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喜马拉雅造山带两种不同类型榴辉岩与印度大陆差异性俯冲

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摘要: 印度与亚洲大陆新生代碰撞—俯冲形成的喜马拉雅造山带核部由高压和超高压变质岩组成.超高压榴辉岩分布在喜马拉雅造山带西段,由石榴石、绿辉石、柯石英、多硅白云母、帘石、蓝晶石和金红石组成.超高压榴辉岩的峰期变质条件为2.6~2.8 GPa和600~620 ℃,其经历了角闪岩相退变质作用和低程度熔融.超高压榴辉岩的进变质、峰期和退变质年龄分别为~50 Ma、45~47 Ma和35~40 Ma,指示一个快速俯冲与快速折返过程.高压榴辉岩产出在喜马拉雅造山带中—东段,由石榴石、绿辉石、多硅白云母、石英和金红石组成.高压榴辉岩的峰期变质条件为>2.1 GPa和>750 ℃,叠加了高温麻粒岩相退变质作用与强烈部分熔融.高压榴辉岩的峰期和退变质年龄可能分别是~38 Ma和14~17 Ma,很可能经历了一个缓慢俯冲与缓慢折返过程.喜马拉雅造山带两种不同类型榴辉岩的存在表明,印度与亚洲大陆约在51~53 Ma碰撞后,印度大陆地壳的西北缘陡俯冲到了地幔深度,导致表壳岩石经历了超高压变质作用,而印度大陆地壳的东北缘平缓俯冲到亚洲大陆之下,导致表壳岩石经历了高压变质作用.

关键词: 高压榴辉岩;超高压榴辉岩;变质作用 *P-T-t* 轨迹;大陆俯冲;喜马拉雅造山带;变质岩;岩石学.
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Two Contrasting Eclogite Types in the Himalayan Orogen and Differential Subduction of Indian Continent

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Abstract: The core of the Himalayan orogen, resulting from the Cenozoic collision between the Indian and Asian continents, consists of high-pressure (HP) and ultrahigh-pressure metamorphic rocks. The ultrahigh-pressure (UHP) eclogites occur in the western segment of the Himalayan orogen, and contain garnet, omphacite, coesite, phengite, zoisite/epidote, kyanite and rutile. The UHP eclogites record a peak metamorphic condition of 2.6—2.8 GPa and 600—620 ℃, and a late stage of amphibolite-facies retrogression and slight partial melting. The prograde, peak and retrograde metamorphic times of the UHP eclogites are ~50 Ma, ~45—47 Ma and ~35—40 Ma, respectively, indicating that the UHP eclogites underwent a rapid subduction and rapid exhumation. The HP eclogites occur in the east-central segment of the Himalayan orogen, and contain garnet, omphacite, phengite, quartz and rutile. The HP eclogites have a peak metamorphic condition of >2.1 GPa and >750 ℃, and experienced a late stage of granulite-facies retrogression and extensive anataxis. The peak and retrograde metamorphic times of the HP eclotites are ~38 Ma and ~14—17 Ma, respectively, indicating that the HP eclogites underwent a slow subduction and slow exhumation. The presence of two contrasting eclogite types in the Himalayan orogen shows that, after the In-

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dia collided with Asia at around 51－53 Ma, the north-western margin of Indian continental crust deeply subducted into the mantle, and underwent UHP metamorphism, and while the north-eastern margin of Indian continental crust shallowly subducted beneath the Asian continent, and experienced HP metamorphism.

Key words: high-pressure eclogite; ultrahigh-pressure eclogite; metamorphic *P-T-t* path; continental subduction; Himalayan orogen; metamorphic rock; petrology.

榴辉岩是一种基性高压或超高压变质岩，主要由石榴石和绿辉石组成，可含多硅白云母、蓝晶石、帘石、蓝闪石、硬柱石、石英、金红石、柯石英和金刚石.高压榴辉岩通常形成在＞1.0 GPa 的压力下，形成深度在平均大陆地壳深度(约 40 km)以下(图 1).青藏高原的加厚下地壳(约 40～70 km)可以形成高压榴辉岩.超高压榴辉岩以含柯石英和(或)金刚石为特征.含柯石英的超高压榴辉岩形成在＞2.7 GPa 的压力下(假定温度为 700～800 ℃)，形成深度＞90 km(图 1).因此，即使是在世界上最厚的地壳，即青藏高原的加厚下地壳也不可能形成超高压榴辉岩，只有当地壳岩石俯冲到地幔深度才可以形成.

20 世纪 80 年代中期，在挪威加里东造山带和西阿尔卑斯造山带的表壳岩中发现了含柯石英的榴辉岩(Chopin, 1984；Smith, 1984)，之后又发现了含金刚石的榴辉岩(Sobolev and Shatsky, 1990；Xu *et al*., 1992)，表明大陆地壳可以俯冲到＞90～120 km 的地幔深度，然后又回返到地表.从那时起，大陆深俯冲和超高压变质作用已经成为地球科学的前沿课题(Chopin, 2003；Liou *et al*., 2009；Zheng *et al*., 2011；Hermann *et al*., 2013；Schertl and O'Brein, 2013).到目前为止，在全球的晚新元古代和显生宙大陆造山带中均发现了超高压变质岩(Gilotti, 2013).最老的(620～630 Ma)超高压榴辉岩分布在巴西和马里的泛非造山带中，最新的(7～8 Ma)超高压榴辉岩产出在巴布亚新几内亚的新生代碰撞造山带中.

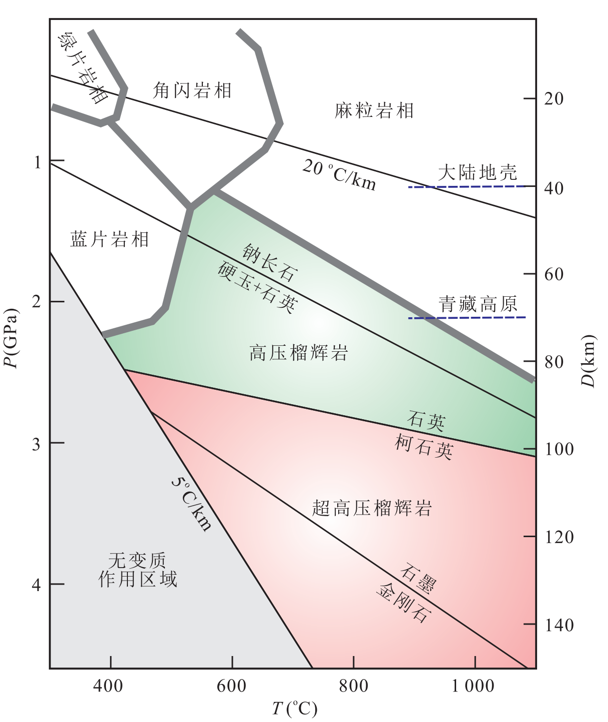

图 1　高压和超高榴辉岩形成条件与深度

Fig.1　Metamorphic conditions and related depths of high- and ultrahigh-pressure eclogites

据 Gilotti(2013)修改

喜马拉雅造山带是新生代印度与亚洲大陆板块碰撞作用的产物，是世界上最典型的，而且正在进行的碰撞造山带.但是，与其他大陆造山带，包括同时代的阿尔卑斯造山带相比，喜马拉雅造山带的典型高压、超高压变质岩——蓝片岩和榴辉岩产出较少.Shams(1972)和 Honegger *et al*.(1989)对产出在印度－雅鲁藏布江缝合带中的白垩纪(80～100 Ma)蓝片岩进行了描述.喜马拉雅造山带西段高喜马拉雅结晶岩系中产出的榴辉岩被发现在 20 世纪 80 年代(Ghazanfar and Chaudhry, 1986, 1987).后来，学者陆续对相关的榴辉岩进行了岩石学和年代学研究(Spencer *et al*., 1990, 1995；Pognante and Spencer, 1991；Tonarini *et al*., 1993；Spencer and Gebauer, 1996；de Sigoyer *et al*., 1997, 2000；Guillot *et al*., 1997；Lombardo *et al*., 2000).O'Brien *et al*.(1999, 2001)和 Mukherjee and Sachan(2001)分别报道了西喜马拉雅 Kaghan 谷和 Tso Morari 地块中产出的含柯石英超高压榴辉岩.Lombardo *et al*.(1998)和 Lombardo and Rolfo(2000)报道了喜马拉雅造山带东段的麻粒岩化榴辉岩.Wang *et al*.(2017)和 Li *et al*.(2018)确证了高压榴辉岩在东喜马拉雅造山带的存在.目前的研究表明，大陆碰撞带的典型岩石——超高压榴辉岩发育在喜马拉雅造山带西段，而喜马拉雅造山带中－东段只有高压榴辉岩相和高压麻粒岩相变质岩(图 2).本文对喜马拉雅造山带两种不同类型榴辉岩的岩石学特征、变质条件和变质时间进行了系统总结，并结合相关研究成

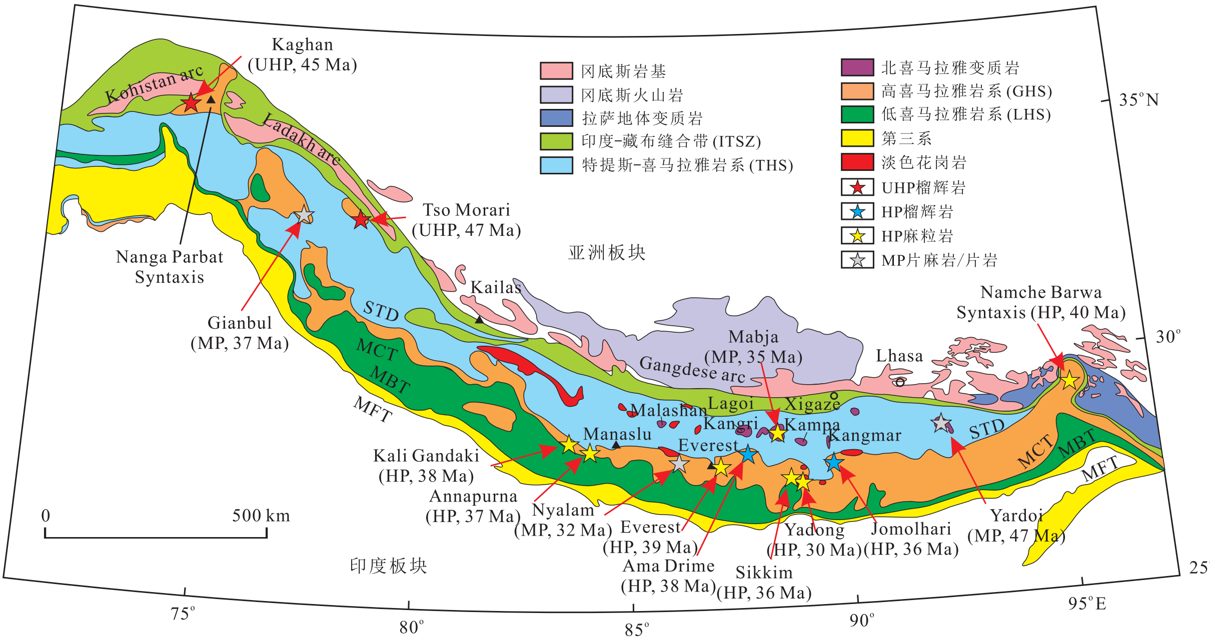

图 2　喜马拉雅造山带与高压和超高压变质岩分布

Fig.2　Geological map of the Himalayan orogen, showing distributions of representative medium-, high- and ultrahigh-pressure metamorphic rocks

据 Ding *et al*.(2016a)和张泽明等(2017, 2018)修改.MFT.主前缘逆冲断裂;MBT.主边界逆冲断裂;MCT.主中央逆冲断裂;STD.藏南拆离系.图中标注了较深入研究的中压、高压和超高压变质岩的地点与变质年龄,资料来源:Ama Drime (Kellett *et al*., 2014), Annapurna (Kohn and Corrie, 2011), Everest (Cottle *et al*., 2009), Gianbul (Horton *et al*., 2014), Jomolhari (Regis *et al*., 2014), Kaghan (Kaneko *et al*., 2003), Kali Gandaki (Iaccarino *et al*., 2015), Mabja dome (Lee and Whitehouse, 2007), Namche Barwa Syntaxis (Zhang *et al*., 2015), Nyalam (Wang *et al*., 2015), Sikkim (Rubatto *et al*., 2012), Tso Morari (Donaldson *et al*., 2013), Yadong (Zhang *et al*., 2017) 和 Yardoi dome (Ding *et al*., 2016b).变质作用类型:MP.中压;HP.高压;UHP.超高压

果,探讨了两种不同类型榴辉岩的形成机制,以及对大陆碰撞时间和俯冲性质的指示意义.

1　喜马拉雅造山带的构造单元与变质作用

喜马拉雅造山带位于青藏高原南部,是印度与亚洲大陆新生代碰撞作用的产物.喜马拉雅造山带呈弓形,从东构造结(南迦巴瓦构造结)至西构造结(南迦巴尔巴特构造)长约 2 300 km(图 2).喜马拉雅造山带由 4 个沿造山带走向分布的构造单元组成,从北向南依次为:特提斯喜马拉雅岩系(Tethyan Himalayan Sequence, THS)、高喜马拉雅结晶岩系(Greater Himalayan Crystalline Sequence, GHS)、低喜马拉雅岩系(Lesser Himalayan Sequence, LHS)和次喜马拉雅单元(Sub-Himalayan Sequence)(Burg *et al*., 1984; Burchfiel *et al*., 1992; Yin and Harrison, 2000).4 个构造单元之间依次被藏南拆离系(South Tibet Detachment, STD)、主中央逆冲断裂(Main Central Thrust, MCT)和主边界逆冲断裂(Main Boundary Thrust, MBT;图 2)所分隔.

特提斯喜马拉雅岩系(THS)位于喜马拉雅造山带的北部,其北界是印度－雅鲁藏布江缝合带(India-Tsangpo Suture Zone, ITSZ),南部边界是藏南拆离系(STD).特提斯喜马拉雅岩系是一个约 100～200 km 宽的复向斜带,由形成在印度大陆北部被动陆缘环境的晚元古代至中生代变质沉积岩组成,未变质到低角闪岩相变质(Kohn, 2014).在西喜马拉雅,特提斯喜马拉雅岩系中发育石炭纪至二叠纪裂谷环境下形成的基性火成岩.在特提斯喜马拉雅岩系中部发育一系列的片麻岩穹窿(图 2),穹窿核部由中级变质岩组成,被称为北喜马拉雅变质岩.大多数片麻岩穹窿核部被始新世至中新世的花岗岩侵入(Yin and Harrison, 2000; Zhang *et al*., 2012; 吴福元等, 2015).

高喜马拉雅结晶岩系(GHS)由 30～150 km 宽的中－高级变质岩系和新生代的淡色花岗岩组成,构成了喜马拉雅造山带的变质核.中－高级变质岩的原岩为中－新元古代至早古生代的沉积岩和岩浆岩.以前的研究普遍认为,高喜马拉雅结晶岩系为印

度与亚洲大陆碰撞过程中形成的典型中压型(巴罗型)变质岩系(Dasgupta *et al*.，2004，2009).从低喜马拉雅岩系上部到高喜马拉雅结晶岩系下部发育一个完整的倒转中压变质带，即从下到上依次是绿泥石带、黑云母带、石榴石带、十字石带、蓝晶石带和矽线石带.从高喜马拉雅结晶岩系上部到特提斯喜马拉雅岩系下部发育一个正常的中压变质带.但是，近来的研究表明，在喜马拉雅造山带西段，高喜马拉雅结晶岩系经历了超高压榴辉岩相变质作用，叠加了中压型角闪岩相退变质作用，而在喜马拉雅造山带中、东段，高喜马拉雅结晶岩系经历了高压榴辉岩相和高压麻粒岩相变质作用，叠加了中、低压麻粒岩相退变质作用(Kohn，2014；张泽明等，2017，2018).低喜马拉雅岩系(LHS)主要由元古代的变质沉积岩和少量的岩浆岩组成，经历了绿片岩相至角闪岩相变质作用.低喜马拉雅岩系包括一系列逆冲叠置岩片，其构造厚度可达 30 km(Kohn，2014).次喜马拉雅单元是喜马拉雅山造山带的前陆盆地，由中新世到更新世的磨拉石组成.

2　喜马拉雅造山带西段的超高压榴辉岩

2.1　超高压榴辉岩及其变质条件

在喜马拉雅造山带西段，超高压榴辉岩产出在巴基斯坦的 Kaghan 谷和印度的 Tso Morari 地块，2 个地区相距约 450 km，但都紧邻印度—雅鲁藏布江缝合带分布(图 2).Kaghan 谷位于西构造结附近，产出在高喜马拉雅结晶岩系之中的含柯石英榴辉岩由石榴石、绿辉石、绿帘石、多硅白云母、金红石和柯石英组成，柯石英在绿辉石中呈包体(图 3).

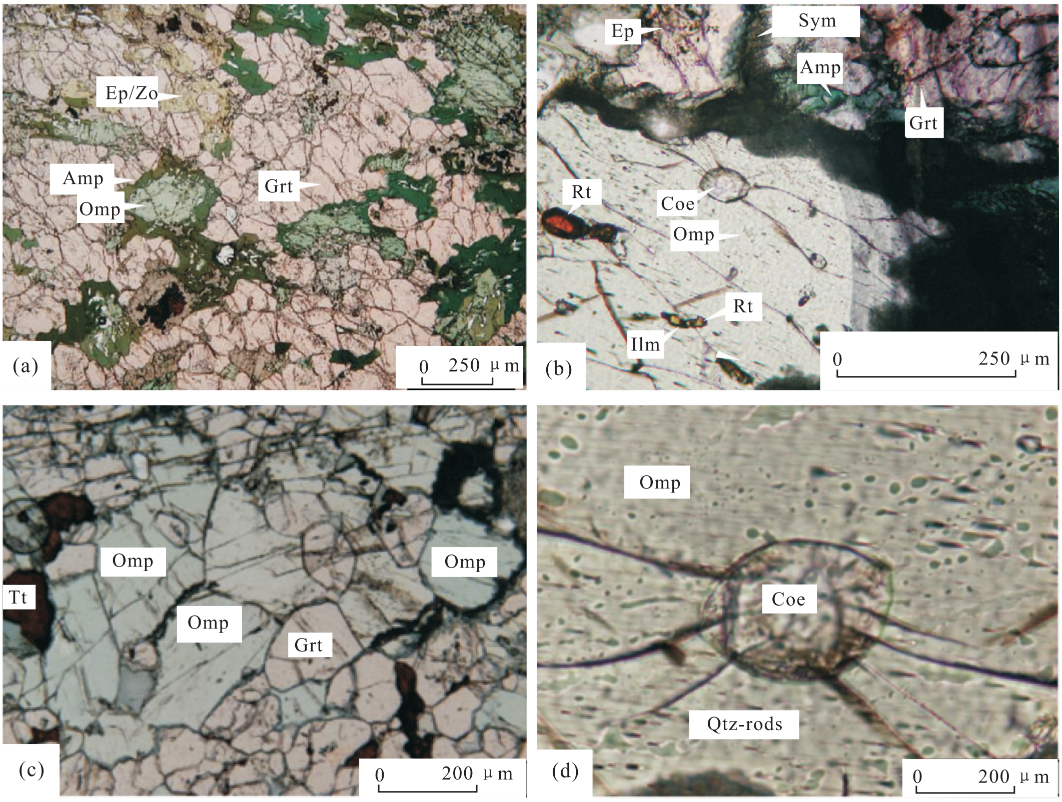

图 3　喜马拉雅造山带西段 Kaghan 超高压榴辉岩显微照片

Fig.3　Photomicrographs of ultrahigh-pressure eclogites from the Kaghan Valley, the western Himalaya

据 Rehman *et al*.(2007，2013).a.超高压榴辉岩由石榴石、绿辉石和绿帘石组成，部分绿辉石边缘被角闪石，或由单斜辉石＋角闪石＋石英组成的合晶替代；b.超高压榴辉岩由石榴石、绿辉石、绿帘石、金红石、钛铁矿和柯石英组成.柯石英呈包裹体产于绿辉石中，发育放射状裂纹.部分石榴石和绿辉石被单斜辉石＋角闪石＋石英合晶替代；c.超高压榴辉岩，由石榴石、绿辉石和榍石组成，部分绿辉石被单斜辉石＋角闪石＋石英合晶冠状体替代；d.超高压榴辉岩绿辉石中的柯石英包体以及沿包体向外发育的放射状裂纹.注意绿辉石中含有出溶的石英棒或页片.矿物代号：Amp.角闪石；Coe.柯石英；Ep.绿帘石；Grt.石榴石；Ilm.钛铁矿；Omp.绿辉石；Qtz.石英；Rt.金红石；Sym.后成合晶；Tt.榍石；Zo.黝帘石

O'Brien *et al*.(2001)认为这里的高喜马拉雅结晶岩系包括 2 个部分,一部分为由正片麻岩和副片麻岩组成的基底岩石,另一部分为由角闪岩、大理岩、石英和云母片岩组成的古生代－早中生代盖层岩石.榴辉岩呈布丁状产于基底岩系的片麻岩中.在大理岩和变泥质岩,以及在花岗质片麻岩中呈薄层状产出的斜长角闪岩很可能是榴辉岩的退变质产物.Kaneko *et al*.(2003)认为,Kaghan 谷超高压变质地块由 3 个单元组成.下部单元主要由副片麻岩和片岩组成,含少量角闪岩透镜体,中部单元主要由长英质片麻岩和大理岩组成,含丰富的榴辉岩层或透镜体,上部单元由石英岩、片岩和大理岩组成.地质温压计算表明,榴辉岩的峰期变质条件为 2.7～2.9 GPa和 690～750 ℃(O'Brien *et al*., 2001).这表明,印度大陆西北缘俯冲到 90～100 km 的地幔深度形成了柯石英榴辉岩.

Rehman *et al*.(2007, 2008, 2013)认为 Kaghan 榴辉岩经历了超高压峰期变质和高压榴辉岩相退变质作用,其峰期和退变质条件分别为～2.9 GPa和 757～786 ℃、～1.8 GPa 和 825±59 ℃.超高压榴辉岩具有一个顺时针型的 *P*-*T* 轨迹,进变质作用为增温与增压过程,退变质为降温与降压过程(图 4).Wilke *et al*.(2010)研究认为,Kaghan 超高压榴辉岩峰期变质条件为 3.0～3.5 GPa和 670～750 ℃,在榴辉岩的退变质过程中叠加了角闪岩相变质作用,其退变质 *P*-*T* 轨迹先是一个缓慢降温、快速降压过程,然后是一个近等压升温过程,最后是降温、降压过程(图 4).退变质过程中的升温导致了榴辉岩的低程度部分熔融,形成了含多硅白云母、石英、黝帘石和蓝晶石的浅色体.

Tso Morari 地块位于印度西北部的 Ladakh 地区,其呈穹窿状产出在特提斯喜马拉雅岩系之中(图 2).该块体的下部由元古代至寒武纪的基底岩石组成,上部是变质的古生代至第三系沉积岩.奥陶纪的花岗岩和基性岩侵入在基底岩石之中.含柯石英榴辉岩呈布丁状产出在基底和变质沉积岩中.榴辉岩的原岩很可能是形成在特提斯洋和印度大陆边缘过渡环境下的基性岩墙(Guillot *et al*., 2008).Tso Morari 地块整体经历了超高压榴辉岩相变质作用(Guillot *et al*., 2003; Mukherjee *et al*., 2003; de Sigoyer *et al*., 2004; Epard and Steck, 2008).超高压榴辉岩的矿物组合是石榴石、绿辉石、多硅白云母、金红石和柯石英.柯石英及其假象在石榴石和绿辉石中呈包裹体产出(图 5).有的榴辉岩中还含有黝帘石、滑石、蓝晶石、菱镁矿、白云石和钠云母等次要矿物.

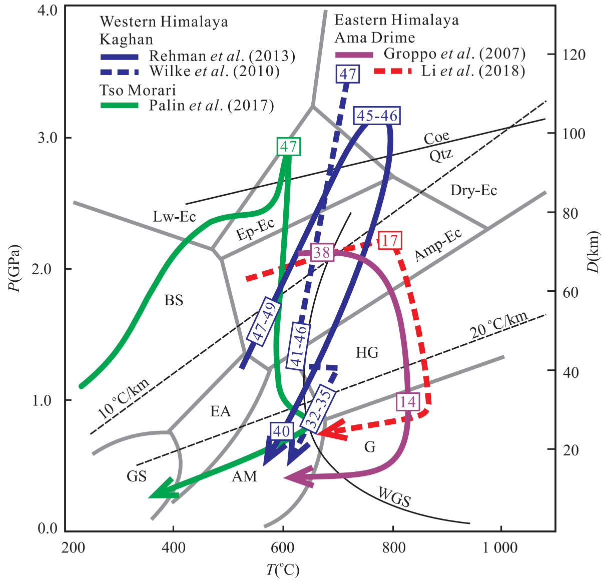

图 4　喜马拉雅造山带高压和超高压榴辉岩变质作用 *P*-*T*-*t* 轨迹

Fig.4　Metamorphic *P*-*T*-*t* paths of the high- and ultrahigh-pressure eclogites in the Himalayan orogen

图中的数字为年龄(Ma),其中 Groppo *et al*.(2007)*P*-*T* 轨迹上的 38 Ma 峰压力年龄和 15 Ma 退变质年龄分别为 Kellett *et al*.(2014)获得的石榴石 Lu-Hf 等时线年龄和锆石 U-Pb 年龄.变质相:AM.角闪岩相;Amp-Ec.角闪石榴辉岩相;BS.蓝片岩相;Dry-Ec.干榴辉岩相;EA.绿帘角闪岩相;Ep-Ec.绿帘石榴辉岩相;G.麻粒岩相;GS.绿片岩相;HG.高压麻粒岩相;Lw-Ec.硬柱石榴辉岩相;WGS.湿的花岗岩固相线.Coe.柯石英;Qtz.石英

St-onge *et al*.(2013)认为 Tso Morari 超高压榴辉岩经历了 4 期变质作用,第 1 期为高压榴辉岩相进变质作用,发生在～2.1 GPa 和 535±15 ℃条件下,第 2 期为超高压榴辉岩峰期变质作用,其变质条件为 2.6～2.8 GPa 和 630～645 ℃,第 3 期为高角闪岩相退变质作用,发生在 1.3 GPa 和 690±25 ℃条件下,第 4 期为角闪岩相退变质作用,发生在～0.8 GPa 和 705～755 ℃条件下.Singh *et al*.(2013)从超高压榴辉岩中识别出 5 阶段矿物组合,并估算了相应的变质条件.前超高压的矿物组合是 Ca 角闪石＋绿帘石±钠云母±金红石±磁铁矿,其变质条件为 0.1 GPa 和 500 ℃,早期超高压变质矿物组合是 Fe＞Mg＞Ca 石榴石＋绿辉石＋柯石英＋多硅白云母＋金红石±钛铁矿,变质条件为＞3.3 GPa和～750 ℃,晚期超高压矿物组合是 Fe＞Mg＞Ca 石榴石＋Na-Ca 角闪石＋多硅白云母±钠云母±方解石±钛铁矿±榍石,变质条件是

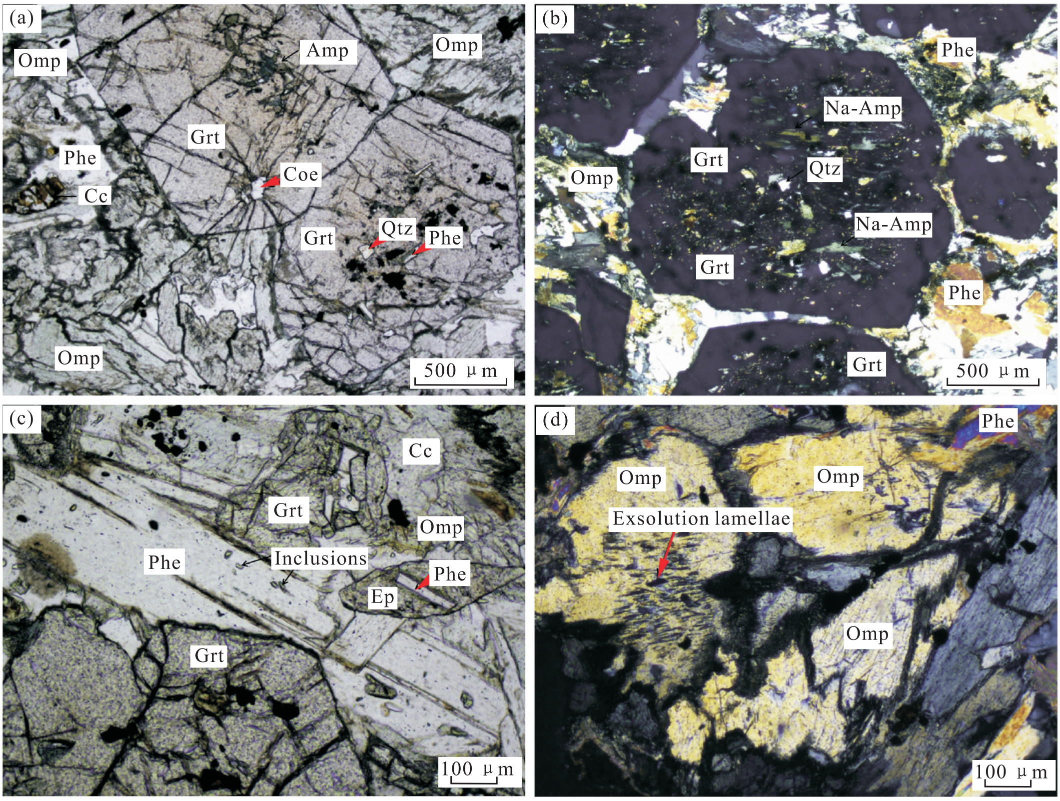

图 5　喜马拉雅造山带西段 Tso Morari 地块超高压榴辉岩显微照片

Fig.5　Photomicrographs of ultrahigh-pressure eclogites from the Tso Morari massif of the western Himalaya

据 Jonnalagadda *et al*.(2017).a.超高压榴辉岩由石榴石、绿辉石、多硅白云母和石英组成.注意，石榴石核部含石英和多硅白云母包体，而石榴石边缘含柯石英包体.部分绿辉石边缘被由极细的角闪石＋斜长石合晶组合的冠状体替代；b.超高压榴辉岩石榴石变斑晶中的角闪石包体定向分布；c.超高压榴辉岩由石榴石、绿辉石、多硅白云母、绿帘石和方解石组成；d.超高压榴辉岩中的绿辉石含有近平行分布的出溶页片.矿物代号：Amp.角闪石；Cc.方解石；Coe.柯石英；Grt.石榴石；Omp.绿辉石；Phe.多硅白云母；Qtz.石英

～2.8 GPa和 700 ℃，后超高压矿物组合是 Fe＞Ca＞Mg 石榴石＋Ca 角闪石＋钠长石＋黑云母＋绿帘石±多硅白云母，变质条件是～1.4 GPa 和 800 ℃，晚期退变质矿物组合是绿泥石＋钠长石＋石英＋多硅白云母＋Ca 角闪石±绿帘石±黑云母±金红石±榍石±钛铁矿，相应的变质条件是～0.7 GPa和 350 ℃.

Wilke *et al*.(2015)认为 Tso Morari 超高压榴辉岩的峰期变质作用很可能发生在 4.4～4.8 GPa 和 560～760 ℃条件下，退变质 *P-T* 轨迹呈 S 形，退变质早期为降温与降压过程，中期叠加了近等压、升温的角闪岩相退变质作用，晚期为降温和降压过程.最近，Palin *et al*.(2017)基于地球动力学和岩石学模拟，再造了 Tso Morari 超高压榴辉岩的进变质 *P-T* 轨迹，并估算了峰期变质条件(图 4).他们认为柯石英榴辉岩的峰期变质条件是 2.6～2.8 GPa 和 600～620 ℃，以前推测的 4.8 GPa 超高压条件是不合理的，可能是矿物化学不平衡导致的错误计算结果.

2.2　超高压榴辉岩的变质时间与俯冲折返速率

由于超高压榴辉岩的变质年龄可以揭示大陆碰撞和俯冲的时间和持续过程，所以对上述 2 个地区的榴辉岩进行了较深入的年代学研究，并再造了变质作用的 *P-T-t* 轨迹.对 Kaghan 谷榴辉岩，Tonarini *et al*.(1993)和 Spencer and Gebauer(1996)用 Sm-Nd 和 U-Pb 定年方法获得了 40～50 Ma 的变质年龄.Kaneko *et al*.(2003)对超高压榴辉岩中的锆石进行了系统的 U-Pb 定年，在含石英包体的锆石幔部域获得了～50 Ma 的进变质年龄，在含柯石英包体的锆石边缘获得了～46 Ma 的峰期变质年龄.由此得出，印度大陆开始俯冲的时间为 55～53 Ma，俯冲到地幔深度的时间为 46 Ma，即经历了一个快速俯冲过程.Parrish *et al*.(2006)通过锆石 U-Pb 定年，获得了柯石英榴辉岩的峰期变质年龄为 46 Ma，用榍石和金红石 U-Pb 定年获得了约 44 Ma的退变质年龄，由此揭示出超高压变质岩经历了快速折返过程，折返速率为 30～80 mm/a.

Wilke *et al*.(2010)通过锆石、榍石和金红石U-Pb定年和白云母Ar-Ar定年，将榴辉岩的峰期变质年龄限定在～47 Ma，后榴辉岩相退变质年龄为41～46 Ma，晚期的角闪岩相至绿片岩相退变质年龄为32～35 Ma(图4).由此，他们认为超高压榴辉岩从地幔深度(约130 km)快速折返到下地壳深度(约40 km)，折返速率为86～143 mm/a，从下地壳至地壳浅部是一个缓慢抬升过程，抬升速率为1～2 mm/a.Rehman *et al*.(2013)通过锆石U-Pb定年，在超高压榴辉岩中获得了250～270 Ma的原岩年龄，47～49 Ma的榴辉岩化年龄，45～46 Ma的峰期变质年龄和约40 Ma的角闪岩相退变质年龄(图4).这进一步表明，Kaghan谷柯石英榴辉岩经历了快速俯冲与快速折返过程.

Tso Morari地块榴辉岩的变质年龄还存在争议.de Sigoyer *et al*.(2000)通过石榴石－单斜辉石Lu-Hf和Sm-Nd定年，独居石U-Pb定年和云母Ar-Ar定年，将榴辉岩相变质年龄限定在～55 Ma，将高压退变质年龄限定在45～48 Ma，将更晚期退变质年龄限定在29～31 Ma.Leech *et al*.(2005)通过锆石U-Pb定年，获得了～53 Ma峰期变质年龄，认为印度与亚洲大陆的初始碰撞发生在～56 Ma，并经历了快速的陡俯冲过程.Leech *et al*.(2007)通过各种不同的定年方法，将超高压榴辉岩的峰期变质年龄限定在～53 Ma，高压退变质年龄限定在45～50 Ma，将晚期的角闪岩相退变质年龄限定在29～34 Ma.这些定年结果表明，Tso Morari超高压榴辉岩经历了快速折返过程.Donaldson *et al*.(2013)的锆石岩石年代学研究揭示，榴辉岩中变质锆石U-Pb年龄在37～53 Ma范围变化，峰期在43～47 Ma.因此，他们认为Tso Morari地块与Kaghan谷超高压榴辉岩的峰期变质年龄是一致的，均发生在～47 Ma，这2个地区的大陆碰撞也同时发生在～51 Ma.

3 喜马拉雅造山带东段的高压榴辉岩

3.1 高压榴辉岩及其变质条件

在东喜马拉雅造山带，高压榴辉岩或麻粒岩化榴辉岩产出在中国西藏定结的Ama Drime地块及附近、锡金北部和不丹西北部(图2).Lombardo and Rolfo(2000)较详细地描述了Ama Drime地块产出的麻粒岩化榴辉岩.这种岩石呈透镜状或薄层状产出在高喜马拉雅结晶岩系的片麻岩和变质沉积岩中.麻粒岩化榴辉岩由石榴石、角闪石、黑云母和后成合晶矿物组成(图6).由单斜辉石＋斜长石＋斜方辉石组成的后成合晶呈绿辉石假象.石榴石边缘也经常被斜长石＋角闪石±单斜辉石±斜方辉石组成的后成合晶冠状体替代.麻粒岩化榴辉岩的峰期矿物组合应为石榴石＋绿辉石＋石英＋金红石，而麻粒岩相退变质矿物组合为斜长石＋角闪石＋单斜辉石＋斜方辉石.Lombardo and Rolfo(2000)推测的榴辉岩相变质条件为＞1.5 GPa和＞600 ℃，麻粒岩相退变质条件在～0.7 GPa和700 ℃.他们第1次提出，喜马拉雅造山带存在两种不同类型的榴辉岩，东喜马拉雅造山带的榴辉岩具有相对低的峰期变质压力，但叠加了高温麻粒岩相退变质作用.Ferrando *et al*.(2007)和Groppo *et al*.(2007)通过系统的岩石学研究与相平衡模拟，认为Ama Drime地块榴辉岩经历了4期变质作用，第1期为高压榴辉岩相，矿物组合是石榴石＋绿辉石(被单斜辉石＋斜长石合晶替代)＋多硅白云母(被黑云母＋斜长石合晶替代)，第2期为麻粒岩相退变质期，以石榴石＋单斜辉石＋斜方辉石＋斜长石＋钛铁矿共生为特征，第3期以围绕石榴石发育的斜长石＋斜方辉石冠状体的形成为特征，第4期为角闪岩相退变质作用，以基质中角闪石＋斜长石组合为特征.因此，麻粒岩化榴辉岩具有一个顺时针型的变质作用 P-T 轨迹(图4).由于榴辉岩相矿物几乎完全消失，榴辉岩相峰期变质条件被推测在＞1.5 GPa和＞580 ℃，早期的麻粒岩相退变质作用被限定在0.8～1.0 GPa和＞750 ℃，晚期的麻粒岩退变质作用发生在～0.4 GPa和～750 ℃条件下，这之后近等压冷却到～600 ℃.Lombardo *et al*.(2016)对东喜马拉雅高压榴辉岩进行了总结，认为其记录了5个变质阶段，包括榴辉岩相阶段(P＞1.5 GPa和 T＞580 ℃)、2个麻粒岩变质阶段(P＝0.8～1.0 GPa和 T＞750 ℃；P≈0.4 GPa和 T≈750 ℃)、一个角闪岩相阶段(P＝0.4～0.6 GPa和 T＝700 ℃)和晚期退变质阶段(P＜0.4 GPa和 T＜690 ℃).

Wang *et al*.(2017)第1次在Ama Drime地块的麻粒岩化榴辉岩中识别出了绿辉石，确证了榴辉岩的存在.绿辉石在石榴石和锆石中呈包体产出，榴辉岩相矿物组合是石榴石＋绿辉石＋多硅白云母＋石英＋金红石.榴辉岩叠加了强烈的麻粒岩相退变质作用，以单斜辉石、斜方辉石、斜长石和角闪石的产出为特征.相平衡模拟和地质温压计计算表明，榴辉岩相变质条件为2.0～2.1 GPa和720～760 ℃，

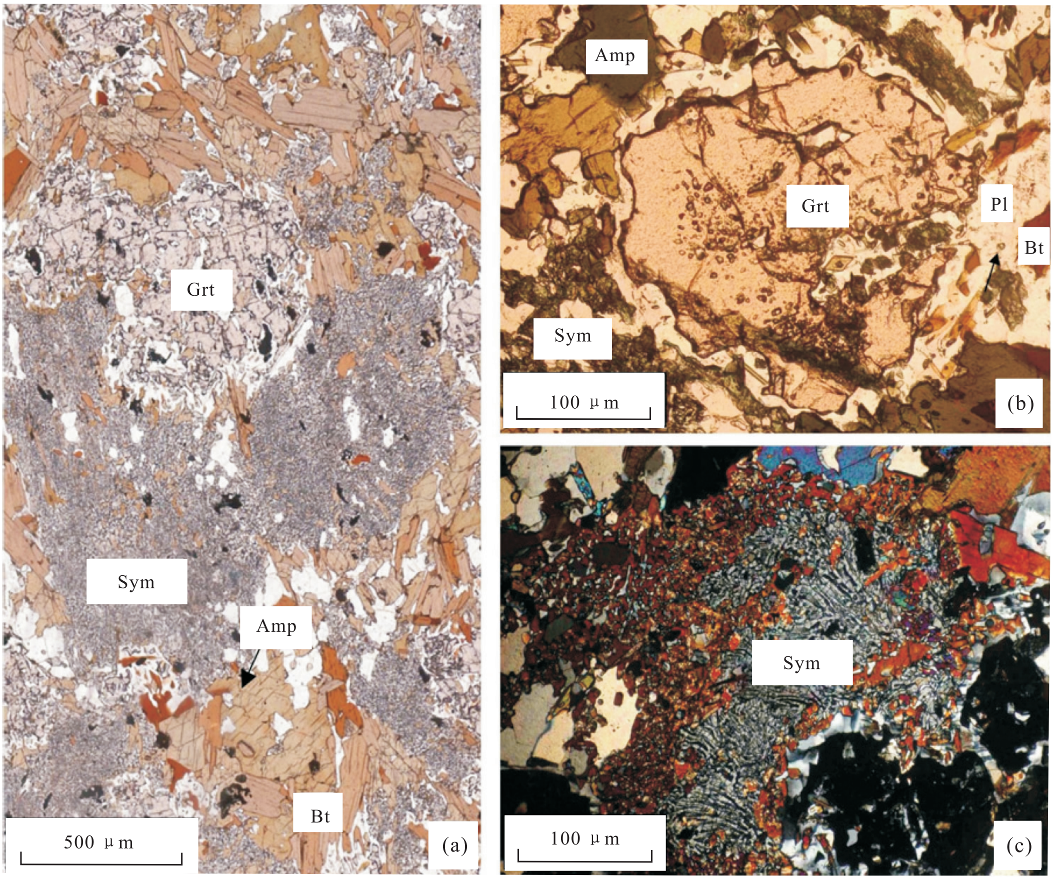

图 6　喜马拉雅造山带中东段 Ama Drime 麻粒岩化高压榴辉岩显微照片

Fig.6　Photomicrographs of granulitized high-pressure eclogites from the Ama Drime massif of the eastern Himalaya

据 Kellett *et al*.(2014).a.麻粒岩化榴辉岩由石榴石、单斜辉石、角闪石、黑云母、斜长石和石英组成.绿辉石全部被由细粒斜长石＋单斜辉石组成的合晶替代；b.榴辉岩石榴石核部含细小的矿物包体，其边缘被由斜长石＋角闪石＋斜方辉石＋黑云母组成的合晶冠状体替代；c.榴辉岩中的绿辉石被由斜长石＋角闪石＋单斜辉石＋斜方辉石组成的合晶替代.矿物代号：Amp.角闪石；Bt. 黑云母；Grt.石榴石；Pl.斜长石；Sym.后成合晶

麻粒岩相退变质作用发生在 0.7～0.9 GPa 和750 ℃条件下.因此，榴辉岩具有近等温降压 *P*-*T* 轨迹.

Li *et al*.(2018)在 Ama Drime 地块东边 Thongmön 地区的高喜马拉雅结晶岩系中发现了新的榴辉岩(图 7).榴辉岩呈透镜状或似层状产于副片麻岩中.在榴辉岩中识别出了早期的进变质过程，其以石榴石＋绿辉石＋多硅白云母＋角闪石＋石英＋金红石共生为特征，在进变质到榴辉岩相峰期变质过程中角闪石发生了脱水熔融.早期的高压进变质作用条件为 1.9～2.0 GPa 和 640～660 ℃，榴辉岩峰期变质条件为＞2.1 GPa 和＞750 ℃(图 4).这一地区的榴辉岩也叠加了强烈的麻粒岩相退变质作用，以单斜辉石、斜方辉石、角闪石、黑云母和斜长石的出现为特征.因此，Thongmön 地区的榴辉岩具有一个顺时针型的变质作用 *P*-*T* 轨迹，进变质为增温和增压过程，早期退变质为弱升温和显著降压过程，晚期退变质为近等压降温过程(图 4).

3.2　高压榴辉岩的变质时间与持续过程

关于东喜马拉雅高压榴辉岩的变质作用时间与过程还存在较大争议.Rolfo *et al*.(2005)对 Ama Drime 榴辉岩中的锆石进行了 U-Pb SHRIMP 定年，在锆石核部获得了 88～110 Ma 年龄.这被认为是榴辉岩的原岩年龄，并因此排除了榴辉岩形成在早古生代或前寒武纪的可能性.定年锆石具有一个薄的边缘，其给出 12～15 Ma 的年龄，这被解释为榴辉岩的麻粒岩相退变质年龄.Li(2003)通过对 Ama Drime 地块北部高压基性麻粒岩(实际是麻粒岩化榴辉岩)的锆石进行 SHRIMP 定年获得了～17 Ma的年龄，认为其是麻粒岩相变质时间.Groppo *et al*.(2007)也认为这些年龄代表榴辉岩的麻粒岩相退变质时间.

Cottle *et al*.(2009)对 Ama Drime 麻粒岩化榴辉岩进行了系统的锆石定年，获得了榴辉岩的原岩年龄为～986 Ma，榴辉岩围岩片麻岩的原岩年龄为

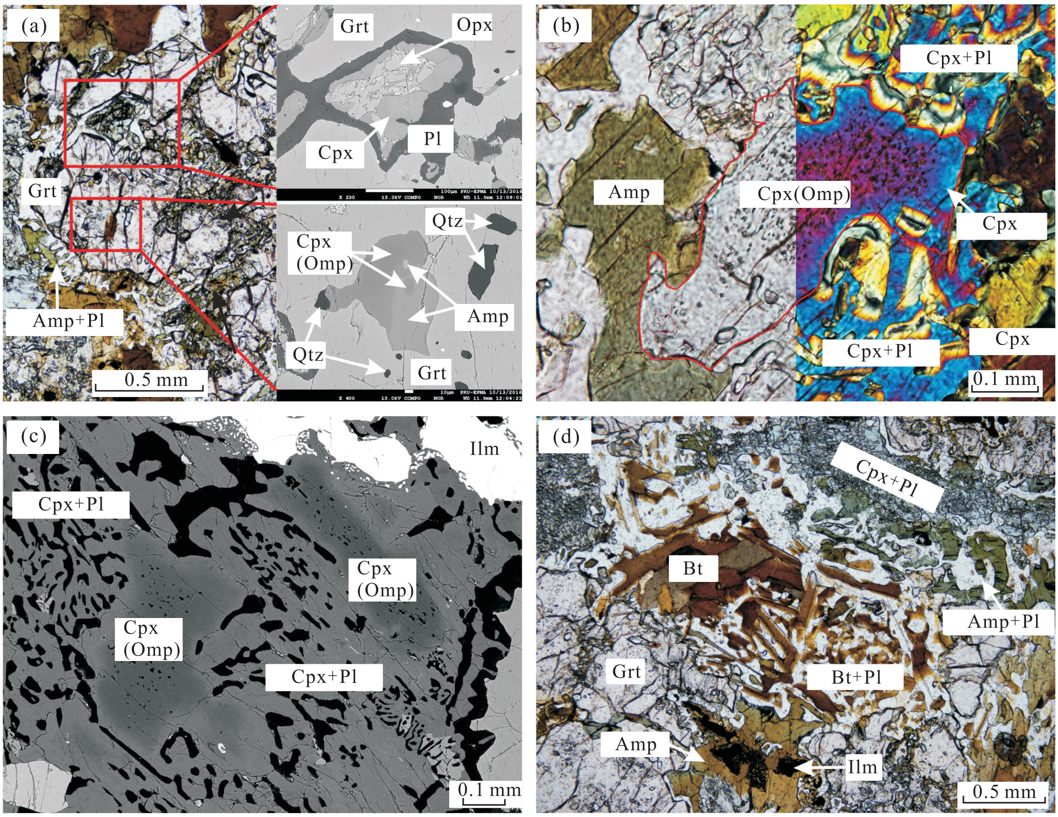

图 7 喜马拉雅造山带中东段 Thongmön 高压榴辉岩显微照片

Fig.7 Photomicrographs of granulitized high-pressure eclogites from the Thongmön of the eastern Himalaya

据 Li *et al*.(2018).a.高压榴辉岩由石榴石和包含的单斜辉石(绿辉石)、角闪石和石英组成,石榴石被由单斜辉石、斜长石和斜方辉石,或角闪石和斜长石组成的合晶冠状体替代;b.高压榴辉岩的单斜辉石(绿辉石)发育由单斜辉石和斜长石组成的冠状体,或被角闪石部分替代;c.高压榴辉岩中残余的单斜辉石(绿辉石)被单斜辉石和斜长石合晶部分替代;d.高压榴辉岩中的多硅白云母被黑云母+斜长石合晶替代,单斜辉石+斜长石替代绿辉石,角闪石+斜长石合晶替代石榴石.矿物代号:Amp.角闪石;Bt.黑云母;Cpx.单斜辉石;Grt.石榴石;Ilm.钛铁矿;Omp.绿辉石;Opx.斜方辉石;Pl.斜长石;Qtz.石英

~1 799 Ma.通过独居石和磷钇石 U-Pb 定年将榴辉岩的麻粒岩相退变质和部分熔融年龄限定在<13 Ma.Corrie *et al*.(2010)通过榴辉岩中的石榴石和角闪石 Lu-Hf 定年,认为榴辉岩相变质年龄约为 21 Ma,麻粒岩相退变质年龄为 14~15 Ma. Grujic *et al*.(2011)通过对不丹西北部基性麻粒岩的锆石 U-Pb 定年,得出榴辉岩相变质年龄在 14~15 Ma.他们认为以榴辉岩为代表的渐新世加厚下地壳经历了快速的同汇聚折返过程.Warren *et al*.(2011)对不丹地区麻粒岩化榴辉岩围岩片麻岩中的独居石进行了 U-Th-Pb 定年,获得了 13~21 Ma 的年龄.这些年龄与以前获得的麻粒岩化榴辉岩年龄一致,所以认为榴辉岩与围岩一起经历了渐新世的高压变质作用,并作为一个构造岩片逆冲到较早期变质的高喜马拉雅结晶岩系下部构造层位之上. Wang *et al*.(2017)和 Li *et al*.(2018)对 Ama Drime 和 Thongmön 地区的榴辉岩进行了锆石 U-Pb 定年,在含榴辉岩相矿物包体的锆石边部域获得了 14~15 Ma 和~17 Ma 的年龄,认为其是榴辉岩相变质时间(图 4).

Kellett *et al*.(2014)对 Ama Drime 榴辉岩中的石榴石进行了 Lu-Hf 定年,获得了 34~38 Ma 的年龄,利用锆石 U-Pb 定年,获得了 13~15 Ma 的年龄.他们认为榴辉岩相变质作用发生在~38 Ma,麻粒岩相退变质叠加发生在~14 Ma(图 4).他们认为,不同于西喜马拉雅的超高压榴辉岩,东喜马拉雅的高压榴辉岩并不是以快速埋藏和快速折返为特征.东喜马拉雅高压榴辉岩形成在大陆碰撞早期的地壳加厚过程中,在其折返和再加热之前在加厚下地壳停留时间超过 20 Ma.这表明东喜马拉雅造山带的地壳在晚始新世就已经加厚到至少 60 km. Lombardo *et al*.(2016)认为,由于强烈的高温麻粒岩相叠加和高压矿物较少保存,东喜马拉雅高压榴辉岩的变质时间难以确定.榴辉岩中锆石边缘获得

的 13～14 Ma 年龄对应麻粒岩相叠加时间，而不是榴辉岩化时间. 他们在榴辉岩的锆石中获得了～90 Ma的年龄，认为其可能是榴辉岩的原岩年龄，指示印度大陆东北缘可能经历了白垩纪的基性岩浆作用.

4　讨论

4.1　印度与亚洲大陆的碰撞时间

印度与亚洲大陆的碰撞时间是揭示喜马拉雅造山带和青藏高原形成演化的关键之一. 目前人们已经从不同角度对此进行了广泛研究，尽管大多数人认为大陆碰撞发生在 55～50 Ma（Yin and Harrison，2000；Najman *et al*.，2010；Meng *et al*.，2012；Zhu *et al*.，2015；Ding *et al*.，2016a，2016b），但也有研究者提出更早（～65 Ma）或更晚（35 Ma）的碰撞时间（Aitchison *et al*.，2007；DeCelles *et al*.，2014；Gibbons *et al*.，2015；Hu *et al*.，2016）. 另外，也有学者提出沿喜马拉雅造山带，印度与亚洲大陆的碰撞时间是不一致的（Guillot *et al*.，2008；Bouilhol *et al*.，2013）. 丁林等（2017）通过综合研究认为，印度与亚洲大陆首先在印度－雅鲁藏布江缝合带中段发生正向碰撞，时间为 65～63 Ma，随后向东西两侧穿时碰撞.

喜马拉雅造山带西段的超高压变质岩紧邻印度－雅鲁藏布江缝合带产出，是印度大陆西北边缘俯冲作用的产物，因此可以指示大陆碰撞时间. 正如前面描述的，前人对于造山带西端 Kaghan 谷超高压榴辉岩进行了系统的年代学研究，大多数学者认为超高压变质作用约发生在 46～48 Ma，表明印度与亚洲大陆碰撞或初始俯冲的时间为 50～53 Ma（Kaneko *et al*.，2003；Wilke *et al*.，2010）. 对 Kaghan 谷东约 450 km 的 Tso Morari 地块超高压榴辉岩，先前的大多数研究认为其超高压变质作用时间在 53～55 Ma，大陆的初始碰撞时间在 56～60 Ma（de Sigoyer *et al*.，2000；Leech *et al*.，2005，2007）. 由于 2 个地区超高压变质作用与大陆碰撞时间相差～6 Ma，Guillot *et al*.（2007，2008）提出，印度大陆西北缘是不整齐的，Tso Morari 地区位于大陆的最北部边缘，这里的大陆先发生碰撞，而在 Kaghan 谷地区的印度大陆北缘位于较南部，这里的大陆碰撞发生较晚. 但是，Donaldson *et al*.（2013）基于系统的锆石岩石年代学研究认为，Tso Morari 地块和 Kaghan 谷柯石英榴辉岩的峰期变质作用均发生在～47 Ma，所以印度大陆西北部边缘与亚洲大陆的碰撞同时发生在～51 Ma，并不存在穿时性碰撞.

现有研究都认为，在喜马拉雅造山带西段，在 2 个大陆拼合之前，在新特提斯洋中存在一个洋内弧，即 Kohistan-Ladakh 弧（图 2），因此存在 2 种不同的碰撞模型. 第 1 种模型认为印度大陆与洋内弧先碰撞，然后印度大陆＋洋内弧再与亚洲大陆碰撞（Bouilhol *et al*.，2013；Jagoutz *et al*.，2015）. 第 2 种模型认为，洋内弧与亚洲大陆先碰撞，然后印度大陆再与洋内弧＋亚洲大陆碰撞（Rehman *et al*.，2008；Ravikant *et al*.，2009；Thanh *et al*.，2011；Ding *et al*.，2016b）. 如果是第 1 种碰撞模型，喜马拉雅造山带西段的超高压变质岩应该是形成在印度大陆与洋内弧的碰撞/俯冲过程中，超高压变质作用时间应早于印度与亚洲大陆的最终碰撞时间. 但是，最近的研究表明，在喜马拉雅造山带西段，亚洲大陆的物质在 50 Ma 已经到达了造山带的前陆盆地和下印度河盆地. 这表明印度、洋内弧和亚洲大陆的碰撞在 50 Ma 已经完成（Zhuang *et al*.，2015；Ding *et al*.，2016b）. 因此，西构造结的超高压变质岩年龄可以指示印度与亚洲大陆（＋洋内弧）的碰撞时间.

如图 2，在喜马拉雅造山带中东段目前获得的大多数变质年龄都在 40 Ma 以下，普遍晚于造山带西段超高压变质岩的形成年龄，所以有人提出印度大陆西北缘与亚洲大陆先碰撞，而印度大陆东北缘与亚洲大陆后碰撞（Guillot *et al*.，2008）. 如上所述，目前从高压榴辉岩中获得的锆石变质年龄在 14～17 Ma，有研究者认为这个年龄并不代表大陆碰撞时间，而代表中渐新世大陆汇聚过程中喜马拉雅造山带的地壳加厚时间. 另一方面，基于石榴石的 Lu-Hf 定年，Kellett *et al*.（2014）认为喜马拉雅造山带东段高压榴辉岩的变质时间在～38 Ma，其麻粒岩相退变质叠加发生在 14～17 Ma，高压榴辉岩经历了一个缓慢俯冲与缓慢折返过程. 喜马拉雅造山带中东段长英质和泥质高压麻粒岩的研究也表明，它们经历了长期的变质演化过程，持续时间超过 20～30 Ma（Imayama *et al*.，2012；Wang *et al*.，2013，2015；Ambrose *et al*.，2015；Iaccarino *et al*.，2015；Zeiger *et al*.，2015；Zhang *et al*.，2015，2017）. 这从另一个角度证明，高压榴辉岩也应该经历了长期演化过程.

喜马拉雅造山带中东段的高喜马拉雅结晶岩系普遍经历了高压榴辉岩相或高压麻粒岩相变质作

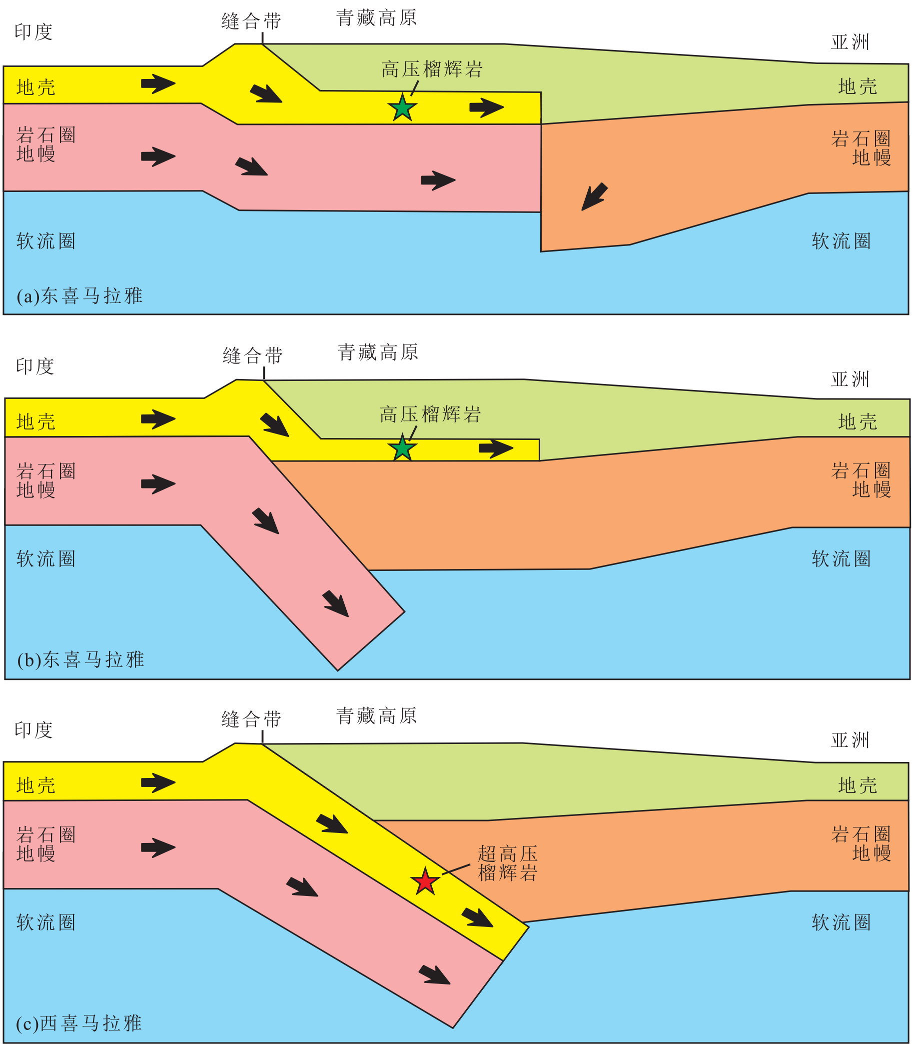

图8 喜马拉雅造山带中始新世(~47 Ma)构造模式

Fig.8 Middle Eocene (~47 Ma) tectonic model of the Himalayan orogen

a.在喜马拉雅造山带中东段,印度岩石圈平缓俯冲到亚洲大陆地壳之下,导致地壳加厚和高压榴辉岩相变质作用;b.在喜马拉雅造山带中东段,印度地壳平缓俯冲到亚洲大陆地壳之下,导致地壳加厚和高压榴辉岩相变质作用,而印度岩石圈地幔与地壳分离,并发生陡俯冲;c.在喜马拉雅造山带西段,印度岩石圈陡俯冲到地幔之中,导致地壳岩石发生超高压榴辉岩相变质作用

用,叠加了高温和低压麻粒岩相退变质作用,并发生了部分熔融(Groppo *et al*., 2007, 2012; Kali *et al*., 2010; Guilmette *et al*., 2011; Zhang *et al*., 2015, 2017, 2018; Wang *et al*., 2016, 2017; Li and Song, 2018; Li *et al*., 2018).因此,高压变质岩的峰期变质年龄应该难以被记录或保存下来,锆石U-Pb定年更可能获得的是其退变质年龄.实际上,在高压榴辉岩的片麻岩和片岩围岩中已经获得了许多>30 Ma的变质年龄(图2),这从另一方面证明从榴辉岩中获得的14~17 Ma年龄是其退变质年龄,而不是峰期变质年龄.在喜马拉雅造山带东段雅拉香波片麻岩穹窿核部的中级变质岩(石榴石十字石蓝晶石云母片岩)中,Ding *et al*.(2016a)获得了~47 Ma的锆石变质年龄(图2),指示印度与亚洲大陆的碰撞时间在~51 Ma.由此表明,造山带西段的超高压变质岩与造山带东段的中压变质岩具有相同的变质年龄,喜马拉雅造山带东段和西段的大陆碰撞时间是一致的.

4.2 印度大陆的差异性俯冲

有关2个大陆碰撞后,印度大陆向亚洲大陆之下俯冲的角度和距离还存在较大争议.较早期的地球物理探测揭示,印度大陆岩石圈平缓俯冲到亚洲大陆之下,导致青藏高原南部具有双倍地壳厚度(Zhao *et al*., 1993; Xu *et al*., 2015).最近,基于喜马拉雅造山带东端地震层析研究,Peng *et al*.(2016)提出94°E以西,印度大陆平缓俯冲到亚洲大

陆之下，而在 94°E 以东，也就是在东喜马拉雅构造结，印度大陆陡俯冲到亚洲大陆之下，并且发生了撕裂.基于穿过东、西喜马拉雅造山带之间(81.5°E)的南北向地震反射剖面，Gao *et al*.(2016)认为有～15 km厚的印度地壳平缓俯冲到亚洲大陆之下，而更多的印度地壳物质从俯冲板片转移到了上板片，形成了地壳尺度的叠置构造.基于喜马拉雅造山带中段的高分辨地震资料分析，Li *et al*.(2018)认为在中段的东部和西部，印度岩石圈地幔平缓俯冲到青藏高原之下，而中间部分先是平缓俯冲，然后变成陡俯冲，并与平缓俯冲的两边撕裂.同样，基于喜马拉雅造山带中段的高分辨地震资料，Guo *et al*.(2018)认为印度地壳基本上没有俯冲到亚洲大陆之下，而印度岩石圈地幔的俯冲角度从西向东变陡，并发生撕裂.由此可见，现有的地球物理研究基本上支持，在喜马拉雅造山带中东段(不包括东喜马拉雅构造结)，印度大陆地壳平缓俯冲到了亚洲大陆之下，而印度岩石圈地幔在造山带中段的俯冲角度是可变的，并且，在平缓与陡俯冲的岩石圈地幔之间发生了撕裂.

深部地球物理资料揭示的是青藏高原现今的岩石圈结构，而印度与亚洲大陆初始碰撞时的深部结构与现今很可能并不相同.正如上面描述的，在喜马拉雅造山带中东段，俯冲的印度大陆地壳经历了高压榴辉岩相或高压麻粒岩相变质作用，表明在中始新世印度大陆地壳发生了平缓俯冲，构成了青藏高原南部的加厚下地壳(图 8a，8b).与其相反，在喜马拉雅造山带西段存在一条近 500 km 长的超高压变质带，这无疑表明，在早始新世晚期大陆碰撞发生后，印度大陆地壳陡俯冲到了地幔深度(图 8c；O'Brien *et al*.，2001；Kaneko *et al*.，2003；Leech *et al*.，2005).

现有研究表明，早新生代是冈底斯岩浆弧的强烈岩浆活动期，其峰值就在～50 Ma(Ji *et al*.，2014；Zhu *et al*.，2017；张泽明等，2019).如果印度大陆地壳与岩石圈地幔从 50 Ma 开始一起平缓俯冲到亚洲大陆地壳之下(图 8a)，很可能会阻断岩浆作用.因此，我们提出在印度岩石圈俯冲过程中地壳与岩石圈地幔之间发生了拆离，印度地壳平缓俯冲或挤入到亚洲大陆地壳之下，而岩石圈地幔发生了陡俯冲(图 8b).Zhao and Morgan(1985)和 Searle(2007)曾认为这是青藏高原可能存在的岩石圈汇聚模型之一.这样的分离俯冲作用既有利于冈底斯弧强烈岩浆作用的发生，又会使该期岩浆岩显示出古老地壳物质加入的特征.这是因为，平缓俯冲到青藏高原加厚下地壳的古老印度陆壳物质可以成为新生代岩浆岩的源区之一.由此我们可以很好地解释冈底斯弧中生代与新生代岩浆岩地球化学特征的差异性.现有研究表明，冈底斯弧中生代岩浆岩更多地显示出起源于亏损地幔的新生地壳特征，而新生代岩浆岩具有起源于新生和古老地壳共同源区的特征.中、新生代岩浆岩的化学成分差异已经被认为是印度陆壳加入到新生代岩浆岩源区导致的，是大陆碰撞和俯冲的重要证据之一(Chu *et al*.，2011；张泽明等，2019).

5　结论

喜马拉雅造山带核部高压与超高压榴辉岩的变质作用条件与变质作用时间研究表明，印度与亚洲大陆的碰撞发生在 51～53 Ma.在喜马拉雅造山带西段，大陆碰撞后，印度大陆地壳的西北缘陡俯冲到地幔深度，经历了超高压变质作用，形成了柯石英榴辉岩，而且以大陆地壳的快速俯冲和快速折返为特征.相反，在喜马拉雅造山带中东段，印度大陆地壳平缓俯冲到亚洲大陆之下，仅经历了高压榴辉岩或高压麻粒岩相变质作用，而且以缓慢俯冲和缓慢折返为特征.在大陆碰撞造山带，大陆地壳的俯冲性质可以存在明显差异.

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