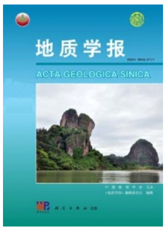

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大陆弧岩浆幕式作用与地壳加厚：以藏南冈底斯弧为例

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内容提要：大陆弧岩浆带位于汇聚板块的前缘，记录了洋陆俯冲过程和大陆地壳生长过程，是研究壳幔相互作用的天然实验室。越来越多的研究发现，大陆弧岩浆的生长与侵位并不是均一的、连续的过程，而是呈现阶段性、峰期性特征，即幕式岩浆作用。弧岩浆峰期与岩浆平静期相比，岩浆增生速率显著增强，易于发生岩浆聚集，继而形成大的岩基，如北美西部科迪勒拉造山带内华达岩基、半岛岩基等。藏南冈底斯岩浆带位于拉萨地体南缘，属于印度-亚洲碰撞带的上盘，其南侧与喜马拉雅地体以雅鲁藏布蛇绿岩带为界。冈底斯弧岩浆形成时代集中在240~50 Ma期间，其形成与演化与新特提斯洋壳岩石圈板片俯冲到拉萨地体之下密切相关。因此，对冈底斯弧型岩浆作用的研究，将很好地揭示大陆型弧岩浆的演化过程，继而反演洋-陆俯冲过程，以及壳幔相互作用过程。通过对冈底斯岩浆带岩浆岩锆石U-Pb及Lu-Hf同位素，以及弧前和前陆盆地碎屑锆石U-Pb和Lu-Hf同位素的收集和整理，结合已经发表的区域地质资料的总结，我们发现冈底斯弧型岩浆演化具有如下特点：①幕式侵位，岩浆峰期为100~80 Ma和65~40 Ma，中间为岩浆平静期；②峰期阶段岩浆聚集，形成巨大岩基；岩石同位素非常亏损，预示着地幔物质的显著参与；③在弧岩浆的峰期阶段，冈底斯地壳厚度有显著增加，说明弧岩浆的峰期侵位对地壳加厚有重大贡献。

关键词：大陆弧岩浆；岩浆幕式作用；岩浆爆发期；地壳加厚；冈底斯；西藏

作为二十世纪人类十大科技发现和进展之一，板块构造学说自20世纪50年代诞生以来开启了人类认识地球自组织系统、壳幔相互耦合过程的序幕。在板块构造中，汇聚板块边界引起最广泛的关注，原因主要有以下两个方面，一是汇聚板块边界蕴含了最丰富的地理景观

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和矿产资源，与人类生存和发展最密切相关；二是汇聚板块边界齐聚了最丰富的岩石组合和地质现象，是壳幔相互作用最典型的区域，非常有利于研究板块构造的机制和深部动力学过程(Stern et al., 2003, 2017; Xu Zhiqin et al., 2016a, 2016b)。

汇聚板块边界最核心的就是俯冲岛弧体系，以巨大的岩基和各种类型岩浆岩出露为主要特征。研究岛弧体系对于揭示俯冲板片深部动力学过程、壳幔相互作用、岩浆形成过程、以及岩浆房的生成和建立等有巨大的学术价值和意义。早先关于地球前寒武纪大陆地壳生长的研究发现，大陆地壳的生长并不是连续的过程，而是呈现阶段性和峰期性特点。比如前寒武纪主要的大陆地壳生长峰期分别为 2.7 Ga、1.9 Ga 和 1.2 Ga，而且具有全球性特点。这些前寒武纪大陆地壳生长的峰期与全球性的超大陆聚合事件密切相关(Cawood et al., 2007; Condie, 1998; Ma Xuxuan et al., 2014)。超大陆的聚合主要是以大洋岩石圈俯冲消减并形成巨量弧型岩浆为主要特点。近年的研究发现，显生宙的大陆地壳生长，特别是以岛弧岩浆作用为代表的新生地壳生长也有类似前寒武纪地壳生长的特点，呈现阶段性和峰期性特征，如中国东北岛弧岩浆岩带(Wu Fuyuan et al., 2003)，华南岛弧花岗岩带(Zhou Xinmin et al., 2006)，中亚造山带中的古生代弧岩浆作用(Jahn et al., 2000)，南亚苏门答腊岛弧岩浆带(Zhang Xiaoran et al., 2019)，新西兰中生代 Median 岩基(Schwartz et al., 2017)。

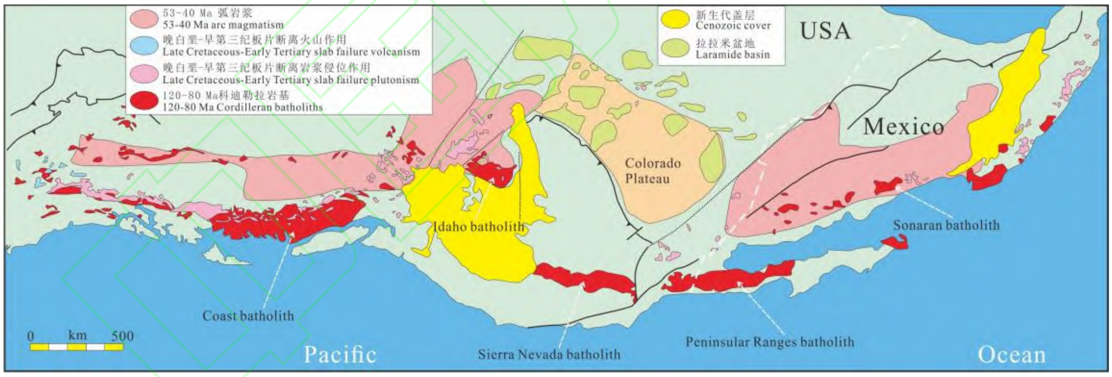

图 1 北美科迪勒拉造山带多个岛弧岩浆带的分布图（据 Hildebrand, 2013）

Fig. 1 Distribution of arc batholiths in the Cordilleran orogen, North America (after Hildebrand, 2013)

作为中、新生代全球最受瞩目的美洲西部科迪勒拉造山带发育大量岛弧岩浆岩，并以巨型岩基的形式展布，如半岛岩基，内华达岩基，海岸山岩基，凯斯凯特岩基，大石岩基，爱达荷岩基等（图 1）(Foster et al., 2001; Hildebrand, 2013; Morton et al., 2014; Paterson et al., 2015)。这些岩基展现非常好的阶段性、峰期性侵位特征，峰期岩浆侵位速率显著增强（图 2)，其岩浆作用与深部动力学过程密切相关(Ardill et al., 2018; Chapman et al., 2019; DeCelles et al., 2015)。在弧岩浆峰期阶段，岩浆易于聚集形成大的侵位杂岩体，如内华达岩基中的

Tuolumne 侵位杂岩体（图 3a）(Schoene et al., 2020)，半岛岩基中的 Box Springs 侵位杂岩体（图 3b）(Morton et al., 2014)。此外，在岩浆峰期阶段，地幔源区物质参与比例明显提高，岩浆的同位素更为亏损，暗示峰期岩浆活动受到深部地幔活动的强烈控制(Attia et al., 2020; Martínez Ardila et al., 2019)。

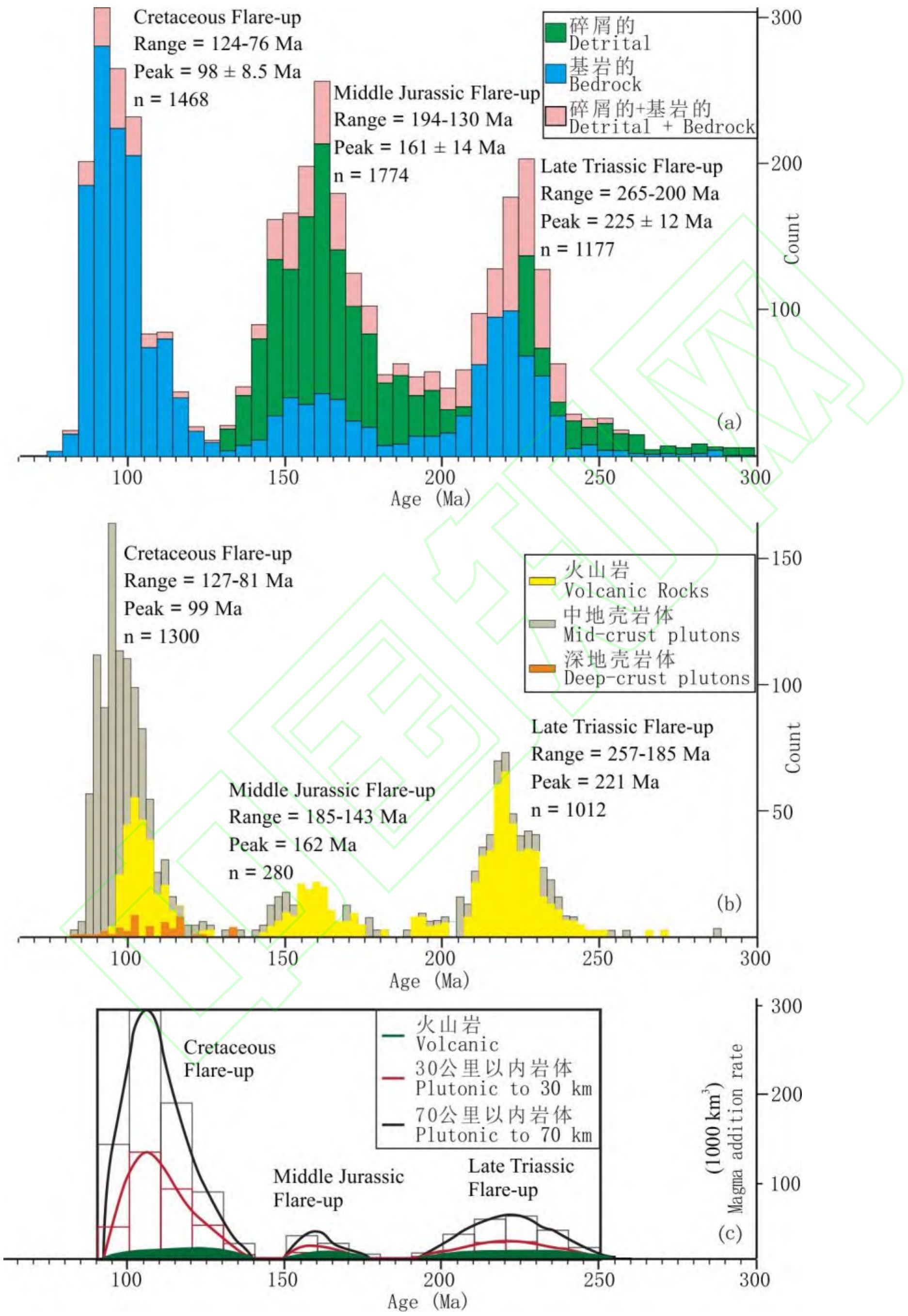

图 2 （a）内华达岩基基岩锆石 U-Pb 年龄峰与碎屑锆石 U-Pb 年龄峰的对比；（b）内华达岩基不同深度基岩锆石 U-Pb 年龄峰对比；（c）内华达岩基岩浆增加速率计算。原图来自(Paterson et al., 2015)

Fig. 2 (a) Comparison of zircon U-Pb age probability of bedrock and detrital zircons from the Sierra Nevada batholith (California, USA); (b) Depth comparison of zircon U-Pb ages for igneous rocks of surface volcanic, shallow plutons and deep plutons from the Sierra Nevada batholith; (c) Magma additiion rates calculated for both plutonic and volcanic materials from the central Sierra Nevada batholith (original figure come from Paterson et al., 2015)

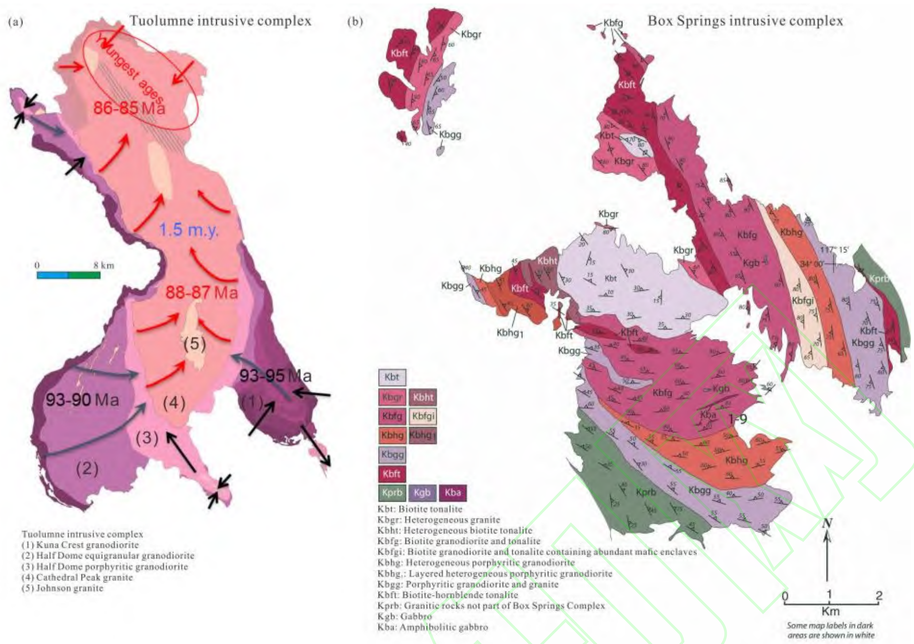

图 3 代表性岛弧背景侵位杂岩体

（a）—内华达岩基 Tuolumne 杂岩体(Ardill et al., 2018)；(b）—半岛岩基 Box Springs 杂岩体(Morton et al., 2014)

Fig. 3 Representative arc-affinity intrusive complex

(a)—The Late Cretaceous Tuolumne intrusive complex in the Sierra Nevada batholith, western USA (Ardill et al., 2018); (b)—Late Cretaceous Box Springs intrusive complex from the Peninsular Ranges batholith (Morton et al., 2014)

冈底斯岩浆带，位于青藏高原南部，拉萨地体南缘，雅鲁藏布江缝合带的北缘，属于印度-亚洲碰撞带的上盘（图 4）。冈底斯弧岩浆形成始于中生代早期，记录了新特提斯洋的演化过程（图 5）(Ma Xuxuan et al., 2019; Wang Chao et al., 2016)。其弧岩浆作用结束于早始新世，记录了新特提斯洋的闭合过程和印度-亚洲陆-陆碰撞过程(Zhu Dicheng et al., 2015)。因此，冈底斯弧岩浆作用的研究对揭示潘吉亚超大陆的裂解、拉萨地体的古地理变迁、新特提斯洋的开启、俯冲启动、演化和闭合、印度-亚洲的陆-陆碰撞过程、青藏高原的形成和后期高原隆升及资源与环境效应等重大科学问题具有重要的学术、经济和社会意义(Molnar et al., 1993; Tapponnier et al., 2001; Veevers, 2004; Xu Zhiqin et al., 2015)。冈底斯岩浆弧整体保

存完好，出露面积巨大，形成时代较为年轻，吸引着国内外同行的广泛关注。然而，与北美西部的内华达岩基、海岸山岩基、大石岩基等、以及南美西部的安第斯岩基等相比，无论在研究广度上，还是在研究深度上，冈底斯岩基的研究都还存在巨大差距。

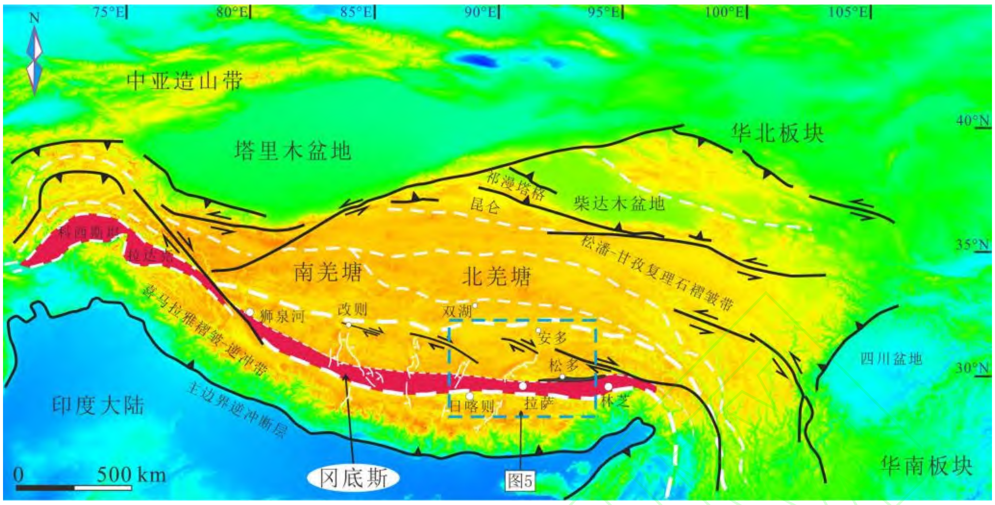

图 4 青藏高原大地构造格架及冈底斯位置图

Fig. 4 Tectonic framework of the Tibetan Plateau and the location of the Gangdese magmatic belt

冈底斯岩基形成起始时间与美洲西部岩基起始时代较近，且保存完好，其形成的阶段性、峰期性特点如何，以及其对深部动力学的响应如何，值得我们进行深入的研究。限于水平和篇幅，本文无意对冈底斯岩浆岩各种数据进行全面的、系统的梳理，只是在近些年作者的野外地质调查和室内分析研究基础上，结合前人的大量研究工作及海量数据积累，就冈底斯弧岩浆的阶段性生长特点、弧岩浆峰期作用与地壳加厚作用的关系等进行探讨。希望本文能抛砖引玉，引起更多学者的关注，并合力把冈底斯弧岩浆岩研究推向更广阔的天地。

1 冈底斯弧岩浆时空分布特征

早期冈底斯带的地理概念特指西起狮泉河，东至伯舒拉岭，南北分别被印度斯-雅鲁藏布江缝合带和班公-怒江缝合带圈闭的东西长约 2500 km、南北宽 100~300 km 的构造岩浆带，即拉萨地体（Mo Xuxuan et al., 2005; Zhu Dicheng et al., 2008）。随着后期研究的不断深入，前人发现拉萨地体并非完整一块，内部存在多个残余缝合带（Yang Jingsui et al., 2007; Liu Fei et al., 2020）。拉萨地体南、中、北部基底性质和中、新生代岩浆岩出露特征存在显著差别。不同的研究团体不约而同地把冈底斯岩浆带的概念缩小为拉萨地体南缘，或南拉萨次级地体了。‘冈底斯’这一概念的进一步收缩可能主要基于以下几个方面：①中拉萨地体存在老基

底，而南拉萨地体基本没有老基底出露；②中、南拉萨地体之间存在一个洛巴堆-米拉山断层，这一断层也可能是残存的蛇绿岩缝合带（Zhu Dicheng et al., 2008）；③中拉萨地体出露岩浆岩主要是零星的三叠纪岩浆岩，并且这些三叠纪岩浆岩以造山期的、同位素较为富集为主要特征；④与新特提斯洋俯冲相关的弧型岩浆岩主要分布在南拉萨（图 6）。相比之下，南拉萨地体弧岩浆岩时间跨度从三叠纪一直到早始新世（图 6），岩浆岩类型较为齐全，同位素较为亏损，地球化学成分偏钙碱性、准铝质（图 7），是典型的弧岩浆岩；⑤南拉萨广泛出露俯冲型斑岩型 Cu-Au 矿，具有找矿的重大潜力（Hou Zengqian et al., 2006; Xu Wenyi et al., 2006; Xu Zhiqin et al., 2012; Hou Zengqian et al., 2015; Ji Weiqiang et al., 2009）。因此，现今的“冈底斯岩浆带”或“冈底斯岩基”特指拉萨地体南缘的巨型岩浆带，以出露大规模岩浆岩和巨大岩基为主要特征（图 6）。

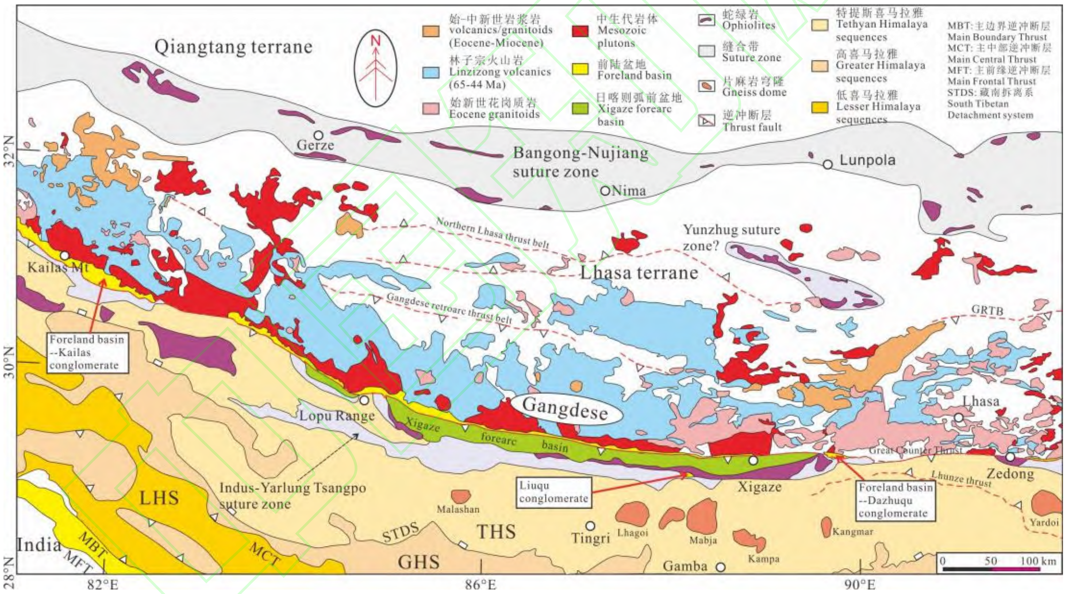

图 5 藏南拉萨地体及冈底斯岩浆带构造格架图（修改自 Kapp et al., 2019）

Fig. 5 Geological map of the Lhasa terrane and the Gangdese magmatic belt (modified from Kapp et al., 2019)

冈底斯岩浆带主要由巨型岩基和复合岩体组成，并伴随有多期火山岩，如侏罗纪叶巴组、比马组（图 8）（Liu Zhichao et al., 2018），早新生代林子宗群（Ding Lin et al., 2003）。以印度-亚洲初始碰撞时间为界（Hu Xiumian et al., 2015），冈底斯岩浆作用可以划分为俯冲期（>60 Ma）、俯冲到碰撞转换期（60~45 Ma）和后碰撞期（<45 Ma）。俯冲期岩浆岩主要为辉长岩、闪长岩、花岗闪长岩及零星花岗岩为主（Meng Yuanku et al., 2018），伴随有火山岩地层，如

拉萨-墨竹工卡一带的侏罗系叶巴组火山岩，拉萨-日喀则一带的侏罗系比马组火山岩等。洋陆俯冲到陆陆碰撞转换期岩浆岩以曲水岩基和林子宗火山岩为典型代表。以曲水岩基为例，出露岩性从辉长岩到二长花岗岩等，并含有丰富的暗色镁铁质包体(Ma Xuxuan et al., 2017a; Mo Xuanxue et al., 2005a; Wang Ruiqiang et al., 2019)。林子宗火山岩主要分布在日喀则以西以及拉萨北部的林周盆地(Ding Lin et al., 2003; Lee Haoyang et al., 2009)。在拉萨-林芝段，林子宗火山岩出露较为稀少, 可能与冈底斯东西向差异性抬升有关(图6)(Cao Wenrong et al., 2020)。后碰撞岩体以花岗斑岩为主，包括石英二长斑岩、二长花岗斑岩和正长花岗斑岩等，具有埃达克质岩石的地球化学特征(Chung Sunlin et al., 2003)。零星分布的钾质和超钾质火山岩和基性岩墙的分布则受南北向横贯青藏高原的多条深大断裂控制(Wang Qiang et al., 2010; Zhao Junmeng et al., 2010)。

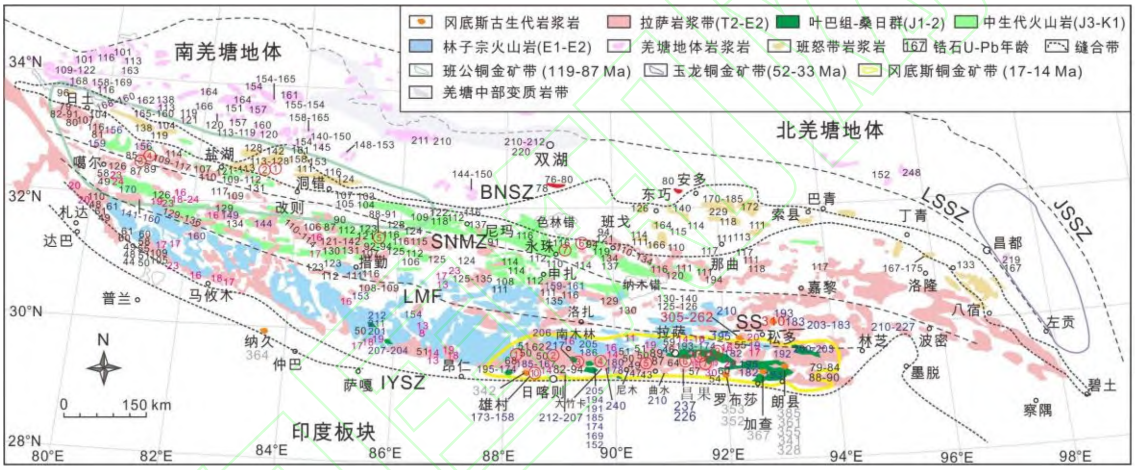

图 6 藏南冈底斯岩浆带岩浆岩分布图（限于篇幅原因，图中所引年龄数据的参考文献不在此文一一列出，如有需要请与作者联系。在此特别感谢数据出处文献和作者们）

Fig. 6 Distribution of magmatic rocks in the Gangdese belt, southern Tibet

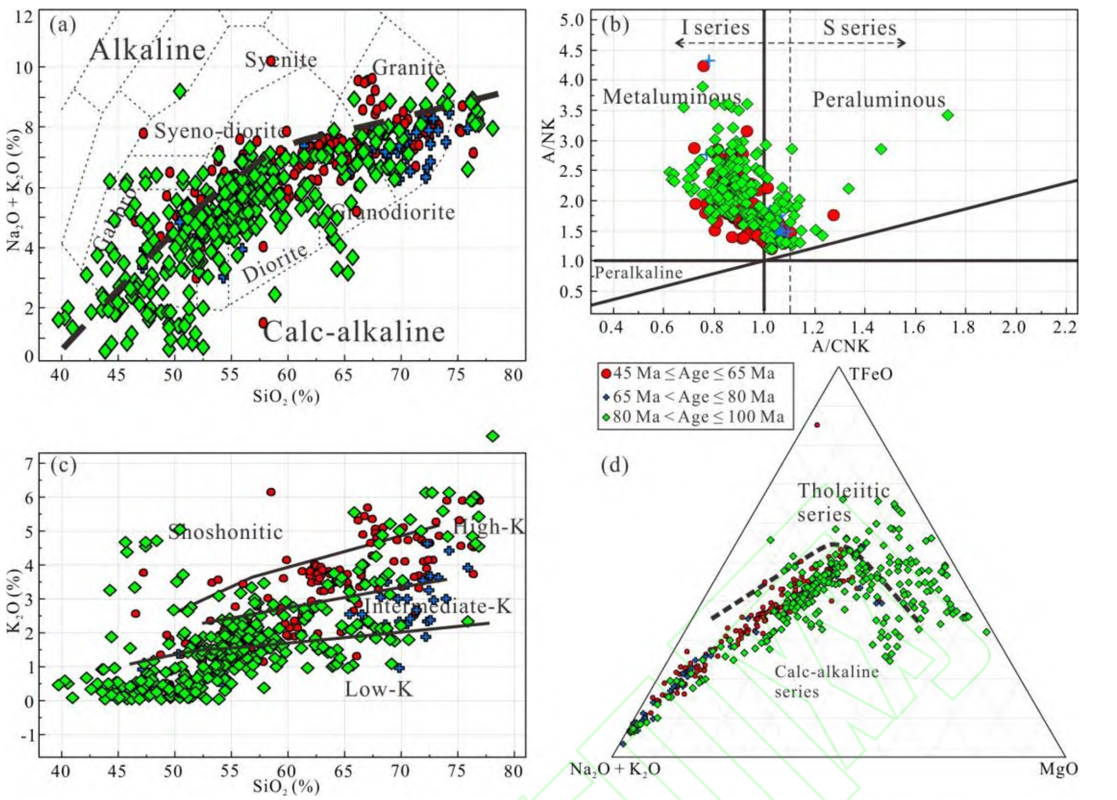

图 7 冈底斯弧岩浆岩地球化学特征判别图。图 a，$Na_2O + K_2O$ vs. SiO_2（修改自 Wilson, 1989）；图 b，A/NK vs. A/CNK （修改自 Maniar et al., 1989）；图 c，K_2O vs. SiO_2 （修改自 Maniar et al., 1989）；图 d， TFeO-(Na_2O + K_2O)-MgO（修改自 Irvine et al., 1971）（限于篇幅原因，图中所引地化数据及相关文献不在此文一一列出，如有需要请与作者联系。在此特别感谢数据出处文献和作者们）

Fig. 7 Geochemical discrimination of the igneous rocks from the Gangdese belt. (a)—Diagram of $Na_2O + K_2O$ vs. SiO_2 (after Wilson, 1989); (b)—Diagram of A/NK vs. A/CNK (after Maniar et al., 1989); (c)—Diagram of K_2O vs. SiO_2 (after Maniar et al., 1989); (d) —Diagram of TFeO-(Na_2O + K_2O)-MgO (after Irvine et al., 1971)

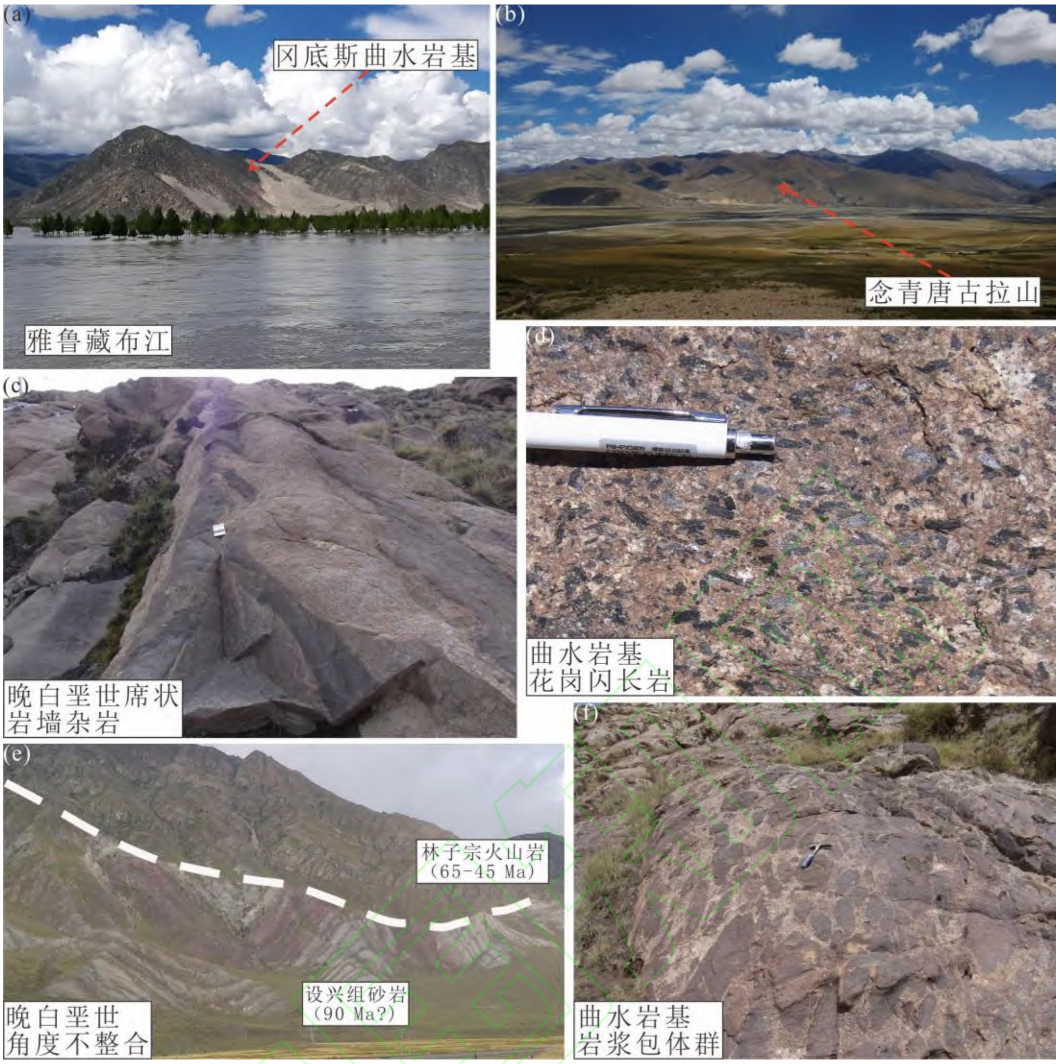

图 8 藏南冈底斯岩浆带代表性野外照片

（a）—冈底斯曲水岩基野外露头；（b）—冈底斯念青唐古拉山；（c）—曲水岩基才纳晚白垩世席状岩墙杂岩体；（d）—曲水岩基早始新世花岗闪长岩；（e）—冈底斯马乡区域不整合；（f）—曲水岩基岩浆包体群

Fig. 8 Representative field photos from the Gangdese magmatic belt, southern Tibet

(a) — Photo of Quxu batholith of the Gangdese belt; (b) — Nyainqentanglha Mountain of the Gangdese belt; (c) — Late Cretaceous sheeted dyke complex; (d) — Early Eocene granodiorite of the Quxu batholith; (e) — Angular unconformity between the overlying Linzizong volcanic sequence and the underlying Shexing Formation sandstones in the Maxiang region of the Gangdese belt; (f) — Magmatic enclaves within the Quxu batholith

2 研究方法

关于弧岩浆的幕式作用的揭示，截止到现在还主要靠区域基岩（岩体和喷出岩）的年代学数据积累（Ducea et al., 2015），以及广泛使用的碎屑锆石年代学统计（Paterson et al., 2015）。

此外，越来越多的研究尝试通过计算弧岩浆体积的变化趋势及岩浆增加速率（MARs）来追踪弧岩浆的幕式作用(Cao Wenrong et al., 2017; Jicha et al., 2015)。但是，这个研究方法有非常大的局限性，即岩浆岩地表面积和地下形态的推测与计算，以及精细的野外填图和岩体出露面积大小。任何一个计算误差都会累积到总的误差中，削弱结果的可信度。限于冈底斯区调工作的不足，大面积区域还是研究空白，计算弧岩浆的体积变化和岩浆增加速率将是一件非常困难的事。本文仍然选择冈底斯基岩（岩体和喷出岩）加权平均年龄的统计，加之冈底斯弧前盆地、前陆盆地、俯冲增生楔、河流砂巨量的碎屑锆石年代学数据收集，辅以岩浆岩锆石 Lu-Hf 同位素和碎屑锆石 Lu-Hf 同位素数据库，来追踪和限定冈底斯的弧岩浆幕式特征(Attia et al., 2020; Sundell et al., 2019)。

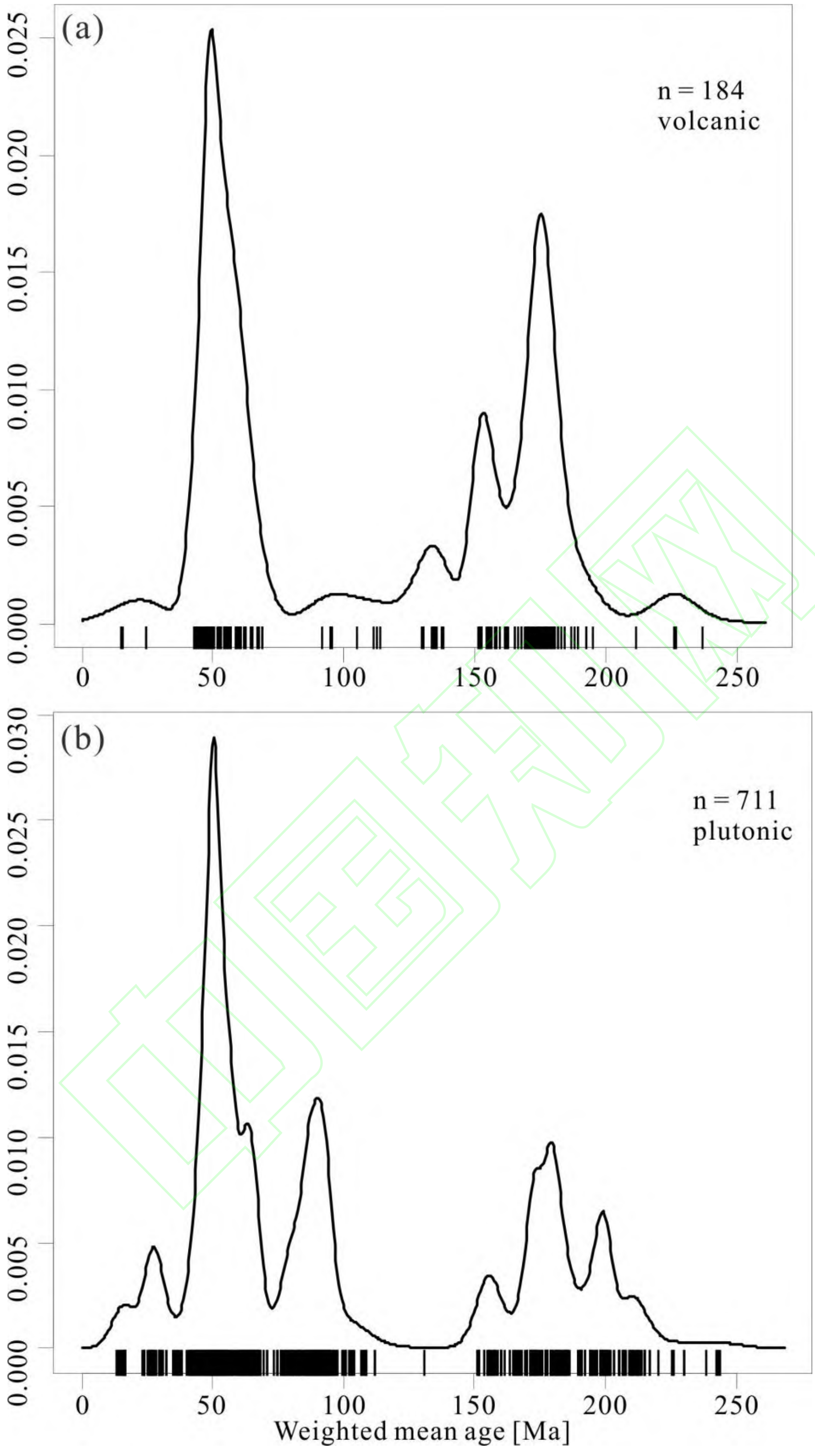

图 9 冈底斯岩浆带岩浆岩加权平均年龄 KDE 统计图。统计方法来自（Vermeesch, 2012）

Fig. 9 Kernel density estimation plot for the weighted mean ages of igneous rocks in the Gangdese belt. Detailed plotting method could be seen in (Vermeesch, 2012)

限于篇幅限制以及巨量的数据和出处文献，在此我们无法一一展示搜集使用的数据表格和索引文献，如有需要相关数据和文献，请与编辑部或作者联系。在此，对所有引用数据来源的文章和作者致以深深的谢意。

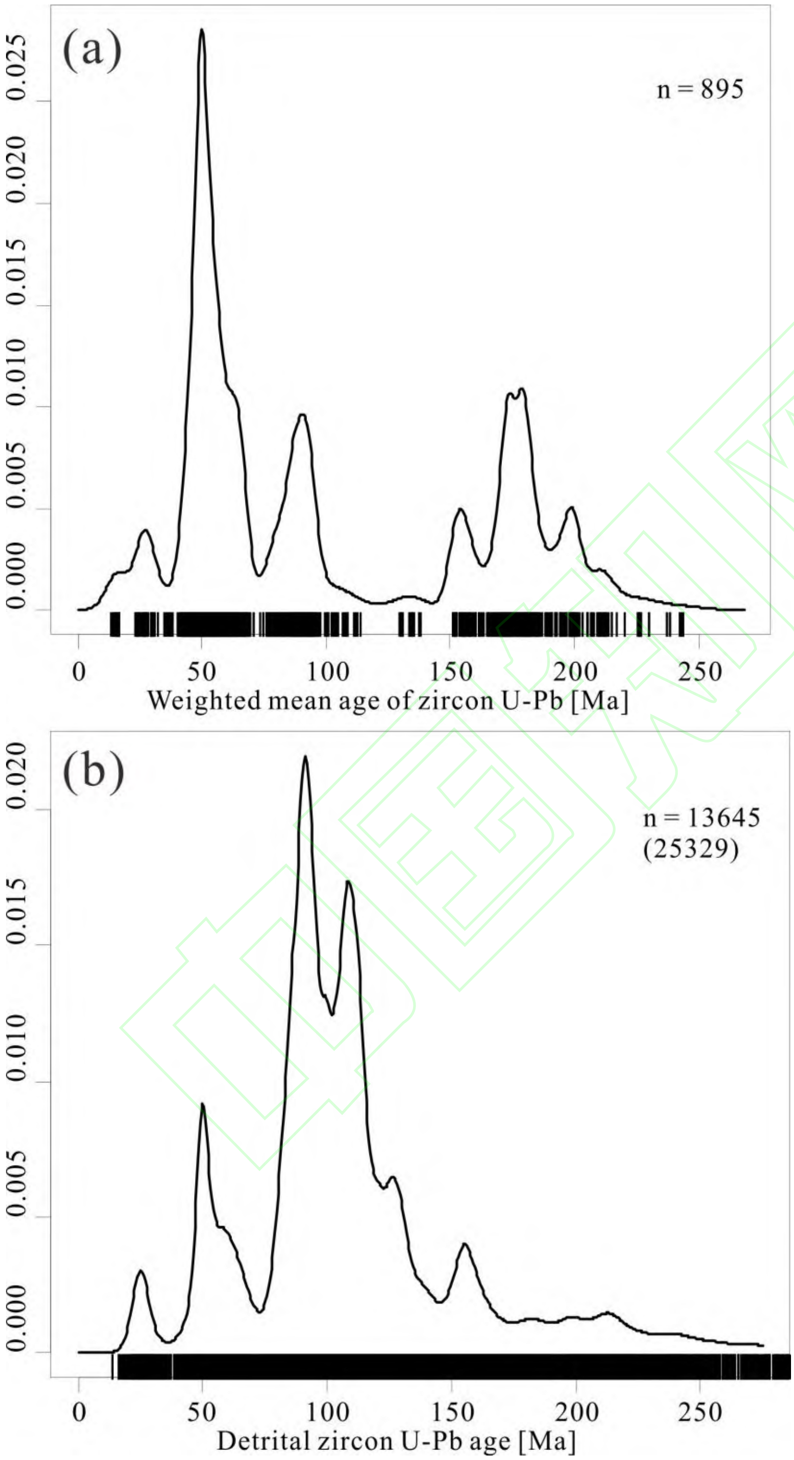

图 10 （a）-冈底斯岩浆岩锆石 U-Pb 加权平均年龄统计分布图；（b）-冈底斯弧前、前陆盆地及河流砂碎屑锆石 U-Pb 年龄统计分布图（总数 25329 中的 13645 个数据参与作图）。统计方法来自(Vermeesch, 2012)

Fig. 10 (a)-Kernel density estimation plots of zircon U-Pb weighted mean ages for igneous rocks from the

Gangdese magmatic belt; (b)-Detrital zircon U-Pb ages from forearc and foreland basins of the Gangdese belt (with only 13645 ages from a total of 25329 ones being plotted). Detailed plotting method could be seen in Vermeesch (2012)

3 研究结果

关于冈底斯弧岩浆活动，前人做过大量的研究工作，并初步发现和提出了冈底斯幕式岩浆活动(Ji Weiqiang et al., 2009; Wen Daren et al., 2008; Wu Fuyuan et al., 2010; Zhu Dicheng et al., 2018)。在图 9 中我们展示了冈底斯岩浆带已经报道的基岩（火山岩和侵入岩）的加权年龄分布，不难发现冈底斯经历了多期显著的岩浆事件，如 200~170 Ma，100~80 Ma 和 65~40 Ma 岩浆峰。需要在此强调的是，火山岩数据不存在明显的 100~80 Ma 的峰期，而存在 200~150 Ma 的峰期（图 9）。这一现象似乎不能用早期火山岩的剥蚀来解释。冈底斯大面积分布侏罗系叶巴组、比马组火山岩，刚好对应于 200~150 Ma 的年龄峰期。相比之下，100~80 Ma 的火山岩分布却极为有限，真实地反应了这段时间内火山喷发的微弱表现，表明这段时间内冈底斯可能处于一个挤压状态，不利于火山岩的就位和喷发，详细分析见下文讨论。

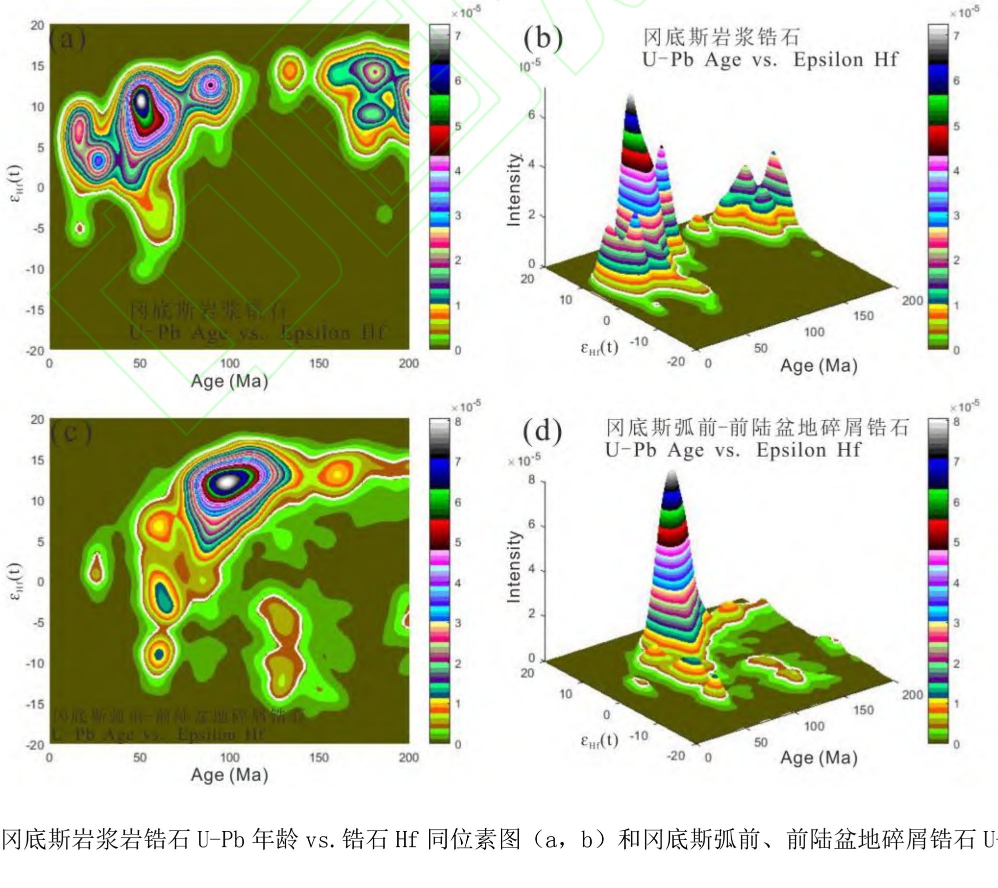

图 11 冈底斯岩浆岩锆石 U-Pb 年龄 vs. 锆石 Hf 同位素图（a，b）和冈底斯弧前、前陆盆地碎屑锆石 U-Pb 年龄 vs. 锆石 Hf 同位素图（c，d）。投图方法来自(Sundell et al., 2019)

Fig. 11 Magmatic zircon U-Pb ages vs. epsilon Hf diagram for the Gangdese belt (a, b) and detrital zircon U-Pb ages vs. epsilon Hf diagram for forearc and foreland basins of the Gangdese belt. Detailed plotting method could be seen in Sundell et al. (2019)

此外，冈底斯弧前和前陆盆地持续接收冈底斯的物源供给，通过研究这些盆地的碎屑锆石U-Pb年龄谱图分布特征，一定程度上可以揭示冈底斯弧岩浆的演化过程(Orme et al., 2016; Wu Fuyuan et al., 2010)。我们搜集了大量前人的数据如图10所展示。通过图10不难发现，冈底斯100~80 Ma和65~40 Ma两个岩浆峰期在这些盆地中也有非常好的记录。碎屑锆石年龄谱图中存在150~100 Ma的年龄峰，但岩浆岩年龄图谱中几乎没有相应的峰值。这一现象刚好说明，在这个时期，拉萨地体南缘的冈底斯刚好处于弧岩浆活动的平静期(Zhang Xiaoran et al., 2019)，而弧前盆地此时却可以接收到中、北拉萨的物源供给（Laskowski et al., 2019)。大部分150-100 Ma碎屑锆石具有相对富集的Lu-Hf同位素，这与同时期中、北拉萨以地壳重熔型岩浆活动为主相吻合（Zhu Dicheng et al., 2011)。由于冈底斯侏罗纪或更早期可能存在洋弧的参与等(Zhu Dicheng et al., 2008; Ma Xuxuan et al., 2018, 2019; Tang Juxing et al., 2015)，且这一岩浆峰期在盆地中记录不佳，故而200~170 Ma的岩浆峰期不在本文进行讨论。

冈底斯岩浆带基岩锆石Lu-Hf同位素和弧前、前陆盆地碎屑锆石Lu-Hf同位素分析结果见图11。分析结果显示锆石ε_{Hf}同位素在100~80 Ma期间，特别是90 Ma左右异常亏损，ε_{Hf}（t）值在+12左右。在65~40 Ma的岩浆峰期，锆石Hf同位素变化范围较大，ε_{Hf}（t）从-10到+15，主体还是在+10左右。

综上所述，冈底斯存在两期显著的岩浆峰期，分别为晚白垩世早期（100~80 Ma）和古新世-早中新世（65~40 Ma），及介于其中的岩浆平静期（80~65 Ma）。

4 峰期岩浆作用与地壳加厚

传统的观点认为巨量的岩浆的生成以伸展背景为主，因为巨大的岩基的形成需要很大的空间。然而，越来越多的研究发现，很多弧岩浆的形成过程却是处于挤压背景状态，岩浆所需的空间可以通过地壳的上部抬升、地壳下部或侧面物质向下运移来提供，并伴随着显著的地壳加厚过程(Cao Wenrong et al., 2016; He Bin et al., 2009; Paterson et al., 1998, 2008, 2011)。那么问题来了，冈底斯100~80 Ma和65~40 Ma的两个岩浆峰期，或岩浆爆发期是否对应于区域挤压背景，是否有显著地壳增厚(Cao Wenrong et al., 2020)？

冈底斯岩浆带在两个岩浆峰期阶段似乎也有显著地壳加厚行为。如图 12a 所示，冈底斯在 100~80 Ma 期间地表海拔高度在缓慢抬升，而此时冈底斯地壳厚度在 100~90 Ma 期间却有显著的增加（图 12b）。冈底斯地壳此时地壳厚度增加的证据主要来自林芝高温-高压麻粒岩相变质(Guo Liang et al., 2013; Zhang Zeming et al., 2014)，其 *P*-*T*-*t* 计算结果显示地壳厚度至少已经达到 55 公里厚（Niu Zhixiang et al., 2019; Qin Shengkai et al., 2019）。而这些高温-高压变质作用主要受 90 Ma 左右幔源来源的、高温的辉长岩、闪长岩和紫苏花岗岩的侵位控制(Dong Xin et al., 2018; Zhang Zeming et al., 2010)。100~80 Ma（峰期在 90 Ma 左右）的岩浆作用在冈底斯岩浆带东西走向广泛发育，多以辉长岩、闪长岩和花岗闪长岩为主，全岩和单矿物同位素显著亏损，形成温度高，源区应该以幔源为主(Ma Xuxuan et al., 2017b; Meng Yuanku et al., 2019)。晚白垩世峰期岩浆侵位与地壳加厚的同期性暗示岩浆侵位对冈底斯地壳加厚的巨大贡献。而此时，冈底斯地壳可能处于一个受新特提斯洋壳岩石圈板片俯冲而形成的一个挤压状态（Zhong Kanghui et al., 2013），没有明显的伸展和裂谷岩浆作用。初步的地壳加厚与岩浆作用的关系模式图如图 13a。

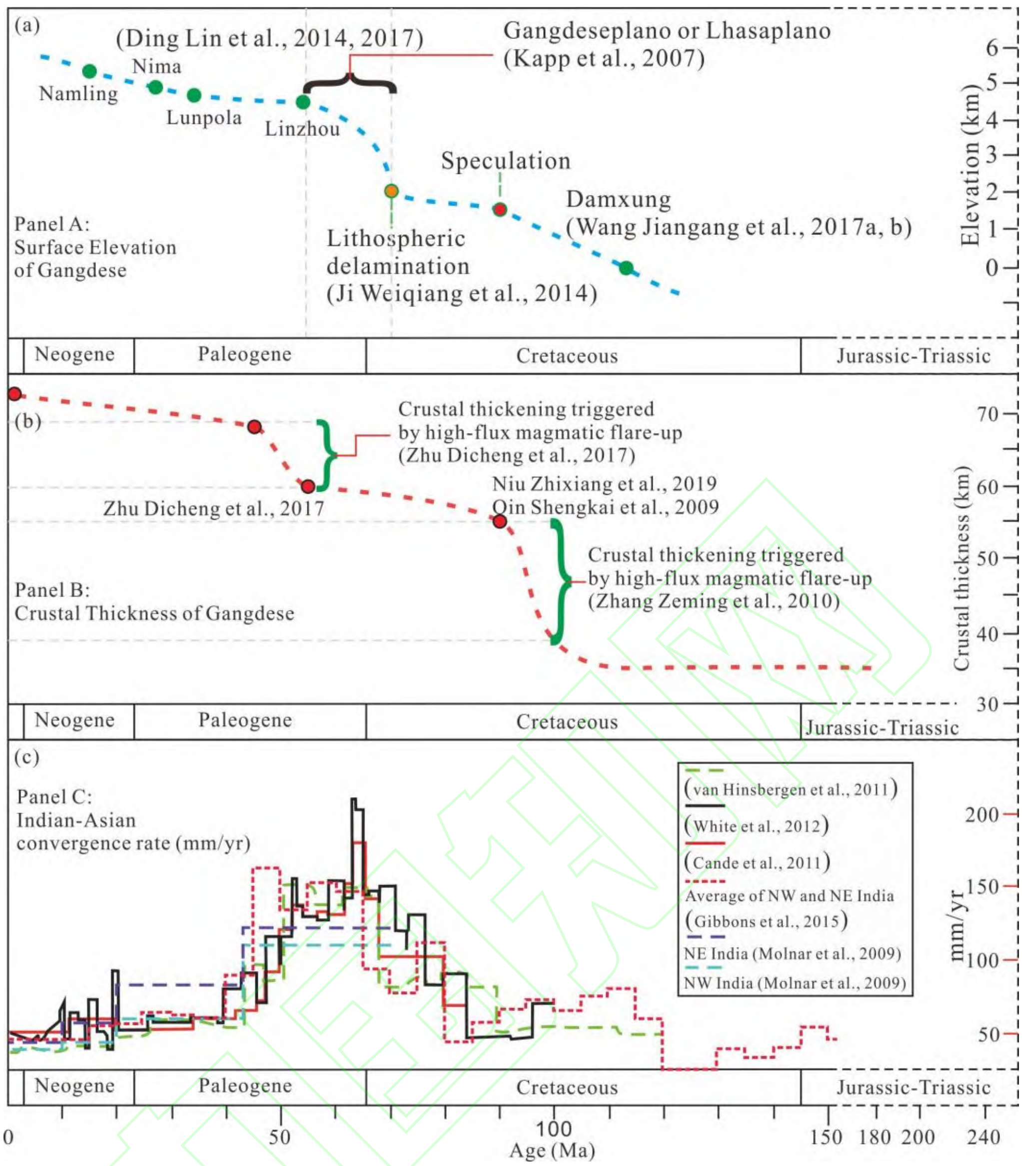

图 12 冈底斯海拔高度（a）、地壳厚度（b）和印度-亚洲汇聚速率（c）与时间的对应关系。引用文献：(Cande et al., 2011; Ding Lin et al., 2014, 2017; Gibbons et al., 2015; Ji Weiqiang et al., 2014; Kapp et al., 2007; Molnar et al., 2009; van Hinsbergen et al., 2011; Wang Jiangang et al., 2017a, 2017b; White et al., 2012; Zhang Zeming et al., 2010; Zhu Dicheng et al., 2017; Niu Zhixiang et al., 2019; Qin Shengkai et al., 2019）

Fig. 12 Gangdese surface elevation vs. age (a), Gangdese crustal thickness vs. age (b), and convergence rate of the Indo-Asian continents vs. age (c). References cited from (Cande et al., 2011; Ding Lin et al., 2014, 2017; Gibbons et al., 2015; Ji Weiqiang et al., 2014; Kapp et al., 2007; Molnar et al., 2009; van Hinsbergen et al., 2011; Wang Jiangang et al., 2017a, 2017b; White et al., 2012; Zhang Zeming et al., 2010; Zhu Dicheng et al., 2017; Niu Zhixiang et al., 2019; Qin Shengkai et al., 2019)

相比 100~80 Ma 的岩浆峰期，65~40 Ma 的冈底斯岩浆峰期特征更明显，以巨大的曲水

岩基和广泛分布的林子宗火山岩为典型代表。林子宗火山岩可能形成于冈底斯弧后伸展背景，与俯冲板片的回撤有关（图 13b）。与弧后伸展相对，此时的冈底斯弧或弧前应该还是处于一个挤压背景，因为俯冲、汇聚还在继续，异常强烈的弧型侵入岩还在持续就位（图 13b）。地球化学研究手段也证实在 55~45 Ma 期间，冈底斯的地壳厚度已达 58~50 公里厚（Zhu Dicheng et al., 2017）。此外，此时冈底斯的地表海拔可能也达到 4500 米以上，为典型的厚地壳、高海拔（Ding Lin et al., 2014）。以上观测再一次证实了俯冲-挤压-弧岩浆作用-地壳加厚的逻辑链条（图 13b）。

5 冈底斯幕式岩浆作用深部动力学过程

关于科迪勒拉造山带弧岩浆的幕式作用成因机制，很多学者提出过很多模型。比如 Matthews et al. (2012)认为科迪勒拉侏罗纪的岩浆峰期是冈瓦纳大陆裂解及相关的板块运动作用的产物，而科迪勒拉晚白垩岩浆爆发则可能是洋壳生长速率增加造成的。Lee et al. (2015)则认为地幔楔的减压熔融是造成科迪勒拉岩浆峰期作用的主要推动因素。此外，阶段性的地幔楔熔融、阶段性的挥发组分淋滤地幔楔、厚的大陆地壳对上升岩浆的调整效应也可能是造成科迪勒拉岩浆幕式作用的推手（Paterson et al., 2015）。多种地质过程的相互回馈效应，如造山、区域地壳加厚/缩短、前陆盆地物质俯冲到弧的下地壳部分、以及阶段性构造和剥蚀作用引发弧上地壳向下运动进入地幔楔等相互作用造成弧岩浆的幕式效应（Ducea et al., 2007, 2015; DeCelles et al., 2009, 2015; Cao Wenrong et al., 2015）。在洋盆闭合前、中和后的过程中，岩石圈和地幔（软流圈？）的相互作用可能是造成科迪勒拉弧岩浆幕式效应的另一种潜在力量（van Hunen et al., 2015）。最新的研究认为板块运动驱动的弧岩浆的迁移过程是控制科迪勒拉造山带弧岩浆幕式作用及物源、成分属性阶段性变化的关键（Ardill et al., 2018; Chapman et al., 2019; Attia et al., 2020）。

关于冈底斯早期岩浆峰期（100-80 Ma）的动力学解释主要有两种模式，即洋中脊俯冲模式（Zhang Liangliang et al., 2019; Zhang Zeming et al., 2010; Zheng Yuanchuan et al., 2014）和俯冲下去的新特提斯洋壳岩石圈板片的回旋模式（Ji Weiqiang et al., 2009; Ma Lin et al., 2015; Meng Yuanku et al., 2019; Xu Wangchun et al., 2015）。两种模式都能很好地解释 100~80 Ma 期间巨量岩浆侵位所需要的热源和物源的问题，但也有各自的局限性。比如，洋中脊俯冲的主要证据来源是冈底斯东段林芝地区的高温辉长岩和紫苏花岗岩侵位，以及高温麻粒岩相变质（Guo Liang et al., 2013; Zhang Zeming et al., 2010; Niu Zhixiang et al., 2019; Qin Shengkai et al.,

2019)，而这些高温岩体和变质作用出露范围非常局限，在冈底斯其他地区鲜有报道。当然，很有可能俯冲下去的洋中脊走向垂直于或高角度斜交于俯冲带走向，故而只在冈底斯东段形成或保留了高温岩浆和高温变质作用。相比之下，俯冲板片的回旋模式确实能解释 100~80 Ma 期间弧岩浆岩在冈底斯东西走向的广泛分布特征。但是，此模式美中不足的地方是：冈底斯缺乏 100~80 Ma 期间的大规模的伸展背景火山作用和火山岩，除去达孜和桑日零星分布的火山岩之外（Ma Lin et al., 2015; Zhang Liangliang et al., 2019）。通过以上论述不难发现，无论是洋中脊俯冲还是板片回旋都代表了俯冲板片俯冲方式的重大转变，由此造成了 100~80 Ma 异常剧烈的岩浆活动并形成显著的岩浆侵位峰期，即所谓的岩浆爆发事件（magma flare-up）。

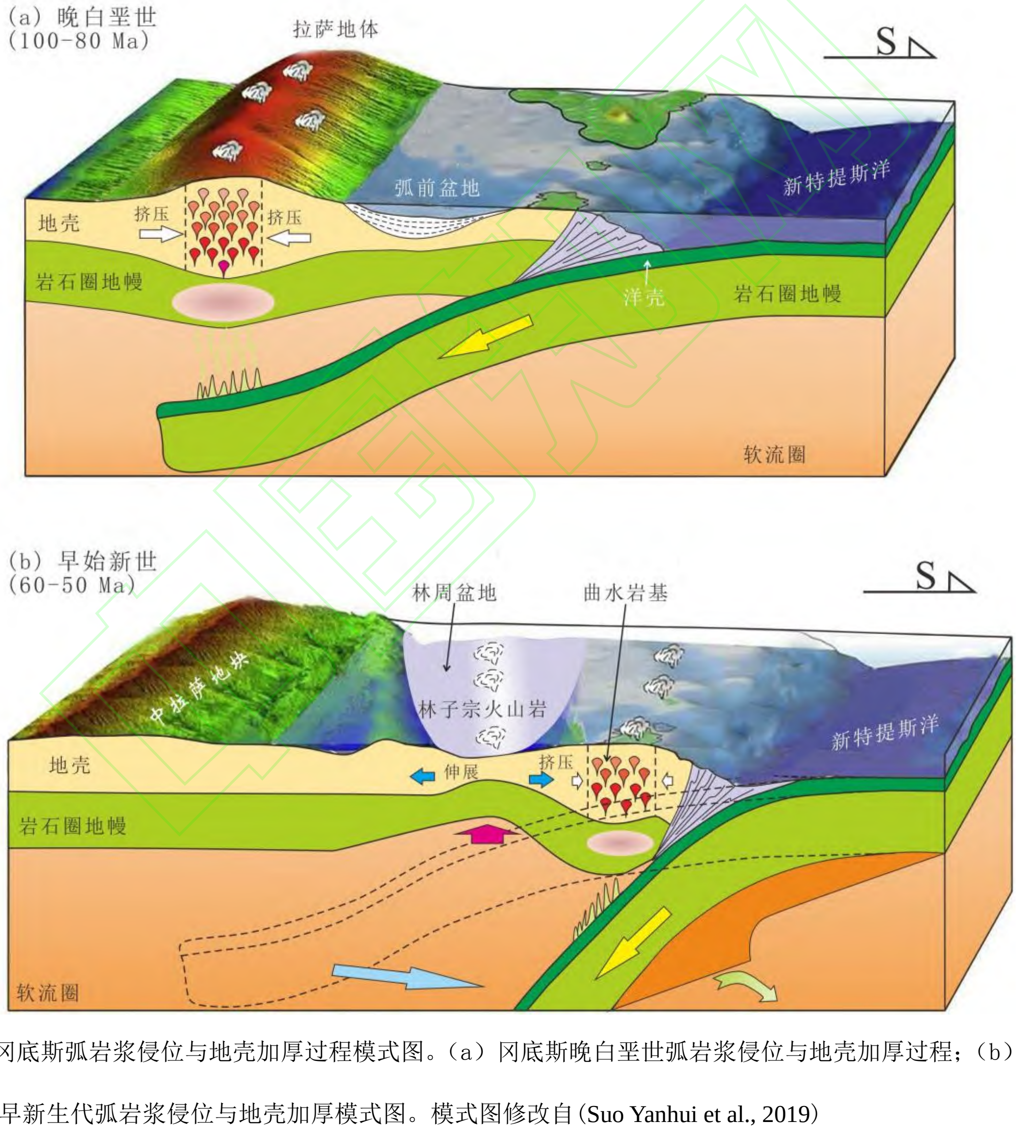

图 13 冈底斯弧岩浆侵位与地壳加厚过程模式图。（a）冈底斯晚白垩世弧岩浆侵位与地壳加厚过程；（b）冈底斯早新生代弧岩浆侵位与地壳加厚模式图。模式图修改自（Suo Yanhui et al., 2019）

Fig. 13 Tectonic models of arc magmatism and crustal thickening for the Gangdese belt. (a) Late Cretaceous arc magmatism and the crustal thickening for the Gangdese belt; (b) Early Eocene arc magmatism and crustal thickening of the Gangdese belt. Cartoons are modified from Suo Yanhui et al. (2019)

与 100~80 Ma 的岩浆峰期相比，65~40 Ma 的岩浆峰期的争论热度也毫不逊色。核心的争论点是这个时期是属于洋陆的俯冲期还是陆陆的碰撞期。关于印度-亚洲的初始碰撞时间问题争论已久，初始碰撞时间从约 70 到 30 Ma(Aitchison et al., 2007; van Hinsbergen et al., 2019; Yi Zhiyu et al., 2011; Yin An et al., 2000)，时间跨度非常之大。大部分报道的初始碰撞时间都集中在 60~50 Ma(DeCelles et al., 2014; Hu Xiumian et al., 2015)，因此，我们暂且认可印度-亚洲大陆的初始碰撞时间在 60-50 Ma 期间。如果这个结论成立，65~40 Ma 期间刚好是洋陆俯冲到陆陆碰撞的转换期。俯冲到碰撞的转换期是俯冲板片俯冲方式和深部动力学剧烈、快速变化的时期，对形成岩浆峰期及岩浆爆发非常有利。首先，洋壳俯冲还在继续，有利于持续形成弧岩浆，这与 65~50 Ma 期间冈底斯广泛分布的林子宗火山岩和规模巨大的曲水岩基的地球化学特征吻合(Lee Haoyang et al., 2012)；其次，碰撞已经开始，俯冲板片开始回旋，也能解释冈底斯弧岩浆从 65 Ma 开始的由北向南的迁移趋势(Wen Daren et al., 2008; Zhu Dicheng et al., 2015)；再者，碰撞过程的俯冲板片的断离非常有利于软流圈的上涌，造成大规模玄武质岩浆底侵，继而形成广泛的辉长岩、基性岩墙和大规模的暗色岩浆包体（图 8）（Dong Guochen et al., 2008; Ma Xuxuan et al., 2017a; Mo Xuanxue et al., 2007）。

有趣的是，冈底斯两次的弧岩浆活动峰期与印度-亚洲的汇聚速率都没有特别好的对应关系：在 100~80 Ma 期间，印度-亚洲大陆的汇聚速率在缓慢增加；而在 65~40 Ma 期间印度-亚洲大陆的汇聚速率却在缓慢下降（图 12c）。由此说明冈底斯弧岩浆的峰期作用不受印度-亚洲大陆汇聚速率的影响（Zhang Xiaoran et al., 2019）。

综合以上所述，不管何种机制及模型，似乎俯冲板片、地幔楔、软流圈和大陆岩石圈的多相耦合作用是弧岩浆生成及幕式作用形成的物质来源、空间载体和推动因素。至于各相因素如何参与、如何协调，进而控制弧岩浆的幕式过程、幅度、强度、持续时间等还有待于更多研究。

6 幕式岩浆作用待解之谜

关于冈底斯弧岩浆的幕式作用过程，依然有很多悬而未决的科学问题有待更多的学者进行持续、深入的研究。根据我们多年冈底斯的工作经验和思考，我们认为如下几个问题值得进一步探讨。

问题一，通过计算壳幔物质参加贡献能很好地反映壳幔相互作用过程，解释深部俯冲板

片动力学过程。在峰期岩浆作用期间，岩浆源区属性如何，壳幔物质比例如何，如何定量计算或区分壳幔来源物质和参与比例。在科迪勒拉造山带内华达岩基、半岛岩基、玻利维亚海岸岩基和智利海岸岩基均发现在弧岩浆爆发期幔源岩浆都有重大贡献(Attia et al., 2020; Martínez Ardila et al., 2019)。那么，在峰期岩浆岩整体都具有异常亏损的同位素特征且不易区分两个截然不同的同位素端元的情况下(Ji Weiqiang et al., 2009; Mo Xuanxue et al., 2009)，如何计算冈底斯 100~80 Ma 和 65~40 Ma 两期岩浆峰期壳幔参与比例？

问题二，在两个岩浆峰期之间有一个短暂的岩浆平静期，即 80~65 Ma(Wen Daren et al., 2008; Ji Weiqiang et al., 2009; Zhu Dicheng et al., 2018; Zhang Xiaoran et al., 2019)。与此同时，新特提斯洋壳岩石圈板片还在持续俯冲，而岩浆活动却平静了下来，原因何在？早前的研究认为此时发生了平板俯冲作用(Ding Lin et al., 2003; Wen Daren et al., 2008; Zheng Yuanchuan et al., 2014)。从岩浆爆发期过渡到岩浆平静期，俯冲板片角度变低的原因是什么，另外，岩浆平静期区域构造表现如何，是否有显著地壳变形及变形特征如何，是一种类似安第斯型造山的地壳缩短吗？

问题三，冈底斯 65~40 Ma 的岩浆爆发期，岩浆作用顶峰在 50 Ma 左右，以曲水岩基为代表。正如前文所述，如果印度-亚洲大陆的初始碰撞在 60~50 Ma 期间，50 Ma 很可能是洋-陆俯冲到陆-陆碰撞转换期，这与印度-亚洲汇聚速率在 50 Ma 有显著降低事件相吻合(van Hinsbergen et al., 2011)。与此同时，高原内部发育了一系列的同碰撞变形盆地(Jin Chunsheng et al., 2018; Li Shihu et al., 2020)。我们不禁要问，同挤压构造如何与同期侵位弧岩浆进行耦合，挤压变形过程有没有通过岩浆构造的形式在曲水岩基留下丰富的岩浆面理记录，这些记录如何追踪和解译？

7 结论

大陆弧岩浆具有典型的阶段性侵位特点，峰期岩浆对地壳加厚有重大贡献。作为中-新生代全球最显著的弧岩浆带，藏南冈底斯岩浆带弧岩浆演化具有显著的幕式作用特点，岩浆爆发期主要为 100~80 Ma 和 65~40 Ma 两期，中间间隔一个岩浆平静期（80~65 Ma）。此外，在冈底斯弧岩浆作用的峰期，幔源物质贡献巨大，冈底斯地壳有显著加厚，表明弧岩浆侵位与地壳加厚的密切关联。

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Continental arc tempos and crustal thickening: a case study in the Gangdese arc, southern Tibet

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Abstract

The continental arc belt, located at the frontier margin of convergent plate, records the subduction of oceanic lithosphere and the continental crustal growth processes. In addition, the continental arc is the best laboratory to address the interaction between crust and mantle. Increasing studies reveal that the growth and emplacement of continental arc magmatism show episodic patterns, rather than a steady or continuous process. Compared with the magmatic lull, the magmatic flare-up is characterized by high magma addition rates (MARs) and magma focusing, which is favorable for the formation of big arc batholith, such as the Sierra Nevada and Peninsular Ranges batholiths in the Cordilleran orogen, western North America. The Gangdese arc belt is located along the southern margin of the Lhasa terrane, belonging to the overlying plate of the Indo-Asian collisional zone. The Gangdese arc belt is separated from the southern Himalayan terranes by the Indus-Yarlung Tsangpo suture zone. The arc magmatism of the Gangdese arc persisted from ~240 to ~50 Ma, is closely related to northward subduction of the Neotethyan oceanic lithosphere beneath the southern margin of the Lhasa terrane. Thus, the on-going studies on the magmatism of the Gangdese arc will help us to better understand the Gangdese arc tempos, the subduction of the Neotethys, as well as the crust-mantle interaction. In the present study, we have collected voluminous zircon

U-Pb ages and Lu-Hf isotopes of igneous rocks from the Gangdese arc and detrital zircon U-Pb ages and Lu-Hf isotopes from forearc and foreland basins. These compiled data, in combination with regional geology, lead to the following concluding remarks: 1) the magmatism of the Gangdese arc shows episodic features, with magmatic flare-ups culminating at 100~80 Ma and 65~40 Ma, respectively; 2) the magmatic flare-up is favorable for the formation of big batholith with depleted isotopes, implying significant involvement of mantle material; and 3) the magmatic flare-ups are coincidently synchronous with the crustal thickening events, revealing that the magmatic flare-up contributed greatly to the crustal thickening.

Key words: continental arc magmatism; magmatic tempos; magmatic flare-up; crustal thickening; Gangdese; Tibet