第 51 卷第 2 期　　中　国　地　质　　Vol.51, No.2
2024 年 3 月　　GEOLOGY IN CHINA　　Mar., 2024

doi: 10.12029/gc20200605004

胡望水, 李希元, 唐永, 李涛, 雷中英. 2024. 地幔对流反转: 来自全球反转构造的透视和构想[J]. 中国地质, 51(2): 483−498.

Hu Wangshui, Li Xiyuan, Tang Yong, Li Tao, Lei Zhongying. 2024. Mantle convection inversion: Perspective and hypothesis of global inversion tectonics[J]. Geology in China, 51(2): 483−498(in Chinese with English abstract).

地幔对流反转: 来自全球反转构造的透视和构想

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提要:【研究目的】全球中生代与新生代油气盆地在其发育某一阶段发生了构造反转, 早期的裂陷盆地在反转期被反转盆地叠加与改造, 本文以地幔对流反转作用(区域性反转作用或局部性反转作用)为视角, 尝试对地壳表层反转构造成因提出深部解决途径。【研究方法】基于地球物理资料, 借助构造地质学、地球物理学研究手段, 对全球中、新生代盆地在白垩纪末期、古近纪末期的构造反转事件及反转构造特征进行归纳与对比, 研究大洋、大陆板内裂陷盆地正构造反转时间, 与其之临近的陆陆板块间造山带内负反转构造事件时间具有同期性, 建立了反转构造发育的地幔对流反转模型, 研究盆山耦合与局部性地幔对流单元及其变化的关联性。【研究结果】大量证据表明大陆板内裂陷盆地正构造反转时间, 与其之临近的陆陆板块间造山带内负反转构造事件时间具有同期性, 例如大别造山带造山挤压、伸展塌陷与南华北盆地及合肥盆地伸展裂陷、收缩反转分别具有对应关联性, 这种盆山耦合推测是由局部性地幔对流单元及其变化所制约关联起来的。造山带的垮塌不是由于板块间的俯冲作用减弱或汇聚速率减小而引起的重力垮塌, 推测根本原因可能是地幔对流方式、方向的改变所引起的间歇性伸展裂陷。大洋板内裂谷(大洋中脊)的正反转构造作用时间与俯冲带内负反转构造作用时间也具有同期性, 尽管目前的证据不是很充分。无论板块间活动带内反转构造事件下的反转构造, 还是板内裂陷盆地内的反转构造作用下产生的反转构造, 都标志着这些构造单元的构造演化进入到一个新的发育演化阶段。【结论】反转构造产生的动力机制涉及到的地幔对流的反向流动, 地幔对流反转所引起的岩石圈或地壳反向收缩运动导致盆地反转收缩变形。本构想的深远意义是对地幔对流状态、动力及其变化的理解、研究将会对板块反向运动启动机制研究产生深远的影响。

关　键　词: 反转构造; 盆地反转; 俯冲带反转; 地幔对流; 地幔对流反转; 反转机制

创　新　点: (1)建立了反转构造发育的地幔对流反转模型, 丰富了板块构造理论内涵; (2)基于地幔对流反转模型, 解析了大陆板内裂陷盆地正构造反转时间, 与其之临近的陆陆板块间造山带内负反转构造事件时间具有同期性及大洋板内裂谷(大洋中脊)的正反转构造作用时间与俯冲带内负反转构造作用时间也具有同期性的根本原因, 由超地幔对流反转系统引起的。

中图分类号: P511; P545　　**文献标志码:** A　　**文章编号:** 1000−3657(2024)02−0483−16

Mantle convection inversion: Perspective and hypothesis of global inversion tectonics

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收稿日期: 2020−06−05; **改回日期:** 2020−12−19

基金项目: 国家重大科技专项项目(2008ZX05030, 2011ZX05030, 2017ZX05032)资助。

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Abstract: This paper is the result of geological survey engineering.

[Objective] Inversion tectonics occurred at a specific period in the evolution of worldwide hydrocarbon basins throughout the Mesozoic and Cenozoic eras. It involved the modification and superimposition of early rift basins to induce inversion. With a focus on regional or localized mantle convection inversion, this study attempts to explain the factors that contribute to inversion tectonics in the Earth's crust. **[Methods]** Based on geophysical data, with the help of tectonic geology and geophysical research methods, summarize and compare the tectonic inversion events and characteristics of the Mesozoic and Cenozoic basins in the late Cretaceous and Paleogene periods worldwide, study the positive tectonic inversion time of oceanic and continental intraplate rift basins, and establish a mantle convection inversion model for the development of inversion structures. The time of negative tectonic inversion events in adjacent continental plate orogenic belts is synchronous, Study the correlation between basin mountain coupling and local mantle convection units and their variations. **[Results]** A large amount of evidence indicates that the time of positive tectonic inversion in continental rift basins is synchronous with the time of negative tectonic inversion events in the adjacent continental plate orogenic belts. For example, the compression and extensional collapse of the Dabie orogenic belt are correspondingly correlated with the extensional rift and contraction inversion of the South Huabei Basin and Hefei Basin, respectively. Although the current evidence may not be exhaustive, the positive and negative inversion tectonics in the rift valleys (mid−ocean ridges) of oceanic plates and the negative inversion tectonics within subduction zones demonstrate a contemporaneous relationship. Irrespective of their origin in rift basins or interplate active zones, inversion tectonics constitute a developmental and evolutionary transition of the tectonic units they represent. Although there is some acceptance regarding the development of these inversion tectonics, the underlying mechanisms that cause their formation in various tectonic units continue to be unclear. Whether it is the reverse structures generated by the reverse tectonic events in the inter plate active zone or the reverse structures generated by the reverse tectonic actions in the intra plate rift basin, all indicate that the tectonic evolution of these structural units has entered a new stage of development and evolution. **[Conclusions]** By capitalizing on the correlation between extensively dispersed inversion tectonics across the exterior of the Earth and preceding tectonic features, we propose that inverse flow in mantle convection underlies the dynamic mechanism that triggers the formation of inversion tectonics. In this study, we lay out a model that explains the inverse contraction movements in the lithosphere or crust that occur as a result of mantle convection inversion and the mechanisms that initiate these movements in inversion tectonics. The theory in consideration holds immense importance due to its capability to greatly influence the comprehension and investigation of mantle convection states, dynamics, and their variations. Consequently, this could have a profound effect on the pursuit of mechanisms that cause inverse plate movements.

Key words: inversion tectonic; basin inversion; subduction zone inversion; mantle convection; mantle convection inversion; inversion mechanism

Highlights: (1) Established a mantle convection inversion model for the development of inversion structures, enriching the theoretical connotation of plate tectonics; (2) Based on the mantle convection inversion model, the fundamental reasons for the synchronicity of the positive tectonic inversion time in the continental rift basin and the negative tectonic inversion time in the adjacent continental plate orogenic belt, as well as the synchronicity of the positive tectonic inversion time in the oceanic rift (mid ocean ridge) and the negative tectonic inversion time in the subduction zone, were analyzed, which were caused by the super−mantle convection inversion system.

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Fund support: Supported by National Major Science and Technology Special Project (No.2008ZX05030, No.2011ZX05030, No.2017ZX05032).

1 引 言

地幔对流学说解释了大陆漂移、裂谷发育的动力机制(Homes, 1931)。近一个世纪的地幔对流研究已经在大陆漂移、海底扩张、地球岩石圈变形等方面取得了许多研究成果(Nicolas et al., 2017)，逐

步形成了板块构造理论。目前地幔对流假说侧重于强调大洋中脊地幔柱上升导致洋中脊的扩张,地幔上升至岩石圈底部后其平流带动板块的漂移,大洋板块移动至海沟处俯冲下沉消减(Hess and Hall, 1960)。地球的构造活动在很大程度上是地幔对流的地球表面表现(Bercovici et al., 2013)。在地表大量构造变形地质、地球物理、地球化学观测信息的基础上,构造地质学家将地表构造特征、板块构造作用及演化历史与深部地幔热化学作用及演化相结合,分析了岩石圈结构和构造,认为地表大型构造是地幔动力的一种表现形式,模拟了岩石圈/地壳构造与深地幔对流的耦合关系,使地幔对流理论得到验证。任何与现有地幔对流模型假说不一致的地表构造观测结果都预示着一种新型的地幔对流方式,如反转构造,大洋关闭板块碰撞造山,之后板块又发生裂陷离散;裂谷盆地反转等发育的地幔对流模型,有待我们去探索发现。我们依据地球表层观测到的反转构造及其发育规律,遵循表层构造与深部地幔对流的因果关系,推测了深部地幔对流反转及扩张带与俯冲带地幔对流反转单元构成的地幔对流反转系统。

板片窗理论基本解释了大洋板块俯冲带内发育弧间裂谷、弧后裂陷槽、火山岩体等负反转构造的成因机制(Tackley, 1998; Koglin et al., 2005; McKenzie, 2010; Santosh, 2010; Bercovici and Ricard, 2014; Yoshida and Santosh, 2014; Müller et al., 2016; Nicolas et al., 2017),但仍然没有给出深部地幔流动的合理解释。地幔柱或热点构造理论认为海底山及山脉是地幔岩浆沿地幔柱或热点喷发至海底而形成的(Dickson and Snyder, 1979; Thorkelson, 1996; Wortel and Sparkman, 2000; Bonnardot et al., 2009; Groome and Thorkelson, 2009)。这些海底类型多样的海山、山系,仅凭地幔柱理论恐怕难以解释,亟需我们给出新的认识。

西菲律宾地区 Palawan 俯冲带最新研究成果显示,除板块边界处洋中脊之外,大洋中脊不仅仅是扩张带,而且是俯冲汇聚带(Harrison et al., 2017),即反转构造叠加带,预示着控制反转构造发育的地幔对流方式可能出现了变化。

全球油气勘探发现在大陆内、大陆边缘盆地演化的末期发育了大量的正反转构造(图 1),其因岩石圈板块运动反转构造作用而产生的,目前仅从板块运动及相互作用的角度探索了盆地反转的机制(Deway, 1988; Wilson and Guiraud, 1992; Genik, 1993; Buchanan and Ruchanan, 1995; Guiraud and William, 1997; Bourgois et al., 2000; Corti, 2009; Keenan et al., 2016),不过对反转构造产生的动力机制的认识仍然让人难以置信。大量的研究结果显示大陆造山带每个演化阶段末期一般发育负反转构造,部分研究者认为这类负反转构造是由于造山挤压末期构造松弛而产生的塌陷构造(Deway, 1988; Royden, 1993; Osmundsen and Andersen, 1994; 王二七等, 2006; 宋述光等, 2015),这属于从岩石圈构造变形角度讨论地壳的构造变形。可见,大陆内引起反转构造作用的地球深部地幔动力学机制目前尚不清楚。

2　对地幔对流的挑战

虽然观测到地球表层存在大量的正、负反转构造(Cooper and Williams, 1989; Buchanan and Ruchanan, 1995),但是目前关于反转构造作用机制的研究受现有地幔对流模型、研究领域、测量范围、区域背景估计的不确定性等限制,结论认识让人难以置信,且研究视角狭隘,忽略了地幔对流方式变化的作用,不足以建立深部地幔流动与表层反转构造作用及构造变形响应的动力学模型。

物质沿大洋中部穿透岩石圈的裂缝或裂谷向两侧扩展并导致新生洋壳。由于洋壳不断向外推移,移动至海沟岛弧一线,便受阻于大陆而俯冲下插于地幔,达到新生和消亡的消长平衡(Dietz, 1961)。依据这种假设,可以推理大洋自始至终处于生长状态,无法缩小直至关闭,这与大洋关闭造

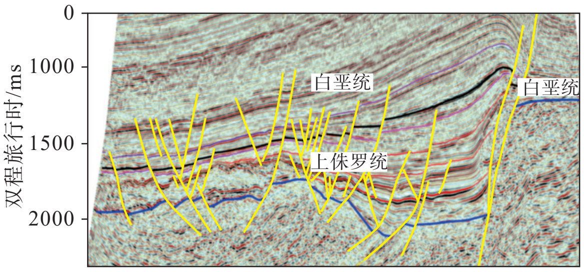

图 1　松辽盆地正反转构造地震解释剖面
Fig.1　Seismic interpretation profile of the Songliao Basin

山构造事实相矛盾（Allegre et al., 1984; Dobretsov et al., 2004; Dilek and Fumes, 2011; Fan et al., 2015）。大西洋与太平洋的扩张形式不同，大西洋在洋中脊处扩张，大洋两侧与相邻的陆地一起向外漂移，大洋与大陆之间不存在俯冲消减带，因此大西洋不断展宽，依据海底扩张假说，大西洋会无休止地扩张下去，始终不会消失。海底扩张和板块运动的动力是地幔对流，因此完善海底收缩和板块构造学说对大洋消失关闭的理论解释，就是需要完善地幔对流说。

大陆漂移和板块运动以及大陆间曾多次碰撞和拼合及数次裂陷和分离等是客观存在的事实。地球上曾存在劳亚古陆（Laurasia）和冈瓦纳古陆（Gondwana）。劳亚古陆大致在石炭纪早中期至二叠纪（即 200~270 Ma 前）才逐步拼合而成。晚古生代末期，劳亚大陆与冈瓦纳大陆逐渐汇聚碰撞，其间大洋关闭，拼合成巨大的 Pangea 泛大陆（Seyfert and Sirkin, 1979）。这个泛大陆在侏罗纪又开始裂解漂移，逐渐形成为现在的大陆板块格局。简而言之，地球大陆从分离到拼合，又从拼合到分离的板块构造周期性研究结果，广泛暗示引起这个过程的动力机制发生了性质的反转变化，即地幔对流方向、结构、方式等发生了变化。目前为止对此研究基本聚焦在现有地幔对流模型的数值模拟上（Wilson and Tuzu, 1963; Dickson and Snyder, 1979; Thorkelson, 1996; Wortel and Sparkman, 2000; Maruyama et al., 2007; Bonnardot et al., 2009; Groome and Thorkelson, 2009; Santosh et al., 2009; Burov and Gerya, 2014; Gerya et al., 2015; Nicolas et al., 2017）。部分认为超级大陆从汇聚到离散的转换是由于碰撞造成的地幔对流逆转而引起的（Gurnis, 1988; Lowman and Jarvis, 1993），或者认为地幔对流循环的结果（Zhong et al., 2007），但是对于引起地球古大陆从分离到汇聚、又从汇聚到分离的状态转换的动力机制变化，与随地幔对流演化过程中的地幔对流方式变化之间的关系还知之甚少，对于板块内反转构造发育的地幔对流方式的转换更是无人问津。

无论全球分离的大陆板块漂移发生汇聚、拼合，又从拼合的联合大陆发生裂陷分离、离散漂移，还是板块构造阶段旋回性构造演化，均经历了由正向亚旋回和反向亚旋回组成的一个完整的构造旋回。依据目前地幔对流理论，推测地球地幔对流发生过正向和反向对流，且两个对流亚旋回构成地幔对流全旋回，这地幔对流全旋回诱发了完整的板块构造运动旋回。基于岩石圈板块构造与深部地幔对流的耦合理论，可以推测地幔对流也应发生过多次的正、反地幔流动，由此可见，无论是超级的地幔对流反转，还是局部的的，都是地幔对流不可缺少的流动型式，是岩石圈反转构造产生的深部地幔流动型式之一。地幔对流反转是在前期地幔对流结构框架控制下地幔为了寻求达到物质、能量等新的平衡而发生的反向流动。反转对流模型的建立，对完善地幔对流理论及板块构造理论具有重要的引领作用。

3 全球表层反转构造

3.1 大西洋及关联大陆反转构造

冈瓦那大陆破裂可能在晚石炭世就开始了。前人研究结果显示在冈瓦那大陆内部发生了 3 期裂陷作用：从晚石炭世到中侏罗世，从晚侏罗世到早白垩世，以及晚始新世到早中新世（Wilson and Guiraud, 1992）。在这 3 期伸展作用影响下，导致大西洋洋盆及非洲、南美及澳大利亚大陆内中新生代裂陷盆地的发育。至白垩末期—古新世，海平面显著下降，加之大洋扩张进一步减缓，以及非洲板块开始缓慢抬升，因此西非大陆边缘东移减缓。渐新世中晚期，大陆边缘达到其最东的位置（Wilson and Guiraud, 1992），渐新世末期或早中新世早期，大洋扩张速度迅速降低，海平面也较快速下降，同时非洲板块收缩抬升，西非大陆边缘开始向西迁移（Broucke et al., 2004）。尽管时间上存在一定的差异，但是共同认识是大洋扩张进一步减缓，非洲板块抬升加强，大陆边缘进一步西撤，直至现今位置。油气勘探结果显示，大西洋大陆边缘、非洲大陆以及南美大陆中新生代裂陷盆地（图 2，图 3，图 4），自白垩纪以来，至少经历了白垩纪末期、古近纪末期的 2 次反转构造作用（Wilson and Guiraud, 1992; Buchanan and Ruchanan, 1995; Guiraud and William, 1997），产生了大量的反转构造（图 5）。无论大西洋扩张的减缓或反转收缩，还是大陆内中新生代盆地的反转，受控于前期控制大西洋扩张及陆内裂陷盆地发育的地幔对流的反转，在这大洋、大

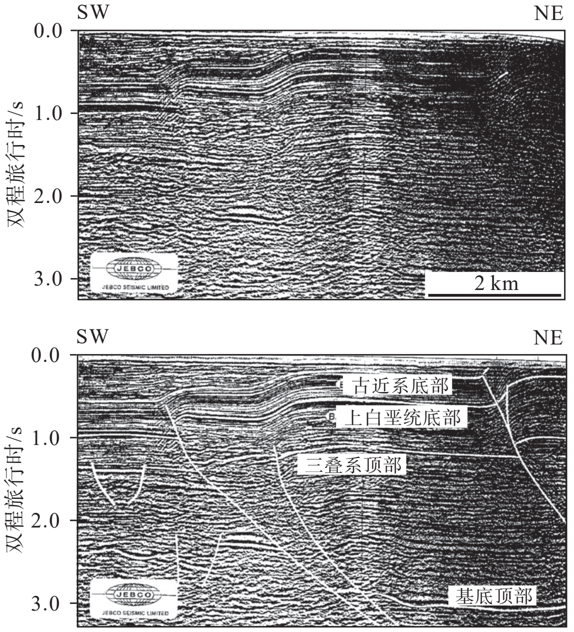

图 2　南波罗的海中央 Rφnne 地堑白垩纪末期盆地反转的地震解释剖面(据 Buchanan and Ruchanan, 1995)
Fig.2　Seismic interpretation profile of basin inversion of the South Baltic Sea at the end of Cretaceous (after Buchanan and Ruchanan, 1995)

陆同一地幔对流反转的作用下，大西洋发生收缩，大陆内盆地产生反转。

3.2　印度洋及其关联大陆反转构造

印度洋两侧的大陆边缘盆地，与西非大西洋边缘盆地一样，自早白垩世以来，至少经历了 2 次构造反转作用(Uenzelmann et al., 2011; Abbasi et al., 2016; Klimke et al., 2016; Rodriguez er al., 2016; Lutz et al., 2018)，而且反转构造作用时间基本一致，表明板块构造反向运动及变形动力机制具有关联性，推测受控于一超地幔对流反转系统。

3.3　太平洋及其大陆边缘反转构造

研究证实洋陆、洋洋等俯冲带内，即存在挤压冲断构造及弧前盆地，又发育弧内及弧间裂谷盆地、小洋盆等伸展构造(Karig, 1971; Taylor and Kamer, 1983; Hilde and Lee, 1984; Miyashiro, 1986; Honza, 1995; Okino et al., 1998)，如马里亚纳弧间海槽或盆(Bibee et al., 1980)，这些不同性质的构造存在同一构造带内，难以用一种动力学成因来解释这些构造同期发育过程。板片窗构造理论解释了俯冲带内拉张型负反转构造的发育由俯冲板片折返而导致的(Dickson and Snyder, 1979; Thorkelson, 1996; Wortel and Sparkman, 2000; Bonnardot et al., 2009; Groome and Thorkelson, 2009)。我们认为这些伸展负反转构造，可能是地幔对流反转所引起的(图 6)。

目前研究发现西太平洋边缘裂陷海盆伸展构造发育期、火山活动期对应于洋壳板块强力俯冲期，为了解释边缘海盆扩张，提出了俯冲带后撤的成因机制及动力学模式(Karig, 1971; Taylor and Kamer, 1983; Hilde and Lee, 1984; Miyashiro, 1986; Honza, 1995)。这些边缘海盆不仅经历了多期次的裂陷作用，发育多期伸展构造，而且几乎每期裂陷作用末期盆地均发生了反转构造作用(图 7)，产生了正反转构造(许红等, 2010; Horne et al., 2017)。

中国东海(盆地)新生代伸展构造发育演化经历了 6 次伸展构造运动作用，从时间上，构造运动的

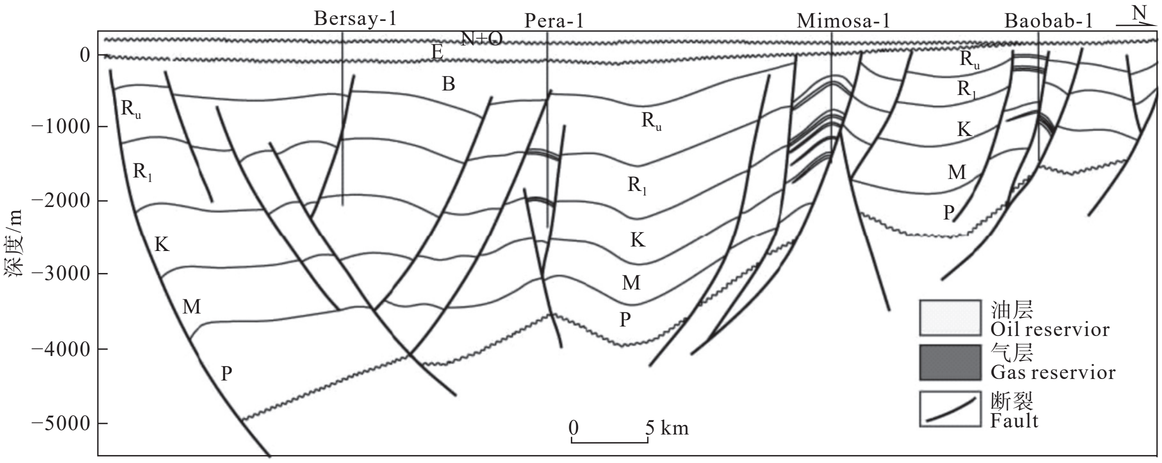

图 3　非洲中部 Bongor 盆地白垩纪末期反转构造作用地震地质解释剖面
Fig.3　Seismic interpretation profile of the inversion tectonics in the Bongor Basin, central Africa at the end of Cretaceous

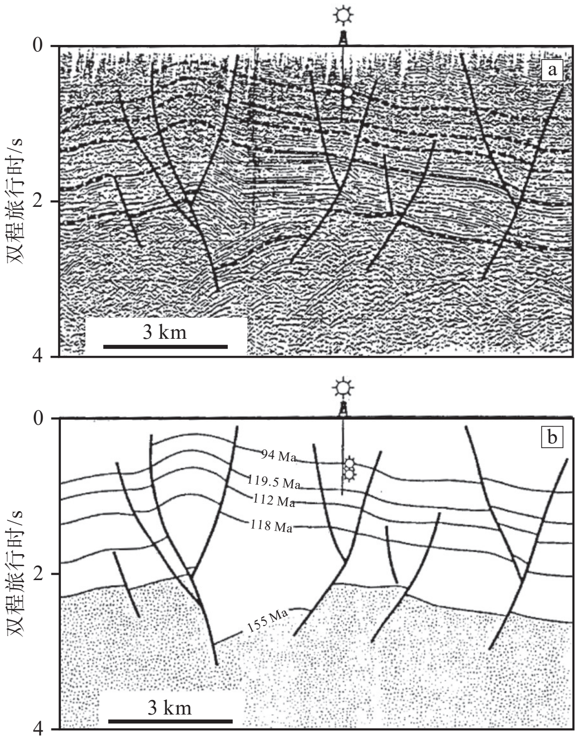

图 4 阿根廷西 San Jorge 盆地白垩纪末期反转构造地震剖面(a)和解释剖面(b)(据 Buchanan and Ruchanan, 1995)
Fig.4 Reversed tectonic seismic profile (a) and interpreted profile (b) of San Jorge Basin in Western Argentina at the end of Cretaceous (after Buchanan and Ruchanan, 1995)

演化呈现自西向东逐步推进的规律，构造发育时间也呈现自西向东的逐渐变新（许红等, 2010; 张国华和张建培, 2015; 索艳慧等, 2017）。每期伸展构造运动的末期几乎发生了一期时间较为短暂的反转构造运动，构造反转作用时间自西向东同样表现由老变新的规律，该迁移特征与同期太平洋板块的后退式俯冲相关联（许红等, 2010; 张国华和张建培, 2015; 索艳慧等, 2017）。假如边缘海伸展构造发育期与太平洋板块俯冲强烈期相对应，那么正反转构造发育期则与太平洋板块俯冲减弱而伸展作用增强期相呼应。事实上，这种构造关联现象推测受同一超地幔对流系统及其反转对流系统所控制。

日本海弧后裂谷盆地（图 8），在中新世至上新世至少经历了 4 次构造反转（Fan et al., 2015），大约在 15 Ma 第一次构造反转发生了，反转构造主要出现在位于日本 Kyushu 与韩国间的 Tsushima 区（Fabbri et al., 1996; Sibuet et al., 2002; Lee et al., 2011）。随后约 10 Ma，强烈盆地反转主要发生在日本东北部 Ou Backbone 区（Sibuet et al., 2002）。8~5 Ma 时期，西南日本海盆地发生了构造反转（Itoh and Nagasaki, 1996; Yoon et al., 2014）。在 3.5 Ma，第四次构造反转主要出现在北东日本海盆地（Sato, 1994）。日本海构造反转可能预示了其东侧俯冲带及太平洋板块构造作用的反转，同样也至少经历了 4 次。

中国南海东部海盆、菲律宾板块西部海盆与马尼拉俯冲带发育演化相关联。在中新世早期西倾的马尼拉俯冲带已经存在，南海洋壳开始沿着马尼拉海沟向菲律宾海板块俯冲，至中新世中期俯冲作用开始停歇，南海海盆扩张以及俯冲停止（Huang et al., 1997; Sibuet and Hsu, 1997; 丁巍伟等, 2006）。马尼拉俯冲带俯冲作用始于南海海盆扩张结束后（16 Ma），从早中新世末期 16 Ma 开始活动，菲律宾海板块开始仰冲于古南海板块之上，从而产生了马尼拉及吕宋岛弧体系（Bachman et al., 1983）。对于马尼拉俯冲带产生的时间及其两侧板块活动的主动性，为何存在上述两种不同的认识呢（Huang et al., 1997; Sibuet and Hsu, 1997; 丁巍伟等, 2006），实际上马尼拉俯冲带是一个由不同时期发育的正、反构造类型构成的叠加构造带，因此才会出现两种相反的结论，实际上两种认识都是正确的，都仅认识到叠加构造带内某一阶段的构造及作用。在地幔柱作用下中国南海海盆扩张，板块向东移动，并沿马尼拉海沟主动俯冲，而菲律宾板块显示为被动仰冲。16 Ma，中国南海板块东部海盆停止扩张，向东的俯冲也就停止，此时马尼拉俯冲带却开始伸展塌陷（如北吕宋海槽 North Luzon Trough），火山活动，产生弧内裂陷盆地，俯冲带的伸展作用导致马尼拉俯冲带向西侧中国南海板块和东侧菲律宾板块上仰冲，从而导致这两个板块发生收缩挤压，产生正反转构造（商继宏和李家彪, 2009）。大约 17 Ma，菲律宾板块上的四国海盆、帕里西维拉海盆开始停止扩张（臧绍先和宁杰远, 2002），暗示菲律宾板块之下的地幔对流也发生了变化。构造作用性质变化的根本原因是地幔对流的反转变化所致，进而表明该时期地幔对流反转不是局部性的，而是区域性的。

研究还发现，一些海山或高原（实际为反转构造）形成于边缘海盆、大洋海盆阶段性扩张减弱暂时停止或结束之时，如西菲律宾海盆的本哈姆高原形成于西菲律宾海盆停止扩张时（Ishizuka et al., 2011）。四国海盆在扩张结束时在其遗迹扩张中心形成了 Kinan 海山链（Hickey−Vargas, 1991; Ishizuka

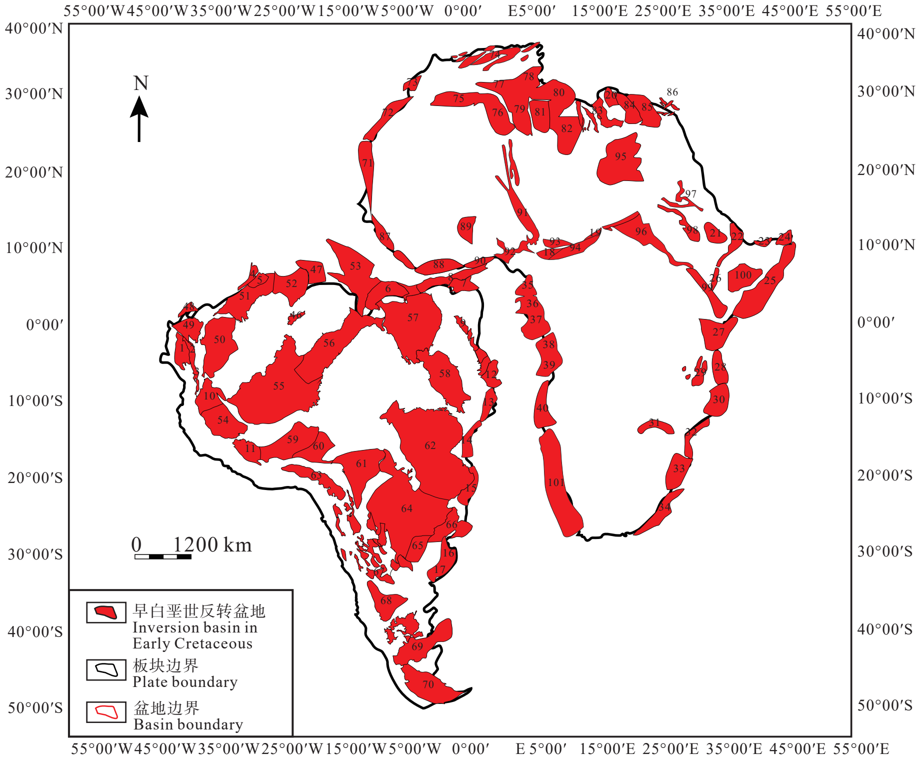

图 5 大西洋及关联大陆早白垩世末期发生构造反转的油气盆地

1—下马格达莱纳盆地; 2—中马格达莱纳盆地; 3—上马格达莱纳盆地; 4—多巴哥盆地; 5—特立尼达盆地; 6—马拉尼昂盆地; 7—泼提哥盆地; 8—费尔南多迪诺罗尼亚盆地; 9—土坎诺盆地; 10—普图马约盆地; 11—乌卡亚利河盆地; 12—圣埃斯皮里图盆地; 13—坎波斯盆地; 14—桑托斯盆地; 15—佩洛塔斯盆地; 16—里约热内卢萨拉多河流域盆地; 17—科罗拉多盆地; 18—多巴盆地; 19—塞拉迈特盆地; 20—普利尼坎盆地; 21—青尼罗河盆地; 22—阿法斯盆地; 23—南部亚丁湾; 24—萨嘎勒盆地; 25—索马里海盆; 26—图尔卡纳盆地; 27—拉姆盆地; 28—坦桑尼亚盆地; 29—赛劳斯盆地; 30—鲁午马盆地; 31—赞比西河流域; 32—赞比亚盆地; 33—莫桑比克盆地; 34—南非东海岸盆地; 35—杜阿拉盆地; 36—里约热内卢盆地; 37—加蓬盆地; 38—下刚果盆地; 39—宽扎盆地; 40—耐诺莎尔盆地; 41—里波利斯盆地; 42—塞拉盆地; 43—森高尔盆地; 44—塔尔法亚盆地; 45—索里拉盆地; 46—塔库地堑; 47—德莫拉拉高原盆地; 48—上瓜西拉盆地; 49—马拉开波盆地; 50—雅诺斯—巴里纳斯盆地; 51—东委内瑞拉盆地; 52—圭亚那盆地; 53—福斯杜—亚马逊盆地; 54—马拉隆盆地; 55—索里莫斯盆地; 56—亚马逊盆地; 57—巴纳伊巴盆地; 58 圣弗朗西斯科盆地; 59—玛德莱德迪奥斯盆地; 60—贝尼盆地; 61—查科盆地; 62—巴拉那盆地; 63—阿尔蒂普拉盆地; 64—查科—巴拉那盆地; 65—罗萨里奥盆地; 66—里奥德拉平原克拉通盆地; 67—库约盆地; 68—内乌肯盆地 69—圣豪尔赫盆地; 70—奥斯特勒尔盆地; 71—塞内加尔盆地; 72—塔尔法亚盆地; 73—索维拉盆地; 74—阿特拉斯盆地群; 75—延杜夫盆地; 76—雷甘盆地 77—蒂米蒙盆地; 78—三叠盆地; 79—阿赫奈特盆地; 80—古达米斯盆地; 81—伊利兹盆地; 82—穆租克盆地; 83—锡尔特盆地; 84—马尔马里卡盆地; 85—西沙漠盆地; 86—尼罗河三角洲; 87—塞拉利昂—利比里亚盆地; 88—科特迪瓦盆地; 89—沃尔特盆地; 90—贝宁盆地; 91—特密特盆地; 92—贝努埃盆地; 93—班戈盆地; 94—多赛奥盆地; 95—库弗腊盆地; 96—穆格莱德盆地; 97—喀土穆盆地; 98—麦卢特盆地; 99—安札盆地; 100—欧加登盆地; 101—奥兰治盆地

Fig.5 Oil−gas basins in the Atlantic and associated continents undergoing tectonic inversion at the end of Early Cretaceous

1–Lower Magdalena Basin; 2–Middle Magdalena Basin; 3–Upper Magdalena Basin; 4–Tobago Basin; 5–Trinidad Basin; 6–Maranion Basin; 7–Pretego Basin; 8–Fernando De Noronha Basin; 9–Tukano Basin; 10–Putumayo Basin; 11–Ucayari Basin; 12–Espirito Santo basin; 13–Campos Basin; 14–Santos Basin; 15–Pelotas Basin; 16–Rio de Janeiro Salado River Basin; 17–Colorado Basin; 18–Toba Basin; 19–Selamat Basin; 20–Pulinikan Basin; 21–Blue Nile Basin; 22–Afar Basin; 23–Southern Gulf of Aden; 24–Sagar Basin; 25–Somali Basin; 26–Turkana Basin; 27–Lamu Basin; 28–Tanzania Basin; 29–Selos Basin; 30–Luoma Basin; 31–Zambezi River Basin; 32–Zambian Basin; 33–Mozambique Basin; 34–East Coast Basin of South Africa; 35–Douala Basin; 36–Rio de Janeiro Municipal Basin; 37–Gabon Basin; 38–Lower Cango Basin; 39–Wanza Basin; 40–Nannosal Basin; 41–Ripolis Basin; 42–Serra Basin; 43–Sengoor Basin; 44–Talfaya basin; 45–Sorilla Basin; 46–Taku Graben; 47–Demorara Plateau Basin; 48–Upper Guasila Basin; 49–Maracaibo Basin; 50–Janos–Barinas Basin; 51–Eastern Venezuela Basin; 52–Guyana Basin; 53–Foz do Amazonas Basin; 54–Maranhao Basin; 55–Solimoes Basin; 56–Amazonas Basin; 57–Banaiaba Basin; 58–San Francisco Basin; 59–Madre de Dios Basin; 60–Beni Basin; 61–Chaco Basin; 62–Parana Basin; 63–Alto Paraguay Basin; 64–Chaco–Parana Basin; 65–Rosario Basin; 66–Rio de la Plata–Craton Basin; 67–Cuyuni Basin; 68–Neuquen Basin; 69–San Jorge Basin; 70–Austral Basin; 71–Senegal Basin; 72–Taouratine Basin; 73–Soufliere Basin; 74–Atlas Mountains Group of Basin; 75–Yendouf Basin; 76–Regan Basin; 77–Timimoun Basin; 78–Triassic Basin; 79–Ahnet Basin; 80–Gudamis bainse; 81–Illizi baibsa; 82–Mzab Basin; 83–Sirt Baisna; 84–Hamada Basin; 85–Western Desert Baisn; 86–Nile Delta Baisn; 87–Sierra Leone–Liberia Baisn ; 88–Ivory Coast Baisn ; 89–Volta Baisn; 90–Benin Baisn; 91–Temimi Baisn; 92–Bechar Baisn; 93–Bangui Baisn; 94–Douze Baisn; 95–Koufra Baisn; 96–Muglad Baisn; 97–Khartoum Baisn; 98–Melut Baisn; 99–Ennedi Baisn; 100–Ougadougou Baisn; 101–Orange Basin

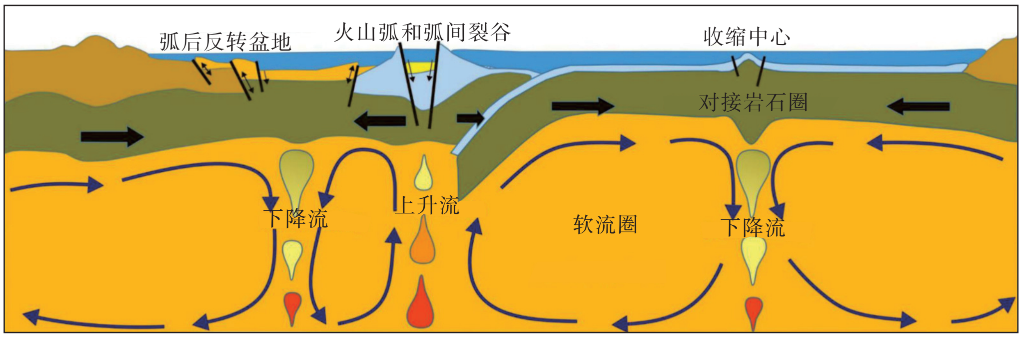

图 6 大洋和俯冲带地幔对流反转模型
Fig.6 Mantle convection inversion model in oceanic and subduction zones

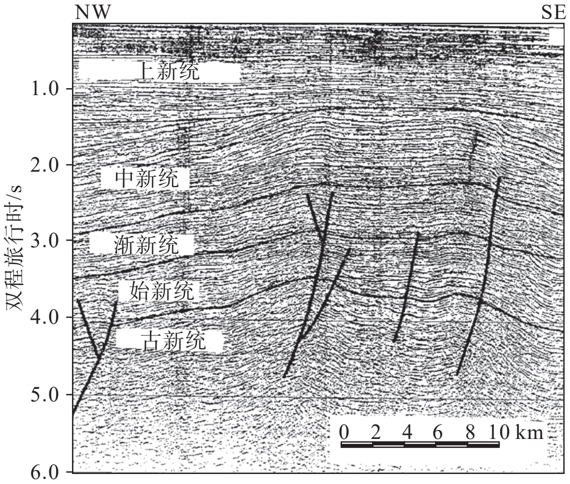

图 7 中国东海盆地中新世末期反转构造地震解释剖面(据 Buchanan and Ruchanan, 1995)
Fig.7 Inversion tectonic seismic interpretation profile at the end of Miocene in the East China Sea basin (after Buchanan and Ruchanan, 1995)

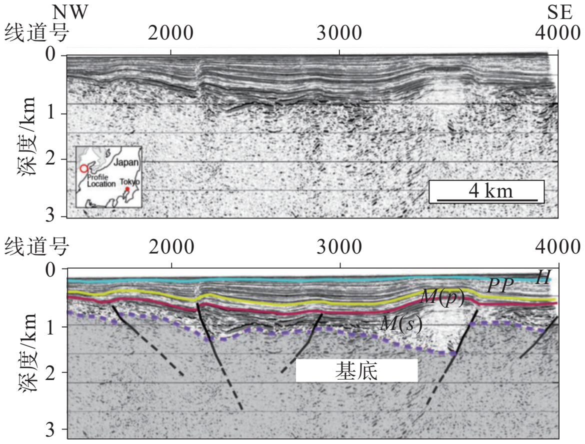

图 8 日本海 Noto peninsula 构造带中中新世末期发育的反转构造(据 Horne et al., 2017)

M(s)—中新统同裂陷期; M(p) —中新统后裂陷期; PP—上新统—更新统; H—全新统

Fig.8 Inversion structures developed at the end of Miocene of the Noto Peninsula tectonic belt in the Sea of Japan (after Horne et al., 2017)

M(s)–Miocene syn-rift; M(p)–Miocene post-rift; PP–Plio–Pleistocene; H–Holocene

et al., 2009),黄岩岛海山链形成于南海扩张结束之时(Yan et al., 2008)。显而易见这些海盆内山系的形成与边缘海板块反转收缩有关,即地幔对流反转引起大陆边缘板块收缩导致板内俯冲造山。

3.4 大陆板块内裂陷盆地收缩反转

大陆板块内油气勘探发现几乎所有的裂谷盆地经历了盆地构造反转(Cooper and Williams, 1989; Buchanan and Ruchanan, 1995),且构造反转出现在盆地演化的某个阶段的末期(图 1),如裂陷期的末期、坳陷期的末期等,反转构造是油气聚集的主要圈闭(Buchanan and Ruchanan, 1995)。裂谷盆地裂陷期构造发育是地幔上升及对流引起岩石圈横向伸展而产生的(Homes, 1931)。既然岩石圈裂陷伸展是地幔上升,横向离散对流作用的结果,那么推测裂谷盆地反转期构造发育则是地幔下降,横向汇聚对流导致岩石圈横向收缩而产生的(图 9)。

中国东部中新生代含油气盆地,如松辽盆地、渤海湾盆地、江汉盆地、苏北盆地等,均经历了与裂陷期伸展构造作用相反的叠加在其之上的反转构造作用,发育正反转构造,大部分正反转构造为储油构造(Allen et al., 1997; Hu et al., 1998; 胡望水等, 2004; 张岳桥等, 2004; Huang et al., 2015; Young, 2015; Guo et al., 2018)。渤海湾盆地、江汉盆地、苏北盆地等,古近纪末期(37.2~22.6 Ma)反转构造作用(胡望水等, 2004; 张岳桥等, 2004)。晚侏罗世—早白垩世,松辽盆地至少经历了裂陷末期、坳陷末

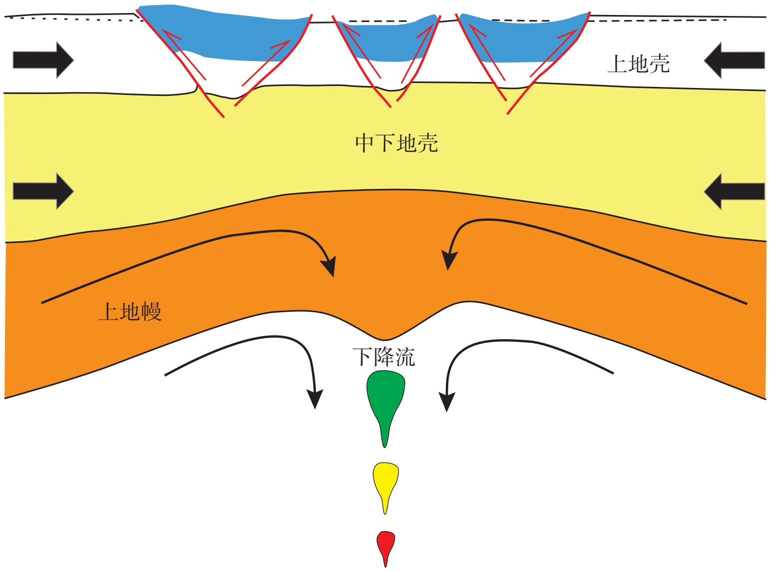

图 9 大陆地幔对流反转引起的裂陷盆地反转的岩石圈收缩模型
Fig.9 Lithospheric shrinkage model of inversion of rifting basin caused by inversion of continental mantle convection

期的盆地构造反转，且大部分主力油田产出在正反转构造上（张岳桥等, 2004）。南华北盆地、蒙古盆地、合肥盆地等，早白垩世末期（100~90 Ma）发生不同程度的构造反转。

中国东部中、新生代古近纪裂陷盆地裂陷阶段与其周边陆内造山作用阶段相对应，可能构成一个关联的盆山作用体系（图 10），受控于同一超地幔对流系统。古近纪末期，中国东部古近纪裂陷盆地普遍发生了收缩性构造反转作用，推测与周边造山带伸展塌陷负构造反转作用相呼应，有待于未来研究证实。

3.5 大陆造山带的伸展反转

板块碰撞造山阶段期末或板块碰撞后的伸展作用已经得到证实，在造山带内发育造山期后的伸展塌陷构造等（Dietz, 1961; McKenzie, 1978; Bird, 1979; Marotta et al., 1998; 宋述光等, 2015）。岩石圈的折返作用或去根导致局部构造环境由挤压向伸展转变，表现为伸展构造的形成、热流值的升高、造山带地壳的区域性伸展–垮塌等（McKenzie, 1978; Bird, 1979; Marotta et al., 1998）。造山带的垮塌是由于板块间的俯冲作用减弱或汇聚速率减小而引起的重力垮塌，板块间的俯冲作用或汇聚速率减小只是表面现象，那么是什么导致板块间的俯冲作用或汇聚速率减小，推测根本原因可能是地幔对流方式、方向的改变所引起的。

早—中侏罗世（200~170 Ma），中国大别山北部发育碰撞后伸展–逆冲推覆构造（Jiang et al., 2003），许多研究者认为该构造是伸展构造与逆冲推覆的叠加构造）（Faure et al., 2010; Harker et al., 2000）。该构造带构造发育演化期次与其邻近的合肥盆地构造发育演化期次，具有较好的对应关系。早—中侏罗世，大别山北部发育碰撞后伸展构造（Suo et al., 2000），合肥盆地属于前陆盆地，则发育逆冲推覆构造（Liu et al., 2003; Li et al., 2004; 刘国生等, 2006; Zhu et al., 2009）；早白垩世，合肥盆地转变为断陷盆地（Liu et al., 2003; Li et al., 2004; 刘国生等, 2006; Zhu et al., 2009, 2010），此时正是大别山造山作用较强时期之一（刘国生等, 2006）。合肥盆地及南华北其他盆地在早白垩末期经历了盆地反转（刘国生等, 2006）（图 10），从此结束了断陷盆地发育阶段。由于板内地幔柱及其对流作用使得大陆板块裂陷扩张，扩张作用促使扩张板块向造山带内俯冲，导致板块间造山作用，即彼此消长。在板块碰撞造山期后，因俯冲岩石圈折返作用或板片窗（Slab Window）作用等诱发的地幔对流反转，在地幔反向对流作用下，引起造山作用终止，甚至伸展塌陷。造山带的这种伸展作用及地幔反向对流共同作用，导致裂陷盆地发育终止，发生反转。在地幔对流反转及地幔柱的回流（冷下降流）作用下，大陆板块沿地幔柱发生深俯冲碰撞，导致大陆板块收缩挤压变形，最终

导致大陆板内造山，如中国华北的燕山、贺兰山等属于陆内造山而成，像大洋板块内俯冲造山一样，如部分海山，均属于板内俯冲碰撞造山。

对于大陆挤压（前陆）盆地，经历了与盆地挤压构造作用相反的负反转构造作用，例如中国塔里木盆地侏罗纪—早白垩世及古近纪—新近纪和柴达木盆地第四纪等经历了负反转构造作用，发育负反转构造（高长林等，2003；赵岩等，2012）。如此同时，塔里木盆地北缘的天山发生了隆升，陆内造山作用进入增强期（王松，2014；高志勇等，2016；张斌等，2016）。前陆盆地挤压之时对应于周缘造山带伸展塌陷之期，反之，前陆盆地反转裂陷之期对应于周缘造山带挤压造山之时。

基于叠加在前期地幔对流系统引起的岩石圈构造变形系统上的反转构造发育特征，依据岩石圈板块构造与深部地幔对流的耦合理论，推测在地幔正向对流阶段末期或期后存在地幔对流反转，这种反转对流型式可表现为全球性的，也可能存在局部性，也可能是旋回性。正是这种多期次地幔对流反转推动岩石圈板块的反向运动而产生了全球性或局部性的多期反转构造。

4 全球地幔对流反转的透视和假设

无论是分层地幔对流假说，还是全地幔对流假说，都假设存在一个完整的对流单元。地幔对流始于上下地幔或幔核边界处，自深部向浅部移动，形成地幔柱（Mantle Plume）或热点（Hotspot），把深部的热量和岩浆输送至浅部，至岩石圈底部部分热量和岩浆喷出地表，另一部分则转向水平向两侧运动，至板块俯冲消减处（大洋海沟、陆内俯冲造山

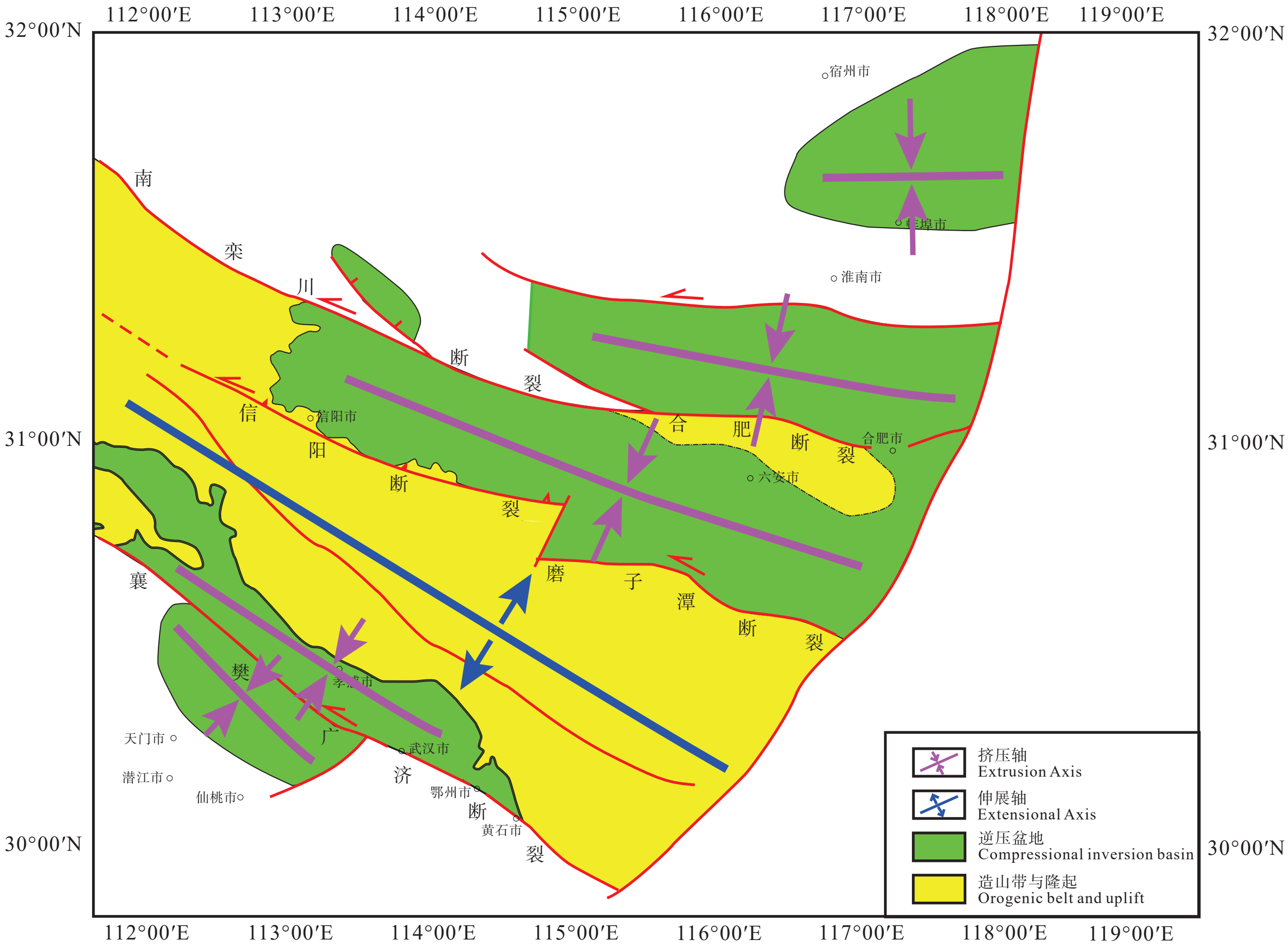

图 10 中国秦岭大别造山带与南华北盆地中、新生代盆山正、负构造反转体系图
Fig.10 Tectonic inversion systems of the Dabei orogenic belt in Qinling Mountains and the Meso−Cenozoic and Cenozoic basins in the South and North China basins

处）下降返回地幔至核幔边界，受热之后沿核幔边界侧向水平运动至地幔柱，补充地幔柱核幔热量和物质的亏损（Homes, 1931; Hess and Hall, 1960; Jellinek et al., 2002; Morgan, 2007; Tosi et al., 2013; French and Romanowicz, 2015; Nicolas et al., 2017）。这种地幔对流假设，认为地幔对流引起的大洋中脊岩石圈扩张生长速率等同于俯冲带岩石圈板块消减速率。事实上，对流中热能和岩浆的亏损量和补充量很难达到一致，即使大洋中脊岩石圈扩张生长速率等同于俯冲带岩石圈板块消减速率。随着大洋板块俯冲消减，大洋俯冲板块拆沉进入地幔，当大洋板片的物质不断进入地幔，以致使地幔物质过剩，地幔就处于不平衡状态，为了寻求平衡就会引起地幔上升流，以致产生地幔反向流动，在这地幔反向流动的作用下地壳或岩石圈就会发生伸展裂陷，产生弧间裂陷盆地。这岛弧扩张作用不仅促使俯冲带后退（海退），而且会抑制俯冲带的俯冲消减作用（图 11）。

在大洋中脊处，由于大量的热能和岩浆喷出地表，在热能和物质补充不及时的情况下，会导致深部热能和岩浆的亏损，进而会导致地幔柱构造带重力不均衡，因重力不均衡作用会引发大洋中脊处浅层岩石圈和软流圈的重力塌陷。在这种重力塌陷的作用下，会引起上地幔的反向流动，其反向流动势必带动大洋板块的反向运动，从而导致两大洋板块在洋中脊处俯冲消减，消减洋壳板片拆沉可进入地幔，甚至沉没至核幔边界上，随着洋壳板片的熔融，从而达到补充深部地幔能量、质量的亏损。地幔亏损强烈，那么重力塌陷就剧烈，地幔对流反转也会强烈，引起洋壳板块强烈反向漂移和收缩，可在地幔柱或热点处俯冲挤压。洋中脊俯冲消减长期强烈作用，可以导致大洋消失。如果地幔轻度亏损，那么重力塌陷也较弱，地幔对流反转也会较弱，洋壳板块反向漂移距离小，洋壳收缩挤压变形弱，洋中脊俯冲消减也弱。这个过程可能是局部的或区域性的、短暂的或长期性的、多期发生的。

如果洋陆俯冲带上升地幔对流反转子系统可与洋中脊的下降地幔对流反转子系统构成一超级大洋地幔对流反转系统。地幔对流反转可能导致大洋板块的反向漂移，大洋板块的反向构造作用，不仅可以抑制大洋脊或中脊的扩张作用，而且可能导致大洋板块沿着洋脊或洋中脊发生洋洋俯冲作用，最终可导致已有大洋消失，板块碰撞褶皱成山。同时可在洋陆俯冲带仰冲板块上产生新生大洋。

与大洋相比，大陆板块也可以发生类似的地幔对流，其差异性表现在由于大陆岩石圈负载较重，即使地幔对流的力大小一样，因此大陆板块漂移的速度就会很慢，这就是为什么大陆板块内构造作用较弱的根本原因。不管大陆内地幔对流速度如何，地幔对流一样存在正向、反向两种型式，其对流机制类似大洋地幔对流机制。在地幔对流反转作用下，大陆板块反向移动，导致大陆板块沿板内热点、地幔柱发生俯冲消减，引起陆内裂陷盆地收缩反转。盆地收缩反转变形的期次、强度受控于深俯冲作用的期次、强度。在多期强烈的深俯冲消减构造

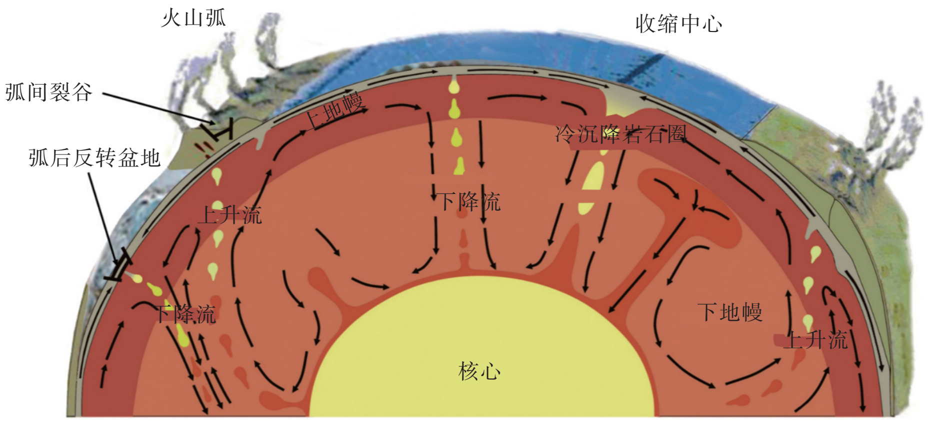

图 11　地球地幔对流反转模型
Fig.11　Inversion model of mantle convection

作用下，盆地会因此发生多期强烈收缩构造变形，最终会因不断的俯冲消减作用而使盆地消亡，导致大陆板内陆陆碰撞造山。

盆-山或山-盆是一具有成因联系的耦合构造体系。陆内裂陷盆地发育与造山可能存在成因联系，如同大洋盆地发育与俯冲造山具有成因关系一样，其成因联系的纽带是地幔对流。陆内造山作用与裂陷盆地发育也可能存在受控于地幔对流体系作用的成因联系，该地幔对流体系如同大洋发育的相互关联的地幔对流体系，尽管目前还没有成果能够证实。裂陷盆地发育具有阶段性，伸展和收缩可以交替发生。造山演化同样具有阶段性，造山和伸展垮塌可以交替发生。据海底扩张理论推测，裂陷盆地拉张裂陷期对应于造山带挤压隆起期，裂陷盆地收缩反转期则对应于造山带伸展塌陷期。这正是盆山耦合的必然结果。

5 讨 论

地幔对流反转过程是地幔乃至地球物质和能量交换、平衡的不可缺少的反向地质过程。无论全球还是局部地幔对流反转，都是在前期地幔对流的条件下发生的地幔反向流动。这种地幔对流反转一般发生在前期地幔对流过程的末期或期后，可能具有广泛性、局部性、短暂性、长期性、频发性、周期性的规律。地幔对流反转起因是当地幔圈层内地幔热能、物质等处于亏损或者过剩状态时，地幔圈层为了寻求均衡状态而引起的热能、物质的反向流动。

对于引起岩石圈扩张增生和俯冲消减的地幔对流而言，地幔对流反转则同样可引起岩石圈扩张增生和俯冲消减，地幔对流由热上升流演变为冷下降流，前期扩张增生带演变为俯冲消减带，地幔对流由下降流演变为上升流，前期俯冲消减带变为扩张增生带。板块会发生反向漂移，板块构造作用便会演变为构造反转作用。板块反转构造作用会导致两类板块构造作用发生，其一，引起板块俯冲消减、消失，甚至板块碰撞造山，洋盆、陆盆等消失；其二，引起板块扩张增生，产生陆盆、边缘海盆，以致出现扩张洋盆。在板块反转构造作用下，地球表层发育反转构造及变形，从而产生与前期构造性质相反的地质构造，形成叠加复合构造样式。

对于因地幔物质和能量亏损的板块构造活动带，地幔对流反转可为其地幔补充继续正向对流的物质和能量，而对于地幔物质和能量过剩的板块构造活动带，则为其地幔消耗继续正向对流的物质和能量，因此地幔对流反转作用是地幔正向对流能够继续进行的不可缺少的地质作用。

对于大洋，如果洋陆俯冲带上升地幔对流反转系统可与洋中脊的下降地幔对流反转系统构成大洋超地幔对流反转系统，那么在这个地幔对流反转系统作用下，最终导致已有大洋消失，板块碰撞褶皱成山，同时可在洋陆俯冲带仰冲板块上产生新生大洋。对于大陆，如果陆内板块间俯冲带上升地幔对流反转系统可与大陆板块内的下降地幔对流反转系统构成大陆超地幔对流反转系统，那么在这个地幔对流反转系统作用下，最终导致已有大陆板块消失，板块碰撞褶皱成山，同时可能在俯冲带产生新生大洋。

在超地幔对流反转体系的控制下，大陆板块内伸展裂陷盆地收缩反转与陆内板块间造山带伸展塌陷，构成从收缩反转到伸展裂陷的完整的大陆构造反转循环系统。加强与构造反转作用相关联的盆山耦合作用研究有利于完善对盆山关系的认识和理解。

地幔对流反转科学是一门涉及地幔流动及方式变化的新兴科学，重点研究地幔对流反转机理、方式、规模、演变及其对盆地反转启动机制、地球表层反转构造发育和演化的制约作用，为地幔流动创新性研究指引了新见解方向和新途径，如大陆拼合后裂陷分离动力来源等。预期为反转构造成因动力及机制研究开辟了崭新的领域，为地球演化史和板块构造演化历史的重建注入了新的活力。

6 结 论

（1）地幔对流反转是由于地幔圈层内地幔热能、物质等处于亏损或者过剩状态时，地幔圈层为了寻求均衡状态而引起的热能、物质的反向流动。地幔对流反转可引起岩石圈扩张增生和俯冲消减，引起板块发生反向漂移，进而导致板块内部构造作用演变为构造反转作用。板块反转构造作用会导致两类板块构造作用发生：引起板块俯冲消减、消失，甚至板块碰撞造山，洋盆、陆盆等消失；引起板

块扩张增生，产生陆盆、边缘海盆，以致出现扩张洋盆。

(2)地幔对流反转过程是地幔乃至地球物质和能量交换、平衡的不可缺少的反向地质过程。无论全球还是局部地幔对流反转，都是在前期地幔对流的条件下发生的地幔反向流动。这种地幔对流反转一般发生在前期地幔对流过程的末期或期后，可能具有广泛性、局部性、短暂性、长期性、频发性、周期性的规律。

(3)无论板块内裂陷盆地的正/负反转构造，还是造山带内的负/正反转构造，均是地壳或岩石圈构造反转作用的结果，地壳或岩石圈构造反转则是地幔对流反转作用引起的浅表层变形响应。在板块反转构造作用下，地球表层发育反转构造及变形，从而产生与前期构造性质相反的地质构造，形成叠加复合构造样式。

(4)地球表层的反转构造产生的动力，来源于现有地幔对流方式的反向对流所诱发的，因此研究地幔对流反转及其方式，有利于推动全球性反转构造研究的进步，更有利于补充完善板块构造学的基础理论的缺陷，推动大陆漂移、板块构造、海底扩张等研究迈向新的领域。

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