Lithos 308–309 (2018) 53–64

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Syn-collisional felsic magmatism and continental crust growth: A case study from the North Qilian Orogenic Belt at the northern margin of the Tibetan Plateau

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ARTICLE INFO

Article history:
Received 17 November 2017
Accepted 5 March 2018
Available online 06 March 2018

Keywords:
Mafic magmatic enclaves
Cumulate
Amphibole
Syn-collisional granodiorite
Crust growth

ABSTRACT

The abundant *syn*-collisional granitoids produced and preserved at the northern Tibetan Plateau margin provide a prime case for studying the felsic magmatism as well as continental crust growth in response to continental collision. Here we present the results from a systematic study of the *syn*-collisional granitoids and their mafic magmatic enclaves (MMEs) in the Laohushan (LHS) and Machangshan (MCS) plutons from the North Qilian Orogenic Belt (NQOB). Two types of MMEs from the LHS pluton exhibit identical crystallization age (~430 Ma) and bulk-rock isotopic compositions to their host granitoids, indicating their genetic link. The phase equilibrium constraints and pressure estimates for amphiboles from the LHS pluton together with the whole rock data suggest that the two types of MMEs represent two evolution products of the same hydrous andesitic magmas. In combination with the data on NQOB *syn*-collisional granitoids elsewhere, we suggest that the syn-collisional granitoids in the NQOB are material evidence of melting of ocean crust and sediment. The remarkable compositional similarity between the LHS granitoids and the model bulk continental crust in terms of major elements, trace elements, and some key element ratios indicates that the *syn*-collisional magmatism in the NQOB contributes to net continental crust growth, and that the way of continental crust growth in the Phanerozoic through syn-collisional felsic magmatism (production and preservation) is a straightforward process without the need of petrologically and physically complex processes.

1. Introduction

While the composition of continental crust (CC) has been well established, its origin and way of growth remain enigmatic (Niu et al., 2013). The first-order complementarity between CC and oceanic crust (OC) in terms of incompatible element abundances has been interpreted as the former being extracted from the primitive mantle with the residual depleted mantle as the source of the present-day ocean crust (Hofmann, 1988). Recognizing the similarity between andesite volcanism that occurs at convergent margins and the andesitic bulk CC (BCC) with "arc-like" trace element patterns, Taylor (1967, 1977) proposed that CC growth resulted from subduction zone magmatism, namely the well-known "island-arc model". Subsequent studies, however, have shown that arc crust (AC) is basaltic in bulk composition (Gill, 1981; Rudnick, 1995), and is too mafic for BCC. This marked difference in major element composition between the andesitic BCC and basaltic arc crust has thus been puzzling (Castro et al., 2013; Niu et al., 2013). To resolve this puzzle, several modified versions of island-arc model have been proposed, including (1) delamination of the more mafic deep portions of AC (Kay and Kay, 1993; Lee et al., 2007; Rudnick, 1995); (2) re-lamination of subducted materials in arcs (Hacker et al., 2011); (3) assimilation or mixing between earlier formed felsic rocks (derived from subducted slabs) and mantle-derived mafic magmas (Kelemen, 1995). While these remedies are interesting, problems persist (see review by Niu et al., 2013). For instance, delamination of mafic garnet pyroxenite cumulate ("arclogite"), which needs the formation of garnet to generate favorable density (Lee et al., 2007; Lee and Anderson, 2015), would inevitably result in the arc melts with the "garnet signature" (depleted in heavy rare elements), but the latter

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https://doi.org/10.1016/j.lithos.2018.03.001
0024-4937/© 2018 Published by Elsevier B.V.

is not compatible with the BCC composition (see Niu, 2015). Also, many studies have shown that there is no net crustal growth at neither island arc nor continental arc settings (Niu and O'Hara, 2009) because AC production and destruction are globally mass balanced (Clift et al., 2009; Scholl and von Huene, 2007). In addition, seafloor spreading/subduction is globally continuous (Condie, 2000), and the "island-arc model" thus cannot account for the episodic CC growth. With all these arc-model difficulties considered and on the basis of their studies on the India-Asia *syn*-collisional (~55 Ma) andesitic rocks in southern Tibet, Niu and co-authors proposed the hypothesis that "collision zones are primary sites of net continental crustal growth" (Mo et al., 2008; Niu et al., 2013; Niu and O'Hara, 2009).

The continental collision zone hypothesis can be effectively tested because abundant *syn*-collisional granitoids (and the volcanic counterparts) are well preserved in continental collision zones on the Tibetan Plateau and along the adjacent orogenic belts, which have been shown to record messages on *syn*-collisional felsic magmatism and CC growth (Chen et al., 2015, 2016; Huang et al., 2014; Mo et al., 2008; Niu et al., 2013; Shao et al., 2017; Zhang et al., 2016). As part of a systematic study of the Early Paleozoic syn-collisional magmatism in the North Qilian Orogenic Belt (NQOB) at the northern Tibetan Plateau margin (Fig. 1a), we present here the results of a comprehensive study of the syn-collisional granitoids and their enclosed mafic magmatic enclaves (MMEs) from the Laohushan (LHS) and Machangshan (MCS) plutons (Fig. 1b). These new data, together with data in the recent literature on syn-collisional granitoids from the NQOB, are used to illustrate (1) the cumulate origin of MMEs, (2) the source of the syn-collisional magmatism, and (3) the mechanisms of CC growth in response to continental collision.

2. Geology and samples

The Qilian orogenic belt (QOB) consists of four nearly NW-SE trending subparallel tectonic units, from north to south, they are: (1) the north Qilian orogenic belt (NQOB), (2) the Qilian Block (QB), (3) the North Qaidam ultrahigh-pressure metamorphic (NQ-UHPM) belt, and (4) the Qaidam Block (QDB) (Song et al., 2013 and references therein).

The NQOB, extending NW-SE, is separated from the northeastern Alxa Block and the southwestern QB, and from the northwestern Altyn-Tagh Fault (Fig. 1a). It represents a typical Early Paleozoic oceanic suture zone, mainly consisting of subduction complexes (Fig. 1a) (Song et al., 2007, 2013; Zhang et al., 2007). Two ophiolite sequences are distributed along the NQOB (Fig. 1a), (i) the southern ophiolite belt, which consists of ultramafic cumulate, peridotite and pillow basalts, represents the oceanic crust formed at an ocean ridge setting (Hou et al., 2006), and (ii) the northern ophiolite belt, which was suggested to generate from a back-arc spreading center (Xia et al., 2003; Xia and Song, 2010).

The QB dominantly consists of Precambrian metamorphic basement, Early Paleozoic intrusive rocks, and Paleozoic to Mesozoic sedimentary sequences (Feng and He, 1996). In the eastern part of the QB, some S-type granitoids (454–445 Ma) (Chen et al., 2008; Huang et al., 2015) and adakitic granitoids (459–440 Ma) (Yang et al., 2015, 2016) have been reported and several different geodynamic processes have been proposed for the origin of these ~450 Ma granitoids, including a *syn*-collisional setting related to continental collision (Huang et al., 2015), a post-collisional setting resulted from delamination of thickened crust (Chen et al., 2008) or slab break-off (Yang et al., 2015, 2016). Although the exact nature of the QB and the origin of Early Paleozoic intrusive rocks in QB remains debatable, it is notable that our study is focus on the plutons from the NQOB, rather than on the QB. It is thus not comparable in terms of the tectonic background.

The North Qaidam UHPM Belt is dominated by granitic and pelitic gneisses with eclogite lenses. The Qaidam Block has a Precambrian meta-crystalline basement overlain by the Paleozoic-Mesozoic sedimentary strata (Song et al., 2013).

Different models have been proposed to explain the tectonic evolution in the whole QOB. The most recent comprehensive studies suggest that the NQOB, QB and NQ-UHPM are different products corresponding to one convergence event, during which the subduction was initiated at ~520 Ma, the ocean basin was closed at 440 Ma, exhumation happened

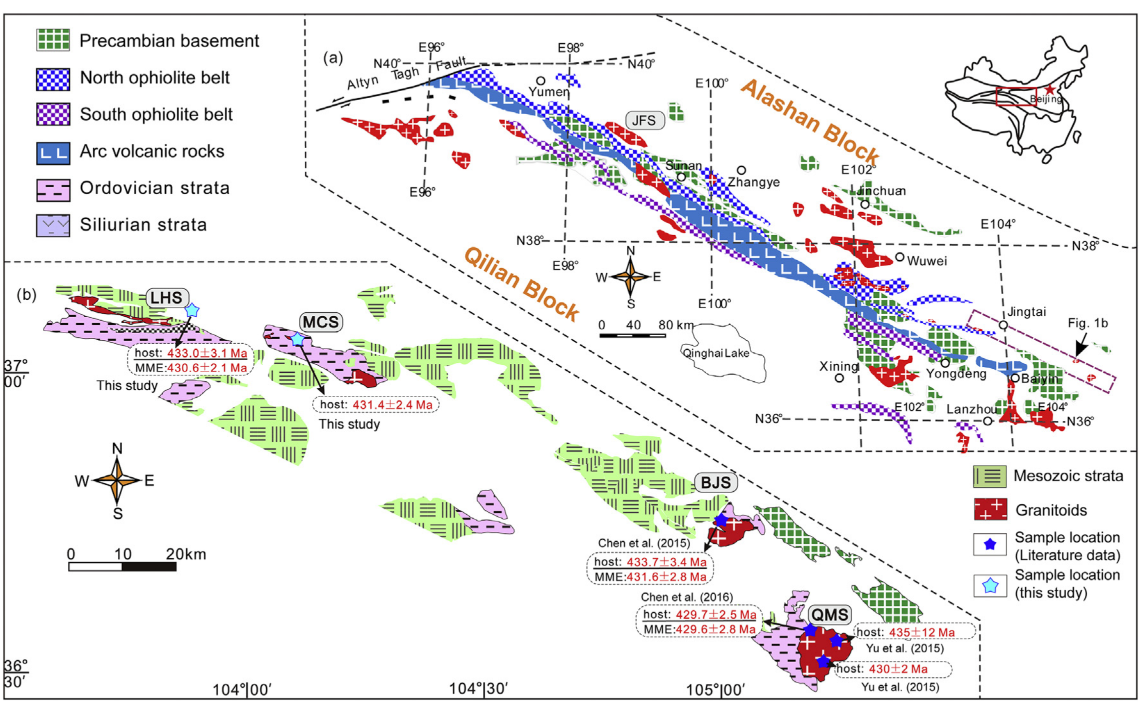

Fig. 1. (a) Simplified geological map of the North Qilian Orogenic Belt (NQOB) showing the main tectonic units (modified after Chen et al., 2016). (b) Simplified map of the Qumushan (QMS), Baojishan (BJS), Machangshan (MCS) and Laohushan (LHS) plutons in the eastern section of the NQOB. U—Pb ages for the *syn*-collisional granodiorite and enclosed MMEs are from Chen et al. (2015, 2016), Yu et al. (2015) and this study as indicated.