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Occurrence of metastable rocks in deeply subducted continental crust from the Dabie Mountains, central China

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A recent study reveals that metamorphic volcanic and sedimentary rocks have survived deep subduction of continental crust in the Dabie Mountains, central China. These low-grade (LG) rocks are intercalated within the ultrahigh-pressure (UHP) metamorphic terrane and well preserve primary volcanic breccia structure and sedimentary bedding. The presence of coherent field relations between LG and UHP rocks suggests that LG rocks are not of exotic origin and therefore suffered from UHP metamorphism. They, however, did not record the UHP event likely due to slow reaction kinetics, and only experienced epidote-amphibolite to greenschist facies metamorphism and deformation at the retrograde stage of UHP rocks. The protolith age of c. 790 Ma and metamorphic age of 232.2 Ma obtained from LG rocks, which agree well with those from UHP rocks, also suggest that both LG and UHP rocks shared the same evolutionary history since Late-Proterozoic. Except for the lack of deformation and fluid during UHP metamorphism, the rapid subduction, short stay at mantle depths and rapid exhumation are necessary for the preservation of primary assemblage and fabric in LG rocks within deeply subducted continental crust.

Introduction

Due to the discovery of coesite in diverse metamorphic rocks, including eclogite, metapelite, marble, jadeite quartzite and gneiss (Xu, 1987; Okay et al., 1989; Wang et al., 1989; Wang and Liou, 1991, 1993; Su et al., 1996; Tabata et al., 1998), the Dabie Mountains in central China have been considered to be a slab of deeply subducted continental crust. Most geologists assumed that the coesite-bearing rocks together with their country rocks in the slab underwent *in situ* UHP metamorphism (e.g. Wang and Liou, 1991; Okay, 1993; Liou et al., 1996; Xue et al., 1996; Rowley et al., 1997; Carswell et al., 2000). However, on the basis of detailed geological research on the field relations, some geologists, especially Chinese investigators, only accepted that the rocks associated closely with eclogite had experienced UHP metamorphism, but argued that the widespread granitic gneisses were of lower metamorphic grade (LG), and were juxtaposed with UHP rocks at crustal level (e.g. Zhai et al., 1995;

Cong et al., 1995, 1999; Liu et al., 1999). In fact, both considerations are problematic because of the lack of index textural and mineralogical evidence.

Are there any non-UHP rocks in the deeply subducted continental crust of the Dabie Mountains? If yes, what are the real relations between them and UHP rocks? A detailed field geological study revealed some LG volcanic and sedimentary rocks in Ganghe (Tang et al., 1995; Dong et al., 1997), and further large scale geological mapping proved that there are many LG rock blocks within the UHP terrane. It is very interesting that a coesite-bearing eclogite was recently found intercalated in the LG volcanic rocks, which led Gao et al. (1997) to propose a magmatic origin of UHP eclogite. This paper summarizes new petrological, structural and geochronological data and gives an interpretation about the origin of LG rocks and its relations to UHP rocks.

Regional geology and field relations

The regional geology of the Dabie Mountains in central China has been described by many geologists (e. g. Dong et al., 1993; Liou et al., 1996; Cong et al., 1996). A large scale (1:50,000) geological mapping by the Anhui Bureau of Geology and Mineral Resources (1996, unpubl.) revealed that the Dabie Mountains UHP terrane comprised two major lithological units, the granitic gneiss unit and the UHP unit (cf. Liu et al., 1999). Recently, based on the 1:10,000 geological mapping in Changpu area (Anhui Bureau of Geology and Mineral Resources, 2000), Schmid et al. (2000) distinguished for the first time basement-cover sequences in the UHP unit (Figure 1A). The basement is composed of quartz-feldspathic orthogneiss with some eclogite lenses or blocks. The cover can be divided into the Changpu unit and the Ganghe unit. The former consists of garnet-biotite-plagioclase gneiss, garnet-phengite schist, garnet-jadeite quartzite, and marble with numerous eclogite pods or lenses. The latter is chiefly constituted by metavolcanic rocks with minor metasedimentary rocks and eclogites (Dong et al., 1997; Schmid, 2001; Schmid et al., 2001). The reconstruction of the pre-UHP stratigraphy of the cover is shown in Figure 1B.

The LG volcanic and sedimentary rocks occur in the Ganghe unit, about 4 km south of Changpu. 11 LG blocks on different scales have been distinguished within 3.5 km² area (Figure 1A). LG rocks consist of laminated metapelitic sandstone, metatuff breccia and phengite-albite-quartz schist. Primary sedimentary structures, such as graded, rhythmic and inclined bedding, and slumping and channel structures, are well preserved in the sedimentary rocks (Figure 2a). Breccia clasts and primary igneous plagioclase crystals are preserved in the volcanic rocks (Figure 2b). Although LG rocks are discontinuously distributed, the regular arrangement from phengite-albite-quartz schist through metatuff breccia to metapelitic sand-

Figure 1 Geological map of Ganghe-Changpu area, southeastern Dabie Mountains (A) and its location in China (after Anhui Bureau of Geology and Mineral Resources, 2000, and Schmid, 2001). B shows the reconstruction of the pre-UHP stratigraphy of the cover. A-B shows the location of Figure 3.

Figure 2 (a) Photograph showing rhythmic bedding in metasedimentary rock. Width of view is 8 cm.

(b) Photograph showing rhyolitic clasts in metatuff breccia. Width of view is 12 cm.

(c) Photographs showing an eclogite intercalated within metatuff breccia.

(d) Photomicrograph showing an igneous lithoclast with intergranular texture composed of albite, Ti-bearing hematite and minor biotite and apatite in metasedimentary rock. Width of view is 0.5 cm.

stone implies that they may be a continuous volcanic-sedimentary sequence.

The lithological and structural section of a typical LG volcanic rock block near Ganghe Bridge is illustrated in Figure 3. There are two metatuff breccia layers about 30 m and 5 m thick. The main components of breccia are rhyolites, with clast content of 10–30 vol.% and grain size ranging from 1 cm to 5 cm. An eclogite 40 cm wide is intercalated in the metatuff breccia (Figure 2c), which may represent an earlier mafic dyke. Three phengite-albite-quartz schist layers occur beside the metatuff breccia. Their protolith may be tuff lava. The country rocks of LG block are mica gneisses with abundant coesite-bearing eclogite bands or lenses. The typical mineral assemblage in such eclogites is garnet + omphacite + phengite + zoisite + quartz/coesite + rutile $\pm$ kyanite. Except for the increasing intensity of foliation, no clear tectonic boundary has been found between LG and UHP rocks.

Deformation, petrology and geochronology

Deformation

Most metapelitic sandstones have not recorded deformational episodes, but sericite in a few samples exhibits a weak orientation parallel to the bedding. Phengite in metatuff breccia is strongly oriented and forms the penetrative S_1 foliation. It can be seen that phengite often grew around the stretched breccia, and that plagioclase phenocrysts were rotated. Both elongation lineations (L_1) of breccia and metamorphic minerals strike NW-SE (S_1 140/40, L_1 170/40), in agreement with the A-type lineation in UHP rocks (Figure 3). The inner part of the eclogite does not exhibit any deformation except later schistosity defined by retrograde minerals developed in its margin. The preferred orientation of phengite in phengite-albite-quartz schist constitutes strong foliation. A small-scale A-type fold developed in the rocks. Two stages of deformation can be recognized near

UHP rocks, and its principal foliation (S_1) corresponds to the second deformation (D_2) in eclogites (Figure 3).

Similar to the descriptions by Xue et al. (1996) in Shima area, three major generations of deformation are also recognized in the UHP rocks in Ganghe. The D_1 deformation, usually forming the S_1 foliation (180/40) and L_1 lineation, consists of banded compositional layer in eclogites, which represents the earlier deformation formed under UHP conditions during subduction. The D_2 was deformed by the compositional layer and S_1 foliation, and A-type fold with the S_2 axial-planar foliation (130/25) and L_2 lineation occurred. The compositional layer (S_1) in the country gneisses of eclogite was entirely replaced by the S_2 foliation. D_2 is a major deformation event in the Dabie Mountains UHP terrane and represents the plastic deformation formed under amphibolite facies during early exhumation of UHP rocks. The D_3 deformation is characterized by open, NE-plunging folds (L_3 25/40) with nearly vertical axial plane, which records the deformation formed at a shallow level during late exhumation of UHP rocks.

Petrology

Metapelitic sandstone is composed of porphyroclasts and detrital matrix. The compositions of porphyroclasts are quartz, feldspar and minor amounts of igneous lithoclasts. They are circular, rectangular or angular with an average grain size of 0.05–0.5 mm, but sometimes gravels as large as 1–2 mm occur. Igneous lithoclasts usually preserved intergranular texture composed of albite (An = 7), Ti-bearing hematite and minor biotite and apatite (Figure 2d). All quartz porphyroclasts have recrystallized to polycrystalline aggregates. Matrix comprises sericite, chlorite, felsic minerals and sometimes a few epidote and biotite crystallites, with an average grain size of < 1 μ m. This mineral assemblage suggests a metamorphic grade of lower greenschist facies.

Metatuff breccia consists of phengite, epidote, feldspar, quartz and a small amount of biotite, sphene and garnet. They crystallized relatively bigger grains as compared with metapelitic sandstone, with an average grain size ranging from 0.01 to 0.02 mm. Garnet is rich in Mn with spessartine content of 25–30 mol.%. Phengite is rich in Fe, with Si values of 3.24–3.39 p.f.u. and Mg/Mg+Fe²⁺ ratio of 0.31–0.39. The metamorphic conditions are difficult to estimate due to the lack of diagnostic mineral assemblages. Phengite barometer calibrated by Massonne and Schreyer (1987) yields a pressure of 6–10 kbar (assumed $T = 500^\circ\text{C}$), but this pressure estimates are only minimum values due to the absence of K-feldspar. The absence of jadeite in presence of albite in the rock limits the pressures to less than 13–14 kbar. The temperature of 460–490 $^\circ\text{C}$ was obtained based on garnet-muscovite geothermometer (Hynes and Forest, 1988) (assumed $P = 8$ kbar).

Phengite-albite-quartz schist is medium-grained with an average grain size of 0.05–0.1 mm. The constituent minerals are phengite, epidote, albite, quartz and minor amounts of biotite and garnet. Garnet is also Mn-rich with spessartine content of 29–46 mol.%. Phengite reveals Si values of 3.24–3.39, but Mg/Mg+Fe²⁺ ratio is higher, ranging from 0.44 to 0.55. The small grains of epidote are euhedral and homogeneous in composition, but a zoisite core often occurs in big crystals. The temperature calculated by garnet-muscovite geothermometer ranges from 490 to 510 $^\circ\text{C}$ (assumed $P = 8$ kbar), in accordance with epidote-amphibolite facies conditions.

The above shows that the mineral assemblage, chemistry and P-T conditions of LG rocks correspond systematically to those of retrograde eclogites and their country rocks (Liou et al., 1996). These identical P-T estimates as well as the

Figure 3 Lithological and structural section of a low-grade metamorphic volcanic rock block in the UHP unit near Ganghe Bridge. UHP—ultrahigh-pressure metamorphic rocks; PS—phengite-albite-quartz schist; TB—metatuff breccia. Amp.—amphibolite; Ecl.—eclogite; Gn.—gneiss. Ab.—albite; Bi.—biotite; Cs.—coesite; Epi.—epidote; Gar.—garnet; Hb.—hornblende; Omp.—omphacite; Phe.—Phengite; Qz.—quartz.

field relations and the textures described in this paper and by Schmid (2001) demonstrate that coherent basement-cover series are present and survived the ultrahigh-pressure metamorphism.

Eclogite intercalated in metatuff breccia comprises fine-grained garnet, omphacite, epidote, quartz and rutile. Coesite occurs as inclusions in garnet and quartz pseudomorph after coesite in both garnet and epidote. The presence of glomeroblastic epidote and quartz, and epidote content up to 30 vol.% indicate that fluid plays an important role during eclogite formation. The metamorphic temperature calculated by garnet-clinopyroxene geothermometer (Krogh, 2000) ranges from 710 to 780°C (assumed $P = 40$ kbar), similar to that of coesite-bearing eclogite ($750 \pm 50^\circ\text{C}$, > 30 kbar) occurring in the UHP unit. This implies that the eclogite was not of magmatic origin, as Gao et al. (1997) suggested. The margin of eclogite has transformed into more fine-grained symplectite of epidote-amphibolite facies.

Geochronology

The age of LG rocks was determined by various dating techniques including the stepwise thermal evaporation-deposition technique for single zircon grains and the whole-rock Sm-Nd and Rb-Sr isochrons in the Laboratory of Isotope Geochronology at the Chinese Academy of Geological Sciences. Analytical procedures and methods have been illustrated by Li

et al. (1993) and Zhao et al. (1995). As a result, the $^{207}\text{Pb}/^{206}\text{Pb}$ ages of four zircons separated from a phengite-albite-quartz schist are 760 ± 9 , 769 ± 7 , 745 ± 6 and 802 ± 3 Ma, respectively (Table 1). The whole-rock Sm-Nd isochronic age for seven samples of such rock is 790.9 ± 18.6 Ma (Table 2, Figure 4a). The coincidence between Pb-Pb age and whole-rock Sm-Nd age indicates that the protolith age of LG rocks is c. 790 Ma, which is not only in accordance with the protolith age of eclogites in the UHP unit (Ames et al., 1996), but also in accordance with that of granitic gneisses (Rowley et al., 1997; Hacker et al., 1998, 2000). The whole-rock Rb-Sr isochronic age of 232.2 ± 8.2 Ma was obtained with the same 7 samples (Table 3, Figure 4b). It is equivalent to the generally recognized metamorphic age of eclogites in the UHP unit in the Dabie Mountains, c. 220–240 Ma

Figure 4 The whole-rock Sm-Nd (A) and Rb-Sr (B) isochronic ages for low-grade metamorphic rocks in Ganghe.

Table 1 Pb/Pb isotopic ratios released from single zircon stepwise evaporation of a phengite-albite-quartz schist from Ganghe.

No.	Order	Group	Isotope of zircon				Result				ages		Description of zircon
			208/206	2σ	207/206	2σ	204/206	2σ	207/206	2σ	Ma	2σ	
1	2	5	0.4819	27	0.07082	36	0.000343	33	0.06454	29	760	9	Colorless, relatively transparent, 380μm × 90μm × 1 170μm × 80μm × 1, (110) (111) faces, less fissure, no corrosion 220μm × 150μm × 1, (110) (111) (311) faces, complex crystal faces 200μm × 120μm × 4, (110) (111) faces, simple crystal faces 170μm × 80μm × 4
2	1	10	0.4523	32	0.07543	48	0.000734	38	0.06482	22	769	7	
3	1	4	0.6155	62	0.0794	10	0.00011	7	0.06409	18	745	6	
5	1	8	0.3782	9	0.07478	17	0.000632	12	0.06566	11			
	2	5	0.04837	18	0.07307	18	0.000475	23	0.06619	12			
			$I_1 + I_2 = 13$ blocks							0.06586	11	802	3

Parameter used: $\lambda_{238} = 1.5513 \times 10^{-10}$, $\lambda_{235} = 9.8485 \times 10^{-10}$, $^{238}\text{U}/^{235}\text{U} = 137.88$; No. = zircon crystal numbers; order = depositional order; groups = data groups measured after a deposition (block number); each block consists of 8 times of scanning; 207/206 in the result column refers to radiogenic Pb isotopic ratio; σ value corresponds to the last two or one number of the ratio, e.g. 208/206 = 0.1732, $\sigma = 17$ for 208/206 = 0.1732 $\pm$ 0.0017.

Table 2 Sm-Nd isotopic compositions of Phengite-albite-quartz schist from Ganghe.

No.	Sm/ 10^{-6}	Nd/ 10^{-6}	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$
94303-2	3.643	29.28	0.07526	0.511521	24
94303-3	4.298	29.83	0.08712	0.511563	20
94303-4	4.372	28.92	0.09145	0.511587	22
94303-5	8.998	57.38	0.09486	0.511601	16
94303-6	9.043	55.01	0.09947	0.511637	15
94303-7	8.987	52.76	0.10310	0.511668	10
94303-8	11.48	55.36	0.12540	0.511770	12

Table 3 Rb-Sr isotopic compositions of Phengite-albite-quartz schist from Ganghe.

No.	Rb/ 10^{-6}	Sr/ 10^{-6}	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
94303-2	78.63	85.04	2.6350	0.718281	22
94303-3	73.64	877.6	0.2391	0.701697	23
94303-4	64.36	168.5	1.0884	0.713204	26
94303-5	68.91	208.6	0.9247	0.712695	18
94303-6	89.45	323.4	0.7882	0.712146	16
94303-7	95.78	430.2	0.6344	0.711440	14
94303-8	120.8	210.8	1.6382	0.715346	12

(Li et al., 1993; Ames et al., 1996; Chavagnac and Jahn, 1996), representing the collision timing of the North China and Yangtze Cratons.

Discussion and conclusions

The preservation of primary sedimentary bedding and volcanic breccia suggests that LG rocks within Ganghe sequence have never transformed into UHP assemblage. The absence of sharp tectonic boundaries between LG and UHP rocks, however, precludes LG rocks from being exotic blocks. The protolith age of *c.* 790 Ma and metamorphic age of 232.2 Ma obtained from LG rocks, which agrees well with those from UHP rocks, also suggest that LG rocks shared the same evolutionary history with UHP rocks. Accordingly, it is assumed that LG rocks occurring within the Dabie Mountains UHP terrane are the relics of the Yangtze continental crust. When the Yangtze slab subducted to mantle depth (more than 100 km), the main part of the slab experienced intense plastic deformation and transformed into UHP assemblage, but in some places of the slab, composed of volcanic and sedimentary rocks, minerals did not transform because of slow reaction kinetics, and therefore preserved primary mineral assemblages. When they were uplifted to the crustal levels, they were subjected to epidote-amphibolite to greenschist facies metamorphism and deformation together with surrounding UHP rocks. The occurrence of undeformed fine-grained eclogite within metatuff breccia supports this hypothesis.

Metamorphic heterogeneity between LG and UHP rocks depends on the chemical compositions of protolith, deformation and fluid conditions. Mafic rocks in the subducted slab are easily transformed into eclogites as compared with intermediate-acid rocks. The most important example comes from a granitoid intrusion (granite and granodiorite) in Monte Mucrone, Sesia-Lanzo zone, Italy (Oberhänsli et al., 1985), where the mafic inclusions within granitoid have entirely been transformed into eclogites, whereas granitoid well preserved primary granitic fabric and assemblage. Only in high-strain zones or fluid-rich places, fine-grained garnet was formed along the rim of biotite, jadeite + zoisite + quartz after plagioclase, and phengite after K-feldspar. Therefore, whether or not granitoid transformed into high-pressure assemblage hinges on the behavior of deformation and the supply of fluid. The similar case has also been found in Kaghan Valley, N Pakistan (O'Brien and Treloar, 2001). Actually, gabbroic structure and mineral assemblage preserved within coesite-bearing eclogite have been found in Yangkou, the Sulu terrane (Zhang and Liou, 1997). The relict LG rocks in Ganghe of the Dabie Mountain seem to supply another example for the fact that primary low-pressure assemblage could be preserved within UHP metamorphic belt.

This study for LG rocks from Ganghe supplies new evidence to understand the protolith of UHP rocks, which have mostly been destroyed under UHP metamorphic condition, and a new clue to seek the basement of Yangtze craton. There is also an important implication to reconstruct the process of collision between North China and Yangtze craton. When discussing the mechanism of continent-continent collision producing UHP rocks, many geologists focused their attention on the exhumation of UHP rocks. They considered that coesite requires a rapid tectonic uplift, and a very short time (*c.* 10–20 Ma) for the exhumation of UHP rocks from mantle depth to crustal level has been suggested (Hacker et al., 1995, 1998; Maruyama et al., 1998; Webb et al., 1999). However, the subducting process seems to be difficult to infer because of the absence of geological information prior to UHP metamorphism. The presence of LG rocks in the UHP terrane gives us a chance to discuss this problem. Actually, although the lack of deformation and fluid plays an important role in the preservation of LG rocks, they would also be transformed to UHP assemblage when the slab slowly subducted leading to increasing geothermal gradient, or the subducted slab stayed at mantle depths for a long time. This suggests that UHP rocks underwent a rapid subduction and a short stay at mantle depths, implying that the subducted continental crust must be rapidly transformed into uplift after subduction. Thus, the tectonic model of

rapid subduction accompanying closely rapid exhumation (Davy and Gillet, 1986; Platt, 1986; Chopin, 1987; Dobretsov, 1991) makes it possible to interpret the geodynamic process of UHP rocks in the Dabie Mountain collisional orogen.

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