What brought them up? Exhumation of the Dabie Shan ultrahigh-pressure rocks

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ABSTRACT

Metamorphic coesite and diamond in the Dabie Shan, eastern China, testify to subduction of continental crust to >100 km depth. Exhumation of these ultrahigh-pressure rocks through the crust encompassed two stages. (1) South-dipping foliation, southeast-plunging stretching lineation, lineation-parallel isoclinal folds, and boudins indicate extreme subhorizontal shortening and subvertical extension during top-to-northwest shearing at 200–180 Ma. Syntectonic recrystallization occurred at eclogite and amphibolite facies temperatures and at pressures below coesite stability. (2) Northwest-southeast subhorizontal extension from 133 to 122 Ma was concentrated within an asymmetric structural dome in a magmatic complex that forms the northern half of the Dabie Shan. Pluton cores at deep structural levels have weak hypersolidus fabrics, and pluton carapaces are mylonitic gneisses formed at upper amphibolite facies conditions. Deformation is concentrated in greenschist facies mylonites and ultramylonites along the Xiaotian-Mozitang detachment fault at the northern topographic limit of the Dabie Shan. Our preferred exhumation model involves two stages: Triassic indentation—vertical extrusion and erosion—followed by Cretaceous plate margin transtension.

INTRODUCTION

The current focus on ultrahigh-pressure (UHP) tectonics derives from the expectation that the study of UHP rocks will enhance our understanding of a wide spectrum of geologic processes, i.e., the role of volatiles in subduction zones, including magma genesis and the generation of intermediate-depth earthquakes; the rheology of subducted rocks undergoing phase transformations; the rate of and controls on eclogitization and the consequent implications for interpreting seismic refraction data; the buoyancy of subducting slabs; the role of phase changes in orogenic cycles; and the rate and mechanism by which UHP rocks are exhumed from profound depth.

Here we analyze the rate and mechanism of exhumation, using structural observations collected within the archetypal UHP orogen, the Qinling-Dabie belt of eastern China (Figs. 1 and 2). This collision orogen is 2000 km long, and UHP rocks crop out in the three easternmost ranges, the Hong'an, Dabie, and Su-Lu. It is believed to have formed by north-directed subduction of the Yangtze craton or a microcontinent beneath the Sino-Korean craton (Liu and Hao, 1989). UHP rocks containing coesite recrystallized in Late Triassic time (Ames et al., 1995; Eide et al., 1994; Hacker et al., 1995) and cover 400 km^2 in the Dabie Shan. Investigation of UHP tectonics in China has focused on the Dabie Shan partly because of the wide variety of continental crustal rocks that were metamorphosed under a broad spectrum of pressures and temperatures. From south to north, the different units are fold-thrust belt, blueschist, amphibolite, "cold" eclogite, coesite eclogite, northern orthogneiss, Luzhenguang orthogneiss, Foziling schist, and Jurassic(?) volcanic rocks (Fig. 1). All are intruded by voluminous Cretaceous plutons, and units on the margins of the mountains are overlain by Cretaceous and younger alluvial sediments. All the pre-Cretaceous units are inferred to have formed during the same single continental collision (e.g., Ernst et al., 1991), and all contain a south-dipping foliation (Fig. 3), contrary to what one might expect from formation in a north-dipping subduction zone.

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EXHUMATION MODELS

Petrologic constraints demand that coesite-bearing rocks cooled during the early stages of exhumation (Liou et al., 1995). Cooling at any stage requires that either the UHP rocks were (1) transported toward the surface in the lower plate of an extensional shear zone, or (2) refrigerated during exhumation by continued deeper level subduction (Davy and Gillet, 1986; Hacker and Peacock, 1994; Platt, 1986; Rubie, 1984). The density contrast between continental crust and mantle means that exhumation of UHP rocks must occur in at least two stages. If buoyancy is the driving force for exhuma-

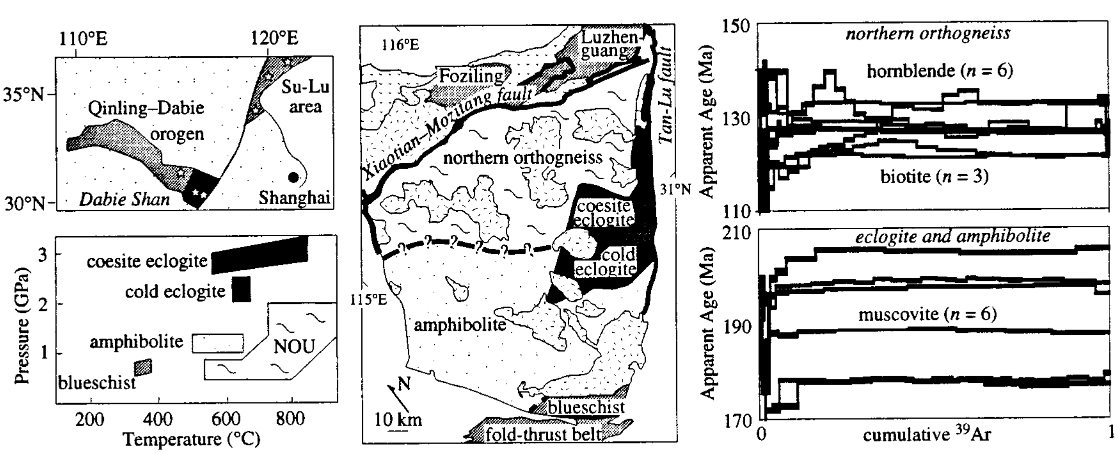

Figure 1. Dabie Shan geologic map, location in Qinling-Dabie orogen (stars show coesite localities), pressure-temperature conditions of rock units, and $^{40}Ar/^{39}Ar$ spectra NOU is northern orthogneiss.

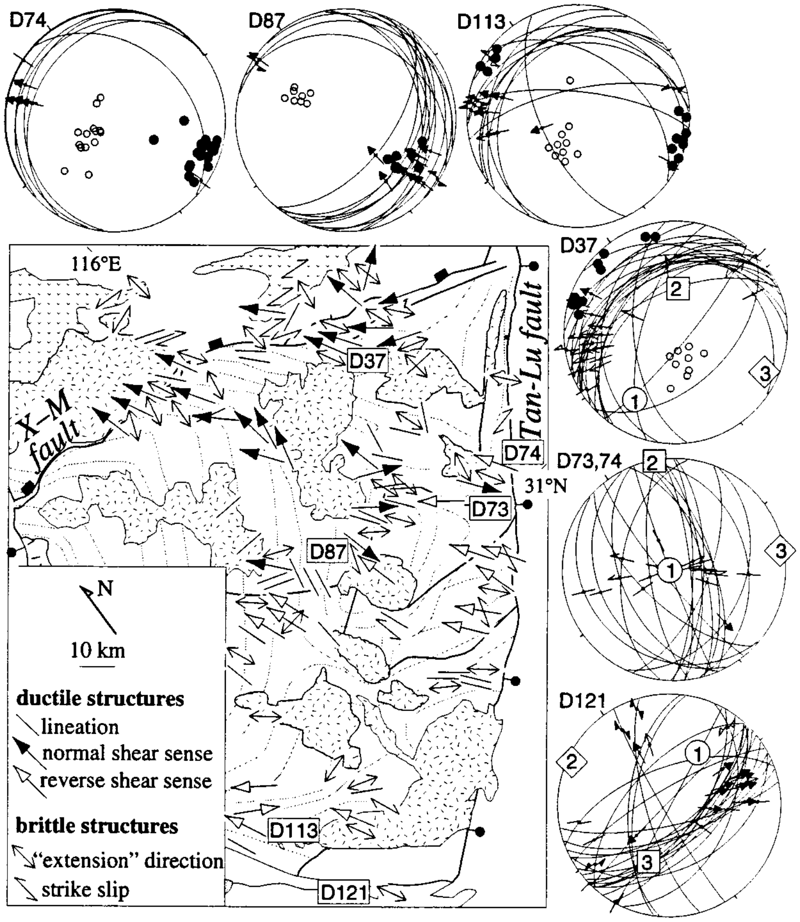

Figure 2. Structural map of Dabie Shan. Top three lower-hemisphere, equal-area stereonets show examples of amphibolite facies foliation (open circles), lineation (solid circles), shear bands (great circles), and shear-band displacement directions (arrows). Lower three nets show sample fault striae data and computed principal stresses σ_1, σ_2, and σ_3 (1, 2, and 3). Faults are shown as great circles; arrows show displacement of hanging wall. Solid, open, half, and headless arrows represent striae of certain, probable, inferred, and unknown displacement sense, respectively. Note rotation of north arrow in map and stereonets.

tion of crustal rocks subducted into the mantle (Cloos, 1993), then exhumation should cease once the UHP rocks have risen through the mantle. Further exhumation could then occur by a different process.

Tectonic models for exhumation in the Dabie Shan call upon either extension or thrusting assisted by erosion. Maruyama et al. (1994) and Ernst and Liou (1995) proposed Triassic subhorizontal extrusion and Cretaceous doming (Fig. 3). In their model, the extruding wedge is bounded above by a normal fault and below by a thrust fault. Cretaceous doming produced the south-dipping structures observed within the UHP units and the peak temperatures recorded in the northern orthogneiss. Okay et al. (1993) proposed that the UHP rocks were exhumed by Triassic thrusting and erosion (Fig. 3). Their model further suggests that the UHP rocks are bounded by thrust faults and that the northern orthogneiss is a UHP unit that reached peak temperatures in Triassic time. Southward dips within the UHP units and the apparent normal sense of faults bounding the units were achieved by Late Triassic rotation.

STRUCTURAL OBSERVATIONS

We characterized the internal deformation and contacts of each of the main rock units to test the existing models. These measurements, in conjunction with existing petrologic and geochronologic data, constrain the exhumation history. We recorded (1) the relative amount of deformation, (2) the sense of displacement or shear, and (3) the

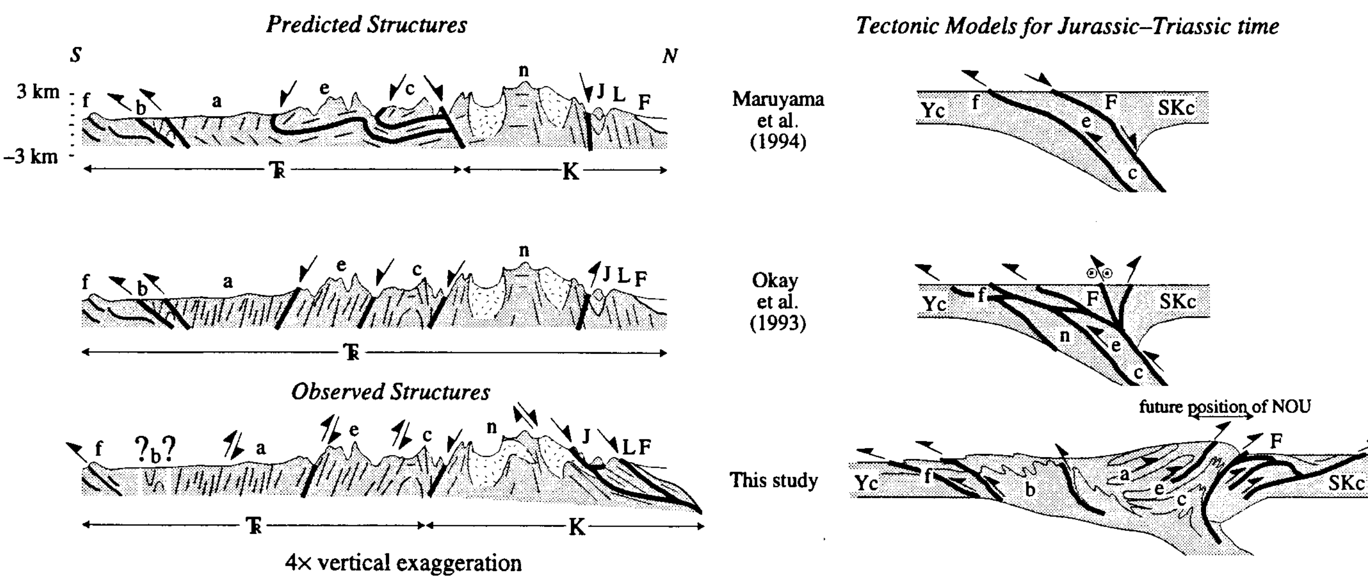

Figure 3. Tectonic models and predicted structures of Maruyama et al. (1994) and Okay et al. (1993), compared with observed structures and our preferred model. Abbreviations: a—amphibolite; b—blueschist; c—coesite eclogite; e—"cold" eclogite; f—fold-thrust belt; F—Foziling schist; J—Jurassic(?) volcanic rocks; L—Luzhenguang orthogneiss; n (and NOU)—northern orthogneiss; SKc—Sino-Korean craton; Yc—Yangtze craton; Te—Triassic; K—Cretaceous.

pressures and temperatures of deformation. The pressures and temperatures of deformation were judged qualitatively by assessing which minerals or melts formed before, during, or after observed deformation features. The amount of deformation was judged from the shape of deformed objects such as xenoliths or crystals, the discrete displacement or distributed shear of markers such as dikes, the thickness and spacing of deformed zones, and the degree of grain-size reduction. The sense of shear was established by means of criteria such as σ clasts, δ clasts, shear bands, and schistosité-cisaillement fabrics. To understand the kinematics of fault arrays, we applied "stress" inversion techniques to mesoscopic fault-slip data.

Ultrahigh-Pressure and High-Pressure Units

The coesite and cold eclogite units in the eastern Dabie Shan are mica-rich paragneisses containing blocks of coesite-bearing and coesite-free eclogite, respectively. The coesite-bearing eclogite and host paragneiss reached peak metamorphic conditions of 550–850 °C and 2.6–3.8 GPa, and coesite-free eclogite reached at least 635 °C and 2.3 GPa (Liou et al., 1995; Okay, 1993). The amphibolite unit is a hornblende-rich orthogneiss that lacks eclogite; peak pressures and temperatures estimated from one locality are >1.0 GPa and ≤650 °C (Liu and Liou, 1994).

We interpret the eclogite and amphibolite units as a single subhorizontally shortened and subvertically lengthened crustal segment. The geometry and kinematics of structures throughout these units emphasize crustal-scale, penetrative deformation. The foliation dips predominantly 20°–40° to 155°–215°, and the lineation plunges 0°–40° to 135°–195° (Fig. 2). Foliation is folded about spectacular isoclinal, lineation-parallel folds, and both show boudinage at all scales, the extension direction being parallel to the stretching lineation. Shear sense is consistently top-to-north-northwest (Fig. 2). A transition within the eclogite units from eclogite facies (omphacite + garnet, no coesite) ductile fabrics to amphibolite facies (hornblende + plagioclase + garnet) brittle-ductile structures indicates decompression and cooling from mantle or lower crustal to mid-crustal depths within the same kinematic framework. This deformation, dated by $^{40}Ar/^{39}Ar$ ages on synkinematic muscovite and biotite at 200–180 Ma or earlier (Fig. 3; Hacker and Wang, 1995), overprints higher temperature fabrics in coesite-bearing eclogite boudins constrained by U/Pb zircon ages of ~210 Ma (Ames et al., 1995).

Northern Orthogneiss Unit

We interpret the northern orthogneiss and Luzhenguang units to represent an asymmetric magmatic-structural dome formed during Cretaceous northwest-southeast subhorizontal extension (Fig. 2); except for a few cases, older protoliths and structures have not been identified. The volcanic-plutonic system includes gabbro, diorite, tonalite, trondhjemite, granodiorite, granite, and syenite. Intermediate-composition rocks predominate over mafic and rare ultramafic rocks. Mafic to ultramafic basement or screens date to ~240 Ma (Li et al., 1993) and recrystallized at pressures of 1.5–2.0 GPa (Wang, 1991). Textures in mafic bodies indicate that hornblende + plagioclase ± quartz melted partially to form clinopyroxene + melt, implying temperatures ≥750 °C in the presence of H_2O (Hacker, 1990). We interpret elongate plagioclase haloes surrounding garnet crystals to have formed during synkinematic decompression from >1.2 to <0.8 GPa (Ito and Kennedy, 1971; Liu et al., 1993), and hornblende barometry suggests that the youngest plutons crystallized at pressures of ~0.4–0.6 GPa (Liou et al., 1995).

The foliation generally dips north along the northern margin and east to southeast elsewhere, outlining a large-scale dome. Lineations plunge 5°–25° north-northwest in northern exposures and 30°–45° south-southeast in southern exposures (Fig. 2). Shear was universally downdip and shear sense was normal (Fig. 2). Mylonitic igneous rocks of the northern orthogneiss intrude the UHP unit, and in the eastern Dabie Shan, the contact is a south-dipping synmagmatic to postmagmatic normal-sense shear zone.

The most impressive feature of the northern orthogneiss is the range of structures that document extension during cooling and decompression. Interior parts are dominated by plutons that are either undeformed or have a weak magmatic fabric. The carapaces of these plutons are typically augen gneisses that developed at subsolidus amphibolite facies conditions. At higher levels farther from plutons, lower amphibolite facies recrystallization accompanied pervasive transposition and formation of banded gneisses. At even higher levels, the deformation was partitioned into discrete upper greenschist facies mylonitic zones. The Xiaotian-Mozitang fault and vicinity are marked by ultramylonites and chlorite ± epidote ± MnO-coated normal faults. Volcanic rocks above the Xiaotian-Mozitang fault contain greenschist to subgreenschist facies cataclastic faults. All these structures, from pluton cores to cataclastic faults indicate sinistral downdip shear within the northern Dabie Shan. U/Pb zircon and $^{40}Ar/^{39}Ar$ hornblende and mica ages from plutonic and metamorphic rocks in the northern orthogneiss are Cretaceous (Fig. 1) (Li and Wang, 1991); precise $^{40}Ar/^{39}Ar$ hornblende and biotite ages demonstrate that extension occurred from 133 to 122 Ma.

Young subgreenschist facies normal faults throughout the Dabie Shan show north-northwest to south-southeast extension (Fig. 2) that is identical in orientation to the higher temperature extension recorded in the northern orthogneiss, suggesting that the two are kinematically related. We interpret the faults to be the shallowest level manifestation of Cretaceous extension; they displace molassic Lower Cretaceous sedimentary rocks and plutons as young as 125 Ma (Li and Wang, 1991). Younger still are subvertical strike-slip fault zones. The dominant set consists of east-striking sinistral faults of late Cenozoic(?) age probably related to the India-Asia collision (Peltzer et al., 1985). The Tan-Lu fault forms the eastern margin of the Dabie Shan. The fault is morphologically well expressed, and has a subvertical to steep east dip and normal or dextral-oblique displacement recorded by subgreenschist facies minerals. In the Dabie Shan the fault does not contain high-temperature ductile structures required by models (Yin and Nie, 1993) that postulate its development as a major transcurrent fault during continental collision.

TECTONIC IMPLICATIONS

The observations and inferences discussed above provide areally extensive modern structural data for evaluating exhumation models for the Dabie UHP rocks (Fig. 3). The boundary between the northern orthogneiss and UHP units—suggested to be a north-dipping ~210 Ma normal fault (Maruyama et al., 1994) or a south-directed thrust fault overturned in the Triassic to a present southward dip (Okay et al., 1993)—is a south-dipping syn- to postmagmatic Cretaceous normal fault. The northern boundary of the UHP unit was obliterated by Cretaceous plutons of the northern orthogneiss and may once have been located farther north. Contacts and deformation fabrics within the UHP rocks have been proposed to be south-directed thrusts overturned subsequently to a south dip in Triassic (Okay et al., 1993) or Cretaceous (Maruyama et al., 1994) time. Both models predict that the UHP and amphibolite units should preserve down-to-south normal shear as a result of overturned top-to-south Triassic thrust imbrication. In contrast, ductile shear is top-to-north and Late Triassic–Early Jurassic. Our observations confirm the suggestion of Maruyama et al. (1994), that peak temperatures in the northern orthogneiss were reached during the Cretaceous and not during the Triassic (Okay et al., 1993).

The expectation that the density contrast between the crust and mantle will cause exhumation of UHP rocks to occur in at least two stages is corroborated by our investigation. We have not made detailed observations of coesite-eclogite facies structures and thus cannot place constraints on the earliest stage of exhumation; farther west in the Qinling-Dabie orogen, Carnian-Norian (~227–210 Ma; Gradstein et al., 1994) flysch in the Songpan-Ganze basin has been interpreted to reflect initial uplift of the Dabie Shan (Nie et al., 1994; Zhou and Graham, 1995). U/Pb zircon ages indicate that Dabie Shan eclogites formed at 210 Ma (Ames et al., 1995) and $^{40}Ar/^{39}Ar$ ages summarized here indicate that cooling to 300–400 °C was achieved by 200–180 Ma. Thus, exhumation through the mantle occurred between ~227 and 200–180 Ma. Evidence presented here illustrates that, in the 200–180 Ma time frame, the UHP rocks were involved in northwest-directed flow over the once-overriding Sino-Korean craton.

What caused this reversal from north-dipping subduction to the northwest-directed flow indicated by the structures? A speculative model is suggested by analogy with the Oligocene-Miocene history of the Central Alps, where indentation by the Apulian plate caused large-scale extrusion of an orogenic crustal wedge onto the European foreland and backward onto the indenter, resulting in a bivergent belt (e.g., Schmid et al., 1990). We hypothesize that the Sino-Korean craton, which had a rigid upper mantle, indented the Dabie orogenic wedge and extruded it onto the Sino-Korean craton at a scale surpassing that envisioned for the Alps (Fig. 3); much of the exhumation of the UHP rocks is inferred to be related to erosion coincident with this large-scale extrusion. The Cretaceous extension is probably unrelated to the Triassic collision and may represent transtension along the Cretaceous Pacific continental margin; it had little effect on exhumation of the UHP rocks.

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