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拉萨地体东南部整体地壳成分及其成因分析

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摘 要: 造山带地壳结构和成分的基本特征对于认识大陆地壳成分演化和区域成矿背景具有重要意义.综合青藏高原拉萨地体东南部地球物理、高温高压岩石物性和岩浆岩地球化学资料,分析该地区地壳整体成分特征,并探讨其可能成因.该地区平均地壳波速显著低于全球大陆和造山带地壳的平均值,表明地壳整体具有中酸性成分,下地壳特征也可由中性岩石(残余体性质的中性含石榴石麻粒岩)解释.拉萨地体东南部整体地壳成分特征应与多阶段长英质化有关,包括碰撞前大陆弧演化阶段(以堆晶或残余体下地壳拆沉为主)和碰撞后高原垮塌阶段(以加厚下地壳拆沉为主,伴随印度古老长英质陆壳物质的俯冲回返/构造底侵).拉萨地体是研究大陆地壳成分演化的绝佳区域,亟待进一步开展多学科综合研究.

关键词: 大陆地壳;成分演化;拆沉;Nd同位素;冈底斯;青藏高原;岩石学.

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The Bulk Crustal Composition of the Southeastern Lhasa Terrane and Its Origin

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Abstract: The structure and composition of orogenic belts are important for understanding the chemical evolution of the continental crust and the background for metallogenesis. This study integrates previously published crustal seismic structures, experimentally determined petrophysical properties of various rock types, and geochemical data of magmatic rocks from the southeastern Lhasa Terrane, in order to discuss the compositional features of the continental crust in this region and their possible causes. The average crustal seismic velocity in this region is lower than the average values of global continental crust and orogenic belts, suggesting a more felsic composition for the bulk continental crust. Moreover, the lower crust could also be composed of intermediate rocks (restitic intermediate garnet granulite). The felsic bulk crustal composition of the southeastern Lhasa terrane is supposed to be related to multiple episodes of felsification, including the pre-collisional continental arc evolution stage (mainly by delamination of cumulate or restitic lower crust) and the post-collisional plateau collapsing stage (mainly by delamination of thickened lower crust, which is accompanied by the relamination/tectonic underthrusting of felsic materials from the ancient Indian continental crust). The Lhasa terrane is one of the best places to study the chemical differentiation of continental crust, which demands further comprehensive studies of multiple disciplines.

Key words: continental crust; chemical differentiation; foundering; Nd isotopes; Gangdese; Tibetan Plateau; petrology.

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0 引言

大陆地壳约占地表面积的40%,具有低密度(~2.7 g/cm^3)和较为演化的中性成分(SiO_2=57%~63%).相比之下,以大洋地壳为代表的幔源新生地壳则具有高密度(~3.0 g/cm^3)和镁铁质成分特征(SiO_2=50.1%).这种大陆地壳与新生地壳之间的成分差别构成了大陆地壳成分之谜,是现代地球科学研究的主要问题之一.为此,前人提出多种模型以解释大陆地壳的中性成分特征,包括(1)榴辉岩相下地壳的拆沉(foundering)(Kay and Kay,1993;Rudnick,1995;Saleeby *et al.*,2003;Gao *et al.*,2004;Jagoutz and Schmidt,2012);(2)俯冲长英质物质的回返(relamination)(Hacker *et al.*,2011)或构造底侵(tectonic underplating)(Ducea and Chapman,2018);(3)幔源安山质初始弧岩浆的形成(Kushiro *et al.*,1968;Grove *et al.*,2002;Mitchell and Grove,2015).榴辉岩相下地壳拆沉可以发生在多种构造环境,如岩浆弧(Kay and Kay,1993;Jagoutz and Schmidt,2012;Ducea *et al.*,2015)和大陆造山带(Meissner and Mooney,1998)底部.在岩浆弧地区,大通量的俯冲带岩浆作用可以在地壳底部快速形成堆晶残余体性质成因的致密下地壳(代表岩性为石榴辉石岩)(Saleeby *et al.*,2003;Jagoutz and Schmidt,2012;Ducea *et al.*,2015).石榴单斜辉石岩常具有堆晶成因,形成条件达到榴辉岩相,又被称为arclogite,以区别于榴辉岩(Lee and Andersen,2015).在造山带地区,加厚基性下地壳可以发生榴辉岩化,形成榴辉岩(Kay and Kay,1993).Arclogite和榴辉岩的密度(~3.5 g/cm^3)高于地幔橄榄岩(~3.3 g/cm^3),此类岩石组成的下地壳可发生拆沉再循环进入地幔,残留地壳将具有更加演化的长英质成分(Rudnick and Gao,2003;Jagoutz and Behn,2013;Lee and Andersen,2015).俯冲长英质物质回返模型则强调俯冲洋壳携带的少量长英质物质(如各种沉积物和中酸性岩浆岩等).在俯冲后变质为低密度的长英质片麻岩,可回返至俯冲带上盘地壳的底部(Hacker *et al.*,2011).虽然回返作用在近年来得到一些俯冲带数值模拟研究的支持(Kelemen and Behn,2016;Maierová *et al.*,2018),但直接地质证据仍比较缺乏;相比之下,更多野外地质现象反映俯冲带长英质物质可通过逆冲断层构造底侵于岩浆弧下地壳(Ducea and Chapman,2018).幔源安山质初始弧岩浆模型认为含水条件下地幔岩石低比例熔融可形成安山质初始岩浆(Kushiro *et al.*,1968;Grove *et al.*,2002;Mitchell and Grove,2015),但地幔低比例熔融生成的熔体有限,无法解释岩浆弧地区观察到的阶段性高通量岩浆,而且出露于地表的岩浆弧下地壳剖面表明下地壳底部以基性-超基性岩石为主,并无大量中性岩浆存在(Jagoutz and Behn,2013;Chapman *et al.*,2014).因此,大陆地壳的长英质化机制可能主要包括致密榴辉岩相下地壳的拆沉和长英质物质的俯冲回返/构造底侵.

大陆地壳的长英质化可以发生在与洋壳俯冲有关的大陆弧造山阶段(南美安第斯造山带中段的Altiplano-Puna高原)(Kay and Kay,1993;DeCelles *et al.*,2009;Jagoutz and Behn,2013;Ducea *et al.*,2015;Kelemen and Behn,2016)或者大陆碰撞造山阶段(青藏高原南部的拉萨地体)(Harrison *et al.*,1992;Meissner and Mooney,1998;Chung *et al.*,2003).南美安第斯造山带中段的Altiplano-Puna高原和我国西南部的青藏高原分别为全球代表性的大陆弧和大陆碰撞造山带.安第斯中段地区作为仍在活跃的大陆弧,其地壳长英质化主要通过弧后盆地地区榴辉岩相下地壳和岩石圈地幔的拆沉作用实现(Beck and Zandt,2002;Ward *et al.*,2016).青藏高原南部地区在中新世发生了大规模抬升和伸展,也被认为与岩石圈根的拆沉有关(Harrison *et al.*,1992;Meissner and Mooney,1998;Chung *et al.*,2003).两个地区的地壳平均波速和泊松比都低于全球造山带地壳和大陆地壳的平均值(Owens and Zandt,1997;Beck and Zandt,2002),表明这些地区的地壳都经历了长英质化过程.青藏高原南部地区不仅是新生代大陆碰撞造山带,在中生代还经历了新特提斯洋长期的俯冲作用,形成的冈底斯大陆弧东西延伸近两千公里,可与安第斯大陆弧类比(Zhu *et al.*,2011;Pan *et al.*,2012;Ding *et al.*,2014).相比于安第斯大陆弧,青藏高原南部大陆地壳可能经历了不同构造背景下的长英质化,目前有关这方面的探讨还非常有限.

本文尝试基于青藏高原拉萨地体东南部已有的地球物理、地质和岩浆岩地球化学资料,结合前人岩石物性实验测定和数值计算结果,分析该地区下地壳成分及地壳长英质化可能发生的阶段.结果显示该地区不仅整体地壳较全球平均大陆地壳更加演化,而且下地壳也存在由中性石榴石麻粒岩

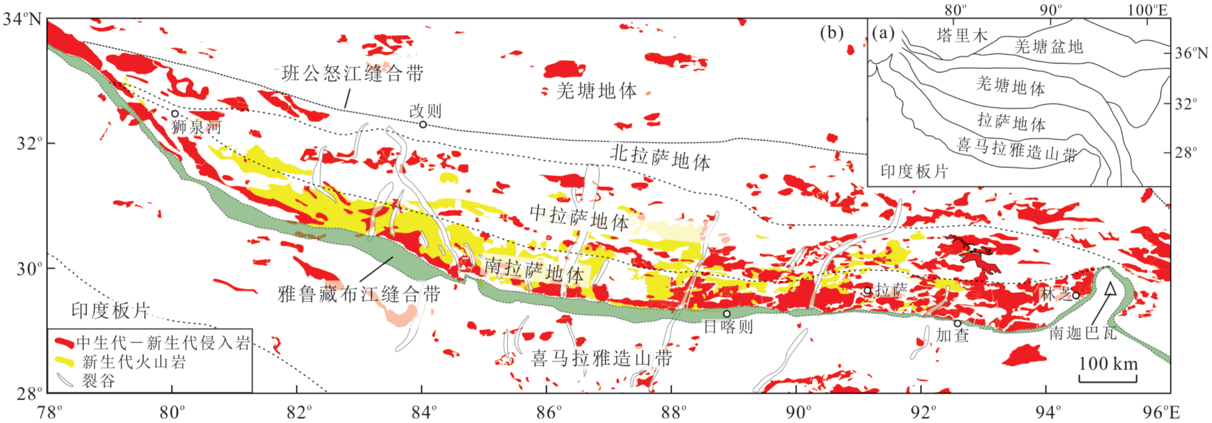

图1　青藏高原拉萨地体岩浆岩分布

Fig.1　Distribution of magmatic rocks in the Lhasa terrane, southern Tibet.

a.青藏高原地质体划分;b.拉萨地体分区和岩浆岩分布;b图改自潘桂棠等(2004),Zhu *et al*.(2011)

(闪长质、残余体性质)组成的可能.该地区地壳成分的长英质化应发生于多个阶段,榴辉岩相下地壳的拆沉与长英质陆壳的俯冲回返/构造底侵可能都扮演了重要角色.

1　地质背景

青藏高原由南向北可划分为喜马拉雅造山带、拉萨地体和羌塘地体(图1a).其中拉萨地体东西延伸约2 000 km,南北分别以雅鲁藏布江缝合带和班公怒江缝合带为界与喜马拉雅造山带和羌塘地块隔开.拉萨地体中生代和新生代的岩浆岩构成了一条东西向展布的岩浆岩带,又被称为冈底斯岩浆带.该岩浆带在中生代为安第斯型大陆弧,与新特提斯大洋岩石圈的北向俯冲有关;新生代转变为印度—欧亚板块拼合形成的大陆碰撞型造山带.以沙莫勒—麦拉—洛巴堆—米拉山断裂和狮泉河—永珠—纳木错—嘉黎蛇绿混杂岩带为界,由北向南可以将拉萨地体进一步划分为北拉萨地体、中拉萨地体和南拉萨地体(Zhu *et al*.,2011)(图1).Zhu *et al*.(2011)在拉萨地体选取了4条南北向剖面,剖面岩浆岩锆石Hf同位素的系统变化反映出中拉萨地体具有古老的前寒武纪基底,而南北两侧以拼贴的新生岩浆弧地壳为主.北拉萨地体地表岩石主要由侏罗系—白垩系火山沉积地层和相关侵入岩组成,在安多一带存在前寒武纪结晶基底(Guynn *et al*.,2012).中拉萨地体地表岩石主要包括古生代—中生代沉积岩、火山岩及相关侵入岩,在申扎和措勤等地出露少量古生界地层,念青唐古拉一带还出露有新元古代变质岩系.南拉萨地体主要由白垩纪—古近纪冈底斯岩基、古新世—始新世林子宗火山岩以及部分侏罗系—白垩系沉积地层构成(朱弟成等,2009).拉萨地体出露有大量碰撞前、同碰撞和碰撞后岩浆岩,它们同位素组成的空间分布特征可以有效揭示不同块体的边界、岩石圈性质及其对不同类型矿床的控制作用(Zhu *et al*.,2011;Hou *et al*.,2015;Chapman *et al*.,2017),随时间的变化特征则反映印度陆壳深俯冲对拉萨地体构造—岩浆过程的影响(Chu *et al*.,2011).

2　拉萨地体东南部地壳波速结构和成分

2.1　地壳波速结构

前人在青藏高原南部开展了大量的地球物理研究(Zhang *et al*.,2011),如早期的中法、中美合作项目,INDEPTH、GEDEPTH和HICLIMB等项目.INDEPTH II和GEDEPTH剖面主要位于东经88°至92°的拉萨地体中东段,剖面南部的平均地壳纵波波速(Vp)为5.9~6.1 km/s(Owens and Zandt,1997;Rodgers and Schwartz,1997),显著低于全球大陆和造山带地壳的平均值(分别为6.45±0.23 km/s和6.39±0.25 km/s)(Christensen and Mooney,1995);南部地壳泊松比为0.25±0.02,向北逐渐升高(Owens and Zandt,1997;Rodgers and Schwartz,1997;Kind *et al*.,2002).下地壳底部存在高速层(Owens and Zandt,1997)(图2),向北大致延伸至拉萨地体中部(或班公怒江缝合带),通常被解释为冷的俯冲印度陆壳(Nelson *et al*.,1996;Yuan *et al*.,1997;Kind *et al*.,2002).但现有研究对该层波

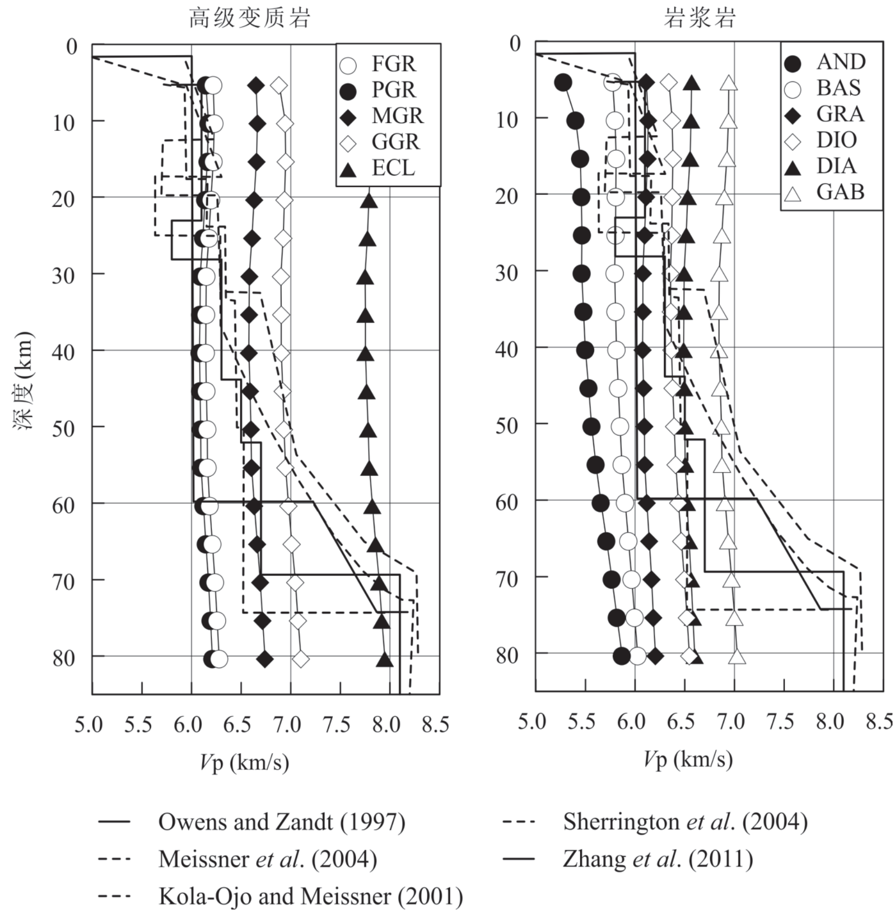

图2 拉萨地体南部地壳波速结构与常见高级变质岩和岩浆岩纵波波速(Vp)对比

Fig.2 Comparison between the crustal velocity structure of South Lhasa terrane and compressional wave velocities (Vp) of typical high-grade metamorphic and igneous rocks

岩石物性资料来自 Christensen and Mooney(1995),根据地温梯度模型(Hetényi *et al.*,2007)对应的温压条件对波速进行了校正.FGR.长英质麻粒岩,PGR.变沉积岩麻粒岩,MGR.基性麻粒岩,GGR.石榴石麻粒岩,ECL.榴辉岩,AND.安山岩,BAS.玄武岩,GRA.花岗岩,DIO.闪长岩,DIA.辉绿岩,GAB.辉长岩

速特征的约束存在很大不确定性,例如Owens and Zandt(1997)认为该高速层波速达7.2~7.5 km/s;Sherrington *et al.*(2004)在研究同地区地壳波速各向异性时,使用的下地壳波速模型速度为6.5~6.8 km/s;Zhang *et al.*(2011)在总结相邻地区下地壳波速时给出的下地壳波速也接近6.8 km/s.因此本文对下地壳底部的波速分两种情况(6.5~6.8 km/s和7.2~7.5 km/s)讨论.该地区地壳横波波速(Vs)结构(Nelson *et al.*,1996;Yuan *et al.*,1997)与Vp结构相似,显示上地壳整体具有高波速特征(3.4~3.6 km/s),与地表广泛出露冈底斯岩基一致;中地壳15~30 km深度存在低速层(<3.5 km/s),与少量熔/流体的存在有关;下地壳底部则存在高速层(~4.0 km/s).

2.2 地壳整体成分对波速和泊松比的影响

拉萨地体东南部整体地壳所具有的低波速和低泊松比可能与多种因素有关,包括壳内部分熔融、地温梯度、地壳岩石成分和变质级别等(Christensen and Mooney,1995).

地壳部分熔融可以导致地震波速的降低,但Vs比Vp衰减得更快.因此随着熔体比例增加,地壳泊松比将明显升高(例如拉萨地体北部、羌塘地体南部和松潘—甘孜地体)(Nelson *et al.*,1996).拉萨地体南部虽然存在中地壳低速层,但整体地壳的低泊松比特征(σ=0.25±0.02)并不支持壳内大规模熔流体的存在(Kind *et al.*,2002;Nábelek *et al.*,2009).

地温梯度对地壳岩石的波速也存在显著影响.常见岩石类型在相同压力下温度每升高100 ℃,Vp降低约0.039~0.057 km / s (Christensen and

Mooney，1995）. 拉萨地体东南部地壳波速（5.9～6.1 km/s）比全球大陆平均值（6.45±0.23 km/s）低 0.35～0.55 km/s，这无法简单归因于区域高地温梯度 . 现今拉萨地体局部地区具有高地表热流值（Francheteau *et al.*，1984），但区域内无火山活动，且壳内不存在广泛熔融，上地幔顶部的高纵波速度（*Pn* 值）反映上地幔具有低温特征（Rodgers and Schwartz，1997），并不支持该地区存在极高的地温梯度 .

因此，拉萨地体东南部地壳整体的低波速特征通常被认为与地壳成分更加长英质有关（Owens and Zandt，1997）. 但对该地区下地壳成分的认识仍非常不足，现有岩石物性实验资料用于解释青藏高原深部地壳岩石类型和成分时存在明显缺陷 . 原因在于物性实验主要针对正常厚度地壳的温压条件，而青藏高原具有巨厚地壳，中下地壳岩石的温压条件和矿物组合与物性实验中的存在明显差别 . 例如物性实验研究中使用的中酸性岩石大多不含石榴石且不具有残余体性质（未经历部分熔融熔体的提取）（图 2），而拉萨地体南缘桑桑－萨嘎地区中新世火山岩中携带的长英质捕掳体多为变沉积岩或具有残余体性质的中酸性麻粒岩，且都含有石榴石（Chan *et al.*，2009；Wang *et al.*，2016）. 石榴石的出现可以导致岩石波速升高（Wang，2005；Wang *et al.*，2005；Kono *et al.*，2009），熔体的提取应具有相似效果 . 目前尚不清楚拉萨地体南部下地壳是否可以由此类残余体性质的中酸性含石榴石麻粒岩组成 .

2.3　拉萨地体东南部下地壳高速层的组成

拉萨地体东南部地壳底部存在厚约 15 km 的壳内双反射层，向北大致延伸至地体中部（Kind *et al.*，2002）. 根据多种手段综合估计该层密度为 3.20～3.30 g/cm^3（Hetényi *et al.*，2007）或 3.15～3.20 g/cm^3（Bai *et al.*，2013），*Vp* 分两种情况：6.5～6.8 km/s（Sherrington *et al.*，2004；Zhang *et al.*，2011）和 7.2～7.5 km/s（Owens and Zandt，1997）. 6.5～6.8 km/s 的波速范围显著低于含石榴石基性岩石（如石榴石麻粒岩和榴辉岩）的波速，只能由不含石榴石的中性或基性岩石来解释（图 2）. 但此类不含石榴石的岩石密度小于 3.1 g/cm^3（Christensen and Mooney，1995），低于拉萨地体东南部下地壳密度估计值，也不符合拉萨地体下地壳普遍存在石榴石的特征（Chan *et al.*，2009；Zhang *et al.*，2014；Wang *et al.*，2016）. 因此，现有实验岩石物性资料并不能很好解释这样高密度、低波速的下地壳特征，可能与该波速估计值低于下地壳实际波速有关 .

下地壳高速层 *Vp* 范围的另一种可能为 7.2～7.5 km/s，高于中性岩浆岩或麻粒岩等变质岩在相同温压条件下的波速特征，需要用富石榴石或辉石的基性－超基性岩石类型（如榴辉岩、辉石岩和石榴石麻粒岩等）来解释（Christensen and Mooney，1995；Hacker *et al.*，2015）. 现有研究也通常将拉萨下地壳高速层解释为部分榴辉岩化的俯冲印度下地壳（Nábelek *et al.*，2009）. 基于对大陆地壳成分结构的认识（Rudnick and Gao，2003），通常认为青藏高原南部下地壳 SiO_2 含量为 53%～54%（如 Hetényi *et al.*，2007）. 不过 Hacker *et al.*（2015）总结全球大陆下地壳的波速和热流特征时发现下地壳通常只含有 10%～20% 基性岩，古生代－中生代造山带下地壳含基性岩比例更低，整体地壳成分可能更加酸性 . Zhang *et al.*（2014）报道了拉萨地体东南部里龙地区晚白垩世辉长闪长质下地壳剖面，该剖面代表的下地壳整体也具有中性成分（SiO_2=57.0%）. 拉萨地体南缘桑桑－萨嘎地区中新世火山岩下地壳捕掳体也以英云闪长质麻粒岩为主（SiO_2=56%～66%），基性－超基性（SiO_2＜52%）岩石类型并不多见（Chan *et al.*，2009；Wang *et al.*，2016）.

那么经历高压变质和/或部分熔融熔体提取后的中性岩石是否可以解释类似拉萨地体下地壳的高波速和高密度特征？Patiño Douce（2004）对含 60.76% 的 SiO_2 和 2.65% 的 MgO 英云闪长岩开展了无水熔融实验，在 15～21 kbar、940～1 025 ℃条件下经过 10%～30% 熔体提取后的石榴石麻粒岩相残余体（SiO_2=56%～60%）密度可以升高至 3.05～3.29 g/cm^3. 笔者利用 Abers and Hacker（2016）的方法计算得到残余体的密度为 3.04～3.26 g/cm^3，与前人结果一致，波速为 6.84～7.42 km/s（15～20 kbar 和 800 ℃条件下）. 这些中性石榴石麻粒岩相残余体与岩石物性实验中常用的闪长岩明显不同，其密度和波速高于闪长岩外推至相同温压条件下的范围（图 2），更加接近拉萨地体下地壳底部高速层的特征 . 这意味着拉萨地体东南部下地壳岩石类型存在中性含石榴石麻粒岩的可能 . 这类岩石在具有高波速的同时，密度（3.0～3.3 g/cm^3）比榴辉岩（＞3.4 g/cm^3）更低，更接近前人研究所得出的拉萨地体下地壳密度结构（Hetényi et al.，2007；Bai *et al.*，2013）.

通常认为拉萨地体南部下地壳只发生了部分榴辉岩化(Nábelek *et al.*,2009),与下地壳高温(导致麻粒岩相变质)或缺水(抑制榴辉岩相变质)有关(Henry *et al.*, 1997).热力学相图模拟结果(De Paoli *et al.*,2012)表明中性的闪长岩发生完全榴辉岩化变质(石榴石－绿辉石)需要的压力大于1.95 GPa(显著高于基性岩),对应深度71~74 km(假定地壳平均密度为2.7~2.8 g/cm³),接近现今拉萨地体地壳底部.因此我们推测中性的下地壳成分可能也是阻碍拉萨地体下地壳发生完全榴辉岩化的原因之一.

综合以上分析,笔者认为拉萨地体东南部整体地壳的低 Vp、低 Vs 和低泊松比反映地壳整体具有高度演化的长英质成分,甚至下地壳高速层也可用残余体性质的中性含石榴石麻粒岩解释.

3 碰撞后岩浆岩对深部地壳岩石组成和化学成分演化的制约

大陆深部地壳的成分除了可以通过地球物理资料约束,还可以利用岩浆岩地球化学进行制约.拉萨地体出露有大量碰撞后岩浆岩,东部地区以高Sr/Y花岗岩类为主,还有少量钾质岩石和具有混合特征的岩浆岩;西部以钾质－超钾质岩石为主(Chung *et al.*,2005;Wang *et al.*,2018).这些中酸性岩石的Nd同位素组成($\varepsilon_{Nd}(t)$)、Eu异常($Eu/Eu^*=Eu_N/(Sm_N\times Gd_N)^{0.5}$)和Cr含量表现出较好的相关性,指示后碰撞岩浆岩有多种岩浆来源(图3):(1)受俯冲印度陆壳物质影响的拉萨地体岩石圈地幔(熔体低$\varepsilon_{Nd}(t)$、高Cr、负Eu异常,以中拉萨地体超钾质岩为代表);(2)古老长英质地壳(熔体低$\varepsilon_{Nd}(t)$、低Cr、负Eu异常,以拉萨地体部分钾质岩为代表,特征接近喜马拉雅淡色花岗岩);(3)新生下地壳及软流圈地幔(熔体高$\varepsilon_{Nd}(t)$、Cr变化范围大、弱Eu异常).

岩浆端元1具有高Cr、及Ni和MgO,表明源自地幔,同时高度富集的不相容元素和亏损的高场强元素,反映源区受到过俯冲印度陆壳物质的强烈交代(Zhao *et al.*,2009).该端元还具有强烈的负Eu异常特征(图3a和3c),异于克拉通型岩石圈地幔典型熔体(金伯利岩和钾镁煌斑岩),后者虽富集不相容元素,但无Eu异常且通常不亏损高场强元素(Becker and Le Roex,2006).碰撞后岩浆岩的Cr与$\varepsilon_{Nd}(t)$以及Eu/Eu^*的变化关系(图3b和3c)显示,Cr含量最高的样品具有更低的$\varepsilon_{Nd}(t)$和强烈的负Eu异常特征,指示这两种特征应继承于交代地幔源区,而非岩浆后期壳内演化过程(如结晶分异或地壳物质同化混染).低$\varepsilon_{Nd}(t)$和负Eu异常特征为古老大陆上地壳典型特征(Rudnick and Gao,2003),最可能的来源就是俯冲的古老印度陆壳或其沉积物产生的熔流体,类似印度陆壳熔融形成的喜马拉雅淡色花岗岩(Chung *et al.*, 2005; 丁林等, 2006; Zhao *et al.*, 2009)(图3).

岩浆端元2具有低$\varepsilon_{Nd}(t)$、低Cr和强烈负Eu异常的特征,以喜马拉雅造山带淡色花岗岩为代表,反映长英质古老地壳熔融.虽然拉萨地体中部和东南部的局部地区(如林芝－米林、加查－朗县和桑日－白堆地区;Ji *et al.*,2012;Ma *et al.*,2013;Dong *et al.*,2014)保留有古生代以前的基底,但拉萨地体碰撞后岩浆岩中低$\varepsilon_{Nd}(t)$样品的Cr含量大体上随$\varepsilon_{Nd}(t)$降低而升高,偏离了喜马拉雅造山带淡色花岗岩所代表的岩浆端元2,其趋势指向岩浆端元1(交代岩石圈地幔熔体)(图3).这种特征表明拉萨地体东南部低$\varepsilon_{Nd}(t)$岩浆岩并非由长英质古老基底直接熔融形成,而是含有来自受俯冲印度陆壳物质交代的拉萨岩石圈地幔熔体,不过并不能排除拉萨基底物质的贡献.

岩浆端元3具有高$\varepsilon_{Nd}(t)$特征,Eu异常和Cr含量情况更接近碰撞前和同碰撞阶段岩浆岩的特征,部分样品具有高Cr特征,表明该端元主要来自冈底斯下地壳的部分熔融,并伴有软流圈地幔物质的加入.整体而言,样品Eu/Eu^*和Cr含量随着$\varepsilon_{Nd}(t)$值的降低而下降(图3),降低趋势指向低$\varepsilon_{Nd}(t)$高Cr的交代岩石圈地幔熔体(即岩浆端元1),反映东部碰撞后岩浆岩存在下地壳熔体和交代岩石圈地幔熔体的混合(Yang *et al.*,2015).该高$\varepsilon_{Nd}(t)$岩浆端元以拉萨地体东部的高Sr/Y岩浆岩为代表,其埃达克质特征进一步反映岩浆源区为富石榴石的加厚下地壳(Hou *et al.*, 2004; Chung *et al.*, 2005; Guo *et al.*, 2007;Zhu *et al.*,2017).通常认为该类下地壳由榴辉岩或石榴斜长角闪岩组成,不过大陆下地壳物质(53% SiO_2)含水熔融实验表明,残余体(角闪岩或石榴石麻粒岩,矿物组合为角闪石±石榴石±单斜辉石±斜长石)中斜长石含量少于20%时,熔体就可以出现Sr的富集和其他埃达克质特征(Qian and Hermann,2013).碰撞后岩浆岩普遍具有不同程度的负Eu异常(图3),即使Nd同位素最亏损的样品

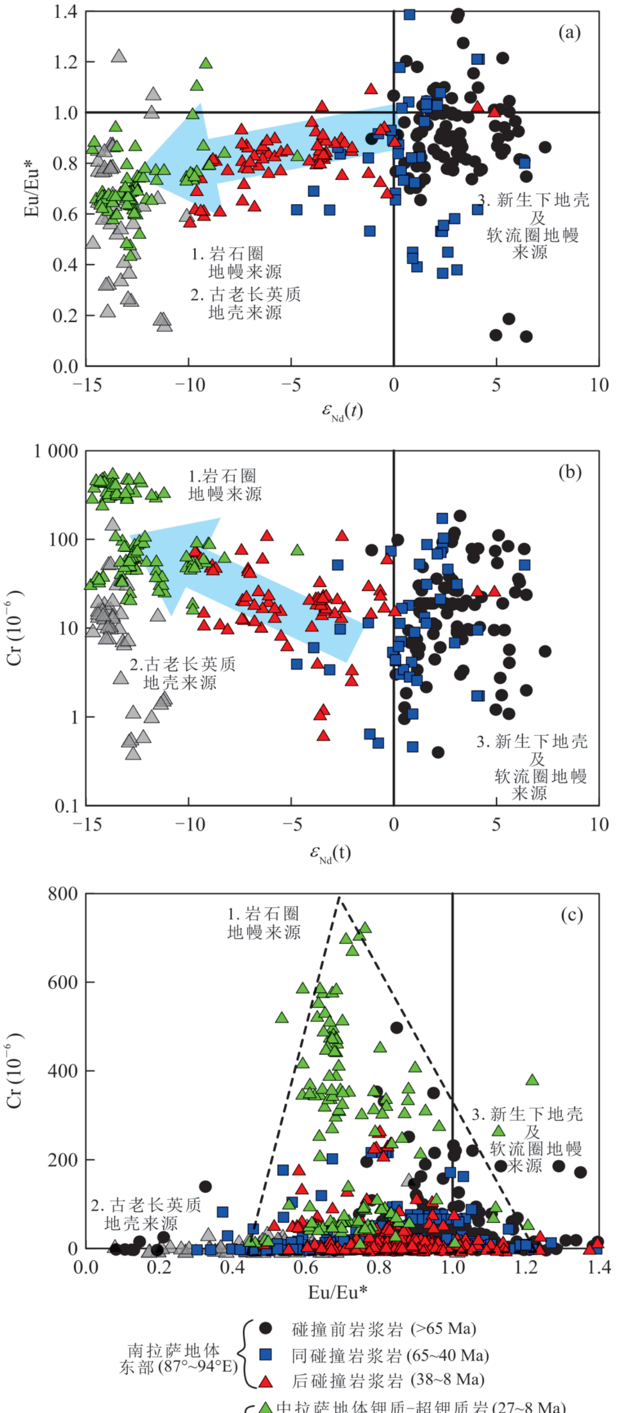

图3　拉萨地体东南部 SiO_2＞52％岩浆岩Nd同位素组成、Eu异常和Cr含量的协变图

Fig.3　$\varepsilon_{Nd}(t)$ vs. Eu/Eu*, $\varepsilon_{Nd}(t)$ vs. Cr, and Cr vs. Eu/Eu* of magmatic rocks with SiO_2＞52％ in the southeastern Lhasa terrane

数据来源以青藏高原岩浆岩数据库(Chapman and Kapp，2017)为主．$Eu/Eu^*=Eu_N/(Sm_N\times Gd_N)^{0.5}$，N代表球粒陨石值均一化，数值来源于McDonough and Sun(1995)

(如东冈底斯米林卧龙镇38 Ma埃达克质花岗岩；Guan *et al.*，2012)也大多具有负Eu异常，表明其源区可能仍存在长石．结合碰撞后岩浆岩的高Sr/Y和La_N/Yb_N特征，表明拉萨地体东南部的加厚下地壳很可能同时含有斜长石和石榴石，并未发生完全的榴辉岩化，与前文推测的深部地壳主要岩石类型可能为中性石榴石麻粒岩残余体并不矛盾．

因此拉萨地体碰撞后岩浆岩的$\varepsilon_{Nd}(t)$、Eu异常和Cr含量的整体特征(图3)可由多个岩浆端元之间的混合来解释，低$\varepsilon_{Nd}(t)$高Cr岩浆端元来自古老陆壳物质交代后的岩石圈地幔低比例熔融，低$\varepsilon_{Nd}(t)$低Cr岩浆端元主要来自古老长英质陆壳，高$\varepsilon_{Nd}(t)$岩浆端元主要为冈底斯加厚下地壳及软流圈地幔．该模型对于拉萨地体南部深部地壳岩石组成和化学成分演化具有启示意义．高$\varepsilon_{Nd}(t)$岩浆端元3普遍具有负Eu异常(图3a)和部分埃达克质特征，表明下地壳源区含石榴石的同时可能仍有少量斜长石存在，岩石类型更接近高压麻粒岩，而非榴辉岩；如前所述，可能与下地壳成分偏中性有关．碰撞后岩浆岩的Nd同位素组成随时间变得更加富集(图4)(Chu *et al.*，2011)，结合负Eu异常的增强和Cr含量的升高，反映印度陆壳长英质物质通过俯冲、地幔交代和熔融对碰撞后岩浆岩的贡献增强，有可能进一步促进下地壳成分的长英质化．

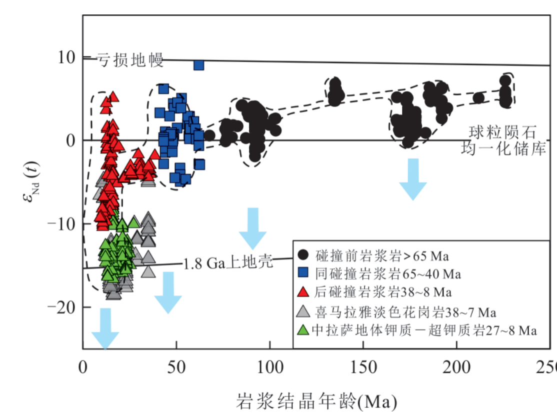

图4　拉萨地体东南部(87°～94°E)岩浆岩Nd同位素组成随时间的变化

Fig.4　$\varepsilon_{Nd}(t)$ vs. ages of pre-collisional, syn-collisional, and post-collisional magmatic rocks in the southeastern Lhasa terrane

早－中侏罗世、晚白垩世、古新世和中新世岩浆阶段Nd同位素组成变化范围增大，存在明显的负偏

4 拉萨地体东南部地壳长英质化阶段和机制分析

大陆地壳发生长英质化的可能机制主要包括两种:(1)榴辉岩相下地壳的拆沉(Kay and Kay,1993;Rudnick,1995;Lee *et al.*,2015);(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).榴辉岩相下地壳的拆沉通常发生在岩浆弧演化阶段或者造山根垮塌阶段(Leech,2001;Ducea,2011;Lee *et al.*,2015),与地壳变形和岩浆作用密切相关.拉萨地体东南部既经历了中生代以来特提斯大洋岩石圈长期俯冲的大陆弧演化阶段,也经历了新生代印度-欧亚大陆碰撞的造山阶段和印度大陆地壳的俯冲,有可能经历了多阶段地壳长英质化.

4.1 碰撞前大陆弧演化阶段

拉萨地体东南部在中生代经历了长期的大陆弧演化阶段,与位于南美西缘的安第斯造山带类似(Zhu *et al.*,2011).后者是现今仍在活跃的大陆弧,与Nazca大洋板片向巴西地盾之下的俯冲有关,其中段(16°~22°S)位于智利北部和玻利维亚,是该造山带最高和最宽的部分,大部分高海拔地区(如Altiplano高原)地壳厚度超过了60 km,最高可达75 km(Beck and Zandt,2002).该地区整体地壳具有低波速(Vp=5.8~6.0 km/s)和低泊松比(σ=0.25)特征,表明地壳主要由富石英的长英质岩石组成,而且底部基本不存在基性下地壳(Beck and Zandt,2002).该地区岩石圈经历了多达500 km的构造缩短(DeCelles and Horton,2003),并强烈缺失加厚的基性下地壳和冷的岩石圈地幔(Beck and Zandt,2002),结合区域构造变形历史和岩浆岩成分变化(Kay and Kay,1993),该地区被认为经历了榴辉岩相下地壳和岩石圈地幔的拆沉,从而留下了一个高度演化的长英质地壳(Beck and Zandt,2002;Ward *et al.*,2016).

DeCelles *et al.*(2009)进一步总结了南、北美洲西部科迪勒拉造山带(包括安第斯造山带中部地区)地表构造变形和区域岩浆作用规律,发现造山系统的演化具有明显的周期性(间隔20~50 Ma).每个周期内低岩浆通量阶段往往伴随地壳挤压、缩短和增厚;随后的高通量弧岩浆阶段形成大量中酸性侵入岩,并在地壳底部快速产生致密的榴辉岩相下地壳;当榴辉岩相下地壳达到一定厚度时,由于重力不稳定将发生拆沉,伴随地壳伸展和抬升,为下一周期的地壳变形和缩短提供空间.该研究的重要发现之一是高通量岩浆阶段总是伴随着岩浆岩Nd同位素变化范围的增大(特别是低$\varepsilon_{Nd}(t)$岩浆的大量出现,即Nd同位素负偏现象,与古老陆壳基底向岩浆弧地壳之下的逆冲有关),而低岩浆通量阶段形成的岩浆岩以高$\varepsilon_{Nd}(t)$为基本特征,伴随地壳缩短和加厚.该周期性演化特征可以和拉萨地体类比.

拉萨地体在中生代经历了多期次弧岩浆作用(包括晚三叠世、早-中侏罗世和晚白垩世),其中晚白垩世岩浆岩出露最广(如Ji *et al.*,2009;Zhu *et al.*,2011;Meng *et al.*,2016).这些中生代岩浆岩的Nd同位素组成在早-中侏罗世和晚白垩世都出现了负偏,很可能反映了同时期壳内古老地壳基底向深部的逆冲和地壳加厚(DeCelles *et al.*,2009)(图4).冈底斯晚白垩世大规模中酸性岩浆岩的形成,必然伴随深部基性-超基性堆晶岩或残余体的形成.由于重力均衡作用,高密度下地壳岩石的形成会导致地表的沉降,其拆沉则会导致地壳的伸展和抬升(DeCelles *et al.*,2009).现有古高程研究和高原隆升历史研究表明,拉萨地体东南部(至少局部地区)在新生代印度-欧亚大陆碰撞之初地表就已隆升至接近现今的高度(Ding *et al.*,2014).拉萨地体晚白垩世很可能就已具有东高西低、南北高中间低的地形特征(Kapp *et al.*,2007;Ding *et al.*,2014;许志琴等,2016;Wang et al.,2017),这暗示着晚白垩世大陆弧岩浆阶段形成的致密下地壳应已发生拆沉,伴随地壳的抬升.拉萨地体东南部95~86 Ma、85~73 Ma和68~60 Ma岩浆岩源区深度(浅→深→浅)和温度(高→低→高)的变化也表明在晚白垩世地壳发生了加厚和减薄(Ji *et al.*,2014);84~83 Ma东西向沿伸的基性岩墙表明同时期存在地壳的南北向伸展(Ma *et al.*,2017).地壳厚度变化和区域伸展作用的出现暗示岩浆弧致密堆晶下地壳可能已被移除.岩浆岩Nd同位素的负偏现象也出现在早中侏罗世,暗示该时期可能存在类似过程.因此,我们初步认为拉萨地体东南部地壳在中生代大陆弧演化阶段可能就已经历过阶段性地壳长英质化作用.

4.2 同碰撞和碰撞后阶段

同碰撞岩浆岩(55±10 Ma)在拉萨地体分布十分广泛,形成大量基性至酸性火山岩(林子宗群)和侵入岩(冈底斯岩基)(Mo *et al.*,2007;Ji *et al.*,

2009).岩石学和同位素特征表明该时期岩浆活动导致大量新生地壳物质形成,并伴随强烈的壳幔岩浆混合,与俯冲新特提斯洋片后撤和断离导致的软流圈地幔上涌有关(Mo *et al.*,2007;Niu *et al.*,2013).大规模幔源岩浆的加入将导致下地壳的生长和加厚(Mo *et al.*,2007),同时期大量中酸性岩浆岩在浅部地壳的侵位也需要在深部地壳形成致密的堆晶或残余体下地壳.不过并不清楚该时期地壳是否发生强烈加厚并伴随致密下地壳的移除.

碰撞后(38~8 Ma)岩浆岩在拉萨地体很常见,以小规模岩株或岩脉的形式存在,多数为中酸性的高Sr/Y花岗岩类(东部)和钾质-超钾质火山岩类(西部),部分表现出混合特征(Chung *et al.*,2005;丁林等,2006;Wang *et al.*,2018).其中高Sr/Y花岗岩类(26~10 Ma)主要分布在拉萨地体东南部,普遍具有高La/Yb_N和Sr/Y等埃达克质特征,以及不同程度升高的$\varepsilon_{Nd}(t)$和Cr含量,反映其源自加厚下地壳熔融并伴随软流圈地幔的贡献(Chung *et al.*,2003).钾质-超钾质岩石主要分布于拉萨地体中西部,以交代岩石圈地幔来源为主,含有再循环印度陆壳物质.该时期岩浆岩的时空分布和地球化学特征反映拉萨地体岩石圈根拆沉应发生于该阶段(约25 Ma),与俯冲印度陆壳的拆离可能存在关联(Fielding, 1996; Miller *et al.*, 1999; Chung *et al.*, 2003,2005).因此碰撞后岩浆阶段应为拉萨地体东南部榴辉岩相下地壳根部及岩石圈地幔拆沉的关键时期之一,东部的拆沉相对彻底,而西部岩石圈地幔仍得以部分保留(Chung *et al.*,2003).碰撞后岩浆岩在27 Ma之后$\varepsilon_{Nd}(t)$发生了最为显著的一次降低(图4),且大部分岩浆岩的$\varepsilon_{Nd}(t)$值与负Eu异常程度及Cr含量正相关(图3),反映了印度长英质古老陆壳物质向拉萨地体之下俯冲的影响,暗示印度陆壳物质的再循环很可能促进了拉萨地体地壳的长英质化.

因此,拉萨地体东南部地壳的长英质化可能发生于多个阶段,包括碰撞前大陆弧演化阶段和碰撞后高原垮塌阶段,榴辉岩相致密下地壳的移除可能扮演了主要角色,伴随印度陆壳物质的俯冲回返/构造底侵.然而必须指出,拉萨地体作为研究大陆地壳成分演化的绝佳地区,其地壳长英质化具体过程仍有待地球物理学、地质学、岩浆岩地球化学和实验岩石学等多学科的综合解析.

5 结论

全球部分造山带(如青藏高原拉萨地体的南部和南美安第斯造山带中段的Altiplano高原)整体地壳具有低地震波速和低泊松比特征,表明这些地区的地壳具有高度演化的中酸性成分.对比前人地球物理资料、岩石物性实验和模拟计算结果,笔者认为拉萨地体东南部地区下地壳也可能由残余体性质的中性含石榴石麻粒岩组成.结合拉萨地体地质演化历史以及中-新生代岩浆岩的年代学和地球化学特征,推测该地区地壳长英质化应发生于多个阶段,包括晚白垩世大陆弧发育阶段(以堆晶或残余体下地壳的拆沉为主)和碰撞后阶段(以加厚下地壳拆沉为主,伴随印度古老长英质陆壳物质的俯冲回返/构造底侵).

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