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海南晚新生代玄武岩对海南地幔柱的启示

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摘　要

地球化学和地球物理证据共同证实了在海南岛下方存在一个晚新生代活动的地幔柱，并对华南地区板内火山活动和构造演化产生了显著影响，但其深部起源机制与岩浆演化过程仍存在争议。海南岛位于华南板块南缘，北部以琼州海峡与雷州半岛相隔，其新生代火山活动自始新世至全新世均有发育，在琼北地区形成百余座火山锥及大面积分布的火山岩台地，构成雷琼裂谷火山岩带的重要组成部分。火山熔岩以灰黑色玄武岩和橄榄玄武岩为主，岩石类型包括拉斑玄武岩系列和碱性系列，具有典型的洋岛型玄武岩(OIB)型微量元素特征和DUPAL同位素异常，估算的地幔潜在温度显著高于全球软流圈地幔。这些玄武岩被认为是海南地幔柱的岩浆产物，对揭示海南地幔柱的起源深度、上升动力学机制及其与被动陆缘伸展作用的耦合关系具有重要意义。本文基于前人发表的海南岛晚新生代玄武岩的地球化学数据，系统综述海南地幔柱的岩浆演化特征和地幔源区性质。

关键词

海南地幔柱，OIB型玄武岩，晚新生代，海南岛

Implications of Late Cenozoic Basalts in Hainan for the Hainan Mantle Plume

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Abstract

Geochemical and geophysical evidence collectively confirms the presence of an active late Cenozoic mantle plume beneath Hainan Island, which has exerted a profound influence on intraplate volcanism and the tectonic evolution of South China. Nevertheless, the deep-seated mechanisms of its origin and magmatic evolution remain subjects of ongoing debate. Situated at the southern margin

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of the South China Block, Hainan Island is separated from the Leizhou Peninsula to the north by the Qiongzhou Strait. Cenozoic volcanism in this region spans from the Eocene to the Holocene, culminating in the formation of over a hundred volcanic cones and extensive basaltic plateaus in northern Hainan, which constitute a vital component of the Leiqiong rift volcanic belt. The volcanic lavas are predominantly composed of grayish-black basalts and olivine basalts, encompassing both the tholeiitic and alkaline series. These rocks exhibit typical ocean island basalt (OIB)-type trace element signatures and DUPAL isotopic anomalies, yielding estimated mantle potential temperatures significantly higher than that of the global ambient asthenospheric mantle. Recognized as the magmatic products of the Hainan mantle plume, these basalts provide crucial insights into the depth of plume origin, its ascent dynamics, and its coupling relationship with passive continental margin extension. Based on a compilation of previously published geochemical data from late Cenozoic basalts on Hainan Island, this paper systematically reviews the magmatic evolution characteristics and mantle source properties of the Hainan mantle plume.

Keywords

Hainan Mantle Plume, OIB-Type Basalts, Late Cenozoic, Hainan Island

1. 引言

地幔柱概念自 Wilson [1]与 Morgan [2]提出以来，已成为解释板内火山活动、大火成岩省的形成及大陆裂解的关键动力学模型。经典地幔柱理论强调其起源于核幔边界(~2900 km)的热物质上涌，且多数被识别的地幔柱与大型低剪切波速省(LLSVPs)存在空间关联，暗示这些深部构造是地幔柱的主要发源地[3] [4]。也有研究指出，深俯冲大洋板片在核幔边界滞留形成的超低速区可诱发地幔柱[5]，但无论何种成因，地幔柱对板块重组、气候演变及生态系统的影响已得到广泛关注[6] [7]。

华南地区晚新生代玄武岩因其独特的板内地球化学特征早在上世纪就引起了关注[8]。Maruyama [9]首次提出东南亚大陆之下可能存在“越南地幔柱”，随后曾维军等[10]综合地质地球物理资料将其命名为“印支地幔柱”。地震层析成像技术已揭示海南岛及南海下方存在近垂直的低速柱状结构[11] [12]，Xu 等[13]则通过系统论证，明确提出了华南地区晚新生带发育有“海南地幔柱”的观点。此后，地球物理学、岩石学及地球化学证据不断涌现，证实海南地幔柱主导着南海及其周缘晚新生代岩浆活动[14]-[21]。

现有研究表明，海南地幔柱影响的晚新生代玄武岩具有典型的洋岛型玄武岩(OIB)微量元素特征和 DUPAL 同位素异常[21]-[23]，估算的地幔潜在温度显著高于全球软流圈地幔[18] [24]，且火山岩中单斜辉石巨晶的出现进一步支持其地幔柱成因[25]。Zou 和 Fan [22]基于过剩 230 Th 约束的地幔柱上升速率(<1 cm/year)指示其低速特征。Yan 等[21]将地幔柱影响的区域向西延伸至泰国素可泰弧地区，其影响范围超过 4 × 10^6 km^2 [17]。Yu 等[26]根据地幔柱头到达浅部时间推断其起始活动于 23.8~20 Ma。

早期地震层析成像显示低速异常从浅部一直延伸至 660 km 地幔转换带[12]，而 Montelli 等[14]与 Zhao [15]的全球成像则显示异常区域可追踪至下地幔(~1900 km)，并将海南地幔柱归为起源于核幔边界的十二个地幔柱之一。形态上，海南地幔柱呈倾斜上升而非经典模型的垂直形态，可能是由于地幔流扰动[16] [27]，且存在双层结构[20] [28]。成因机制方面，既有模型强调地幔转换带滞留的古老俯冲板片对海南地幔柱上升的阻挡作用[11]，亦有观点认为双向深俯冲及拆沉作用提供了触发条件[19]。然而，海南地幔柱

的起源及其上升的动力学机制仍存在争议，关于其物质组成和物理形态是否受到了古太平洋俯冲板片的影响，受到了何种程度的影响的问题仍然亟待解决。

近年来，学者们通过对华南新生代玄武岩的年代学、岩石学及地球化学研究，初步研究了海南地幔柱活动的时空格架与地下形态，但关于其岩浆演化机制、地幔源区性质及其深部构造运动仍有待深入研究。本文结合目前已有的较为充足的海南岛火山地质资料和岩石地球化学等数据信息，梳理了海南岛火山地质特征并剖析了火山活动形式，深入解析华南晚新生代玄武岩岩浆的成因机制、地幔源区，为海南地幔柱的区域构造－岩浆演化活动提供新的约束。

2. 区域地质概况

2.1. 华南区域地质构造

华南地理位置处于中国大陆东南部，其东南是我国最大的边缘海——南海，构造整体位于太平洋板块、亚欧板块和印度洋板块的汇聚边缘。华南板块是由扬子板块和华夏板块在新元古代拼合而成，其北界为秦岭－大别造山带，向西和西南延伸到西藏和印度支那板块[29] [30]。华南板块作为欧亚板块或者西太平洋边缘的一个重要组成部分，经历了亚欧板块和太平洋板块、以及多阶段特提斯洋的复杂俯冲汇聚过程[31]-[33]。

关于华南板块的构造演化，前人进行了很多研究工作，总结可以划分为四个阶段：

(1) 华南古大陆是由扬子地块与华夏地块于中元古代末至新元古代初沿着江南(亦称四堡、晋宁)造山带碰撞拼贴形成[34]-[36]。晋宁运动是华南地区最古老的造山事件，标志着扬子陆块与华夏陆块的初步拼合。Li 等[35]对赣东北蛇绿岩的锆石 U-Pb 定年获得 1.0~0.9 Ga 的年龄，证实该时期存在古洋盆的闭合。晋宁运动使扬子东南缘与华夏陆块发生弧－陆碰撞，形成江南造山带[30]。约 820 Ma，受全球罗迪尼亚超大陆裂解事件的影响，扬子块体与华夏块体聚合而成的华南联合陆块发生裂解，形成大小不等的裂解块体和裂谷盆地[30] [37] [38]；

(2) 南华纪期间，华南联合陆块(由扬子块体与华夏块体拼合形成)发生了裂解。震旦纪－奥陶纪海盆(槽)区位于裂解块体之间，形成的多岛格局与现今西南太平洋的多岛格局类似。自晚奥陶世始，在全球板块碰撞聚合的背景下，发生了以武夷基底为核部，南侧的南海－东海块体、北侧的扬子块体与华夏块体碰撞；南岭、云开、武夷等区块与周围的震旦纪－早古生代海盆发生碰撞－堆叠作用，导致华夏块体边界及其内部发生强烈的褶皱和推覆、低绿片岩相变质与同构造期花岗岩浆活动，形成早古生代陆内造山带，最终形成统一的华南陆块，并奠定了 NE 向的构造格架[30]；

(3) 早－中三叠世期间，位于东亚的古特提斯洋关闭导致华南地区发生强烈的构造－岩浆作用，华北与华南两大块体沿大别山一带碰撞，形成近 EW 向的褶皱造山带和前陆盆地[39] [40]；华南板块与缅泰马块体沿碧土－昌宁－孟连－马江一带拼合，形成印支期蛇绿杂岩带、韧性剪切带、过铝质花岗岩带和厚达数千米的前陆盆地粗碎屑岩堆积[41] [42]。在此南北两大构造体制的挟持下，华南板块内部晚古生代滨海－浅海相地层发生了强烈的褶皱和推覆，导致前泥盆纪构造层被强烈再造乃至置换，使华南最终与印支地块拼合，古特提斯构造域演化完成；

(4) 早中生代构造事件后，特提斯构造域与古太平洋构造域发生了由近 EW 向构造线朝 NE 向构造线的转换[43]。古太平洋沿东亚陆缘发生低角度俯冲，导致下插板片物质在深部熔融并上涌，受到俯冲扰动的地幔源区岩浆沿着断裂上涌(玄武质岩浆底侵)导致上覆板块的中、下地壳物质被高热软化，发生部分熔融或花岗岩化，导致晚中生代伸展型构造岩浆组合和伸展盆地广泛发育，最终奠定了华南区域的“东火山、西花岗”岩浆格局[44] [45]。

华南地区的长期俯冲过程以及对印度－欧亚板块碰撞前新特提斯洋的动力学重建表明，新特提斯洋东南段和印度－澳大利亚板块北向俯冲以俯冲消减、地块拼贴的方式形成东南亚现今大陆岩石圈和弧形

的苏门答腊－爪哇俯冲带；太平洋的西向俯冲以俯冲后撤－弧后扩张的方式形成了东侧菲律宾俯冲带和一系列边缘海盆地。早白垩世以来新特提斯东南段的分支，北澳大利亚洋的扩张使得澳大利亚陆块长期停滞在南半球高纬地区，直到 45 Ma 北澳大利亚洋发生相背俯冲，快速消减，澳大利亚陆块才开始快速向北漂移，其北端与巽他陆块拼贴。这些长期的俯冲过程逐渐形成了现在的东南亚环形俯冲体系[46]。

2.2. 海南岛地质概况

海南岛位于欧亚板块东南缘，地处菲律宾海板块、印度－澳大利亚板块相互作用的交汇区域，并受南海盆地扩张作用的强烈影响[16]。该区构造变形复杂，地震活动频繁，新生代火山作用发育，区域伸展作用形成了一系列近东西向断裂及北西－南东向走滑断裂，其中王五－文教断裂是重要的区域性断裂带，而北西－南东向断裂体系与晚新生代火山活动关系密切[47]。

晚新生代火山喷发集中于海南岛北部、毗邻雷州半岛的地区，形成面积近 5000 km^2、厚度超过 100 m 的玄武岩熔岩台地[48] [49]。目前研究认为，该期火山活动表现为两种喷发型式：一是受伸展裂隙控制的裂隙式喷发，形成以石英拉斑玄武岩或橄榄石拉斑玄武岩为主的大规模溢流玄武岩台地；二是中心式爆炸喷发，形成火山渣锥、玄武岩盾及凝灰环等火山构造，其岩石类型以碱性橄榄玄武岩和碧玄岩为主[50] [51]。

海南岛北部火山活动可划分为五个喷发期(由老至新)：上新世－中新世石峁沟－石马村期、早－中更新世多文期、中更新世东营期、晚更新世道堂期及全新世石山期[49] [52]。区域火山活动始于晚渐新世，中新世至上新世逐渐增强，更新世达到鼎盛，至全新世基本结束[18]。其中，多文期是喷发强度最大的时期，形成的火山岩在区内分布最广，厚度在 5~250 m，可分为上下两段：下段(早－中更新世)以少量碱性橄榄玄武岩为主；上段(中更新世)主体为石英橄榄拉斑玄武岩，火山碎屑含量较低[50] [51]。东营期火山岩以零散分布的石英橄榄拉斑玄武岩为特征，厚度 4~200 m [49]。道堂期火山岩分布面积超过 600 km^2，可划分为下、中、上三段，中段由多孔橄榄拉斑玄武岩组成，上下两段以火山碎屑岩为主[50]。石山期为区内最年轻的喷发期次，熔岩厚度超 95 m，主要岩石类型包括橄榄拉斑玄武岩和碱性橄榄玄武岩[53]。

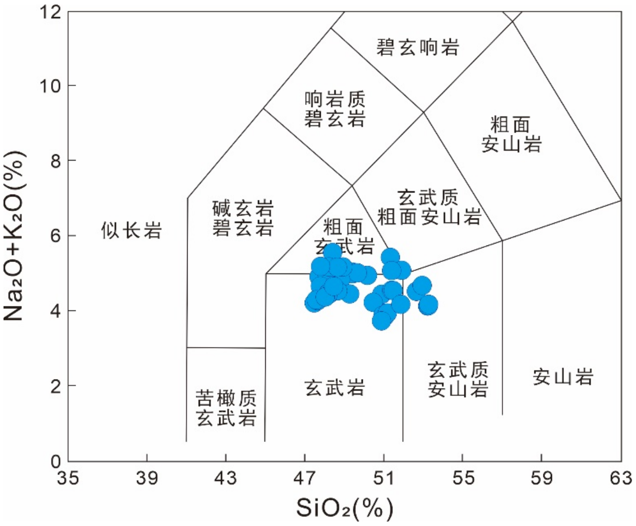
3. 讨论

3.1. 地壳混染与结晶分异

海南－雷琼地区玄武岩的 TAS 图解(图 1)与微量元素配分曲线(图 2)显示其具有典型碱性 OIB 型玄武岩的地球化学特征，与华南晚新生代板内玄武岩相似。研究表明，东南亚地区新生代玄武岩主要起源于上地幔，地壳混染作用可忽略不计[22] [24] [54] [55]。海南岛玄武岩中发育尖晶石二辉橄榄岩和方辉橄榄岩地幔捕虏体，指示岩浆上升速率较快，限制了岩浆与地壳物质的相互作用时间及混染机会[56]。

相较于洋壳环境下形成的玄武岩，大陆板内玄武岩在喷发至地表前通常需要穿越较厚的大陆地壳，因而在上升过程中更易与地壳物质发生相互作用，可能受到不同程度的地壳混染。海南－雷琼地区玄武岩的 Nb/U 比值介于 24.93~74.41 之间，Ce/Pb 比值介于 6.16~33.56 之间，远高于大陆地壳的平均 Nb/U 比值(3.91)和 Ce/Pb 比值(6.15) [57] [58]，接近典型地幔衍生玄武岩的平均值；87Sr/86Sr 与 MgO、SiO2 之间没有相关关系，说明地壳混染作用非常微弱(图 3)，结合微量元素蛛网图上 Nb 和 Ta 正异常的特征(图 2)，共同表明海南－雷琼地区玄武岩在形成与上升过程中未经历显著的地壳混染作用，较好地保留了其幔源岩浆的原始地球化学属性。

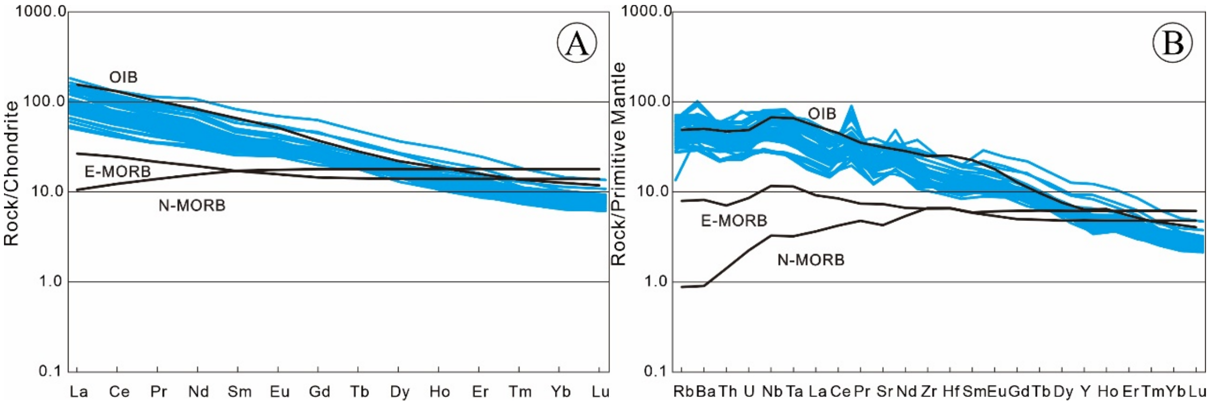
岩浆演化过程中，分离结晶作用起到了重要控制作用。海南岛玄武岩变化的 MgO 含量(4.41~14.59 wt.%)表明其受到了分离结晶作用的影响。Mg#值(48~70)、Cr ($114~559 \times 10^{-6}$)和 Ni ($31~478 \times 10^{-6}$)含量均相对偏低，进一步支持了其经历了分离结晶作用的观点。此外，哈克图解显示 MgO 与 SiO_2、CaO/Al_2O_3 比值及 Ni、Cr 之间的线性相关性与橄榄石和/或单斜辉石的分离结晶一致(图 4)。



注：数据引用文献包括：Li 等[87]；王国庆等[88]；Yu 等[89]。

Figure 1. Plots of $Na_2O + K_2O$-SiO_2 for late Cenozoic basalt from Hainan-Leiqiong

图 1. 海南–雷琼地区晚新生代玄武岩的 $Na_2O + K_2O$-SiO_2 图解



注：E-MORB = 富集型洋中脊玄武岩，N-MORB = 正常型洋中脊玄武岩，OIB = 洋岛型玄武岩。标准化值引自 Sun 和 McDonough [90]。文献数据来源同图 1。

Figure 2. Chondrite-normalized REE patterns (A) and primitive-mantle-normalized trace element diagram (B) for late Cenozoic basalt from Hainan-Leiqiong

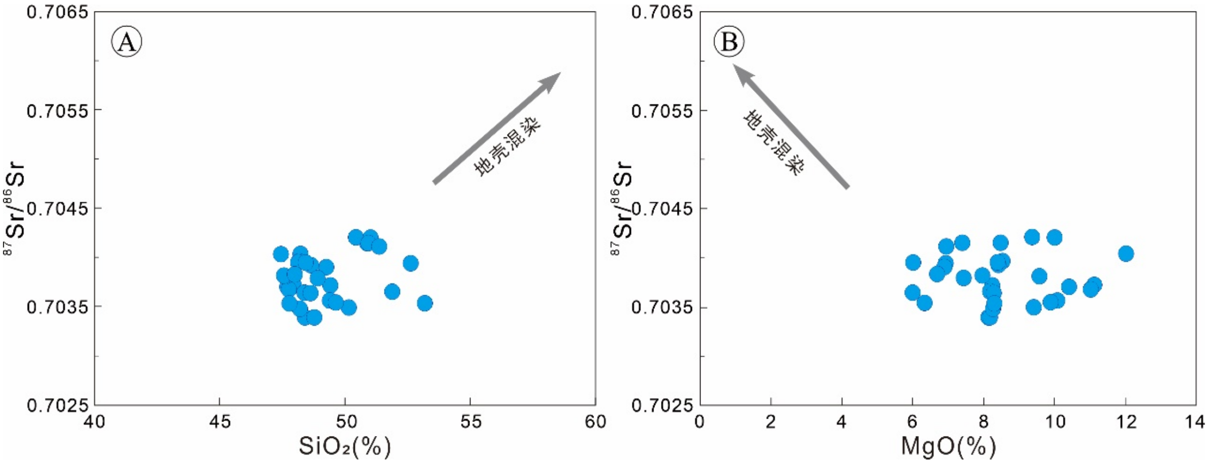
图 2. 海南–雷琼地区晚新生代玄武岩的球粒陨石标准化稀土元素配分模式(A)和原始地幔标准化微量元素蛛网图(B)

3.2. 地幔源区性质

全球大洋玄武岩的 Sr-Nd-Hf-Pb 同位素体系可划分为四个主要端元：HIMU (高 μ 值，$\mu = {}^{238}U/{}^{204}Pb$)、EM1 (富集地幔 1 型)、EM2 (富集地幔 2 型)和 DMM (亏损型洋中脊玄武岩地幔) [59] [60]。海南岛玄武岩及华南块体同时期的板内玄武岩的 Sr-Nd 同位素组成呈现 EM2 型的演化趋势([61] [62])。

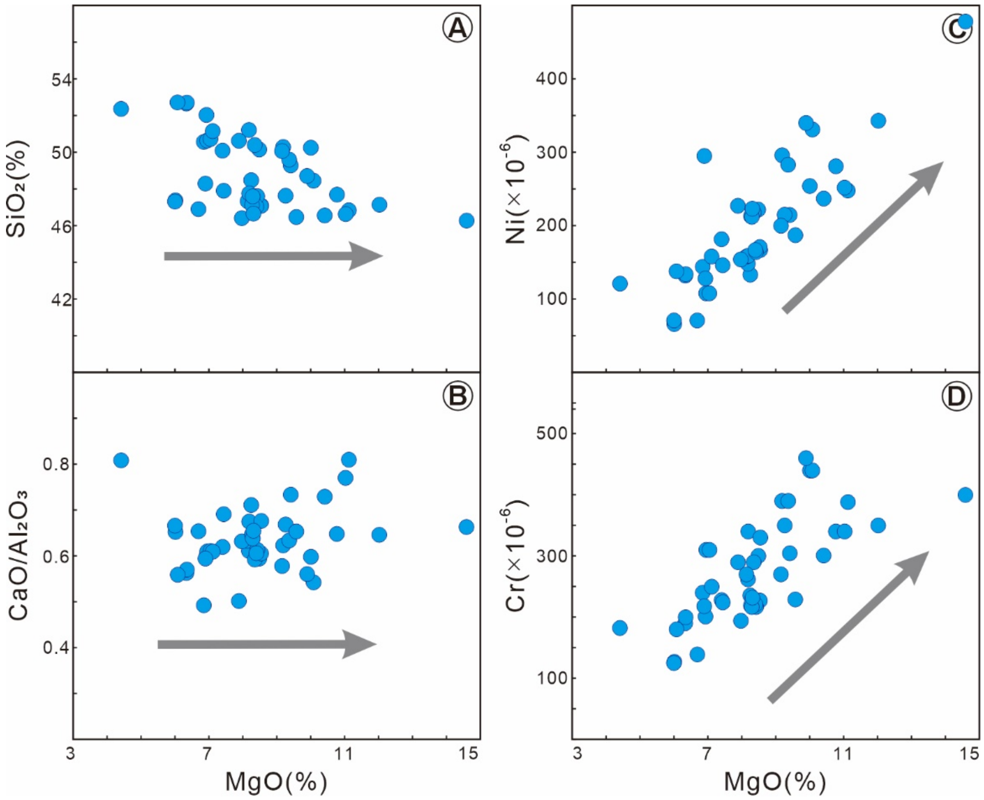
在微量元素蛛网图中，所有海南–雷琼地区玄武岩均呈现轻稀土元素富集、重稀土元素亏损的特征(图 2)，与 OIB 的微量元素配分曲线一致。值得注意的是，海南–雷琼地区玄武岩的 Sr/Sr*和 Eu/Eu*基本都大于 1，具明显的正异常特征且与 Al_2O_3、MgO 无相关关系(图 5)，暗示源区中存在斜长石组分。地幔中潜在的富斜长石端元主要包括两类：一是俯冲洋壳下部的辉长岩层(现以榴辉岩或辉石岩形式存在；[63])，二是大陆下地壳物质(如镁铁质麻粒岩；[64])。海南–雷琼地区玄武岩的 Sr/Sr*和 Eu/Eu*呈现出良

好的正相关关系(图 6)，反映的是源区中存在再循环洋壳辉长岩部分；且大陆下地壳的混入通常伴随 Pb 同位素比值的降低，这与海南岛玄武岩的 Pb 同位素组成不符[54] [65]。因此，我们认为源区中存在再循环的辉长岩洋壳作为俯冲洋壳的一部分是解释 Sr、Eu 正异常的最合理机制[18] [47] [66]。



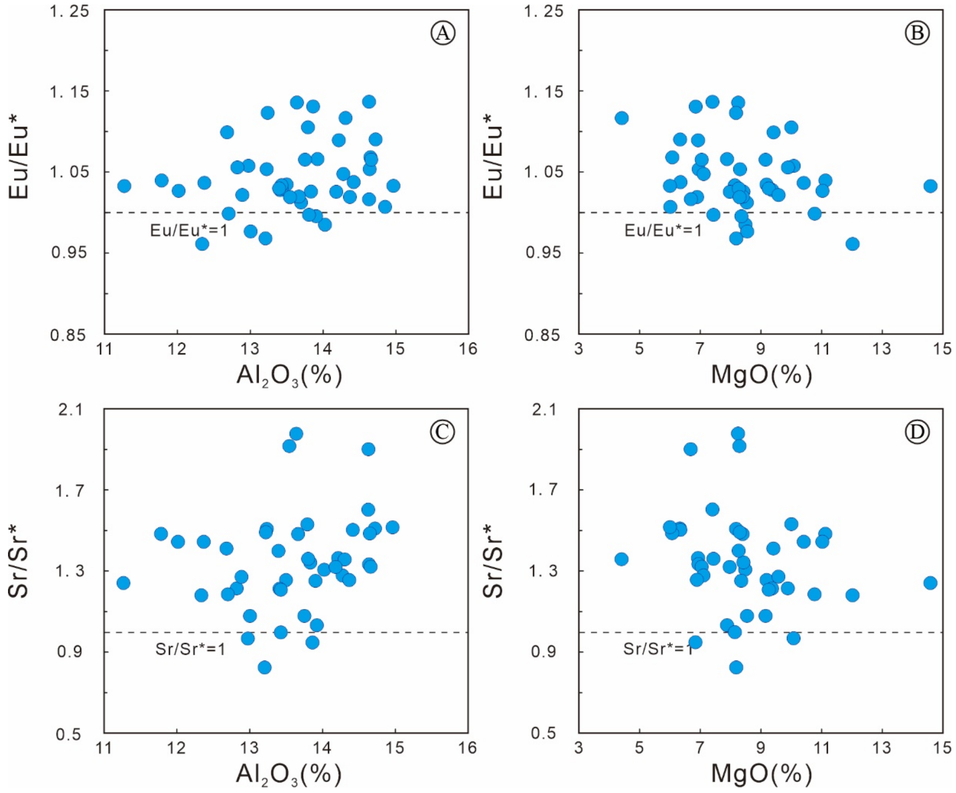
注：文献数据来源同图 1。

Figure 3. Plots of (A) ^{87}Sr/^{86}Sr-SiO$_2$ and (B) ^{87}Sr/^{86}Sr-MgO for late Cenozoic basalt from Hainan-Leiqiong
图 3. 海南–雷琼地区晚新生代玄武岩(A) ^{87}Sr/^{86}Sr-SiO$_2$ 和(B) ^{87}Sr/^{86}Sr-MgO 图解



注：文献数据来源同图 1。

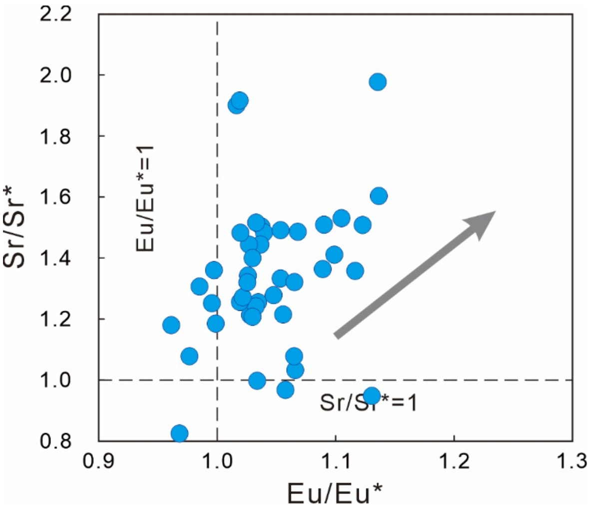
Figure 4. Selected elemental contents and ratios plotted versus MgO for the late Cenozoic basalts from Hainan-Leiqiong
图 4. 海南–雷琼地区晚新生代玄武岩特征元素含量、比值与 MgO 协变关系图



注：文献数据来源同图 1。Eu/Eu* = $Eu_N/(Sm_N*Gd_N)^{0.5}$，Sr/Sr* = $2*Sr_N/(Pr_N + Nd_N)$。

Figure 5. Plots of Eu/Eu*, Sr/Sr* and Al_2O_3, MgO for late Cenozoic basalt from Hainan-Leiqiong

图 5. 海南–雷琼地区晚新生代玄武岩的 Eu/Eu*、Sr/Sr*与 Al_2O_3、MgO 图解



注：文献数据来源同图 1。

Figure 6. Plots of Eu/Eu*-Sr/Sr* for late Cenozoic basalt from Hainan-Leiqiong

图 6. 海南–雷琼地区晚新生代玄武岩的 Eu/Eu*-Sr/Sr 图解

3.3. 地球物理成像特征

地球物理研究工作为东南亚之下的深部构造框架提供了重要的约束[14] [15] [67] [68]。地震学数据表

明，东南亚现代构造框架主要由两大系统组成：横向俯冲与汇聚系统，以及垂直地幔柱系统[46] [69]-[71]。东南亚广阔的俯冲系统与欧亚板块之下特提斯域和太平洋域的双向俯冲有关。地幔深度的俯冲板块以高速异常为特征，东南亚的板块几何成像识别出向东北倾斜的印度–澳大利亚板块以及向西倾斜的菲律宾海板块和太平洋板块[72]-[75]，这也得到了浅层地震观测的支持[46] [76]-[78]。高分辨率地幔层析成像显示，俯冲板块在地幔转换带(410~660 km)普遍存在停滞现象，随后穿透 660 km 不连续面进入下地幔，这被下地幔中间歇分布的高速异常所证实[74] [79]-[81]。

大规模层析成像模型已识别出南海北部陆缘中部海南岛下方存在一个大型连续低速异常体，高分辨率地震波观测结果显示，这一显著的低速异常不仅在浅部软流圈中广泛存在，更在深部呈现出柱状结构，贯穿整个上地幔并向深部延伸[15] [69] [71] [82]。该异常体被定义为海南地幔柱，起源于下地幔乃至核幔边界[14] [15]。地震层析成像技术显示，海南地幔柱表现为从下地幔穿透而上的近垂直低速柱状体，其影响范围从核幔边界一直延伸至上地幔底部乃至浅表[14] [16]。在深部热物质向上运移的过程中，410 km 间断面下沉和 660 km 间断面抬升表明地幔转换带异常变薄[83] [84]，这归因于地幔温度受地幔柱的影响升高[85] [86]。东南亚地球物理成像和地球化学证据共同表明海南地幔柱来自于下地幔乃至深部地幔。

3.4. 地球化学–地球物理综合约束下的动力学模型

综合前文的地球化学与地球物理证据，海南地幔柱的深部起源与岩浆演化过程并非受控于单一的动力学过程中，而是与深部地幔构造(尤其是地幔转换带中的滞留板片)存在强烈的时空耦合与热化学交换。东南亚下方地幔转换带普遍存在的古太平洋或古特提斯洋俯冲滞留板块，及源自下地幔深部的近垂直低速异常体，暗示了起源于核幔边界或下地幔的高温物质流在上升过程中必然会与滞留于地幔转换带的冷俯冲板片相互作用，高温热异常会导致原本滞留在此的再循环洋壳发生局部脱水或部分熔融并释放出富含不相容元素、挥发分以及再循环洋壳辉长岩组分的富集流体或硅酸盐熔体；这些富集熔/流体随后会与周边及持续上涌的地幔柱物质发生交代，导致原本的亏损或原始地幔柱物质转变形成具有 EM2 特征，且含有再循环洋壳组分的混合岩浆源区。

地幔转换带中滞留板片的脱水与部分熔融，极大增加了上覆软流圈及地幔转换带顶部的挥发分(如H_2O、CO_2)及局部熔体含量。由于地震波速对流体和局部熔体的存在极为敏感，这种被富集熔/流体交代的区域在地震层析成像上必然表现为极其显著的低速异常。这合理解释了在海南岛及周边区域浅部及上地幔中能够观测到强烈的柱状低速结构的特征。此外，地幔柱的高温热力学侵蚀与交代流体的物理化学效应共同作用，导致了地幔转换带结构的显著变薄(410 km 界面下沉与 660 km 界面抬升)，降低了地幔固相线，为地幔柱岩浆的减压熔融和快速上升提供了持续的动力与物质基础。

综上所述，海南晚新生代玄武岩的形成受控于“深部地幔柱上涌–滞留板片脱水/熔融–流体交代地幔柱”的动力学机制。下地幔起源的原始地幔柱在穿过地幔转换带时，其热侵蚀作用诱发了滞留洋壳的熔融，交代并融合了 EM2 组分和辉长岩物质。这一热化学演化过程既赋予了海南玄武岩独特的地球化学特征，又因挥发分和熔体的局部富集，在宏观上造就了贯穿上地幔的显著低速异常体，实现了地球化学示踪与地球物理观测在深部动力学过程上的统一。

4. 结论与展望

本文基于对海南岛及雷琼地区晚新生代玄武岩的岩石学、微量元素地球化学及区域地球物理研究得出以下结论：

(1) 海南–雷琼地区晚新生代玄武岩具有典型 OIB 的主微量元素特征。海南岛玄武岩的 Nb/U 和 Ce/Pb

比值远高于大陆地壳平均值，表明幔源岩浆在快速上升至地表的过程中未经历显著地壳混染作用，高度保留了原始地幔的地球化学特征。其相对较低的主微量元素协变关系指示岩浆在演化过程中经历了以橄榄石和单斜辉石为主的结晶分异过程；海南－雷琼地区晚新生代玄武岩的微量元素特征显示出 EM2 端元亲缘性。玄武岩普遍存在的轻稀土富集、重稀土亏损以及显著的 Sr、Eu 正异常的特征，指示了地幔源区中存在富斜长石的组分，源区中可能存在俯冲再循环的辉长岩洋壳；

(2) 地球化学证据与地球物理学研究共同证实了海南地幔柱的深部下地幔起源。海南地幔柱以近垂直的连续低速柱状体形态从下地幔向上穿透，其携带的异常高温热物质导致地幔转换带的显著减薄(410 km 间断面下沉与 660 km 间断面抬升)；

(3) 尽管针对海南地幔柱的研究已取得显著进展，但当前的深部构造－岩浆演化模型仍面临诸多知识空白。首先，关于地幔柱的精细三维几何形态及其与停滞板片交互的流体动力学细节(如穿透、绕流或是部分被阻断)仍不够清晰。其次，深部地幔源区中再循环物质的确切来源、俯冲时代以及其在源区岩浆贡献中的定量比例依然存在较大争议。单纯依靠传统的 Sr-Nd-Pb 同位素体系和主微量元素存在多解性，已难以在这些精细问题上取得实质性突破。建议在琼州海峡、雷州半岛、北部湾及周边南海海域部署宽频带地震台阵，通过结合全波形反演等高精度地震层析成像技术，进一步提高分辨率，精准刻画海南地幔柱在上下地幔边界及转换带内的三维精细形态，明确其上升通道的连续性及分支情况，并突破传统同位素体系的局限，针对该区新鲜的玄武岩及地幔捕虏体开展非传统稳定同位素(如 Mg、Zn、Ba、He)分析，精准识别和定量评估源区中下地幔原始深部物质的真实贡献；同时，引入 Re-O 同位素体系分析，利用其对地壳物质的高度敏感性，在限定再循环洋壳的俯冲时代提供决定性证据。

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