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泰国东南部黎府带晚三叠世碰撞后火山岩成因及其古特提斯构造意义

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摘 要:泰国位于东古特提斯构造域的核心位置,保存了多条与古特提斯洋俯冲－碰撞－闭合演化有关的构造岩浆岩带.但目前对于其中黎府带早中生代火山岩的研究仍存在不足,其相关的岩石成因和构造属性未能得到有效限定.因此,针对泰国东南部黎府带出露的晚三叠世火山岩开展了详细的岩相学、锆石 U-Pb 年代学、地球化学以及 Sr-Nd-Hf 同位素研究,并结合区域对比综合分析了东古特提斯构造域晚三叠世岩浆活动及其动力学机制.该套样品包括了玄武岩、流纹岩和英安岩,锆石 U-Pb 定年表明其形成年龄为晚三叠世(204～200 Ma).其中玄武岩样品具有富铌玄武岩的特征,其对应的($^{87}Sr/^{86}Sr$)$_i$＝0.703 98～0.704 00,$\varepsilon_{Nd}(t)$＝＋5.0～＋5.3,$\varepsilon_{Hf}(t)$＝＋0.3～＋15.5.长英质火山岩样品具有 A 型特征,且与玄武岩样品具相似的同位素组成,其对应的($^{87}Sr/^{86}Sr$)$_i$＝0.702 71～0.704 72,$\varepsilon_{Hf}(t)$＝＋4.0～＋4.2,$\varepsilon_{Nd}(t)$＝＋6.8～＋16.0.地球化学特征表明该套玄武岩样品来自类似 OIB 特征的亏损软流圈地幔源区,而长英质火山岩可能来自该套新底侵的基性岩经低程度部分熔融.区域对比表明该套晚三叠世火山岩形成于古特提斯洋碰撞后伸展背景,是东古特提斯洋碰撞闭合后最晚期的岩浆活动.年代学数据对比显示黎府带与清孔－南邦－塔克火山岩带均具有相似的三叠纪年龄谱系,证实了在中-晚三叠世时期黎府带也同样记录了东古特提斯洋碰撞及碰撞后的岩浆作用.

关键词:泰国东南部;黎府带;晚三叠世;碰撞后岩浆作用;东古特提斯洋;岩石学;构造.

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Petrogenesis of Late Triassic Post-Collisional Volcanic Rocks from Loei Zone in Southeastern Thailand and Its Paleotethyan Tectonic Implications

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Abstract: Thailand is located in the core region of the East Paleotethyan Domain, preserves numerous tectonic-magmatic belts related to the subduction-collision-closure evolution of the Paleotethyan Ocean. However, the study on the Early-Middle Mesozoic volcanic rocks in the Loei zone remains unclear and the related petrogenesis and tectonic setting have not been constrained. Therefore, this study carries out detailed petrographic, zircon U-Pb geochronology, geochemistry and Sr-Nd-Hf isotopic studies on the Late Triassic volcanic rocks along the Loei zone in southeastern Thailand. Our study along with regional comparisins comprehensively analyze the Late Triassic magmatism and geodynamics process in the East Paleotethyan Domain. The study samples include basalts, rhyolites and dacites, with Late Triassic zircon U-Pb ages of 204－200 Ma. The basalts exhibit characteristics of Nb-enriched basalts, with $(^{87}Sr/^{86}Sr)_i$＝0.703 98－0.704 00, $\varepsilon_{Nd}(t)$＝＋5.0 － ＋5.3, $\varepsilon_{Hf}(t)$＝＋0.3 － ＋15.5. The felsic volcanic samples exhibit A-type characteristics and share similar isotopic compositions with the basalt samples, with $(^{87}Sr/^{86}Sr)_i$＝ 0.702 71－0.704 72, $\varepsilon_{Nd}(t)$＝＋4.0 － ＋4.2, $\varepsilon_{Hf}(t)$＝＋6.8 － ＋16.0. Geochemical characteristics indicate that these basalts originated from a depleted OIB-like asthenospheric mantle source, while the felsic volcanic rocks possibly originated from the low level partial melting of these newly underplated mafic rocks. Regional comparisons indicate that these Late Triassic volcanic rocks were formed in a post-collisional extensional setting, representing the latest magmatism after the collision and closure of the East Paleotethyan Ocean. Comparison of chronological data shows that the Loei zone and the Chiang Khong-Lampang-Tak zones share similar Triassic age-spectra pattern, confirming that the Loei zone also recorded the collisional and post-collisional magmatism related to the Eastern Paleotethyan evolution during the Middle-Late Triassic.

Key words: southeastern Thailand; Loei zone; Late Triassic; post-collisional magmatism; East Paleotethyan Ocean; petrology; tectonic.

0　引言

古特提斯洋是早古生代至早中生代存在于冈瓦纳大陆和劳亚大陆之间的古大洋,该大洋西起现今阿尔卑斯途经中亚、西藏、滇西并南延至东南亚等地,其中滇西和东南亚地区隶属于该构造域的东段,是古特提斯洋构造演化地质记录保存最为完整的地区(如 Metcalfe, 1996, 2006, 2011, 2013, 2021; 钟大赉, 1998; Yin and Harrison, 2000; Cawood *et al.*, 2007; Sone and Metcalfe, 2008; Oliver *et al.*, 2014; Wang *et al.*, 2018, 2022; Qian *et al.*, 2019; Song *et al.*, 2020; 吴福元等, 2020; Fan *et al.*, 2024).以往的研究表明东古特提斯构造带经过了缅甸东部、泰国北部以及老挝西部并向南可进一步延伸至马来半岛及印尼邦加岛—勿里洞岛等地区,并系统记录了东古特提斯洋演化过程中有关的构造、岩浆、变质和沉积记录(如 Sone *et al.*, 2012; Qian *et al.*, 2015, 2020, 2021, 2022; Wang *et al.*, 2016, 2021a; Zhao *et al.*, 2016; Zhang *et al.*, 2019; 徐畅等, 2020; 余小清等, 2021; Yu *et al.*, 2022, 2023; 李慧玲等, 2023; Hara *et al.*, 2024).

泰国地处东古特提斯构造域的核心部位,由西部的滇缅马陆块和东部的印支陆块所组成,区域内由西向东包括了清迈—清莱带、素可泰带、难河带和黎府带(图 1a),以往的研究在这些构造带识别出了与古特提斯洋构造演化相关的俯冲、碰撞和碰撞后的岩浆及沉积作用(如 Charusiri *et al.*, 1993, 2002; Ueno and Hisada, 2001; Metcalfe, 2002, 2013; Sone *et al.*, 2012; Qian *et al.*, 2013, 2017b, 2022; Wang *et al.*, 2020).其中素可泰岛弧带包括了清孔—南邦—塔克火山岩带和中部及东部两个花岗岩亚省,为中—晚三叠世东古特提斯洋俯冲—碰撞作用的产物,带内出露的平行于缝合带展布的中—酸性火山岩均认为代表了古特提斯洋由俯冲向碰撞转换及碰撞后两期主要的岩浆作用,其向北可以与滇西的临沧带相连(如 Barr *et al.*, 2000, 2006; Metcalfe, 2011; Wang *et al.*, 2016, 2017; Qian *et al.*, 2017a).难河构造带是素可泰岛弧带与印支陆块的分界,被认为是古特提斯洋弧后盆地的残余(如 Ueno and Charoentitirat, 2011; Qian *et al.*, 2015, 2016b; Yang *et al.*, 2016; Wang *et al.*, 2020).

泰国境内黎府带主要出露于碧差汶和黎府等地区,向北被认为可以延伸至老挝西部地区,是东南亚重要的铜—金多金属成矿带(Qian *et al.*,

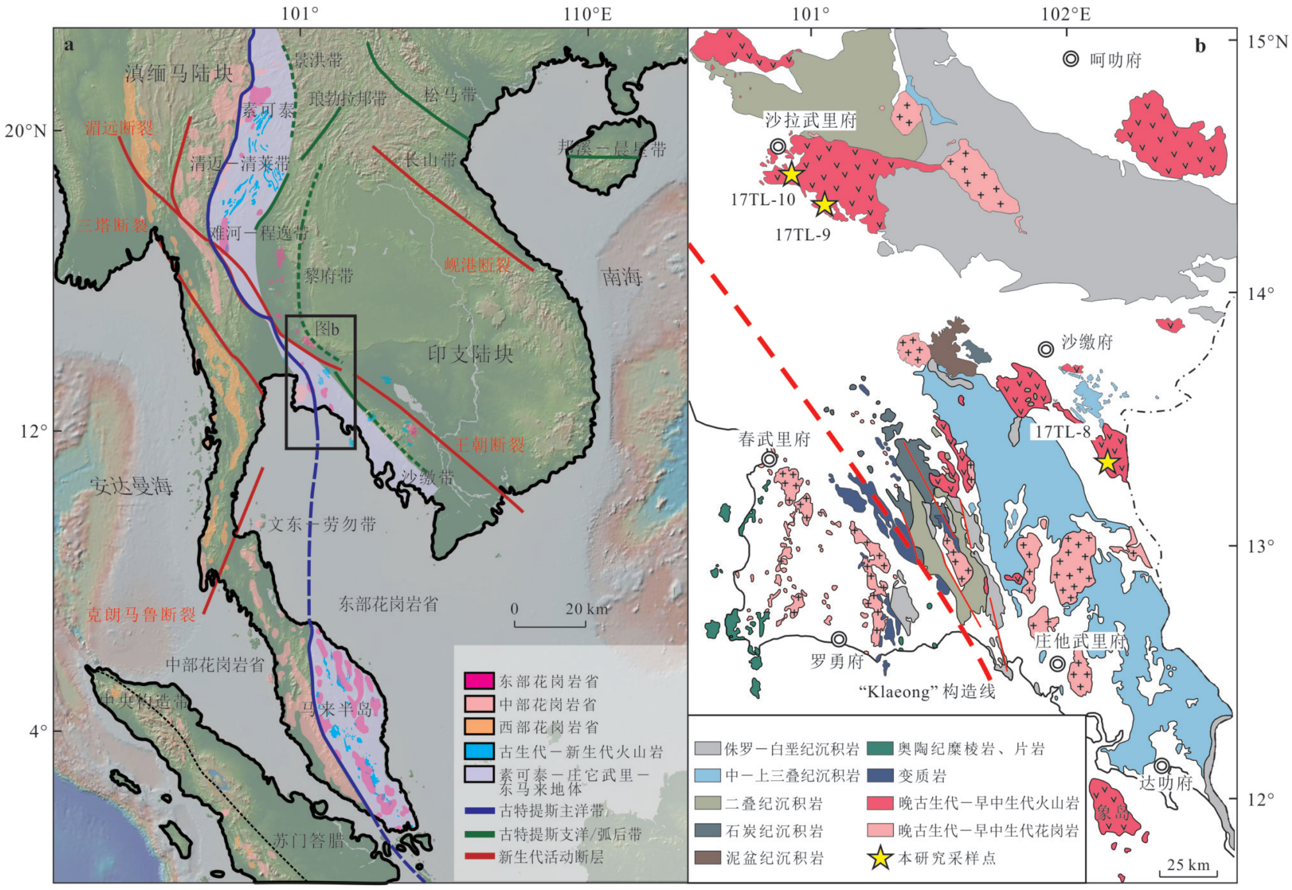

图1　东南亚地区区域构造图(a)和研究区地质简图(b)

Fig.1　Regional tectonic framework (a) and simplified geological map of study area (b)

图a据Wang *et al*.(2018);余永琪等(2024);图b据Qian *et al*.(2022)

2015; Guo *et al*., 2024).但是以往对该带的研究主要集中在晚古生代岛弧岩浆作用及与成矿关系上,缺少对其中生代时期岩浆作用及构造属性的研究,此外该带与清孔—南邦—塔克火山岩带的关系也未能得到有效限定(如Barr *et al*., 2000, 2006; Srichan *et al*., 2009; Qian *et al*., 2013, 2015, 2016a, 2016b, 2017a, 2017b, 2021, 2022; Kamvong *et al*., 2014; Salam *et al*., 2014; Arboit *et al*., 2016; Fanka *et al*., 2016; Yang *et al*., 2016; Shi *et al*., 2019, 2021; Wang *et al*., 2020; Jin *et al*., 2024).

因此为解决上述问题,本研究对泰国东南部黎府带开展了详细的野外地质调查和样品采集,并于泰国沙缴府、庄他武里府和沙拉武里府地区新识别出一套保存完好的晚三叠世火山岩组合(图1b).针对其中的粗面玄武岩、流纹岩和英安岩样品开展了详细的锆石U-Pb年代学、锆石原位Hf同位素、全岩主—微量元素和Sr-Nd同位素的分析研究,并结合收集到的黎府带及其周缘火山岩带年代学和地球化学数据进行综合的对比与讨论,为探究黎府带晚三叠世岩浆作用特征及其构造演化提供新的约束.

1　地质概况与岩相学特征

泰国地处中南半岛的核心部位,区域内主要包含了滇缅马陆块和印支陆块两大构造单元,它们被清迈—清莱东古特提斯带所分隔(如Metcalfe, 2011; Sone *et al*., 2012; Wang *et al*., 2018).其中位于泰国西部的滇缅马陆块在早二叠世与冈瓦纳大陆分离,陆块内发育了冰碛砾岩和泥岩且保存有冷水相的动物群,这些特征表明该陆块具有冈瓦纳大陆的亲缘性(如聂泽同等, 1997; Ueno and Charoentitirat, 2011).而位于泰国东部的印支陆块在泥盆纪就与冈瓦纳大陆分离,陆块内发育有石炭纪—二叠纪热带—亚热带古动植物群,具有华夏陆块的亲缘性(如Metcalfe, 2000; Hutchison and Tan, 2009).

清迈—清莱带位于泰国西北部,带内出露有远

洋放射虫硅质岩、高级变质岩、寒武纪砂岩、奥陶纪灰岩及石炭－二叠纪蛇绿混杂岩等(如 Ueno and Hisada, 2001; Feng *et al.*, 2004, 2008; Ridd *et al.*, 2011; Ridd, 2015; Wang *et al.*, 2016).此外带内还存留了较为完整的上泥盆统牙形石动物群及覆盖于碱性洋岛玄武岩之上的浅水含蜓碳酸盐岩(如 Ueno *et al.*, 2003; Ueno and Charoentitirat, 2011; Wang *et al.*, 2017).该带进一步向南可与马来半岛内的文冬－劳勿带相连,代表了东古特提斯洋主洋盆的缝合位置(图 1a; Ueno and Hisada, 2001; Wang *et al.*, 2018, 2021b; Zhang *et al.*, 2023).

素可泰地体是古特提斯洋向印支陆块俯冲过程中的岛弧系统,主要分布有石炭－三叠纪陆源碎屑岩和岛弧火山岩(如 Barr *et al.*, 2000; Metcalfe, 2011, 2013; Qian *et al.*, 2013, 2017a).难河－沙缴带可延伸至柬埔寨贡布省,带内主要出露了早二叠－中三叠世放射虫硅质岩及蛇绿混杂岩带,已有的研究表明其中的基性火山岩形成于 315 Ma,且具有弧后盆地的地球化学特征(如 Qian *et al.*, 2015; Yang *et al.*, 2016; Wang *et al.*, 2020).黎府带向北可延伸至老挝中部,向东可延伸至柬埔寨西部,前人研究表明在该构造带存在晚泥盆－石炭纪和晚二叠－三叠纪两期较为集中的弧岩浆作用(如 Barr and Charusiri, 2011; Salam *et al.*, 2014; Qian *et al.*, 2016a, 2016b).

本次研究区位于泰国东南部沙拉武里府至庄他武里府地区,区域内出露最老的地层为前志留系 Na Mo 群,主要由变形程度较为明显的低绿片岩相岩石组成(Bunopas, 1981).志留纪至白垩纪地层分布较为广泛且时代连续,其中志留纪－泥盆纪地层主要出露砂岩、泥岩、层状硅质岩等,且在硅质岩中发现了晚泥盆世－早石炭世的放射虫化石(Sashida *et al.*, 1993).石炭纪地层主要出露在呵叻高原西缘,主要由近岸砂岩、页岩和灰岩构成,可见有孔虫化石(Chairangsee *et al.*, 1990).二叠纪－早三叠世地层属于浅海沉积单元,包含页岩、砂岩和石灰岩等,且在中二叠世地层中发现了双壳类动物群,而中晚三叠世地层主要为深海沉积单元(Feng *et al.*, 2009; Udchachon *et al.*, 2024).侏罗－白垩纪地层分布于帕府和呵叻高原等地区,以一套由页岩、砂岩、砾岩和黏土岩组成的红层陆相碎屑岩沉积为特征(Charusiri *et al.*, 1993).

如前所述泰国地区的黎府带火山岩主要出露于黎府和碧差汶地区,主要由泥盆－石炭纪和二叠－三叠纪的安山岩和流纹岩组成,可见少量玄武岩和斑岩,该带的岩浆活动时间在二叠－三叠纪较为活跃,向南认为可以与那空他地区出露的二叠至三叠纪中酸性火山岩相连,其年龄主要集中于 294～207 Ma(如 Kamvong *et al.*, 2014; Salam *et al.*, 2014; Qian *et al.*, 2015, 2022; Arboit *et al.*, 2016; Fanka *et al.*, 2016; Shi *et al.*, 2019, 2021; Wang *et al.*, 2020).

本研究样品采自泰国东南部黎府带南部地区,其中粗面玄武岩样品 17TL-8 采于沙缴府与庄他武里府的交界地区(N13°20′08.04″, E102°10′15.21″)(图 1b),样品呈灰绿色(图 2a),镜下可见斑状结构,斑晶主要为斜长石和辉石,其中斜长石发育聚片双晶,基质由微晶斜长石和少量辉石所组成,部分辉石可见绿泥石化现象(图 2d).流纹岩样品 17TL-9 采于沙缴府 Nan Bang 北部与沙拉武里府交界处 3222 号公路旁(N14°22′42.98″, E101°05′32.36″),呈浅灰色出露,显微镜下观察样品具有斑状结构,斑晶主要由石英(20%～25%)和透长石(5%～10%)组成,基质由玻璃质组成(图 2e).英安岩样品 17TL-10 采于沙拉武里府 Pholoyothin Rd 高速路天桥旁(N14°29′18.83″,E100°54′55.79″),呈现深灰色,镜下观察样品具有斑状结构,斑晶以斜长石(10%～20%)和石英(20%～25%)为主,可见其熔蚀反应边结构(图 2f).

2　分析方法

2.1　锆石 U-Pb 定年及原位 Lu-Hf 同位素测定

本文将采集到的样品通过重液法和磁选法分选锆石颗粒,利用双筒体视显微镜挑选出其中无色干净、无明显裂纹、晶形较好的锆石,并将其固定于环氧树脂靶上并抛光至锆石中心位置.锆石 U-Pb 同位素定年分析在中山大学地球动力作用与地质灾害广东省重点实验室使用激光剥蚀系统与电感耦合等离子体质谱仪联用(LA-ICP-MS)完成.ICP-MS 型号为 iCAP RQ,分析采用的激光束斑直径和频率分别为 32 μm 和 5 Hz,详细的测试过程参考 Wang *et al.* (2020).选取锆石标样 91500(1 062.4±0.6 Ma)和玻璃标准物质 NIST610 用于 U-Pb 同位素分馏校正.对原始数据用软件 GLITTER(Griffin *et al.*, 2008)进行分析处理,用 ISOPLOT 软件对锆石 U-Pb 年龄进行谐和图的绘制并对年龄加权平均

图 2　泰国东南部黎府带火山岩野外露头(a～c)和正交偏光镜下显微岩相学特征(d～f)

Fig.2　Field photo (a－c) and photomicrographs (d－f) for the volcanic rocks in the Loei zone of SE Thailand

矿物缩写：Pl. 斜长石；Qtz. 石英；Cpx. 辉石；Chl. 绿泥石

值(Ludwig, 2001)进行计算．锆石原位 Lu-Hf 同位素分析在中山大学广东省地球动力作用与地质灾害重点实验室进行，将 Neptune Plus 型多接收电感耦合等离子体质谱(MC-ICP-MS)和 Geolas HD 型 193 nm Ar F 激光剥蚀系统联合使用完成测试．详细的分析过程参考 Hu *et al*. (2012). 采用标准锆石样品 91500 和 Plešovice 校正同位素的分馏校正并监测仪器状态．计算 $\varepsilon_{Hf}(t)$ 的各项参数中 ^{176}Lu 的衰变常数选用 $1.867\times10^{-11}a^{-1}$(Scherer *et al*., 2001)，现今球粒陨石的 $^{176}Hf/^{177}Hf$ 和 $^{176}Lu/^{177}Hf$ 值选用 0.282 772 和 0.033 2(Blichert-Toft and Albarede, 1997)，亏损地幔的 $^{176}Hf/^{177}Hf$ 值选用 0.283 250 (Vervoort *et al*., 1999).

2.2　全岩主、微量元素及 Sr-Nd 同位素分析

将代表性样品粉碎至 200 目进行全岩主微量元素和 Sr-Nd 同位素测试，测试均在中山大学地球科学与工程学院广东省地球动力作用与地质灾害重点实验室完成．使用 ARL Perform'X 4200 型 X 射线荧光光谱仪(XRF)进行全岩主量元素测试，选用熔片法进行样品制备，称量烘干后的样品和硼酸锂混合熔剂称量至坩埚中，加入饱和碘化铵(NH_4I)溶液，放入铂金坩埚中加热至 1 050 ℃共熔制片，分析精度优于 5%，详细的实验方法见 Wang *et al*. (2020). 全岩微量元素溶液分析使用 Thermo Scientific iCAP-RQ-ICP-MS 进行，分析精度优于 5%，详细的实验方法见 Wang *et al*. (2020). Sr-Nd 同位素测试使用 Neptune Plus 型多接收电感耦合等离子体质谱仪(MC-ICP-MS)完成，采用国际标准 NIST NBS-987 对样品 Sr、Nd 同位素比值进行监控，测定过程中采用 $^{86}Sr/^{88}Sr=0.119\ 4$ 和 $^{146}Nd/^{144}Nd=0.721\ 9$ 进行分馏校正，详细分析测试流程见 Yang *et al*. (2006).

3　分析结果

3.1　锆石 U-Pb 年代学及原位 Hf 同位素特征

本研究对泰国东南部黎府带的粗面玄武岩样品(17TL-8-6, 17TL-8-10)和长英质火山岩样品(17TL-9-1, 17TL-9-6, 17TL-10-1)开展了详细的 LA-ICP-MS 锆石 U-Pb 年代学分析和原位 Lu-Hf 同位素分析，分析结果见附表 1 和 2.

粗面玄武岩样品 17TL-8-6 和 17TL-8-10 的锆石颗粒多具自形的短柱状无色透明特征．17TL-8-6 样品中的 5 颗锆石的表观年龄较为接近为 203.2～204.8 Ma，其 Th/U 比值为 0.71～1.68，加权平均年龄为 204.1±1.3 Ma(MSWD=0.51；图 3a)．17TL-8-10 样品中的 10 颗锆石的表观年龄较为接近(198.4～202.5 Ma)，其 Th/U 比值为 0.46～0.96，加

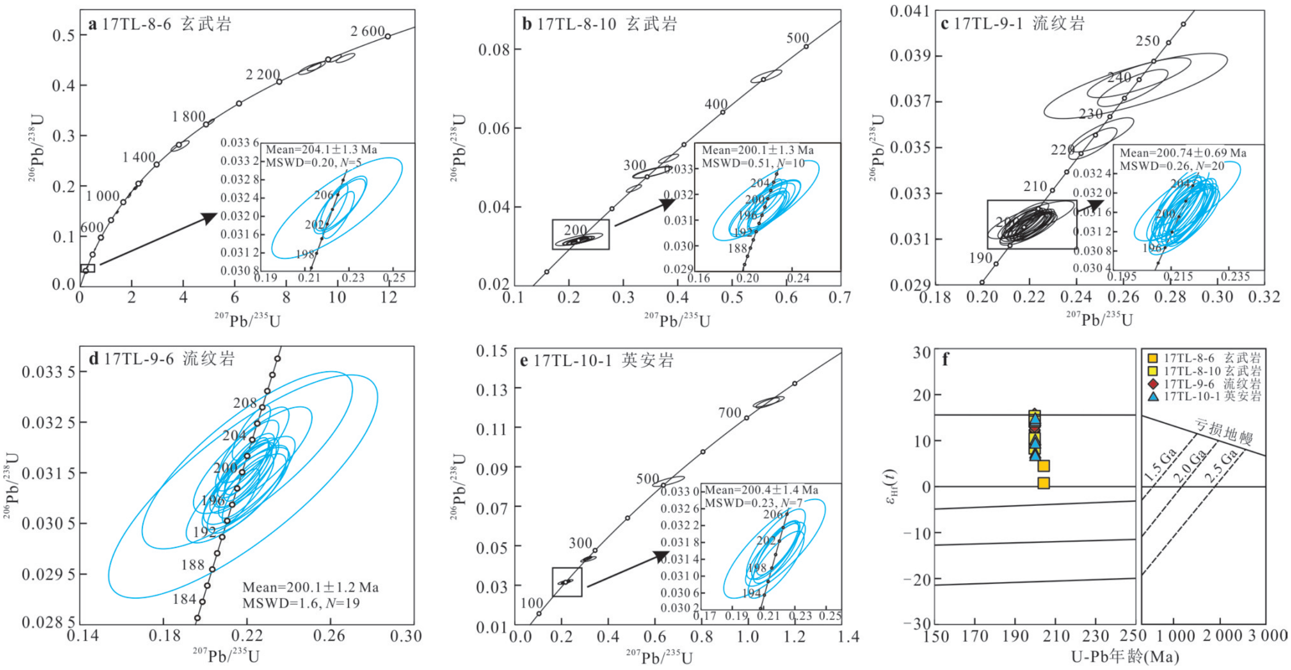

图 3　泰国东南部黎府带火山岩锆石 U-Pb 年龄谐和图 (a～e) 和锆石年龄-$\varepsilon_{Hf}(t)$ 图解 (f)

Fig.3　U-Pb concordia diagrams (a—e) and plot of age (Ma) vs. $\varepsilon_{Hf}(t)$ for zircon grains (f) from the volcanic rocks in the Loei zone of SE Thailand

权平均年龄为 200.1±1.3 Ma(MSWD=0.20；图 3b).针对两个样品共 12 颗锆石开展了原位 Lu-Hf 同位素组成分析，测试结果显示两个样品均具有正的 $\varepsilon_{Hf}(t)$ 值，分别为 +0.3～+4.1 和 +8.3～+15.5(图 3f)，其模式年龄(T_{DM1})分别为 698～859 Ma 和 230～526 Ma.

流纹岩样品 17TL-9-1 和 17TL-9-6 的 Th/U 比值为 0.47～2.50，39 颗锆石样品的表观年龄集中在 197.1～204.9 Ma，所得 U-Pb 加权平均年龄分别为 200.74±0.69 Ma(MSWD=0.26)和 200.1±1.2 Ma (MSWD=1.6)(图 3c～3d).英安岩样品 17TL-10-1 的 Th/U 比值为 0.04～1.98，7 颗锆石样品的表观年龄集中在 198.5～201.5 Ma，其 U-Pb 加权平均年龄为 200.4±1.4 Ma(MSWD=0.26)(图 3e).针对流纹岩 17TL-9-6 样品的 13 颗锆石和英安岩 17TL-10-1 样品的 7 颗锆石开展了原位 Lu-Hf 同位素组成分析，结果显示两个样品对应的锆石 $\varepsilon_{Hf}(t)$ 值分别为 +12.1～+16.0 和 +6.8～+15.0(图 3f)，其模式年龄(T_{DM1})年龄分别为 209～366 Ma 和 249～582 Ma.

3.2　岩石地球化学特征

本研究对采自泰国东南部黎府带东南部的 25 件火山岩样品开展了全岩主—微量元素和 Sr-Nd 同位素分析，详细结果见附表 3.

玄武岩样品具有相对高的烧失量(LOI)为 1.87%～4.41%，但样品的主量元素与烧失量间无明显的线性关系，表明样品的主量元素受后期蚀变作用的影响较小.样品的 SiO_2 含量为 48.95%～52.44%，MgO 为 4.49%～7.12%，Al_2O_3 为 13.88%～16.89%，CaO 为 7.15%～10.46%，Fe_2O_3t 为 11.00%～13.57%.在 TAS 和 Co-Th 图解中样品落入粗面玄武岩和钙碱性玄武岩范围内(图 4a 和 4b).该组样品具有较高的 Nb 含量为 9.7×10^{-6}～19.0×10^{-6}，在 Nb/U-Nb 图解中落入富铌玄武岩区域(图 4c).在哈克图解中样品的 Fe_2O_3t、CaO、Al_2O_3 和 SiO_2 呈负相关关系，TiO_2、Na_2O 和 SiO_2 呈正相关关系，而 K_2O、MgO、P_2O_5 和 SiO_2 无明显相关关系(附图 1).长英质火山岩样品的 LOI 较小为 1.08%～2.95%，表明样品受后期蚀变作用较弱.样品具有较高的 SiO_2(64.44%～70.83%)和 K_2O(3.75%～4.79%)含量，较低的 MgO(0.66%～1.91%)，CaO(2.03%～3.49%)，Fe_2O_3t(3.62%～5.82%)和 TiO_2(0.61%～1.00%)含量.在 TAS 和 Co-Th 图解(图 4a 和 4b)中样品落在高钾钙碱性英安岩和流纹岩范围，并可进一步划分为 A2 型(图 4d 和 4e).在哈克图解中长英质火山岩主量元素特征总体与黎府带同期火山岩相类似，样品的 Fe_2O_3t、Al_2O_3、TiO_2、MgO、P_2O_5 和 SiO_2 呈负相关关系，而 CaO、Na_2O、K_2O 和 SiO_2 无明显相关关系(附图 1).

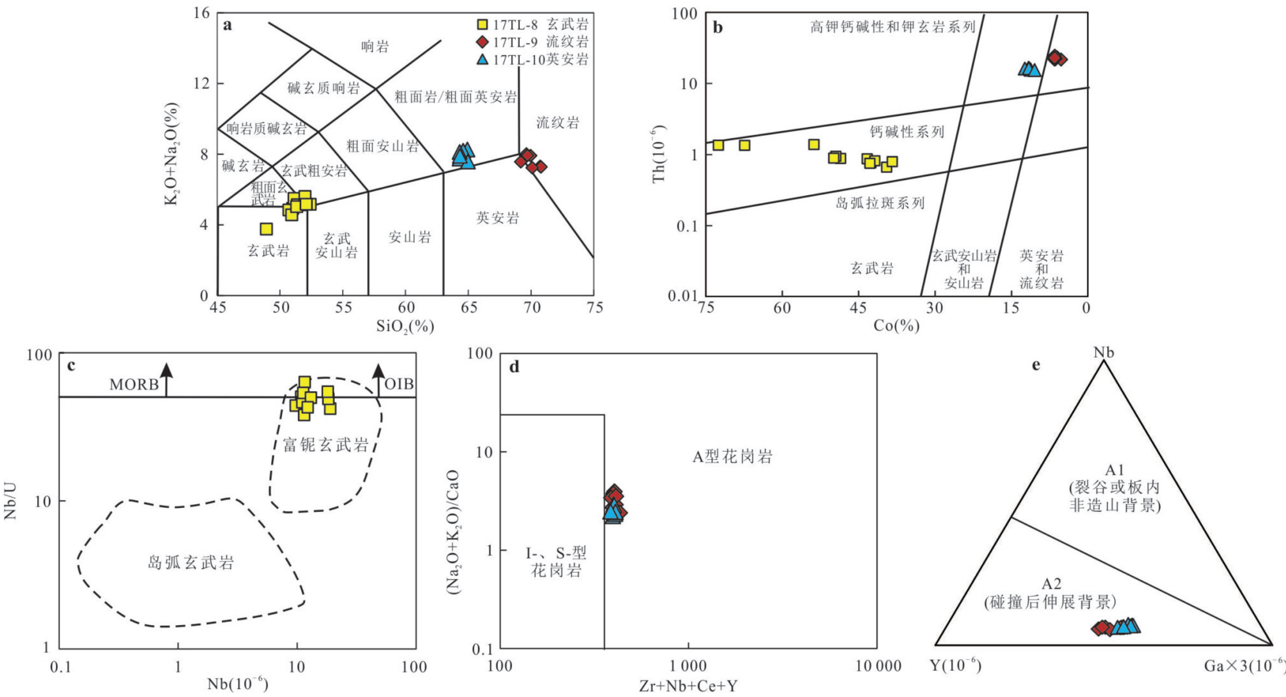

图4　泰国东南部黎府带火山岩图解

Fig.4　Diagrams for the volcanic rocks in the Loei zone of SE Thailand

a. TAS，据 Le Maitre *et al*. (1989)；b. Co-Th，据 Hastie *et al*. (2007)；c. Nb-Nb/U，据 Kepezhinskas *et al*. (1996)；d. Zr＋Nb＋Ce＋Y-(K_2O＋Na_2O)/CaO；e. Nb-Y-Ga

球粒陨石标准化稀土元素配分图显示玄武岩样品轻稀土元素含量高于重稀土元素含量，无明显的Eu异常(图5a).原始地幔标准化微量元素蛛网图显示该组样品均富集高场强元素，并具有显著的Nb、Ta、Ti正异常，这些特征与典型的富铌玄武岩相似(图5b；如 Aguillón-Robles *et al*.，2001；Castillo，2008).长英质火山岩样品的总稀土元素含量偏高，具有明显的Eu负异常(Eu/Eu^*＝0.59～0.73)(图5c).原始地幔标准化微量元素蛛网图显示样品以富集大离子亲石元素(如Rb、U)而亏损高场强元素(如Nb、Ta、Ti)为特征，并具有显著的Ba、P、Sr的负异常(图5d).通过数据收集和对比发现，本文的长英质火山岩具有与黎府带同期火山岩相类似的稀土和微量元素配分模式(图5c～5d；Qian *et al*.，2017a；Nualkhao *et al*.，2018；Shi *et al*.，2019，2021；Uchida *et al*.，2022，2023).

玄武岩样品的初始($^{87}Sr/^{86}Sr$)$_i$范围为0.703 98～0.704 00，$\varepsilon_{Nd}(t)$为＋5.0～＋5.3.而长英质火山岩样品具有相类似的初始($^{87}Sr/^{86}Sr$)$_i$比值为0.702 71～0.704 72和$\varepsilon_{Nd}(t)$值为＋4.0～＋4.2.所以这些火山岩样品的Sr-Nd同位素组成均类似区域上晚三叠碰撞后火山岩，但是明显不同于黎府带内同期花岗岩，且更靠近亏损地幔端元(图6；Qian *et al*.，2016a，2016b，2017a，2020；Wang *et al*.，2018；Uchida *et al*.，2022，2023).

4　讨论

4.1　岩石成因

在岩石形成过程中，分配系数较低的元素(如Th、La、Ce、Sm)在分离结晶过程中浓度变化缓慢，但在部分熔融过程中变化较大.本文研究玄武岩样品的Th/Ce比值为0.03～0.04，Th/La比值为0.08～0.11，远低于大陆地壳范围(Th/Ce＝～0.15，Th/La＝～0.30；Plank，2005).在La/Sm-La图解中(图7a)，样品沿着部分熔融趋势分布.样品呈现低且变化的Cr、Ni和$Mg^{\#}$值，表明这些玄武岩样品在岩浆演化的过程中可能经历了橄榄石和辉石的分离结晶作用.此外多数样品具有Sr和Eu的正异常，这些特征结合CaO/Al_2O_3和$Mg^{\#}$之间的相关性表明在岩浆演化分异的过程也存在斜长石的分离结晶作用(图7b).深部地幔的岩浆具有较低的La/Ta比值(8～15)，受到岩石圈地幔混染后该比值会迅速上升(La/Ta＞25)，而La/Sm比值几乎保持不变，但在受到地壳物质混染后La/Sm比值会迅速增

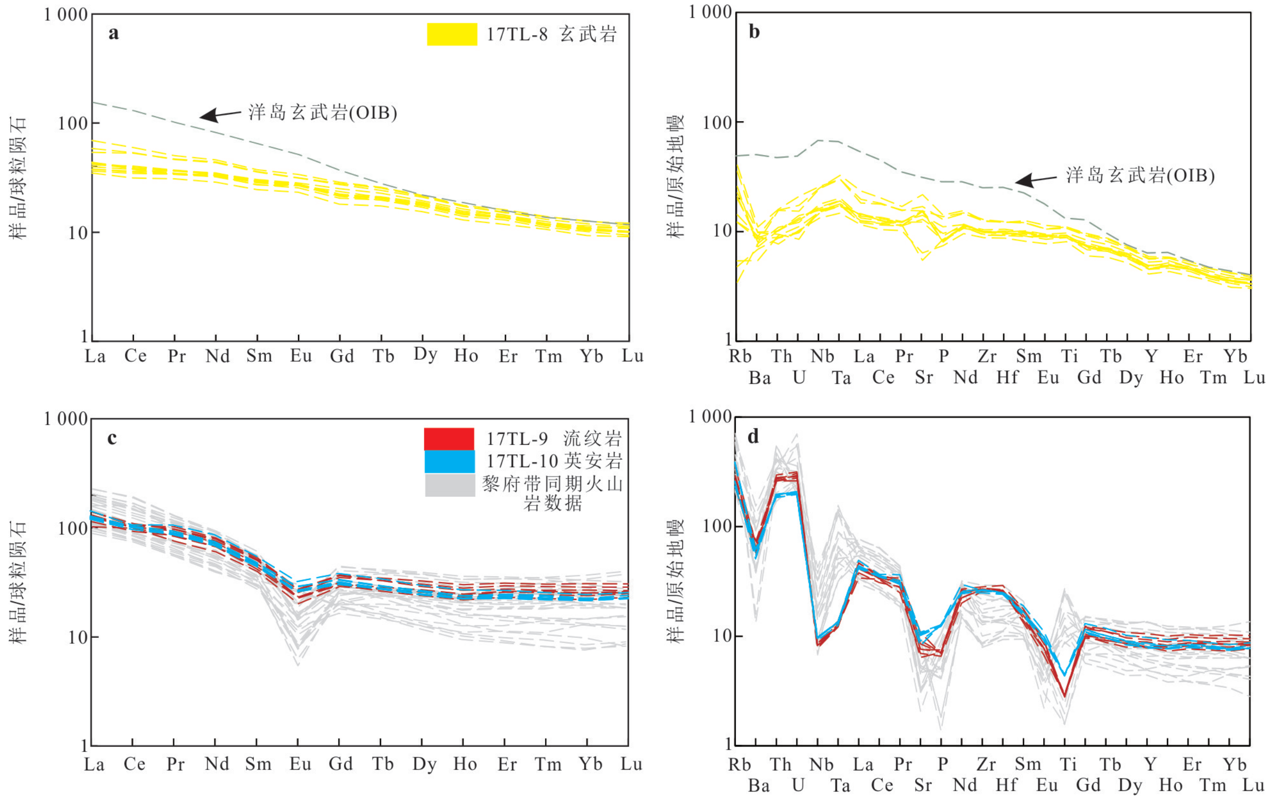

图 5　泰国东南部黎府带火山岩球粒陨石标准化稀土元素配分曲线(a、c)和原始地幔标准化微量元素蛛网图(b、d)

Fig.5　Primitive mantlenormalized spidergram (a, c) and Chondritenormalized REE pattern (b, d) for the volcanic rocks in the Loei zone of SE Thailand

背景数据引自 Qian *et al*.(2017a)；Nualkhao *et al*.(2018)；Shi *et al*.(2019，2021)；Uchida *et al*.(2022，2023)；球粒陨石和原始地幔标准化数据引自 Sun and McDonough(1989)

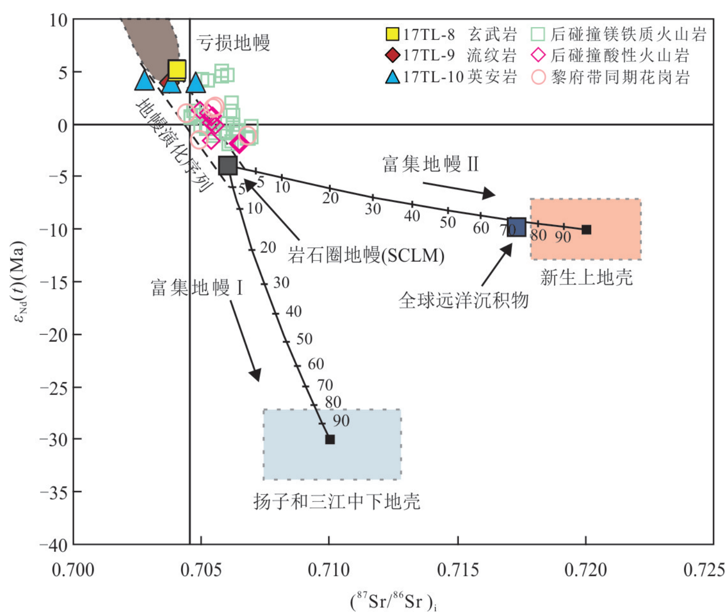

图 6　泰国东南部黎府带火山岩 Sr-Nd 同位素图解

Fig.6　Plot of Sr vs. Nd isotopic data for the volcanic rocks in the Loei zone of SE Thailand

底图据 Zi *et al*.(2012)；Qian *et al*.(2021)；背景数据来自 Qian *et al*.(2016a，2016b，2017a，2020)；Wang *et al*.(2018)；Uchida *et al*.(2022，2023)及其参考文献

大到5以上(如张招崇等, 2004).如前所述该组样品主要为一套钙碱性的富铌玄武岩,表现出与洋岛玄武岩相类似的配分模式(图5a和5b),且具有明显亏损的Sr-Nd-Hf同位素组成(图3f和图7),这些地化特征结合样品较低的La/Ta比值(11.04～14.44)和较为稳定的La/Sm比值(1.90～2.51),表明玄武岩样品来自深部地幔而非岩石圈衍生的熔体,且形成过程中无明显的地壳混染.在Th/Ta-Zr图解中(图7c),样品具OIB地幔的分布趋势,进一步说明玄武岩样品主要来自类似OIB特征的亏损软流圈地幔源区.

长英质火山岩样品同样相对富集LREE和Rb、U等大离子亲石元素,但Nb、Ta、Ti等高场强元素相对亏损且具有明显的Eu负异常,表明在岩浆演化过程中存在斜长石的分离结晶.此外样品具有较高的Na_2O+K_2O值、Ga/Al和FeOt/MgO比值且富集Zr、Nb和REE元素,这些特征和典型的A型花岗岩相似,在图4d中样品也集中落入了A型花岗岩区域(如Whalen *et al*, 1987).A型花岗岩与I型和S型花岗岩相较具有较高的形成温度(如Collins *et al.*, 1982),通过计算研究得出该套长英质火山岩样品的锆石饱和温度在805～836 ℃(平均温度为821 ℃),这个温度高于S型花岗岩的平均温度764 ℃和I型花岗岩的平均温度781 ℃(King *et al.*, 1997; 刘昌实等, 2003).因此,上述特征均表明本研究长英质火山岩样品具有A型花岗岩的特征.

目前对于具有A型特征的长英质火山岩的成因主要包括了:(1)下地壳镁铁质岩石的部分熔融(Whalen *et al.*, 1987; Frost and Ronald Frost, 1997; 张旗和李承东, 2012);(2)地幔碱性玄武质岩浆的分离结晶作用(Vander Auwera *et al.*, 2003; Namur *et al.*, 2011);(3)幔源基性岩浆与地壳来源花岗质岩浆的混合作用(Kerr and Fryer, 1993; Mingram *et al.*, 2000).如前所述长英质火山岩样品具有相对较高的SiO_2(64.44%～70.83%)和较低的MgO(0.66%～1.91%),Fe_2O_3t(3.62%～5.82%)和TiO_2(0.61%～1.00%)含量,富集大离子亲石元素(图5c和5d),这些特征与幔源岩浆作用的产物不相符.在图7d中,该套长英质火山岩均落入贫粘土物质源区并靠近玄武质派生熔体端元(Sylvester, 1998).此外,这些样品还与区内同期的玄武岩样品具有近乎一致的形成年龄和相类似的Sr-Nd-Hf同

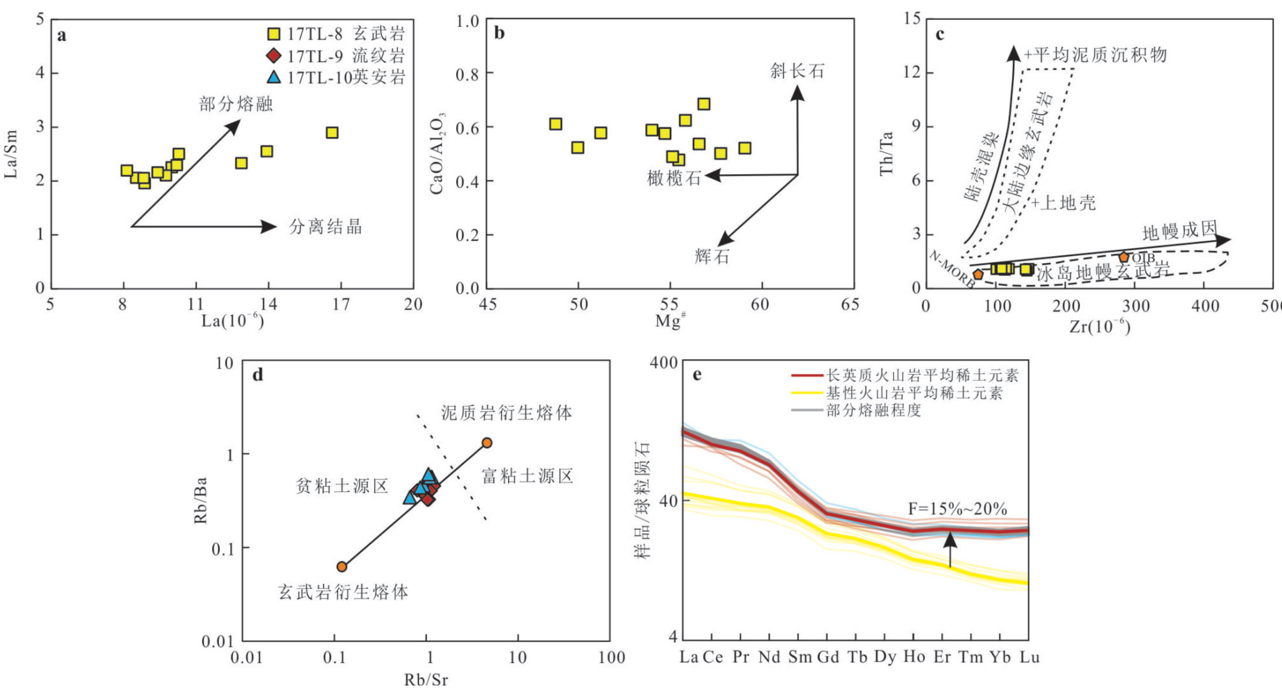

图7　泰国东南部黎府带火山岩La-La/Sm (a)、$Mg^{\#}$-CaO/Al_2O_3 (b)、Zr-Th/Ta (c)、Rb/Sr-Rb/Ba(d)和部分熔融程度(e)模拟图解

Fig.7　Plots of La-La/Sm (a), $Mg^{\#}$-CaO/Al_2O_3 (b), Zr-Th/Ta (c), Rb/Sr-Rb/Ba (d) and partial melting degree simulation (e) for the volcanic rocks in the Loei zone of SE Thailand

图c据Liu *et al.* (2021); 图d据Sylvester (1998)

位素组成，这些特征表明这套长英质火山岩可能具有与该套玄武岩相类似的源区特征．本文基于平衡部分熔融模型进行模拟，选取了玄武岩样品的稀土元素均值作为固相母岩，而本套长英质火山岩样品的稀土元素均值落在玄武岩部分熔融程度为15%～20%的范围中（图7e），这一结果表明黎府带长英质火山岩可以是该套新底侵的基性岩经15%～20%低程度部分熔融而形成．

4.2　构造意义

东南亚地区已有的放射虫古生物记录、岩石年代学结果、地球化学及地质野外观测资料表明古特提斯洋在晚二叠世至早三叠世期间持续向东俯冲，并在早三叠世（～237 Ma）左右最终闭合，发生由古特提斯洋闭合向滇缅马与印支陆块碰撞的构造转换（如 Feng *et al.*, 2004；Ito *et al.*, 2016；Wang *et al.*, 2018；Yu *et al.*, 2023）．这之后出露的火山岩及同期碎屑锆石普遍存在两期年龄峰值，表明在中－晚三叠世（～237～230 Ma），东南亚主要陆块拼合导致了地壳增厚，并沿着古特提斯缝合带发生了同碰撞的岩浆作用（如 Peng *et al.*, 2013；Qian *et al.*, 2016a, 2016b, 2017a）．之后在晚三叠世（～230～200 Ma），发生板片断离及造山带垮塌，引起软流圈上涌从而导致了大规模的碰撞后岩浆作用的发生，并在泰国、柬埔寨、马来半岛等地区形成了以中部和东部花岗岩省为代表的碰撞后花岗岩（图8a；如 Searle *et al.*, 2012；Oliver *et al.*, 2014；Wang *et al.*, 2016；Uchida *et al.*, 2023；余永琪等，2024）．而本文研究的泰国东南部黎府带内玄武岩和长英质火山岩的形成时代为晚三叠世（204～200 Ma），在时代上属于碰撞后阶段，且与区域上临沧及庄他武里－东马来以及柬埔寨地区碰撞后岩浆作用的形成时代相一致（如 Peng *et al.*, 2006；Wang *et al.*, 2010；Dong *et al.*, 2013；Qian *et al.*, 2017b；Uchida *et al.*, 2022, 2023；余永琪等，2024）．此外，玄武岩和长英质火山岩具有相似的亏损的Sr-Nd-Hf同位素组成，部分熔融模拟结果表明长英质火山岩可能来源于新底侵的基性岩经低程度部分熔融而形成，这些特征也与双峰式火山岩的组合相类似（如 Davies and Macdonald., 1987；Frisch *et al.*, 2000；Li *et al.*, 2021）．

如前所述，黎府带玄武岩和长英质火山岩样品分别具有富铌玄武岩和A型特征，地球化学特征也表明它们分别来自具有OIB特征的亏损地幔源区和新底侵基性岩的部分熔融．一般富铌玄武岩的形成通常与局部或区域的伸展背景相联系，这种伸展作用可以是弧后盆地伸展，也可以是碰撞后伸展或裂谷背景（如 Brown et *al.*, 2002；Wang *et al.*, 2010；Liu *et al.*, 2017）．在弧后伸展背景下富铌玄武岩通常表现出E-MORB的地球化学特征且具有Nb和Ta的负异常，同时具有较为亏损的同位素组成（如 Cawood and Williams, 1988；Fan *et al.*, 2010；Liu *et al.*, 2021）．而本文研究的玄武岩样品形成于碰撞后阶段，且具有明显的Nb和Ta正异常（图5a和5b），这些特征与弧后盆地背景的起源不相符（如 Qian *et al.*, 2016b）．在地球化学判别图解（图9a）中，玄武岩样品也分布在板内玄武岩区域．此外具有A型特征的长英质火山岩也同样形成于地壳减薄的伸展背景，根据构造背景的差异进一步分为A1型和A2型两类（Eby, 1990, 1992），其中A1型指示裂谷或板内的非造山背景，A2型指示碰撞后的伸展背景．在地球化学判别图解中（图4e），本文研究样品落入A2型区域，而在Rb-（Y＋Nb）图解中（图9b），样品集中落入碰撞后背景区域内．此外区域的地质资料表明，泰国的三叠纪地层中发育有包含浅海沉积物的地堑盆地（如 Ridd *et al.*, 2011），这些特征进一步说明该套类似双峰式的火山岩可能形成于碰撞后伸展背景．如前所述在中－晚三叠世，印支陆块与滇缅马陆块发生碰撞导致岩石圈因挤压而缩短增厚，而这之后发生板片断离及造山带垮塌，促使软流圈地幔上涌，形成了区域内呈带状展布的碰撞后火山岩系列，如临沧－素可泰－庄他武里带内的花岗岩体及相关火山岩，其形成时代也主要集中在230～200 Ma（Barr *et al.*, 2000, 2006；Srichan *et al.*, 2009；Wang *et al.*, 2010, 2016；Qian *et al.*, 2013, 2016a, 2017b, , 2022）．此外，在研究区接壤的柬埔寨地区也同样出露有200 Ma左右的花岗质岩石（如 Uchida *et al.*, 2023），均证实了在晚三叠世晚期该区还存在大量的岩浆作用．因此，本研究认为随着软流圈的上涌，在研究区形成了一套具有OIB特征的富铌基性岩，同时促使这套新底侵的基性岩发生低程度的部分熔融从而形成了本研究中的长英质火山岩（图10）．

泰国区域内发育了大规模与古特提斯演化相关的火成岩，它们的岩浆记录可从石炭纪追溯至三叠纪，本文将已发表的与黎府带及其周缘火山岩带相关的年代学数据进行了汇总表明黎府带最早的

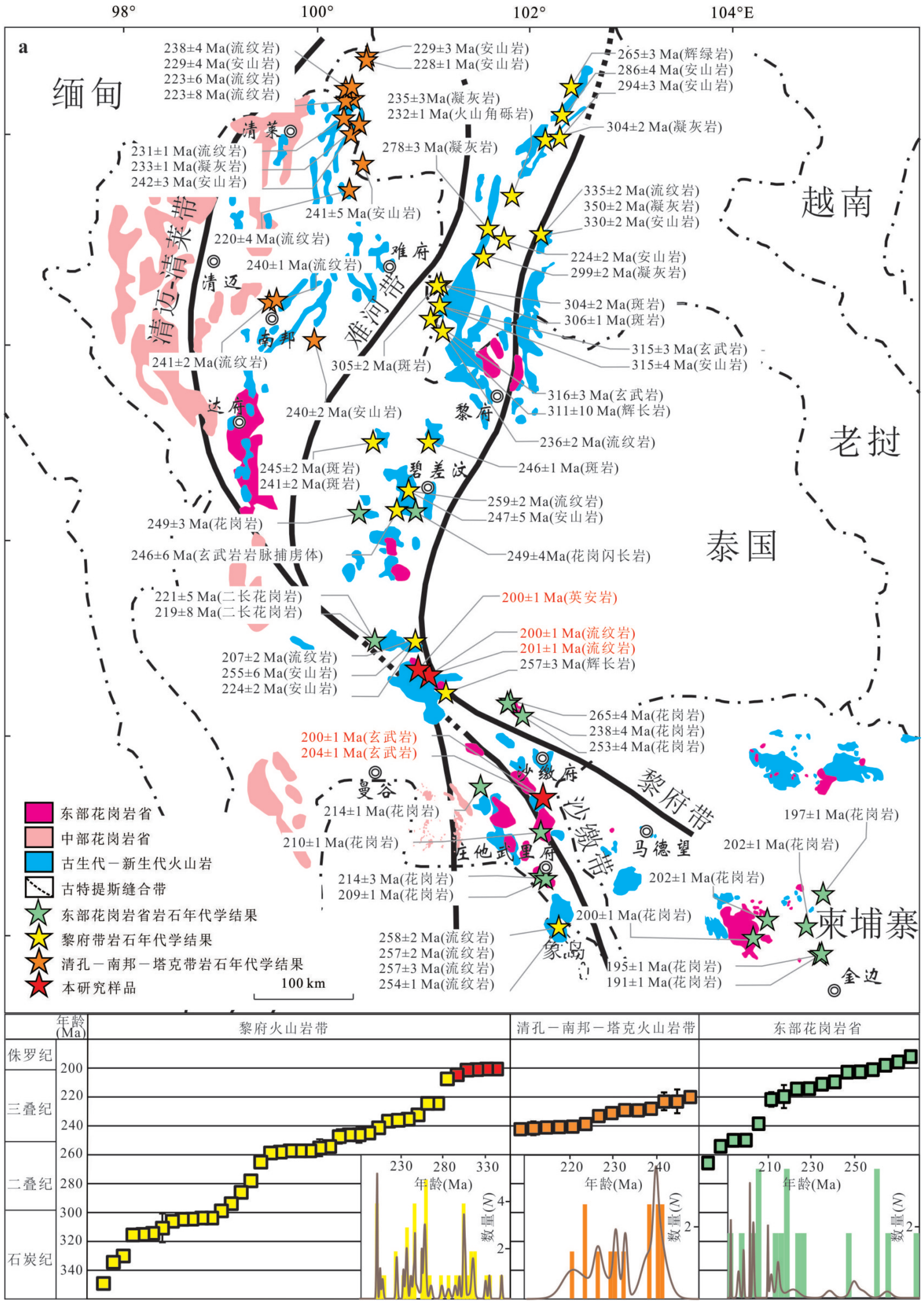

图8　黎府带及其邻区火成岩年龄分布图(a)和年龄频谱图(b)

Fig.8　The distribution (a) and spectrogram (b) of formation ages for the igneous rocks along the Loei zone and surrounding areas

年代学数据来自 Barr *et al*.(2000, 2006); Srichan *et al*.(2009); Qian *et al*.(2013, 2015, 2016a, 2016b, 2017a, 2021, 2022); Kamvong *et al*.(2014); Salam *et al*.(2014); Arboit *et al*.(2016); Fanka *et al*.(2016, 2018); Yang *et al*.(2016); Shi *et al*.(2019, 2021); Wang *et al*.(2020), Nualkhao *et al*.(2018); Uchida *et al*.(2022, 2023)和本研究

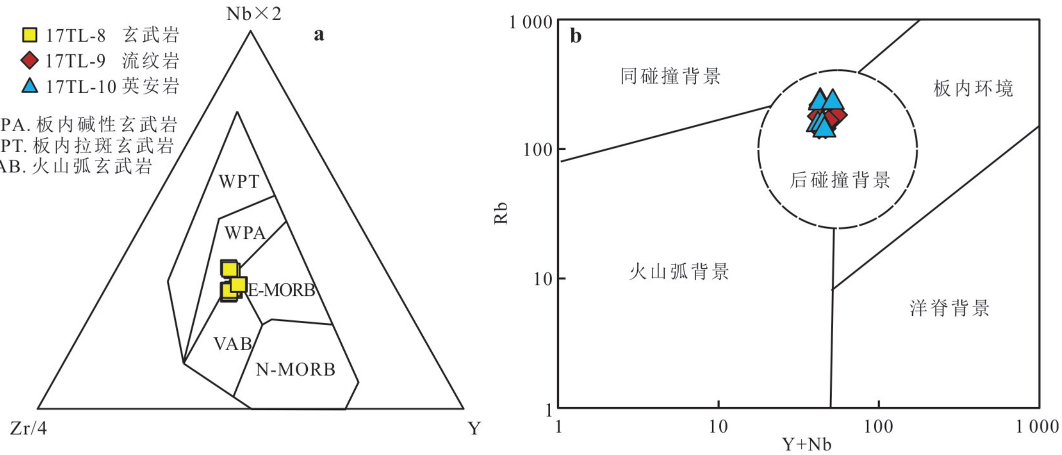

图 9　泰国东南部黎府带火山岩构造环境判别图

Fig.9　Tectonic discrimination diagrams for the volcanic rocks in the Loei zone of SE Thailand

图 a 据 Meschede (1986)；图 b 据 Pearce *et al*. (1996)

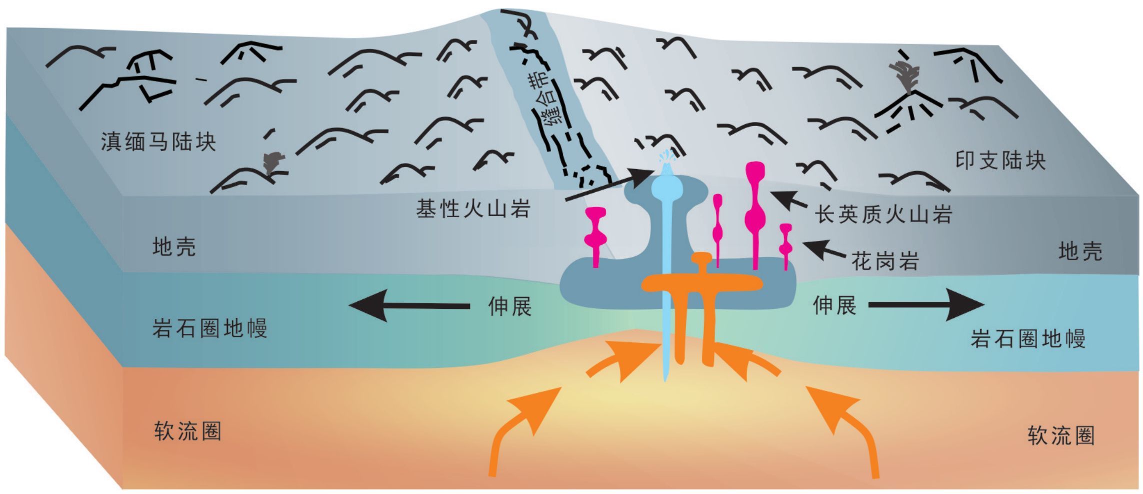

图 10　东古特提斯晚三叠世后碰撞伸展背景岩浆活动示意图

Fig.10　Tectonic cartoon showing the Paleotethyan extensional regime following the post-collision during the Late Triassic

岩浆作用记录主要集中在 350～304 Ma 或更早，并一直持续至中三叠世(图 8a；Kamvong *et al*., 2014；Qian *et al*., 2015；Yang *et al*., 2016；Shi *et al*., 2021)．其中岛弧岩浆作用则主要分布在泰国境内黎府至碧差汶地区，年龄集中在 278～241 Ma (Kamvong *et al*., 2014；Salam *et al*., 2014；Fanka *et al*., 2016；Shi *et al*., 2019；Wang *et al*., 2020；Qian *et al*., 2022)．在老挝地区出露的部分 237～232 Ma 的火山岩被解释为同碰撞岩浆作用的产物(Shi *et al*., 2019, 2021)．而泰国 Khao Khwang 褶皱带地区出露的 224～207 Ma 的火山岩和泰国东南部及柬埔寨西部地区出露的 232～191 Ma 花岗岩均被解释为碰撞后岩浆作用的产物(Arboit *et al*., 2016；Uchida *et al*., 2022, 2023)．而本文研究的泰国东南部黎府带火山岩的形成时代为约 200 Ma，是该构造带内最晚期的岩浆记录，同时也是东古特提斯洋闭合后最末期的岩浆作用．此外通过区域内的对比和分析发现，黎府带与素可泰地区清孔－南邦－塔克火山岩带具有相类似的三叠纪年龄谱系(图 8b)，证实了黎府带在中－晚三叠世时期也同样记录了碰撞及碰撞后的岩浆作用．

5　结论

(1) 泰国东南部黎府带玄武岩和长英质火山岩的锆石 U-Pb 定年为 204～200 Ma，均形成于晚三叠世，区内构成类似双峰式组合．

(2) 泰国东南部黎府带晚三叠世火山岩具有相似的 Sr-Nd-Hf 同位素组成，其中玄武岩样品源自具

OIB 特征的亏损地幔源区,而长英质火山岩可能源自该套新底侵基性岩的低程度部分熔融.

(3)泰国东南部黎府带晚三叠世火山岩形成于东古特提斯碰撞后的伸展背景,为东古特提斯洋碰撞闭合后最晚期的岩浆作用.

附件资料见地球科学官网:https://doi.org/10.3799/dqkx.2024.112

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