

柬埔寨西部晚三叠世花岗岩成因及其与东古特提斯的关联

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摘要: 中南半岛晚三叠世岩浆作用对于理解东古特提斯洋闭合后的构造体制及转换具有重要的意义, 但是以往的研究多集中在滇西及泰-老-越地区, 对其南延的柬埔寨境内同期火成岩的成因及其动力学机制尚不明确, 其与东古特提斯巨型火成岩带的关系也未能得到有效限定。因此, 本研究通过系统的野外考察、锆石年代学与全岩元素-同位素地球化学分析, 系统揭示了柬埔寨西部科卓尔花岗岩的源区特征及构造属性, 为东古特提斯构造域碰撞后的演化及延伸提供新的证据。研究表明, 柬埔寨西部的花岗质岩石主要由黑云母二长花岗岩和花岗闪长岩组成, 锆石 U-Pb 年龄为 209~203 Ma, 均为晚三叠世晚期。其中黑云母二长花岗岩样品, 具有高钾-钙碱性特征, 其 SiO₂ 含量为 69.7%~72.0%, K₂O 含量为 3.24%~5.35%, 锆石原位 $\epsilon_{\text{Hf}}(\text{t})$ 值在 -2.2~+12.7 之间, $\epsilon_{\text{Nd}}(\text{t})$ 值为 -4.2~ -1.5。而花岗闪长岩样品 SiO₂ 含量为 63.1%~63.5%, K₂O 含量 2.25%~3.04%, $\epsilon_{\text{Hf}}(\text{t})$ 值为 +0.4~+5.4, $\epsilon_{\text{Nd}}(\text{t})$ 值为 -2.6。地球化学特征表明, 这些晚三叠世花岗质岩石为中-高分异的 I 型花岗岩, 其源区具有以新生镁铁质下地壳为主, 并有一定的变沉积岩的混合, 它们是古特提斯洋闭合后, 滇缅马与印支陆块碰撞后软流圈上涌引起的下地壳部分熔融的产物。区域年代学数据对比表明东部花岗岩省具有自

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230 Ma 持续至 200 Ma 的岩浆活动序列，表明柬埔寨西部的科卓尔花岗岩可能与东特提斯巨型火成岩带东部花岗岩省向东的延伸有关，它们共同响应了东古特提斯碰撞后深部动力学过程。

关键词：柬埔寨西部；晚三叠世；碰撞后岩浆作用；锆石 U-Pb 年代学；元素-同位素地球化学

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Late Triassic Magmatism in Western Cambodia and Its Relationship with the Eastern Paleotethys

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Abstract: Late Triassic magmatism in the Indochina Block is significance for understanding the tectonic regime and transition following the closure of the Eastern Paleotethys Ocean. However, previous studies have predominantly focused on western Yunnan and Thailand-Laos-Vietnam region. The petrogenesis and geodynamic mechanisms of contemporaneous granitic rocks extending southward into the Cambodia remain poorly constrained, and their relationship with the giant Eastern Paleotethyan igneous belt has not been effectively defined. Therefore, this study, through systematic field investigations, zircon U-Pb geochronology, and whole-rock elemental and isotopic geochemical analyses, systematically reveals the source characteristics and tectonic affinity of the Kchol granites in western Cambodia and provides a new evidence for the post-collisional evolution and extension of the Eastern Paleotethyan tectonic domain. Research suggests that the granitoid rocks in western Cambodia are primarily composed of biotite monzogranite and granodiorite, with zircon U-Pb ages of 209–203 Ma, belonging to the late Late Triassic. The biotite monzogranite samples are high-K calc-alkaline, with SiO₂ contents of 69.7%–72.0%, K₂O contents of 3.24%–5.35%, zircon in-situ $\epsilon_{\text{Hf}}(t)$ values ranging from –2.2 to +12.7, and $\epsilon_{\text{Nd}}(t)$ values of –4.2 to –1.5. In contrast, the granodiorite samples have SiO₂ of 63.1%–63.5%, and K₂O of 2.25%–3.04%, with $\epsilon_{\text{Hf}}(t)$ values of +0.4 to +5.4, and $\epsilon_{\text{Nd}}(t)$

value of -2.6 . Geochemical characteristics indicate that these Late Triassic granitoids are medium- to highly-fractionated I-type granites. Their source is characterized by a hybrid nature, dominated by juvenile mafic lower crust with a subordinate contribution from metasedimentary rocks. These granites are interpreted as the products of partial melting of the lower crust, triggered by asthenospheric upwelling in a post-collisional setting following the closure of the Paleo-Tethys Ocean and the collision between the Sibumasu and Indochina blocks. Regional geological data and geochronological comparisons reveal a magmatic sequence in the Eastern Granite Province spanning from ~ 230 Ma to ~ 200 Ma. This indicates that the Kchol granite in western Cambodia may represent an eastward extension of the Eastern Granite Province within the giant Eastern Paleotethyan igneous belt. They likely responded to a post-collisional deep geodynamic process in the Eastern Paleo-Tethys.

Keywords: Western Cambodia; Late Triassic; Post-collisional magmatism; Zircon U-Pb geochronology; Elemental and isotopic geochemistry

引言

古特提斯洋是晚古生代-早中生代期间存在于东基梅里大陆和东南亚陆块群之间的主体大洋，其范围西至现今欧洲阿尔卑斯附近，向东经过中亚地区延伸至我国西南地区，并向南穿过泰国、老挝，进入马来半岛等地(如 Qian *et al.*, 2017, 2025a; Wang *et al.*, 2016, 2018, 2024; Metcalfe, 2021)。其中东南亚地区位于欧亚板块，印澳板块及太平洋板块交汇区域，隶属于特提斯构造域东段，保存了完整的古特提斯洋构造演化的构造、沉积、岩浆和变质记录，随着古特提斯洋的俯冲消减和闭合，东基梅里的滇缅马地块与华夏地块群的印支陆块发生拼贴，进而形成了现今东南亚的主体构造格架(如 Metcalfe, 1996, 2006, 2011, 2013, 2021; 钟大赟, 1998; Yin and Harrison, 2000; Cawood *et al.*, 2018; Sone and Metcalfe, 2008; Sone *et al.*, 2012; Oliver *et al.*, 2014; Wang *et al.*, 2016, 2018, 2022; Zhao *et al.*, 2016; Zhang *et al.*, 2019; Yu *et al.*, 2022, 2023; 徐畅等, 2020; 李慧玲等, 2023; 闫秋彤等, 2025)。同时在东南亚地区形成了一条沿临沧-素可泰-庄他武里-东马来岛弧系统展布，南北走向，长约 3000 km 的巨型火成岩带，系统记录了东古特提斯洋的俯冲消减以及随后滇缅马与印支/思茅的拼合过程(图 1a; Qian *et al.*, 2017, 2020, 2021, 2025a; Liu *et al.*, 2020; Yu *et al.*, 2022, 2023; Zhang *et al.*, 2023)。目前的研究认为该巨型火成岩带中出露的花岗岩从东至西可以依次划分为东、中、西 3 个不同的花岗岩省，其中东部花岗岩省主要分布于老挝北部、泰国东部以及东马来半岛东段，中部花岗岩省主要分布在泰国西部、西马来半岛并延伸至印度尼西亚的“锡岛”地区，而西部花岗岩省则主要出露于泰国西南部与缅甸东部(图 1a; 如 Cobbing, 2005; Searle *et al.*, 2012; 余小清等, 2021; Qian *et al.*, 2025a)。此外，也有学者认为该巨型火成岩带可以延伸至苏门答腊岛中部，并可能影响到了柬埔寨西部地区(如 Nong *et al.*, 2022; Wang *et al.*, 2024; Qian *et al.*, 2025b)。

柬埔寨位于印支陆块西南缘，其西部受到贡布褶皱带影响，在印支运动期间经历了两个主要构造挤压事件，形成大量褶皱、逆冲构造及中生代火山岩和侵入岩，该褶皱的形成可能与巽他地块周围的碰撞事件有关(如 Booth and Sattayarak, 2011; Fyhn *et al.*, 2016)。柬埔寨贡布省及金边以北出露有晚古生代至晚三叠世的花岗质岩岩体，以往的研究认为这些岩体主要为经历过剪切作用的黑云母花岗岩所组成，并认为其成因可能与东古特提斯洋的碰撞-闭合演化有关(如 Cheng *et al.*, 2019)。但是这些研究仅局

限于有限的年代学数据上，并未系统厘定它们的地化特征、岩石成因及构造归属，此外这些岩浆作用与东古特提斯巨型火成岩带的关系也未能得到有效限定。

为解决上述问题，本研究对柬埔寨西部菩萨-贡布褶皱带内出露的科卓尔(Kchol)侵入岩体开展了详细的野外地质调查和样品采集，并在该岩体中新识别出一套保存完好的晚三叠世黑云母二长花岗岩与花岗闪长岩组合，并针对这些岩石开展了详细的岩相学、锆石 U-Pb 年代学、锆石原位 Hf 同位素、全岩主-微量元素及 Sr-Nd 同位素分析，综合探明它们的成因属性及构造背景。此外，结合已收集到的东部花岗岩省的年代学及地球化学数据进行综合对比与讨论，为柬埔寨西部晚三叠世东古特提斯岩浆作用特征以及巨型火成岩带的东延提供新的约束。

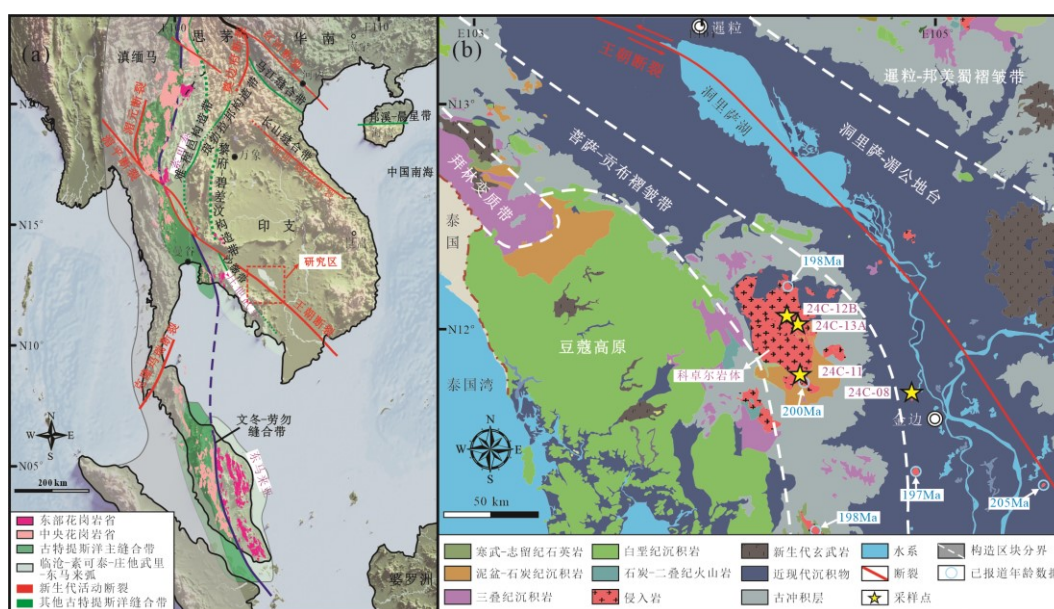


图 1 东南亚地区区域构造图(a)及柬埔寨西部研究区地质图(b)

Fig.1 Regional tectonic map of Southeast Asia (a) and geological map of the study area in western Cambodia (b)

图 a 据 Wang *et al.* (2018); Qian *et al.* (2025a); 图 b 据 UN. ESCAP. (1993)

1 区域地质背景及岩相学特征

柬埔寨位于中南半岛西南端，东特提斯构造域中部，是印支陆块西南缘的关键组成部分，柬埔寨西部的贡布褶皱带位于滇缅马与印支陆块的主缝合带(昌宁-孟连-因他暖-文东-劳勿缝合带)的东南延伸部位，该缝合带系统记录了古特提斯洋在晚二叠世-中三叠世的俯冲闭合及随后的陆-陆碰撞的响应(Wang *et al.*, 2021; Cheng *et al.*, 2019)。菩萨-贡布(Pursat-Kampot)褶皱带作为泰国黎府带的延续，其褶皱和逆冲构造形成于印

支造山期，与滇缅马和印支陆块的碰撞拼贴有关(如 Barber *et al.*, 2011; Nong *et al.*, 2022)。柬埔寨东北缘被认为是越南昆嵩地体的一部分，主要由前寒武纪结晶基底及盖层组成，代表了印支陆块的古老基底(Hutchison, 1989)。其西缘出露有与古特提斯演化有关的拜林杂岩，该杂岩体主要由角闪岩、基性片麻岩、变辉长岩及长英质火成岩组成(Udchachon *et al.*, 2018)。目前已有研究认为该杂岩体代表了古特提斯弧后盆地的蛇绿混杂岩序列(Hara *et al.*, 2020)。柬埔寨北部与东部区域主要受印支期暹粒-邦美蜀(Siam Reap-Buon Ma Thuot)褶皱带的影响，出露三叠-侏罗纪花岗岩和一套中生代沉积岩(UN. ESCAP, 1993)。柬埔寨中部主要出露第四纪河流沉积物，沿洞里萨-湄公地台分布，同时 NW-SE 走向的王朝断裂带由泰国西北部延伸至柬埔寨境内，穿过洞里萨湖，到达越南南部，是区内重要的一条左行走滑断裂带(图 1b; Morley *et al.*, 2013)。该断裂带在泰国西北部出露了约 5km 宽的强糜棱岩化高级变质岩及少量未变形的岩浆岩组合，即兰桑片麻岩杂岩(Lan Sang gneiss complex)(Lacassin *et al.*, 1997)，Österle *et al.* (2019) 对该杂岩体中的过铝质高钾变质岩开展了锆石和独居石年代学分析，限定了与王朝断裂左行走滑剪切相关的韧性变形始于 46-37 Ma，并在 33-30 Ma 停止。

研究区位于柬埔寨西部菩萨省至贡布省地区，区内主要出露一套泥盆-石炭纪的沉积地层，其中泥盆纪地层主要以页岩、砂质页岩、砂岩、泥灰岩和硅化页岩为主，下石炭世砂质灰岩以角度不整合覆盖其上。中生代地层以三叠-白垩纪沉积地层为主，其中三叠纪地层主要以角砾岩、砂岩、泥岩与凝灰岩互层为特征，主要出露于拜林及其以东的部分地区，其西部的中三叠世灰岩向上演变为砂岩和粉砂岩。白垩纪地层出露于柬埔寨西部豆蔻高原大部分地区，是一套陆相沉积，由红色砂岩、粉砂岩和泥岩组成。第四纪河流相及湖泊相沉积物在湄公河流域及洞里萨湖所在的中部平原广泛分布。中-晚三叠世至侏罗纪是区内岩浆作用的主要时期，在柬埔寨主要表现为其西部及北部的晚三叠世花岗岩侵入体以及侏罗纪的浅灰色流纹岩、英安岩、凝灰岩与火山碎屑岩(图 1b; UN. ESCAP, 1993)。此外，在柬埔寨菩萨-贡布褶皱带内还出露有晚古生代至中生代的侵入岩岩体，主要为一套角闪岩、花岗闪长岩及黑云母花岗岩的组合，同期的次火山岩群及部分花岗闪长岩侵入体则主要分布于该国北部区域(Tien, 1991)。

本文研究样品采自柬埔寨西部奥拉尔山(Phnom Aural)附近出露的科卓尔侵入岩体中，该岩体在区域内呈岩株状产出，与泥盆纪-石炭纪砂岩层呈明显的侵入接触关

系。黑云母二长花岗岩野外露头呈灰白色，中-细粒半自形粒状结构，镜下可见主要矿物组合为石英(25~30%)、碱性长石(30~35%)、斜长石(25~30%)及黑云母(10%)，副矿物可见磷灰石和锆石，石英多以他形粒状充填于长石间隙，钾长石发育卡式双晶，斜长石发育聚片双晶且部分发生轻微绢云母化。花岗闪长岩露头呈灰色至浅灰色，具中粒半自形粒状结构，主要矿物为斜长石(40~45%)、石英(20~25%)、钾长石(10~15%)及角闪石(10%)和少量黑云母(5%)，副矿物可见磷灰石。镜下可见斜长石环带结构，部分斜长石具绿帘石化，黑云母和角闪石共生且边缘可见暗化蚀变(图 2)。



图 2 柬埔寨西部花岗岩野外露头(a-b)和正交偏光镜下显微岩相学特征(c-f)

Fig.2 Field photo (a-b) and photomicrographs (c-f) for the granites in western Cambodia

矿物缩写: Pl: 斜长石; Kfs: 钾长石; Qz: 石英; Hbl: 普通角闪石; Bt: 黑云母

2 锆石年代学研究和地球化学特征

2.1 锆石 U-Pb 年代学特征

本次研究选取了 4 个代表性样品开展了 LA-ICP-MS 锆石 U-Pb 定年和原位的 Lu-Hf 同位素分析，分析方法详见附件 1，测试数据见附表 1-2。这些样品的锆石颗粒

均为透明至半透明的具棱柱状的晶体，长度为 80~240 μm 之间，长宽比为 1:1~3:1，其 CL 图像均显示明显的岩浆成因震荡环带，其对应的 Th/U 比值较高，分别为 0.29~1.33，0.22~0.54，0.27~0.74 和 0.12~1.01 (图 3a~d)。样品 24C-08-1，24C-11-1，24C-12B-1 均为细粒黑云母二长花岗岩，24C-08-1 采自金边北部达比(Ta Pich)地区，其中 12 颗锆石 $^{206}\text{Pb}/^{238}\text{U}$ 年龄较为接近，为 208~197 Ma，其加权平均年龄为 202.9 \pm 2.3 Ma (MSWD=1.5, N=12; 图 3a)。样品 24C-11-1 和 24C-12B-1 采自贡布省科卓尔岩体中，年龄集中于 211~206 Ma 和 208~200 Ma，加权平均年龄分别为 208.6 \pm 1.4 Ma (MSWD=0.58; N=16; 图 3b)，203.7 \pm 1.3 Ma (MSWD=0.91, N=17; 图 3c)。花岗闪长岩样品 24C-13A-1 采自科卓尔岩体南部，其 20 颗锆石的 $^{206}\text{Pb}/^{238}\text{U}$ 年龄为 206~199 Ma，加权平均年龄为 203.4 \pm 1.2 Ma (MSWD=0.32, N=20; 图 3d)。

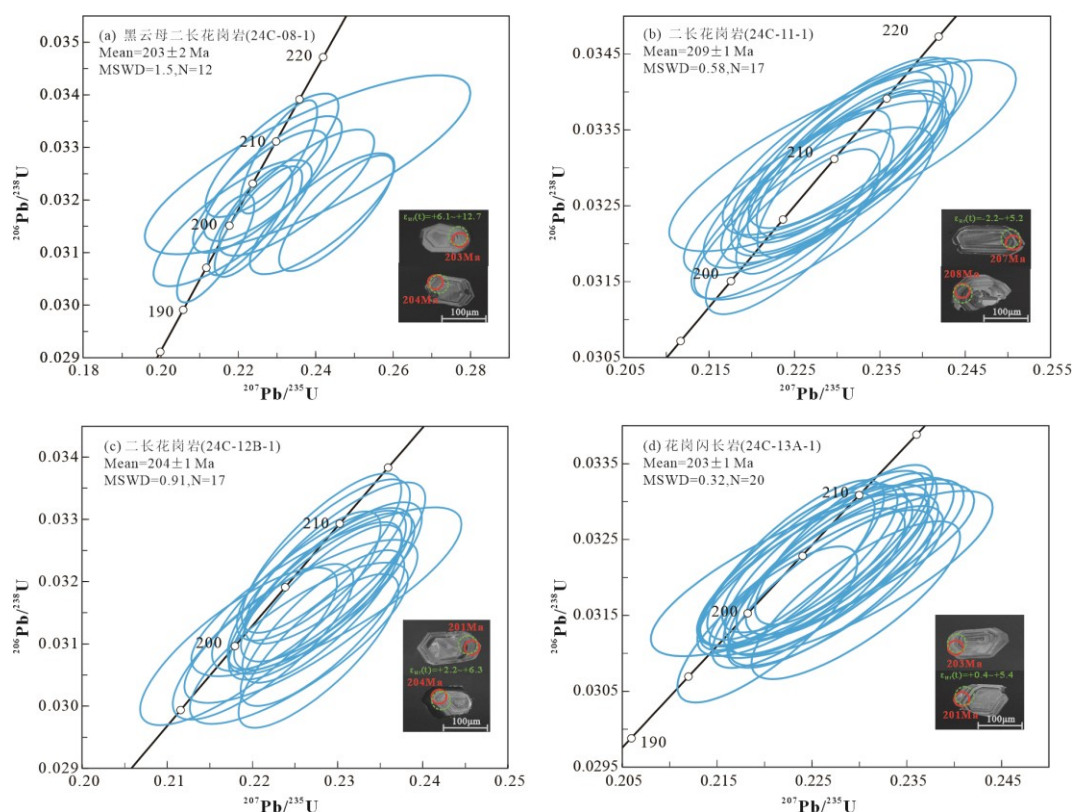


图 3 柬埔寨西部花岗岩锆石 U-Pb 年龄谱和图

Fig.3 U-Pb Concordia diagram of zircon from the granite in western Cambodia

2.2 全岩主-微量元素地球化学特征

本研究所采集的所有花岗岩样品的烧失量为 0.97%~2.86%，且大多数小于 1.5%，表明这些样品并未受到明显的后期风化蚀变作用影响。黑云母二长花岗岩样品的 $\text{SiO}_2 = 69.7\% \sim 72.0\%$, $\text{Al}_2\text{O}_3 = 13.7\% \sim 15.4\%$, $\text{K}_2\text{O} = 3.24\% \sim 5.35\%$, $\text{Na}_2\text{O} = 2.65\% \sim 3.14\%$, $\text{Fe}_2\text{O}_3^{\text{T}} = 2.02\% \sim 2.54\%$, $\text{MgO} = 0.23\% \sim 0.57\%$; 花岗闪长岩样品的 SiO_2 以及 Na_2O 、 K_2O 含量相对降低，其 $\text{SiO}_2 = 63.1\% \sim 63.5\%$, $\text{Al}_2\text{O}_3 = 15.5\% \sim 15.7\%$, $\text{K}_2\text{O} = 2.25\% \sim 3.04\%$, $\text{Na}_2\text{O} = 2.10\% \sim 2.56\%$, $\text{Fe}_2\text{O}_3^{\text{T}} = 4.93\% \sim 5.30\%$, $\text{MgO} = 2.06\% \sim 2.17\%$ ，所有样品均具有较高的 K_2O 含量(2.25%~5.35%)。在 QAP 图解中(图 4a)，上述样品均落在二长花岗岩及花岗闪长岩区域内，且均属于高钾-钙碱性系列(图 4c)。在图 4d-f 中，这些花岗岩样品均落入 I-、M-、S-型花岗岩区内。

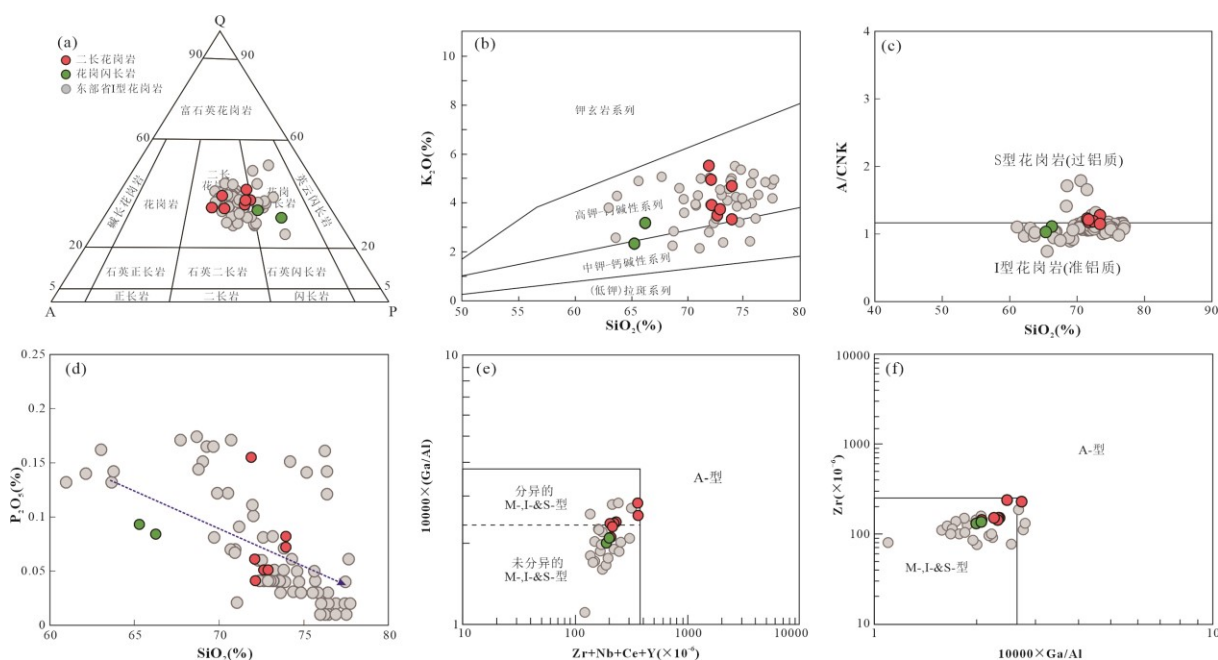


图 4 柬埔寨西部花岗岩 (a) QAP、(b) K_2O - SiO_2 、(c) A/CNK - SiO_2 、(d) P_2O_5 - SiO_2 、(e) $10000 \times (\text{Ga}/\text{Al}) - (\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ 和(f) $\text{Zr} - 10000 \times \text{Ga}/\text{Al}$ 图解

Fig.4 (a) QAP, (b) K_2O vs. SiO_2 , (c) A/CNK vs. SiO_2 , (d) P_2O_5 vs. SiO_2 , (e) $10000 \times (\text{Ga}/\text{Al}) - (\text{Zr} + \text{Nb} + \text{Ce} + \text{Y})$ and (f) $\text{Zr} - 10000 \times \text{Ga}/\text{Al}$ diagrams for the granite in western Cambodia

图 a 据 Le Bas *et al.*(1986); 图 b 据 Winchester and Floyd (1977); 图 c 据 Chappell and White (1974); 图 d-c 据 Whalen *et al.* (1987); 东部花岗岩省碰撞后花岗岩数据引自 Qian *et al.* (2017, 2020); Nualkhao *et al.* (2018); Cheng *et al.* (2019); Wang *et al.* (2021); Waight *et al.* (2021); Nong *et al.* (2022), 详见附表 3-4

在球粒陨石标准化稀土配分图中(图 5a), 所有样品均明显富集轻稀土元素, 并具有明显的 Eu 的负异常, 黑云母二长花岗岩样品的 $(La/Yb)_N = 3.13\sim 7.65$, $(Gd/Yb)_N = 1.15\sim 2.19$, $Eu/Eu^* = 0.31\sim 0.71$; 而花岗闪长岩样品 $(La/Yb)_N = 4.23\sim 4.47$, $(Gd/Yb)_N = 1.42\sim 1.45$, $Eu/Eu^* = 0.70\sim 0.72$ 。在原始地幔标准化的微量元素蛛网图中(图 5b), 样品总体均以富集大离子亲石元素, 亏损高场强元素 (如 Nb、Ti 等)为特征, 且表现出 Sr 和 P 的负异常。此外, 本研究中的花岗岩与东部花岗岩省碰撞后花岗岩具有相似的稀土和微量元素配分模式(图 5a-b; Wang *et al.*, 2016; Qian *et al.*, 2017, 2020; Nualkhao *et al.*, 2018; Cheng *et al.*, 2019; Nong *et al.*, 2022)。

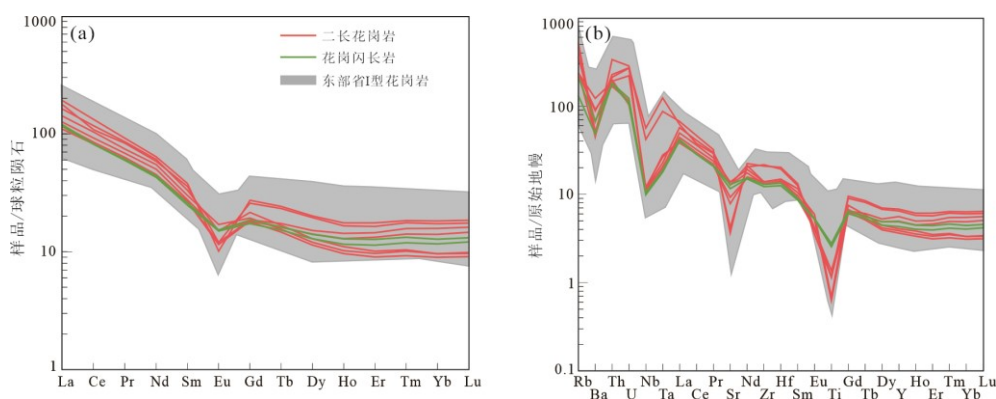


图 5 柬埔寨西部花岗岩球粒陨石标准化稀土模式图 (a)和原始地幔标准化微量元素蛛网图 (b)

Fig.5 Chondrite-normalized REE diagram (a) and primitive mantle-normalized trace element spider diagram (b) for the granite in western Cambodia

球粒陨石和原始地幔标准化数据引自 Sun and McDonough(1989), 东部花岗岩省碰撞后花岗岩背景数据来源同图 4

2.3 Sr-Nd-Hf 同位素结果

黑云母二长花岗岩样品 24C-08-1 的锆石原位 $\epsilon_{Hf}(t)$ 值为+6.1~+12.7, 二阶段模式年龄(T_{DM2})为 0.43~0.85 Ga, 其全岩的 $\epsilon_{Nd}(t)$ 值和 $(^{87}Sr/^{86}Sr)_i$ 比值为-4.2 和 0.70760, Nd 二阶段模式年龄为 0.47 Ga。样品 24C-11-1 和 24C-12B-1 的锆石原位 $\epsilon_{Hf}(t)$ 值分别为 -2.2~+5.2 和+2.2~+6.3, 二阶段模式年龄(T_{DM2})分别为 0.91~1.38 Ga 和 0.84~1.10 Ga, $\epsilon_{Nd}(t)$ 值分别为-2.4 和-1.5, $(^{87}Sr/^{86}Sr)_i$ 值为 0.70727 与 0.70603; 花岗闪长岩 24C-13A-1 的锆石原位 $\epsilon_{Hf}(t)$ 值为+0.4~+5.4, 其对应的二阶段模式年龄(T_{DM2})为 0.90~1.21 Ga, $\epsilon_{Nd}(t)$ 值和 $(^{87}Sr/^{86}Sr)_i$ 比值分别为-2.6 和 0.70693, 在 $\epsilon_{Hf}(t)$ -年龄图解中(图 6a), 本文研究样品

的 $\epsilon_{\text{Hf}}(t)$ 值均以正值为主。在 $\epsilon_{\text{Nd}}(t)-(^{87}\text{Sr}/^{86}\text{Sr})_i$ 图解中(图 6b)，本研究的样品也都落入拉克兰褶皱带 I 型花岗岩、冈底斯 I 型花岗岩以及东古特提斯火成岩带东部花岗岩省碰撞后花岗岩区域内。

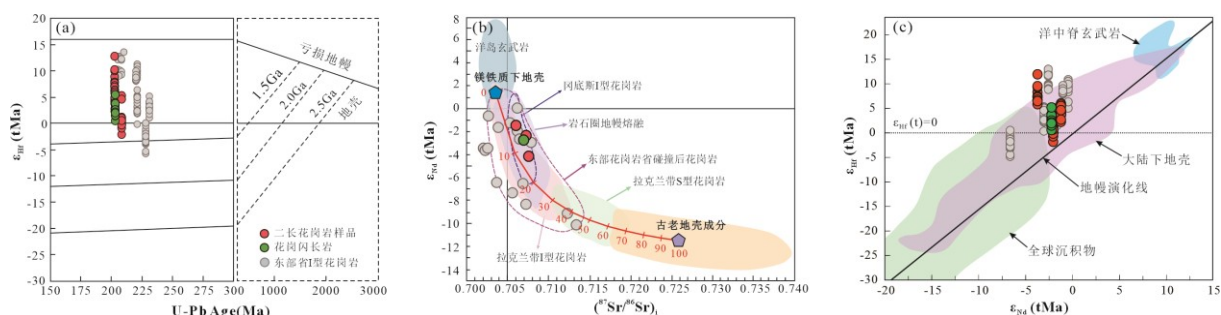


图 6 柬埔寨西部花岗岩(a)锆石年龄- $\epsilon_{\text{Nd}}(t)$ 图解, (b) Sr-Nd 同位素二元混合模型, (c) $\epsilon_{\text{Hf}}(t\text{Ma})-\epsilon_{\text{Nd}}(t\text{Ma})$ 图解
Fig.6 Zircon age vs. $\epsilon_{\text{Nd}}(t)$ (a), Sr-Nd isotopic diagram (b), $\epsilon_{\text{Hf}}(t\text{Ma})$ vs. $\epsilon_{\text{Nd}}(t\text{Ma})$ (c) diagrams for the granite in western Cambodia

图 b 据 Liew and McCulloch. (1985); Peng *et al.* (2008, 2013); Sun and McDonough (1989); Lan *et al.* (2003); Wang *et al.* (2020a, 2020b), 端元数据引自 Lan *et al.* (2003), 图 c 据 Vervoort *et al.* (1999), 东部花岗岩省碰撞后花岗岩数据来源同图 4

3 讨论

3.1 柬埔寨西部晚三叠世花岗岩成因类型

本研究的黑云母二长花岗岩和花岗闪长岩样品中，均未见如堇青石、白云母、电气石等高铝矿物组合。它们在 CIPW 标准矿物计算中，刚玉含量在 0.5%-3.5 vol% 之间，其中黑云母二长花岗岩 A/CNK 值为 1.14-1.28，A/NK 值为 1.47-1.73，而花岗闪长岩样品 A/CNK 值为 1.02-1.10，A/NK 值为 2.30-2.36，在 A/CNK-SiO₂(%)图解中，样品大致落在 I 型花岗岩和 S 型花岗岩的分界线附近(如图 4c)，总体具有准铝质向过铝质过渡的特征。

此外，两组花岗岩样品表现出显著的 Sr、Ba、Eu 负异常，具有较高的 Zr/Hf 比值(33.8-40.6)，较低的 P₂O₅ 的含量 (0.04-0.15%)以及 P₂O₅ 与 SiO₂ 的负相关关系(如图 4d, 图 5a, b)，并有较高的锆石饱和温度(814-883 °C，平均 842 °C)。黑云母二长花岗岩和花岗闪长岩样品分异指数(DI = Q + Or + Ab + Ne + Lc + Kp)分别介于 83.1-89.3 和 63.3-66.7 之间，且均具有较低的 Zr+Nb+Ce+Y 含量以及 Ga/Al 比值(图 4d-f)。这些地

球化学特征均表明样品具有中-高分异 I 型花岗岩的亲缘性(如 Chappell and White, 1992)。

3.2 源区特征及岩浆演化

如前所述, 本文研究的花岗岩样品相对富集轻稀土元素($(La/Yb)_N = 3.13 \sim 7.65$), 重稀土元素表现为相对平坦至略有亏损, 同时富集大离子亲石元素, 且 Nb、Ti 等高场强元素相对亏损, 指示它们经历了较高的分异。一般的岩浆演化过程中, 元素伴随着矿物的分离结晶会发生不同程度的分异(如 Wu *et al.*, 2017)。在稀土元素配分模式图及微量元素蛛网图中(图 5), 样品 Eu、Sr、Ti 元素的负异常指示了熔体中斜长石以及部分含钛矿物的分离结晶, 同时表明岩浆演化或源区熔融处于中-高压环境中(Lee *et al.*, 2023)。此外, 图 7a-b 均表明本研究的样品在岩浆演化过程中发生了斜长石与钾长石的分离结晶作用。现有的岩石学与地球化学数据表明, 花岗质岩浆一般来源于地壳的部分熔融, 同时大部分过铝质花岗岩是通过大陆地壳物质(包括变泥质岩、杂砂岩及变火成岩)的部分熔融而形成的(如 Beard *et al.*, 1993; Clemens, 2003; Miller, 1985; Sylvester, 1998; Wang *et al.*, 2007, 2014, 2016)。本文的黑云母二长花岗岩样品具有较低的 Mg#(20.1~36.5)与极低的 Cr、Ni 含量($Cr < 3.93 \text{ ppm}$; $Ni < 2.59 \text{ ppm}$), 代表来自陆壳的长英质熔体, 而花岗闪长岩样品较高的 Mg#(48.9~49.4)以及较高的 Cr、Ni 含量($Cr > 32.7 \text{ ppm}$; $Ni > 6.72 \text{ ppm}$)则暗示有部分幔源物质的参与。利用 Sr-Nd-Hf 同位素体系, 可以追溯 I 型花岗岩的源区特征(Wu *et al.*, 2016; Cao *et al.*, 2018a, 2018b, 2020)。本研究的花岗岩样品具有相对亏损至略微富集的同位素组成, 其变化范围较宽且主体为正的 $\epsilon_{Hf}(t)$ 值(-2.2~+12.7)表明岩浆源区不均一, T_{DM2} 年龄在 0.35 Ga~1.38 Ga 之间, 与东部省晚三叠世花岗岩相似, 而相关研究认为这些花岗岩来源于古老变质基底与新生底侵镁铁质组分组成的混合源区(Wang *et al.* 2016, 2018; Qian *et al.*, 2020)。此外, 样品的 $\epsilon_{Nd}(t)$ 值(-4.2~-1.5)与 $\epsilon_{Hf}(t)$ 值并未出现协同变化, 而是表现出变化范围集中且均为负值的特征, 这进一步排除了后期混染的可能性, 且相对富集的 $\epsilon_{Nd}(t)$ 值表明可能有古老富集地壳组分的参与。如果一个富集的壳源熔体(如具负 $\epsilon_{Nd}(t)$ 值和负 $\epsilon_{Hf}(t)$ 值的古老地壳)与一个亏损的幔源熔体(如具正 $\epsilon_{Nd}(t)$ 与极高 $\epsilon_{Hf}(t)$ 的幔源物质)混合, 其混合产物的 $\epsilon_{Nd}(t)$ 值和 $\epsilon_{Hf}(t)$ 值应当具有明显的线性协同变化关系, 而在 $\epsilon_{Nd}(t)$ - $\epsilon_{Hf}(t)$ 图解中,

所有样品均落在地幔演化线以上，并落入大陆下地壳范围内(图 6c; 如 Vervoort *et al.*, 1999), $\epsilon_{Nd}(t)$ 值和 $\epsilon_{Hf}(t)$ 值之间无协同变化的趋势，且在研究区也并未发现暗色微粒包体(MME)的存在，这表明在岩浆就位浅部没有大规模幔源熔体的直接加入(Barbarin, 2005; 陈国超等, 2016; 翟明国等, 2017), 而部分样品具有较高的 $\epsilon_{Hf}(t)$ 值也排除了单一的古地壳熔融模型。通过 Sr-Nd 同位素二元混合模型可知岩浆源区以镁铁质下地壳部分熔融为主，并有少部分古老地壳物质成分的参与(如图 6b)。这些特征也与拉克兰褶皱带和冈底斯 I 型花岗岩的特征相吻合，而这些 I 型花岗岩的源区通常被解释为由变沉积岩与变火成岩的混合源区组成(图 6b; Healy *et al.*, 2004; Ma *et al.*, 2014)。

区域上，印支陆块的基底以出露于越南昆嵩地块的古元古代和中元古代麻粒岩为代表(如 Katz, 1993; Lan *et al.*, 2003; Metcalfe *et al.*, 2013a)，而本研究的黑云母二长花岗岩样品 Nd 二阶段模式年龄为 1.10~1.32 Ga，类似区域中元古代地壳形成时代，表明柬埔寨西部花岗岩的源区可能包含了与昆嵩地块时代相近的古地壳物质。此外，花岗岩样品具有 0.35~1.38 Ga 的 Hf 二阶段模式年龄，也与印支陆块 0.65~0.5 Ga, ~0.95 Ga、1.16~1.08 Ga 的沉积岩碎屑锆石主要年龄峰值吻合(如 Usuki *et al.*, 2013; Wang *et al.*, 2016)。因此，这些特征表明本研究的花岗岩源区存在物质与区域沉积物源区具有亲缘性，共同记录了区域中元古代地壳演化事件。

在图 7f 中，样品的 Hf/Sm 与 Zr/Y 比值显示正相关关系，表明其具有混合源区的特征(如 Altherr and Siebel, 2002; Wang *et al.*, 2021)。此外，本研究的花岗岩样品具有变化的 Rb/Sr 和 Rb/Ba 比值，同样表明源区的非均一性(图 7c)。在图 8d-e 中，样品主要落在变杂砂岩以及变火成岩与变杂砂岩重叠区域，表明本研究的花岗岩样品主要由变杂砂岩和角闪岩部分熔融形成，同时较高的锆石饱和温度(814~883 °C)支持源区为较高温的下地壳熔融。因此，这些地球化学特征均表明本研究的花岗岩样品源于新生的镁铁质下地壳与变杂砂岩的混合源区。

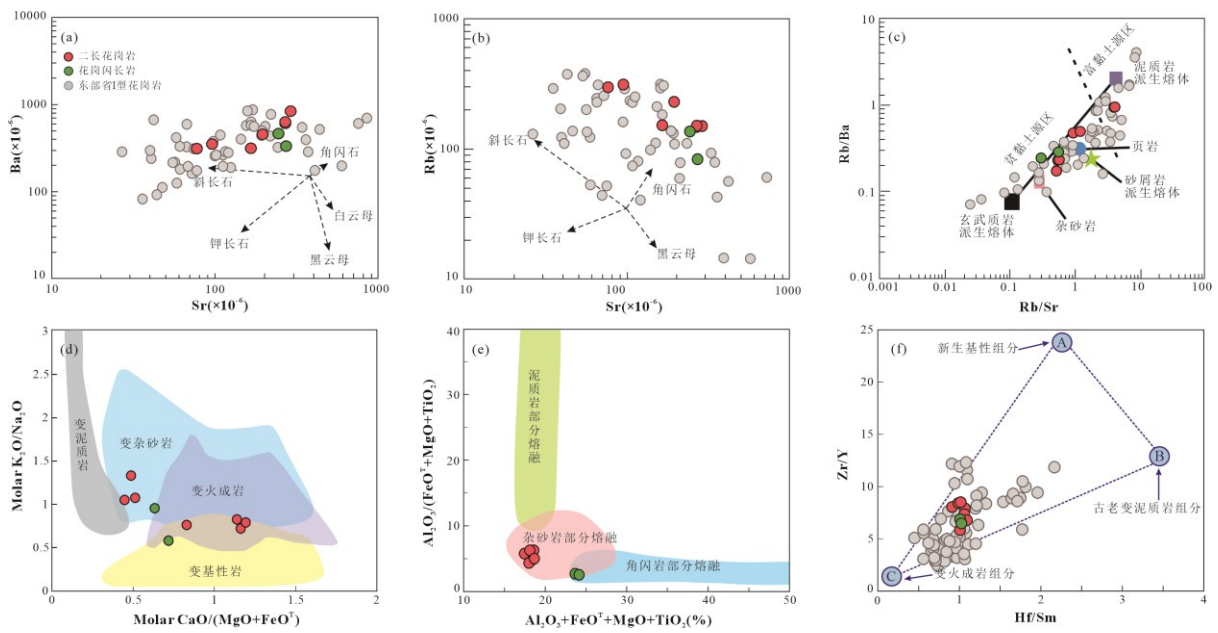


图7 柬埔寨西部花岗岩(a) Sr-Ba; (b) Sr-Rb; (c) Rb/Ba-Rb/Sr; (d) $K_2O/Na_2O-CaO/(MgO+FeO^T)$ Molar; (e) $Al_2O_3/(FeO^T+MgO+TiO_2)-Al_2O_3+FeO^T+MgO+TiO_2$; (f) Zr/Y-Hf/Sm 图解

Fig.7 Sr vs. Ba (a), Sr vs. Rb (b), Rb/Ba vs. Rb/Sr (c), K_2O/Na_2O vs. $CaO/(MgO+FeO^T)$ Molar (d), $Al_2O_3/(FeO^T+MgO+TiO_2)$ vs. $Al_2O_3+FeO^T+MgO+TiO_2$ (e) and Zr/Y-Hf/Sm (f) diagrams for the granite in western Cambodia

图 a-b 据余永琪等, 2024; 图 c-f 据 Patiño-Douce and Harris(1998); Sylvester(1998); Patiño-Douce(1999), 图 d 据 Altherr and Siebel (2002); 图 f 据 Wang *et al.* (2021), 东部花岗岩省碰撞后花岗岩类数据来源于图 4

3.2 古特提斯构造意义

已有的地层古生物、地球化学及年代学数据均表明东古特提斯洋在晚二叠世至早三叠世期间曾持续向东俯冲，并在中-晚三叠世闭合(如 Metcalfe, 2006, 2011, 2013a, b; Sone and Metcalfe, 2008; Deng *et al.*, 2018)。同时 Wang *et al.*(2018)通过系统总结东南亚古特提斯岩浆、沉积和变质记录，综合证实了东古特提斯洋的闭合时间为~237 Ma，而之后 230-200 Ma 为碰撞后背景。此外，已有研究通过昌宁-孟连带退变质榴辉岩中的变质锆石年龄结合蓝片岩变质 P-T 轨迹，提出古特提斯洋在早-中三叠世发生快速俯冲，在晚三叠世(231–214 Ma)已开始被剥蚀(Wang *et al.*, 2018, 2019)，而这样的演化时序也被 Qian *et al.*(2016a, 2020, 2021)通过研究泰国及老挝西北部的三叠纪岩浆作用所证实。

本研究在柬埔寨西部新识别出的这一套晚三叠世黑云母二长花岗岩及花岗闪长岩组合，其形成时代与先前已报道的柬埔寨西部同期花岗岩一致，均在 209~190 Ma

之间,同时该时间也与东古特提斯碰撞后的时间相一致,证实在柬埔寨西部存在一期晚三叠世的岩浆事件(图 1b; Cheng *et al.*, 2019; Waight *et al.*, 2021; Uchida *et al.*, 2023)。同时,前人的研究表明该套晚三叠世岩浆作用的构造背景与东古特提斯洋的演化有关,如 Cheng *et al.* (2019) 认为柬埔寨西南地区的火成岩与泰国黎府构造带晚三叠世至早侏罗世火成岩相似,并将这一期晚三叠世岩浆事件与古特提斯洋闭合后滇缅马与印支的碰撞相联系。而 Nong *et al.* (2022) 则认为越南和柬埔寨南部晚三叠-早侏罗世花岗岩可以与泰国黎府构造带晚三叠世花岗岩相对应,并认为它们是碰撞后岩浆作用的产物。此外, Uchida *et al.* (2023) 最近也从柬埔寨西部识别出了 232~191 Ma 的花岗岩,并认为这些花岗岩的形成对应了滇缅马与印支陆块的碰撞拼合。因此,本研究认为柬埔寨西部的这一套晚三叠世花岗岩属于东古特提斯碰撞后背景。

东南亚巨型火成岩带呈近南北向延伸,自中国西南部临沧地块,经素可泰、庄他武里,东马来亚陆块,进一步延伸至印度尼西亚锡岛附近,包含晚古生代至早中生代的花岗岩组合,这些花岗岩类被进一步划分为西部、中部以及东部花岗岩省(如 Liew and McCulloch, 1985; Cobbing *et al.*, 1992; Charusiri *et al.*, 1993; Cobbing, 2011)。前人研究表明,中部花岗岩省形成于中晚三叠世晚期(238-200 Ma),具有 S 型花岗岩地球化学特征,主要由上地壳变沉积岩及变质岩部分熔融形成(如 Liew and McCulloch, 1985; Searle *et al.*, 2012; Oliver *et al.*, 2014; Ng *et al.*, 2015a, 2015b; Wang *et al.*, 2021; Qian *et al.*, 2025a)。而东部花岗岩省的花岗岩包含晚石炭世-中三叠世弧花岗岩及晚三叠世碰撞后花岗岩,它们主要以岩株和岩基的形式侵入前三叠纪地层中,时代跨度在 315~200 Ma (如 Liew and McCulloch, 1985; Hennig *et al.*, 2009; Searle *et al.*, 2012; Oliver *et al.*, 2014; Ng *et al.*, 2015a, 2015b; Gardiner *et al.*, 2016b; Wang *et al.*, 2016; Qian *et al.*, 2017b, 2020; Fanka *et al.*, 2018; Liu *et al.*, 2020; Yu *et al.*, 2022; Qian *et al.*, 2025a)。最近的研究认为,西婆罗洲晚二叠世-三叠纪(256~207 Ma)花岗岩代表了东部花岗岩省的在东南方向的延伸(Wang *et al.*, 2021)。此外,靠近研究区的泰国东南部及庄他武里地块也报道有 222~218 Ma 的花岗质岩石,并被认为是古特提斯洋闭合后,滇缅马地块与印支陆块碰撞所形成的(Sone *et al.*, 2012, Qian *et al.*, 2017),其源区也被解释为新生的基性地壳的部分熔融为主,同时存在古老变沉积物的参与。已有的研究表明东部花岗岩省碰撞后花岗岩属于中-高钾钙碱性花岗岩及花岗闪长岩,并源于古老变基性岩及变沉积岩组

成的混合源区，同时具有新生下地壳基性成分的参与(如 Wang *et al.*, 2016, 2018c; Qian *et al.*, 2025a)。而本文研究的样品源区属性为变沉积岩与新生镁铁质下地壳的混合源区，同时主体为正的 $\epsilon_{\text{Hf}}(\text{t})$ 值和负的 $\epsilon_{\text{Nd}}(\text{t})$ 值均类似于东部花岗岩省晚三叠世碰撞后花岗岩的特征，证实它们属于东部花岗岩省的一部分(图 6, 7)。东部花岗岩省在素可泰-庄他武里-东马来亚地块出露的具碰撞后特征的花岗质岩石形成时代集中于 231~216 Ma (如 Barr *et al.*, 2006; Sone and Metcalfe, 2008; Searle *et al.*, 2012; Metcalfe, 2013; Ng *et al.*, 2015; Qian *et al.*, 2017, 2020)，并显示出 230 Ma 与 220 Ma 两个主要的岩浆活动峰期，而柬埔寨西部三叠纪岩浆作用则记录了约 200 Ma 的年龄集中区，代表了该区域晚三叠世晚期构造-岩浆作用的延续，两者共同构成了东古特提斯碰撞后岩浆演化序列(图 8)。

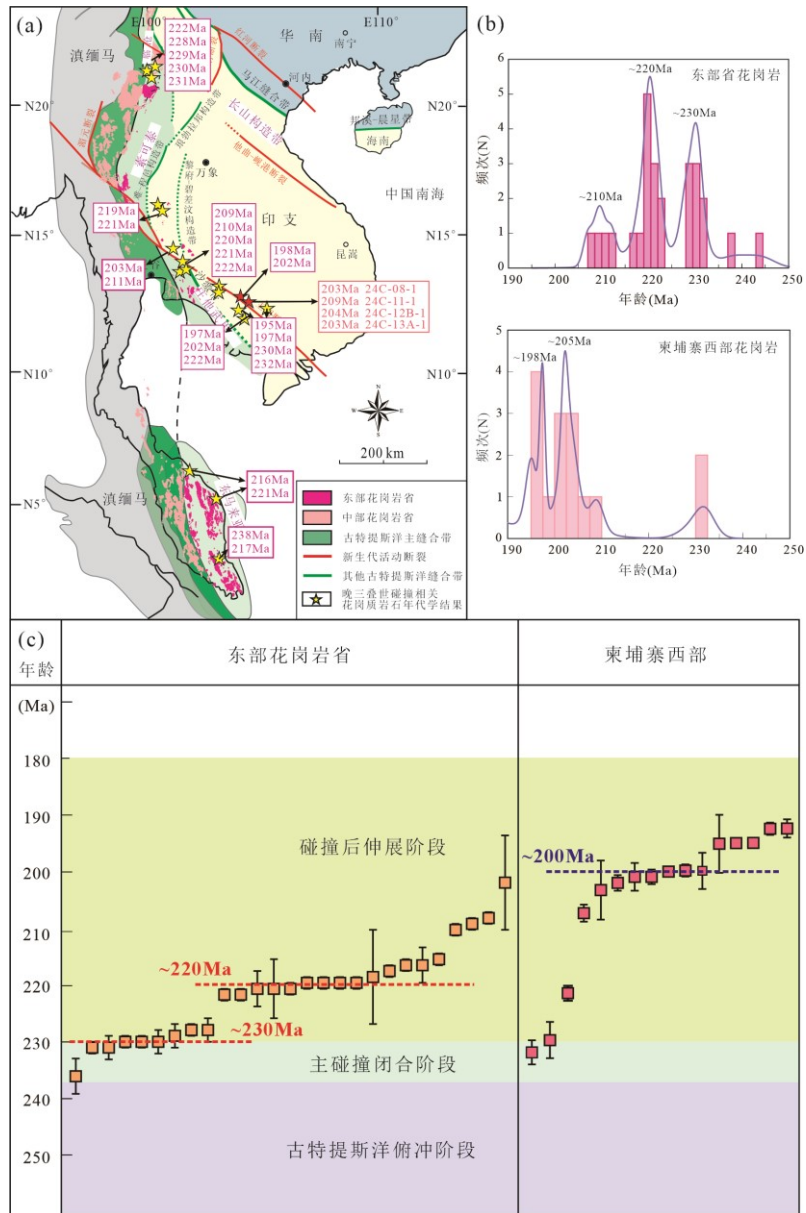


图 8 东南亚地区东部花岗岩省花岗质岩石分布(a)和年龄汇总图(b)

Fig.8 Distribution map of granitic rocks (a) and age summary diagram (b) for the Eastern Southeast Asian Granite Province

(东部花岗岩省碰撞后花岗岩年代学数据引自 Qian *et al.* (2017, 2020); Dew *et al.* (2018); Nualkhao *et al.* (2018); Wang *et al.* (2021); Uchida *et al.* (2022); 余永琪等 (2024); 柬埔寨西部花岗岩年代学数据引自 Cheng *et al.* (2019); Waight *et al.* (2021); Uchida *et al.* (2023)和本研究; 详见附件 5)

古特提斯于晚三叠世早期(~237 Ma)发生同碰撞转换, 在此过程中, 俯冲板片发生回卷, 其引起的热扰动导致脱水熔融, 产生了富水幔源岩浆, 并底侵于加厚的下地壳而产生大量中酸性岩浆(如 Collins *et al.*, 2020; 朱弟成等, 2025)。随后, 在约 230 Ma

发生俯冲板片的断离，持续的幔源岩浆底侵作用最终在东部省形成一系列晚三叠世中酸性火山岩(如 Qian *et al.*, 2016b, 2017; Yu *et al.*, 2023)。在 230 Ma~200 Ma 期间，随着滇缅马与印支陆块碰撞的进行，岩石圈不断挤压增厚。先前加厚的岩石圈在碰撞后因重力不稳而发生拆沉，从而引起软流圈上涌，加热减薄的岩石圈地幔和加厚地壳，产生富钾的镁铁质岩浆和长英质岩浆(郑永飞等, 2022, 2024; 朱第成等, 2025)，而大部分 I 型和少量 S 型花岗岩来源于下地壳重熔，所需热量可能来自岩石圈拆沉引起的幔源镁铁质岩浆(Finger 等, 1997)。与研究区接壤的泰国境内报道了 200 Ma 左右指示碰撞后伸展背景的玄武岩与 A2 型长英质火山岩组合(闫秋彤等, 2025)，而东古特提斯 230 Ma~200 Ma 的碰撞后火山岩系列在临沧-素可泰-庄他武里区域内呈带状展布，也表明在该时期区域上发生了板片断离及造山带垮塌(Barr *et al.*, 2000, 2006; Srichan *et al.*, 2009; Wang *et al.*, 2016; Qian *et al.*, 2013, 2016a, 2022)。

一般的岩石圈拆沉存在两种主要模式，其一是整个岩石圈地幔快速剥离，常触发大规模镁铁质岩浆作用；其二则是其底部发生部分拆离，诱发持续的软流圈上涌及多期岩浆作用(Houseman and Molnar, 1997; Drew *et al.*, 2009; Ducea, 2011, 朱第成等, 2025)。本研究在区域上并未发现埃达克岩以及地表快速隆升，表明东部花岗岩省和柬埔寨西部所记录的自 230 Ma 持续至 200 Ma 的连续岩浆演化序列可能与区域上一次持续时间较长的岩石圈拆沉事件相吻合：该拆沉事件可能始于约 220 Ma 并在约 200 Ma 结束，其导致加厚的岩石圈根部发生失稳和下沉，在此过程中，持续上涌的软流圈为下地壳提供了长期而稳定的热流，并触发了包括本研究区在内的广泛区域的下地壳熔融。在软流圈上涌过程中，其顶部发生减压熔融而产生镁铁质熔体(如 Mahéo *et al.*, 2002)，这些熔体底侵到下地壳底部，形成新的镁铁质下地壳，并与先存的中-新元古代变杂砂岩基底在深部构成了一个混合源区。随后，软流圈持续上涌带来的热扰动导致这个混合源区发生部分熔融而产生不同成分的熔体，这些熔体在上升过程中经历了较高分度的分异，并于晚三叠世晚期侵位，最终形成了柬埔寨西部具混合源区特征的高分异 I 型花岗岩(图 9a-b)。

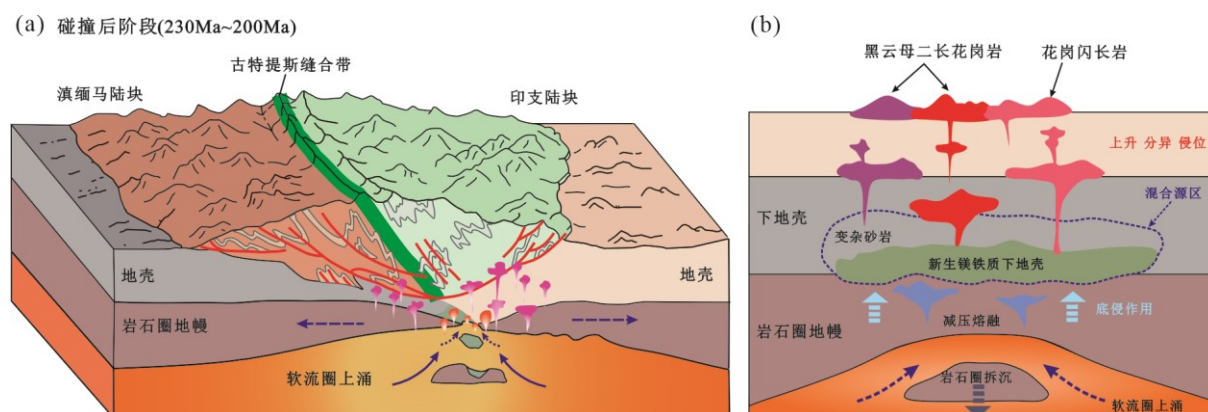


图9 滇缅马与印支陆块晚三叠世碰撞后岩浆演化模式图(a)和混合源区熔融模式图(b)

Fig. 9 A model illustrating post-collisional magmatic evolution between the Sibumasu and Indochina blocks during the Late Triassic (a) and Model of Melting from Mixed Sources (b)

4 结论

本研究对柬埔寨西部晚三叠世晚期的花岗岩开展了系统的年代学、地球化学及区域构造分析，取得了如下的主要结论：

(1) 柬埔寨西部科卓尔岩体主要由黑云母二长花岗岩及花岗闪长岩组成，其锆石 U-Pb 年龄为 209~203 Ma，均形成于晚三叠世晚期。

(2) 全岩地球化学及同位素数据表明该套花岗岩源于新生的镁铁质下地壳与变沉积岩的混合源区，并经历了斜长石与钾长石的分离结晶作用

(3) 柬埔寨西部晚三叠世花岗岩形成于东古特提斯碰撞后背景，与软流圈上涌引发的中-下地壳部分熔融有关。表明东古特提斯巨型火成岩带可能延伸至柬埔寨西部地区，两者共同响应了东古特提斯碰撞后的深部动力学过程。

References

- Altherr, R., Siebel, W., 2002. I-type plutonism in a continental back-arc setting: Miocene granitoids and monzonites from the central Aegean Sea. *Greece. Contrib. Mineral. Petrol*, 143 (4), 397–415. <https://doi.org/10.1007/s00410-002-0352-y>
- Barbarin, B., 2005. Mafic magmatic enclaves and mafic rocks associated with some granitoids of the central Sierra Nevada batholith, California: nature, origin, and relations with the hosts. *Lithos*, 80 (1–4): 155–177. <https://doi.org/10.1016/j.lithos.2004.05.010>
- Barr, S. M., MacDonald, A. S., Dunning, G. R., et al., 2000. Petrochemistry, U-Pb (zircon) age, and palaeotectonic setting of the Lampang volcanic belt, northern Thailand. *Journal of the Geological Society*, 157 (3): 553–563. <https://doi.org/10.1144/jgs.157.3.553>
- Barr, S. M., Charusiri, P., 2011. Volcanic rocks. *The Geology of Thailand*, Geological Society, London, pp. 273-334. <https://doi.org/10.1144/GOTH.15>
- Barber, A. J., Ridd, M. F., Crow, M. J., 2011. The origin, movement and assembly of the pre-Tertiary tectonic units of Thailand. *The Geology of Thailand*, Geological Society, London, pp. 507–537. <https://doi.org/10.1144/GOTH.19>
- Beard, J. S., Abirz, R. J., Lofgren, G. E., 1993. Experimental melting of crustal xenoliths from Kilbourne Hole, New Mexico and implications for the contamination and genesis of magmas. *Contributions to Mineralogy and Petrology*, 115: 88–102. <https://doi.org/10.1007/BF00712981>
- Booth, J., Sattayarak, N., 2011. Subsurface Carboniferous-Cretaceous geology of NE Thailand. *The Geology of Thailand*, Geological Society, London, pp. 185–222. <https://doi.org/10.1144/GOTH.9>
- Cao, J.Y., Wu, Q.H., Yang, X.Y., et al., 2018a. Geochronology and genesis of the Xitian W-Sn polymetallic deposit in Eastern Hunan Province, South China: evidence from Zircon U–Pb and Muscovite Ar–Ar Dating, petrochemistry, and Wolframite Sr–Nd–Pb Isotopes. *Minerals*, 8(3), 111. <https://doi.org/10.3390/min8030111>
- Cao, J.Y., Yang, X.Y., Du, J.G., et al., 2018b. Formation and geodynamic implication of the Early Yanshanian granites associated with W-Sn mineralization in the Nanling range, South China: an overview. *International Geology Review*, 60(11–14), 1744–1771. <https://doi.org/10.1080/00206814.2018.1466370>
- Cao, J. Y., Yang, X. Y., Du, G. F., et al., 2020. Genesis and tectonic setting of the Malaysian Waterfall granites and tin deposit: Constraints from LA–ICP (MC)–MS zircon U–Pb and cassiterite dating and Sr–Nd–Hf isotopes. *Ore Geology Reviews*, 118, 103336. <https://doi.org/10.1016/j.oregeorev.2020.103336>
- Cawood, P. A., Zhao, G. C., Yao, J. L., et al., 2018. Reconstructing South China in Phanerozoic and Precambrian supercontinents. *Earth-Science Reviews*, 186: 173–194. <https://doi.org/10.1016/j.earscirev.2017.06.001>
- Chappell, B. W., White, A. J. R., 1992. I- and S-type granites in the Lachlan Fold Belt. *Geological Society of America*, 83(1–2): 1–26. <https://doi.org/10.1130/SPE272-p1>
- Chappell, B.W., White, A.J.R., 1974. Two contrasting granite types. *Pacific geology*, 8 (2), 173–174.
- Chen, G. C., Pei, X. Z., Li, R.B., et al., 2016. Genesis of magma mixing and mingling of Xiangjiananshan granitic batholith in the eastern section of East Kunlun Orogen: Evidence from Mafic Microgranular Enclaves (MMEs). *Earth Science Frontiers*, 2016, 23(4): 226-240. <https://doi.org/10.13745/j.esf.2016.04.019>. (in Chinese with English abstract)
- Cheng, R., Uchida, E., Katayose, M., et al., 2019. Petrogenesis and tectonic setting of Late Paleozoic to

- Late Mesozoic igneous rocks in Cambodia. *Journal of Asian Earth Sciences*, 185:104046. <https://doi.org/10.1016/j.jseaes.2019.104046>.
- Clemens, J. D., 2003. S-type granitic magmas-petrogenetic issues, models and evidence. *Earth-Science Reviews*, 61, 1–18. [https://doi.org/10.1016/S0012-8252\(02\)00107-1](https://doi.org/10.1016/S0012-8252(02)00107-1).
- Cocks, L. R. M., Torsvik, T. H., 2013. The dynamic evolution of the Paleozoic geography of eastern Asia. *Earth-Science Reviews*, 117, 40–79. <https://doi.org/10.1016/j.earscirev.2012.12.001>.
- Collins, W. J., Murphy, J. B., Johnson, T. E., et al., 2020. Critical role of water in the formation of continental crust. *Nature Geoscience*, 13: 331–338.
- Deng, J., Wang, C. M., Zi, J. W., et al., 2018. Constraining subduction-collision processes of the Paleo-Tethys along the Changning-Menglian Suture: New zircon U-Pb ages and Sr-Nd-Pb-Hf-O isotopes of the Lincang Batholith. *Gondwana Research*, 62: 75–92. <https://doi.org/10.1016/j.gr.2017.10.008>.
- Dew, R. E. C., Collins, A. S., Glorie, S., et al., 2018. Probing into Thailand's basement: New insights from U-Pb geochronology, Sr, Sm-Nd, Pb and Lu-Hf isotopic systems from granitoids. *Lithos*, 320–321: 332–354. <https://doi.org/10.1016/j.lithos.2018.09.019>.
- Drew, S. T., Ducea, M. N., Schoenbohm, L. M., 2009. Mafic volcanism on the Puna Plateau, NW Argentina: Implications for lithospheric composition and evolution with an emphasis on lithospheric foundering. *Lithosphere*, 1(5): 305–318. <https://doi.org/10.1130/L54.1>
- Douce, A. E. P., Beard, J. S., 1995. Dehydration-melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar. *Journal of Petrology*, 36: 707–738. <https://doi.org/10.1093/petrology/36.3.707>
- Ducea, M. N., 2011. Fingerprinting orogenic delamination. *Geology*, 39(2): 191–192. <https://doi.org/10.1130/focus022011.1>
- Fan, W. M., Wang, Y. J., Zhang, A. M., et al., 2010. Permian arc-back-arc basin development in the Ailaoshan tectonic zone: Geochemical, isotopic and geo-chronological evidence from the Mojiang volcanic rocks, Southwest China. *Lithos*, 119 (3–4): 553–568. <https://doi.org/10.1016/j.lithos.2010.08.010>.
- Faure, M., Nguyen, V. V., Hoai, L.T.T., et al., 2018. Early Paleozoic or Early-Middle Triassic collision between the South China and Indochina Blocks: The Controversy resolved? Structural insights from the Kon Tum Massif (Central Vietnam). *Journal of Asian Earth Sciences*, 166: 162–180. <https://doi.org/10.1016/j.jseaes.2018.07.015>
- Fontaine, H., 2002. Permian of Southeast Asia: An overview. *Journal of Asian Earth Sciences*, 20 (6): 567–588. [https://doi.org/10.1016/S1367-9120\(01\)00076-1](https://doi.org/10.1016/S1367-9120(01)00076-1).
- Feng, Q. L., Chongpan, C., Dietrich, H., et al., 2004. Long-lived Paleotethyan pelagic remnant inside Shan-Thai block: evidence from radiolarian biostratigraphy. *Science in China Series D: Earth Sciences*, 47: 1113–1119. <https://doi.org/10.1360/03yd0085>
- Feng, Q. L., Chonglakmani, C., Helmcke, D., et al., 2005. Correlation of Triassic stratigraphy between the Simao and Lampang-Phrae basins: Implications for the tectonopaleogeography of Southeast Asia. *Journal of Asian Earth Sciences*, 24(6): 777–785. <https://doi.org/10.1016/j.jseaes.2004.11.008>.
- Ferrari, O. M., Hochard, C., Stampfli, G. M., 2008. An alternative plate tectonic model for the Palaeozoic-Early Mesozoic Palaeotethyan evolution of Southeast Asia (Northern Thailand–Burma). *Tectonophysics*, 451(1–4): 346-365. <https://doi.org/10.1016/j.tecto.2007.11.065>.
- Fyhn, M. B. W., Green, P. F., Bergman, S. C., et al., 2016. Cenozoic deformation and exhumation of the Kampo Fold Belt and implications for south Indochina tectonics. *Journal of Geophysical Research: Solid Earth*, 121. <https://doi.org/10.1002/2016JB012847>

- Gardiner, N. J., Searle, M. P., Morley, C. K., et al., 2016. The closure of Palaeo-Tethys in eastern Myanmar and northern Thailand: new insights from zircon U–Pb and Hf isotope data. *Gondwana Research*, 39: 401–422. <https://doi.org/10.1016/j.gr.2015.03.001>.
- Hara, H., Tokiwa, T., Kurihara, T., et al., 2018. Permian-Triassic back-arc basin development in response to Paleo-Tethys subduction, Sa Kaeo-Chanthaburi area in Southeastern Thailand. *Gondwana Research*, 64: 50–66.
- Hara, H., Ito, T., Tokiwa, T., et al., 2020. The origin of the Pailin crystalline complex in western Cambodia, and back-arc basin development in the Paleo Tethys Ocean. *Gondwana Research*, 82: 299–316. <https://doi.org/10.1016/j.gr.2020.01.007>
- Healy, B., Collins, W. J., Richards, S.W., 2004. A hybrid origin for Lachlan S-type granites: the Murrumbidgee batholith example. *Lithos*, 78(1–2): 197–216. <https://doi.org/10.1016/j.lithos.2004.04.047>.
- Hieu, P. T., Li, S. Q., Yu, Y., et al., 2016. Stages of late Paleozoic to early Mesozoic magmatism in the Song Ma belt, NW Vietnam: Evidence from zircon U-Pb geochronology and Hf isotope composition. *International Journal of Earth Sciences*, 106(3): 855–874. <https://doi.org/10.1007/s00531-016-1337-9>
- Houseman G. A, Molnar P. 1997. Gravitational (Rayleigh-Taylor) instability of a layer with non-linear viscosity and convective thinning of continental lithosphere. *Geophysical Journal International*, 128(1): 125–150. <https://doi.org/10.1111/j.1365-246X.1997.tb04075.x>
- Hoa, T. T., Anh, T. T., Phuong, N. T., et al., 2008. Permo-Triassic intermediate-felsic magmatism of the Truong Son belt, eastern margin of Indochina. *Comptes Rendus Geoscience*, 340(2–3): 112–126. <https://doi.org/10.1016/j.crte.2007.12.002>.
- Hutchison, C. S., 1989. The Palaeo-Tethyan Realm and Indosinian Orogenic System of Southeast Asia. Tectonic Evolution of the Tethyan Region. *Springer, Dordrecht*, 259: 585–643. https://doi.org/10.1007/978-94-009-2253-2_25
- Hutchinson, C. S., 2014. Tectonic evolution of southeast Asia. *Bulletin of the Geological Society of Malaysia*, 60, 1–18. <https://doi.org/10.7186/bgsm60201401>
- Ito, T., Qian, X., Feng, Q.L., 2016. Geochemistry of Triassic siliceous rocks of the Muyinhe Formation in the Changning-Menglian belt of SW China. *Journal of Earth Science*. 27 (3): 403–411. <https://doi.org/10.1007/s12583-016-0672-x>
- Jian, P., Liu, D.Y., Sun, X.M., 2008. SHRIMP dating of the Permo-Carboniferous Jinshajiang ophiolite, southwestern China, geochronological constraints for the evolution of Paleotethys. *Journal of Asian Earth Sciences*, 32 (5–6): 371–384. <https://doi.org/10.1016/j.jseaes.2007.11.006>.
- Jian, P., Liu, D.Y., Kroner, A., et al., 2009a. Devonian to Permian plate tectonic cycle of the Paleotethys Orogen in southwest China (I): Geochemistry of ophiolites, arc/back-arc assemblages and within-plate igneous rocks. *Lithos*, 113 (3–4): 748–766. <https://doi.org/10.1016/j.lithos.2009.04.004>.
- Jian, P., Liu, D.Y., Kroner, A., et al., 2009b. Devonian to Permian plate tectonic cycle of the Paleo-Tethys Orogen in southwest China (II): Insights from zircon ages of ophiolites, arc/back-arc assemblages and within-plate igneous rocks and generation of the Emeishan CFB Province. *Lithos*, 113 (3–4), 767–784. <https://doi.org/10.1016/j.lithos.2009.04.006>
- Jiang, H., Li, W. Q., Zhao K. D., et al., 2021. Middle Triassic diorites from the Loei Fold Belt, NE Thailand: Petrogenesis and tectonic implications in the context of Paleotethyan subduction. *Lithos*, 382–383, 105955. <https://doi.org/10.1016/j.lithos.2020.105955>.
- Kong, S., Watanabe, K., Imai, A., 2012. Magnetic susceptibility and geochemistry of granitic rocks in

- Cambodia. *ASEAN Engineering Journal*, Part C 2: 113-132. <https://doi.org/10.11113/aej.v2.15363>
- Lacassin, R., Maluski, H., Leloup, P. H., et al., 1997. Tertiary diachronic extrusion and deformation of western Indochina: Structural and $^{40}\text{Ar}/^{39}\text{Ar}$ evidence from NW Thailand. *Journal of Geophysical Research*, 102, 10013–10037. <https://doi.org/10.1029/96JB03831>
- Lan, C.Y., Chung, S.L., Long, T.V., et al., 2003. Geochemical and Sr-Nd isotopic constraints from the Kontum massif, Central Vietnam on the crustal evolution of the Indochina block. *Precambrian Research*, 122(1–4): 7-27. [https://doi.org/10.1016/S0301-9268\(02\)00205-X](https://doi.org/10.1016/S0301-9268(02)00205-X).
- Le Bas M. J., Le Maitre, R. W., Streckheisen, A., et al., 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. *Journal of Petrology*, 27(3): 745-750. <https://doi.org/10.1093/petrology/27.3.745>
- Lee, S. G., Tanaka, T., Lee, M. J., 2023. Geochemical implication of Eu isotopic ratio in anorthosite: new evidence of Eu isotope fractionation during feldspar crystallization. *Geosciences Journal*, 27, 271–284. <https://doi.org/10.1007/s12303-023-0009-6>
- Li, H. L., Qian, X., Yu, X. Q., et al., 2023. Petrogenesis of Triassic Granites from Kontum Massif in Vietnam and Its Tethyan Tectonic Implications. *Earth Science*, 48(4): 1441-1460(in Chinese with English abstract).
- Liew, T. C., McCulloch, M. T., 1985. Genesis of granitoid batholiths of Peninsular Malaysia and implications for models of crustal evolution: evidence from a Nd-Sr isotopic and U-Pb zircon study. *Geochimica et Cosmochimica Acta*, 49 (2): 587-600. [https://doi.org/10.1016/0016-7037\(85\)90050-X](https://doi.org/10.1016/0016-7037(85)90050-X).
- Liu J. L., Tran M. D., Tang Y., et al., 2012. Permo-Triassic granitoids in the northern part of the Truong Son belt, NW Vietnam: Geochronology, geochemistry and tectonic implications. *Gondwana Research*, 22(2): 628–644. <https://doi.org/10.1016/j.gr.2011.10.011>.
- Ma, L.Y., Wang, Y.J., Fan, W.M., et al., 2014. Petrogenesis of the early Eocene I-type granites in West Yingjiang (SW Yunnan) and its implication for the eastern extension of the Gangdese batholiths. *Gondwana Research*, 25(1): 401–419. <https://doi.org/10.1016/j.gr.2013.04.010>.
- Mahéo, G., Guillot, S., Blichert-Toft, J., et al., 2002. A slab breakoff model for the Neogene thermal evolution of South Karakorum and South Tibet. *Earth and Planetary Science Letters*, 195(1–2), 45–58. [https://doi.org/10.1016/S0012-821X\(01\)00578-7](https://doi.org/10.1016/S0012-821X(01)00578-7)
- Maluski, H., Lepvrier, C., Leyreloup, A., et al., 2005. ^{40}Ar - ^{39}Ar geochronology of the charnockites and granulites of the Kan Nack Complex, Kontum Massif, Vietnam. *Journal of Asian Earth Sciences*, 25(4): 653–677. <https://doi.org/10.1016/j.jseas.2004.07.004>.
- Metcalf, I., 1996. Gondwanaland dispersion, Asian accretion and evolution of eastern Tethys. *Australian Journal of Earth Sciences*, 43(6): 605–623. <https://doi.org/10.1080/08120099608728282>
- Metcalf, I., 1998. Paleozoic and Mesozoic geological evolution of the SE Asian region multidisciplinary constraints and implications for biogeography. *Biogeography and Geological Evolution of SE Asia*. Backhuys Publishers Amsterdam, The Netherlands. pp. 25–41.
- Metcalf, I., 2002. Permian tectonic framework and palaeogeography of SE Asia. *Journal of Asian Earth Sciences*, 20 (6): 551–566. [https://doi.org/10.1016/S1367-9120\(02\)00022-6](https://doi.org/10.1016/S1367-9120(02)00022-6)
- Metcalf, I., 2006. Paleozoic and Mesozoic tectonic evolution and palaeogeography of East Asian crustal fragments: the Korean Peninsula in context. *Gondwana Research*, 9(1–2): 24–46. <https://doi.org/10.1016/j.gr.2005.04.002>.
- Metcalf, I., 2011. Palaeozoic-Mesozoic history of SE Asia. *Geological Society*, London, Special Publications, Spec. Pub. 355 (1): 7–35. <https://doi.org/10.1144/SP355.2>
- Metcalf, I., 2013a. Tectonic evolution of the Malay Peninsula. *Journal of Asian Earth Sciences*, 76:

- 195-213. <https://doi.org/10.1016/j.jseaes.2012.12.011>.
- Metcalfé, I., 2013b. Gondwana dispersion and Asian accretion: Tectonic and palaeogeographic evolution of eastern Tethys. *Journal of Asian Earth Sciences*, 66: 1-33. <https://doi.org/10.1016/j.jseaes.2012.12.020>.
- Metcalfé, I., Henderson, C.M., Wakita, K., 2017. Lower Permian conodonts from Palaeotethys ocean plate stratigraphy in the Chiang Mai-Chiang Rai suture zone, northern Thailand. *Gondwana Research*, 44: 54–66. <https://doi.org/10.1016/j.gr.2016.12.003>.
- Metcalfé, I., 2021. Multiple Tethyan Ocean basins and orogenic belts in Asia. *Gondwana Research*, 100: 87–130. <https://doi.org/10.1016/j.gr.2021.01.012>.
- Miller, C.F., 1985. Are strongly peraluminous magmas derived from pelitic sedimentary sources? *Journal of Geology*, 93: 673–689. <https://doi.org/10.1086/628995>
- Morley, C.K., 2012. Earth-science reviews late cretaceous – early palaeogene tectonic development of SE Asia. *Earth-Science Reviews*, 115(1–2): 37–75. <https://doi.org/10.1016/j.earscirev.2012.08.002>.
- Müller, C.J., 1999. Geochemistry, fluid characteristics and evolution of the French mine gold skarn system, Eastern Thailand. *ARC Centre of Excellence in Ore Deposits (CODES)*, University of Tasmania, Hobart, Australia. p.145.
- Nam, T. N., Sano, Y., Terada, K., et al., 2001. First SHRIMP U–Pb zircon dating of granulites from the Kontummassif (Vietnam) and tectonothermal implications. *Journal of Asian Earth Sciences*, 19(1–2): 77–84. [https://doi.org/10.1016/S1367-9120\(00\)00015-8](https://doi.org/10.1016/S1367-9120(00)00015-8).
- Ng, S.W.-P., Whitehouse, M.J., Searle, M.P., et al., 2015. Petrogenesis of Malaysian granitoids in the Southeast Asian tin belt: Part 2. U–Pb zircon geochronology and tectonic model. *GSA Bulletin*, 127(9–10): 1238-1258. <https://doi.org/10.1130/B31214.1>
- Nong, A. T. Q., Hauzenberger, C.A., Gallhofer, D., et al., 2022. Early Mesozoic granitoids in southern Vietnam and Cambodia: A continuation of the Eastern Province granitoid belt of Thailand. *Journal of Asian Earth Sciences*, 224: 105025. <https://doi.org/10.1016/j.jseaes.2021.105025>.
- Nualkhao, P., Takahashi, R., Imai, A., et al., 2018. Petrochemistry of Granitoids Along the Loei Fold Belt, Northeastern Thailand: Petrochemistry of Granitoids along Loei Fold Belt. *Resource Geology*, 68(4): 395–424. <https://doi.org/10.1111/rge.12176>
- Österle, J. E., Klötzli, U., Stockli, D. F., et al., 2019. New age constraints on the Lan Sang gneiss complex, Thailand, and the timing of activity of the Mae Ping shear zone from in-situ and depth-profile zircon and monazite U–Th–Pb geochronology. *Journal of Asian Earth Sciences*, 181, 103886. <https://doi.org/10.1016/j.jseaes.2019.103886>
- Patiño-Douce, A. E., Harris N., 1998. Experimental constraints on Himalayan anatexis. *Journal of Petrology*, 39(4): 689-710. <https://doi.org/10.1093/петroj/39.4.689>
- Patiño-Douce, A. E., 1999. What do experiments tell us about the relative contributions of crust and mantle to the origin of granitic magmas. *Geological Society*, London, Special Publications, 168(1): 55-75.
- Pearce, J. A. 1996. Sources and settings of granitic rocks. *Episodes*, 19(4): 120-125. <https://doi.org/10.18814/EPIIUGS/1996/V19I4/005>
- Peng, T. P., Wang, Y. J., Zhao, G. C., et al., 2008. Arc-like volcanic rocks from the southern Lancangjiang zone, SW China: geochronological and geochemical constraints on their petrogenesis and tectonic implications. *Lithos*, 102: 358-373. <https://doi.org/10.1016/j.lithos.2007.08.012>.
- Peng, T. P., Wilde, S. A., Wang, Y. J., et al., 2013. Mid-Triassic felsic igneous rocks from the southern Lancangjiang Zone, SW China: petrogenesis and implications for the evolution of Paleo-Tethys. *Lithos*, 168-169: 15-32.

- Qian, X., Feng, Q. L., Chonglakmani, C., et al., 2013. Geochemical and geochronological constrains on the Chiang Khong volcanic rocks (northwestern Thailand) and its tectonic implications. *Frontiers of Earth Science*, 7(4): 508–521. <https://doi.org/10.1007/s11707-013-0399-2>
- Qian, X., Wang, Y. J., Feng, Q. L., 2016a. Petrogenesis and tectonic implication of the Late Triassic post-collisional volcanic rocks in Chiang Khong, NW Thailand. *Lithos*, 248-251: 418-431. <https://doi.org/10.1016/j.lithos.2016.01.024>
- Qian, X., Wang, Y. J., Feng, Q. L., et al., 2016b. Zircon U–Pb geochronology, and elemental and Sr–Nd–Hf–O isotopic geochemistry of post-collisional rhyolite in the Chiang Khong area, NW Thailand and implications for the melting of juvenile crust. *International Journal of Earth Sciences*, 106: 1375-1389. <https://doi.org/10.1007/s00531-016-1338-8>
- Qian, X., Feng, Q. L., Wang, Y. J., et al., 2017. Late Triassic post-collisional granites related to Paleotethyan evolution in SE Thailand: Geochronological and geochemical constraints. *Lithos*, 286–287: 440–453. <https://doi.org/10.1016/j.lithos.2017.06.026>
- Qian, X., Wang, Y. J., Zhang, Y. Z., et al., 2020. Late Triassic Post-Collisional Granites Related to Paleotethyan Evolution in Northwestern Lao PDR: Geochronological and Geochemical Evidence. *Gondwana Research*, 84: 163-176. <https://doi.org/10.1016/j.gr.2020.03.002>
- Qian X, Ma S., Lu X. H., Wu S. N., et al., 2022. Late Permian ultrapotassic rhyolites in SE Thailand: Evidence for a Palaeotethyan continental rift basin. *Journal of the Geological Society*, 179(2): 2021–079. <https://doi.org/10.1144/jgs2021-079>
- Qian, X., Jin, S. J., Wang, Y. J., et al., 2025a. Nature and tectonic setting of the Paleotethyan giant igneous belt in Southeast Asia. *Gondwana Research*, 141: 228-245. <https://doi.org/10.1016/j.gr.2025.02.014>.
- Qian, X., Jin, S. J., Bai, T. X., et al., 2025b. Triassic tectonic affinity to Indochina-East Malaya Block for West Sumatra and Paleo-Tethys implications: Constraints from Late Triassic igneous rocks. *Geochemistry, Geophysics, Geosystems*, 26, e2024GC012030. <https://doi.org/10.1029/2024GC012030>
- Salam, A., 2013. A geological, geochemical and Metallogenic study of the Chatree epithermal deposit, Phetchabun Province, Central Thailand (PhD Thesis). *ARC Centre of excellence in ore deposits (CODES)*, University of Tasmania, Hobert, 268p.
- Sanematsu, K., Murakami, H., Duangsurigna, S., et al., 2011. $^{40}\text{Ar}/^{39}\text{Ar}$ ages of granitoids from the Truong Son fold belt and Kontum massif in Laos. *Journal of Mineralogical and Petrological*, 106(1): 13-25. <https://doi.org/10.2465/jmps.091216>
- Searle, M. P., Whitehouse, M. J., Robb, L. J., et al., 2012. Tectonic evolution of the Sibumasu-Indochina terrane collision zone in Thailand and Malaysia: constraints from new U-Pb zircon chronology of SE Asian tin granitoids. *Journal of the Geological Society*, 169 (4): 489-500. <https://doi.org/10.1144/0016-76492011-107>
- Shi, M. F., Lin F. C., Li X. Z., et al., 2011. Stratigraphic zoning and tectonic events in Indochina and adjacent areas of southwest China. *Geology in China*, 38(5): 1244-1256(in Chinese).
- Shi, M. F., Lin, F. C., Fan, W. Y., et al., 2015. Zircon U-Pb ages and geochemistry of granitoids in the Truong Son terrane, Vietnam: Tectonic and metallogenic implications. *Journal of Asian Earth Sciences*, 101: 101–120. <https://doi.org/10.1016/j.jseaes.2015.02.001>.
- Sone, M., Metcalfe, I., 2008. Parallel Tethyan Sutures in mainland SE Asia: new insights for Palaeo-Tethys closure. *Comptes Rendus Geoscience*, 340(2–3): 166-179. <https://doi.org/10.1016/j.crte.2007.09.008>.
- Sone, M., Metcalfe, I., Chaodumrong, P., 2012. The Chanthaburi terrane of southeastern Thailand:

- Stratigraphic confirmation as a disrupted segment of the Sukhothai Arc. *Journal of Asian Earth Sciences*, 61: 16–32.
- Srichan, W., Crawford, A.J., Berry, R.F., 2009. Geochemistry and geochronology of Late Triassic volcanic rocks in the Chiang Khong region, northern Thailand. *Island Arc*, 18: 32-51. <https://doi.org/10.1111/j.1440-1738.2008.00660.x>
- Sun, S. S., McDonough, W. F., 1989. Chemical and isotopic systematics of oceanic basalt: implications for mantle composition and processes. *Geological Society*, London, Special Publications, 42:313-345. <https://doi.org/10.1144/GSL.SP.1989.042.01.19>
- Sylvester P. J. 1998. Post-collisional strongly peraluminous granites. *Lithos*, 45(1): 29-44. [https://doi.org/10.1016/S0024-4937\(98\)00024-3](https://doi.org/10.1016/S0024-4937(98)00024-3).
- Thuy, N. T. B., Satir, M., Siebel, W., et al., 2004. Geochemical and isotopic constraints on the petrogenesis of granitoids from the Dalat zone, southern Vietnam. *Journal of Asian Earth Sciences*, 23(4): 467-482. <https://doi.org/10.1016/j.jseaes.2003.06.001>
- Tien, P. C., 1991. Geology of Cambodia, Laos and Viet Nam, Explanatory note to the Geological map of Cambodia, Laos and Viet Nam at 1:1,000,000 scale. Geological Survey of Vietnam, Hanoi, 158 p.
- Turner, S.P., Platt, J.P., George, R.M.M., Kelley, S.P., Pearson, D.G., & Nowell, G.M., 1999. Magmatism associated with orogenic collapse of the Betic- Alboran Domain, SE Spain. *Journal of Petrology*, 40(6), 1011-1036.
- Uchida, E., Nagano, S., Niki, S., et al., 2022. Geochemical and radiogenic isotopic signatures of granitic rocks in Chanthaburi and Chachoengsao provinces, southeastern Thailand: Implications for origin and evolution. *Journal of Asian Earth Sciences: X*, 8: 100111. <https://doi.org/10.1016/j.jaesx.2022.100111>.
- Uchida, E., Nagano, S., Niki, S., et al., 2023. U–Pb dating for zircons from granitic rocks in southwestern Cambodia. *Heliyon*, 9(9): e19734. <https://doi.org/10.1016/j.heliyon.2023.e19734>.
- Udchachon, M., Thassanapak, H., Burrett, C., 2018. Early Permian radiolarians from the extension of the Sa Kao Suture in Cambodia- tectonic implications. *Geological Magazine*, 155(7): 1449–1469. <https://doi.org/10.1017/S0016756817000322>
- Ueno, K., 1999. Gondwana/Tethys divide in East Asia: solution from Late Paleozoic foraminiferal paleobiogeography. *Proceedings of the International on Shallow Tethys*. Chiang Mai, 1–5 February 45–54.
- Ueno, K., 2003. The Permian fusulinoidean faunas of the Sibumasu and Baoshan blocks: their implications for the paleogeographic and paleoclimatologic reconstruction of the Cimmerian continent. *Palaeogeography Palaeoclimatology Palaeoecology*, 193(1): 1–24.
- Ueno, K., Charoentitirat, T., 2011. Carboniferous and Permian. *The Geology of Thailand*, Geological Society of London, pp.1–136. <https://doi.org/10.1144/GOTH.5>
- United Nations, 1993. Cambodia explanatory brochure. *Atlas of Mineral Resources of the ESCAP (Economic and Social Commission for Asia and the Pacific) Region*. Volume 10: 87p.
- Usuki, T., Lan, C. Y., Wang, K. L., et al., 2013. Linking the Indochina block and Gondwana during the early Paleozoic: evidence from U–Pb ages and Hf isotopes of detrital zircons. *Tectonophysics*, 586, 145–159. <https://doi.org/10.1016/j.tecto.2012.11.010>
- Vervoort, J. D., Patchett, P. J., Blichert-Toft, et al., 1999. Relationships between Lu-Hf and Sm-Nd isotopic systems in the global sedimentary system. *Earth and Planetary Science Letters*. 168 (1–2), 79–99. [https://doi.org/10.1016/S0012-821X\(99\)00047-3](https://doi.org/10.1016/S0012-821X(99)00047-3)
- Waight, T., Fyhn, M. B. W., Thomsen, T. B., et al., 2019. Permian to Cretaceous granites and felsic volcanics from SW Vietnam and S Cambodia: Implications for tectonic development of Indochina,

- Journal of Asian Earth Sciences*, 219: 104902. <https://doi.org/10.1016/j.jseaes.2021.104902>.
- Wang, C., Liang, X. Q., Foster, D. A., et al., 2016. Detrital zircon U–Pb geochronology, Lu–Hf isotopes and REE geochemistry constrains on the provenance and tectonic setting of Indochina Block in the Paleozoic. *Tectonophysics*, 677–678, 125–134. <https://doi.org/10.1016/j.tecto.2016.04.008>
- Wang, Y. J., Fan, W. M., Sun, M., et al., 2007. Geochronological, geochemical and geothermal constraints on petrogenesis of the Indiosinian peraluminous granites in the South China block: a case study in the Hunan Province. *Lithos*, 96(3–4): 475–502. <https://doi.org/10.1016/j.lithos.2006.11.010>.
- Wang, Y. J., Xing, X. W., Cawood, P. A., et al., 2013. Petrogenesis of early Paleozoic peraluminous granite in the Sibumasu terrane Of SW Yunnan and diachronous accretionary orogenesis along the northern margin of Gondwana. *Lithos*, 182–183: 36–47. <https://doi.org/10.1016/j.lithos.2013.09.010>.
- Wang, Y. J., Zhang, Y. Z., Fan, W. M., et al., 2014. Early Neoproterozoic accretionary assemblage in the Cathaysia block: Geochronological, Lu–Hf isotopic and geochemical evidence from granitoid gneisses. *Precambrian Research*, 249: 144–161. <https://doi.org/10.1016/j.precamres.2014.05.003>.
- Wang, Y. J., He, H. Y., Cawood, P. A., et al., 2016. Geochronological, elemental and Sr–Nd–Hf–O isotopic constraints on the petro-genesis of the Triassic post-collisional granitic rocks in NW Thailand and its Paleotethyan implications. *Lithos*, 266–267: 264–286. <https://doi.org/10.1016/j.lithos.2016.09.012>.
- Wang, Y. J., Qian, X., Cawood, P. A., et al., 2018. Closure of the East Paleotethyan Ocean and amalgamation of the Eastern Cimmerian and Southeast Asia continental fragments. *Earth-Science Reviews*, 186: 195–230. <https://doi.org/10.1016/j.earscirev.2017.09.013>
- Wang, Y. J., Wang, Y. K., Qian, X., et al., 2020a. Early Paleozoic subduction in the Indochina interior: revealed by OrdoSilurian mafic-intermediate igneous rocks in South Laos. *Lithos*, 362–363: 105488. <https://doi.org/10.1016/j.lithos.2020.105488>.
- Wang, Y. J., Yang, T. X., Zhang, Y. Z., et al., 2020b. Late Paleozoic back-arc basin in the Indochina block: Constraints from the mafic rocks in the Nan and Luang Prabang tectonic zones, Southeast Asia. *Journal of Asian Earth Sciences*, 195: 1367–9120. <https://doi.org/10.1016/j.jseaes.2020.104333>.
- Wang, Y. J., Qian, X., Zhang, Y. Z., et al., 2021. Southern extension of the Paleotethyan zone in SE Asia: Evidence from the Permo-Triassic granitoids in Malaysia and West Indonesia. *Lithos*, 398–399: 106336. <https://doi.org/10.1016/j.lithos.2021.106336>.
- Whalen J. B., Currie K. L., Chappell B. W., 1987. A-type granites: Geochemical characteristics, discrimination and petrogenesis. *Contrib Mineral Petrol*, 95(4): 407–419. <https://doi.org/10.1007/BF00402202>
- Wang, H. N., Liu, F. L., Li, J., et al., 2018. Petrology, geochemistry and P–T–t path of lawsonite-bearing retrograded eclogites in the Changning–Menglian orogenic belt, southeast Tibetan Plateau. *Journal of Metamorphic Geology*, 37(4): 439–478. <https://doi.org/10.1111/jmg.12462>
- Wang, H. N., Liu, F. L., Schertl, H.-P., et al., 2019. Paleo-Tethyan tectonic evolution of Lancangjiang metamorphic complex: Evidence from SHRIMP U–Pb zircon dating and $^{40}\text{Ar}/^{39}\text{Ar}$ isotope geochronology of blueschists in Xiaoheijiang–Xiayun area. Southeastern Tibetan Plateau. *Gondwana Research*, 65: 142–155. <https://doi.org/10.1016/j.gr.2018.08.007>.
- Winchester J. A., Floyd P. A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Chemical Geology*, 20(4): 325–343. [https://doi.org/10.1016/0009-2541\(77\)90057-2](https://doi.org/10.1016/0009-2541(77)90057-2)

- Wu, F. Y., Liu, X. C., Ji, W. Q., et al., 2017. Highly fractionated granites: Recognition and research. *Science China: Earth Sciences*, 60(7): 1201–1219. <https://doi.org/10.1007/s11430-016-5139-1>
- Xu, C., Wang Y. J., Qian X., et al., 2020. Geochronological and Geochemical Characteristics of Early Silurian S-Type Granitic Gneiss in Takengon Area of Northern Sumatra and Its Tectonic Implications. *Earth Science*, 45(6): 2077-2090(in Chinese with English abstract).
- Yan, Q. T., Qian, X., Zhang, F. F., et al., 2025. Petrogenesis of Late Triassic Post-Collisional Volcanic Rocks from Loei Zone in Southeastern Thailand and Its Paleotethyan Tectonic Implications. *Earth Science*, 50(6): 2144–2162(in Chinese with English abstract).
- Yu, X. Q., Qian, X., Lu, X. H., et al., 2021. Zircon U-Pb Geochronology of Late Triassic Granites from Sibolga Area in Western Sumatra and Its Tethyan Tectonic Implications. *Earth Science*, 46(8): 2873–2886(in Chinese with English abstract).
- Yu, X. Q., Qian, X., Wang, Y. J., et al., 2024. Late Triassic Magmatism in Eastern Peninsular Malaysia and Its Paleotethyan Tectonic Implications. *Geotectonica et Metallogenia*, 48(3):493–511(in Chinese with English abstract).
- Yu, Y. Q., Qian, X., Ghani, A. A., et al., 2023. Triassic felsic magmatism in SE Peninsular Malaysia: Petrogenesis and geodynamic implications for the Eastern Paleotethyan tectonic transition. *Lithos*, 462-463: 107399. <https://doi.org/10.1016/j.lithos.2023.107399>.
- Zahirovic, S., Matthews, K.J., Flament, N., et al., 2016. Tectonic evolution and deep mantle structure of the eastern Tethys since the latest Jurassic. *Earth-Science Reviews*, 162: 293-337. <https://doi.org/10.1016/j.earscirev.2016.09.005>.
- Zhai M. G., 2017. Granites: Leading study issue for continental evolution. *Acta Petrologica Sinica*, 33 (5): 1369–1380. (in Chinese with English abstract)
- Zhang, R.Y., Lo, C.H., Li, X.H., Chung, S.L., Anh, T.T., Tri, T.T., 2014. U-Pb dating and tectonic implication of ophiolite and metabasite from the Song Ma suture zone, northern Vietnam. *American Journal of Science*, 314 (2): 649–678. <https://doi.org/10.2475/02.2014.07>
- Zhang, Z. W., Shu, Q., Yang, X. Y., et al., 2019. Review on the Tectonic Terranes Associated with Metallogenic Zones in Southeast Asia. *Journal of Earth Science*, 30(1):1-19. <https://doi.org/10.1007/s12583-019-0858-0>
- Zhao, T. Y., Qian, X., Feng, Q. L., 2016. Geochemistry, Zircon U-Pb Age and Hf Isotopic Constraints on the Petrogenesis of the Silurian Rhyolites in the Loei Fold Belt and Their Tectonic Implications. *Journal of Earth Science*, 27(3): 391–402. <https://doi.org/10.1007/s12583-016-0671-y>.
- Zheng, Y. F., Chen, Y. X., Chen, R. X., et al., 2022. Tectonic evolution of convergent plate margins and its geological effects. *Science China Earth*, 67(7): 1247–1276(in Chinese with English abstract).
- Zheng, Y. F., Chen, R. X., Gao, P., 2024. Anatectic Metamorphism and Granite Petrogenesis in Continental Collision Zones. *Earth Science*, 49(1): 1-28(in Chinese with English abstract).
- Zhong, D. L., 1998. The Gutethys Orogenic Belt in Western Yunnan and Sichuan. Science Press, Beijing (in Chinese).
- Zhu, D.C., Wang, Q., Li, S. M., et al., 2025. Magma genesis and crustal evolution in continental collision zones. *Science China Earth Sciences*, 68(5): 1346–1370 (in Chinese).

附中文参考文献

- 陈国超, 裴先治, 李瑞保, 等, 2016. 东昆仑东段香加南山花岗岩基的岩浆混合成因:来自镁铁质微粒包体的证据. *地学前缘*, 23 (04): 226-240.
- 李慧玲, 钱鑫, 余小清, 等, 2023. 越南昆嵩地体三叠纪花岗岩岩石成因及其特提斯构造意义. *地球科学*, 48(4): 1441–1460.
- 施美凤, 林方成, 李兴振, 等, 2011. 东南亚中南半岛与中国西南邻区地层分区及沉积演化历史.

- 中国地质, 38(5): 1244–1256.
- 徐畅, 王岳军, 钱鑫, 等, 2020. 苏门答腊岛北部 Takengon 早志留世 S 型花岗片麻岩年代学、地球化学特征及构造意义. 地球科学, 45(6): 2077-2090.
- 闫秋彤, 钱鑫, 张菲菲, 等, 2025. 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. 地球科学, 50(06): 2144-2162.
- 余小清, 钱鑫, 卢向红, 等, 2021. 西苏门答腊实武牙地区晚三叠世花岗岩锆石年代学及其特提斯构造意义. 地球科学, 46(8): 2873-2886.
- 余永琪, 钱鑫, 王岳军, 等, 2024. 马来半岛东部晚三叠世岩浆作用及其古特提斯构造意义. 大地构造与成矿学, 48(3): 493-511.
- 郑永飞, 陈伊翔, 陈仁旭, 等, 2022. 汇聚板块边缘构造演化及其地质效应. 中国科学: 地球科学, 52: 1213–1242
- 郑永飞, 陈仁旭, 高彭. 2024. 大陆碰撞带深熔变质与花岗岩成因. 地球科学, 49: 1–28
- 钟大赉, 1998. 滇川西部古特提斯造山带. 北京: 科学出版社.
- 翟明国, 2017. 花岗岩: 大陆地质研究的突破口以及若干关键科学问题——“岩石学报”花岗岩专辑代序. 岩石学报, 33 (05): 1369–1380.
- 朱弟成, 王青, 李世民, 等, 2025. 大陆碰撞带岩浆成因与地壳演化. 中国科学: 地球科学, 55(5): 1398–1423.