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SHRIMP zircon U-Pb dating for two episodes of migmatization in the Dabie orogen

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Zircon CL imaging and SHRIMP U-Pb dating were carried out for migmatite in the Dabie orogen. Zircons from the Manshuihe migmatite show clear core-rim structures. The cores display sector or weak zoning and low Th/U ratios of 0.01 to 0.17, indicating their precipitation from metamorphic fluid. They yield a weighted mean age of 137±5 Ma. By contrast, the rims exhibit planar or nebulous zoning with relatively high Th/U ratios of 0.35 to 0.69, suggesting their growth from metamorphic melt. They give a weighted mean age of 124±2 Ma. Zircons from the Fenghuangguan migmatite also display core-rim structures. The cores are weakly oscillatory zoned or unzoned with high Th/U ratios of 0.21 to 3.03, representing inherited zircons of magmatic origin that experienced different degrees of solid-state recrystallization. SHRIMP U-Pb analyses obtain that its protolith was emplaced at 768±12 Ma, consistent with middle Neoproterozoic ages for protoliths of most UHP metaigneous rocks in the Dabie-Sulu orogenic belt. By contrast, the rims do not show significant zoning and have very low Th/U ratios of 0.01 to 0.09, typical of zircon crystallized from metamorphic fluid. They yield a weighted $^{206}Pb/^{238}U$ age of 137±4 Ma. Taking the two case dates together, it appears that there are two episodes of zircon growth and thus migmatization at 137±2 Ma and 124±2 Ma, respectively, due to metamorphic dehydration and partial melting. The appearance of metamorphic dehydration corresponds to the beginning of tectonic extension thus to the tectonic switch from crustal compression to extension in the Dabie orogen. On the other hand, the partial melting is responsible for the extensional climax, resulting in formation of coeval migmatite, granitoid and granulite. They share the common protolith, the collision-thickened continental crust of mid-Neoproterozoic ages.

Dabie, migmatite, zircon, U-Pb age, metamorphic dehydration, partial melting

Metamorphic dehydration and partial melting are critical processes in the evolution of collisional orogens because they strongly affect the thermal and rheological features of orogenic crust[1], and may eventually result in orogenic collapse[2,3]. In an exhumed orogen, although it is difficult to determine the relationships between metamorphic dehydration, partial melting and tectonic extension, it is generally considered that the appearance of partial melting indicates the beginning of extensional deformation[1,4,5]. Moreover, partial melting has been taken as the links between metamorphism and felsic magmatism in an orogen[6−8]. Precise dating of partial melting in an exhumed orogen is, therefore, significant for understanding the effect of partial melting on orogenic evolution and the relationships between partial melting and coeval granitoid formation. Furthermore, dating of metamorphic dehydration can be used to constrain the time of transformation in tectonic regime from

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compressional to extensional states.

Migmatite widely occurs in the Dabie orogen. However, there are only a few zircon U-Pb ages available from its leucosome by traditional TIMS dating[9]. Zircons in leucosome of migmatites are very complex, including those inherited from protolith and grown during different types of metamorphism. Thus it is usually difficult to acquire the precise ages for migmatitization by the TIMS dating for different origins of zircon[10]. In this paper, we report Cl images and SHRIMP U-Pb date for zircons in two leucosomes of migmatite at Manshuihe and Fenghuangguan in the North Dabie zone. The results provide for the first time dating of different types of migmatitization during extensional collapse of a continental collision orogen.

1 Geological setting and samples

The North Dabie zone is mainly composed of tonalitic orthogneiss, with minor mafic-ultramafic rocks and lenses of eclogite and granulite (Figure 1). It was extensively intruded by Cretaceous granitoid[11 − 14]. Two domes of migmatite have been documented in this region, named the Yuexi dome in the north and the Luotian dome in the west[9,11]. They have similar features of tectonics and lithology. From centre to margin of both domes, metamorphic conditions were changed from granulite to amphibolite facies, with a gradual decrease in the intensity of migmatization[9,15].

Two samples of migmatite were used in this study, which were collected from Manshuihe in the Yuexi dome and from Fenghuangguan in the Luotian dome, respectively (Figure 1). They are the leucosome. Their protoliths are considered as typical granitic gneiss in the same area. The leucosome of sample 04NDB14 cuts the foliation of its mesosome, and does not show significantly deformed features. Sample 04NDB23 is stromatitic, and has deformed characteristics consistent with its wall rock. The two leucosomes of migmatite consist of quartz + plagioclase + K-feldspar + biotite, with minor accessory minerals such as zircon and apatite.

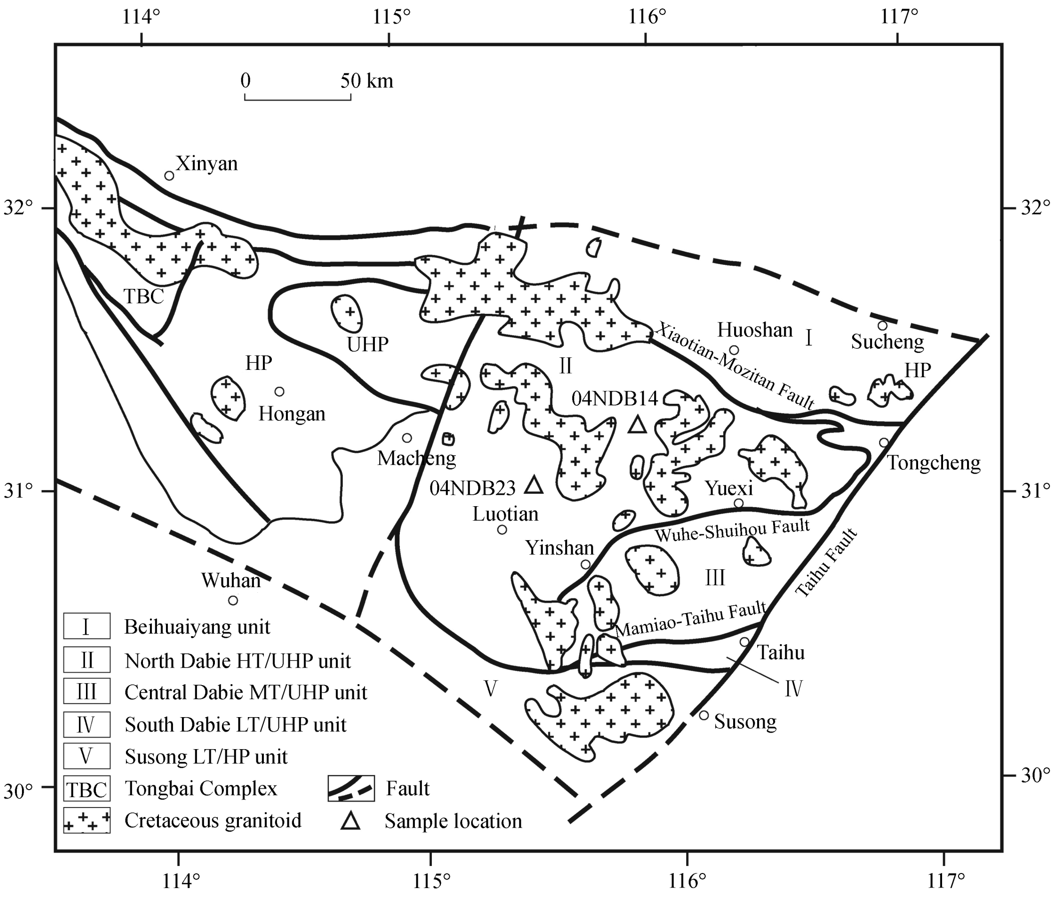

Figure 1 Sketch geological map of the Dabie terrane, and sample location of migmatites.

2 Analytical methods

Zircons were separated using the standard techniques (Wilfley table, Frantz magnetic separator, heavy liquid). Transparent zircons without crack were selected by binocular microscope, mounted in epoxy resin, and then polished down to expose the grain centers. Zircons were imaged using a JEOL JXA-8900RL electron microprobe at the Institute of Mineral Resources of the Chinese Academy of Geological Sciences, Beijing. The working conditions during the CL imaging were 15 kV and 20 nA.

Zircon U-Pb dating for samples 04NDB14 and 04NDB23 was performed using the sensitive high resolution ion microprobe (SHRIMP II) at Beijing SHRIMP Center in the Chinese Academy of Geological Sciences, Beijing. The standard operating conditions and data acquisition methods follow Williams[16]. TEMORA standard zircon was used to calibrate U/Pb isotopic discrimination during analysis. U, Th and Pb abundances were calibrated against standard zircon SL13. The measured ^{204}Pb was used for common Pb correction. The data were reduced using the ISOPLOT program[17]. Individual analyses were reported with 2σ uncertainties; weighted average of ages was also reported at the 2σ level.

3 Results

3.1 Zircon morphology

Zircons in sample 04NDB14 are short to long prismatic, transparent and colorless. In CL images, most of them show clear core-rim structures (Figure 2(a)). The cores are sector zoned or weakly zoned, typical for metamorphic zircons[18]. Some cores have resorption structures, indicating that they have been modified by later metamorphism. The rims show planar or nebulous zoning, suggesting that they crystallized from metamorphic melt[19]. Thin and discontinuous rims occur around the cores with stronger CL brightness, indicating that the cores and the rims represent two episodes of metamorphic zircon growth.

The sample 04NDB23 contains zircons with short to long prismatic, translucent and colorless features. CL imaging reveals that most zircons have core-rim structures (Figure 2(b)). The cores exhibit weak oscillatory zoning or no zoning, indicating that they are magmatic zircons suffering different degrees of solid-state recrystallization[18,20]. The rims are weakly zoned, typical for metamorphic zircons[18].

3.2 Zircon U-Pb ages

Nine spot U-Pb analyses were carried out on 5 zircon grains from sample 04NDB14 (Table 1 and Figure 3(a)). Five analysis spots were located on the metamorphic rims, while the other 4 analysis spots were obtained from the metamorphic cores (Table 1). The four analyses on the metamorphic cores yield very low Th contents of 3 to 19 ppm to result in very low Th/U ratios of 0.01 to 0.17, consistent with their metamorphic origin. Their U-Pb ages are concordant and have coherent ^{206}Pb/^{238}U ages between 135.4±4.7 Ma and 138.5±4.8 Ma (Figure 3(a)), with a weighted mean of 137±5 Ma (MSWD = 0.10). The remaining five analyses on the metamorphic rims gave relatively high Th concentrations of 64 to 177 pm, corresponding to high Th/U ratios of 0.35 to 0.69. Their U-Pb ages are also concordant with ^{206}Pb/^{238}U ages of 122.3±4.3 to 125.3±4.3 Ma (Figure 3(a)), yielding a weighted mean of 124±4 Ma (MSWD = 0.065).

Seven zircon grains were dated by 9 spot analyses for

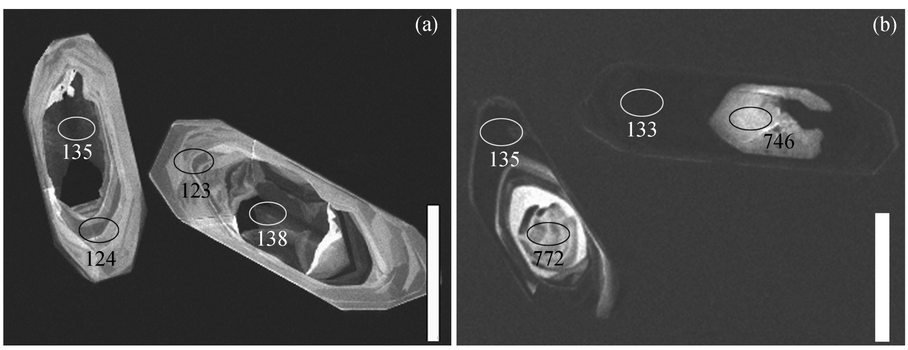

Figure 2 Typical CL images for zircons in migmatite from the Dabie orogen. (a) Sample 04NDB14; (b) Sample 04NDB23. Short white lines represent the scale bar of 50 μm.

Table 1 SHRIMP zircon U-Pb data for migmatites 04NDB14 and 04NDB23

Spot	$^{206}Pb_c$ (%)	U (ppm)	Th (ppm)	$^{232}Th/^{238}U$	$^{206}Pb^*$ (ppm)	$^{206}Pb/^{238}U$ age (Ma)	$^{207}Pb/^{206}Pb$ age (Ma)	$^{207}Pb^*/^{206}Pb^*$	±%	$^{207}Pb^*/^{235}U$	±%	$^{206}Pb^*/^{238}U$	±%
04NDB14													
1.1	4.63	258	3	0.01	4.97	138.3±4.8	157±96	0.0492	4.1	0.1471	5.3	0.02169	3.4
1.2	3.67	183	64	0.35	5.25	123.3±4.1	129±89	0.0486	3.8	0.1294	5.1	0.01931	3.3
2.1	2.52	363	16	0.04	6.75	135.4±4.7	143±75	0.0489	3.2	0.1431	4.6	0.02123	3.4
2.2	3.48	142	78	0.57	2.54	123.7±4.4	133±209	0.0487	8.9	0.1301	9.5	0.01937	3.5
3.1	1.12	230	9	0.04	4.32	138.5±4.8	124±85	0.0485	3.6	0.1452	5.0	0.02171	3.4
3.2	5.07	200	100	0.52	3.58	125.3±4.3	138±127	0.0488	5.4	0.1320	6.4	0.01962	3.4
4.1	6.38	112	19	0.17	2.05	136.2±5.0	129±113	0.0486	4.8	0.1431	5.2	0.02136	3.6
4.2	4.71	165	111	0.69	2.80	122.3±4.3	114±134	0.0483	5.7	0.1275	6.7	0.01915	3.5
5.1	3.61	333	177	0.55	6.61	123.1±4.2	135±85	0.0487	3.6	0.1296	5.0	0.01929	3.4
04NDB23													
1.1	0.97	176	91	0.54	20.6	793±24	772±67	0.06492	3.2	1.1712	4.6	0.1308	3.3
1.2	1.20	3223	273	0.09	59.2	135±4	200±53	0.05011	2.3	0.1460	4.0	0.0211	3.3
2.1	0.44	3174	65	0.02	59.2	138±5	144±42	0.04891	1.8	0.1459	3.7	0.0216	3.3
3.1	0.36	4118	55	0.01	79.5	143±5	97±36	0.04796	1.5	0.1480	3.6	0.0224	3.3
4.1	0.92	248	121	0.50	21.0	600±19	734±64	0.06377	3.0	0.8582	4.5	0.0976	3.3
5.1	0.29	1409	286	0.21	106	541±17	732±25	0.06371	1.2	0.7695	3.5	0.0876	3.3
6.1	2.24	350	76	0.22	8.20	170±6	331±88	0.05304	3.9	0.1953	4.1	0.0267	3.7
7.1	0.17	5011	44	0.01	89.6	133±4	122±28	0.04847	1.2	0.1388	3.5	0.0208	3.3
7.2	7.87	50	146	3.03	5.05	664±23	746±114	0.06412	5.4	0.9583	5.7	0.1084	3.7

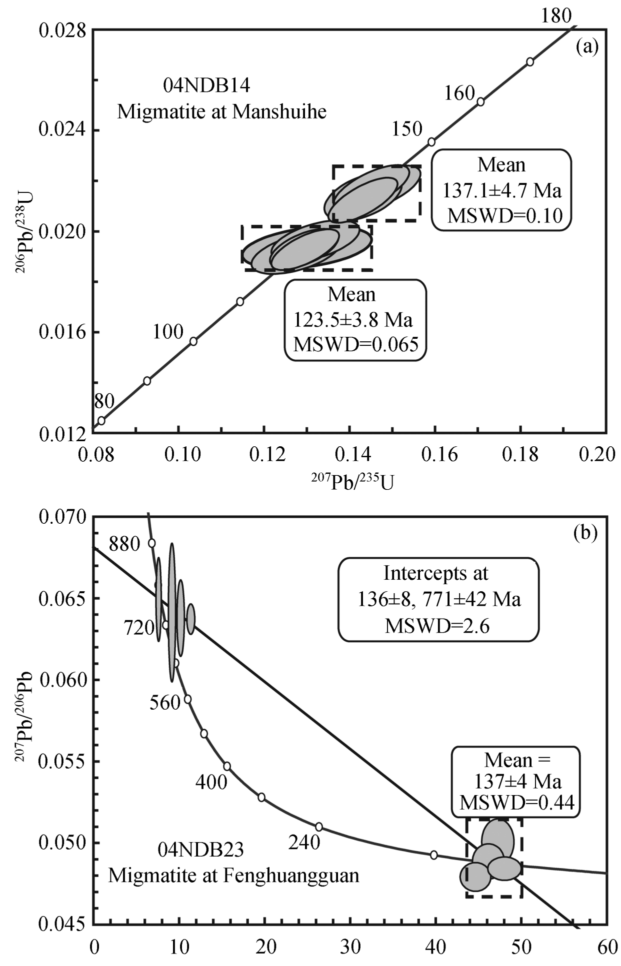

Figure 3 Concordia diagrams of SHRIMP zircon U-Pb dating for migmatite from the Dabie orogen. (a) Sample 04NDB14; (b) Sample 04NDB23.

sample 04NDB23 from Fenghuangguan (Table 1). Five analysis spots were acquired from the recrystallized protolith magmatic domains, giving Th and U contents of 44 to 286 ppm and 50 to 1409 ppm, respectively. Correspondingly, their Th/U ratios are 0.21 to 3.03, consistent with igneous origin. The other four spots from the metamorphic rims yield very high U contents of 3174 to 5011 ppm, resulting in very low Th/U ratios of 0.01 to 0.09, consistent with metamorphic origin. In the concordia plot (Figure 3(b)), the nine analyses yield a discordia line intersecting the concordia curve at 768±12 Ma and 135±10 Ma, respectively (MSWD = 2.5). The four analyses on the metamorphic rims have coherent $^{206}Pb/^{238}U$ ages of 133±4 to 143±5 Ma, with a weighted average of 137±4 Ma (MSWD = 0.44). This is similar to the lower intercept age within the analyzed uncertainties.

4 Discussion

The zircons in sample 04NDB14 from Manshuihe display clear core-rim structures (Figure 2(a)). The cores are characterized by sector or weak zoning and very low Th/U ratios of 0.01 to 0.17. This suggests that they crystallized from metamorphic fluid, and no breakdown of high Th minerals such as allanite and monazite occurred during their formation[21]. By contrast, the rims show high Th/U ratios of 0.35 to 0.69, but their planar or nebulous zoned features indicate the metamorphic origin. Because high Th/U ratios for metamorphically grown zircon can result from the breakdown of the high Th minerals during their formation[21,22], the metamorphic rims of high Th/U ratios may be precipitated from metamorphic melt in association with partial melting of epidote-group minerals. Therefore, the two groups of ages at 137±5 Ma and 124±4 Ma for the metamorphic zircons are interpreted to record two episodes of metamorphism, respectively, corresponding to different types and conditions. The first episode is characterized by dehydration at relatively low temperatures, whereas the second one involves partial melting at relatively high temperatures.

The zircons in sample 04NDB23 from Fenghuangguan also show core-rim structures (Figure 2(b)). The cores display magmatic oscillatory zoning modified by subsequent metamorphism and high Th/U ratios of 0.21 to 3.03, indicating that they are inherited magmatic protolith. The rims show no zoning and very high U contents of 3174 to 5011 ppm with low Th/U ratios of 0.01 to 0.09, suggesting their crystallization from metamorphic fluid. The nine analyses yield a discordia chord in the concordia diagram with upper and lower intercept ages of 768±12 Ma and 135±10 Ma, respectively (MSWD = 2.5). The four analyses on the metamorphic rims give a weight mean $^{206}Pb/^{238}U$ age of 137±4 Ma (MSWD = 0.44), which is identical to the lower intercept age within the analytical errors, but has a smaller uncertainty. Therefore, the age of 768±12 Ma is considered as the time of protolith emplacement, and the age of 137±4 Ma is taken as the time of zircon growth from metamorphic fluid.

Wang et al.[9] reported a U-Pb age of 131.7±1.1 Ma obtained by traditional TIMS technique for leucosome in tonalitic migmatite from the North Dabie zone, and took it as the time of migmatization. However, our CL imaging shows that the zircons from the leucosomes in the Dabie migmatites have complex structures, so that it is not easy to obtain the ages of multistage metamorphism by the TIMS method. Our SHRIMP U-Pb dating indicates the two episodes of zircon growth in the migmatite. In particular, the consistent low Th/U ratios occur in the metamorphic zircons of 137±4 Ma, indicating the event of metamorphic dehydration. On the other hand, the high Th/U ratios occur in the metamorphic zircons of 124±4 Ma, suggesting the event of partial melting. In either case, migmatization took place at the two episodes due to different metamorphic conditions. The migmatite protolith has middle Neoproterozoic ages of 768±12 Ma, consistent with protolith ages for most UHP metaigneous rocks in the Dabie-Sulu orogen[23−26].

Orogenic evolution generally comprises a period of crustal thickening followed by extension and thinning of the previously thickened crust[3,6]. In the Dabie-Sulu orogenic belt, the formation of migmatite may be relative to the extension and thinning of thickened crust formed by the Triassic continental collision. Ma et al.[27] suggested that the transition of tectonic regime from compression to extension occurred at ca. 135 Ma. This was based on the observations that granites with high Sr/Y ratios were dated at 135.4±2.7 Ma, while mafic plutons and granites with negative Sr and Eu anomalies were all dated at 105 to 130 Ma. Hou et al.[28] took an Sm-Nd isochron age of 136±18 Ma for the Huilanshan granulite in the North Dabie zone as the time of the tectonic switch from compression to extension. Xie et al.[29] considered that granite in the North Dabie zone was formed by partial melting of thickened continental crust during the orogenic extension, and interpreted zircon U-Pb ages of 128±2 Ma for the granite as the time of extensional collapse resulting in large-scale melting. In the processes of the switch of tectonic regime in post-collisional orogens, the onset of extensional tectonics is commonly associated with an increase in heat flow; crustal thinning is usually marked by partial melting and granite intrusion[4,5]. Thus the maximum age for partial melting is taken as the minimum time that extension reaches its climax[1,4,5]. Therefore, our zircon U-Pb dates for the migmatite in the North Dabie zone suggest that the switch of tectonic regime occurred at no later than 137±4 Ma in association with metamorphic dehydration.

In high-grade metamorphic terranes, partial melting shows a close spatial and temporal relationship to granitoid emplacement and granulite formation. If felsic melts were extracted from their source and accumulated together, these would eventually result in the formation of granite. And the restites correspond to mafic granulite. The age of 124±4 Ma for the second episode of migmatization in the North Dabie zone is not only consistent with known ages of ca. 120 to 130 Ma for widely post-collisional granitoids in the Dabie orogen[13,14 29,30], but also comparable with the age of 136±18 Ma for granulite-facies metamorphism in the North Dabie zone[28]. Furthermore, the protolith age for the migmatite is middle Neoproterozoic, which is consistent with the protolith ages for most UHP metaigneous rocks in the Dabie-Sulu orogenic belt[23−26], ages for inherited zircons in the post-collisional granitoids in the Dabie-Sulu orogenic belt[13,14,30,31], and protolith ages for the Huilanshan granulite in the North Dabie zone[28]. All these suggest that the migmatites have genetic relations to the coeval granitoids and granulites in the Dabie orogen, which may all be produced by partial melting of the thickened subducted Yangtze continental crust in Early Cretaceous[13,14,31]. Therefore, the second episode of migmatitization at 124±4 Ma is responsible for the climax of partial melting during the extensional collapse.

5 Conclusions

SHRIMP zircon U-Pb dating for migmatite in the Dabie orogen reveals two episodes of zircon growth at 137±4 Ma and 124±4 Ma, respectively. The first episode is characterized by metamorphic dehydration, and its age represents the onset of the tectonic switch from compression to extension in postcollisional stage. Partial melting occurred at the second episode, contemporaneously with granitoid emplacement and granulite-facies metamorphism in this region. In either case, two episodes of migmatization are well recorded in metamorphic zircons of different structures and chemical compositions. Migmatite protolith has a U-Pb age of 768±12 Ma, consistent with protolith ages of most UHP meta-igneous rocks in the Dabie-Sulu orogenic belt. Therefore, the migmatite shares common genetic relationships with coeval granitoid and granulite in the Dabie orogen. They were all produced by partial melting of the thickened subducted Yangtze continental crust in Early Cretaceous.

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