Early Cretaceous magmatism of the Southern Qiangtang terrane and its tectonic significance

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Abstract. The tectonic evolution of the Bangong-Nujiang Tethys is known as the most important event in the late Mesozoic in the central Qianghai-Tibet Plateau. Magmatism is a probe and window for detecting deep crust, which also records the process of tectonic evolution. The magmatic arc formed at Early Cretaceous in the Southern Qiangtang subterrane, was products of the Mesozoic magmatism during the long-term subduction of the Bangong-Nujiang Tethys oceanic lithosphere and the subsequent Qiangtang-Lhasa terrane collision. This article summarizes zircon U-Pb geochronology, major and trace elements, and Sr-Nd-Pb-Hf isotopic data for the Early Cretaceous magmatic rocks located in the southern Qiangtang subterrane of central Tibet. However, there are three hypotheses about the tectonic background of the Early Cretaceous magmatism of the South Qiangtang subterrane: (1) oceanic ridge subduction; (2) slab roll-back; (3) slab break-off.

1. Introduction
Magmatic arcs are usually formed at the boundaries of converging plates, which are the products of magmatism related to subduction. Moreover, it is a natural laboratory for studying plate tectonics, crust-mantle interaction, and crust growth of continental. The tectonic evolution of the Bangong-Nujiang Tethys is known as the most important event in the late Mesozoic in the central Qianghai-Tibet Plateau [1-3]. Although predecessors have conducted long-term studies on the Bangong-Nujiang Tethys suture, there are many different ideas on the closure of the Bangong-Nujiang Tethys. Some scholars believe that Bangong-Nujiang Tethys closure occurred before the Early Cretaceous which was caused by the unconformity contact relationship of sedimentary rocks, oceanic crust residues composed of flysch deposits, and Early Cretaceous granitic rocks. However, in recent years, more and more evidence of Early Cretaceous ophiolite and radioactive siliceous rocks, marine strata, magmatic arcs, and paleomagnetism indicate that the closure of Bangong-Nujiang Tethys was not earlier than Late Early Cretaceous. We summarize the Early Cretaceous magmatism exposed in Southern Qiangtang subterrane and discuss the evolution process of the Cretaceous in central Qinghai-Tibet Plateau.

2. Geological setting
The Qinghai-Tibet Plateau is a part of the eastern part of the Tethyan-Himalaya Tectonic belt. According to the research of geophysics, petrology, and geological structure, the Qinghai-Tibet
Plateau is generally divided into five terranes, separated by four suture zones. From north to south, they are: Kunlun terrane, Kunlun suture, Songpan-Ganzi terrane, Jinshajiang suture, Qiangtang terrane, Bangong-Nujiang suture, Lhasa terrane, India-Yarlung Zangbo suture, and Himalayan terrane.

The Bangong-Nujiang suture in the central area of the Qinghai-Tibet Plateau is a remnant of the Bangong-Nujiang Tethys. It is an important suture that divides the central part of the Qinghai-Tibet Plateau into the Lhasa terrane in the south and the Qiangtang terrane in the north.

The Qiangtang terrane is also located in the central area of the Qinghai-Tibet Plateau, bounded by the Bangong-Nujiang suture and on the south and Jinshajiang suture on the north, with a width of about 500-600 km. The Shuanghu-Longmu Co suture divides the Qiangtang terrane into the Northern Qiangtang subterrane and the Southern Qiangtang subterrane. The Shuanghu-Longmu Co suture zone mainly composed of the central uplift zone include eclogite, metasediment, metasedimentary schist, gneiss, and marble.

The northern boundary of the Lhasa terrane is the Bangong-Nujiang suture, and the southern boundary is the India-Yarlung Zangbo suture area. Previous studies suggest that the Lhasa terrane was likely to be a continental fragment split from the northern part of the Australian continent.

3. Magmatism in the Southern Qiangtang subterrane

3.1. Magmatism associated with oceanic ridge subduction

The Early Cretaceous magmatic rocks formed during the ridge subduction of the Bangong-Nujiang Tethys are mainly distributed in the western part of the magma belt (Table 1). In recent years, the presence of Duolong basalt (126 and 127 Ma), Zhaga basalt and rhyolite (112 and 117 Ma) indicates that the ridge subduction of the Bangong-Nujiang Tethys [4-5]. The Duolong basalt include Nb-enriched and high-Nb basalts. The geochemical characteristics of Th, Yb and Hf isotopes indicate that the magma source is the adakite-metasomatized mantle wedge. The Zhaga bimodal volcanic rocks (rhyolites and basalts) occur as layers within the Zhaga Formation and were generated from the partial melting of asthenospheric mantle, which is accompanied by the fractional crystallization of pyroxene, chromite, and olivine. Previous studies suggest that the generation of mafic dykes can be caused by mantle plumes and a generation of a hot spot, slab break-off, slab roll-back, delamination, post-orogenic collapse, and oceanic ridge subduction.

Based on the following points, we suggested that oceanic ridge subduction is a possible mechanism that occurred during the Early Cretaceous: (1) arc-like geochemical signatures; (2) Bangong-Nujiang Tethys ocean may have existed in the Early Cretaceous; (3) a non-linear region of magmatic arc in the southern Qiangtang subterrane.

Table 1. Magmatism associated the oceanic ridge subduction

| Number | Locality | Lithology          | Age (Ma) | Dating    | Literature |
|--------|----------|--------------------|----------|-----------|------------|
| 1      | Duolong  | Basalt             | 126-127  | Zircon U-Pb | [5]        |
| 2      | Zhaga    | Basalt and rhyolite| 112-117  | Zircon U-Pb | [6]        |

3.2. Magmatism associated with slab roll-back

Early Cretaceous magmatism related to slab roll-back was mainly emplaced at the central and western parts of the Southern Qiangtang subterrane (Table 2). Moreover, the magmatism related to slab roll-back mainly includes Bizha, Rena co, Maierze, Xiabieco, Mudijiangya and Geize volcanic rocks [6-12]. Zircon U-Pb dating data of these magmatism shows that the age is 106-123 Ma, belonging to the late Early Cretaceous. Major element geochemical data show that the SiO₂ content of the magmatism has a large variation range, and the lithology including basalt, andesite, dacite, rhyolite, granodiorite,
and granite. Based on the trace and major element, Sr-Nd-Pb-Hf isotopic characteristics of the Early Cretaceous magmatism related to slab roll-back, different magma source have been proposed: (1) partial melting of newly underplated basaltic crust; (2) partial melting of mélange rocks; (3) enriched lithospheric mantle area contaminated by melts or fluids; (4) partial melting of high- to medium-K$_2$O basalts in the lower to middle crust; (5) liquids fractionated from the mush chamber via crystal-liquid separation; (6) magma mingling/mixing of interstitial and crystals melt; (7) mingling/mixing of diverse crust-derived magmas; (8) mixing of crustal material and mantle-derived components; (9) slab melt-metasomatized mantle wedge; (10) mantle-slab interaction.

Table 2. Magmatism associated with slab roll-back

| Number | Locality | Lithology                | Age (Ma) | Dating | Literature |
|--------|----------|--------------------------|----------|--------|------------|
| 1      | Bizha    | Diorite                  | 121-123  |        | [8]        |
| 2      | Rena     | Granodiorite porphyry    | 112      |        | [7]        |
| 3      | Maierze  | Bimodal volcanic rock    | 120-122  |        | [4]        |
| 4      | Xiabieco | Granite                  | 120      |        | [10]       |
| 5      | Mudijiangya | Rhyolite              | 114      | Zircon U-Pb | [1]    |
| 6      | Geize    | Granodiorite; Andesite   | 107-112  |        | [12]       |
| 7      | Geize    | Basalt, andesite, dacite, rhyolite | 106-108 |        | [9]        |
| 8      | Xiabieco | Granite porphyry         | 107      |        | [11]       |

According to the previous research results, it indicated that there was a late Early Cretaceous magmatic burst occurred at the Southern Qiangtang subterrane. During the evolution of ocean-continent subduction, the subducted slab roll-back usually occurs after low-angle or flat-slab subduction, which will cause subsequent magmatic flare-up. An obviously 125-145 Ma magmatic lull in Southern Qiangtang subterrane caused by flat-slab or low-angle subduction. Thus, the best explanation for the flare-up of magmatism in the Southern Qiangtang subterrane and the subsequent underplating of basaltic magma is the slab roll-back of the northward subducted Bangong-Nujiang Tethys ocean. Summarized as follows, the slab roll-back caused the rising of asthenospheric magma, which provided a lot of heat and material for the magmatic source. In summary, based on evidence from sedimentology, petrology, and geochemistry, we believe that the slab roll-back is a possible mechanism that occurred during the evolution of the Bangong-Nujiang Tethys ocean in the late Early Cretaceous (123-106 Ma).

3.3. Magmatism associated with slab break-off
Based on previous studies, the Early Cretaceous magmatism related to slab break-off was mainly emplaced in the central and western parts of the Southern Qiangtang subterrane (Table 3). Research suggests that the mafic dikes, rhyolites, Gaize bimodal volcanic rocks (basalt and rhyolite) and...
granites in the Muku area are probably related to the slab break-off of the northern subduction of Bangong-Nujiang Tethys (Table 3).

There is increasing evidence that as the ocean finally closes, the subducting/subducted oceanic slab break-off after or during collision. The break-off of the slab caused rising of the deep asthenosphere mantle, causing decompression melting of the mantle, and crustal anatexis caused by the mantle-derived melt. The following facts also support this geodynamic interpretation of the Early Cretaceous magmatism: (1) the eruption of the Early Cretaceous magmatic rocks and the Lhasa-Qiangtang terrane collision are almost at the same period; (2) A large number of recent studies have shown that the lithosphere of Bangong–Nujiang Tethys ocean experienced continuous northward subduction; (3) the magmatic rocks were generated from remelting of the ancient crust and mixed with part of the asthenosphere material, which is like what is predicted by the slab break-off model.

Table 3. Magmatism associated the slab break-off

| Number | Locality | Lithology                  | Age (Ma) | Dating | Literature |
|--------|----------|----------------------------|----------|--------|------------|
| 1      | Gaize    | Mafic dikes                | 126-127  |        | [13]       |
| 2      | Gaize    | Rhyolite                   | 110-111  | Zircon U-Pb | [14]       |
| 3      | Gaize    | Bimodal volcanic rocks     | 108-113  |        | [15]       |
| 4      | Muku     | Granite                    | 100      |        | [16]       |

Based on the above facts and combined with the evidence from sedimentology, petrology, and geochemistry, a tectonic model for the formation of Early Cretaceous magmatism (126-100 Ma) can be summarized as follows. Before the Qiangtang-Lhasa collision, the lithosphere of Bangong–Nujiang Tethys ocean subducted northward under the Qiangtang terrane. With the continuous subduction, under the influence of slab gravity and other factors, the subducting slab broke-off. The slab break-off of the Bangong-Nujiang Tethys caused the upwelling of the asthenospheric magma, resulting in the Early Cretaceous magmatism in the Southern Qiangtang terrane.

4. Conclusion

There is an Early Cretaceous magmatic arc extending east-west over 2000 km in the southern Qiangtang terrane. Sedimentology, petrology, and geochemistry suggest that the northward subduction of the Bangong-Nujiang Tethys ocean. The tectonic mechanism of Early Cretaceous magmatism was probably related to the ridge subduction, slab roll-back or slab break-off of the Bangong-Nujiang Tethys ocean.

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