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柴北缘超高压变质带变质蛇绿岩组合及其地质意义

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摘 要:柴北缘超高压变质带为典型的早古生代大陆型俯冲、碰撞造山带,在都兰地区保存有 2 条蛇绿岩剖面,其代表了陆壳俯冲之前的大洋俯冲残片。笔者选取野马滩和沙柳河 2 条蛇绿岩剖面,对其岩石学、地球化学和年代学研究进展进行综述,并结合整个柴北缘超高压变质带的研究进展,探讨这些变质蛇绿岩组合的地质意义。野马滩变质蛇绿岩剖面由出露于片麻岩中的榴辉岩、石榴辉石岩、蛇纹石化橄榄岩组成。榴辉岩中保存有 K-cymrite 及绿辉石中出溶白云母的超高压变质作用证据,峰期变质作用条件为 $P=2.9\sim3.2$ GPa, $T=631\sim687$ ℃。榴辉岩的地球化学数据表明其原岩类似于 N-MORB 和 E-MORB,锆石 U－Pb 定年显示变质时代约为 445～457 Ma。沙柳河变质蛇绿岩剖面由 3 类榴辉岩、方辉橄榄岩及异剥钙榴岩组成。榴辉岩中保存有柯石英,峰期变质作用条件为 $P=2.7\sim3.4$ GPa, $T=610\sim725$ ℃。榴辉岩的地球化学数据表明其原岩包括了堆晶辉长岩和 E-MORB;而方辉橄榄岩属于地幔橄榄岩,且第二期橄榄石高 Mg 的特征表明其经历过俯冲变质。锆石 U－Pb 定年显示原岩时代约为 520 Ma,变质时代为 440～445 Ma。对野马滩和沙柳河 2 条蛇绿岩剖面的深入研究有助于理解大洋深俯冲向大陆深俯冲和碰撞的转换过程。

关键词:蛇绿岩;榴辉岩;都兰;野马滩;沙柳河;柴北缘超高变质带

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Petrological Study of the Meta-ophiolite from the North Qaidam UHP Metamorphic Belt and Its Geological Implications

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Abstract: The North Qaidam ultra-high pressure (UHP) metamorphic belt is a typical early Paleozoic continental orogenic belt of subduction and collision. Two meta-ophiolite cross-sections in Dulan area is among the oceanic relicts before the continental subduction. Taking two meta-ophiolite cross-sections from Yematan and Shaliuhe as examples, the authors described the research

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progress in this area from aspects of petrology, geochemistry and geochronology, and discussed their geological significance as well. The Yematan meta-ophiolite cross-section consists of eclogite exposed in gneiss, garnet pyroxenite and serpentinized peridotite. Eclogite witnessed UHP metamorphism in k-cymrite and exsolution muscovite in omphacite. The peak metamorphism conditions are P=2.9—3.2 GPa, T=631—687 ℃. Protoliths of the eclogites resemble N-MORB and E-MROB geochemically, and zircon U－Pb age of metamorphic geochronology is of 445—457 Ma. The Shaliuhe meta-ophiolite cross-section consists of eclogites, harzburgites and rodingite. Coesite is preserved in eclogite with the peak metamorphic conditions of P=2.7—3.4 GPa and T=610—725 ℃. Geochemical information of eclogite indicates that the protoliths include cumulate gabbro and E-MORB while the harzburgite is abyssal peridotite and the high $Mg^{\#}$ in the second-generation olivine indicates that it underwent a subduction metamorphism. Zircon U－Pb of the protolith age is at about 520 Ma and the metamorphic age is at 440～445 Ma. Detailed studies of these two meta-ophiolite cross-sections are of great help to understand the transition process from the oceanic subduction to the continental subduction and collision.

Keywords: ophiolite; eclogite; Dulan; Yematan; Shaliuhe; North Qaidam UHP metamorphic belt

造山带中的高压和超高压变质岩石记录了大陆俯冲和碰撞的动力学过程。大洋和大陆岩石圈俯冲折返的过程可以划分为阿尔卑斯型(Alpine-type 或者 A-type)和环太平洋型(B-type)(ERNST, 1988, 2001; MARUYAMA, et al., 1996)。区别于大陆俯冲/折返带主要以花岗质片麻岩为主,夹杂少量变沉积岩、榴辉岩及超基性岩,而大洋俯冲/折返带中的岩石类型以出露包括蛇绿混杂岩、岛弧杂岩以及低温/高压变质岩组合为特征。尽管全世界范围被确认的超高压变质地体已超过 20 多个(CARSWELL, et al., 2003; LIOU, et al., 2004),但其中只有西阿尔卑斯的 Zermatt-Saas (RENECKER, 1991; BUCHER, et al., 2005)和中国的西天山(ZHANG, et al., 2002a, 2002b, 2019)被认为是由洋壳物质发生深俯冲而形成的。而其他多为大陆型俯冲碰撞带,其中的超高压榴辉岩和围岩均为大陆地壳物质俯冲的产物。如中国大别－苏鲁造山带(JAHN, et al., 1999)和挪威的西片麻岩地区(CARSWELL, et al., 2003b)。

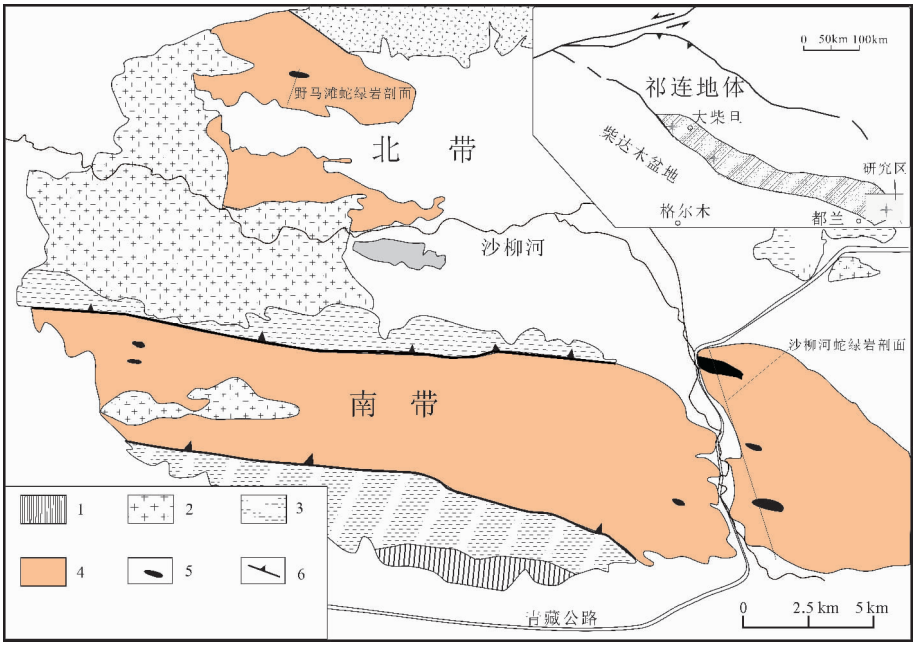
柴北缘超高压变质带作为典型的大陆型俯冲、碰撞造山带,其岩石组合主要为花岗质片麻岩和含有超高压变质作用证据的副片麻岩(YANG, et al., 2001; SONG et al., 2003)、石榴橄榄岩和少量榴辉岩(ZHANG GB, et al., 2009; ZHANG JX, et al., 2009; LIU, et al., 2012, ZHANG C, et al., 2017)。此带中出露的 2 类榴辉岩的原岩时代具有明显区别,分别为元古代和寒武纪(ZHANG GB, et al., 2016)。其中具有寒武纪原岩年龄的榴辉岩来自于都兰地区的沙柳河典型蛇绿岩组合与相邻的野马滩蛇绿岩剖面,代表了柴北缘超高压变质带大陆深俯冲之前的大洋俯冲残片(赵磊等,2019)。

变质蛇绿岩组合作为古大洋俯冲带的标志性产物,对于理解超高压变质带及板块构造过程具有重要研究意义。笔者对柴北缘超高压变质带中出露的典型变质蛇绿岩组合研究进展进行了综述,探讨其对变质带构造演化的限定。

1 地质背景

柴北缘超高压变质带位于中国西部的青海省境内,青藏高原的东北缘,沿柴达木盆地的北缘呈北西西—南东东走向展布。北侧是祁连地体,南侧为柴达木地体,东接秦岭造山带(图 1),其西端被阿尔金断裂所切。阿尔金断裂以西为阿尔金山的主体,北临塔里木盆地;其山体主要呈北东东—南西西走向;但研究表明阿尔金区域内的地质体构造线走向同样为近东西走向。柴北缘超高压变质带北部相距 300 km处即为北祁连加里东期缝合带,发育典型的蛇绿岩和低温高压变质岩组合。

柴北缘超高压变质带自西向东主要出露于鱼卡、绿梁山、锡铁山和都兰 4 个区域。该带中泥质片



1. 泥盆纪沉积;2. 花岗岩;3. 奥陶纪—志留纪沉积;4. 含榴辉岩达肯达坂片麻岩;5. 超基性岩;6. 断层

图 1　柴北缘超高压变质带都兰地区地质图及其中的变质蛇绿岩剖面(据 ZHANG GB, et al., 2009a)

Fig. 1　Geological setting and meta-ophiolite cross-sections in the Dulan terrane, north Qaidam UHPM belt, China

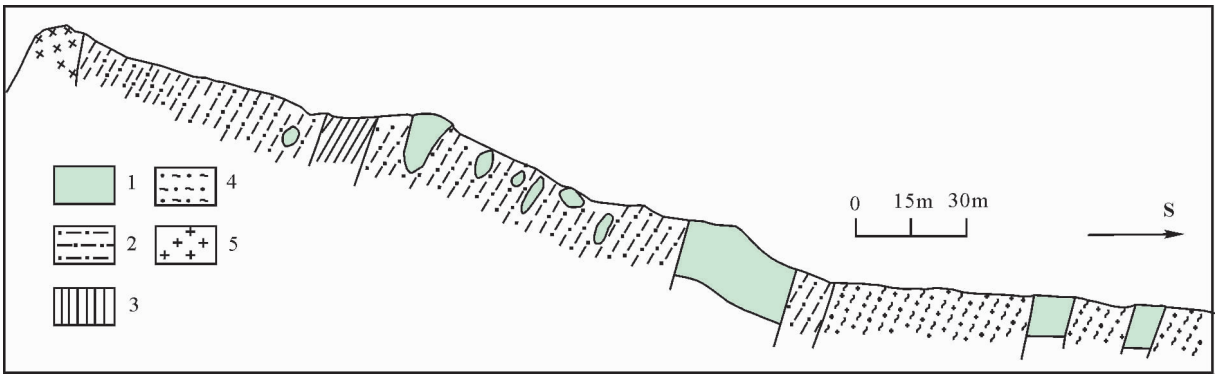
麻岩和榴辉岩中均有柯石英报道(YANG, et al., 2001; SONG, et al., 2003a; ZHANG GB, et al., 2009a, 2009b; ZHANG JX et al., 2009; LIU et al., 2012),而在石榴橄榄岩的锆石中发现有金刚石包裹体(SONG, et al., 2005a),表明柴北缘曾作为一个整体发生了深俯冲而经历过超高压变质作用。

都兰地体位于柴北缘超高压变质带的最东端,青海省都兰县城北东约 40 km 的野马滩—沙柳河一带(图 1)。对于此区的研究较早, YANG, et al. (1994)及张雪亭等(1999)最先对沙柳河和青藏公路并行区域的榴辉岩进行了报道。之后的研究是根据榴辉岩的岩石、矿物组合及地球化学特征的差异,以沙柳河东西流向段为界将本区划分为南北两带(杨经绥等,2000, 2001, 2003;宋述光等,2001; SONG et al., 2003a, 2003b)。北带出露面积较小,其东部为野马滩第四纪沉积物所覆盖,西部则被约 400 Ma 的花岗岩体所侵入(WU et al., 2002)。南带呈东西向被限定于 2 条逆冲断裂之间,出露宽度大于 5 km,向东延伸到青藏公路与沙柳河并行为界。最近,在都兰北带向西北方向约 10 km 的艾日克汗森地区新报道了类似的榴辉岩出露(王启蒙,2020)。

2　野马滩变质蛇绿岩剖面

野马滩变质蛇绿岩剖面位于都兰北带,主要岩石组合为围岩正副片麻岩中夹榴辉岩、石榴辉石岩及蛇纹石化橄榄岩(图 2)(SONG, et al., 2003)。剖面西部有大量的花岗岩侵入,东部覆盖大量的第四纪沉积物(图 1)。根据岩相学特征可以区分出 3 类榴辉岩:多硅白云母榴辉岩、绿帘石榴辉岩和双矿物榴辉岩,矿物组合以 Grt+Omp+Phn+Rt 和 Grt+Omp+Ep+Ttn+Amp 为主(图 3a)。石榴子石辉石岩被解释为具有高 MgO(18.8%)、Cr(1 095×10^{-6})和 Ni (333×10^{-6})的超镁铁质岩石(SONG, et al., 2003b)。此外,由于该区内榴辉岩富含金红石副矿物,成为了潜在的金红石矿的开采对象(林成贵等,2017)。

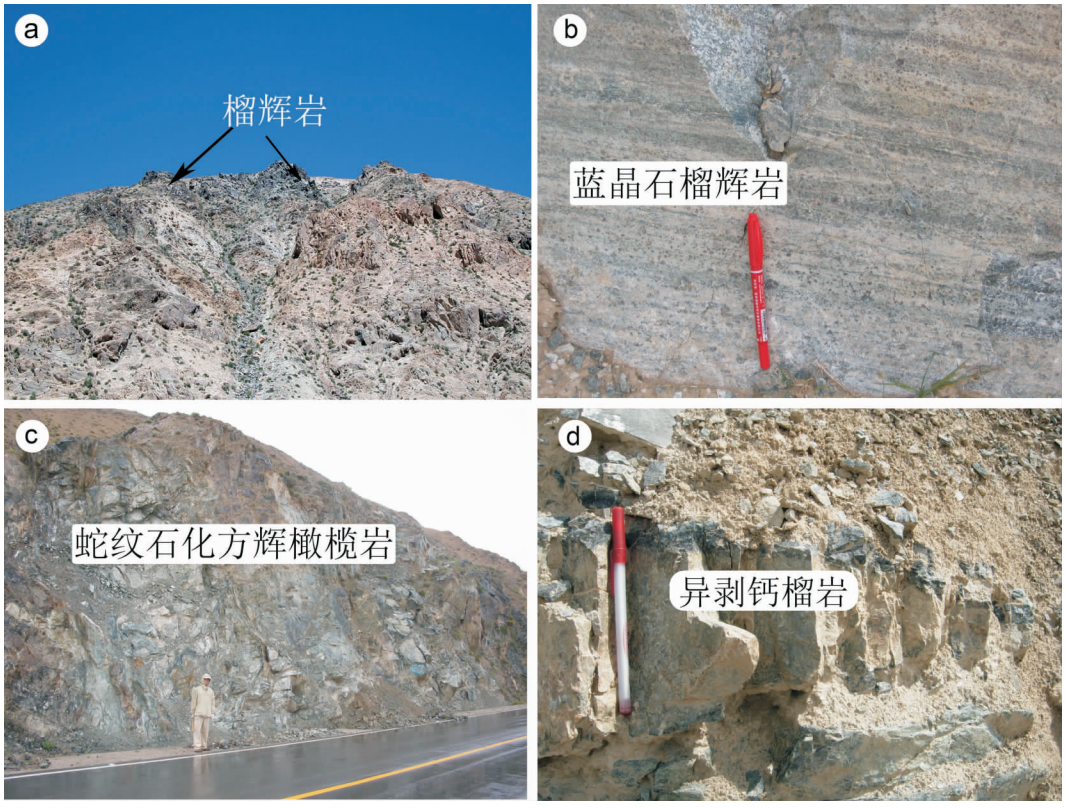
早期对该地区的研究中,首先在围岩中的石榴子石蓝晶石云母片岩锆石中发现了柯石英包裹体,从而提供了确凿的超高压变质作用证据(宋述光等,2001;SONG, et al., 2003a,2003b;杨经绥等,2001)。而榴辉岩中的石榴石和绿辉石都保存有超高压变质作用的痕迹,包括早期发现的柯石英假象,石英出溶



1. 榴辉岩;2. 石榴石云母片岩;3. 云母石英岩;4. 混合花岗质片岩;5. 花岗岩

图 2 都兰北带野马滩变质蛇绿岩实测剖面图(据 SONG,et al. , 2003b)

Fig. 2 Geological cross-section of Yematan meta-ophiolite suite in the northern Dulan terrane, north Qaidam UHP metamorphic belt, China (After SONG, et al. , 2003b)



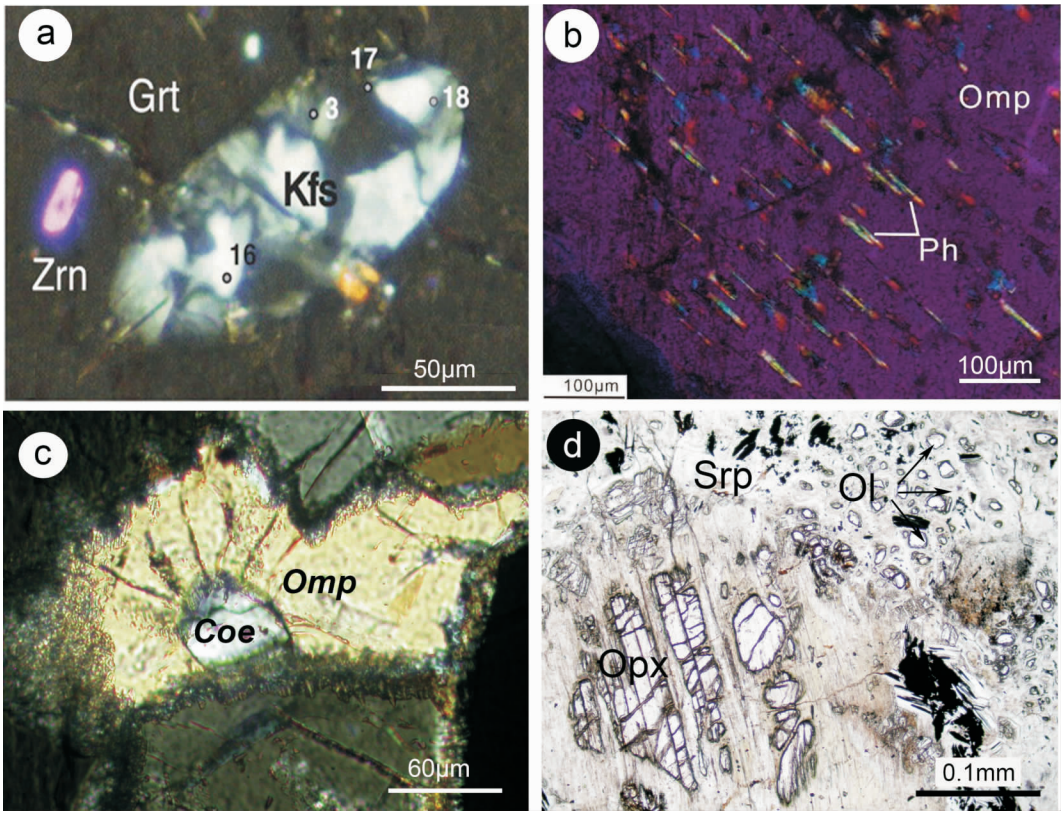
a. 粗粒榴辉岩(野马滩剖面);b. 条带状蓝晶石榴辉岩(沙柳河剖面);c. 蛇纹石化方辉橄榄岩(沙柳河剖面);d. 夹于蛇纹石化方辉橄榄岩中的异剥钙榴岩(沙柳河剖面)

图 3 都兰地区变质蛇绿岩剖面中的代表性岩石野外产状图

Fig. 3 Field photos for representative rocks of meta-ophiolite suits from Dulan terrane, north Qaidam UHP metamorphic belt, China.

及透长石+石英的包裹体(宋述光等,2001;SONG, et al. , 2003a,2003b),以及近期在薄片下绿辉石中发现柯石英包裹体(韩磊,2015)。此外,ZHANG RY, et al. (2009)在榴辉岩中发现了 K-cymrite 包体,指示压力至少大于 3 GPa(图 4a);而 HAN, et al. (2015) 在双矿物榴辉岩样品中发现了绿辉石中

出溶多硅白云母,出溶前单斜辉石可能含有～1.09% K_2O,对应的最小峰期压力约为 76 GPa(图 4b)。SONG et al.(2003a)通过岩相学观察以及 Grt+Cpx 温度计和 Grt+Cpx+Phn 矿物温度计计算,得到该地区榴辉岩在峰期(2.9～3.2 GPa,631～687 ℃)之后经历了一个近等温降压的快速折返。另外,在超基性岩中发现了残留的 Grt+Ol+Opx+Cpx 组合(MATTINSON, et al., 2007)。



a. 保存于榴辉岩石榴子石中的 K-cymrite 假象包体(野马滩剖面)(ZHANG RY, et al., 2009);b. 绿辉石中的多硅白云母出溶(野马滩剖面)(HAN, et al., 2015);c. 榴辉岩中的柯石英包体(沙柳河剖面)(ZHANG GB, et al., 2009a);d. 蛇纹石化方辉橄榄岩镜下矿物组合(沙柳河剖面)(ZHANG GB, et al., 2008)

Grt. 石榴子石;Zrn. 锆石;Kfs. 钾长石;Omp. 绿辉石;Ph. 多硅白云母;Coe. 柯石英;Srp. 蛇纹石;Ol. 橄榄石

图 4　都兰地区变质蛇绿岩组合中代表性岩石的显微照片

Fig. 4　Photomicrographs for representative rocks of meta-ophiolite suits from Dulan terrane, north Qaidam UHP metamorphic belt, China.

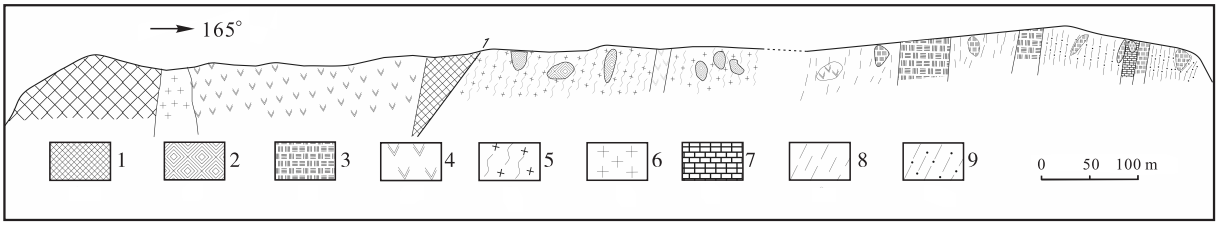
榴辉岩锆石定年结果显示其变质年龄为 446～457 Ma (SONG, et al., 2006, ZHANG GB, et al., 2014),而围岩泥质片麻岩锆石中含柯石英局部微区的年龄为(423±6) Ma (SONG, et al., 2006);MATTINSON, et al. (2006) 对同一个区域内的榴辉岩锆石进行的年代学研究认为,榴辉岩相的变质时代持续了 20～30 Ma(422～450 Ma),解释为板块俯冲的持续过程。同时锆石及金红石 U-Pb 定年及锆石钛温度计和金红石锆温度计所限定出的 $T-t$ 冷却轨迹显示出北带榴辉岩经历了～3～4 ℃/Ma的冷却速率(ZHANG GB, et al., 2014)。而韩磊(2015)在其博士论文中,在一个新鲜榴辉岩样品的锆石中发现了残留岩浆核,定年结果显示为约 500 Ma。

榴辉岩的全岩地球化学特征类似于 N-MORB 和 E-MORB,$(^{87}Sr/^{86}Sr)_i$ 初始值(0.704～0.723)和 $\varepsilon_{Nd}(t)$ 值(3.4～7.6)反应其原岩起源于地幔,并受俯冲带环境的影响(韩磊,2015)。对含石榴子石辉石岩的分析,推测其为具有 E-MORB 特征的富镁堆晶岩(SONG, et al., 2003);结合此剖面同时产出蛇纹石化石榴子石橄榄岩、含石榴子石角闪辉石岩(超基性堆晶岩)以及大量的榴辉岩,推测野马

滩剖面为古洋壳残留(地幔橄榄岩-堆晶岩-基性熔岩),构成一条变质蛇绿岩剖面。

3 沙柳河变质蛇绿岩剖面

沙柳河蛇绿岩剖面分布在沙柳河与青藏公路交汇并行的南北向地区,沿此剖面榴辉岩呈透镜体产于花岗质和泥质片麻岩中,或者以夹层的形式与大理岩互层(图 5)(ZHANG GB, et al., 2008, 2009a)。根据岩相学可以区分出 3 类榴辉岩:蓝晶石榴辉岩(图 3b)、绿帘石榴辉岩和多硅白云母榴辉岩,同时与榴辉岩共生的有蛇纹石化橄榄岩(图 3c)和异剥钙榴岩 (图 3d)。3 类榴辉岩和共生的橄榄岩构成了肢解的蛇绿岩组合。



1. 蓝晶石榴辉岩;2. 绿帘石榴辉岩;3. 多硅白云母榴辉岩;4. 蛇纹石化橄榄岩;5. 花岗片麻岩;6. 花岗岩;7. 大理岩;8. 白云母片岩;9. 石榴子石白云母片岩

图 5 都兰南带沙柳河变质蛇绿岩剖面图(据 ZHANG G B, et al., 2008)

Fig. 5 Geological cross-section of the Shaliuhe meta-ophiolite suite in the southern Dulan terrane, north Qaidam UHP metamorphic belt, China (After ZHANG GB, et al., 2008)

在这 3 类榴辉岩中,在显微镜下,蓝晶石榴辉岩薄片中可见柯石英包裹体(图 4c,ZHANG GB, et al., 2009)。其中,蓝晶石榴辉岩经历了峰期前,峰期和退变质 3 个阶段,对应的温压条件分别为:①峰期前:P=0.49～0.67 GPa, T=410～490 ℃。②峰期矿物组合 Grt+Omp+Ky+Rt+Phn+Qtz,对应温压条件为 P=2.7～3.4 GPa, T=610～700 ℃。③初期退变质阶段为:P=0.7～1.0 GPa, T=630～720 ℃。④晚期绿片岩相退变。多硅白云母榴辉岩的峰期温压条件为:P=2.7～2.9 GPa, T=645～725 ℃,退变质阶段所确定出温压条件为:P=1.2～1.4 GPa,T=610～670 ℃。

全岩主微量元素数据表明蓝晶石榴辉岩和绿帘石榴辉岩的原岩可能是堆晶辉长岩,前者继承了原岩的堆晶条带;它们具有一致的$(^{87}Sr/^{86}Sr)_i$初始值(0.703～0.704)和$\varepsilon_{Nd}(t)$值(5.9～8.0)。而多硅白云母榴辉岩的原岩具有 E-MORB 的特征,具有高$(^{87}Sr/^{86}Sr)_i$初始值(0.705～0.716)和低$\varepsilon_{Nd}(t)$值(1.4～4.1)的特征。

锆石 U-Pb 定年结果表明蓝晶石榴辉岩的原岩年龄为(516±8) Ma,而变质年龄为 440～445 Ma (ZHANG GB, et al., 2008)。锆石的 Hf-O 同位素数据显示,锆石的岩浆继承核部具有典型的地幔特征(5.1‰±0.3‰),并且 2 组亏损地幔模式年龄(与表观地质年龄接近的年轻模式年龄和>700 Ma 的较老模式年龄)揭示新生地壳和循环地壳参与到了幔源岩浆和地壳物质的混合过程中。锆石边部较高的氧同位素组成($\delta^{18}O$=6.6‰±0.3‰)表明在变质过程中经受了高氧同位素组成的变质流体交代(ZHANG GB, et al., 2016)。

蛇纹石化橄榄岩中所识别出的 2 期橄榄石为其经历过俯冲变质提供了直接证据,其中的第一期橄榄石及残留斜方辉石的成分能够与现代大洋和蛇绿岩底部地幔橄榄岩对比,表明其为典型的尖晶石相方辉橄榄岩,是经过高度部分熔融形成深度较浅的地幔方辉橄榄岩(图 4d)(张贵宾等,2005)。而第一期橄榄石在经历蛇纹石化过程中发生了 Fe 丢失,受俯冲带变质作用的影响发生了变质重结晶作用,从而生成了 Fo 值偏高的第二期橄榄石(张贵宾等,2005;ZHANG GB, et al., 2008)。最近的全岩氧同位素及 Sr 同位素数据也表明这些蛇纹石化方辉橄榄岩经历了洋底水化和俯冲带变质作用(ZHANG L, et al., 2019)。

结合野外地质工作,沙柳河 3 类榴辉岩与具有蛇绿岩型地幔橄榄岩特征的方辉橄榄岩构成了地幔橄榄岩-堆晶岩-玄武质岩石一个较完整的蛇绿岩剖

面。这一蛇绿岩组合可能是奥陶纪—志留纪大陆深俯冲碰撞前的洋壳俯冲的残留(ZHANG GB, et al., 2008)。同时与蛇纹石化方辉橄榄岩共生的异剥钙榴岩主要由钙铝榴石、透辉石、绿泥石、碳酸盐矿物及少量葡萄石和黝帘石组成。异剥钙榴岩通常被认为是洋底变质作用的标志性产物,它为此洋壳组合的确定提供了又一证据(张贵宾等,2011)。

4　柴北缘超高压变质带变质蛇绿岩组合的地质意义

柴北缘超高压变质带出露有 2 类榴辉岩:一种类型为原岩时代属于元古代,在此超高压变质带 4 个地体中都有分布。如鱼卡榴辉岩的原岩都属于元古代,其多数榴辉岩的残留岩浆锆石核限定的原岩时代约为 850～875 Ma(SONG, et al., 2010; ZHANG GB, et al., 2016),氧同位素显示具有与地幔一致的组成(5.2±0.7‰, ZHANG GB, et al., 2016)。这些新元古代的基性幔源岩石的形成可能与地幔柱相关(SONG, et al., 2010)或者来源于夭折的初始洋盆产物(ZHANG JX, et al., 2005; CHEN, et al., 2009);另一类为少量出露的蓝晶石榴辉岩,其原岩时代约为 1 273 Ma(REN et al., 2018),且含有硬柱石假象,结合地球化学数据,可能为中元古代的洋壳残片。所有这些中—新元古代的基性岩石同大陆地壳物质的主体长英质片麻岩都经历了志留纪的大陆深俯冲,且榴辉岩相变质过程中的柯石英包体指示其至少俯冲到了 80 km 的深度(ZHANG GB, et al., 2009b, 2016;REN, et al., 2017, 2018)。

都兰地区出露并确定的 2 条典型蛇绿岩剖面的岩石组合、岩相学及年代学都很相似(图 2、图 5)(SONG, et al., 2003a, 2003b; ZHANG GB, et al., 2008, 2009a, 2016; 韩磊,2015)。2 条剖面中都出露有完整的变质基性岩和超基性岩的组合,榴辉岩的地球化学特征表明,它们起源于亏损地幔,其岩浆源区包括了亏损地幔与循环组分的混合(ZHANG GB, et al., 2016)。此外,2 条剖面中的榴辉岩原岩时代为 500～520 Ma, 区别于上述的中—新元古代的榴辉岩原岩时代,揭示出它们有可能来自于寒武纪时期在祁连和柴达木地块之间的大洋洋壳。

柴北缘超高压变质带的变质时代数据多集中于 460～420 Ma, 但对其有 2 种不同的解释:①大陆连续深俯冲的持续时间(MATTINSON, et al.,2006; ZHANG JX, et al., 2010, 2015)。②2 期变质时间(ZHANG GB, et al., 2016; SONG et al., 2019),以 440 Ma 为界,>440 Ma 应代表洋壳深俯冲时代,主要来自于上述 2 条蛇绿岩剖面中的榴辉岩锆石定年数据。而鱼卡榴辉岩及此带中的长英质片麻岩所记录的变质时代均小于 440 Ma(SONG, et al., 2014; ZHANG GB, et al., 2016)。因此, 440 Ma 有可能是洋陆俯冲转换的时间节点(ZHANG GB, et al., 2016)。CHEN et al. (2019) 基于都兰相同地区的榴辉岩锆石年代学研究也得出了类似的结论,尽管其认为这些蛇绿岩组合有可能为 SSZ 型,但洋陆俯冲转换的时代类似,约为 445 Ma。

近几年相应的研究表明,其北部乌兰地区出露有低压-高温麻粒岩和与岛弧成因有关、同时代的花岗质和镁铁质岩浆侵入体(LI et al., 2018; 李秀财, 2015)。锆石年代学研究表明,其低压-高温变质作用时代为 446～476 Ma,与上述早期柴北缘大洋俯冲高压变质作用的年龄相一致。相平衡模拟指示麻粒岩经历了顺时针演化的 P-T 轨迹,其峰期变质条件为 800～900 ℃,5.5～7 kbar,对应的地热梯度较高(130～150 ℃/kbar)(LI, et al., 2018)。推测其热量是由洋壳俯冲过程中岛弧岩浆侵入(LI, et al., 2019)和板块回撤引起弧后盆地伸展、软流圈上涌共同作用形成。基于以上认识,都兰地区出露并确定的 2 条典型蛇绿岩剖面结合乌兰地区低压高温的岩石组合构成了典型的早古生代双变质带。

综上所述,都兰地体的野马滩和沙柳河 2 条蛇绿岩剖面为大陆俯冲之前的大洋俯冲残片。对其进行更深入的进一步研究有助于对于大洋深俯冲向大陆深俯冲和碰撞的转换过程的理解。

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