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二叠纪泛大陆球壳三维力学模拟及其构造意义

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内容提要:二叠纪时期,泛大洋包围泛大陆并向其俯冲,在此背景下泛大陆内部洋盆呈现剪刀差式旋转关闭,并具有此消彼长的特征。前人通过自俯冲平面模型来解释泛大陆裂解过程中裂谷盆地的成因和泛大陆内部简单的应力状态,但是该模型与实际的地质背景相差较大。本文通过球壳三维模型,并考虑非洲核幔边界低速带以及阿拉伯地幔柱对泛大陆的影响,建立了二叠纪时期泛大陆所处的力学模型,模拟了泛大陆形成后古特提斯洋盆俯冲、关闭对大陆内部产生的应力应变影响。模拟结果显示三维球壳模型能够较好地解释该时期中亚区域发育的大型断裂、残余洋盆,也支持古特提斯洋盆剪刀差式关闭、新特提斯洋盆从古特提斯洋盆被动陆缘后侧张开的地质现象;非洲—阿拉伯板块的地幔垂向作用为新特提斯洋盆的张开提供了力学支持。由于在泛大陆分裂过程中,新老洋盆此消彼长、早期洋盆剪刀差式关闭的模式并不仅局限于古特提斯—新特提斯洋,本模拟结果可适当推广到其他洋盆。

关键词:二叠纪;泛大陆;古特提斯洋;新特提斯洋;三维球壳模型;力学模拟

二叠纪时期,泛大陆周缘的泛大洋向内俯冲,在这种整体汇聚的背景下,由泛大陆中心点向外,不同板块之间运动幅度逐渐增大,古特提斯洋等许多古洋盆呈剪刀差式旋转关闭(图 1),以古特提斯洋与新特提斯洋为代表,新老洋盆此长彼消(杨树锋等, 2002; Collins, 2003; Metcalfe, 2006; Cawood and Buchan, 2007),并制约了此时期的盆地发育。但目前对造成这些现象的力学机制尚不清晰。针对泛大洋俯冲背景下泛大陆的裂解模式,前人曾使用“华力西—阿利根尼期”造山带垮塌模型,超大陆地幔柱模型和多种裂解机制结合的模型来进行模拟解释,但是这些模型都未能为泛大陆内部放射状裂谷盆地的形成提供较为合理的解释。Gutiérrezalonso 等(2008)在前人研究的基础上,提出自俯冲平面模型(Self-subduction),认为泛大陆在形成后立即发生了全球范围的构造活动(305 Ma),在泛大陆内部乌拉尔缝合带、沃其塔—阿利根尼—华力西缝合带等区域仍存在构造挤压,其外部被泛大洋包围并受泛大洋的俯冲作用,导致泛大陆内部应力应变发生快速变化;在古特提斯洋向北俯冲的晚期(299 Ma),古特提斯洋洋脊停止扩张并向北发生洋脊俯冲,而南侧发育被动大陆边缘,洋盆面积缩小;对应地,超大陆面积增大,出现外侧扩张、内部挤压的环境,进而在外侧拉张出一系列放射状裂谷,而内部则发育转换断层并在泛大陆内部形成一系列放射状裂谷(图 2a,2b)。自俯冲平面模型较好的解释了泛大陆裂解过程中裂谷盆地的成因和泛大陆内部简单的应力状态,但该模型尚存一些不合理之处:①泛大陆面积约占地球表面的三分之一,使用平面模型分析这种尺度的陆壳难免与实际情况存在不一致;②未将泛大陆周围一圈俯冲带(泛大洋)视为与特提斯洋同级别的构造单元,同时也未考虑现今位于非洲的大型核幔边界低速带(LLSWVPs, Large Low Shear wave Velocity Provinces)(Torsvik et al., 2008; Lü Ziqiang et al., 2018)以及阿拉伯板块之下地幔活动(Saccani et al., 2013),其力学影响考虑不足。

为此,本文在前人关于地壳应力场模拟的基础上(Dai et al., 2016),建立球壳立体模型,通过有限元数值模拟方法研究古特提斯洋盆的俯冲对泛大陆内部的应力作用。首先通过二叠纪时期泛大陆的构

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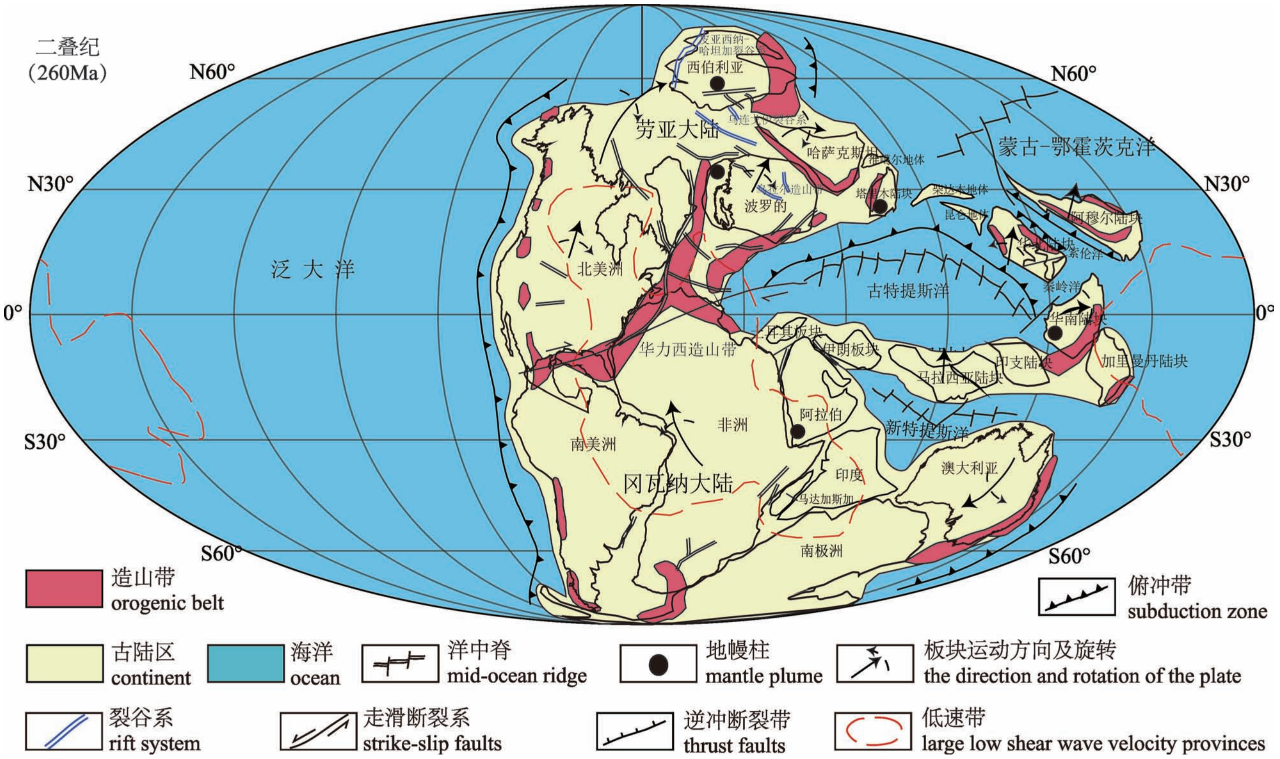

图 1 晚二叠世(260 Ma)泛大陆古板块再造图(古地磁数据源自全球古地磁数据库:GPMDB 4.6,http://www.ngu.no/geodynamics/gpmdb/;非洲核幔边界低速带范围据 Torsvik et al., 2008)

Fig. 1 Late Permian (260 Ma) reconstruction map of Pangaea (paleomagnetic data based on Global paleomagnetic database: GPMDB 4.6, HTTP://www.ngu.no/geodynamics/gpmdb/; Africa large low shear velocity provinces from Torsvik et al., 2008)

造格局建立地质构造格架与地质模型;再通过对地质模型简化,建立球壳三维几何模型,设定力学边界条件、岩石力学参数赋值和力学加载,建立力学模型;力学模型确立后,将该模型输入到 ANSYS 11.0 弹性有限元软件进行计算(张洪信和管殿柱, 2009;赵远和李时, 2008),最终输出构造应力相关结果,分析泛大陆内部应力应变状态及其与二叠纪时期泛大陆构造演化的关系。

1 模型设定

本文设计了两种球壳三维模型用于模拟二叠纪时期泛大陆演化过程中,古特提斯洋盆俯冲、关闭对泛大陆内部产生的应力应变影响(图 1)。模型 1 设定为三维立体模型,材料属性为花岗岩,设定杨氏模量为 2.6×10^6 MPa,泊松比为 0.25,密度 2.6×10^3 kg/m^3(洪有密, 1993 , 张咸恭, 2000);以球体上存在 60°缺口的壳体模拟泛大陆,其周缘存在 60 MPa 的应力模拟泛大洋对泛大陆的俯冲力(数量级参考现今太平洋—北美板块边界挤压应力(Flesch et al., 2000));以缺口模拟古特提斯洋,固定其左侧对应古特提斯洋南端的被动大陆边缘(图 2c,2d 中 AB 边),根据前人的研究结果认为古特提斯洋盆南部板块 50 mm/a 的速度向北东方向推挤,换算后施加到实际模型中相当于在其右侧加载 100 MPa 的应力对应古特提斯洋盆向北的俯冲(图 2c,2d 中 BC 边)(杨兴悦等, 2013);在球壳下方设置空心球体(赋予花岗岩属性,参数同上)模拟地壳下结构,并固定其内壁以进行模拟运算。此外,在球壳外表面仅加载了 10 MPa 的应力模拟垂向构造应力对泛大陆的影响,该应力大小表示模型构造垂向的构造应力释放的较为完整,减少垂向构造应力积累过大对模型内部应力状态造成影响(高尚华等, 2016)。模型 2 在模型 1 的基础上,进一步在 AB 边左侧添加径向向外的力 1.2×10^{11} N(图 2d),以模拟非洲 LLSWVPs 以及阿拉伯地幔柱对于泛大陆的影响(图 3c、e 中 MP)。

2 模拟结果

根据俯冲模型的模拟结果显示,随着古特提斯洋的俯冲,在泛大陆内部会出现一系列放射状裂谷,

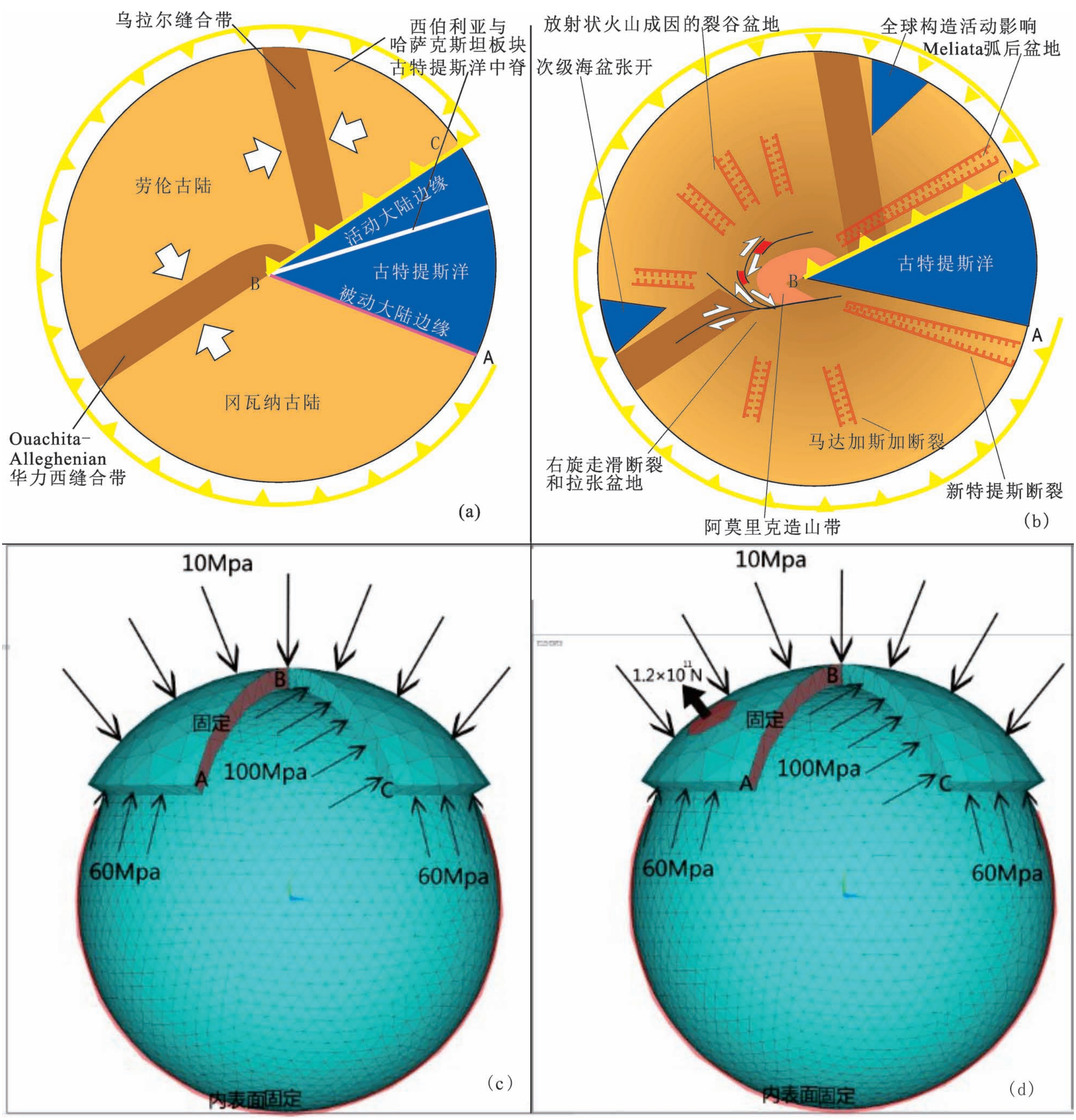

图 2 两种泛大陆球壳三维模型与自俯冲平面模型对比图(自俯冲模型据 Gutiérrezalonso et al., 2008 修改)

Fig. 2 Comparison of two Pangaea spherical shell 3D models and self-subduction model (modified after Gutiérrezalonso et al., 2008)

(a) 泛大陆自俯冲平面模型(305 Ma);(b) 泛大陆自俯冲平面模型(299 Ma);(c) 泛大陆球壳三维模型 1(无径向外力);(d) 泛大陆球壳三维模型 2(有径向外力)

(a) Pangaea self-subduction plane model (305 Ma); (b) Pangaea self-subduction plane model (299 Ma); (c) Pangaea spherical shell 3D model 1 (no radial external force); (d) Pangaea spherical shell 3D model 2 (with radial force)

且规模最大的两条裂谷出现在古特提斯洋盆南北两侧的主动大陆边缘和被动大陆边缘上(图 3a)。

泛大陆三维球壳模型 1 的模拟结果表明,轴向上拉应力主要集中于泛大陆核部位置(图 3d,箭头指示方向,其长度指示应变大小),在对应海西造山带和古特提斯洋南侧被动大陆边缘的南部也有拉应力存在;轴向上压应力分布呈同心状,由外向内依次增大(图 3d,箭头指示方向,其长度指示应变大小),

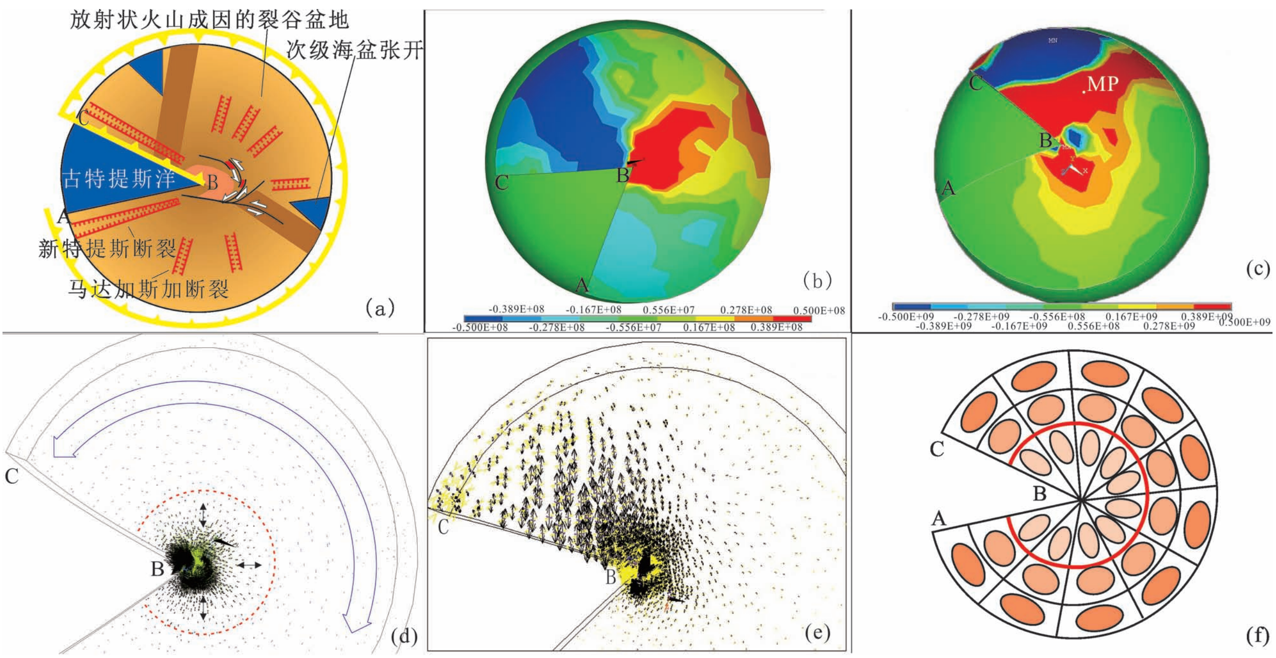

图 3 泛大陆自俯冲平面模型(据 Gutiérrezalonso et al., 2008)与球壳三维模型模拟结果图

Fig. 3 Simulation results of Pangea self-subduction model (modified after Gutiérrezalonso et al., 2008) and spherical shell models

(a) 泛大陆自俯冲平面模型(209 Ma);(b)、(c) 泛大陆球壳三维模型 1,2 差应力分布图(色阶中部为 0,左右正负值对称);(d)、(e) 泛大陆球壳三维模型 1,2 应变大小及方向分布图(箭头指示方向,其长度指示应变大小,宽箭头表示伸展方向);(f) 自俯冲平面模型应变分布图;(c),(e)中 MP 为阿拉伯地幔柱;(d)、(f) 中红线表示中性面

(a) Pangaea self-subduction plane model (209Ma); (b), (c) the difference stress distribution diagram of 1 and 2 of the Pangaea spherical shell 3D model (0 in the middle of the color scale, and the left and right positive and negative values are symmetric); (d), (e) the strain size and direction distribution diagram of Pangaea spherical shell 3D model 1 and 2 (arrow indicating direction, its length indicating strain size, and wide arrow indicating extension direction); (f) the strain distribution of the self-subduction plane model. The MP in (c) and (e) is Arabian mantle plume. The red line in (d) and (f) represents the neutral plane

该模拟结果与 Gutiérrezalonso 等(2008)的模拟结果相符合(图 3f);差应力分布在欧亚大陆中部和新特提斯洋部位的绝对值较大(图 3b,色阶中部为 0,左右正负值对称)。

泛大陆三维球壳模型 2 的模拟结果表明,拉应力主要分布在古特提斯洋被动大陆边缘之后(图 3e,箭头指示方向,其长度指示应变大小),同时该地区差应力绝对值最大(图 3c,色阶中部为 0,左右正负值对称),容易发生构造断裂活动。该模型的应变矢量图显示,在古特提斯洋被动大陆边缘之后,拉应力最大,易出现平行于被动大陆边缘的破裂。

3 讨论

自俯冲平面模型能够解释泛大陆内部放射状裂谷系的产生,但其结果显示在古特提斯洋的主动、被动大陆边缘均产生该时期最大的裂谷系,并认为被动大陆边缘一侧的裂谷系发育成为新特提斯洋盆,而主动大陆边缘一侧的裂谷系则仅发育成弧后盆地(Domeier and Torsvik, 2014),这种差异性的产生比较缺乏力学支持。相比自俯冲平面模型,球壳三维模型更接近泛大陆尺度的力学状态,且考虑了泛大洋俯冲、地幔柱垂向作用,模拟更为真实,实验结果更能反映当时的形成演化过程。

综合球壳单位模型力学模拟结果,可以发现:①球壳三维模型 1 内部的应变方向及大小与自俯冲平面模型内部应变分布基本相符,反映泛大陆内部应力状态由外围的轴向压缩到核部的轴向拉张的应力转变;②在泛大陆核部,同时分布有拉应力与压应力,且核部也为差应力异常区的汇聚地带,故而在该区域易发育大型断裂,这与中亚区域晚古生代的构造现象相一致(Dong L H et al., 2009 , Yang Gaoyue et al., 2012);③泛大陆核部为拉应力主要分布区之一,为残余洋盆可能出现的环境(巴尔喀什—准噶尔残余洋盆),在古特提斯洋南侧出现的拉应力反

映了古特提斯洋洋脊南侧处于构造伸展状态，发育被动大陆边缘。在海西造山带出现的拉应力则可能反映海西造山运动期间短暂的伸展构造作用(冯建伟等, 2009)或是后期的伸展崩塌阶段(Zhang Xiuzheng et al., 2016；Zhai Qingguo et al., 2017；尹和珍等, 2017)；④压应力分布区由内向外逐渐降低，故而洋盆关闭模式可能为剪刀差式关闭；⑤在泛大陆内部呈放射状的拉应力与差应力分布，则可解释该时期泛大陆内部出现的若干放射状裂谷的出现(徐均涛, 1996)；在古特提斯洋南侧被动大陆边缘南部的拉应力分布区，显示了后期新特提斯洋张开所需要的应力环境(李江海等, 2013, 2014)；⑥被动大陆边缘内侧(非洲、阿拉伯板块之下)的地幔垂向作用，有助于平行于被动大陆边缘断裂的出现，为后期新特提斯洋盆的张开创造了力学条件(Nerlich et al., 2016；Vicente et al., 2018；Zahirovic et al., 2018)。

值得说明的是，在古特提斯洋逐渐关闭、新特提斯洋逐渐张开的过程中，泛大陆内部不只存在这两个洋盆，还存在蒙古—鄂霍茨克洋、古亚洲洋—索伦洋等其它洋盆(Natal'In and Şengör, 2005；Metcalfe, 2006；Voo et al., 2006；Abrajevitch et al., 2008；Metelkin et al., 2010；Domeier et al., 2012；Torsvik et al., 2012)，并且很多在泛大陆内部出现的大型走滑断裂与劳伦超大陆范围内古亚洲洋、索伦洋的演化相关(Gutiérrezalonso et al., 2008)。这些洋盆也遵循“剪刀式”关闭的模式，且轴端和古特提斯洋盆接近，均位于泛大陆核部。因此，本模型的模拟结果不仅能应用于古特提斯洋，也同样适用于部分其它泛大陆发育过程中逐渐关闭的洋盆。

4　结论

三维球壳模型模拟了二叠纪泛大陆形成后古特提斯洋盆俯冲、关闭对泛大陆内部产生的应力应变影响，模拟结果显示在泛大陆核部同时存在拉应力与压应力，且也为差应力异常区的分布地带；泛大陆核部为拉应力主要分布区之一，压应力分布则较为均匀，由内向外逐渐降低，这些力学特征能够较好地解释该时期中亚区域发育的大型断裂、残余洋盆，也支持古特提斯洋盆剪刀差式关闭、新特提斯洋盆从古特提斯洋盆被动陆缘后侧张开的地质现象。被动大陆边缘内侧(非洲、阿拉伯板块之下)的地幔垂向作用，有助于形成平行于被动大陆边缘的断裂，为后期新特提斯洋盆的张开创造了力学条件。本模拟结果从泛大陆演化过程中内部应力状态分布的角度，填补了前人研究从假设到结论缺失的中间环节，并指出可将这一模拟结果适当推广到其它泛大陆发育过程中逐渐关闭的洋盆。

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Mechanical simulation of 3D spherical shell model for Permian Pangaea supercontinent and its tectonic significance

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Objectives:In the Permian period, the Panthalassa encircled and subducted the Pangaea. In this context, the ocean basin within the Pangaea appears to be rotating and closing like a scissors, with the fluctuation of each other. Previous studies have explained the genesis of rift basins and the simple stress states of the interior of Pangaea by using the self-subduction plane model, but this model is quite different from the actual geological background. By means of numerical simulation, a more accurate mechanical model conforming to the geological background at that time will be established in this paper to analyze and discuss the mechanical state in the process of the Permian Pangaea pyrolysis.

Methods:In this paper, a mechanical model of Pangaea in the Permian period was established by using a 3D spherical shell model and considering the effects of low-velocity zone of the African nuclear mantle boundary and the Arabian mantle plume on Pangaea, and the effects of subduction and closure of the Paleo-Tethys Ocean basin on the internal stress and strain of the continent after the formation of Pangaea were simulated.

Results:The simulation results of Pangaea 3D spherical shell model 1 show that the axial tensile stress is mainly concentrated in the core of Pangaea, and there is also tensile stress in the south of the passive continental margin corresponding to the Hercynian orogenic belt and the southern side of the Paleo-Tethys Ocean. The axial compressive stress distribution is concentric and increased successively from the outside to the inside. The absolute value of the differential stress is larger in the central Eurasia and the Neo-Tethys Ocean. The simulation results of the pan-continental 3D spherical shell model 2 show that the tensile stress is mainly distributed behind the passive continental margin of the Paleo-Tethys Ocean, and the absolute value of differential stress is the largest in this region, which is prone to tectonic fracture. The strain vector diagram of the model shows that the maximum tensile stress occurs after the passive continental margin of the Paleo-Tethys Ocean, and the rupture is prone to occur parallel to the passive continental margin.

Conclusions:The simulation results show that the 3D spherical shell model can well explain the large faults and residual ocean basins developed in the central Asian region during this period, and also support the geological phenomena of the clipping closure of the Paleo-Tethys Ocean basin and the opening of the Neo-Tethys Ocean basin from the back of the passive continental margin of the Paleo-Tethys Ocean basin. The mantle vertical action of the Afro—Arabian plate provides mechanical support for the opening of the Neo-Tethys Ocean basin. Because the old and new ocean basins were not limited to the old and new ocean basins in the process of the Pangaea splitting, the simulation results can be extended to other ocean basins.

Keywords: Permian; Pangaea supercontinent; Paleo-Tethys ocean; Neo-Tethys ocean; 3D spherical shell model; mechanical simulation

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