Gondwana Research 21 (2012) 167–179

Contents lists available at ScienceDirect

Gondwana Research

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

# Geochemistry and zircon U–Pb ages of adakitic rocks from the Dulan area of the North Qaidam UHP terrane, north Tibet: Constraints on the timing and nature of regional tectonothermal events associated with collisional orogeny

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A R T I C L E I N F O

*Article history:*
Received 31 January 2011
Received in revised form 30 June 2011
Accepted 21 July 2011
Available online 7 August 2011

*Keywords:*
North Qaidam Mountains
Adakitic rock
Geochemistry
Zircon geochronology
Leucosome
Tonalite
Tectonothermal event

A B S T R A C T

Geochemistry and U–Pb ages of leucosomes and tonalites in a high pressure granulite unit of the Dulan area have been determined to constrain the tectonothermal evolution related to collision and thickening of lower crust in the North Qaidam Mountains (NQD). Leucosomes and tonalites show a marked chemical resemblance to adakites: (1) high La/Yb and Sr/Y, and low Y and HREE; (2) high $Al_2O_3$ and low $Mg^{\#}$ values with obvious positive Eu anomalies; and (3) slightly positive $\varepsilon_{Nd}(t)$ values. Zircon U–Pb analysis of leucosomes and tonalites yielded $^{206}Pb/^{238}U$ ages of 428–437 Ma and 436–437 Ma respectively, which constrain the emplacement ages of the adakitic rocks. Petrological, geochronological and geochemical characters indicate that the adakitic rocks may have been derived from partial melting of a thickened mafic lower crust (>50 km), suggesting a dominating source regime of synchronous high-pressure mafic granulites. Contemporary magmatism in other units of the NQD shows evidence of a widespread tectonothermal event during early Silurian (420–450 Ma) that includes metamorphism, magmatism and anatexis related to collision and thickening of lower crust.



## 1. Introduction

Adakite, characterized by intermediate $SiO_2$ (>56%), elevated $Al_2O_3$ (>15%), Sr/Y (>40), and La/Yb (>20), and low Y (<18 ppm) and Yb (<1.9 ppm), was originally defined as granitoid magma in convergent plate margins formed by partial melting of subducted young (<25 Ma), hot and hydrated oceanic slab (Defant and Drummond, 1990; Martin, 1999,2005). Recent studies suggest that adakitic magmas can also form in a variety of non-subduction-related tectonic settings through different petrogenetic processes including: (1) partial melting of thickened lower crust (Chung et al., 2003; Wang et al., 2005; Wen et al., 2008; Tseng et al., 2009); (2) assimilation and fractional crystallization processes involving basaltic magma (Feeley and Hacker, 1995; Castillo et al., 1999); (3) partial melting of delaminated lower crust (Xu et al., 2002; Gao et al., 2004; Wang et al., 2006a,b); and (4) partial melting of hydrous garnet peridotite (Stern and Killian, 1996). The various origins for adakites provide important constraints on crustal growth and evolution throughout the Earth's history.

However, most of the evidence supporting formation of adakitic rocks has come from high-level adakitic volcanic and plutonic rocks (e.g., Chung et al., 2003; Xu et al., 2007), and from experimental studies (e.g., Şen and Dunn, 1994), which are further complicated because our understanding of the abundance and distribution of many trace elements during high-pressure (HP) partial melting remains poor (Bea et al., 1994; Stevenson et al., 2005). Direct evidence is lacking, and only a few direct observations on the formation of adakitic rocks were reported in Fiordland, New Zealand (Stevenson et al., 2005) and Kohistan arc, northern Pakistan (Garrido et al., 2006). In this contribution, we provide direct evidence for the generation of adakitic rocks in a deeply exposed, thickened lower crustal section in the Dulan area, which forms part of the north Qaidam (NQD) HP and ultrahigh-pressure (UHP) metamorphic terrane (Yang and Deng, 1994; Yang et al., 1998; Zhang et al., 2001; Yang et al., 2001, 2002; Song et al., 2003, 2004, 2005; Zhang et al., 2005a,b; Mattinson et al., 2006a,b; Song et al., 2006; Yang et al., 2006; Zhang et al., 2006; Mattinson et al., 2007; Song et al., 2007; Zhang et al., 2007a; Yang and Powell, 2008; Zhang et al., 2008a,b, 2009a,b,c, 2010b). We present petrological, geochemical, isotopic and geochronological data of leucosome and tonalite with an adakitic signature and discuss the origin of these adakitic rocks and their relationship to the crustal evolution in a collisional orogen.

## 2. Geological setting and field relationships

The northwest–southeast trending NQD, located at the northern margin of Qinghai–Tibet Plateau, extend over a distance of 350 km

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doi:10.1016/j.gr.2011.07.024

and are bounded by the Qaidam basin to the southwest, the Altyn Tagh fault to the northwest and the Qilian block to the northeast (Fig. 1a). The basement of the NQD is the Proterozoic Dakendaban group, composed mainly of paragneiss and orthogneiss, rare marble, granulite, amphibolite, locally eclogite and various ultramafic rocks. They are in depositional contact (locally faulted) with the overlying lower Paleozoic volcanic and sedimentary rocks of the Tanjianshan Group, and are intruded by granite plutons (Fig. 1b). Based on rock associations, petrologic criteria, and field relationships, four HP/UHP metamorphic units could be distinguished along the NQD from east to west (Zhang et al., 2008a): (1) the Dulan eclogite-gneiss unit (DLU), which consists of granitic gneiss, paragneiss, eclogite and ultramafic rock lenses enclosed within gneiss; (2) the Xitieshan eclogite-gneiss unit (XTU), dominated by kyanite-bearing paragneiss (schist) and granitic orthogneiss with rare marble and amphibolite and intruded by granite plutons dated at 428 Ma (Meng et al., 2005); (3) the Luliangshan garnet peridotite-gneiss unit (LLU), consisting of sillimanite-bearing paragneiss and granitic gneiss with ultramafic rocks (garnet peridotite and garnet pyroxenite) as lenses and intruded by Silurian granite plutons; and (4) the Yuka eclogite-gneiss unit (YLU), comprising eclogite, HP metapelite, granitic gneiss and rare marble.

The DLU, which is the focus of this contribution, is located approximately 30 km to the northeast of Dulan town, Qinghai Province, China (Fig. 1b). It consists predominantly of granitic orthogneiss, paragneiss (schist), eclogite lenses enclosed within gneiss and minor ultramafic rocks, and was intruded by granite plutons dated at ca. 400 Ma (Wu et al., 2004a). The foliation in the gneiss strikes northwest, and dips steeply northeast, modified by tight to isoclinal folds. A locally developed subhorizontal to shallowly northwest plunging lineation trends northwest (Mattinson et al., 2007, 2009). On the basis of spatial

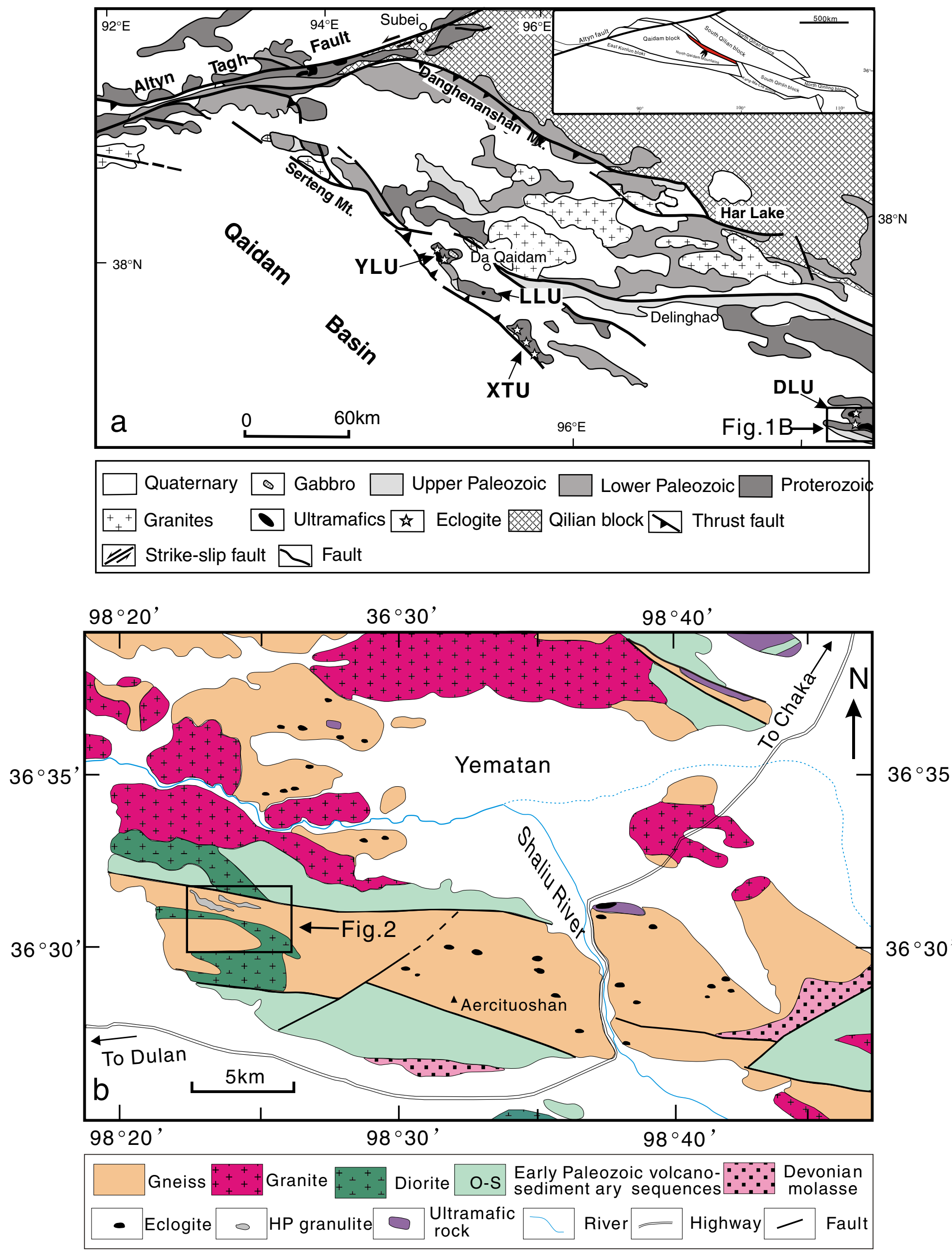


**Fig. 1.** (a) Schematic map of the North Qaidam Mountains showing major tectonic units, and locations of the eclogite and garnet peridotite (Modified from Zhang et al., 2005a). (b) Geologic sketch map showing the geological setting of the Dulan area. DLU—the Dulan eclogite-gneiss unit, XTU—the Xitieshan eclogite-gneiss unit, YLU—the Yuka eclogite-gneiss unit, LLU—the Luliangshan garnet peridotite-gneiss unit.