Subduction, collision and exhumation in the ultrahigh-pressure Qinling–Dabie orogen

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Abstract: High-pressure metamorphism and ophiolite emplacement (Songshugou ophiolite) attended suturing of the Yangtze craton to Rodinia during the *c.*1.0 Ga Grenvillian orogeny. The Qinling microcontinent then rifted from the Yangtze craton at *c.*750 Ma. The Erlangping intraoceanic arc formed in the Early Ordovician, was emplaced onto the Qinling microcontinent in the Ordovician–Silurian, and then both units were accreted to the Sino-Korea craton before being stitched together by the *c.*400 Ma Andean-style Qinling arc. Subsequent subduction beneath the Qinling–Sino-Korean plate created a Devonian–Triassic accretionary wedge that includes eclogites, and formed a coeval volcano-plutonic arc that stretches from the Longmen Shan to Korea. In the Late Permian–Early Triassic, the northern edge of the South China Block was subducted to >150 km depth, creating the diamond- and coesite-bearing eclogites of the Dabie and Sulu areas. Exhumation from the mantle by lithosphere-scale extension occurred between 245 and 195 Ma during clockwise rotation of the craton. The Yangtze–Sino-Korea suture locally lies tens of km north of the exhumed UHP–HP part of the South China Block, implying perhaps that the very tip of the South China Block was not subducted, or that the UHP–HP rocks rose as a wedge that peeled the upper crust of the unsubducted South China Block from the lower crust. The Tan–Lu fault is an Early Cretaceous to Cenozoic feature. The apparent offset of the Dabie and Sulu UHP terranes by the Tan–Lu fault is a result of this Cretaceous to Cenozoic faulting combined with post-collisional extension north of Dabie.

The Sino-Korean craton and the Qinling microcontinent collided in the Ordovician–Silurian. The North China Block (NCB) and the South China Block (SCB) collided in the Permo-Triassic. The orogenic belt associated with these collisions and intervening tectonism extends *c.*2000 km west–east through the Qinling, Tongbai, Dabie Shan and Sulu areas and into Korea (Fig. 1). It is of special interest because it contains high-pressure (HP) rocks of four different ages: Grenvillian, Devonian, Carboniferous and Triassic. This paper aims to provide a review of the collision zone as both a summary of what conclusions have been drawn where and with which data, and as a guide to future research.

Sino-Korean craton

In our usage, the Sino-Korean and Yangtze cratons comprise Precambrian basement and cover as described below; in principle, all Precambrian basement outcrops can be assigned either a Sino-Korean or Yangtze craton affinity, whereas the affinity of areally extensive domains of sedimentary strata or of volcano-plutonic complexes can be ambiguous. 'North China Block' and 'South China Block' are used to refer to the continental blocks north and south of the Qinling–Dabie–Sulu suture.

The Sino–Korean craton is subdivided into three units: the western, eastern and central blocks. The western and eastern blocks are Archean cratons linked by a central suture belt that formed during collision at *c.*1.8 Ga (Zhao *et al.* 2000). The U–Pb zircon ages from the Sino-Korean craton cluster at *c.*3.8, 3.3, 3.0, 2.5 and 1.7–1.8 Ga (Song *et al.* 1996; Yu *et al.* 1996; Zhao *et al.* 2000). The craton consists of a basement of Archaean to Proterozoic metamorphic rock overlain by a relatively uninterrupted 4–8 km thick superjacent section of Sinian (Late Proterozoic to Early Cambrian) to

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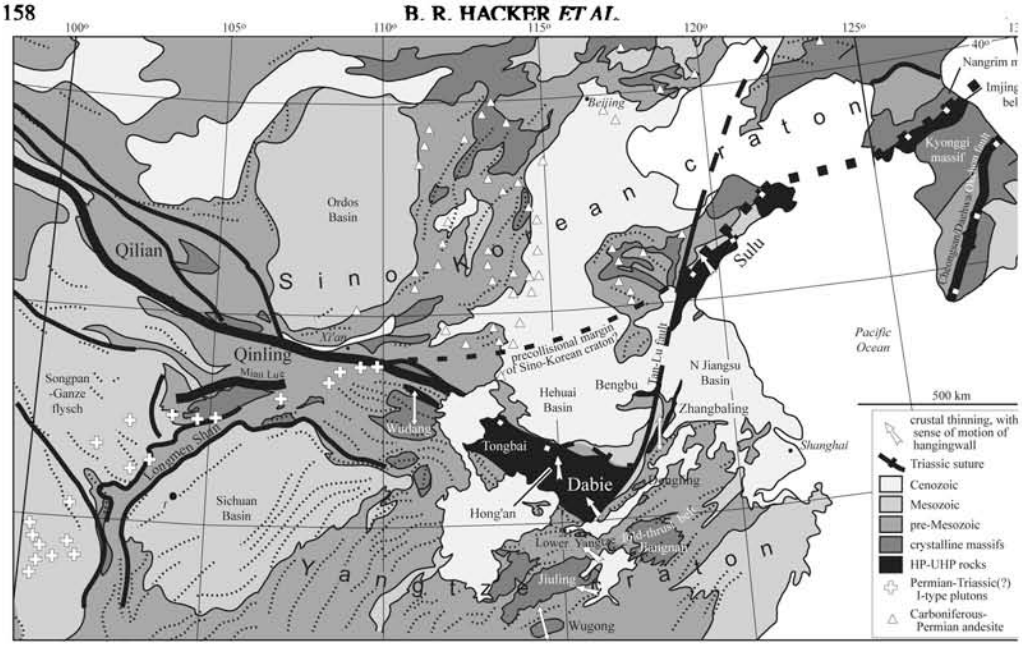


Fig. 1. The Qilian–Qinling–Tongbai–Hong'an–Dabie–Sulu–Imjingang collisional orogen in eastern Asia (modified after Cluzel *et al.* 1991; Ree *et al.* 1996; Wallis *et al.* 1997; Hacker *et al.* 2000). Structural interpretations from previous studies (Faure *et al.* 1996; Wallis *et al.* 1997; Schmid *et al.* 1999; Hacker *et al.* 2000; Lin *et al.* 2000; Ratschbacher *et al.* 2000; Webb *et al.* 2001). Andesitic volcanic rocks from Zhang (1997) and Permian–Triassic plutons from Regional Geological Survey of Sichuan (1991) and Regional Geological Survey of Shaanxi (1989) suggest a pre-Late Permian arc related to subduction.

Triassic age (Hsü *et al.* 1987; Ma 1989; Regional Geological Survey of Henan 1989). Sinian through Late Ordovician rocks are platform-facies sandstone, stromatolitic dolomite, limestone, mudstone and rare evaporites, basaltic flows and pyroclastic rocks. Late Ordovician through Early Carboniferous rocks are locally absent in the Qinling orogen, probably indicating tectonism (as discussed below). Devonian to Permian (and locally Triassic in Henan Province) rocks are shallow-marine limestone and dolomite or lacustrine sandstone, mudstone, limestone, gypsum and coal. The Middle Carboniferous to Lower Permian coal-bearing series contains andesitic volcanic rocks (Zhang 1997). Sediment deposition changed markedly on the Sino-Korean craton in the Early Triassic, when lacustrine-to-alluvial conglomerate, arkosic sandstone, and siltstone were laid down; this continental environment persisted throughout the Mesozoic (Regional Geological Survey of Anhui 1987; Regional Geological Survey of Henan 1989; Regional Geological Survey of Hubei 1990).

Some crystalline materials within the core of the Qinling orogenic belt can also be assigned to the Sino-Korean craton (Figs 2 and 3). The Kuanping unit, chiefly amphibolite- to greenschist-facies marbles and two-mica quartz schists, contains detrital zircon with a Pb/Pb age of 638 Ma, is intruded and metamorphosed by *c.*434 Ma diorite and is unconformably overlain by middle Carboniferous to Permian sedimentary rocks (see summary in Ratschbacher *et al.* in press). It could represent the metamorphosed south-facing passive margin of the Sino-Korean craton (Wang 1989). The upper part of the Qinling unit consists of marble with minor amphibolite and garnet–sillimanite gneiss (You *et al.* 1993) that might be correlative with the Kuanping unit (Huang & Wu 1992).

Yangtze craton

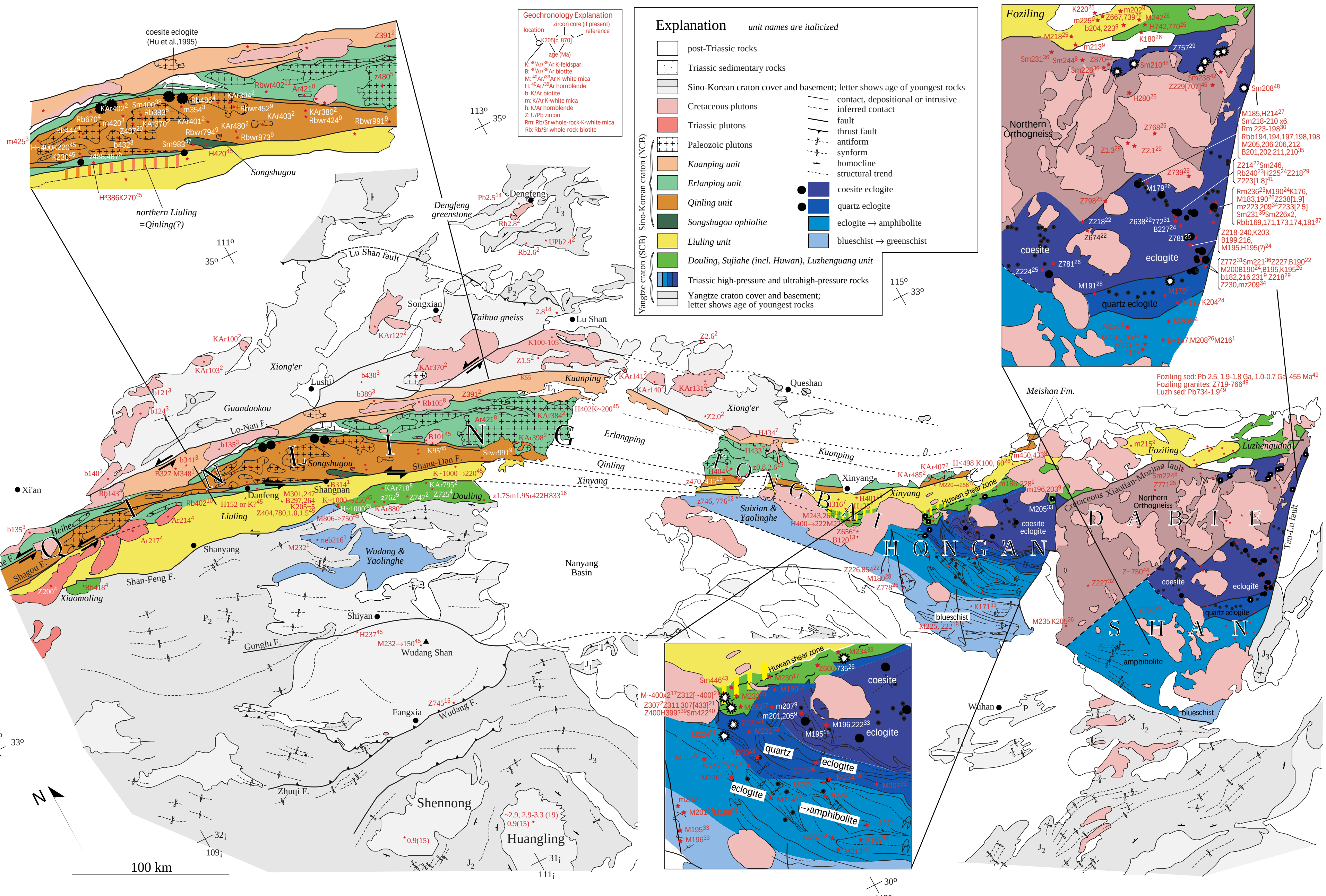
The oldest rocks in the Yangtze craton, exposed in the classic Yangtze Gorge section in the Shennong and Huangling areas (Fig. 2), comprise gneissic trondhjemites with *c.*2.9 Ga zircons (U–Pb SHRIMP ages) and paragneisses with 2.9–3.3 Ga detrital zircons (Ames *et al.* 1996; Qiu *et al.* 2000). Zircons from elsewhere in the Yangtze craton, including the Zhangbaling and Dongling areas (Fig. 1), range from *c.*2.5 Ga to *c.*700 Ma (see review in Grimmer *et al.* in press). The youngest zircon signature that is widespread in the Yangtze craton, and constitutes its most useful fingerprint, is the *c.*650 Ma and *c.*750 Ma signature of Neoproterozoic rifting (Li 1999; Hacker *et al.* 2000).

Overlying the Precambrian basement are *c.*12 km of weakly metamorphosed Upper Sinian to Triassic sedimentary rocks (Regional Geological Survey of Hubei 1990). Cambrian through Carboniferous rocks are mostly platform-shelf carbonates and shelf-slope clastic rocks formed on the north-facing passive margin of the Yangtze craton, except for minor Lower Silurian (423–443 Ma) volcanic flow and volcaniclastic rocks. Locally, Lower, Middle and Upper Devonian fluvial conglomerate, quartz sandstone, and mudstone lie unconformably on Upper Silurian rock. Permian platform-facies carbonates give way up section to coal-bearing clastics and phosphorite deposits indicative of restricted shelf and lagoonal deposition. Early and Middle Triassic evaporite, carbonate and argillite indicate shallow-marine platform sedimentation with restricted circulation (Regional Geological Survey of Hubei 1990).

Some crystalline materials within the core of the Qinling orogenic belt can also be equated with the Yangtze craton (Figs 2 and 3). Crystalline rocks in the Hong'an and Dabie areas are likely of Yangtze affinity, as most of their zircons have Precambrian cores that range from *c.*625 to 800 Ma, with peaks in the distribution at *c.*660 Ma and *c.*735 Ma (Hacker *et al.* 1998; Hacker *et al.* 2000). Where well exposed, in the Hong'an, Suixian, Wudang and Yaolinghe areas, these Late Proterozoic rocks are typified by intercalated mafic and felsic volcanic rock, siliciclastic rocks, and carbonates (Regional Geological Survey of Hubei 1990). Xue *et al.* (1996*b*) used the prevalence of 0.7–0.8 Ga zircon and Rb/Sr ages to correlate the lower part of the Qinling unit with the crystalline basement of the Yangtze craton; this assignment is supported by the presence of Grenvillian (*c.*1.0 Ga, Li 1999) zircons in both the lower Qinling unit and the Yangtze craton and their absence from the Sino-Korean craton. Ratschbacher *et al.* (in press) followed Xue *et al.* by assigning the lower Qinling unit a Yangtze affinity up until the Late Proterozoic, when it rifted from the Yangtze craton (Li *et al.* 1999*b*) to form the 'Qinling microcontinent'. The northern part of the Liuling unit (and the correlative Xinyang Group in Tongbai–Hong'an and the Foziling unit in Dabie) comprises fossiliferous Upper Devonian through Lower Carboniferous–Permian(?) fore-arc deposits (Yu & Meng 1995). Detrital zircon ages of *c.*782 Ma and 1.0 Ga from the northern Liuling unit suggest derivation from a Yangtze source (Ratschbacher *et al.* in press). The Douling unit is correlated with Yangtze basement exposed in the Huangling area based on lithology and age, specifically the presence of zircon ages of 747 and 725 Ma (summary in Ratschbacher *et al.* in press). Hacker *et al.* (2000) correlated the Luzhenguang unit of northern Dabie with the Yangtze craton, based on the presence of 742 and 770 Ma $^{40}Ar/^{39}Ar$ hornblende ages.

Thus, crystalline rocks with 750 Ma ages characteristic of the Yangtze craton are found as far north as the lower Qinling unit in the Qinling and Tongbai areas, the Huwan unit in Hong'an, and in the Luzhenguang unit of northern Dabie (Fig. 4). Detrital (?) zircons with these ages are found in the Foziling unit in Dabie and the northern Liuling unit in the Qinling area. In contrast, the southern margin of the Sino-Korean craton in the Qinling–Dabie area is represented by the upper Qinling and Erlangping Groups, which yield zircons of Ordovician–Devonian age (summary in Ratschbacher *et al.* in press). As discussed below, these age differences define the Ordovician–Silurian Sino-Korean craton–Qinling microcontinent suture in the Qinling and Tongbai areas, and help to define the Triassic

Fig. 2. Correlation of Palaeozoic rock units through Qinling–Dabie, zones of Triassic HP and UHP metamorphism, distribution of Early Cretaceous plutons, trend of major Triassic fold trains in the Yangtze craton foreland cover fold–thrust belt (adapted from 1 : 500 000 province maps of China), reliable geochronological ages (after references cited in the text and Ratschbacher *et al.* in press) (post-Triassic geochronology in Dabie Shan is not shown, for clarity). Geochronology references: 22, Ames (1995); 34, Ayers *et al.* (2002); 27, Cao & Zhu, (1995); 30, Chavagnac & Jahn (1996); 35, Chavagnac, *et al.* (2001); 9, Chen, N. *et al.* (1992); 28, Chen, J. *et al.* (1995); 32, Chen N.-S. *et al.* (1996); 42, Chen, D. *et al.* (1998); 18, Eide *et al.* (1994); 24, Hacker & Wang (1995); 25, Hacker *et al.* (1998); 26, Hacker *et al.* (2000); 38, Hu *et al.* (1996); 39, Jian *et al.* (1997); 12, Kröner *et al.* (1993); 14, Kröner *et al.* (1988); 6, Lerch *et al.* (1995); 8, Li, X. X. *et al.* (1992); 10, Li, S. G. *et al.* (1989); 36, Li, S. G. *et al.* (2001); 37, Li, S. G. *et al.* (2000); 40, Li *et al.* (1995); 43, Li, S. *et al.* (1998); 47, Li, S. *et al* (1991); 48, Liu, Y.-C. *et al.* (2001); 41, Maruyama *et al.* (1998); 1, Mattauer *et al.* (1985); 13, Niu *et al.* (1994); 23, Okay *et al.* (1993); 19, Qiu *et al.* (2000); 45, Ratschbacher *et al.* (in review); 2, Regional Geological Survey of Henan (1989); 15, Regional Geological Survey of Hubei (1990); 31, Rowley *et al.* (1997); 16, Shen *et al.* (1997); 11, Sun *et al.* (1996); 21, Sun *et al.* (in press); 20, Wang & Li (1996); 33, Webb *et al.* (1999), 44, Xie *et al.* (1998); 46, Xie *et al.* (2001); 17, Xu *et al.* (2000); 5, Xue *et al.* (1996a); 29, Xue *et al.* (1997); 7, Zhai *et al.* (1998); 3, Zhang, Z. Q. *et al.* (1991); 4, Zhang *et al.* (1997).


Explanation
unit names are italicized
post-Triassic rocks
Triassic sedimentary rocks
Sino-Korean craton cover and basement; letter shows age of youngest rocks
Cretaceous plutons
Triassic plutons
Paleozoic plutons
Kuanping unit
Erlanping unit
Qinling unit
Songshugou ophiolite
Liuling unit
Douling, Sujiahe (incl. Huwan), Luzhenguang unit
Triassic high-pressure and ultrahigh-pressure rocks
Yangtze craton cover and basement; letter shows age of youngest rocks
Sino-Korean craton (NCB)
Yangtze craton (SCB)
contact, depositional or intrusive
inferred contact
fault
thrust fault
antiform
synform
homocline
structural trend
coesite eclogite
quartz eclogite
eclogite → amphibolite
blueschist → greenschist
Geochronology Explanation
location
zircon core (if present)
reference
age (Ma)
K: 40Ar/39Ar K-feldspar
B: 40Ar/39Ar biotite
M: 40Ar/39Ar K-white mica
H: 40Ar/39Ar hornblende
b: K/Ar biotite
m: K/Ar K-white mica
h: K/Ar hornblende
Z: U/Pb zircon
Rm: Rb/Sr whole-rock-K-white mica
Rb: Rb/Sr whole-rock-biotite
coesite eclogite
(Hu et al.,1995)
Songshugou
northern Liuling
=Qinling(?)
Dengfeng greenstone
Dengfeng
Lu Shan fault
Songxian
Taihua gneiss
Lu Shan
Xiong'er
Lushi
Guandaokou
Lo-Nan F.
Kuanping
Erlanping
Qinling
Xinyang
Shang-Dan F.
Danfeng
Shangnan
Douling
Liuling
Xi'an
Heihe
Chenhe F.
Shagou F.
Shan-Feng F.
Shanyang
Xiaomoling
Wudang & Yaolinghe
Nanyang Basin
Shiyan
Gonglu F.
Wudang Shan
Wudang F.
Fangxia
Zhuqi F.
Shennong
Huangling
Queshan
Suixian & Yaolinghe
Huwan shear zone
Xinyang
Meishan Fm.
Fozliling
Luzhenguang
Cretaceous Xiaotian-Mozitan fault
Northern Orthogneiss
Tan-Lu fault
coesite
eclogite
quartz eclogite
blueschist
amphibolite
Wuhan
Fozliling sed: Pb 2.5, 1.9-1.8 Ga, 1.0-0.7 Ga, 455 Ma
Fozliling granites: Z719-766
Luzh sed: Pb734-1.9
quartz
eclogite
→amphibolite
Q I N L I N G
T O N G B A I
H O N G A N
D A B I E
S H A N
N
100 km

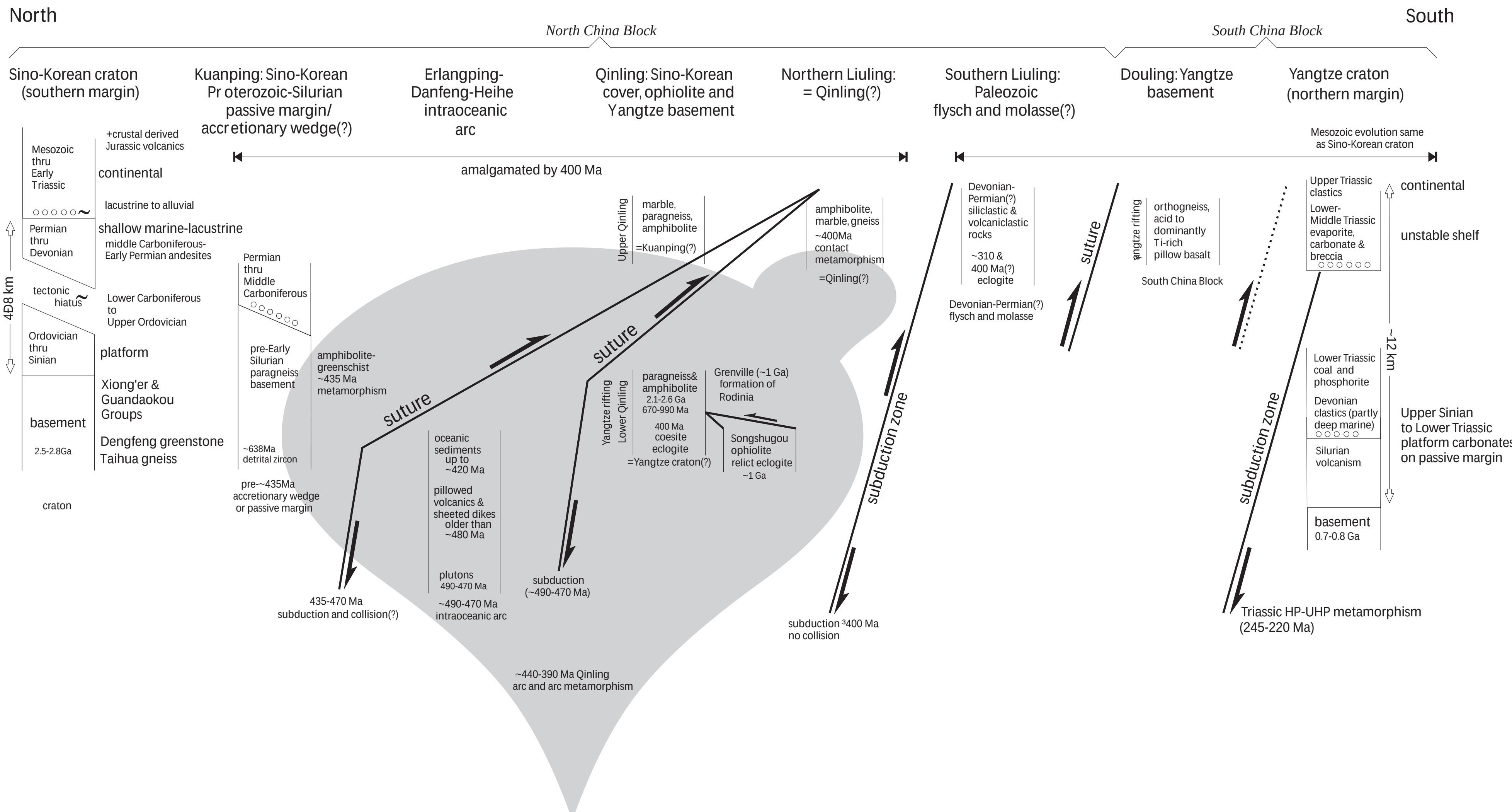


Figure 3: Geologic units, tectono-thermal/sedimentary events, facies interpretation, radiometric ages, and tectonic interpretation of the Paleozoic-early Mesozoic Qinling orogenic belt. Formation of the intra-oceanic Erlangping arc between ~490-470 Ma was followed by accretion of the lower Qinling micro-continent to the intra-oceanic arc, and to the Sino-Korean craton. Subduction underneath the northernmost Liuling unit imprinted the ~400 Ma Qinling arc on the Sino-Korean + Qinling collage. A subduction signature is again evident during the mid-Carboniferous to Late Permian on the Sino-Korean craton, when the Paleo-Tethys was subducted northward, producing the andesitic magmatism on the Sino-Korean craton. In the Late Permian-Early Triassic, the leading edge of the Yangtze craton was subducted to >150 km and subsequently exhumed by crustal extension (after Ratschbacher et al. in press).

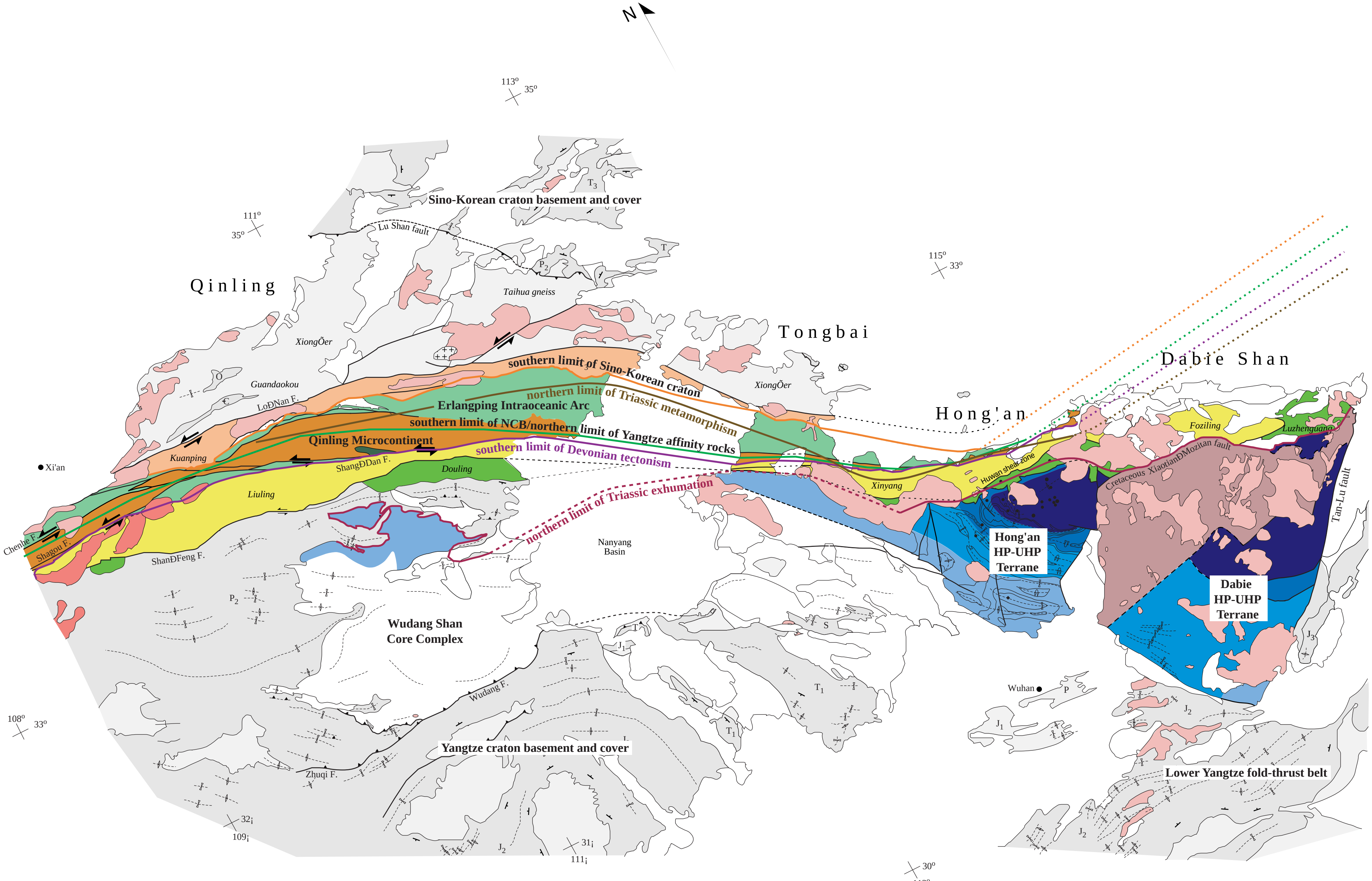


Figure 4: Major units and unit boundaries of the Qinling-Dabie orogen (see Figure 2 and its caption).

North China Block–South China Block suture in the Hong'an–Dabie areas.

High-pressure metagabbro, amphibolitized eclogite and felsic granulite associated with *c.*1.0–1.2 Ga ophiolitic rocks were emplaced on to the lower part of the Qinling unit in the Songshugou area, following high-pressure metamorphism in an oceanic setting (Liu *et al.* 1996; Song *et al.* 1998; Zhang 1999). The amphibolitized eclogite was derived from MORB, is in fault contact with mantle peridotite and contains decompression textures common in many eclogites, including symplectites of plagioclase and diopside derived from omphacite estimated to have formed at pressures $\geq$1.5 GPa (Zhang 1999). A Sm–Nd mineral isochron of 983 Ma is taken to date later cooling. The high-*P* felsic granulite includes garnet + kyanite + microperthite + quartz + rutile assemblages formed at 800–900 °C and 1.3–1.6 GPa (Liu *et al.* 1996).

Palaeoclimatic, palaeobiogeographical and palaeomagnetic data imply that the North China and South China blocks were close to or part of near-equatorial East Gondwana through the Late Devonian, and that rifting of the NCB from Gondwana took place after the Devonian (Zhao *et al.* 1996; Huang *et al.* 2000).

Ophiolites and accretionary complexes

Early Ordovician Erlangping Ophiolite, the Qinling Microcontinent and their amalgamation with the Sino-Korean Craton

The distribution of ophiolites within the Qinling–Dabie–Sulu orogen provides important information about the (partial) closure of ocean basins. The oldest Palaeozoic orogenic event in the Qinling orogen was the formation of the Erlangping intra-oceanic arc, which includes the Heihe, Danfeng and Erlangping units (Fig. 3). Sediments associated with the arc contain Cambrian–Ordovician through Ludlovian–Wenlockian (419–428 Ma) radiolaria, and trondjhemites, tonalites, gabbros, and rare pyroxenites with single-zircon Pb/Pb ages of 470–488 Ma that intrude a volcanic sequence (see summary in Ratschbacher *et al.* in press). Ratschbacher *et al.* (in press) proposed south-directed emplacement of this arc on to the lower Qinling unit (the Qinling microcontinent) between *c.*470 and 435 Ma, based on the present geographical positions of the arc, the upper Qinling unit and the lower Qinling unit. The Erlangping–Qinling collision may have been related to the collision of the Pamir–South Tarim–Qaidam continent with the NCB (Yin & Nie 1993). This intra-oceanic arc can be traced eastward as far as Hong'an, where it disappears beneath Cenozoic sediments (Figs 2 and 4). No such ophiolite is known from Sulu or Korea, but there are several candidates for Palaeozoic ophiolites in the Kunlun–Altyn Tagh–Qaidam–Qilian area (Matte *et al.* 1996; Sobel & Arnaud 1999).

Silurian–Early Devonian Qinling arc

Following emplacement of the Early Ordovician Erlangping intra-oceanic arc, a continental margin arc was built on the Kuanping, Erlangping and Qinling units from *c.*438–395 Ma; this implies that the Erlangping and Qinling units were amalgamated with the Kuanping unit (and thus the Sino-Korean craton) prior to *c.*440 Ma (Fig. 3) (Ratschbacher *et al.* in press). Significantly, none of these Silurian–Early Devonian plutons crop out within the Liuling unit. However, the northern part of the Liuling unit, which Ratschbacher *et al.* (in press) correlated with the Qinling unit, experienced the regional contact metamorphism produced by this batholith, and Silurian to Lower Devonian strata in the northern Liuling unit received metamorphic detritus (Mattauer *et al.* 1985) from the Qinling arc and *c.*780 Ma and *c.*1.0 Ga detrital zircons (see above). We thus interpret the southern NCB, and units as far south as the northern Liuling unit, as having been stitched together by the 400 Ma magmatic–metamorphic event, and suggest that an Andean-type continental margin arc was built along the southern margin of the NCB at this time; we place the subduction zone producing the Silurian–Devonian arc south of the northern Liuling unit (Ratschbacher *et al.* in press). The local absence of Upper Ordovician (*c.*445 Ma) through Lower Carboniferous (*c.*350 Ma) rocks from the NCB in the Qinling orogen probably reflects uplift related to the formation of this Andean-style Qinling arc.

High-pressure rocks that may be associated with the Qinling arc have been found by Hu *et al.* (1995, 1996) in the northern Qinling area (Fig. 2, offset). Hu *et al.* reported lenses and blocks of eclogite, coesite-bearing eclogite and retrogressed amphibolite within garnet-bearing quartz and phengitic mica schist. While the individual outcrops are no more than a few metres wide, the belt of eclogites extends more than 10 km (Fig. 2). The eclogites consist of garnet + omphacite + rutile + quartz + zoisite $\pm$ phengite (3.5 Si atoms per formula unit) $\pm$ amphibole; many have been extensively retrogressed. Inclusions of coesite and its pseudomorphs in garnet and omphacite were identified in a few samples, based on optical properties and the presence of radial fractures around the inclusions; this identification, however, should be confirmed by Raman spectroscopy. Pressure–temperature estimates based on mineral composition range from 1.3 to 1.5 GPa and 590 to 758 °C; coesite of course would indicate $P > 2.6$ GPa. A Sm–Nd isochron for garnet, omphacite, rutile, amphibole and whole rock is reportedly 400±16 Ma (although we are unable to reproduce this age from the reported isotopic ratios).

The Qinling continental arc can be traced eastward as far as Hong'an, where it disappears beneath Cenozoic sedimentary rocks (Figs 2 and 4). No such arc is known from Sulu or Korea, but possible correlatives exist in the Kunlun Mountains of northern Tibet (Matte *et al.* 1996; Yang *et al.* 1996).

Devonian–Carboniferous accretionary wedge

A probable fossil accretionary complex, also with high-pressure rocks, lies south of the Silurian–Early Devonian arc in the Liuling and Sujiahe units (Fig. 3). The Liuling unit is a mixture of siliciclastic and volcaniclastic rocks, amphibolite and minor carbonate (You *et al.* 1993). Correlative rocks include the Xinyang Group in Tongbai–Hong'an and the Foziling unit in Dabie. Devonian fossils in the Tongbai area (Du 1986; Niu *et al.* 1993) have been used to infer a Devonian age for the entire Liuling; however, Yu and Meng (1995) showed that several conglomerate-bearing, volcaniclastic deposits, locally containing metabasalts and metacarbonates, have proven Upper Devonian and Lower Carboniferous and suspected Carboniferous to Permian ages. The Sujiahe unit mainly contains volcaniclastic rocks and 'mélange' (Ratschbacher *et al.* in press).

Blocks of eclogitic rocks and retrograde amphibolites occur in a shear zone 1–3 km wide near the southern edge of the Sujiahe unit 5–20 km northwest of Tongbai. The eclogites contain garnet, omphacite, quartz, rutile, phengite and barroisitic amphibole, and have yielded P–T estimates of 480–550 °C and 1.3–1.8 GPa (Wei *et al.* 1999). Ye *et al.* (1994) reported Sm–Nd mineral/rock isochrons of 533 ± 13 Ma and 544±14 Ma and a $^{40}Ar/^{39}Ar$ barroisite age of 399±4 Ma. This belt of HP rocks in the Sujiahe unit extends as far east as the Xiongdian area of Hong'an, where eclogite lenses or layers crop out in quartzite and felsic gneiss. These eclogites contain minor glaucophane and phengite in addition to garnet, omphacite and rutile, and formed at $P \geq 1.3$–1.5 GPa, $T \geq 590$–680 °C, similar to tectonic blocks in the Franciscan Complex of California (Ye *et al.* 1994; Liu *et al.* 1996). They have yielded SHRIMP U–Pb zircon ages of *c.*310 Ma (Sun *et al.* 2002), 400 Ma (Jian *et al.* 1997), a Sm/Nd isochron of 422 Ma (Li *et al.* 1995), an amphibole $^{40}Ar/^{39}Ar$ age of 400 Ma (Jian *et al.* 1997), and a muscovite $^{40}Ar/^{39}Ar$ age of 400 Ma (Xu *et al.* 2000a). Sun *et al.* (2002) directly tied their *c.*310 Ma age to high-pressure recrystallization with laser ICP-MS trace-element analyses that demonstrated zircon growth while garnet was stable and plagioclase was not stable.

During and after the formation of the Qinling Andean-style volcano-plutonic arc, the southern margin of the NCB was dissected by sinistral wrenching along the Lo-Nan and Shang-Dan shear systems at 420–380 Ma (Fig. 2) (Ratschbacher *et al.* in press). We assume that oblique subduction imposed these spectacular transpressive wrench zones. Muscovite and biotite $^{40}Ar/^{39}Ar$ ages ranging from 348 to 314 Ma have been interpreted to reflect a continuation of this strike-slip motion into the Permian (Mattauer *et al.* 1985). On a larger scale, the NCB and SCB rifted from Gondwana in the Late Devonian–Early Carboniferous (Li & Powell 2001).

Devonian–Triassic volcano-plutonic arc

It is unclear whether the inferred Devonian–Permian subduction beneath the NCB produced a continental margin arc. Younger, Permian and Triassic metaluminous, probably I-type plutons with low Sr_i ratios (Xue *et al.* 1996a) intrude the Kuanping, Erlangping, Qinling and Liuling units as far east as Xi'an (Figs 2 and 4). Coeval intrusions pierce the western edge of the Yangtze Craton in the Xue Shan, Longmen Shan, the Songpan–Ganze flysch and the SCB cover south of the Qinling mountains (Fig. 1, Regional Geological Survey of Gansu 1989, Regional Geological Survey of Shaanxi 1989). The plutons intruding the SCB cover raise an important problem, as they appear to be south of the inferred north-dipping subduction zone. East of Xi'an this arc may end, disappear under Cenozoic sedimentary rocks, or be covered by younger thrust slices. Middle Carboniferous to Early Permian andesites form a NE-trending belt across the eastern half of the NCB (Fig. 1) (Zhang 1997), but the belt is surprisingly far north of and oblique to the inferred NCB–SCB suture.

We suggest that the pre-collisional, Permo-Carboniferous NE trend of the NCB–SCB suture in Tongbai–Hong'an–Dabie and the suture–arc distance were modified by the Triassic, syn-collisional clockwise rotation of the SCB described below (e.g. Zhao & Coe 1987), and the Late Jurassic–Cenozoic extension within the Hehuai Basin (e.g. Han *et al.* 1989; Ren *et al.* 2002). The apparent intrusion of subduction-related plutons into the SCB cover can most easily be reconciled by attributing them to Late Triassic subduction along the cryptic Mianlue 'suture' of the southwestern Qinling orogen (Fig. 1) (Meng & Zhang 2000). The Mianlue rock assemblage, containing volcaniclastic and ophiolitic remnants with proven or suspected Early–Middle Triassic metamorphic ages (Li *et al.* 1999a), apparently terminates in the southwestern Qinling orogen, but might connect with the Liuling unit through the central and eastern Qinling orogen.

Triassic collision

Palaeomagnetic data (Zhao & Coe 1987; Lin & Fuller 1990; Enkin *et al.* 1992) suggest that the NCB and SCB moved farther apart during the Middle Permian to Middle–Late Triassic, but then approached each other and underwent 60° of relative rotation between Middle–Late Triassic and Middle–Early Jurassic times (Fig. 5) (Zhao & Coe 1987; Gilder *et al.* 1999). A regional unconformity and a cusp on the NCB apparent polar wander path imply that collision ended at the Middle to Late Jurassic boundary (Gilder & Courtillot 1997).

Collisional metamorphism

The UHP–HP metamorphism of the Qinling–Dabie Orogen constitutes the most readily identifiable feature of the North China Block–South China Block collision. Triassic HP rocks occur in four distinct areas: (1) the northern Wudang core complex, which tapers eastward into the Suixian and Yaolinghe areas; (2) the Hong'an–Dabie area, which forms an eastward-thickening wedge of UHP rocks (including eclogite relits recently discovered within northeastern Dabie

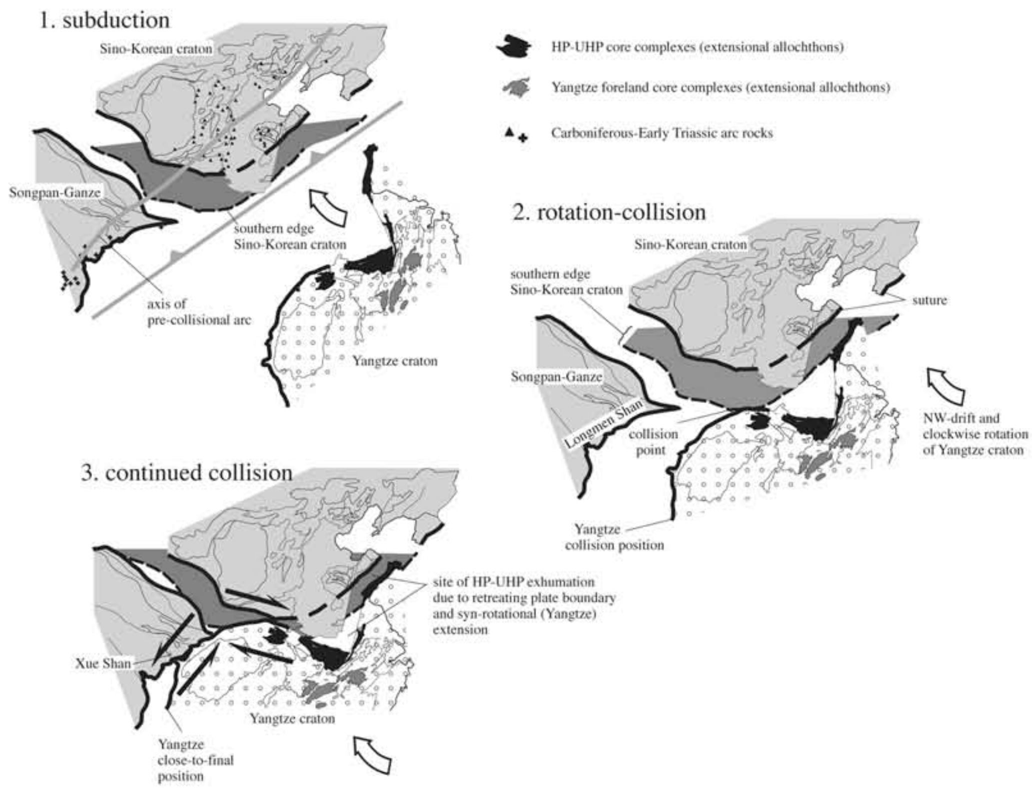


Fig. 5. Carboniferous–Triassic tectonic evolution of eastern Asia. (1) Formation of a Carboniferous–Permian magmatic arc, oblique to the presently east–west-trending Triassic suture along the Qinling–Dabie belt. (2–3) Palaeomagnetically supported rotation–collision scenario for the Permian–Triassic Sino-Korean–Yangtze approach, illustrating transpressive wrenching along the Qinling–Dabie belt and extensional exhumation of the Dabie–Sulu HP–UHP rocks by retreat of the Sino-Korean plate boundary due to rotation during collision.

(Wei *et al.* 1998; Tsai & Liou 2000; Xu *et al.* 2000b; Zhou *et al.* 2000; Liu *et al.* 2001); (3) the Zhangbaling and Bengbu areas, a mostly blueschist-facies extensional complex (our observations); and (4) the Sulu area (Wallis *et al.* 1999) (Fig. 1).

The evidence of Triassic HP and UHP metamorphism comes chiefly from a few per cent of eclogite and garnet peridotite boudins that are hosted by paragneiss plus less granodioritic–tonalitic orthogneiss (Fig. 6) (Cong 1996; Liou *et al.* 2000). The highest temperatures and pressures attained in the coesite- and, locally, diamond-bearing Dabie eclogites were 825–850 °C and 3.3–4.0 GPa (Carswell *et al.* 1997). The coesite-free eclogites reached somewhat lower peak conditions of 625–700 °C and 2.2–2.4 GPa in the Dabie Shan (Okay 1993; Liou *et al.* 1996; Carswell *et al.* 1997), and have been divided into kyanite-bearing and kyanite-absent eclogites in Hong'an, with estimated physical conditions of 550–650 °C, 1.6–2.5 GPa and 450–550 °C, 0.8–1.2 GPa, respectively (Eide & Liou 2000). The amphibolite unit is a hornblende-rich orthogneiss; peak pressure and temperature estimated from one locality are >1.0 GPa and ≥650 °C (Liu & Liou 1995). Blueschists reached conditions of only 400–800 MPa at 350–450 °C (Eide & Liou 2000). While most of the evidence of UHP derives from eclogites, the paragneiss also contains local unambiguous indications of metamorphism at similar pressure and temperature, such that the eclogites clearly were metamorphosed *in situ* (Liou *et al.* 1996), the same may not hold true for ultramafic blocks, some of which record recrystallization pressures >4 GPa (Okay 1994; Hacker *et al.* 1997; Liou & Zhang 1998). The spatial distribution and metamorphic conditions of these HP through UHP rocks indicate subduction-zone metamorphism on a regional scale.

The age of UHP metamorphism in the Dabie Shan is now well constrained to be Middle–Late Triassic (e.g. Hacker *et al.* 2000). The most recent data indicate that UHP recrystallization may have begun as early as 245 Ma and extended through *c.*225–230 Ma (Okay 1993; Hacker *et al.* 1998; Hacker *et al.* 2000; Li *et al.* 2000; Chavagnac *et al.* 2001; Ayers *et al.* 2002). High-pressure rocks in Hong'an (the area least affected by Cretaceous reheating) indicate that the regional amphibolite-facies overprint at 500–650 °C and 0.8 GPa occurred during the 195–225 Ma time span ($^{40}Ar/^{39}Ar$ phengite

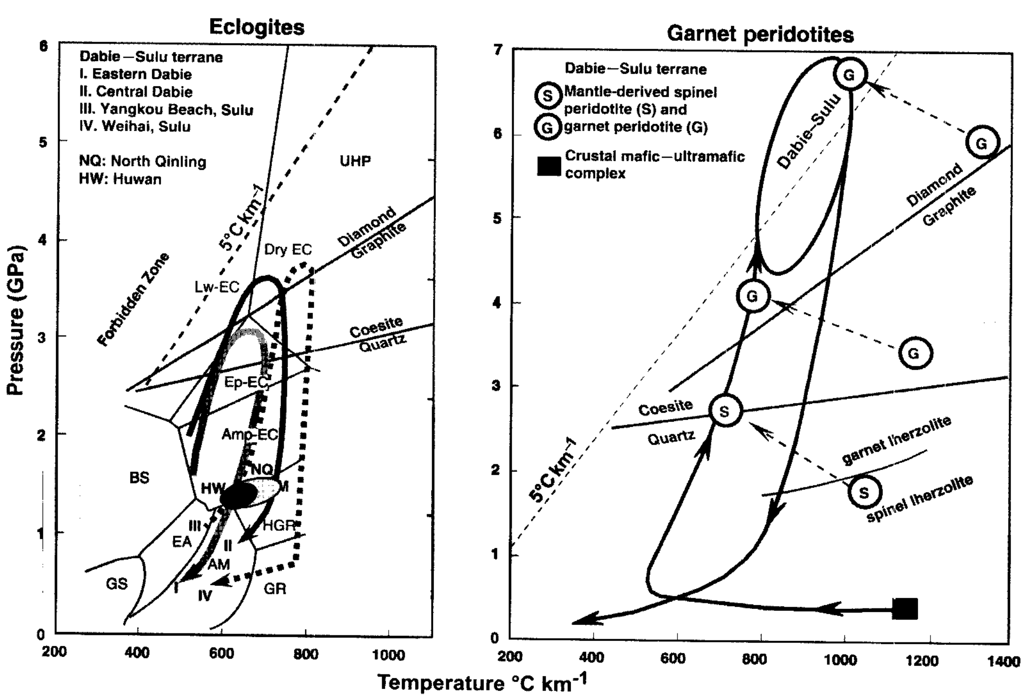


Fig. 6. Metamorphic pressures and temperatures for eclogites and peridotites of the Qinling–Dabie–Sulu orogen (modified after Liou *et al.* 1999; Zhang *et al.* 2001).

ages). Most of the K-feldspar $^{40}Ar/^{39}Ar$ spectra have inflections indicating cooling below *c.*200 °C near 170 Ma, although some rocks were this cool as early as 200 Ma. Such *P–T* paths, with concomitant decompression and cooling are only possible if exhumation was rapid or the slab was refrigerated by deeper level subduction (Hacker & Peacock 1995; Ernst & Peacock 1996). The exhumation rate is only crudely constrained to *c.*3–15 mm/year.

Geochronology shows that the Middle–Late Triassic thermal event associated with the UHP metamorphism in the eastern Dabie Shan and Hong'an areas extended as far north as the Erlangping unit in the Qinling area, the Xinyang unit in the Tongbai and Hong'an areas, and the Foziling and Luzhenguang units in the Dabie Shan (Hacker *et al.* 1998; Hacker *et al.* 2000). The absence of HP metamorphism means that these northernmost units were not subducted during the collision, but the Late Triassic metamorphism is certainly related to the collision.

Collisional deformation

The Triassic NCB–SCB collision produced a distinct set of structures throughout the Qinling-Dabie orogen: NW–SE to N–S contraction by folding and thrusting throughout the belt, subhorizontal NW–SE to N–S extension within core complexes along the northern margin of the South China Block, and dextral transpressive reactivation of existing shear zones in the Qinling area (Fig. 5).

The UHP rocks in both Dabie–Hong'an (Faure *et al.* 1999; Hacker *et al.* 2000) and Sulu (Wallis *et al.* 1999; Faure *et al.* 2001) form the cores of structural domes, exhibit a top-NW sense of shear and are overlain by extensional faults that exhumed the UHP rocks. At least in Hong'an–Dabie, the entire crystalline core of the orogen constitutes a normal-sense shear zone *c.*15 km thick; the Huwan shear zone, a normal-sense detachment that reactivated the plate suture, tops the extensional allochthon in Hong'an (Hacker *et al.* 2000; Webb *et al.* 2001). Associated Triassic metamorphic core complexes in the northern part of the SCB include the Wudang Shan (Ratschbacher *et al.* in press) and Zhangbaling–Bengbu (our unpublished data); whether the Lu Shan (Lin *et al.* 2000), Wugong Shan (Faure *et al.* 1996), Dongling (Grimmer *et al.* in press), and Jiuling Shan (Lin *et al.* 2001) basement uplifts within the foreland SCB fold-thrust belt south and east of Hong'an–Dabie, which show a Triassic to Cretaceous extensional overprint, are related to extensional exhumation of the HP–UHP rocks remains unclear.

The HP to UHP rocks of Dabie–Hong'an are mostly a structural homocline with SE-dipping foliation, SE-plunging lineation, and overall top-to-NW flow that includes significant coaxial stretching (Fig. 7). In northern Hong'an, however, the S-oriented structures roll over through horizontal into a 5-km-thick zone of N(W)-dipping foliations, N(W)-plunging lineations, and a N(W)-directed sense of shear. This, the Huwan shear zone (Webb *et al.* 2001), effectively straddles the Triassic suture. It developed out of the high-strain gneisses of typical Yangtze affinity in northern Hong'an, contains strongly retrogressed eclogite boudins of pre-Triassic age in the Sujiahe complex (see above), and dies out northward in the phyllitic quartzites typical of the southern Liuling unit. The Huwan shear zone can be followed – with interruptions by Cretaceous plutons – into northern Dabie, where it is truncated by a large Cretaceous pluton. The pseudostratigraphy of the Hong'an area also defines a series of km-scale NW-trending synforms and antiforms that are overturned to the north in central Hong'an, and are upright to south facing in southern Hong'an. The coesite-bearing eclogite unit forms the core of the northernmost antiform; the lowest pressure rocks, blueschist, are present only on the south limb of this orogen-scale fold. The westward decrease in peak metamorphic pressures reveals that the antiform plunges west. This antiform extends eastward into Dabie where it is partially overprinted by the dominantly Cretaceous intrusions and structures of the Northern Orthogneiss (Ratschbacher *et al.* 2000), and then terminates against the Tan–Lu fault.

The large-scale Wudang Shan dome (Fig. 4) that lies west of the UHP Hong'an–Dabie area is an extensional core complex overprinted by foreland folding and thrusting. Deformation in the Wudang Shan began with an early unresolved, but possibly contractional deformation, was followed by sub-vertical contraction and sub-horizontal N–S extension during blueschist–greenschist-facies metamorphism of the basement and basement–cover contact zone; $^{40}Ar/^{39}Ar$ dating of syn- to post-kinematic hornblende and muscovite puts the extension at, or prior to, 230–235 Ma. Subsequent folding and thrusting of the basement and Palaeozoic cover sequence occurred during N–S contraction.

The northern limit of the Triassic extensional deformation (Fig. 4) is located at different positions along the Qinling orogen. In the Qinling mountains, the northern limit of extension is the Wudang basement; the Douling unit

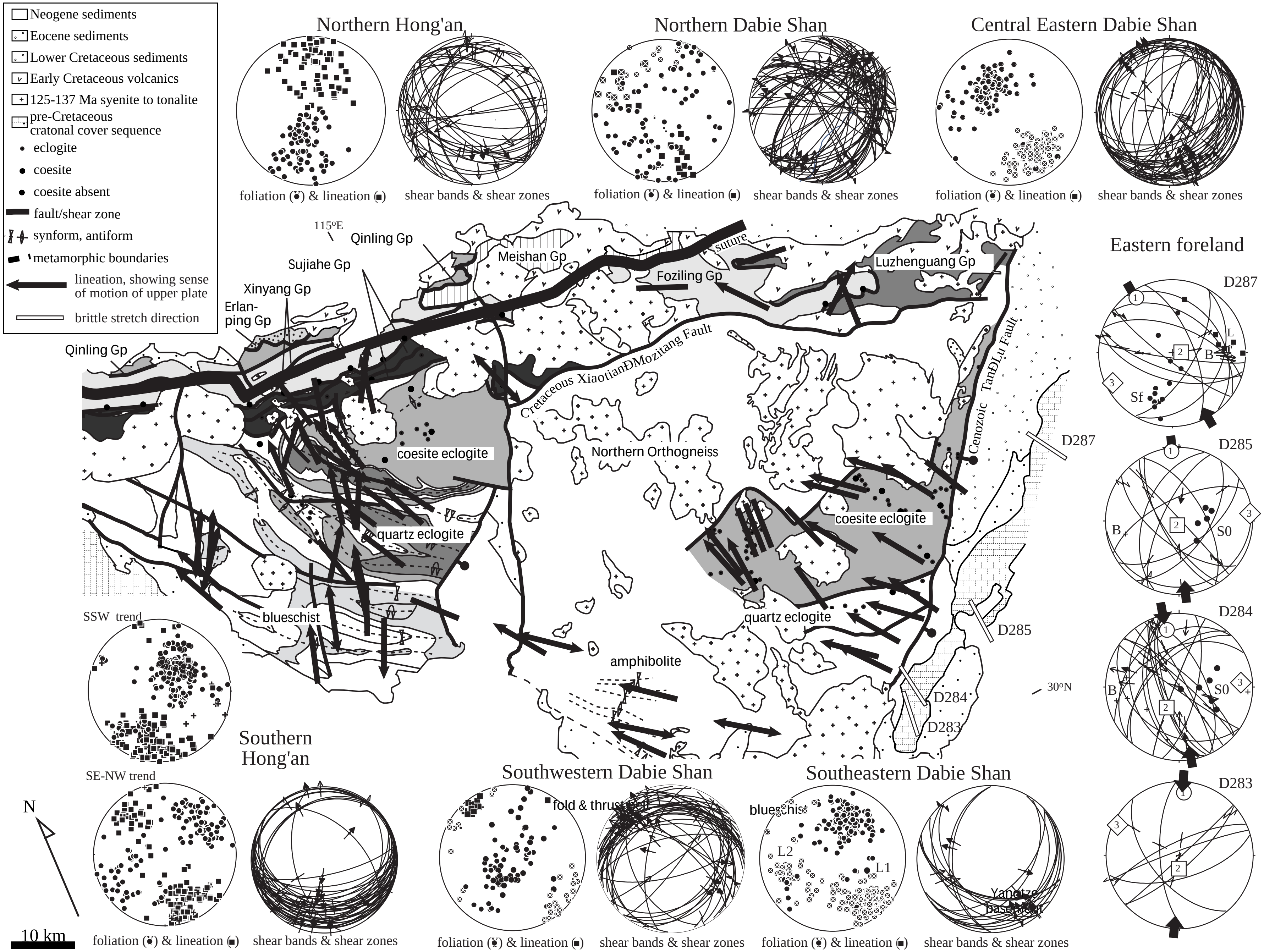


Figure 7: Structural overview of the Dabie-Hong'an area (after Schmid et al. 1999; Hacker et al. 2000; Ratschbacher et al. 2000; Webb et al. 2001). Areas disturbed by Cretaceous plutons are not included in the synoptic stereonets. Stereonets from eastern foreland show dominantly brittle faults: (1), (2), and (3) indicate principal stress directions; B, fold axis; S0, bedding; and Sf, foliation.

is non-mylonitic and lacks significant Triassic metamorphism. In northern Hong'an, the Huwan shear zone constitutes a lithosphere-scale reactivation of the Devonian–Triassic subduction complex. In Dabie, the Huwan detachment cannot be mapped, as Cretaceous tectonism has obliterated earlier fabrics, but the northern limit of extension must be south of the Foziling and Luzhenguang units, which have clear Yangtze craton affinity and were unaffected by HP metamorphism, very likely coinciding with the Early Cretaceous Xiaotian–Mozitang crustal-scale shear zone (Hacker *et al.* 2000; Ratschbacher *et al.* 2000).

Much of the area shown in Figure 2 has WNW-trending folds and craton-directed thrusts of millimeter to kilometre scale that formed during the collision (Mattauer *et al.* 1985; Regional Geological Survey of Henan 1989; Regional Geological Survey of Shaanxi 1989; Regional Geological Survey of Hubei 1990). On the NCB, the north-directed Lu Shan thrust, placing crystalline basement over Palaeozoic cover, was active in the Middle Triassic and Late Jurassic (Huang & Wu 1992). Huang and Wu (1992) also identified a series of Mesozoic S-directed thrusts imbricating the Sino-Korean basement, Kuanping, Qinling, Erlangping and Douling units. The fold–thrust belt along the Lower Yangtze river began to develop through NW–SE contraction in the Middle Triassic and continued through the Early Jurassic, by which time the shortening direction had rotated to NNE–SSW (Schmid *et al.* 1999).

The Early Palaeozoic core of the Qinling orogen was reactivated during the relatively early stages of the NCB–SCB collision by overall top-south imbrication during a change from NW–SE (dextral transpression) to NE–SW shortening. Ratschbacher *et al.* (in press) documented *c.*200–250 Ma low-grade metamorphism and dextral transpression along the Lo-Nan, Shang-Xian and Shang-Dan faults, and N–S shortening within the Liuling and Douling units.

Syn- to post-collisional overlap assemblage

Changes in sedimentation patterns are often among the best guides to collisional timing. Depositional facies up through the Permian trend E–W in the southern NCB, and NNE in the northern SCB (Han *et al.* 1989; Sun *et al.* 1989; Wang *et al.* 1989; Zhang *et al.* 1989). Although collision-related (?) shortening began on the SCB in the Early to Middle Triassic, the major sedimentological change occurred in the Middle Triassic, which was marked locally by either a depositional hiatus, continental sedimentation (Huang & Opdyke 2000) or unconformable deposition of coarse carbonate breccias (Breitkreuz *et al.* 1994). Yin & Nie (1993) proposed that the transition from marine to continental sedimentation was diachronous: Early Permian in Shandong and Korea, Lower/Upper Permian south of Sulu, Lower/Middle Triassic SE of Dabie.

Nie *et al.* (1994) and Zhou & Graham (1996) proposed that detritus eroded from the active Qinling–Dabie mountain range was channeled westward and deposited to form the Songpan–Ganze flysch from the Anisian through the Norian (*c.*240–210 Ma). Bruguier *et al.* (1997) found detrital zircons with U/Pb ages of 233 and 231 Ma within the Songpan–Ganze flysch that match the ages of zircons found in Dabie (Hacker *et al.* 2000).

Post-collisional, Jurassic, continental clastic sedimentation on both cratons was accompanied by deposition of up to 5 km of calc-alkaline, crustal-derived, intermediate-composition volcanic rocks: tuff, volcanogenic sandstone, and some lava in the Late Jurassic (Regional Geological Survey of Anhui 1987; Regional Geological Survey of Henan 1989; Regional Geological Survey of Hubei 1990). Gneiss cobbles, presumably derived from the Dabie Mountains, first appeared in the Zhuji Formation on the northern slope of the Dabie Mountains in Middle Jurassic time (Ma 1991). Middle Jurassic sedimentary rocks in the Lower Yangtze fold–thrust belt show clear evidence of erosion of the Dabie UHP core, including Triassic-Jurassic detrital micas with high-Si contents and zircon grains as young as *c.*218 Ma (Grimmer *et al.* in press) their oldest mica ages indicate that exhumation in Hong'an-Dabie might have started at 240 ± 5 Ma.

Plate-scale collision model

While there is still much that we do not know, some key structural observations constrain the exhumation mechanism of the UHP rocks (Hacker *et al.* 2000):

(1) Unfolding the 'Hong'an antiform' – the orogen-scale fold trending NW–SE across Hong'an–Dabie – yields a N-dipping lithospheric slab with coesite eclogite in the north and lower pressure rocks progressively farther south and closer to the interior of the SCB. The upper boundary of the slab is the Huwan shear zone, which encompasses the suture between the NCB and the SCB, implying that it is essentially a plate boundary reactivated as a lithosphere-scale, normal-sense shear zone.

(2) The size of the UHP outcrop and the peak pressures diminish westward, indicating that the depth of exhumation increased eastward.
(3) Stretching lineations within Hong'an and Dabie show a clockwise rotation with depth of exhumation (Fig. 5).

These features are most easily reconciled with a model involving subduction of an triangular promontory of the SCB that reached its greatest depth in the east (Fig. 8, Hacker *et al.* 2000). At some point, the buoyant, subducted continental crust tore away from the oceanic part of the plate and began to rise within the channel between the two cratons. The tear began at the deepest point of subduction of the buoyant slab and ripped upward along the promontory. The shape and orientation of the subducted crust, combined with the dependence of buoyancy on depth below the Moho, imply that the promontory might have pivoted about its shallow end, producing the curved lineations and an extruded wedge of formerly subducted SCB plate. The E–W trend of the southern margin of the NCB in the Qinling–Dabie area, coupled with the observed motion within the extrusion channel, implies that the UHP slab was extruded eastward along the plate margin during exhumation. We suggest that this occurred toward an eastern re-entrant in the plate margin that imposed a weak constraint on the extruding lithosphere (Ratschbacher *et al.* 1991).

Such a model makes no significant predictions about the apparent sinistral offset of the Qinling–Dabie–Sulu suture along the Tan–Lu fault. Yin and Nie (1993) explained the left-lateral offset along the Tan–Lu fault and the orientations of sedimentary facies patterns on the

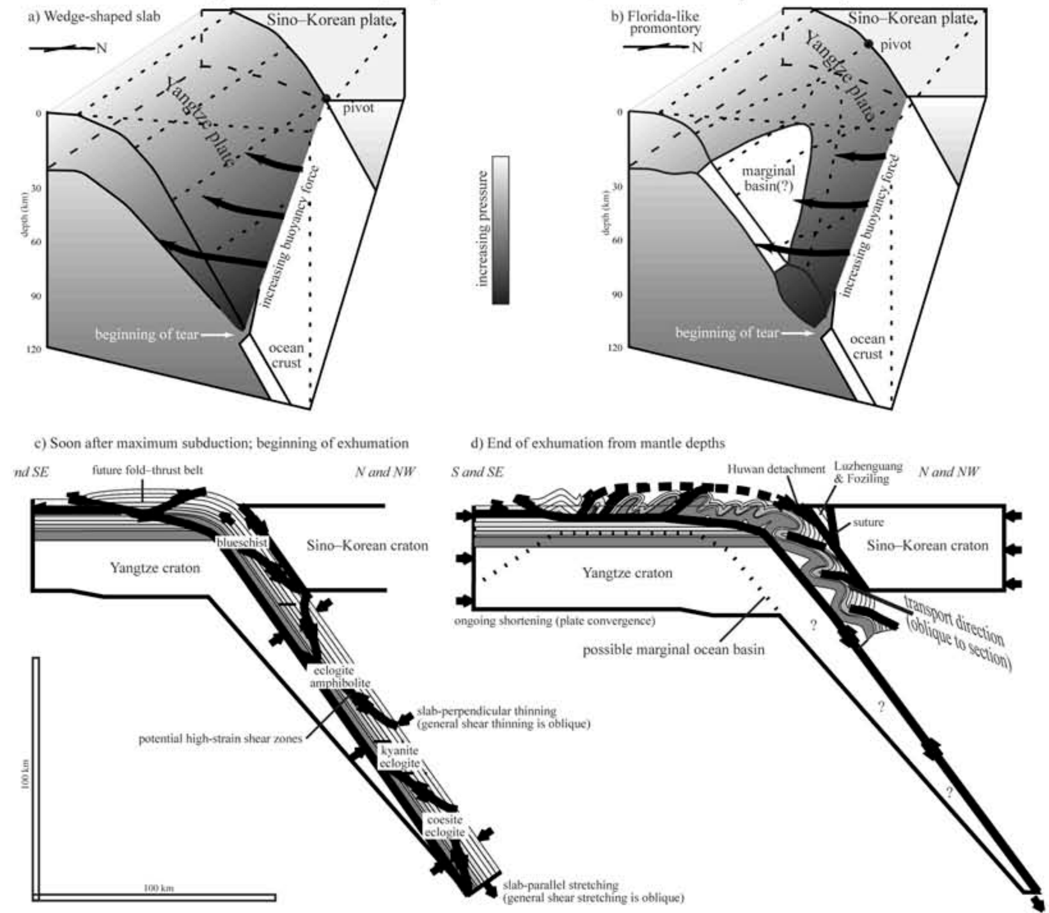


Fig. 8. Exhumation model. (**a**) Subduction of wedge-shaped continental promontory; arrow shows pivoting of slab during exhumation. (**b**) Subduction of Florida-like continental promontory (dark) attached to oceanic crust (white). (**c**) 2D representation of subducted continental crust, with detached sliver beginning to exhume. (**d**) 2D representation of continental crust exhumed by buoyancy plus subhorizontal extrusion.

two plates as the result of Late Permian–Early Triassic indentation of the NCB by the SCB; they rationalized that the active margin of the NCB should have been relatively straight and that the passive margin of the SCB could have been relatively complex. Gilder *et al.* (1999) criticized this idea because of a 'lack of significant folding of Phanerozoic rocks ... north of the Sulu belt', and proposed instead that the older NCB acted as a rigid indentor to deform the SCB in the Early to Middle Jurassic – leading to the palaeomagnetically recorded bending of the Lower Yangtze fold–thrust belt (Gilder *et al.* 1999), formation of the Tan–Lu fault, and 60° of relative rotation between the NCB and SCB (Zhao & Coe 1987). While there is structural and thermochronological evidence of Late Cretaceous and Cenozoic strike-slip and normal faulting (Ratschbacher *et al.* 2000; e.g. Grimmer *et al.* 2002), no well-documented structural data demonstrate sinistral Triassic or Jurassic motion along the Tan–Lu fault. However, Mid-Triassic NW–SE contraction and Late Triassic–Early Jurassic N–S contraction in the eastern Dabie foreland (Schmid *et al.* 1999) implies that if the Tan–Lu fault existed at that time then it would have been sinistral. Note that the age of Triassic metamorphism in the Qinling area is similar to that in Dabie; the proposed younging and westward migration of collision (e.g. Zhao & Coe 1987; Yin & Nie 1993; Zhang 1997) is not supported by extant geochronology (Hacker & Wang 1995).

Problems and possible solutions

The preceding sections have outlined a number of important problems within the Qinling–Dabie orogen.

(1) The boundary between rocks of Sino-Korean and Yangtze affinity appears to be a suture of Ordovician–Silurian age. This interpretation could benefit from further analysis of the tectonic histories of key units in the Qinling orogen.

(2) Devonian–Triassic rocks of the Liuling, Xinyang, and Foziling units separate the NCB from the SCB. These relatively monotonous units thus potentially experienced quite a varied history. Can this history be read from these rocks?

(3) The northern boundary of Triassic exhumation is generally south of the northern edge of the SCB. In the Qinling mountains, it lies south of the Douling unit and south of the Yangtze craton cover. In Tongbai and Hong'an it coincides with the northern edge of the SCB. In Dabie, it lies south of the Luzhenguang unit. This implies that the Douling, Luzhenguang and other units (i) represent the leading edge of the SCB but were not subducted; (ii) were originally south of the HP–UHP rocks and ended up in their present position as a result of exhumation of the HP–UHP rocks; or (iii) are part of the NCB (although of Yangtze affinity, like the Qinling unit), but are now mysteriously south of the Liuling, Xinyang and Foziling units and escaped intrusion by the Qinling arc.

(4) A weakness of the exhumation model outlined in the previous section is that we have not identified a sole thrust along the southern and eastern edges of Dabie–Hong'an. SE-directed extrusion of the wedge of UHP–HP rocks should have induced equivalent shortening at the tip of the extruding wedge, but one of the characteristics of the Triassic/Jurassic foreland deformation east of Dabie is upright folding and a combination of hinterland- and foreland-directed thrusting with relatively moderate shortening (Schmid *et al.* 1999; Grimmer *et al.* in press). To explain the apparent lack of the mega-thrust and the distinctive structural style, we can envision at least three scenarios. (i) The leading edge of the UHP–HP rocks forms a wedge that is buried beneath the cover strata of the foreland. This implies that the crust of the foreland was detached at middle to upper crustal levels and thrust northwestward on to the crystalline core. (ii) The UHP–HP rocks were exhumed by buoyancy into the middle/lower crust, and the overlying rocks were removed by extension and erosion. A plate rotation model proposes that after initial collision in the eastern part of the orogen, continued closure of the 'Songpan–Ganze Sea' by subduction of oceanic lithosphere caused the SCB to rotate 60° clockwise (required by palaeomagnetic data), pulling parts of the subducted SCB back toward the surface.

Summary

Grenvillian orogeny, involving oceanic subduction with HP metamorphism and ophiolite emplacement (Songshugou ophiolite), assembled the Yangtze craton, including the Qinling microcontinent, into Rodinia. Rifting at *c.*750 Ma separated the Qinling microcontinent from the Yangtze craton. Intra-oceanic arc formation (Erlangping–Danfeng–Heihe) between *c*.490–470 Ma was followed by the accretion of the lower Qinling unit to the intra-oceanic arc and the North China Block. Oceanward (northward in present coordinates) subduction beneath the northern Liuling unit imprinted the *c*.400 Ma Andean-type magmatic arc on to the North China Block. Oblique subduction imposed the spectacular Early Devonian left-lateral transpressive wrench zones. A subduction signature is again evident during the mid-Carboniferous to Late Permian on the North China Block, when the Palaeo-Tethys was subducted northward, producing the andesitic magmatism on the North China Block. In the Late Permian–Early Triassic the leading edge of the South China Block was subducted to >150 km and subsequently exhumed by crustal extension during clockwise rotation of the craton.

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