TECTONICS, VOL. 14, NO. 4, PAGES 994-1006, AUGUST 1995

Ar/Ar geochronology of ultrahigh-pressure metamorphism in central China

Bradley R. Hacker

Department of Geological and Environmental Sciences, Stanford University, Stanford, California

Qingchen Wang

Laboratory of Lithosphere Tectonic Evolution, Institute of Geology, Academia Sinica, Beijing China

Abstract. The Dabie Shan of China contain the largest areal exposure of ultrahigh-pressure regional metamorphic rock known on Earth. The thermal history of these unusual rocks is central to understanding the tectonic processes responsible for their creation, preservation, and exhumation. Published ages of ultrahigh-pressure metamorphism and subsequent cooling range from Archean to Jurassic. By analyzing 21 Dabie hornblende, phengite, and biotite samples by the $^{40}Ar/^{39}Ar$ method, we find that (1) cooling from peak metamorphic temperatures to ~300°C occurred between about 206 and 178 Ma; (2) widespread Cretaceous ages reflect reheating by a post-ultrahigh-pressure magmatic/extensional episode; (3) $^{40}Ar/^{39}Ar$ and K/Ar ages older than 230 Ma, and perhaps 210 Ma, are geologically meaningless due to the incorporation of excess ^{40}Ar; and (4) Dabie ultrahigh-pressure metamorphic rocks are temporally related to blueschist-facies rocks farther west in the suture zone.

Introduction

Discovery of regionally extensive areas of ultrahigh-pressure (UHP) metamorphic rock containing coesite and/or diamond [*Chopin*, 1984; *Smith*, 1984; *Okay*, 1993] has raised many exciting questions. How is continental crust subducted to profound depths in excess of 100 km? How and why are UHP metamorphic minerals preserved during decompression and cooling rather than being destroyed during thermal reequilibration? What tectonic process is responsible for exhumation, and what are the rates of exhumation and cooling? Study of UHP terranes is the most direct means by which to address these questions and glean more information about the physical and chemical properties of the crustal lithosphere during and after collisional orogenesis. *Wang and Liou* [1991] reported that the Dabie Shan of east-central China (Figures 1 and 2) contain >2500 km^2 of continental crust that was subducted to depths of ~100 km and later exhumed. If so, the Dabie Shan and related Su-Lu and Hong'an areas constitute the largest known UHP orogen and should probably be considered the archetype.

Paper number 95TC00932.
0278-7407/95/95TC-00932$10.00

The tectonic history of UHP rocks is partially recorded by geologic structures, mineral compositions and parageneses, and radiometric ages. Multiple studies of Dabie mineral compositions and parageneses have revealed portions of the pressure-temperature paths experienced by these rocks. Structural studies are just beginning to reveal the deformation history [*Hacker et al.*, 1995a]. Knowledge of metamorphic and structural aspects is essential to unraveling the tectonic history of UHP metamorphic rocks, but thermochronology, study of temperature-time paths, is also important. Temperature-time histories can, in principle, be combined with pressure-temperature paths to yield pressure-time paths. In concert, pressure-temperature-deformation-time data are central to constraining aspects of the tectonic process responsible for the exhumation of UHP metamorphic rocks. For example, the decompression portion of a pressure-time path reveals the rate of exhumation; rapid cooling of rocks in the footwall of a normal fault might be related to slip along that structure, and so on. Unfortunately, the thermochronology of Dabie Shan rocks is clouded by published radiometric ages for the UHP metamorphism ranging from Triassic [*Li et al.*, 1993 *Ames et al.*, 1993] through Ordovician [*Sang et al.*, 1987], Proterozoic [*Mattauer et al.*, 1991] and Archean [*Dong et al.*, 1986; *Dong*, 1993]. We present new $^{40}Ar/^{39}Ar$ data for hornblende, white mica, and biotite from plutons, gneiss, and eclogite that, in conjunction with existing Sm/Nd, Rb/Sr, and U/Pb data, document Late Triassic to Early Jurassic cooling to ~300°C following UHP metamorphism.

Metamorphic rocks ranging from blueschist to diamond- and coesite-bearing UHP eclogite crop out along the ~2000-km long, east-west trending collision zone between the Yangtze and Sino-Korean cratons in east-central China (Figure 1) [*Wang et al.*, 1989; *Ernst et al.*, 1991; *Xu et al.*, 1992]. Ultrahigh-pressure coesite-bearing rocks are restricted to the Hong'an area, the Dabie Shan, and the Su-Lu area, whereas blueschist and greenschist extend along the suture 700 km farther west through the Tongbai, Qinling, and Wudang Mountains [*Ernst et al.*, 1991; *Zhang et al.*, 1994]. Diamond is known only from the Dabie Shan [*Xu et al.*, 1992; *Okay*, 1993], and thus that range has become the principal target of investigation.

Metamorphic rocks of the Dabie Shan (Figure 2) are divisible into a northern orthogneiss unit, a central UHP terrane, and, farther south, amphibolite- and blueschist-facies rocks [*Hacker et al.*, 1995b]. All units are intruded

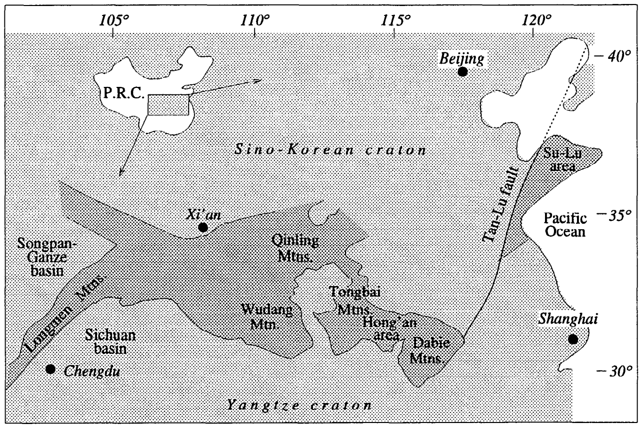

Figure 1. Collisional orogen in central China, comprising the Wudang, Qinling, Tongbai, Hong'an, Dabie Shan, and Su-Lu areas.

by Cretaceous granitoids [*Li and Wang*, 1991; *Mattauer et al.*, 1991; L. Ames et al., unpublished manuscript 1995].

The northern orthogneiss unit (NOU) has been interpreted to represent predominantly an asymmetric magmatic/structural dome formed during NW–SE subhorizontal extension [*Hacker et al.*, 1995a]. It includes igneous rocks that range from undeformed plutons and dikes to penetratively deformed banded orthogneisses and older screens between plutons. The plutonic, volcanic, and gneissic rocks span gabbro, diorite, tonalite, trondhjemite, granodiorite, granite, and syenite. Intermediate composition gneisses predominate over mafic and rare ultramafic rocks, and the least deformed plutons are commonly the most felsic representatives of the suite. No indications of metamorphism or intrusion at ultrahigh pressure have been found. Mafic minerals include hornblende (common), biotite (less common), clinopyroxene (rare), and orthopyroxene (very rare). Structures in the NOU document extension during cooling and decompression. At deep structural levels pluton cores bear weak hypersolidus fabrics, and pluton carapaces are upper amphibolite facies mylonitic gneisses. At higher levels farther from plutons, pervasive transposition and formation of banded gneisses occurred at lower amphibolite-facies conditions. The most concentrated deformation zone is within greenschist-facies mylonites and ultramylonites along the Xiaotian–Mozitang detachment fault at the northern topographic limit of the Dabie Shan. Mylonitic igneous rocks of the NOU intrude the coesite eclogite unit, and in the eastern Dabie Shan, the contact is a south dipping synmagmatic to postmagmatic normal-sense shear zone [*Hacker et al.*, 1995a]. Because deformation in the NOU began at hypersolidus conditions and continued through greenschist-facies metamorphism, $^{40}Ar/^{39}Ar$ ages on hornblende and mica from this unit would indicate not only the time of cooling but also the duration of deformation.

The coesite and cold eclogite units preserve evidence of metamorphism at ultrahigh pressure. They comprise quartzofeldspathic micaceous paragneiss with subordinate amphibolite and ultramafic rock, enclosing boudins of coesite-bearing eclogite and marble [*Wang et al.*, 1990; *Wang and Liou*, 1991; *Xu et al.*, 1992; *Wang and Liou*, 1993; *Schertl and Okay*, 1994; *Zhang et al.*, 1994]. All these rock types are host to abundant Cretaceous plutons that are identical in composition and deformational style to those that make up the NOU. Indeed, the plutonic rocks are so abundant in the western Dabie Shan that it is difficult to delineate any sort of structural boundary between the NOU and the UHP unit. The paragneiss contains phengite, quartz, and plagioclase, with variable amounts of epidote, garnet, K-feldspar, biotite, and sphene. Petrologic studies have demonstrated that the eclogites and their host paragneiss and marble underwent a clockwise pressure-temperature evolution with peak conditions of 550–850°C and 2.6–3.8 GPa for rocks containing coesite and diamond (coesite eclogite) and at least 635°C and 2.3 GPa for rocks lacking coesite and diamond but containing sodic amphibole (cold eclogite) [*Okay*, 1993; *Liou et al.*, 1995]. This was followed by granulite-, amphibolite-, and then greenschist-facies retrogression at decreasing pressures [*Okay et al.*, 1989; *Wang et al.*, 1989; *Wang et al.*, 1992; *Okay*, 1993; *Zhang et al.*, 1994]. 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 et al*, 1994].

The UHP and amphibolite units contain a south dipping foliation, southeast plunging stretching lineation, lineation-parallel isoclinal folds, and boudins indicating extreme subhorizontal shortening and subvertical extension during top-to-NW shearing [*Hacker et al.*, 1995a]. Syntectonic recrystallization occurred at eclogite- and amphibolite-facies temperatures and at pressures below coesite stability. *Hacker et al.* [1995a] suggested that this deformation and recrystallization occurred during postsubduction extrusion of the Dabie orogenic wedge northward onto the Sino-Korean craton. Deformation in the UHP and amphibolite units involved hornblende and mica, such that $^{40}Ar/^{39}Ar$ ages on these minerals constrain the time of cooling and the duration of deformation.

Previous Geochronologic Data

The continent-continent collision that produced the high-pressure metamorphism in the Qinling-Dabie orogen was initially assumed to be Archean or Proterozoic [*Dong et al.*, 1986; *Jin*, 1989; *Dong*, 1993] based on two interpretations. The first is that the blueschist-facies rocks in the southern Dabie Shan [*Regional Geological Survey Anhui*, 1987; *Sang et al.*, 1987; *Ma and Zhang*, 1988], the Hong'an area [*Yang et al.*, 1986], and the Wudang area [*Regional Geological Survey Hubei*, 1990] are correlative and depositionally overlain by Sinian sedimentary rocks unaffected by high-pressure metamorphism. K/Ar sodic amphibole "ages" of ~1200 Ma have been cited in support of this [*Regional Geological Survey Henan*, 1989]. The second is that Proterozoic zircon and apatite ages from the Dabie Shan and Hong'an area reflect metamorphism at that time [*Xu et al.*, 1986; *Regional Geological Survey Anhui*, 1987; *Regional Geological Survey Hubei*, 1990]. Potential inaccuracies in the first interpretation include the possibilities (1) of more than one collisional event; (2) that

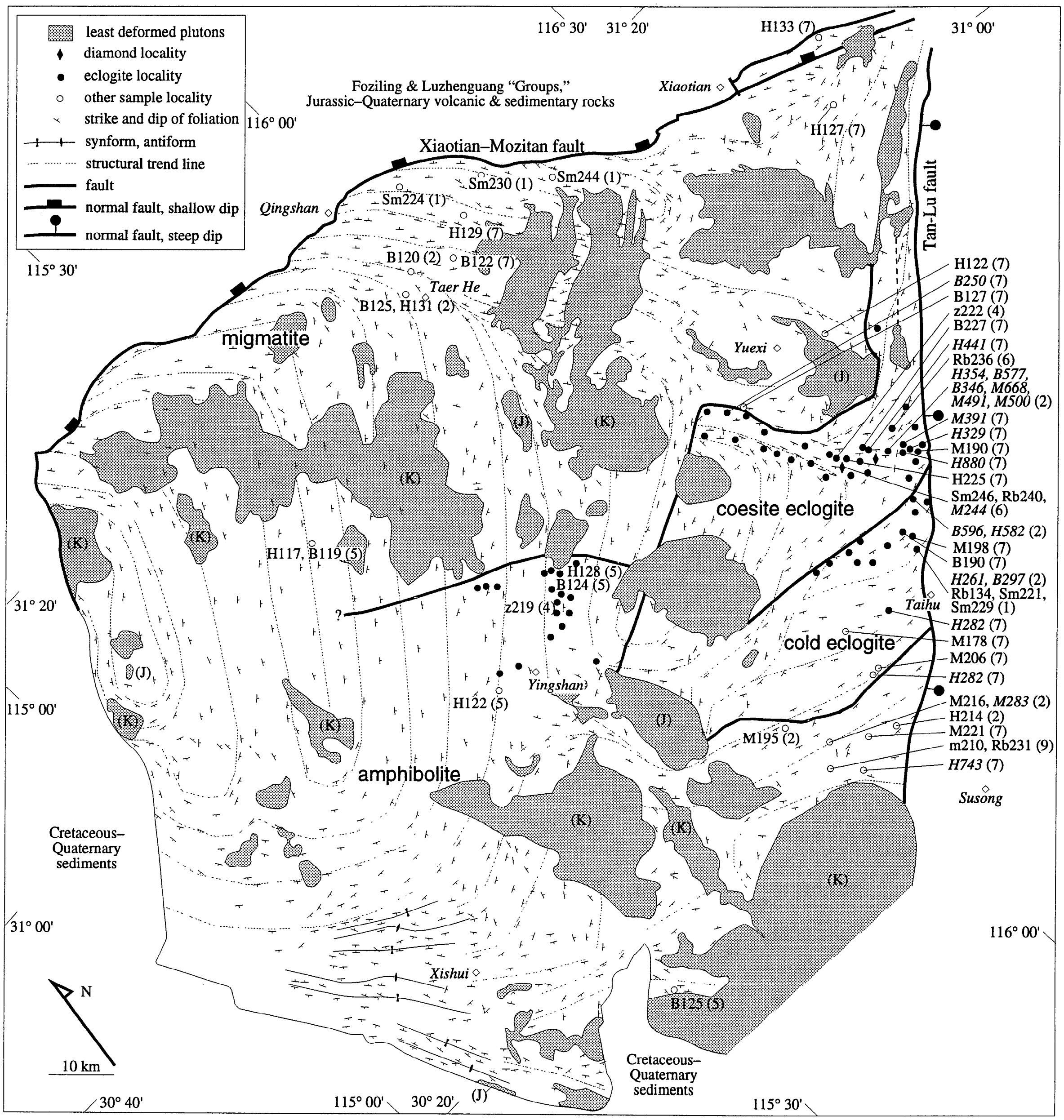

Figure 2. Map of the Dabie Shan drawn from our personal observations and *Regional Geological Survey of Anhui* [1987], *Regional Geological Survey of Henan* [1989], *Regional Geological Survey of Hubei* [1990], *Okay et al.* [1993], and *Hacker et al.* [1995a]. Fault boundaries between units are poorly known. (J) and (K) refer to plutons with Jurassic and Cretaceous radiometric ages taken from the Chinese literature [*Li and Wang*, 1991]. Radiometric ages are abbreviated as a letter code followed by the age in Ma, followed by the reference in parentheses: H: $^{40}Ar/^{39}Ar$ hornblende; B, $^{40}Ar/^{39}Ar$ biotite; M, $^{40}Ar/^{39}Ar$ white mica; m, K/Ar white mica; Sm, Sm/Nd mineral-whole rock isochron; Rb, Rb/Sr mineral-whole rock isochron; z, U/Pb zircon. References are 1, *Li et al.* [1989a; 1993]; 2, *Mattauer et al.* [1991]; 3, *Chen et al.* [1992]; 4, *Ames et al.* [1993]; 5, *Eide et al.* [1994]; 6, *Okay et al.* [1993]; 7, this study; 8, *Maruyama et al.* (SHRIMP U-Pb geochronology of ultrahigh-pressure metamorphic rocks of the Dabie Mountains, central China, submitted to *Earth and Planetary Science Letters,* 1995).

the correlations are incorrect or the observed contacts are not depositional; and (3) that the metamorphism dies out up section and is not visible in the Sinian and younger strata. The interpretation that the Proterozoic zircon ages are metamorphic is likely faulty because the reported isotopic ages are not accompanied by analytical data and may reflect mixing of old crystal cores and young rims of unknown age, as has been seen in U/Pb studies using

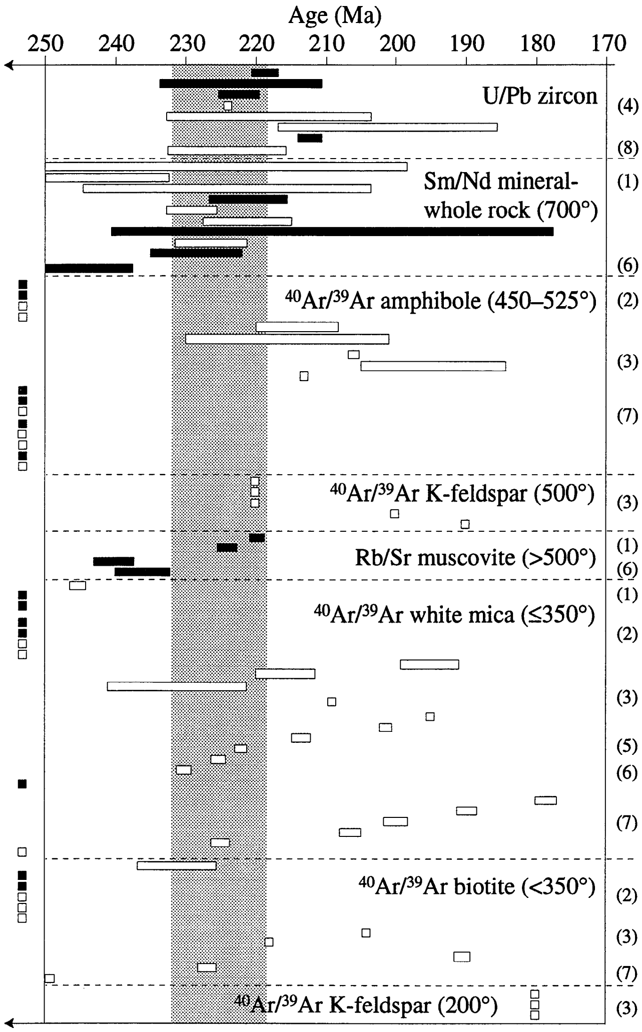

Figure 3. Radiometric ages ($\pm 2\sigma$) related to UHP metamorphism, with approximate closure temperatures of isotopic systems shown in parentheses [*Harrison*, 1981; *Harrison et al.*, 1985; *Snee et al.*, 1988; *Harland et al.*, 1989]. K-feldspar ages come from diffusion domain interpretations of cyclic heating experiments and thus the uncertainties shown are somewhat arbitrary. Samples with excess Ar are shown with their total gas ages. Data are listed and discussed by *Hacker et al.* [1995b]. References are as in Figure 2.

multiple zircon fractions from these rocks [e.g., *Ames et al.*, 1993].

Preliminary work by *Mattauer et al.* [1991] seemed to support a Precambrian age for continental collision, as they obtained $^{40}Ar/^{39}Ar$ hornblende, biotite, and white mica ages as old as 685 Ma from a variety of rock types in the eastern Dabie Shan and Su-Lu area (Figures 2 and 3). They did not publish release spectra or isochron diagrams but interpreted their ages to be minimum ages for coesite eclogite formation. Two Paleozoic ages also interpreted as records of high-pressure metamorphism were published by *Sang et al.* [1987]. More recently, L. Ames et al. (unpublished manuscript, 1995) reported three U/Pb zircon lower intercept ages of 218.6 ± 1.6, 222 ± 11, and 222.3 ± 2.4 Ma from UHP eclogites in the Dabie Shan, which they inferred to closely postdate the UHP metamorphism. Apparent confirmation of Triassic metamorphism has come from *Li et al.* [1989a, b, 1993], who reported eight Sm/Nd and two Rb/Sr mineral–whole rock isochron ages ranging from 209 ± 31 Ma to 243.9 ± 5.6 Ma on ultramafic, amphibolite, and eclogite from the Dabie Shan and the Su-Lu area; the ages were inferred to be metamorphic.

Equivalent, 195–230 Ma, internally concordant $^{40}Ar/^{39}Ar$ ages have been reported for phengites from blueschist- to eclogite-facies rocks in the Hong'an area immediately west of the Dabie Shan [*Eide et al.*, 1994]. Farther west in the Tongbai Shan, L. Ames et al. (unpublished manuscript) obtained a U/Pb zircon age of ~224 Ma on gneiss. Work in the Su-Lu area several hundred km NNE of the Dabie Shan has revealed U/Pb zircon ages of 222 ± 1.1 and 211 ± 15 Ma (L. Ames et al., unpublished manuscript), three hornblende ages of 213–195 Ma, one white mica age of 209 Ma, and two biotite and six K-feldspar spectra suggesting cooling in the 200–500°C range from 180 to 220 Ma [*Chen et al.*, 1992]. An eclogite from the Dabie Shan yielded externally concordant Sm/Nd, Rb/Sr, and $^{40}Ar/^{39}Ar$ ages of ~244 Ma [*Okay et al.*, 1993]. *Sang et al.* [1987] studied amphibolite in the southern Dabie Shan and produced an Rb/Sr mineral–whole rock isochron age of 231 ± 48 and a K/Ar phengite age of 210 ± 30 Ma. *Mattauer et al.* [1985] interpreted $^{40}Ar/^{39}Ar$ plateau ages of 232 ± 5 and 216 ± 7 Ma on riebeckite and phengite from the fold belt on the northern margin of the Yangtze craton north of Wudang Mountain to represent the age of thin-skinned, intracontinental thrusting.

Thus the aforementioned data leave open the possibility that the zircon ages postdate the UHP metamorphism, that the $^{40}Ar/^{39}Ar$ data of *Mattauer et al.* [1991] truly reflect Precambrian UHP metamorphism, and that the Hong'an blueschist rocks are unrelated to the Dabie UHP rocks. Just such an ambiguity exists in the Dora Maira UHP locality of the western Alps. There, one group of rocks yields U-Th-Pb zircon, ellenbergerite, and monazite ages of 38–30 Ma [*Tilton et al.*, 1991] and $^{40}Ar/^{39}Ar$ phengite ages of ~100 Ma [*Monié and Chopin*, 1991] despite the considerably higher temperature for zircon crystallization as compared to Ar retention in muscovite [*Snee et al.*, 1988].

New $^{40}Ar/^{39}Ar$ Data

Twenty-one samples from the eastern Dabie Shan in Anhui Province were analyzed at Stanford University by the $^{40}Ar/^{39}Ar$ method (Tables 1 and 2[1]). The mineral separates were prepared by standard heavy liquid and

[1] An electronic supplement of this material may be obtained on a diskette or Anonymous FTP from KOSMOS.AGU.ORG (LOGIN to AGU's FTP account using ANONYMOUS as the username and GUEST as the password. Go to the right directory by typing CD APEND. Type LS to see what files are available. Type GET and the name of the file to get it. Finally, type EXIT to leave the system.) (Paper 95TC00932, Ar/Ar geochronology of ultrahigh-pressure metamorphism in central China, B.R. Hacker and Q. Wang). Diskette may be ordered from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, DC 20009; $15.00. Payment must accompany order.

Table 1. Sample descriptions and locations.

92W-5	weakly foliated gneiss from NOU (bio+plg+qtz); 30°49.3'N, 116°12'E
9290.1	weakly foliated diorite from NOU (hbl+plg+qtz+sph); 31°08'N, 116°45' E
92314	weakly to moderately foliated tonalite from NOU (qtz+plg+hbl+bio(chl)); 31°18.8'N, 116°05.8'E
92905	gabbroic block within intermediate gneiss of NOU (hyp+aug+hbl+plg+bio+qtz+sph+zir); 31°04'N, 116°44.5'E
92332	weakly deformed granodioritic gneiss from NOU (qtz+plg+hbl+cpx+bio(chl)+sph); 30°16.4'N, 116°02.2'E
92256	banded tonalitic gneiss from NOU (qtz+plg+hbl+ap+sph+ep+bio(chl)); 30°49.5'N, 116°25.7'E
92THOL	paragneiss from UHP unit (qtz+plg+gar+mu+ep); 30°27.5'N, 116°08'E
PRC78	paragneiss from UHP unit (plg+qtz+mu+bio+sph); 30°36.5'N, 116°24.5'E
92127	paragneiss from UHP unit (qtz+plg+ep+bio(chl)); 30°31.2'N, 116°18.8'E
PRC131	paragneiss from UHP unit (mu +plg+qtz); 30°30.5'N, 116°18.7'E
PRC49d	paragneiss from UHP unit (mu+gar+plg+qtz); 30°23.9'N, 116°06.2'E
92SU6a	paragneiss from amphibolite unit (qtz+plg+mu+ep); 30°38.9'N, 116°02.4'E
W92H-1	paragneiss from UHP unit (qtz+plg+mu+ep); 30°40'N, 116°20.2'E
92194	amphibolite vein (qtz+plg+hbl+ep) cutting eclogite; 30°40'N, 116°19.2'E
PRC104b	biotite selvage in gneiss from UHP unit (biotite only); 30°49.3'N, 116°11'E
PRC55b	garnet amphibolite from UHP unit (gar+hbl+plg+ep+qtz); 30°23.8'N, 116°06.1'E
PRC80c	amphibolite vein (hbl+plg+qtz+ep+chl) cutting eclogite; 30°36.8'N, 116°24.5'E
92H23	gneiss from UHP unit (gar+mu+bio+qtz+plg+sph); 30°37.8'N, 116°24'E
PRC129d	amphibolite vein (hbl+plg+qtz+ep) cutting eclogite; 30°40'N, 116°19.8'E
92PH1	garnet amphibolite from amphibolite unit (gar+amph+qtz+plg); 30°36.9'N, 116°00'E
PRC81b	amphibolite vein from UHP unit (hbl+plg+qtz+ep) cutting eclogite; 30°37'N, 116°24.5'E

gravity/magnetic separation methods. The separates are very pure; because they were only a few milligrams, every grain was examined repeatedly with a microscope, and undesired phases were picked out by hand. The samples were wrapped in Al foil and irradiated at the TRIGA reactor at the University of Oregon. Gas was extracted in 8-minute periods with a double-vacuum (Staudacher-type) resistance furnace with a Ta crucible and replaceable Mo liner. Extracted gas was equilibrated with SAES Zr-Al getters for 5–10 min and analyzed in static mode with a MAP 216 mass spectrometer over ~10–15 min. Dynamic and 1200°C static blanks of ^{40}Ar at were typically $1x10^{-17}$ and $2x10^{-15}$ mol, respectively. Isotopic abundances were calculated by linear extrapolation to time zero of peak heights above background during 6–12 serial scans of ^{40}Ar to ^{36}Ar. These data were corrected for neutron flux gradients (using sanidine standard 85G003 with an assumed age of 27.92 Ma), decay since irradiation, mass discrimination, and interference of Cl-, Ca-, and K-produced Ar isotopes. Reported uncertainties are one sigma, determined using uncertainties in monitor age; decay rates of ^{37}Ar, ^{39}Ar, and ^{40}K; rates of reactor-produced Ar isotopes;duration of irradiation; time between irradiation and analysis; peak heights; blank values; and irradiation parameter *J*.

Hornblende, white mica, and biotite were chosen from key localities and rock types in the major Dabie lithotectonic units. Samples from the NOU include weakly deformed granodiorite, tonalite, and diorite, weakly foliated tonalitic gneiss, banded tonalitic gneiss, and a gabbroic block from within tonalitic gneiss. From the UHP unit we dated amphibolitized eclogite, amphibolite veins cutting eclogite, and the dominant paragneiss that hosts the eclogite blocks. Our two samples from the amphibolite unit are paragneiss and garnet amphibolite. Although we have not dated the low-K_2O eclogite blocks themselves, there is ample evidence that the country rock paragneiss underwent the same UHP metamorphism as the eclogites: quartz pseudomorphs after coesite have been found in garnet crystals within marble and micaceous gneiss [*Wang and Liou*, 1991], and Sm and Nd isotopic abundances indicate that the crustal signature of the eclogites is as strong or stronger than that of the intercalated gneisses (L. Ames et al., unpublished manuscript).

The ^{40}Ar within any crystal derives from in situ decay of radiogenic K and from gas either trapped within or introduced into the crystal. Commonly, the composition of nonradiogenic Ar within a crystal matches that of the atmosphere; that is, the $^{40}Ar/^{36}Ar$ ratio is 295.5. On an isotope correlation diagram relating released ^{39}Ar to ^{36}Ar (e.g., Figure 4), such samples yield gas fractions that appear to result from mixing of a "radiogenic" ^{39}Ar component and an "atmospheric" ^{36}Ar component. The intercept of the correlation line on the $^{36}Ar/^{40}Ar$ axis is ideally 1/295.5 (the isotopic ratio of the atmosphere), and the intercept on the $^{39}Ar/^{40}Ar$ axis is inversely related to the age of the sample.

Two biotite and three hornblende separates from the orthogneiss unit yielded Cretaceous ages in a tight cluster of 124–133 Ma (Figure 4, Table 2). Biotite sample 92W5 from a weakly foliated gneiss yielded a spectrum that is internally concordant for 84% of the ^{39}Ar released; this is reflected in the isochron diagram, which yielded a trapped $^{40}Ar/^{36}Ar$ ratio indistinguishable from the atmosphere (295.5) and an age that is identical to the weighted mean plateau age. Because the trapped component is atmospheric, we use the plateau age of 127.0 ± 0.4 Ma as the age of the biotite. Hornblende from weakly foliated diorite sample 9290.1 produced a spectrum characterized by increasing ages for much of the gas release, followed by an internally concordant group of nine temperature increments that comprise 37% of the total ^{39}Ar. These highest temperature steps contain unsupported ^{40}Ar and ^{36}Ar in an atmospheric ratio, thus we choose the plateau age of 133.2 ± 0.7 Ma. Four other samples, 92314, 92905,

Table 2. Summary of $^{40}Ar/^{39}Ar$ data

Sample	Mineral	*J*	Weight, mg	Grain Size, µm	Total Fusion Age, Ma	Isochron Age, Ma	MSWD	$^{40}Ar/^{36}Ar$	Weighted Mean Plateau Age, Ma	Steps Used	%^{39}Ar Used
					Samples With Cretaceous Ages						
92W5	bi	0.0045979	0.9	200–300	126.8 ± 0.4	126.8 ± 0.4	1.0	361 ± 30	127.0 ± 0.4	4–8/8	84
9290.1	hbl	0.0039823	14.3	200–300	129.7 ± 0.6	133.0 ± 0.8	0.5	301 ± 12	134.0 ± 0.4	16–26/26	37
92314	hbl	0.0046641	9.4	150–200	130.2 ± 0.6	127.2 ± 0.7	2.0	407 ± 16	128.5 ± 0.6	7–12/23	36
92905	hbl	0.0039990	15.0	200–300	127.0 ± 0.4	128.8 ± 1.2	0.1	451 ± 11	130.1 ± 0.6	11–23/23	72
92332	bi	0.0045749	1.3	200–300	120.5 ± 0.4	122.0 ± 0.6	1.8	463 ± 20	121.3 ± 0.4	8–17/22	46
92256	hbl	0.0046088	13.0	150–200	151.3 ± 0.7	undefined	undefined	~122	5–25/25	91	
					Samples With Ages Near 200 Ma						
92THOL	phe	0.0046672	1.2	200–300	177.9 ± 0.9	178.4 ± 0.9	0.9	289.3 ± 6.0	178.3 ± 0.9	3–19/20	93
PRC78	phe	0.0045774	1.4	400–500	188.4 ± 0.6	188.6 ± 0.6	1.5	291.5 ± 6.9	188.6 ± 0.6	7–11/11	74
92127	bi	0.0046002	1.0	150–200	190.4 ± 0.6	190.3 ± 0.6	3.9	306 ± 13	190.2 ± 0.6	3–8/8	77
PRC131	phe	0.0045698	1.1	400–500	198.1 ± 0.6	199.8 ± 1.0	0.1	260 ± 32	199.7 ± 1.0	8–24/25	66
PRC49d	phe	0.0045939	1.2	400–500	205.4 ± 0.6	206.1 ± 0.7	0.3	286 ± 63	206.0 ± 0.6	9–12/12	64
92SU6A	phe	0.0045882	2.6	200–300	221.5 ± 0.6	225.0 ± 0.7	1.6	307 ± 20	225.2 ± 0.7	5–10/10	47
W92H-1	bi	0.0045724	1.8	200–300	228.3 ± 0.7	228.9 ± 0.7	2.4	262 ± 113	228.7 ± 0.7	5–8/8	67
					Samples With Excess Ar						
92194	hbl	0.0046577	22.1	150–200	230.4 ± 1.1						
PRC104b	bi	0.0045799	1.4	400–500	249.8 ± 0.7						
PRC55B	hbl	0.0046478	15.0	200–300	282.5 ± 0.9						
PRC80c	hbl	0.0046172	15.2	400–500	329.5 ± 0.9						
92H23	phe	0.0045923	1.6	200–300	391.0 ± 1.1						
PRC129d	hbl	0.0046361	14.1	400–500	440.7 ± 1.2						
92PH1	hbl	0.0040172	16.5	200–300	734.3 ± 1.9						
PRC81b	hbl	0.0046430	11.9	400–500	880.1 ± 2.6						

J is the irradiation parameter; MSWD is the mean square weighted deviation [*Wendt and Carl*, 1991], which expresses the goodness of fit of the isochron [*Roddick*, 1978]; isochron and weighted mean plateau ages are based on temperature steps and fraction of ^{39}Ar listed in the last two columns. Abbreviations are hb, hornblende; bi, biotite; phe, K-white mica. For complete tabulated data see the electronic supplement.

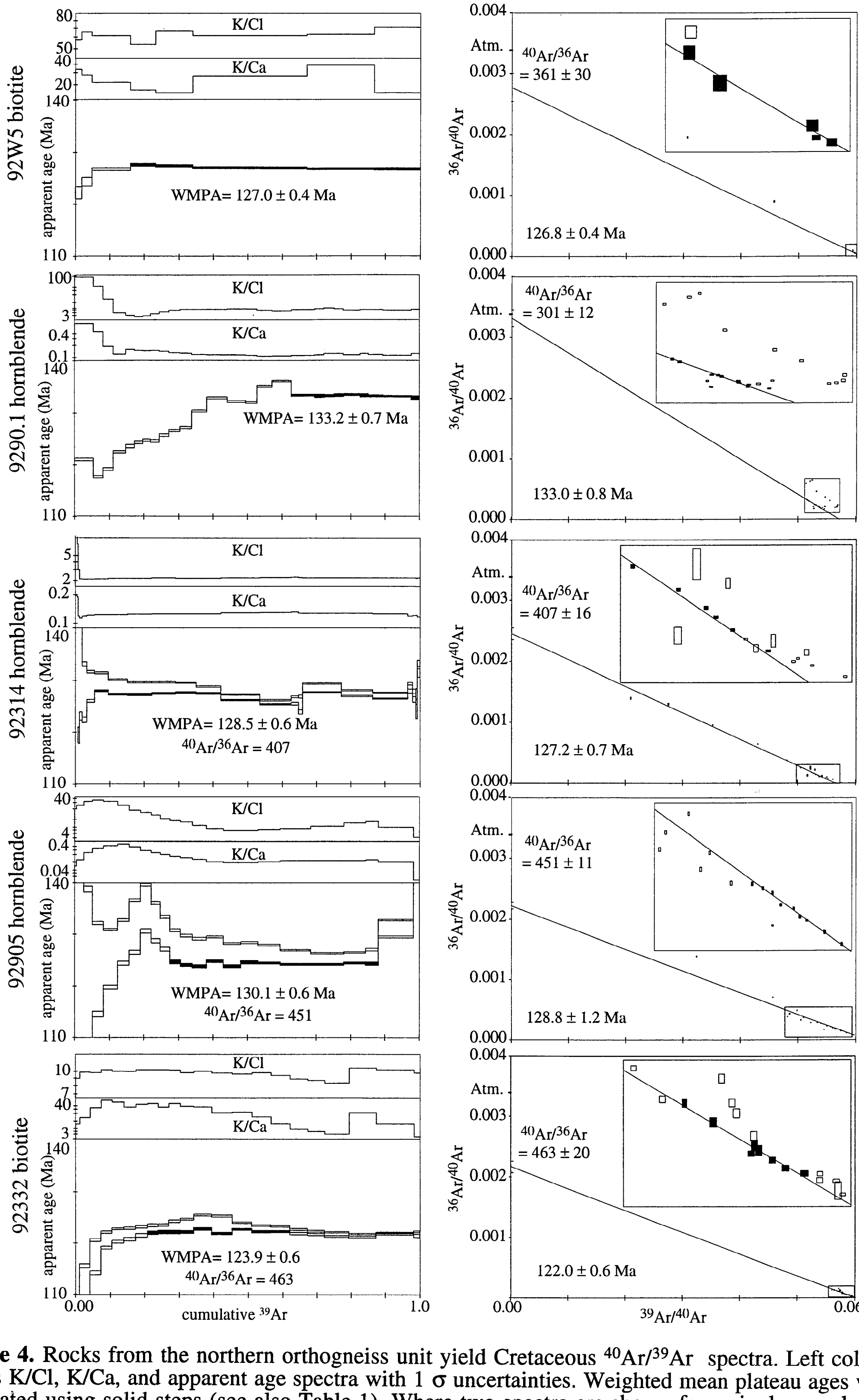

Figure 4. Rocks from the northern orthogneiss unit yield Cretaceous $^{40}Ar/^{39}Ar$ spectra. Left column shows K/Cl, K/Ca, and apparent age spectra with 1 σ uncertainties. Weighted mean plateau ages were calculated using solid steps (see also Table 1). Where two spectra are shown for a single sample, the older unfilled spectrum was calculated assuming a trapped $^{40}Ar/^{36}Ar$ ratio of 295.5, while the younger partially filled spectrum was calculated using the indicated $^{40}Ar/^{36}Ar$ ratio. Right column shows inverse isochron diagrams; because each datum shown at 1 σ standard deviation is nearly invisible, the most radiogenic points are redrawn in the inset rectangles. WMPA is the weighted mean plateau age; Atm. is the $^{36}Ar/^{40}Ar$ ratio of the atmosphere (1/295.5).

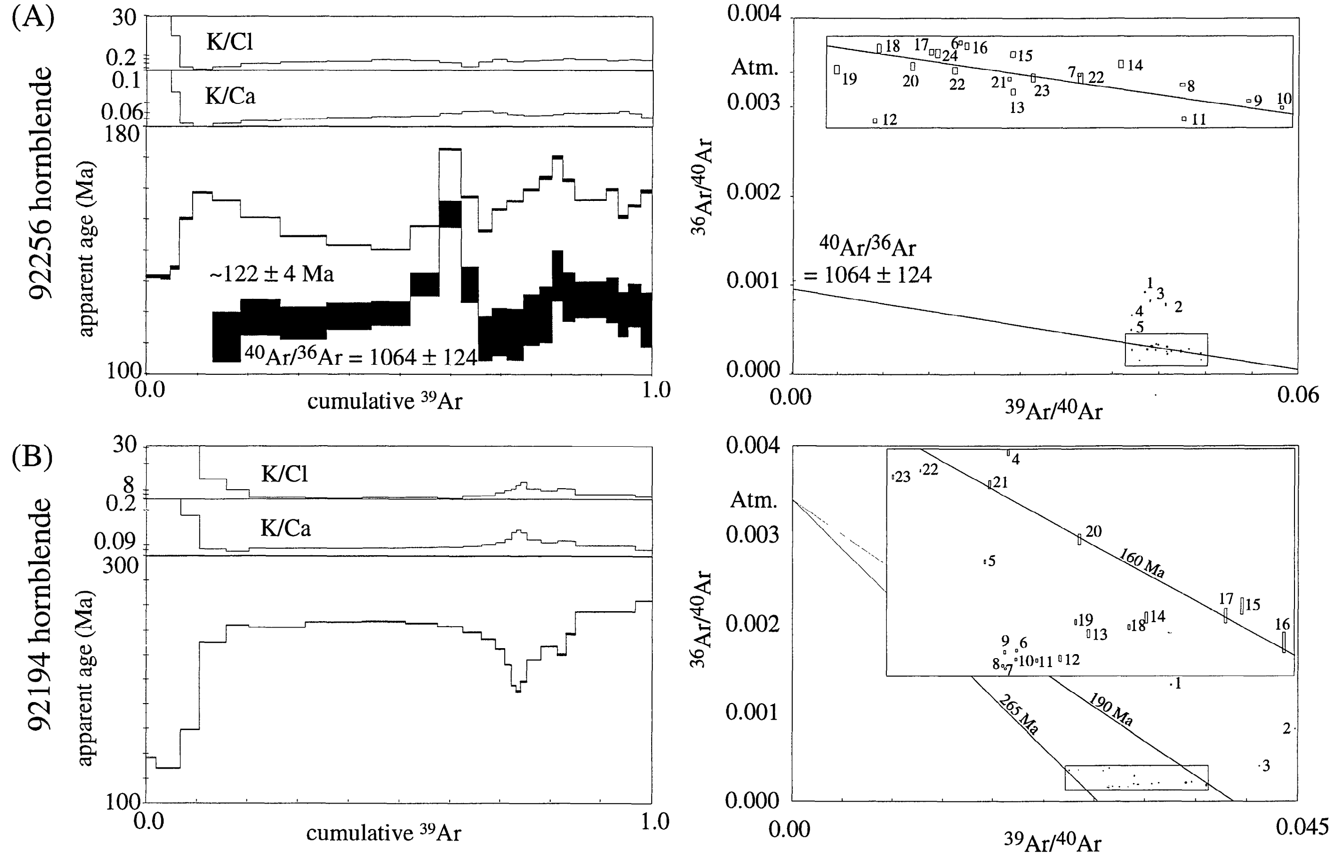

Figure 5. Examples of $^{40}Ar/^{39}Ar$ age spectra and isotope correlation diagrams for samples with inhomogeneously released excess ^{40}Ar. Numbers on inverse isochron diagrams show the order in which the gas steps were released. (a) Sample 92256. The spectrum with older ages was calculated assuming a trapped $^{40}Ar/^{36}Ar$ ratio of 295.5. The spectrum with younger ages was calculated for a trapped $^{40}Ar/^{36}Ar$ ratio of 1064 ± 124, with the effect of the ± 124 uncertainty illustrated. (b) Sample 92194. The inverse isochron diagram includes reference isochrons for 165, 190, and 265 Ma.

92332, and 92256, contain excess ^{40}Ar. As shown in the isochron diagrams, the $^{40}Ar/^{36}Ar$ ratios of unsupported Ar in three of these samples (weakly deformed tonalitic gneiss, gabbro, and granodiorite) are only modestly larger than atmospheric, ranging from 407 to 463. Note, moreover, that the data for each sample cover a negatively correlated, linear range of $^{39}Ar/^{40}Ar$ and $^{36}Ar/^{40}Ar$ ratios. A subset of the data from each sample can be chosen to yield an isochron that is a good fit (as judged by the mean squared weighted deviate, MSWD) to the data within analytical uncertainty. This is apparent in that the release spectra recalculated for the trapped $^{40}Ar/^{36}Ar$ ratios are internally concordant (Figure 4). The isochron ages for these samples are 127.2 ± 0.7, 128.8 ± 1.2, and 122.0 ± 0.6 Ma.

The fourth sample, 92256, a banded tonalitic gneiss, contains a trapped component with a notably higher $^{40}Ar/^{36}Ar$ ratio of approximately 1064 (Figure 5a). The isotope correlation diagram for this sample also reveals that the isotopic ratios measured for this sample cannot be interpreted as a simple mixture of two components. This behavior was evident in samples 92314, 92332, and 9290.1 (Figure 4) but is more pronounced in sample 92256. Although some of the $^{39}Ar/^{40}Ar$ and $^{36}Ar/^{40}Ar$ ratios for sample 92256 show a negatively correlated, linear relationship, the correlation is poor. Six or seven isotopic ratios with anomalously low or high $^{36}Ar/^{40}Ar$ values are not part of this semilinear array. Moreover, in contrast to all samples previously discussed, the fraction of radiogenic ^{40}Ar in each measured step of sample 92256 never exceeded 95% (Table 2); this is graphically evident in the displacement of the data toward the $^{36}Ar/^{40}Ar$ axis (Figure 5a).

Eide et al. [1994] also reported five Cretaceous $^{40}Ar/^{39}Ar$ ages from hornblende and/or biotite-bearing orthogneisses of the Dabie Shan: ~119 Ma biotite from the NOU; 124 Ma biotite, ~122 Ma hornblende, and ~128 Ma hornblende from the UHP unit; and ~125 Ma biotite from the amphibolite unit (Figures 2 and 3). *Mattauer et al.* [1991] published two biotite $^{40}Ar/^{39}Ar$ ages of 120 and 125 Ma and one hornblende $^{40}Ar/^{39}Ar$ age of 131 Ma from the NOU. In conjunction with our data, these $^{40}Ar/^{39}Ar$ data demonstrate that much of the Dabie Shan underwent cooling through hornblende and biotite closure between 133 and 119 Ma. The hornblende ages, as a whole, are generally greater than the biotite ages, but there is no systematic spatial distribution of ages within the mountain

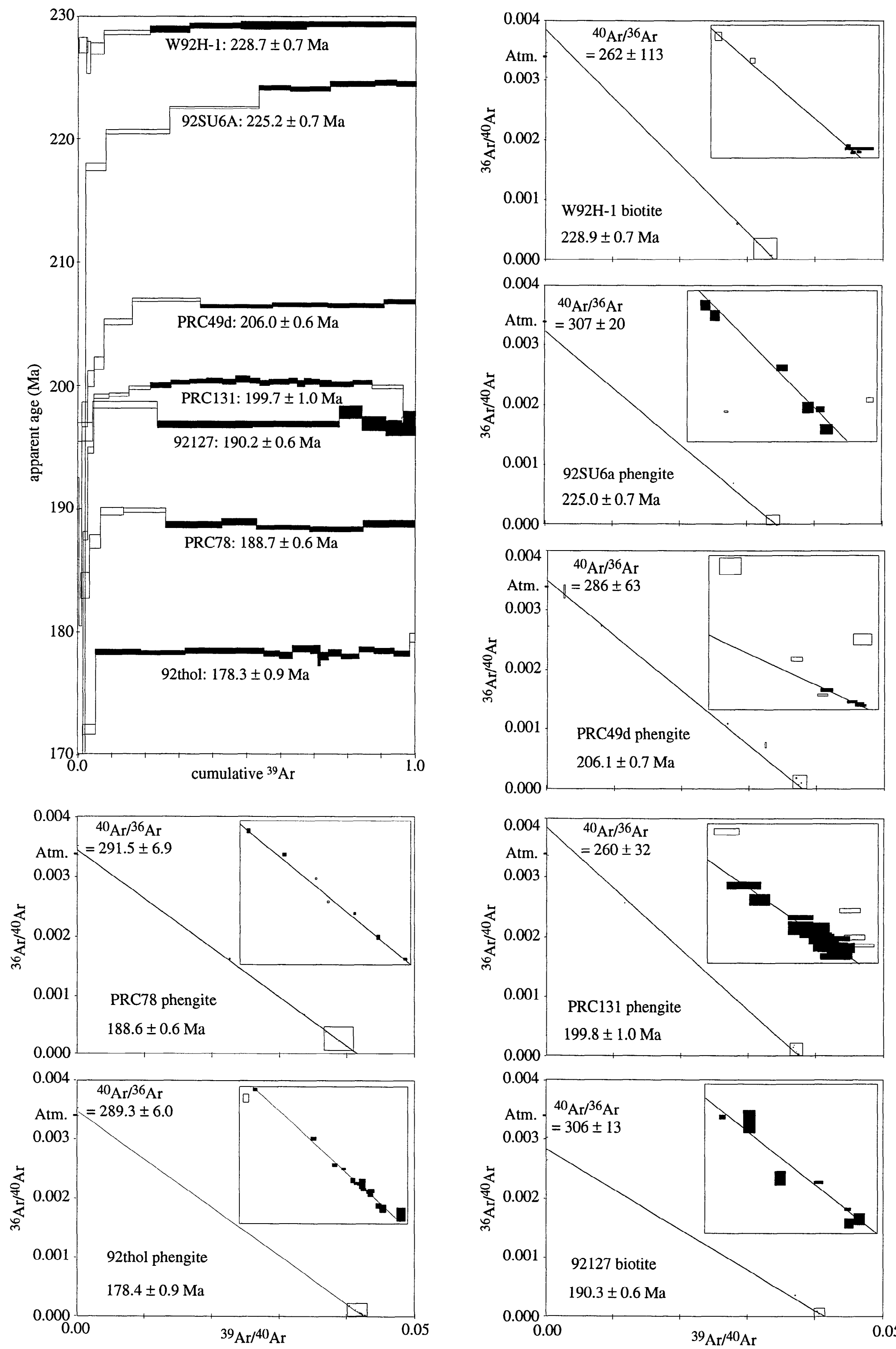

Figure 6. Micas from paragneisses in the UHP and amphibolite units yield $^{40}Ar/^{39}Ar$ age ages interpreted to reflect cooling following UHP metamorphism. Symbols are as in Figure 4.

range. We interpret these Cretaceous ages of 118–133 Ma to reflect cooling following emplacement of the granitoid plutons that are widespread through the Dabie Shan. Some of these plutons have Cretaceous U/Pb zircon ages [*Li and Wang*, 1991; L. Ames et al., unpublished manuscript, 1995], and the present $^{40}Ar/^{39}Ar$ ages suggest that many undated plutons and orthogneisses in the Dabie Shan are probably Cretaceous as well. Hornblende barometry on metamorphic rocks associated with emplacement of these plutons suggests crystallization at pressures of ~400–600 MPa [*Liou et al.*, 1995]. Thus the current level of exposure was probably at ~15 km depth in mid-Cretaceous time. As mentioned above, deformation within the NOU involved began at hypersolidus conditions and extended through greenschist facies retrogression. The $^{40}Ar/^{39}Ar$ ages reported here indicate that this deformation occurred between 118 and 133 Ma.

Seven mica samples taken from paragneiss that makes up the bulk of the UHP unit gave $^{40}Ar/^{39}Ar$ ages ranging from 178 to 229 Ma (Figure 6, Table 2). These spectra are composed of very radiogenic gas fractions; most required atmospheric corrections of less than 5%. The apparent ages of at least 50% of the gas fractions released from each sample are internally concordant. Isotope correlation diagrams indicate that the gas released from each of these samples is a mix between radiogenic and atmospheric sources. Not all the samples produced unambiguous plateaus, however. The spectrum from the youngest sample, 92thol, includes 17 concordant steps that comprise 93% of the total ^{39}Ar released. Samples PRC78, 92127, and PRC49d also gave concordant spectra but of lower resolution. The high-resolution spectrum from PRC131 is also statistically concordant, but the slight convex upward shape of the spectrum causes us to regard this age as somewhat suspect. The samples that yielded the two oldest ages, W92H-1 and 92SU6a, both exhibit spectra with serially increasing ages. Although both spectra contain a reasonable number of steps that are concordant and yield isochrons that are statistically acceptable, we also regard these ages with suspicion. It is possible that these serially increasing spectra resulted from Ar loss during reheating or slow cooling, but these ages may also be geologically meaningless. Thus the internally concordant, "flat" age spectra with plateaus from 178 to 206 Ma are interpreted to reflect cooling after UHP metamorphism; the two ages of 225 and 228 Ma may or may not be part of this group. The preservation of 178–206 Ma phengites within the UHP unit is noteworthy because orthogneisses of the type that yielded Cretaceous ages are locally dominant in the UHP unit. The restriction of ~200 Ma ages to the eastern Dabie Shan indicates that the Cretaceous thermal event was less pronounced in that area; this is reasonable because plutons and orthogneiss are abundant in the western Dabie Shan but much less abundant in the east.

The remainder of the samples from the UHP unit yielded strongly discordant release spectra (Figures 5b and 7; Table 2). Most of these samples are hornblendes, but this group also includes one white mica and one biotite. Total gas ages range from ~250 to 880 Ma, and apparent ages of individual steps are as old as 1.5 Ga. Isotope correlation

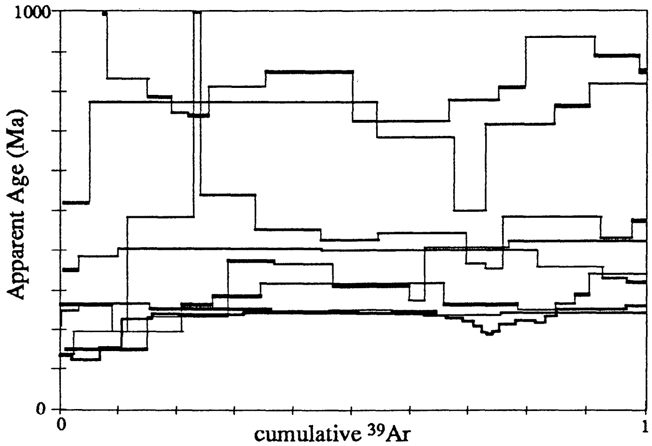

Figure 7. The $^{40}Ar/^{39}Ar$ age spectra for samples dominated by excess ^{40}Ar.

diagrams for these samples reveal that the isotopic ratios cannot be interpreted as mixtures of two components (Figures 5b and 7). Some of the $^{39}Ar/^{40}Ar$ and $^{36}Ar/^{40}Ar$ ratios for these samples have a negatively correlated, linear relationship that suggests a trapped $^{40}Ar/^{36}Ar$ component considerably greater than atmospheric, but there is considerable scatter. More typically, the isotopic ratios are positively correlated, or the $^{36}Ar/^{40}Ar$ ratios are essentially constant over a range of $^{39}Ar/^{40}Ar$ values. This sort of behavior is typical of samples with excess ^{40}Ar [e.g., *Hannula and McWilliams*, 1995].

Similarly old biotite, white mica, and hornblende $^{40}Ar/^{39}Ar$ ages were obtained by *Mattauer et al.* [1991] and *Li et al.* [1994]. *Mattauer et al.* interpreted their 550–668 Ma ages to indicate cooling following Proterozoic UHP metamorphism. Although their preliminary report does not include spectra or isochrons, the ages they report are presumably total gas ages. Given the recent reports of circa 220 Ma U/Pb zircon ages from eclogites (L. Ames et al., unpublished manuscript, 1995) and the presence of excess ^{40}Ar demonstrated in this paper, Mattauer et al.'s old ages more likely result from the presence of excess ^{40}Ar rather than from Proterozoic metamorphism. *Li et al.* [1994] recognized that their white mica ages of 848 and 943 Ma are so much older than Sm/Nd and Rb/Sr ages (219–228 Ma) on the same rocks that the micas must contain excess ^{40}Ar. They described their white mica spectra as "plateaus" and warned that plateau spectra may be affected by excess ^{40}Ar; however, their spectra are better described as internally discordant and share some of the same features of our spectra shown in Figure 7.

More than half of the $^{40}Ar/^{39}Ar$ ages reported for samples collected from widespread locations within the UHP unit of the Dabie Mountains are severely affected by excess ^{40}Ar. This renders all existing and future K/Ar whole rock and mineral ages from the Dabie Shan suspect. The $^{40}Ar/^{39}Ar$ spectra from this mountain range that are hump-shaped [e.g., *Okay et al.*, 1993] or composed of few steps [e.g., *Li et al.*, 1993] should also be viewed with caution.

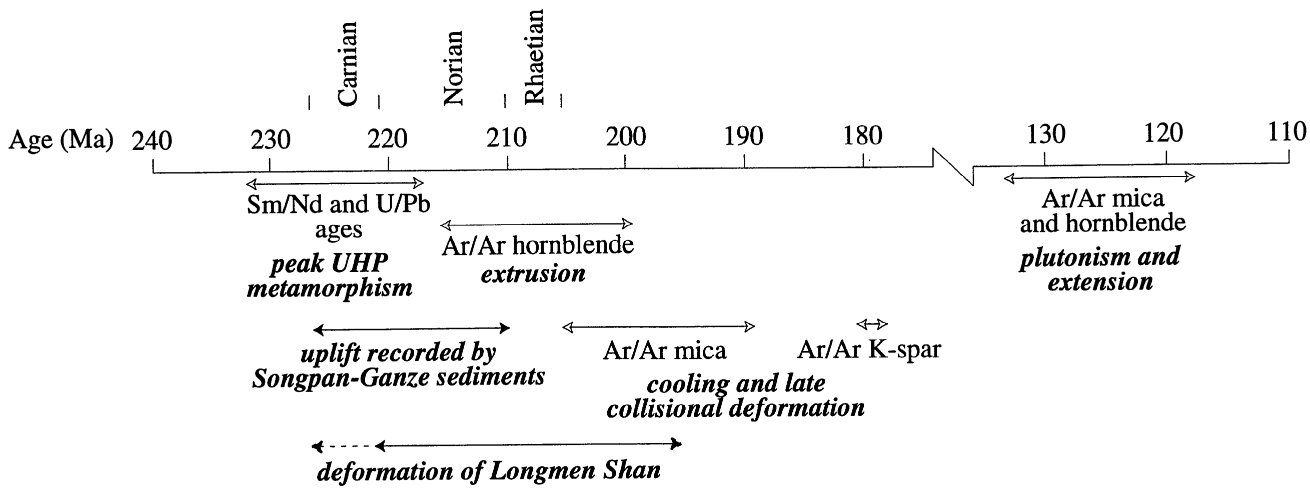

Figure 8. Summary of tectonic events in the Dabie–Sulu and related areas as generalized from data in Figure 3 and discussed in the text.

Discussion

Our data firmly indicate that cooling after ultrahigh- and high-pressure metamorphism in the Qinling-Dabie orogen occurred from ~228 Ma or ~206 Ma to 178 Ma and that older apparent ages are the result of contamination. Most of the U/Pb zircon and Sm/Nd ages cluster between ~232 and ~218 Ma, suggesting that the peak of metamorphism occurred in that time frame. The closure temperatures for $^{40}Ar/^{39}Ar$ and Rb/Sr are lower than those for U/Pb and Sm/Nd (see references in Figure 3); thus the $^{40}Ar/^{39}Ar$ and Rb/Sr ages in Figure 3 should be younger than the U/Pb and Sm/Nd ages. Four of the hornblende ages, four of the K-feldspar ages, perhaps eleven of the $^{40}Ar/^{39}Ar$ white mica ages, and four of the biotite ages are reasonably younger than the U/Pb and Sm/Nd ages. The other $^{40}Ar/^{39}Ar$ and Rb/Sr ages are comparable to or older than the U/Pb and Sm/Nd ages and may be anomalously old. Most $^{40}Ar/^{39}Ar$ ages in Figure 3 that are older than 250 Ma are from eclogite, whereas all of the younger $^{40}Ar/^{39}Ar$ ages are from UHP paragneisses. This is conveniently explained by reasoning that any ^{40}Ar that may have streamed into the rock in a fluid or vapor would influence low-K eclogite far more than K-rich rocks like white mica paragneiss.

The expected decrease in $^{40}Ar/^{39}Ar$ ages from hornblende to white mica to biotite, reflecting decreasing closure temperatures, is not evident in Figure 3. This complexity displayed by the isotopic ages from the Dabie Shan may reflect (1) unusual isotopic behavior at ultrahigh pressures (á la the age discordance observed at Dora Maira; [*Monié and Chopin*, 1991; *Tilton et al.*, 1991]); (2) unrecognized contributions of excess Ar in the Triassic ages; or (3) unresolved geological complexity, such that the samples with different ages are in different structural domains.

Sedimentologic and paleomagnetic data are in agreement with the radio-isotopic data indicating that the collision was Triassic (Figure 8). Recent summaries of paleomagnetic data [*Zhao and Coe*, 1987; *Lin and Fuller*, 1990; *Enkin et al.*, 1992] suggest that the Sino-Korean craton and Yangtze craton approached one another and collided between Middle to Late Triassic and Early Jurassic time. In the Songpan–Ganze basin, ~1000 km west of the Dabie Shan, Carnian–Norian (~227–210 Ma [*Gradstein et al.*, 1994]) siliciclastic flysch has been interpreted to reflect initial uplift of the Dabie Shan [*Nie et al.*, 1994; *Zhou and Graham*, 1995]. The southeast flank of the Songpan–Ganzi basin was folded and thrust SE over the Yangtze craton beginning in Norian time, culminating in the Rhaetian, and finishing by ~196 ± 6 Ma [*Dirks et al.*, 1995]. Further work is required to discern the specific tectonic links among these features.

Conclusions

Previous workers have inferred a wide range of ages from Archean to Triassic for post-UHP cooling of coesite- and diamond-bearing rocks in the Dabie Shan. Our $^{40}Ar/^{39}Ar$ analysis of 21 hornblende, white mica, and biotite samples indicates that cooling from peak metamorphic temperatures to ~300°C occurred between 229 or 206 Ma and 178 Ma. Dabie UHP metamorphic rocks cooled at the same time as high-pressure rocks farther west and east along the suture zone, indicating that the initial stages of exhumation occurred coevally over a wide area. Apparent $^{40}Ar/^{39}Ar$ and K/Ar ages older than ~230 Ma (and possibly older than 210 Ma) are contaminated with excess ^{40}Ar. Minerals with nonatmospheric Ar contamination are widespread, and all K/Ar ages from the Dabie Shan should be treated with caution. Areally extensive Cretaceous granites, 118–133 Ma, caused substantial reheating of the entire mountain range, except in some areas where coesite is preserved. These conclusions are consonant with radiometric studies from other parts of the orogen, with radiometric studies in the Dabie Shan using different isotopic systems, and with paleomagnetic constraints.

Acknowledgments. Thanks are extended to L. Ames and K. Hodges for reviewing the manuscript; B. Cong, J.G. Liou, X. Liu,

X. Wang, and R. Zhang for field and logistical assistance; M.O. McWilliams for making available his Ar lab; and M.M. Jia for help purifying mineral separates. Research reported here was supported by U.S. National Science Foundation grant EAR 92-04563, the Stanford-China Geoscience Industrial Affiliates Program, and the Chinese National Natural Science Foundation.

References

Ames, L., G.R. Tilton, and G. Zhou, Timing of collision of the Sino-Korean and Yangtse Cratons: U-Pb zircon dating of coesite-bearing eclogites, *Geology, 21*, 339–342, 1993.

Chen, W., T.M. Harrison, M.T. Heizler, R. Liu, B. Ma, and J. Li, The cooling history of melange zone in north Jiangsu–south Shandong region: Evidence from multiple diffusion domean ^{40}Ar-^{39}Ar thermal geochronology, *Acta Pet. Sin., 8*, 1–17, 1992.

Chopin, C., Coesite and pure pyrope in high-grade blueschists of the western Alps: A first record and some consequences, *Contrib. Mineral. Petrol., 86*, 107–118, 1984.

Dirks, P.H.G.M., C.J.L. Wilson, S. Chen, Z.L. Luo, and S. Liu, Tectonic evolution of the NE margin of the Tibetan Plateau; evidence from the central Longmen Mountains, Sichuan Province, China, *J. Southeast Asian Earth Sci., 9*, 181–192, 1995.

Dong, S., Metamorphic and tectonic domains of China, *J. Metamorph. Geol., 11*, 465-481, 1993.

Dong, S., Q. Shen, D. Sun, and L. Lu, Metamorphic map of China with an explanatory text, scale 1:4,000,000, Geological Publishing House, Beijing, China, 1986.

Eide, L., M.O. McWilliams, and J.G. Liou, ^{40}Ar/^{39}Ar geochronologic constraints on the exhumation of HP-UHP metamorphic rocks in east-central China, *Geology, 22*, 601–604, 1994.

Enkin, R.J., Z. Yang, Y. Chen, and V. Courtillot, Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the present, *J. Geophys. Res., 97*, 13,953-13,989, 1992.

Ernst, W.G., G. Zhou, J.G. Liou, E. Eide, and X. Wang, High-pressure and superhigh-pressure metamorphic terranes in the Qinling-Dabie mountain belt, central China; early to mid-Phanerozoic accretion of the western Paleo-Pacific Rim, *Pac. Sci. Assoc. Inf. Bull., 43*, 6–15, 1991.

Gradstein, F.M., F.P. Agterberg, J.G. Ogg, J. Hardenbol, P. van Veen, J. Thierry, and Z. Huang, A Mesozoic timescale, *J. Geophys. Res., 99*, 24,051–24,074, 1994.

Hacker, B.R., L. Ratschbacher, L. Webb, S. Dong, What brought them up? Exhumation of the Dabie Shan ultrahigh-pressure rocks, *Geology*, in press, 1995a.

Hacker, B.R., X. Wang, E.A. Eide, and L. Ratschbacher, Qinling–Dabie ultrahigh-pressure collisional orogen, in *Tectonic Evolution of Asia*, edited by A. Yin and T.M. Harrison, Prentice-Hall, Englewood Cliffs, N.J., in press, 1995b.

Hannula, K.A., and M.O. McWilliams, Reconsideration of the age of blueschist facies metamorphism on the Seward Peninsula, Alaska, based on phengite ^{40}Ar/^{39}Ar results, *J. Metamorph. Geol., 13*, 125–139, 1995.

Harland, W.B., R.L. Armstrong, A.V. Cox, L.E. Craig, A.G. Smith, and D.G. Smith, *A Geologic Time Scale*, New York, Cambridge University Press, 1989.

Harrison, T.M., Diffusion of ^{40}Ar in hornblende, *Contrib. Mineral. Petrol., 78*, 324-331, 1981.

Harrison, T.M., I. Duncan, and I. McDougall, Diffusion of ^{40}Ar in biotite: temperature, pressure, and compositional effects, *Geochim. Cosmochim. Acta, 49*, 2461–2468, 1985.

Jin, F., Carboniferous paleogeography and paleoenvironment between the North and South China blocks in eastern China, *J. Southeast Asian Earth Sci, 3*, 219–222, 1989.

Li, S., and T. Wang, *Geochemistry of granitoids in the Tongbaishan-Dabieshan, central China*, China University of Geosciences Press, Wuhan, 1991.

Li, S., et al., Collision of the North China and Yangtze blocks and formation of coesite-bearing eclogites: Timing and processes, *Chem. Geol., 109*, 89–111, 1993.

Li, S., S. Wang, Y. Chen, D. Liu, J. Qiu, H. Zhou, and Z. Zhang, Excess argon in phengite from eclogite: Evidence from the dating of eclogite minerals by the Sm-Nd, Rb-Sr and ^{40}Ar/^{39}Ar methods, *Chem. Geol., 112*, 343–350, 1994.

Li, S.G., S.R. Hart, S.G. Zheng, D.L. Liou, and A. Guo, Sm-Nd isotopic evidence for the timing of the collision between the north and south China cratons—the Sm-Nd isotopic evidence, *Sci. China, ser. B, 32*, 1391–1400, 1989a.

Li, S.G., S.R. Hart, S.G. Zheng, D.L. Liu, G.W. Zhang, and A.L. Guo, Timing of collision between the north and south China blocks - The Sm-Nd isotopic age evidence, *Sci. China, ser. B, 32*, 1393-1400, 1989b.

Lin, J.L., and M. Fuller, Paleomagnetic constraints on relative motions of the Asian blocks and terranes, in *Terrane Analysis of China and the Pacific Rim*, edited by T.J. Wiley, D.G. Howell, and F.L. Wong, pp. 195–210, Circum-Pacific Council for Energy and Mineral Resources, Houston, Tex., 1990.

Liou, J.G., R.Y. Zhang, E.A. Eide, S. Maruyama, X. Wang, and W.G. Ernst, Metamorphism and tectonics of high-P and ultrahigh-P belts in Dabie-Sulu Regions, eastern central China, in *Tectonic Evolution of Asia*, edited by A. Yin and T.M. Harrison, Prentice-Hall, Englewood Cliffs, N.J., in press, 1995.

Liu, J., J.G. Liou, and B.R. Hacker, Kyanite anthophyllite schist and the southwest extension of the Dabie Mountains ultrahigh to high pressure belt., *Eos, Trans. AGU, 75 (44), Fall Meet. suppl.*, 744, 1994.

Ma, B., and Z. Zhang, The features of the paired metamorphic belts and evolution of paleotectonics in the east part of Dabie Mountains, *Seismol. Geol., 10*, 19–28 (in Chinese), 1988.

Mattauer, M., P. Matte, J. Malavieille, P. Tapponnier, H. Maluski, Z.Q. Xu, Y.L. Lu, and Y.Q. Tang, Tectonics of the Qinling belt: Build-up and evolution of eastern Asia, *Nature, 317*, 496-500, 1985.

Mattauer, M., P. Matte, H. Maluski, Z. Xu, Q.W. Zhang, and Y.M. Wang, La limite Chine du Nord-Chine du Sud au Paléozoïque et au Trias. Nouvelles données structurales et radiométriques dans le massif de Dabie-Shan (chaîne des Qinling) (Paleozoic and Triassic plate boundary between North and South China; New structural and radiometric data on the Dabie-Shan, eastern China) (in French), *C. R. Acad. Sci., Ser. II, 312*, 1227-1233, 1991.

Monié, P., and C. Chopin, ^{40}Ar/^{39}Ar dating in coesite-bearing and associated units of the Dora Maira massif, western Alps, *Eur. J. Mineral., 3*, 239–262, 1991.

Nie, S., A. Yin, D.B. Rowley, and Y. Jin, Exhumation of the Dabie Shan ultrahigh-pressure rocks and accumulation of the Songpan–Ganzi flysch sequence, central China, *Geology, 22*, 999–1002, 1994.

Okay, A.I., Petrology of a diamond and coesite-bearing metamorphic terrain: Dabie Shan, China, *Eur. J. Mineral., 5*, 659–675, 1993.

Okay, A.I., S.T. Xu, and A.M.C. Sengör, Coesite from the Dabie Shan eclogites, central China, *Eur. J. Mineral., 1*, 595-598, 1989.

Okay, A.I., A.M.C. Sengör, and M. Satir, Tectonics of an ultrahigh-pressure metamorphic terrane: The Dabie Shan/Tongbai Shan orogen, China, *Tectonics, 12*, 1320–1334, 1993.

Regional Geological Survey Anhui, *Regional Geology of Anhui Province*, Geological Publishing House, Beijing, China, 1987.

Regional Geological Survey Henan, *Regional Geology of Henan Province*, Geological Publishing House, Beijing, China, 1989.

Regional Geological Survey Hubei, *Regional Geology of Hubei Province*, Geological Publishing House, Beijing, China, 1990.

Roddick, J.C., The application of isochron diagrams in ^{40}Ar-^{39}Ar dating: A discussion, *Earth Planet. Sci. Lett., 41*, 233–244, 1978.

Sang, B., Y. Chen, and G. Shao, The Rb-Sr ages of metamorphic series of the Susong Group at the southeastern foot of the Dabie Mountains, Anhui province, and their tectonic significance, *Reg. Geol. China, 4*, 364–370, 1987.

Schertl, H.-P., and A.I. Okay, A coesite inclusion in dolomite in Dabie Shan, China: Petrological and rheological significance, *Eur. J. Mineral., 6*, 995–1000, 1994.

Smith, D.C., Coesite in clinopyroxene in the Caledonides and its implications for geodynamics, *Nature, 310*, 641–644, 1984.

Snee, L.W., J.F. Sutter, and W.C. Kelly, Thermochronology of economic mineral deposits: Dating the stages of mineralization at Panasqueira, Portugal, by high-precision 40Ar/39Ar age spectrum techniques on muscovite, *Econ. Geol., 83*, 335–354, 1988.

Tilton, G.R., W. Schreyer, and H.-P. Schertl, Pb-Sr-Nd isotopic behavior of deeply subducted crustal rocks from the Dora Maira massif, western Alps, Italy, II, What is the age of the ultrahigh pressure metamorphism, *Contrib. Mineral. Petrol., 108*, 22–33, 1991.

Wang, X., and J.G. Liou, Regional ultrahigh-pressure coesite-bearing eclogitic terrane in central China: Evidence from country rocks, gneiss, marble, and metapelite, *Geology, 19*, 933-936, 1991.

Wang, X., and J.G. Liou, Ultrahigh-pressure metamorphism of carbonate rocks in the Dabie Mountains, central China, *J. Metamorph. Geol., 11*, 575–588, 1993.

Wang, X., J.G. Liou, and H.K. Mao, Coesite-bearing eclogite from the Dabie Mountains in central China, *Geology, 17*, 1085-1088, 1989.

Wang, X., Y. Jing, J.G. Liou, G. Pan, W. Liang, M. Xia, and S. Maruyama, Field occurrences and petrology of eclogites from the Dabie

Mountains, Anhui, central China, *Lithos, 25*, 119-131, 1990.

Wang, X., J.G. Liou, and S. Maruyama, Coesite-bearing eclogite from the Dabie Mountains, central China: Petrology and P-T path, *J. Geol., 100*, 231–250, 1992.

Wendt, I., and C. Carl, The statistical distribution of the mean squared weighted deviation, *Chem. Geol., 86*, 275–285, 1991.

Xu, S., H. Zhou, S. Dong, G. Chen, and W. Zhang, Deformation and evolution of the predominant structural elements in Anhui Province, China (in Chinese), *Dizhi Kexue, 2*, 311–322, 1986.

Xu, S., A.I. Okay, S. Ji, A.M.C. Sengör, W. Su, Y. Liu, and L. Jiang, Diamond from the Dabie Shan metamorphic rocks and its implication for the tectonic setting, *Science, 256*, 80-82, 1992.

Yang, Z., Y. Cheng, and H. Wang, *The Geology of China*, Clarendon Press, Oxford, 1986.

Zhang, R.Y., J.G. Liou, and B. Cong, Petrogenesis of garnet-bearing ultramafic rocks and associated eclogites in the Su-Lu ultrahigh-P metamorphic terrane, eastern China, *J. Metamorph. Geol., 12*, 169–186, 1994.

Zhao, X., and R.S. Coe, Palaeomagnetic constraints on the collision and rotation of North and South China, *Nature, 327*, 141-144, 1987.

Zhou, D., and S.A. Graham, Songpan-Ganzi complex of the west Qinling Shan as a Triassic remnant ocean basin, in *Tectonics Evolution of Asia*, edited by A. Yin and T.M. Harrison, Prentice-Hall, Englewood Cliffs, N.J., in press, 1995.

B. R. Hacker, Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305-2115. (e-mail: hacker@geo.stanford.edu)

Q. Wang, Laboratory of Lithosphere Tectonic Evolution, Institute of Geology, Academia Sinica, Beijing 100029, China.

(Received April 28, 1994;
revised March 13, 1995;
accepted March 16, 1995.)