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Diachroneity of continental subduction and exhumation: Constraints from the Permian-Triassic HP metamorphic terrane in the Tongbai orogen, central China

LIU XiaoChun[1*], JAHN Bor-Ming[2] & LI SanZhong[3]

[1] *Key Laboratory of Paleomagnetism and Tectonic Reconstruction of Ministry of Land and Resources, Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China;*
[2] *Department of Geosciences, Taiwan University, Taipei 10699, Taiwan, China;*
[3] *College of Marine Geosciences, Ocean University of China, Qingdao 266100, China*

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High-pressure (HP) metamorphic terrane in the Tongbai orogen comprises two HP slices (I and II) and a tectonic mélange zone in the northeast and a blueschist-greenschist zone in the southwest. HP slice I is represented by the northern and southern eclogite zones on the two sides of the Tongbaishan antiform. HP slice II is represented by retrograded eclogite-bearing metamorphic enclaves in Cretaceous gneissic granites in the Tongbai Complex. U-Pb, Lu-Hf, Rb-Sr and $^{40}Ar/^{39}Ar$ multichronometric data indicate that the peak metamorphism of HP slice I took place at ~255 Ma, whereas the metamorphic ages of HP slice II are as young as 232–220 Ma. By contrast, the tectonic mélange zone near the suture was metamorphosed at ~256 Ma. Such a diachroneity of different slices across the direction of the orogen in the Hong'an-Dabie-Sulu HP/UHP terrane is ubiquitous, and it can be interpreted by a syn-subduction detachment/exhumation model. Furthermore, the metamorphic age of HP slice I in the Tongbai orogen is older than that of the equivalent HP slice in the Hong'an orogen by ~15 Ma, suggesting that the diachroneity may have also existed along the direction of the orogen. A seesaw-type subduction/exhumation model is proposed to explain this age disparity and the subduction of the South China Block becomimg shallower towards the west.

Permian-Triassic, syn-subduction detachment/exhumation, seesaw-type subduction/exhumation, HP metamorphic terrane, Tongbai orogen

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The processes and mechanism of exhumation of ultrahigh-pressure (UHP) metamorphic rocks to the Earth's surface from mantle depths exceeding ~100 km remain as one of the most difficult problems in earth science. It appears that a simple mechanism involving buoyancy and erosion is unable to explain the rapid exhumation required for the preservation of coesite. Much attention should be paid to the deep-seated tectonic processes of continental slab. Based on the nature of structural contacts and existence of metamorphic gaps between different HP/UHP metamorphic units in the Dora Maira Massif of the western Alps, Chopin [1] and Schreyer [2] inferred that the end of the downgoing slab might have successively broken to several slices during its subduction along very low geothermal gradients (~7°C/km). The earlier subducted slices could be uplifted as the overlying hanging-walls during the subduction of the later underlying slices. Liu and Hu [3] have formerly noticed the similarity of HP/UHP terrane from the Dabie Mountains and the Dora Maira Massif. Lately Liu et al. [4,5] distinguished UHP, HP and low-temperature (LT) HP slices and a tectonic mélange zone with the time difference of exhumation of ~30 Ma in the Hong'an orogen on the basis of thermobaric structure and geochronological data, and proposed a diachronous subduction/exhumation model for the formation of

*Corresponding author (email: liuxchqw@cags.ac.cn; liuxchqw@yahoo.com.cn)

different HP/UHP slices. Similarly, three HP/UHP slices with different peak metamorphic ages were also recognized in the Dabie-Sulu orogen in the light of precise isotopic dating, and multi-slice or differential subduction/exhumation model was established accordingly [6–12]. It seems that the idea of differential subduction and exhumation of continental slab has been generally accepted for the formation and evolution of the UHP terranes in China [12].

The Tongbai orogen is located in a key tectonic position linking the Qinling orogen to the west and the Hong'an-Dabie-Sulu orogen to the east. Unlike the Hong'an-Dabie-Sulu orogen, this orogen has received little attention because of the absence of UHP rocks. We recently undertook petrological and geochronological studies on the Tongbai orogen, and identified diachronous subduction and exhumation between different medium-pressure (MP) and HP slices [13–15]. Furthermore, a comparative study of the Tongbai orogen with the Hong'an orogen also revealed a diachroneity along the same MP/HP slices. Our findings provide new constraints on the processes and mechanism of HP/UHP rocks. In this paper we briefly summarize the diachronous characteristics of the Tongbai HP metamorphic terrane, and propose possible models for the diachroneity across and along the directions of the orogen.

1 Diachroneity of the Tongbai HP metamorphic terrane

The Tongbai HP metamorphic terrane comprises two HP slices (I and II) and a tectonic mélange zone in the northeast and a blueschist-greenschist zone in the southwest (Figure 1). The tectonic mélange zone is separated from the Nanwan Devonian flysch and the northern eclogite zone by two NE-dipping faults. It consists mainly of muscovite-albite gneisses, muscovite-quartz schists and greenschists, with strongly elongated metagabbro and metagranodiorite blocks. Metamorphism of the tectonic mélange zone only reached greenschist facies conditions. However, except large metagabbro and metagranodiorite blocks, all the rocks have undergone strong ductile shear deformation and formed diverse mylonites or mylonitic rocks. Since zircon U-Pb age data obtained for the equivalent unit in the Hong'an orogen are concentrated in the Neoproterozoic, it is generally accepted that the tectonic mélange zone represents a crustal segment of the South China Block [5,16–18]. Huang et al. [19] obtained a muscovite $^{40}Ar/^{39}Ar$ age of 256±1 Ma in the ductile shear zone and interpreted it as the time of deformation. This tectonic mélange zone appears to be comparable with the Luzhenguan complex in the Dabie orogen in terms of similar rock associations, metamorphism and deformation.

HP slice I is represented by the northern and southern eclogite zones on the two sides of the Tongbaishan antiform. It comprises granitic mylonites, muscovite-albite gneisses, muscovite-quartz schists, quartzites and marbles, with numerous eclogite and garnet amphibolite bands, lenses and blocks. Using conventional geothermometers and geobarometers, the peak metamorphic conditions were estimated to be 530–610°C and 1.7–2.0 GPa for the northern zone and 460–560°C and 1.3–1.9 GPa for the southern zone [13]. These are roughly in agreement with the *P-T* estimates of 490–540°C and 1.8–2.1 GPa using the THERMOCALC calculations [20]. Taking into account the similarity of rock associations and difference in metamorphic conditions between the two zones, we infer that they may belong to the different portion of the same HP slice. Two zircon U-Pb ages of 255±6 Ma and 257±16 Ma, two garnet-whole rock Lu-Hf isochron ages of 252.3±3.4 Ma and 256.4±2.6 Ma, and one mineral-whole rock Rb-Sr isochron ages of 253±11 Ma were obtained for eclogites from the HP slice I [13,20]. Since inclusions of garnet, omphacite, amphibole, paragonite, epidote, quartz and rutile were found in metamorphic zircon domains, and omphacite occur as inclusions in garnet, the age of ~255 Ma was regarded as the timing of eclogite facies metamorphism. On the other hand, muscovite $^{40}Ar/^{39}Ar$ dating for 3 muscovite-albite gneisses and 1 quartzite surrounding eclogites yielded ages of 238±2 Ma, 238±2 Ma, 234±2 Ma and 217±1 Ma, respectively [13], which reflects the time of muscovite cooling through its closure temperature of ~350°C.

HP slice II is represented by the metamorphic enclaves in the Tongbai Complex. The Tongbai Complex constitutes the core of the Tongbaishan antiform. To the northeast it is separated by a sinistral ductile fault from the northern eclogite zone, and to the southwest by a dextral ductile fault from the southern eclogite zone. The majority of the Tongbai Complex is strongly deformed coarse-grained granites, which make up ~80% of the complex. The metamorphic enclaves on varying scales consist of fine-grained TTG gneisses and subordinate amphibolites, paragneisses, calc-silicates and marbles, with a few retrograded eclogite lenses. The conventional thermobarometries yielded *P-T* conditions of 660–700°C and 0.80–1.03 GPa for the retrograde amphibolite facie metamorphic stage, whereas the peak metamorphic conditions were inferred to be within the eclogites facies field at <700°C and >1.2 GPa [14]. Zircon U-Pb geochronology for retrograded eclogites, garnet amphibolites and dioritic-trondhjemitic gneisses reveals a long-term magmatism from 933±22 Ma to 742±30 Ma, and metamorphic ages ranging from 232±6 Ma to 220±3 Ma [14]. The coarse-grained gneissic granites dominating the Tongbai Complex were dated at ~140 Ma. On the other hand, $^{40}Ar/^{39}Ar$ thermochronology on hornblende, muscovite and biotite from diverse gneisses and amphibolites yielded two age groups at 135–119 Ma and 99–92 Ma [21–23], implying that the Tongbai Complex may have involved two episodes of heating during the Cretaceous extension.

The blueschist-greenschist zone is located in the southwest of the southern eclogite zone, bounded by a ductile shear zone. To the southwest it is in contact with the South

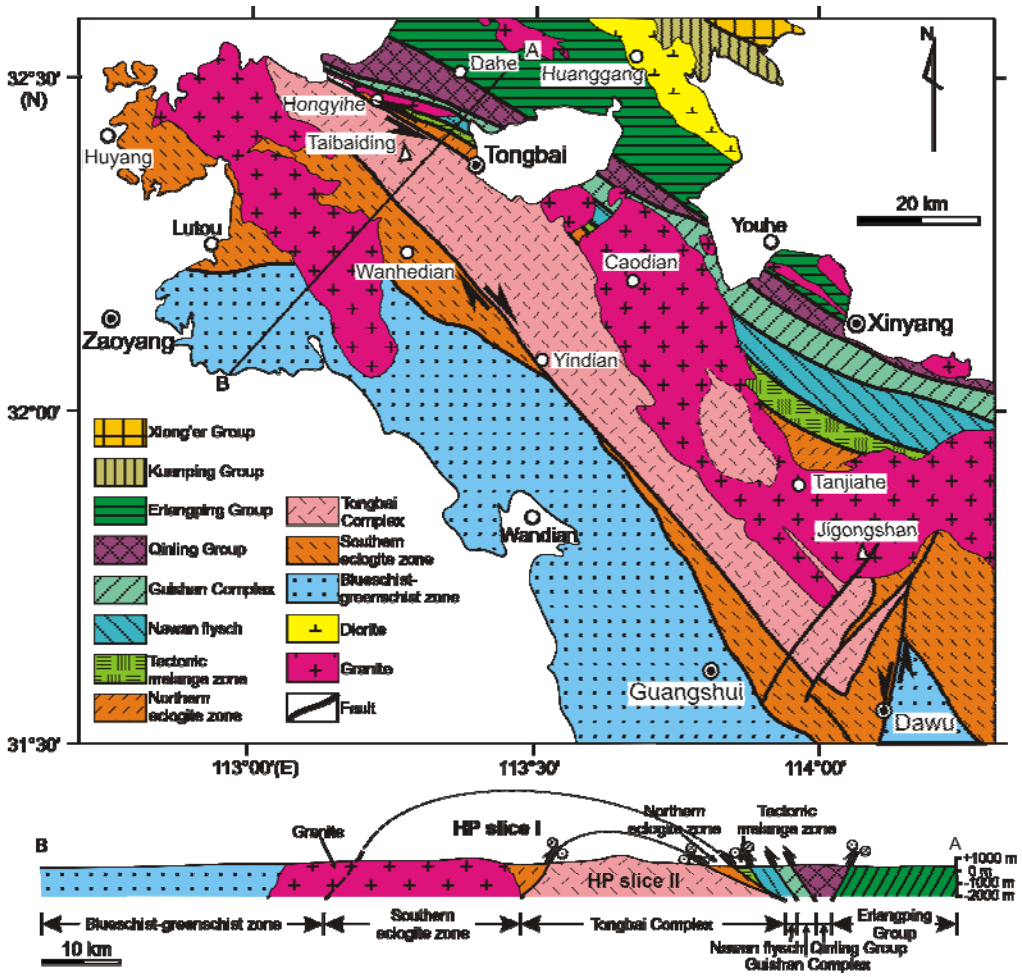

Figure 1 Simplified geological map of the Tongbai orogen and a generalized profile (A-B) across the orogen (modified after Liu et al. [14]).

China Block by the Xiangfan-Guangji fault. The lower part of the blueschist-greenschist zone is dominated by metamorphosed Neoproterozoic bimodal volcanic rocks with some metasedimentary rocks, whereas the upper part is mainly composed of interbedded greenschists, muscovite schists, muscovite-quartz schists and marbles. These two parts constitute a wide and gentle synclinal structure. The *P-T* conditions of blueschist facies metamorphism were estimated to be 350°C and 0.7 GPa, and the transition of metamorphism from blueschist facies to greenschist facies were widely observed [24]. The metamorphic age of the blueschist-greenschist zone has not yet obtained in the Tongbai orogen. However, a phengite $^{40}Ar/^{39}Ar$ age of 231±1 Ma was reported from its equivalent part in the Hong'an orogen [25].

2 Interpretation of diachroneity across the direction of the orogen: A syn-subduction detachment/exhumation model

The age of ~255 Ma obtained for HP slice I marks the oldest date of HP metamorphism in the Tongbai-Hong'an-Dabie-Sulu orogen. This signifies that the onset of continental subduction and subsequent continent-continent collision between the North and South China Blocks were not later than Late Permian. The conclusion is supported by the following two facts. (1) The garnet-whole rock Lu-Hf and Sm-Nd isochron ages of the oceanic-type eclogites from Xiongdian and adjacent area in the Hong'an orogen are concentrated to 271–252 Ma [26–29], which are later than the metamorphic zircon U-Pb ages of ~315 Ma obtained for the same eclogites [27,30–32]. This suggests that these Carboniferous oceanic-type eclogites may have been reworked by continental subduction during the Late Permian. (2) A muscovite $^{40}Ar/^{39}Ar$ age of 261.5±1.6 Ma is obtained for a metapsammite (sample XY24-1; 31°59′52″N, 114°05′02″E) from the Nanwan flysch of the Tongbai orogen (Table 1, Figure 2). This age is in agreement with muscovite $^{40}Ar/^{39}Ar$ ages (271–261 Ma) obtained from the Foziling Group of the Dabie orogen [33–35]. These two Devonian flysch sequences may represent the hangingwall accretionary complex formed during the northerly subduction of the South China Block in the latest Paleozoic [36–38]. Considering that the metamorphic ages of 340–310 Ma for the Guishan

Table 1 Muscovite $^{40}Ar/^{39}Ar$ analyses for metapsammite (sample XY24-1) from the Nanwan flysch[a)]

Step	T (°C)	$(^{40}Ar/^{39}Ar)_m$	$(^{36}Ar/^{39}Ar)_m$	$(^{37}Ar/^{39}Ar)_m$	$(^{38}Ar/^{39}Ar)_m$	^{40}Ar(%)	F	^{39}Ar ($\times10^{-14}$ mol)	^{39}Ar (Cum.) (%)	Age (Ma)	±1 s (Ma)
1	700	17.8654	0.0096	0.0000	0.0141	84.01	15.009	0.31	0.53	209.9	3.8
2	800	20.0199	0.0051	0.0594	0.0142	92.52	18.524	1.13	2.48	255.6	2.5
3	850	19.3101	0.0011	0.0000	0.0125	98.27	18.976	2.84	7.37	261.5	2.4
4	900	19.3174	0.0010	0.0000	0.0125	98.43	19.015	8.77	22.49	262.0	2.4
5	950	19.0761	0.0004	0.0033	0.0124	99.34	18.949	16.30	50.60	261.1	2.4
6	980	19.0711	0.0004	0.0005	0.0123	99.38	18.952	5.39	59.90	261.2	2.4
7	1020	19.1622	0.0008	0.0170	0.0125	98.77	18.926	3.22	65.45	260.8	2.4
8	1060	19.1930	0.0009	0.0154	0.0125	98.64	18.932	4.01	72.37	260.9	2.4
9	1100	19.1164	0.0004	0.0107	0.0124	99.35	18.992	6.92	84.31	261.7	2.4
10	1140	19.1292	0.0003	0.0176	0.0124	99.55	19.043	7.66	97.52	262.3	2.4
11	1180	19.1687	0.0005	0.0000	0.0123	99.20	19.015	1.32	99.80	262.0	2.5
12	1300	21.3820	0.0017	0.2287	0.0142	97.66	20.886	0.12	100.00	285.8	8.6

a) The $^{40}Ar/^{39}Ar$ analyses of muscovite were carried out using stepwise incremental heating at the Institute of Geology, Chinese Academy of Geological Sciences. The lower case letter "m" represents the measured isotopic ratios. Sample mass (W)=29.60 mg; J-value=0.008219; $F=^{40}Ar^*/^{39}Ar$.

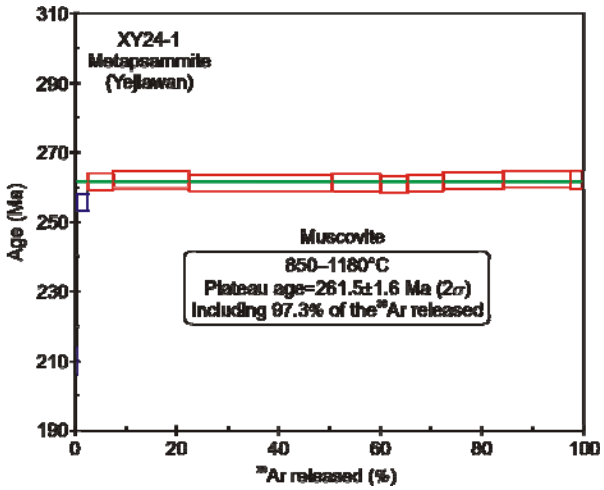

Figure 2 Muscovite $^{40}Ar/^{39}Ar$ plateau age spectra for metapsammite from the Nanwan flysch.

complex [39] are comparable with those of the Xiongdian eclogites, we infer that the oceanic subduction prior to the final collision between the North and South China Blocks may have lasted for ~60 Ma (Figure 3(a), (b)).

More importantly, the muscovite $^{40}Ar/^{39}Ar$ cooling age of HP slice I is ~238 Ma, which is older than the metamorphic age (232–220 Ma) of HP slice II. This suggests that, when HP slice II was subducted to deep levels and underwent HP metamorphism, the overlying HP slice I had probably been exhumed to middle to upper crustal levels. It is obvious that the subducted continental crust was detached at deep levels. Pb isotopic geochemical study indicates that the Pb isotopic compositions of HP slice II are more radiogenic than those from the Northern Dabie Complex, but less radiogenic than those from the Central Dabie UHP zone [40], roughly equivalent to those of mid-crustal rocks. Therefore, the detachment of HP slices I and II may occur between the middle and upper crusts. On the other hand, the muscovite $^{40}Ar/^{39}Ar$ age of 256±1 Ma was obtained for the greenschist facies tectonic mélange zone north of HP slice I [19], suggesting that this low-grade metamorphic unit represents another mixed slice derived from both Neoproterozoic basement complex of the south China Block and Paleozoic volcanic rocks of the northern Qinling terrane [41]. This mixed slice took its place at a shallow level during the subduction of HP slice I. As mentioned previously, syn-subduction detachment and exhumation of HP/UHP slices have been widely recognized in the Hong'an-Dabie-Sulu orogen [8,12]. However, it seems that the detachment of continental slab at middle to lower crustal levels is especially prominent in the Tongbai orogen. Based on the continental subduction channel model [42], the crustal slices detached at different depths could enter into the subduction channel during the subduction of continental lithosphere. These crustal slices would undergo metamorphism and deformation in varying degrees and then successively exhumed along the subduction channel. Therefore, syn-subduction detachment and exhumation might be a major mechanism for the preservation and uplifting of HP/UHP rocks in the Tongbai-Hong'an-Dabie-Sulu orogen (Figure 3(b),(c)). The final exposure of these rocks on the surface is ascribed to the Early Cretaceous extensional event (Figure 3(d)) [23].

The LT/HP blueschist-greenschist zone south of HP slice I could extend continuously eastward to the Hong'an-Dabie orogen. The metamorphic volcanic-sedimentary rocks with a better sequence in this zone may represent surficial rocks deposited on the northern margin of the South China Block. These rocks structurally show south-dipping in the Hong'an orogen [4] and top-to-the-south thrusting in the Tongbai

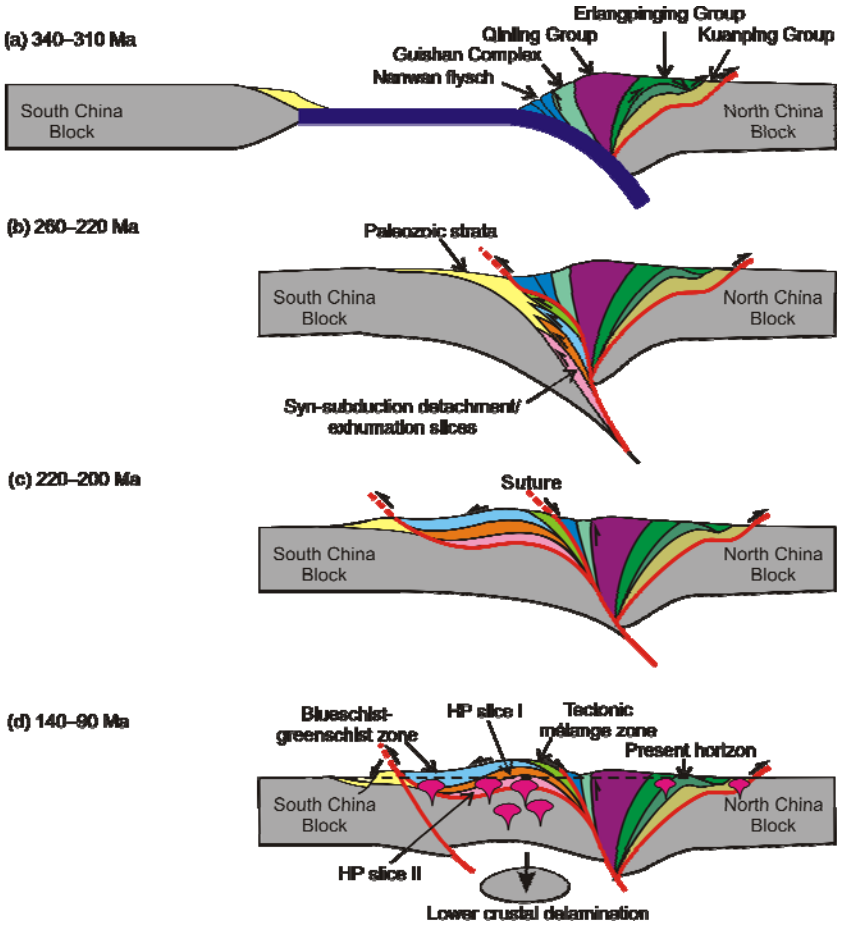

Figure 3 Tectonic evolution of the Tongbai orogen from oceanic subduction/accretion to continental collision during the Late Paleozoic to Mesozoic (modified after Liu et al. [38]).

orogen [43]. Therefore, the blueschist-greenschist zone was regarded as a large-scale nappe extruded from the northern suture in our tectonic model [5,38]. In fact, this LT/HP zone should represent an earlier detached slice. However, because the equivalent metamorphic rocks were not observed near the suture, it is difficult to determine its positional relationship with other MP/HP slices. We positioned it on HP slices I due to the direct contact and the fitness of rock associations and metamorphic environment between them. Obviously, this assumption needs to be verified by geochronological dating.

3 Interpretation of diachroneity along the direction of the orogen: A seesaw-type subduction/exhumation model?

It is generally considered that the Tongbai HP metamorphic terrane is the westward continuation of the Hong'an-Dabie HP/UHP metamorphic terrane. In addition to the absence of a UHP metamorphic zone, the major tectonic units (i.e. slices) in the Tongbai orogen correspond one-to-one to those in the Hong'an-Dabie orogen. However, the precise isotopic dating also reveals a difference of metamorphic ages in the same slice between the two areas. As previously stated, the metamorphic age of HP slice I in the Tongbai orogen is ~255 Ma [13,20]. Whilst metamorphic zircon grains from amphibolite and quartz-rich leucosome from the Huwan eclogite zone in the Hong'an orogen, which is equivalent to the northern eclogite zone in the Tongbai orogen, yielded $^{206}Pb/^{238}U$ ages of 243±4 Ma and 241±1 Ma, respectively [44]. These zircon grains contain inclusions of garnet and omphacite, and show flat HREE patterns with weak negative Eu anomalies, suggesting that they formed at eclogite facies conditions. Similarly, three garnet-whole rock Lu-Hf isochron ages of 243.3±4.1 Ma, 240.7±1.2 Ma and 238.3±1.2 Ma were obtained from the Hong'an eclogite zone [45], which is equivalent to the southern eclogite zone in the Tongbai orogen. Apparently, HP slice overlaying UHP slice in the Hong'an orogen should have formed at ~240 Ma, postdating HP slice I in the Tongbai orogen by ~15 Ma. The muscovite $^{40}Ar/^{39}Ar$ age obtained from the Balifan tectonic mélange zone north of the Huwan eclogite zone is 242±2 Ma [25], also younger than that of the equivalent slice in the Tongbai orogen by ~15 Ma. This suggests that the diachroneity may have also existed at least in

non-UHP slices along the direction of the Tongbai-Hong'an orogen.

Two groups of zircon U-Pb ages of 245–240 Ma and 225–220 Ma are common for UHP metamorphic rocks from the central and southern Dabie orogen [46–49]. The former was generally interpreted as the age of metamorphic dehydration event occurring in the transition from HP to UHP conditions during continental subduction, and the latter as the age of metamorphic dehydration event in the transition from UHP to HP conditions during the exhumation of deeply subducted continental crust [42,50]. The peak UHP metamorphism in the diamond stability field may have took place at 238–235 Ma [12]. In contrast, UHP metamorphism in the northern Dabie orogen occurred at ages as young as 226–214 Ma [7,51]. The Northern Dabie Complex shows typical structural characteristics of metamorphic core complexes [52], which could be comparable with the Tongbai Complex. The reconstruction of crustal architecture of the Dabie orogen indicates that, during the Triassic continental subduction, the Northern Dabie UHP slice underlay the Central Dabie UHP slice, and the Southern Dabie UHP slice overlay the Central Dabie UHP slice [53,54]. In comparison with the Northern Dabie UHP slice, HP slice II in the Tongbai orogen shows lower metamorphic *P-T* conditions [14], but the peak metamorphic ages are pretty much the same.

How to understand the diachroneity of metamorphism for some of the same slices along the direction of the orogen? One possible interpretation is that the passive margin of the South China Block is irregular; hence the continental collision and accompanying metamorphism may occur diachronously in different areas. We can assume that the collision between the North and South China Blocks during the Late Permian to Triassic commenced at ~255 Ma in the Tongbai area. Towards the east the age of final closure of intercontinental basin is later than the onset by ~15 Ma. This essentially fits an anticlockwise scissor-type diachronous collision model, which is different from the clockwise scissor-type diachronous collision model established for the Qinling-Tongbai-Hong'an-Dabie-Sulu orogenic belt on the basis of paleomagnetic data [55,56]. However, if this assumption is correct, HP slice in the Tongbai and Hong'an areas would not be the same slice proper, but truly two detached slices with similar geological features. If HP slice in two areas is the same slice proper, the diachroneity along the direction of the orogen could be interpreted by a seesaw-type subduction/exhumation model. It is inferred that, when the western part of HP slice in the Tongbai area was subducted to deep levels and underwent HP metamorphism at ~255 Ma, the eastern part of the same slice in the Hong'an area was also positioned at shallow levels. Subsequently, when the eastern part was subducted to deep levels and underwent HP metamorphism at ~240 Ma, the western part might have been exhumed to middle to upper crustal levels and cooled to below ~350°C. Likewise, the western and eastern parts of the tectonic mélange zone in the Tongbai and Hong'an areas were perched at shallow levels at ~255 Ma and ~240 Ma, respectively. The seesaw-type subduction/exhumation of the same slices may be triggered by a gradual steepening of the subducted slab towards the east. This model can also explain why the subduction of the South China Blocks becomes shallower towards the west and the absence of UHP rocks in the Tongbai orogen [14]. However, the diachroneity along the direction of HP/UHP slices became indistinct during the late stage of continental subduction/collision. At this period the continental slab might have only maintained subduction style with shallowing in the west and deeping in the east, but without age disparity.

4 Conclusions

The diachronous exhumation of the subducted continental slab is one of the most important features of the Tongbai-Hong'an-Dabie-Sulu HP/UHP metamorphic terrane. Such a process could have worked for other large HP/UHP metamorphic belts, such as, the Dora Maira Massif of the western Alps. The syn-subduction detachment/exhumation model can reasonably explain the difference of metamorphic ages between different HP/UHP slices in the Hong'an-Dabie-Sulu orogen. The age spectra of HP metamorphic terrane in the Tongbai orogen provide further evidence supporting this model. Furthermore, it seems that the diachroneity also exists in the same slice along the direction of the orogen. This may be important for understanding the processes and mechanism of subduction and exhumation of HP/UHP rocks. In this paper, we tentatively propose a seesaw-type subduction/exhumation model to interpret this along-strike diachroneity. However, the relations between this model and continental channel model need to be further investigated.

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