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U/Pb zircon ages constrain the architecture of the ultrahigh-pressure Qinling–Dabie Orogen, China

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Abstract

New SHRIMP and TIMS zircon ages, $^{40}Ar/^{39}Ar$ ages, and eclogite locations contribute significantly to our understanding of the ultrahigh-pressure Dabie Shan. (1) The geographic extent of the Yangtze craton that was subducted to ultrahigh pressure extends to the northern edge of the Dabie Shan. (2) The northern half of the Dabie Shan is a magmatic complex, intruded over a 10-Myr interval between 137 and 126 Ma, that accommodated ~100% N–S stretching of the pre-existing collisional architecture. (3) Granitic orthogneisses and enclosing ultrahigh-pressure paragneisses have indistinguishable zircon populations. The population of Triassic zircon ages ranges from ~219 to ~245 Ma, leading us to question the prevailing assumption that 219 Ma zircons formed at ultrahigh pressure, and to propose instead that they reflect late retrogression at crustal pressures following the bulk of exhumation.

Keywords: Dabie Mountains; zircon; absolute age; Sino–Korean platform; high pressure; orogenic belt

1. Introduction

The Dabie–Hong'an–Tongbai–Qinling are a 2000-km long ultrahigh-pressure (UHP) orogen formed chiefly in the Triassic by attempted N-directed subduction of the Yangtze craton or a microcontinent beneath the Sino–Korean craton (Fig. 1) [1,2]. Investigation of UHP tectonics has focused on the Dabie Shan because of the wide variety of continental crustal rocks that were metamorphosed under a complete range of low to ultrahigh pressures and temperatures. From S to N, the main rock units are a fold-and-thrust belt, blueschist, high-pressure amphibolite, quartz eclogite, coesite eclogite, the Northern Orthogneiss unit (NOU), the Luzhenguang Group, and the Foziling Group (Fig. 2). All are intruded by voluminous Cretaceous plutons, and units on the margins of the mountains are overlain by Cretaceous and younger alluvium (references in Fig. 1). The blueschist through eclogite units constitute a prograde metamorphic se-

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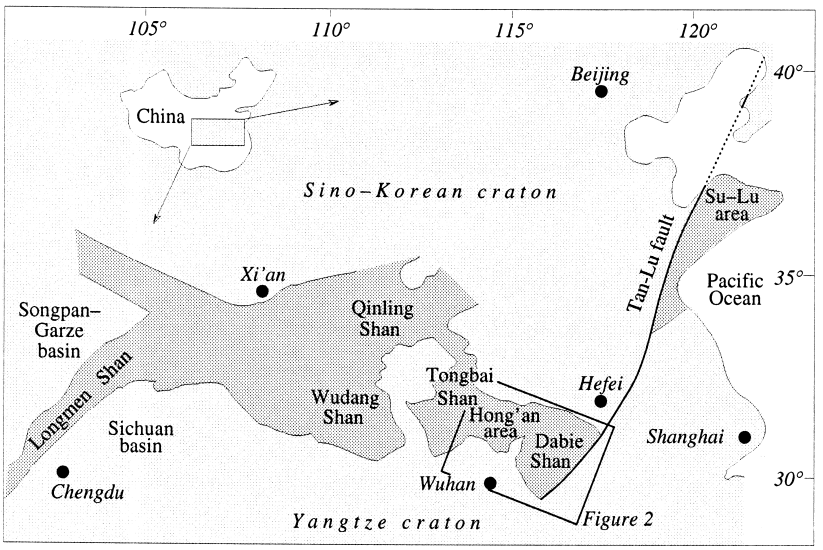

Fig. 1. Collisional orogen in central China, comprising the Wudang, Qinling, Tongbai, Hong'an, Dabie Shan, and Su-Lu areas.

quence, with the coesite-bearing eclogites indicating subduction of continental crust to >120 km [3,4]. Hacker et al. [5] interpreted these units as a single transpressionally (dextral) shortened crustal segment exhumed by extrusion over the Sino–Korean craton combined with erosion. The NOU is a magmatic-structural dome formed during Cretaceous NW–SE subhorizontal extension [5] that overprints an earlier granulite-facies basement sequence. The Luzhenguang and Foziling Groups are less well known units that may represent continental basement and cover, respectively.

In the Hong'an area (Figs. 1 and 2), blueschist-facies rocks are better developed and distinct greenschist, prograde amphibolite, and eclogite-retrogressed-to-amphibolite units have been mapped (e.g., [6]). Also, a wider variety of metamorphic rocks not generally grouped with the ultrahigh- and high-pressure units crop out in E–W trending fault-bounded units at the northern limit of the mountain range (i.e., the Sujiahe through Erlangping Groups in the NW corner of Fig. 2). Many of these units are well known in the Qinling area (Fig. 1; e.g., [7]).

This paper summarizes new geochronological/petrological/structural data that address significant questions about the architecture of this orogen: (1) Where is the suture between the collided Sino–Korean and Yangtze cratons? (2) What is the spatial extent of the UHP metamorphism? Were, for instance, the Northern Orthogneiss, Luzhenguang, or Foziling units subjected to UHP? (3) Were all rock types in the UHP units metamorphosed at UHP or are some of them lower pressure rocks that were juxtaposed at a later date? (4) What is the temporal relationship between the UHP metamorphism and the granulite-facies metamorphism of the NOU?

2. Qinling–Dabie orogenic architecture and UHP metamorphism

The Triassic suture between the Sino–Korean and Yangtze cratons has been proposed to be located either in the central Dabie Shan (Fig. 2) between the NOU and the coesite eclogite unit (e.g., [8]), or along the Xiaotian–Mozitang Fault near the northern edge of the Dabie Shan (e.g., [9]). Neither of these is a primary feature; the former is a Cretaceous normal fault, and the latter is a Cretaceous sinistral transtensional fault [5]. The location of the suture constrains the size and composition of the material that was subducted to UHP depths and is central to understanding the scale and mechanism of exhumation. We report a new location for the suture based on U/Pb zircon ages, $^{40}Ar/^{39}Ar$ ages, and the description of a new eclogite locality.

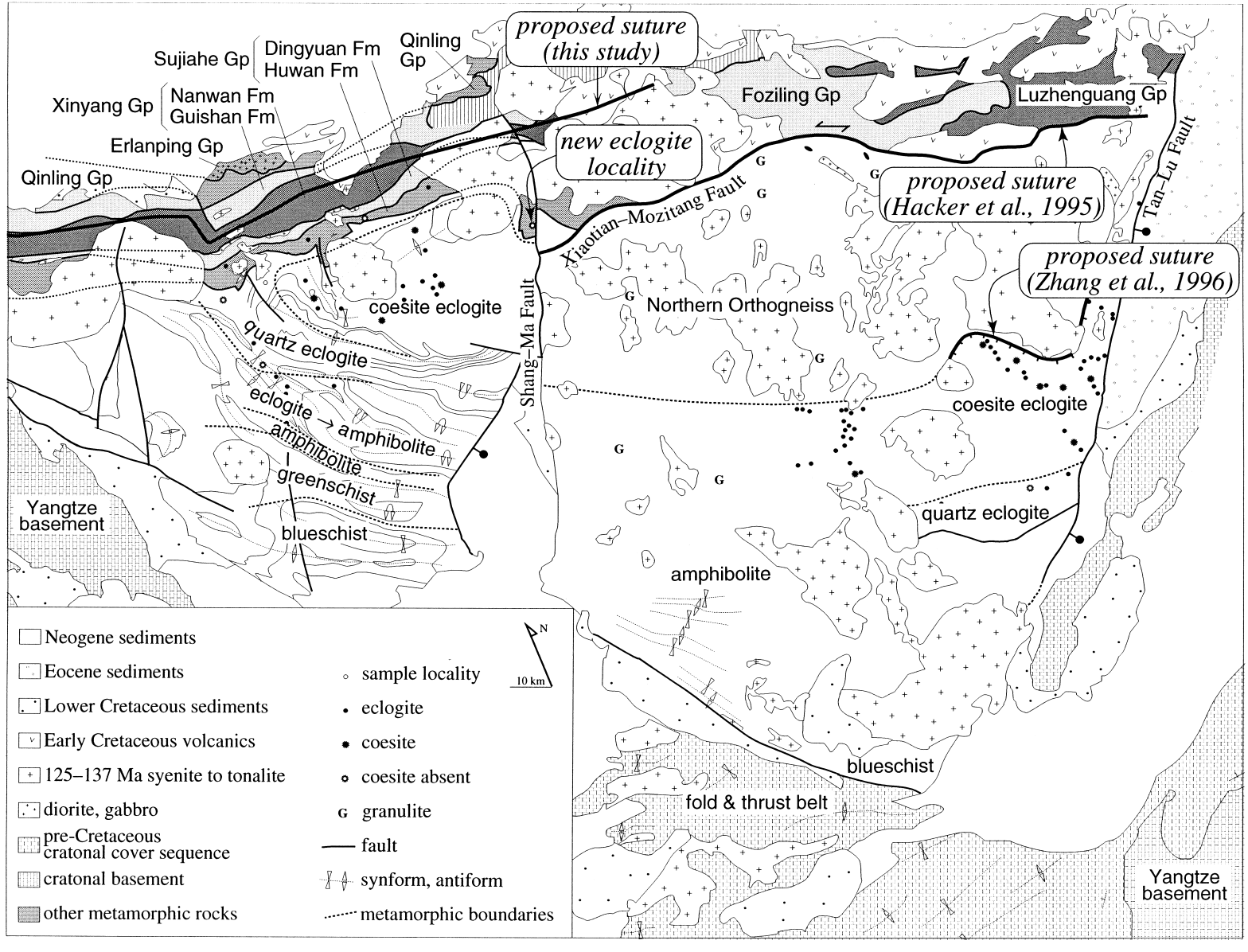

Fig. 2. Map of the Dabie Shan and Hong'an areas drawn from our mapping in 1993–1997 and Regional Geological Survey of Anhui [30], Regional Geological Survey of Henan [29], Regional Geological Survey of Hubei [45], Okay et al. [9].

Interpretation of the eclogite units as a coherent UHP terrane (e.g., [10]), has come under increased scrutiny. 'Eclogite' units exposed in the Dabie and Hong'an blocks are composed of micaceous paragneiss, granitic orthogneiss, and ~2 vol% eclogite blocks. Coesite has been found in a modest number of eclogite localities and rarely within the micaceous paragneiss [3,4], but the granitic orthogneiss lacks any evidence of UHP metamorphism and has been suggested to postdate the UHP event [11]. If true, the granitic orthogneiss might represent (1) magmas that postdate the UHP event and were intruded at relatively low pressure; or (2) slices of low-pressure rocks interleaved with the eclogites and UHP paragneiss at crustal levels. We evaluate this controversy with a SHRIMP U/Pb study.

Because the UHP rocks make up only a minor fraction of the Dabie Shan, the tectonic history of the huge NOU has been an issue of major interest. What is the temporal relationship between the UHP metamorphism recorded by the eclogites and the granulite-facies metamorphism recorded by the NOU? Do the granulite-facies rocks represent: (1) part of the Precambrian metamorphic core of the Sino–Korean or Yangtze cratons; (2) material at the leading edge of the subducted craton that was metamorphosed and melted at even greater depths than the eclogite units; or (3) products of 'post-collisional' Cretaceous magmatism? The age of the granulite-facies metamorphism of the basement of the NOU is central to answering these questions and is evaluated below using U/Pb zircon ages.

3. Data and interpretations

3.1. Analytical methods

We analyzed zircons by thermal ionization mass spectrometry (TIMS) at the University of Kansas and by sensitive high-resolution ion microprobe (SHRIMP II) at the Australian National University (**EPSL Online Background Dataset** [1], Tables 1 and 2). Operating procedures for SHRIMP II followed Muir et al. [12] and those for TIMS are given in **EPSL Online Background Dataset** [1] (Table 1). The common Pb estimation for SHRIMP ages was derived from the extrapolation of data to concordia based on the $^{207}Pb/^{206}Pb$ ratio. Data are shown in Fig. 3, an example cathodoluminescence image of analyzed grains is provided in Fig. 4, and the sample localities are shown in Fig. 5.

3.2. Pluton and orthogneiss samples

Sample DS25 represents the common tonalitic orthogneiss found throughout the NOU. It contains tschermakitic hornblende with 2.5 wt% TiO_2, sphene, An_{32-35} plagioclase, magnetite, ilmenite, zircon and quartz; Al-in-hornblende barometry suggests an equilibration pressure of 450 MPa. All ten zircons analyzed by SHRIMP are oscillatorily zoned and contain pre-Triassic cores; the bulk have Late Precambrian apparent ages consonant with our TIMS upper intercept age of 771 ± 28 Ma. One grain of approximately fifty examined contained a high-U, low Th/U rim visible with cathodoluminesence from which three spots were analyzed. The weighted mean error of the rim analyses has a high MSWD of 10.1 and so the standard error is used because it is not possible to determine whether Pb loss or inheritance caused the overdispersion. The SHRIMP age for the rims is 138 ± 6 Ma, concordant with our TIMS lower intercept age of 129 ± 26 Ma. It is significant that this rock type, which appears to be the oldest widespread unit within the NOU, gave the oldest Cretaceous zircon age of this study.

Sample DS58, a gabbro weakly deformed by the Xiaotian–Mozitang fault, contains magnesian hastingsitic hornblende with 1.7% TiO_2, plagioclase, epidote, sphene, apatite, monazite, and zircon. Hornblende barometry indicates crystallization at 550 MPa. Zircons from this gabbro are prismatic with oscillatory zoning and are dominated by Cretaceous growth, except for a few cores — one of which gave an apparent age of ~900 Ma. The SHRIMP data appear slightly overcorrected for common Pb using the ^{204}Pb correction method, so the age was calculated from the common Pb-concordia intercept. The weighted mean age of the Cretaceous spots is overdispersed with an MSWD of 2.54, so the standard error was used. The SHRIMP age of 129 ± 2 Ma agrees with our TIMS age of 125 ± 2 Ma. This

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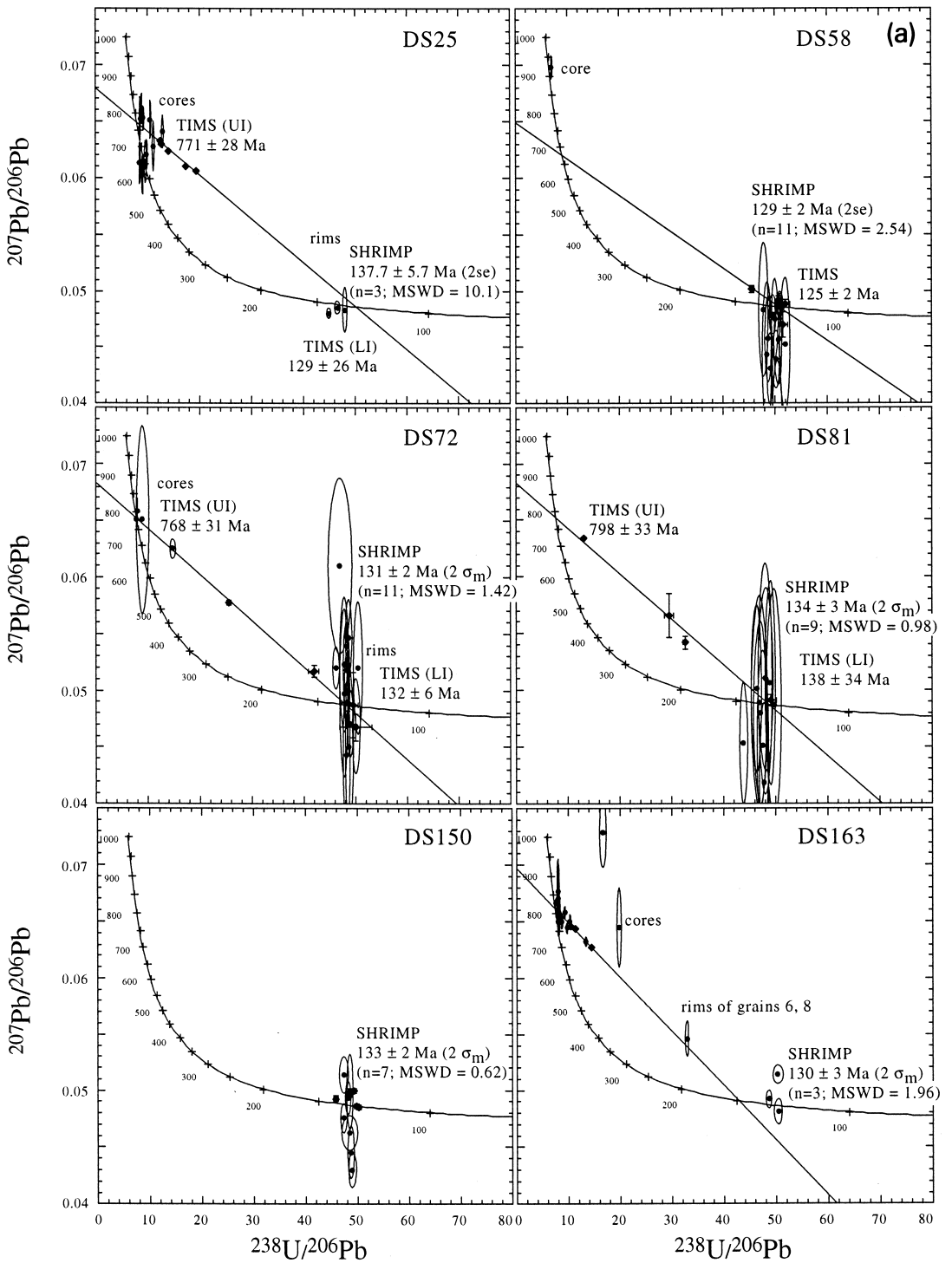

Fig. 3. U/Pb zircon ages. (A) Tera-Wasserburg concordia plots (corrected for common Pb) showing SHRIMP (filled circles with 1σ error ellipses) and TIMS (filled diamonds, 2σ error bars). The errors in the SHRIMP analyses are dominated by uncertainty in the common Pb correction producing subvertical dispersion. Age estimates are based on the intersection of the common Pb locus with concordia. TIMS regressions are shown as the thin line. These rocks are dominated by 600–800 Ma Precambrian cores, with Cretaceous overgrowths and new zircon.

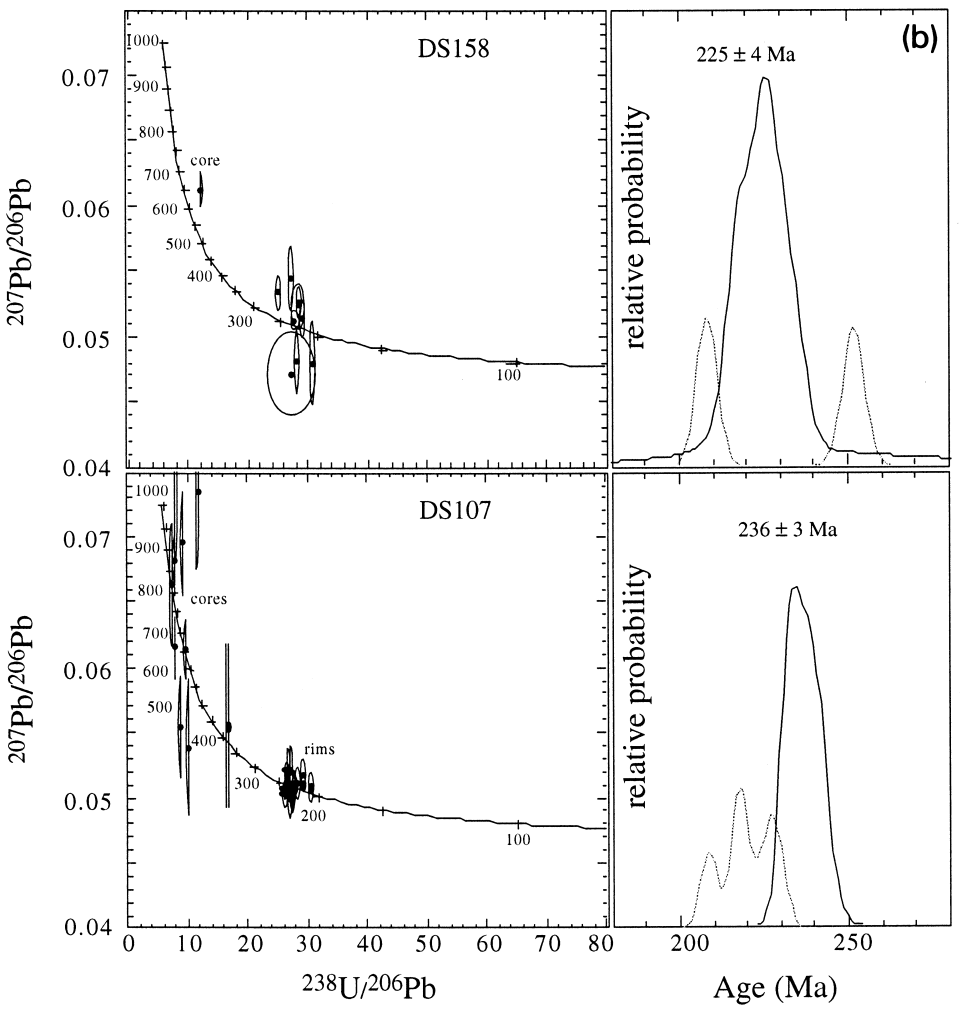

Fig. 3 (continued). (B) Triassic ages. SHRIMP ages are shown on Tera-Wasserburg plots and also as relative probability curves which are derived from the cumulative probability of common-Pb corrected $^{206}Pb/^{238}U$ ages. These rocks again show Precambrian inheritance with Triassic metamorphic zircon growth. Two ages are apparent in the cumulative probability plots. DS158 has a dominant peak that is 225 ± 4 Ma while the main peak in DS107 is 236 ± 3 Ma, with a contribution from younger zircon similar in age to DS158. These U/Pb ages are consistent with the presence of 230 Ma Ar ages from some eclogites.

is the youngest U/Pb zircon age from the Dabie area that we report.

Sample DS72 is a tonalite with a hypersolidus fabric; it contains magnesiohornblende with 1.3% TiO_2, biotite, K-feldspar, sphene, An_{28-38} plagioclase, quartz, monazite, and zircon. Hornblende barometry indicates equilibration at 530 MPa. Zircons are prismatic to acicular, with oscillatory and sector zoning; three examined by SHRIMP contain cores whose ages are consistent with our TIMS upper intercept age of 768 ± 31 Ma. Thirteen SHRIMP analyses of rims yielded a weighted mean $^{206}Pb/^{238}U$ concordia intercept age of 131 ± 2 Ma (MSWD = 1.42), concordant with our TIMS lower intercept age of 132 ± 6 Ma.

Sample DS81, from the weakly deformed Tuanling tonalite includes tschermakitic hornblende with 1.6 wt% TiO_2, sphene, An_{24-28} plagioclase, apatite, monazite, ilmenite, and zircon. The hornblende Al content suggests a crystallization pressure of 530 MPa. Zircons are prismatic with oscillatory and sector zoning; nine of ten examined by SHRIMP gave a weighted mean age of 134 ± 3 Ma (MSWD =

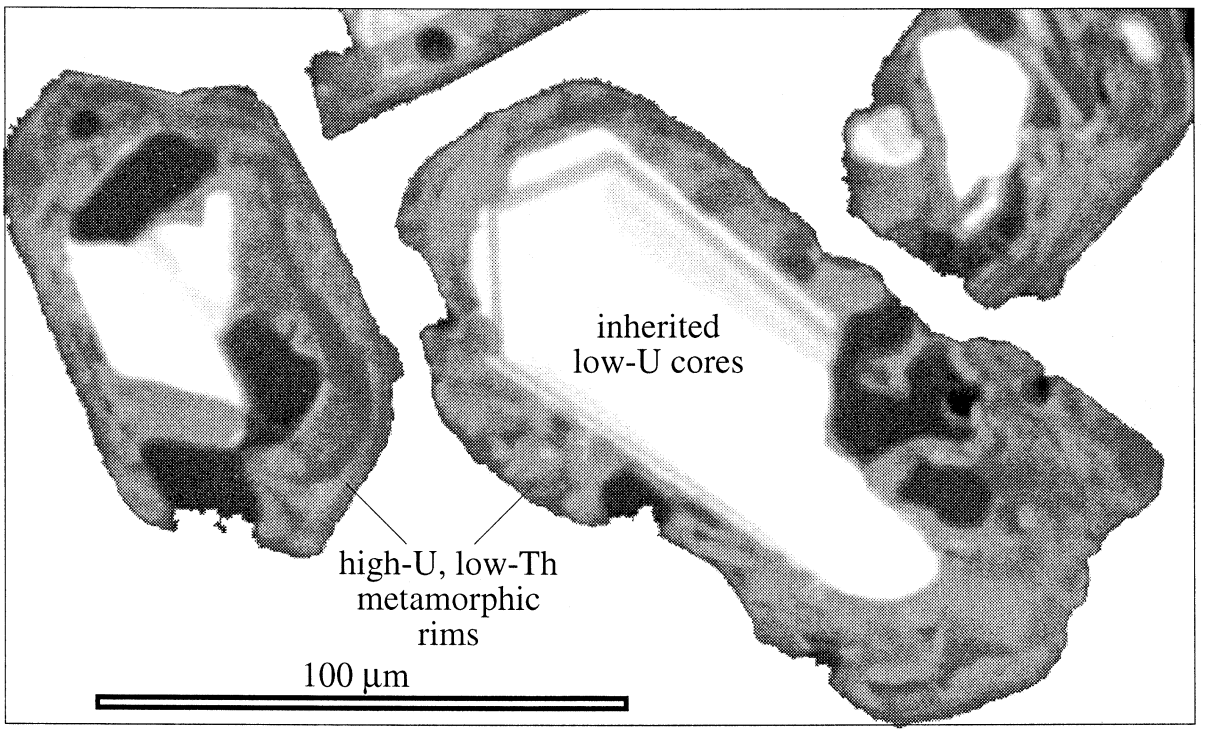

Fig. 4. Cathodoluminescence image of zircons from UHP orthogneiss DS107. Light areas are generally low U inherited cores. Medium gray zircon is high U (low Th/U) metamorphic zircon intergrown with a nonluminescent phase.

0.98), concordant with our TIMS lower intercept of 138 ± 34 Ma (MSWD = 8). Inherited cores were not visible with cathodoluminesence, but a single slightly older SHRIMP age (~140 Ma) may be due to mixing of Cretaceous and inherited material, as indicate by TIMS data, which have an upper intercept age of 798 ± 33 Ma.

Sample DS150 is a granitic gneiss. The zircons are large prismatic grains with oscillatory zoning. SHRIMP analyses of three grains yielded a weighted mean concordia intercept age of 133±2 Ma (MSWD = 0.62). Five of the TIMS fractions range in age from 127 to 132 Ma, suggesting partial Pb loss, but a single TIMS fraction has a slightly older age, suggesting inheritance.

Zircons in sample DS163, an undeformed granite, are similar to DS25 in appearance and isotopic characteristics. Two grains had high-U, low Th/U rims visible in cathodoluminesence, from which three analyses gave a weighted mean concordia intercept age of 130 ± 3 Ma (MSWD = 1.96). Most of the material in this sample is Precambrian (~800 Ma) as indicated by the TIMS analyses and the SHRIMP ages of the cores. Hornblende barometry indicates crystallization at 430 MPa.

3.3. Eclogite unit samples

Sample DS158 is a paragneiss from the coesite eclogite unit. Zircon grains are small and rounded. Under cathodoluminesence, two grains contained highly luminescent cores, while the rims of these grains and the other grains were uniformly low luminescent. The rounded form and the very low Th/U (0.02–0.08) of the low-luminescence zircon are characteristic of metamorphic zircon. The small size of the grains allowed only one clean core analysis, which is Precambrian and apparently experienced minor Pb loss. The ten analyses of metamorphic zircon range from ~210–250 Ma. The weighted mean is 224 ± 4 Ma but the MSWD of 13 indicates excess dispersion. There are two clear outliers in this population. The oldest analysis is from grain 6, which has an inherited core; this analysis may therefore be

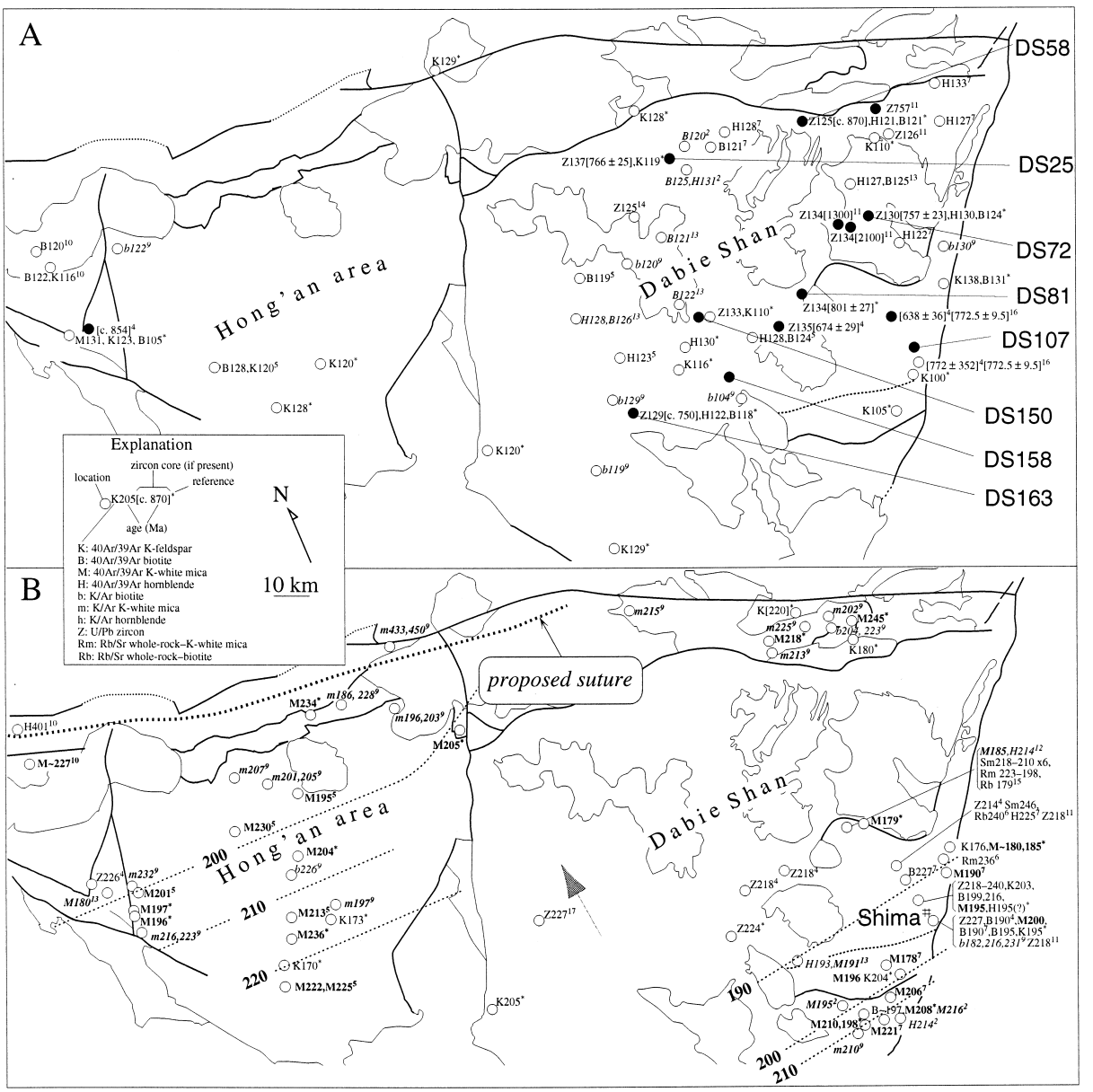

Fig. 5. Simplified map of the Dabie Shan and Hong'an areas showing (A) Precambrian and Cretaceous radiometric ages, and (B) Silurian–Jurassic radiometric ages. Contacts are the same as Fig. 2. Filled circles (•) indicate zircons with Precambrian cores. Italicized ages are those for which no spectrum was published or the spectrum was judged to be poor; we have re-interpreted some of these published spectra such that the quoted age is different than that originally published. Sources: *, this study; *1*, Li et al. [16,46]; *2*, Mattauer et al. [13]; *3*, Chen et al. [47]; *4*, Ames [48]; *5*, Eide et al. [17]; *6*, Okay et al. [9]; *7*, Hacker and Wang [18]; *8*, Liou et al. [3]; *9*, Chen et al. [49]; *10*, Niu et al. [50]; *11*, Xue et al. [24]; *12*, Cao and Zhu [51]; *13*, Chen et al [52]; *14*, Zhang and Sun [53]; *15*, Chavagnac and Jahn [54]; *16*, Rowley et al. [14]; *17* Chen et al. [55].

compromised by a slight overlap onto core material. The youngest analysis is also well removed from the population but in this case is on the younger side of the main population. If these two analyses are removed, the weighted mean concordia intercept age is 225 ± 4 Ma with a satisfactory MSWD of 1.90.

Sample DS107 is an orthogneiss from the coesite eclogite unit that contains garnet, phengite, $An_{03\text{-}16}$ plagioclase, quartz, and sphene. Zircons from this sample comprise low-U oscillatorily zoned cores that are partially resorbed and overgrown by high-U, low-Th rims. Isotopically, DS107 is similar to DS158, with Precambrian cores and 'Triassic' rims ranging from 209–243 Ma. A weighted mean of all 'Triassic' ages from DS107 is 231 ± 2 Ma, but the high MSWD (10.9) indicates this is not a single population. The probability density plot (Fig. 3B) suggests that Pb loss is a factor because of the presence of points younger than the main peak and the distribution is skewed to lower ages. As lower points are successively removed, the distribution becomes more Gaussian but it is still slightly overdispersed, with the weighted mean of the eleven oldest analyses being 236 ± 3 Ma (MSWD = 2.12). The cores show a range from 380–850 Ma but the two ages younger than 640 Ma may have experienced Pb loss.

The geologic significance of the mean ages of DS158 and DS107 requires further investigation. Rowley et al. [14] obtained precise U/Pb TIMS ages of 219.5 ± 0.5 Ma for two other samples from the coesite eclogite unit, and Ames et al. [15] reported similar, although less precise ages. The mean age from DS158 is broadly consistent with these TIMS data — although slightly, but possibly not significantly, older. However, the majority of zircons from DS107 are significantly older, with a mean age of 236 Ma. It is unlikely that this older age is due to overlap of analyzed spots onto older cores. The zircons in DS107 are quite large (>200 μm) and clean spots were obtained on the rims. Furthermore, random degrees of contamination would not produce the observed peak in the spectrum. It is more likely that there is an earlier metamorphic zircon crystallization event. This may explain why some Sm/Nd ages from the Dabie Shan are as old as 245 Ma [9,16] and many $^{40}Ar/^{39}Ar$ ages are older than 219 Ma [16–18]. We tentatively suggest that zircon growth occurred at ~240 Ma and ~219 Ma in these samples.

3.4. Location of the Triassic Sino–Korean/Yangtze suture

The suture between the Sino–Korean and Yangtze cratons can potentially be identified by mapping the distribution of rocks, isotopic signatures, deformation styles and ages, and metamorphic facies and ages. We have collected three kinds of data that suggest that the suture lies N of the Xiaotian–Mozitang Fault, probably along the northern boundary of the Nanwan Formation (Fig. 2).

3.4.1. U/Pb zircon ages

The predominant (re)crystallization ages of rocks from the Yangtze and Sino–Korean cratons are beginning to be defined through zircon dating. Uncertainty over which craton a given zircon age 'belongs to' arises from two sources: disagreement over where the boundaries between 'true' parts of the cratons and (presumed) microcontinents should be drawn; and the realization that unlike other parts of the world, cratons in Eurasia underwent substantial growth and development during the Phanerozoic.

The southern margin of the Sino–Korean craton in the Qinling–Dabie area is represented by the Qinling and Erlangping Groups (Fig. 2). These rocks have yielded single-grain Pb/Pb evaporation ages of Ordovician to Devonian; most fall in two groups: 488 ± 10 to 470 ± 20 Ma for deformed metaigneous rocks and 410 ± 10 to 395 ± 6 Ma for undeformed plutons [19–23]. In contrast, many zircons from the Yangtze craton are ~750–800 Ma. Gneiss from Tongbai Shan (Fig. 1) yielded Pb/Pb single-zircon ages of 746 ± 10 Ma and 776 ± 8 Ma [19] and one upper intercept U/Pb zircon age of ~850 Ma [15]. A leucogranite from the Wudang Shan (Fig. 1) gave a Pb/Pb single grain age of 762.0 ± 0.7 Ma [22]. In her comprehensive study of zircons from eclogite and UHP gneiss, Ames [15] reported U/Pb upper intercept ages of 674 ± 29, 638 ± 36, and 772 ± 352 Ma from the Dabie Shan (Fig. 5A) and 731 ± 8, 728 ± 25, 782 ± 32, and 762 ± 28 Ma from the Sulu area (Fig. 1). Rowley et al. [14] published a more precise upper intercept age of 772.5 ± 9.5 Ma for two gneisses from the Dabie eclogite unit (Fig. 5A). The geologic significance of the less well-constrained upper intercept and single-grain ages is uncertain, but it is clear that the southern margin of the Sino–Korean craton is characterized by zircons of ~400 and 480 Ma, whereas the Yangtze craton contains zircons of ~770 Ma. This subdivision serves as a useful starting point for determining the suture location.

To pinpoint the location of the suture in the Dabie Shan and Hong'an areas, we determined U/Pb ages from zircons of seven orthogneiss or plutonic samples; most were analyzed by both TIMS and SHRIMP. We focused on the NOU and on Cretaceous plutons with the objective of finding inherited, xenocrystic zircons that we could use to identify the provenance of the NOU. We expected to find either ~400–480 Ma or ~750 Ma ages, indicating a Sino–Korean or Yangtze craton provenance, respectively. Six samples revealed zircon cores with Pb/Pb SHRIMP ages and/or TIMS multi-grain upper intercept U/Pb ages of ~700-800 Ma (Fig. 3B and Fig. 5A; **EPSL Online Background Dataset** [2], Tables 1 and 2). Xue et al. [24] previously reported a concordant U/Pb zircon age of 756.6 ± 0.8 Ma from mylonitic granite S of the Xiaotian–Mozitang Fault. These ages imply that the entire Dabie Shan as far N as the Xiaotian–Mozitang Fault was derived from the Yangtze craton.

If the Yangtze craton was subducted northward beneath the Sino–Korean craton, as is commonly assumed, it is reasonable to expect that the most northerly part of the subducted craton — the NOU — was subjected to UHP in the Triassic. However, none of our (or any other published) Northern Orthogneiss samples contain U–Pb or Ar isotopic evidence for a Triassic thermal event. It is possible that the NOU was subducted to UHP and that any zircon growth at that time was subsequently erased during the Cretaceous magmatic episode, but we consider it more plausible that none of the sample we dated (and, by inference, the bulk of the NOU) experienced UHP.

3.4.2. Distribution of Triassic eclogites

Evidence of UHP metamorphism in the Dabie Shan N of the coesite eclogite unit has long been sought because of the prospect of recovering even higher pressure metamorphic rocks. In its type section in the north-central Hong'an block, the Huwan Formation (Fig. 2) was recently reported to contain quartz-bearing eclogites equilibrated at 590–680ºC and pressures of 1.3–1.5 GPa [25]. In 1995 we discovered quartz-bearing eclogite within the Huwan Formation at the very eastern edge of the Hong'an block (Fig. 2). Temperatures calculated using Fe–Mg exchange [26] between garnet and omphacite inclusions within the garnet suggest peak temperatures of 725ºC, while cores of discrete garnet and omphacite grains yield temperatures of 600ºC. Minimum pressures calculated from the jadeite component of the omphacite [27] are 1.4–1.6 GPa, and the phengite–garnet–clinopyroxene barometer of Waters and Martin [28] yields a pressure of 1.3 GPa. Phengitic white mica from this eclogite gave a $^{40}Ar/^{39}Ar$ age of ~205 Ma, similar to UHP rocks in the Dabie Shan [18]. The Huwan Formation extends along strike across the Shang-Ma Fault into the NW Dabie Mountains N of the Xiaotian–Mozitang Fault [29], leaving little doubt that eclogites, although not coesite-bearing, crop out in the NW Dabie Shan. Prospecting for eclogites in the northeastern Dabie Shan within the Luzhenguang Group might even be profitable because the Huwan Formation may correlate with the Luzhenguang Group [30]. The occurrence of eclogites N of the Xiaotian–Mozitang Fault implies that the suture between the Sino–Korean craton and Yangtze craton is N of the Xiaotian–Mozitang Fault. This appear to be at odds with the suggestion above and in Xue et al. [24] that the bulk of the NOU was not subjected to UHP metamorphism, unless the NOU is part of the Yangtze craton that was only subducted to shallow depths.

3.4.3. Metamorphic cooling ages

The polyphase history and potential for multiple high-pressure events within the Qinling–Dabie orogen [31] means that determining ages of metamorphic episodes is a powerful analytical tool. Fig. 5 shows our new data along with previously published ages that were accompanied by data or spectra that we could evaluate. The age of UHP metamorphism in the Dabie Shan is now well constrained to be Late Triassic [18]. Eclogites and associated UHP gneisses in the Dabie Shan and Hong'an block yield zircon ages of 227–214 Ma, phengite ages of 225–196 Ma (Hong'an) and 221–179 Ma (Dabie), and K-feldspar initial cooling ages of 204–176 Ma (Fig. 5B). The zircon ages likely record times of peak temperature or fluid influx, but whether this corresponds to the time of peak pressure is debatable. The zircons contain coesite inclusions [32], implying that they are

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either coeval with or postdate the UHP event (but see [33]). $^{40}Ar/^{39}Ar$ ages in this 220–180 Ma range are widespread within the high-pressure and UHP units and document a northward decreasing age gradient (initially observed in Hong'an by Eide et al. [17]) that is subparallel to the regional stretching lineation (Fig. 5). In contrast, as discussed above, the more northerly Qinling and Erlangping Groups (Fig. 2) have yielded ~480 and 400 Ma zircon ages in the Qinling area (e.g., [22]) and give 400–434 Ma $^{40}Ar/^{39}Ar$ hornblende ages in the northern Tongbai and Hong'an areas (only the easternmost three fall within the area of Fig. 5); Zhai et al. [34] interpreted these ages and associated amphibolite- to granulite-facies parageneses to reflect Siluro-Devonian metamorphism accompanying arc magmatism. These ~400 Ma metamorphic ages occur as far E as the Shang-Ma fault, but have not been found S of the Guishan Formation of the Xinyang Group (Fig. 5B).

Significantly, $^{40}Ar/^{39}Ar$ ages now document that the ~200 Ma thermal event associated with UHP metamorphism in the eastern Dabie Shan and Hong'an areas extends as far N as the Huwan Formation in the Tongbai and Hong'an areas and as far N as the Foziling and Luzhenguang Groups in the Dabie Shan (Fig. 5B). Thus, all eclogites in the Hong'an and Dabie Shan are related to Triassic continental collision and did not form during the Ordovician–Devonian orogenies discussed by Xue et al. [7]. Whether the ~200 Ma recrystallization of the Foziling Group, Luzhenguang Group and Dingyuan Formation (Fig. 5B) — all of which lack eclogite — is related to UHP metamorphism is unclear. However, the presence of kyanite in Foziling-correlative rocks in the Qinling (Liuling Formation, [35]) leads us to suspect that the 200 Ma metamorphism of the Foziling is also subduction related. If true, the surface expression of the suture between the Sino–Korean and Yangtze cratons may be either the northern or southern contact of the Nanwan Formation; the strongest difference in lithology occurs across the northern contact.

3.5. Low-pressure granitic orthogneiss

While the bulk of the UHP unit is a paragneiss with blocks of eclogite, it also contains granitic orthogneiss that lacks blocks of eclogite. The orthogneiss contains Mn garnet, phengite, sphene rather than rutile, and quartz rather than coesite [36]. Zhai et al. [37] suggested that these granitic orthogneisses never experienced UHP, and were tectonically juxtaposed with the UHP gneisses and eclogites at mid- to upper crustal levels. This interpretation was recently questioned by Carswell et al. [38], but if true, means that the Dabie Shan do not contain a regionally extensive, structurally coherent UHP terrane [39], but instead are a mixture of UHP and low-pressure rocks [11].

To evaluate Zhai et al.'s hypothesis, we dated zircons from one granitic orthogneiss (DS107) (Fig. 3 and Fig. 5B). Field structures and feldspar recrystallization textures indicate that the granitic orthogneiss and eclogite-bearing paragneiss experienced the same deformation history at temperatures of ~500ºC. Orthogneiss DS107 is identical to that of Cong et al. [36] in that it contains $alm_{33\text{-}43}grs_{28\text{-}36}prp_{02}sps_{25\text{-}33}$ garnet, $Si_{3.14\text{-}3.20}$ phengite, $An_{03\text{-}16}$ plagioclase, quartz, and sphene, but lacks rutile. This sample yielded SHRIMP U/Pb ages of 218–240 Ma on crystal rims and 700–800 Ma ages from crystal cores (**EPSL Online Background Dataset** [3], Table 1). As discussed earlier, the population of ages is similar to that obtained from paragneiss DS158, the youngest ages are concordant with 218.5 ± 1.9 Ma U/Pb age determinations on nearby eclogites and UHP paragneiss, and the cores ages match TIMS upper intercept ages from paragneisses and eclogites [14,15]. Thus, in terms of their zircon crystallization history, the orthogneiss is indistinguishable from the paragneiss and eclogite; the most probable explanation for the apparent lack of UHP minerals in the orthogneiss [36] is extensive retrogression [38].

3.6. Age of granulite-facies metamorphism and the tectonic affinity of the northern orthogneiss

The NOU, which makes up ~50% of the Dabie Shan [5] is most notably different from the UHP rocks in composition. The oldest rocks are gabbroic to dioritic, garnet-granulite orthogneisses with minor marble and alpine-type ultramafic rocks (Fig. 2).

[3] http://www.elsevier.nl/locate/epsl;
mirror site: http//www.elsevier.com/locate/epsl

This ultramafic + mafic + carbonate basement sequence was intruded by Cretaceous plutons that caused local partial melting and decomposition of garnet to hornblende + plagioclase [5,8]. The Cretaceous plutons are chiefly granite, granodiorite, and tonalite, and were intruded during large-scale NNW–SSE extension [18]. A typical pluton consists of a core with a weak, magmatic foliation zoned outward to a carapace with increasingly localized deformed zones formed at decreasing temperatures [5]. Maps of the NOU only show the least deformed portions of these bodies as plutons and grossly under-represent the volume fraction of igneous rocks. We estimate, based on field mapping and zircon ages, that >90% of this unit is Cretaceous igneous rocks, much of which is so deformed as to be indistinguishable in degree and style of deformation from the older ultramafic + mafic + carbonate basement. The 'migmatite' appellation often applied to this rock unit is, in most locales, not migmatite, but strongly deformed Cretaceous igneous rocks.

The basement sequence includes local occurrences of granulite that predate the characteristic amphibolite-facies metamorphism of the NOU [5,8,9,40,41]. Rare garnet–clinopyroxene rocks have been interpreted to have undergone an even earlier eclogite-facies metamorphism [42]. Determining the ages of these events is a primary means for understanding whether the NOU is (1) a part of the slab subducted even deeper than the UHP units [9]; (2) the hangingwall of the subduction zone [8]; (3) a pre-collisional magmatic arc [37]; or (4) younger than the UHP metamorphism. We dated five samples from the NOU in an effort to resolve these hypotheses. Four samples from undeformed to moderately deformed plutons gave U/Pb zircon ages of 129–134 Ma (**EPSL Online Background Dataset** [4], Tables 1 and 2). Including the 125.6 ± 0.3 Ma age reported by Xue et al. [24], this indicates a range of crystallization ages from ~126 to ~134 Ma (Fig. 5A). We obtained an age of 136.8 ± 5.1 Ma for the common tonalitic gneiss that includes blocks of garnet clinopyroxenite and is itself cut by younger deformed plutonic rocks. Combined with Xue et al.'s orthogneiss zircon ages of 133.7 ± 2.3 and 134.0 ± 2.8 Ma, these data suggest that the common orthogneisses of the NOU are restricted to a narrower, slightly older, age range of ~134–137 Ma.

Because the weakly deformed plutons have crystallization pressures of ~500 MPa that are coincident with the inferred pressure of metamorphism [8], and because the crystallization temperature for zircon and the closure temperature for Ar in hornblende and mica straddle the metamorphic temperatures, the amphibolite-facies metamorphism must be Cretaceous. Our data do not directly constrain the age of the granulite-facies or eclogite(?)-facies event in the ultramafic + mafic + carbonate basement sequence. The best indications of the metamorphic age of the basement come from Sm/Nd mineral–whole rock isochron ages of 244 ± 11 and 224 ± 20 Ma on garnet pyroxenite [16]. The dearth of indications from U/Pb and $^{40}Ar/^{39}Ar$ data for a pre-Cretaceous thermal event within the common tonalitic orthogneiss emphasizes that only a small fraction of the NOU can be considered pre-Cretaceous basement. We need no longer build tectonic models for the pre-Cretaceous evolution of the NOU because, aside from a few scraps of ultramafic + mafic + carbonate basement, it did not exist prior to ~137 Ma.

3.7. Implications for orogenic architecture

If the bulk of the NOU is a Cretaceous extensional-magmatic complex, the pre-Cretaceous configuration of the Hong'an–Dabie area can be provisionally reconstructed by subtracting the Cretaceous extension (Fig. 6) recorded by structures documented by Hacker et al. [5]. Roughly 70 km of restoration along a 325° trend brings contacts between various units in the Hong'an and Dabie areas into general contiguity and closes most gaps between pre-Cretaceous units; this implies ~100% subhorizontal extension. The isotopic data presented and summarized in this paper, along with the new eclogite locality (Fig. 2) reveal the pre-Cretaceous Hong'an–Dabie Shan as an orogen-scale antiform with coesite–eclogite facies rocks in the core surrounded by progressively lower pressure rocks. The S limb of the antiform dips S moderately at 20–40°, is ~40 km thick and preserves apparent top-N thrusting [5], whereas the N limb, only preserved in the Hong'an area and along the northern edge of the Dabie Shan,

[4] http://www.elsevier.nl/locate/epsl;
mirror site: http//www.elsevier.com/locate/epsl

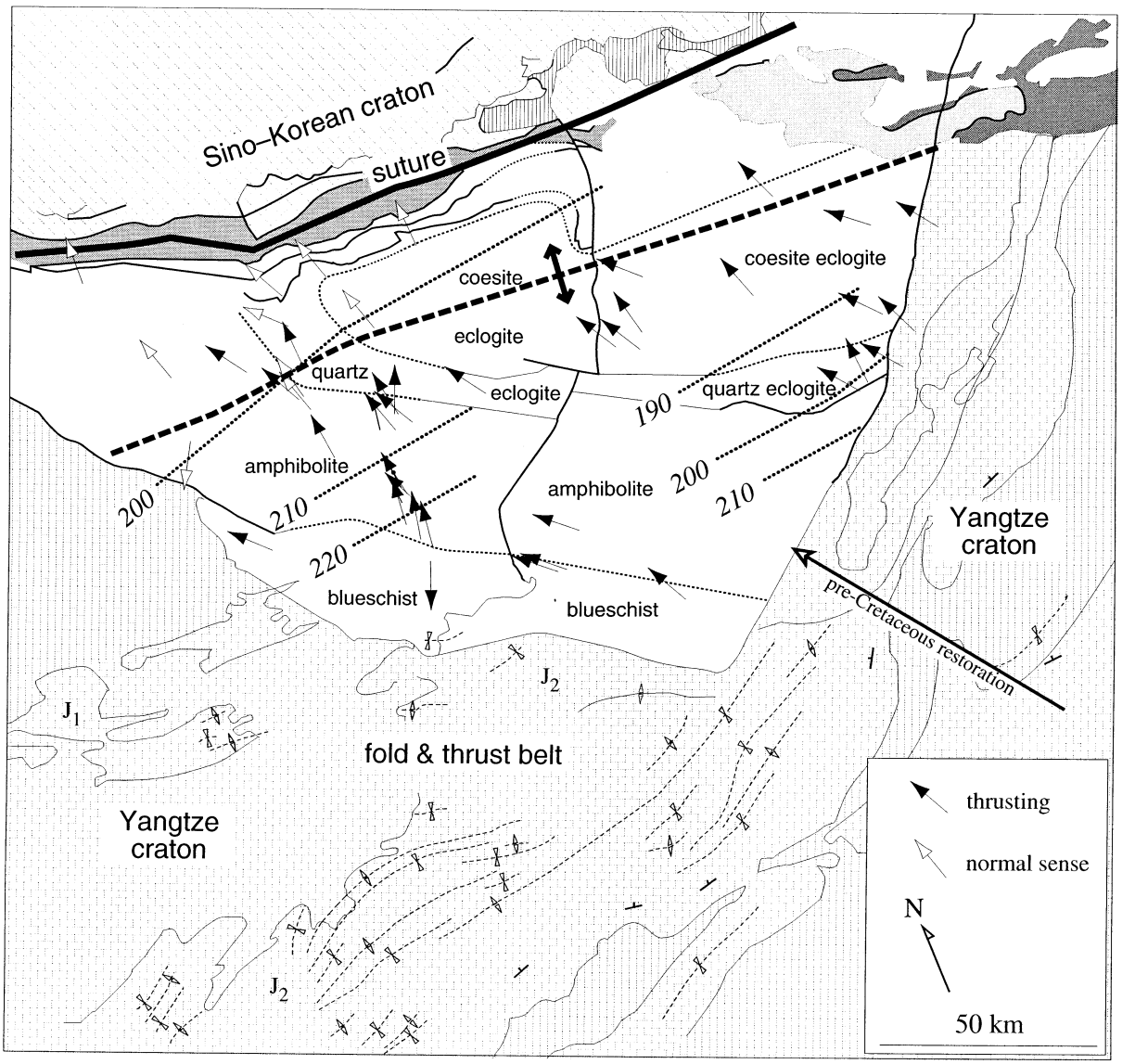

Fig. 6. Palinspastic reconstruction of the Dabie-Hong'an area prior to Cretaceous magmatism and deformation; the figure was constructed by moving the Dabie Shan S of the suture plus the fold–thrust belt E of the Dabie Shan, NNW along the Cretaceous extension direction until the pre-Cretaceous units fit together (direction and magnitude of restoration shown by long, thick arrow). Contacts are the same as Fig. 2. Solid line shows suture between Sino–Korean and Yangtze cratons as defined by isotopic data discussed in this paper. Thin dashed lines show isochronous contours of $^{40}Ar/^{39}Ar$ K-white mica ages, ranging from 190 to 220 Ma. Thick dashed line is antiformal axis defined by outcrop pattern of coesite eclogite and quartz eclogite units, top-N thrusting on the SSE limb, and top-N normal-sense shearing on the NNW limb.

dips much more steeply northward at ~70°, is ~20 km thick, and records normal-sense shearing [43]. The westward decrease in peak metamorphic pressures [3], combined with map-scale structures visible in Fig. 2 reveal that the antiform plunges W; the E edge of the antiform is abruptly truncated by the Tan-Lu fault. Exhumation of the UHP and high-pressure rocks was accommodated by normal-sense displacement along a shear zone immediately S of the suture [43,44]. The 190–220 Ma isochrons in

Fig. 6 might have developed as a result of cooling during exhumation or they might reflect the passage of isotherms through the rocks from 190–220 Ma and the subsequent exhumation of those surfaces. The first hypothesis requires that exhumation lasted for a rather long time period of 30 Myr, whereas the second requires that the isotherm coinciding with Ar closure in K-white mica passed through ~40 km of structural thickness in ~30 Myr — a reasonable rate for erosion-driven exhumation and cooling. In either case, the southern limb of the antiform represents the back-tilted footwall of the extensional shear zone. If the Hong'an–Dabie rocks were undergoing slow cooling beginning at 220 Ma, and cooled from high structural levels downward, they cannot have been buried at mantle depths undergoing UHP metamorphism, but must have been at crustal levels. We speculate then, that the zircon ages so precisely defined at 219 Ma [14,15] might reflect post-UHP zircon growth at crustal depths, perhaps driven by the influx of metamorphic fluids, and that peak pressures and temperatures may have occurred much earlier at ~240 Ma, and are recorded in the enigmatic ~240 Ma Sm/Nd ages [9,16] and the U/Pb SHRIMP ages presented in Fig. 3A.

4. Conclusions

Widespread U/Pb zircon ages of ~770 Ma imply that the entire Dabie Shan as far N as the Xiaotian–Mozitang Fault was derived from the Yangtze craton. The presence of Triassic $^{40}Ar/^{39}Ar$ ages as far N as the Dingyuan Formation, the Foziling Group, and the Luzhenguang Group, and the presence of Devonian $^{40}Ar/^{39}Ar$ ages as far S as the Guishan Formation, delineate the thermal effects of the Triassic collision. The discovery of quartz-bearing eclogites in the easternmost Huwan Formation implies that all this metamorphism is collision related. We tentatively place the suture between the Yangtze and Sino–Korean cratons along the northern contact of the Nanwan Formation. This is a geochronologically defined suture and further fieldwork will be necessary to evaluate precisely how the suture is manifest in surface geology.

Granitic orthogneiss in direct contact with UHP paragneiss and eclogite — and which has been interpreted by some authors not to have experienced UHP — yielded U/Pb SHRIMP ages indistinguishable from the paragneiss and eclogite. Both orthogneiss and paragneiss gave a spectrum of rim ages as young as TIMS lower intercept U/Pb ages on eclogite and paragneiss (~219 Ma) and as old as Sm/Nd ages on inferred UHP rocks (~245 Ma). We suggest that the 245 Ma ages resulted from UHP metamorphism and that the 219 Ma ages, commonly inferred to represent peak pressures, instead reflect a late retrogression at crustal pressures.

Cretaceous U/Pb zircon ages document that virtually the entire northern half of the Dabie Shan is a 137–126 Ma igneous complex that postdates Triassic metamorphism; only rare scraps of ultramafic + mafic + carbonate basement within the Northern Orthogneiss predate the Cretaceous. The absence of Triassic U/Pb and $^{40}Ar/^{39}Ar$ ages emphasizes that only a small fraction of the NOU existed prior to ~137 Ma. The Cretaceous extension widened the 70 km wide Dabie Shan by another 70 km, resulting in the present 140-km wide mountain belt. Undoing this large-scale extension and removing the volume occupied by the Cretaceous orthogneiss returns the UHP rocks close to the suggested location of the Triassic suture.

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