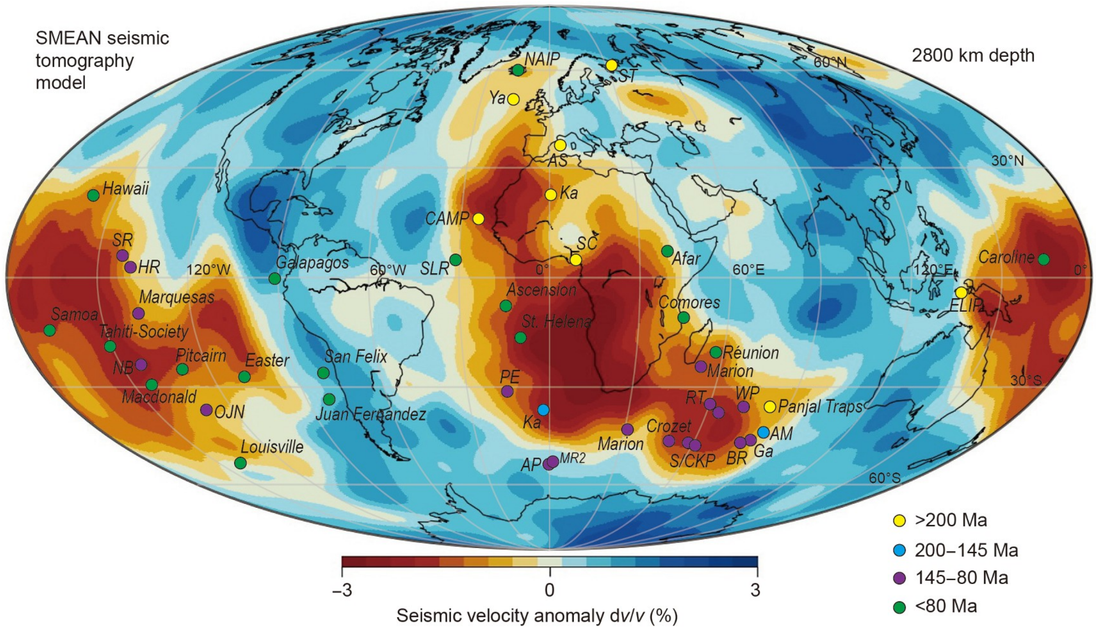

图 1 (网络版彩色)板块重建显示大火成岩省喷发时所处的位置. 200~80 Ma之间的大火成岩省(large igneous provinces, LIPs)均在南半球喷发. 大型剪切波异常省(large low-shear-velocity provinces, LLSVP)数据引自文献[32], LIPs数据引自文献[31]. SR和HR位置是基于文献[33]最新的太平洋板块重建结果. CRB: 哥伦比亚河玄武岩(15 Ma), Afar: 阿法尔地幔柱(31 Ma), NAIP: 北大西洋大火成岩省(61 Ma)[34], Réunion(留尼旺地幔柱): 65 Ma, SLR: 塞拉利昂隆起(73 Ma), Ma: 马达加斯加地幔柱(87 Ma), Marion: 马里恩地幔柱(90 Ma), BR: 布罗肯海岭(95 Ma), HR: 赫斯隆起(100 Ma), CKP: 中凯尔盖朗高原(100 Ma), AP: 厄加勒斯高原(100 Ma), NB: 瑙鲁玄武岩(111 Ma), SKP: 南凯尔盖朗高原(114 Ma), RT: 拉杰马哈尔玄武岩(118 Ma), MR1: 麦哲伦隆起(121 Ma), OJN: 翁通-爪哇大火成岩省(123 Ma), WP: 瓦拉比高原(124 Ma), MR2: 毛德海隆(125 Ma), BB: 班伯里玄武岩(132 Ma), PE: 巴拉那艾腾得卡(134 Ma), Ga: 加斯科恩(136 Ma), SR: 沙茨基隆起(144 Ma), AM: 阿尔贡边缘(155 Ma), Ka: 卡鲁(183 Ma), CAMP: 中大西洋大火成岩省(201 Ma), ST: 西伯利亚大火成岩省(252 Ma), ELIP: 峨眉山大火成岩省(260 Ma), 潘佳玄武岩: ~290 Ma, SC: 中斯卡格拉克(297 Ma), Ya: 雅库茨克(360 Ma), AS: 阿尔泰-萨岩(400 Ma), Ka: 咔咔仁济(510 Ma)

Figure 1 (Color online) Locations of large igneous provinces during their eruption revealed from paleogeographic reconstructions. Large igneous provinces in the age of 200–80 Ma are mainly located in the south hemisphere. Data of large low-shear-velocity provinces (LLSVP) are from Ref. [32]. Data of large igneous provinces (LIPs) are from Ref. [31]. Locations of SR and HR are based on the new reconstruction of the Pacific Ocean [33]. CRB: Columbia River Basalts (15 Ma), Afar: 31 Ma, NAIP: North Atlantic Igneous Province (61 Ma)[34], Réunion: 65 Ma, SLR: Sierra Leone Rise (73 Ma), Ma: Madagascar (87 Ma), Marion: 90 Ma, BR: Broken Ridge (95 Ma), HR: Hess Rise (100 Ma), CKP: Central Kerguelen Plateau (100 Ma), AP: Agulhas Plateau (100 Ma), NB: Nauru Basalts (111 Ma), SKP: South Kerguelen Plateau (114 Ma), RT: Rajhmahal Traps (118 Ma), MR1: Magellan Rise (121 Ma), OJN: Ontong Java Nui (123 Ma), WP: Wallaby Plateau (124 Ma), MR2: Maud Rise (125 Ma), BB: Bunbury Basalts (132 Ma), PE: Paraná-Etendeka (134 Ma), Ga: Gascoyne (136 Ma), SR: Shatsky Rise (144 Ma), AM: Argo Margin (155 Ma), Ka: Karroo (183 Ma), CAMP: Central Atlantic Magmatic Province (201 Ma), ST: Siberian Traps (252 Ma), ELIP: Emeishan Large Igneous Province (260 Ma), Panjal Trap: ~290 Ma, SC: Skagerrak Centred (297 Ma), Ya: Yakutsk (360 Ma), AS: Altay-Sayan (400 Ma), Ka: Kalkarindji (510 Ma)

态下, 地幔柱也会诱发大洋扩张脊的死亡与跃迁. 洋中脊的跃迁与不对称的洋壳扩张或地幔柱-洋中脊相互作用有关[42]. 地球动力学数值模拟显示, 若不考虑地幔柱岩浆对上覆板片的热侵蚀, 当地幔柱和初始裂谷距离很近时, 可以形成对称的大洋扩张, 而随着二者距离的增加, 会导致大洋非对称扩张; 而当地幔柱和裂谷距离太远, 导致地幔柱和裂谷的相互作用很弱, 地幔柱对上覆板块的影响近乎忽略不计, 洋壳的扩张则会沿着初始裂谷处进行[43]. 当考虑地幔柱岩浆对岩石圈底部的热侵蚀, 上覆岩石圈由于热侵蚀而导致强度降低, 会引发裂谷向地幔柱位置跃迁[43]. 例如, 马里恩(Marion)地幔柱的作用导致印度-马达加斯加在~90 Ma的裂解[44,45]和Mascarene洋盆逐渐打开, 以及印度陆块向北漂移过程中沿洋中脊发育非对称分布的磁条带[46]. 留尼旺(Réunion)地幔柱大约于75 Ma上升到印度大陆岩石圈底部, 诱发从印度大陆北缘裂解出微陆块——特提斯喜马拉雅[47]. 留尼旺地幔柱还使得印度陆块岩石圈减薄、强度显著降低, 导致塞舌尔(Seychelles)微陆块在62 Ma从印度陆块裂解, Mascarene洋盆原先的洋中脊停止发育, 洋中脊跃迁至塞舌尔微陆块和印度陆块之间的Laxmi洋脊[42,46], 进一步使印度陆块向北加速漂移(图2). 在特提斯的长期演化中, 地幔柱的作用有可

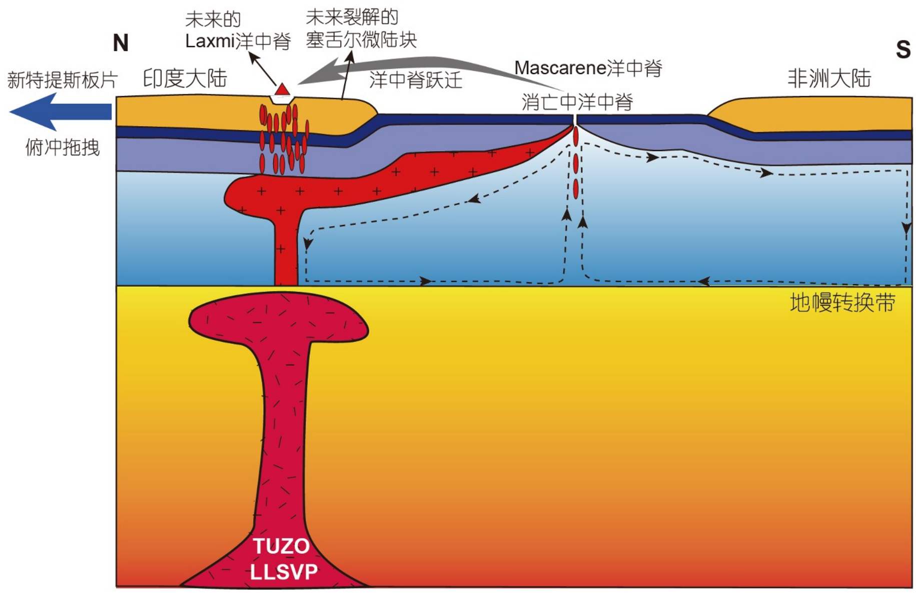

图 2 (网络版彩色)地幔柱诱发的大火成岩省与洋中脊跃迁模式
Figure 2 (Color online) Model of mantle plume induced large igneous province eruption and ridge jump

能诱发洋中脊的跃迁，这也是维系从冈瓦纳大陆裂解的陆块不断向北漂移的原因之一.

板块构造和地幔柱是地球上两大主要的构造体系，两者既相对独立，又紧密联系，控制着地球上主要的地质过程. 地幔柱源区与俯冲板块再循环有关[48~50]，而与地幔柱头相关的大火成岩省的喷发往往导致上覆板块的巨大改造，引起破裂，形成新的扩张中心[25,26,39,40]，甚至堵塞原来的大洋中脊和俯冲带. 地球动力学模拟显示，地幔柱与洋脊相互作用影响的距离可以达到1000 km[51]. 例如，Ontong Java大火成岩省的喷发导致原来的洋中脊死亡，新的扩张中心移到了Ellice Basin和Osbourne Trough[51]. 据此，我们认为，冈瓦纳大陆的不断裂解以及持续向北漂移与地幔柱/大火成岩省和南北半球地幔温差存在密切的相关性.

需要指出的是，虽然我们强调地幔柱在冈瓦纳大陆裂解过程中的重要作用，但关于冈瓦纳大陆裂解机制仍存在不同认识. 例如，由于菲尼克斯板块俯冲诱发的弧后扩张被认为是触发冈瓦纳大陆最终裂解的重要因素[52]. 但弧后盆地伸展可能很难解释冈瓦纳大陆不同阶段的裂解. 首先，晚侏罗世-早白垩世，东、西冈瓦纳的裂解呈北东-南西向，基本与菲尼克斯俯冲带方向垂直，这种正交关系难以用弧后盆地扩张解释. 其次，东冈瓦纳裂解的位置位于大陆中心，菲尼克斯板块的俯冲引起跨越南极洲的东冈瓦纳大陆中心发生裂解，仅依靠弧后盆地扩张可能很难解释. 再次，冈瓦纳每一期次裂解均伴随地幔柱/热点的作用，单纯的弧后盆地伸展无法导致这种地幔柱/热点的持续出现. 因此，我们认为，虽然菲尼克斯板块的俯冲可能在某一或者某些时刻促进了冈瓦纳大陆的裂解，但不是冈瓦纳多期裂解的主因.

1.2 洋中脊俯冲消亡与冈瓦纳裂解的关系

洋中脊俯冲能诱发被动大陆边缘裂解的观点是较早时期提出的概念模型[53]. 万博等人[5]进一步分析了特提斯演化历史，认为这种模型可能在特提斯具有一定的普遍性，然而该模型最主要的问题是缺乏地质实例与动力学模拟. 近年来，他们在伊朗北侧开展的岩石大地构造研究发现，古特提斯洋中脊俯冲具有自东向西迁移的特征，并提出1000 km长的古特提斯洋中脊在约380~360 Ma俯冲至欧亚大陆下方[54]. 该现象与南美地区正在发生洋中脊俯冲的Taitao地区完全可以对比[55]. 洋中脊俯冲之后，连接冈瓦纳大陆的古特提斯洋板片才能开始俯冲，倘若50 km厚的大洋板块俯冲至700 km深，它能够提供1.0 GPa的拉张力[54]. 大部分大陆的强度在0.1 GPa，假设仅十分之一的力能够被传递至冈瓦纳被动陆缘，俯冲提供的拉力足以提供裂解冈瓦纳被动陆缘的应力. 从伊朗的实例来看，自古特提斯洋中脊俯冲后，俯冲板片的长度与冈瓦纳被动大陆边

缘的伸展、热隆升、裂解的实际地质资料较吻合. 最新的地球动力学数值模型对洋中脊俯冲导致被动陆缘裂解过程开展了详细的研究[56,57], 其结果支持洋中脊俯冲和被动大陆边缘裂解有成因联系, 且认同俯冲板片俯冲至地幔过渡带之后开始对被动陆缘起到拉伸作用, 因此洋中脊俯冲之后一段时间, 大陆才开始裂解. 但对于俯冲板片的拉伸是否能使被动陆缘裂解, 不同模型存在差异[56,57].

总而言之, 地幔柱作用和俯冲拖拽作用应该在冈瓦纳大陆裂解中都扮演了重要角色, 目前的研究大多在争论地幔柱还是俯冲起到主导作用. 然而, 还有一种可能性是, 在大陆裂解的不同阶段, 地幔柱和俯冲所起的主导或辅导作用在相互转换. 这些问题在未来值得深入研究.

2 欧亚大陆南缘俯冲起始

特提斯洋近五亿年持续北向俯冲的一个重要原因是, 随着老洋盆的关闭, 在新的欧亚大陆南缘不断出现新的俯冲带. 例如, 基梅里陆块群与欧亚大陆发生碰撞, 导致新的欧亚大陆南缘转变为被动大陆边缘, 新特提斯洋在新的欧亚大陆南缘发生俯冲起始, 特提斯这种俯冲起始可归类为诱发型俯冲起始的俯冲带迁移[7,19,58]. 随着轻的基梅里陆块群到达古特提斯俯冲带并与欧亚大陆发生碰撞, 古特提斯洋闭合. 随后, 在古特提斯俯冲板片拖曳力和南北半球地幔温差共同作用下, 基梅里陆块群和新特提斯洋壳继续向北运动, 并在新特提斯洋陆结合处产生应力集中, 并最终导致欧亚大陆刚形成的洋陆过渡带发生破裂——俯冲起始. 地球动力学模拟显示, 俯冲带跃迁需要弱的被动大陆边缘(先存薄弱带)以及持续汇聚来触发并维持初始俯冲[8,59]. 同时, 碰撞后持续的汇聚需要大约10 Ma的应力积累才能触发俯冲起始[8].

对于基梅里陆块群南侧的俯冲起始, 目前还缺乏系统性研究, 但已有结果显示从东向西穿时俯冲起始. 在特提斯东段, 滇缅泰马陆块晚三叠世(214 Ma)I型花岗岩被认为与新特提斯洋向北的俯冲有关. 拉萨地块南缘冈底斯岩基内形成于205 Ma的二长花岗岩[60]和早侏罗世具有典型弧岩浆作用地球化学特征的花岗岩指示, 冈底斯俯冲早在三叠纪-侏罗纪已经启动[61]. 在特提斯西段, 伊朗新特提斯俯冲的弧岩浆记录最早为187 Ma[62,63]. 假设一个地区俯冲启动, 岩石记录应当从变质作用开始(30~90 km), 随后在弧下深度(100 km)脱水, 导致地幔楔熔融, 形成弧岩浆. 因此, 最老的变质时间更接近俯冲启动的时间. Wan等人[64]对伊朗南侧原岩具有洋中脊玄武岩性质的榴辉岩进行研究, 通过金红石U-Pb定年厘定其峰期变质时代约为190 Ma. 结合变质岩时代和板块破裂所需时间范围(2~20百万年), Wan等人[64]提出新特提斯洋在伊朗地区的俯冲启动时间为212~192 Ma. 上述年龄对比结果可以一定程度说明, 基梅里陆块群南侧俯冲起始是从东向西渐进式发生的, 总体滞后于古特提斯洋的闭合[5].

地球动力学模拟还显示, 相对"湿"的上地幔有利于在岩石圈顶部形成剪切断裂, 并触发俯冲起始[65]. Tuzo大型剪切波异常的长期存在(至少300 Ma已稳定存在)[30]引发地幔柱对冈瓦纳大陆的持续加热, 并导致冈瓦纳大陆岩石圈相对贫水, 不利于俯冲起始, 因此无法在新特提斯洋南侧形成俯冲带. 与之相反, 基梅里陆块群碰撞拼贴的欧亚大陆南缘显生宙以来, 先后经历了多期造山作用, 形成了一系列造山带[66~68]. 造山带的基本特征是大洋板块不断向大陆板块之下俯冲、消亡, 同时将大量的水等挥发分带到地球深部. 将水带入地球深部的最主要矿物是角闪石和蛇纹石. 其中, 蛇纹石水含量可达13%(wt)[69], 在深度200 km以内保持稳定[70,71]. 在~200 km的深度, 蛇纹石脱去部分水, 转化为高压含水相——Phase A($Mg_7Si_2O_8(OH)_6$), 含水量仍可以高达12%[71]. 在大于300 km的深处, Phase A进一步脱水相变为Phase B、Phase C、Phase D等高压含水矿物. 蛇纹岩可以将2%左右的水带到上地幔底部, 这是导致地幔楔和上覆岩石圈水化及成矿的关键[72].

基梅里陆块南侧洋陆过渡带破裂导致的俯冲启始是否与其上地幔富含蛇纹岩有关? 首先, 古特提斯洋长期的俯冲导致欧亚大陆南缘下方软流圈地幔含水量升高. 由于基梅里陆块主要是一些东西向展布的长条形陆块, 南北宽度一般在200~500 km, 碰撞后, 古特提斯大洋岩石圈板片断离, 导致与俯冲带平行展布的基梅里陆块下方地幔含水量的增加和黏滞度降低, 有利于俯冲起始. 其次, 在基梅里陆块裂解过程中, 由于强烈的拉伸作用, 地壳快速减薄且深部地幔不断被抬升至近地表, 也是有利于俯冲起始的另一个因素. 最近的研究表明, 基梅里从冈瓦纳裂解时形成一系列的伸展断层, 导致大量海水渗透到基梅里陆块岩石圈[73], 海水进入地幔时, 发生了广泛的蛇纹岩化. 由于基梅里很快裂离了冈瓦纳, 并漂离地幔上涌高温区, 从而长时间保留了基梅里南侧的蛇纹岩地幔. 上述这些因素共同导致

了欧亚大陆南缘的俯冲起始, 并且要晚于陆陆碰撞.

与欧亚大陆南侧被动陆缘在三叠纪-侏罗纪俯冲起始不同的是, 新特提斯洋内可能在白垩纪形成过新的洋内俯冲带. 例如, 大约在晚白垩世早期, 西缅甸和印度尼西亚两个微陆块漂移到赤道附近, 并与喜马拉雅西构造结附近的科西斯坦-拉达克岩浆弧构成了洋内俯冲体系(图3). 这个时期, 欧亚大陆南侧仍然是主动陆缘, 因此在东特提斯洋发育两条向北的俯冲带(图3). 现有的古地磁证据的确指示该时期, 该处存在一个洋内弧. 最新研究指出, 该洋内弧的产生可能与冈瓦纳下方在该时期形成的大火成岩省推力有关系[74,75].

3 结论

(1) 冈瓦纳大陆下方Tuzo大型剪切波低速省的长期存在(至少300 Ma), 导致晚古生代以来冈瓦纳大陆下方具有高的地幔热流, 持续的地幔上升流引发其周

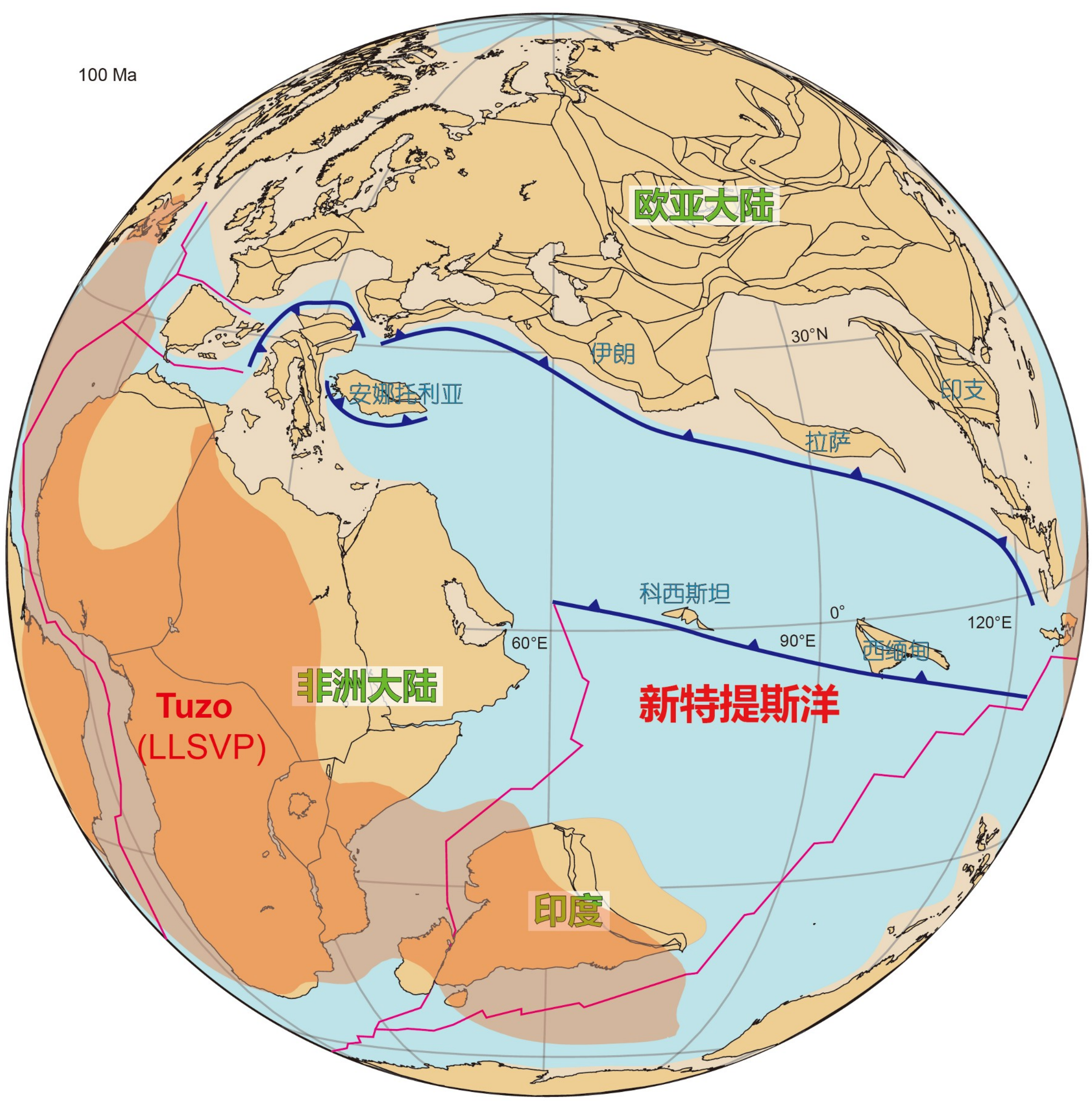

图 3 (网络版彩色)晚白垩世初(100 Ma)古地理重建图, 显示新特提斯洋双俯冲体系. 晚白垩世, 欧亚大陆南缘存在向北俯冲的大陆边缘弧; 位于赤道附近的科西斯坦、西缅甸构成新特提斯洋内岛弧. 为强调主体位于中低纬度的新特提斯洋, 我们采取3D正射投影

Figure 3 (Color online) Late Cretaceous paleogeographic reconstruction (100 Ma) shows double subduction system in the Neo-Tethys Ocean. In the Late Cretaceous, continental marginal arc was situated along the southern margin of the Eurasia continent, and an intra-oceanic arc was located along the Kosistan-West Burma near the equator. For emphasizing the Neo-Tethys Ocean located mainly in the middle-low latitude, we use 3D orthographic projection

缘形成不同时代的地幔柱，对上覆岩石圈产生顶托与抬升甚至裂解．南北半球地幔温差会造成地幔柱岩浆向北扩散并与新特提斯洋中脊发生相互作用，大火成岩省诱发原来大洋中脊的堵塞和跃迁，形成新的洋中脊, 促进了从冈瓦纳裂解的陆块不断向北漂移.

(2) 欧亚大陆南缘不同时代洋陆过渡带不断产生诱发俯冲起始的主要因素可概况为两个原因：特提斯洋持续的俯冲和陆块碰撞导致欧亚大陆南缘下方地幔含水量较高，碰撞后高含水地幔向碰撞块体迁移造成的蛇纹石化以及大陆裂解时期继承的蛇纹岩有利于俯冲起始; 微陆块碰撞后, 持续的推挤力汇聚于欧亚大陆南缘最薄弱的洋陆过渡带.

(3) 地球大约85%的热量是通过板块构造诱发的地幔对流损失的, 只有约10%的热量是通过地幔柱喷发散失[2]. 从冈瓦纳大陆北缘裂解的基梅里陆块群与欧亚大陆南缘碰撞不仅导致古特提斯洋的消亡，同时由于拼贴在大陆边缘外来体的持续俯冲以及高含水特征，还诱发俯冲带的跃迁, 导致新特提斯洋不断向北俯冲, 最终使新特提斯洋闭合．新特提斯主要海沟系统位于欧亚大陆南缘，这就是我们今天看到的阿尔卑斯-喜马拉雅系统的前身. 新特提斯演化过程中, 从冈瓦纳裂解的陆块向欧亚大陆边缘不断增生，短暂的南向俯冲可能与下沉板片的反转或弧后闭合有关，但主大洋长期俯冲方向是向北的, 这与200~80 Ma之间地球南北半球地幔温差是一致的.

(4) 驱动新特提斯大洋岩石圈持续向北俯冲的主要动力是俯冲板片拖曳力/重力，其次是中生代地球南半球高地幔温度和洋中脊产生的向北推力.

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Summary for “新特提斯单向俯冲的动力学机制”

Geodynamics of the one-way subduction of the Neo-Tethys Ocean

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The one-way northward subduction of the Neo-Tethys Ocean involves two essential processes: Persistent rift of blocks from northern margin of Gondwanaland and subduction initiation after collision of drifted blocks of the Eurasian continent. Therefore, uncovering the mechanism of the two processes is a key target to decipher the geodynamics of the one-way subduction of the Neo-Tethys Ocean. From a compilation of large igneous provinces (LIPs), we find that plume related Mesozoic LIPs are mainly distributed in the southern hemisphere, indicating higher southern hemisphere mantle temperature than that of the northern hemisphere. The high mantle temperature can be ascribed to the existence of the Tuzo large low-shear-velocity province (LLSVP) beneath the Gondwanaland. The Tuzo LLSVP resulted in upwelling of mantle plumes of different ages, leading to uplift and rupture of overlying lithosphere that induced the continuous rifting of blocks from the northern margin of Gondwanaland. With the northward subduction of the oceanic slab, the rifted blocks drifted northward away from Gondwanaland. Hemispheric mantle temperature difference also induced northward transfer of plume head magma to mid-ocean ridges. Under exceptional circumstances, the interaction between plume head magma and mid-ocean ridges can block the ridges and lead to ridge jumps, forming new mid-ocean ridges, which can promote the expansion of the Neo-Tethys Ocean and northward drift of rifted blocks. For subduction initiation along the new southern margin of the Eurasian continent, after closure of the Paleo-Tethys Ocean, the drag force from the still on-going subduction of subducted Paleo-Tethys oceanic slab and push force from Neo-Tethys mid-ocean ridge led to stress accumulation that induced rupture of the Neo-Tethys slab in the ocean-continent transition zone along the northern margin of the Neo-Tethys Ocean, which is the weakest region for slab rupture. Meanwhile, the southern margin of the Eurasian continent experienced multistage orogenic events during the Phanerozoic, where water-rich minerals such as hornblende and serpentine were formed in the upper mantle beneath the orogenic belts. Due to the limited size of the Cimmerian blocks, after the Paleo-Tethys orogenesis, break off the Paleo-Tethys oceanic slab resulted in increased mantle water content beneath the Cimmerian blocks and decreasing of viscosity, which favored subduction initiation along the northern margin of the Neo-Tethys Ocean. We propose that the one-way subduction of the Neo-Tethys Ocean was controlled by two factors: (1) Hemispheric mantle temperature difference causing upwelling of mantle plumes of different ages, leading to persistent rifting of blocks from Gondwanaland, and (2) high-water content of the southern Eurasian lithosphere and stress accumulation induced slab rupture in the ocean-continent transition zone, facilitating the subduction initiation along the southern margin of the Eurasian continent. The main driving force that maintained continuous northward subduction of the Neo-Tethys oceanic slab is the negative buoyancy of subducting oceanic slabs. Furthermore, high mantle temperature in the southern hemisphere during the Mesozoic and the pushing force from mid-oceanic ridge can be considered as subordinate driving forces contributing to the one-way northward subduction of the Neo-Tethys Ocean.

Neo-Tethys Ocean, one-way subduction, subduction initiation, hemispheric mantle temperature difference, water-rich lithosphere along southern margin of Eurasia continent

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