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冈底斯弧南缘侏罗纪火成岩时空分布和地球化学组成变化特征及其对地壳增生的指示

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摘　要: 冈底斯弧南缘广泛出露有中生代和新生代火成岩, 是青藏高原火成岩最发育的地区之一, 记录了新特提斯洋北向俯冲、消减和随后的印度大陆与欧亚大陆碰撞等地质过程。对中生代尤其是侏罗纪火成岩的研究对于理解新特提斯洋早期俯冲及青藏高原南缘早期增生具有显著意义。对位于冈底斯南缘平行于雅鲁藏布江缝合带东西向展布的侏罗纪火成岩年代学和地球化学数据进行了总结, 结果表明: (1) 侏罗纪岩浆活动高峰期集中于早中侏罗世(192~168 Ma); (2) 侏罗纪岩浆作用主要活动范围位于雅鲁藏布江以北附近, 在北纬 29.48° 以北相对缺乏中晚侏罗世岩浆活动, 而且早侏罗世岩浆活动相对于南边也更加平静, 且以酸性岩浆活动为主; (3) 侏罗纪火成岩微量元素也呈一些规律性变化, 如 Ba/La、Ba/Th 比值随着时代的演化呈现出递增的趋势, 很可能表明板片来源流体贡献逐渐增加, Nb/Th 和 Nb/La 由西向东均呈现递减趋势, 表明地壳混染作用很可能逐渐增强; (4) 侏罗纪火成岩的微量元素组成空间上的变化特征指示在早侏罗世早期冈底斯弧南缘就已经存在正常地壳厚度, 并且随着新特提斯洋的北向俯冲, 其有逐渐增厚的趋势。

关键词: 侏罗纪; 岩浆活动; 地球化学; 地壳增生; 冈底斯弧; 青藏高原

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Distribution and geochemical characteristics of Jurassic igneous rocks in the sourthern Gangdese Arc and their implications for crustal accretion

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Abstract: Mesozoic and Cenozoic igneous rocks are widely exposed in the southern part of the Gangdese Arc and record the subduction of the Neo-Tethys ocean, and subsequent collision between India and Eurasia. These Mesozoic igneous rocks, and Jurassic igneous rocks in particular, are important for understanding arc accretion and the early subduction characteristics of the Neo-Tethys Ocean. Based on previous chronological and geochemical research into the EW-trending Jurassic igneous rocks distributed along the southern Gangdese Arc, we found that: (1) Jurassic magmatic activity reached a peak between the early and middle Jurassic (192~168 Ma); (2) major Jurassic magmatism developed an EW-trending region between the northern Yaluzangbu sutures and 29.48°N; (3) trace element ratios of these Jurassic igneous rocks show consistent trends, such as Ba/La and Ba/Th ratios increasing over time, and Nb/Th and Nb/La ratios decreasing from west to east, possibly indicating increased fluid contribution from the slab and gradually strengthening assimilation of the crust, respectively; and (4) in the early

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Jurassic, the southern margin of the Gangdese Arc had a normal crustal thickness, which increased gradually with the northward subduction of the Neo-Tethys ocean.

Key words: Jurassic; magmatism; geochemistry; crustal accretion; Gangdese arc; Qingzang Plateau

0　引　言

冈底斯弧南缘广泛发育有与新特提斯洋北向俯冲以及随后印度与欧亚大陆碰撞相联系的中-新生代岩浆作用，记录了新特提斯洋俯冲消减、弧-陆、陆-陆碰撞导致高原增生和加厚隆起的整个地质过程。虽然相对于冈底斯岩基大面积出露的晚白垩世和古新世(103~42 Ma)火成岩来说，侏罗纪火成岩分布较为有限且规模较小[1]，但因这些早期的岩浆作用可以反映冈底斯弧初始增生及与之相关的特提斯洋的演化历史，从而在近年来逐渐成为人们研究的热点。

冈底斯带火成岩作用的研究工作始于 20 世纪 60 年代，主要集中在花岗岩的年代学、岩浆源区和成因机制的研究上；人们对该区域侏罗纪火成岩的研究时间并不长，最早是对雄村矿区和甲玛-驱龙矿区的斑岩和火山岩 U-Pb 定年，获得了早-中侏罗世的年龄(190~174 Ma)[2–5]。与此同时，前人对于侏罗纪火成岩的研究也主要集中在岩石成因、源区特征以及构造环境的判别，而对该时期冈底斯弧的俯冲增生过程的研究相对有限。由于地壳均衡，大陆岩石圈厚度的变化会影响造山带海拔的高低，进而影响区域气候条件，因此古岩石圈结构特别是俯冲增生过程中地壳厚度的变化对于反演古气候条件的演变具有重大意义。

目前的研究结果显示，冈底斯弧南缘侏罗纪岩浆作用从西部的鸭洼地区一直断续分布到东部的米林地区，东西向空间跨度约 800 km (图 1)。本文在收集和归纳前人对冈底斯弧南缘侏罗纪火成岩年代学和地球化学数据的基础上，尝试解决以下三个

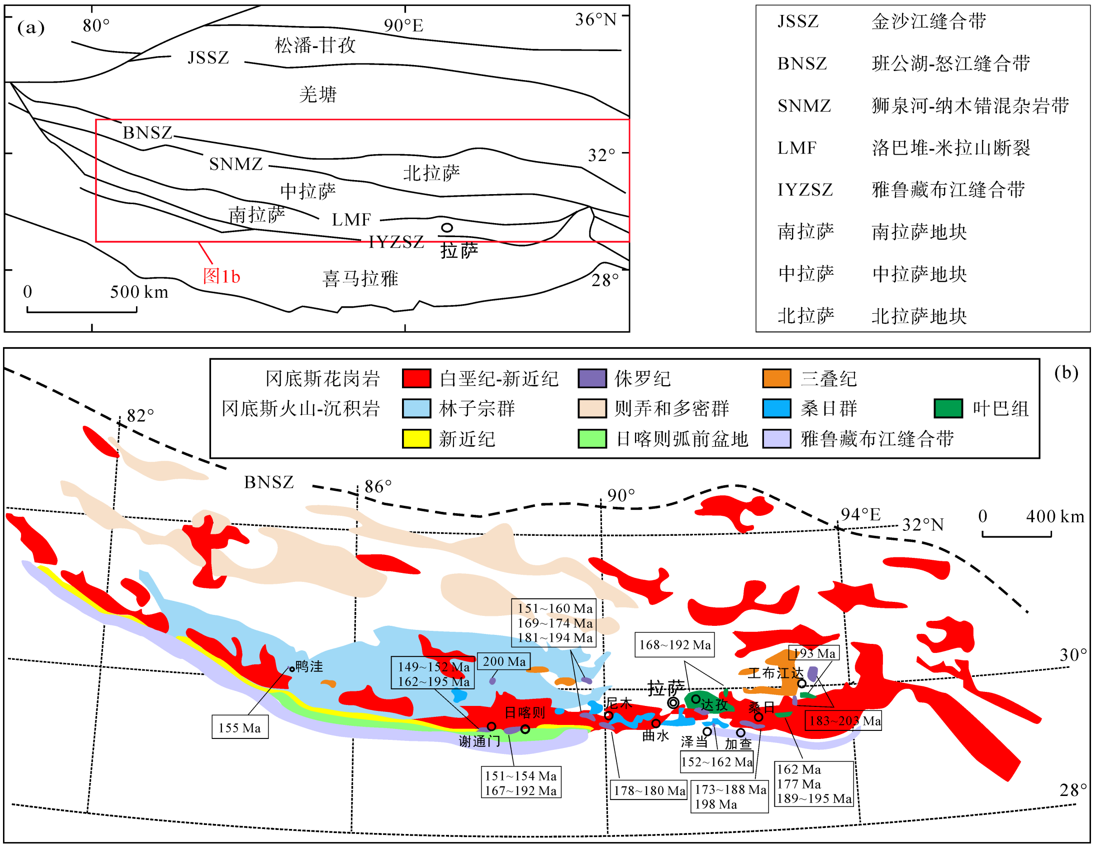

图 1　青藏高原和拉萨地块区域构造图

Fig.1　Regional tectonic map of the Qingzang plateau and Lhasa terrane

(a) 青藏高原构造简图; (b) 拉萨地块火成岩分布图(据文献[6–7]略有修改)。图 1b 中侏罗纪年龄数据来源于文献[5,8–36]

(a) The brief structural map of the Qingzang plateau; (b) distribution map of igneous rocks in the Lhasa terrane (modified from references [6–7]). In Fig.1b, age data for Jurassic igneous are from references [5,8–36]

问题: (1) 冈底斯弧南缘侏罗纪岩浆作用时空分布特征; (2) 侏罗纪冈底斯弧南缘火成岩地球化学组成时空变化特征; (3) 了解新特提斯洋北向俯冲早期冈底斯弧南缘地壳增生过程。

1 地质概况

青藏高原是我国火成岩最发育的地区之一, 出露着太古宙到新生代各个地质时期多种类型的火山岩和侵入岩, 各类火山岩与侵入岩出露面积为30万km^2, 占全区面积的10%以上[37]。上述火成岩记录了大陆裂解、微陆块漂移到陆陆碰撞及最后隆升成为“世界屋脊”等一系列过程。自北向南依次以昆仑-阿尼玛卿缝合带、金沙江缝合带、班公湖-怒江缝合带和雅鲁藏布江缝合带为界, 将其分割为松潘-甘孜地体、羌塘地体、拉萨地体和喜马拉雅地体(图 1a)。目前, 班公湖-怒江缝合带所代表的晚二叠世-早白垩世的古特提斯洋的俯冲极性还存在争议, 主要存在其向北俯冲到羌塘地体之下或是向南俯冲到拉萨地体之下亦或者是双向俯冲的分歧, 而雅江缝合带普遍认为代表了向北俯冲的晚三叠世-晚白垩世新特提斯洋的残留体。

位于班公湖-怒江缝合带和雅鲁藏布江缝合带之间的拉萨地块由于具有造山属性, 因此也被称为冈底斯带。冈底斯带是青藏高原最为重要也最具特色的一条岩浆-构造-成矿带, 东西长约2000 km, 南北宽约 100~300 km, 向西逐渐变窄, 在喀喇昆仑右旋断裂与拉达克-科希斯坦地体相接, 向东绕过东构造结并入三江带[37–39]。按照基底性质和沉积盖层的不同, 以区域性断裂或者蛇绿混杂岩带, 冈底斯带由南向北划分为南冈底斯、中冈底斯和北冈底斯带[40–41] (图 1a)。

本文涉及的冈底斯弧位于洛巴堆-米拉山断裂以南, 雅江缝合带以北。由于位于冈底斯带最南端, 不仅是大洋俯冲时期的活动陆缘还是碰撞阶段的主前锋区, 记录了新特提斯洋俯冲消减和印度-欧亚大陆碰撞整个地质过程, 是整个冈底斯带中岩浆活动最为频繁和集中的区域, 广泛分布中新生代火成岩(图 1b)。

2 冈底斯带南缘侏罗纪火成岩时空分布特征

已有研究表明, 冈底斯弧南缘中生代火山岩以早中侏罗世叶巴组和晚侏罗世-白垩纪桑日群为典型代表, 新生代以林子宗火山岩以及渐新世到中新世火成岩为典型代表。通过对冈底斯弧花岗岩带的研究, Ji *et al.*[8]发现在冈底斯岩基主要发育有四期岩浆活动, 分别是205~152 Ma、109~80 Ma、65~41 Ma和33~13 Ma。在上述几期岩浆作用中, 早期的侏罗纪火成岩由于出露面积较小、分布较为零星并且发现较晚, 因此研究程度远不如白垩纪和新生代火成岩。但随着人们对冈底斯弧岩浆-构造-成矿带研究的不断深入, 沿着东西向不断有新的侏罗纪火成岩露头发现(图 1), 结合最新的研究成果, 初步统计冈底斯带南缘侏罗纪岩浆作用东西向展布约800 km (图 1)。

2.1 叶巴组火山岩

早-中侏罗世叶巴组主要由火山岩和沉积岩组成。火山岩以钙碱性双峰式组合为主(酸性岩厚度变化范围为7000~2000 m、基性岩厚度约为3000 m), 同时可见少量安山质岩层; 沉积岩主要位于叶巴组顶部, 由细粒砂岩、钙质板岩、生物碎屑岩和石灰岩等以夹层形式存在于硅质岩中, 总体分布于达孜-工布江达一带(约 250 km)[28,40,42]。叶巴组和上部上侏罗统多底沟组以及白垩系门中组为不整合接触, 同时发育有一些侵入岩。由于后期构造作用的影响, 叶巴组火山岩普遍发生了绿片岩相的变质作用。虽然双壳类动物群的发现将叶巴组限制在中侏罗世[43], 但随后越来越多的精确火山岩锆石年代学研究表明叶巴组形成于早侏罗世(193~174 Ma)。如达孜巴嘎雪村-色岗村一带(182 Ma)[44], 达孜大桥南桥头(174 Ma)[3]、甲马沟(174 Ma)[5], 得明顶(193 Ma)[45]。最近研究表明墨竹工卡以东日多地区叶巴组(177~162 Ma)[19], 再次确认达孜县叶巴组驱龙(188 Ma)和甲马沟(175 Ma)[9]、达孜县(183~168 Ma)[27,42]、得明顶(189 Ma)[20]、林周地区(193~189 Ma)[46](图 1 和图 2a)。因此上述有关叶巴组火山岩形成的年代学统计结果表明, 叶巴组火山岩形成年代限制在早-中侏罗世, 是新特提斯洋早期俯冲事件产物[47]。

2.2 桑日群火山岩

桑日群主要由下部的麻木下组和上部的比马组组成, 麻木下组(137~93 Ma)以埃达克质安山岩为主夹少量英安岩和沉火山角砾岩, 比马组为灰岩质角砾夹安山岩, 顶部为结晶灰岩。桑日群火山岩东起桑日、加查一带, 向西经曲水、尼木、谢通门最终可达萨嘎一带, 东西展布超过 800 km[47–48]。虽然

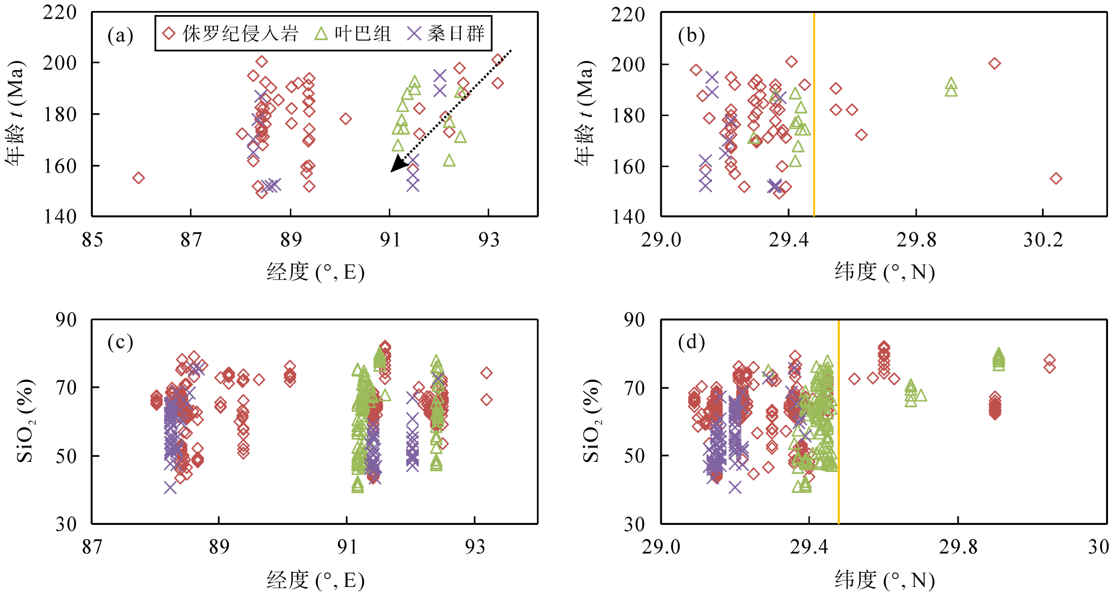

图 2　研究区侏罗纪侵入岩、叶巴群和桑日群年龄-经度(a)、年龄-纬度(b)、SiO_2-经度(c)、SiO_2-纬度(d)

Fig.2　Diagrams of age-longitude (a), age-latitude (b), SiO_2-longitude (c), SiO_2-latitude (d) for Jurassic intrusive rocks, Yaiba Group, and Sangri Group in the study area

早期海娥螺化石的存在表明桑日群既有上侏罗统成分也有下白垩统成分[49], 但随后的精确 SHRIMP 火山岩锆石同位素年代学研究发现麻木下组最老的火成岩属于早白垩世(137 Ma)[50]。

对麻木下组年代学进行精确厘定之后, 学者将注意力转向之前一直通过古生物化石进行定年的比马组, 从而对新特提斯洋持续俯冲时间进行有效约束。虽然前人认为比马组主要为晚于麻木下组的白垩纪安山质火山岩组合, 但近年精确的年代学研究结果逐步显示在比马组中存在相当数量的侏罗纪火山岩, 如日喀则扎西定乡(178 Ma)[14]、荣玛(175~165 Ma)[32], 泽当(160 Ma)[23], 桑日县卡玛当(195~189 Ma)[48](图 1 和图 2a)。因此结合叶巴组年代学和地球化学特征, 有学者[51]提议将桑日地区比马组划归到叶巴组。

2.3　侏罗纪侵入岩

侏罗纪的侵入岩以石英闪长岩、花岗闪长岩和二长花岗岩等中酸性岩为主, 含有少量基性侵入岩, 是冈底斯岩基的重要组成部分[8,21,52,53]。它们主要沿着雅鲁藏布江北部呈东西向展布, 但分布宽度比白垩纪-新生代花岗岩窄。早中侏罗世侵入岩由西至东主要位于谢通门-尼木-驱龙-加查一带。如谢通门成矿区(200~168 Ma)[16,24,29–31,34,54]、乌郁盆地(188 Ma)[52]、日喀则西北部(180~170 Ma)[10,34]、日喀则以北东嘎乡(192~177 Ma)[17,22,33,55,56]、仁布县奴玛乡(191~169 Ma)[22,26]、大竹卡(194~159 Ma)[8,36]、彭措林(172 Ma)[36]、南木林以南 20 km (182 Ma)[34]、拢布村(157 Ma)[13]、塘白村(184~168 Ma)[28]、尼木县尼木大桥北侧(188~178 Ma)[21,28]、加查(202~179 Ma)[18,57,58]、桑日沃卡电站(180 Ma 和 190 Ma)[18]、墨竹工卡县驱龙铜矿西部(182 Ma)[11]、得明顶(192 Ma)[15]、米林(192 Ma)[25]; 而中晚侏罗世侵入岩(164~149 Ma), 主要分布于拉萨以西, 以及东部泽当、日多等少数地区[8,12,23,34–36](图 1 和图 2a)。

为避免数据的重复使用, 笔者对所收集的 185 个年代学数据, 采取以下方案进行有效过滤: (1) 针对同一篇文章研究的同一岩体, 如果两个年龄在误差允许范围内具有重叠, 则两者只取其中精度较高的年龄; (2) 如果多篇文章研究同一岩体, 且所测年龄在误差允许范围内具有重叠, 则两者只取其中精度较高的年龄。经过以上过滤方案后仅剩 78 个有效年代学数据, 确保了年龄频谱图能够更加真实反映岩浆活动事件。此外, 本文还利用 482 个主量数据进行投图(图 2c 和 2d), 以了解侏罗纪岩浆活动特点。

由上面冈底斯弧南部侏罗纪火成岩形成时代统计发现: (1) 新特提斯洋在侏罗纪期间是持续俯冲的阶段, 且岩浆作用主要发育在早中期(192~168 Ma), 冈底斯带东部以火山岩为代表, 含有相当数量同时代侵入岩, 而西部主要是侵入岩(图 1、图 2a 和图 3); (2) 90°E 以东的侏罗纪岩浆活动似乎有由东向西逐

渐变年轻的趋势，然而 90°E 以西岩浆活动时间变化范围较大，无明显趋势(图 2a); (3) 29.48°N 以北相对缺乏中晚侏罗世岩浆活动，早侏罗岩浆活动相对于 29.48°N 以南也更加平静，且以酸性岩浆活动为主(图 2b 和 2d); (4) 冈底斯带无论是东段还是西段，均有基性-酸性岩浆活动(图 2c)。

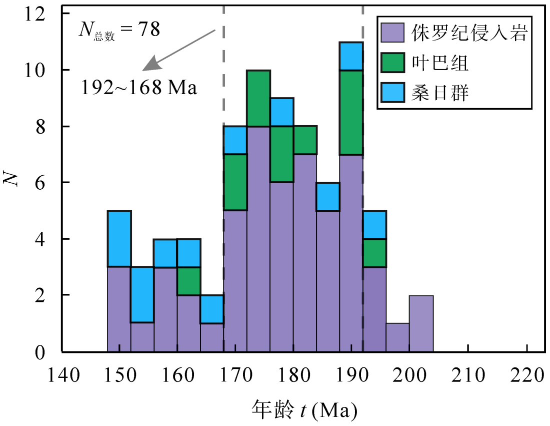

图 3 研究区侏罗纪侵入岩、叶巴群和桑日群年龄谱图

Fig.3 Histogram of ages for Jurassic intrusive rocks, Yaiba Group, and Sangri Group in the study area

3 冈底斯带侏罗纪火成岩地球化学特征的变化

位于俯冲增生区域的岩浆作用，其物质成分主要受俯冲的大洋板片及其上覆的沉积物所控制，因此研究冈底斯弧侏罗纪火成岩微量元素地球化学组成特征可以尝试了解俯冲大洋板片及其沉积物对岛弧增生过程中的贡献。

Ba 和 Sr 是大离子亲石元素，活动性强，易受俯冲流体影响并随之发生迁移。Ba/La 比值变化不仅可以反映出富集不相容元素(Ba 和 Sr 等)的流体贡献而且也可以反映地幔楔的部分熔融程度[34,59]。高 Ba/Th 比值表明弧岩浆形成过程中流体主要是板片来源而非大洋沉积物来源 [34,60,61]。在相对基性的源于与俯冲富集交代的地幔楔火成岩的地球化学组成数据中，Ba/La 比值呈现出随着年龄的减小而增大的趋势(图 4a)，似乎表明随着新特提斯大洋板片俯冲的持续进行，弧岩浆过程中流体组分的贡献以及地幔楔部分熔融程度呈现出一个递增的趋势。Ba/Th 比值的增加(图 4b)，表明流体组分呈现出早期以俯冲沉积物来源为主逐渐过渡到以板片来源为主的转变。这很可能进一步表明俯冲深度在逐渐增加，因为 Rupke *et al.*[59]研究表明俯冲深度较浅时流体主要来源于俯冲沉积物，而随着俯冲深度的逐渐增加，俯冲沉积物到达 50 km 深处时水分基本脱离，该深度以下俯冲的玄武质洋壳和蛇纹石化橄榄岩开始逐步释放大量流体并成为流体主要来源。

前人通过对古老以及现代岛弧系统的研究发现上地壳大约占全地壳体积的三分之一，主要由中酸性火山岩、沉积岩和侵入岩组成；下地壳主要由辉长岩、超镁铁质堆晶岩和相关变质岩组成。在俯冲带，新生代的弧岩浆会受到前期岩浆作用形成的围岩的同化混染作用，会导致弧火成岩微量元素比值(如 Nb/Th 和 Nb/La)的降低[62]。冈底斯弧南缘由西向东呈现下降趋势，很可能说明东部的初始弧岩浆在上升过程中受到围岩的混染程度高于西部(图 4c 和 4d)。

4 冈底斯弧早期地壳增生特征

冈底斯弧南缘持续的侏罗纪岩浆作用很可能说明其在新特提斯洋俯冲过程中存在增生作用。目前人们普遍认为大陆主要通过以下两种方式增长：(1) 新生的岩浆弧；(2) 伸展背景下地幔物质的输入[63]。地球物理研究证实，青藏高原具有正常地壳两倍的厚度(60~80 km)[64–65]。青藏高原虽然被认为是典型的碰撞型造山带，但是在中生代它经历了典型的增生造山过程，具有典型的增生造山特征(大洋俯冲、弧岩浆作用和弧-陆碰撞)，是大陆生长主要位置[66]。

目前对于冈底斯带造山过程及其地壳厚度演化的研究主要集中在白垩纪和新生代。大量加厚下地壳成因的埃达克质岩[67–69]以及日喀则沉积盆地中大量白垩纪火山弧型继承锆石(130~80 Ma)[1]的出现，表明晚白垩纪时期高原南部发生了明显的地壳加厚、地形隆升以及剥蚀作用。同时前人的研究表明青藏高原南部在新生代早期-中新世时期经历明显地壳增厚和抬升[70–73]。然而，同白垩纪和新生代地壳增厚和隆升过程的研究相比，青藏高原南部冈底斯弧在侏罗纪时期地壳增生过程的研究则相对比较薄弱。

地壳增长是指地幔物质输入地壳，使地壳总体积增大的过程。大洋板片俯冲过程中，地幔楔在洋壳来源的熔体和流体作用下，发生部分熔融形成弧岩浆作用。弧岩浆底侵下地壳并在弧根堆积形成新生下地壳或者新形成的下地壳发生部分熔融底侵

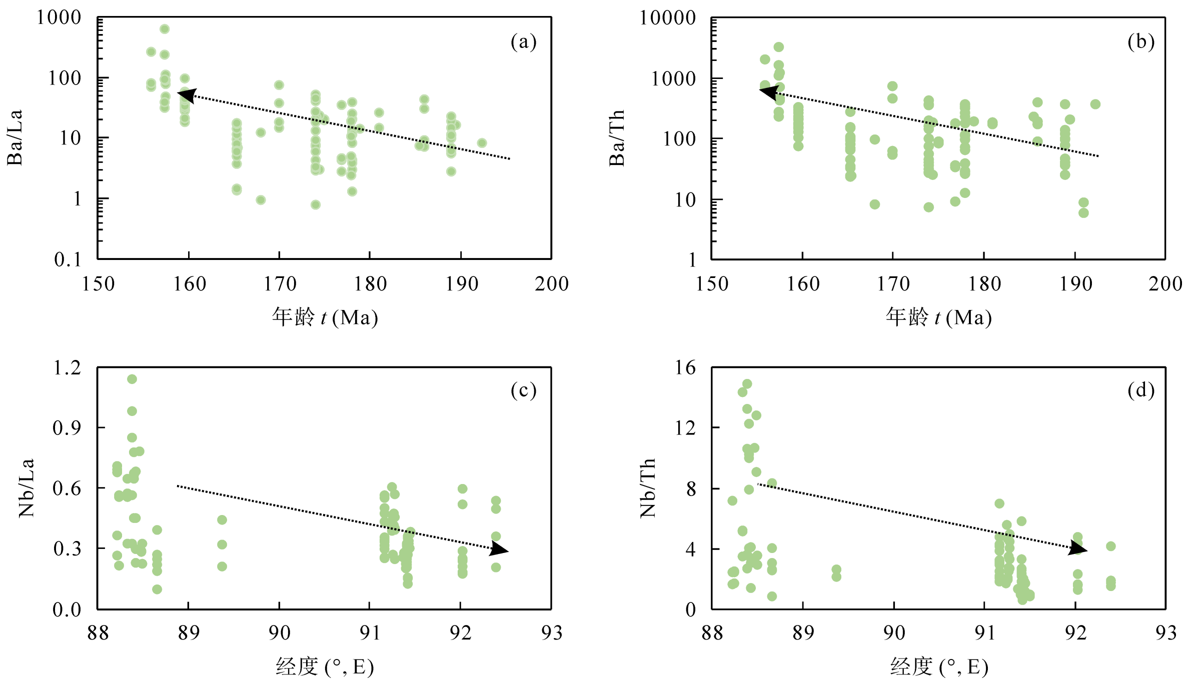

图 4　研究区侏罗纪火成岩 Ba/La-年龄(a)、Ba/Th-年龄(b)、Nb/La-经度(c)、Nb/Th-经度图解(d)

Fig.4　Diagrams of Ba/La-age (a), Ba/Th-age (b), Nb/La-longitude (c), and Nb/Th-longitude (d) for the Jurassic igneous rocks in the study area

浅绿色圆点代表镁铁质岩石($SiO_2 < 53\%$)元素比值

The light green dots represent element ratio of the mafic rocks ($SiO_2 < 53\%$)

中上地壳，从而使地壳发生增长，并使地壳厚度增大。前人[7,33,56] 通过对冈底斯弧南缘镁铁质物质及其相应的长英质侵入岩的研究认为，在晚三叠世-早侏罗世期间就已经存在镁铁质岩浆底侵并与早期形成的新生地壳相互作用形成长英质熔体从而使地壳发生纵向生长。同时，Xie *et al.*[36]发现冈底斯带中侏罗世火成岩表现出低锆石钛温度以及高 La/Yb 和 Sr/Y 比值，表明在中侏罗世冈底斯带部分区域已经存在加厚的地壳。有学者[23,74]发现了泽当晚侏罗世便存在加厚下地壳部分熔融形成的埃达克质岩，说明此时的地壳厚度已经超过了 40 km，进入了角闪石-石榴子石稳定区域。上述前人的研究结果指示在中生代侏罗纪时期冈底斯弧处于一个持续增生的过程。

Haschke *et al.*[75]通过对安第斯陆壳中部研究发现岩浆底侵增厚影响虽然没有构造挤压增厚明显，但是岩浆底侵增厚是一个长时间持续的过程，因此岩浆底侵作用对于地壳生长的贡献同样不可忽视。他们根据平衡公式计算，得出构造增厚和岩浆底侵增厚对于地壳加厚的贡献约为 2∶1。基于此和前人对冈底斯弧侏罗纪岩浆作用的研究成果，本文认为冈底斯弧南缘侏罗纪的岩浆作用很可能指示该区域在新特提斯洋俯冲早期存在地壳增生过程。

目前，出现了基于大量地球化学数据对地壳厚度进行估算的经验公式，如 (1) 幔源火山岩用主元素 K_2O 和 CaO 指示地壳厚度，壳源火山岩以 Sm/Yb、La/Yb 和 Ce/Y 指示地壳厚度；(2) 基于基性岩 Ce/Y 比值确定地壳厚度；(3) 基于中性岩$(La/Yb)_N$值估算地壳厚度。

虽然目前人们利用火成岩的地球化学组成可以估算出岩浆形成时的地壳厚度[76–79]，但考虑到研究区缺乏大量的基性岩以及冈底斯弧在侏罗纪时期主要处于俯冲增生时期和研究区主要出露花岗质侵入岩，因此我们主要利用 Profeta *et al.*[78]的经验公式($y = 21.277 \times \ln(1.0204 \times (La/Yb)_N)$)探讨研究区侏罗纪时期是否存在地壳增生过程。

另外，由于 Rb 在长石中是不相容的，而 Sr 是相容的，长石结晶会增加残留长英质岩浆的 Rb/Sr 比值，因此 Rb/Sr 比值的增加可以作为岩浆分异程度的指标。为了消除原始岩浆分异的影响，本文将采用 Zhu *et al.*[65]的方法对所使用的样品进行过滤，过滤方案是限制 SiO_2 含量(55%~68%)、MgO 含量(1%~6%)、Rb/Sr 比值(0.05~0.2)。通过对条件的制约，确保所利用的岩石为初始熔体，而非演化或者上地壳变沉积岩的产物。

简单的计算结果显示(图 5)，冈底斯弧南缘厚度从早侏罗世(201~174 Ma)约 39 km 增长到中侏罗世

(174~164 Ma) 43 km 再到晚侏罗世(163~145 Ma) 47 km，这表明该时期冈底斯弧处于一个逐渐加厚的过程(图 5)。以上所述以及地壳均衡作用，暗示冈底斯弧在侏罗纪时期很可能具有与环太平洋东岸安第斯弧相似的演化特征。

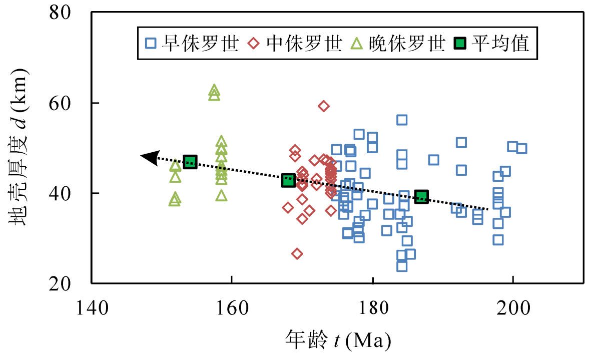

图 5 侏罗纪冈底斯弧地壳厚度变化图

Fig.5 Crustal thickness variations of the Gangdese Arc during Jurassic

深绿色方块分别为早侏罗世、中侏罗世和晚侏罗世地壳厚度平均值

The dark green squares are the average crustal thickness of early, middle, and late Jurassic

5 结 论

(1) 新特提斯洋俯冲早期，岩浆活动的高峰期是 192~168 Ma。整个冈底斯带均存在侏罗纪的岩浆侵入活动，但是西部相对缺乏相应的火山喷出作用。

(2) 随着新特提斯洋俯冲的持续进行，火成岩中的一些微量元素比值发生了明显的变化趋势。Ba/La 比值的变化表明俯冲流体的贡献以及部分熔融程度呈现出随着演化而逐渐增加的趋势; Ba/Th 比值变化表明随着俯冲的进行，俯冲流体发生以沉积物来源为主到以板片来源为主的转变。此外，Nb/Th 和 Nb/La 比值由西向东的降低趋势很可能表明东部初始弧岩浆上升过程中受到围岩的混染程度高于西部。

(3) 冈底斯弧南部在侏罗纪时期经历了一个地壳逐渐加厚的过程，即侏罗纪地壳从早期(约 39 km)变化到晚期(约 47 km)，表明冈底斯带在新特提斯洋俯冲早期发生了明显俯冲增生，这种俯冲增生过程类似于环太平洋东岸安第斯弧的增生过程。

黄思华、舒楚天和舒坦同学在撰稿过程中给予了大量帮助；两位审稿专家提供了宝贵的意见和建议；编辑对本文顺利发表做了大量工作，笔者在此一并表示衷心的感谢。

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