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Spatial and Temporal Changes of the Mesozoic-early Tertiary Magmatism in the Lhasa Terrane: Implications for Geodynamical Setting and Continental Growth

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The making of the Tibetan Plateau with double normal crustal thickness witnessed the formation of continental crust as a result of the subduction of Tethyan Oceans and the collisions of several Gondwana-derived terranes (e.g., Qiangtang, Amdo, and Lhasa) or continents (e.g., India) with Eurasia since the Paleozoic. However, how and when the Tibetan crust was formed is debatable. A comprehensive understanding for the specific mechanism and precise timing of the growth of the Tibetan crust awaits multidisciplinary joint investigations, especially from magmatic petrology, geochronology, and geochemistry. This is because the growth of continental crust is best recorded by continental margin and collisional zone magmatism that is the direct response to deep tectonic and chemical processes in time and space operating at subduction and collisional settings. To unravel the spatial and temporal changes of the Mesozoic-early Tertiary magmatism and to explore the history of crustal growth of the Lhasa Terrane in terms of magmatic perspective, we synthesize the zircon U-Pb geochronological and Hf isotope data published in the literature and unpublished data in our dataset from the Lhasa Terrane (excluding the Amdo microcontinent). Several important observations and favored interpretations are summarized below.

(1) The Late Triassic–Middle Jurassic magmatism (215–160 Ma) is found not only in the southern Lhasa subterrane (i.e. the Gangdese Batholith) but also in the central Lhasa subterrane, a magmatic belt of ca. 190 Ma is likely present along the both sides of the Shiquan River–Nam Tso Mélange Zone (SNMZ), implying that the back-arc basin represented by the SNMZ may have not opened until the Early Jurassic. The Late Jurassic magmatism (154–140 Ma) is minor and is currently found to be

confined to the central Lhasa subterrane, indicating that the magmatism may have migrated northward from Middle Jurassic (174–160 Ma) to Late Jurassic (154–140 Ma). Such younging magmatism from south to north is tentatively attributed to the southward subduction and subsequent rollback of the Bangong–Nujiang Tethyan Ocean lithosphere rather than to the northward subduction of the Yarlung–Zangbo Tethyan Ocean because the southern margin of the narrow central Lhasa subterrane (probably < 300 km wide) had only just formed as a passive margin at that time.

(2) The very Early Cretaceous magmatism (137–127 Ma) is scattered in the Lhasa Terrane, while the late Early Cretaceous magmatism (125–103 Ma) is extensive, forming a zonal magmatic flare-up at 113 ± 5 Ma along the strike of the central and northern Lhasa subterrane. The sporadic occurrence of the Early Cretaceous magmatic rocks and the abundant detrital zircons exhumed from the currently missing coeval Gangdese arc (130–100 Ma) are indicative of the northward subduction of the Yarlung–Zangbo Tethyan Ocean lithosphere. Considering the restoration width (> 600 km) of the Lhasa Terrane during the Early Cretaceous, the presence of calc-alkaline volcanic rocks (135–116 Ma) and the positive zircon $e_{\text{Hf}}(t)$ values documented in the northern Lhasa subterrane, indicate that the Early Cretaceous magmatism in the central and northern Lhasa subterrane is most likely associated with the southward subduction and subsequent slab breakoff of the Bangong–Nujiang Tethyan Ocean lithosphere and can not be attributed to the low-angle northward subduction of the Yarlung–Zangbo Tethyan Ocean lithosphere.

(3) The early Late Cretaceous magmatism (100–80) is extensive in the southern margin of the southern Lhasa subterrane. It can be interpreted to be associated with the

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ridge subduction of the Yarlung-Zangbo Tethyan Ocean to provide the high heat and material flux required for the generation of voluminous magmatism. Abundant geochronological data indicate the presence of the very Late Cretaceous magmatism (80-65 Ma) that is previously considered to be lacking in the southern and central Lhasa subterrane. The northward migration of magmatism from 100-80 Ma to 80-65 Ma is consistent with the normal progressive northward subduction rather than the slab rollback of the Yarlung-Zangbo Tethyan Ocean lithosphere. Growing geochronological data reveal the presence of magmatism of ca. 90 Ma along the strike of the northern Lhasa subterrane. Its emplacement postdates the development of a regional angular unconformity between an Upper Cretaceous molasse deposit and its underlying strata and the proposed lithospheric stacking or crustal thickening occurred in the northern Lhasa subterrane. It can thus be interpreted as a result of lithospheric delamination-induced deep processes beneath the northern Lhasa subterrane after the Lhasa-Qiangtang collision.

(4) The very early Tertiary magmatism (65-56 Ma) inherits the spatial distribution of the 80-65 Ma magmatism, while the 56-46 Ma and 46-37 Ma magmatism migrates southward. The late stage magmatism (46-37 Ma) is mainly confined to the southern margin of the southern Lhasa subterrane. Such spatial variation is consistent with the slab rollback (65-56 Ma) and subsequent slab breakoff (ca. 52 Ma) of the Yarlung-Zangbo Tethyan Ocean lithosphere.

(5) The Lhasa Terrane experienced multiphase crustal growth since the Mesozoic as documented by the mafic enclave-host granitoid pairs that emplaced at ca. 200-195 Ma, 112 Ma, 84 Ma, 70 Ma, 50 Ma, and 38 Ma, respectively. The voluminous magmatism with strong inputs of mantle-derived materials manifests the significant net growth of the Lhasa crust at ca. 113 Ma, 90 Ma, and 52 Ma. It is suggested that slab window-related deep processes are the primary mechanism that led to the net crustal growth in continental margin (e.g., ridge window) and collisional zone (e.g., slab breakoff window).