Tectonophysics 712–713 (2017) 10–29

Contents lists available at ScienceDirect

Tectonophysics

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

Thermochronology of the Sulu ultrahigh-pressure metamorphic terrane: Implications for continental collision and lithospheric thinning

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ARTICLE INFO

Article history:
Received 13 May 2016
Received in revised form 30 March 2017
Accepted 3 May 2017
Available online 5 May 2017

Keywords:
Thermochronology
Sulu UHP terrane
Continental collision
Lithospheric thinning
North China
Crustal detachment model

ABSTRACT

The thermal history of the Dabie-Sulu orogenic belt provides important constraints on the collision process between the South China and North China blocks during the Mesozoic, and possible lithospheric thinning event(s) in the eastern North China Block. This study reports on the thermal evolution of the Sulu ultrahigh-pressure metamorphic (UHP) terrane using zircon U-Pb geochronology and multiple thermochronology methods such as mica and hornblende $^{40}Ar/^{39}Ar$, zircon and apatite fission track, and zircon and apatite (U-Th)/He dating. $^{40}Ar/^{39}Ar$ and zircon (U-Th)/He data show that the UHP terrane experienced accelerated cooling during 180–160 Ma. This cooling event could be interpreted to have resulted from extensional unroofing of an earlier southward thrusting nappe, or, more likely, an episode of northward thrusting of the UHP rocks as a hanging wall. A subsequent episode of exhumation took place between ca. 125 Ma and 90 Ma as recorded by zircon (U-Th)/He data. This event was more pronounced in the northwest section of the UHP terrane, whereas in the southeast section, the zircon (U-Th)/He system retained Jurassic cooling ages of ca. 180–160 Ma. The mid-Cretaceous episode of exhumation is interpreted to have resulted from crustal extension due to the removal of thickened, enriched mantle. A younger episode of exhumation was recorded by apatite fission track and apatite (U-Th)/He ages at ca. 65–40 Ma. Both latter events were linked to episodic thinning of lithosphere along the Sulu UHP terrane in an extensional environment, likely caused by the roll-back of the Western Pacific subduction system.

1. Introduction

The Dabie-Sulu orogenic belt, with the core exposed as ultrahigh-pressure and high-pressure metamorphic (UHP-HP) rocks, formed as a result of collision between the South China and the North China blocks (SCB and NCB, respectively) during Early Triassic–Middle Jurassic times (Hacker et al., 2004; Yin and Nie, 1993; Zhao and Coe, 1987), and the orogenic process, from subduction and mountain building to orogenic collapse, has been a matter of debate for decades (Faure et al., 2003a; Hacker et al., 2000; Li, 1994; Lin et al., 2015; Okay and Şengör, 1992; Ratschbacher et al., 2000; Yin and Nie, 1993). A better understanding of this process can be gained through elucidating the exhumation history of the UHP-HP rocks.

Previous studies highlighted three prominent periods of exhumation of the UHP terrane — exhumation from the mantle to amphibolite facies depth by 210 Ma, and extensional exhumation in the Early Cretaceous and again in the Paleogene (Hu et al., 2006; Li et al., 2011; Li et al., 2010; Lin et al., 2015; Ratschbacher et al., 2000; Wu et al., 2016). However, little data was available regarding the thermal history of the UHP-HP rocks during the latter stage of the orogenic process in the Jurassic (Chen et al., 1992; Hacker and Wang, 1995; Webb et al., 2006). Existing knowledge on the exhumation of the Dabie-Sulu orogenic belt has been derived primarily from structural and chronological studies. The earliest exhumation from a depth of up to 125 km to the crustal levels was achieved by vertical extrusion between ~230 Ma and 210 Ma, as recorded by amphibole and mica $^{40}Ar/^{39}Ar$ dating on predominant southeast dipping ductile foliation and top-to-NW shear zones (Hacker et al., 2000; Z. Xu et al. 2009; Xu et al., 2006), although it is still debated whether the HP-UHP rocks were exhumed as one single slice or as discrete slices during protracted continental subduction (F.L. Liu et al. 2009; Liu and Li, 2008; Xu et al., 2006). The subsequent

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http://dx.doi.org/10.1016/j.tecto.2017.05.003
0040-1951/

crustal exhumation history has been better studied for the Dabie belt than for the Sulu belt. In the Dabie belt, the north-directed Northern Huaiyang nappe at the northern edge (Yuan et al., 2003) and surface top-to-NW shearing on SE-diping foliation in the eclogite and amphibolite units of the Dabie belt illustrate top-to-northwest motion at 200–180 Ma as recorded by $^{40}Ar/^{39}Ar$ ages of synkinematic muscovite and biotite (Hacker et al., 1995). This may have resulted from the indentation of a more rigid NCB lithosphere into the crustal wedge of the orogen (Hacker et al., 2000; Hacker et al., 1995; Yuan et al., 2003). An Early Cretaceous transtensional event there led to another rapid exhumation phase, accompanied by magmatic intrusion in northern Dabie (Hu et al., 2006; Lin et al., 2015; Ratschbacher et al., 2000; Y. Wang et al. 2011). Orthogneiss units in the Dabie belt were reheated to above 200 °C by Early Cretaceous magmatism, and thus yielded widespread Cretaceous $^{40}Ar/^{39}Ar$ ages (Faure et al., 2003b; Hacker et al., 2000; Ratschbacher et al., 2000). The low-temperature cooling history (200–40 °C) was recorded by ZHe, AFT and AHe data (Hu et al., 2006; Reiners et al., 2003). The ZHe ages (effective closure temperature 180 ± 20 °C; Guenthner et al., 2013) range from 155 ± 12 Ma (2σ) to 76 ± 6 Ma, showing an overall increase in age with increasing distance from the center of the range, whereas AFT and AHe ages clustered at Paleogene ages (Reiners et al., 2003). The data were interpreted to reflect a steady exhumation over the last 115 myr, or an increased exhumation between 80 and 40 Ma (Reiners et al., 2003). Grimmer et al. (2002) proposed an enhanced cooling at ~45 ± 10 Ma in eastern Dabie based on AFT and structural data, and attributed it to the far-field effect related to the India-Asia collision.

For the Sulu orogenic belt, early work by Chen et al. (1992) reported Jurassic cooling to ~200 °C from 196 to 172 Ma, using $^{40}Ar/^{39}Ar$ thermochronology of both high grade and low grade metamorphic rocks, but no clear kinematic explanation was provided for the cooling event. In contrast, Webb et al. (2006) and Lin et al. (2015) suggested that the UHP rocks were exhumed directly to upper-crustal levels (T ≈ 100 °C) by the Late Triassic using the same approach, and that subsequent exhumation was aided by extensional detachment faulting of the Wulian-Qingdao-Yantai fault during 130–120 Ma. AFT analyses of core samples spanning depths from 0 to 4000 m (China Continental Scientific Drilling main hole) revealed a general decreasing age trend with increasing depth, from 87 ± 11 Ma at the surface to 3 ± 1 Ma at depth, which was broadly interpreted to indicate a reheating during the Late Cretaceous and Eocene, and cooling thereafter (S.S. Liu et al. 2009). AHe data by Wu et al. (2016) exhibit a peak cooling age at ~45 Ma and they suggested an enhanced exhumation in early to middle Eocene, linked to the combined effect of Pacific back-arc extension and the far-field effect of India–Asia collision. Current thermochronological work on the Sulu belt therefore suffer from two major shortfalls: (1) It is still unclear whether the Sulu UHP-HP rocks underwent a Jurassic exhumation event, and if they did, the tectonic significance of such an event needs to be assessed; (2) There is no detailed history of Cretaceous and Cenozoic exhumation and its tectonic significance in terms of speculated regional lithospheric thinning (Menzies et al., 1993; Menzies and Xu, 1998; Qiu et al., 2016).

This study aims to reconstruct the thermal history of the Sulu UHP terrane at the crustal level and explore the exhumation trajectory of the UHP terrane during the latter stage of the orogenic process. To achieve this, a combination of SHRIMP zircon U-Pb dating, mica and hornblende $^{40}Ar/^{39}Ar$ geochronology, zircon and apatite fission track (ZFT and AFT) dating, and zircon and apatite (U-Th)/He (ZHe and AHe) analyses, covering the temperature range from 900 °C to 40 °C, were used to reconstruct the cooling trajectories of Mesozoic metamorphic and intrusive rocks in the Sulu UHP terrane.

2. Geological setting

The Sulu orogenic belt consists of a UHP terrane in the north and a high-pressure metamorphic terrane in the south (Fig. 1b). The Sulu UHP terrane is geographically located in the southern part of the Jiaodong Peninsula and is separated from the NCB by the west-northwest dipping Wulian-Qingdao-Yantai (WQY) fault (Fig. 1) (Wallis et al., 1999; Zhai et al., 2000; Zhai and Liu, 1998). The Jiaobei region, defined as the region north of the Wulian-Qingdao-Yantai fault, tectonically belongs to the southeast margin of the NCB, with its basement consisting mainly of Archean tonalite-trondhjemite-granodiorite (TTG) gneiss (~2.9–2.7 Ga), granitic gneiss (~2.5 Ga), and Paleoproterozoic amphibolite-facies metasedimentary rocks and granulites metamorphosed at ~1.9–1.85 Ga (Jahn et al., 2008; Liu et al. 2013a; 2013b; Tam et al., 2011; Wan et al., 2006; Wu et al., 2014; Zhou et al. 2008b).

The Sulu UHP terrane consists dominantly of banded gneisses enclosing layers or lenses of eclogite, coesite-bearing marbles and peridotites (Liou et al., 1996; Ye et al., 2000b; R.Y. Zhang et al. 2010; Zhang et al., 2003). Micro-diamond and coesite occur as inclusions in minerals such as garnet, clinopyroxene and zircon, indicating temperature-pressure conditions of 750–850 °C and >28 kbar consistent with UHP metamorphic conditions (Xu et al., 2006). The timing of regional UHP metamorphism in the Sulu belt spans from 243 ± 4 to 218 ± 2 Ma based on U-Pb dating of zircon with UHP mineral inclusions from a wide range of rocks, including eclogite, amphibolite, marble, quartzite, ortho- or paragneisses (Ames et al., 1996; Leech and Webb, 2013; Liu et al., 2007; J. Liu et al., 2005; F. Liu et al., 2005; Liu et al., 2003; Liu et al., 2006; F.L. Liu et al. 2009; Liu and Liou, 2011; Ye et al., 2000b; Zong et al., 2010a). Zircon cores commonly preserve protolith U-Pb ages of ca. 790 to 700 Ma and 2.05 to 1.85 Ga (Ames et al., 1996; Tang et al., 2008; Zheng et al., 2004; Zheng et al., 2008), suggesting an affinity to the SCB. The UHP rocks have been interpreted as having been recrystallized during Triassic subduction of SCB crustal materials to a depth of approximately 200 km (Yang et al., 2003; Ye et al., 2000a). Syn-exhumation syenite and gabbro were emplaced at ca. 210 Ma as indicated by zircon U-Pb data (Zhao et al., 2012) (Upper Triassic intrusive body in Fig. 1).

Both the Jiaobei region and the Sulu UHP terrane were intruded by massive Upper Jurassic to Lower Cretaceous granitoids (J.H. Guo et al. 2005; Jiang et al., 2012; Yang et al., 2005b; Yang et al., 2012; J. Zhang et al. 2010) and are, in places, unconformably overlain by Cretaceous clastic and bimodal volcanic rocks (Fan et al., 2001; F. Guo et al. 2005). The Cenozoic stratigraphy consists of Eocene to Quaternary strata that are in angular unconformity contact with underlying rocks (Wu et al., 2016).

3. Sampling and analytical methods

The sampling strategy was designed to address two main questions. (1) Was there a discernible Jurassic exhumation event in the Sulu UHP terrane? (2) What are the characteristics of low-temperature exhumation related to the Cretaceous and Cenozoic extension of the NCB? Thirteen samples were collected south of the Wulian-Qingdao-Yantai fault, predominantly in the northeast and southwest ends of the Sulu UHP terrane (Fig. 1c and Table 1). The rock types range from Neoproterozoic granitic gneiss and Triassic UHP rocks to Lower Cretaceous intrusive rocks. Analysis of the metamorphic rocks can serve to establish the Jurassic cooling history of the Sulu UHP terrane, whereas Upper Jurassic and Lower Cretaceous plutons could reveal Cretaceous and Cenozoic exhumation process. One sample (11LX178B) was collected from a foliated Neoproterozoic granite with affinity to the SCB north of the Wulian-Qingdao-Yantai fault (Huang et al., 2006; X. Zhou et al. 2008; Zhou et al., 2003). Although it is unclear if this sample experienced UHP metamorphic conditions, in view of the post-orogenic reactivation of the Wulian-Qingdao-Yantai fault and the SCB affinity of the outcrop, it is here considered as being from the Sulu UHP terrane. This sample might provide additional information on possible Jurassic exhumation of the Sulu UHP terrane.

Mineral concentrates of zircon, apatite, mica and hornblende from rock samples were separated using standard density and magnetic separation procedures at the mineral separation laboratory of the