Lithos 120 (2010) 490–510

Contents lists available at ScienceDirect

Lithos

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

Melting-induced fluid flow during exhumation of gneisses of the Sulu ultrahigh-pressure terrane

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ARTICLE INFO

Article history:
Received 5 January 2010
Accepted 22 September 2010
Available online 26 September 2010

Keywords:
Fluid flow
Quartz vein
Partial melting
Zircon U–Pb dating
UHP metamorphism
Sulu

ABSTRACT

Hydrothermally altered rocks are products of fluid–rock interactions, and typically preserve numerous quartz veins that formed as chemical precipitates from fluids that fill up cracks. Thus, quartz veins are the record of the fluid system that involved fracture flow in the direction of changing temperature or pressure. In order to decipher the fluid activity in the Sulu ultrahigh-pressure (UHP) terrane in eastern China, quartz veins together with an adjacent eclogite lens and the host gneiss were studied. In one location a deformed quartz vein is located at the boundary between the host gneiss and the eclogite lens. The amphibolite-facies overprinting of the eclogite lens decreases from the rim to the core of the lens, with fresh eclogite preserved in the core. The foliated biotite gneiss contains felsic veins and residual phengites. Zircon rims from the gneiss are characterized by melt-related signatures with steep HREE patterns, high Hf contents and negative Eu anomalies, and a pool of weighted average $^{206}Pb/^{238}U$ analyses reveal an age of 219 ± 3 Ma (2σ), which is younger than the UHP metamorphic age (236 ± 2 Ma, 2σ) recorded by zircons from the eclogite lens. This suggests that the gneiss in the Sulu UHP terrane could have suffered from partial melting due to phengite dehydration during the “hot” exhumation stage.

The formation age of the quartz vein (219 ± 2 Ma, 2σ) defined by zircon rims agrees well with the partial melting time (219 ± 3 Ma, 2σ) of the host gneiss. The initial $^{176}Hf/^{177}Hf$ ratios of zircon rims from the quartz vein are obviously lower than zircons from the eclogite lens, but overlap with the coeval zircon domains from the nearby granite dikes produced by partial melting of orthogneiss. These observations suggest that the quartz vein and corresponding fluid flow could be associated with partial melting of the host gneiss. On the other hand, amphibole-bearing and HREE-rich zircon rims from the amphibolite pool an amphibolite-facies metamorphic age of 217 ± 5 Ma (2σ), overlap with the formation age of the quartz vein. This implies that retrogression of the eclogite lens could have been caused by melting-induced fluid flow. Based on the above observations, we speculate that partial melting of the gneiss in the continental subduction-related UHP belt could have induced a significant fluid flow during the exhumation stage, and thus contributed significantly to the extensive retrogression of eclogites in the Sulu UHP terrane.

1. Introduction

Fluid plays a key role in subduction-zone processes (Manning, 2004; Hermann et al., 2006; Zheng, 2009). The availability of fluid or fluid-associated melt can significantly influence rheology, elemental mobility, mineral assemblages, formation and preservation of high pressure (HP) or ultrahigh-pressure (UHP) rocks (e.g., Wallis et al., 2005; Hermann et al., 2006; Zhao et al., 2007b; Ragozin et al., 2009). Partial melting could also be triggered by adding fluid (Rubatto et al., 2009) or dehydration reactions of hydrous minerals (Skjerlie and Patiño Douce, 2002). Extensive studies have been conducted on fluid/melt release during the subduction of oceanic crust (e.g., Manning, 2004). However, little attention has been paid to fluid activity of subducted continental crust (e.g., Zheng et al., 2003; Zheng, 2009). Although the subducted continental crust contains less fluid than oceanic crust (Rumble et al., 2003), experiments of Hermann (2002) and Auzanneau et al. (2006) demonstrated that partial melting of deeply-subducted continental crust could occur during exhumation. Considering that the water contents of melt increase with increasing pressure (Hermann, 2003) and the complete miscibility between fluid and melt at HP/UHP conditions (Bureau and Keppler, 1999), it makes

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doi:10.1016/j.lithos.2010.09.013

us speculate that melt generated at HP/UHP conditions would be more hydrous and melt-related fluid flow could be generated during decompression. The geochemical, petrologic and geophysical properties of HP/UHP rocks can be remarkably affected by such melting-induced fluid flow in subduction-zones.

Quartz veins in HP or UHP rocks are commonly considered as the products of fluid–rock interaction, and thus provide insight into fluid flow in subduction-zones (Franz et al., 2001; Breeding and Ague, 2002; Zheng et al., 2007; Wu et al., 2009; Zheng, 2009). The Dabie–Sulu orogen is the largest known UHP terrane in the world (Zheng, 2008; Liou et al., 2009). The exhumed HP/UHP rocks in this terrane provide an excellent natural laboratory to study subduction-related processes. Although abundant quartz veins were found in the Dabie–Sulu UHP terrane, the previous work entirely focused on the quartz veins in the eclogite that occurs as scattered blocks or lenses enclosed in gneiss (Zheng et al., 1998; Franz et al., 2001; Li et al., 2004; Zheng et al., 2007; Wu et al., 2009). The veining fluid was commonly suggested to be derived from the host eclogites (Zheng et al., 1998; Franz et al., 2001; Li et al., 2004; Zheng et al., 2007; Wu et al., 2009). However, the Dabie–Sulu UHP rocks are dominated by felsic gneiss (>90%) (Liou et al., 2009). Thus, the behavior of gneiss would dominate the geodynamic processes of the Dabie–Sulu UHP terrane during exhumation. UHP gneiss always contains many hydrous minerals (e.g., phengite) and could be considered as a potential source of fluid. However the detailed study of gneiss-related quartz veins and corresponding fluid flow is absent. Zircon, a common accessory mineral in HP/UHP rocks, has strong stability and high closure temperatures for Th, U, Pb and rare earth elements (REE) (Cherniak et al., 1997; Lee et al., 1997). Thus, combined with petrological investigation, zircons in the quartz veins could not only serve as a powerful tool to constrain the timing of fluid activity, but also provide constraints on the origin of fluids.

In this study, based on detailed field work, petrological and geochemical investigations, U–Pb ages, trace element and Lu–Hf isotope compositions of zircons from a suite of rocks (quartz vein + amphibolite + host gneiss + eclogite lens) in the Sulu UHP terrane were studied in detail in order to decipher the fluid activity. The results show that hydrous melt was produced by partial melting of the host gneiss during exhumation at ~219 Ma. Consequently, melting-induced fluid flow and corresponding quartz veins were formed at the same time (~219 Ma) as a result of evolution of hydrous melt. Such fluid activity could have caused retrogression of eclogites in the Sulu UHP terrane.

2. Geological background

The Dabie–Sulu UHP terrane, which formed during the Triassic continental collision between the North China craton and the Yangtze craton, is the largest UHP terrane in the world (Zheng, 2008; Liou et al., 2009). Because of the discovery of UHP-index coesite and diamond in eclogites (Okay et al., 1989; Wang et al., 1993; Xu et al., 2003), this region has become one of the most important places to study continental subduction-related UHP metamorphism. The NNE trending Tanlu fault separated this orogenic belt into two segments, the E–W trending Dabie orogen in the west and the NE-trending Sulu orogen in the east. The Sulu UHP metamorphic terrane is bounded by the Wulian–Qingdao and Mishan faults in the north, the Jiashan–Xiangshui and Wendeng–Rongcheng faults in the south (Fig. 1a). The Sulu UHP terrane is mainly composed of gneiss with subordinate amounts of coesite-bearing eclogite and other rare UHP metamorphic rocks such as ultramafic rocks, marbles and pelitic schists (Wang et al., 2010).

The Sulu UHP terrane is characterized by the following signatures: (1) overprint of granulite-facies metamorphism in the early exhumation stage (Wang et al., 1993; Banno et al., 2000; Nakamura and Hirajima, 2000; Yao et al., 2000), (2) occurrence of partial melting in the dominant gneiss (Wallis et al., 2005; Zhao et al., 2007b), (3) exposures of syn-metamorphic magmatism (Chen et al., 2003; Yang et al., 2005), and (4) record of ultrahigh ε_{Nd} (Jahn et al., 1996) and extreme ^{18}O depletion (Zheng et al., 1996; Tang et al., 2008a).

3. Samples

A suite of representative samples of quartz veins, host gneiss, amphibolite and eclogite lenses (Fig. 2) were collected from Liugong Island, ~5 km east of Weihai city (Fig. 1b). Gneiss (WH0801), the country rock, is foliated and characterized by the presence of felsic veins (Fig. 2) that define a migmatitic structure (Sawyer, 1999). The host gneiss is mainly composed of plagioclase + K-feldspar + quartz + biotite (Fig. 3a) with rare apatite + titanite + garnet + ilmenite + magnetite + zircon. Compared to the host gneiss, the felsic veins are composed of large K-feldspar and quartz grains with some plagioclase and a few phengite, titanite and zircon grains (Fig. 3b and c). The plagioclase in the felsic veins is turbid and contains some residual phengite (Fig. 3c).

The deformed quartz vein (WH0802) is in sharp contact with the gneiss and amphibolite, and parallel to the foliation of the host gneiss (Fig. 2). The shape of the quartz vein is irregular and has the largest volume in the pressure shadow near the tail of the eclogite lens (Fig. 2). The quartz vein is nearly entirely composed of quartz with a few titanite and zircon grains. Numerous two phase (liquid + vapor) fluid inclusions are present in the quartz (Fig. 3f). The ratios of liquid to vapor vary largely among these individual inclusions. Some fluid inclusions are distributed along healed cracks in the quartz.

Eclogite occurs as lenses in the host gneiss (Fig. 2). It suffered from different degrees of amphibolite-facies metamorphism from the rim to the mantle, while the central domain of the eclogite lens is relatively fresh (Fig. 2). The outside part in contact with the quartz vein was entirely retrograded to amphibolite during amphibolite-facies metamorphism (Fig. 2). The weakly retrograded eclogite (WH0804) is coarse-grained and mainly composed of eclogite-facies garnet and omphacite with minor apatite + rutile + ilmenite + zircon (Fig. 3d). A few amphibolite-facies plagioclase grains and amphibole are present on the margin of garnet and omphacite (Fig. 3d). Amphibole and omphacite inclusions were identified within garnet (Fig. 3d). Omphacite contains quartz exsolution needles (Fig. 3d). The amphibolite (WH0803) is mainly composed of amphibole + biotite + plagioclase (Fig. 3e), with minor rutile + apatite + titanite + zircon + quartz. Worm-like plagioclase grains are found in the coarse amphibole (Fig. 3e).

4. Analytical methods

4.1. Major and trace element analysis of whole rock

Whole rock samples were first crushed to less than 5 mm in a corundum jaw crusher. About 100 g was powdered in a vibratory disc mill (RS200, Retsch GmbH, Germany) equipped with a tungsten carbide milling cup to less than 200 mesh. Major elements were analyzed by X-ray fluorescence (Rikagu RIX 2100) at the State Key Laboratory of Continental Dynamics, Northwest University, China. Analytic precision and accuracy for major elements are the same as Rudnick et al. (2004). Trace elements were analyzed by an Agilent 7500a ICP-MS at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan. About 50 mg samples were digested by $HF + HNO_3$ in Teflon bombs for ICP-MS analysis. The detailed sample-digestion procedure for ICP-MS analyses and analytical precision and accuracy for trace elements are the same as described by Liu et al. (2008b).

4.2. Major element analysis of minerals

Major element compositions of minerals were determined by JXA-733 electron microprobe (EMP) at the State Key Laboratory of Geological Processes and Mineral Resources, China University of