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青藏高原南部拉萨地体的变质作用与动力学

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摘 要: 拉萨地体位于欧亚板块的最南缘, 它在新生代与印度大陆的碰撞形成了青藏高原和喜马拉雅造山带。因此, 拉萨地体是揭示青藏高原形成与演化历史的关键之一。拉萨地体中的中、高级变质岩以前被认为是拉萨地体的前寒武纪变质基底。但新近的研究表明, 拉萨地体经历了多期和不同类型的变质作用, 包括在洋壳俯冲构造体制下发生的新元古代和晚古生代高压变质作用, 在陆-陆碰撞环境下发生的早古生代和早中生代中压型变质作用, 在洋中脊俯冲过程中发生的晚白垩纪高温/中压变质作用, 以及在大陆俯冲带上盘加厚大陆地壳深部发生的两期新生代中压型变质作用。这些变质作用和伴生的岩浆作用表明, 拉萨地体经历了从新元古代至新生代的复杂演化过程。(1)北拉萨地体的结晶基底包括新元古代的洋壳岩石, 它们很可能是在 Rodinia 超大陆裂解过程中形成的莫桑比克洋的残余。(2)随着莫桑比克洋的俯冲和东、西冈瓦纳大陆的汇聚, 拉萨地体洋壳基底经历了晚新元古代的(~650 Ma)的高压变质作用和早古代的(~485 Ma)中压型变质作用。这很可能表明北拉萨地体起源于东非造山带的北端。(3)在古特提斯洋向冈瓦纳大陆北缘的俯冲过程中, 拉萨地体和羌塘地体经历了中古生代的(~360 Ma)岩浆作用。(4)古特提斯洋盆的闭合和南、北拉萨地体的碰撞, 导致了晚二叠纪(~260 Ma)高压变质带和三叠纪(~220 Ma)中压变质带的形成。(5)在新特提斯洋中脊向北的俯冲过程中, 拉萨地体经历了晚白垩纪(~90 Ma)安第斯型造山作用, 形成了高温/中压型变质带和高温的紫苏花岗岩。(6)在早新生代(55~45 Ma), 印度与欧亚板块的碰撞, 导致拉萨地体地壳加厚, 形成了中压角闪岩相变质作用和同碰撞岩浆作用。(7)在晚始新世(40~30 Ma), 随着大陆的继续汇聚, 南拉萨地体经历了另一期角闪岩相至麻粒岩相变质作用和深熔作用。拉萨地体的构造演化过程是研究汇聚板块边缘变质作用与动力学的最佳实例。

关键词: 青藏高原; 拉萨地体; 变质作用; 造山作用; 板块汇聚
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Metamorphism and Dynamics of the Lhasa Terrane, South Tibet

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Abstract: The Lhasa terrane in southern Tibet has long been accepted as the last crustal block accreted with Eurasia prior to its collision with the northward drifting of Indian continent in the Cenozoic. Thus, the Lhasa terrane is the key to studying the origin and evolution of the Tibetan Plateau. The Lhasa terrane experienced multistage metamorphism, which included the Neoproterozoic and Late Paleozoic HP metamorphism in the oceanic subduction realm, the Early Paleozoic and Early Mesozoic MP metamorphism in the continent-continent collisional zone, the Late Cretaceous HT/MP metamorphism in the mid-oceanic ridge subduction zone, and two

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stages of Cenozoic MP metamorphism in the thickened crust above the continental subduction zone. These metamorphic events and the associated magmatism suggest that the Lhasa terrane experienced a complex tectonic evolution from the Neoproterozoic to Cenozoic. (1) The crystalline basement of the North Lhasa terrane includes Neoproterozoic oceanic crustal rocks, representing probably the remnants of the Mozambique Ocean derived from the break-up of the Rodinia supercontinent. (2) The oceanic crustal basement of North Lhasa witnessed a Late Cryogenian (~650 Ma) HP metamorphism and an Early Paleozoic (~485 Ma) MP metamorphism in the subduction realm associated with the closure of the Mozambique Ocean and the final amalgamation of eastern and western Gondwana, suggesting that the North Lhasa terrane might have been partly derived from the northern segment of the East African Orogen. (3) The Lhasa and Qiangtang terranes witnessed Middle Paleozoic (~360 Ma) magmatism, suggesting an Andean-type orogeny that was derived from the subduction of the Paleo-Tethys Ocean. (4) The closure of Paleo-Tethys Ocean between the North and South Lhasa terranes and subsequent terrane collision resulted in the formation of Late Permian (~260 Ma) HP metamorphic belt and Triassic (220 Ma) MP metamorphic belt. (5) The South Lhasa terrane experienced Late Cretaceous (~90 Ma) Andean-type orogeny, characterized by the regional HT/MP metamorphism and coeval intrusion of the voluminous Gangdise batholith during the northward subduction of the Neo-Tethyan Ocean. (6) During the Early Cenozoic (55~45 Ma), the continent-continent collisional orogeny resulted in the thickening of the crust of the South Lhasa terrane and the generation of MP amphibolite-facies metamorphism and syn-collisional magmatism. (7) Following the continuous continent convergence, the South Lhasa terrane also experienced MP metamorphism during Late Eocene (40~30 Ma). The tectonic imprints from the Lhasa terrane provide excellent examples for understanding geodynamics of metamorphic processes along convergent plate boundaries.

Key words: Tibetan Plateau; Lhasa terrane; metamorphism; orogeny; plate convergence

青藏高原是特提斯洋盆多期扩张与消减和其间陆块多期俯冲-碰撞作用的产物，具有长期、复杂的地质演化历史(图 1)。一般认为，青藏高原自北向南由松潘—甘孜、羌塘、拉萨地体和喜马拉雅带组成，它们之间依次为金沙江(JS)、班公湖—怒江(BN)和印度—雅鲁藏布江(IYZ)缝合带，这些缝合带分别代表古特提斯、中特提斯和新特提斯洋盆的残余(图 1, 2)。研究表明，拉萨地体是由南、北拉萨地体拼合而成的，它们之间为洛巴堆—米拉山断裂(LM)，羌塘地体是由南、北羌塘地体拼合而成的，它们之间为龙木措—双湖缝合带(LS)(图 2)。

拉萨和羌塘地体在古生代位于冈瓦纳超大陆北缘，它们与亚洲之间为古特提斯洋(图 1a，3)。在中生代早期，随着中特提斯洋和新特提斯洋的打开，羌塘和拉萨地体从冈瓦纳大陆北缘分离，向北漂移，并在侏罗纪时期汇聚到欧亚板块南缘(图 1b，c)。在早白垩纪，南印度洋打开，印度板块从澳大利亚和南极板块分离(图 1d)。从白垩纪开始，随着新特提斯洋向欧亚大陆之下俯冲，印度板块迅速向北漂移，并在约 55 Ma 与位于欧亚板块南缘的拉萨地体发生碰撞，形成了青藏高原和喜马拉雅造山带。因此，拉萨地体是揭示青藏高原形成与演化历史的关键之一。但是，以往的研究普遍认为拉萨地体中的变质岩形成于前寒武纪，并没有意识到它们是拉萨地体显生宙多期造山作用的产物，忽视了它们在揭示拉萨地体形成与演化历史中的重要限定作用。

我们最近几年研究发现，拉萨地体经历了多期和不同类型的变质作用，从北向南，拉萨地体包括四个变质带(图 2)，它们分别是北部的安多高压变质带，形成在早侏罗纪陆-陆碰撞造山过程中，中部的纳木措高压变质带，形成在晚新元古代洋壳俯冲过程中，南、北拉萨地体之间的松多高压/中压复合变质带，形成在晚古生代的洋壳俯冲至早中生代陆-陆碰撞造山带过程中，南部的冈底斯高温/中压复合变质带，形成在中、新生代的洋壳俯冲到陆-陆碰撞过程中(Zhang et al., 2013)。这些变质作用及其同时发生的岩浆作用表明拉萨地体经历了从新元古代到新生代的长期构造演化。

1 北拉萨地体中部的新元古代的高压变质作用，拉萨地体起源与早期构造演化

新元古代的高压变质带分布于北拉萨地体中部，与古生代的变质沉积岩之间呈断层接触关系。高压变质岩主要由基性麻粒岩组成，含少量片麻岩、片岩和大理岩(张泽明等, 2010)。岩石学和年代学研究表明，高压基性麻粒岩的原岩为形成于新元古代(~900 Ma)的辉长岩，并具有典型洋中脊型玄武岩的地球化学特征。这些岩石经历了新元古代晚期

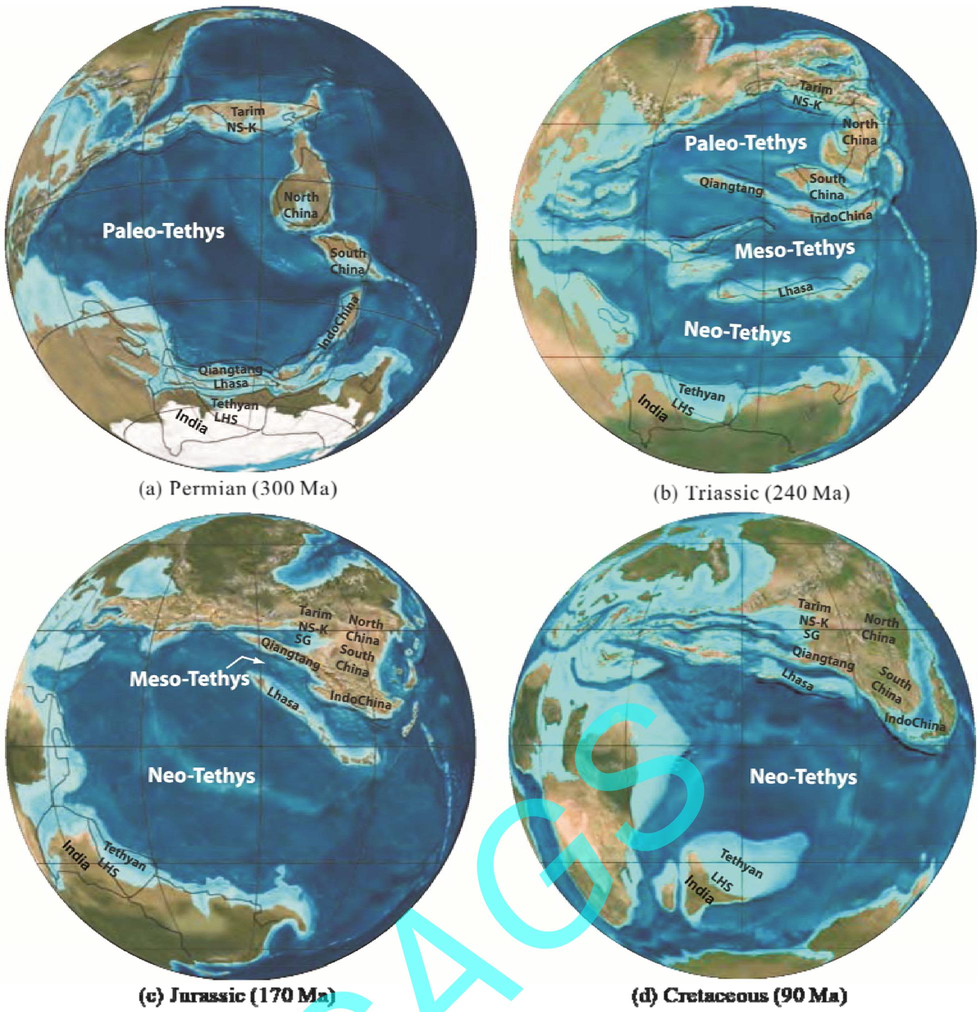

图 1　拉萨地体与特提斯洋形成演化的古地理图(据 Gehrels et al., 2011)

Fig. 1　Paleogeographic maps of the evolution of the Lhasa terrane and Tethyan Ocean (after Gehrels et al., 2011)

a-在晚古生代，拉萨和羌塘地体位于冈瓦纳超大陆的印度大陆北缘；b-在三叠纪，随着中特提斯洋和新特提斯洋盆的先后打开，羌塘和拉萨地体从印度大陆北缘分离，向北部的欧亚板块漂移；c-在侏罗纪，古特提斯洋闭合，羌塘地体与欧亚板块碰撞，而中特提斯洋快速消减、新特提斯洋扩张，拉萨地体向北漂移；d-晚白垩纪，印度大陆从冈瓦纳大陆分离，并随着新特提斯洋的消减，快速地向北部的欧亚板块汇聚

a-during late Paleozoic time, the Lhasa and Qiangtiang terranes were located at the northern margin of the Gondwana Indian continent; b-during Triassic time, following the opening of the Meso-Tethys and Neo-Tethys ocean basins, the Lhasa and Qiangtiang terranes rifted from the northern margin of Indian continent, and began their northward migration across the Tethys ocean basins; c-during the Jurassic time, the Qiangtang terrane collided with the Asian continent following the closure of the Paleo-Tethys ocean, and the Lhasa terrane drifted northward following the subduction of Meso-Tethys ocean and opening of the Neo-Tethys ocean; d-during the Cretaceous time, India continent rifted from Gondwana, and began its northward migration toward Asia following the subduction of Neo-Tethys ocean

(~650 Ma)的高压变质作用，并叠加了早古生代的中压型变质作用(Dong et al., 2011a; Zhang et al., 2012a)。相关的证据很可能说明北拉萨地体部分地起源于东、西冈瓦纳超大陆之间的莫桑比克洋的北部，在超大陆的汇聚过程中发生了深俯冲和高压变质作用。因此，位于印度大陆西北缘的北拉萨地体很可能是东非造山带的一部分，分布在北拉萨地体、马达加斯加、南印度、东非和东南极的高压变质岩构成了一条巨型的南北向高压变质带(图 3; Zhang et al., 2012a, 2013)。

2　南、北拉萨地体之间的三叠纪中压变质带与早中生代碰撞造山作用

在南、北拉萨地体之间分布的一套中、高级变质岩以前被认为是拉萨地体的前寒武纪结晶基底，被命名为念青唐古拉群。实际上，这套岩石的原岩主要由古生代的沉积岩组成，它们经历了三叠纪的中压角闪岩相变质作用，并伴随有同变质的岩浆作用和强烈的变形作用。结合二叠纪榴辉岩在这个变质带中的产出，拉萨地体中部存在一条东西向的板

块汇聚边界(图 2)。古特提斯洋的俯冲和南、北拉萨地体的拼合导致了晚古生代到中生代的造山 作用(Yang et al., 2009; Zeng et al., 2009; Zhu et al., 2011; Dong et al., 2011b; Zhang et al., 2013)。

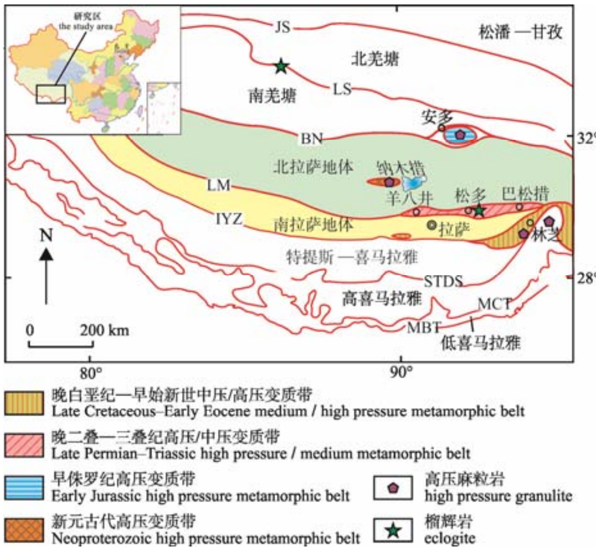

图 2 拉萨地体变质简图

Fig. 2 Metamorphic map of the Lhasa terrane

BN-班公湖—怒江缝合带; IYZ-印度—雅鲁藏布江缝合带; JS-金沙江缝合带; LM-洛巴堆—米拉山断裂; LS-龙木措—双湖缝合带; MBT-主边界断裂; MCT-主中央断裂; STDS-藏南拆离系

BN-Bangong–Nujiang River suture zone; IYZ-India–Yarlung Zangbo River suture zone; JS-Jinsha River suture zone; LM-Luobadui–Milashan fault; LS-Longmucuo–Shuanghu suture zone; MBT-main boundary fault; MCT-main central fault; STDS-south Tibetan detachment system

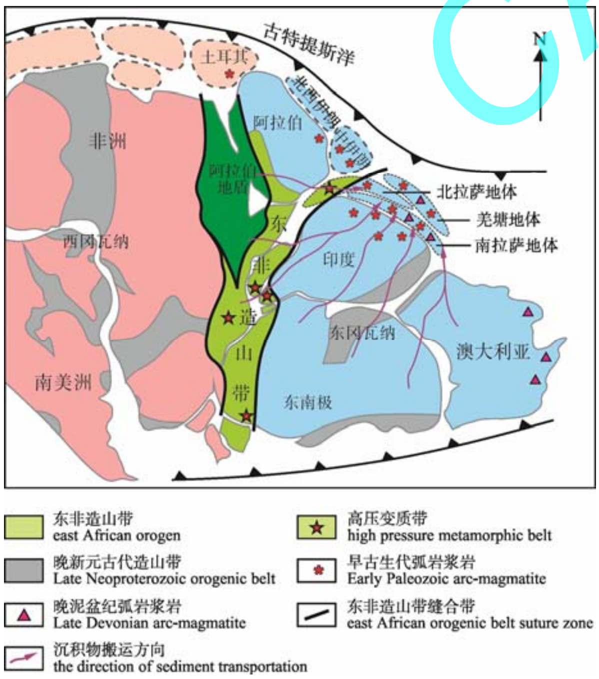

图 3 冈瓦纳超大陆及东非造山带、拉萨和羌塘地体再造图(据 **Zhang et al., 2013**)

Fig. 3 Reconstruction of the East African orogen, Lhasa and Qiangtang terranes (after Zhang et al., 2013)

3 晚白垩纪的紫苏花岗岩与新特提斯洋中脊俯冲造山作用

晚白垩纪的紫苏花岗岩分布于冈底斯岩浆弧的东南部，以前被认为是中新元古代的麻粒岩。紫苏花岗岩由中长石、微斜长石、顽火辉石、透辉石、石英、黑云母和角闪石组成，为典型的镁质、钙碱性、准铝质紫苏花岗岩，并具有埃达克岩的地球化学特征。锆石 U-Pb 定年给出的结晶年龄为 85 Ma。紫苏花岗岩的矿物中含高密度的 CO_2 流体包裹体和赤铁矿包体。相关证据表明，紫苏花岗岩形成在干的、高氧逸度、高温(850～950°C)和高压(0.7～1.0 GPa)条件下，很可能形成在新特提斯洋中脊俯冲形成的板片窗构造环境。软流圈沿板片窗上涌为紫苏花岗岩和同期麻粒岩相变质作用的形成提供了有力条件(张泽明等, 2009; Zhang et al., 2010a, b, 2011)。

4 晚泥盆纪的花岗岩与冈瓦纳超大陆北缘的古生代造山作用

晚泥盆纪至石炭纪花岗岩分布在拉萨地体南部，很可能是冈瓦纳超大陆北缘古生代安第斯型造山作用的产物(图 3; 董昕等, 2010)。大多数研究认为，从泥盆纪至石炭纪，冈瓦纳大陆北缘处于一个相对宁静的构造期(Gehrels et al., 2011)，但在拉萨和羌塘地体中陆续发现的中、晚古生代岩浆作用，为冈瓦纳大陆北缘的构造演化提供了新信息(董昕等, 2010; Pullen et al., 2011; Ji et al., 2012)。

5 冈底斯岩浆弧深部的变质作用与增生造山

在拉萨地体南部广泛分布的中、新生代冈底斯岩浆弧形成在新特提斯洋壳向北俯冲的安第斯型造山过程中，为大陆地壳显著生长的产物。研究发现，与冈底斯岩基伴生的高级变质岩同样形成在中、新生代，与中、基性深层侵入岩一起构成了冈底斯岩浆弧的中、下地壳组成。这表明幔源岩浆岩的不断增生导致了岩浆弧地壳的加厚和加热，形成了同侵入期的高压高温麻粒岩相变质作用、深熔作用和 S 型花岗岩，显示出增生造山带地壳生长与岩浆作用、变质作用之间的成因联系(薛光琦等, 2005; 王金丽等, 2008, 2009; 董昕等, 2009, 2012; 李奋其等, 2010; 唐菊兴等, 2012; Dong et al., 2010; Zhang et al., 2010a, b, 2012b; Guo et al., 2011, 2012; 刘峰等, 2011; Searle et al., 2011; Guan et al., 2012)。

6 安多地块的多期构造热事件与造山作用记录

位于拉萨地体北部的安多地块普遍经历了高级变质作用，被认为是拉萨地体的结晶基底。研究表明，安多地块最老岩石为新元古代(820 Ma)的岩浆岩，形成在环 Rodinia 超大陆周缘的安第斯型造山过程中(Guynn et al., 2012; Zhang et al., 2012c)。安多地块发育早古生代(~500 Ma)的双峰式岩浆岩，很可能形成在环冈瓦纳超大陆周缘的安第斯型造山过程中(图 3; Zhang et al., 2012c)。安多地块在侏罗纪经历了深俯冲和高压麻粒岩相变质作用，很可能发生在中特提斯大洋岩石圈闭合过程中(Zhang et al., 2012c, 2013)。

上述研究成果表明，拉萨地体中北部含有新元古代的洋壳残余，并经历了新元古代至早古生代的高压/中压变质作用，拉萨地体中部经历了晚古生代至早中生代的高压/中压型变质作用，拉萨地体南部经历了晚中生代至新生代的多期高温变质作用，拉萨地体北部的安多地块经历了早中生代的高压变质作用。这些变质作用记录揭示出，拉萨地体经历了多期洋-陆或陆-陆汇聚造山作用过程，丰富了青藏高原前新生代的构造演化历史，成为研究汇聚板块边缘变质作用与动力学典型实例。

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