青藏高原巨厚地壳:生长、加厚与演化

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内容提要:大陆地壳约占地表面积的40%，其成因与生长，是一个关乎人类生存和资源供给的基础地学问题。人们普遍认为，大洋俯冲通过岛弧拼贴和幔源岩浆底侵形成造山带新生陆壳,大陆碰撞过程只对现存地壳进行再造,不产生新生地壳。青藏高原经历古/新特提斯大洋俯冲和印-亚大陆强烈碰撞，拥有全球最厚的陆壳(65～80km)，是研究大陆地壳的形成、生长、加厚、演化与保存的天然实验室。我们研究表明，古/新特提斯大洋的相继俯冲消减，产生多期次的幔源镁铁质弧岩浆(270～66Ma)，在弧地壳下部底侵和上部侵位，导致地壳侧向加积和垂向生长并加厚约10km。在同(软)碰撞期(65～41Ma)，印度大陆岩石圈俯冲导致俯冲前缘的洋壳板片回转和断离，诱发软流圈地幔熔融及其幔源岩浆上升侵位，在冈底斯碰撞带形成新生地壳，并导致地壳加厚6～9km。在晚(硬)碰撞期(40～26Ma)，冈底斯碰撞造山带内不同地壳块体(地体)间发生逆冲叠覆，导致中深层次地壳缩短加厚10～20km；在碰撞带的后陆区，印度大陆岩石圈地幔俯冲诱发软流圈沿地幔通道上涌，侵蚀和吞噬地幔岩石圈，并诱发其部分熔融，向地壳注入大量幔源镁铁质岩浆，形成新生地壳，维持高原生长。在后碰撞期(<25Ma)，碰撞带和后陆区均发生地壳伸展与有限减薄，伴有新生地幔组分少量注入和高原陆表强烈剥蚀。粗略估计:形成并保存于大陆碰撞造山带的新生地壳量占整个陆壳的28%，大洋俯冲与大陆碰撞分别为青藏高原贡献了75%和25%的新生地壳。我们提出，青藏高原巨厚地壳的形成发育，实际上是幔源岩浆向地壳注入添加与中下地壳缩短加厚连续或交互作用的结果。伴随大洋俯冲与大陆碰撞，巨厚地壳物质组成发生以新生地壳形成和古老地壳再造为特征的动态演变。镁铁质新生下地壳的大规模重熔与长英质岩浆大量侵位可能是巨厚地壳长英质化的主要机制。

关键词:大洋俯冲;大陆碰撞;岩浆底侵;地块叠置;新生地壳;加厚机制

大陆地壳生长主要发生在两种构造环境:板内环境和板缘环境。板内环境的大陆地壳生长与地幔柱岩浆活动密切相关，如大面积溢流玄武岩省对应的玄武质岩浆底垫产生的地壳生长，以及洋底高原侧向拼贴导致的陆壳增生。板缘环境的大陆地壳生长主要与大洋俯冲诱发的弧岩浆作用密切相关，岩浆弧侧向拼贴和弧岩浆直接注入导致地壳增生(Jahn，2004；Cawood et al.，2009；Collin et al.，2011)。据估算，至少有80%的陆壳，其形成与弧岩浆密切相关(Plank and Langmuir，1998；Barth et al.，2000)。然而，在全球尺度,陆壳形成常以洋壳消减为代价,俯冲过程常使弧下地壳遭受侵蚀作用和/或加厚拆沉(Hawkesworth et al.，2010)。相比之下，大陆碰撞带更有利于大陆地壳的保存(Moyen et al.，2017)，但是，大陆碰撞能否形成、何时形成和如何形成新生地壳并维持地壳的净生长，仍是一个涉及地球物质循环和大陆形成演化的未解科学问题。

喜马拉雅是全球规模最宏大、特征最典型、时代最年轻的大陆碰撞造山带，而青藏高原作为一个卷入了新生代大陆碰撞过程的显生宙复合造山带,无疑是研究大陆碰撞带地壳生长与改造等问题的天然实验室，这是因为:① 青藏高原既经历早期大洋俯冲，又发生晚期大陆碰撞。古-新特提斯大洋俯冲消减，自270Ma以来产生了一系列火山-岩浆弧，增生于亚洲大陆南缘(Mo Xuanxue et al.，1993)，

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Hou Zengqian，Zheng Yuanchuan，Lu Zhanwu，Xu Bo，Wang Changming，Zhang Hongrui. 2020. Growth，thickening and evolution of the thickened crust of the Tibet Plateau. Acta Geologica Sinica，94(10)：2797～2815.

而始于 65Ma 的印-亚大陆碰撞(Mo Xuanxue et al.，2003)，导致喜马拉雅山脉在印度大陆北缘崛起(Zheng Yongfei et al.，2013；Zheng Yongfei and Wu Fuyuan，2018)，青藏高原在亚洲大陆南缘隆升(Yin and Harrison，2000)，从而为研究增生与碰撞对地壳生长的相对贡献提供了独特机遇。② 特提斯大洋俯冲和印-亚大陆碰撞，不仅导致规模达 1500km 的南北汇聚量和范围达 3000km 的陆内变形域(Xu Zhiqin et al.，2006，2016)，而且引发长期而强烈的幔源岩浆注入(Mo Xuanxue et al.，2007；Hou Zengqian et al.，2020)和高温麻粒岩相变质及地壳深熔(Liu et al.，2013)，产生全球最厚的大陆地壳(65～80km；Zhao Wenjin et al.，1993，2002；Wittlinger et al.，2004；Wang Chunyong et al.，2008；Yakovlev and Clark，2014)，因而是研究大陆地壳的生长、加厚与保存的最佳地区。③ 上述重大地质事件，主要发生于晚近以来，较少遭受后期改造与破坏，因此可被现代地质观察和精细年代学研究予以准确标定，其物质演变及其深部过程也可被同位素填图和地球物理探测予以明确限定。

对于青藏高原巨厚地壳的成因与生长，前人已提出了若干模式，如印度大陆地壳楔入模式(Zhao Wuling and Morgan，1985；Nábelek et al.，2009)、地壳缩短与加厚模式(England and Houseman，1986)、新生幔源岩浆注入模式(Niu Yaoling et al.，2013；Hou Zengqian et al.，2015a)、地壳连续生长加厚模式(Zhu Dicheng et al.，2017)等。然而，地球物理探测发现，印度大陆岩石圈地幔可能以低缓角度俯冲于青藏高原之下(Owens and Zandt，1997；Zhao Weijing et al.，2002；Tilmann et al.，2003；Huang and Zhao，2006；Wang Zewei et al.，2019)，但大陆地壳因具有较低的密度(2.7g/cm^3)而难以整体楔入亚洲大陆内部(Gao Rui et al.，2016)；大陆碰撞可以导致地壳缩短加厚，但广泛分布于拉萨地体之上的林子宗同碰撞巨厚火山岩系仅发生轻微变形(Murphy et al.，1997；Kapp et al.，2007)，反映高原南部上地壳没有发生强烈的缩短加厚(Mo Xuanxue et al.，2007；Kapp et al.，2007)，因此，单纯的中下地壳缩短不足于使高原地壳加厚至正常地壳的两倍。幔源岩浆注入碰撞造山带可以形成新生地壳(Mo Xuanxue et al.，2007；Zhu Dicheng et al.，2011；Niu Yaoling et al.，2013；Hou Zengqian et al.，2015a，2015b)，但局域性的幔源岩浆添加能否引起全局性的地壳整体加厚仍须谨慎论证。由此可见，现有的单一模式无法完美地解释青藏高原大陆地壳的整体加厚，需要多种模式或机制的联合作用。这些方式如何导致地壳的生长与增厚，以及各自对巨厚地壳的相对贡献有待于进一步厘定。

本文拟在前人研究基础上，结合笔者研究成果，从物质记录与构造变形两个角度，系统剖析青藏高原从俯冲到碰撞全过程的地壳生长与加厚原因，半定量评估俯冲与碰撞、岩浆与构造对地壳生长和加厚的相对贡献，深入揭示大陆碰撞引发地壳生长与物质演化的作用机制和深部过程。

1 大洋俯冲过程中的弧岩浆侵位与地壳增生

在增生造山带，新生物质(juvenile materials)，或作为残余洋壳拼贴于造山带，或作为幔源弧岩浆注入地壳内部，导致陆壳的形成与生长(Hawkesworth et al.，2010)。伴随大洋岩石圈俯冲消减，上盘大陆岩石圈常常遭受改造与破坏，部分古老地壳被俯冲侵蚀，新生下地壳得以形成发育(Collins et al.，2011)。这些地质过程也同样出现于青藏高原形成之前的特提斯俯冲增生造山阶段，期间，幔源弧岩浆注入导致地壳垂向生长，新生地壳作为岩浆弧和弧根保存于大陆碰撞造山带内(Zhang Zeming et al.，2020；Hou Zengqian et al.，2020)。

1.1 碰撞前的火山-岩浆弧记录

特提斯洋自古生代以来的持续消减闭合导致多个微陆块(如，拉萨、羌塘、松潘-甘孜地体)经历多次俯冲增生和向北漂移，逐渐拼贴至亚州大陆南缘，构成欧亚大陆的重要组成部分，最终于古近纪与印度大陆碰撞(Yin and Harrison，2000)。古特提斯洋(即，龙木措-双湖-昌宁-孟连、金沙江、甘孜-理塘缝合带)和新特提斯洋(即，雅鲁藏布江和班公湖-怒江缝合带)相继俯冲闭合，在青藏高原至少产生了 4 条火山-岩浆弧(图 1)。

江达-维西弧：发育于羌塘地体东段，长达数百千米(图 1)，弧岩浆带主要由早二叠世—中三叠世(272～235Ma)镁铁质至长英质火山岩和少量同时代花岗岩类组成。岩石富集 LREE (La、Ce、Pr、Nd)和 LILE (Rb、Ba)，亏损 HFSE (Nb、Ta)，$\varepsilon_{Hf}(t)$变化于+9.7～+16.7，反映岩浆源于俯冲交代的亏损地幔，并混有一定量的地壳物质。该岩浆弧究竟是龙木措-双湖-昌宁-孟连洋向东(Yang

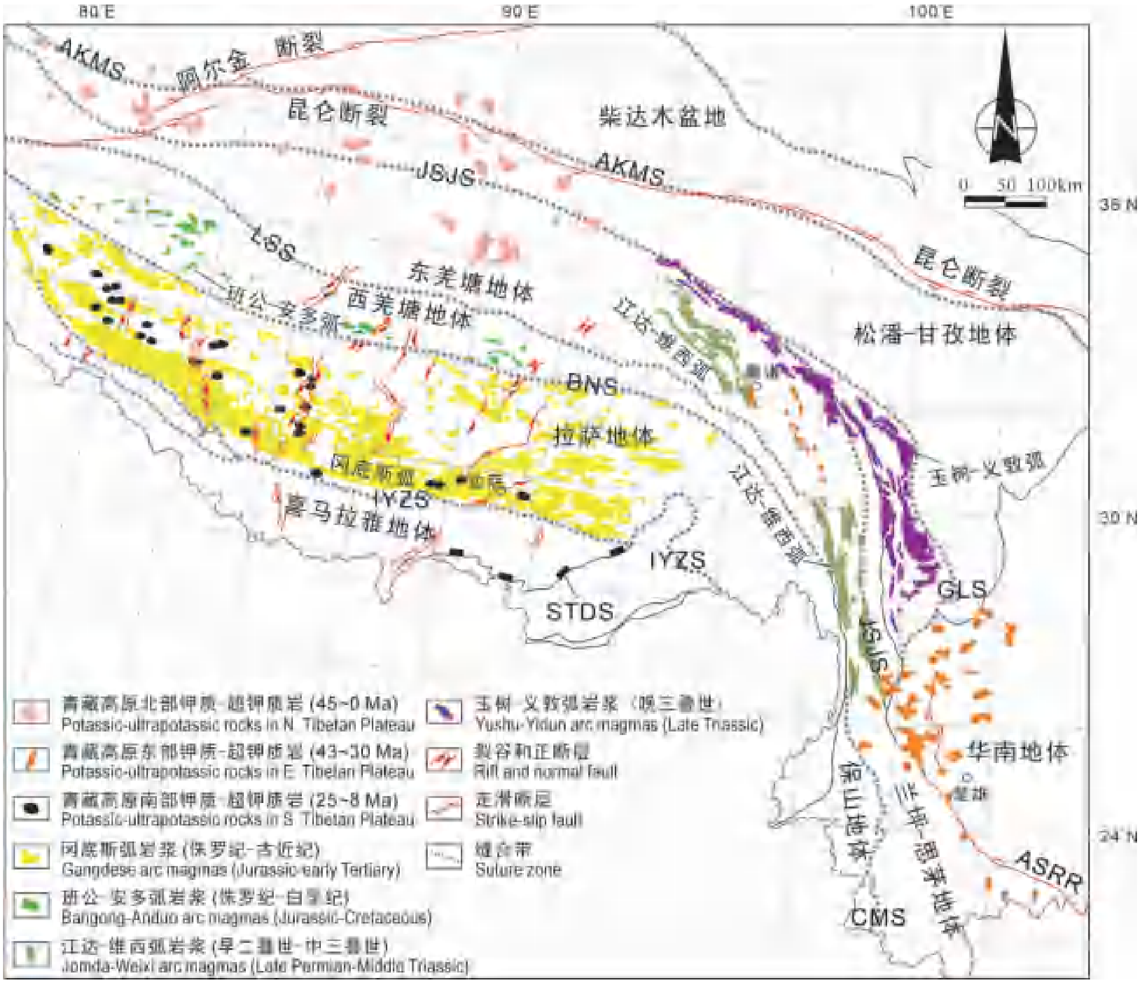

图 1　青藏高原重要弧岩浆带和碰撞幔源岩浆活动与分布图（据 Yang Zhiming et al.，2014；Pan Guitang et al.，2015；Guo Zhengfu et al.，2015；Zhu Dicheng et al.，2016）

Fig. 1　Tectonic framework of the Tibetan Plateau, showing the distribution of post-collisional potassic-ultrapotassic magmatic rocks and major arc magmatic belts (modified after Yang Zhiming et al.，2014；Pan Guitang et al.，2015；Guo Zhengfu et al.，2015；Zhu Dicheng et al.，2016)

STDS—藏南拆离系；AKMS—阿尼玛卿-昆仑-木孜缝合带；JSJS—金沙江缝合带；LSS—龙木措-双湖缝合带；BNS—班公湖-怒江缝合带；IYZS—雅鲁藏布缝合带；GLS—甘孜-理塘缝合带；CMS—昌宁-孟连缝合带；ASRR—哀牢山-红河剪切带

STDS—South Tibet detachment system；AKMS—Anyimaqin-Kunlun-Muztagh suture；JSJS—Jinsha suture；LSS—Longmu Tso-Shuanghu suture；BNS—Bangong-Nujiang suture；IYZS—Indus-Yarlung-Tsangpo suture；GLS—Ganzi-Litang suture；CMS—Changning-Menglian suture；ASRR—Ailao Shan-Red River shear zone

Tiannan et al.，2011；Yang Zhiming et al.，2014），还是金沙江洋向西俯冲的产物（Mo Xuanxue et al.，2003；Deng Jun et al.，2014），目前尚存争议。

玉树-义敦弧：系甘孜-理塘洋于晚三叠世向西南俯冲的产物（图 1；Hou Zengqian et al.，2004b；Yang Tiannan et al.，2019）。北段玉树弧（32°N 以北）长达数百千米，弧岩浆带主要由钙碱性安山岩-英安岩-流纹岩（220～210Ma）和同时代花岗闪长质侵入体构成（Yang Tiannan et al.，2012，2019）。中段昌台弧（32°N～30°N）为张性弧，其外弧发育雀儿山-稻城弧花岗岩带（238～206Ma）和钙碱性安山岩-英安岩系，弧间裂谷发育玄武岩-流纹岩双峰岩石组合（217Ma），内弧发育花岗岩-流纹岩组合（Hou Zengqian et al.，2004b）。南段中甸弧（30°N 以南）为压性弧，主要发育岛弧钙碱性安山岩-英安岩系和大规模花岗岩基及含铜斑岩体（Yang Yueqing et al.，2002；Li Wenchang et al.，2014）。三段弧岩浆稀土配分曲线呈右倾模式，富集 LILE（Rb、K 和 Ba）和 LREE，亏损 HFSE（Nb、Ta 和 Ti 等），$(^{87}Sr/^{86}Sr)_i$ 值为 0.708～0.7060，$\varepsilon_{Nd}(t)$ 为 −8.4～+0.7，反映岩浆是交代地幔楔部分熔融的

产物，并受到不同程度的地壳混染(Yang Tiannan et al.，2012；Leng Chengbiao et al.，2012，2014；Li Wenchang et al.，2014)。

班公-安多弧：沿羌塘地体南缘发育，东西延伸约 1200km(图 1)，主要由晚侏罗世—早白垩世(169～113Ma)岛弧岩浆带构成，系班公湖-怒江洋向北俯冲而成(Zhu Dicheng et al.，2016)。弧岩浆带分东西两段(西段日土-改则；东段北拉-那曲)，岩浆活动主要集中于侏罗纪(169～150Ma)和白垩纪(127～113Ma)(Li Jinxiang et al.，2014；Li Shimin et al.，2020)。火山岩主要为高钾钙碱性安山岩、英安岩和流纹岩，其中侏罗纪火山岩的全岩 $\varepsilon_{Nd}(t)$为－8.6～－7.9 和$(^{87}Sr/^{86}Sr)_i$值为 0.7064～0.7077，锆石 $\varepsilon_{Hf}(t)$值为－13.3～－0.5。侵入岩主要为含丰富的镁铁质-闪长质包体的花岗岩类，具有富集 LILE(如 Cs、Rb 和 K 等)，亏损 Nb、Ta 和 Ti 等 HFSE，以及明显的 Ba 负异常。岩石具有宽泛的锆石 $\varepsilon_{Hf}(t)$组成(－19.4～＋11.2)，显示出大量亏损地幔物质注入古老的羌塘地体地壳之中。

冈底斯弧：沿整个拉萨地体发育，东西延伸 1500km(图 1)。弧岩浆活动最早沿南拉萨地体发育，在 88°E 到 94°E 形成长达 600km 的侏罗纪火山-岩浆弧(210～170Ma；Ji Weiqiang et al.，2009；Kang Zhiqiang et al.，2014；Xu Wei et al.，2019)。其中，东段叶巴组火山岩显示双峰式特征(Geng Quanru et al.，2005)，西段火山岩显示玄武岩至英安岩连续演化特征。相伴侵入岩自晚三叠世(210Ma)至晚白垩世(72Ma)连续发育，呈弧花岗岩基产出(图 1)。这些岩浆岩整体显示出相对亏损的 Nd 和 Hf 同位素组成($\varepsilon_{Nd}(t)$：－3～＋7；$\varepsilon_{Hf}(t)$：－5～＋18)(Kang Zhiqiang et al.，2014；Wang Ruiqiang et al.，2017；Xu Wei et al.，2019)。中拉萨地体厚达 1000m 的早白垩世长英质火山岩大量发育，同时代的花岗岩类侵入体零星出露(Zhu Dicheng et al.，2011)。岩石稀土配分曲线整体呈平缓右倾，岩石富集 LILE (Rb、Ba、Th 和 U)和亏损 HFSE (Nb、Ta 和 Ti)，具有相对富集的 Nd 和 Hf 同位素组成($\varepsilon_{Nd}(t)$：－14～＋1；$\varepsilon_{Hf}(t)$：－14～＋7)，其为雅鲁藏布江洋向北俯冲的产物(Mo Xuanxue et al.，2003；Chu Meifei et al.，2006；Zhu Dicheng et al.，2009，2011)。北拉萨地体的岩浆带东西延伸 1200km，大量发育早白垩世(131～107Ma)火山沉积系(Zhu Dicheng et al.，2011)和同时代(130～80Ma)花岗岩侵入体(Xu Ronghua et al.，1985；Harris et al.，1990)。岩浆富集 LILE、亏损 HFSE，ε_{Hf}值变化范围较宽(－14～＋18)，其成因被归结为班公湖-怒江洋的南向俯冲(Zhu Dicheng et al.，2011)或雅鲁藏布江洋向北俯冲和板片回转(Hou Zengqian et al.，2015a)。

总之，这些火山-岩浆弧，作为大洋俯冲增生产物，向亚洲大陆南缘拼贴，导致陆壳侧向增生，弧岩浆大量喷发侵位，导致弧地壳垂向生长。

1.2 碰撞前的新生地壳形成与分布

由火山岩浆弧及弧根构成的新生地壳，其组成与演变可以通过区域岩浆岩的 Hf-Nd 同位素来示踪；其空间分布与总体规模可以通过地体尺度的锆石 Hf 同位素填图来刻画(Hou Zengqian and Wang Tao，2018；Wang Tao and Hou Zengqian，2018)。

图 2a 展示了青藏高原碰撞前的长英质岩浆岩 Hf 同位素组成随时间变化。两个特征十分明显：① ε_{Hf}值显示很宽的变化范围(＋15～－18)，反映碰撞前弧岩浆具有明显的两元性：部分母岩浆来源于流体交代的地幔楔(软流圈地幔部分)的部分熔融，部分来自于古老地壳的重熔或混染；② 自 270Ma 至 66Ma，长英质岩最高 ε_{Hf}显示 5 个峰值，分别出现于 250±2Ma，210±5Ma，180±5Ma，120±5Ma 和 80±5Ma，大致对应于古特提斯洋俯冲形成的江达-维西弧和义敦-玉树弧，以及新特提斯洋俯冲形成的班公-安多弧和冈底斯弧的主要发育期，证实来自软流圈地幔的新生物质为弧地壳生长做出了重要贡献。

图 3a 是青藏高原俯冲期岩浆岩的锆石 ε_{Hf}等值线图，反映了印-亚大陆碰撞前新生地壳与古老地壳的空间分布(Hou Zengqian et al.，2020)。至少有 5 个高 ε_{Hf}值域(＞0)，嵌布于大面积分布的低 ε_{Hf}值域内(＜0)。这些高 ε_{Hf}(＞0)域所代表的新生地壳块多出现于地体边界附近，空间上大致与上述 4 个主要火山-岩浆弧相对应，证明弧岩浆活动形成新生陆壳。应该指出，这些高 ε_{Hf}值长英质岩石从其岩浆源区向上侵位至浅部地壳就位，主要反映上部地壳出现的局域性生长。然而，下列证据表明：碰撞前的镁铁质弧岩浆在地壳底部发生了大规模底侵，形成了镁铁质新生下地壳。

首先，在冈底斯弧南侧喜马拉雅东构造结附近，即，拉萨地体东部新生地壳块区内(图 3a)，构造剥露了视厚度达 20～30km 的下地壳剖面(Zhang Zeming et al.，2014，2020；Xu Wei et al.，2019)，主要由经历麻粒岩相变质的变辉长岩、石榴石角闪

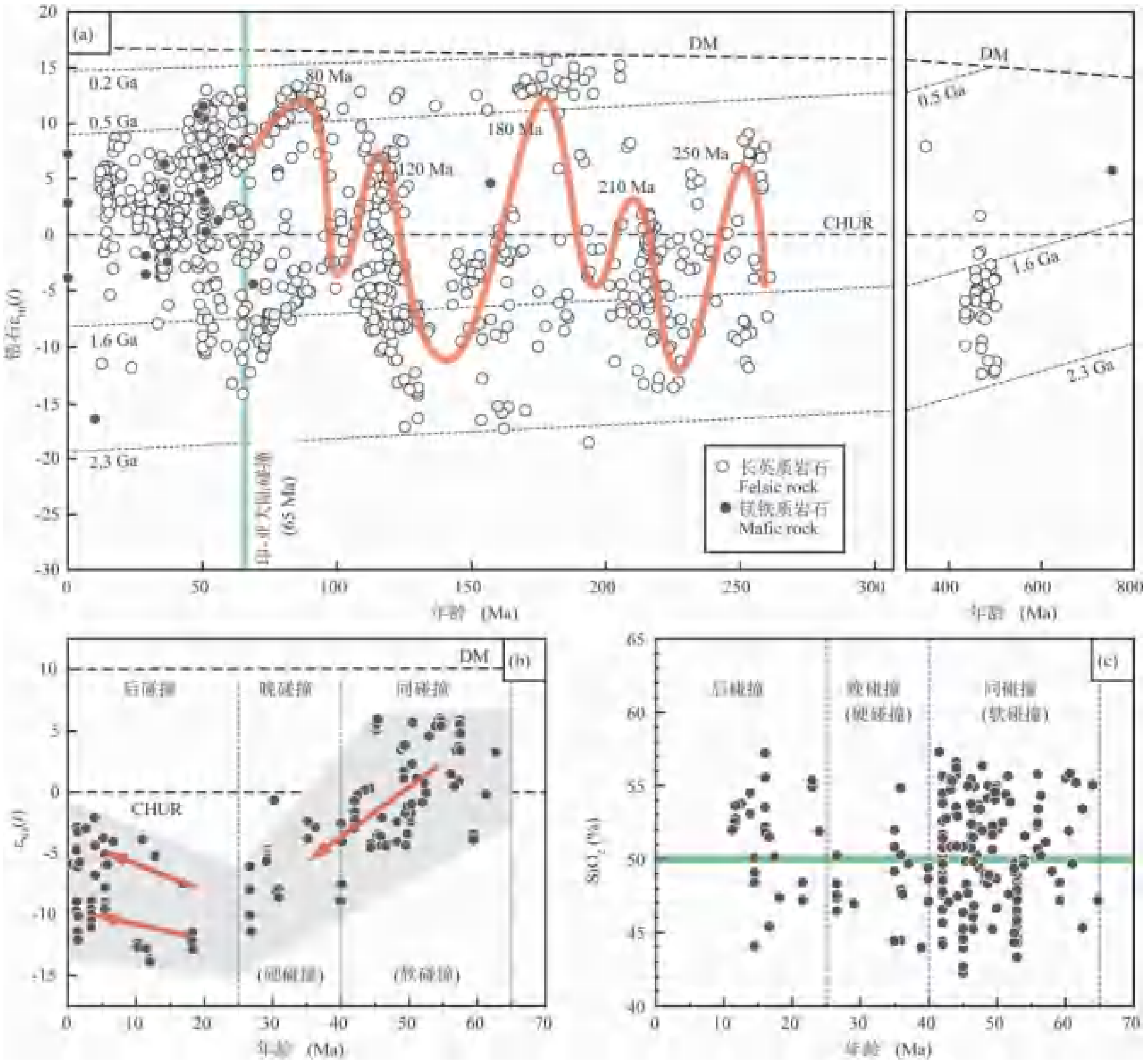

图 2　青藏高原古生代以来岩浆岩的 Hf 同位素组成(a)以及中基性岩石的 Nd 同位素组成(b)及其 SiO_2 含量随时间变化(c)（据 Hou Zengqian et al.，2020）

Fig. 2　Zircon Hf (a) and whole-rock Nd isotopic compositions (b) and SiO_2 contents (c) of the Mesozoic-Cenozoic felsic and mafic igneous rocks from the Himalayan-Tibetan orogen in Tibet (after Hou Zengqian et al.，2020)

(a)—0.5 Ga、1.6 Ga 和 2.3 Ga 的地壳演化线，采用平均大陆地壳 $^{176}Lu/^{177}Hf = 0.015$ 计算，0.2 Ga 的镁铁质下地壳演化线使用平均下地壳 $^{176}Lu/^{177}Hf = 0.022$ 计算；(b)—亏损地幔演化线的两个端元为 $\varepsilon_{Nd}(4.56\ Ga) = 0$ 和 $\varepsilon_{Nd}(0) = 10$；(c)—样品包括拉萨地体的辉长岩、辉绿岩脉、镁铁质的超钾质岩和林子宗火山岩，羌塘地体的镁铁质火山岩，以及特提斯喜马拉雅带具有洋岛玄武岩特征的辉长岩；DM—亏损地幔演化线；CHUR—球粒陨石演化线

(a)—The three crustal evolution lines labelled 0.5 Ga，1.6 Ga and 2.3 Ga are presumably average continental crust with $^{176}Lu/^{177}Hf = 0.015$，the evolution line of mafic lower crust generated at 0.2 Ga with $^{176}Lu/^{177}Hf = 0.022$ was shown for comparison；(b)—the depleted mantle growth curves of Nd were shown，using linear depletion from $\varepsilon_{Nd} = 0$ at 4.56 Ga to $\varepsilon_{Nd} = 10$ at present；(c)—samples presented here include gabbros，diabase dykes，mafic ultrapotassic volcanics and Linzizong volcanics in the Lhasa terrane，mafic volcanics in the Qiangtang terrane，and OIB-type gabbros in the Tethyan Himalaya；DM—a generalized ‘Depleted Mantle’ growth curve；CHUR—the chondritic reference

岩和角闪石堆晶岩组成。其原岩锆石 U-Pb 年龄变化于 200～85Ma（Xu Wei et al.，2019；Zhang Zeming et al.，2020），与雅鲁藏布江洋俯冲时限一致。变辉长岩及堆晶岩显示岛弧型地球化学特征，具有强亏损的 Hf 同位素组成(ε_{Hf}：+9～+16)，反映其岩浆来源于被俯冲板片流体交代的软流圈成因地幔楔（Zhang Zeming et al.，2014；Xu Wei et al.，2019）。这些镁铁质岩作为冈底斯弧的弧根出

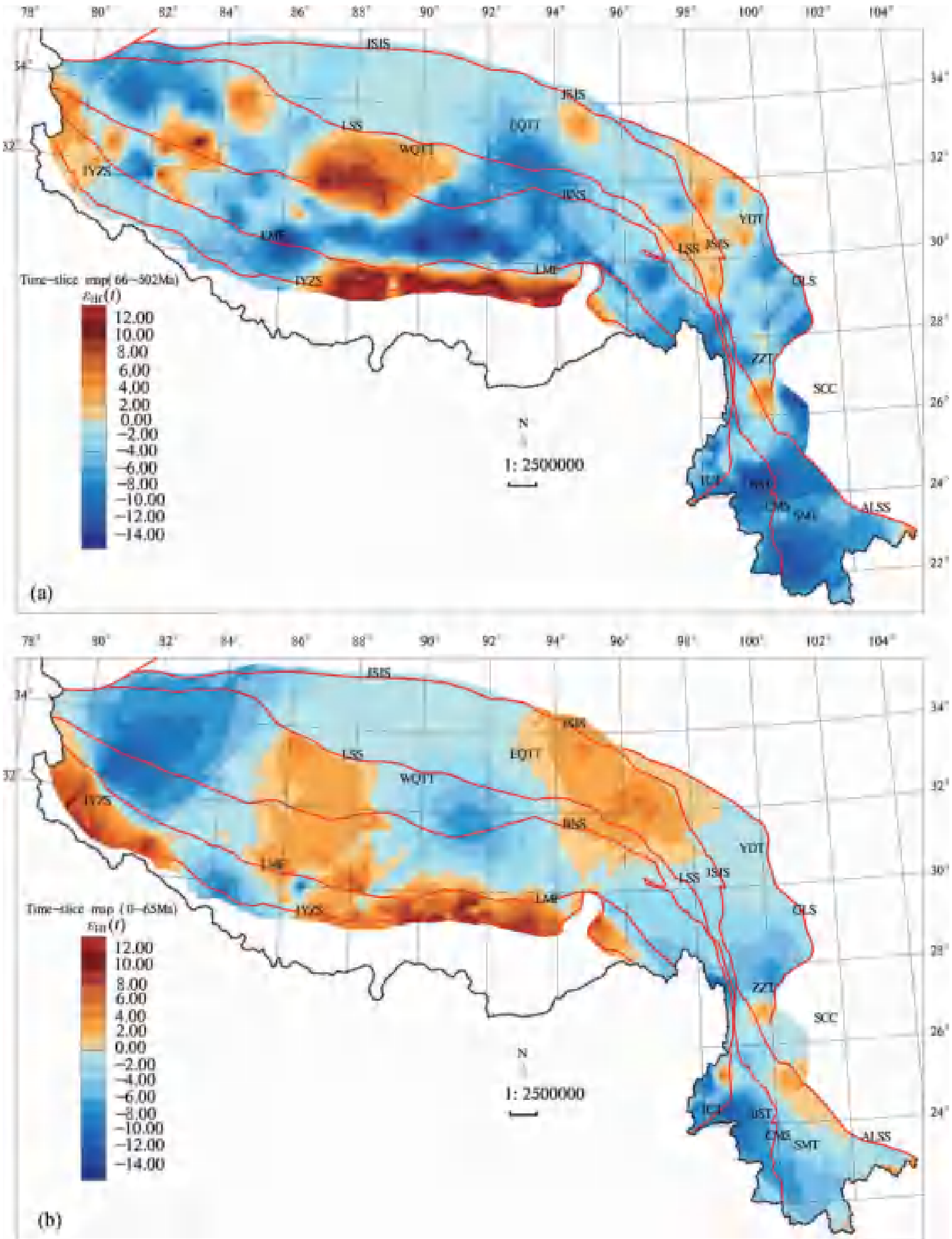

图 3 青藏高原碰撞前(a)与碰撞后(b)的岩浆锆石 Hf 同位素填图结果(据 Hou Zengqian et al.，2020)

Fig. 3 Pre-collisional time slice (a) and collisional time slice (b) for lithospheric architecture of the Tibetan orogeny (after Hou Zengqian et al.，2020)

现，为侏罗纪—白垩纪弧岩浆底侵与堆积提供了直接证据。此外，在高原东部六合—北衙等地，处于新生地壳块区内的钾质火山岩和含矿斑岩(35～33Ma)携带了许多下地壳包体，其岩相以石榴石角闪岩和角闪岩为主，经历麻粒岩相变质，平衡压力估算其来自于深部地壳 45～37km 处(Hou Zengqian et al.，2017)。其原岩年龄为 783±10Ma，微量元素和 Hf 同位素组成与扬子西缘新元古代弧岩浆一致(Hou Zengqian et al.，2017)，反映更早时期的大洋俯冲诱发了镁铁质弧岩浆活动，并大规模地底侵于下地壳底部，形成了镁铁质新生下地壳。

其次，位于拉萨地体东段的冈底斯同碰撞花岗岩基(55～50Ma)，以高 Hf 和高 Nd 为特征，被认为来自于新生下地壳重熔(Chu Meifei et al.，2006)或俯冲洋壳板片熔融(Niu Yaoling et al.，2013)。它们在空间上分布于碰撞时间切面的新生地壳块体内(图 3b)，与碰撞前时间切面内的高 ε_{Hf}

值域相对应(图 3a)。此外，沿拉萨地体南缘分布的中新世后碰撞花岗质斑岩和钾质火山岩，通常显示岛弧型地球化学特征和 adakite 亲和性，具有新生的 Sr-Nd-Hf 同位素组成(Hou Zengqian et al.，2004a，2015c)，与侏罗纪镁铁质弧岩浆的同位素组成类似，被认为来自于镁铁质新生下地壳的重熔(Hou Zengqian et al.，2015c)，是侏罗纪幔源弧岩浆在高原南部地壳底部大规模底侵的直接证据。

最后，地球物理探测发现，在高原南部下地壳 60km 深处发育一层厚约 14km 的高速层，其 V_p 变化于 7.2～7.5km/s，V_s 为 6km/s (Kind et al.，1996；Owens and Zandt，1997)，被解释为高密度(＞3.0 g/cm^3)含石榴子石下地壳(Nábelek et al.，2009)，由幔源岩浆底侵而成(Owens and Zandt，1997)。类似的镁铁质新生下地壳或壳幔过渡带也大量发育在高原东部三江地区(Zhong Dalai et al.，2000)。

根据青藏高原俯冲和碰撞阶段长英质岩石的高 ε_{Hf} 值分布面积(ε_{Hf}＞0)估算，青藏高原的新生地壳量(俯冲＋碰撞)约占全部地壳量的 1/3 (28%)，其中，大洋俯冲诱发的幔源弧岩浆为新生地壳贡献了 21% (Hou Zengqian et al.，2020)，也即，75%的新生地壳可能是由幔源弧岩浆底侵或侵位形成的。根据喜马拉雅构造结剥露的新生下地壳剖面视厚度(20～30km)和地球物理探测揭示的深地壳高速层厚度(14km)，考虑到碰撞以来新生幔源组分对新生地壳的额外贡献(25%)，我们估计，碰撞前的幔源弧岩浆大规模侵位，使青藏高原南部地壳增厚了约 10km，占地壳总厚度的 12%～13%。这一结果与 Zhu Dicheng et al. (2017)的估计结果基本一致。他们根据碰撞弧岩浆$(La/Yb)_n$值，估计在 70Ma 前后，西藏冈底斯地壳由原来的正常厚度(30km)平均加厚至 49km。

2　大陆碰撞过程中的幔源岩浆注入与地壳生长

前期研究表明：对接于 65Ma 的印-亚大陆，经历同碰撞(或主碰撞，或软碰撞；65～41Ma)、晚碰撞(或硬碰撞；40～26Ma)和后碰撞过程(25～0Ma)(Hou Zengqian et al.，2006a，2006b，2006c；Hou Zengqian and Cook，2009)。下述碰撞岩浆记录表明，不同碰撞阶段形成不同的构造-岩浆组合，每个碰撞阶段均伴有不同的幔源岩浆活动，引起三段式地壳生长。

2.1　碰撞期岩浆记录

同碰撞幔源岩浆：在青藏高原主要发育三套幔源岩浆组合。一是林子宗火山岩系，位于印度大陆俯冲带上盘，其 U-Pb 年龄为 64～43Ma (Mo Xuanxue et al.，2003)，厚度超过 5000m，大面积分布于拉萨地体中南部。岩系底部典中组以安山岩系为主，中部年波组以英安岩系为主，顶部帕那组则以流纹岩为主体，但中下部岩组局部发育厚度不一的玄武质岩夹层(图 2c)。火山岩总体上以钙碱性系列为主，随时间向钾玄岩系列演变。岩石富集 LILE (Rb、K 和 Ba 等)，亏损 HFSE (Nb、Ta、P 和 Ti 等)(图 4)，ε_{Nd}变化于－5～＋3(图 2b)，反映岩浆主要来源于俯冲板片流体交代的软流圈地幔(Mo Xuanxue et al.，2003，2007)。二是同碰撞辉长岩(52.5～47.0Ma)，沿拉萨地体南缘断续成带，产出于大陆碰撞缝合带(IYZS)北侧，局部侵位于同碰撞花岗岩基内部(Dong Guochen et al.，2005)。其 SiO_2 含量 49%～55%(图 2c)，稀土配分曲线平缓右倾，缺乏 Eu 异常，ε_{Nd}变化于＋2～＋7(图 2b)，反映岩浆源于未遭受强烈交代的软流圈地幔(Dong Guochen et al.，2005)。三是特提斯喜马拉雅带同碰撞晚期辉绿岩(45Ma)，位于 IYS 南侧，富集 HFSE 和 LILE 及 REE(图 4)，ε_{Nd}变化于＋4.9～＋5(图 2b)，显示洋岛玄武岩(OIB)特征，记录了印度大陆岩石圈俯冲前缘板片断离及随后的软流圈熔融过程(Ji Weiqiang et al.，2016)。

晚碰撞幔源岩浆：主要分布于藏北羌塘地区和藏东三江地区。羌塘地区主要发育钾质钙碱性和钾玄岩系列的镁铁质至长英质火山岩，年龄为 47～18Ma (Li Cai et al.，2002；Xu Jifeng and Wang Qiang，2003；Wang Qiang et al.，2008，2016；Zhao Zhi et al.，2009；Wang Baodi et al.，2010；Zhang Rui et al.，2018)。镁铁质岩石轻稀土中度富集，弱负 Eu 异常，亏损 HFSE (Nb、Ta 和 Ti)，但富集 Sr 和 Ba，$(^{87}Sr/^{86}Sr)_i$值为 0.7048～0.7104，ε_{Nd}为－10.5～＋3.9，ε_{Hf}为－4.2～＋4.0 (图 2b)，反映其岩浆来源于遭受流体强烈交代的富集岩石圈地幔(Wang Qiang et al.，2010，2016)。三江地区大量产出超钾质火山岩和煌斑岩，年龄变化于 40～33Ma (Wang Jianghai et al.，2001；Guo Zhengfu et al.，2005；Lu Yongjun et al.，2013)。岩石富集 LILE，亏损 HFSE，以高$(^{87}Sr/^{86}Sr)_i$，低 ε_{Nd}，富集放射性 Pb 同位素为特征(Jai Liqiong et al.，2013；He Wenyan et al.，2014)，来源于板片流体交代的

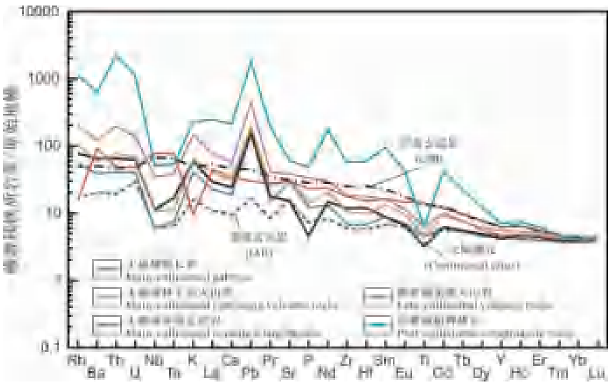

图 4 青藏高原碰撞以来的镁铁质岩浆岩微量元素配分图解
Fig. 4 Primitive mantle normalized trace element diagram to compare compositions of the collision-related mafic magmas from the Himalayan-Tibetan orogen

主碰撞辉长岩平均值来自 Dong Guochen et al.，2008，2011；Jia Lili et al.，2014；Wen Daren，2007；主碰撞林子宗火山岩平均值来自 Lee et al.，2009，2012；Mo Xuanxue et al.，2007，2008；主碰撞洋岛玄武岩平均值来自 Ji Weiqiang et al.，2016；晚碰撞羌塘火山岩平均值来自 Ding Lin et al.，2007；Guo Zhengfu et al.，2006；后碰撞超钾质岩平均值来自 Guo Zhengfu et al.，2013；Liu Dong et al.，2015；Zhao Zhidan et al.，2009；平均大陆地壳成分引自 Rudnickz and Gao，2003；岛弧玄武岩成分引自 Sun and McDonough，1989；洋岛玄武岩成分引自 Elliott，2003

Data for main-collisional average gabbros from Dong Guochen et al.，2008，2011；Jia Lili et al.，2014；Wen Daren，2007；main-collisional average Linzizong volcanic rocks from Lee et al.，2009，2012；Mo Xuanxue et al.，2007，2008；main-collisional average oceanic island basalts from Ji Weiqiang et al.，2016；late-collisional average volcanic rocks in Qiangtang from Ding Lin et al.，2007；Guo Zhengfu et al.，2006；post-collisional average ultrapotassic rocks from Guo Zhengfu et al.，2013；Liu Dong et al.，2015；Zhao Zhidan et al.，2009；bulk continental crust from Rudnickz and Gao，2003；oceanic island basalts from Sun and McDonough，1989；island arc basalts from Elliott，2003

富集岩石圈地幔（Guo Zhengfu et al.，2005；Jia Liqiong et al.，2013；Xu Heng et al.，2015；Chen Fuchuan et al.，2015）。

后碰撞幔源岩浆：主要发育于三江南部马关地区和西藏冈底斯带（图 1）。前者以含地幔包体的玄武岩为主，年龄集中于 12.4～11.9Ma（Wang Jianghai et al.，2001）。岩石 Mg# 为 0.49～0.72，富集 LREE 和 LILE，以低（$^{87}Sr/^{86}Sr$）$_i$（0.7041～0.7060）和高 ε_{Nd}（＋5.5～＋7.0）为特征，与 OIB 类似，来源于上涌的软流圈地幔（Xia Ping and Xu Yigang，2004；Huang Kaixing et al.，2012），或来源于熔体交代的软流圈成因地幔楔（Zheng Yongfei，2019）；后者沿拉萨地体发育，以含地幔包体的超钾质火山岩和煌斑岩为主，其同位素地球化学上类似于三江地区煌斑岩，岩浆来源于富集的岩石圈地幔（Zhao Zhidan et al.，2009；Xu Bo et al.，2017）。

总之，伴随着印-亚大陆碰撞，从同碰撞经晚碰撞至后碰撞，幔源岩浆活动在青藏高原分布广泛。尽管地表点多量少，但从其成分变化看（图 2c），幔源岩浆在深部地壳曾经历岩浆底侵与分异演化，它们作为新生幔源组分导致了高原地壳的不断生长。

2.2 碰撞期新生地壳形成与分布

图 3b 反映了青藏高原碰撞以来的新生地壳块与古老地壳块的镶嵌分布特征。古老地壳块以低 Hf 为特征，大致与拉萨地体、羌塘地体和松潘-甘孜地体相对应，其 ε_{Hf} 值变化反映这些古老地体因碰撞而发生程度不等的活化再造；新生地壳块以高 Hf 为特征，空间上与碰撞前时间切片中的高 ε_{Hf} 域大致对应，但也有明显差别。在南拉萨地体东段，碰撞前与碰撞后的新生地壳块规模相当，空间吻合。这里出露新生下地壳剖面，发育同碰撞高 Hf-高 Nd 花岗岩基，并伴有碰撞有关的镁铁质岩浆侵位（图 3b），反映俯冲与碰撞过程导致新生地壳的不断加积。在拉萨地体西段，碰撞前局部发育的新生地壳物质在碰撞期得以扩展加积，形成完整的新生地壳块，沿拉萨地体南缘分布（图 3b）。在拉萨地体中部，碰撞前以古老地壳为主，碰撞期产生新生地壳，其空间分布与厚达 5000m 的林子宗火山岩系相对应。在青藏高原的东缘，碰撞期新生地壳块较碰撞前的范围明显扩大，显示向北和向南扩展之势（图 3b），反映碰撞期特别是晚碰撞以来新生地壳大量增生。在班公湖-怒江洋缝合带沿线，碰撞前的新生地壳块自碰撞以来出现缩小甚至局部消失趋势，反映原来的新生下地壳或因大陆碰撞而发生改造，或在碰撞期缺乏重熔而无壳源岩浆记录。总之，同位素填图结果证实，青藏高原碰撞前与碰撞后的岩石圈架构既有继承性，又有差异性。碰撞前的新生地壳既有保存，又有破坏，碰撞期的新生物质既有在原有新生地壳上的不断加积，又有在古老地壳上的大量添加。

碰撞以来新生幔源组分注入产生的新生地壳的厚度和规模，尚难定量估计。采用新生地壳总量减去俯冲产生的新生地壳量（75％）进行估算，结果显示大陆碰撞为青藏高原贡献了不超过 25％的新生地壳（Hou Zengqian et al.，2020）。Zhu Dicheng et al.（2017）根据冈底斯同碰撞花岗岩基多处地方

(如乃卡,62Ma;林周,52.5Ma;聂当,51Ma)发育的埃达克质岩(Jiang Ziqi et al.,2014;Mo Xuanxue et al.,2007;Ji Weiqiang et al.,2012;Zhu Dicheng et al.,2015),估算高原南部地壳在同碰撞期(65～45Ma)加厚了 5～10km(图 5)。我们根据林子宗火山系厚度(～5km)以及碰撞以来幔源岩浆的空间分布和出露规模(图 3b),考虑到这些幔源岩浆在下地壳的底侵(～4km),估计碰撞以来的幔源镁铁质岩浆至少使青藏高原南部地壳加厚了 6～9km。这些结果表明,要达到青藏高原现今的地壳厚度(65～80km),除碰撞前后新生幔源组分贡献外,还要求额外的地质过程(如构造变形)使地壳再增厚 10～20km。

3　碰撞过程中的构造变形与地壳加厚

构造地质研究揭示,在缺乏碰撞期岩浆活动的后陆区(图 3b),白垩纪以来(99～69Ma)的强烈褶皱逆冲已引起了安第斯型地壳的再度加厚(Murphy et al.,1997;Kapp et al.,2007)。在同样缺乏同碰撞岩浆活动的青藏高原东部(如玉树—囊谦地区),同碰撞产生一系列 NNW 走向的始新世逆冲褶皱系(Yin and Harrison,2000;Wang Jianghai et al.,2001),也导致了地壳缩短加厚。相反,在岩浆活动异常强烈的大陆碰撞带(如拉萨地体),上部地壳变形微弱,缩短量有限(Murphy et al.,1997;Kapp et al.,2007),这暗示,除碰撞前大洋俯冲引发的大陆增生和地壳加厚外,同碰撞期幔源岩浆大规模侵位也是大陆碰撞带地壳加厚的主导机制(Mo Xuanxue et al.,2007;Zhu Dicheng et al.,2017)。

在晚碰撞期(41～26Ma),后陆区岩浆活动强烈,形成长达数千千米的钾质岩浆带(Wang Jianghai et al.,2001;Wang Qiang et al.,2008),新生幔源物质通过地幔通道流输送到地壳内部,实现了地壳生长与加厚(见后)。而在碰撞带(冈底斯造山带),岩浆活动相对寂静,仅有少量壳源长英质岩浆侵位(38～26Ma;Chung Sunlin et al.,2005;Guan Qi et al.,2012;Zheng Yuanchuan et al.,2012)。这些岩浆岩显示 adakite 特征,具有高 $(La/Yb)_n$ 比值(25～55),指示其源区地壳厚达 68～86km(图 5;Zhu Dicheng et al.,2017),反映碰撞带地壳在岩浆活动微弱的晚碰撞期发生了快速加厚。

DeCelles et al.(2009)总结了科迪勒拉造山带地表构造变形和区域岩浆作用规律,发现造山过程

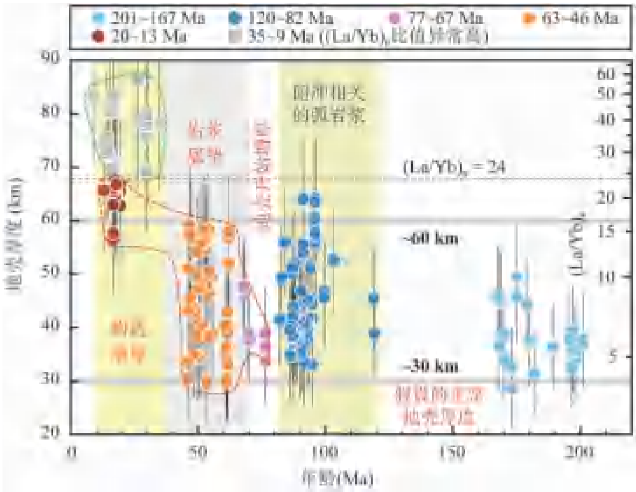

图 5　青藏高原碰撞前锋带(冈底斯带)侵入岩的 $(La/Yb)_n$ 与估算地壳厚度变化(据 Zhu Dicheng et al.,2017 修改)

Fig.5　Plot of changes in $(La/Yb)_n$ in intrusive rocks and calculated crustal thickness over time for the collisional front zone (modified from Zhu Dicheng et al.,2017)

中低岩浆通量阶段往往伴随地壳挤压缩短和增厚。在青藏高原南部,晚碰撞期低岩浆通量与地壳挤压缩短加厚的对应关系也得到了最新地球物理资料证实。

穿越拉萨地体的深反射地震探测结果(Lu Zhanwu et al.,2018,《青藏高原主碰撞带岩石圈精细结构与深部过程》中期评估报告)揭示,拉萨地体 15～20km 深处发育较为平直的水平反射层,与 INDEPTH 项目的亮点(Bright-spot)深度大致相当(Brown et al.,1996;Nelson et al.,1996;Zhang Zhongjie et al.,2011)。以该水平反射层为界,上下地壳显示不同的反射特征,反映该反射层很可能是一条规模巨大的、局部熔融的拆离构造层,其作为一个构造转换带,调节了地壳内部的构造形变。在 20km 界面之上,地壳上部(＜15km)发育以向北仰冲为主的短轴反射,与上地壳发育有限规模的薄皮构造相一致,表明基底没有卷入区域构造变形。界面之下的中下地壳范围则显示三个不同的反射区,即,与南拉萨地体对应的透明弱反射区、与中萨拉地体对应的北倾弧形反射区、与北拉萨地体对应的伴有局部近水平的弱反射区,三者之间显示空间叠覆关系(Lu Zhanwu et al.,2018)。对比 Hf 同位素填图结果发现,三个不同的反射区分别与南拉萨新生地壳块、中拉萨古老地壳块和北萨拉新生地壳块相对应(图 6a;Hou Zengqian et al.,2015a),反映三个地壳块体间发生强烈的叠加并置,即,中

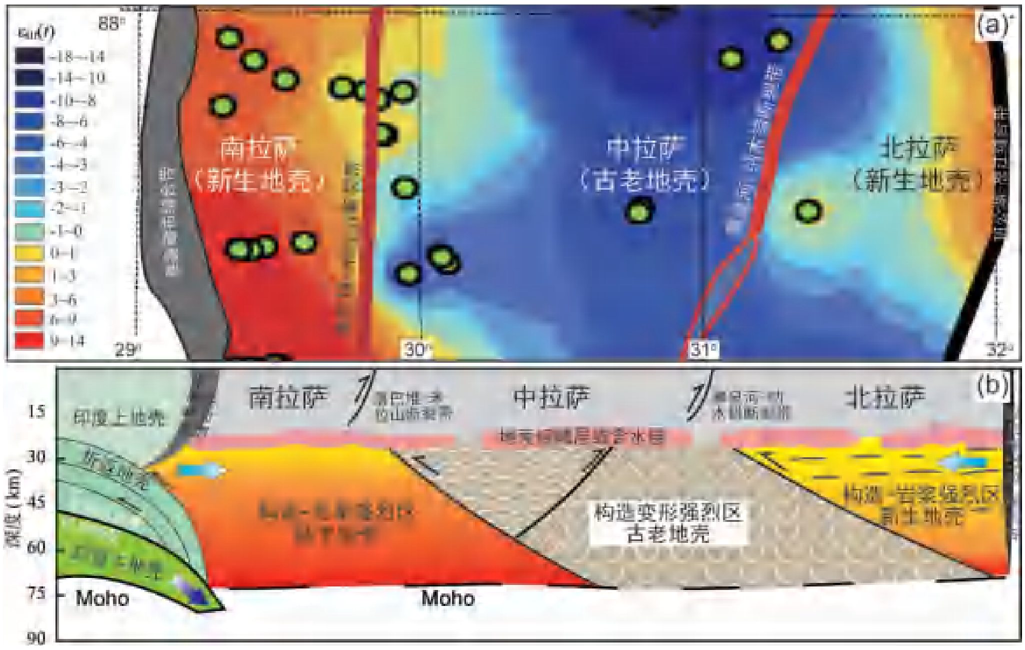

图 6 青藏高原南部 Hf 同位素填图结果(a)与基于反射地震资料的地质解释(b)

Fig. 6 Hf isotope mapping result (a) (modified from Hou Zengqian et al., 2015a) and possible geological interpretation (b) based on reflect seismic profile across the southern Tibet (after Lu Zhanwu et al., 2018)

(a)—拉萨地体长英质岩 Hf 同位素等值线，反映拉萨地体不同的地壳块特征，南拉萨主要为新生地壳，中拉萨为古老地壳，北拉萨由新生与古老混合而成（Hou Zengqian et al., 2015a)；图中圆圈代表样品数据点；(b)—拉萨地体地壳结构与构造解释，主要基于跨越拉萨地体的深反射地震剖面资料（Lu Zhanwu et al., 2018)和 Hf 同位素填图结果（Hou Zengqian et al., 2015a)

(a)—Hf isotope contour maps showing the spatial variation of zircon $\varepsilon_{Hf}(t)$ values for felsic igneous rocks in the Lhasa terrane. Juvenile crustal block marked by positive $\varepsilon_{Hf}(t)$ values appears in the southern Lhasa subterrane, ancient crustal block marked by negative $\varepsilon_{Hf}(t)$ values appears in the central Lhasa subterrane, the northern Lhasa subterrane contains both ancient and juvenile crustal materials. Black point represents sample location; (b)—interpretation of lithospheric architecture of the Lhasa terrane based on reflect seismic profile across the southern Tibet (Lu Zhanwu et al., 2018) and Hf isotope mapping result (Hou Zengqian et al., 2015a)

拉萨古老地壳块体逆冲叠覆于南拉萨新生地壳块之上，北拉萨新生地壳块逆冲叠覆于中拉萨地壳块之上(图 6b)。Hf 同位素填图证实，北拉萨新生地壳块的形成与班公湖-怒江洋双向俯冲和弧岩浆大规模注入有关，形成于 76Ma 前(Hou Zengqian et al., 2015a)，由此限定该块体向南的逆冲叠置发生于大陆碰撞以来(<65 Ma)；南拉萨新生地壳块主体由 200Ma 至 43Ma 的幔源镁铁质岩浆持续注入而成，后因晚碰撞岩浆间歇(40～26Ma)而停止生长(Hou Zengqian et al., 2015a)，由此限定中拉萨地块向南逆冲叠置发生于晚碰撞期。在南拉萨与中拉萨边界断裂的北侧，部分同碰撞期的壳源岩浆仍显示相对较高的 ε_{Hf} 值，反映中拉萨南部的下地壳仍以新生地壳为主，向南与南拉萨新生地壳块在深部相连(图 6b)，也暗示中拉萨古老地壳块在晚碰撞期向南逆冲叠置。因此，在晚碰撞期，不同地壳块体间的逆冲叠置很可能是碰撞带地壳快速加厚的主要机制。

后碰撞期构造变形以跨越碰撞造山带的 NS 向正断层系统或裂谷带为特征。这些裂谷带最早启动于 20Ma (Hou Zengqian et al., 2006)，在藏南活跃于 8Ma，在碰撞带活动于 13～10Ma (Blisniuk et al., 2001)。后碰撞钾质—超钾质幔源岩浆岩(16～13Ma)沿碰撞带近 WE 向展布，但受 NS 向裂谷带控制(Gao Yongfeng et al., 2008)。这些资料表明，青藏高原自 20Ma 以来发生 WE 向地壳伸展，一度加厚至 80 余千米的高原南部地壳可能由此开始减薄。幔源岩浆的注入虽然形成了少量新生地壳，但因高原伸展(10 mm/a; Avouac et al., 1993)与构造侵蚀，无法继续维持地壳的净生长。

4 巨厚陆壳长英质化的形成机制

理论上，新生幔源镁铁质组分向青藏高原的不断注入将导致高原陆壳渐变基性。然而，青藏高原南部(如拉萨地体)地壳平均纵波波速(V_p: 5.9～6.1km/s; Owens and Zandt, 1997; Rodgers and

Schwartz，1997）显著低于全球大陆（6.45 ± 0.23km/s）和造山带地壳的平均值（6.39 ± 0.25km/s）（Christensen and Mooney，1995）则表明，不断吸纳幔源镁铁质物质的南部陆壳却变得比全球大陆和其他造山带成分更偏酸性（Guo Jingliang et al.，2019）。什么机制导致高原陆壳发生长英质化值得探究。

前人认为，大陆地壳发生长英质化主要有两种可能机制：① 榴辉岩相下地壳的拆沉（Kay and Kay，1993；Lee et al.，2015）和② 长英质地壳物质的俯冲回返或构造底侵（Hacker et al.，2011；Kelemen and Behn，2016；Ducea and Chapman，2018）。然而，有三个重要观察事实并不支持榴辉岩相下地壳拆沉机制。首先，碰撞带下地壳底部发育 14km 厚的高速层（V_p：7.2～7.5km/s，V_s：4.0km/s；Owens and Zandt，1997），向北大致延伸至拉萨地体中部。该高速层不管是榴辉岩化的镁铁质岩浆底侵体（Owens and Zandt，1997；Hou Zengqian et al.，2020），还是冷的榴辉岩化印度俯冲下地壳（Nelson et al.，1996；Kind et al.，2002），均反映碰撞以来的加厚下地壳都不曾发生拆沉；其次，在喜马拉雅东构造结附近剥露的新生下地壳，不仅发育晚三叠世弧根角闪石堆晶岩和角闪辉长岩(Xu Wei et al.，2019)，而且发育晚白垩世弧根变辉长岩和同碰撞期石榴石角闪岩(Zhang Zeming et al.，2020)，经历麻粒岩相变质，局部出现榴辉岩化。其稳定发育表明部分榴辉岩化的俯冲期新生下地壳不曾拆沉；第三，同样在高 Hf 域内(图 3)，中新世后碰撞埃达克质岩大量产出，也指示其源区的角闪榴辉岩或石榴石角闪岩原岩在 45～60km 深度稳定发育（Hou Zengqian et al.，2004a）。向北俯冲的印度大陆下地壳因前缘的新特提斯洋板片发生断离(Ji Weiqiang et al.，2016)，可能发生折返，产于特提斯喜马拉雅的同碰撞二云花岗岩(46～35Ma)记录了折返下地壳的熔融过程（Hou Zengqian et al.，2012）。然而，这些岩浆记录在拉萨地体及高原腹地并没出现。印度大陆岩石圈北向俯冲过程中或许会出现少量的长英质陆壳物质在亚洲大陆之下构造底侵，然而，最新的深反射地震探测资料揭示，印度大陆的长英质地壳几乎没有跨越雅鲁藏布江缝合带(Gao Rui et al.，2016)。地体规模的 Hf 同位素填图结果也没有显示印度与亚洲大陆间发生强烈的物质交换(图 3a,b)。

青藏高原碰撞带巨厚陆壳的长英质化，很可能与镁铁质新生下地壳的广泛重熔和长英质岩浆的大规模侵位有关。从俯冲到碰撞，幔源岩浆在地壳底部发生大规模底侵，并经历 MASH 过程（Hildreth and Moorbath，1988），演化的长英质岩浆大量注入中上部地壳，镁铁质—超镁铁质堆晶岩则堆积于地壳底部。特别是碰撞以来，镁铁质新生下地壳发生广泛重熔，产生了高 ε_{Nd}-高 ε_{Hf} 的同碰撞花岗岩和后碰撞埃达克质岩浆(Hou Zengqian et al.，2020)，沿冈底斯带大量侵位和喷发，导致了高原南部地壳长英质化，而熔融残余相或岩浆堆晶相则变质转为地幔或壳幔过渡层(Xu Wei et al.，2019)。这种转化，可能是青藏高原南部地壳平均纵波波速偏低的主要原因。此外，在晚(硬)碰撞期，不同地壳块体间因强烈挤压而发生逆冲叠覆和缩短加厚，中上地壳长英质和沉积物则因挤压和叠覆而向下进入深部地壳，由此导致碰撞带下地壳整体上以中性成分为主，SiO_2 平均含量为 57.1%(Zhang Zeming et al.，2020)。

5　巨厚地壳生长与加厚的深部过程

综上所述，青藏高原巨厚陆壳的形成主要与洋壳俯冲和大陆碰撞诱发的新生岩浆作用和机械挤压变形增厚相关。大陆碰撞前锋带的拉萨地体拥有元古宙变质结晶基底，暗示地壳初始厚度约为 30km。随着幔源弧岩浆的注入，拉萨地体地壳逐渐增生与加厚，其物质组成也随之演化。～200Ma(侏罗纪早期)在 MASH 带弧岩浆底垫形成的新生下地壳，主要由基性—超基性堆晶辉石角闪岩、堆晶角闪岩以及角闪辉长岩组成(Xu Wei et al.，2019)。弧岩浆结晶分异而成的中—酸性岩浆上侵至中-上地壳，形成大体积的花岗岩岩基，喷出地表形成长英质弧火山岩，使拉萨地体地壳增厚至～37km（图 7a；Xu Wei et al.，2019）。至 80Ma，随着岛弧岩浆的注入，拉萨地体地壳进一步垂向生长增厚至 50km（图 7a），成分也随之演化（Zheng Yuanchuan et al.，2014；Zhang Zeming et al.，2014，2020）。此时，拉萨地体新生下地壳发生明显变质，并主要由石榴石角闪岩和正片麻岩组成。石榴石角闪岩原岩以基性辉长岩为主，超基性辉石岩或角闪岩少许，正片麻岩原岩为中酸性的闪长岩和花岗岩（Zhang Zeming et al.，2014，2020）。相关地壳垂向生长与加厚主要集中在南北拉萨地体，中拉萨古老地壳的重熔则促进了中—下地壳成分的分异。类似的过程也发生于其他三个火山岩浆弧。由此可见，伴随特

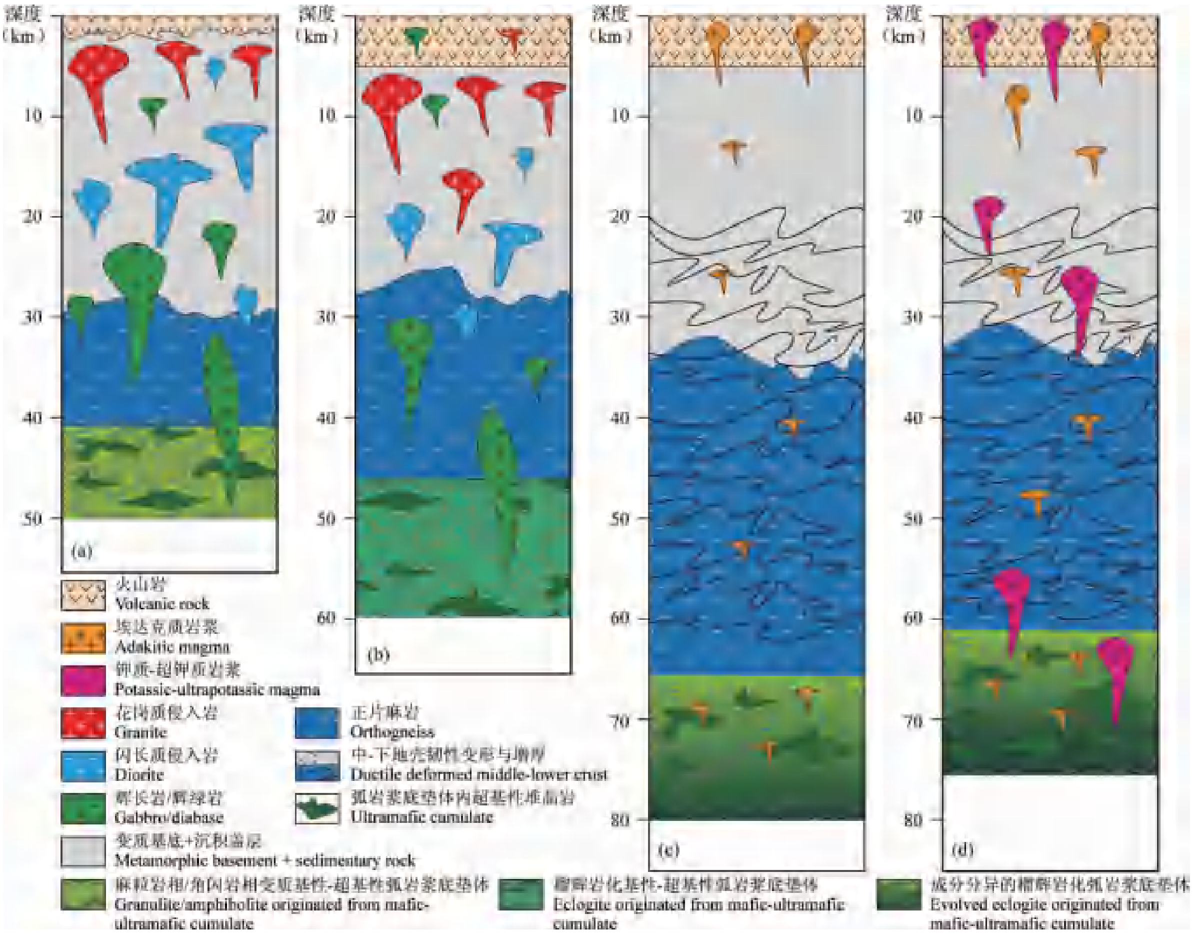

图 7 青藏高原南部巨厚地壳的物质组成与时间演变

Fig. 7 Compositional and temporal evolution of thickened crust underneath southern Tibet

(a)—碰撞前俯冲期地壳结构；(b)—同碰撞期地壳结构；(c)—晚碰撞期地壳结构；(d)—后碰撞期地壳结构

(a)—Crustal architecture of the Lhasa terrane piror to Indo-Aisia collision; (b)—during syn-collisional; (c)—late-collisional; (d)—post-collisional periods

提斯大洋消减闭合，一系列弧地体增生于亚洲大陆南缘，弧地壳发生 10km 量级的生长与加厚(图 8a)。

伴随印度-亚洲大陆对接碰撞(～65Ma)，印度大陆在洋壳板片拖拽下初始俯冲，处于俯冲前缘的特提斯洋壳板片发生回卷(Chung Sunlin et al.，2005)，并于 45±5Ma 最终断离(Ji Weiqiang et al.，2016)，诱发软流圈地幔大规模上涌，引发爆发式岩浆活动(Chung Sunlin et al.，2005；Niu Yaoling et al.，2017)。被俯冲板片流体交代的软流圈地幔最先熔融，产生林子宗火山岩系之镁铁质岩，持续上涌的亏损软流圈地幔熔融依次产生辉长岩和 OIB 玄武岩，高原南部地壳于此时期已增厚至约 60±5km (图 5)，其下地壳底部的基性—超基性堆晶岩可能已变质为榴辉岩(图 7b)。在青藏高原腹地，同碰撞岩浆作用的相对缺失以及逆冲褶皱系的大量发育，指示青藏高原北部地壳增厚以机械挤压变形为特征(图 8b)。

大洋板片断离引发印度大陆岩石圈俯冲板片回弹，导致俯冲角度变缓。印度大陆岩石圈俯冲前缘的板片撕裂(Hou Zengqian et al.，2006)，导致出现差异俯冲(Chen Yun et al.，2015)，西段俯冲角度较缓，印度下地壳可能少量进入南拉萨地体内部(Gao Rui et al.，2016)，东段俯冲角度较陡，下地壳向北俯冲止于拉萨地体南缘(Guo Xiaoyu et al.，2019)。尽管印度陆壳仅发生有限俯冲，但印度岩石圈地幔却以低角度长距离俯冲于青藏高原腹地之下(Owens and Zandt，1997；Tilmann et al.，2003；Wang Zewei et al.，2019)，并诱发亚洲大陆的软流圈大规模上涌，形成以大型低速体为标志的地幔通道流(Hou Zengqian et al.，2020)。于晚碰撞期，软流圈上涌体热蚀并吞噬地幔岩石圈，并诱发富集

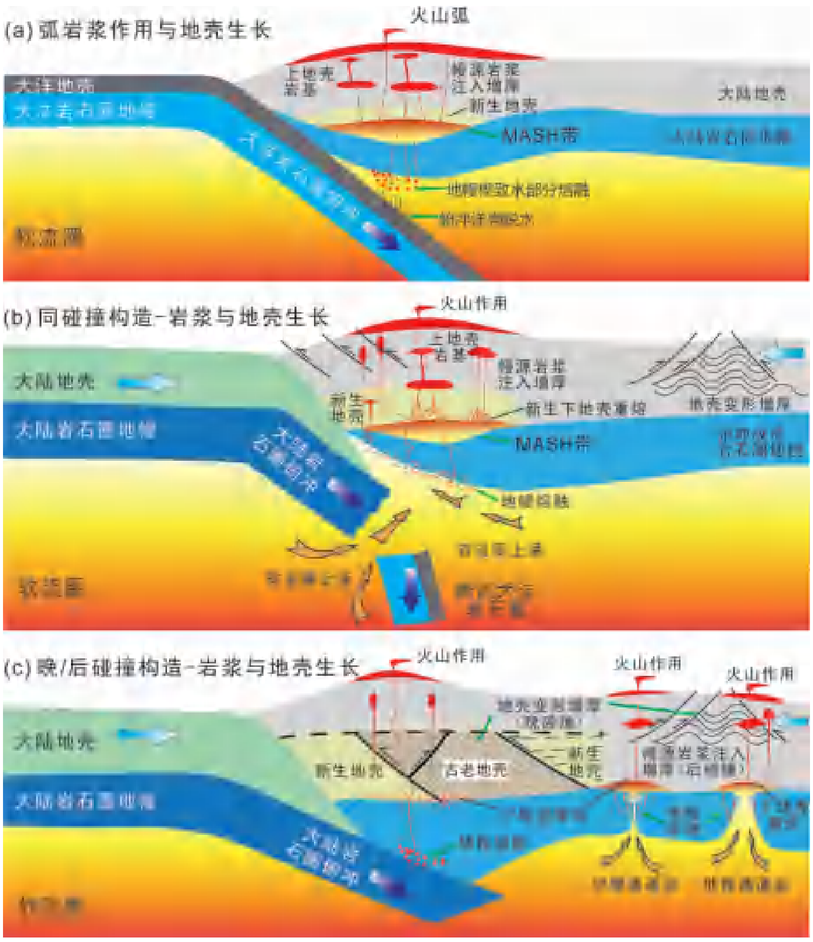

图 8　青藏高原新生地壳形成与深部过程示意图

Fig. 8　Cartoon cross sections illustrating the formation of juvenile crust and relevant deep dynamic processes in the Himalayan-Tibetan orogen

的岩石圈地幔部分熔融，产生大量超钾质煌斑岩和镁铁质岩浆(40～30Ma；图 2b)，侵位于高原腹地，导致后陆区地壳生长。广泛发育的中新世—渐新世埃达克质岩暗示，在高原腹地下地壳已发生榴辉岩化，且地壳整体增厚至 50km 以上。

在后陆区发育地幔通道流的同时，高原南部碰撞带在晚碰撞期则发生地壳缩短加厚(图 7c)。拉萨地体上地壳发生有限程度的构造变形，而深部地壳则发生块体间的逆冲叠覆(图 8c)，进而导致地壳由同碰撞期的 60±5km 快速加厚至晚碰撞期的 80±5km (Guan Qi et al.，2012)，暗示下地壳榴辉岩化进一步增强。小体量的下地壳源埃达克质岩指示了拉萨地体下地壳长英质成分的抽离，残余下地壳则变得更基性，但地壳总体成分未发生明显变化。

进入后碰撞时期，隆升的青藏高原自 20Ma 开始发生东西向地壳伸展，跨越碰撞造山带形成 NS 向正断层系统或裂谷带，为幔源镁铁质超钾质岩浆运移并注入地壳提供了上升通道。中新世钾质—超钾质岩的发育指示拉萨地体仍有一定量的地壳增生，但规模应明显弱于俯冲和同碰撞期。来自榴辉岩化下地壳的中新世埃达克质岩指示拉萨地体地壳成分进一步变异，即镁铁质下地壳因岩浆抽取而变得更为基性，甚至变为上地幔组成部分，而中上地壳成分则因酸性岩浆注入而更加长英质化(图 7d)。与晚碰撞期相比，后碰撞期埃达克质岩浆的$(La/Yb)_n$比值有所降低，暗示拉萨地体地壳在后碰撞阶段停止增厚甚至有所减薄(图 5)。在高原东南部，岩石圈—软流圈过渡带的地幔交代岩部分熔融产生洋岛型玄武岩浆(Zheng Yongfei，2019)，注入上地壳。该阶段地壳伸展和构造剥蚀可能超越新生地壳生长，并导致了地壳有所减薄。

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Growth, thickening and evolution of the thickened crust of the Tibet Plateau

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Abstract

The continental crust covers 40% of the Earth's surface area, and its genesis and growth is fundamental to maintain life and supply resources to our society. Growth of the continental crust is commonly ascribed to tectonic accretion of island arc and underplating of mantle-derived magmas, but lacks in the period of continental collision. The Tibet Plateau has the thickest crust on Earth, and thus it is the most outstanding natural laboratory for studying formation, growth, thickening, evolution and preservation of the continental crust. Together with the published data, we found that the emplacement and underplating of the mantle-derived mafic magmas (270～66 Ma) induced by subduction of the Paleo- and Neo-Tethys oceanic slab resulted in horizontal accretion and vertical growth of the continental crust and contributed to 10 km of crustal thickening. In the period of syn-collisional stage (65～41 Ma), Paleocene-Eocene mantle-derived magmatisms were triggered by rollback and breakoff of the subducted Neo-Tethyan oceanic slab during Indo-Asian collision, which resulted in the formation of juvenile crust and 6～9 km vertical growth of continental crust in the Gangdese belt. In the period of late-collisional stage (40～26 Ma), 10～20 km of crustal thickening can be attributed to tectonic thickening due to intracontinental thrusting, while partial melting of lithospheric mantle induced by upwelling of asthenosphere along the mantle-flow channel produces basaltic rocks and lamprophyres which emplaced in the hinterland of the Tibet Plateau. In the post-collisional stage (25～0 Ma), crustal extension has contributed little to crustal thinning both in the collisional front and in the hinterland, accompanying with emplacement of small-volume juvenile mantle-derived magmas and strong denudation. Our results indicate that the proportion of juvenile crust generated and preserved in collisional orogens exceeds 28% of the whole crust in the Tibet Plateau, while 75% and 25% of these juvenile crustal materials were associated with oceanic subduction and continental collision, respectively. We propose that the formation of the thickest crust on Earth can be attributed to both addition of mantle-derived magmas into the crust and tectonic shortening of the middle-lower crust. Thus, formation of the thickened Tibet crust is characterized by growth of juvenile crust and reworking of ancient crust. The thickened Tibet continental crust has an andesitic bulk composition, which could be mainly resulted from intensive remelting of mafic juvenile lower crust and volumious emplacement of felsic magmas.

Key words: oceanic subduction; continental collision; magma underplating; intracontinental thrusting; crustal thickening