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AN INDENTATION MODEL FOR THE NORTH AND SOUTH CHINA COLLISION AND THE DEVELOPMENT OF THE TAN-LU AND HONAM FAULT SYSTEMS, EASTERN ASIA

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Abstract. Passive continental margins are geometrically irregular as a consequence of either triple-junction evolution or the development of transfer zones in detachment fault systems, whereas active continental margins are smoothly arc-shaped due to subduction of plates on the Earth's spherical surface. We propose that this basic difference in boundary geometry has played an important role in the latest Paleozoic-early Mesozoic collision of North and South China. In particular, we suggest that prior to collision, the active southern margin of the North China Block (NCB) was contiguous across the Qilian Shan, Qinling, Dabie Shan, Shandong peninsula of east central China to the Imjingang area of central Korea. The passive northern margin of the South China Block (SCB), in contrast, had a more irregular shape, such that its northeastern segment in northern Jiangsu and eastern Anhui provinces of China extended some 500 km farther north than its western counterparts in northern Sichuan, southern Shaanxi, and northern Hubei provinces. Collision of the NCB and the SCB began by indentation of the northeastern SCB into the eastern NCB in the late Early Permian and lasted until the Late Triassic-Early Jurassic. The indentation produced the left-slip Tan-Lu fault in northeastern China and the right-slip Honam shear zone in southeastern Korea and caused the northward displacement of the Shandong and the Imjingang metamorphic belts. This model predicts that collision along the Dabie and Qinling metamorphic belt occurred significantly later than along the Shandong belt, which is consistent with radiometric and depositional constraints on the time of collision. The proposed model accounts for the abrupt termination of the Tan-Lu fault at its south end and the drastic decrease in slip along the Tan-Lu fault north of the Shandong metamorphic belt. The model also predicts the distribution and ages of metamorphism along the suture and the observed local but intense Triassic deformation (=Indosinian orogeny) in northeastern China and northern Korea, which was previously an enigmatic feature in this region.

INTRODUCTION

The Eurasian continent consists of a collage of microplates (Figure 1). Major amalgamation of the continental blocks (microplates with continental basement) occurred during the collision of the North China Block (NCB) and the South China Block (SCB) [Sengor, 1987]. Although intense research has been conducted for more than two decades since the concept of plate tectonics was first applied to Chinese geology [Li, 1975], many controversies regarding the nature of the collision remain. It has been debated whether the collision occurred during the middle Paleozoic [Zhang et al., 1984; Mattauer et al., 1985; Liu and Hao, 1989] or the Triassic [Sengor, 1985; Hsu et al., 1987; Lin and Fuller, 1990; Zhao and Coe, 1987; Wang et al., 1992] and how the collision between the SCB and the NCB was accomplished [Okay and Sengor, 1992; Yin and Nie, 1992].

Related to the problem of the North and South China collision is the origin of the Tan-Lu fault [Xu et al., 1987], a prominent left-lateral strike-slip fault along the eastern margin of the Eurasian continent. The Tan-Lu fault offsets the collisional belt between the North and South China blocks by about 500 km (Figure 2), however, displacement decreases sharply north of the Shandong suture zone and diminishes to zero immediately south of Dabie Shan [Xu et al., 1987; Okay and Sengor, 1992] (Figure 2).

Recently, a Triassic right-lateral strike-slip fault, the NE trending Honam shear zone, has been recognized in South Korea in the Ogcheon belt (Figure 2) [Kim and Lee, 1984; Yanai et al., 1985]. Although Cluzel et al. [1991a] suggest that the shear zone juxtaposes the SCB to the north and the NCB to the south, and has a minimum displacement of 200 km, the development of this shear zone has not been discussed in the context of the NCB-SCB collision.

In this paper, we first review the regional geologic setting before and during the collision and the extent and geometry of the North and South China blocks prior to collision. We then show that the collision occurred diachronously, starting from the east in Shandong and northern Korea in late Early Permian and progressing to the west in Qinling in the latest Triassic to earliest Jurassic. Finally, we propose a tectonic model that explains the diachroneity of the collision and the development of the left-slip Tan-Lu fault in eastern China and the right-slip Honam fault in southeastern Korea.

GEOLOGIC SETTING

North and South China Blocks

The locus of the North China-South China collision is well constrained in China along the Qinling, Dabie, and Shandong belts (Figure 2). The eastern extension of the Shandong belt in Korea is not clear, because ophiolites, representing the existence of an ocean(s), have not been found in Korea [Reedman and Um, 1975; Lee, 1987]. However, the presence of ophiolites is a necessary but not a sufficient condition for the existence of a suture, because ophiolites are commonly accreted to continental margins prior to collision. It is also possible that certain segments of an active continental margin have no accretionary ophiolites so that the collisional suture is marked only by deformation and metamorphism. On the basis of lithostratigraphy, the Korean peninsula is divided by the Imjingang and Ogcheon belts into three tectonic blocks (Figure 2). The blocks are, from north to south, the Nangrim-Pyeongnam (NPB), the Gyeonggi (GB), and the Ryeongnam (RB) [Reedman and Um, 1975; Lee, 1987; Cluzel et al., 1990]. Despite the lack of ophiolites in Korea, the Imjingang belt has been correlated with the Shandong suture zone [e.g., Ernst, 1988; Hsu et al., 1990]. Following Cluzel et al. [1990], we use the Honam shear zone as the boundary between the NPB and the GB (Figure 2). Thus, the traditionally defined Ogcheon belt [e.g., Reedman and Um, 1975] consists of rocks belonging to both the NPB and GB.

The Nangrim-Pyeongnam and Ryeongnam Blocks have Cambrian fauna of North China affinity [Kobayashi, 1966]. In contrast, the Gyeonggi Block in central Korea consists of Cambrian strata bearing South China affinity fauna

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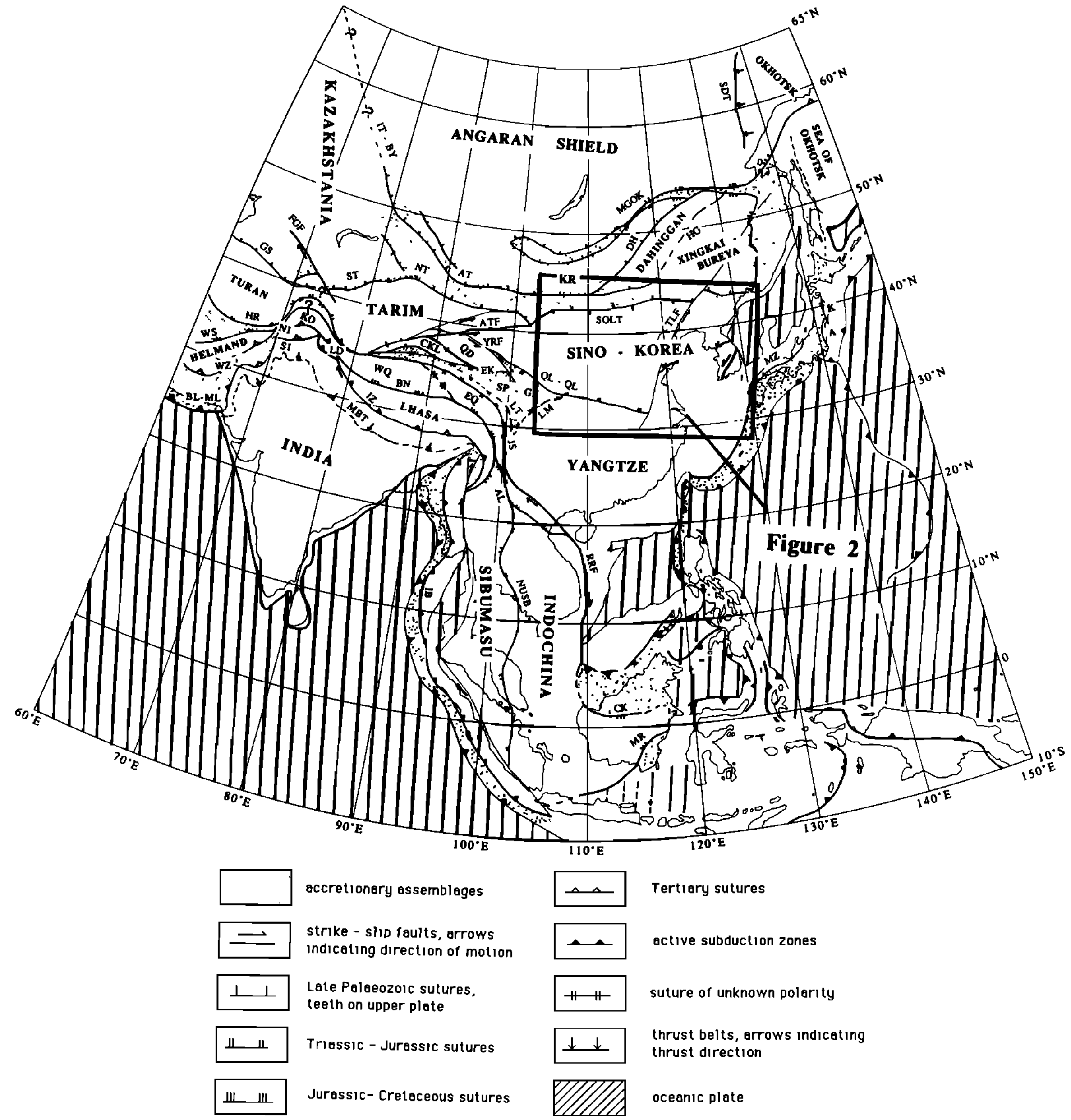

Fig. 1a. Tectonic subdivisions and sutures of eastern Asia and location of Figure 2, after Nie et al. [1991]. Key: Sino-Korea is North China; Yangtze is South China, A is Abukuma; CKL is Central Kunlun; DH is Dahinggan; EQ is eastern Qiangtang, K is Kitikami; KO is Kohistan; QD is Qaidam; WQ is western Qiangtang. Sutures: Al is Ailaoshan; AT is Altai; BL-ML is Bela-Muslimbagh; CK, Crocker; GS is Ghissar; HG is Heganshan; HR is Herat; IB is Indo-Burma; IT-BY is Irtysh-Baayitik; IZ is Indus-Zangpo; JS is Jinshajiang; KR is Kerulan; LD + Ladakh; LM is Longmenshan; LT is Litang; MGOK is Mongolo-Okhotsk; MR is Meratus; MZ is Maizuru; NI is north Indus; NT is north Tianshan; NUSB is Nan-Tardit-Sra-Kaeo-Bentong; QL-QL is Qilian-Qinling; SI is south Indus; SOLT is Solon-Obo-Linxi-Tumen; ST is south Tianshan; WS is Waser; WZ is Wazaristan. Major strike-slip faults: ATF is Altyn Tagh fault; FGF is Fergana fault; RRF is Red River fault; TLF is Tan-Lu fault; YRF is Yellow River fault. Thrust belts: MBT is Main Boundary thrust; SDT is Sette-Daban thrust. Accretionary complex: SP-GZ is Songpan-Ganzi.

[Kobayashi, 1966]. It has long been known that Jurassic basins in the southwestern part of the Nangrim-Pyeongnam Block directly north of the Imjingang belt contain boulders with Silurian fossils [Shimizu et al., 1934]. These fossils cannot have been derived from the Nangrim-Pyeongnam Block, which lacks Silurian or Devonian strata. Thus, the Gyeonggi Block south of the Imjingang belt was the most likely source of the fossils. As Silurian strata are characteristic of the SCB, the preservation of Silurian fossils in the Jurassic basins suggests that the Gyeonggi Block was part of the SCB and

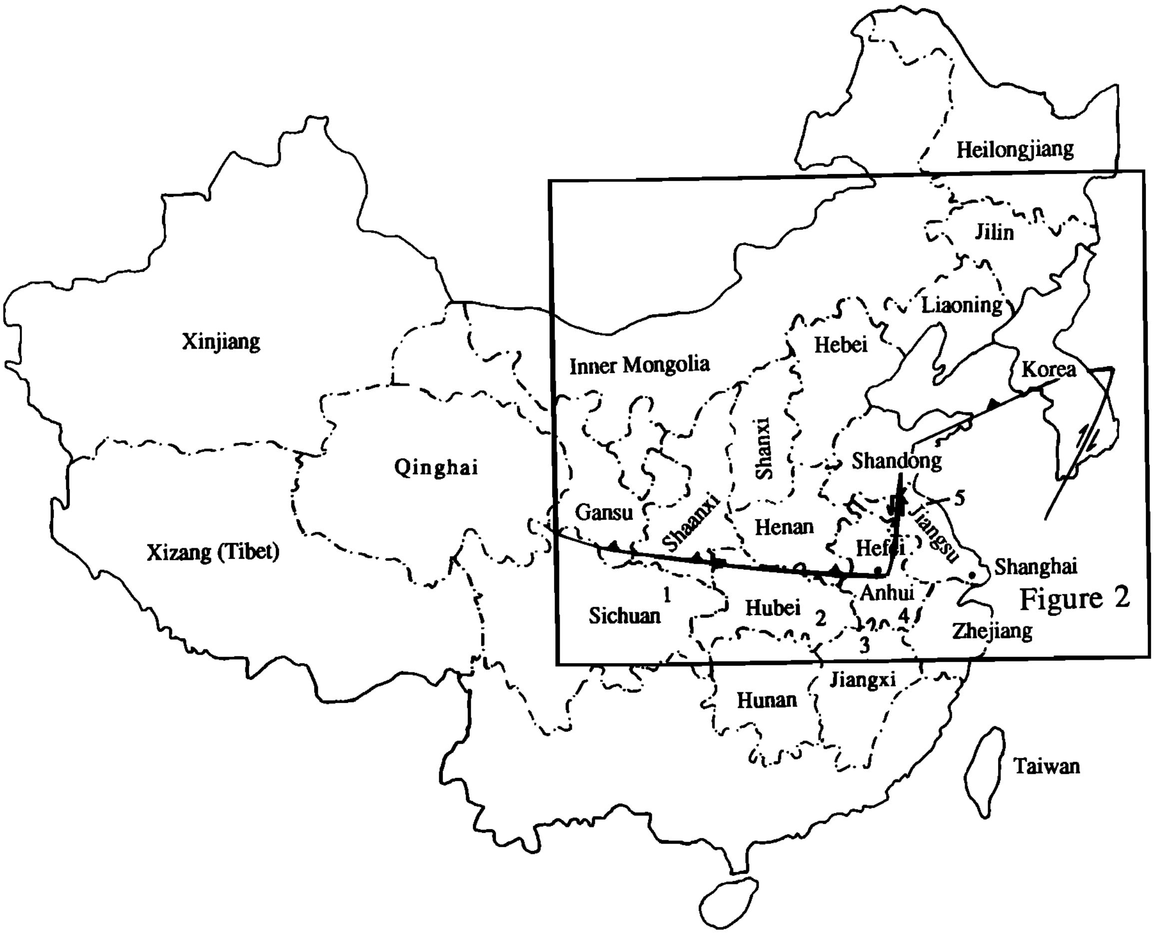

Fig. 1b. Locations of Figure 2 and stratigraphic sections shown in Figure 4.

shed detritus across the Imjingang belt to the Nangrim-Pyeongnam Block during the Jurassic.

The Ogcheon belt underwent three main pre-Cretaceous tectonic events marked by regional unconformities and/or sedimentary hiatus [Cluzel et al., 1990]: (1) Late Silurian-Early Devonian contractional tectonism that closed an early Paleozoic intracontinental rift; (2) development of the Triassic right-lateral Honam shear zone; and (3) intrusion of widespread Jurassic and Cretaceous plutons that cut the Honam shear zone. The middle Paleozoic contractional event was synchronous with the Caledonian/Guangxian orogeny that folded lower Paleozoic sequences in the southeastern SCB [Yang et al., 1986; Rowley et al., 1989]. Thus, the deformational history of the southwestern part of the Ogcheon belt is similar to that of the SCB [Cluzel et al., 1990, 1991a, b; Cluzel, 1991]. On the basis of Paleozoic lithostratigraphy, paleontology, and tectonic history, Cluzel et al. [1990, 1991b] suggest that the Nangrim-Pyeongnam and the Ryeongnam Blocks belong to the NCB, whereas the Gyeonggi Block and the early Paleozoic Ogcheon rift sequence west of the Honam shear zone belong to the SCB. The presence of fossiliferous Silurian rocks and the unconformable contact between the Carboniferous and earlier rocks [Lee et al., 1988] also suggest that part of the Ogcheon belt belongs to the SCB. Such division implies that the Imjingang belt and the Honam shear zone are the boundaries between the North and South China Blocks. We correlate the Imjingang belt with the Shandong belt, because they lie along strike of one another (Figure 2).

Continent-continent collisions may change the shape of the collided continents by intraplate deformation [Tapponnier et al., 1982; England and Houseman, 1988]. On the other hand, knowledge of the original shape of the collided continents can help us understand the nature of the collision. Dewey and Burke [1973, 1974] noticed the fundamental difference in shape between convergent and divergent margins. In general, convergent margins are smooth and arc-shaped due to subduction of inclined plates on a spherical surface [see Turcotte and Schubert, 1982, p. 12], whereas divergent margins are irregular due to triple-junction development during the rifting episode of continental breakup [Dewey and Burke, 1973, 1974] or by the development of transfer structures in extensional fault systems during the formation of passive continental margins [Wernicke and Tilke, 1989; Etheridge et al., 1989]. Collision of the two fundamentally different boundaries can produce complex structural evolution both in space and time [e.g., Sengor, 1976].

The initial geometry of the northern margin of the SCB was probably irregular. As shown by Zhang et al. [1989], the sedimentary facies and isopachs of the upper Precambrian to Lower Triassic rocks trend N-NE east of the Tan-Lu fault in the northeastern SCB (Figure 3). This trend is parallel to the Tan-Lu fault but is discordant to the eastern projection of the Dabie suture zone (Figure 2), a relationship suggesting that the original northern edge of the SCB was not a straight, E-W-

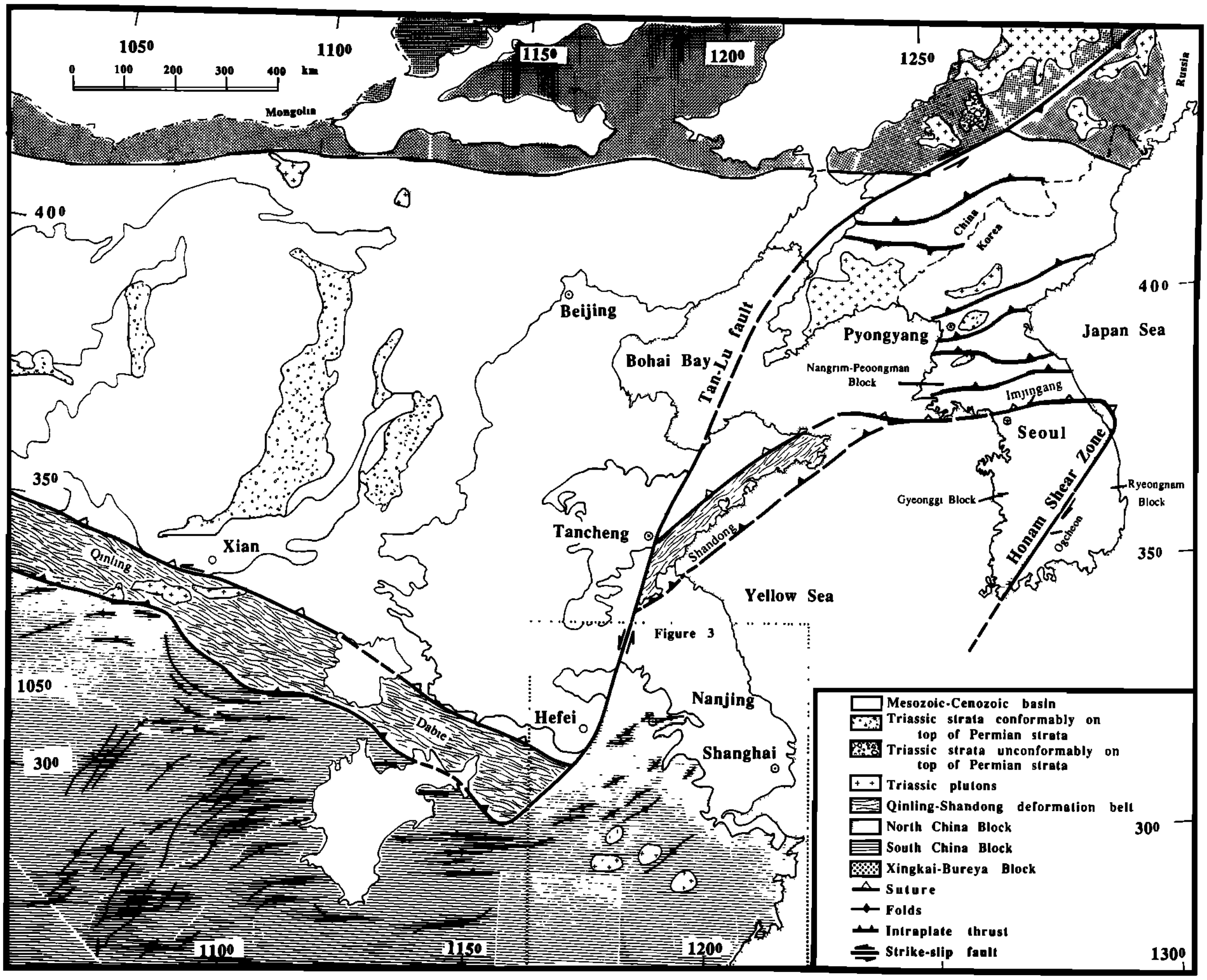

Fig. 2. Simplified geologic map of east-central Asia and location of Figure 3, after Y.Q. Chen [1989].

trending boundary. In contrast, the precollisional facies distribution in the southern margin of the NCB west of the Tan-Lu fault is E-W trending [Sun et al., 1989, pp. 67-68], parallel to the Qinling-Dabie collisional belt. This trend, however, is truncated by the N-NE striking Tan-Lu fault, as suggested by subsurface data for Paleozoic and Lower Mesozoic strata immediately north of the Dabie Shan [Han et al., 1989, p. 128].

Abundant geological and paleomagnetic evidence suggests that in the Paleozoic NCB and SCB were two widely separate tectonic entities that did not join each other until the Permo-Triassic [Nie, 1991]. Although transform faults can cause juxtaposition of different plates, we believe that it was a convergent plate boundary that brought them together. This is not only suggested by the presence of metamorphic sequences in Dabie and northern Jiangsu and eastern Shandong [Xiao and Wang, 1984] and the recently discovered ultrahigh-pressure metamorphic rocks [e.g., Wang et al., 1992], but also by the presence of a series of early Mesozoic foreland basins preserved along the northern margin of the SCB, all indicating contractional tectonics. Because the northern margin of the SCB experienced virtually continuous passive-margin sedimentation during the entire Paleozoic, it suggests that the southern margin of the NCB had to be an active plate boundary in order to consume an ocean between the SCB and the NCB. The record for this active plate boundary is best preserved in the west in the Qilian Shan within Gansu province where andesites and granodiorites exist for every period from the Cambrian to the Triassic [Gansu Bureau of Geology, 1989, pp. 341-447]. Farther to the east in the northern Qinling within Shaanxi province, the evidence for a "Caledonian" and, to a lesser degree, "Hercynian" arc is also unmistakable [Shaanxi Bureau of Geology, 1989, pp. 369-445], but as we move farther east into Henan, Anhui, and Shandong provinces, the record for an Andean margin becomes unclear. For example, the only volcanic rocks described from the Paleozoic to Triassic of Henan are several "acid volcanic" interbeds from the Tangzhuang Formation of Late Triassic age [Henan Bureau of Geology, 1989, p. 231]. However, one interesting feature for the Carboniferous - Triassic sequences is the dominance of clay layers in southern Henan north of the Qinling. We suspect that some of these clay beds might be tuffaceous layers. Still farther east in Anhui and Shandong provinces, there is no record of Paleozoic to Triassic volcanism, though andesitic volcanism is reported as commonplace in the pre-Cambrian metamorphic sequences. It is probable that some of these "pre-Cambrian" volcanic units might actually be Paleozoic-Triassic in age. We raise this possibility because it was not uncommon in the early investigations of Chinese geology that a rock unit assigned to be pre-Cambrian is not so

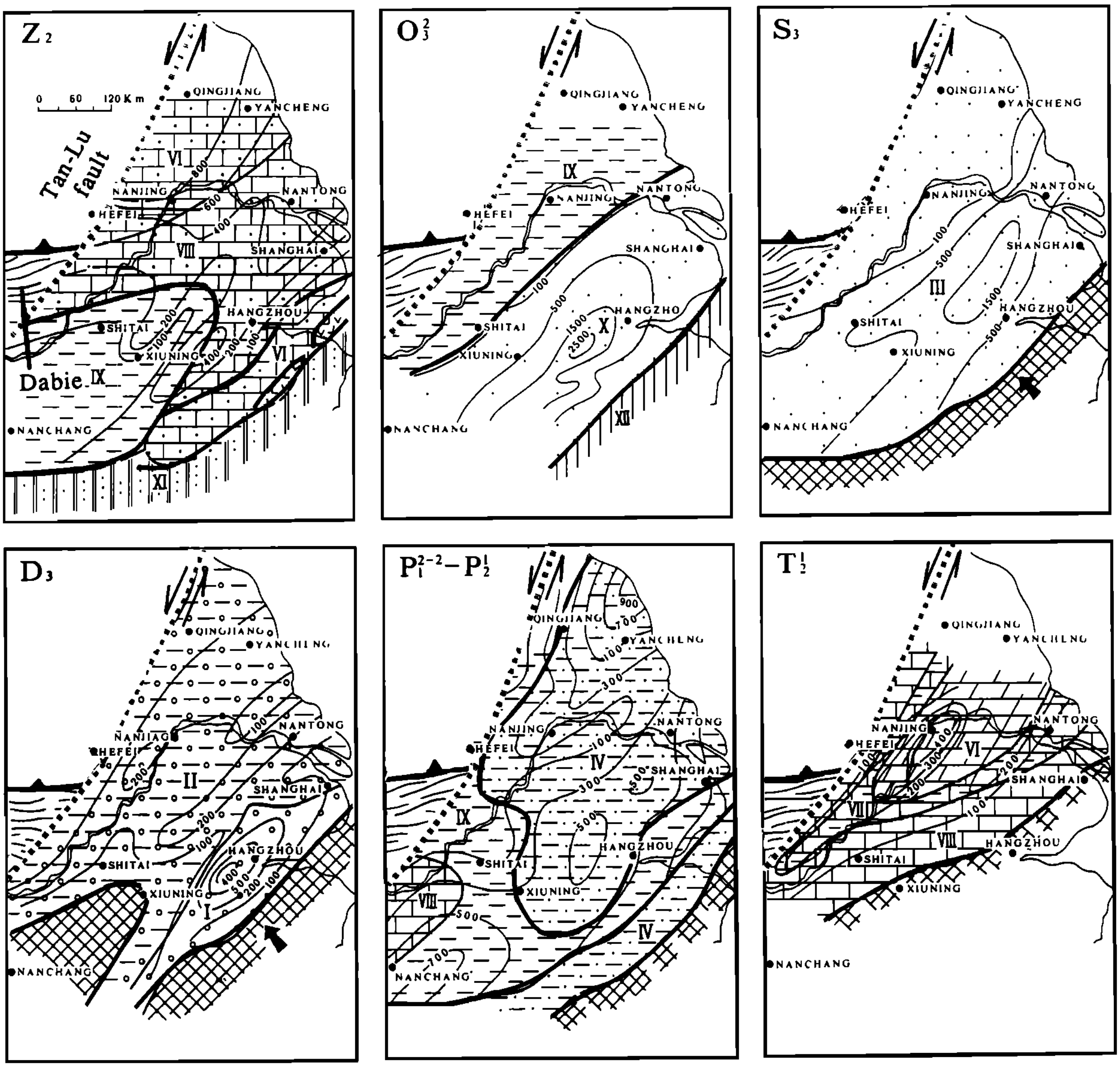

Fig. 3. Isopach and sedimentary facies map of upper Precambrian (= Sinian) to lower Middle Triassic sequences in the northeastern part of South China, after Zhang et al. [1989]. See Figure 2 for location. Z_2 is upper Precambrian; O_3^2 is Upper Ordovician; S_3 is Upper Silurian; D_3 is Upper Devonian; P_1^2 - P_2^1 is upper Lower Permian to lower Upper Permian; T_2^1 is lower Middle Triassic. Sedimentary facies: I is fluvioclastic facies; II is fluvioclastic and swamp facies; III is near-shore clastic facies; IV is tidal flat facies; V is platform evaporite facies; VI is shallow beach carbonate facies interbedded with clastic facies; VIII is broad and restricted platform carbonate facies; IX is marginal siliciclastic and flysch facies; XI is bathyal volcanoclastic and flysch facies; XII is bathyal trough flysch facies. Note that the tidal flat and deltaic facies initiated during the Late Permian that may signal the initial contact between the NCB and the SCB.

much based on either stratigraphic relations or radiometric dating, but rather on its spatial association with high-grade metamorphic rocks. Mesozoic dates have recently been reported on some of these previously assigned pre-Cambrian metamorphic and intrusive rocks from the Dabie Shan [Li et al., 1989; Ames et al., 1993]. Future geochronologic investigation in this area might reveal this problem to be more extensive. The aforementioned relationships provide evidence for an Andean-type plate margin in the western portion of the Qilian-Qinling-Dabie system, but not in the east. This might be the result of differential erosion so that we are seeing a profile of different crustal levels from shallow in the west to deep in the east across the suture zone. This speculation seems to be supported by the increase in metamorphic grade in the same direction as discussed by Wang and Liou [1991].

Timing and Duration of North China-South China Collision

Mattauer et al. [1985] suggest a Devonian collision in the Qinling belt on the basis of $^{40}Ar/^{39}Ar$ metamorphic mineral ages of 314-348 Ma (biotite and muscovite) and the unconformable relationship between the Devonian units and the underlying lower Paleozoic rocks in the central Qinling metamorphic complex. The collision was followed by Mesozoic intracontinental deformation, as indicated by $^{40}Ar/^{39}Ar$ mineral ages of 232 Ma (phengite) to 216 Ma (riebeckite) in the foreland fold belt of the northern SCB. Because the closure temperatures for biotites and muscovites are generally lower than 350°C [McDougall and Harrison, 1988], the Paleozoic metamorphic ages from the central metamorphic complex of the Qinling could have been a result of metamorphism in an Andean-type plate margin, that is, intra-arc thrusting and normal faulting can result in cooling of crustal sections recorded by $^{39}Ar/^{40}Ar$ thermochronology. This situation is typical of the North American Cordillera, which was an Andean-type margin through much of the Mesozoic [e.g., Ernst et al., 1988]. Distinguishing collision-related versus subduction-related metamorphism is possible if the age of the youngest arc magmatism is known with respect to the age of metamorphism, that is, metamorphism prior to the last phase of arc magmatism is likely to be related to subduction, whereas metamorphism younger than the last phase of arc magmatism may be related to collision. The crystallization age of a granite in the Qinling belt was determined by U-Pb zircon analyses as 211 Ma [Reischmann et al., 1990]. This granite is characterized by a low Sr initial ratio and Sm-Nd values with strong mantle signatures and thus is interpreted to be related to subduction [Reischmann et al., 1990]. This age indicates that the collision in the Qinling belt did not begin before the Late Triassic.

Li et al. [1989] obtained a Sm-Nd isotopic date from an eclogite (243 ± 5.6 Ma) in the northeastern Dabie Shan. They interpret this date to represent the time of ultramafic intrusion prior to ultrahigh-pressure metamorphism that led to formation of the eclogites and was related to the continental collision. Using the same method, Li et al. also dated a diorite (230.6 ± 30 Ma) in the northeastern Dabie Shan. On the basis of low Nd initial isotopic ratios, Li et al. [1989, pp. 1397-1398] suggest that the diorite was formed by mixing between pyroxenitic magma and the wall rocks of the continental crust and may have occurred in an island-arc setting. These dates suggest that the collision did not start in the Dabie region prior to about 230 Ma. U-Pb dating of zircon from ultrahigh-pressure eclogites in the Dabie Shan yields a metamorphic age of 209 ± 2 Ma [Ames et al., 1993]. This date provides the youngest age for the initial collision between the SCB and the NCB.

Isotopic dates on the age of collision in Shandong are few. Application of $^{40}Ar/^{39}Ar$ multidomain analysis of K-feldspars [Lovera et al., 1989, 1991] from the ophiolitic melange reveals three intervals of cooling at 105-125 Ma, 172-196 Ma, and 260 Ma [Chen et al., 1992]. Chen et al. attributed the earliest cooling event of 260 Ma to the North and South China collision, because this sample was collected directly from the suture between the North and South China Blocks. The above isotopic dates suggest that collision started first in Shandong during the late Early Permian (~260 Ma) and propagated westward to the Dabie region in the Middle to the Late Triassic (~240-208 Ma) and to the Qinling in the Late Triassic to the Early Jurassic (i.e., after ~210 Ma).

Diachroneity of the collision is illustrated also by sedimentological records. Figure 4 includes five representative Permian to Middle Jurassic stratigraphic columns from the northern margin of the SCB, in an east-west transect. Ages of units in these sections are well constrained, because they contain rich fossil records. Sections 1, 2, and 3 are from northern Sichuan, southwestern Hubei, and northwestern Jiangxi in the west, whereas sections 4 and 5 are from southeastern Anhui (30.5°N/117.0°E) southeast of Dabie Shan and northern Jiangsu (34°N/119.8°E) in the east (Figure 2). All sections were taken from actual measured outcrops except section 5 which is based exclusively on drill hole data. Sections 1, 2, and 3 contain shallow marine carbonates from the Lower Permian to the Middle Triassic. The Lower to Middle Triassic carbonate sequences in these sections are thick (>2000 m), which might represent enhanced sedimentation on top of a flexually loaded margin. They are overlain by a regional disconformity and thousands of meters of transitional to terrestrial coarse clastics. These clastics were derived from the north [Jiang et al., 1979]. We suggest the initial sedimentation of the clastic sequence to mark the onset of collision between the SCB and the NCB.

Sections 4 and 5, on the other hand, reveal an earlier transition from carbonate to clastic deposition. In southeastern Anhui (section 4) thick coarse clastics began to accumulate in the Middle Triassic, whereas in northern Jiangsu (section 5), it began earlier in the latest Early Permian to the earliest Late Permian. Using the time scale of Harland et al. [1990], we observe a diachroneity in the initiation of the continental collision, starting at about 258 Ma in northern Jiangsu and about 243 Ma in southeastern Anhui east of the Tan-Lu fault, to about 231 Ma in Hubei and Sichuan west of the Tan-Lu fault. Note that the presence of the typical South China lower and middle Paleozoic sequence in section 5 is critical to extend the northern boundary of the SCB along the Shandong suture zone.

Clastic deposition prevailed during the Permian as shown in section 5 (Figure 4). During this time, other regions in central and southern Jiangsu were still dominated by carbonate deposition. However, farther to the south, Permian clastic deposition dominated [Jiangsu Bureau of Geology, 1984, pp. 196-214], indicating that there were two source areas, one to the south, represented by the Cathaysian Oldland of Wang [1985], and another to the north, which we interpret as the site of collision between the SCB and the NCB. The Permian clastic unit in section 5 is the thickest and closest to the Shandong suture zone of all such units in Jiangsu, suggesting a northerly clastic source [Jiangsu Bureau of Geology, 1984].

In the Nangrim-Pyeongnam Block north of the Imjingang belt and the Ryeognam Block south of the Honam shear zone (Figure 2), the transition from marine to terrestrial deposition occurred during the Artinskian at about 268-263 Ma (latest Early Permian) [Reedman and Um, 1975, p. 51]. This transition was associated with crustal shortening in and north of the Imjingang belt [Um and Chun, 1984], and the right-slip faulting along the Honam shear zone [Cluzel et al., 1991a] during the Triassic Songrim orogeny. This age relationship suggests that the change in depositional setting and the Triassic deformational events in Korea were closely related and may represent the closure of an ocean between the North and South China Blocks.

Collision-Related Deformation

Deformation due to the collision of the NCB and the SCB can be observed both within the collisional belt and in a broad area in eastern Asia. The belt in China typically consists of, from north to south, (1) synmetamorphic thrusts and recumbent folds involving Precambrian basement with its Sinian (= late Precambrian) and Paleozoic cover of the North China facies, (2) a metamorphic complex with ophiolite and synkinematic to postkinematic granite, (3) flysch nappes, and (4) folded Paleozoic and Triassic strata of the South China facies [Mattauer et al., 1985; Hsu et al., 1987; Liu and Hao, 1989]. Deformation related to the collision is characterized by crustal shortening, indicated by the widely developed thrusts and folds within and outside the collisional belt, and by left-

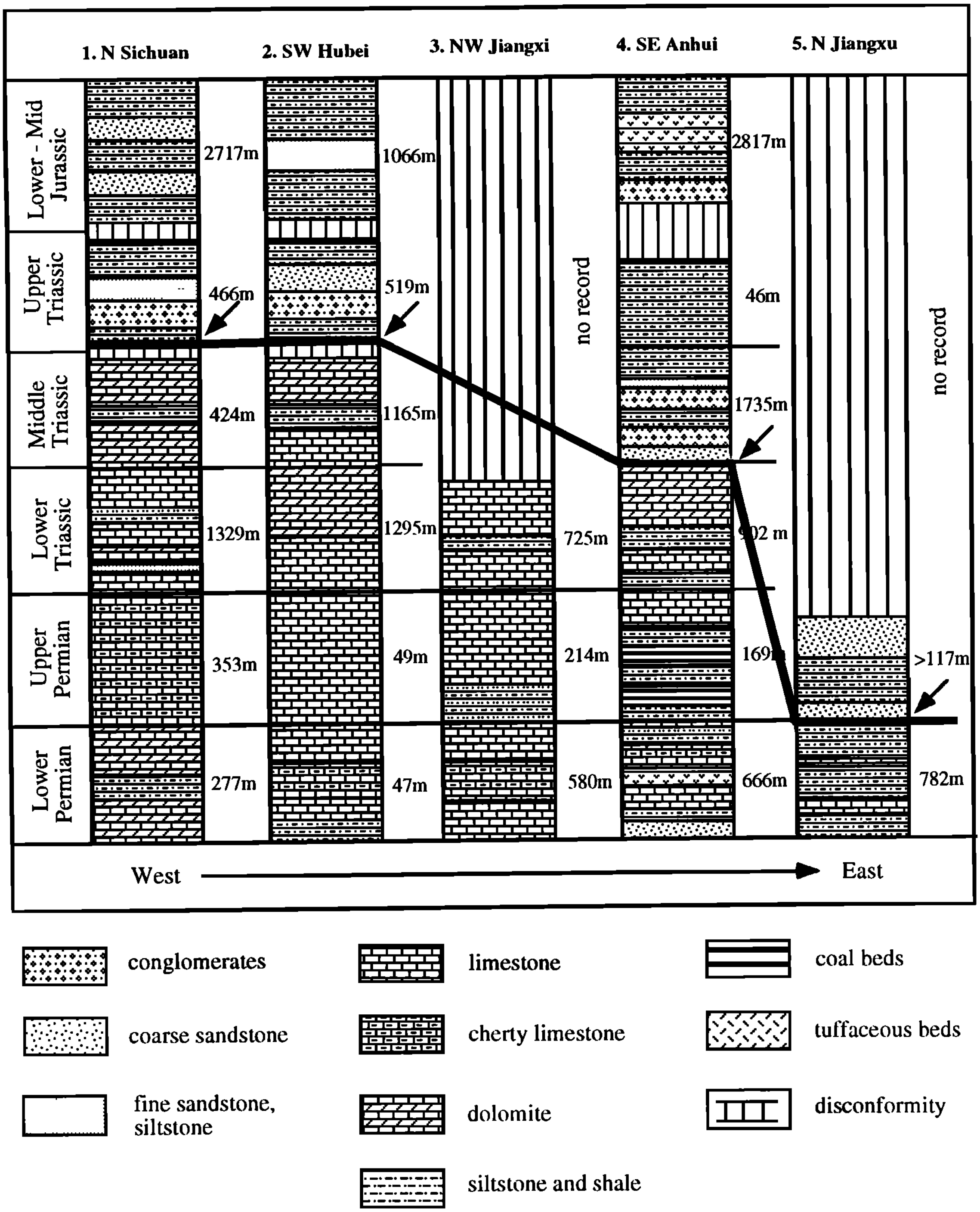

Figure 4. Five representative Permian-Middle Jurassic stratigraphic sections from the northern margin of the SCB. All the sections are scaled by thicknesses in meters. These columns are taken from regions immediately south of the Qinling-Dabie-Shandong suture zone (see Figures 1 and 2b for location). Note the diachroneity of initiation of thick clastic units from the Late Permian in the east to the Middle Triassic in the west as marked by arrows. These sections are taken from the recently published provincial geologic summaries [Sichuan Bureau of Geology, 1991; Hubei Bureau of Geology, 1990; Jiangxi Bureau of Geology, 1984; Anhui Bureau of Geology, 1987; Jiangsu Bureau of Geology, 1984], with supplementary data from the provincial stratigraphic tables published about a decade ago. Section 5 from northern Jiangsu is based on drill hole data, whereas others are based on sections measured in the field. Stratigraphic correlation is based on Nanjing Institute of Geology [1982] and Yang et al. [1986].

lateral strike-slip faults along the suture zone west of the Tan-Lu fault [Mattauer et al., 1985; Liu and Hao, 1989]. Some low-angle faults in the Dabie suture zone juxtapose lower-grade metamorphic rocks over higher-grade metamorphic rocks, although their relationship to the collision remains poorly understood [Ames et al., 1993]. The left-lateral faults are inferred to have displacements of several hundreds of kilometers on the basis of (1) the fault zone width (>1 km), (2) the apparent absence of a Paleozoic magmatic arc north of the Qinling and Dabie belts, and (3) the correlation of clasts in Triassic rocks in the Qinling area with rocks in Qilian Shan about 700 km farther west [Mattauer et al., 1985]. These faults do not offset the Tan-Lu fault and the folds and thrusts to the east. This suggests that the left-slip faulting probably occurred either prior to or synchronously with the collision. One left-slip shear zone in the Qinling belt was active during ~211 Ma [Reischmann et al., 1990]. This date permits synchroneity of collision and left-slip along the suture. Thus, the left-slip faulting along the suture could have been a result of either escaping of small crustal blocks along the suture during collision, a situation similar to that along the Indus-Tsangpo suture as proposed by Peltzer and Tapponnier [1988] or accommodation of the irregular margin of the SCB against the NCB.

Closure of the ocean between the North and South China Blocks was accomplished by a northward dipping subduction [Hsu et al., 1987; Sengor, 1985]. Precollisional, arc-related plutons are few on either side of the collisional belt. Exceptions exist in the Qinling metamorphic belt where Late Triassic (210 Ma) granites related to subduction were recognized [Reischmann et al., 1990]. The lack of arc-related plutons near the suture zone may be due to syncollisional and/or postcollisional intraplate thrusting (i.e., the magmatic arc could have been thrust beneath back arc crust). This mechanism has been recently proposed to explain the partial absence of the Gangdese magmatic arc in southern Tibet [Harrison et al., 1992; Yin et al., 1992]. Alternatively, the arc may have been translated from its original position by large-magnitude, postcollisional strike-slip faults [Mattauer et al., 1985]. Cenozoic left slip on the order of several tens of kilometers has occurred along brittle faults in the Qinling suture zone [Peltzer et al., 1985] and may have further contributed to offset of the magmatic arc.

Coesite-bearing eclogites were recently discovered in the Dabie and Shandong suture belts [Okay et al., 1989; Wang et al., 1989]. They could be the result of a subduction of continental protoliths, continent-continent collision [Wang and Liou, 1991], or postcollision intracontinental thrusting [Okay and Sengor, 1992]. In any case, the metamorphism had to occur at a depth of at least 90 km. Peak metamorphic conditions of these rocks show systematic spatial variation. Peak metamorphic pressures and temperatures decrease westward along the suture and southward across the suture. As summarized by Wang and Liou [1991], the inferred temperature for the formation of the eclogites is 880°C in easternmost Shandong, decreasing to 650°-710°C in eastern Dabie Shan, and reaching even lower metamorphic temperatures farther to the west in western Dabie Shan. The peak metamorphic temperatures in northern Dabie Shan are between 698°-813°C and decrease to 582°-611°C in southern Dabie Shan. Estimated pressures show the same systematic trend. Coesite-bearing, ultrahigh-pressure rocks are not present in the Qinling belt [Mattauer et al., 1985], an observation consistent with the aforementioned regional pattern of metamorphism.

Triassic to Early Jurassic deformation is widespread in the NCB north of the Shandong suture zone and was probably related to the North China-South China collision. In the northeastern NCB, E to E-NE trending thrusts and folds involving Permian strata are unconformably overlain by Jurassic strata [Geologic Map of Liaoning Province, 1989] (Figure 2). This implies Triassic crustal shortening in the N-S direction. Triassic to Early Jurassic deformation during the Songrim (=Indosinian) orogeny is widespread in Korea. In particular, E to E-NE trending thrusts and folds developed along and north of the Imjingang belt [Um and Chun, 1984]. Numerous small Triassic and Jurassic intermontane basins developed in this belt. Typically, they consist of terrestrial conglomerate and red sandstone that were deposited during thrusting and folding [Reedman and Um, 1975].

The Tan-Lu and Honam Fault Systems

The Tan-Lu fault system has a slip of about 540 km, as indicated by the offset of the Qinling-Dabie and Shandong metamorphic belts (Figure 2) [Wang and Liou, 1989; Okay and Sengor, 1992]. The fault slip decreases northward to about 100-150 km north of the Shandong belt [Xu et al., 1987], and southward to zero near the Dabie suture zone where the precollisional Paleozoic sedimentary facies of the SCB are not offset [Ji and Fang, 1987; Chen, 1989; Zhang et al., 1989] (Figure 2). Such a slip distribution makes the Tan-Lu fault one of the most enigmatic tectonic elements in eastern Asia [e.g., Fitches et al., 1991].

The age of the Tan-Lu fault has variably been assigned to the Precambrian [Zhang et al., 1984], Paleozoic [Watson et al., 1987], Mesozoic [Okay and Sengor, 1992; Xu et al., 1987; Xu, 1985], and Cenozoic [Ma, 1986], because the fault apparently controls the distribution of rocks formed in these geologic periods. The oldest possible age of the Tan-Lu fault is constrained as latest Paleozoic to early Mesozoic, the age of the Dabie-Shandong collisional belt that is offset by the Tan-Lu fault. The youngest possible age of the fault is constrained

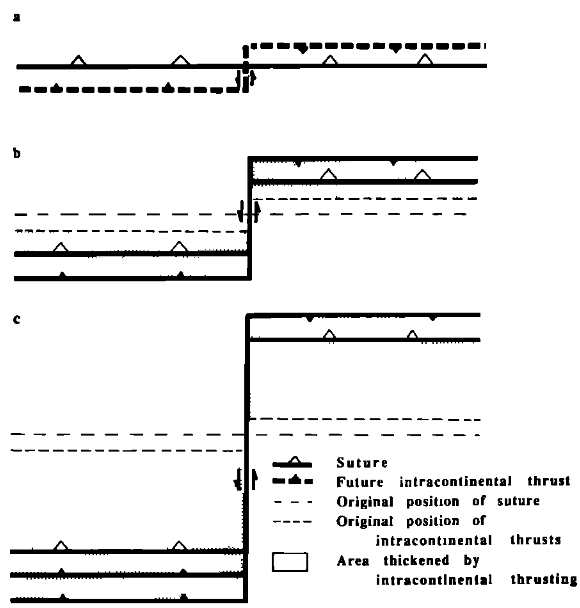

Fig. 5. Kinematic implications of the Okay and Sengor model [1992] for the development of the Tan-Lu fault and the Dabie and Shandong ultrahigh-pressure metamorphic rocks. Note that the model predicts a truncational relationship between the Tan-Lu fault and precollisional sedimentary facies on both sides of the fault. It also predicts synchroneity of development of the Dabie belt, the Shandong belt, and the Tan-Lu fault.

by the age of several small basins that contain Cretaceous volcanic rocks. These basins overlap segments of the Tan-Lu fault [Anhui Bureau of Geology, 1987]. The younger age limit has also been constrained by the age of fault gouge collected from the Tan-Lu fault zone. Dating of this material by K-Ar and Rb-Sr methods yielded model ages of 90-110 Ma and 106.8 ± 2.8 Ma, respectively [Chen et al., 1988].

Numerous models have been proposed for the development of the Tan-Lu fault. Xu et al. [1985] suggest that the Tan-Lu fault is a Cretaceous normal fault, because it bounds Cretaceous basins. Although the Tan-Lu fault may indeed have had a normal faulting history in the Early Cretaceous as implied by rapid cooling and possibly rapid unroofing of rocks adjacent to it during 105-123 Ma [Chen et al., 1992], this model does not explain the apparent separation of the Dabie and Shandong suture zones and the juxtaposition of the NCB and the SCB Paleozoic stratigraphy in Jiangsu and Anhui provinces. Xu et al. [1987] suggest that the Tan-Lu fault is a left-lateral strike-slip fault resulting from oblique subduction of the Pacific plate during the Jurassic [cf. Okay and Sengor, 1992], but they do not specify how and where the Tan-Lu fault terminates. Watson et al. [1987] propose that the Tan-Lu fault initiated during the Carboniferous along the N-NE trending eastern margin of the NCB. The SCB later came into contact with the NCB along the Tan-Lu fault. It seems unlikely that the precollisional geometries of the North and South China Blocks could fit perfectly along the fault without producing observable contraction or extension. Furthermore, precollisional Paleozoic to Early Triassic lithofacies in the NCB were truncated by the Tan-Lu fault (Figure 3) [Sun et al., 1989; Han et al., 1989], suggesting that the Tan-Lu fault cannot be a Carboniferous structure that paralleled the Paleozoic eastern margin of the NCB. Kimura et al. [1990] attributed the development of the Tan-Lu fault to Jurassic-Cretaceous back arc extension in the N-S direction. The proposed axis of the spreading center was oriented E-W, linking with the Tan-Lu fault. As slip along the Tan-Lu fault is at least 540 km, the proposed back arc extension should have produced Jurassic-Cretaceous oceanic crust east of the Dabie suture belt. Contrary to this prediction, the proposed site of the back arc basin consists of Permian to Triassic marine sequence overlain by the Jurassic and younger terrestrial deposits (section 5 in Figure 4) [Chen, 1989; Zhang et al., 1989], precluding the existence of a Jurassic-Cretaceous ocean in east central China.

To explain the occurrence of ultrahigh-pressure rocks in the Dabie and Shandong belts, Okay and Sengor [1992] proposed that the Tan-Lu fault is a postcollisional transfer fault that links the intracontinental thrust systems with opposite polarity in Dabie and Shandong. The kinematic implications of this model are shown diagrammatically in Figure 5. The model requires that the North and South China suture zone trend E-W and be relatively straight prior to initiation of the Tan-Lu fault, and that the precollisional and syncollisional sedimentary facies on both the NCB and SCB be truncated and offset by the Tan-Lu fault. Clearly this is not the case for the SCB. As discussed above [Zhang et al., 1989] (Figure 3), sedimentary facies in the SCB are parallel to the Tan-Lu fault. Because the intracontinental thrust systems in the Dabie and Shandong belts were linked by the Tan-Lu fault in Okay and Sengor's [1992] model, synchroneity of these three structures is required from the beginning to the end. This contradicts the 25- to 50-m.y. difference in age of the ultrahigh-pressure eclogites in the Shandong and the Dabie belts and the stratigraphic record along the northern margin of the SCB.

Mesozoic ductile right-lateral strike-slip faults in the Ogcheon belt were first recognized by Kim and Lee [1984] and Kim et al. [1984]. Yanai et al. [1985] named this fault system the Honam shear zone. Recent kinematic, geochronologic, and lithostratigraphic studies by Cluzel et al. [1991a] suggest that right slip along this fault system was at least 200 km, the length of the exposed Honam shear zone on the Korean Peninsula, because the fault juxtaposes the South China Paleozoic lithofacies on its northwest side with the North China lithofacies on its southwest side. The fault system was active during the Late Triassic, as constrained by synkinematic granite with a Rb-Sr whole rock age of 211 Ma [Choo and Kim, 1985].

TECTONIC MODEL

The lithofacies distribution along the northern margin of the SCB and southern margin of the NCB is consistent with an interpretation that the southern edge of the NCB was originally a smooth, E-W trending boundary prior to collision, whereas the SCB had an irregular geometry with its eastern part extending some 500 to 550 km farther to the north than its western counterpart. This geometrical configuration of the NCB and the SCB is somewhat similar to that proposed by Mattauer et al. [1991]. However, their interpretation of the NCB-SCB collision system is markedly different from ours. The collision of the NCB and the SCB produced the Tan-Lu fault, which truncates the trend of lithofacies to the west but is concordant with the trend of lithofacies in the east. Radiometric dating and stratigraphic data discussed above indicate that (1) the collision between the SCB and the NCB occurred in the latest Paleozoic to early Mesozoic, not middle Paleozoic as proposed by Mattauer et al. [1985], and (2) on a finer time scale, there is a diachroneity in this suture zone. The collision occurred first in the east in the latest Early Permian, proceeded into the Middle Triassic in the regions west of the Tan-Lu fault, and finished in the Late Triassic to Early Jurassic. The duration of the diachroneity is at least 20-25 m.y.

On the basis of these geologic relationships, we propose a tectonic model for the collision of the North and South China Blocks (Figure 6). In order to make our reconstruction as realistic as possible, we restore the known Cenozoic left slip along the Altyn Tagh fault of the northwesternmost Tibetan Plateau and the Longmen Shan deformation belt along the western edge of the SCB [Peltzer and Tapponnier, 1988; Burchfiel et al., 1989; Peltzer et al, 1989; Burchfiel and Royden, 1991]. The position of the SCB and the NCB in the Late Carboniferous to the early Early Permian is schematically shown in Figure 6a. During this time interval, the southern margin of the NCB was the locus of a relatively straight, E-W trending, northward dipping subduction zone, whereas the northern edge of the SCB was irregular, with its eastern part extending 550 km farther north than its western counterpart. The collision started along the segment of the NCB between the present Tan-Lu fault and the Honam shear zone during the latest Early Permian to early Late Permian due to the indentation of the northeastern SCB into the NCB (Figure 6b). The Tan-Lu and the Honam fault systems are similar to the Chaman and the Ninety East Ridge faults on the west and east sides of the Indian plate accommodating collision of India into Asia [Tapponnier et al., 1982; Farah et al., 1984]. Thrusts, folds, and thrust-related basins developed near the collision zone in the North and South China blocks. The model predicts that volcanism could have been active west of the Tan-Lu fault and east of the Honam shear zone during the Late Permian to Early Triassic (Figure 6b). A sequence of Triassic flysch deposits up to 7-8 km thick is present over a vast area of the Songpan-Ganzi region west of the SCB [Yang et al., 1986, pp. 128; Chen, 1989], which may be eroded from the

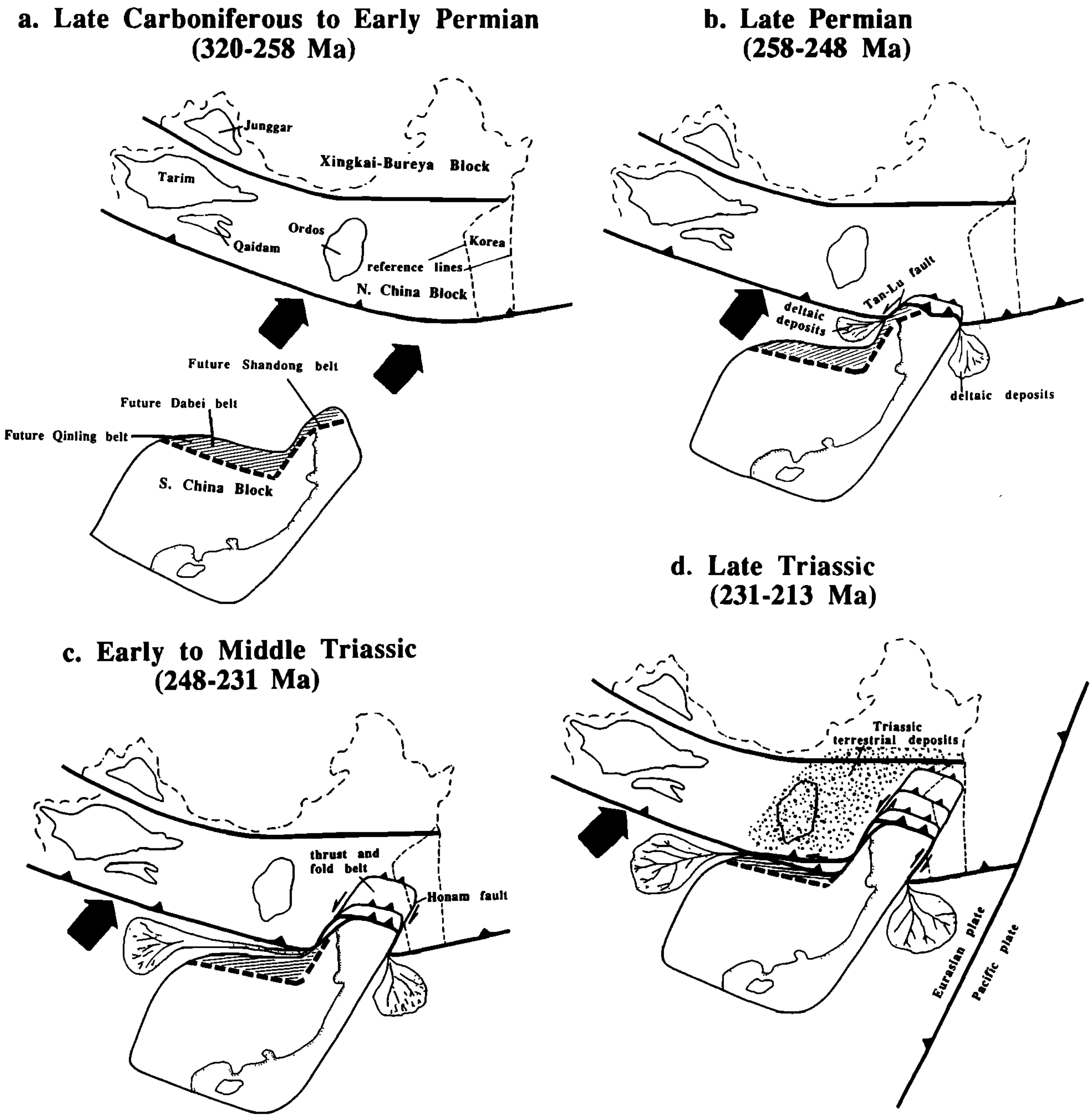

Fig. 6. Tectonic model for the processes related to the collision of the North and South China Blocks. (a) Late Carboniferous to Early Permian (320-258 Ma). The southern margin of the NCB was a straight northward dipping subduction zone, whereas the northern margin of the SCB was irregular with its eastern part extending 550 km farther north than its western counterpart. (b) Late Permian (258-248 Ma). The collision started between the Tan-Lu fault and the Honam shear zone due to indentation of the northeastern part of the SCB into the NCB. Thrusts, folds, and the related foreland basins developed near the collision zone. Volcanism is expected to be continuous east of the Tan-Lu fault and west of the Honam shear zone. Sediments eroded from the collision zone were deposited on both sides of the SCB, a situation similar to the present Bengal and Indus fans on the east and west sides of the Indian continent. (c) Early to Middle Triassic (248-231 Ma). Due to the irregularity of the northern margin of the SCB, the ocean in the eastern part of the future Dabie belt was closed first. (d) Late Triassic (231-213 Ma). In response to this diachronous closure of the ocean, volcanism related to subduction had systematically shut down westward from the Tan-Lu along the suture zone. Part of the earlier flysch deposits were subducted underneath the NCB during the closure of the ocean between the two blocks. The irregular geometry of the northern margin of the SCB may also have produced left-slip faults west of the Tan-Lu fault along the suture zone. Triassic clastic sediments were deposited in a wide area of North China. The westward subduction of the Pacific plate underneath the Eurasian plate began to develop. (e) Early Jurassic (213-188 Ma). Indentation of the irregular northern margin of the SCB caused left-slip motion along the suture zone. The Tan-Lu fault propagated northward and offset the northern boundary of the Sino-Korean craton. The westward subduction of the Pacific plate produced a continuous magmatic arc along the entire eastern edge of the Eurasian continent (not shown).

e. Early Jurassic (213-188 Ma)

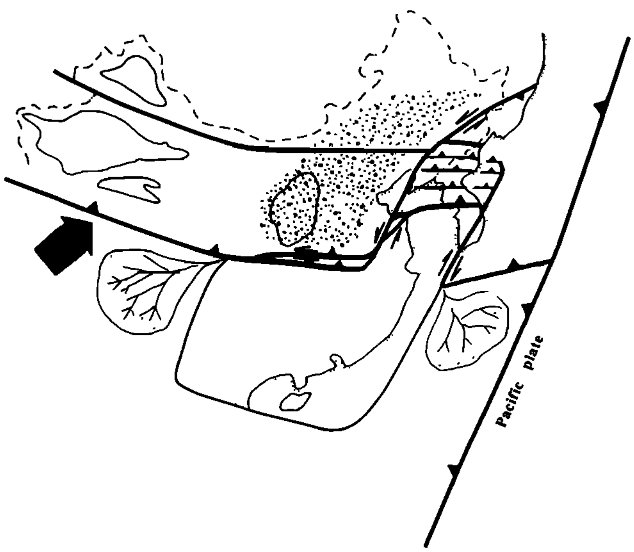

Fig. 6 (continued)

collisional belt and deposited in a remnant ocean to the west (Figures 6b to 6e). The depositional setting of these Triassic sediments may be similar to that of the present Bengal and Indus fans on the east and west sides of the Indian continent as proposed by Sengor [1985]. Besides the modern example of the Himalaya-Bengal system, the proposed depositional and tectonic settings for the collision of the NCB and the SCB are also similar to those of the Appalachian-Ouachita system as investigated by Graham et al. [1975]: both are diachronous collisional belts with flysch sediments deposited diachronously in response to the progressive collision. Because of the irregularity of the northern margin of the SCB, the ocean in the east near Shandong closed first in the Late Permian (Figure 6b). In response to diachronous closure of this ocean, volcanism related to subduction is predicted to have systematically shut down westward from the Tan-Lu fault and eastward from the Honam shear zone along the suture zone in the Late Triassic and the Early Jurassic (Figures 6d and 6e). During the final collisional stage, Triassic clastic sediments that may have been derived from the collisional belt to the east and south were deposited in a wide area of North China. The irregular northern margin of the SCB caused greatest shortening along the Shandong-Imjingang belt, less shortening along the Dabie belt, and least shortening along the Qinling belt. As the grade of tectonically induced metamorphism corresponds with the magnitude of shortening, this model predicts the observed decrease in metamorphic grades from the Shandong and Dabie suture belts to the Qinling belt [Wang and Liou, 1991]. In addition, the irregular northern margin of the SCB produced left-lateral strike-slip faults along the Qinling-Dabie suture zone as a means of accommodating the collision (Figure 6d). Meanwhile, the Tan-Lu fault began to propagate northward and offset the northern boundary of the Sino-Korean craton. Final suturing of the NCB and the SCB occurred in the latest Triassic. However, continuous collision after the ocean closure possibly lasted until the Early Jurassic (Figure 6e). Initiation of westward dipping subduction of the Pacific plate underneath the Eurasian plate could have occurred during or immediately after the collision (Figures 6 d and 6e), producing a continuous magmatic arc along the eastern margin of the Eurasian continent.

SUMMARY

A tectonic model is proposed for the North and South China collision. Sedimentary-facies distribution and the tectonic nature of continental margins suggest that the rifted northern edge of the SCB was irregular and that the active southern edge of the NCB was smooth. In particular, the northeastern part of the SCB was rectangular and extended at least 550 km farther north than its western counterpart. Collision of two continental margins with such different shapes controlled the diachronous collision and the complex evolution of structures that involved thrusting, strike-slip faulting, sedimentary-basin development, and systematic variation of metamorphic grades and ages along the suture zone. In this model, we suggest that the collision was accomplished by the indentation of the northeastern part of the SCB into the NCB that began in the latest Early Permian and lasted to the Late Triassic and possibly Early Jurassic. The left-slip Tan-Lu fault system in northeastern China and the right-slip Honam fault system in southeastern Korea were lithospheric-scale transform faults accommodating the northward indentation of the SCB. The Tan-Lu and the Honam faults are analogous to the Chaman and the Ninety East Ridge fault systems on the west and east sides of the Indian continent that is presently colliding into the Eurasian plate. Left-slip faulting along the suture zone during the collision may be a result of either escaping of crustal blocks or translation of the irregular northern margin of the SCB. Our model explains the abrupt termination of the Tan-Lu fault in both ends. It also requires significant amount of crustal shortening in the Triassic in regions north of the Shandong suture. Although the Triassic/Jurassic thrusts are widespread in these areas, the magnitude of shortening accommodated by these faults is poorly constrained and requires further structural investigation.

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