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实验流变学的发展现状与趋势

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摘　要: 实验流变学是通过高温高压实验手段研究地球内部主要组成物质在差应力的作用下发生变形和流动的学科.伴随着流变实验技术的不断发展,实验流变学在过去30年中得到了快速发展,研究范畴和研究对象不断扩大,在地球和行星科学的研究领域发挥着重要的作用.主要简要介绍了实验流变学技术的发展历史,围绕岩石圈、软流圈、转换带和下地幔流变学实验研究和中深源地震机制的研究总结了实验流变学领域的主要研究进展与存在问题,提出由物质成分和热结构控制的地球不同圈层流变学性质的三维结构是当前实验流变学研究需要解决的核心科学问题,并在此基础上展望了实验流变学未来的优先发展方向.

关键词: 实验流变学;研究进展;发展趋势;优先发展方向.

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Development Status and Trends of Experimental Rheology

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Abstract: Experimental rheology is a discipline that studies the deformation and flow of the main components of the Earth under the action of differential stress by means of high temperature and high pressure experiments. With the continuous development of experimental technology, experimental rheology has developed rapidly in the past three decades. The research scope and research objects have been continuously expanded, playing an important role in the research field of Earth and planetary sciences. This paper briefly introduces the development history of experimental rheology technology, and summarizes the main research progresses and existing problems in the field of experimental research on the rheology of the lithosphere, asthenosphere, transition zone and lower mantle and the study of the intermediate and deep focused earthquake mechanisms. It is proposed that the three-dimensional structure of the rheological properties of different layers of the Earth controlled by composition and thermal structure is the citical scientific problem to be solved in the current experimental rheology research, and on this basis, the priority development directions of experimental rheology in the future is prospected.

Key words: experimental rheology; research progress; development trend; priority development direction.

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实验流变学，是通过高温高压实验手段研究地球内部主要组成物质在差应力的作用下发生变形和流动的学科. 在常温常压下表现为脆性固体的岩石和矿物在地球内部高温高压条件下具有塑性和粘性变形的特征，其在高温高压条件下的力学性质是实验流变学研究的主要研究对象(Poirier, 1985; Wenk *et al*., 2000; Karato, 2008). 实验流变学可以在相对真实的温度和压力条件下模拟地球深部的动力学过程，是了解地球深部构造、流变性质和动力学过程的重要窗口和手段，可以起到与地球化学、岩石学和矿物学研究相互印证和补充的重要作用，也可以为数值模拟研究大尺度地球动力学过程提供关键基础参数(章军锋和金振民, 2013; 章军锋等, 2021). 地球内部的动力学和演化过程在很大程度上都取决于其内部物质的流变性质，如地幔对流、高原的隆升、盆地的凹陷、地震的诱发等都与地球深部高温高压条件下矿物和岩石的流变息息相关.

1　实验流变技术发展简史

现代实验流变学的研究工作是在20世纪50年代由美国加州大学洛杉矶分校Griggs教授开创的(Griggs and Miller, 1951). 在过去几十年用Griggs命名的固体/液体介质的活塞圆筒式流变仪得到了广泛的应用和发展，仪器和实验技术得到了不断的完善和改进，到20世纪90年代，Griggs固体介质流变仪的压力和温度分别可以达到5 GPa和1 500 ℃(Tingle *et al*., 1993)(图1). 与此同时，澳大利亚国立大学的Paterson教授致力于气体介质流变仪的技术研发和实验研究工作，实验的最高温度由最初的1 000 ℃逐步增加到了1 423 ℃，压力维持在0.5 GPa(相当于地球深部15 km)以内(Paterson, 1970, 1990). 气体介质流变仪具有比固体介质流变仪更高的应力测量精度(0.5 MPa以内)，并且具有静水围压、温度梯度小、样品尺寸大以及氧逸度、水逸度和孔隙流体压力可控等优势，在矿物单晶和橄榄石变形及部分熔融研究上获得了很好的应用. 由于5 GPa压力仅能对应上地幔浅部的深度范围，随着对地球深部物质变形实验的需求，伴随同步辐射技术的快速发展，高压条件下应力和应变的原位测量成为可能(Weidner, 1998)，可达5～20 GPa压力条件下的新一代流变仪(D-DIA)2000年以来在美国数所大学和国家实验室联合攻关下研制成功并

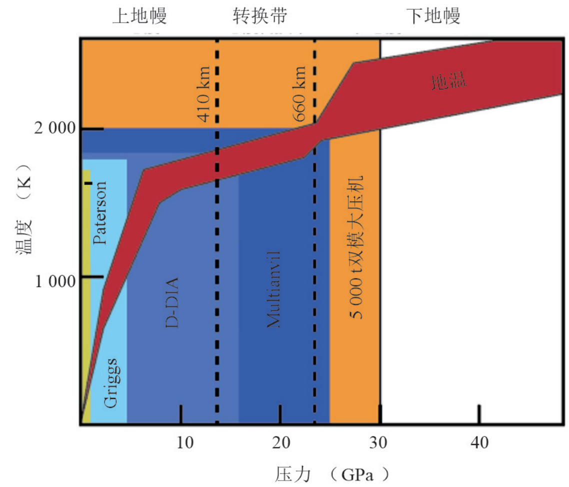

图1　常见高温高压流变仪设备能实现的温压范围

Fig.1　Temperature and pressure range of common high temperature and high pressure deformation apparatus

Paterson. Paterson流变仪；Griggs. Griggs流变仪；MultiAnvil. 多面砧压机

投入使用(Durham *et al*., 2002; Wang *et al*., 2003; Wang *et al*., 2010)(图1). 虽然D-DIA流变仪在应力和应变的测量精度方面存在不少需要改进的地方，但是首次实现了对深部地幔物质的定量流变学实验研究. 但由于D-DIA流变仪的使用需借助同步辐射X-射线衍射和成像技术测量样品的应力和应变，这在很大程度上限制了它的推广和广泛应用.

除了这3种主流流变仪外，还有一些为了特定目的建造的高温高压变形仪器，譬如研究脆性破裂和摩擦滑动的变形仪(Byerlee and Brace, 1968; Lockner and Byerlee, 1977). 在特定条件下多面砧压机(MultiAnvil)和金刚石压腔(DAC)也被用来进行超高压(>20 GPa)甚至核幔边界条件下的变形实验研究(Byerlee and Brace, 1968; Green *et al*., 1990; Karato and Rubie, 1997; Wenk *et al*., 2000; Merkel *et al*., 2002; Wu *et al*., 2017).

我国的实验流变学研究工作是从20世纪50年代后期的"长江-500型"液体介质三轴试验机开始起步，从常温低压逐步发展到高温高压，到80年代初期国家地震局地质研究所成功研制气体介质(0.4 GPa, 600 ℃)和固体围压介质三轴仪(2GPa, 1 000 ℃). 中国科学院地球物理研究所在80年代末成功研制了800 t大型伺服控制高温高压流变仪和3 GPa固体围压介质三轴流变仪(Kie *et al*., 1989; 石泽全和于智海, 1986; 孙天泽, 1989). 但是随后高温高压流变实验技术和仪器研制工作便基本处

于停滞阶段，人才损失严重，同国际实验流变学之间的差距越拉越大.2005年以来重新起步，中国地震局地质研究所和中国地质大学(武汉)先后研发了新一代的固体熔融盐介质的高温高压流变仪和相关技术(Liu *et al.*, 2016, 2017; Shi *et al.*, 2015, 2018; Shao *et al.*, 2021; Wen *et al.*, 2021)，以及气体介质高温高压流变仪(Zhou *et al.*, 2017)，中国科学院广州地球化学研究所引进了Paterson流变仪(Song *et al.*, 2014). 2020年以来中国地质大学(武汉)建设了5 000 t双模大压机，该大压机的D-DIA流变仪为实现厘米级样品在地幔转换带及下地幔顶部条件下的岩石流变学实验奠定了硬件条件.

2 研究现状与发展趋势

实验流变学主要通过高温高压流变实验对地球内部主要组成岩石和矿物的流变性质进行系统性的科学研究，聚焦解决固体地球科学的前沿科学问题，为相关的地质现象和地球物理观测结果的合理解释提供实验依据和进行有效的约束，是推动地球动力学发展的基础性科学.近30年以来，伴随着高温高压流变实验技术的发展，实验流变学的研究范畴、研究对象和研究内容在不断的扩大，围绕着地球和行星科学的重大问题和学科的发展需要，在越来越多的研究领域发挥着重要的作用.实验流变学按岩石和矿物变形性质的不同，可分为流变学(塑性)变形实验研究和地震机制(脆性)变形实验研究.按研究对象的不同，又可以将流变学变形实验分成岩石圈、软流圈、转换带和下地幔流变学实验研究.

2.1 岩石圈流变学实验研究

岩石圈流变学研究进展主要聚焦于岩石圈主要组成岩石橄榄岩、榴辉岩、麻粒岩和石英岩流变学力学强度的研究.岩石圈流变学强度的不均一性是决定岩石圈力学结构的重要因素(Bürgmann and Dresen, 2008)，因此通过实验流变学建立的岩石圈主要组成矿物的本构方程是建立其力学结构的基础.经典的岩石圈流变结构模型指示大洋岩石圈过于刚性而无法解释大洋板块的弯曲和初始俯冲，大陆岩石圈则过于软弱而无法合理解释大陆山根的长期保存(图2).大陆岩石圈横向和纵向上的成分不均一性可能是其主要原因，但目前对流体和熔体组分影响岩石圈流变结构的流变实验和数值模拟的研究依然十分匮乏.我国学者最近在建立岩石圈流变学本构方程领域做出了重要贡献，分别建立了"干"和"湿"条件下榴辉岩及其主要组成矿物绿辉石的流变学本构方程(Jin *et al.*, 2001; Zhang *et al.*, 2006)、下地壳主要组成岩石镁铁质麻粒岩和长英质麻粒岩(Wang *et al.*, 2012; Zhou *et al.*, 2017; Wen *et al.*, 2021)、辉长岩(He *et al.*, 2003; Zhou *et al.*, 2012)，以及地壳重要组成矿物钾长石(Chen *et al.*, 2021)的流变学本构方程，讨论了熔体对基性岩流变的影响(Zhou *et al.*, 2012, 2017).

相对于岩石圈中其他组成矿物的流变学性质的研究，上地幔的主要组成矿物橄榄石的研究程度最高(Cooper and Kohlstedt, 1986; Mei *et al.*, 2010)，已建立了其在不同地质环境下的流变学本构方程，发现结构水可以导致橄榄石流变强度的降低和组构的转变，但是对于水对橄榄岩流变强度的影响也仍旧存在争议(Mei and Kohlstedt, 2000; Jung and Karatao, 2001; Fei *et al.*, 2013).由于实验技术的局限性，压力对于橄榄石流变学强度影响的实验数据目前仍比较缺乏(Li *et al.*, 2006)，导致目前关于压力对橄榄石强度影响程度的认识依然存在很大的不确定性.岩石圈流变学实验研究中除橄榄石之外，我国学者还分别建立了辉石和石榴石的流变学本构方程(辉石：Zhang *et al.*, 2006; Zhang *et al.*, 2017, 2020; 石榴石：Xu *et al.*, 2013).总的来说，岩石圈流变学实验研究还有很大的发展空间，现有大多数实验成果只是阐明了水饱和与水不饱和条件下岩石强度的变化趋势，(结构)水含量对岩石和矿物流变强度定量影响的实验数据仍旧很少.

2.2 软流圈流变学实验研究

软流圈是地球深部强地震波各向异性区，与地幔循环和深地流变息息相关. Kohlstedt and Holtzman(2009)提出软流圈较低的流变强度、较强的各向异性和高导电性主要是由于其具有较高的熔体含量引起的. Karato(2012)提出软流圈流变学模型，认为富流体和颗粒边界滑移可以用来解释软流圈较低的强度和地震波速度的衰减. Miyazaki *et al.* (2013)通过对细粒橄榄石集合体的流变学实验揭示细粒橄榄石在扩散蠕变机制下发育强组构，可以解释软流圈各向异性和低流变强度. Mierdel *et al.* (2007)在分析变形橄榄石的超显微构造时发现，橄榄石颗粒边界在差异应力作用下形成的熔体诱发了颗粒边界滑移，提出斜方辉石含水量随深度

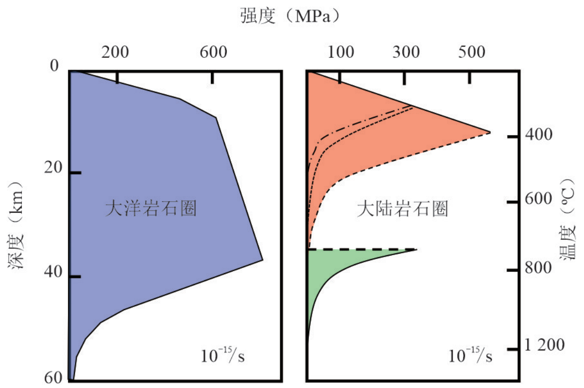

图 2　典型岩石圈流变结构

Fig.2　Typical lithosphere rheological structure

据 Kohlstedt *et al*.(1995)

的增加而减小，额外释放的水形成的熔体可以用来解释软流圈的低流变强度. 显然，虽然对于软流圈成因模型已有大量的研究成果，但是对于其合理解释依然存在很大争议，究竟是熔体、水和变形机制中的哪种因素起到主导作用，或是软流圈的形成是不同影响因素共同作用的结果？这些科学问题是固体地球科学研究的最前沿，解决这些科学问题需要高压条件下(4～7 GPa)原位流变学实验、地质学、地球化学和地球物理观测、数值模拟研究的协同攻关.

2.3　转换带和下地幔流变学实验研究

转换带和下地幔流变性质的研究随着对下地幔物质组成认识的逐渐深入，也越来越多地成为关注的焦点. 地球物理探测的结果表明地幔转换带存在剪切波各向异性(Trampert and van Heijst，2002)，下地幔也存在大低速剪切波速区域(LLSVPs)和强的剪切波速各向异性特征(Garnero *et al*.，2016)，但目前对这些观测结果的解释还缺乏实验数据的支撑和约束. 瓦兹利石(Wadsleyite)和林伍德石(Ringwoodite)是地幔转换带的主要组成矿物. 前人已有一些对于它们流变学强度的实验研究，结果表明林伍德石比布里奇曼石以及瓦兹利石的强度要小(Hustoft *et al*.，2013；Kawazoe *et al*.，2016)，可能是导致地幔转换带下部强变形的主要因素，其变形机制以位错蠕变为主. Mohiuddin *et al*.(2020)在橄榄石向林伍德石相变实验的显微构造中发现，橄榄石在相变过程的相变产物以细粒的林伍德石为主，因此提出冷的俯冲板片在地幔转换带深部主要以粗粒的橄榄石和细粒的相变产物组成，可以发生较强的变形，而热的俯冲板片在地幔转换带深部主要以粗粒的相变产物为主，变形可能较弱. 总的来说，对地幔转换带矿物流变学性质的研究依然非常薄弱，还缺乏物理机制来合理解释地幔转换带地震波各向异性.

下地幔流变学研究是最近几年随着实验技术和计算模拟技术的提高才开始有少量成果出现. Girard *et al*.(2016)通过对布里奇曼石和镁方铁石多晶集合体的流变性质的实验研究，发现布里奇曼石比铁方镁石的强度要大，提出铁方镁石承担了下地幔的主要应变. Tsujino *et al*.(2016)通过对布里奇曼石在下地幔顶部温压条件的变形实验推测其主滑移系为[001](100). 对下地幔矿物的模拟计算结果显示扩散控制的纯攀移蠕变控制了下地幔的黏度(Reali *et al*.，2019). Wu *et al*.(2017)通过实验首次获得了D″层后钙钛矿的组构特征，发现该组构可以产生弱地震波各向异性，可以用于解释D″层的波速结构.

2.4　中深源地震机制的研究

实验流变学在塑性变形之外的另一个重要的研究方向是脆性变形研究，也就是对深部地震活动物理机制的研究. 传统的地震物理机制认为地震的产生是由岩石的脆性破裂造成. 地球内部随深度的增加，温度的增加使岩石的强度逐渐下降，压力的增加使岩石破裂所需要的应力增大，因此一般认为地球深部(＞70 km)是无法产生岩石的脆性破裂或地震活动的，但是地球物理观测结果显示以往认为不可能产生地震的俯冲带深部同样观测到了大量地震活动，说明深部地震不能简单地以浅部地震的物理机制来解释.

深部地震主要集中在大洋俯冲带，随着地震分析精度的提高，深部地震的观测可以为认识地球内部结构和构造提供直接依据，直观地展示俯冲板片的几何形态，以及俯冲板片和周围地幔物质的流变学性质等(Isacks and Molnar，1969；Goes *et al*.，2017；Hayes *et al*.，2018). 深部地震活动物理机制的研究，还可提供俯冲板片的温度，含水状态和相变等重要物理参数(Green *et al*.，2010). 因此，深部地震成因物理机制的研究对认识和了解地球内部结构、物质状态和动力学过程具有重要的意义.

中深源地震(深度＞70 km)数量占据全球地震数量的2/3. 过去30年已有大量关于深部地震物理机制的研究成果(详见 Kirby *et al*.，1996；Green and Marone，2002；Frohlich，2006；Hasegawa and

Nakajima, 2017; Zhan, 2020等的综述). 由于俯冲板片在中源(70～300 km)和深源(＞300 km)地震发生的深部物质状态的不同, 中源地震和深源地震的物理机制也被认为存在不同. 中源地震的成因物理机制主要有: 脱水致裂(Dobson *et al.*, 2002; Jung and Green, 2004; Zhang *et al.*, 2004; Okazaki and Hirth, 2016)和剪切热失稳(Kelemen and Hirth, 2007). 深源地震的成因物理机制主要包括橄榄石相变为其高压相尖晶石相时形成的反裂隙诱发(Burnley *et al.*, 1991; Green and Zhou, 1996; Kirby *et al.*, 1996; Schubnel *et al.*, 2013; Wang *et al.*, 2017). 剪切热失稳(Karato *et al.*, 2001)和脱水致裂(Omori *et al.*, 2004). 越来越多的地球物理观测数据表明, 上述每一种物理机制都可能在特定的俯冲带条件下占主导地位, 但任何单一的机制都无法解释全部的俯冲带深部地震(Zhan, 2020), 特别是中源地震. 如果它们都是由于脱水反应诱发的, 那么就需要俯冲板片界面以下较深的地幔物质存在大量含水矿物(Peacock, 2001; Hacker *et al.*, 2003; Zhan, 2020). 如果热失稳是诱发中源地震的主要机制(Kelemen and Hirth, 2007; John *et al.*, 2009; Prieto *et al.*, 2013), 那么就需要俯冲板片具有较低的含水量. 目前关于中深源地震成因物理机制还存在很大的不确定性, 这些争议的合理解释需要对高温高压条件下俯冲板片主要组成岩石力学性质的深入认识.

中源地震最显著的特点是双地震带(double seismic zones; DSZ). 双地震带是指在俯冲板片中间隔一定距离呈条带分布的地震震源区域(图3), 在全球绝大多数的俯冲带中均被观察到(Brudzinski *et al.*, 2007). 其深度范围在50～300 km, 随着深度的增加, 双地震带的上下地震带最终会在一定的深度汇聚(Brudzinski *et al.*, 2007; Hasegawa and Nakajima, 2017; Florez and Prieto, 2019), 形成舌状结构. 目前的主流观点认为, 这种舌状结构是俯冲板片脱水, 从而诱发高压条件下的脆性破裂(地震)形成的(Peacock, 2001). 该观点也得到了一些俯冲带含水矿物脱水致裂实验证据的支持, 例如: 蛇纹石(Dobson *et al.*, 2002; Jung and Green, 2004; Gasc *et al.*, 2011)、硬柱石(Okazaki and Hirth, 2016; Incel *et al.*, 2017)、名义上无水矿物微量结构水(Zhang *et al.*, 2004)诱发的脱水致裂. Dobson *et al.* (2002)和Jung *et al.* (2009)通过蛇纹石的高温高压脱水实验结合声发射技术, 在脱水过程中观察到了声发射信号, 为蛇纹石脱水造成中源地震提供了关键实验依据.

但是最新的一些实验研究表明, 蛇纹石脱水反应并不是导致不稳定滑动的直接因素, 同时蛇纹石脱水反应还会阻止不稳定滑动即破裂的形成(Brantut *et al.*, 2010, 2012; Chernak and Hirth, 2010, 2011; Proctor and Hirth, 2015; Okazaki and Hirth, 2016; Ferrand *et al.*, 2017; Shao *et al.*, 2021, 2022a). Plümper *et al.* (2017)通过对天然样品的分析提出蛇纹石脱水反应产生的流体并不能明显的增加孔隙流体压力, 并提出脱水反应可能不是造成中源深度地震的主要原因. 而且, 高的孔隙流体压并不一定会导致脆性破裂(Chernak and Hirth, 2011), Shao *et al.* (2022b)通过对叶蛇纹石脱水动力学的实验研究提出脱水反应产物的粒度可能对蛇纹岩的力学行为起着重要的制约作用. Barcheck *et al.* (2012)对全球主要俯冲带中深源地震的发震频率同含水矿物脱水的相关性统计指出含水矿物脱水同地震发震频率之间不存在强烈的相关性, 提出含水矿物脱水并不是造成中源深度地震的主要因素. Florez and Prieto (2019)对全球典型双地震带的地震数据进行了重新定位, 同时对其地震参数进行了系统分析, 指出上下地震带的*b*-值(Gutenberg-Richter *b* value: 地震震级同发震频率之间的关系)存在明显的差异, 提出上地震带的形成同含水矿物的脱水反应相关, 而下地震带的形成环境是在"干"的岩石圈地幔物质中形成的.

显然, 这些新的实验和地球物理观测结果都对脱水致裂是中源地震主要成因物理机制的主流观点提出了挑战, 特别是中源地震的下地震带的成因机制. 这些下地震带中的地震主要出现在俯冲大洋岩石圈板片的方辉橄榄岩(Irifune and Ringwood, 1987)中, 其主要组成矿物是橄榄石、辉石和石榴石等其它矿物, 一般不含含水矿物. 俯冲带海隆位置处的深大断裂被认为是运输水进入到20～40 km深处的大洋岩石圈的主要途径. 但是, 俯冲带中源地震的下地震带附近虽然观察到了低速层(低V_p和低V_p/V_s)(Tsuji and Iturrino, 2008; Shiina *et al.*, 2013), 其成因可能并不是含水矿物脱水形成的(Nakajima *et al.*, 2009; Hasegawa and Nakajima, 2017), 因为通常较高的V_p/V_s才指示蛇纹石化程度较高的橄榄岩或指示岩石富流体(Dorbath *et al.*,

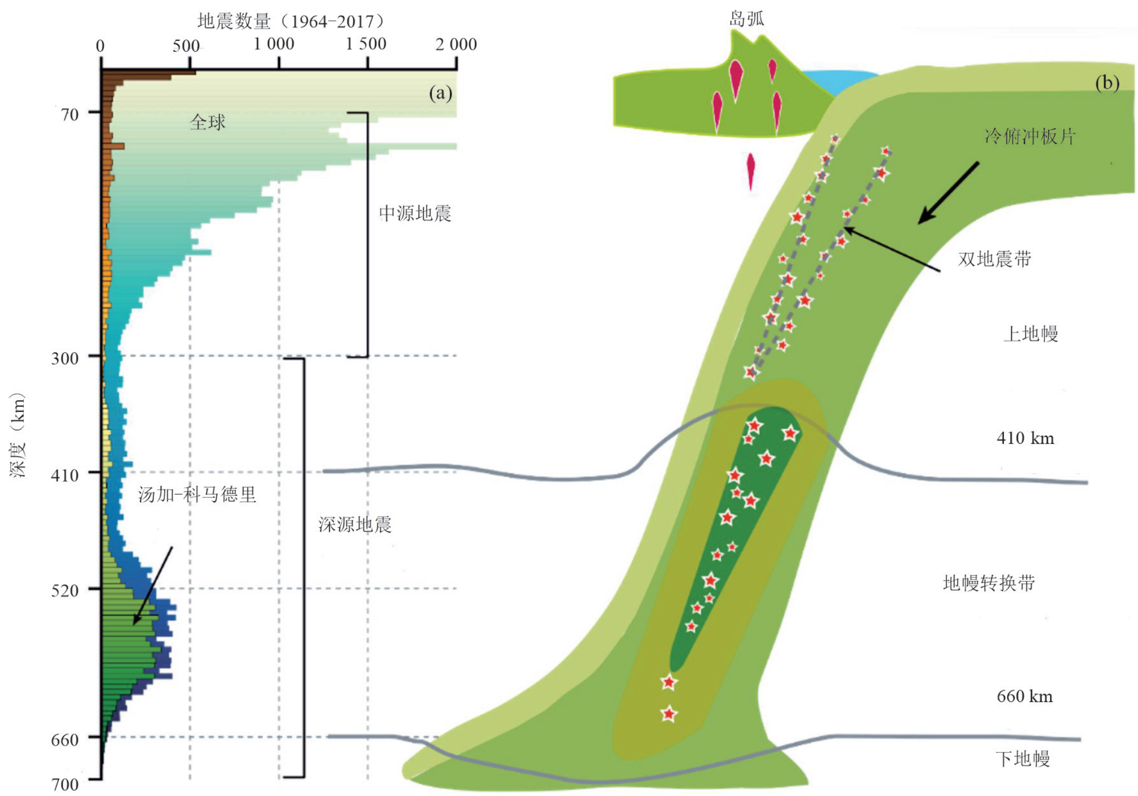

图 3　俯冲板片地震分布特征

Fig. 3　Seismic distribution characteristics of a subducting slab

据 Zhan(2020)；a. 中深源地震发震数量(1964～2017 年)随深度的变化，汤加－克马德里俯冲带深源地震(＞300 km)约占全球深源地震的 3/4；b. 俯冲板片中中深源地震分布示意

2008)，而较低的 V_p/V_s 指示了下地震带是在“干”的环境中形成的，可能与变形橄榄石的各向异性有关(Reynard *et al.*, 2010).

相变致裂机制是深源地震的重要机制之一. 在实验室条件下观察到的高压脆性破裂的显微构造(Burnley *et al.*, 1991)和地球物理观测结果揭示的全球多个俯冲带中亚稳态橄榄石为相变致裂机制提供了关键证据(Lidaka and Suetsugu, 1992; Jiang and Zhao, 2011; Kawakatsu and Yoshioka, 2011; Shen and Zhan, 2020). 随着 D-DIA 实验技术的发展，尤其是声发射技术和同步辐射成像技术的应用，以及使用地震分析方法中的 HyPODD 等高精度定位方法在声发射信号处理中的使用，在实验条件下可以原位观察到样品中破裂的孕育和传播，为相变致裂机制作为深源地震物理机制提供了更进一步的证据(Schubnel *et al.*, 2013; Wang *et al.*, 2017)(图 4). 但是，相变致裂机制也存在一些较难解释的问题，例如，天然地震中散失的大量热能最后都是以熔体的形式传播出去，但是在实验样品中并未观察到熔体的存在；地震观测结果显示地震的发生可能比准稳态橄榄石存在的范围要大. 以往实验室是使用的单一相的类质同相体镁锗橄榄石作为实验室的起始材料，而地幔转换带中准稳态橄榄石的组分是镁硅橄榄石，由于实验仪器的限制，直接以镁硅橄榄石作为起始材料的实验还存在很大的困难和挑战. 俯冲板片的主要组成是以方辉橄榄岩为主，关于辉石对深源地震活动影响的研究还基本属于空白. Zhan(2020)通过对深源地震性质的分析结果提出深源地震物理机制可能是多种机制共同作用的结果，但是目前对于这一结论缺乏流变学实验证据的支撑.

3　关键科学问题与挑战

3.1　研究背景

实验流变学是推动地球动力学发展的基础性科学. 地球物质流变学包括岩石圈流变学、软流圈流变学、转换带流变学、下地幔流变学和俯冲带流变学等. 基于刚性大洋板块运动的板块构造理论曾极大促进了固体地球科学的发展，并发展成为固体

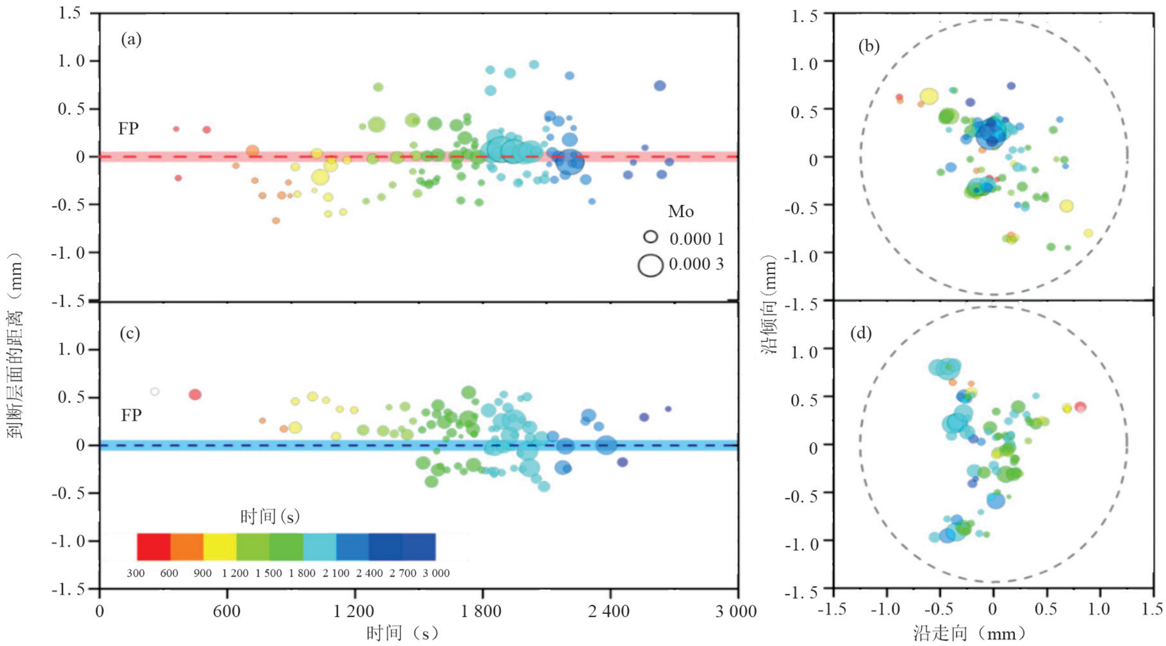

图4　镁锗橄榄石相变致裂实验声发射信号分析

Fig.4　Acoustic emission signal analysis of a faulting experiment on Mg_2GeO_4

据 Wang *et al*.(2017)

地球科学的指导学说.岩石圈流变学的兴起，发展了经典板块构造的理论(Bürgmann and Dresen, 2008)，合理解释了大陆岩石圈变形的横向不均一性和纵向分层性，推动了板块构造的登陆和大陆动力学研究的发展.如何进一步发展甚至超越板块构造理论，从地球物质流变学的角度来解译地球这个由密度和热不均一态驱动下的超级流变体系，是当前固体地球科学研究的最前沿之一(Gerya *et al*., 2015)，受到了国际同行的高度重视，如欧盟的Horizon 2020中的CREEP研究计划，美国自然科学基金会的流变学大挑战研究计划和正在积极推动的DEFORM联盟研究计划.

岩石圈的流变学性质控制了克拉通形成后的长期稳定性、板内地震和地壳变形的样式及过程、板块俯冲的起始方式和过程(Bürgmann and Dresen, 2008; Goes *et al*., 2017; Hayes *et al*., 2018).经典岩石圈流变结构模型中，大洋岩石圈过于刚性而较难解释大洋板块弯曲和俯冲，大陆岩石圈则过于软弱而无法解释大陆山根的长期保存.大陆岩石圈横向和纵向上的成分不均一性可能是主要原因，特别是熔体和流体组分对岩石圈流变结构影响的流变实验和数值模拟研究仍旧十分匮乏，深部地壳是岩石圈流变学研究的关键区域(Wang *et al*., 2012; Wen *et al*., 2021).认识整个岩石圈的流变学变化也被美国基金委学科愿景报告列为地质学面临的重大科学挑战之一.

软流圈、转换带和下地幔流变学性质控制了地幔对流、地幔柱运动、地球深部的成分和波速各向异性层.软流圈、转换带、D"层是地球深部的强地震波各向异性层(Trampert and van Heijst, 2002; Garnero *et al*., 2016)，与地幔循环和深地流变息息相关，但我们目前对深部地幔粘度(流变性质)估计的误差在10～100倍(图5).我们对软流圈成因的认识正在随着实验流变学研究的进展发生深刻的转变，由部分熔融导致的地幔低速带成因正在经历水和变形机制不同成因的挑战(Mierdel *et al*., 2007; Karato, 2012).我们也已经开始涉及以前完全是研究禁区的转换带主要组成矿物瓦兹利石、林伍德石和下地幔主要矿物布里奇曼石的流变强度或变形组构的开拓性研究(Hustoft *et al*., 2013; Kawazoe *et al*., 2016; Wu *et al*., 2017; Reali *et al*., 2019; Mohiuddin *et al*., 2020).目前存在的问题仍旧是实验技术难度非常大，定量实验数据少，争议大，尚未建立任何可靠的力学本构方程.虽然已经有个一个良好的开始，高压(4～7 GPa)和极高压(＞20 GPa)地球内部原位条件下的流变学实验和数值模拟仍旧是巨大的技术和科学挑战，但也是深刻理解流变学性质控制下的地球内部动力学过程与构造

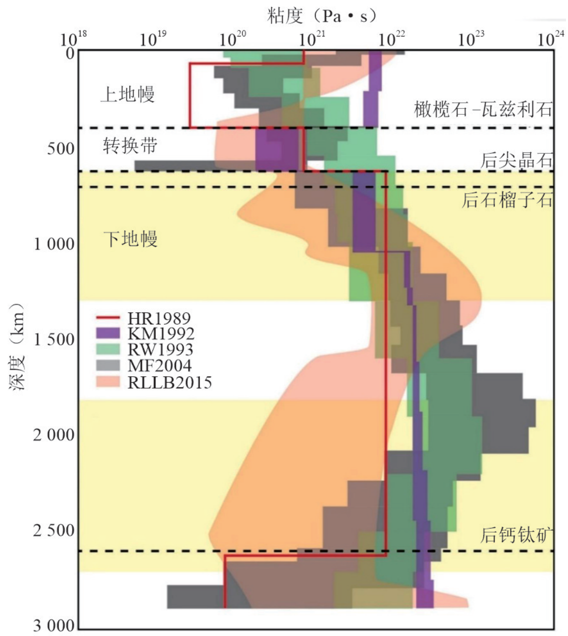

图 5　地幔粘度随深部的变化

Fig. 5　Variation of mantle viscosity with depth

据 Faccenda and Dal Zilio(2017)

演化的关键和推动固体地球科学理论发展创新的源泉.

3.2　关键科学问题

由物质成分和热结构控制的地球不同圈层流变学性质的三维结构是实验流变学研究需要解决的核心科学问题.地球不同圈层的流变学性质研究需要以地质学和地球物理观测为基础，以实验和数值模拟为主要手段，建立地球不同圈层流变学性质的三维结构，探讨地球内部矿物和岩石的强度和变形行为，进而揭示地球内部构造演化过程.当前实验流变学面临的核心科学问题包括：

3.2.1　微量结构水和熔体对常见壳幔矿物流变性质的影响　已有的研究结果表明岩石和矿物集合体中少量的结构水或熔体会对其流变学强度造成很大的影响，但其中绝大多数实验只是简单地对比了水饱和与水不饱和条件或无熔体和有少量熔体下岩石强度的变化.由于岩石中水活度的不同，会造成在同一岩石中不同矿物之间存在水的分配，现有的研究缺乏水在常见壳幔岩石主要组成矿物间的分配系数的系统了解，同时结构水含量对常见壳幔岩石主要组成矿物流变强度定量影响的实验数据依然很少(Mei and Kohlstedt，2000；Jung and Karatao，2001；Kohlstedt and Holtzman，2009；Fei *et al.*，2013)，考虑的熔体体系也存在相对单一和与矿物体系化学不平衡的现象.厘清微量结构水和熔体对常见壳幔矿物流变性质的影响是深入认识由物质成分和热结构控制的地球不同圈层流变学性质三维结构的基础.

3.2.2　中深源地震的成因物理机制　深部地震成因物理机制的研究对认识和了解地球内部结构、物质状态和动力学过程具有重要的意义.过去几十年虽已有大量关于深部地震物理机制的研究成果(Kirby *et al.*，1996；Green and Marone，2002；Frohlich，2006；Hasegawa and Nakajima，2017)，但不断积累的地球物理观测和实验数据提出了新的认识和挑战，深部地震的成因物理机制仍存在很大的争议和不确定性(Zhan，2020)，开展高温高压条件下俯冲板片主要岩石类型及其组成矿物力学性质的流变学研究是解决这些争议的重要途径.

4　主要研究方向和应对策略

针对上述提到的关于由物质成分和热结构控制的地球不同圈层流变学性质的三维结构科学问题，实验流变学未来的主要研究方向包括：

(1)矿物变形对地球流变性质的约束.结合天然和实验变形样品，开展地球不同圈层(岩石圈、软流圈、转换带、下地幔)主要造岩矿物的变形构造－显微构造－亚微构造－组构分析，查明不同温压条件下不同矿物变形规律及其对岩石物性和地震波各向异性的约束及影响因素，确定矿物变形对于地球不同层圈流变学性质的贡献.

(2)研究流/熔体活动与地球流变分层和地震活动成因.通过高温高压变形(流变)实验，定量确定实验体系中熔体或流体的含量，查明不同含量熔体和流体对岩石流变强度、变形组构和变形机制的影响，明确其对岩石的高压脆性破裂的贡献，揭示地球的流变不均一性和俯冲带地震成因的物理机制.

(3)地球流变性质三维结构研究.结合天然岩石变形观察和流变学实验研究成果，并根据已有的全球地幔密度异常、地幔对流和历史动态地形模型，进行多尺度地幔－地壳变形数值模拟，为下地壳流动、克拉通长期稳定性、岩石圈拆沉或俯冲、俯冲带和转换带变形、地幔对流等地球动力学过程提供约束.

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