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陆壳超深俯冲到斯石英稳定域地幔深度(~300 km)的新证据

刘 良[1],陈丹玲[1],章军锋[2],康 磊[1],王 超[1],杨文强[1],廖小莹[1],任云飞[1],盖永升[1]

1. 西北大学地质学系,大陆动力学国家重点实验室,陕西西安 710069
2. 中国地质大学地球科学学院,地质过程与矿产资源国家重点实验室,湖北武汉 430074

摘 要: 南阿尔金高压-超高压变质岩带泥质片麻岩中发现先存斯石英出溶蓝晶石+尖晶石的显微结构证据,将陆壳深俯冲的深度推进到了斯石英稳定域的地幔深度(≥300 km).然而,该类岩石是局部出现的还是具有一定的普遍性以及又是如何折返出露地表的?十多年来一直困惑着地球科学界.针对这一科学问题,通过系统的岩石学研究,在南阿尔金榴辉岩中首次发现了斯石英副象,重新厘定南阿尔金英格利萨依石榴辉石岩中石榴子石出溶单斜辉石和北秦岭松树沟长英质片麻岩中石榴石出溶石英棒状体岩石的峰期变质压力为9~10 GPa的斯石英稳定域,结合先期南阿尔金泥质片麻岩中发现先存斯石英出溶显微结构的研究成果,论证提出陆壳俯冲到斯石英稳定域的地幔深度(~300 km),然后再折返回地表的地质现象可能更为普遍,其岩石类型也可能具有多样性.通过高温高压实验研究,明确 SiO_2 饱和岩石体系中石榴子石超硅的最小稳定条件为≥9~10 GPa斯石英稳定域,为识别辨认陆壳岩石俯冲到斯石英稳定域地幔深度的研究提供了新的借鉴和思路.

关键词: 陆壳超深俯冲;斯石英副象;超硅石榴石;斯石英稳定域;地幔深度;折返机制.
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New Evidence of an Ultra-Deep Continental Subduction to Mantle Depth (~300 km) in Stishovite Stability Field

Liu Liang[1], Chen Danling[1], Zhang Junfeng[2], Kang Lei[1], Wang Chao[1], Yang Wenqiang[1], Liao Xiaoying[1], Ren Yunfei[1], Gai Yongsheng[1]

1. *State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xi'an* 710069, *China*
2. *State Key Laboratory of Geological Processes and Mineral Resources, School of Earth Sciences, China University of Geosciences, Wuhan* 430074, *China*

Abstract: The discovery of kyanite+spinel exsolutions in former stishovite of pelitic gneisses from the South Altyn HP - UHP metamorphic belt suggests an ultra-deep subduction and exhumation of the South Altyn continental rocks to/from mantle depths in the stability field of stishovite (≥300 km). Whether such an ultra-deep subducted rock is specific sample or common case is still enigmas to geologists for more than a decade. To solve this problem, through a series of petrological studies, it is found for the first time quartz paramorphs after stishovite in omphacite and garnet of eclogite from Jianggalesayi, South Altyn UHP belt, and the peak metamorphic pressures of Yinggelisayi garnet pyroxenite with clinopyroxene exsolutions in garnet and Songshugou felsic gneiss with quartz exsolutions in garnet are re-estimated to be ≥9-10 GPa in the stability field of stishovite. These lines of new

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作者简介: 刘良(1956-)男,教授,从事岩石大地构造研究. ORCID:0000-0001-5833-9451. E-mail:liuliang@nwu.edu.cn

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evidence, together with the previous discovery of kyanite+spinel exsolutions in the former stishovite of the pelitic gneiss from the South Altyn UHP belt, suggest that ultra-deep subduction of continental materials might be more common and diverse than previous thought. The minimum stability pressure of super-silicon garnet in SiO_2-saturated rock system is estimated to be ≥9－10 GPa based on high temperature and high pressure experiments, which provides a new method to confirm the ultra-deep subduction of continental materials to mantle depth in stishovite stability field (～300 km).

Key words: ultra-deep subduction of continental crust; stishovite paramorph; super-silicon garnet; mantle depth; stishovite stability field; exhumation mechanism.

20世纪60年代发展起来的板块构造理论预测的许多地质现象得到了广泛的证实，成为20世纪自然科学的10大进展之一.按照传统的板块构造学说，大陆地壳由于密度较低，不可能俯冲到高密度的地幔中去.然而，20世纪80年代地球科学家们分别在西阿尔卑斯和挪威西部的变质表壳岩中，发现了超高压变质矿物柯石英（Chopin，1984；Smith，1984），之后又分别在哈萨克斯坦Kokchetav地块和大别山等地区的变质表壳岩中（Sobolev and Shatsky，1990；Xu *et al.*，1992）发现了金刚石，证明大陆地壳曾俯冲到大于80～120 km的地幔深度发生超高压变质，然后折返回地表.这些发现改变了传统的地球动力学观念，在国际上引发了大陆深俯冲和超高压变质作用的研究热潮（Coleman and Wang，1995；Hacker and Liou，1998；Carswell and Compagnoni，2003）.

30多年来，地球科学家通过深入的研究，相继在全球至少20多个碰撞造山带中发现了超高压变质岩石及其大陆深俯冲作用的存在，完善和丰富了板块构造理论.其中，关于大陆俯冲深度的研究又取得了两次重要的新突破.Ye *et al.*（2000）在苏鲁榴辉岩的石榴石中发现了单斜辉石、金红石和磷灰石出溶体，首次在大陆地壳变质岩中找到了大于200 km深俯冲的矿物学证据.Liu *et al.*（2007a）在南阿尔金非陨石撞击成因泥质岩中首次发现先存斯石英显微出溶结构，超越了柯石英与金刚石记录的地壳俯冲深度，率先把陆壳俯冲/折返深度由柯石英稳定域推进到斯石英稳定域的地幔深度（＞300 km）.与这些研究几乎同步，挪威西部片麻岩区的石榴橄榄岩中石榴石出溶辉石的最新研究揭示其俯冲深度为350 km（Spengler *et al.*，2006）；哈萨克斯坦Kokchetav不纯大理岩中的金刚石含文石＋菱镁矿，指示其俯冲深度为190～280 km（Dobrzhinetskaya and Green，2007）.柴北缘石榴橄榄岩中石榴子石出熔钠质角闪石，指示俯冲深度大于200 km（Song *et al.*，2005）.大别造山带超高压石榴橄榄岩的普通辉石内出溶斜顽辉石棒状体或针状体，指示这些岩石的俯冲深度可能超过300 km（Liu *et al.*，2007b）.这些重要突破性研究引发了国际地学界新的探索与思考：陆壳岩石究竟能被俯冲到地幔多深？陆壳岩石被俯冲到斯石英稳定域的地幔深度（即超深俯冲）是否具有普遍性及其又是如何折返的？深俯冲陆壳的命运如何？等.本文概述了我们近年来围绕“陆壳岩石被俯冲到斯石英稳定域的地幔深度是否具有普遍性？”这一科学问题，持续研究所取得的一些新进展.

1　南阿尔金超高压榴辉岩中发现斯石英副象

一种同质多象变体矿物转变为另一种变体矿物后继承保留了先期矿物晶体形态的现象称为矿物的副象，副象的存在是判断矿物之间发生过同质多象转变的重要证据.最近，我们在南阿尔金超高压榴辉岩的绿辉石和石榴子石中发现了长柱状或针状体形态的多晶石英集合体以及呈近四方形或平行四边形的单晶石英包裹体（图1），长度最长可达25～50 μm，宽度为10 μm，长宽比分别为8∶1、18∶1和38∶1.前人研究表明，柯石英为单斜晶系，结构中Si-O四面体共角顶连接形成架状结构，结晶习性通常呈短柱状或板柱状；而斯石英为四方晶系，具金红石型结构，结构中Si-O八面体沿*C*轴共棱连接形成链状结构，结晶习性呈柱状或长柱状.因此，实验合成的斯石英与柯石英的形态分别为长柱状和短柱状.综合上述矿物包裹体的形态、成分、EBSD测试研究以及与高温高压实验合成的斯石英晶体形态的对比分析，确定这些特定形态多晶石英集合体应为斯石英的副象（Liu *et al.*，2018）.因此，南阿尔金榴辉岩的峰期压力至少应在8～10 GPa（当温度为800～1 000 ℃时）的斯石英稳定域.这一研究与之前该地区泥质片麻岩中发现先存斯石英出溶蓝晶石＋尖晶石的研究结果一致，共同表明陆壳俯冲

到斯石英稳定域的地幔深度(~300 km),然后再折返回地表的地质现象可能更为普遍,其岩石类型也可能具有多样性.这一认识对深入理解超深俯冲陆壳的组成、规模、形成/折返机制及其相关的壳幔相互作用提供了关键的约束条件.同时,该研究还为在超高压变质带中识别辨认先存斯石英的研究提供了新的思路.

2　SiO_2饱和岩石体系中超硅石榴子石最小稳定压力条件的实验岩石学研究及其地质意义

石榴石在超高压条件下的晶体化学行为在幔源岩石以及与板块深俯冲有关的超高压变质作用研究方面具有重要意义.大量针对SiO_2不饱和超镁铁质岩体系的实验岩石学研究(Ringwood and Major, 1971; Irifune *et al.*, 1986; Gasparik, 1989; Ono and Yasuda, 1996)证明,在>5 GPa的压力条件石榴子石出现$Si^{Ⅵ}+M^{Ⅵ}=Al^{Ⅵ}+Al^{Ⅵ}$和$Si^{Ⅵ}+Na^{Ⅷ}=Al^{Ⅵ}+M^{Ⅷ}$(M=Mg,Fe,Ca)偶合置换使石榴子石具有超硅和亏铝的特点,并且这种偶合置换的程度随压力增高而增加,使超硅石榴子石分子中的$Si^{Ⅵ}$与压力呈正相关而$Al^{Ⅵ}$与压力呈负相关.这一实验结果为深入认识深源地幔包体和一些超高压岩石中观察到的石榴子石出溶辉石显微结构的形成机制和反演出溶前超硅石榴子石形成的压力条件奠定了理论基础(Haggerty and Sautter, 1990; Sautter *et al.*, 1991; van Roermund *et al.*, 1998; Ye *et al.*, 2000).然而,目前针对SiO_2饱和岩石体系的高温高压实验岩石学研究虽有一些报道(Irifune *et al.*, 1994; Ono, 1998; Dobrazhinetskya and Green, 2007; Wu *et al.*, 2009),但关于其中石榴子石超硅的最小稳定压力条件还缺乏统一认识.为此,我们选择长英质岩石体系在6~12 GPa和1 000~1400 ℃的条件下进行了高温高压实验研究,并结合前人的实验资料,试图探讨SiO_2饱和岩石体系中超硅石榴子石的最小稳定压力条件及其地质意义.

实验结果表明,长英质岩石体系中石榴子石超硅的最小压力是在≥10 GPa的斯石英稳定域(Liu *et al.*,待刊资料),其趋势与Irifune *et al.*(1994)报道的实验结果类似.同时,我们又分析对比了Ono(1998)、Dobrazhinetskya and Green(2007)和Wu *et al.*(2009)等关于SiO_2饱和体系不同起始材料的实验岩石学资料,结果显示,石榴子石超硅的最小压力条件主要为≥9~10 GPa.由此可见,SiO_2饱和岩石体系中石榴子石超硅最小的稳定压力条件完全不同于SiO_2不饱和的超镁铁质岩石体系,前者最小压力为≥9~10 GPa,后者为≥5 GPa.因此,在超高压岩石中观察到超硅石榴子石出熔产物并反演其峰期压力时,一定还要考虑其矿物组合或岩石属性是否SiO_2饱和.

我们先期研究在南阿尔金英格利萨依地区(也

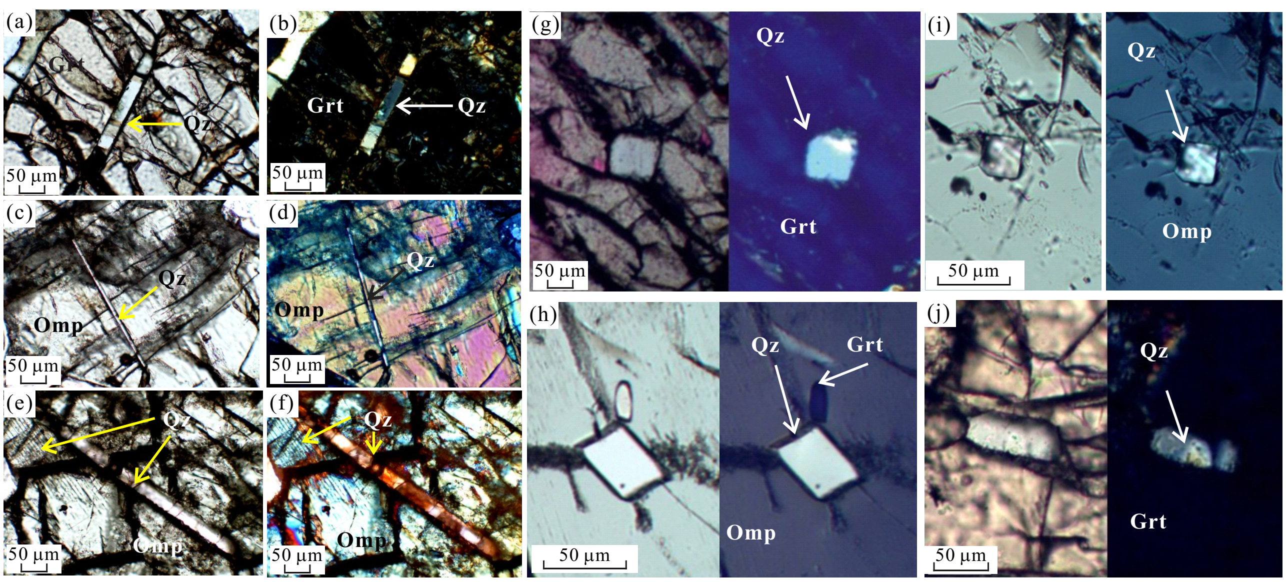

图1　南阿尔金榴辉岩中先存斯石英副象的显微结构

Fig.1　Microstructures of the paramorphs of the former stishovite of eclogite in South Altyn Tagh

据Liu *et al.*(2018);Qmp.绿辉石;Grt.石榴子石;Qz.石英

称巴什瓦克地区）石榴辉石岩中发现石榴子石出溶单斜辉石（图 2）（Liu *et al.*，2005），在北秦岭松树沟长英质片麻岩石榴子石中发现出溶金红石或磷灰石和石英＋金红石棒状体（图 3）（Liu *et al.*，2003），

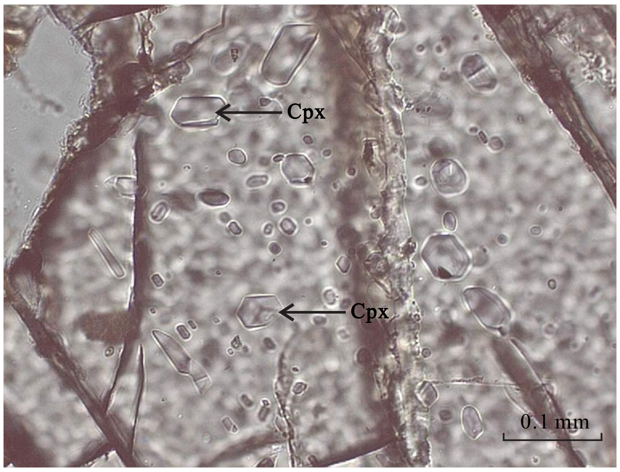

图 2　南阿尔金石榴子石辉石岩中石榴子石出溶单斜辉石的显微结构

Fig.2　The microstructure of garnet dissolved clinopyroxene of garnet pyroxenite in South Altyn Tagh

Cpx. 单斜辉石；Liu *et al.*(2005)

表明这两种岩石中的石榴子石出溶前超硅．依据 SiO_2 饱和岩石体系石榴子石超硅的最小稳定压力条件的实验结果，我们重新厘定这两种岩石的峰期变质压力为≥9～10 GPa，指示二者所代表的陆壳岩石俯冲深度达到了斯石英稳定域的地幔深度（～300 km）．最近，Dong *et al.*（2018）通过对南阿尔金巴什瓦克地区长英质麻粒岩细致的岩相学研究和相平衡模拟计算估算其峰期压力为 3～9 GPa，其最大压力与我们对该区岩石重新估算的压力值基本一致．

3　结语

综合上述研究成果，可获得以下几点新认识：（1）陆壳俯冲到斯石英稳定域的地幔深度（～300 km）然后再折返回地表的地质现象可能更为普遍，其岩石类型也可能具有多样性；（2）SiO_2 饱和岩石体系中石榴石超硅的最小稳定压力条件为≥9～10 GPa 的斯石英稳定域，这对识别辨认陆壳岩石俯冲到斯石英稳定地幔深度的研究提供了新的借鉴和思路．

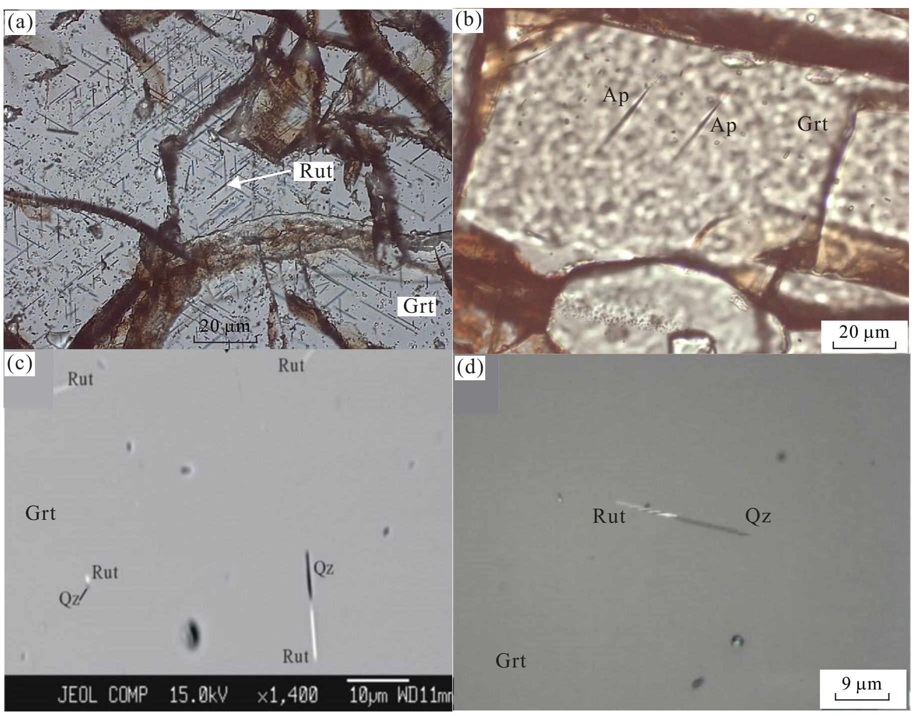

图 3　北秦岭松树沟长英质片麻岩中石榴子石出溶金红石(a)、磷灰石(b)和石英＋金红石(c，d)的显微结构

Fig.3　Microstructures of garnet dissolved rutile (a), apatite (b) and quartz＋rutile (c，d) of Songshugou felsic geniss in North Qinling

据 Liu *et al.*(2003)；Grt. 石榴子石；Rut. 金红石；Ap. 磷灰石；Qz. 石英

前述研究表明南阿尔金和北秦岭都存在陆壳超深俯冲到斯石英稳定域地幔深度的矿物学证据，但这些岩石仅发现在有限的几个露头的少数标本上.那么，这究竟是退变质改造导致斯石英相变难以保存的问题还是仅有一小部分陆壳经历了超深俯冲?目前尚无定论，今后要深入研究确定.

另外，超深俯冲到斯石英稳定域地幔深度的陆壳岩石是如何折返的?其规模如何?俯冲陆壳能影响深部地幔的空间尺度如何?控制(陆壳)超深俯冲的必要条件及其动力学机制是什么?等，这些都是今后需要进一步深入研究的重要科学问题.

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