Crustal structure and exhumation of the Dabie Shan ultrahigh-pressure orogen, eastern China, from seismic reflection profiling

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ABSTRACT

Crustal-penetrating seismic reflection data across the ultrahigh-pressure (UHP) Dabie Shan orogen show that the Yangtze craton was subducted beneath the Sino-Korean craton, forming a bivergent orogenic fabric strikingly similar to ''normal'' (non-UHP) collision belts. Hence preservation of UHP minerals (coesite and diamond) may be unrelated to differences between collisional histories, but may be due to opportunities for subsequent intracrustal uplift of material that is routinely returned from mantle depths into the lower crust in most collisional orogens. Only a narrow channel (≤5 km) now exists from the mantle into the crust through which UHP material was returned to lower-crustal depths as thin slabs. We image the Dabie Shan as a crustal-scale dome formed during postcollisional intracrustal uplift by core-complex–type exhumation of the lower crust, tectonically unrelated to the earlier exhumation from >100 km to <35–40 km.

Keywords: ultrahigh-pressure metamorphism, seismic reflection data, crustal structure, Dabie Shan, China.

INTRODUCTION

One of the most revolutionary geologic discoveries of recent years is the presence at Earth's surface of coesite (an ultrahigh-pressure [UHP] polymorph of quartz requiring pressure [P] ≥ 2.7 GPa at a temperature [T] ≈ 600 °C) and diamond (the UHP polymorph of graphite) in metamorphosed continental sedimentary rocks, implying their exhumation from depths of >100 km. Plate tectonics shows how buoyant continental crust can be subducted to depths of >100 km, but the mechanisms by which these rocks return to the surface remain controversial. Discoveries of UHP minerals in upper-crustal rocks require a revision in our understanding of crustal-scale processes in continental-collision zones. About one dozen UHP terranes have been documented, all of which formed in continental-collision orogens at pressures >3 GPa during subduction to depths as great as 135 km (Ernst and Liou, 2000; Liou, 2000).

The Qinling-Hong'an-Dabie-Sulu belt of east-central China marks the east-trending collisional orogen between the Sino-Korean and Yangtze cratons (Fig. 1), which is offset by the Tan-Lu left-lateral strike-slip fault (Xu et al., 1993; Ratschbacher et al., 2000). The Dabie Shan provides the world's most extensive exposures of UHP rocks and is perhaps the best-studied belt (Cong, 1996) of the UHP terranes thus far documented (Ernst and Liou, 2000; Liou, 2000). The major rock units of the Dabie Shan orogen (Fig. 1) are, from south to north, the Yangtze fold-and-thrust belt; the South Dabie block, consisting of a high-pressure terrane (blueschist, amphibolite, quartz eclogite) and the UHP coesite eclogite; the amphibolite-to-granulite North Dabie block (or Northern orthogneiss unit), largely consisting of Cretaceous granitoids; and the lower metamorphic grade (greenschist-to-amphibolite) Luzhenguan and Foziling ''Groups,'' overlain farther north by Jurassic and younger Hefei Basin sedimentary rocks. Geochronologic and structural evidence places the Triassic suture between the cratons (Fig. 1) north of the Luzhenguan and Foziling Groups (Hacker et al., 2000).

Protoliths of the Dabie Shan UHP rocks are the Sinian (Late Proterozoic) continental-margin strata of the Yangtze craton (Rowley et al., 1997; Hacker et al., 2000). The rare but widespread UHP coesite-bearing rocks in the Dabie-Sulu terrane formed by north-directed Triassic subduction of the Yangtze craton or a Dabie microcontinent beneath the Sino-Korean craton at ca. 245 Ma to ~120 km depth at temperatures of 800–825 °C (Xu et al., 1992; Hacker et al., 2000). Timing and perhaps process vary along strike from Hong'an to Dabie to Sulu, but muscovite closure ages of 230–200 Ma from the Dabie Shan show that there the subduction event was followed by rapid return of the UHP rocks into the lower or middle crust, and cooling below temperatures of 350–400 °C at depths <35–40 km (Webb et al., 1999; Hacker et al., 2000). Exhumation of the Dabie Shan UHP rocks into the upper crust was accomplished during Cretaceous core-complex–type extension accompanying intrusion, at 15–20 km depth, of gabbroic-to-syenitic plutons ca. 140–120 Ma (Hacker et al., 2000; Ratschbacher et al., 2000). The Xiaotian-Mozitang fault acted as a major down-to-the north normal and sinistral strike-

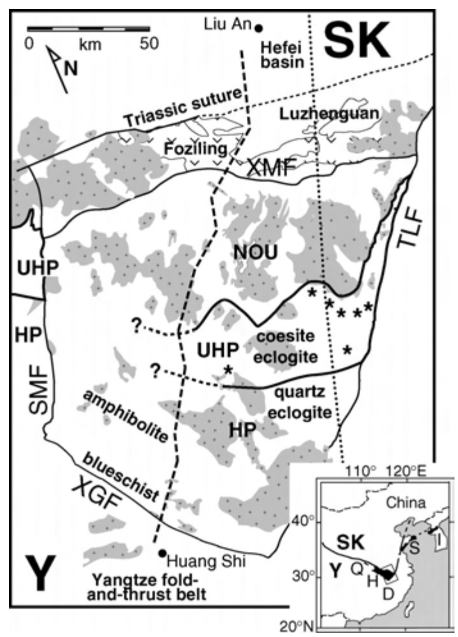

Figure 1. Generalized geologic map of Dabie Shan (Ratschbacher et al., 2000; Hacker et al., 2000). SK—Sino-Korean craton; Y—Yangtze craton; HP—high-pressure zone (blueschist to quartz eclogite); UHP—ultrahigh-pressure (coesite-bearing) eclogite (stars show known coesite localities); NOU—Northern orthogneiss unit; XMF—Xiaotian-Mozitang fault; TLF—Tan-Lu fault; XGF—Xiangfan-Guangji fault; SMF—Shang-Ma fault. Gray regions are Early Cretaceous plutons. Heavy dashed line—our reflection profile (Fig. 2). Dotted line—refraction profile (Wang et al., 2000). Inset shows location of HP-UHP terranes: Q—Qinling, H—Hong'an, D—Dabie, and S—Sulu in eastern China, and Imjingang (I) in Korea, offset by Tan-Lu fault.

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slip fault at this time. Final denudation of <5 km and exposure at the surface occurred in Tertiary time (Ratschbacher et al., 2000). Although the UHP eclogites comprise only ~5 vol% of the UHP terrane, field and petrologic evidence demonstrates that the volumetrically dominant paragneiss country rocks also record UHP metamorphism (Liou et al., 1996) and that the coesite eclogites were metamorphosed in situ, arguably within 5–10-km-thick fault-bounded sheets (Hacker et al., 2000; Ernst, 2001).

NEW SEISMIC REFLECTION DATA

The Chinese Geological Survey has collected a comprehensive suite of crustal-scale geophysical data across the Dabie Shan, including a 224-km-long crustal-penetrating seismic reflection profile (Fig. 2A). This first reflection profile to cross this largest region of UHP metamorphism is the best seismic data yet recorded across any UHP orogen. New refraction-velocity and gravity data help validate our structural interpretations of the seismic reflection data. Previous seismic studies in the Dabie Shan include (1) a Sino-German test reflection profile (Schmid et al., 2001) across the Tan-Lu fault, which is too short to provide a crustal-scale image of the collisional belt, and (2) a regional refraction profile running north-northeast–south-southwest through the easternmost Dabie Shan and across the Tan-Lu fault (40–80 km east of our reflection profile; Fig. 1), which provides a two-dimensional velocity profile to 40 km depth but little structural information (Wang et al., 2000).

The profile discussed here (Fig. 2A) was acquired by using a 240-channel SUMMIT system with 192 active channels, geophone groups spaced at 50 m, and single-hole 31–41 kg dynamite sources spaced at 400 m to give an average CMP (common midpoint) fold of 12. Data were recorded to 16 s, sampled at 2 ms, and processed using PGS Tensor seismic processing software. Crooked-line processing used CMP bins with a 25 m in-line and 300 m cross-line dimension. First-arrival refraction static corrections to a floating datum were followed by spherical-divergence correction and surface-wave suppression. Surface-consistent amplitude compensation and deconvolution were followed by DMO (dip moveout) velocity analysis, residual static correction, DMO stack and steep-dip migration using smoothed stacking velocities, and F-X deconvolution. Data were corrected to a fixed datum plane 300 m above sea level using a 3500 m/s replacement velocity.

INTERPRETATION OF REFLECTION PROFILE

In this paper we focus only on the first-order features (Fig. 2B) evident on the reflection

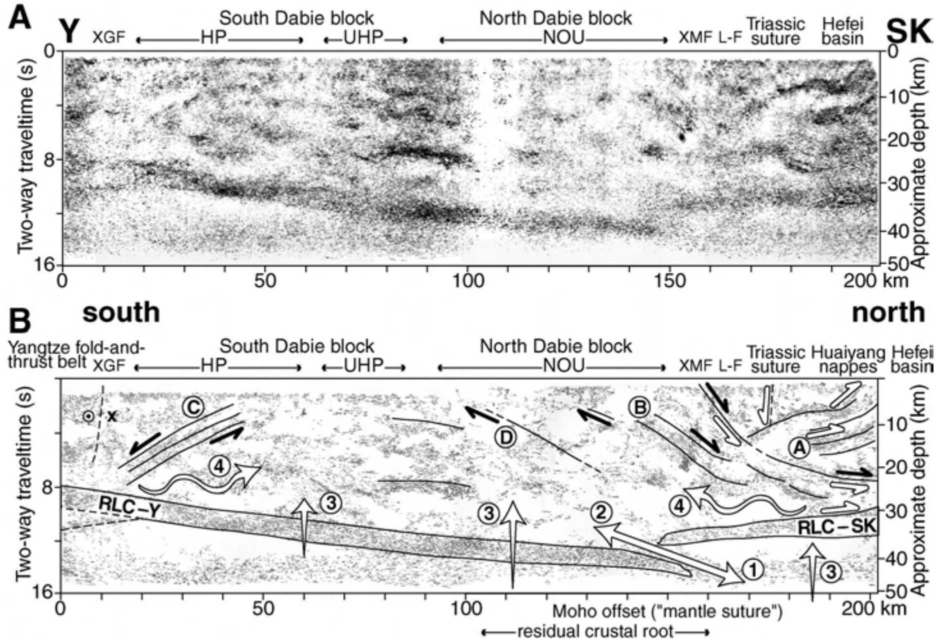

Figure 2. A: Migrated seismic reflection profile, Huang Shi to Liu An. Abbreviations as in Figure 1; L-F: Luzhenguan and Foziling Groups. True scale (no vertical exaggeration) at a velocity of 6.7 km/s. Display processing used a 4 s AGC window and time-varying filter, 8–12–35–45 Hz from 0 to 8 s and 5–8–25–35 Hz from 8 to 16 s. B: Line drawing of reflection profile, with principal reflection structures highlighted (dashed where more speculative). Half arrows show inferred direction of movement on faults and shear zones, open during subduction, solid during exhumation. Numbers 1–4 with open arrows show inferred sequence of mass transport, and letters A–D mark prominent dipping reflections, described in text.

profile (Fig. 2A). On most reflection profiles worldwide the base of the crust is defined by the reflection Moho that typically shows smooth variations in depth except across major fault or suture zones (Cook, 2002). On our profile the reflection Moho and reflective lowermost crust (RLC) of the Yangtze craton are unequivocally observed to dip gently north from 10.5 s two-way traveltime (~34 km) beneath surface position km 20 (measured from the southern end of the reflection profile in Fig. 2A) to 14 s (~45 km) at km 150 (RLC-Y in Fig. 2B), at which point there is an abrupt break; the reflection Moho beneath the northern end of the profile (below lower crust of the northern, Sino-Korean craton, RLC-SK in Fig. 2B) is at 11.5–12 s (~37–38 km). The reflective lowermost crust is clearly distinct from the middle- and upper-crustal basement, which is characterized by patchier, and sometimes steeply dipping, reflectivity. The observed variation in Moho depths (Fig. 2) is consistent with that measured in the nearby refraction profile (Wang et al., 2000) and implied by the Bouguer gravity low over the central Dabie Shan (Liou et al., 1996); it allows us to reliably interpret the Moho offset at km 150 as the relict collisional suture between the Yangtze and Sino-Korean cratons. Because our Moho offset (Fig. 2) is 40 km east along Triassic strike (Fig. 1) from the analogous feature on the refraction profile (Wang et al., 2000), we are confident that the offset is a Triassic feature. This Moho offset is clearly south of the surface expression of the Triassic suture (Figs. 1 and 2), which lies north of the Foziling and Luzhenguan Groups. We therefore infer that a crustal-scale wedge of Dabie (Yangtze) crust indented into the Sino-Korean craton, beneath the known Yangtze-affinity Luzhenguan and Foziling Groups and above the reflective lower crust observed north of the mantle suture, which must therefore be Sino-Korean. Because the Moho offset and maximum thickness of the residual crustal root are approximately below the surface position of the Xiaotian-Mozitang fault, previous interpretations based solely on refraction data suggested that young strike-slip faulting along and north of this zone was the cause of the Moho offset (Wang et al., 2000). This interpretation should now be discarded on the basis of our reflection data that show north-dipping panels of reflections in the middle crust at km 140–170, unbroken by young strike-slip faulting.

North of the Xiaotian-Mozitang fault and the Moho break, we interpret the mid-crustal reflections from 5 to 20 km depth that dip to the south (A in Fig. 2B, km 180–200) as representing the north-verging Huaiyang nappes known in the subsurface of the Hefei Basin from petroleum-industry seismic data and drill penetrations (Wang et al., 1997). These south-dipping reflections mirror the north-dipping reflections at similar depths (B in Fig. 2B, km 140–170) across the Triassic suture zone in the northern Dabie Shan, and the north-dipping shears mapped in the Luzhenguan and Foziling Groups (Hacker et al., 2000), thereby forming a bivergent pattern around the suture zone. This pattern, of bivergent crustal reflections above a Moho offset and residual crustal root, has been identified in numerous orogens that are not known to have associated UHP metamorphism and that are of Proterozoic (e.g., Svecofennides, BABEL Working Group, 1990), Paleozoic (e.g., Caledonides, Freeman et al., 1988), and Mesozoic (e.g., Pyrenees, Choukroune and ECORS Team, 1989) age. These patterns have also been reproduced in sandbox experiments and numerically modeled as a consequence of detachment and asymmetric subduction of the underlying lithosphere (Beaumont and Quinlan, 1994).

The north-dipping reflections in the northern Dabie Shan (B in Fig. 2B) are further mirrored by south-dipping fabrics in the southern Dabie Shan (C, km 20–40) as far south as the Xiangfan-Guangji fault that forms the southern boundary of exposed Dabie Shan rocks. Dominantly subhorizontal reflections in the central part of the profile (km 80–100) complete the picture of the Dabie Shan as a crustal-scale dome. A north-dipping reflection and change in reflective character (D in Fig. 2B) projects upward to the boundary between the North Dabie and South Dabie blocks, mapped at the surface as a change in metamorphic facies (Hacker et al., 2000) but as a south-dipping (Ratschbacher et al., 2000) normal sense shear zone.

RETURN OF UHP MATERIAL TO HIGH LEVELS IN THE CRUST

The formation of UHP minerals is not controversial in that continental collision is widely expected to subduct at least fragments of upper-crustal material to depths of ≥100 km (Chemenda et al., 1996). The controversies concern the mechanisms of return of this UHP material, first back to lower-crustal levels (≤40 km) and then within the crust back to the surface, perhaps by two independent mechanisms. It has been debated whether the exhumation from ≥100 km to ≤40 km is achieved in equidimensional diapiric volumes, controlled only by buoyancy forces, or in thin sheets, controlled not only by buoyancy but also by boundary forces (faulting and shearing). Only thin sheets, <5–10 km, are inferred from surface exposures in the Dabie Shan (Hacker et al., 2000) and in other UHP belts worldwide (Ernst, 2001), though the base of the UHP rocks is not seen in the Dabie Shan. It is often asserted that only thin sheets can preserve the characteristic UHP metamorphic assemblages, because bodies of larger characteristic dimension cannot be sufficiently quickly cooled from the peak temperature of >800 °C to the temperatures of <400 °C at which reaction rates are too slow to destroy the index minerals coesite and diamond (Ernst, 2001). However, this argument only tells us that equidimensional volumes will not preserve UHP mineral assemblages, not that such volumes do not return to the surface. During initial exhumation, with continued subduction and minimal internal heat generation, the thickness of the UHP material is irrelevant to the mineral preservation (Hacker and Peacock, 1994).

The geometry of the Moho offset and the subhorizontal reflective lower crust of the Yangtze and the Sino-Korean cratons must have been created during the Triassic Dabie orogeny, because the locations of the Moho offsets imaged by us (Fig. 2) and inferred from refraction profiling (Wang et al., 2000) lie along Triassic strike, and therefore must represent the geometry of subduction of the leading edge of the Yangtze craton. This single Moho offset between the two plates is the only plausible route by which Yangtze supracrustal material could first be subducted into the mantle (arrow 1 in Fig. 2B) and then returned to lower-crustal depths along the same subduction channel (arrow 2 in Fig. 2B). If the bands of reflective lower crust represent the limits of older crustal material, then the channel between the edge of each continent is now ≤5 km. Clearly this channel must have been broad enough during Triassic subduction to admit supracrustal rocks (now exposed in coesite eclogite facies) and hence presumably the entire thickness of the Yangtze crust, even if this was only the thinned leading margin of the Yangtze continent (~10 km thick). Hence the preserved reflection geometry represents the later stages of the collision and has been modified by syn- and postorogenic uplift; the present channel between the reflective lower crust of each craton has only limited meaning for the shape of this channel in the Triassic. We suggest that initial postorogenic uplift was a long-wavelength isostatic response to overthickening of the Dabie Shan internides (diagrammed by the vertical arrows numbered 3 in Fig. 2B, largest beneath the thickest part of the orogen), perhaps triggered initially by slab break-off (Davies and von Blanckenburg, 1998; Xu et al., 2001) or delamination (Leech, 2001). To the extent that regurgitation of UHP materials occurs after slab break-off or delamination, rather than during continued subduction, the narrow (≤5 km) remnant channel that we observe may have limited the thickness of UHP slices that returned to crustal depths.

UHP material returned to the lower crust must still be exhumed to its present surface exposure. The crustal seismic reflections and the surface geology (Hacker et al., 2000) suggest that a crustal-scale dome has formed between the Xiaotian-Mozitang fault and the Xiangfan-Guangji fault, yet the lowermost crustal reflectors and reflection Moho are subhorizontal, implying that the return of UHP sheets to the surface was accomplished solely by ductile flow, or, if in part by brittle faults, then that these faults are decoupled from the Moho by a ductile lower crust. We infer a pre-Triassic age for the material of the reflective lower crust that is offset at the Moho. Because the Moho is not deformed except by a single offset, we infer that the doming did not involve mantle material or the deepest (highly reflective) crust, but was instead driven by lateral inflow of middle and lower crust from the margins of the orogen (arrows numbered 4 in Fig. 2B). Such doming and thickening of the middle crust are seen beneath the most extended parts of metamorphic core complexes of the southwestern United States (McCarthy et al., 1991). In our model, following Ratschbacher et al. (2000), the Dabie Shan acted as a core complex, unroofed largely by the Xiaotian-Mozitang fault, on which ~40 km of Cretaceous normal displacement has been inferred (Ratschbacher et al., 2000), and by other parallel shear zones, perhaps including the north-dipping reflective boundaries B and D in Figure 2B. Doming was enabled by low mid-crustal viscosities during formation and intrusion of the voluminous Early Cretaceous plutons and was tectonically unrelated to the earlier exhumation from >100 km to <35–40 km. Channel flow of the middle crust originating in partially molten crust and leading to ductile extrusion of high-grade metamorphic rocks has recently been used to explain the evolution of active orogens such as the Himalaya (Beaumont et al., 2001). It has been argued that the Early Cretaceous deformation and plutonism in the Dabie Shan were consequences of new plate-tectonic conditions unrelated to the Triassic Dabie orogen (Ratschbacher et al., 2000), and hence the uplift of the UHP rocks from the lower crust and their preservation and eventual exposure are also unrelated to any unusual features of the collision of the Yangtze and Sino-Korean cratons.

IMPLICATIONS FOR UHP NATURE OF COLLISIONAL OROGENS

Because the overall crustal-scale geometry of the Dabie Shan, the archetypal UHP orogen, is indistinguishable from the crustal-scale geometry of normal (non-UHP) orogens, we infer that the distinction between UHP and non-UHP orogens lies not in the geometry of continental convergence or collision, but in the late stages of uplift, which likely must be very rapid to preserve the UHP index minerals (Hacker et al., 2000; Rubatto and Hermann, 2001). We suggest that in many if not all continental collisions, UHP material returns to lower-crustal levels. This point of view is supported by the growing list of orogenic belts in which vanishingly rare coesite or diamond are found by increasingly dedicated searches (e.g., Lardeaux et al., 2001; Mposkos and Kostopoulos, 2001). However, in only a select few orogens is this UHP material subsequently exhumed to the surface sufficiently rapidly that the UHP record is preserved in large tracts. Many if not all collisional belts may contain cryptic UHP provinces, either at the surface or at depth, in which parts of the crust formerly metamorphosed in UHP facies have undergone retrograde metamorphism and are now beyond easy recognition. Intermediate stages of the process have been recognized in some orogens by the presence of relict textures indicative of the former, rather than current, presence of coesite (Gilotti and Ravna, 2002) and diamond (Leech and Ernst, 1998).

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Forum

Crustal structure and exhumation of the Dabie Shan ultrahigh-pressure orogen, eastern China, from seismic reflection profiling: Comment and Reply

COMMENT

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Yuan et al. (2003) published a deep seismic reflection profile of the Dabie Shan ultrahigh-pressure (UHP) orogen, acquired by the Chinese Geological Survey. The seismic profile provides new insight into the crust structures of the orogen and gives us a better understanding of this specific UHP collisional belt. We welcome the authors' interpretation that the Moho discontinuity at km 150 represents a relic subduction feature and that the Yangtze plate was subducted down to the north beneath the North China plate. They also interpreted a crustal-scale dome structure at the middle-upper crust level across the orogen (km 20–170) and related the doming to the Early Cretaceous extension tectonics. We question the interpretation of an orogen-scale dome. The observed surface geology does not support this interpretation. They interpreted a major top-to-the-south normal fault at km 20–40 (Yuan et al., 2003, their Fig. 2B), which is in conflict with the existing field data. Detailed structural studies by many workers have shown that the high-pressure (HP) belt and the UHP belt are dominated by north-verging structures with south-southeast–dipping foliation and northwest-southeast–stretching lineation, which developed at amphibolite facies metamorphic conditions, and that kinematic indicators suggest top-to-the-northwest sense of motion (e.g., Xu et al., 1996; Hacker et al., 1995, 2000; Faure et al., 1999). The top-to-the-south normal fault is not observed by surface geology work. The interpretation of an Early Cretaceous deformation of the structures is also problematic. The structures were clearly developed at amphibolite facies conditions (see references herein), and $^{40}Ar/^{39}Ar$ dating on the muscovite/phengite of various groups from the HP-UHP belts suggests that the white mica cooled down to closure temperature at 180–227 Ma (Hacker et al., 2000), implying that amphibolite facies metamorphism took place in the Late Triassic to Early Jurassic and hence the amphibolite facies deformation took place at the same time, not the Early Cretaceous.

We suggest an alternative interpretation of the seismic profile, which may better fit the surface geology data (Fig. 1). We suggest that the south-dipping seismic reflections at 0–5 s two-way traveltime (TWTT) interval at km 20–50 (Yuan et al., 2003, their Fig. 2A) represent the blueschist-amphibolite-cold eclogite belt exposed at the surface. The south-dipping seismic reflection is underlain by moderately north-dipping multicycle and high-energy reflections at 5–8 s TWTT. These mid-crust reflections look similar in character to the gently north-dipping reflections under the UHP belt at mid-crust level (Yuan et al., 2003, their Fig. 2A). We interpret the multicycle and high-energy reflections to be stacked lower-crust rocks of the Yangtze plate, which are not exposed on the surface but are overlain by the HP-UHP sheets partially exposed on the surface. The south-dipping fault (Yuan et al., 2003, their Fig. 2B) is a top-to-the-north thrust that juxtaposes the HP and the UHP rocks against the stacked lower crust. Two phases of deformation are envisaged: (1) an early south-directed thrusting of the lower crust of the Yangtze plate and the HP-UHP sheets, which are probably related to the early stage of exhumation, seen as gently north-dipping reflections at mid-crust level (4–8 s TWTT) between km 30 and 100 (Yuan et al. 2003, their Fig. 2A); and (2) a later north-directed thrust of the HP-UHP belts over the stacked lower crust during amphibolite facies metamorphism (as observed by surface geology), which is probably related to the continued northward motion of the Yangtze plate in the Early Jurassic. It is this later phase of deformation that has produced the dominant structures and fabrics exposed at the surface today.

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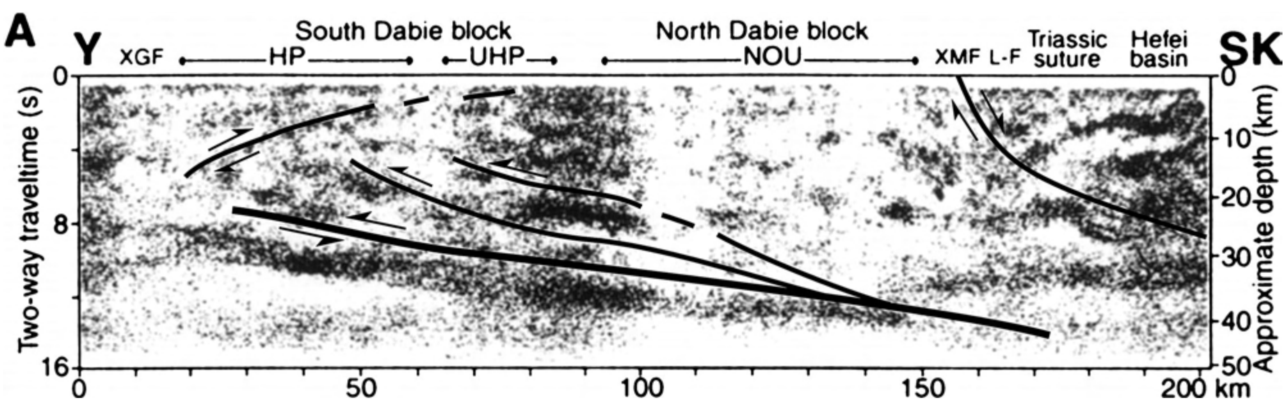

Figure 1. Reinterpreted Figure 2A of Yuan et al. (2003). XGF—Xiangfan-Guangji fault; HP—high-pressure zone; UHP—ultrahigh-pressure eclogite; NOU—Northern orthogneiss unit; XMF—Xiaotian-Mozitang fault; L-F—Luzhenguan and Foziling Groups.

Yuan, X.-C., Klemperer, S.L., Teng, W.-B., Liu, L.-X., and Chetwin, E., 2003, Crustal structure and exhumation of the Dabie Shan ultrahigh-pressure orogen, eastern China, from seismic reflection profiling: Geology, v. 31, p. 435–438.

REPLY

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We welcome the reinterpretation of our seismic profile (Yuan et al., 2003) as a reminder that any interpretation is just that: an attempt to infer the origins of seismic reflections, based on their geometries and relationships to surface geology. But it is important to recognize the relative importance of different aspects of our interpretation.

We are glad that Zhao and Fang accept our most fundamental interpretation, that the Yangtze plate was subducted down to the north beneath the North China (Sino-Korean) plate, since these authors have previously argued (Zhang et al., 2002) for the opposite polarity (southward subduction of the North China plate) to create the Dabie Shan ultrahigh-pressure (UHP) belt. We are glad they accept our recognition of the Moho offset (''mantle suture'') defining the subduction polarity that leads to our most important conclusion, that this archetypal UHP orogen is geometrically indistinguishable from non-UHP orogens, hence that many, if not all, collisional belts may contain cryptic UHP provinces.

Zhao and Fang take issue with a less-important aspect of our paper, our interpretation of south-dipping reflection fabrics in the southern Dabie Shan as representing a south-dipping normal fault or shear zone. In contrast, they interpret these and other reflections as a south-dipping, north-directed thrust fault. Zhao and Fang state that kinematic indicators in the high-pressure (HP) and UHP belt (km 20–80 in their Fig. 1) show top-to-northwest sense of motion (Hacker et al., 1995, 2000), and they infer this to represent northwest-directed thrusting, in contrast to Hacker et al. (2000) and Ratschbacher et al. (2000) who map these top-to-northwest structures as extensional faults rotated into their present geometry by later up-doming. Zhao and Fang then extrapolate the surface top-to-northwest structures to depth and interpret the origin of reflections as deep as 15 km as northwest-directed thrust zones. This aspect of their interpretation may lack internal consistency, because Zhao and Fang show the northward-directed thrust as cutting off a series of south-directed thrusts and shears in the middle and lower crust. In their interpretation, the northward-directed thrust sheet must carry northward rocks that contain top-to-the-southeast indicators, so equally at odds with the exposed geology, unless this early phase has been entirely obliterated and overprinted by younger structures. Thus the Zhao and Fang interpretation shows structures of two different ages, lower-crustal Triassic south-directed thrusts that are overprinted in the upper crust by Early Jurassic north-directed thrusts.

Readers of our paper will recall that our interpretation (Yuan et al., 2003, Fig. 2B) similarly includes elements of different ages. It is important to note that we suggest the south-dipping reflections may represent a structure active during Cretaceous exhumation of the UHP belt, following Ratschbacher et al. (2000) in recognizing that a major part of the exhumation of the Dabie Shan took place in the Cretaceous (see also Xu et al., 2002). We also note that there is outcrop evidence of top-to-south normal shear zones along the boundary between the Northern orthogneiss unit (Yuan et al., 2003, Fig. 2) and the UHP belt (Hacker et al., 1995; Ratschbacher et al., 2000; Suo et al., 2000), though there is remaining disagreement on the magnitude and importance of these shear zones.

In our paper (Yuan et al., 2003) we took no position on whether the south-dipping reflective structures might have had an earlier contractional history. Thus the ''alternative interpretation'' of Zhao and Fang is not in conflict with our interpretation; it merely suggests a richer and more complex history for some of the shallow reflections along our profile.

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