Geology

Exhumation of the Dabie Shan ultra-high-pressure rocks and accumulation of the Songpan-Ganzi flysch sequence, central China

Shangyou Nie, An Yin, David B. Rowley and Yugan Jin

Geology 1994;22;999-1002
doi: 10.1130/0091-7613(1994)022<0999:EOTDSU>2.3.CO;2

Exhumation of the Dabie Shan ultra–high-pressure rocks and accumulation of the Songpan-Ganzi flysch sequence, central China

Shangyou Nie, An Yin — Department of Earth and Space Sciences, University of California, Los Angeles, California 90024
David B. Rowley — Department of Geophysical Sciences, University of Chicago, Chicago, Illinois 60637
Yugan Jin — Nanjing Institute of Geology and Paleontology, Academia Sinica, Nanjing, China

ABSTRACT

The presence of coesite- and diamond-bearing ultra–high-pressure (UHP) metamorphic rocks in the Dabie and Sulu regions, central China, suggests that a >100-km-thick crustal section (4×10^6 km^3 in volume) has been denuded. This volume is comparable to that represented by the 10–15-km-thick Middle to Upper Triassic flysch rocks in the Songpan-Ganzi region. Regional geology and radiometric dates are compatible with an interpretation that the majority of these sedimentary rocks were derived from denudation of the orogenic belt between North and South China blocks following their latest Paleozoic to Triassic collision. This correlation implies a high denudation rate of ~4 mm/yr that may have been in part promoted by tropical precipitation and extreme topographic relief for as long as 25 m.y.

INTRODUCTION

Recent petrological studies of the Qinling-Dabie-Sulu suture between the North and South China blocks have revealed the presence of ultra–high-pressure (UHP) coesite- and diamond-bearing metamorphic assemblages (Fig. 1; Wang et al., 1992; Okay et al., 1993). These rocks have attracted a great deal of attention because they represent the largest exposure of crustal rocks that were once buried deeper than 100 km and metamorphosed at pressures >30 kbar. Together with the other occurrences of nonimpact coesites and diamonds from Norway, Khazakhstan, and the western Alps, these UHP rocks further accentuate the long-standing controversy surrounding the mechanisms and rates of exhumation of high-pressure metamorphic assemblages (e.g., Cloos, 1993). Although thermochronologic studies (Li et al., 1989; Ames et al., 1993; Eide et al., 1994) are beginning to provide important age constraints on the exhumation history of the UHP rocks from the Dabie Shan, a coherent tectonic model is not yet available because of the scarcity of the ages and the lack of structural constraints. This study uses a different approach by correlating sedimentation with denudation associated with exhumation of the UHP rocks.

The amount of material that had to be removed to expose the UHP rocks in the Dabie and Sulu regions can be estimated to be comparable to the Cenozoic rocks in the Bengal Fan, the largest sedimentary fan on earth (Curray, 1991). Such a large amount of denudation from the Qinling-Dabie-Sulu suture cannot be accounted for by the sedimentary rocks within the North and South China blocks, a problem realized by Okay and Şengör (1992), who suggested that most of the sediments were probably carried eastward into the Pacific Ocean. Alternatively, we hypothesize that as much as 80%–90% of the sediments were transported westward and deposited in the Songpan-Ganzi remnant oceanic basin (Nie et al., 1993), a view shared by Zhou and Graham (1993). The Songpan-Ganzi region (Fig. 1) contains the largest exposure of Triassic rocks on Earth; the total volume is 2.2×10^6 km^3, and a source area has not been identified before (Huang and Chen, 1987). In this paper, we present details from regional geology, geochronology, and volumetric estimates in support of this hypothesis, which, if correct, would allow an independent estimate on the denudation rate for the Dabie UHP rocks.

REGIONAL GEOLOGY

The Songpan-Ganzi region in the northeastern Tibetan Plateau occupies an area of ~2×10^5 km^2, 90% of which exposes Mid-

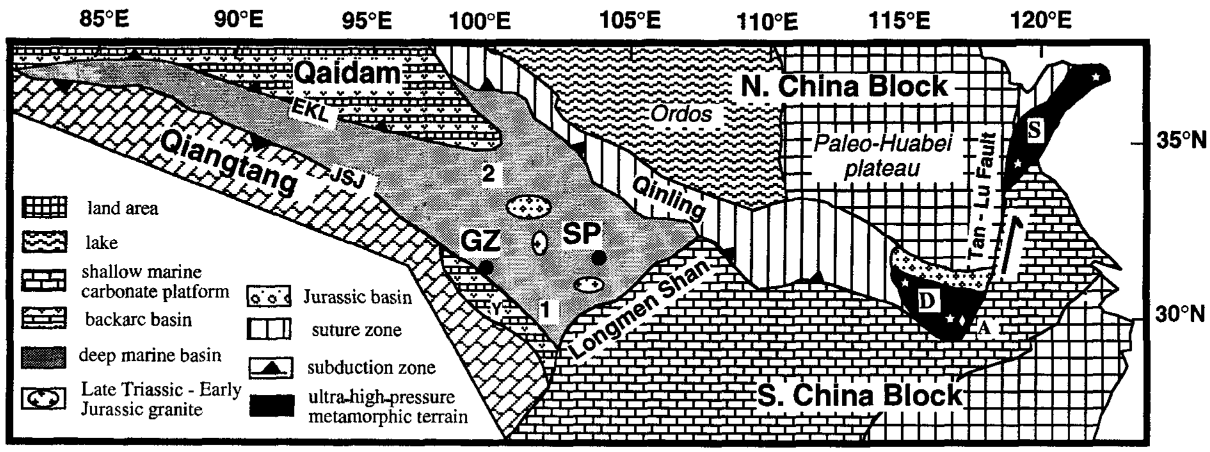

Figure 1. Simplified Middle to Late Triassic geography of central China. Paleogeography is modified after Wang (1985). Sutures: EKL—East Kunlun, JSJ—Jinshajiang. Ultra–high-pressure terranes: D—Dabie, S—Sulu. A—Anqing, Y—Yidun, GZ—Ganzi, SP—Songpan. Numbers 1 and 2 indicate location for Triassic sections in Figure 2. Also shown are Upper Triassic–Lower Jurassic granites in the Songpan-Ganzi region and Jurassic basins in northern Dabie Shan and Songpan-Ganzi region that unconformably overlie older rocks. Stars indicate coesite localities; diamond indicates diamond locality.

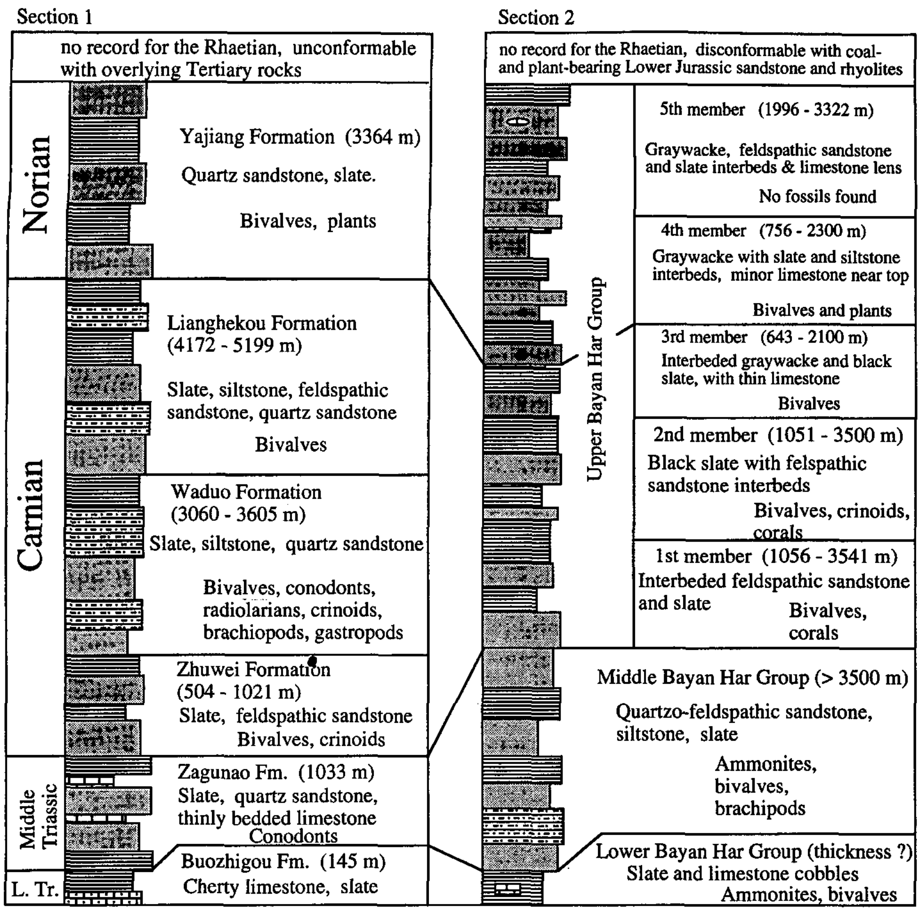

Figure 2. Triassic stratigraphic sections from Songpan-Ganzi region. Section 1 is from Yajiang (after Hou et al., 1991) and section 2 is from Maqin (after Qinghai Bureau of Geology, 1991). See Figure 1 for localities.

dle to Upper Triassic flysch sedimentary rocks dominated by slate and quartzo-feldspathic sandstone (Fig. 2). Fossils found in the rocks include, from bottom to top, ammonites, bivalves, brachiopods, conodonts, gastropods, and plants. They indicate that the majority of the 10–15-km-thick units belong to the Carnian and Norian stages of the Late Triassic (Fig. 2). We note that accurately measuring the thickness in the highly deformed Songpan-Ganzi region is difficult, and the uncertainties are in part reflected by the large ranges of thicknesses shown in Figure 2. The fossil record indicates a gradual shallowing upward from the Middle Triassic ammonite- and conodont-bearing deep-marine facies to the Upper Triassic plant-bearing terrestrial facies, reflecting a progressive infilling of the Songpan-Ganzi basin. The Triassic rocks are conformably underlain by thin (<200 m) pre-Triassic chert, shale, and siltstone that were probably deposited on an oceanic floor (Şengör, 1987).

The Songpan-Ganzi region is surrounded by sutures in all directions except for the east, where the Triassic flysch sequences onlap the Sinian Triassic slope and platformal sedimentary units of the South China block, suggesting that the Songpan-Ganzi region was probably its oceanic extension (Fig. 1). Thus, the Longmen Shan was probably the continental shelf-to-slope transition rather than a plate boundary. East of the Longmen Shan, the South China block contains Lower—Middle Triassic shallow-marine and Upper Triassic terrestrial rocks (Wang, 1985). In the southwest, the Songpan-Ganzi region is juxtaposed with the Qiangtang block across the Jinshajiang and Litang sutures. Much of the Qiangtang block contains Upper Triassic shallow-marine carbonates, whereas the Yidun back-arc basin is dominated by interbedded andesites and shallow-marine clastic rocks (Ruo et al., 1987). Both sutures were closed by latest Triassic time, when the Qiangtang block collided with Asia. In the northwest, the Songpan-Ganzi region is separated from the Qaidam block by the East Kunlun suture, which marks a north-dipping subduction zone (Fig. 1). Interbedded Paleozoic to Middle Triassic andesites and shallow-marine carbonate and clastic rocks along the southern margin of Qaidam are interpreted to have evolved with this subduction zone (Şengör et al., 1993). To the northeast, the Songpan-Ganzi region is separated from the North China block by the Qinling, where upper Paleozoic shallow-marine rocks are preserved (Wang, 1985).

Scattered outcrops in the Animaqian Shan reveal an unconformable relation between the Lower Jurassic coal-bearing rocks and the Triassic flysch (Fig. 1; Qinghai Bureau of Geology, 1991). If this is representative of the entire Songpan-Ganzi region, it implies that folding of the Triassic rocks occurred in the latest Triassic. This is compatible with the widespread 210–195 Ma syn- to postkinematic anatectic granitoids within the region (Fig. 1) and with latest Triassic initiation of overthrusting along the Longmen Shan at the western margin of the Sichuan Basin. This folding marks the final closure of the Songpan-Ganzi basin.

The above geologic relation suggests that the Songpan-Ganzi region was an oceanic basin trapped by two oppositely dipping subduction zones that received a large amount of Middle to Upper Triassic sedimentary rocks. Furthermore, the immediately adjacent regions could not have been the main source area, because they either have coeval shallow marine rocks or contain a relatively complete Paleozoic and early Mesozoic sedimentary record; this record suggests an insignificant amount of denudation.

TIMING OF NORTH AND SOUTH CHINA COLLISION AND EXHUMATION OF DABIE UHP ROCKS

Estimates of the timing of the North and South China collision range from the middle Paleozoic (Mattauer et al., 1985) to the earliest Mesozoic (Wang et al., 1982; Klimetz, 1983; Şengör, 1987). In two recent discussions (Yin and Nie, 1993; Nie and Rowley, 1994), we cited several stratigraphic lines of evidence to argue that there could not have been a major middle Paleozoic continental collision along the northern margin of the South China block, simply because it contains a continuous Sinian to Middle Triassic marine record. The stratigraphic data further suggest that the collision happened diachronously from east to west, similar to the model of Zhao and Coe (1987), on the basis of paleomagnetic results and compatible with the paleogeography of the overriding North China block, having a highland (the Paleo-Huabei plateau) in the east and a major lake (the Ordos) in the west in the early Mesozoic (Figs. 1 and 3). Strong support for an early Mesozoic collision also comes from newly obtained 230 ± 30 Ma metamorphic ages from the Dabie and Sulu regions (Li et al., 1989; Ames et al., 1993; Okay et al., 1993; Eide et al., 1994).

As to the timing of the exhumation of the UHP rocks, we know that peak metamor-

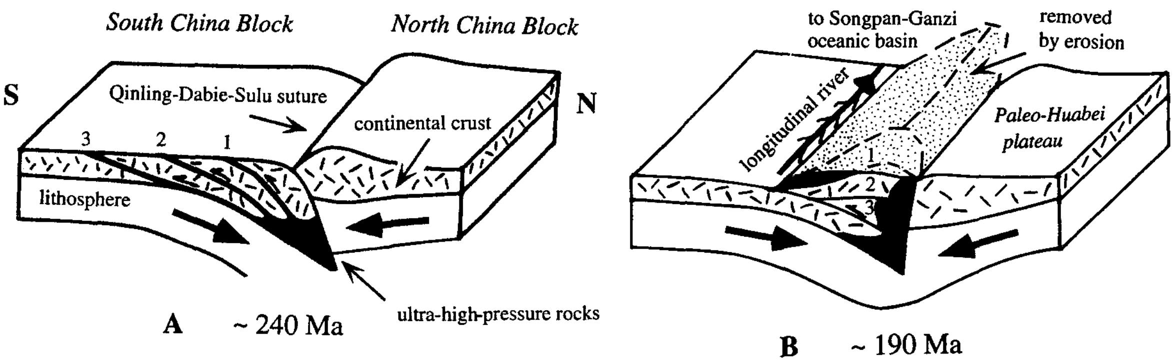

Figure 3. Sketch illustrating postcollisional evolution of Dabie Shan and exhumation of ultra-high-pressure rocks (modified after Okay and Şengör, 1992). Numbers 1, 2, and 3 indicate progressive southward activation of thrusts (A). Ultra-high-pressure metamorphic assemblages are brought up to surface by thrusting and rapid erosion (B). Erosional products are then transported westward to Songpan-Ganzi remnant oceanic basin.

phism occurred around 240 ± 10 Ma (Wang et al., 1992), and that the phengite $^{40}Ar/^{39}Ar$ dates of 195–230 of Eide et al. (1994) imply that the UHP rocks may have ascended to shallow crustal depths by the Early Jurassic. There is no direct data control on when the UHP rocks reached the surface. Circumstantial evidence suggests that by the Middle Jurassic some high-grade metamorphic rocks were exposed at the surface, on the basis of conglomerates found in the Anqing area south of the suture, whereas in northern Dabie Shan, a Middle–Late Jurassic basin unconformably overlies the metamorphic rocks and contains mylonitic cobbles (Fig. 1; Anhui Bureau of Geology, 1987; B. Hacker, personal commun.).

VOLUMETRIC ESTIMATES

Regional presence of the UHP rocks in the Dabie and Sulu regions suggests that a significant part of that area was raised from below 100 km (Wang et al., 1992; Okay et al., 1993). Okay and Şengör (1992) estimated the amount of denudation as 1.6×10^6 km^3 for the Dabie Shan alone, using a wedge model of 160 km wide and 100 km deep that pinches out westward over a 400 km distance. On the basis of the localities of coesites and quartz pseudomorphs, we estimate that half of the Sulu region (with an area of 4.8×10^4 km^2) has undergone UHP metamorphism and been brought up subsequently. Therefore, an additional volume of 2.4×10^6 km^3 can be estimated to give a total volume of about 4×10^6 km^3. This figure is probably an underestimation, because it has taken into account only the removal of the vertical column immediately above the UHP terrane. If the lateral sections that were involved in thrusting and subsequent erosional denudation are also included, the total volume of denudation can be higher by as much as 50%–100% (Rowley, 1994; Fig. 3).

The area of the Songpan-Ganzi region covered by the Middle–Upper Triassic flysch sequence is estimated at 2×10^5 km^2 (Fig. 1); the thicknesses range from 10 to 15 km, and the total volume is $2–3 \times 10^6$ km^3. This estimate is smaller than but comparable with the amount of denudation from the Qinling-Dabie-Sulu suture. These numbers should be regarded as only a first-order approximation because of the many assumptions and uncertainties, some of which can be significant. For example, surface geology suggests that substantial shortening has occurred in the Songpan-Ganzi region and thus the present surface area is only a minimum for this basin. If we use crustal shortening of 50%, as estimated for Cenozoic deformation within the Tibetan Plateau (Chang et al., 1986), the size of the Songpan-Ganzi basin would be doubled and the volume would be $4–6 \times 10^6$ km^3 for the Middle–Upper Triassic rocks. However, the density of the denuded lower crust rocks from the Qinling-Dabie-Sulu suture should be higher than that of the sedimentary rocks by as much as 10%–20%. We also do not know what part of the Yellow Sea, East China Sea, and Korean Peninsula should be included as continuation of the Qinling-Dabie-Sulu suture, which may also have been significantly denuded. Regardless, the above estimates suggest that (1) both the volume of material denuded from the suture zone and that of the Middle–Upper Triassic sedimentary rocks within the Songpan-Ganzi region are unusually large, and (2) these two numbers are of the same order of magnitude.

DISCUSSION

Studies of modern river systems suggest that surface denudation is controlled by three main factors, local topographic relief, amount of annual precipitation, and rate of surface uplift (Summerfield, 1991). Ahnert (1970) showed that a linear relation exists between topographic relief and surface denudation. Ohmori (1983) suggested that annual precipitation and surface denudation are generally positively correlated, except for the intermediate precipitation rates because of the surface protection effect of rain forests once they are developed. The positive correlation between surface uplift and denudation is supported by the observation that regions with the highest surface uplift, such as the Southern Alps of New Zealand, also have the highest rates of surface denudation (~5–8 mm/yr; Summerfield, 1991), although this correlation is difficult to quantify because of the complexities associated with differentiating the interplay of surface uplift, rock exhumation, and isostatic rebound (England and Molnar, 1990). In the Dabie and Sulu regions, all three factors appear to favor very rapid denudation. Data from paleomagnetism (Zhao and Coe, 1987), phytogeography, and paleoclimatology (Nie et al., 1990) lead us to suggest that both the North and South China blocks were at equatorial latitudes during Permian-Triassic time. The presence of coesites and metamorphic diamonds suggests that continental crust of the South China block was subducted beneath the North China block more than 100 km, deeper than that of the downgoing subduction slab of the Indian plate underneath the Tibetan plateau, as revealed by recent deep seismic reflection (Zhao et al., 1993). Thus, it is possible that the Dabie Shan reached heights similar to, if not greater than, that of the Tibetan plateau, because it represented the leading mountain range for the early Mesozoic Paleo-Huabei plateau (Fig. 3). Therefore, the local relief around the Dabie Shan in the Triassic could have been extraordinary, given the height of the Dabie Shan and the near sea level elevation of the northern South China block (Fig. 1).

Correlating denudation of the Dabie Shan with accumulation of the Songpan-Ganzi flysch sequences provides an independent estimate of denudation rate. Figure 2 shows that the thickness of the sediments for the Carnian and Norian (i.e., 235–

210 Ma from the time scale of Harland et al., 1990) represents the majority of the entire Middle–Upper Triassic section. Therefore, by assuming that these sediments were derived from denudation of the Qinling-Dabie-Sulu suture and transported instantaneously to the Songpan-Ganzi basin, we obtain an average denudation rate of about 4 mm/yr to bring up the UHP rocks from below 100 km in ~25 m.y. by tectonic processes that are not yet understood.

It is less likely that most of the sediments denuded from the Dabie Shan were carried east into the Pacific (Okay and Şengör, 1992) because (1) recent offshore drilling has revealed only thin (<500 m) Triassic and Jurassic sedimentary units in the Yellow Sea and East China Sea (Editorial Committee, 1990) and (2) an Andean-type margin existed along the eastern margin of China from the Late Permian to the Cretaceous in response to the west-dipping Pacific subduction (Şengör et al., 1993). This arc was probably part of a north-trending mountain chain that was unfavorable to major eastward sediment transportation, analogous to the present situation in western South America. In contrast, the Songpan-Ganzi oceanic basin in the west provided an ideal site for the sediments carried by the longitudinal rivers that may have developed south of and parallel to the Qinling-Dabie-Sulu suture (Fig. 3). This is similar to the present Ganges River and the Bengal Fan system accommodating sediments derived from the Himalayas and the Tibetan Plateau (Graham et al., 1975; Burbank, 1992). The westward sediment transport may have been further aided by the diachronous east to west collision between the North and the South China blocks.

ACKNOWLEDGMENTS

Research supported by the National Science Foundation. We thank Elizabeth Forshee, Peter Rumulhart, and Zhuang Peiren for comments on an earlier version of the manuscript, and Mark Cloos, Steve Graham, Brad Hacker, and Juhn Liou for constructive reviews.

REFERENCES CITED

Ahnert, F., 1970, Functional relationships between denudation, relief and uplift in large mid-latitude drainage basins: American Journal of Science, v. 268, p. 243–263.

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

Anhui Bureau of Geology, 1987, Regional geology of Anhui Province: Beijing, Geological Publishing House, 721 p. (in Chinese with English summary).

Burbank, D. W., 1992, Causes of recent Himalayan uplift deduced from deposited patterns in the Ganges basin: Nature, v. 357, p. 680–683.

Chang, C. F., and 27 others, 1986, Preliminary conclusions of the Royal Society and Academia Sinica 1985 geotraverse of Tibet: Nature, v. 323, p. 501–507.

Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737.

Curray, J. R., 1991, Possible greenschist metamorphism at the base of a 22-km sediment section, Bay of Bengal: Geology, v. 19, p. 1097–1100.

Editorial Committee, 1990, Petroleum Geology of China, Volume 16A, Continental shelf and its neighboring regions: Beijing, Petroleum Industry Press, 458 p. (in Chinese).

Eide, E. A., McWilliams, M. O., and Liou, J. G., 1994, $^{40}Ar/^{39}Ar$ geochronology and exhumation of high-pressure to ultrahigh pressure metamorphic rocks in east-central China: Geology, v. 22, p. 601–604.

England, P., and Molnar, P., 1990, Surface uplift, uplift of rocks, and exhumation of rocks: Geology, v. 18, p. 1173–1177.

Graham, S. A., Dickinson, W. R., and Ingersoll, R. V., 1975, Himalayan-Bengal model for flysch dispersal in Appalachian-Ouachita system: Geological Society of America Bulletin, v. 86, p. 273–286.

Harland, W. B., Armstrong, R. L., Cox, A. V., Criag, L. E., Smith, A. G., and Smith, D. G., 1990, A geological timescale: Cambridge, United Kingdom, Cambridge University Press, 263 p.

Hou, L. W., Luo, D. X., Fu, D. M., Hu, S. H., and Li, K. Y., 1991, Triassic sedimentary-tectonic evolution in western Sichuan and eastern Xizang (Tibet) region: Beijing, Geological Publishing House, 220 p. (in Chinese with English abstract).

Huang, T. K., and Chen, B. W., 1987, The evolution of the Tethys in China and adjacent regions: Beijing, Geological Publishing House, 109 p. (in Chinese and English).

Klimetz, M. P., 1983, Speculations on the Mesozoic plate tectonic evolution of eastern China: Tectonics, v. 2, p. 139–166.

Li, S. G., Hart, S. R., Ahen, S., Guo, A., Liu, D., and Zhang, Z., 1989, Sm-Nd age for collision between the Sino-Korean and Yangtze cratons: Academia Sinica, v. 8, p. 312–319.

Mattauer, M. and 7 others, 1985, Tectonics of the Qinling Belts, build-up and evolution of eastern Asia: Nature, v. 327, p. 496–500.

Nie, S. Y., and Rowley, D. B., 1994, Comment *on* "Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the Present" by Enkin et al. (1992): Journal of Geophysical Research (in press).

Nie, S. Y., Rowley, D. B., and Ziegler, A. M., 1990, Constraints on the locations of Asian microcontinents in Paleo-Tethys during the late Paleozoic, *in* McKerrow, W. S., and Scotese, C. R., eds., Paleozoic paleogeography and biogeography: Geological Society of London Memoir 12, p. 397–408.

Nie, S. Y., Yin, A., Rowley, D. B., and Jin, Y. G., 1993, History of northeastern Tibetan plateau before India-Asia collision: Formation of the Songpan-Ganzi flysch sequence and exhumation of the Dabie Shan ultra-high pressure rocks: Geological Society of America Abstracts with Programs, v. 25, no. 6, p. 117.

Ohmori, H., 1983, Erosion rates and their relation to vegetation from the viewpoint of worldwide distribution: University of Tokyo Department of Geography Bulletins, v. 15, p. 77–91.

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

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

Qinghai Bureau of Geology, 1991, Regional geology of Qinghai Province: Beijing, Geological Publishing House, 857 p. (in Chinese with English summary).

Rowley, D. B., 1994, A simple geometric model for estimating the syn-kinematic erosional denudation of metamorphic thrust fronts: Earth and Planetary Science Letters (in press).

Ruo, R. B., Xu, J. F., Chen, Y. M., and Zou, D. B., 1987, The Triassic system of the Qinghai-Xizang (Tibet) Plateau: Beijing, Geological Publishing House, 239 p. (in Chinese with English summary).

Şengör, A. M. C., 1987, Tectonic subdivisions and evolution of Asia: Istanbul Technical University Bulletin, v. 40, p. 355–435.

Şengör, A. M. C., Cin, A., Rowley, D. B., and Nie, S. Y., 1993, Space-time patterns of magmatism along the Tethysides: A preliminary study: Journal of Geology, v. 101, p. 51–84.

Summerfield, M. A., 1991, Global geomorphology: New York, Longman, 537 p.

Wang, H. Z., chief compiler, 1985, Atlas of the paleogeography of China: Beijing, Cartographic Publishing House, 85 p.

Wang, H. Z., Xu, C. Y., and Zhou, Z. G., 1982, Tectonic development of the continental margins on both sides of the Qinling marine realm: Acta Geologica Sinica, v. 63, p. 270–280 (in Chinese with English abstract).

Wang, X. M., Liou, J. G., and Maruyama, S., 1992, Coesite-bearing eclogites from the Dabie Mountains, central China: Petrogenesis, P-T paths and implications for regional tectonics: Journal of Geology, v. 100, p. 231–252.

Yin, A., and Nie, S. Y., 1993, An indentation model for the North and South China collision and the development of the Tan-Lu and Honam fault systems, eastern Asia: Tectonics, v. 12, p. 801–813.

Zhao, W. J., Nelson, K. D., and Team, P. I., 1993, Deep seismic reflection evidence of continental underthrusting beneath southern Tibet: Nature, v. 366, p. 557–559.

Zhao, X. X., and Coe, R., 1987, Paleomagnetic constraints on the collision and rotation of North and South China: Nature, v. 327, p. 141–144.

Zhou, D., and Graham, S. A., 1993, Songpan-Ganzi Triassic flysch complex as a remnant ocean basin along diachronous Qinling collisional orogen, central China: Geological Society of America Abstracts with Programs, v. 25, no. 6, p. 118.

Manuscript received April 5, 1994
Revised manuscript received July 12, 1994
Manuscript accepted July 22, 1994

 Printed in U.S.A.