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海南岛印支-燕山期花岗岩年代学格架与成因*

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Abstract　In recent years, a series of work on granites have been conducted on the widespread Indosinian-Yanshannian granites in Hainan Island which constitute part of the magmatic rocks of South China. However, the geochronological framework, genetic type and regional tectonic setting of these granites still need to be constrained. We made a detailed analysis of relevant literature as well as our own study regarding the ages and geochemical properties of the Indosinian-Yanshannian granites in Hainan Island, and a further discussion on the magmatic source and tectonic background controlling them. In Hainan Island, the Indosinian granites are mainly composed of granodiorite and monzogranite, and part of them show gneissic structure. The summary of high precision geochronology data suggests that they emplaced during 278 ~ 225Ma, and the main age peak is ca. 240Ma. The geochemical features indicate they can be divided into S-, I- and A-type granites. Both S-type (278 ~ 241Ma) and I-type (272 ~ 233Ma) granites are high-K calc-alkaline, and their whole-rock zircon saturation temperatures (average < 750℃) are lower than the dehydration melting of amphibolite, indicating that these two types of granites might be products of water-flux melting. In contrast, the high whole-rock zirconium saturation temperatures (> 800℃) of A-type granites (257 ~ 225Ma) indicate they are generated from vapour-absent melting of the residue remaining in the lower crust after production of a previous granite. Furthermore, there are very limited Jurassic magmatic rocks developed in Hainan Island, i. e., the newly identified 161Ma granite is high-K calc-alkaline with I-type affinity; while the Cretaceous granites (mainly monzogranite and granodiorite) can be divided into three periods: ca. 120Ma, ca. 110 ~ 90Ma and ca. 70Ma, with a peak at ca. 100Ma. The geochemical evidence implies that these granites are I-type granites with the source involving juvernile mantle components. On the basis of the above information, we propose that: (1) the large volume Indosinian-Yanshannian magmatic rocks are developed under the subduction of the Paleo-Pacific plate; (2) the initiation of the Paleo-Pacific plate subduction started since Early Permian (ca. 280Ma), and the Andean-type active continental margin of South China lasted to Late Cretaceous (ca. 70Ma); (3) Hainan Island preserves the subduction-related Indosinian-Yanshannian magmatism under the setting of the Andean-type active continental margin of east-southeast Asia.

Key words　Granite; Hainan Island; Indosinian; Yanshannian; Paleo-Pacific plate subduction; South China

摘　要　海南岛分布着大面积的印支-燕山期岩浆岩,是华南岩浆活动的重要组成部分。近年来,对这些花岗岩已开展了一系列工作,但其年代学格架仍需完善,成因类型及源区性质仍需限定,区域构造机制仍存在争议。本文详细梳理了已发表的

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海南岛晚古生代-中生代花岗岩地球化学和年代学数据,结合作者近年来的相关工作,对海南岛花岗岩的年代学格架和岩石地球化学特征进行总结,并对源岩、岩浆演化过程和地球动力学背景进行讨论。海南岛印支期(二叠纪-三叠纪)花岗岩(部分具有片麻状构造)整体以NE走向展布,形成于278~225Ma,峰期为240Ma。岩相学和地球化学研究表明,此期岩浆活动形成了具有不同地球化学特征的S型、I型和A型花岗岩。其中,S型花岗岩(278~241Ma)与I型花岗岩(272~233Ma)均为高钾钙碱性花岗岩,具有较低的全岩锆饱和温度(平均<750℃),低于大规模角闪石分解引起的脱水熔融所需的温度,可能是由底侵玄武质岩浆释放的水加入到下地壳诱发部分熔融的产物;A型花岗岩(257~225Ma)的全岩锆饱和温度较高(>800℃),表明源区无流体加入或为已有花岗岩生成的去水源岩在高温条件下脱水熔融形成。此外,本区还存在少量燕山期花岗岩,包括燕山早期(侏罗纪)岩浆活动(如本研究识别出的161Ma高钾钙碱性I型花岗岩)以及集中在白垩纪的三期侏罗纪-白垩纪岩浆活动(按年龄可分为:ca. 120Ma、ca. 110~90Ma和ca. 70Ma,峰期为ca. 100Ma)。地球化学数据表明燕山期花岗岩具有高钾钙碱性I型特征,源区中有幔源年轻组分的加入。据此,本文作者认为:(1)印支-燕山期大规模的花岗岩浆作用与古太平洋板块向华南大陆俯冲有关;(2)古太平洋板块向华南大陆的俯冲可能起始于早-中二叠世(ca. 280Ma),结束于晚白垩世末期(ca. 70Ma);(3)自二叠纪起至白垩纪末期安第斯型活动大陆边缘结束,海南岛保存了古太平洋俯冲相关的岩浆活动记录。

关键词 花岗岩;海南岛;印支期;燕山期;古太平洋俯冲;华南

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花岗岩是大陆地壳的重要组成部分,其形成和演化反映了壳幔相互作用中物质、能量的传输和转化,记录了地球分异演化和大陆地壳形成与演化及相关地球深部过程等重要信息,是研究地球动力学的重要"岩石探针"(吴福元等,2007)。华南陆块在晚古生代至中生代期间,发育大规模的岩浆活动(图1a)、变质作用及构造变形,形成了广泛分布的岩浆岩及丰富的矿产资源(Zhou and Li, 2000; Zhou *et al.*, 2006; Li and Li, 2007; Li *et al.*, 2012a, 2014, 2020; Mao *et al.*, 2013a; Wei *et al.*, 2023)。华南是我国花岗岩研究程度较高的区域,由于该地区花岗岩与大规模金属成矿作用关系密切,长久以来持续受到地质学家们的关注与研究。但仍有如下一些关键问题需要持续深入研究:(1)形成时代:20世纪时已有大量的利用全岩或单矿物K-Ar、Ar-Ar和Rb-Sr等同位素定年方法得出的一批年龄数据,但这些同位素体系的封闭温度较低,所得到的年龄误差较大,只能提供大致的形成年龄或者是岩体后期遭受热事件的年龄,无法对花岗岩精确的时空分布规律提供有效约束。近年来,随着锆石微区定年技术的使用,已得到了一批精细的花岗岩年代学数据。而不同学者通过对花岗岩年龄数据进行综合得出不同的时空分布规律,如Li and Li (2007)得到华南中生代花岗岩随时间有从沿海向内陆迁移的趋势,进而提出古太平洋平板块俯冲模型。而Wang *et al.* (2013a)则认为华南大陆三叠纪花岗岩无明显时空分布规律,是碰撞造山的产物。因此,建立精确的时空格架,厘定不同类型花岗岩及其岩石组合的时空关系十分必要。(2)岩石类型:华南中生代岩浆岩以花岗岩为主,且大部分具有很高的SiO_2含量(>70%)。这些花岗岩具有一些共同地球化学特征,这些特征除与源区组成物质相关外,很可能与岩浆形成过程有关(Wang *et al.*, 2000)。华南中生代很多花岗岩与单一的沉积岩或火成岩熔融形成的S型或I型花岗岩存在差异。很难确定花岗岩源岩的地球化学特征,导致成因类型也难以厘定(邱检生等,2005,2008;李献华等,2007),甚至同一个花岗岩体可以被先后判定为I型、A型或者S型,以至于对岩体的成因和构造解释均有差异(如佛冈岩体;李献华等,2007)。因此,准确厘定花岗岩类型是进一步确定其成因和源区性质,合理解析华南中生代构造演化历史的前提条件。(3)构造背景:古太平洋板块俯冲模式能够较好的解释华南晚中生代的岩浆活动的时空分布规律(Li and Li, 2007; Li *et al.*, 2012b),但用该模式解释华南晚中生代岩浆活动也存在一些困难,如与经典安第斯型活动大陆边缘弧以安山岩为主不同,华南晚中生代的火成岩以酸性火山岩占主导(Wang *et al.*, 2013)。另一种主要观点是:华南内陆印支期花岗岩,斜向逆冲和左旋张扭等陆内变形是其西南侧特提斯洋闭合后印支与华南陆块碰撞,以及北部的华北与华南碰撞的远程效应的结果(Zhou *et al.*, 2006; Mao *et al.*, 2013b; Wang *et al.*, 2013a;王岳军等,2022)。另外,古太平洋板片向华南陆块俯冲的起始时间以及结束时间,以及晚古生代以来的岩浆活动特征与古太平洋板块的俯冲之间的关系也需要进一步的研究。

海南岛位于华南陆块南端,其构造位置靠近古太平洋俯冲带,出露大规模印支-燕山期花岗岩(图1b),是探讨华南花岗岩成因的理想研究区。然而,海南岛经历了多期次的构造运动,发育多期次岩浆活动和构造事件及其叠加以及由此产生的壳幔相互作用、岩浆分异演化等,从而给认识该地区岩浆时空分布和源区属性等带来困难。而这些因素也造成了对海南岛岩浆构造活动研究认识的复杂局面,使得对于诸如印支-燕山期花岗岩精细的时空分布、成因机制和侵位时的构造体制等关键问题上仍存在着诸多争议(Li *et al.*, 2006; Xie *et al.*, 2006; Jiang and Li, 2014; Yan *et al.*, 2017; Shen *et al.*, 2018; He *et al.*, 2020; Dilek and Tang, 2021;刘飞等,2022)。以上问题可以概括为以下几点:(1)花岗岩年代学格架及成因类型的进一步明确;(2)印支期岩浆活动是印支板块碰撞为主导还是受古太平洋构造域的控制?(3)燕山期岩浆活动的具体期次及持续时间如何?因此,需要对海南岛花岗岩的研究工作进行综合梳理,准确厘定海南岛花岗岩的时

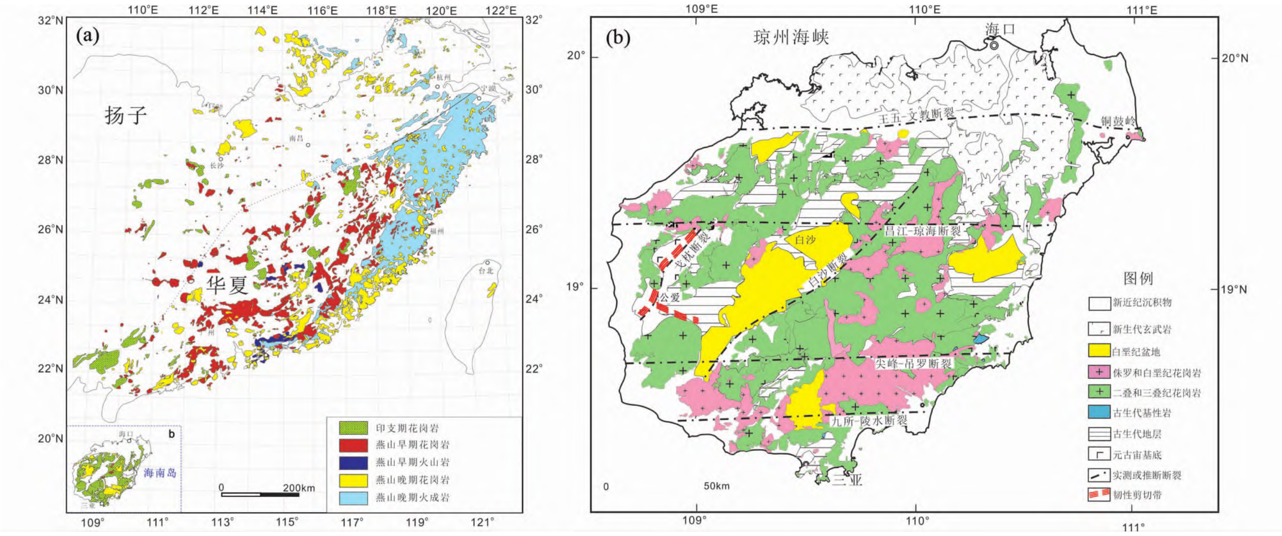

图 1 华南印支-燕山期岩浆岩分布简图（a，据 Li *et al.*，2012a）及海南岛地质简图（b，据 Li *et al.*，2006）

Fig. 1 Schematic map showing the distribution of Mesozoic magmatic rocks distribution in South China（a，modified after Li *et al.*，2012a）and schematic geological map of Hainan Island（b，modified after Li *et al.*，2006）

空分布，解析花岗岩的源区特征和成岩过程，以更深入地探讨华南在印支-燕山期期间的岩浆作用对构造演化的响应和指示。基于上述考虑，本文归纳总结了近年来有关海南岛印支-燕山期的花岗岩年龄（微区原位锆石 U-Pb 年龄）和地球化学（全岩主微量元素、Sr-Nd 同位素及锆石 Hf-O 同位素）数据，并结合本文作者针对海南岛花岗岩的工作，深入讨论了海南岛印支-燕山期花岗岩形成的地球动力学过程。

1 区域地质背景

显生宙以来，中国由华北、华南和塔里木及其他诸多小陆块拼合而成，位于古太平洋、古特提斯洋和古亚洲洋三大构造域之中，是全球大陆构造演化和深部作用最复杂的大陆（许志琴等，2010；董树文等，2014）。华南陆块由东南部的华夏陆块和西北部的扬子克拉通于新元古代沿江南造山带拼合焊接而成（图 1a），北部与华北陆块相邻，西南部被哀牢山-松马缝合带与印支地块分隔，向西以龙门山断裂为界与松潘-甘孜地体相邻（Li *et al.*，2009；Cawood *et al.*，2018）。华南陆块经历了漫长而复杂的地质演化，包括多次强烈的板块拼贴、拉张裂解和多旋回、多期次的构造-岩浆活动事件（Li and Li，2007；Faure *et al.*，2009；Li *et al.*，2014；Cawood *et al.*，2018，2020；Shu *et al.*，2021）。

海南岛是位于我国南缘的大陆型岛屿，以琼州海峡与华南大陆相连，位于欧亚板块、印度-澳大利亚板块和太平洋板块的交接部位，具有特殊的大地构造位置，受到特提斯构造域和太平洋构造域的双重作用，经历了多期次复杂的地壳演化历史（Li *et al.*，2002；葛小月，2003；图 1）。多次强烈的构造运动使海南岛形成了东西向、南北向、北东向、北北东向和北西向多种构造形迹（图 1b）。这些不同方向的构造形迹，是控制海南岛不同时期沉积建造和岩浆活动的主要构造（汪啸风等，1991a）。海南岛地层发育较全，除侏罗系尚无可靠证据外，自元古代至第四纪地层皆有分布，但由于后期岩浆活动和构造运动的破坏，不同时代的地层多呈“岛状”展布（汪啸风等，1991a）。抱板群是目前海南岛出露的最老地层，其下部的戈枕村组为混合岩化的斜长片麻岩，其上部的峨文岭组为片岩和石英岩类，变质程度为高绿片岩相至高角闪岩相、局部达麻粒岩相，原岩可能为复理石沉积，形成时代约为 1800～1420Ma（马大铨等，1997；龙文国等，2005；Yao *et al.*，2017）。石碌群是中元古代的一套火山-碎屑-碳酸盐序列，其中凝灰岩中的锆石定年结果为 1439Ma（Li *et al.*，2008；Yao *et al.*，2017）。石灰顶组为一套浅海相变质含铁火山碎屑岩和镁质碳酸盐岩建造，最大沉积年龄被限定为 1200Ma（Li *et al.*，2008；Yao *et al.*，2017）。下古生界出露齐全，包括寒武系及奥陶系的浅变质页岩、砂岩、粉砂岩、板岩和下志留统砂岩（姚华舟和黄照先，1999；曾庆銮等，2003）。上古生界包括泥盆系灰岩、砂岩、粉砂岩及泥岩，石炭系板岩、变火山岩和二叠系灰岩、砂岩等（唐作友和冯少南，1998；胡宁等，2002；龙文国等，2007）。中生界主要为下三叠统粗碎屑岩、泥页岩及广泛分布的白垩系红色粗碎屑岩夹泥岩、页岩、火山岩等（汪啸风等，1991a）。新生界地层出露较全，其中古近纪是一个多中心、多物源、多环境、多旋回的复杂沉积体系，以砂岩和黏土沉积为主，新近系发育多期火山岩（汪啸风等，1991a）。

海南岛岩浆活动强烈，具有多期次活动特征。侵入体的总面积为 $12420km^2$，约占全岛面积的 37%，90% 以上为花岗岩类岩石。其中，以印支-燕山期花岗岩类分布最为广泛（图 1b），元古代和早古生代花岗岩类零星出露（汪啸风等，

1991b;海南省地质调查院,2012[①])。喷出岩以新生代玄武岩为主,主要分布在王五-文教断裂以北(汪啸风等, 1991a)。二叠纪侵入岩面积约为 5200km^2,以中酸性岩石为主,主要岩性包括石英闪长岩、花岗闪长岩、二长花岗岩等,部分具有片麻状构造(Li *et al.*, 2006; 温淑女等,2013;Shen *et al.*, 2018; He *et al.*, 2020)。早二叠世花岗岩类主要分布于海南岛昌江邦溪-霸王岭-石碌-长塘岭、乐东县大安水库-毛阳-长征农场、万宁县新风岭及袁水水库-岗岭,中二叠世花岗岩主要分布在东方市、昌江县、通什市及万宁乐来一带,晚二叠世花岗岩类分布在乐东、五指山、万宁禄马、东方大田和儋州西庆等地(海南省地质调查院,2012;图 1b)。三叠纪侵入岩面积(约 6900km^2) 比二叠纪侵入岩面积略大,主要岩性为(角闪石) 黑云母二长花岗岩、黑云母正长花岗岩、花岗闪长岩、花岗斑岩、石英二长岩、霓辉石正长岩和石英正长岩,少量辉绿岩、闪长岩和辉长岩等(谢才富等,2006;唐立梅等,2010a;Tang *et al.*, 2013; Yan *et al.*, 2017; Shen *et al.*, 2018;刘飞等,2022)。早-中三叠世花岗岩类主要分布在万宁进岭和袁水-儋州-琼中-乐东和尖峰-昌江保梅岭等,晚三叠世花岗岩类主要分布在昌江-霸王岭和琼海迈州岭、排岭等地(海南省地质调查院,2012;图 1b)。侏罗纪岩浆岩出露十分有限。白垩纪岩浆岩广泛分布,主要为高钾钙碱性花岗岩(部分含有闪长质包体)及高钾钙碱性中酸性火山岩和双峰式火山岩,基性岩多以岩脉的形式产出(葛小月等,2003;唐立梅等, 2010b;Wang *et al.*, 2012a; Jiang and Li, 2014; Yan *et al.*, 2017; Dilek and Tang, 2021)。花岗岩体主要有千家、保城、吊罗山和屯昌复式岩体,另外有一些小岩体如昌化、龙楼、雅亮和天涯海角等(汪啸风等, 1991b;海南省地质调查院,2012;图 1b)。总体来看,海南岛晚中生代的侵入岩体主要分布在海南岛东南部和西南部,东北部零星出露小岩株(图 1b)。

2 海南岛印支-燕山期花岗岩岩相学特征

2.1 印支期花岗岩岩相学特征

海南岛印支期花岗岩主要类型有黑云母二长花岗岩和黑云母花岗闪长岩,少数石榴石花岗岩、电气石花岗岩和二云母花岗岩。根据岩石构造,可以分为片麻状构造和块状构造花岗岩:(1)片麻状构造花岗岩为早-中二叠世花岗岩,主要分布在岛中部地区。中粒-中粗粒巨斑状花岗结构/中细粒似斑状花岗结构,斑晶为钾长石(粒度较大,普遍在 0.5 ~ 3cm 之间,自形-半自形,沿 NE 或 NEE 向定向排列),为同构造花岗岩(葛小月,2003;Li *et al.*, 2006)。主要组成矿物有石英、钾长石、斜长石,黑云母和角闪石等暗色矿物含量较低,一般呈相对细小颗粒分布于长英质颗粒之间。其中,斜长石半自形-他形,可见聚片双晶,有些可见简单的岩浆环带结构;石英多为细粒集合体;黑云母为片状,多色性明显,多呈细粒集合体或鳞片状集合体出现。副矿物有褐帘石、磷灰石、榍石、锆石、磁铁矿等(汪啸风等, 1991b;葛小月,2003);(2) 块状构造花岗岩主要为三叠纪花岗岩,矿物组合无定向,为似斑状结构(斑晶主要为钾长石和石英,钾长石粒度较大,普遍在 0.5 ~ 3cm 之间)、中粗粒结构、粒状镶嵌结构等。主要矿物组成为钾长石、斜长石和石英,暗色矿物主要为角闪石和黑云母。此外还可见褐帘石、磷灰石、榍石、锆石、铁钛氧化物等副矿物(汪啸风等, 1991b;葛小月,2003)。

2.2 燕山期花岗岩岩相学特征

晚中生代花岗岩岩性主要为黑云角闪二长花岗岩、黑云母二长花岗岩、黑云母正长花岗岩和黑云母花岗闪长岩。主要为块状构造,根据结构可以大致分为:(1)似斑状结构。斑晶为碱性长石,基质为中细粒花岗结构。矿物包括碱性长石、斜长石和石英,次要矿物为黑云母和角闪石,副矿物有磷灰石、锆石和榍石等。碱性长石主要为条纹长石,多为条纹结构,卡斯巴双晶发育;斜长石见柱状和板状,聚片双晶发育;石英呈他形分布于长石和暗色矿物之间(汪啸风等, 1991b;葛小月,2003)。(2)花岗结构。主要矿物为碱性长石、斜长石和石英,次要矿物为黑云母和角闪石,副矿物有磷灰石、锆石和榍石等。其中,碱性长石呈他形板柱状,主要为条纹长石和微斜长石;斜长石呈自形-半自形板状,发育聚片双晶;石英呈他形粒状,充填于其他矿物空隙之间;黑云母呈自形-半自形鳞片状;角闪石为半自形-自形,部分绿泥石化。局部可见嵌晶结构,斜长石以及石英被包裹在钾长石内,且斜长石被钾长石熔蚀(汪啸风等,1991b;葛小月,2003)。

3 海南岛印支-燕山期花岗岩年代学格架

3.1 印支期花岗岩年代学格架

华南陆块印支期花岗岩分布广泛,但是出露面积有限(图 1a)。主要为过铝质黑云母花岗岩和二云母花岗岩,而准铝质花岗岩相对较少(Zhou *et al.*, 2006; Li and Li, 2007; Wang *et al.*, 2007)。海南岛是华南陆块印支期花岗岩出露的主要区域(Li *et al.*, 2006)。到目前为止,此阶段华南花岗岩的年代学格架及时空分布仍存有争议:一种观点认为此期花岗岩分为两个阶段,呈面状分布,没有明显的时空规律(Zhou *et al.*, 2006; Wang *et al.*, 2007; Yu *et al.*, 2007);另外一种观点是此期岩浆活动连续,不分期次,具有从沿海向内陆逐渐变年轻的趋势(Li and Li, 2007; Li *et al.*, 2012b)。鉴于此,本文对该期海南岛花岗岩体的高精度年龄数据进行总结(电子版附表 1),旨在构建可靠的年代学格架,为华南陆块印支期花岗岩的时空分布提供佐证。

海南岛印支期花岗岩遍布全岛,早期数据以 Rb-Sr 等时线法较多,高精度数据多集中于二叠纪中晚期岩浆事件的年

① 海南省地质调查院. 2012. 海南省区域地质志. 海口: 1-950

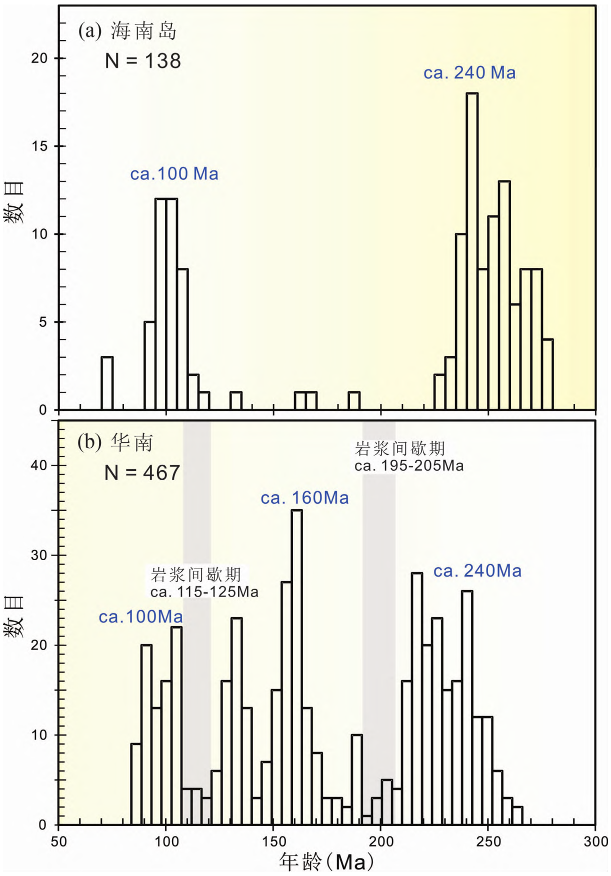

图 2 海南岛(a)和华南(b)花岗岩年龄分布频谱图

Fig. 2 Histograms and cumulative probability plots of isotopic ages for granites from Hainan Island (a) and South China (b)

龄(谢才富等,2005; Li *et al.*, 2006; Xie *et al.*, 2006; 温淑女等,2013),而对于大面积的三叠纪花岗岩还需更多精确年龄数据的约束。

综合近年来的微区原位锆石 U-Pb 定年结果表明,海南岛印支期花岗岩始于早二叠世,集中在中-晚二叠世。目前年龄较老的二叠纪花岗质岩石主要分布在海南岛中南部五指山及其邻区(花岗岩年龄分布于 278~254Ma 范围内;Li *et al.*, 2006; Xie *et al.*, 2006;温淑女等,2013;Shen *et al.*, 2018;He *et al.*, 2020;刘飞等,2022)。即海南岛中南部二叠纪中酸性侵入岩形成时间较早,且持续时间较长。三叠纪花岗岩年龄分布范围是 250~231Ma(葛小月,2003;谢才富等,2006;Yan *et al.*, 2017; Shen *et al.*, 2018; He *et al.*, 2020; Dilek and Tang, 2021;刘飞等,2022;齐重向等,2023)。岩体遍布全岛,岩体呈 NE、NEE 方向展布。基于以上数据,海南岛印支期花岗岩年龄范围是 278~231Ma,呈连续分布趋势,以 240Ma 为主峰期,以及一个次峰 270Ma(图 2a)。三叠纪华南大陆上花岗岩的时代范围为 ca. 250~200Ma (图 2b)。海南岛位于华南陆块的更靠海的位置,其岩浆活动时间为 ca. 250~230Ma(图 2a)。与华南大陆东南福建、浙江沿海三叠纪花岗岩的活动时代(ca. 250~230Ma)相同,而内陆湖南、江西等地却出露较年轻的(ca. 230~200Ma)花岗岩体(Li and Li, 2007)。所以总体看来,三叠纪时期海南岛岩浆活动与华南东南部在形成时代上显示出基本一致的特性。

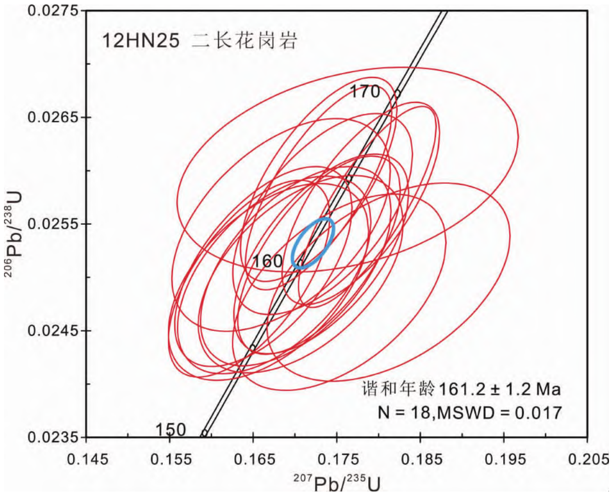

图 3 侏罗纪铜鼓岭花岗岩岩体锆石 SIMS U-Pb 年龄图

Fig. 3 SIMS U-Pb concordia age plot for zircons from the Jurassic Tongguling granite

3.2 燕山期花岗岩年代学格架

燕山期是华南陆块岩浆活动最为强烈的时期,大面积发育的花岗岩使得华南成为大花岗岩省之一(Huang *et al.*, 2015)。除"岩浆间歇期"(ca. 125~115Ma),岩浆活动几乎连续发生(Jiang *et al.*, 2015)。岩浆活动带大多数与海岸线平行分布,北东向延伸可达 1000km(图 1a)。花岗岩类型主要为二长花岗岩、正长花岗岩和花岗闪长岩,其中白垩纪花岗岩伴随大量火山岩(Zhou *et al.*, 2006; Li and Li, 2007; Li *et al.*, 2014; Huang *et al.*, 2015)。

海南岛燕山期花岗质岩浆活动相对较弱,主要发生于白垩纪,侏罗纪花岗岩浆活动十分有限。早期研究认为海南岛没有侏罗纪花岗岩浆活动(汪啸风等, 1991b),直到葛小月(2003)在儋县岩基北部识别出 186Ma 的花岗岩,表明海南岛存在燕山早期的岩浆活动。之后,黄芳燕(2017)发现在陵水断裂带上的勤赛地区分布有侏罗纪辉长岩-正长岩套(八宝坡正长岩 165.2±1.6Ma)。另外,Xu *et al.* (2014)报道的亚龙湾地区的碎屑锆石中有明显的 ca. 155Ma 的年龄峰值,Jiang *et al.* (2015)报道白沙盆地鹿母湾群砂岩中的碎屑锆石存在 ca. 170Ma 的侏罗纪峰值年龄。本文作者在东北部铜鼓岭海边识别出 161.2±1.2Ma 的高钾钙碱性 I 型花岗岩(本文数据见电子版附表 2、图 3)。这些发现都表明海南岛存在一定规模的侏罗纪岩浆活动。

早期的研究认为海南岛燕山晚期的白垩纪岩浆活动发生在 ca. 110Ma 和 ca. 90Ma 两个时期(Rb-Sr 等时线;汪啸风

等, 1991b)。近些年,已报道的高精度锆石微区原位 U-Pb 年龄数据显示,海南岛白垩纪的岩浆活动主要发生于 110 ~ 90Ma(唐立梅, 2010; Wang *et al.*, 2012a; 梁飞刚, 2013; 陈沐龙, 2014; 付王伟等, 2014)。本文作者利用高精度的 SIMS 锆石 U-Pb 定年方法在海南岛东南部和南部地区识别出 118Ma 的花岗岩(华南主陆岩浆间歇期 ca. 125 ~ 115Ma),在昌江地区识别出若干个 ca. 95Ma 的小花岗岩体(待发表数据)。值得注意的是,海南岛东北部 73Ma 的龙楼岩体,是迄今为止报道的最为年轻的华南中生代花岗岩体,可能暗示华南燕山期岩浆活动持续至 ca. 70Ma(Jiang and Li, 2014)。总之,白垩纪花岗岩发育于 ca. 120Ma, ca. 110 ~ 90Ma 和 ca. 70Ma 三个时期(图 2a),集中于 ca. 110 ~ 100Ma。缺失 150 ~ 120Ma 的岩浆岩,而这个时期岩浆活动在华南大陆则比较发育(图 2b)。由此可见,在燕山期期间,海南岛与华南大陆可能具有不同的岩浆活动期次。

综上所述,海南岛印支期岩浆活动可能起始于 ca. 280Ma持续至 ca. 230Ma,无间歇性。而燕山期岩浆活动不连续,呈幕式出现。其中,侏罗纪岩浆活动极少,白垩纪花岗岩大致可分为三期: ca. 120Ma, ca. 110 ~ 90Ma 和 ca. 70Ma。与华南大陆内部花岗岩活动的差别表现为:(1)海南岛印支期花岗岩起始时间早于华南大陆;(2)海南岛燕山期花岗岩呈阶段性出现,与华南大陆内部“岩浆间歇期”并不吻合。

4 海南岛印支-燕山期花岗岩地球化学特征及岩石类型

4.1 印支期花岗岩地球化学特征及岩石类型

二叠纪花岗岩的主量元素变化范围较大: SiO_2(64.0% ~ 75.2%)、Al_2O_3(12.6% ~ 16.8%)、CaO (0.24% ~ 4.63%)、Na_2O(1.91% ~ 4.47%)、K_2O(1.99% ~ 8.41%), TiO_2(0.07% ~ 1.34%)、MgO (0.24% ~ 2.15%)和 MnO (<0.08%)含量相对较低(电子版附表 3)。在 TAS 图解中多落入亚碱性范围(图 4a),铝饱和指数 A/CNK 值变化范围 0.91 ~ 1.23,从准铝质到强过铝质(图 4b),以高钾钙碱性为主(图 5)。Harker 图解中, SiO_2 与 TiO_2、Al_2O_3、CaO、MgO 和 P_2O_5 呈负相关关系(图 5)。虽然这种负相关关系存在多解性,但很可能暗示随着岩浆演化,斜长石、钛铁氧化物和磷灰石等均发生了明显的结晶分异作用。球粒陨石标准化稀土元素配分图表现出右倾的稀土配分模式(图 6a),具有明显 Eu 负异常。在原始地幔标准化微量元素蛛网图中,富集大离子亲石元素,相对亏损 Nb、Ta、Ba、Sr 和 Eu (图 6b)。花岗岩全岩锆饱和温度大部分低于 800℃。全岩 Sr-Nd 同位素显示 I_{Sr} 值变化范围是 0.7039 ~ 0.7174, $\varepsilon_{Nd}(t)$ 值为 -3.1 ~ -9.3,二阶段模式年龄 1.29 ~ 1.78Ga(图 7;电子版附表 4)。锆石微区原位 Hf 同位素 $\varepsilon_{Hf}(t)$ 变化从 -7.2 到 2.8(图 8),对应的地壳模式年龄为 1.1 ~ 1.7Ga(电子版附表 5)。

三叠纪花岗岩多为块状构造,大面积分布在岛内不同区域。花岗岩的主量元素中 SiO_2(64.7% ~ 78.9%)、Na_2O(2.4% ~ 3.87%)和 K_2O(3.12% ~ 6.50%)变化范围较大(附表 3),在 TAS 图解中落入亚碱性范围(图 4a)。在 SiO_2-K_2O 图中落入高钾钙碱性和钾玄质区域(图 5)。Al_2O_3 含量从 10.9% 到 15.6%,铝饱和指数 A/CNK 值变化范围 0.88 ~ 1.31,从准铝质到强过铝质(图 4b)。其他主量元素变化范围较大,如 CaO 含量在 0.35% ~ 4.14% 之间变化,而 TiO_2(0.06% ~ 1.16%)、MgO (0.03% ~ 1.73%)、MnO (<0.11%)和 P_2O_5(0.01% ~ 0.35%,大部分 <0.1%)含量相对较低。Harker 图解中, SiO_2 与 Al_2O_3、CaO、TiO_2、MgO 和 P_2O_5 呈负相关关系(图 5)。稀土元素配分模式表现出右倾的趋势(图 6a),以及明显的 Eu 负异常。微量元素蛛网图显示明显的 Nb、Ta、Sr 和 Ba 负异常(图 6b)。花岗岩全岩锆饱和温度变化范围大,从 648℃ 至 884℃。在 Ga/Al 比值和 HFSE(Zr + Nb + Ce + Y)判别图中,部分三叠纪花岗岩落入 A 型花岗岩区域(图 9)。海南岛三叠纪花岗岩的全岩 I_{Sr} 值变化于 0.7027 ~ 0.7186, $\varepsilon_{Nd}(t)$ 值为 -1.1 ~ -8.9(图 7)。与二叠纪花岗岩相比,三叠纪的锆石微区原位 Hf 同位素变化范围更大, $\varepsilon_{Hf}(t)$ 值变化从 1.6 到 -13.4(图 8a),相应的模式年龄为 0.98 ~ 1.73Ga(附表 5),表明源区由存留年龄为中-古元古代的基底物质组成。少量锆石微区原位 $\delta^{18}O$ 值较高,为 8.9‰ ~ 11.4‰(图 8b)。

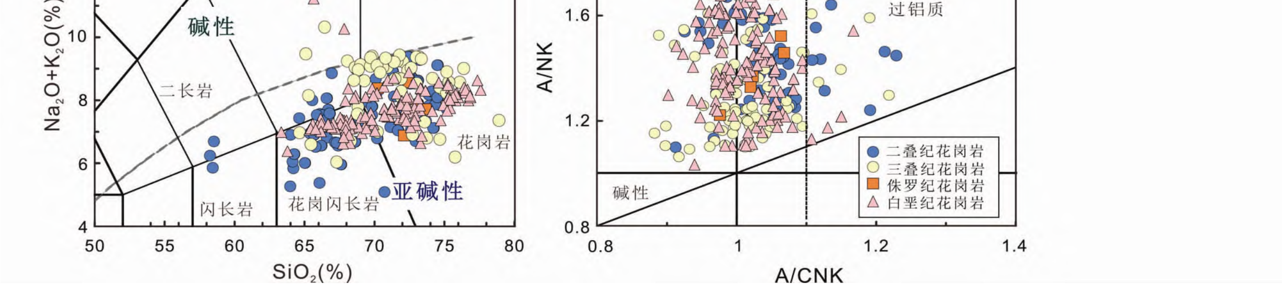

图 4 海南岛印支-燕山期花岗岩 TAS 图解(a)和 A/CNK-A/NK 图解(b)

Fig. 4 TAS (a) and A/CNK vs. A/NK (b) diagrams of Indosinian-Yanshannian granites in Hainan Island

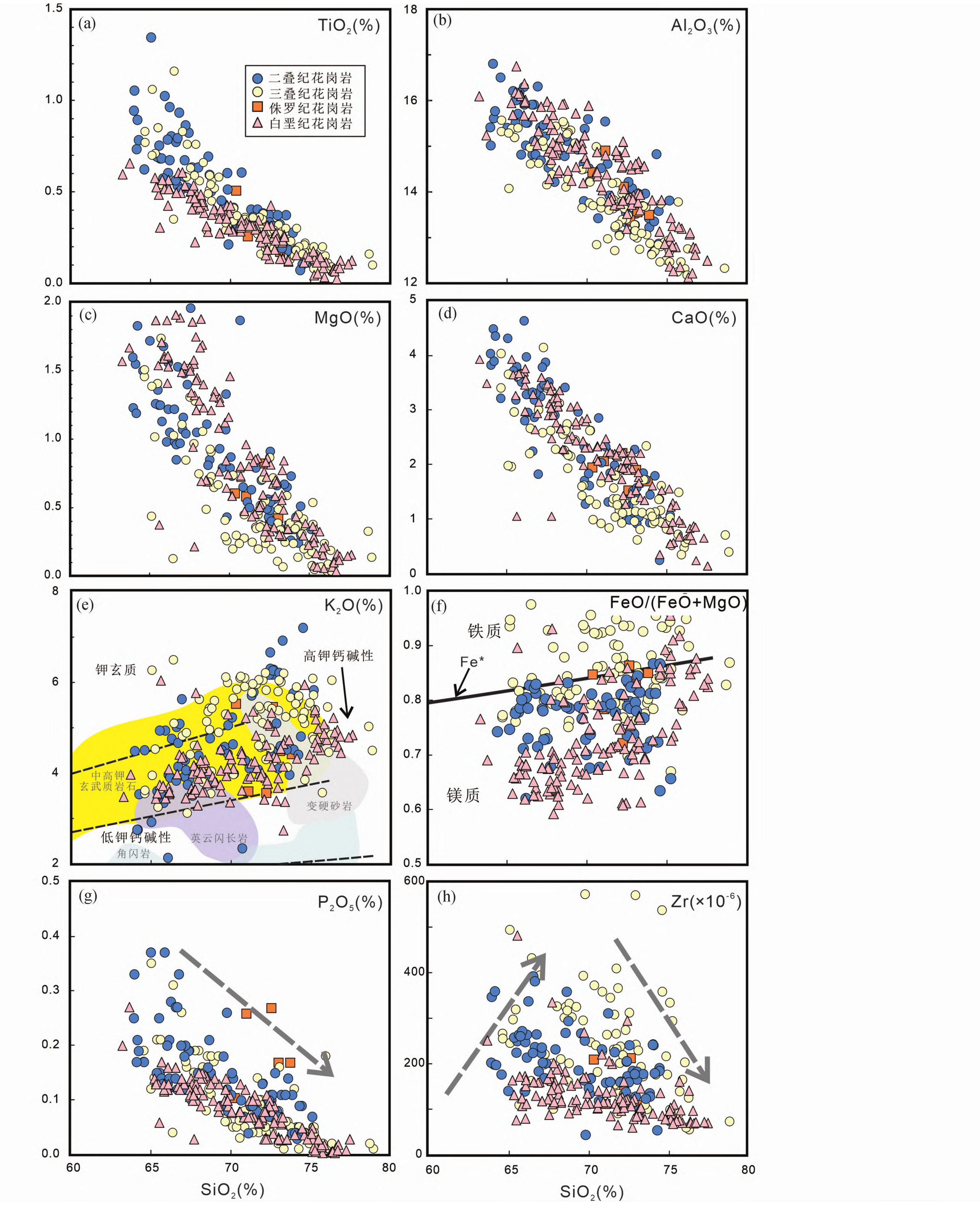

图 5 海南岛印支-燕山期花岗岩 Harker 图解

图 5e 中实验岩石学数据来源：中高钾玄武质岩石据 Sisson *et al.*（2005）；角闪岩据 Patiño Douce（1999），Rapp *et al.*（1991）和 Wolf and Wyllie（1994）；英云闪长岩据 Singh and Johannes（1996）；变硬砂岩据 Montel and Vielzeuf（1997）.（f）$Fe^{*}=(FeO+0.9Fe_2O_3)/(FeO+0.9Fe_2O_3+MgO)$，据 Frost and Frost（2008）

Fig. 5 Harker-type major and trace element plots for the Indosinian-Yanshannian granites in Hainan Island

Data sources for different protoliths of the experimental melts in Fig. 5e: medium to high-K basaltic rocks from Sisson *et al.*（2005）; amphibolites from Patiño Douce（1999）, Rapp *et al.*（1991）and Wolf and Wyllie（1994）; tonalites from Singh and Johannes（1996）; metagraywacks from Montel and Vielzeuf（1997）.（f）$Fe^{*}=(FeO+0.9Fe_2O_3)/(FeO+0.9Fe_2O_3+MgO)$ from Frost and Frost（2008）

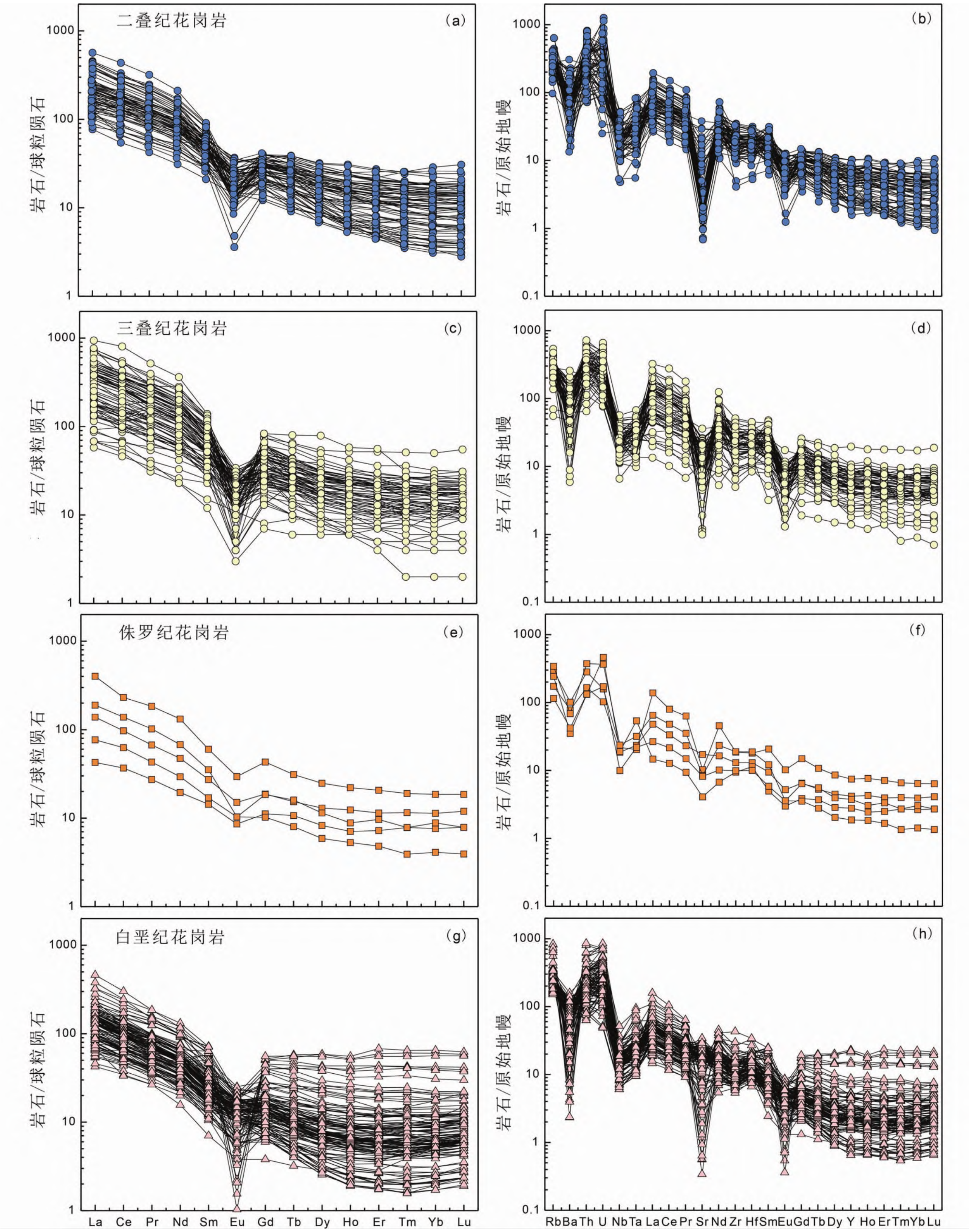

图6　海南岛印支-燕山期花岗岩球粒陨石标准化稀土元素配分图和原始地幔标准化微量元素蛛网图(标准化数值来自 Sun and McDonough, 1989)

Fig. 6　Chondrite-normalized REE diagrams and primitive mantle-normalized trace element diagrams of the Indosinian-Yanshannian granites in Hainan Island (normalization values from Sun and McDonough, 1989)

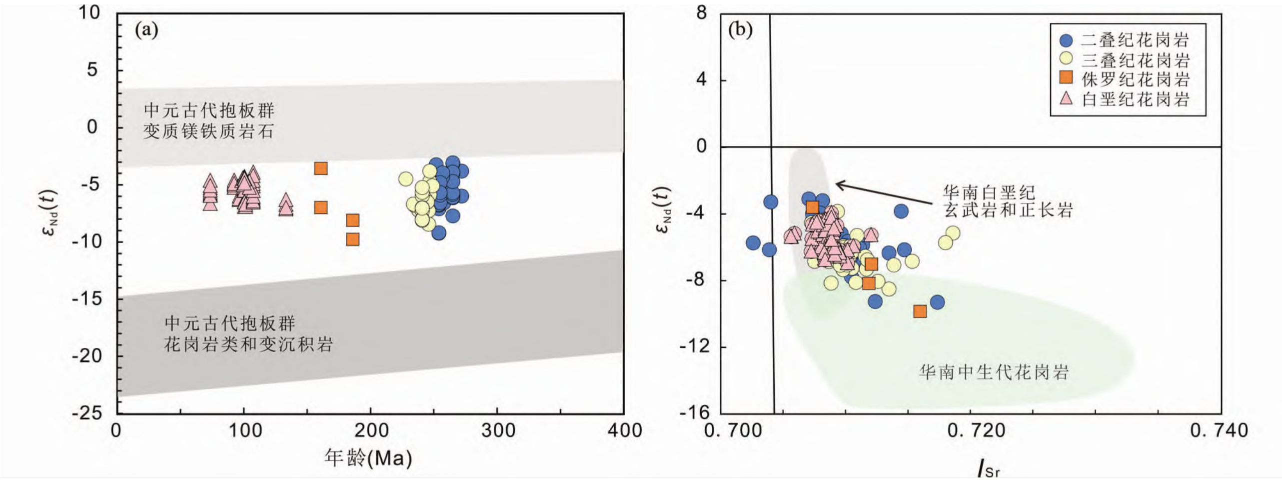

图 7 海南岛印支-燕山期全岩 Nd 同位素-年龄图解(a，据 Shen *et al.*，2018 修改)及 Sr-Nd 同位素图解(b)

海南岛印支-燕山期花岗岩 Sr-Nd 同位素数据见附表 4. 海南岛中元古抱板群花岗岩类和变沉积岩数据来自许德如等(2002)和 Li *et al.*(2008)，变镁铁质岩石数据来自许德如等(2000)和 Zhang *et al.*(2018). 华南中生代花岗岩数据来自：Cai *et al.*(2013)，Chen *et al.*(2004，2013)，Hsieh *et al.*(2008)，Lan *et al.*(1995)，Li *et al.*(2012b)，Liu *et al.*(2014)，Mao *et al.*(2011，2013b)，祁昌实等(2007)，邱检生等(2011)，Qiu *et al.*(2014)，Sun *et al.*(2005，2011)，Wang *et al.*(2005，2007，2012b，2013b)，Zhao *et al.*(2013)；华南白垩纪玄武岩和正长岩数据来自 He and Xu(2012)及其引用数据

Fig. 7 Whole-rock Nd isotopic compositions vs. $\varepsilon_{Nd}(t)$ plot (a，modified after Shen *et al.*，2018) and initial $^{87}Sr/^{86}Sr$ (I_{Sr}) vs. $\varepsilon_{Nd}(t)$ plot (b) for the Indosinian-Yanshannian granites in Hainan Island

The data of Indosinian-Yanshannian granites in Hainan Island in Appendix Table 4. The data for the Mesoproterozoic Baoban granitoids and meta-sedimentary rocks from Xu *et al.*(2002) and Li *et al.*(2008)，and the data for the Mesoproterozoic Baoban meta-mafic rocks from Xu *et al.*(2000) and Zhang *et al.*(2018). The data of Mesozoic granites in South China from Cai *et al.*(2013)，Chen *et al.*(2004，2013)，Hsieh *et al.*(2008)，Lan *et al.*(1995)，Li *et al.*(2012b)，Liu *et al.*(2014)，Mao *et al.*(2011，2013b)，Qi *et al.*(2007)，Qiu *et al.*(2011)，Qiu *et al.*(2014)，Sun *et al.*(2005)，Sun *et al.*(2011)，Wang *et al.*(2005，2007，2012b，2013b)，Zhao *et al.*(2013)；the Cretaceous basalts and syenites of South China from He and Xu (2012) and references therein

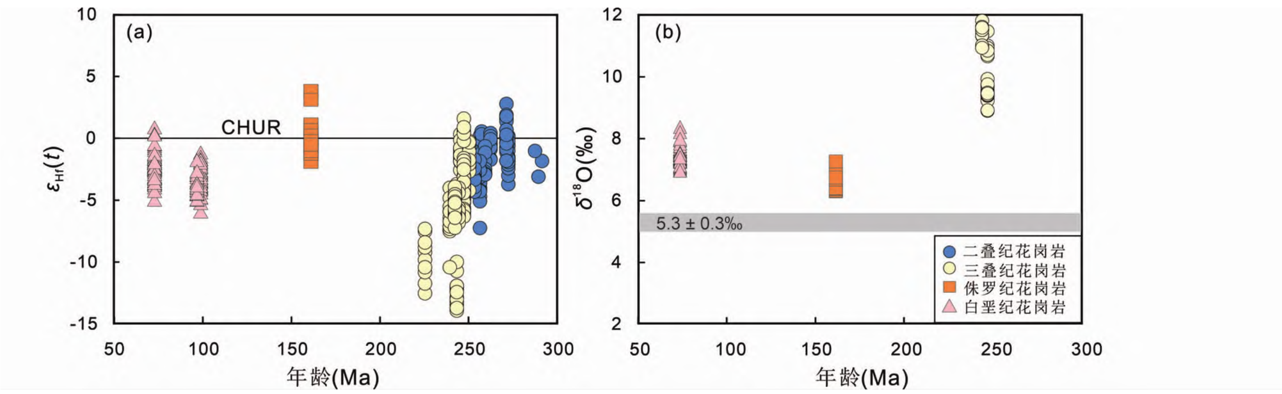

图 8 海南岛印支-燕山期花岗岩锆石 Hf 同位素图解(a)及 O 同位素图解(b)

Fig. 8 Plots of zircon $\varepsilon_{Hf}(t)$ vs. age (a) and $\delta^{18}O$ vs. age (b) for the Indosinian-Yanshannian granites in Hainan Island

4.2 燕山期花岗岩地球化学特征及岩石类型

海南岛侏罗纪花岗岩出露极为有限，本文报道作者识别出的一个侏罗纪 161Ma 花岗岩体的露头(图 3)，岩体由粗粒黑云母花岗岩组成。综合前人工作中发现的 182Ma 黑云母二长花岗岩数据，探讨侏罗纪花岗岩的地球化学特征及岩石成因。在 TAS 图解中侏罗纪岩浆岩落入花岗岩系列(图 4a)，为准铝质到弱过铝质(ACNK = 0.98 ~ 1.06；图 4b)。其 SiO_2 = 70.3% ~ 73.8%，Al_2O_3 = 13.4% ~ 14.9%，CaO = 1.51% ~ 2.20%，P_2O_5 = 0.04% ~ 0.11%(附表 3)，具有高钾钙碱性特征(图 5e)。$FeO^T/(MgO+FeO^T)$比值 0.72 ~ 0.85，落入镁质花岗岩范围(图 5f)。TiO_2、Al_2O_3、K_2O 和 P_2O_5 与 SiO_2 呈现明显的负相关系(图 5)。微量元素以高 Sr、Ba、Zr 元素含量及低 Nb、Ta 含量为特征。球粒陨石标准化稀土元

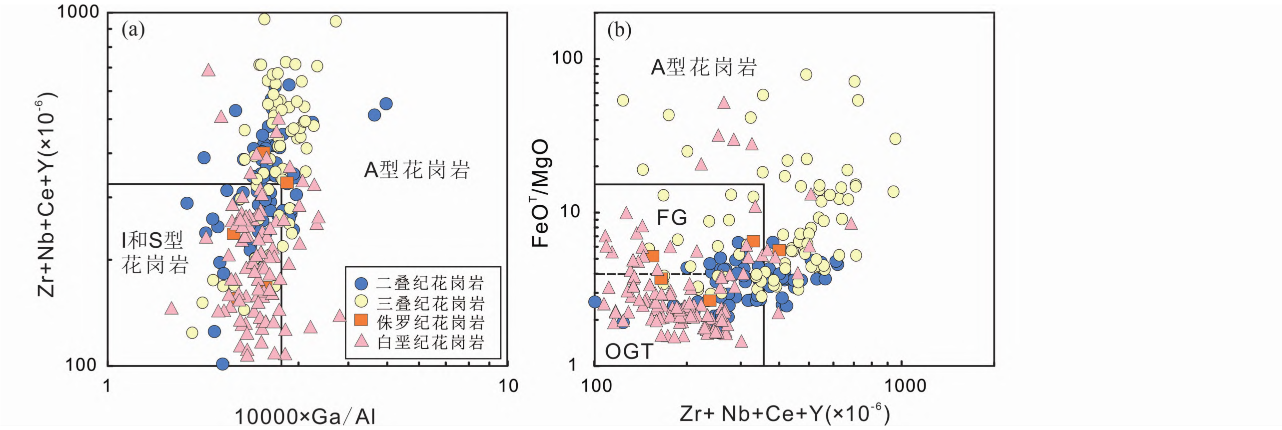

图9 海南岛印支-燕山期花岗岩A型花岗岩类型判别图解(据 Whalen *et al.*, 1987)

FG代表分异花岗岩; OGT代表未分异的M-、I-和S型花岗岩

Fig.9 Discrimination diagrams for the Indosinian-Yanshannian A-type granites in Hainan Island (after Whalen *et al.*, 1987)

FG: fractionated felsic granite; OGT: unfractionated M-, I- and S-type granites

素配分图上,样品的稀土元素配分曲线呈右倾趋势,呈LREE富集,HREE亏损的模式,具有相对弱到中等的Eu负异常(0.40~0.79)(图6e)。原始地幔标准化图解中,富集Rb、Th-U,亏损Nb-Ta、Sr(图6b)。Ga/Al比值变化范围2.06~2.80,Zr+Ce+Y+Nb总量小于350×10^{-6}(仅有一个样品为399.7×10^{-6},但其Ga/Al比值为2.44)(图9)。根据Boehnke *et al.* (2013)修正的全岩锆饱和温度计算公式,获得的温度为692~759℃。两个侏罗纪岩体的I_{Sr}为0.7062~0.7160,$\varepsilon_{Nd}(t)$为-9.8~-3.6(图7),相应的二阶段模式年龄1.2~1.8Ga。作者对铜鼓岭花岗岩进行的微区原位锆石Hf-O同位素分析结果显示,它们具有较为均一的Hf-O同位素组成,$^{176}Hf/^{177}Hf$为0.282642~0.282787,$\varepsilon_{Hf}(t)$值从3.8到-2.0(主要集中在-1~0之间)(图8),对应的大陆地壳模式年龄为0.96~1.27Ga。$\delta^{18}O$值变化为6.3‰~7.2‰(图8)。综合以上地球化学特征,海南岛侏罗纪花岗岩为I型花岗岩,岩浆演化过程中经历了一定程度的分离结晶作用。

海南岛燕山期主体白垩纪花岗岩主量元素变化范围较大。SiO_2为63.3%~77.6%,Al_2O_3在12.0%~16.8%之间变化、CaO含量为0.14%~3.92%,Na_2O和K_2O含量分别为2.41%~5.21%和2.75%~6.05%,TiO_2(0.03%~0.66%)、MgO(0.03%~2.12%)和P_2O_5(0.005%~0.27%,大部分<0.1%)含量较低(附表3)。在TAS图解中,它们落入亚碱性范围(图4a),以高钾钙碱性为主(图5e)。A/CNK=0.90~1.17,绝大多数为准铝质到弱过铝质(图4b)。主量元素SiO_2与Al_2O_3、CaO、TiO_2、MgO和P_2O_5呈明显的负相关关系(图5)。在球粒陨石标准化图解中,总体表现出轻稀土富集重稀土亏损(图6a),但$(La/Yb)_N$比值(0.91~67)及Eu异常程度变化较大。在原始地幔标准化微量元素蛛网图中,富集大离子亲石元素(Rb、Th、U等),亏损高场强元素Nb-Ta(图6b)。全岩锆饱和温度变化范围667~820℃。大部分样品具有低的Ga/Al比值和高场强元素含量(Zr+Nb+Ce+Y),落入I型或S型花岗岩区域(图9)。全岩的初始Sr同位素比值为0.7057~0.7121(大多数点小于0.7090),$\varepsilon_{Nd}(t)$值变化于-3.9~-7.1(图7),相应的二阶段模式年龄为1.0~1.5Ga之间。这一时期锆石的Hf同位素组成,$^{176}Hf/^{177}Hf$值为0.282459~0.282752,$\varepsilon_{Hf}(t)$值为-6.3至+2.4(图8),Hf同位素二阶段模式年龄为1.0~1.7Ga。具有相对均一的O同位素组成形成高斯分布,$\delta^{18}O$=6.9‰~8.3‰(图8),平均值为7.4±0.5‰(2SD)。综合以上地球化学信息表明,海南岛白垩纪岩体都属于I型花岗岩。根据微量元素构造环境判别指标,这些花岗岩很可能形成于岛弧或活动陆缘环境(图10)。

5 海南岛印支-燕山期花岗岩源区及成因讨论

Chappell and White (1974)基于对澳大利亚Lachlan褶皱带(Lachlan Fold Belt,LFB)的研究,通过特征矿物(如S型花岗岩含有堇青石和石榴子石,I型花岗岩含有角闪石)和地球化学指标(如A/CNK值)将花岗岩分为I型和S型,并提出I型花岗岩源区物质组成为相对均匀的变火成岩,而S型花岗岩的源区物质为变沉积岩。但需要注意的是LFB的基底物质组成比较单一,所以S型和I型花岗岩的区分比较明显,其他具有复杂演化历史的大陆是否可以用特征矿物和A/CNK等指标准确区分I型和S型花岗岩却尚存疑虑(吴福元等,2015)。如华南大陆经历多期次构造运动,基底物质组成比较复杂,所以其熔融形成的花岗岩无特别明显的岩相学和地球化学特征。另外,岩浆演化过程中的结晶分异,也导致花岗岩组分趋近于低共熔花岗岩组分,即近相等的石英和两种长石含量的花岗岩(Chappell and White, 2001; Jahn *et al.*,

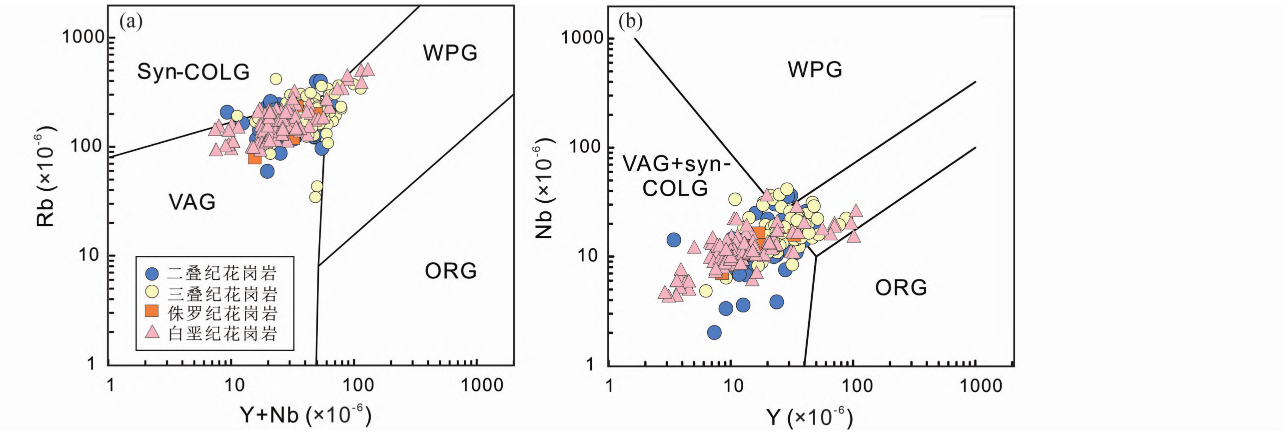

图 10　海南岛印支-燕山期花岗岩构造背景判别图解(据 Pearce *et al.*, 1984)

VAG：火山弧花岗岩；syn-COLG：同碰撞花岗岩；WPG：板内花岗岩；ORG：洋脊花岗岩

Fig. 10　Tectonic discrimination diagrams for the Indosinian-Yanshannian granites in Hainan Island (after Pearce *et al.*, 1984)

VAG：volcanic arc granite；syn-COLG：syncollisional granite；WPG：within-plate granite；ORG：ocean ridge granite

2001；吴福元等，2015)。尽管无明显的岩相学特征和简单地球化学参数(如 A/CNK)比较难以区分华南的 I 型和 S 型花岗岩，但是一些元素的协变关系(如 I 型花岗岩的 SiO_2 和 P_2O_5 呈负相关关系，S 型花岗岩的 P_2O_5 随 SiO_2 增加无明显降低的趋势；Chappell, 1999；李献华等，2007)和微区原位同位素数据(如锆石氧同位素，起源于变沉积物的花岗岩的锆石 $\delta^{18}O$ 值通常大于 9‰，甚至可以达到 15‰；Kemp *et al.*, 2006)可以对类型的划分提供有力证据。而 A 型花岗岩相对较容易区分，因其通常具有碱性暗色矿物或明显的地球化学特征，如高 Ga/Al 比值和高场强元素含量(Collins *et al.*, 1982；Whalen *et al.*, 1987；Eby, 1992)。

5.1　印支期花岗岩源区性质及成因讨论

海南岛二叠纪花岗岩的钾长石斑晶定向于 NE 或 NEE 方向，并且被发现定向矿物的粒间存在代表残余熔体存在的微粒交生结构，可能指示了其侵位时受到了区域应力场的作用(谢才富，2002；Li *et al.*, 2006；Xie *et al.*, 2006)。这些花岗岩普遍以准铝质-弱过铝质为主，具有大陆岛弧 I 型花岗岩特征，可能暗示形成于板块汇聚的挤压环境(Li *et al.*, 2006；He *et al.*, 2020；刘飞等，2022)。关于海南二叠纪花岗岩的成因及其源区属性前人做过一些研究，如 Li *et al.* (2006)在五指山地区识别出的 267～262Ma 准铝至弱过铝质的片麻状花岗岩，地球化学特征指示其为钙碱性 I 型花岗岩，源区组分为经历分异的幔源的镁铁质-中性岩浆与地壳熔体混合。刘飞等(2022)在海南岛中部金波地区识别出的二叠纪花岗岩为高分异 I 型花岗岩。这些花岗岩在 Pearce 图解中分布在火山弧和同碰撞花岗岩区域中(图 10)，指示它们可能形成于板块汇聚的挤压环境。全岩同位素暗示古-中元古代壳源物质参与了花岗岩岩浆的形成。该认识与海南岛晚二叠世通什、大岭、长塘岭、石碌等岩体的成因类似(温淑女等，2013；Yan *et al.*, 2017；He *et al.*, 2020)。此外，也有少量同期 S 型花岗岩(吕方等，2023)和 A 型花岗岩的报道(谢才富等，2005；Yin *et al.*, 2022)。海南岛二叠纪花岗岩全岩 $\varepsilon_{Nd}(t)$ 值为 −9.3～−3.1(图 7)，锆石 $\varepsilon_{Hf}(t)$ 变化为 −7.2～2.8(图 8)，表明在岩浆过程中除古老地壳组分外，还有亏损同位素特征的基性组分参与。

海南岛三叠纪花岗岩主微量元素变化范围较大，类型多样，具有 S 型、I 型和 A 型花岗岩。部分花岗岩锆石微区原位 $\delta^{18}O$ 值较高(9.2‰～11.4‰)，说明此部分花岗岩很可能由变质沉积物部分熔融而成，为 S 型花岗岩。另一部分花岗岩具有碱性长石含量高和黑云母富铁的矿物学特征，地球化学显示贫镁富铁的特征(图 5)，以及高 Ga/Al 比值($10000\times Ga/Al=2.57\sim4.12$)和高 HFSE 含量($Zr+Nb+Ce+Y=320\times10^{-6}\sim849\times10^{-6}$)(图 9)，可以判断这些岩体为 A 型花岗岩。三叠纪大部分花岗岩为准铝质到弱过铝质，P_2O_5 含量与 SiO_2 含量呈现明显的负相关系，为高钾钙碱性 I 型花岗岩(图 5)。同时，三叠纪也发育 245～237Ma 基性岩(辉长岩、辉绿岩和闪长岩)和 244Ma 霓辉石正长岩等岩石类型(唐立梅等，2010a；Tang *et al.*, 2013；何慧莹等，2016；Shen *et al.*, 2018；Dilek and Tang，2021；刘飞等，2022)。这些特征指示了它们形成于伸展构造背景。

温度是花岗岩形成时的重要物理化学条件之一，对岩浆温度的估算是理解花岗岩成因的重要方面(Watson and Harrison, 1983；Boehnke *et al.*, 2013)。全岩锆石饱和温度计结果显示印支期花岗岩的锆石饱和结晶温度范围较大。鉴于 Zr 含量和 SiO_2 含量之间的关系(图 5h)，计算的最高锆石饱和温度为 SiO_2 含量在约 68% 时可能接近代表岩浆初始熔融温度(Collins *et al.*, 2016)。所以，初始岩浆温度可能在 750℃ 左右，低于角闪石或黑云母脱水熔融温度。如前所述，从同位素地球化学特征上看，海南岛此期花岗岩类岩石很可

能是地幔玄武质岩浆底侵引起古-中元古代中基性下地壳部分熔融的产物，而较低的锆石饱和温度（ca. 750℃）可能暗示了岩浆熔融过程中水的存在。

根据以上分析，结合前人研究，本文提出一个研究区内可能的大规模岩浆岩成岩的模型（图 11）。随着印支期古太平洋板片向华南大陆内陆平板俯冲，洋底高原南界在大容山附近，由于受力差异在此部位发生板片撕裂（Jiao *et al.*, 2015），海南岛位于正常俯冲角度的大洋板片之上，故海南岛在印支期后可能处于板片后撤所造成的伸展环境下。在含水条件下，岩浆初始熔融温度会大量降低，钙碱性岩浆初始熔融温度可能在 700℃左右（Collins *et al.*, 2016）。海南岛印支期 S 型（278～241Ma）与 I 型（272～233Ma）花岗岩根据全岩锆饱和温度计计算得到的岩浆温度主要在 650～750°C 范围之间，与此一致（未发表数据）。Collins *et al.*（2016）指出在环太平洋造山带，岩浆弧底部发生地壳部分熔融的临界温度 >700℃（0.8GPa），当含水基性岩浆底侵时会引起部分熔融。但基性岩浆固结时，析出水量不足以满足大量岩石发生水饱和熔融，所以岩浆体系为水不饱和熔融（Weinberg and Hasalová, 2015）。在俯冲带构造背景下，*P-T* 条件变化或不同含量的转熔矿物进入熔体时，水致熔融过程可产生不同成分的花岗质熔体，尤其是源区存在多种岩石类型的条件下更为显著（Holtz *et al.*, 2001; Davidson *et al.*, 2007; Symington *et al.*, 2014）。另有部分 A 型花岗岩（257～225Ma；未发表数据）可能是已有花岗岩熔体产生析出的源区中残留麻粒岩相物质在高温下再次熔融产生。因此，在此古太平洋板片俯冲作用下，海南岛印支期发育具有不同地球化学性质的花岗岩。

5.2 燕山期花岗岩源区性质及成因讨论

海南岛燕山期花岗岩以准铝质到弱过铝质为主，不同于 S 型花岗岩的强过铝质特征（A/CNK 通常大于 1.1; Chappell, 1999）。同时，燕山期花岗岩具有低的 FeO^T/MgO 值、Zr、Nb、Y 和 LREE 含量及 10000×Ga/Al（<2.7）（图 5、图 9），明显不同于 A 型花岗岩（Collins *et al.*, 1982; Whalen *et al.*, 1987）。另外，锆石 $\delta^{18}O$ 值不超过 8‰（图 8），也低于 S 型花岗岩 $\delta^{18}O$ 值（Valley, 2003）。以上特征表明，海南岛燕山期花岗岩以 I 型花岗岩为主，部分经历了高分异过程。

海南岛燕山期花岗岩类岩石具有演化的地球化学特征：高的 SiO_2 含量，低 P_2O_5 和 TiO_2 含量及明显的 Ba、Nb、Sr 和 Eu 负异常（图 5、图 6）。这些元素的亏损很可能是由富集该元素的矿物分离结晶所致，如 Sr、Ba 和 Eu 的负异常与长石的分离结晶有关，Zr、Nb、Ti 和 P 的亏损则分别与富集 Zr、Ti 和 P 的副矿物锆石、独居石和磷灰石等矿物的结晶有关（Li *et al.*, 2007）。此期花岗岩中的元素行为表明岩体经历了显著的结晶分异作用。角闪石、黑云母和/或长石的分离结晶会导致 Al_2O_3、Na_2O、$Fe_2O_3^T$、MgO 和 CaO 含量随着 SiO_2 含量的升高而降低。角闪石的分离结晶会导致残余熔体中 Dy/Yb 比值下降以及 Zr/Sm 比值上升（角闪石 $D^{Dy/Yb}>1$, $D^{Zr/Sm}<1$; Sisson, 1994; Drummond *et al.*, 1996）。海南岛燕山期花岗岩的 Dy/Yb 和 Zr/Sm 比值在协变图解中散乱分布（图 12a）且稀土配分图解中无显著中稀土亏损（图 6），表明岩浆

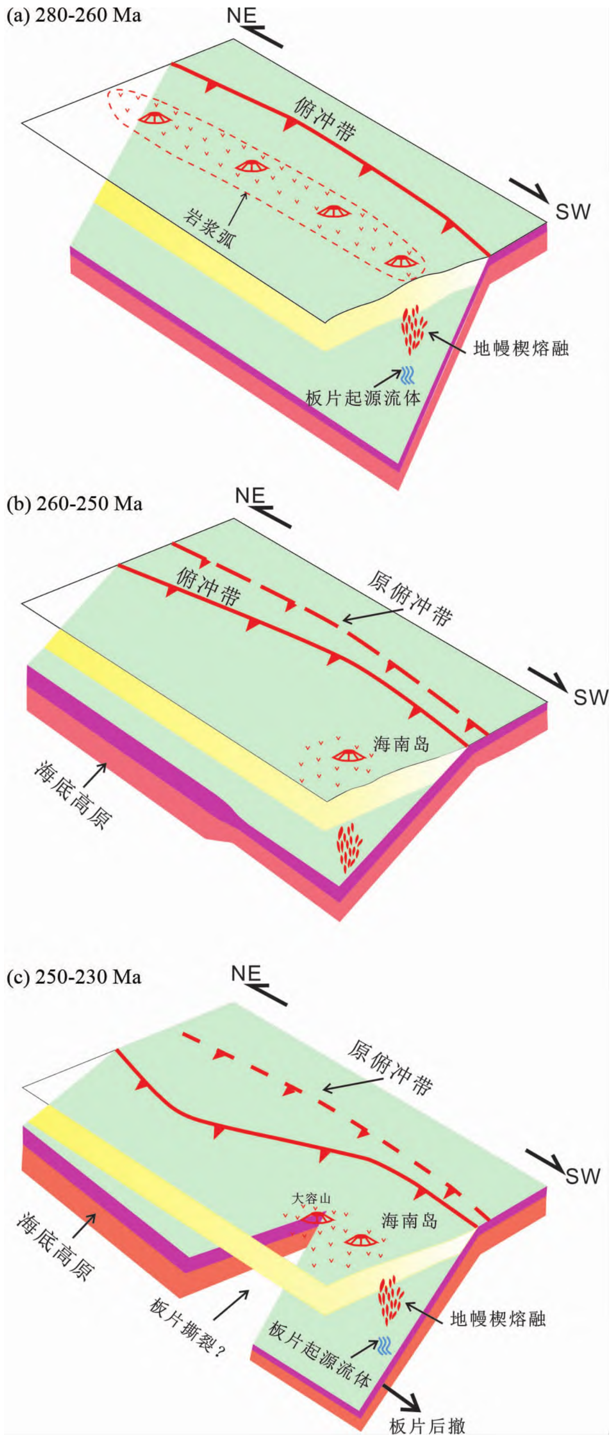

图 11 海南岛早二叠世-三叠纪构造演化卡通图（据 Jiao *et al.*, 2015 改编）

Fig. 11 Cartoon of Indosinian tectonic evolution process of Hainan Island (modified after Jiao *et al.*, 2015)

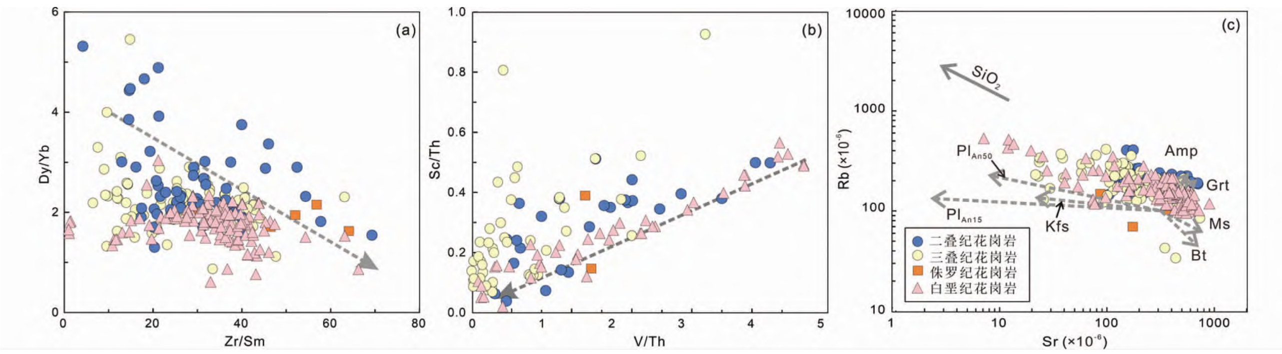

图 12　海南岛印支-燕山期花岗岩分离结晶过程图解(据 Janoušek *et al.*, 2004)

Pl-长石;Kfs-钾长石;Bt-黑云母;Ms-白云母;Amp-角闪石;Grt-石榴石

Fig. 12　Plots of Indosinian-Yanshannian granites in Hainan Island illustrating that fractional crystallization is responsible for chemical variations of the granites (after Janoušek *et al.*, 2004)

Pl-plagioclase; Kfs-K-feldspar; Bt-biotite; Ms-muscovite; Amp-amphibole; Grt-garnet

演化过程中几乎没有发生角闪石的分离结晶。黑云母中 Sc 和 V 分配系数高($D_{Sc}^{bt/melt}=42.4$,$D_{V}^{bt/melt}=79.5$),但 Th 分配系数较低($D_{Th}^{bt/melt}=0.01$)(Bea *et al.*, 1994)。残余熔体中 Sc/Th 和 V/Th 比值的持续下降表明黑云母是主要的分离结晶矿物相(图 12b)。Sr 和 Rb 之间的负相关系,表明熔体演化过程中也存在不同程度的长石分离结晶(图 12c)。综上,黑云母、长石、磷灰石等矿物不同程度的分离结晶是导致海南岛燕山期花岗岩化学组分变化的主要因素。

实验研究表明角闪岩、变硬砂岩、英云闪长岩和玄武质岩石熔融都可以形成花岗岩类岩石(Rapp *et al.*, 1991; Vielzeuf and Montel, 1994; Rapp and Watson, 1995; Singh and Johannes, 1996; Montel and Vielzeuf, 1997; Patiño Douce, 1999; Sisson *et al.*, 2005)。而高钾钙碱性 I 型花岗岩通常由钙碱性和高钾钙碱性镁铁质或中性岩部分熔融形成(Rapp *et al.*, 1991; Roberts and Clemens, 1993; Rapp and Watson, 1995)。Sisson *et al.* (2005)利用中-高钾玄武质组分为初始物质,熔融得到的花岗质熔体 K_2O 含量较高($SiO_2>65\%$, $Na_2O/K_2O<1$),与燕山期花岗岩中 SiO_2 含量较低的花岗岩成分相似。徐德明等(2006)报道琼中地区古-中元古代斜长角闪岩、斜长角闪片麻岩的 SiO_2 含量为 51.34%~58.94%,属于基性-中基岩类。K_2O/Na_2O 值较高(>0.6),表现出高钾的特点,在 SiO_2 vs. K_2O 关系图上落入高钾钙碱性系列岩系区。因此,中-高钾变玄武质岩石最有可能是海南岛燕山期 I 型花岗岩的源岩。

I 型花岗岩是壳内变火成岩部分熔融形成的产物(Chappell and White, 2001),也可能有地幔物质的直接参与(于津海等,2005;Kemp *et al.*, 2007)。海南岛燕山期岩浆活动以长英质为主,目前尚未有大规模与花岗岩伴生的基性组分的发现,这些岩石直接起源于地幔的可能性较小。海南岛此期花岗岩全岩 Sr-Nd 同位素组成($I_{Sr}=0.7057\sim0.7160$, $\varepsilon_{Nd}(t)=-9.8-\sim3.6$)显示富集的同位素特征。依据全岩 Nd 同位素计算的二阶段模式年龄和锆石 Hf 同位素大陆地壳演化模式年龄表明岩石源区为古元古代晚期到中元古代(1.0~1.8Ga)的地壳物质。已有研究表明海南岛最古老的基底包括 >1.4Ga 的变岩浆岩和变沉积岩(Li *et al.*, 2008),其 $\varepsilon_{Nd}(t)$ 值范围为 −8.7~−2.7(谭忠福等, 1991; 张业明等, 1997; 许德如等, 2000, 2001, 2006; 雷裕红等, 2005)。故可能是不同阶段的基底岩石部分熔融形成了此期岩浆岩。此期花岗岩锆石 Hf 同位素组成($\varepsilon_{Hf}(t)=-6.3\sim2.4$)表明源区有幔源年轻组分加入,暗示这些花岗岩很可能是古老地壳物质与亏损幔源岩浆相互作用的产物。在白垩纪伸展环境下,海南岛发育多期次岩浆活动。海南岛白垩纪发育的镁铁质岩墙群具有与弧相关玄武岩的地球化学属性,可能是俯冲交代岩石圈地幔部分熔融的产物(葛小月等, 2003;唐立梅等, 2010b;Dilek and Tang, 2021)。在俯冲大陆边缘的弧环境下,软流圈持续上涌会促使上覆岩石圈地幔的部分熔融产生基性岩浆。随后,这些基性岩浆上升并底侵到海南岛下地壳底部诱发其部分熔融产生岛内高钾钙碱性 I 型花岗岩。

6　海南岛印支-燕山期花岗岩的构造背景启示

前人对海南岛印支-燕山期的岩浆活动、变质作用和构造行迹开展了大量工作,但仍有两个方面存在较大争议:(1)印支期岩浆活动是印支板块碰撞为主导(古特提斯构造域)还是受古太平洋俯冲作用(古太平洋构造域)的控制?(2)燕山期岩浆活动的期次及持续时间。

6.1　印支期:古太平洋还是古特提斯构造域?俯冲何时启动?

目前,关于海南岛印支期岩浆岩的形成于何种构造背景仍存在广泛的争议。Li *et al.* (2006)在海南岛识别出 ca. 270Ma 的高钾钙碱性 I 型、具有原生片麻状构造的花岗岩,认

为其是印支期构造事件的产物,综合岩相古地理和岩石地球化学特征,提出这些海南岛二叠纪片麻状花岗岩代表古太平洋向华南俯冲的起始。后期学者们通过不同方面的研究工作对此模式提供支持证据。如陈泽超(2013)通过构造解析认为海南岛早中生代构造事件的运动学表现为上部指向NE的变形,变形年龄为250~243Ma;Jiang *et al.* (2015)通过对海南岛内最大的陆相盆地中碎屑锆石的分析,认为海南岛岩浆活动是华南陆块印支期岩浆活动的重要组成部分;Shen *et al.* (2018)、Dilek and Tang (2021)和刘飞等(2022)对海南岛印支期岩浆活动及构造变形的工作也支持此观点。另一方面,Xie *et al.* (2006)通过对早-中二叠世偏碱性岩石的研究,提出它们受控于东古特提斯洋北支的闭合。这一观点也得到了许多学者的支持。如陈新跃(2006)和Zhang *et al.* (2011)从构造解析的角度,提出海南岛发育的早三叠世NW向韧性剪切带及中-晚三叠世NE向的褶皱带和韧性剪切带,分别是印支板块与华南陆块碰撞及后期伸展的结果;其他学者主要通过对花岗岩年代学和地球化学方面的分析工作,认为是古特提斯演化过程中构造-岩浆作用的产物(温淑女等,2013;Yan *et al.*, 2017; 温淑女和庞崇进,2018; He *et al.*, 2020)。总之,关于控制海南岛印支期岩浆活动的构造背景观点可以分为古太平洋构造域和古特提斯洋构造域两类。

高钾钙碱性花岗岩通常出现在两种构造环境中:一种是活动大陆边缘或大陆弧环境;另一种是大陆碰撞导致的地壳加厚后造山垮塌环境(Roberts and Clemens, 1993; Barbarin, 1999)。形成于大陆弧环境下的花岗岩通常富集不相容元素,且元素和同位素显示出流体或沉积物组分加入的特征(Hildreth and Moorbath, 1988; Luhr, 1992; Roberts and Clemens, 1993)。海南岛印支期花岗岩主要为准铝质-弱过铝质的高钾钙碱性岩石,没有淡色花岗岩等典型地壳加厚环境下的岩石出露,且富集大离子亲石元素。尤其值得注意得是全岩锆石饱和温度和锆石氧同位素暗示存在流体或沉积物组分。另外,海南岛二叠纪侵入岩中不仅有典型钙碱性I型花岗岩(Li *et al.*, 2006),也出现钾玄质中性侵入岩(Xie *et al.*, 2006)。其微量元素特征与俯冲有关的钾玄质岩浆的特征相似,暗示了俯冲的构造背景。此外,也有学者报道形成于伸展构造背景受俯冲流体交代作用影响的富集地幔源区的245~237Ma基性岩(Tang *et al.*, 2013;刘飞等,2022)。

海南岛印支期花岗岩可以分为具有片麻状的同构造特征的(同造山278~250Ma)和块状的(后造山245~225Ma)两个阶段(葛小月,2003; Shen *et al.*, 2018;刘飞等,2022)。与此同期,在西菲律宾、日本岛和朝鲜半岛发育大量282~240Ma与古太平洋俯冲有关的岩浆岩(Knittel *et al.*, 2010; Yi *et al.*, 2012; Ogasawara *et al.*, 2016; Hara *et al.*, 2018)。而受控于古特提斯洋俯冲以及华南-印支陆陆碰撞形成的松马-哀牢山缝合带的岩浆活动则分为同造山(250~230Ma)和造山后伸展(240~220Ma)(Faure *et al.*, 2014; Liu *et al.*, 2015; Van Thanh *et al.*, 2019; Hieu *et al.*, 2020; Svetlitskaya *et al.*, 2022; Xu *et al.*, 2022)。从变质作用角度,海南岛发育原岩为364Ma的大洋玄武岩、进变质和峰期-退变质的时代分别约为340~330Ma和310~300Ma的榴辉岩(夏蒙蒙等,2019; Xia *et al.*, 2022;刘晓春等,2022)。与西南日本发育的晚古生代榴辉岩(Hida Gaien榴辉岩峰期变质年龄347Ma, Yoshida *et al.*, 2021)类似,但明显早于松马-哀牢山榴辉岩的变质年龄(247~230Ma)(Nakano *et al.*, 2008, 2010; Zhang *et al.*, 2013, 2014a; Ji *et al.*, 2020)。此外,考虑到新生代青藏高原隆升造成的大规模走滑(许志琴等,2016; Cai *et al.*, 2017),可将海南岛复位到北部湾的位置(图13)。从岩浆岩空间分布来看,海南岛印支期岩浆岩整体以NE走向展布方向(图13),与古太平洋向西北俯冲的大方向吻合,但与古特提斯洋NW-SE向的俯冲近于垂直(刘飞等,2022)。这种俯冲极性差异进一步支持了海南岛印支期岩浆岩的形成与古太平洋的俯冲有关。还有一点值得注意的是,海南岛西北的广西十万大山发育向NNW的逆冲,被认为是古太平洋俯冲的影响(张岳桥等,2009)。综上,我们倾向于海南岛大规模印支期岩浆活动是古太平洋石炭纪-早二叠世向华南陆块俯冲的产物。

6.2 燕山期花岗岩构造背景:岩浆活动期次以及俯冲持续时间

燕山期海南岛内岩浆活动明显不同于华南大陆的岩浆活动。岛内侏罗纪岩浆岩出露十分有限,而白垩纪岩浆活动相对较多。以往的研究显示白垩纪的花岗质岩浆活动主要发生于ca. 110~100Ma(Wang *et al.*, 2012a; Xu *et al.*, 2016; Sun *et al.*, 2018; Dilek and Tang, 2021),而基性岩脉活动有135Ma、117~105Ma和96~81Ma三期(葛小月等,2003;唐立梅等,2010b; Dilek and Tang, 2021)。本文作者通过精细的SIMS U-Pb锆石年代学研究,识别出岛内118Ma、101~93Ma(待发表数据)和73Ma的花岗岩,表明海南岛白垩纪花岗质岩浆活动也可分为三期,至少持续至晚白垩世末期73Ma(Jiang and Li, 2014)。

尽管海南岛的花岗岩活动的时间分布不如华南陆块内部广泛,但基性脉岩的活动期次总体上与粤北、江西和福建沿海在古太平洋俯冲后撤的伸展背景下的白垩世基性岩脉(ca. 140Ma、ca. 105Ma、ca. 90~80Ma)的形成时代相对应(李献华等,1997;葛小月等,2003;唐立梅等,2010b; Dilek and Tang, 2021; Guo *et al.*, 2021)。海南岛白垩纪基性脉岩SiO_2含量介于49%~57%,高Al_2O_3、低TiO_2含量,属于高钾钙碱性系列岩石,稀土元素配分形式和微量元素配分形式相似于活动大陆边缘或岛弧火山岩,富集的同位素信息暗示源区为EMII型富集地幔或亏损地幔与EMII地幔混合形成(葛小月等,2003;唐立梅,2010; Dilek and Tang, 2021)。

华南岩浆活动整体上存在ca. 125~115Ma的"岩浆间歇期"(图2b; Jiang *et al.*, 2015; Li *et al.*, 2015; Wei *et al.*, 2015, 2023),但在海南岛却有该段时间内岩浆岩的发现,如

图 13 华南印支期花岗岩分布图(据 Chen *et al.*, 2014; Li *et al.*, 2012a; Replumaz and Tapponnier, 2003 改编)

Fig. 13 Distribution of Indosinian granintes in the South China Block (modified after Chen *et al.*, 2013; Li *et al.*, 2012; Replumaz and Tapponnier, 2003)

白沙盆地鹿母湾群碎屑锆石年龄存在 ca. 120Ma 峰期(Jiang *et al.*, 2015),以及本人发现的 ca. 118Ma 花岗岩体(待发表),均表明存在 ca. 120Ma 的岩浆活动。这与大陆内部岩浆活动的差别暗示这期的岩浆活动很可能主要发生在华南大陆的边缘或外侧(图 14)。尽管华南大陆主要水系中均无 ca. 120Ma 的碎屑锆石,但在台湾岛南部恒春半岛中新世增生楔(Zhang *et al.*, 2014b)以及西菲律宾陆块变沉积物中(Suggate *et al.*, 2014; Yan *et al.*, 2018; Shao *et al.*, 2019)均有此期碎屑锆石。另外,在南海微陆块中也发现 ca. 130～110Ma 的花岗岩及火山岩(Yan *et al.*, 2010, 2014; Li *et al.*, 2018)。而在新生代南海张开前,这些微块体都曾是华南大陆的一部分(Chung *et al.*, 1997; Shao *et al.*, 2015)。另外,也有学者认为古太平洋俯冲时所驮负的西菲律宾微陆块与华南的碰撞是造成华南大陆 ca. 130～105Ma 的向北西的逆冲推覆变形和岩浆活动微弱的主导机制(Faure, 1989; Li *et al.*, 2015; Wei *et al.*, 2015, 2023),但西菲律宾陆块是一个面积稍小的陆块,该碰撞仅仅影响了华南部分区域,东亚活动陆缘仍处于古太平洋俯冲影响之下(Wei *et al.*, 2023 及其中参考文献)。事实上,正是因为古太平洋的俯冲,才导致西菲律宾陆块不断靠近华南,并最终在 130～110Ma 期间与华南发生碰撞(Wei *et al.*, 2023)。综上所述,ca. 120Ma 期间古太平洋板片的俯冲导致了华南和西菲律宾微陆块间的增生,造成了长乐-南澳构造带的变质变形及华南大陆的"岩浆间歇期",但仍有岩浆弧活动存在。

古太平洋板块的俯冲主导华南晚中生代岩浆活动及构造演化过程是毋庸置疑的(Li, 2000; Zhou and Li, 2000; Zhou *et al.*, 2006; Li and Li, 2007; Li *et al.*, 2014)。关于华南东南部中生代岩浆活动的截止时间,通常认为是 ca. 90～85Ma (Chen *et al.*, 2004, 2008; Wong *et al.*, 2009; Li *et al.*, 2014; Cui *et al.*, 2021),即安第斯型活动大陆边缘在此时停止,之后转换进入西太平洋型活动大陆边缘。另有一种观点认为古太平洋板块向华南东南部的俯冲结束于新生代早期 56Ma(火山岩;Chen *et al.*, 2016)。Jiang and Li(2014)利用高精度 SIMS U-Pb 锆石定年技术测得龙楼花岗岩结晶年龄为晚白垩世晚期坎帕阶 73Ma,是目前为止华南东南部发现的最为年轻的晚中生代花岗岩。而且,在东亚大陆边缘的其他地区也识别出了同期的岩浆活动,如韩国 94～71Ma 的花岗岩以及同期被认为是俯冲产生的玄武岩(Sagong *et*

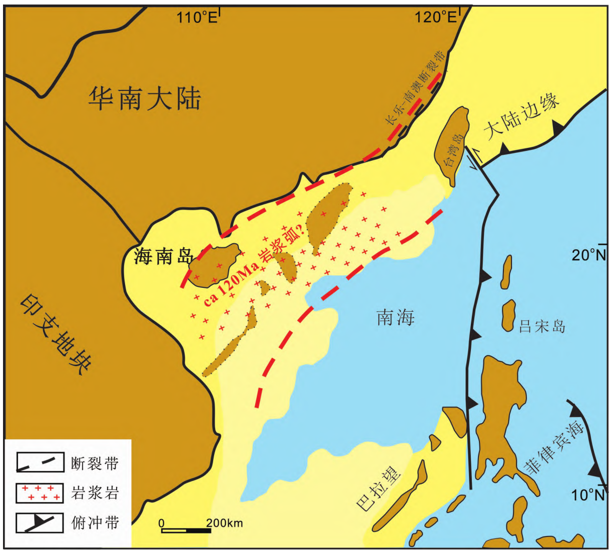

图 14 白垩纪 ca. 120Ma 华南大陆边缘岩浆活动分布简图(据 Shao *et al.*, 2015;Hennig-Breitfeld *et al.*, 2021 改编)

Fig. 14 Sketch map of possible location of ca. 120Ma magmatic activities in continental margin of South China (modified after Shao *et al.*, 2015; Hennig-Breitfeld *et al.*, 2021)

al., 2005; Martynov *et al.*, 2006; Hwang, 2011; Zhang *et al.*, 2012),日本西南部受俯冲影响的白垩纪岩浆活动持续至 70Ma(Nakajima, 1996; Morioka *et al.*, 2000; Yuhara *et al.*, 2000, 2003; Sonehara and Harayama, 2007)。这些晚白垩世岩浆岩均形成于古太平洋俯冲作用下的活动大陆边缘。因此,古太平洋板片向华南陆块俯冲引起的安第斯型岩浆活动可能持续至 ca. 70Ma。

7 结论

综合前人有关海南岛印支-燕山期花岗岩的数据和作者的研究工作,本文划分了海南岛印支-燕山期花岗岩岩浆活动期次、探讨花岗岩的成因类型及区域构造动力学机制,取得的主要认识如下:

(1)通过统计文献中已发表的高精度年龄数据和作者本人工作得出,大面积分布于海南岛中东部地区的印支期花岗岩,形成于 278~225Ma,早于华南印支期花岗岩。燕山早期侏罗纪岩体出露极其有限,作者新识别出 161Ma 的黑云母二长花岗岩。燕山晚期白垩纪花岗岩呈幕式出现,主要集中于 ca. 120Ma、ca. 110~90Ma 和 ca. 70Ma 三个阶段。其中,海南岛龙楼 73Ma 花岗岩是华南迄今为止发现的最年轻的中生代岩浆岩,代表华南燕山期岩浆活动的结束。

(2)依据地球化学特征,印支期花岗岩可分为 S 型(278~241Ma)、I 型(272~233Ma)和 A 型(257~225Ma)花岗岩。S 型和 I 型花岗岩的岩浆初始熔融温度较低(平均<750℃),可能是含水熔融过程的产物。A 型花岗岩的岩浆初始熔融温度较高(>800℃),是脱水熔融的产物,源区可能经历过前期岩浆的提取。燕山期花岗岩均为高钾钙碱性 I 型花岗岩,为古老基底部分熔融的产物,同位素组成暗示可能存在年轻幔源组分的加入。

(3)结合他人在构造和岩石方面的工作,作者认为海南岛印支期(早-中二叠世至中三叠世)为同一期次连续岩浆活动,形成于古太平洋俯冲的构造背景下。燕山晚期,海南岛与西菲律宾、日本西南端、朝鲜半岛南端和台湾岛的岩浆活动记录,支持古太平洋俯冲的构造背景,俯冲过程及其所导致的活动大陆边缘可能持续至 ca. 70Ma。

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