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TECTONICS OF AN ULTRAHIGH-PRESSURE METAMORPHIC TERRANE: THE DABIE SHAN/TONGBAI SHAN OROGEN, CHINA

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Abstract. Ultrahigh-pressure metamorphic rocks with coesite and diamond form a tectonic slice over 20 km thick, called the eclogite zone, within the Dabie Shan complex in the Qinling orogen in central China. The orogen separates the Sino-Korean block in the north from the Yangtze block in the south. The Dabie Shan Complex is a composite terrane made up of eclogite facies and amphibolite facies gneiss slices and represents fragments of the lower continental crust of the Yangtze block. The Dabie Shan Complex is bounded in the south by a Triassic foreland fold-thrust belt and in the north by a greenschist facies metaclastic unit, the Foziling Group, which probably represents the passive continental apron deposits of the Yangtze block. Farther north is a granulite facies gneiss complex, the Qinling Group, which has ultramafic slivers and includes the remnants of an island arc with two bounding suture zones. North of the Qinling Group are early Paleozoic active margin deposits of the Sino-Korean block. The eclogite zone in the Dabie Shan Complex is sandwiched between amphibolite facies gneiss slices. Dating by Sm-Nd, Rb-Sr, and Ar-Ar of two eclogite samples from the eclogite zone gives early to middle Triassic ages (236-246 Ma); the initial ε_{Nd} values indicate reworking of a 2.11 and 1.55 Ga continental crust. A Himalayan-type tectonic evolution is envisaged for the Qinling orogen with the creation of a 100-km-thick crustal thrust wedge through continuous underplating during the subduction of the Yangtze continental lithosphere. Exhumation of the ultrahigh-pressure metamorphic rocks was chiefly achieved by the southward propagation of the thrust planes, thereby isostatically uplifting and eroding the earlier deeply subducted parts of the orogen. A total of 680 km of southward thrusting in front of Dabie Shan is inferred, based on the abrupt termination of the Tanlu fault. Normal faulting possibly caused by gravitational collapse probably also had a role in the exhumation process.

INTRODUCTION

The recent recognition of ultrahigh-pressure minerals, such as coesite and diamond in crustal rocks in orogenic belts [e.g., Chopin, 1984; Smith, 1984; Sobolev and Shatsky, 1990], indicates that contrary to the common assumption, the continental crust can be subducted to asthenospheric depths. This poses difficult tectonic problems involving burial of crustal rocks to depths of over 100 km and subsequent uplift to the surface. This problem is especially significant in the Dabie Shan in China, where ultrahigh-pressure metamorphic rocks with coesite and diamond occur as a crustal slice of over 500 km^2 in area [Okay et al., 1989; Wang et al., 1989; Xu et al., 1992a]. Understanding the tectonic setting of these ultrahigh-pressure metamorphic rocks within the orogen is of critical importance in solving problems related to the subduction and uplift of these rocks. Here we report the results of our fieldwork and petrological and geochronological work in the eastern part of the Qinling orogen in Dabie Shan and Tongbai Shan.

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QINLING OROGEN

The Qinling orogen is an east-west trending south vergent mountain belt separating the Sino-Korean block in the north from the Yangtze block in the south [Mattauer et al., 1985; Şengör, 1985; Hsü et al., 1987; Huang and Wu, 1992] (Figure 1). The Qinling orogen is characterized by fault-bounded, laterally continuous tectonic zones. In the north are the relatively little-deformed active margin units of the Sino-Korean block separated by a fault zone from a gneiss terrane with ultramafic lenses. This Qinling Group is in fault contact in the south with a thick monotonous sequence of metapelites, the Foziling Group. In the western part of the Qinling orogen the Foziling Group is tectonically juxtaposed against a 180-km-wide Triassic foreland fold-thrust belt, whereas toward the east a triangular-shaped, eastward widening block of gneiss and eclogite (Dabie Shan Complex) with the ultrahigh-pressure rocks is interposed between the metapelites and the foreland (Figure 1). In the east the sinistral Tanlu fault abruptly truncates and offsets the Qinling orogen 500-600 km northward to Shandong, where coesite was also described [Hirajima et al., 1990].

We studied the Qinling orogen in the Dabie Shan and Tongbai Shan, which together exhibit a complete north-south cross section. The large-scale structure in this region, as envisaged by us, is shown in cross section in Figure 2a. The various tectonic units in these two areas are described from south to north.

TECTONIC UNITS IN DABIE SHAN AND TONGBAI SHAN

Foreland Fold-Thrust Belt: Cover of the Yangtze Block

This unit includes the folded Proterozoic-Triassic rocks of the Yangtze block. The foreland belt comprises at the base a thick series of late Proterozoic acidic volcanic rocks and fine-grained sediments overlain by Sinian to middle Triassic sandstone, limestone, and shale. To the south of Dabie Shan the foreland belt is characterized by east-west trending folds with several-kilometers-long wavelengths which go right across the southward projection of the Tanlu fault and bend toward the northeast in the eastern part of the Tanlu fault (Figure 1). Farther west in the Qinling Mountains these upright folds pass structurally down to south vergent recumbent folds as the decollement surfaces in the late Proterozoic acidic volcanic rocks are approached [Mattauer et al., 1985].

The structurally lower parts of the foreland fold-thrust belt south and east of Dabie Shan show a low-grade, high-pressure greenschist facies metamorphism with the development of barroisite and, rarely, blue crossitic amphibole in the Proterozoic volcanic rocks. Sodic amphibole also occurs in the Proterozoic volcanic rocks in the Qinling Mountains, where it

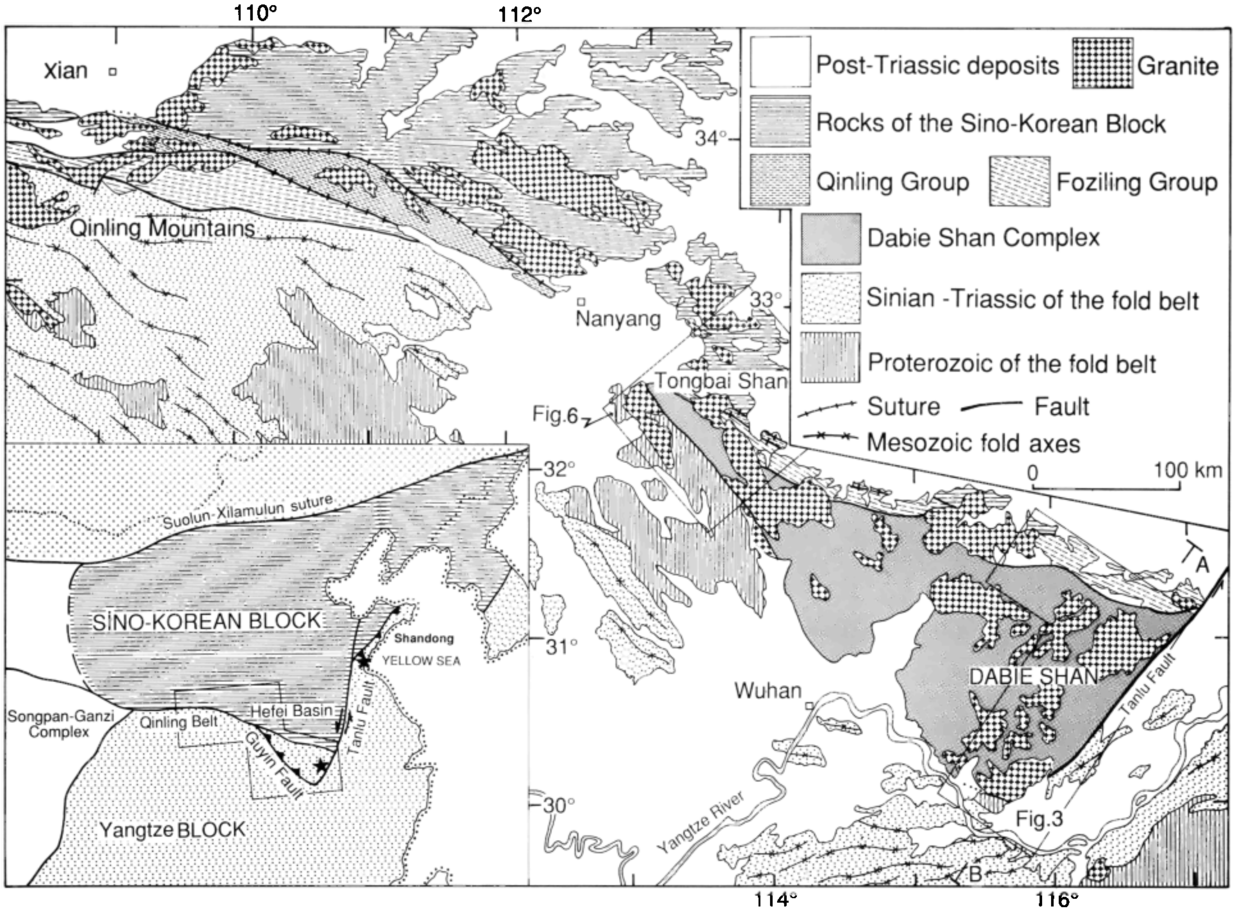

Fig. 1. Simplified tectonic map of the Qinling orogen (modified from Geological Publishing House [1971]).

is dated by the $^{40}Ar/^{39}Ar$ method as Late Triassic [Mattauer et al., 1985].

The Guyin fault (shortened for the Guangji-Yingshan fault), now largely covered by the post-Cretaceous sediments, forms the 380-km-long tectonic boundary between the foreland fold-thrust belt and the Dabie Shan Complex (Figure 1). Gravity and magnetic data indicate that the Guyin fault is a major thrust that extends 60 km north of the exposed fault line at a depth of 10 km [Liu and Hao, 1989]. The present-day contact between the Proterozoic felsic metavolcanic rocks of the foreland fold-thrust belt and the high-grade metamorphic and granitic rocks of the Dabie Shan Complex to the south of Dabie Shan is a post-Cretaceous, south dipping normal fault, as shown by the very narrow outcrop of the deformed Cretaceous sediments along this fault zone (Figure 3).

Dabie Shan Complex: Subducted Basement Slices of the Yangtze Block

Dabie Shan is a large composite crystalline complex dominated by felsic gneiss and with lesser amounts of amphibolite, marble, and eclogite and lenses of ultramafic rock all intruded by a large number of Mesozoic granitic bodies (Figures 1 and 3). The Dabie Shan Complex consists of at least three major tectonic slices with different metamorphic and structural features; these slices are from base upward the northern zone, the eclogite zone, and the Susong Group.

Northern zone. The northern zone is made up of gneiss, augen-gneiss and migmatite and minor amphibolite, calc-silicate, mafic granulite, and rare ultramafic blocks. These rocks are intruded by plutons that range from orthogneiss to undeformed granite. The common gneiss in the northern zone is a banded, strongly foliated, medium-grained, frequently porphyroblastic, felsic variety with the mineral assemblage of quartz + plagioclase + K-feldspar + hornblende + biotite + opaque ± chlorite.

Migmatitic gneisses occur in several localities including the Taer He reservoir (Figure 3). The gneisses show typical partial melt structures with mafic restites of hornblende + diopside + biotite + plagioclase + sphene forming blocks in the leucosome and with pegmatitic veins cutting the unmelted gneiss. The zones of partial melting also form ductile shear zones suggesting syndeformational partial melting.

Calc-silicate and marble make up less than 1% of the northern zone and are mainly observed northwest of Qingtian and west of Tongcheng (Figure 3). The calc-silicate and marble form few-meters-thick boudined bands in the felsic gneiss; northwest of Qingtian they are spatially closely associated with migmatites. Apart from these rock types, there are rare mafic granulites with garnet + clinopyroxene + plagioclase + hornblende that occur as small (0.7 m) ellipsoidal boudins in mylonitized felsic gneiss.

Ultramafic rocks form rare, exotic lithologies in the northern zone. The largest is the Raobazhai ultramafic body

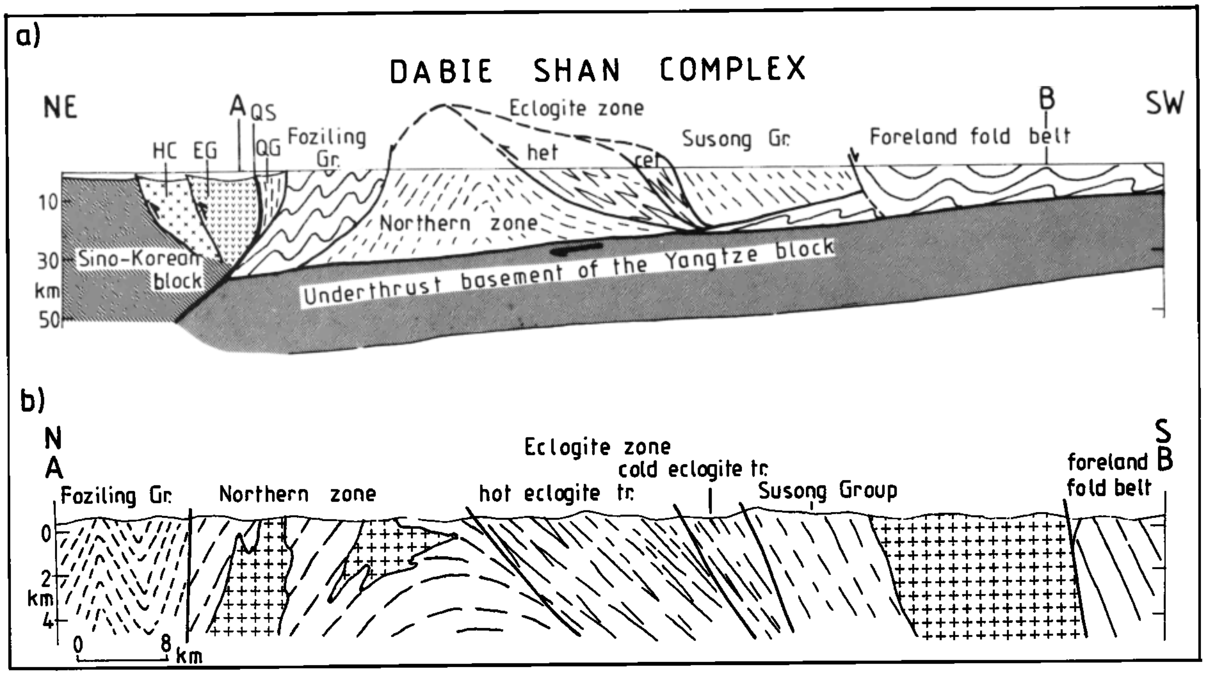

Fig. 2. (a) Speculative cross section illustrating the large-scale structure in the eastern part of the Qinling orogen. The line of section is shown in Figure 1. The granitic intrusions are omitted for clarity. EG, Erlangping Group; HC, Huanggang Complex; QG, Qinling Group; QS, Qinling suture; het, hot-eclogite terrane; cet, cold-eclogite terrane. (b) Cross section through the Dabie Shan. The line of section is shown in Figure 3. Notice the difference in scale from that of Figure 2. The topography is schematic.

that forms a 800-m-thick slab dipping to the north and sandwiched between the felsic gneiss (Figure 3). The Raobazhai ultramafic body consists of lherzolite, dunite, amphibole-dunite, and harzburgite that show a well-annealed metamorphic texture. Garnet-pyroxenite occurs as a few tens of meters thick slice along the southern contact of the ultramafic body. A Sm-Nd isochron from this rock gives an early Triassic age (243.9 ± 5.6 Ma [Li et al., 1989]). Smaller ultramafic bodies surrounded by desilicified corundum-bearing gneiss occur south of Foziling.

The banding in the gneisses in the northern zone generally dips to the north and northeast at moderate angles (30-60°). Ductile shear zones, subparallel to banding, are generally located in the migmatitic gneisses, strike NW-SE, and show a displacement with the north side down.

The northern zone is characterized by amphibolite facies metamorphism and partial melting. However, the presence of rare mafic granulites suggests that the northern zone may have undergone an initial granulite facies metamorphism that was strongly overprinted by the amphibolite facies and associated partial melting.

The eclogite zone overlies the northern zone along a south dipping band of strongly foliated, flattened leucocratic orthogneiss with slices of virtually undeformed coarse-grained granite. We found no clear shear sense direction in these orthogneisses; however, the sharp but structurally conformable contact between the two zones is interpreted as a deep-seated thrust (Figure 3).

Eclogite zone. The bulk of the eclogite zone consists of white, pale grey, fine-grained, banded quartzo-feldspathic gneiss. The gneiss is readily distinguished from that of the northern zone by the finer grain size and the general absence of the porphyroblastic texture. The common mineral assemblage in the gneiss is quartz + plagioclase + phengite + epidote + garnet ± microcline ± biotite ± opaque ± sphene. On the whole the gneisses now lack high-pressure minerals, except high-Si phengites in the garnet cores [Okay, 1993] and some rare jadeite-gneiss bands with quartz + jadeite + garnet paragenesis (Figure 3). The gneisses show color banding on a 5- to 30-cm scale which dips consistently to the south and southeast (Figure 4a). At several localities, intense isoclinal folds with locally isolated fold hinges were observed that have completely transposed the banding (Figure 5). Through such isoclinal folding the eclogite-bearing gneisses show a total structural thickness of over 20 km. A mineral-stretching lineation in the gneisses is defined largely by quartz and shows a consistent southeasterly moderate plunge (Figures 3 and 4a) and indicates top to the southeast shearing [cf. Mattauer et al., 1991]. The fold axes of the isoclinal folds are parallel with this stretching lineation, and both are perpendicular to the strike of the shear zones separating the eclogite zone from the northern zone and the Susong Group (compare with Figure 3). This dominant fabric in the gneiss is locally modified by late gentle folds with southeast trending and south plunging fold axes. The gneisses are frequently cut by thick, irregular quartz or pegmatite veins and generally N-S trending diorite, andesite, and aplite dykes related to the Mesozoic felsic magmatism. In contrast to the northern zone, no evidence of partial melting is found in the gneisses of the eclogite zone.

Variably amphibolitized eclogite bands and boudins generally 0.2 m to several meters thick occur frequently in the gneisses. The largest eclogite body, the Bixiling eclogite, is about 1 km long and 400 m wide (Figure 3). The eclogites form banded, green, medium-grained rocks with garnet +

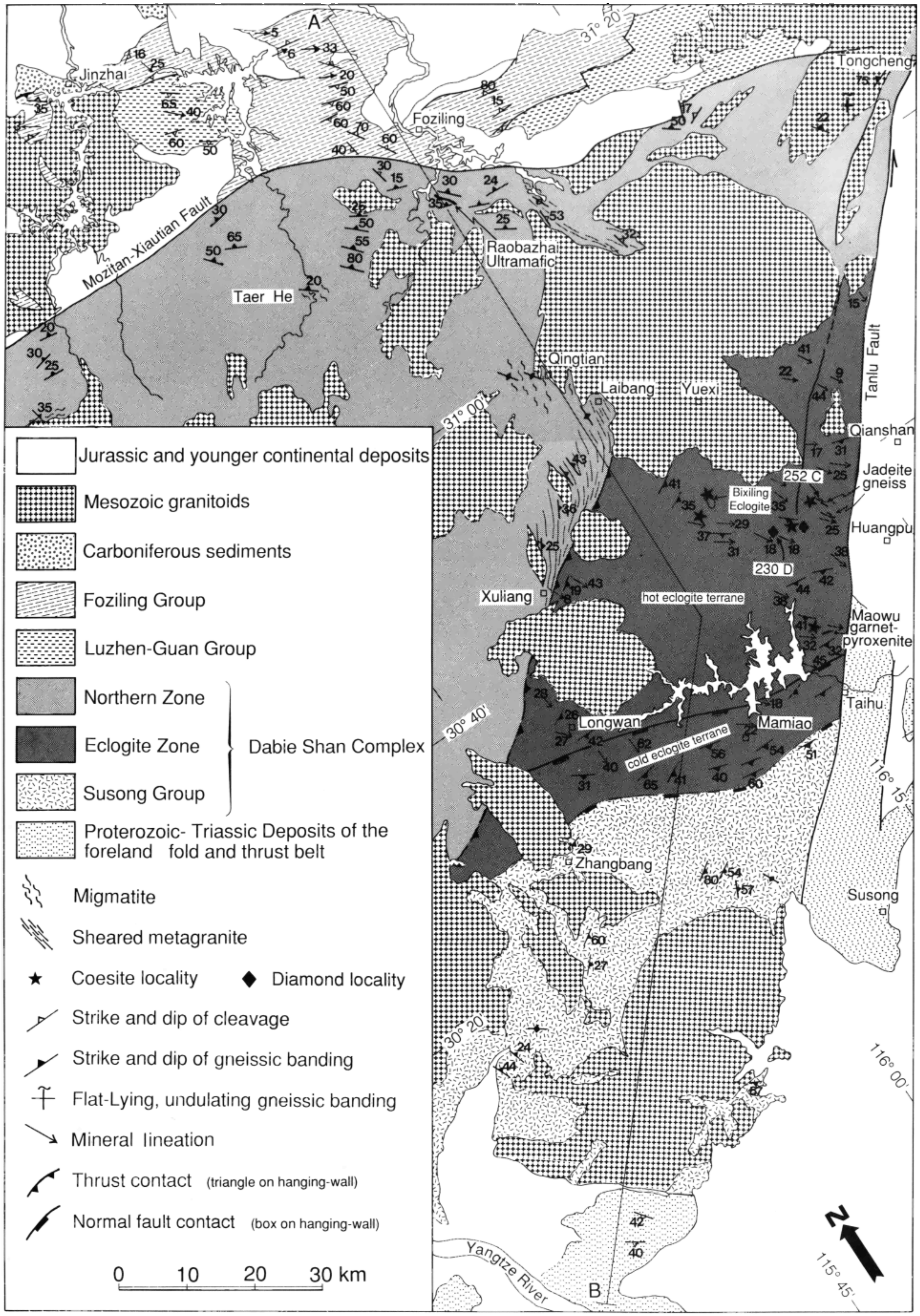

Fig. 3 caption on page 1324.

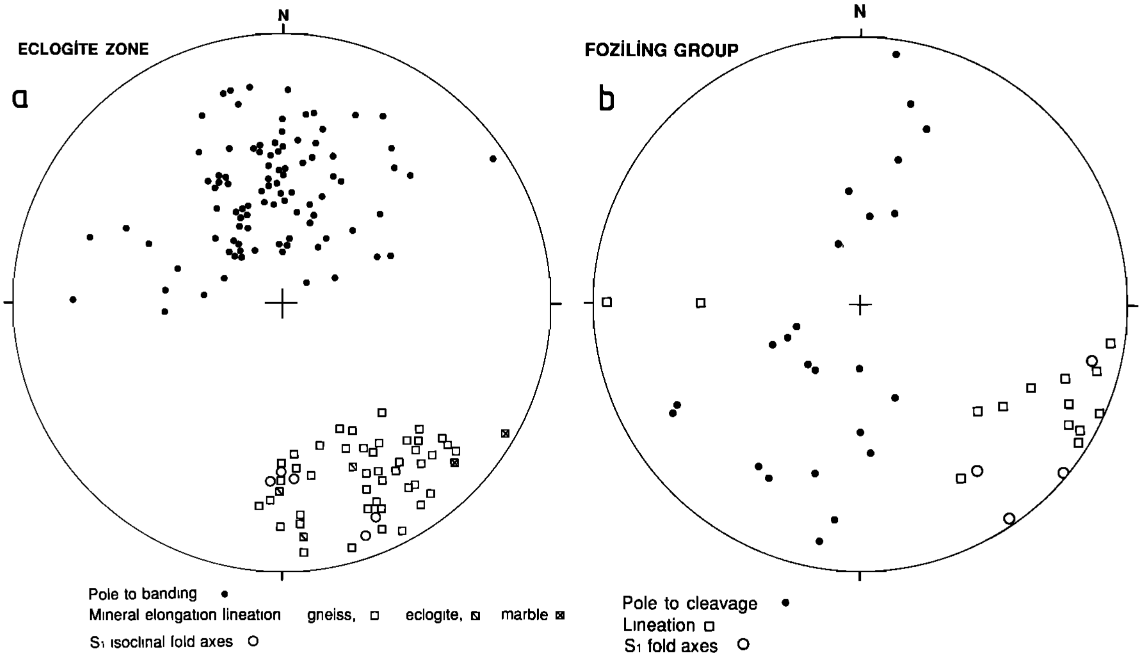

Fig. 4. Equal-area lower hemisphere projection of the structural elements (a) in the eclogite zone of the Dabie Shan Complex and (b) in the Foziling Group.

omphacite ± clinoamphibole ± kyanite + zoisite ± phengite ± coesite/quartz + rutile. Some eclogite bodies show a weak mineral lineation defined by zoisite and/or late hornblende crystals that is subparallel to the more conspicuous lineation in the gneiss (Figure 4a).

Discontinuous, greenish grey, impure marble bands, 0.2 m to several meters thick, frequently contain lensoid eclogite blocks that may originally have been marly interlayers. The impure marble is irregularly banded and locally shows a strong mineral lineation that is subparallel with the lineation in the gneiss (Figure 4a). The eclogites occur as 0.5-cm to 2-m-large, rotated, ellipsoidal, distinct blocks in the carbonates. Coesite and diamond are generally found in these eclogite blocks as inclusions in garnet or pyroxene [Okay et al., 1989; Wang et al., 1989; Xu et al., 1992a]. The Ca-rich mineral compositions of these eclogites, as compared with those from the gneiss [Okay, 1993], indicate that both the carbonate matrix and the blocks have experienced the same ultrahigh-pressure metamorphism.

Ultramafic rocks occur as rare, structurally conformable small lenses in the gneiss. Most lenses are antigorite-serpentinites a few meters thick and a few tens of meters long. One exception is the Maowu ultramafic body that forms a 200-m-long and 40-m-thick lens and consists of a meter-scale intercalation of garnet-pyroxenite, eclogite, and gneiss (Figure 3).

Close intercalation of gneiss and eclogite generally with no mylonitization along their contacts, inclusions of quartz pseudomorphs after coesite in garnet in some gneisses [Wang and Liou, 1991], high-Si phengites preserved in the garnet cores in the gneiss, and jadeite-bearing paragenesis in some gneiss bands [Okay, 1993] indicate that the whole of the eclogite zone has undergone an ultrahigh-pressure metamorphism. The only exotic lithologies in the eclogite zone are the rare ultramafic lenses and associated eclogites.

Geothermobarometry of the eclogites suggests the presence of two eclogite terranes with different PT regimes (Figure 3). The PT conditions in the structurally lower hot-eclogite terrane in the north were about 800±50°C and 38±5 kbar, while the rocks in the cold-eclogite terrane in the south equilibrated at 635±40°C and 23±3 kbar [Okay, 1993]. The cold-eclogite terrane is lithologically and structurally similar to the hot-eclogite terrane except for the absence of coesite and diamond and the marble bands and the presence of sodic amphibole-bearing eclogites. The south dipping tectonic contact between these two terranes, across which there is a decrease in pressure of about 15 kbar, is interpreted as a shear zone with a normal sense of displacement.

The transition from the eclogite zone to the overlying Susong Group was studied along the river valley south of Mamiao and along the road between Zhangbang and Longwan (Figure 3); southward the fine-grained granoblastic gneisses of the eclogite zone are recrystallized with the formation of feldspar augen that coalesces and forms a streaky banding with a concomitant increase in grain size and loss of the lineation, and the eclogites are recrystallized to garnet-amphibolites. This zone is followed by a 700-m-thick orthogneiss that is traceable for over 10 km along strike and is probably emplaced along the tectonic boundary between the Susong Group and the eclogite zone. This boundary between the underlying eclogite facies and overlying amphibolite facies rocks is regarded as a shear zone with a downdip displacement.

Fig. 3. Geological map and cross section of the eastern Dabie Shan (modified from the 1:200 000 scale geological map of the Anhui province). All the structural data are based on our own measurements. The location of the isotopically dated samples are also shown. For orientation, see Figure 1.

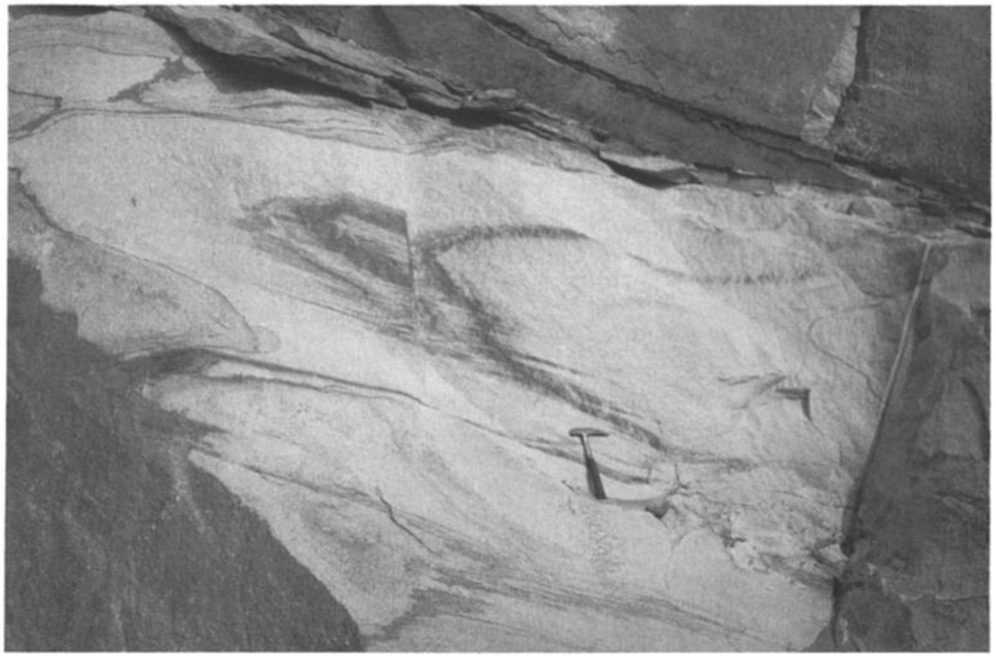

Fig. 5. Early isoclinal folds in the gneisses of the eclogite zone. Notice the conspicuous compositional banding; the dark bands are rich in biotite.

Susong Group. The Susong Group comprises banded gneiss, garnet-micaschist, garnet-amphibolite, marble, kyanite-bearing metaquartzite, phosphorite beds, and rare ultramafic lenses. This sequence differs from that of the eclogite zone by the presence of the phosphorite beds and the absence of eclogites. The mineral assemblage in the amphibolites, garnet + hornblende + plagioclase + epidote + biotite, indicates amphibolite facies conditions. No migmatization is observed in the Susong Group and there is no petrographic evidence that it has undergone the eclogite facies metamorphism. We also did not observe the flattened, strongly elongated, isoclinal folds so characteristic for the eclogite zone; the Susong Group shows disharmonic folds with steeply plunging fold axes.

Origin of the Dabie Shan Complex. The Dabie Shan Complex is in direct tectonic contact in the south with the foreland-fold belt of the Yangtze block with no intervening tectonic zone that can be interpreted as a suture; in contrast, suture zones, marked by subvertical elongate serpentinite slivers, exist north of the Dabie Shan Complex (to be discussed later), indicating that the Dabie Shan Complex was originally part of the Yangtze block. The predominantly gneissic lithology of the Dabie Shan Complex suggests that it represents slices of the Precambrian continental crust of the Yangtze block that were subducted during the Triassic. The ε_{Nd} values of the eclogites also imply reworking of a Precambrian continental crust (discussed later in this paper). A Precambrian continental-crustal origin for the Dabie Shan Complex is also indicated by the late Proterozoic zircon ages from the western part of the Dabie Shan Complex south of Tongbai Shan [Kröner et al., 1993]. Only the Susong Group with the phosphorite deposits may include some supracrustal material.

Şengör et al. [1988], Liu and Hao [1989], and Xu et al. [1992b] claim the existence of several ophiolitic mélange zones in the Dabie Shan Complex characterized by ultramafic blocks in a mylonitized gneiss matrix. These mélange zones are depicted as forming klippen on the gneisses of the eclogite and northern zones [cf. Xu et al., 1992b, Figure 1]. However, in the field there is no evidence for any such distinct mélange zones. The ultramafic rocks occur throughout the Dabie Shan Complex, including the Susong Group, but form a very minor (<1%) part of it and are regarded as upper mantle rather than ophiolite fragments. The regular homoclinal structure of the eclogite zone (compare with Figures 3 and 4a) precludes the presence of several kilometer wide, flat-lying discordant klippen, as depicted by Liu and Hao [1989] and Xu et al. [1992b].

Foziling and Luzhen-Guan Groups: The Passive Continental Margin of the Yangtze Block

A WNW-ESE trending, steeply dipping, major sinistral strike-slip fault, the Mozitan-Xiautian fault [Mattauer et al., 1985], separates the Dabie Shan Complex from the metaclastic rocks of the Foziling Group and the associated gneisses (Figures 1 and 3). The Foziling Group can be traced with almost no change in lithology as a 13-km-wide zone from the north of the Dabie Shan westward for over 400 km to Tongbai Shan (Figure 1). Farther west in the Qinling Mountains this zone is correlated with the Devonian trough of Mattauer et al. [1985] and the flysch nappes of Hsü et al. [1987]. The bulk of the Foziling Group, or the Xinyang Group as it is known in Tongbai Shan, is made up of a very thick, monotonous, fine-grained to very fine grained, thin- to medium-bedded, locally laminated sequence of dark green, dark grey siltstones and shales metamorphosed in greenschist facies and with the mineral assemblage of quartz + plagioclase + muscovite + biotite + ilmenite ± opaque. Locally, the metaclastics show preserved cross-bedding indicating that the sequence youngs northward. In the south, near the Mozitan-Xiautian fault and near the base of the metasiltstones, there are thinly bedded, white, clean metaquartzites and grey, laminated, recrystallized limestones. The Foziling Group shows a well-developed, NW-SE trending, bedding-parallel foliation and a distinct southeast plunging, subhorizontal, mineral-stretching lineation that is especially strongly developed in the north (Figure 4b). The subhorizontal lineation is cut by Jurassic andesitic dykes, suggesting pre-Jurassic sinistral strike-slip motion. The metaclastics show tight to isoclinal, upright folds with fold axes subparallel to the lineation (Figure 4b). No evidence for thrust imbrication was found within this sequence, although thrust imbrication might well be present. This well-developed early fabric is locally slightly overprinted by a steeply dipping, northwest striking crenulation cleavage and late northward vergent kink folds.

The Foziling Group is cut by Mesozoic andesite and lamprophyre dykes and microdiorite intrusions and is unconformably overlain by the Jurassic volcanoclastic rocks and red sandstones. In the northwest near Jinzhai the Foziling Group lies with a subhorizontal thrust contact on small exposures of medium- to thick-bedded, dark grey, Carboniferous sandstone, black siltstone, and shale of the Sino-Korean block [cf. Xu et al., 1992b, Figure 3]. The Carboniferous clastics are moderately deformed into northwest trending disharmonic folds.

Molassic foredeep, accretionary wedge, and forearc settings are proposed for the Foziling Group by Mattauer et al. [1985], Hsü et al. [1987], and Xu et al. [1992b], respectively. In contrast, we regard the Foziling Group as a thick clastic wedge deposited at the northern passive continental margin of the Yangtze plate similar to the Lamayuru Unit in the Himalaya [e.g., Frank et al., 1987]. Our proposal is based on the following characteristics of the Foziling Group. (1) The Foziling Group consists dominantly of typical metapelitic rocks with biotite and muscovite that make up at least 20 mode % of the rock. Such K-bearing pelites are unlikely to have been derived from a magmatic-volcanic arc. (2) The Foziling Group has a very monotonous lithology that can be traced for over 400 km along strike. Absent are conglomerates or grain flows that would be expected in a molassic foredeep; slices of serpentinite, radiolarian chert, or metabasic rock that would be characteristic in an accretionary wedge; and metatuffs and agglomerates that would be typical for an forearc setting. (3) At the stratigraphic base of the Foziling Group there are clean metaquartzites and limestones characteristic for prograding passive continental margin sequences. The location of the Foziling Group to the south of the suture (discussed later in this paper) suggests that it was part of the Yangtze plate and not that of the Sino-Korean plate as suggested by Şengör et al. [1988]. Because of the general absence of fossils, the age of the Foziling Group is controversial, with estimates ranging from Devonian [Mattauer et al., 1985; Xu et al., 1992b] to Triassic [Hsü et al., 1987], the total range of which may indeed be represented by the Foziling Group.

The Foziling Group is in steep fault contact with a sequence of medium-grained, banded, orthopyroxene-bearing felsic gneiss and with augen-gneiss that has occasional discontinuous bands of mafic gneiss. This gneiss complex, the Luzhen-Guan Group, is thought to represent part of the crystalline basement of the Foziling Group that unlike the Dabie Shan Complex, has escaped continental subduction [Şengör et al., 1988].

Qinling Group: An Island Arc Basement Bounded by Sutures?

In the Dabie Shan the northward continuation of the Qinling orogen is hidden under the Jurassic and younger deposits of the Hefei Basin but crops out 250 km westward in the Tongbai Shan (Figure 1). Between these two areas the metaclastics of the Foziling Group indicate the structural continuity of the units. In the Tongbai Shan the Foziling Group is in steeply dipping fault contact in the north through a thin zone of metabasic rocks, with a granulite facies metamorphic complex, the Qinling Group, consisting of close and repeated intercalation of subvertical felsic and mafic granulite, gneiss, amphibolite, marble with siliceous nodules and several kilometers long and a few hundred meters thick ultramafic slivers (Figure 6). The whole sequence has undergone a granulite facies metamorphism later overprinted by amphibolite facies. Our interpretation of this sequence differs markedly from that of Kröner et al. [1993], who regard the granulites as enclaves in orthogneiss and the marbles as thrust sheets, although the marbles are locally intercalated on meter scale with gneisses and granulites. Geothermobarometry indicates temperatures of 820°C and pressures of 10 kbar for the granulites. Zircons from the granulites and orthogneiss give protolith crystallization ages of around 470 Ma and 435 Ma, respectively [Kröner et al., 1993]. On the basis of the assumption that the orthogneiss has intruded the granulites, Kröner et al. [1993] suggest an Ordovician age for the metamorphism. However, in our interpretation the orthogneisses represent retrograded granulites, and thus the zircon ages give an Early Silurian maximum age for the granulite facies metamorphism.

In the Tongbai Shan the Qinling Group makes up a 5-km-wide eastward tapering zone. In the Qinling region this zone is much wider and includes large metaophiolite slabs and corresponds to zone 3 of Mattauer et al. [1985] and the Qinling metamorphic complex of Hsü et al. [1987]. We regard this zone as a composite tectonic unit made up of segments of island arc basement represented by the orthogneiss [cf. Kröner et al., 1993], and of slivers of ophiolitic mélange represented by the ultramafic rocks and cherty limestone [cf. Hsü et al., 1987].

Erlangping Group and the Huanggang Complex: Magmatic Forearc Deposits and the Magmatic Arc

North of the Qinling belt and separated from it by a steeply dipping fault there is a 20-km-wide zone of volcanic and pyroclastic rocks with minor sediments all metamorphosed in greenschist and lower amphibolite facies (Figure 6). Mafic volcanic rocks comprising pillow lava-breccia, pyroclastic rock, and tuff make up the bulk of this Erlangping Group, which also includes rare, felsic to intermediate volcanic rocks. The volcanic rocks are intercalated with thinly bedded/laminated, dark siltstone, graywacke, shale, and rare, black to green chert. The rocks immediately north of the Qinling Group are metamorphosed in low-greenschist facies; however, they retain most of the primary features. The metamorphism increases northward and reaches amphibolite facies in the center of the zone before decreasing again farther north.

The Erlangping Group with its abundant volcanic rocks and its location north of the suture zone is regarded as the intra-arc to forearc deposits in the south facing active margin of the Sino-Korean plate. Kröner et al. [1993] regard the Erlangping Group as an ophiolite, although it does not show any of the ophiolite pseudostratigraphy. The age of the Erlangping Group is generally regarded as early Paleozoic, largely Ordovician, based on macrofossils from the limestones [e.g., Li et al., 1990] and radiolaria from the cherts [Zhang and Tang, 1983].

North of the Erlangping Group and separated from it by a

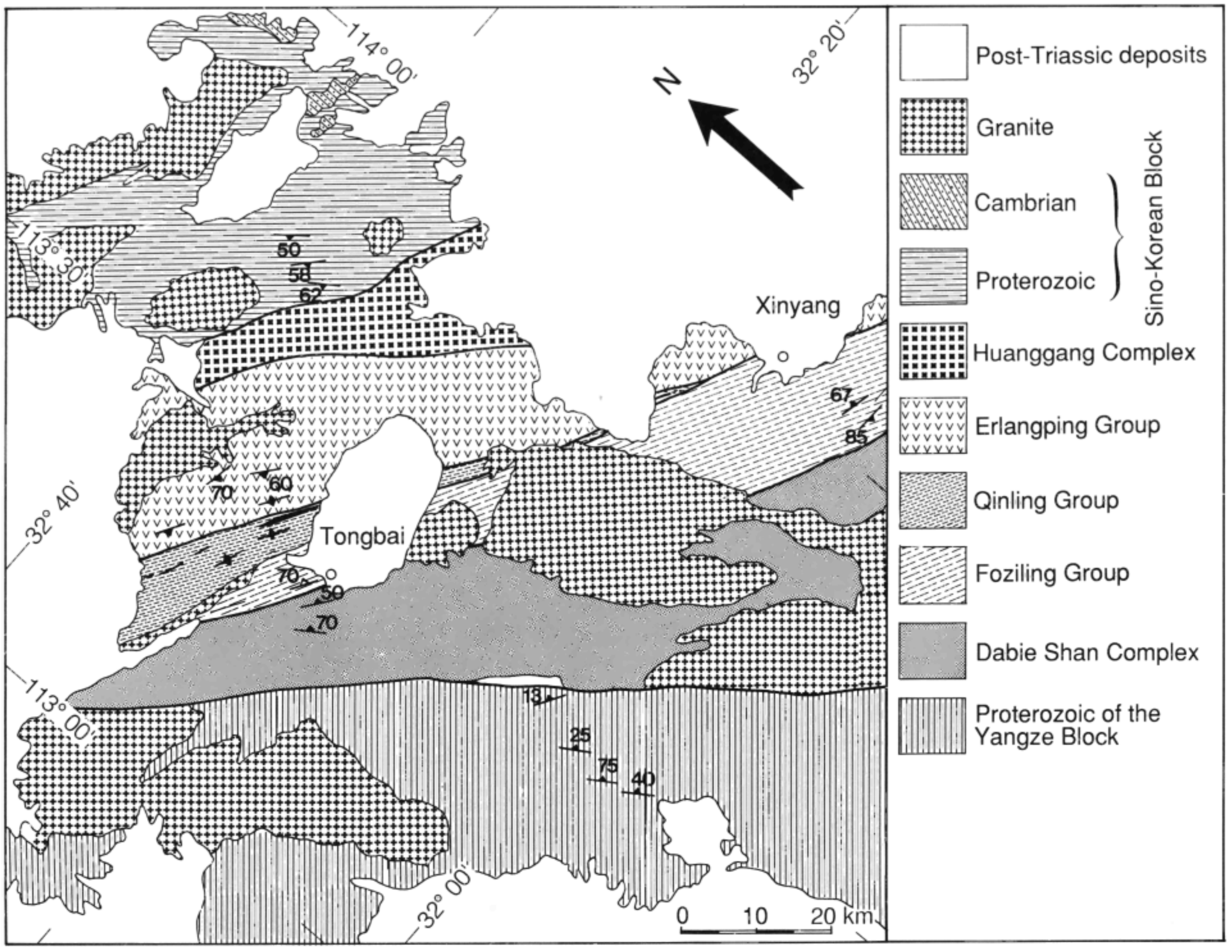

Fig. 6. Geological map of the Tongbai Shan (modified after the 1:200 000 scale geological maps of the Henan province).

steeply dipping fault is the 10-km-wide plutonic Huanggang Complex consisting of diorite, gabbro, quartz-diorite, granodiorite, and pyroxenite (Figure 6). The plutonic rocks are relatively little deformed and show a very low grade metamorphism. Kröner et al. [1993] quote uncertain Devonian K-Ar ages (375-400 Ma) from the Huanggang Complex. The Huanggang Complex is regarded as the magmatic arc at the leading edge of the Sino-Korean block. To the north of the Huanggang Complex there is a thick sequence of Proterozoic micaschist, marble, quartzite, and amphibolite with clear Sino-Korean affinities; these are overlain by the Cambrian sediments of the Sino-Korean block (Figure 6).

GEOCHRONOLOGY AND ORIGIN OF THE DABIE SHAN COMPLEX

Analytical Method

We have isotopically dated two eclogite samples from the hot-eclogite terrane using Sm-Nd, Rb-Sr, and Ar-Ar methods (Table 1 and Figures 7 and 8). Analyses using Rb-Sr and Sm-Nd were carried out at the Department of Geochemistry, University of Tübingen. Mineral separation was performed by heavy liquids, magnetic separation, and handpicking. For Rb-Sr age dating, sample splits of about 50-100 mg were dissolved in Teflon beakers (perfluoralkoxy) with HF and $HClO_4$. The total procedure blank for Sr and Rb is less than 0.5 ng. Rb and Sr of the whole rock were determined by XRF using lithium-borate fusion disks and powder tablets, respectively, with an accuracy better than 2%. Regression lines were calculated by the least squares cubic method of York [1969] using the ISOPLOT software of Ludwig [1988]. Age determinations are based on the ^{87}Rb decay constant of 1.42×10^{-11} yr^{-1} as recommended by Steiger and Jaeger [1977]. Isotope analyses were made on a Finnigen MAT 262 mass spectrometer. Analyses of Sr standards National Bureau of Standarts (NBS) 987 and U.S. Geological Survey (USGS) whole rock standard, Columbia River basalt (BCR-1) gave $^{87}Sr/^{86}Sr$ ratios of 0.710236±20 (2 sigma of 35 analyses) and 0.705028±17 (2 sigma, n=11), respectively. Concentrations of Rb and Sr of the BCR-1 standard were determined as 46.8 and 330.7 ppm, respectively. The input error for age calculations are 1% (2 sigma) for the $^{87}Rb/^{86}Sr$ ratios and 0.003% (2 sigma) for the $^{87}Sr/^{86}Sr$ ratios.

Dissolution of the whole rock powders and garnet separates for the Sm-Nd analyses (HF and $HClO_4$) was done in Teflon bombs at 170°C over 1 week. Rb, Sr, and light rare earth elements (LREE) were separated by cation exchange chromatography, and Sm and Nd were separated using the

Table 1. Sm-Nd and Rb-Sr Data for the Dabie Shan Eclogites

Sample	Nd, ppm	Sm, ppm	$^{147}Sm/^{144}Nd^a$	$^{143}Nd/^{144}Nd^b$	Age, Ma
Garnet (230D)	1.73	2.19	0.7647	0.512569±15	
Rock (230D)	31.87	5.43	0.1030	0.511504±15	246 ± 8
Garnet (252C)	1.02	0.23	0.1344	0.512198±15	
Rock (252C)	18.87	4.09	0.1310	0.512192±15	
Sample	**Rb, ppm**	**Sr, ppm**	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	**Age, Ma**
Phengite (230D)	373	20.8	52.75	0.89011	
Rock (230D)	18	347	0.150	0.71062	240 ± 2.4
Phengite (252C)	196	68.3	8.323	0.73294	
Rock (252C)	12	616	0.0563	0.70522	236 ± 3.4

[a] Two sigma error is 0.2%.
[b] Estimated external precision was usually better than 1×10^{-5}.

Teflon-Di-2-ethylyhexyl phosphate (HDEHP) method of Richard et al. [1976]. Total blanks were better than 0.02 ng for Sm and 0.05 ng for Nd. The $^{143}Nd/^{144}Nd$ ratios were normalized to $^{143}Nd/^{144}Nd = 0.72190$. During the study the La Jolla standard was measured as $^{143}Nd/^{144}Nd = 0.511854 \pm 13$ (2 sigma, n=6), and the California Institute of Technology (CIT) Nd standard was determined to be $^{143}Nd/^{144}Nd = 0.511902 \pm 7$ (2 sigma, n=5). All data reported here are adjusted for instrumental bias to a $^{143}Nd/^{144}Nd$ value of 0.511840 for the La Jolla standard. Precision was better than 2×10^{-5}. A single analysis of the USGS standard BCR-1 gave $^{143}Nd/^{144}Nd = 0.512629 \pm 6$ (2 sigma, n=8). The ε_{Nd} values are based on 6.56 ppm of Sm and 28.69 ppm of Nd and $^{147}Sm/^{144}Nd = 0.1383$. Neodymium model ages ($Nd_{TDM}$) are calculated using the depleted mantle model of De Paolo [1988].

The $^{40}Ar/^{39}Ar$ isotopic measurements were carried out at the Department of Mineralogy, University of Lausanne. The production ratios of different isotopes produced in the TRIGA reactor (Denver, Colorado) for the mass range of 36-44 were given by Dalrymple et al. [1981]. The sample was heated in steps in an induction furnace and equilibrated with hot Ti and Zr/Al getters, and gases were analyzed statically with a mass spectrometer. System blanks were measured periodically throughout the analyses, yielding ^{40}Ar values of $4.6\text{-}7.6 \times 10^{-15}$ mol. Using the accepted age of 519.4 Ma for the McClure Mountain hornblende (MMhb-1) [Alexander et al., 1978], gradients in neutron flux (J) were calculated along the length of the sample package in two separate irradiations with intralaboratory precisions in calculated J values of 0.25% and 0.50%.

Sample Description

Sample 230D comes from a small eclogite block in marble from a roadside quarry south of Wumiao [Okay, 1993] (Figure 3); the mineral assemblage and the modal amounts in 230D are garnet (47%)+ sodic augite (41%) + zoisite (5%) + phengite (2%)+ dolomite (4%) + rutile (0.1%) + diamond (traces). Garnet forms up to 1.5 cm large grains that overgrow and enclose the other minerals. The other eclogite sample, 252C, comes from north of Huangpu (Figure 3) and has the mineral assemblage of garnet (47%) + omphacite (29%) + kyanite (1%) + quartz (5%) + epidote (6%) + blue-green amphibole (7%) + phengite (4%) + rutile (1%). It has an equigranular fabric with 0.2-mm large idioblastic garnet crystals associated with omphacite, which is partially replaced by a symplectite of diopside and oligoclase.

Sm-Nd Isotope Systematics

Samarium-Neodymium isotopic analyses of samples 230D and 252C are presented in Table 1. In the case of sample 230D, using the method of York [1969], the Sm-Nd regression of garnet-whole rock corresponds with an age of 246±6 Ma and with an initial ratio of 0.51134±3 equivalent to $\varepsilon_{Nd} = -19.2$. Surprisingly, the ratios of $^{143}Nd/^{144}Nd$ in the whole rock and garnet separate of sample 252C are identical within the error limits, precluding an age calculation.

Interestingly, the garnets in sample 252C are distinctly enriched in LREE; in contrast, those garnets from sample 230D indicate a strong depletion in LREE that is typical for the REE distribution in garnets. The reason for the LREE enrichment in the garnet in 252C is not clear but could be due to heterogeneity with respect to LREE.

Rb-Sr results

Rubidium-Strontium isotopic measurements were obtained from two phengites and two whole rocks (Table 1 and Figure 7). Sample 230D gives a phengite-whole rock age of 240 ± 2.4 Ma (2 sigma) with an initial $^{87}Sr/^{86}Sr$ ratio of 0.7101±10.

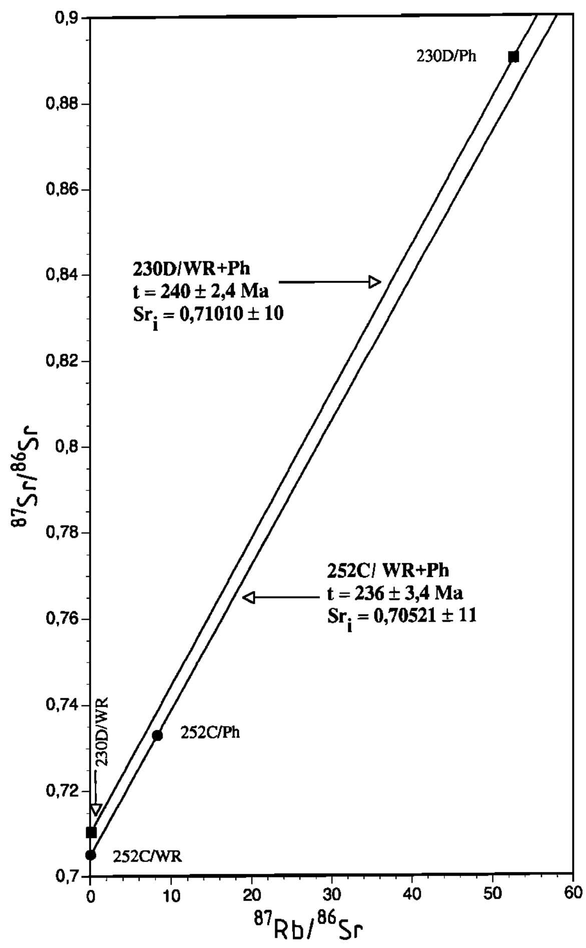

Fig. 7. Rb-Sr whole rock-phengite isochrons for eclogite samples 230D and 252C from the Dabie Shan Complex.

The whole rock and phengite of sample 252C define a regression line, which corresponds with an age of 236 ± 3.4 Ma and with an initial ratio of 0.70521±11. Within the error limits the ages are the same for both samples. The temperature at the peak of the ultrahigh-pressure metamorphism was estimated to be 800°C [Okay, 1993], which is well above the inferred closure temperature for Sr retention in phengite (500±50°C [Purdy and Jaeger, 1976]); therefore the phengite-whole rock age of 236-240 Ma provides a minimum age for the ultrahigh-pressure metamorphism in the Dabie Shan Complex.

$^{40}Ar/^{39}Ar$ Results

The age spectrum of phengite from sample 252C displays a plateau of 244 ± 1.8 Ma defined by 10 successive heating steps that represent more than 80% of the total amount of argon released (Figure 8). Again, this is interpreted as a cooling age below 400°C. Mattauer et al. [1991] report $^{40}Ar/^{39}Ar$ ages from the gneisses and eclogites of the eclogite zone and Susong Group of the Dabie Shan Complex ranging from 600 to 195 Ma. This spread of ages is probably due to the variable Triassic metamorphic overprint on a Proterozoic metamorphic basement. The $^{40}Ar/^{39}Ar$ phengite age from sample 252C is older than the Rb-Sr phengite age from the same sample, in contrast to the commonly accepted sequence of isotopic closure of the two systems. This may be the result of the interaction of several effects such as the presence of excess argon, growth of phengite [Cosca et al., 1991], variability of closure temperature in the muscovite group [Purdy and Jaeger, 1976; Snee et al., 1988], and multistage tectonothermal evolution during the uplift of the ultrahigh-pressure rocks. The reversal of the Ar-Ar and Rb-Sr closure ages of phengite were discussed in the ultrahigh-pressure rocks from the Dora Maira massif in the Western Alps by Monie and Chopin [1991].

Age of the Dabie Shan Complex

The Sm-Nd, Rb-Sr, and Ar-Ar data indicate Triassic ages (236 to 246 Ma) for the ultrahigh-pressure metamorphism.

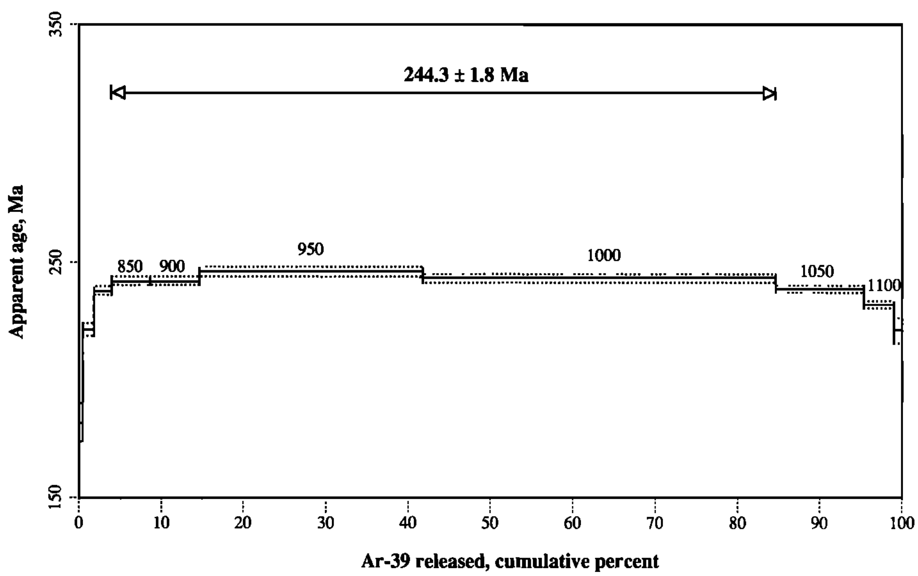

Fig. 8. The $^{40}Ar/^{39}Ar$ age spectra of phengites from eclogite sample 230D from the Dabie Shan Complex.

Similar Triassic Sm-Nd cooling ages of 221 ± 5 Ma were recently obtained from the eclogites of the eclogite zone by Li et al. [1993]. Wang et al. [1992] also report U-Pb zircon ages of 212 ± 2 Ma from the Dabie Shan gneisses. Although there is some spread of ages, all fall in the Triassic and suggest an early Triassic or possibly late Permian age for the ultrahigh-pressure metamorphism. The ε_{Nd} values of the eclogite samples 230D and 252C are -19.2 and -6.4, respectively, and indicate reworking of a 2.11 and 1.55 Ga continental crust.

LATE OROGENIC TO POSTOROGENIC MAGMATISM

Granites and associated rocks cover one half to one third of the investigated area. There are at least two granite generations; an early generation shows a distinct, heterogeneously developed tectonic foliation and metamorphic differentiation. Although the foliation in these metagranites is generally subparallel with that in the gneisses, crosscutting relations were observed in some localities. Furthermore, in several regions, for example, between the Xuliang and Laibang (Figure 3), the tectonically foliated metagranites were observed to pass gradually to little deformed granites, indicating that the main metamorphism and deformation of the Dabie Shan Complex predate the intrusion and deformation of these early granites.

Most of the granitic rocks in the Dabie Shan, however, do not show tectonic foliation and clearly crosscut the banding in the gneisses. The granitic rocks are generally K-feldspar-rich and range in composition from granite (sensu stricto) to syenite and monzonite. There are also rare, small diorite and gabbroic intrusions. The largest granitic body that occurs around Yuexi (Figure 3) is a composite intrusion and consists mainly of a porphyritic granite with up to 2 cm large orthoclase phenocrysts associated with plagioclase, hornblende, biotite and quartz; this large granitic body has intruded an earlier but similarly undeformed aphyric granite and is closely associated with the migmatites along its western margin.

A large number of north to northeast trending dykes and sills cut all the metamorphic rocks. The dykes and sills consist of microsyenite, dacite, andesite, and lamprophyre that are invariably porphyritic and carry quartz, K-feldspar, plagioclase, hornblende, and biotite phenocrysts.

There are very few isotopic data on the age of the granitic rocks which are generally considered to be late Mesozoic in age. Ar/Ar mineral isotopic data from the granite northwest of Yuexi indicate ages of 120-130 Ma [Mattauer et al., 1991]. The K-feldspar-rich granites in the Dabie Shan Complex most probably represent late stage crustal melts produced as a result of crustal thickening analogous to the Himalayan leucogranites [e.g., Le Fort, 1989].

TECTONIC EVOLUTION

A major controversy in the Qinling belt is between those advocating a Devonian continental collision [e.g., Zhang et al., 1984; Mattauer et al., 1985] and those favouring a Triassic collision [e.g., Şengör, 1985; Hsü et al., 1987; Huang and Wu, 1992]. The continuation of the marine sedimentation in the foreland fold-thrust belt up to the Late Triassic, the paleomagnetic data [e.g., Opdyke et al., 1986; Zhao and Coe, 1987; Enkin et al., 1992], and the Triassic isotopic ages from the Dabie Shan Complex argue strongly for a Triassic terminal collision.

The age of the Erlangping Group and that of the zircons in the Qinling Group indicate the existence of an active margin south of the Sino-Korean block as early as Ordovician (Figure 9a). A Devonian tectonometamorphic event is suggested by some isotopic data from north of the Qinling Zone [Mattauer et al., 1985]. This event is probably related to the collision of the Qinling island arc with the Sino-Korean active margin represented by the Erlangping and Huangang groups (Figure 9b). Thereafter the accreted Qinling Zone became the active margin of the Sino-Korean plate, as indicated by the presence of Triassic I-type granitoids along the southern margin of the Qinling Group in the Qinling Mountains [Reischmann et al., 1990].

The isotopic data from the Dabie Shan Complex suggest that the terminal continent-continent collision started in the late Permian and involved the delamination and northward subduction of the Yangtze continental crust under the Sino-Korean plate (Figure 9c). The clastic apron of the passive continental margin, the Foziling Group, was sheared off from its basement, was deformed and metamorphosed in greenschist facies and was accreted, while its basement was subducted more deeply. The deep subduction of the light continental crust was most likely achieved by the slab-pull of the attached oceanic lithosphere [cf. Royden, 1988]. During the subduction of the crystalline basement the decoupling occurred within the lower crust, at the crust-mantle interface, and the various off-scraped crystalline slices were underplated, leading to the formation of a crustal thrust wedge [cf. Mattauer, 1986] represented by the Dabie Shan Complex. Thus there were two major decollement horizons, one at the cover-basement interface and the other at the crust-mantle interface. The northern and eclogite zones in the Dabie Shan Complex represent crystalline slices within the basement duplex. The different PT histories of these crustal slices are probably due to the variable depths of decoupling. The maximum pressures recorded in the Dabie Shan Complex correspond to the base of the lithosphere, indicating that the crustal thrust wedge reached lithospheric thickness.

An estimate of the amount of southward thrusting in Dabie Shan can be obtained from the displacement along the Tanlu fault [cf. Okay and Şengör, 1992]. The Tanlu fault terminates abruptly south of the Yangtze River and does not cut the foreland fold-thrust belt (Figure 1), indicating that the sinistral movement along the Tanlu fault must have been transferred to thrusting of the Dabie Shan Complex over the foreland along the Guyin fault. A similar thrust but with an opposite vergence is envisaged in Shandong so that the Tanlu fault acted during the late Permian-middle Triassic as a tear fault connecting two intracontinental thrusts with opposite vergences. The situation was the continental analogue of the present-day Alpine fault in New Zealand. In our model the length of the Tanlu fault should be similar to the displacement along it. Estimates of offset based on the correlation of tectonic units and faunal and floral provinces across the Tanlu fault indicate a value of 740 km [Xu et al., 1987], which is similar to the 680-km length of the fault between Dabie Shan and Shandong, indicating southward thrusting of about 680 km and not half of this value, as inadvertently stated by Okay and Şengör [1992].

A model for the initiation and evolution of the Tanlu fault is shown in Figure 10. The Tanlu fault probably initiated along a former, similarly facing, oceanic trench-trench type transform fault. The initial contact of the Yangtze margin with the oceanic trench (Figures 10a and 10b) resulted in the change of polarity of the subduction zone which was maintained during the continental collision (Figure 10c). In the foreland fold-thrust belt south of Dabie Shan, rocks as young as middle

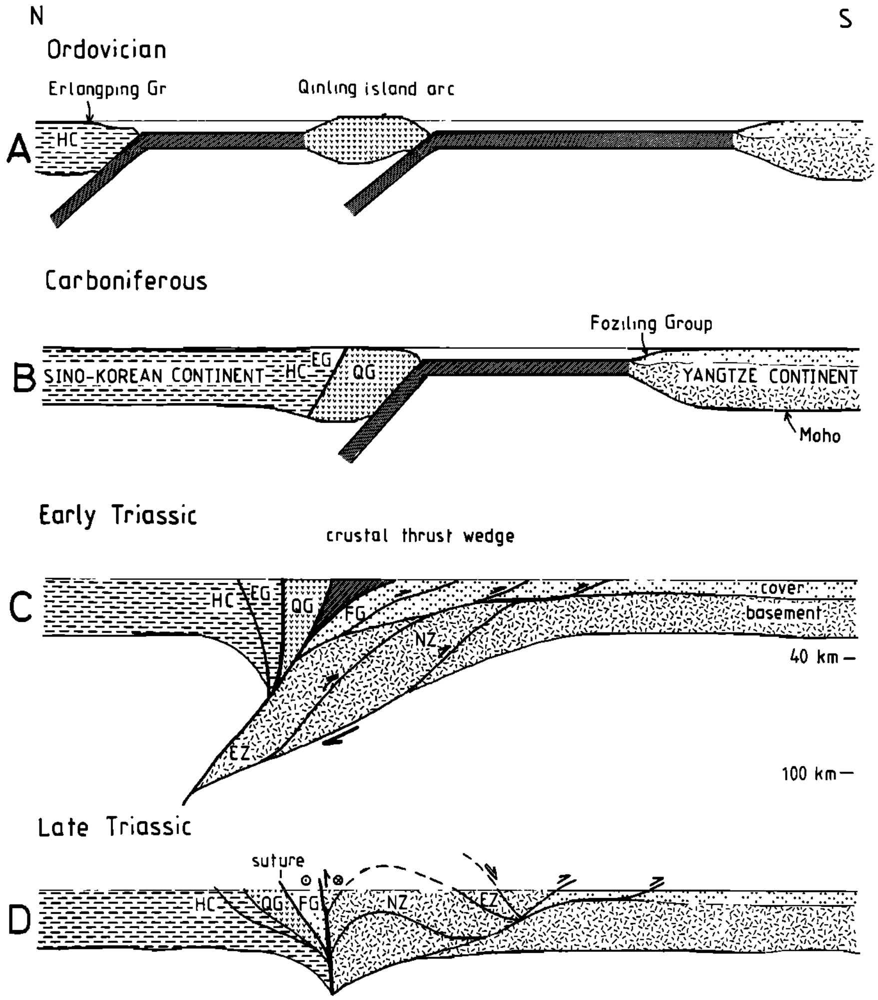

Fig. 9. Cartoons depicting a possible tectonic evolution of the eastern part of the Qinling orogen. (A) Ordovician, Qinling island arc forms an independent plate between the Sino-Korean plate in the north and the Yangtze plate in the south. (B) Carboniferous, Qinling island arc collided with the active Sino-Korean plate margin during the Devonian resulting in deformation and metamorphism of the Erlangping and Qinling groups. Foziling Group is being deposited on the passive margin of the Yangtze continent. (C) Early Triassic, collision of the Yangtze and Sino-Korean continents resulting in the delamination and subduction of the Yangtze continental crust under the Sino-Korean continent. During the continental subduction the decollement occurs at the lower crust-upper crust and crust-mantle interfaces and results in deep subduction and ultrahigh-pressure metamorphism of the lower crust of the Yangtze continent, pieces of which are now represented by the eclogite zone of the Dabie Shan Complex. (D) Late Triassic uplift of the Dabie Shan thrust stack by southward propagation of the thrust planes thereby isostatically uplifting the earlier deeply buried parts of the thrust stack, and exhumation by normal faulting due to increased continental crustal thickness. EG, Erlangping Group; HC, Huanggang Complex; QG, Qinling Group; FG, Foziling Group, EZ; Eclogite zone; NZ, Northern zone. The small solid arrows indicate thrust movement, while the open arrow denotes normal faulting.

Triassic are affected by deformation, indicating that most of the 680 km of thrusting occurred in the late Permian-middle Triassic interval for a period of 20 m.y. This is comparable to the about 800 km of convergence of India and Asia in the Himalaya in 40 m.y. [e.g., Molnar and Tapponnier, 1975; Dewey et al., 1989].

Yin and Nie [1993] suggest that the northern margin of the Yangtze block had a reversed L shape with the eastern segment extending 500 km farther north than the western segment, and the indentation of this northern prong led to the development of the left-slip Tanlu fault. Yin and Nie's model would predict early collision and much stronger intracontinental convergence in Shandong compared to later collision and weaker convergence in Dabie Shan and a gradual shortening of the length of the Tanlu fault with time. These predictions are not borne out by the available geological evidence. Recent Sm-Nd dating of eclogites in Dabie Shan and Shandong has yielded very similar results (221 ± 5 Ma in

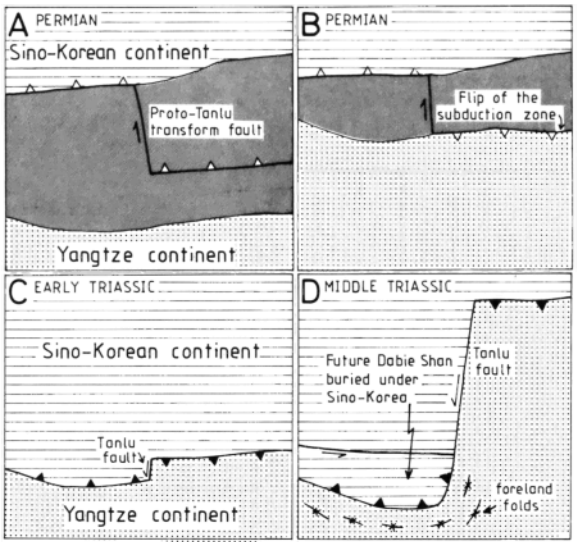

Fig. 10. Schematic maps showing a possible evolution of the Tanlu Fault. The dark gray areas denote oceanic crust, the open triangles show the oceanic subduction zones and the solid triangles indicate major intracontinental thrusts. (A) Permian, the boundary between the Sino-Korean and Yangtze plates is represented by a northward dipping subduction zone offset by the proto-Tanlu transform fault, (B) Permian, the collision of the Yangtze continental crust with the subduction zone results in the flip of the polarity of the subduction zone, thereafter the length of the proto-Tanlu fault is gradually reduced, (C) Early Triassic, collision of the Yangtze and Sino-Korean continents, the opposing polarities of the subduction zones on both sides of the proto-Tanlu transform fault are maintained during the collision, the Tanlu Fault is initiated and increases its length concomitant with thrusting, (D) Middle Triassic, continuation of southward directed thrusting in Dabie Shan and northward directed thrusting in Shandong, initiation of orogen parallel sinistral strike-slip faults.

Dabie Shan and 221 ± 6 Ma in Shandong [Li et al., 1993]), suggesting that the collision was also synchronous in these two regions, now separated by 650 km.

One feature of major continent-continent collision zones is the lateral expulsion of crustal blocks from the zone of collision along major strike-slip faults [e.g., McKenzie, 1970; Tapponnier et al., 1983; Mattauer, 1986]. The pre-Jurassic subhorizontal strike-parallel lineations in the Foziling Group, which are oblique to those in the Dabie Shan Complex, are probably a manifestation of major sinistral expulsion of crustal blocks away from the zone of compression. The northward thrusting of the Foziling Group over the Carboniferous sediments may have occurred along a transpressive segment of this strike-slip system. This major strike-slip fault was north of the Foziling Group, and the Mozitan-Xiaotian fault was generated later as a consequence of southward migration of the continental subduction zone. One consequence of the contemporaneous activity of the sinistral east-west trending faults and northeast trending Tanlu fault was oblique eastward thrusting of the Dabie Shan Complex (Figure 10d), which explains the foreland-style deformation and high-pressure greenschist facies metamorphism in the Yangtze sediments to the east of the Dabie Shan Complex.

Two mechanisms were probably responsible for the exhumation of the ultrahigh-pressure rocks. First, continuing intracontinental convergence would have resulted in the progressive southward younging of the thrust planes thus isostatically exhuming the earlier deeply buried internal parts of the orogen (Figure 9d). Late out-of-sequence thrusting would have displaced the eclogite zone above the northern zone. The situation must have been comparable to the Himalaya where the individual thrusts show a southward younging from Oligocene in the north to Pliocene in the south [cf. Le Fort, 1989]. The 680-km southward thrusting estimated from the offset along the Tanlu fault is more than sufficient to exhume rocks buried 100 km. Second, with continuing intracontinental convergence and underplating, the crustal thickness at the leading edge of the Sino-Korean block must have increased, leading to the gravitational collapse and development of normal faults within the crustal wedge [cf. Burchfiel and Royden, 1985]. Evidence for such normal faults in the Dabie Shan Complex are those between the Susong Group and the hot-eclogite terrane and the faults between the hot- and cold-eclogite terranes; in both contacts there is a downward jump in metamorphic pressures equivalent to several tens of kilometers. The eventual detachment of the lithospheric root must have given impetus to the uplift.

CONCLUSIONS

The Tongbai-Dabie Shan orogen exhibits a deeply eroded section of a Himalayan-type continent-continent collision zone dominated by infracrustal crystalline rocks and characterized by the absence of sedimentary cover nappes and obducted ophiolites. Within this orogen the ultrahigh-pressure metamorphic rocks occur as a coherent tectonic unit in a crustal thrust wedge made up of crustal slices with different metamorphic PT histories. Such wedges form as a result of crustal subduction and accretion processes following continent-continent collision; they have been described from the Alps [e.g., Chopin et al., 1991] and from the Taurides in Turkey [Okay, 1989]. Shear planes separating such slices are difficult to recognize as distinct structural features in the field because of the later strong structural imprint, and their recognition is largely based on the distinctive PT histories of the individual slices.

The exhumation of the ultrahigh-pressure rocks seems to have been achieved by a combination of thrusting and normal faulting in a compressive regime. A total of 680-km southward thrusting can be determined in Dabie Shan based on the offset along the sinistral Tanlu fault.

The continent-continent collision results in the subduction of continental lithosphere. Evidence for this process, apart from the ultrahigh-pressure metamorphism affecting the crustal rocks, is in the deep focus earthquakes in the Pamirs, interpreted as being due to the subduction of the continental crust [Roecker, 1982]. The scarcity of the upper mantle fragments in the crustal thrust wedges indicates that during the continental subduction the decollement occurs largely within the crust or at the crust-mantle boundary. It is likely that during this event, part of the continental crust is deeply subducted and completely lost, and probably only in exceptional circumstances are the diamond- and coesite-bearing crustal rocks exhumed. This has major implications in crustal shortening during the orogenesis, in mantle heterogeneity and magma genesis [cf. Schreyer et al., 1987], and in calculations of the growth of the continental crust.

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REFERENCES

Alexander, E.C., G.M. Michelson, and M.A. Lanphere, MMhb-1: A new $^{40}Ar/^{39}Ar$ dating standard, in Fourth International Conference on Geochemistry, Cosmochemistry and Isotope Geology, edited by R.E. Zartman, *U.S. Geol. Surv. Open File Rep.*, *78-701*, 6-8, 1978.

Burchfiel, B.C., and L.H. Royden, North-south extension within the convergent Himalayan region, *Geology*, *13*, 679-682, 1985.

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.

Chopin, C., C. Henry, and A. Michard, Geology and petrology of the coesite-bearing terrane, Dora Maira massif, Western Alps, *Eur. J. Mineral.*, *3*, 263-291, 1991.

Cosca, M.A., J.F. Sutter, and E.J. Essene, Cooling and inferred uplift/erosion history of the Grenville orogen, Ontario: Constraints from $^{40}Ar/^{39}Ar$ Thermochronology, *Tectonics*, *10*, 959-977, 1991.

Dalrymple, G.B., E.C. Alexander, M.A. Lanphere, and G.P. Kraker, Irridation of samples for $^{40}Ar/^{39}Ar$ dating using the Geological Survey TRIGA reactor, *U.S. Geol. Surv. Prof. Pap.*, *1176*, 55 pp., 1981.

De Paolo, D.J., *Neodymium Isotope Geochemistry: An Introduction*, Springer-Verlag, New York, 1988.

Dewey, J.F., S. Candy, and W.C. Pitman III, Tectonic evolution of India-Eurasia collision zone, *Eclogae Geol. Helv.*, *82*, 717-734, 1989.

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

Frank, W., A. Baud, K. Honegger, and V. Trommsdorff, Comparative studies on profiles across the northwestern Himalayas, in *The Anatomy of Mountain Ranges*, edited by J.-P. Schaer and J. Rodgers, pp. 261-276, Princeton University Press, Princeton, N.J., 1987.

Geological Publishing House, *Geological Atlas of China*, 150 pp., Beijing, 1971.

Hirajima, T., A. Ishiwatari, B. Cong, R. Zhang, S. Banno, and T. Nozaka, Coesite from Mengzhong eclogite at Dhonghai county, northeastern Jiangsu province, China, *Mineral. Mag.*, *54*, 579-583, 1990.

Hsü, K.J., Q.C. Wang, J.L. Li, D. Zhou, and S. Sun, Tectonic evolution of Qinling Mountains, China, *Eclogae Geol. Helv.*, *71*, 611-635, 1987.

Huang, W., and Z.W. Wu, Evolution of the Qinling orogenic belt, *Tectonics*, *11*, 371-380, 1992.

Kröner, A., G.W. Zhang, and Y. Sun, Granulites in the Tongbai area, Qinling Belt, China: Geochemistry, petrology, single zircon geochronology, and implications for the tectonic evolution of eastern Asia, *Tectonics*, *12*, 45-255, 1993.

Le Fort, P., The Himalayan orogenic segment, in *Tectonic Evolution of the Tethyan Region*, edited by A.M.C. Şengör, pp. 289-386, Kluwer Academic, Norwell, Mass., 1989.

Li, C.Y., J.G. Ma, R.B. Chen, and J.M. Zhao, New recognition of the stratigraphic sequence and age of the Erlangping Group in Henan Province, *Reg. Geol. China*, *2*, 181-185, 1990.

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, 1989.

Li, S.G., Y.L. Xiao, D.L. Liou, Y.Z. Chen, N.J. Ge, Z.Q. Zhang, S.S. Sun, B.L. Cong, R.Y. Zhang, S.R. Hart, and S.S. Wang, Collision of the North China and Yangtse blocks and formation of coesite-bearing eclogites: Timing and processes, *Chem. Geol.* in press, 1993.

Liu, X.H., and J. Hao, Structure and tectonic evolution of the Tongbai-Dabie Range in the east Qinling collisional belt, China, *Tectonics*, *8*, 637-646, 1989.

Ludwig, K.R., A plotting and regression program for radiogenic-isotope data for IBM-PC compatible computers, *U.S. Geol. Surv. Open File Rep.*, *88-557*, 1-16, 1988.

Mattauer, M., Intracontinental subduction, crust-mantle decollement and crustal stacking wedge in the Himalayas and other collision belts, *Geol. Soc. Spec. Publ. London.*, *19*, 37-50, 1986.

Mattauer, M., P. Matte, J. Malavieille, P. Tapponnier, H. Maluski, X.Z. Qin, L.Y. Lun, and T.Y. Qin, Tectonics of the Qinling Belt: Build-up and evolution of eastern Asia, *Nature*, *317*, 496-500, 1985.

Mattauer, M., P. Matte, H. Maluski, Z.Q. Xu, Q.W. Zhang, and Y.M. Wang, La limite Chine du Nord-Chine du Sud au Paleozoique et au Trias: Nouvelles donnees structurales et radiometriques dans le massif de Dabie-Shan (chaine des Qinling), *C. R. Acad. Sci., Ser. 2*, *312*, 1227-1233, 1991.

McKenzie, D.P., Plate tectonics of the Mediterranean region, *Nature*, *226*, 239-243, 1970.

Molnar, P., and P. Tapponnier, Cenozoic tectonics of Asia: Consequences and implications of a continental collision, *Science*, *189*, 419-426, 1975.

Monie, 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.

Okay, A.I., An exotic eclogite/blueschist slice in a Barrovian-style metamorphic terrane, Alanya Nappes, southern Turkey, *J. Petrol.*, *30*, 107-132, 1989.

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

Okay, A.I., and A.M.C. Şengör, Evidence for intracontinental thrust-related exhumation of the ultra-high-pressure rocks in China, *Geology*, *20*, 411-414, 1992.

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

Opdyke, N.D., K. Huang, G. Xu, W.Y. Zhang, and D.V. Kent, Paleomagnetic results from the Triassic of the Yangtze Platform, *J. Geophy. Res.*, *91*, 9553-9568, 1986.

Purdy, J.W., and E. Jaeger, K-Ar ages on rock-forming minerals from the Central Alps, *Mem. Inst. Geol. Mineral. Univ. Padova*, *30*, 1-30, 1976.

Reischmann, T., U. Altenberger, A. Kröner, G. Zhang, Y. Sun, and Z. Yu, Mechanism and time of deformation and metamorphism of mylonitic orthogneisses from the Shagou Shear Zone, Qinling Belt, China, *Tectonophysics*, *185*, 91-109, 1990.

Richard, P., N. Shimizu, and C.J. Allegre, $^{143}Nd/^{144}Nd$, a natural tracer: An application to oceanic basalts, *Earth Planet. Sci. Lett.*, *31*, 269-278, 1976.

Roecker, S.W., Velocity structure of the Pamir-Hindu Kush region: Possible evidence of subducted crust, *J. Geophys. Res.*, *87*, 945-959, 1982.

Royden, L., Flexural behavior of the continental lithosphere in Italy: Constraints imposed by gravity and deflection data, *J. Geophys. Res.*, *93*, 7747-7766, 1988.

Schreyer, W., H.J. Massone, and C. Chopin, Continental crust subducted to depths near 100 km: Implications for magma and fluid genesis in collision zones, in Magmatic Processes: Physicochemical Principles, edited by B.O. Mysen, *Spec. Publ. Geochem. Soc.*, *1*, 155-163, 1987.

Şengör, A.M.C., East Asian tectonic collage, *Nature*, *318*, 16-17, 1985.

Şengör, A.M.C., D. Altıner, A. Cin, T. Ustaömer, and K.J. Hsü, Origin and assembly of the Tethyside orogenic collage at the expense of Gondwana Land, *Geol. Soc. Spec. Publ. London*, *37*, 119-181, 1988.

Smith, D.C., Coesite in clinopyroxene in the Caledonites 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 Panasquiera, Portugal, by high-precision $^{40}Ar/^{39}Ar$ age spectrum techniques on muscovite, *Econ. Geol.*, *83*, 335-354, 1988.

Sobolev, N.V., and V.S. Shatsky, Diamond inclusions in garnets from metamorphic rocks: A new environment for diamond formation, *Nature*, *343*, 742-746, 1990.

Steiger, R.H., and E. Jaeger, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology, *Earth Planet. Sci. Lett.*, *36*, 359-362, 1977.

Tapponnier, P., G. Peltzer, Y. Ledain, R. Armijo, and P. Cobbold, Propagating extrusion tectonics in Asia: New insight from simple experiment with plasticine, *Geology*, *10*, 611-616, 1983.

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

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., J.G. Liou, and S. Maruyama, Coesite-bearing eclogites from the Dabie Mountains, central China: Petrogenesis, P-T paths and implications for regional tectonics, *J. Geol.*, *100*, 231-250, 1992.

Xu, J.W., G. Zhu, W.X. Tong, K.R. Cui, and Q, Lui, Formation and evolution of the Tancheng-Lujiang wrench fault system: A major shear system to the northwest of the Pacific Ocean, *Tectonophysics*, *134*, 273-310, 1987.

Xu, S.T., A.I. Okay, J. Shouyuan, A.M.C. Şengör, S. Wen, L. Yican, and J. Laili, Diamond from the Dabie Shan metamorphic rocks and its implications for tectonic setting, *Science*, *256*, 80-82, 1992a.

Xu, S.T., L.L. Jiang, Y.C. Liu, and Y. Zhang, Tectonic framework and evolution of the Dabie Mountains in Anhui, eastern China, *Acta Geol. Sin.*, *5*, 221-238, 1992b.

Yin, A., and S.Y. Nie, An indentation model for the North and South China collision and the development of the Tan-Lu and Honam fault systems, eastern Asia, *Tectonics*, in press, 1993.

York, D., Least-square fitting with a straight line with correlated errors, *Earth Planet. Sci. Lett.*, *5*, 320-324, 1969.

Zhang, S.C., and S.W. Tang, The discovery of early Paleozoic radiolarian chert and plate tectonics in northern Qinling, *Geol. Shanxi*, *1*, 1-19, 1983.

Zhang, Z.M., J.G. Liou, and R.G. Coleman, An outline of the plate tectonics of China, *Geol. Soc. Am. Bull.*, *95*, 295-312, 1984.

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

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