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柴北缘鱼卡含硬柱石假象榴辉岩的发现、*P*-*T*-*t*轨迹及控制硬柱石形成的主要因素

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摘 要： 硬柱石是大洋冷俯冲带的代表性矿物之一，富含水和Sr、Pb及稀土等微量元素，其形成和分解对于俯冲带流体活动、壳幔水和微量元素循环、地幔楔交代和熔融及岛弧岩浆作用等具有重要影响. 但由于硬柱石对温度和压力的改变非常敏感，在板片折返过程中很容易分解，因此目前全球出露的硬柱石榴辉岩极为稀少. 总结了榴辉岩中早期硬柱石存在的识别标志，并据此确定柴北缘超高压带西段鱼卡地区的含蓝晶石榴辉岩和斜黝帘石榴辉岩是峰期硬柱石榴辉岩退变质改造的结果. 该发现说明柴北缘成为继大别造山带之后全球第二例出露硬柱石榴辉岩的大陆俯冲型造山带. 利用相平衡计算方法恢复了这两种榴辉岩的变质演化过程，其中含蓝晶石榴辉岩的*P*-*T*轨迹和峰期变质条件均与区内大陆俯冲型含柯石英多硅白云母榴辉岩相似，而斜黝帘石榴辉岩峰期变质温压则略低. 锆石定年获得含蓝晶石榴辉岩和斜黝帘石榴辉岩的变质时代分别为437 Ma和436 Ma，与带内已有超高压榴辉岩相变质时代相同，同时获得含蓝晶石榴辉岩的原岩结晶时代为1 273 Ma. 相似的变质*P*-*T*轨迹和变质时代表明含蓝晶石榴辉岩与同剖面含柯石英多硅白云母榴辉岩共同经历了大陆深俯冲作用. 这一结果表明，硬柱石榴辉岩并非大洋冷俯冲带特有，决定榴辉岩中是否出现硬柱石的主要因素是原岩成分和变质条件. 在鱼卡地区，榴辉岩的矿物组合中能否出现硬柱石的最主要控制因素是原岩中的Mg含量，由高Mg#的基性岩变质形成的榴辉岩峰期矿物组合中易出现硬柱石.

关键词： 硬柱石假象；榴辉岩；*P*-*T*-*t*轨迹；鱼卡；柴北缘；岩石学.

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Discovery and *P*-*T*-*t* Paths of Lawsonite Pseudomorph-Bearing Eclogites in the Yuka Terrane, North Qaidam Ultrahigh Pressure Metamorphic Belt and Exploration on Key Factors Controlling Lawsonite Formation

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Abstract: Lawsonite is a representative mineral in cold oceanic subduction zone. It contains high water and trace element contents, such as Sr, Pb, and REE, and thus its formation and breakdown greatly influence fluid activity in subduction channel, deep water and trace element recycling, metasomatism and partial melting of mantle wedge as well as arc volcanism. However, lawsonite-bearing eclogite is rarely exposed because lawsonite is very delicate that seldom survives exhumation. In this paper, we summarize the methods to identify former presence of lawsonite in eclogite and determine that clinozoisite eclogite and kyanite-bearing eclogite

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in the Yuka terrane, North Qaidam UHPM belt (NQUB) are retrograde products of lawsonite eclogite. This makes the NQUB being the second continental subduction-type orogenic belt which contains lawsonite eclogite. Phase equilibrium modelling obtains clockwise *P*-*T* paths for these two eclogites. The *P*-*T* path and peak metamorphic conditions of the kyanite-bearing eclogite are similar to the coesite-bearing phengite eclogite in the Yuka terrane, whereas the clinozoisite eclogite has slightly lower peak *P*-*T* conditions. Zircon dating yields metamorphic ages of 437 Ma and 436 Ma for the kyanite-bearing eclogite and clinozoisite eclogite, respectively, which are similar to UHP eclogite facies metamorphic ages in the NQUB, and a protolith age of 1 273 Ma for the kyanite-bearing eclogite. The similar *P*-*T* path and metamorphic age of the kyanite-bearing eclogite with coesite-bearing eclogite indicate that these two eclogites underwent continental deep subduction together. This results show that lawsonite eclogite is not peculiar to oceanic cold subduction zone. The main factors controlling the formation of lawsonite eclogite are bulk composition and metamorphic conditions. In the Yuka terrane, eclogite with high $Mg^{\#}$ favors lawsonite-bearing peak assemblage.

Key words: lawsonite pseudomorph; eclogite; *P*-*T*-*t* path; Yuka terrane; North Qaidam; pertology.

硬柱石[$CaAl_2Si_2O_7(OH)_2$•H_2O]是低温、高压/超高压条件下的重要含水矿物之一,其含有高达11.5%的水,以及大量的稀土元素(尤其是轻稀土元素)和Sr、Pb、Th、U等微量元素(Spandler *et al.*, 2003; Vitale Brovarone *et al.*, 2014).实验岩石学结果表明,硬柱石的稳定压力可达8~10 GPa (Poli and Schmidt, 1995),因此硬柱石可携带大量的水及微量元素到达地幔深度,这些水和微量元素会随着硬柱石的分解被释放出来,形成俯冲带流体,导致地幔楔交代作用和岛弧岩浆作用;同时低密度硬柱石的分解还会极大的改变俯冲板片的强度,导致深源地震作用(Martin *et al.*, 2014; Tsujimori and Ernst, 2014; Vitale Brovarone *et al.*, 2014).对造山带中硬柱石榴辉岩的详细研究,可为俯冲板片轨迹、地热梯度、折返速率、俯冲带流体活动、元素迁移和循环、壳幔相互作用等方面提供重要信息,因此其是目前俯冲带变质岩石学研究的热点和前缘.但是由于硬柱石对于温度升高、压力降低、局部变形以及流体灌入十分敏感,在折返过程中极易发生分解(陈丹玲等, 2005; Whitney and Davis, 2006; Wei and Clarke, 2011),目前地表发现的硬柱石榴辉岩仅有大约20处(Tsujimori *et al.*, 2006; Tsujimori and Ernst, 2014),且绝大多数形成于大洋俯冲带中.本文总结了榴辉岩中早期硬柱石存在的识别标志,并据此确定柴北缘超高压带西段鱼卡地区的含蓝晶石榴辉岩和斜黝帘石榴辉岩是峰期硬柱石榴辉岩退变质改造的结果,通过相平衡计算方法恢复重建了这两种榴辉岩的变质*P*-*T*轨迹,并探讨了控制鱼卡地区榴辉岩变质过程中是否形成硬柱石的主要因素.

1 榴辉岩中早期硬柱石的识别标志

硬柱石是斜方晶系的钙铝硅酸盐矿物,纵切面为矩形,横切面为菱形,因此硬柱石分解时常形成具有矩形或菱形外貌的以斜黝帘石/绿帘石为主的多晶集合体,这是识别硬柱石存在最直观的判别标志.但硬柱石消耗反应多为滑动反应,当温压条件和参与反应的矿物不同时,构成硬柱石假象的多晶矿物集合体可出现不同的矿物组合.据统计,目前常见的构成硬柱石假象的矿物组合有:(1)斜黝帘石/绿帘石+蓝晶石+石英(Li *et al.*, 2004; Mattinson *et al.*, 2004; Guo *et al.*, 2013; Orozbaev *et al.*, 2015);(2)斜黝帘石/绿帘石+钠云母+多硅白云母+钠长石(Altherr *et al.*, 2004);(3)斜黝帘石/绿帘石+钠云母±石英(Schmädicke and Will, 2003; Groppo and Castelli, 2010; Wei *et al.*, 2010; Orozbaev *et al.*, 2015);(4)斜黝帘石/绿帘石+绿泥石±石英(Ballevre *et al.*, 2003; Orozbaev *et al.*, 2015);(5)斜黝帘石/绿帘石+多硅白云母+角闪石±钠长石±石英(El Korh *et al.*, 2009; Liu *et al.*, 2013);(6)斜黝帘石/绿帘石集合体(Castelli *et al.*, 1998; Usui *et al.*, 2003, 2006; Mattinson *et al.*, 2006)等.尽管构成硬柱石假象的矿物组合种类繁多,但根据各组成矿物的成分、含量及密度对其进行早期成分回算,去除Na、K等来自绿辉石、多硅白云母等反应矿物的元素后,通常可得到与天然硬柱石相似的成分(Orozbaev *et al.*, 2015; Ren *et al.*, 2017),这也是证明早先硬柱石存在的主要手段之一.

近年来,由于热力学数据库的不断完善,依据全岩成分,通过矿物相平衡计算结合矿物成分等值线确定岩石变质温压范围是否位于硬柱石稳定域内,也成为判别岩石中是否曾经存在过硬柱石的重要方法之一.由于石榴石是高压-超高压变质榴辉岩中最常见的变质矿物,可以在很宽的温压范围内保持稳定,且具有难熔和流体中低溶解能力的特点,因此石榴石是最常见的硬柱石假象的载体.这些石榴石通常具有保存完好的从核部到边部,锰铝榴石和钙

铝榴石组分降低，镁铝榴石组分升高的进变质环带（Wei and Clarke，2011）.如果包裹硬柱石假象的石榴石成分在 P-T 视剖面图中落于硬柱石稳定域内，那么其内部的硬柱石假象应代表早期的硬柱石.

另外，由于硬柱石强烈富集 Sr 和轻稀土，因而必然导致与硬柱石共生的矿物亏损这些元素，而硬柱石消失后的矿物假象中必然富含这些元素.因此，借助高精度的 LA-ICP-MS 和离子探针原位分析技术，通过不同世代矿物微量元素的质量平衡计算来判断岩石中早期硬柱石的存在，也是非常有效的方法（Guo *et al.*，2013）.

2　柴北缘鱼卡地区两种含硬柱石假象榴辉岩的发现

利用上述早期硬柱石的识别标志，本课题组在柴北缘超高压带西段鱼卡地区识别出两种含硬柱石假象榴辉岩，即含蓝晶石榴辉岩和斜黝帘石榴辉岩，其均发现于鱼卡河剖面中部，呈透镜状出露于花岗片麻岩中.其中含蓝晶石榴辉岩十分新鲜，主要由石榴石、绿辉石、多硅白云母、角闪石、斜黝帘石、石英及少量的金红石和滑石组成.而斜黝帘石榴辉岩则退变质较为强烈，主要由石榴石、角闪石、斜黝帘石、石英及少量滑石和金红石组成，绿辉石仅见于部分角闪石的核部，发育透辉石＋钠长石的反应边.

详细的岩相学观察，在这两种榴辉岩石榴石内部或基质中发现大量呈规则菱形或矩形的多晶斜黝帘石、斜黝帘石＋钠云母±多硅白云母±石英、斜黝帘石＋角闪石＋石英±斜长石±榍石和斜黝帘石＋蓝晶石＋石英的多晶集合体（图 1；Ren *et al.*，2017，2018）.对这些具有规则外形的多晶集合体的原始矿物成分回算，得到 Si＝1.97～2.04，Al＋Fe^{3+}＝1.86～1.98，Ca＝0.96～1.28（以 8 个氧元素计算），与天然硬柱石成分十分类似.结合这两种榴辉岩中石榴石具有从核部到边部镁铝榴石组分逐渐升高，钙铝榴石和锰铝榴石组分逐渐下降的成分环带特征，以及这些石榴石的生长条件位于硬柱石稳定域的相平衡计算结果，确定含蓝晶石榴辉岩和斜黝帘石榴辉岩中的规则菱形或矩形的多晶矿物集合体为早期硬柱石分解的产物.

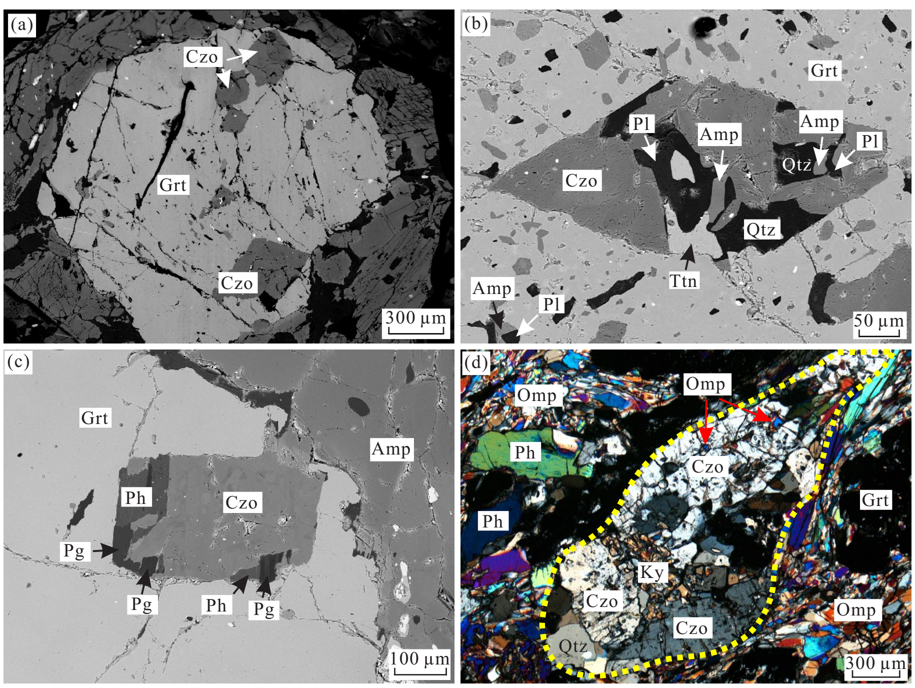

图 1　斜黝帘石榴辉岩(a～c)及含蓝晶石榴辉岩(d)中的硬柱石假象

Fig.1　The lawsonite pseudomorphs in the clinozoisite eclogite (a-c) and kyanite-bearing eclogite (d)

Grt.石榴石；Omp.绿辉石；Ph.多硅白云母；Amp.角闪石；Pg.钠云母；Czo.斜黝帘石；Ky.蓝晶石；Pl.斜长石；Ttn.榍石；Qtz.石英

3　柴北缘鱼卡含硬柱石假象榴辉岩的变质演化

依据石榴石成分环带、不同部位包裹体种类和成分以及各种反应结构，结合相平衡计算结果，含蓝晶石榴辉岩变质演化可划分为4个阶段（图2；Ren *et al.*，2018）. 第一阶段为进变质阶段，以石榴石核部成分及其中包裹的绿辉石、多硅白云母、滑石、硬柱石假象和石英为特征，变质条件为22～23 kbar/585 ℃；第二阶段为峰期变质阶段，以石榴石幔部及基质中的硬柱石假象、细粒的绿辉石、多硅白云母、金红石为特征，利用石榴石和多硅白云母成分及石榴石－绿辉石－多硅白云母－石英/柯石英温压计（Krogh Ravna，2000；Krogh Ravna and Terry，2004）共同限定温压条件为32.5 kbar/670 ℃；第三阶段为早期退变质阶段，在此过程中硬柱石大量脱水分解形成了粗粒的蓝晶石和多硅白云母，以及呈菱形的蓝晶石＋斜黝帘石＋石英多晶集合体，利用多硅白云母的Si值限定变质条件约为27.1～30.0 kbar/670 ℃；第四阶段为晚期退变质阶段，以晚期角闪石和斜黝帘石的出现为特征，其稳定压力小于18.7 kbar.

斜黝帘石榴辉岩变质演化可划分为3个阶段，其中峰前变质阶段以石榴石核部成分和包裹体绿泥石＋绿辉石＋硬柱石假象＋金红石＋石英为代表，变质条件为20.5 kbar/520 ℃. 峰期变质阶段以石榴石边部成分、边部包裹体和基质中残留的绿辉石、滑石及金红石为特征，利用石榴石镁铝榴石和钙铝榴石含量限定变质条件为27.0 kbar/570 ℃. 退变质阶段以石榴石最边部成分以及基质中广泛存在的角闪石、斜黝帘石和石英为特征，变质条件为12.8 kbar/620 ℃（图2；Ren *et al.*，2017）. 在此过程中，基质中的硬柱石完全分解，而石榴石中的硬柱石包裹体由于石榴石的保护还可识别出早期的晶形，绿辉石多发育单斜辉石＋斜长石后成合晶，并大部分退变为角闪石.

从图2可以看出，含蓝晶石榴辉岩的变质 *P*-*T* 轨迹及峰期变质条件均与区内大陆俯冲成因的含柯石英多硅白云母榴辉岩相似，而斜黝帘石榴辉岩的峰期变质温度和压力都略低，这是由于其变质过程确实与其他榴辉岩不同，还是由于石榴石成分受到了强烈的退变质改造，影响了峰期变质条件的计

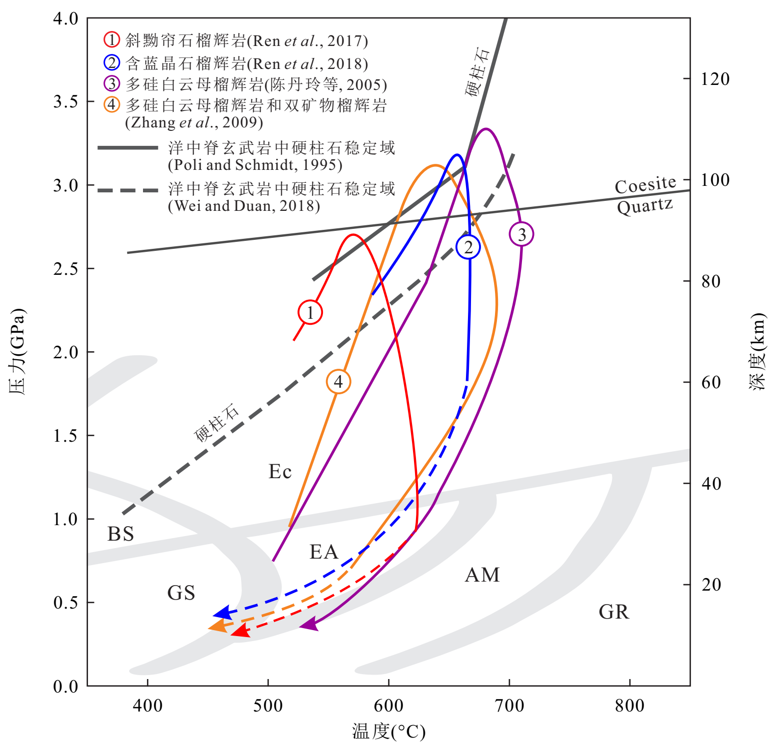

图2　鱼卡不同榴辉岩的 *P*-*T* 轨迹

Fig.2　The *P*-*T* paths for eclogites in the Yuka terrane

Ec. 榴辉岩相；GR. 麻粒岩相；AM. 角闪岩相；EA. 绿帘角闪岩相；BS. 蓝片岩相；GS. 绿片岩相

算，有待进一步的研究.

4 含硬柱石假象榴辉岩的原岩属性及变质时代

岩石地球化学研究显示，含蓝晶石榴辉岩和斜黝帘石榴辉岩均具有较高的Mg#(56～62)和较低的TiO_2(0.49%～1.14%)含量，与平均MORB相当；而且除Rb、Ba、Th、Sr等活动性元素外，其余不活动元素均显示出与当今N-MORB或E-MORB相似的平坦型或左倾型的元素配分曲线特征，没有明显的Nb、Ta和Ti负异常(图3).在不同构造判别图中，这两种榴辉岩均落在MORB区域.

斜黝帘石榴辉岩中的锆石均呈浑圆状或短柱状形态，含有大量的石榴石、绿辉石、斜黝帘石、金红石和石英包裹体，为榴辉岩相变质锆石.SIMS定年获得其变质时代为436.1±6.8 Ma（图4a；Ren *et al.*，2017）.这些锆石的氧同位素组成均与地幔的$\delta^{18}O$值在误差范围内一致，表明斜黝帘石榴辉岩的原岩直接起源于地幔，未经历明显的陆壳混染.

含蓝晶石榴辉岩中的锆石为短柱状，具有明显的核－边结构.其中核部具有岩浆振荡环带，为原岩锆石残留，边部无环带，含有石榴石、绿辉石、滑石、绿帘石、金红石和石英等榴辉岩相变质矿物包裹体.LA-ICP-MS定年获得其原岩形成时代为1 273±20 Ma，变质时代为437±2 Ma（图4b；Ren *et al.*，2018）.锆石核部的$\varepsilon_{Hf}(t)$值与当时的亏损地幔在误差范围内一致，模式年龄也与其原岩结晶

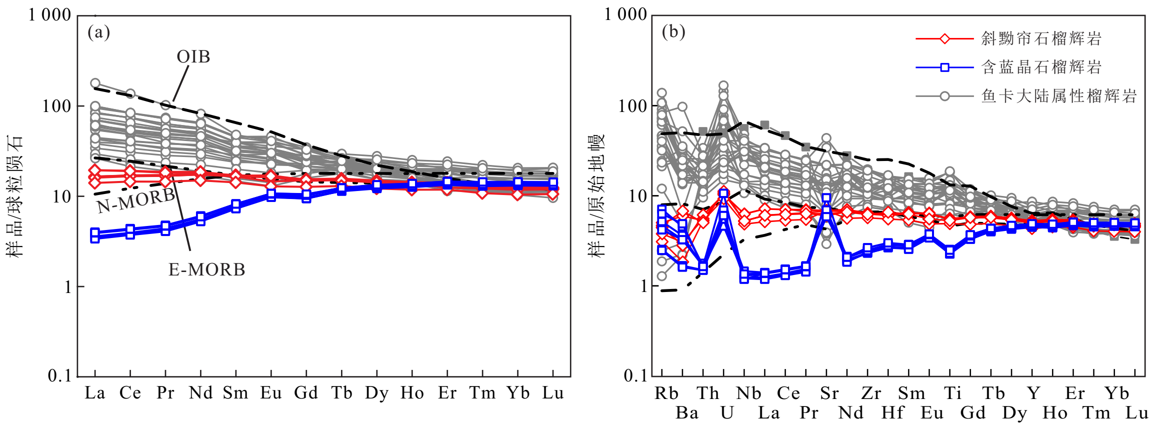

图3　鱼卡不同榴辉岩球粒陨石标准化稀土图(a)及原始地幔标准化蛛网图(b)

Fig.3　Chondrite-normalized REE diagram (a) and primitive mantle-normalized trace element diagram (b) for Yuka eclogites

数据引自Chen *et al.*(2009)；Song *et al.*(2010)；Ren *et al.*(2017，2018)

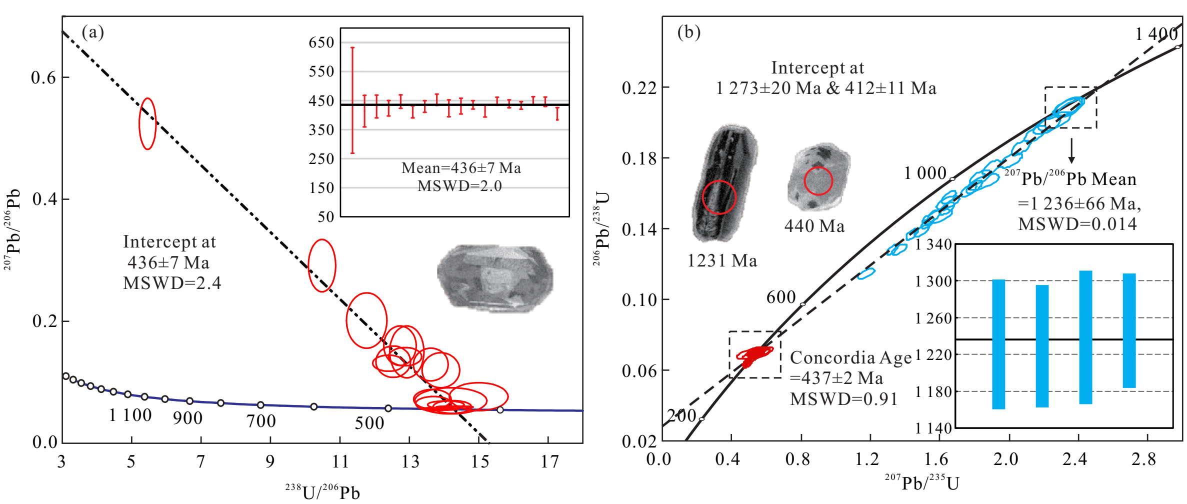

图4　斜黝帘石榴辉岩(a)及含蓝晶石榴辉岩(b)锆石定年结果

Fig.4　Zircon dating results of the clinozoisite eclogite (a) and kyanite-bearing eclogite (b)

据Ren *et al.*(2017，2018)

时代相似，表明含蓝晶石榴辉岩的原岩也是直接起源于地幔，未经历明显的陆壳混染.

综合岩石地球化学和定年结果，含蓝晶石榴辉岩的原岩为中元古代晚期古洋壳残片，在大洋俯冲消减过程中就位于柴达木板块边缘成为大陆的一部分，在早古生代与陆壳岩石一起经历了大陆深俯冲作用(Ren *et al.*，2018).而斜黝帘石榴辉岩，由于未获得其原岩结晶年龄，因此其原岩是中元古代晚期古洋壳还是早古生代洋壳有待进一步研究，但其峰期变质时代(436 Ma)与同剖面大陆俯冲型超高压榴辉岩(440～420 Ma)完全相同(Chen *et al.*，2009；Song *et al.*，2010)，因此，如果是早古生代洋壳，也应该是洋陆转换带处的洋壳(Ren *et al.*，2017).

5 影响硬柱石榴辉岩形成的关键因素

目前发现的硬柱石榴辉岩绝大多数都形成于大洋冷俯冲带，本文的研究表明硬柱石榴辉岩并非大洋俯冲带独有，榴辉岩在变质过程中是否形成硬柱石主要取决于原岩成分和变质条件.从图 2 可以看出，在鱼卡河剖面存在多种类型的榴辉岩，除本文研究的两种含硬柱石假象榴辉岩外，还有含柯石英的多硅白云母榴辉岩和细粒双矿物榴辉岩等.这些榴辉岩与含硬柱石假象的榴辉岩具有近乎一致的变质 *P*-*T* 轨迹和峰期变质条件，但其中并不存在硬柱石.那么，控制区内榴辉岩矿物组合中能否出现硬柱石的因素到底是什么？为探讨这一问题，我们对鱼卡不同榴辉岩的全岩成分进行了对比，发现含蓝晶石榴辉岩的 Al_2O_3 和 CaO 含量以及 A/CNK，*X*(CaO)[$=CaO/(CaO+FeO^T+MgO+MnO+Na_2O)$]比值与同剖面其他榴辉岩相似，但其 $Mg^\#$ 明显偏高.利用 Thermocalc 软件计算了 32 kbar/655 °C 条件下的 *P*-*T*-$Mg^\#$ 视剖面图(图 5)，结果显示随着全岩 $Mg^\#$ 的增大，含硬柱石和滑石的稳定域增大，当温度为 650～700 °C 时，高镁岩石($Mg^\#>0.55$)会形成含硬柱石的矿物组合(石榴石＋绿辉石＋硬柱石＋金红石＋柯石英±多硅白云母)，而低镁岩石则会形成无硬柱石的矿物组合(石榴石＋绿辉石＋金红石＋柯石英±多硅白云母).这与我们在鱼卡河剖面观察到的现象一致.因此，对鱼卡地区的榴辉岩而言，全岩 $Mg^\#$ 是其变质过程中是否出现硬柱石的关键控制因素.

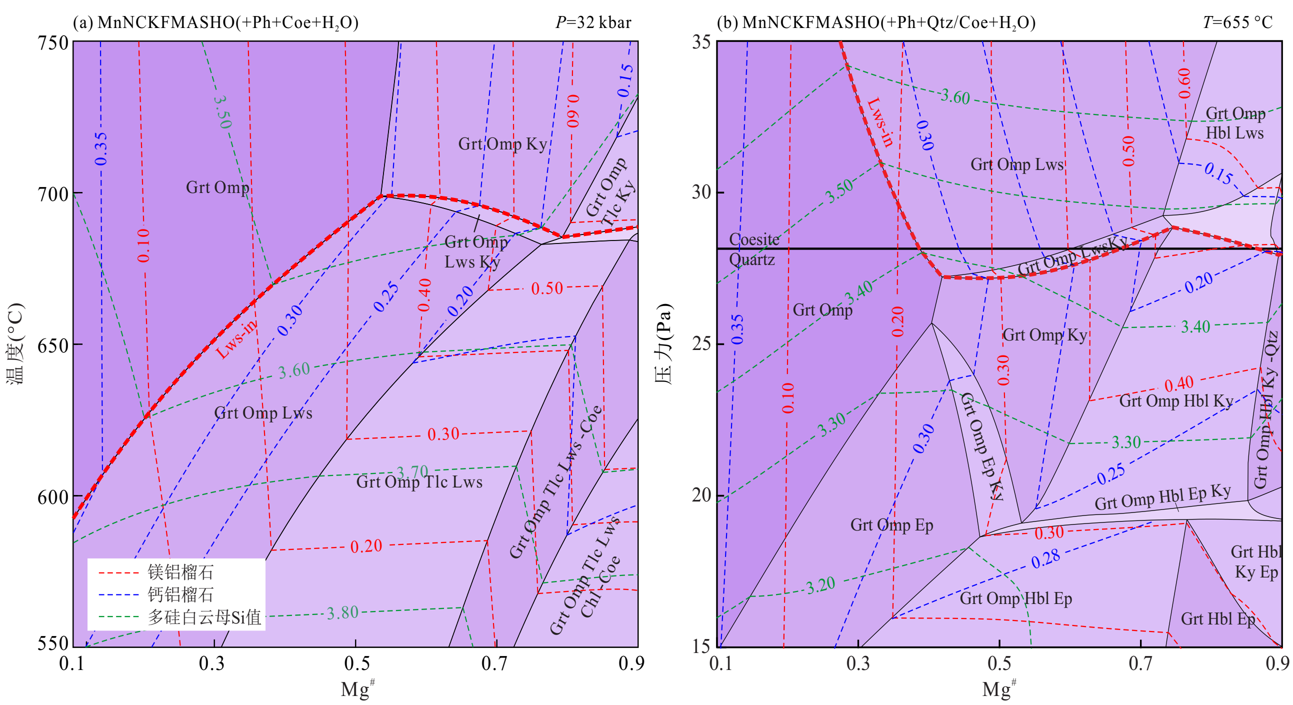

图 5 全岩 $Mg^\#$ 对鱼卡榴辉岩峰期矿物组合的影响

Fig.5 *P*-*T*-$Mg^\#$ pseudosections showing the peak metamorphic mineral assemblage controlled by bulk $Mg^\#$

Lws.硬柱石；Tlc.滑石；Chl.绿泥石；Hbl.普通角闪石；Ep.绿帘石；Coe.柯石英；其余同图 1；据 Ren *et al.* (2018)

References

Altherr, R., Topuz, G., Marschall, H., et al., 2004. Evolution of a Tourmaline-Bearing Lawsonite Eclogite from the Elekdağ Area (Central Pontides, N Turkey): Evidence for Infiltration of Slab-Derived B-Rich Fluids during Exhumation. *Contributions to Mineralogy and Petrology*, 148(4): 409—425. https://doi. org/10.1007/s00410-004-0611-1

Ballevre, M., Pitra, P., Bohn, M., 2003. Lawsonite Growth in the Epidote Blueschists from the Ile de Groix (Armorican Massif, France): A Potential Geobarometer. *Journal of Metamorphic Geology*, 21(7): 723—735. https://doi.org/10.1046/j.1525-1314.2003.00474.x

Castelli, D., Rolfo, F., Compagnoni, R., et al., 1998. Metamorphic Veins with Kyanite, Zoisite and Quartz in the Zhu-Jia-Chong Eclogite, Dabie Shan, China. *The Island Arc*, 7(1—2): 159—173. https://doi. org/10.1046/j. 1440-1738.1998.00185.x

Chen, D.L., Liu, L., Sun, Y., et al., 2009. Geochemistry and Zircon U-Pb Dating and Its Implications of the Yukahe HP/UHP Terrane, the North Qaidam, NW China. *Journal of Asian Earth Sciences*, 35(3—4): 259—272. https://doi.org/10.1016/j.jseaes.2008.12.001

Chen, D.L., Sun, Y., Liu, L., et al., 2005. Metamorphic Evolution of the Yuka Eclogite in the North Qaidam, NW China: Evidences from the Compositional Zonation of Garnet and Reaction Texture in the Rock. *Acta Petrologica Sinica*, 21(4): 1039—1048 (in Chinese with English abstract).

El Korh, A., Schmidt, S.T., Ulianov, A., et al., 2009. Trace Element Partitioning in HP-LT Metamorphic Assemblages during Subduction-Related Metamorphism, Ile de Groix, France: A Detailed LA-ICPMS Study. *Journal of Petrology*, 50(6): 1107—1148. https://doi. org/10.1093/petrology/egp034

Groppo, C., Castelli, D., 2010. Prograde *P-T* Evolution of a Lawsonite Eclogite from the Monviso Meta-Ophiolite (Western Alps): Dehydration and Redox Reactions during Subduction of Oceanic FeTi-Oxide Gabbro. *Journal of Petrology*, 51(12): 2489—2514. https://doi. org/10.1093/petrology/egq065

Guo, S., Ye, K., Wu, T.F., et al., 2013. A Potential Method to Confirm the Previous Existence of Lawsonite in Eclogite: The Mass Imbalance of Sr and LREEs in Multistage Epidote (Ganghe, Dabie UHP Terrane). *Journal of Metamorphic Geology*, 31(4): 415—435. https://doi. org/10.1111/jmg.12027

Krogh Ravna, E.J., 2000. The Garnet-Clinopyroxene Fe^{2+}-Mg Geothermometer: An Updated Calibration. *Journal of Metamorphic Geology*, 18(2): 211—219. https://doi.org/10.1046/j.1525-1314.2000.00247.x

Krogh Ravna, E.J., Terry, M.P., 2004. Geothermobarometry of UHP and HP Eclogites and Schists: An Evaluation of Equilibria among Garnet-Clinopyroxene-Kyanite-Phengite-Coesite/Quartz. *Journal of Metamorphic Geology*, 22(6): 579—592. https://doi. org/10.1111/j. 1525-1314.2004.00534.x

Li, X.P., Zheng, Y.F., Wu, Y.B., et al., 2004. Low-T Eclogite in the Dabie Terrane of China: Petrological and Isotopic Constraints on Fluid Activity and Radiometric Dating. *Contributions to Mineralogy and Petrology*, 148(4): 443—470. https://doi.org/10.1007/s00410-004-0616-9

Liu, Q., Hermann, J., Zhang, J.F., 2013. Polyphase Inclusions in the Shuanghe UHP Eclogites Formed by Subsolidus Transformation and Incipient Melting during Exhumation of Deeply Subducted Crust. *Lithos*, 177: 91—109. https://doi.org/10.1016/j.lithos.2013.06.010

Martin, L.A.J., Hermann, J., Gauthiez-Putallaz, L., et al., 2014. Lawsonite Geochemistry and Stability: Implication for Trace Element and Water Cycles in Subduction Zones. *Journal of Metamorphic Geology*, 32(5): 455—478. https://doi.org/10.1111/jmg.12093

Mattinson, C.G., Wooden, J.L., Liou, J.G., et al., 2006. Age and Duration of Eclogite-Facies Metamorphism, North Qaidam HP/UHP Terrane, Western China. *Geochimica et Cosmochimica Acta*, 70(18): A401. https://doi. org/10.1016/j.gca.2006.06.809

Mattinson, C.G., Zhang, R.Y., Tsujimori, T., et al., 2004. Epidote-Rich Talc-Kyanite-Phengite Eclogites, Sulu Terrane, Eastern China: P-T-f_{O_2} Estimates and the Significance of the Epidote-Talc Assemblage in Eclogite. *American Mineralogist*, 89(11—12): 1772—1783. https://doi.org/10.2138/am-2004-11-1224

Orozbaev, R., Hirajima, T., Bakirov, A., et al., 2015. Trace Element Characteristics of Clinozoisite Pseudomorphs after Lawsonite in Talc-Garnet-Chloritoid Schists from the Makbal UHP Complex, Northern Kyrgyz Tian-Shan. *Lithos*, 226: 98—115. https://doi. org/10.1016/j. lithos.2014.10.008

Poli, S., Schmidt, M.W., 1995. H_2O Transport and Release in Subduction Zones: Experimental Constraints on Basaltic and Andesitic Systems. *Journal of Geophysical Research: Solid Earth*, 100(B11): 22299—22314. https://doi. org/10.1029/95jb01570

Ren, Y.F., Chen, D.L., Kelsey, D.E., et al., 2017. Petrology and Geochemistry of the Lawsonite (Pseudomorph)-Bearing Eclogite in Yuka Terrane, North Qaidam

UHPM Belt:An Eclogite Facies Metamorphosed Oceanic Slice. *Gondwana Research*, 42: 220−242. https://doi.org/10.1016/j.gr.2016.10.011

Ren, Y.F., Chen, D.L., Kelsey, D.E., et al., 2018. Metamorphic Evolution of a Newly Identified Mesoproterozoic Oceanic Slice in the Yuka Terrane and Its Implications for a Multi-Cyclic Orogenic History of the North Qaidam UHPM Belt. *Journal of Metamorphic Geology*, 36(4): 463−488. https://doi.org/10.1111/jmg.12300

Schmädicke, E., Will, T.M., 2003. Pressure-Temperature Evolution of Blueschist Facies Rocks from Sifnos, Greece, and Implications for the Exhumation of High-Pressure Rocks in the Central Aegean. *Journal of Metamorphic Geology*, 21(8): 799−811. https://doi.org/10.1046/j.1525-1314.2003.00482.x

Spandler, C., Hermann, J., Arculus, R., et al., 2003. Redistribution of Trace Elements during Prograde Metamorphism from Lawsonite Blueschist to Eclogite Facies: Implications for Deep Subduction-Zone Processes. *Contributions to Mineralogy and Petrology*, 146(2): 205−222. https://doi.org/10.1007/s00410-003-0495-5

Song, S.G., Su, L., Li, X.H., et al., 2010. Tracing the 850 Ma Continental Flood Basalts from a Piece of Subducted Continental Crust in the North Qaidam UHPM Belt, NW China. *Precambrian Research*, 183(4): 805−816. https://doi.org/10.1016/j.precamres.2010.09.008

Tsujimori, T., Ernst, W.G., 2014. Lawsonite Blueschists and Lawsonite Eclogites as Proxies for Palaeo-Subduction Zone Processes: A Review. *Journal of Metamorphic Geology*, 32(5): 437−454. https://doi.org/10.1111/jmg.12057

Tsujimori, T., Sisson, V., Liou, J., et al., 2006. Very-Low-Temperature Record of the Subduction Process: A Review of Worldwide Lawsonite Eclogites. *Lithos*, 92(3−4): 609−624. https://doi.org/10.1016/j.lithos.2006.03.054

Usui, T., Nakamura, E., Helmstaedt, H., 2006. Petrology and Geochemistry of Eclogite Xenoliths from the Colorado Plateau: Implications for the Evolution of Subducted Oceanic Crust. *Journal of Petrology*, 47(5): 929−964. https://doi.org/10.1093/petrology/egi101

Usui, T., Nakamura, E., Kobayashi, K., et al., 2003. Fate of the Subducted Farallon Plate Inferred from Eclogite Xenoliths in the Colorado Plateau. *Geology*, 31(7): 589−592.

Vitale Brovarone, A., Alard, O., Beyssac, O., et al., 2014. Lawsonite Metasomatism and Trace Element Recycling in Subduction Zones. *Journal of Metamorphic Geology*, 32(5): 489−514. https://doi.org/10.1111/jmg.12074

Wei, C.J., Clarke, G.L., 2011. Calculated Phase Equilibria for MORB Compositions: A Reappraisal of the Metamorphic Evolution of Lawsonite Eclogite. *Journal of Metamorphic Geology*, 29(9): 939−952. https://doi.org/10.1111/j.1525-1314.2011.00948.x

Wei, C.J., Duan, Z.Z., 2019. Phase Relations in Metabasic Rocks: Constraints from the Results of Experiments, Phase Modelling and ACF Analysis. *Geological Society, London, Special Publications*, 474(1): 25−45. https://doi.org/10.1144/sp474.10

Wei, C.J., Li, Y.J., Yu, Y., et al., 2010. Phase Equilibria and Metamorphic Evolution of Glaucophane-Bearing UHP Eclogites from the Western Dabieshan Terrane, Central China. *Journal of Metamorphic Geology*, 28(6): 647−666. https://doi.org/10.1111/j.1525-1314.2010.00884.x

Whitney, D.L., Davis, P.B., 2006. Why is Lawsonite Eclogite So Rare? Metamorphism and Preservation of Lawsonite Eclogite, Sivrihisar, Turkey. *Geology*, 34(6): 473−476. https://doi.org/10.1130/g22259.1

Zhang, G.B., Ellis, D.J., Christy, A.G., et al., 2010. UHP Metamorphic Evolution of Coesite-Bearing Eclogite from the Yuka Terrane, North Qaidam UHPM Belt, NW China. *European Journal of Mineralogy*, 21(6): 1287−1300.

附中文参考文献

陈丹玲,孙勇,刘良,等,2005. 柴北缘鱼卡河榴辉岩的变质演化:石榴石成分环带及矿物反应结构的证据. 岩石学报, 21(4):1039−1048.