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Late Triassic island-arc–back-arc basin development along the Bangong–Nujiang suture zone (central Tibet): Geological, geochemical and chronological evidence from volcanic rocks

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ABSTRACT

A major debate related to the evolution of the Tibetan Plateau is centered on whether or not an island arc–back-arc basin system occurred along the Bangong–Nujiang suture zone, central Tibet. Here we present new zircon U–Pb geochronology, rare earth elements (REEs) and bulk-rock geochemistry of these magmatic rocks in the Amdo area, the middle Bangong–Nujiang suture zone, central Tibet, to identify significant and new records of Mesozoic tectonomagmatic processes. Zircon U–Pb dating using LA-ICP-MS techniques yields a concordant age with a weighted mean $^{206}Pb/^{238}U$ age of 228.6 ± 1.6 Ma (n = 7, MSWD = 1.19) for the Quehala basalts, and a mean age of 220.0 ± 2.1 (n = 8, MSWD = 1.5) for the Amdo pillow lavas. On the normalized REE patterns of zircon, significant Ce enrichment indicates that the magma sources of these magmatic rocks have been subjected to modification of slab-derived fluid. Geochemical features suggest that the Quehala basalts (ca. 228 Ma), displaying an island arc tholeiites (IATs) affinity, resulted from partial melting of an relatively enriched mantle wedge in the subduction zone, whereas the Amdo pillow lavas (ca. 220 Ma) characterized by both arc-like and N-MORB-like geochemical characteristics occurred as associated back-arc basin basalts (BABBs) at the spreading center of back-arc basin after the formation of island arc tholeiites. In conclusion, the volcanic rocks in the Amdo area have documented the magmatic processes from early-stage subduction to development of associated back-arc basin, confirming the occurrence of intra-oceanic subduction within the Bangong–Nujiang Tethys during the late Triassic. Furthermore, the spatial relationships among the Quehala formation, Tumengela formation and Amdo pillow lavas indicate likely northward subduction of the Bangong–Nujiang Tethyan Ocean during the Late Triassic to middle Jurassic.

1. Introduction

Arc–back-arc basin system has been extensively studied during the last several years because such a system is closely associated with mantle heterogeneity, melting dynamics, and back-arc extension (e.g., Escuder-Viruete et al., 2010; Ewart et al., 1998; Gribble et al., 1996, 1998; Pearce and Stern, 2006; Shinjo et al., 1999). Two types of plate convergence, namely ocean–ocean subduction (Mariana-type) and ocean–continent subduction (Chile-type), form intraoceanic island arc–back-arc basin and continental arc–back-arc basin, respectively. Classic examples of modern island arc–back-arc basin include the Mariana arc–Mariana Trough (e.g., Gribble et al., 1996, 1998; Marske et al., 2011), the Tonga Arc–Lau Basin (e.g., Caulfield et al., 2012; Ewart et al., 1998), and Caribbean island arc–back-arc system (e.g., Escuder-Viruete et al., 2010; Jolly et al., 2001). A typical example of modern continental arc–back-arc basin is the Ryukyu arc–Okinawa Trough (e.g., Shinjo et al., 1999).

The geological and geochemical information about the process of the tectonic cycle from initial subduction to late-stage back-arc extension is recorded in the spatially and temporally associated igneous rocks. In addition, the two systems have significantly different tectonomagmatic evolution processes and systematic compositional variations between different subduction systems and within individual subduction zones (from arc volcanic rocks to corresponding back-arc basin basalts (BABBs)) (e.g., Pearce et al., 2005; Shinjo et al., 1999). Therefore, systematic investigations of subduction-related volcanic rocks are fundamental for understanding convergent-margin processes. Furthermore, by

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comparison with modern typical arc–back-arc basin system magmatism, we can probe magma petrogenesis and paleotectonic reconstruction of an extinct paleo-ocean.

The Bangong–Nujiang suture zone in the central Tibet, is an ideal place for investigating and understanding pre-Cenozoic tectonic evolution of the Tibetan Plateau, due to the widespread presence of Mesozoic ophiolites and magmatic rocks along the Bangong–Nujiang suture zone, separating the Qiangtang terrane to the north and the Lhasa terrane to the south (e.g., Girardeau et al., 1984; Guynn et al., 2006; Kapp et al., 2003, 2005; Pearce and Deng, 1988; Shi, 2007 a; Shi, 2007 a, 2008, 2012a, 2012b; Yin and Harrison, 2000). SSZ and MOR ophiolitic suites, boninitic volcanic rocks, oceanic island basalts, and granitoid intrusions have been identified in the Bangong–Nujiang suture zone (e.g., Guynn et al., 2006, 2012; Liu et al., 2014; Pearce and Deng, 1988; Shi, 2007 a; Shi et al., 2004, 2007, 2008, 2012a, 2012b; Wang et al., 2008; Zhang and Yang, 1985; Zhang et al., 2008; Zhou et al., 1998). The geological and geochemical investigations have greatly enhanced our knowledge of tectonomagmatic evolution of the Bangong–Nujiang Tethys.

It's widely accepted that boninitic magmatism has been spatially and temporally restricted to forearc regions in the ocean–ocean convergence setting during the early stage of arc development (e.g., Bloomer and Hawkins, 1987; Taylor and Nesbitt, 1995; Whattam and Stern, 2011). The outcrops of boninitic series volcanics in the Bangong Lake and Dingqing areas strongly indicate occurrence of ocean–ocean subduction in the Bangong–Nujiang Tethys (e.g., Shi et al., 2004, 2008; Zhang and Yang, 1985; Zhang et al., 2008). This interpretation is consistent with the presence of the peak high-pressure metamorphism (ca. 190 Ma, 860–920 °C, 1.46–1.56 GPa) and subsequent amphibolite-facies retrogression (ca. 181 Ma, 550–670 °C, 0.52–0.65 GPa) recorded in the high-pressure (HP) mafic granulites in the Amdo area (Zhang et al., 2014). However, island arc tholeiites, commonly thought to be generated in the intra-ocean setting, have not been discovered along the Bangong–Nujiang suture zone.

Here, we report the results of research on volcanic rocks recently sampled in the Amdo area, central Tibet. It has long been known that ophiolite and granite are well exposed in the Amdo terrane or both sides of the terrane (e.g., Allègre et al., 1984; Coward et al., 1988; Guynn et al., 2006, 2012, 2013; Shi et al., 2012a). However, the information about the Bangong–Nujiang Tethys evolution inferred from the investigations of ophiolite and granite is relatively limited. To complement the spectrum of magmatism, we systematically investigate the Mesozoic volcanic rocks in the Amdo area. In this contribution, we report newly discovered island arc tholeiites from the Late Triassic Quehala Formation along the Bangong–Nujiang suture zone, and present detailed zircon U–Pb geochronology, rare earth elements and bulk chemistry of these island arc tholeiites. In addition, we also collected the Amdo pillow lavas from the upper part of the Amdo ophiolite, representing associated back-arc basin magmatism. These new data allow us to provide new insights into paleotectonic reconstruction of island-arc–back-arc basin system and associated magma petrogenesis during the Bangong–Nujiang Tethys evolution during the Mesozoic.

2. Regional tectonic setting and Sample

The Bangong–Nujiang suture zone (BNSZ) can be subdivided into the western (Bangong Lake-Gaize), the middle (Dongqiao-Amdo), and the eastern (Dingqing–Nujiang) sectors (e.g., Dewey et al., 1988; Yin and Harrison, 2000). The discontinuous ophiolites within the Bangong–Nujiang suture zone mainly occur in the Bangong Lake, Gerze, Dongqiao, Amdo and Dingqing, and most of the ophiolitic units along the BNSZ are formed above a supra-subduction zone and their formation age and emplacement age are considered to be the Late Triassic to Middle Jurassic (e.g., Pearce and Deng, 1988; Shi et al., 2012a; Wang et al., 2008). This character indicates that these ophiolites may represent the remnants of oceanic lithosphere in different tectonic settings such as surpra-subduction zone (SSZ) and mid-ocean ridge (MOR) environments (Girardeau et al., 1984; Lai and Liu, 2003; Pearce and Deng, 1988; Shi et al., 2004, 2008; Wang et al., 2008; Zhou et al., 1998). Particularly, ophiolitic components with boninite signature have been found along the BNSZ such as Dongqiao, Dingqing, and Bangong Lake (Pearce and Deng, 1988; Shi, 2007 a; Shi et al., 2004, 2008; Zhang and Yang, 1985; Zhang et al., 2008), suggesting the presence of intra-oceanic subduction within the Bangong–Nujiang Tethys. In the case of the Amdo ophiolite, Pearce and Deng (1988) proposed that the Amdo ophiolite formed in a supra-subduction zone environment. Recently, the formation of Amdo ophiolite was considered to be associated with back-arc basin tectonic setting (Lai and Liu, 2003), however, the nature of back-arc basin (intraoceanic island arc–back-arc basin vs. continental arc–back-arc basin) also remains unclear.

The middle (Dongqiao–Amdo) suture zone is characterized by preservation of the Amdo terrane, consisting mainly of foliated gneisses, massive granitoid intrusions, metasedimentary rocks and surrounding sedimentary rocks (e.g., Coward et al., 1988; Guynn et al., 2006, 2012; Xu et al., 1985). The Amdo terrane is situated on the suture between the Lhasa terrane to the south and the Qiangtang terrane to the north. Previous investigations have suggested that the Amdo terrane was an isolated microcontinent during the Permian–Triassic and subjected to northward subduction in the Early Jurassic (e.g., Coward et al., 1988; Zhang et al., 2014), indicating that the middle Bangong–Nujiang Tethys has been subjected to different geological evolution during the Mesozoic.

The Amdo ophiolite and Nagqu ophiolite, cropping out along both sides of the Amdo terrane, are considered to be derived from the Bangong–Nujiang suture zone (e.g., Coward et al., 1988; Pearce and Deng, 1988; Xu et al., 1985). The Amdo ophiolite is mainly composed of pillow lava, cherts, metamorphic peridotite, gabbro, and plagiogranite and is unconformably overlain by early Cretaceous Jurassic Sewa Formation. The Amdo ophiolite occurs along the northern margin of Amdo terrane, and zircons from its plagiogranite yield a SHRIMP U–Pb age of 175.1 ± 5.1 Ma (BGTAR, 2005). The Nagqu ophiolite crops out in the southern margin and zircons from its gabbro yields a SHRIMP U–Pb age of 183.7 ± 1 Ma (Huang et al., 2013). Both ophiolitic slivers are in systematic tectonic contact with each other and the surrounding rocks.

The late-Triassic materials in the Amdo area is mainly composed of the Quehala Formation to the south and the Tumengela Formation to the north, separated by a suture zone which consists of the early–middle Jurassic limestone, mudstone, siltstone and quartz sandstone (Fig. 1b; BGTAR, 2005). Spatially, the Quehala meta-volcanic rocks and the Amdo pillow lavas are located to the south of the suture zone (Fig. 2a). On the other hand, in comparison with the northern Tumengela Formation, the Quehala Formation is characterized by the presence of calcic slate and sandy slate (Fig. 2b). The Jurassic strata are significantly characterized by an anticline in the fold belt, with old J_{1-2} Sewa Formation in the core and relatively young J_2j Jiebuqu Formation strata in the flanks of the anticlinal structure (Fig. 2a; BGTAR, 2005). It's noteworthy that these spatial relationships are a key to understanding arc–back-arc basin system within the Bangong–Nujiang Tethys.

The Amdo ophiolite is overlain by the Jurassic Sewa Formation, which is predominantly composed of terrigenous clastic rocks and minor marine sedimentary (BGTAR, 2005). Geographically, the exceptionally well-preserved pillow lavas occurring as the upper part of the Amdo ophiolite mainly crop out near Amdo bridge in the southeast part of the Amdo Country, with thickness up to approximately 300 m. The lavas display typical pillow structure, with the size of pillows highly variable from centimeters to ~2 m across and the chilled glassy rims 1–2 cm thick, indicating subaqueous eruptive environment (Lai and Liu, 2003). The Quehala Formation represents a late-Triassic meta-volcanic and metasedimentary sequence and mainly consists of calcic slates, sandy slates, interbedded meta-volcanic rocks and crystalline limestone, exhibiting flysch facies sedimentary characteristics (Fig. 2b–c; BGTAR, 2005). The location of newfound meta-volcanic rocks in this study