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U-Pb isotopic compositions of the ultrahigh pressure metamorphic (UHPM) rocks from Shuanghe and gneisses from Northern Dabie zone in the Dabie Mountains, central China: Constraint on the exhumation mechanism of UHPM rocks

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Abstract The U-Pb isotopic study of the ultrahigh pressure metamorphic (UHPM) rocks and gneisses from the Dabie Mountains shows that the UHPM rocks exposed in the Southern Dabie zone have relatively low Pb contents (most < 4×10^{-6}), high U/Pb ratios (most > 0.1), and a large variation of Pb isotopic ratios with relatively high radiogenic Pb ($^{206}Pb/^{204}Pb$ = 17.026—20.781). Their low Pb contents could be the result of Pb loss caused by fluid expulsion during continental subduction, while their high radiogenic Pb values can be explained by the mixing of the upper crust Pb and the mantle Pb. In contrast, the gneisses exposed in the Northern Dabie zone have higher Pb contents (most > 4×10^{-6}), lower U/Pb ratios (< 0.07), and lower Pb isotopic ratios ($^{206}Pb/^{204}Pb$ = 15.799—17.204), which are similar to those of the Mesozoic granites developed in both Northern and Southern Dabie zones. It is suggested that the Northern Dabie zone may have experienced a smaller fluid expulsion and Pb loss during the continental subduction, and their Pb isotopic compositions could be explained by the mixing of the lower crust Pb and the mantle Pb. Their initial Pb isotope ratios at 230 Ma suggest that the U/Pb ratios of the UHPM rocks in the Southern Dabie zone are higher than those of the gneisses in the Northern Dabie zone in a long period of time before the continental subduction. The above observations suggest that the protoliths of the UHPM rocks in the Southern Dabie zone are upper crustal rocks in the subducted continental crust, while the gneisses in the Northern Dabie zone have the middle-lower crust features. Based on these observations, a model for the exhumation of UHPM rocks is proposed, i.e. the detachment between the upper crust and lower crust in the subducted continental crust could have occurred during subduction, thus the subducted upper crust was uplifted by buoyancy and moved southward along the thrust.

Keywords: ultrahigh pressure metamorphic rocks, Dabie Mountains, U-Pb isotopic geochemistry.

The occurrence of ultrahigh pressure (UHP) minerals, such as coesite and diamond in crustal rocks in orogenic belts suggests that a huge amount of continental crust can be subducted to mantle depth during the continental-continental collision[1—6]. This has raised an intriguing question about how the ultrahigh pressure metamorphic (UHPM) rocks were exhumed from the depth of

> 100 km to the surface, and in the process the UHP minerals were preserved during decompression and cooling rather than being destroyed. Investigation of structure in orogenic belt is very important for the understanding of this scientific question. The study of chemical structure of subducted continental crust is a useful means to give constraint on the division of tectonic slabs and their natures in subducted continental crust.

The Dabie-Sulu collisional orogenic belt in central China is the largest known UHPM belt on the earth[4—6]. The Nd isotopic compositions of metamorphic and granitic rocks from the Dabie Mountains have been investigated. The initial results show that the Nd model ages (T_{DM} = 1.5—1.8 Ga) of the UHPM orthogneisses from the Southern Dabie zone are lower than the Nd model ages (T_{DM} = 2.0—2.6 Ga) of orthogneisses from the Northern Dabie zone[7—9], while the Mesozoic granitic intrusions developed in both the Northern and Southern Dabie zones have the same old Nd model ages (T_{DM} = 2.2—2.6 Ga)[8,9]. The Nd isotope data suggest that the crust in the Southern Dabie UHPM zone has a structure with double-layers: i.e. the upper younger crust containing UHPM rocks and deeper older crust, and the crust in the Northern Dabie zone is homogeneous old crust with no difference in Nd isotopic composition between the surface and the deep part.

The Nd isotopic model age can indicate the average age of the crust, but cannot indicate the nature of the crust. However, the upper crust and lower crust have a significant difference of Pb isotopic compositions[10]. Thus, Pb isotope could be a useful means to trace the nature of the crust. The purposes of this paper are: (ⅰ) to investigate the U-Pb isotopic compositions of UHPM rocks and gneisses from the Dabie Mountains in order to reveal the Pb isotopic structure of the subducted continental crust and the crustal natures of the Northern and Southern Dabie zones; (ⅱ) on the ground of Pb isotopes, to discuss the exhumation process and mechanism of UHPM rocks in the Dabie Mountains.

1 Geologic setting

The Dabie orogenic belt is a collision zone between the North China Block (NCB) and the South China Block (SCB). The eastern section of the Dabie orogenic belt can be subdivided into four tectonic zones from the north to the south (fig. 1(a)); they are (ⅰ) the Beihuaiyang flysch formation zone (BFZ), (ⅱ) the Northern Dabie high T/P metamorphic zone (NDZ), (ⅲ) the Southern Dabie UHPM zone (SDZ), and (ⅳ) the Susong high pressure metamorphic zone (SHPZ)[9]. They are separated each other by the Xiaotian-Mozitan fault (XMF), the Wuhe-Shuihou fault (WSF) and the Taihu-Mamiao fault (TMF), respectively (fig. 1(a)). It is, in general, accepted that the Beihuaiyang flysch formation was the southern active continental margin of the NCB before collision; while the SDZ and SHPZ belong to the subducted continental crust of the SCB[9]. Although the tectonic setting of the NDZ is a controversial issue for a long time, recent discovery of the Triassic eclogite in the NDZ suggests that the NDZ is also a part of the subducted continental crust of the SCB[11—13]. Hence, the suture between the NCB and SCB in the Dabie Mountains should be located to the north of the NDZ[9]. The NDZ, SDZ and SHPZ located to the south of the Xiaotian-Mozitan fault may represent the different parts of the subducted continental crust.

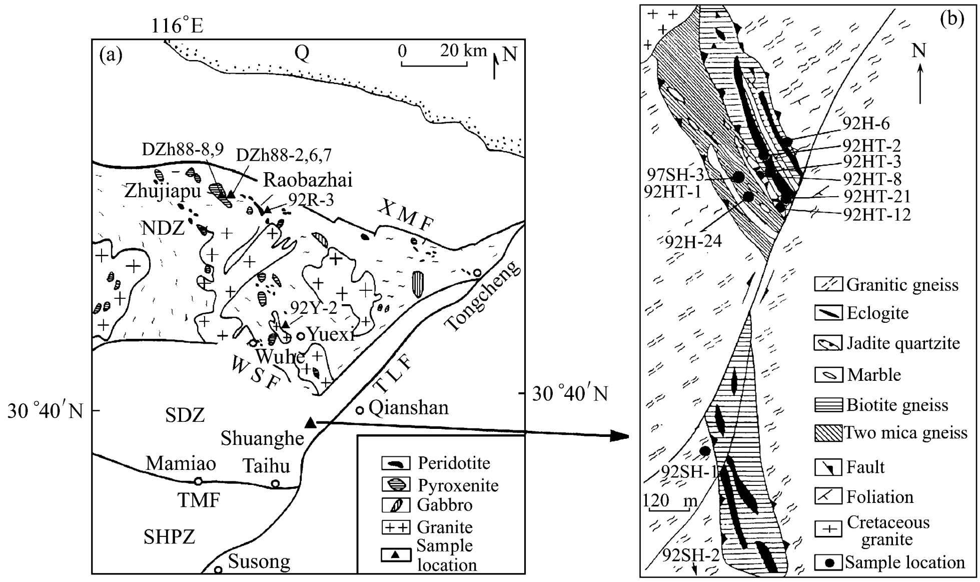

Fig. 1. (a) Geological sketch map showing the four tectonic subzones in the eastern Dabie Mountains and sample locations. BFZ, Beihuaiyang flysch formation zone; NDZ, Northern Dabie high T/P metamorphic zone; SDZ, Southern Dabie UHPM zone; SHPZ, Susong high P metamorphic zone; XMF, Xiaotian-Mozitan fault; WSF, Wuhe-Shuihou fault; TMF, Taihu-Mamiao fault; TLF, Tan-Lu fault. (b) Simplified geological map of the Shuanghe area showing the UHPM rocks and their country rocks (granitic gneiss) as well as the sample locations.

Besides huge amounts of the early Cretaceous granitic and deformed dioritic intrusions, the NDZ is mainly composed of banded grey gneisses with strong foliation. The protoliths of the banded grey gneiss were formed in late Proterozoic (700—800 Ma)[14]. All peridotites and eclogites in the NDZ are encased in these banded gneisses. The samples collected from the NDZ are such banded grey gneisses. Though the banded grey gneisses are amphibolite facies rocks, the clinopyroxene partially replaced by amphibole in these gneisses suggests that the metamorphic grade of the banded grey gneisses should be higher than amphibolite facies[15]. The NDZ is only a place to find the granulite facies rocks in the Dabie Mountains[16]. The eclogites without coesite in the NDZ have relatively high metamorphic temperature of 800—850℃. After the HP metamorphism, those eclogites were firstly retrograded at granulite facies, and then retrograded to amphibolite facies[11]. All these features mentioned above suggest that the NDZ could be the lower crust with higher temperature in the subducted continental crust, but may have not been subducted to the great depth where coesite could be formed.

The SDZ is characterized by the UHPM rock units, which are encased in the regional granitic gneisses. The UHPM units are composed of coesite-bearing eclogite, garnet-peridotite, jadite quartzite, marble with eclogite nodule and UHP metapelite (UHP paragneiss), which are interbedded each other. The relationship between the UHPM unit and the country granitic gneiss, i.e. “foreign" or "*in situ*", was a controversial issue in the past years. However, the recent discoveries of coesite or omphacite inclusions in zircons from the granitic gneiss and UHPM mineral relics in the granitic gneiss suggest that the granitic gneiss also experienced the UHP metamorphism[17,18]. Therefore, the whole SDZ has been subducted to the great depth and experienced the UHP metamorphism. The analyzed samples in this paper are mainly collected from the Shuanghe area where most kinds of UHPM rocks mentioned above are exposed (fig. 1(b)).

The early Cretaceous granites are very well developed in the Dabie Mountains. They are exposed in both the NDZ and the SDZ, and carry the information of the deep crustal compositions. The Pb isotopes of feldspar from these granites have been studied[19]. The available data show that the granites developed in both the NDZ and the SDZ have lower radiogenic Pb while no difference in Pb isotopes of feldspar is observed (fig. 1)[19]. This suggests that the lower crusts in the NDZ and SDZ have no difference.

2 Analytical procedures

Rock chunks were broken into pieces approximately 0.5 cm in size. Approximately 100 g of materials were selected to avoid altered portions in an attempt to obtain a fresh and representative sample. These pieces were cleaned in 2 mol/L HCl at 70—80℃ for 1 h, followed by washing with distilled water in order to remove contamination materials. The samples were ground in agate.

The Pb and U isotopic data were obtained at the Tianjin Institute of Geology and Mineral Resources using the VG 354 mass-spectrometer. The Pb and U contents were determined by the isotope dilution method using Pb spike H208 and U spike H235. About 0.2 g powder was dissolved using $HF+HNO_3$ for most samples, but 0.4 g powder was dissolved for a few samples with low Pb contents. Pb was first separated in HBr solution, and then U was next separated in HNO_3 solution. Pb blanks are routinely measured accompanying each analytical process with lower than 2.24 ng for analyses of the high Pb content (>2 ppm) samples or lower than 0.56 ng for analyses of the low Pb content (<2 ppm) samples using special ultraclean water and acids. Therefore, the blank correction is much lower than 0.1% or within run-uncertainties. Fractionations of Pb isotopes during analysis of mass-spectrometer were corrected with standard NBS981. The analytical results are listed in table 1.

3 Results and discussion

3.1 U and Pb contents

Table 1 and fig. 2 show that the U and Pb contents of the gneisses from the NDZ are lower than the averages of lower crust, but their U/Pb ratios (0.015—0.068) are roughly equal to the average of lower crust. The U contents of the UHPM rocks and granitic gneiss from Shuanghe mostly are lower than the average of upper crust, but higher than the average of lower crust (fig. 2(b)). The Pb contents of the UHPM rocks and granitic gneiss are largely lower than the averages

Table 1 U-Pb isotopic compositions of ultrahigh-pressure metamorphic rocks and gneisses from the Dabie Mountains

Sample No.	Rock type[a)]	Location	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{204}Pb$ (t = 130 Ma)	$^{207}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$ (t = 130 Ma)	$^{208}Pb/^{204}Pb$	Pb ($\times 10^{-6}$)	U ($\times 10^{-6}$)	U/Pb
Dzh-88-6	bi-amph-gneiss	Zhujiapu, NDZ	15.844	15.798	15.209	15.206	36.916	8.164	0.3079	0.03772
Dzh-88-7	migmatite gneiss	Zhujiapu, NDZ	16.129	16.067	15.286	15.283	37.233	8.215	0.4185	0.05095
Dzh-88-8	bi-amph-gneiss (xenolith)	Zhujiapu, NDZ	16.384	16.322	15.367	15.364	37.418	4.531	0.2254	0.049745
Dzh-88-9	bi-amph-gneiss (xenolith)	Zhujiapu, NDZ	16.473	16.430	15.338	15.336	37.351	3.928	0.1371	0.03492
Dzh-88-2	bi-amph-gneiss	Zhujiapu, NDZ	16.707	16.647	15.531	15.528	37.867	6.894	0.3290	0.04773
92R-3	mulonite gneiss	Raobazhai, NDZ	15.799	15.781	15.209	15.208	36.940	6.569	0.09574	0.01457
92Y-2	migmatite gneiss	Yuexi, NDZ	17.204	17.119	15.448	15.444	37.730	7.470	0.5060	0.06774
92HT-21	eclogite	Shuanghe, SDZ	17.026	16.818	15.400	15.390	37.564	3.986	0.6672	0.1674
92SH-2	granitic gneiss	Shuanghe, SDZ	17.524	17.195	15.423	15.407	38.759	3.611	0.9313	0.2579
92HT-1	UHP metapelite	Shuanghe, SDZ	18.815	17.939	15.684	15.641	39.927	1.675	1.116	0.6664
92HT-2	elogite	Shuanghe, SDZv	17.900	17.706	15.539	15.530	37.620	0.7055	0.1100	0.1559
92HT-3	UHP gneiss	Shuanghe, SDZ	18.341	17.916	15.566	15.545	38.430	3.086	1.023	0.3314
92H-6	UHP gneiss	Shuanghe, SDZ	17.343	16.524	15.278	15.238	38.368	1.342	0.8781	0.6541
92H-24	UHP gneiss	Shuanghe, SDZ	18.347	16.658	15.607	15.525	39.887	2.167	2.802	1.293
92SH-1	granitic gneiss	Shuanghe, SDZ	17.712	17.590	15.392	15.386	37.794	9.450	0.9115	0.09645
97SH-3	UHP metapelite	Shuanghe, SDZ	19.029	17.876	15.588	15.532	40.274	1.553	1.355	0.8725
92HT-12	eclogite in marble	Shuanghe, SDZ	20.687	20.405	15.881	15.867	38.057	6.299	1.339	0.2126
92HT-8	jadite quartzite	Shuanghe, SDZ	20.781	19.990	15.875	15.836	42.237	2.527	1.445	0.5717

a) bi, biotite; amph, amphibole.

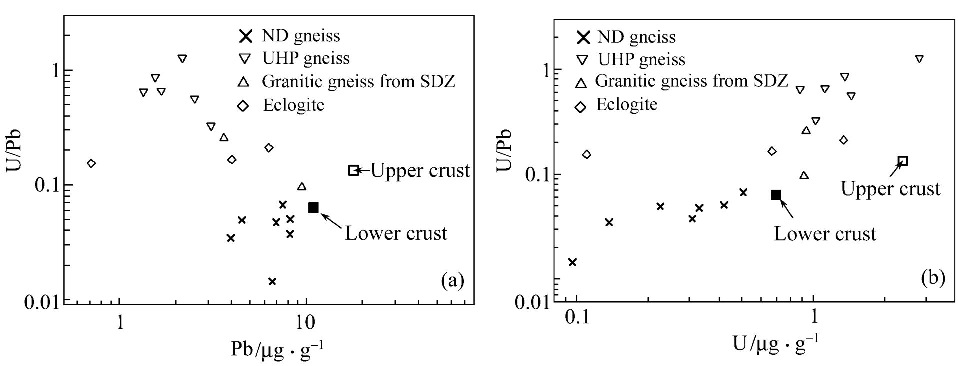

Fig. 2. U/Pb-Pb (a) and U/Pb-U (b) diagrams of the UHPM rocks and gneisses from the Dabie Mountains. Note that the UHP gneiss, granitic gneiss and eclogite are from the SDZ. The average values of U, Pb contents and U/Pb ratios of upper and lower crusts are from Taylor and McLennan (1985)[20].

of upper crust, and mostly lower than those of the gneisses from the NDZ (fig. 2(a)). Therefore, the U/Pb ratio (0.096—1.293) of the UHPM rocks and their country rocks from Shuanghe are significantly higher than the U/Pb ratios (0.015—0.068) of the gneisses from the NDZ as well as the average of lower crust, but slightly higher or equal to the average of upper crust[20]. Among the UHPM rocks, the UHP metapelites have much higher U/Pb ratios than other rocks.

The relatively low U and Pb contents of these rocks could be results of U and Pb loss through fluid expulsion of subducted continental crust during subduction. The dehydration experiments on natural amphibolite have demonstrated that Pb is more readily transported by aqueous fluids during amphibolite dehydration than U, which may result in large decrease in Pb contents and increase in U/Pb ratios of subducted oceanic crust[21]. The above observations, i.e. the Pb contents of all metamorphic rocks from the NDZ and SDZ are lower than the averages of upper and lower crusts, suggest that the subducted continental crust of the SCB experienced dehydration and a U-Pb loss process. The U and Pb data also indicate that the amount of lost Pb from UHPM rocks is not only much higher than the amount of lost U, but also much higher than the amount of lost Pb of the gneisses from the NDZ. This implies that the UHPM rocks in the SDZ suffered a stronger dehydration process than the NDZ. Since water content of upper crust is higher than that of lower crust, it is reasonable to expect that the dehydration may mainly occur in the subducted upper crust. Therefore, the above discussion suggests that the UHPM rocks exposed in the SDZ is probably the exhumed deeply subducted upper crust, while the gneisses in the NDZ could be the subducted middle-lower crust. In addition, fig. 2(b) shows that the U contents of UHPM rocks could be only a result of U loss of the upper crust, because their U contents are only lower than the average of upper crust but higher than the average of lower crust, while the U contents of the gneiss from the NDZ could be a result of U loss of lower crust.

3.2 Pb isotopes

Fig. 3 shows that the Pb isotope compositions of the gneisses from the NDZ are similar to those of the early Cretaceous granites developed in both the NDZ and SDZ. They are all characterized by lower radiogenic Pb and fall between lower crustal Pb and the mantle Pb in Pb isotopic evolution diagram of the four reservoirs computed by the plumbotectonics model proposed by Doe and Zartman (1979) (fig. 3)[10]. In contrast, the Pb isotope compositions of UHPM rocks from Shuanghe have a large variation with more abundant radiogenic

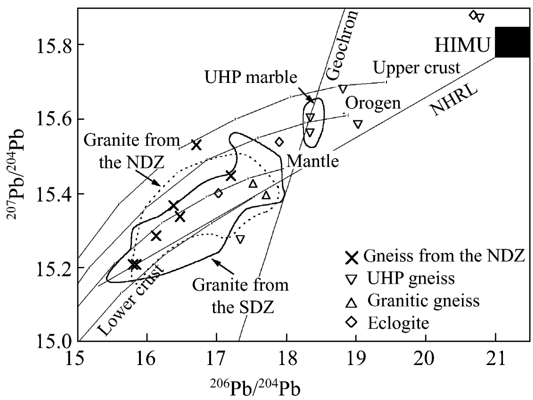

Fig. 3. $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagram of the UHPM rocks and gneisses from the Dabie Mountains. The data of granites in the NDZ and SDZ are from Zhang[19]; the data of UHP marbles are from Zheng et al.[26]; the Pb isotopic evolution lines of upper crust, orogen, mantle and lower crust are drawn after Doe and Zartman[10]. HIMU component is from Zindler and Hart[22]; NHRL, Northern Hemisphere Reference Line.

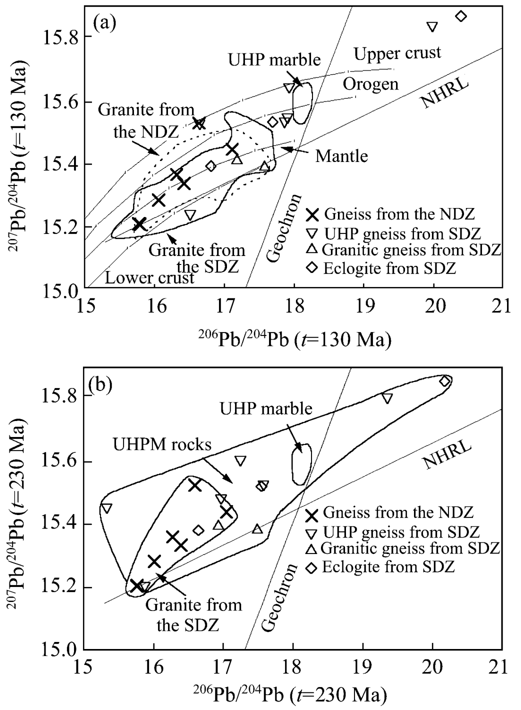

Fig. 4. $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ diagrams of the UHPM rocks and gneisses from the Dabie Mountains using the Pb isotopic data calculated back to t = 130 Ma (a) and t = 230 Ma (b). Diagram (a) is for comparison with the Pb isotopic data of feldspar from the Cretaceous granites, and diagram (b) shows their initial isotopic composition before subduction.

Pb. Their highest $^{206}Pb/^{204}Pb$ ratio of 20.781 is close to the HIMU component in the mantle, which may originate from subducted oceanic crust[22, 23]. They fall between the mantle Pb and upper crust Pb in fig. 3. In order to compare them with Pb isotopes of feldspar from the Mesozoic granites, we calculated the Pb isotope ratios back to 130 Ma corresponding to the age of the Mesozoic granites (see table 1). Table 1 and fig. 4(a) show that since the U/Pb ratios of UHPM rocks are relatively high, the Pb isotope ratios after age correction are lower than the present ratios, but their general character has no significant change.

In order to compare the Pb isotopic compositions before UHP or HP metamorphism between the UHPM rocks from the SDZ and the gneisses from the NDZ, the initial Pb isotopic compositions at 230 Ma[24, 25] have been calculated (see table 1). Table 1 and fig. 4(b) show that their initial Pb isotope compositions also have a large difference. The UHPM rocks from the SDZ also contain much more radiogenic Pb, and their variation of initial Pb isotopes is much larger than that of the gneisses from the NDZ. It is suggested that the protoliths of the UHPM rocks from the SDZ have higher U/Pb ratios for a long time period before the continental subduction, indicating its upper crustal origin; while the protoliths of the gneisses from the SDZ have lower U/Pb ratios for a long time period before subduction, indicating its lower crustal origin.

Zheng et al. (1997) reported the U-Pb isotopic data of 16 UHP marble samples from the Shuanghe-Shima area in the SDZ[26]. The Pb isotopic compositions are very homogeneous in these marbles, e.g. $^{206}Pb/^{204}Pb$ ranging from 18.077 to 18.210 and $^{207}Pb/^{204}Pb$ ranging from 15.544 to 15.640. It is interesting that the Pb isotopic composition of the marbles is very similar to the average ($^{206}Pb/^{204}Pb$ = 18.500, $^{207}Pb/^{204}Pb$ = 15.567) of Pb isotopic composition of the UHPM rocks from Shuanghe. Obviously, this Pb isotopic composition is a typical feature of upper crust.

4 Exhumation model of UHPM units

Two conclusions can be drawn based on the above U-Pb data: (ⅰ) The UHPM rocks represented by the UHPM unit at Shuanghe in the SDZ are the subducted upper crustal rocks. The unusual low $\delta^{18}O$ values of the UHPM rocks from Shuanghe also suggest that their protoliths should have been undergone the interaction with meteoric water in shallow depth before subduction[27, 28]. (ii) The gneisses in the NDZ could be the subducted middle-lower crustal rocks. The granulites exposed in the NDZ and the high temperature eclogites without coesite as well as their granulite facies retrometamorphism support this point.

If these two conclusions are true, a question is raised, which is why the NDZ as a subducted middle-lower crust, located on the northern front mostly close to the suture of the Dabie collision zone, has not experienced the UHP metamorphism (without coesite), and on the contrary, the UHPM units subducted a great depth (>100 km) are exhumed in the SDZ far from the suture. In other words, on condition of the northward subduction, what is the mechanism that makes the deeper subducted upper crust exhumed to the south of the shallower subducted lower crust? The following model provides a very simple mechanical explanation.

The subduction of continental crust is driven by both the force from the ocean stretching out at the back of the continental block and the drag force from the subducted oceanic crust in front of the subducted continental crust. These driven forces are counteracted by the buoyancy force, which is generated by density contrast between the subducted continental crust and the surrounding mantle. This buoyancy force grows with the increasing volume of subducted continental crust. Because the density of upper crust is smaller than that of lower crust, the buoyancy force applied on the subducted upper crust is larger than that applied on the lower crust. Hence, the upper crust layer finally fails under the increasing shear stress within the subducted crust and a thrust fault in between the upper crust and lower crust is formed. In this case, the subduction driven force for the upper crust layer drops, while the buoyancy force remains the same. It is this buoyancy force that causes the subsequent uplift of the deep subducted upper crust along the thrust fault. Thus, the uplifted deep subducted upper crust layer is finally overriding on the relatively shallow subducted lower crust (fig. 5(a)). The Wuhe-Shuihou ductile shear zone (fault) between the NDZ and SDZ could be this thrust fault. During the Cretaceous, the whole subducted continental crust was further uplifted by magmatic doming in the Dabie Mountains. Since the doming core located in the NDZ, the elevation of the NDZ should be the largest in the Dabie Mountains so that the UHPM rocks overlying above the NDZ may be removed by erosion and the underlying relatively shallow subducted lower crust was exhumed. Due to the lower elevation of the SDZ, most of the overriding deep subducted upper crust is preserved (fig. 5(b)). Chemenda

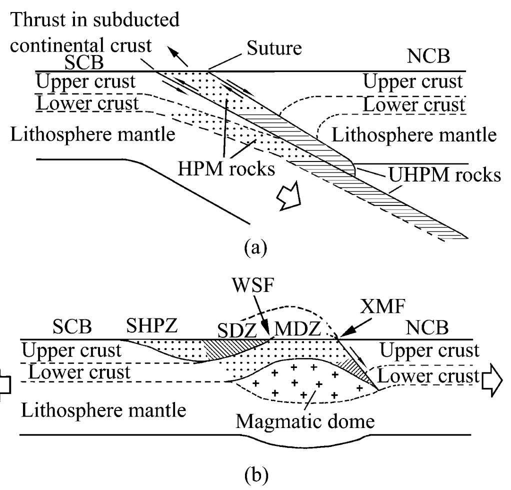

Fig. 5. Exhumation model of the UHPM rocks in the SDZ and HPM rocks in the NDZ and SHPZ of the Dabie Mountains (see text for details).

et al. (1995) have demonstrated the feasibility of the above thrust-related exhumation process through physical modeling experiments[29]. Okay and Sengör (1992)[30] and Webb et al. (1999)[31] have also proposed the similar thrust-related exhumation models. The major contributions of this paper are to identify the upper crustal nature of the exhumed UHPM units in the SDZ and the middle-lower crustal nature of the NDZ using Pb isotope tracer, and propose that the major thrust fault within the subducted continental crust occurred in between the upper and lower crustal layers during subduction. Therefore, the exhumed UHPM unit by thrust is the deeply subducted upper crust, while the exhumation of subducted middle-lower crust needs other tectonic process, such as the break off of subducted plate and post-collisional delamination or doming.

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