Collision and rotation of the South China block and their role in the formation and exhumation of ultrahigh pressure rocks in the Dabie Shan orogen

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ABSTRACT

Studies of regional plate-scale processes that may influence the exhumation of ultra-high pressure (UHP) metamorphic rocks are few despite their potential importance. Here, we review and summarize available age constraints along with the Qinling-Dabie Shan orogen, which separates the North China Block (NCB) from the South China Block (SCB). We find that collision-related events in the west and extension-related events in the east, where the large Dabie Shan UHP terrane is located, were contemporaneous. Available palaeomagnetic data indicate clockwise rotation of the SCB relative to the NCB during this time. Previous work indicated that the collision propagated from east to west where indentation of the SCB into the Qinling-Dabie Shan orogen was active in the Hanan Dome area at 165 ± 3 Ma as constrained by new 40Ar/39Ar dates on synkinematic sericite in an indentation-related mylonitic shear zone. While this contraction was occurring in the west, exhumation of the UHP terrane was occurring in the Dabie Shan in the east. We propose that the collision of the SCB with the NCB occurred not only in a scissor-like fashion, as previously suggested, but also involved a later rotation about a pole west of the Dabie Shan during the closure of the Mianlue Ocean. As a consequence of this rotation, extension occurred between the South China Block and North China Block east of the pole of rotation leading to extensional exhumation of the Dabie Shan orogen. This microcontinent-scale rotation of the SCB may have provided an important component in the exhumation of the largest UHP terrane in the world.

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Introduction

The Qinling-Dabie-Sulu orogenic belt was produced as a result of the collision between the North China block (NCB) and South China block (SCB) (e.g. Hacker et al., 1995; Meng and Zhang, 1999). It extends east–west for ~2,000 km (e.g. Li and Gerya, 2009), forming a prominent orogenic belt in China from the West Qinling to the Dabie Shan area in the east (Fig. 1). The Sulu orogen is located in the northern Jiangsu and eastern Shandong Peninsula in the east (inset in Fig. 1). It extends NE–SW for ~750 and ~180 km wide (Li and Gerya, 2009).

Among the tectonic units of the Qinling-Dabie-Sulu orogen, the Dabie Shan orogen and Sulu orogen in the east are well known for their large exposures of HP/UHPM rocks (e.g. Webb et al., 1999; Hacker et al., 2000, 2006). The rocks of the Dabie-Sulu UHP terrane show petrological and geochemical affinities with the Yangtze craton (Rowley et al., 1997; Hacker et al., 1998, 2006; Faure et al., 2003), which forms the northern part of the SCB. In the Dabie Shan orogen, deep subduction of SCB lithosphere followed by exhumation of HP/UHPM units were proposed to have occurred as a fairly coherent slab (Webb et al., 1999), which was made possible due to the old, cold continental lithosphere (Chemenda et al., 1996). Detailed structural studies of the Dabie Shan UHP metamorphism and subsequent exhumation have been made by several previous workers (e.g. Hacker et al., 1998, 2000; Webb et al., 1999; Grimm et al., 2003). The Dabie Shan orogen exhibits an orogen-scale antiformal structure with fold axes plunging to the west and a westward and southward decrease in peak metamorphism (Liou et al., 1996; Hacker et al., 1998, 2000, 2004). Similar UHP rocks crop out in the Sulu terrane (e.g. Hacker et al., 1995, 2000; Faure et al., 2003). The Sulu HP/UHPM terrane is bounded to the north by the Wulian-Qingdao-Yantai (WQY) extensional fault zone and to the south by the Jiashan-Xiangshui (JXS) fault zone (Hacker et al., 2006; Zhao et al., 2006). The metamorphic gradient of the Sulu HP/UHPM terrane decreases towards the south from the UHP rocks in the north to VHP and HP rocks in the south (Li and Gerya, 2009).

Numerous papers have dealt with metamorphism of UHP rocks in the Dabie Shan orogen (e.g. Okay and Sengor, 1992; Maruyama et al., 1994; Ernst and Liou, 1995; Hacker et al., 1995; Faure et al., 1999; Webb et al., 1999; Suo et al., 2000; Ratschbacher et al., 2003; Wang et al., 2003) and diverse exhumation driving mechanisms, such as buoyancy-driven, lateral and vertical extrusion and thrusting, have been proposed (e.g. Okay and Sengor, 1992; Ernst and Liou, 1995; Hacker et al., 1995; Wang et al., 2003). These models have different implications for driving forces of exhumation. However, regional changes in large-scale plate motions between the SCB and NCB and their implications to the evolution of the Qinling mountain range in general, and the exhumation of the Dabie Shan orogen in particular, have largely not been considered.
In this article, we review the available age constraints on the timing of convergence, collision, and exhumation/extension along the Qinling-Dabieshan orogen. In addition, we provide new age constraints on the timing of contraction-related deformation in the northwestern part of the Daba Shan fold-thrust belt in the western Qinling orogen to shed light on the orogen-scale tectono-thermal events and their possible relationships (Fig. 1). The model proposed in this paper provides a framework for understanding the tectonic evolution of the Dabieshan orogen, as well as the whole Qinling mountain range.

Spatial-Temporal constraints on the Early Mesozoic collision

Previous Palaeomagnetic constraints

In recent years, palaeomagnetic studies on the geologic terranes of China have seen great advances with increasing accuracy and reliability (e.g. Zhao and Coe, 1987; Wu et al., 1990, 1999; Enkin et al., 1992; Yokoyama et al., 2001; Huang et al., 2008; Sun and Huang, 2009). Published palaeomagnetic data from the NCB and SCB include data for all the geologic periods from the Palaeozoic. After selecting palaeomagnetic data from previously published papers on the NCB and SCB (Zhao and Coe, 1987; Wu et al., 1990; Gilder and Courtillot, 1997; Huang et al., 2008), it has been shown that apparent polar wander paths (APWPs) of the NCB and the SCB are different. Before Permian time, rotation and variable movement occurred in both the NCB and SCB. Based on declinations, Zhao and Coe (1987) proposed that suturing between the NCB and SCB first occurred in the east during Early Triassic time and propagated to the west in a scissor-like closure of the intervening ocean. This scissor-like closure was accompanied by 7° ± 18° relative rotation between the NCB and SCB, in which the NCB rotated about 41° anticlockwise and the SCB rotated about 35° clockwise relative to their current positions (Zhao and Coe, 1987; Zhao et al., 1996). Gilder and Courtillot (1997) suggested, on the basis of a cusp in the APWP of the NCB, that full collision between NCB and SCB occurred around Early Jurassic time (23 in Fig. 2). In addition, concordance of the APWPs after the cusp around the Middle to Late Jurassic boundary (~160 Ma) suggests that the two blocks have been one since then (Gilder and Courtillot, 1997).

Previous geochronological constraints

Available geochronological constraints are summarized and plotted in Fig. 2 (see Table S1), which includes ages that are deemed the best age constraints for contractional and extensional deformation. Geochronological constraints on individual tectonic events document a westward decrease in age. This age progression is consistent with the diachronous scissor-like collision between the NCB and SCB inferred from the Palaeomagnetic data. Events that are related to retrogression/extension and contraction are discussed further below.

Retrograde metamorphism

Initial exhumation of HP/UHPM rocks is proposed to have begun at ~240 Ma soon after peak metamorphism, which is constrained by U-Pb sensitive high-resolution ion microprobe (SHRIMP) single zircon rim ages of the UHP units (Hackert et al., 1998, 2006), Sm/Nd ages (Li et al., 1993; Okay et al., 1993), as well as the oldest detrital mica ages in the southern and eastern Dabie Shan foreland basins (Grimmer et al., 2003) (2 in Fig. 2). Retrograde metamorphism at midcrustal levels is constrained at ~225-205 Ma by 40Ar/39Ar white mica cooling ages (3 in Fig. 2) (e.g. Webb et al., 1999), and in the upper crust by 200-180 Ma in the Early Jurassic (7 in Fig. 2) (Hacker and Wang, 1995; Webb et al., 1999; Wang et al., 2003). The first evidence of exposure of the HP/UHPM rocks at the surface by the Middle Jurassic (5 in Fig. 2) is found in HP/UHP detritus in adjacent sedimentary basins, such as the Yangtze foreland basin in the south (Grimmer et al., 2003) and
Fig. 2 Geochronologic constraints on tectonothermal events association with the Mesozoic collision between the North China and South China blocks. Error bars on some data points are errors on individual isotopic ages. Long boxes with open circles represent ages of non-marine molasse in category of collisional-related events; others boxes represent the span of the event based on several data points. HP data 7, 10, 14, 19; long box of data 6 represents contemporaneous deposition of some data points are errors on individual isotopic ages. Long boxes with open circles represent ages of non-marine molasse in category of collisional-related events; others boxes represent the span of the event based on several data points. HP/UPM units in the Hong’an-Dabie Shan are taken as a whole unit as shown by the dashed box. Stars represent new age data presented here on indentation-related faults in the Hannan Dome area. Normal faults bounding the northern Dabie Shan orogen is edited after Webb et al., 1999 and Xiang et al., 2008; Extensional features exhuming the Wudang Dome are edited after Ratschbacher et al., 2003.

the Hefei basin in the north (Wang et al., 2002; Wan et al., 2005).

Syn-rotational normal-sense displacements along the northern boundary of the Dabie Shan

Contemporaneous with the HP/UHP retrogression, large-scale Triassic crustal extension of the Dabie Shan orogen was initiated along the Huwan and Xiaotian-Mozitan normal-sense shear zones at the northern boundary of the Dabie Shan orogen (e.g. Webb et al., 1999; Ratschbacher et al., 2003, 2006; Hacker et al., 2004). North-northwest-down normal-sense displacement along the boundary of the Dabie Shan orogen foot range (e.g. Webb et al., 1999; Xiang et al., 2008) shows an orogen-scale extension and doming of the Dabie Shan orogen (e.g. Hacker et al., 2004). Exhumation of HP/UHPM rocks was facilitated by this orogen-scale extension faulting of the mountain range (Webb et al., 1999; Ratschbacher et al., 2003; Hacker et al., 2004). Analysis of mineral deformation and geobarometry of synkinematic minerals in the mylonites within the extensional fault zones indicates formation of mylonites was associated with granulite to amphibolite-facies retrogression (Webb et al., 1999; Zhang et al., 2008; Xiang et al., 2009).

A minimum age for initiation of the north-dipping Huwan normal-sense ductile shear zone is constrained at 237–206 Ma by ⁴⁰Ar/³⁹Ar white mica metamorphic cooling ages (8 in Fig. 2) (Ye et al., 1993; Niu et al., 1994; Webb et al., 1999; Hacker et al., 2000; Ratschbacher et al., 2006). Eastward extension of the Huwan shear zone cannot be traced in the eastern Dabie Shan orogen as it might have been reworked by later tectonism (Hacker et al., 1998, 2004). The Xiaotian-Mozitan ductile fault zone is the northern boundary of the eastern Dabie Shan orogen. Between the Xiaotian-Mozitan ductile fault zone and Huwan shear zone, there is the NNE-striking Tuamaa dextral-shear fault zone (Fig. 1) (Wang et al., 2000). A banded gneiss zone is found in the northern part of the Xiaotian-Mozitan shear zone. It is superposed by the Xiaotian-Mozitan fault zone (Xiang et al., 2008). Ages of 218 ± 3 Ma and 199 ± 10 Ma were obtained by U/Pb SHRIMP dating on zircon mantle and rims, respectively, of the banded gneiss, which represent peak metamorphism and granulite-facies retrogression respectively (Liu et al., 2006). In addition, a temperature of 600–650 °C and pressure of 1.1 GPa was obtained from formations surrounding the mylonites in the Xiaotian-Mozitan ductile fault zone (Xiang et al., 2008). It was therefore proposed that the Xiaotian-Mozitan normal-sense ductile shearing was initiated around 199 Ma from a lower crustal level of upper amphibolite-facies (4 in Fig. 2). In addition, the northeast-southwest extension in the ductile fabrics discovered in the western Dabie Shan orogen is constrained at 198–194 Ma (Webb et al., 1999), which is consistent with the extension direction discovered elsewhere in the western Dabie Shan (Webb et al., 1999).

Collision-related tectonothermal events

In the Dabie Shan orogen (Fig. 1), a Proterozoic protolith crystallization age of 772 Ma was obtained from the high-grade metamorphic rocks (Rowley et al., 1997), which supports the tectonic affinity of the protoliths of the HP/UHPM rocks with the SCB. Samples collected from both orthogones and paragneisses UHPM rocks in the Dabie Shan orogen have yielded zircon SHRIMP and Sm/Nd isochron ages of ~245 Ma (Okay et al., 1993; Hacker et al., 1998; Grimmer et al., 2003) (1 in Fig. 2). This age is important as it supports the idea that collision between the NCB and SCB already began by the Early Triassic when UHP metamorphism was experienced by an eastern salient of continental crust in the SCB as it was
dragged down to mantle depths (e.g., Hacker et al., 2000).

The diachronous amalgamation of the NCB and SCB is recorded by synorogenic depositional sequences in the foreland basins of the Qinling-Dabie Shan orogen. During the early Carnian of the Late Triassic, Palaeocontinental reconstructions show that a nonmarine foreland basin system developed adjacent to the Dabie Shan (the southeast Hubei basin), although major portions of the basin were buried by contemporaneous overthrusting and are not exposed (Liu et al., 2005) (6 in Fig. 2). Detrital provenance analysis indicates the Dabie Shan orogen-derived sediment thickness gradually decreases towards the south (Liu et al., 2005). Terrestrial-facies molasse in the foreland basin of the Huashan area, however, were not built up until the late Carnian and early Norian of the Late Triassic (Dong, 1997; Zhao et al., 2010) (9 in Fig. 2). Studies of deformation in Lower and Middle Triassic strata constrain deformation to within the Middle Triassic (Dong et al., 1999). The Zigui and northwest Sichuan basins are located in the foreland of the east Qinling, west of the Dabie Shan. These basins have evidence of terrestrial deposition of varicoloured sandstone with some intercalated coal seams that occur later in the middle Norian of the Late Triassic (Wu et al., 1999; Liu et al., 2005) (14 and 19 in Fig. 2). In situ early Norian strata of the Late Triassic, as well as Carnian strata of the Late Triassic and Ladinian strata of the Middle Triassic consist of marine molasse and marine flysch sediments, respectively (Liu et al., 2005).

In the east Qinling, the Huangling Massif is located south of the Wudang (WD), and is separated from the WD by the Mianluo suture zone (Fig. 1). The Huangling Massif produced distinct indentation structures in the Qinling-Dabie Shan orogen, including two indentation-related NNW and NNE-striking strike-slip faults on its eastern and western sides (Li et al., 2002; Wang et al., 2003). The orogenic belt to the north of the Huangling Massif is convex northwards. The timing of deformation along the NNW and NNE-striking strike-slip faults adjacent to the Huangling Massif is poorly constrained but has been suggested to be Late Triassic at 217 ± 7 Ma to 206 ± 7 Ma by 40Ar/39Ar dating of presumed deformation-related alteration of diabase within the fault zones (the alteration phase analysed is reported as “epidote”, but the Ar analysis likely comes from white mica impurities in the sample; Li et al., 2002) (10 and 11 in Fig. 2). Synorogenic southward thrusting occurred in the southern WD due to the oblique collision between the NCB and SCB (Lei and Tang, 1996). The south-directed fold-and-thrust belt is observed to have overprinted the extensional zones that presumably exhumed the WD (Ratschbacher et al., 2003). N-S extension exhuming the WD is inferred to have occurred at 237–232 Ma by 40Ar/39Ar cooling ages on muscovite and hornblende samples from the WD. The subsequent S-directed thrusting is constrained at a minimum age of 223 ± 1 Ma (cooling age) by 40Ar/39Ar dating of phengite in the shearing-related fault zone (Lei and Tang, 1996) (12 in Fig. 2). Detailed field mapping and microstructural analysis has shown that the south-directed thrusting of basement and cover occurred in the Middle Triassic (Huang, 1993). S-directed thrusting was still active into the Early Jurassic based on the strata contact relationship with adjacent areas (Ratschbacher et al., 2003) (13 in Fig. 2). Ratschbacher et al. (2003) related the Middle Triassic extensional exhumation in the WD area to an overall syn-convergence setting during the subduction of northern SCB.

In the west Qinling, synorogenic Triassic magmatism is abundant. Such abundant magmatism is absent in the Dabie Shan orogen. Break-off of the subducting oceanic slab in the west Qinling might have occurred at a shallower depth (Sun et al., 2002) so that it produced more significant, shallow decompression melting of asthenosphere compared with the Hong’an-Dabie Shan area where the break-off of the subducting oceanic slab happened at a depth of about 200 km (Hacker et al., 2000), a depth where rising asthenosphere did not cross the solidus. Synorogenic magmatism is recognized along the north part of the Mianlue suture zone in the Dongjiangkou, Wulong and Guantoushan, areas (Fig. 1). Detailed geochemical and geochronological investigation have been carried out on the granitoid zones and they are recognized as I-type granites (e.g., Sun et al., 2000, 2002; Wang et al., 2008b; Gong et al., 2009; Wu et al., 2009).

Formation of the Shahewan intrusion of the eastern Dongjiangkou granitoid belt (Fig. 2) is constrained at 213–197 Ma by U/Pb (LA-ICPMS) dating on zircons (Zhang et al., 1999, 2009a; Gong et al., 2009) (15 in Fig. 2). The Caoping granitoid of the central Dongjiangkou belt has an age of 224.0 ± 1.1 Ma on U/Pb (LA-ICPMS) dating on zircons (Gong et al., 2009) (16 in Fig. 2). Intrusion of the Zhashui granitoids in the central Dongjiangkou belt occurred at 213.0 ± 1.8 Ma (Hu et al., 2004) and 209 ± 2 Ma (Yang et al., 2009) as constrained by U/Pb dating on zircons (17 in Fig. 2). The western part of the Dongjiangkou granitoid belt has yielded 219 ± 2 Ma (Yang et al., 2009), 218.0 ± 2.4 Ma (Jiang et al., 2010) and 210 ± 3 Ma (Sun et al., 2000) U/Pb zircon ages (18 in Fig. 2).

The Wulong synorogenic batholith is located between the Dongjiangkou and Guantoushan, and intrudes the Mesoproterozoic Foping Dome (e.g., Wang et al., 2008a). The Yanzhiba granitoid in the eastern Wulong has yielded a 210 ± 5 Ma U/Pb zircon SHRIMP age (Jiang et al., 2010) (20 in Fig. 2) and a 208 ± 2 Ma U/Pb zircon LA-ICPMS age (Qin et al., 2008) (21 in Fig. 2). Granitoids in the western Wulong have an age of 219 ± 1 Ma from U/Pb zircon LA-ICPMS (Zhang et al., 2009b) (24 in Fig. 2). Along with these intrusives, granulite was formed in the Foping Dome area, which has been dated at 212–197 Ma by U/Pb zircon rim ages (Yang et al., 1999) (22 in Fig. 2).

Formation of the Guantoushan granitoids is constrained at 220–205 Ma by U/Pb dating on zircons (Sun et al., 2000, 2002; Wu et al., 2009) (25 in Fig. 2). The Jiangjiaping granitoids in the western Guantoushan yielded a zircon U-Pb age of 206 ± 2 Ma (Sun et al., 2000) (27 in Fig. 2). The adjacent Zhangjia granitoid yielded a 219 ± 2 Ma U/Pb zircon age (Sun et al., 2000) (28 in Fig. 2). The Miba granitoid has
a 211 ± 2 Ma U/Pb zircon age (Sun et al., 2000) (29 in Fig. 2). Granulites also formed in the Anazhish areas of the Guangtoushan and have been dated at 206 ± 55 Ma by Sm-Nd isochron dating of whole rock, plagioclase and biotite (Zhang et al., 2002). A biotite cooling age from the granulites is 199.7 ± 1.7 Ma (2r) by the 40Ar/39Ar method (Zhang et al., 2002) (26 in Fig. 2). These ages are consistent with the age of granulites in the Foping Dome area.

Formation of the Yangba granitoids in the western Qinling orogen (Fig. 2) is constrained as 207 ± 2 Ma (Qin et al., 2009), 208 ± 2 Ma (Qin et al., 2009), 209 ± 2 Ma (Qin et al., 2008), and 215 ± 8 Ma (Qin et al., 2005) by U/Pb zircon LA-ICPMS ages (30 in Fig. 2). In the westernmost part of the Qinling, the Guangjiagou formation in Wenxian County (Fig. 1) of Gansu Province is identified as sediments in a remnant oceanic basin, containing granite- and volcanic rock-bearing conglomerates (Yan et al., 2004). The granites and volcanic rocks yielded a 219.7 ± 0.5 Ma 40Ar/39Ar feldspar cooling age and a 216.5 ± 0.6 Ma 40Ar/39Ar plagioclase cooling age, respectively (Yan et al., 2004) (31 in Fig. 2). The exact origin of these igneous fragments in these conglomerates is uncertain. They could be syn-collisional magmatic rocks or pre-collisional, subduction-related magmatic rocks filling a rapidly closing oceanic basin.

It is worth noting that detritus produced from erosion of the upper parts of the HP/UHP terranes are found in the thick Triassic flysch deposits (5–15 km) (Xu et al., 1992) of the Songpan-Ganzi terrane further west (e.g. Yin and Nie, 1993) along with other provenance sources (e.g. Xu et al., 1992; Yin and Nie, 1993; Sengor and Natalin, 1996; Bruguier et al., 1997). Migration of the Dabie Shan detritus westward occurred during closure of the intervening Mianlue Ocean between the NCB and SCB (Yin and Nie, 1993).

The available ages along the Qinling-Dabie orogen are summarized in Fig. 2, which includes metamorphic crystallization and cooling ages for HP/UHP metamorphism, crystallization and cooling ages on convergence/collision-related granitoids, ages of collision-related molasse, and ages of strata in angular unconformity. As seen in Fig. 2, the time of contraction-convergence related events decreases, in general, from east to west. This trend is consistent with the progressively westward scissor-like collision between the NCB and SCB as proposed by Zhao and Coe (1987) from the Paleomagnetic data. However, an additional important observation from these data is that contraction-related events appear to have been continuing in the west while extensive cooling and extension-related detachment faulting were occurring in the Dabie Shan area of the east. To further better constrain the timing of contraction in the west, we obtained additional ages on a prominent contractional feature in the Daba Shan fold-thrust belt of the west, namely faults associated with the indentation of the Hannan Dome into the Qinling orogen (Wang et al., 2003).

New geochronological constraints on indentation in the northwestern Daba Shan

The east Qinling is dominated by the south-southwestward convex Daba Shan fold-thrust belt. It is terminated by the Hannan Dome and Huangling Massif at its northwestern and southwestern ends, respectively (Fig. 1). The Hannan Dome and Huangling Massif are prominent basement terranes composed of Neoproterozoic intrusions into the Archean to Proterozoic basement of the Yangtze craton (Zhou et al., 2002; Ling et al., 2006). The narrowest part of the Qinling-Dabie Shan orogen at the western end of the Daba Shan fold-thrust belt reflects the prominent indentation of the Hannan Dome (Wang et al., 2003) (Fig. 1). Sinistral and dextral transpressional strike slip shear zones occur on the west and east sides of the Hannan Dome, respectively, associated with indentation of the more rigid Hannan Dome into the Qinling orogen (Wang et al., 1997, 2003). A field investigation was carried out on the northeast side of the Hannan Dome where prominent dextral transpressional shearing took place (Fig. 1). Right-lateral ductile shearing and thrusting were observed in carbonate and granitic-dioritic mylonites (Fig. 3a,b).

Samples CS (2) and CS (5) were collected from a ductile shear zone (Fig. 1). They are dioritic mylonites, exhibiting low-grade metamorphism. Millimetre-scale porphyroclasts of hornblende quartz diorite (predominantly hornblende + plagioclase + quartz) are in a sheared matrix of mainly quartz and sericite (see Table S1). Mineral concentrates of these two samples were obtained by conventional mineral separation techniques and were handpicked under a binocular microscope. Synkinematic sericites were extracted from the sheared matrix of samples CS (2) and CS (5) and relatively undeformed hornblende (as observed in thin section) were obtained from CS (5) (Fig. 3e,f, respectively).

The Ar analyses were done at the Berkeley Geochronology Centre in Berkeley, California. Mineral separates were loaded into wells drilled into 2 mm thick aluminum discs, interspersed with standards in a circular pattern to facilitate calculation of lateral flux gradients. Sanidine from the Fish Canyon Tuff of Colorado was used as the monitor reference, with an accepted, astronomically calibrated age of 28.201 (Kuiper et al., 2008). The hornblende and sericite were irradiated for 5 and 100 hours, respectively, in the in-core, Cd-shielded CLICIT facility of the Oregon State University TRIGA reactor operating at 1 MW. After radiological cooling, approximately 10–30 mg of hornblende and one mg (a single grain) of sericite material were loaded into a UHV extraction line and heated progressively by a 5 × 5 mm integrated CO2 laser. Samples were analysed with a MAP-215 mass spectrometer for 40Ar through 36Ar over a period of about 30 minutes. Further details of the dating procedure can be found in Deino et al. (2010). Results are displayed in Figs 4–6.

Two aliquots of each mineral separate were analysed. Results from the hornblende in sample CS (5) (Figs 3f and 4) show discordance in the argon ages of each release step. Excluding the lowest T step, the ages start at about 300 Ma and rise progressively to a highly discordant “plateau” with ages of 600–700 Ma. Although the individual steps are discordant, the age range is broadly consistent with the known geologic history of the area.
The Neoproterozoic ages (~600–700 Ma) from the hornblende, which are igneous crystals in the quartz diorite porphyroclasts, correspond to known ages for igneous basement in the SCB (Rowley et al., 1997). We therefore interpret these older ages as close to the igneous crystallization age of the mylonite protolith. The younger steps approaching ~300–400 Ma correspond in age to bimodal volcanic rocks that were formed during early Palaeozoic rifting (Lai et al., 2000). Therefore, the 300–400 Ma ages in the Ar release spectrum could represent partial resetting and disturbance of the Neoproterozoic hornblende due to heating of the quartz diorite protoliths at the time of bimodal magmatism along the northern margin of the SCB. The sericite incremental heating spectra from four aliquots (Figs 5 and 6) all exhibit a similar pattern, of low apparent ages through the first 10–15% of the total % 39Ar release, followed by pseudo-plateau behaviour until the last 15% of the gas, when ages tend to increase again. The pseudo-plateau ages (and one mathematically valid plateau of >50% of the gas in three consecutive steps with ages that are within 95% confidence of each other) fall within ~164–168 Ma; this likely represents the age of formation of the mineral (as discussed below). The slight discrepancy in the steps might be due to actual variation in the crystallization ages of the sericites over a few Myr (since these sericites probably crystallized at or below the closure temperature for Ar as argued later), slight contamination in the mineral separates by older phases such as hornblende as suggested by the higher Ca/K ratios (inferred from the higher 37Ar/39Ar) of the older steps, or slight Ar loss from a later thermal event. Regardless, the ~165 Ma ages very likely reflect a late Middle Jurassic thermal event that we interpret as close to the metamorphic crystallization ages of these sericites during mylonitic shearing.

As mentioned earlier, based on the regional disposition of structures and the kinematic symmetry of mylonitic shearing on the east and west sides of the Hannan Dome, the deformation seen in CS (5) and CS (2) is likely the result of the indentation of the Hannan Dome into the Qinling orogen. Based on the petrology and apparent ages from the hornblende discussed above, samples CS (2) and (5) represent the sheared margins of the SCB as it indented into the NCB. Sericite in the two samples crystallized during shearing-related to indentation. The time of crystallization of the sericites therefore would indicate the time of indentation of the Hannan Dome. Below, we argue that the Ar ages obtained are probably crystallization ages, rather than cooling ages, and therefore the Ar ages obtained here provide the timing of indentation-related deformation in the area.

Figs 3a–d show the ductile shearing in the area where CS (2) and CS (5) were collected. Quartz veins have been deformed into lens-shaped boudins and in thin section quartz clearly shows plastic deformation textures (Figs 3a, b, e and f). The lack of epidote in the chlorite + quartz + plagioclase-bearing rocks (the dioritic mylonites) suggests that temperatures did not exceed 300 ± 30 °C (Winkler, 1976; Bucher and Frey, 1994). The ductile deformation of quartz (Fig. 3a, b) but brittle fracturing of plagioclase as seen in thin section (Fig. 3e,f) broadly constrain the temperature of deformation in the ductile shear zone where the samples were collected to around 300–350 °C (Pryer, 1993; Sinha et al., 2010). Accordingly, the deformation temperature and therefore the crystallization T of the sericite during shearing as a result of the indentation of the Hannan Dome was
close to or below the closure temperature of sericite (375 °C ± 25 °C, Dodson, 1979). The 40Ar/39Ar age of the synkinematic sericite is thus probably a metamorphic crystallization age, i.e. the deformation age. This age (~165 Ma) corresponds with the suggested end of collision in the Late Jurassic based on the Palaeomagnetic data as discussed earlier. In summary, the geochronologic and microstructural results indicate that shearing related to the indentation of the Hannan Dome was still active by the late Middle Jurassic when exhumation in the Dabie Shan was well underway.

A testable, plate-scale tectonic model for the evolution of the Qinling-Dabie Shan orogen and exhumation of UHP rocks

From the Palaeomagnetic data, Zhao and Coe (1987) proposed a scissor-like closure of the intervening ocean between the NCB and SCB due to the clockwise rotation of the SCB during progressive collision with the NCB, probably ending in the Late Jurassic (Gilder and Courtillot, 1997). Syn-rotational extension in the Dabie Shan area in the east and contemporaneous contraction in the west, such as at the Hannan Dome area, during the continent-continent collision suggests to us that there was a change in the pole of rotation between the SCB and NCB from a pole that was initially located in the far east near the east end of the Dabie Shan during onset of scissor-like closure to a pole located further west between the Huangling Massif area and the Dabie Shan. We tentatively suggest that the westward shift in the pole of rotation probably occurred because of the resistance to convergence of the Huangling Massif in the SCB with the Wudang Dome in the Qinling orogen (Fig. 1), leading to that area being a “pivot” and thus resulting in migration of the rotation pole.

Figure 7 shows the model with the expected velocities at several points on a rigid SCB. This simple model explains the penecontemporaneous contraction/indentation in the Daba Shan in the west and the extension/exhumation in the Dabie Shan in the east. Although the role of extensional detachment faults has been recognized in the exhumation of HP/UHPM rocks in the Dabie Shan (e.g. Webb et al., 1999; Ratschbacher et al., 2003; Hacker et al., 2004), the driving force for this extension has been poorly understood. In addition to providing a reason for the extension, this model also explains other characteristics of the Dabie Shan orogen. The triangular
exposure of the Dabie Shan HP/UHP terrain and the westward decrease in peak metamorphism is predicted by this model because the amount of extension should increase eastward further away from the pole of rotation (Fig. 7). The timing, kinematics, and amount of extension of these orogen scale events can be simply explained by rotation of the SCB relative to the NCB about a pole centred west of the Dabie Shan orogen, probably near the western tip of the Dabie Shan orogen and east of the Huaping Massif area (Fig. 7). Ratschbacher et al. (2003) illustrated a similar model although with different locations for the pole of rotation.

The amount of horizontal extension at various points can be obtained simply from amount of extension = (angle of rotation, in radians) × (distance from the pole. If we take the maximum angle of rotation of 70 degrees between the NCB and SCB inferred from the Palaeomagnetic data and use a distance to the pole from the east end of the Dabie Shan of about ~400 km, then the amount of extension at the eastern end of the Dabie Shan would be about 409 km. The amount of extension due to this rotation is likely to be less, because the initial phase of relative rotation of the SCB and NCB occurred prior to the proposed westward migration of the pole. Regardless, there is potentially a large amount of rotation-related extension that could have affected the Dabie Shan area.

We hypothesize that the clockwise rotation was driven by slab pull on the western segment of the SCB where oceanic subduction continued while continent-continent collision was happening in the east. Granitoids from subduction of the Palaeo-Tethys Ocean underneath the East Kun orogenic belt have been constrained at around the Triassic of Indosinian orogeny (e.g. Guo et al., 1998; Mo et al., 2007), which is one of the lines of evidence in support of continuous oceanic subduction in the west while continental collision was fully in progress in the east.

Continental subduction of the SCB underneath the NCB to UHP conditions occurred by Early Triassic time in the eastern SCB. The eastern segment was subducted to greater depths into the mantle, where peak metamorphism was attained around 245–230 Ma (e.g. Hacker et al., 2006) (Fig. 8a). Onset of clockwise rotation of the SCB relative to the NCB took place at that time while oceanic subduction continued in the west. During this process, the Huaping Massif area may have developed into a point of resistance in the collision causing the pole of rotation to migrate to that

![Figure 6](image-url)  
**Fig. 6** $^{40}$Ar/$^{39}$Ar incremental release spectra for two aliquots of sericite separated from the granitic mylonite CS (2); vertical axis represents age (Ma); horizontal axis is cumulative per cent $^{39}$Ar released. Aliquot (b) has an acceptable plateau age of ~166 Ma. The thickness of the bars on the age spectrum plots is ±1σ, whereas the uncertainties on the reported plateau ages are ±2σ.

![Figure 7](image-url)  
**Fig. 7** Regional kinematic model for the Qinling-Dabie Shan orogeny involving rotation of a relatively rigid SCB relative to the NCB. Dashed concentric circles represent traces of points on the rigid block about the pole of rotation leading to contraction in the west and extension in the east; big dashed arrows indicate coeval extension and exhumation of HP/UHPM rocks in the Dabie Shan orogeny and contractual indentation of both the Huaping Massif and Hannan Dome in the middle and west, respectively.
area from the east. As a consequence, the underthrusting of the continental slab in the Dabie Shan area would have to reverse and rotate southward away from the NCB (Fig. 8b). Friction at shallow levels of the crust and viscous coupling deeper in the crust as the SCB rotated south and southwest would have led to extension in the overlying NCB (the eventual area of the Dabie Shan) facilitating exhumation. Meanwhile, due to the less dense nature of the SCB continental crust with respect to the mantle, positive buoyancy drove the deeply subducted continental crust to rise to the lower crust as proposed by other workers based on P-T-t data (Ernst and Liou, 1995), which may have led to doming of the upper crust (Fig. 8c). The exhumation of UHP rocks from the lower crust to the surface, however, cannot be driven by positive buoyancy, as was possible from mantle depths to the lower crust, due to the lack of significant density contrast. Exhumation driven primarily by regional extension due to southward rotation of the SCB therefore may have been an important mechanism for UHP exhumation at this stage of the orogen (Fig. 8d). First exposure of HP/UHPM rocks to the surface after unroofing probably occurred by the Late Jurassic based on the stratigraphic and tectonothermal analysis in the Heifei basin and the Lower Yangtze fold-thrust belt. Clockwise rotation of the SCB relative to the NCB appears to have ceased by Late Jurassic time based on previous Palaeomagnetic evidence, broadly coinciding with the deep indentation-related shearing in the Hannan Dome area as constrained by the new ages presented here. The final amalgamation between the NCB and SCB was completed by this time (Fig. 8e).

The model outlined here does not necessarily rule out other mechanisms of exhumation that have been previously proposed. Models of buoyancy-driven exhumation, lateral and vertical extrusion, thrusting, and the SCB rotation model proposed here are not mutually exclusive. All the different mechanisms could be working together producing variable extension directions recorded in the Dabie Shan. However, the model proposed here incorporates several regional constraints that were previously not considered and provides an additional mechanism that could have been important in exhuming the Dabie UHP terrane, namely, it provides a plate-scale cause for the orogen-scale extension that occurred in the Dabie Shan area while contraction continued in the west. Future research regarding the Dabie Shan orogen, therefore, might benefit by considering the possible role of rotation and “withdrawal” of the SCB.

The similar geology of the Sulu terrane to that of the Dabie Shan terrane has been noted by others (e.g. Hacker et al., 1995, 2000; Faure et al., 2001). It is thought to be the eastern extension of the Dabie UHP terrane (e.g. Faure et al., 2003). In some models, the Sulu and Dabie Shan orogen were originally contiguous (e.g. Zhao et al., 2006) and the Sulu terrane was sinistrally displaced ~500 km northwards from the Dabie Shan terrane by the Tanlu fault zone (e.g. Liou et al., 1996; Hacker et al., 2000; Zhao et al., 2006). Both terranes have a migmatitic dome overprinting the UHP rocks, and have top-to-the-northwest ductile extensional shearing bounding the northern margin of the UHP terranes. Also, both have a northward increasing metamorphic gradient with UHP metamorphic ages of 240 Ma (Faure et al., 2001; Hacker et al., 2006; Li and Gerya, 2009).

The Tanlu fault zone sits at the eastern boundary of the Dabie Shan orogen and is the western truncation of the Sulu UHP terrane, and is recognized by some as a zone of Late Triassic-Early Jurassic sinistral displacement (Xu et al., 1987; Zhu et al., 2009). If the Dabie and Sulu terranes were once contiguous and later separated by sinistral motion along the fault, this would predict that the Tanlu fault should have formed as a large intraplate fault that should continue south of the southern edge of the Dabie Shan. Most geologic maps do not show the fault extending further south, although lack of exposure and covering or truncation by younger rocks (such as Mesozoic plutons) may obscure the fault. Detailed geophysical surveys might be able to test whether the fault does, or does not, continue south of its current assigned termination within the Dabie Shan. The apparent timing of motion along the fault, which partly overlaps the timing of UHP metamorphism,
however, argues for a different model for the Tanlu fault.

An alternative scenario is one in which the crust on the east side of the Tanlu fault may have been part of the same proposed rigid rotating SCB block. In this scenario, the Sulu terrane has not been displaced from the Dabieshan terrane; it formed in situ and the Tanlu fault acted as a transform zone between the two zones of underthrusting/subduction during HP/UHP metamorphism (e.g. Zhu et al., 2009).

The subsequent clockwise rotation of the SCB would then lead to extension aiding exhumation of both the Dabieshan and Sulu terranes. In this case, the eastern boundary of the rigid clockwise-rotating SCB might have been the Andean-type plate margin of southeast China (e.g., Li and Li, 2007) and/or a wide zone of distributed sinistral deformation in eastern China.

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References


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**Supporting Information**

Additional Supporting Information may be found in the online version of this article:

**Table S1.** Summary of geochronologic constraints on various tectonic units within the Qinling-Dabie Shan orogen

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