Mesozoic basin development and tectonic evolution of the Dabieshan orogenic belt, central China

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[1] The Dabieshan orogenic belt is a zone of long-lived shortening with late-stage extension that formed during Mesozoic time in central China. Regional basin analysis coupled with structural cross sections provides a means of reconstructing the paleogeography of the region from Triassic continental collision through early Tertiary extension. The overall distribution of different basin types in the orogenic belt indicates that there was a prolonged period of shortening throughout the Mesozoic that became less intense over time. Meanwhile, extension became more common from Jurassic into Tertiary time. Either compression or extension was isochronous but limited to different geographic regions and/or crustal levels or alternated repeatedly orogen-wide through time. Nonetheless, the orogen underwent gradual transition from overall shortening and crustal thickening to dominantly extension and rift basin formation although these events overlapped in time from the Jurassic through Early Cretaceous. Penecontemporaneous compression and extension across the orogen may reflect long-term (>100 m.y.) shortening and crustal thickening leading to gravitational spreading of the resultant thick crustal welt. We suspect that this prolonged history of shortening across two nearby (~100 km apart) suture zones played some role in the exhumation of ultrahigh-pressure rocks from beneath the Dabieshan. *INDEX*

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1. Introduction

[2] The late Paleozoic to early Mesozoic history of China includes large-scale continental collision (North China-Yangtze continental fragments), which generated a complex suture zone that trends east-west across the entire country (from east to west: the Dabieshan, Qinling, and Kunlun ranges; shan denotes mountain range). While the evolution of the Qinling Range is well known [Zhang *et al.*, 1995, 2001; Meng and Zhang, 1999, 2000; Liu and Zhang, 1999], the eastern limits of deformation are primarily constrained by petrologic and structural studies of metamorphic rocks in the core of the Dabieshan [e.g., Maruyama *et al.*, 1994; Liou *et al.*, 1996; Suo and Zhong, 1999; Zhong *et al.*, 1999; Wang and Cong, 1997, 1999; Suo *et al.*, 2000; Hacker *et al.*, 2000; Ratschbacher *et al.*, 2000; Zhang *et al.*, 2000]. Postorogenic erosion has removed many of the supracrustal units, limiting structural reconstructions of this area. However, sedimentation into adjacent foreland basins provides another constraint on at least the late stages of collisional deformation of the Dabieshan. Such information adds to our understanding of the orogen-parallel evolution of this major continental suture.

[3] Mesozoic deformation of the Dabieshan orogenic belt (Figure 1a) includes the final stages of continental collision and subsequent shortening that continued from late Paleozoic through Early Cretaceous time [Liu, 1997]. In latest Jurassic time, rift deformation of the Dabieshan began, representing collapse of the orogen. Ever since ultrahigh-pressure metamorphic (UHP) rocks were first discovered in the Dabieshan [Okay *et al.*, 1989; Xu *et al.*, 1992a, 1992b], the area has received much attention. Geochronology and metamorphic studies suggest that the UHP rocks formed during subduction of the Yangtze plate under the North China plate at 220–240 Ma [e.g., Cong, 1997; Wang and Cong, 1997; Liou *et al.*, 1996; Li *et al.*, 1993]. Subsequently, the UHP rocks were exhumed in two phases, at 226–219 Ma and 180–170 Ma [e.g., Li *et al.*, 1999; S. Li *et al.*, 2000; Li *et al.*, 2002; Liu *et al.*, 2001a; Chen *et al.*, 1995]. Some authors

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suggest the time between the two exhumation events was a period of relative quiescence [S. Li *et al.*, 2000; Liu *et al.*, 2001a]. In addition, the Dabieshan core underwent another rapid doming episode in the Early Cretaceous (130–110 Ma) [Li *et al.*, 2002]. Unfortunately, much of the structural evidence of orogeny has been eroded away; therefore here we attempt to reconstruct the orogenic evolution of the Dabieshan by combining available structural and petrologic constraints with the sedimentary history recorded in adjacent basins.

[4] The Middle Yangtze Basin bounding the southern margin of the Dabieshan and the Hefei Basin along the northern margin contain thick sedimentary fills of Late Triassic through Jurassic age. In addition, there are several small basins within and beside the mountain range filled with Upper Jurassic through Lower Tertiary rocks. These basins provide a relatively continuous record of source-area deformation and unroofing. The structure, sedimentation and provenance of these basins allow us to develop a framework for deformation and exhumation of the orogen.

2. Tectonic and Structural Style of the Orogenic Belt

[5] The Dabieshan orogenic belt is linked with the East Qinling orogenic belt across the Nanyang Basin [Zhang *et al.*, 1997] (Figure 1a). The structural stacking of thrust plates and basement rocks exposed in the ranges are identical [Liu, 1997]. The two main suture belts bounding the Qinling Range, the Shangdan and Mianlue belts, are exposed, respectively, in the northern Dabieshan, between Nanyang and Xinyang, along the Xinyang-Shucheng fault, and in the southern Dabieshan, along the Xiangfan-Guangji fault (XGF) [Zhang *et al.*, 2001; Liu, 1997] (Figure 1a). Bounded by the these sutures, the Dabieshan orogenic belt contains, from north to south, the North China plate, the Qinling-Dabieshan plate and the Yangtze plate (Figure 1). In addition, the orogen can be broken into three generalized structural units: the northern Yangtze fold-thrust belt (NYFB) along the southern margin; the North Huaiyang fold-thrust belt (NHFB) along the northern margin; and the axial Dabieshan core zone [Liu, 1997] (Figure 1b).

[6] The basis for structural interpretations shown in Figure 2 are three cross sections, mapped between 1995

and 2001 by the first author, and two other cross sections taken from Zhao *et al.* [2000] and Liu [1998]. The cross sections incorporate previous mapping, petrologic studies and geophysical cross sections from various published and unpublished sources including: Liu [1997], Northwest University (Xi'an, China), Dai *et al.* [2000] and the SINOPEC Company.

2.1. Northern Yangtze Fold-Thrust Belt (NYFB)

[7] The NYFB is discontinuously exposed along the southern Dabieshan (Figure 1). The fold-thrust belt extends 150 km southward from the XGF (Figure 1a). The XGF locally buries older deformation including the Mianlue suture and the NYFB. The NYFB is also unconformably overlapped by Cretaceous to early Tertiary deposits of the Jiangnan Basin, formed during later rifting. The thrust belt pinches out to the west along a basement high, the Huangling dome (Figure 1b). To the east the thrust belt is buried by thrust Dabieshan basement near the city of Guangji (Figure 1). Thrusted chert and carbonate rocks of Paleozoic age [Liu and Zhang, 1999; Feng, 1991; Feng *et al.*, 1997] found in the NYFB, as well as local ophiolite remnants [Dong *et al.*, 1999; Lai and Zhang, 1996] caught up in the XGF, suggest that the older Mianlue suture between the Qinling-Dabieshan and Yangtze plates is cutoff at depth below the Dabieshan [Zhang *et al.*, 2001]. The abundance of deep marine sedimentary rocks suggests that in late Paleozoic time a now closed ocean basin existed between the two plates [Liu and Zhang, 1999]. The fold-thrust belt also involves younger sedimentary rocks (T_3 - J_2), particularly to the south that had been deposited in its adjacent foreland basin (Figure 2a). To the south of the NYFB the northward verging Jiangnan fold-thrust belt started at about the same time as, and continued later than, the NYFB (Figures 1, 2b, and 2c).

2.2. North Huaiyang Fold-Thrust Belt (NHFB)

[8] The NHFB is found north of the Dabieshan core (Figures 1b and 2a). The belt extends over 100 km northward from the Xiaotian-Mozitan fault (F20 on Figure 1a). Cross-cutting relationships and age of basin-filling deposits demonstrate that the NHFB was a long-lived (Triassic-Early Cretaceous) thrust deformation belt but superposed by several periods of supracrustal extension during the latest Jurassic to Cretaceous [Z. Li *et al.*, 2000] (Figures 2a, 2d,

Figure 1. (opposite) Tectonic framework of basins and orogen in Dabieshan and adjacent region. (a) Map showing distribution of basins, sutures and major faults. (b) Simplified map of major structural belts and the location of cross sections in Figure 2. Ages of basin fills are as follows: T_3 - J_2 , Late Triassic to Middle Jurassic; J, Jurassic; J_3 - K_1 , Late Jurassic to Early Cretaceous; K_1 , Early Cretaceous; K_2 -E, Late Cretaceous to early Tertiary; E, early Tertiary. The names of major faults and suture belts are as follows: F1, Shangdan suture (Xinyang-Shucheng fault); F2, Xiangfan-Guangji fault (XGF) (which buried the Mianlue suture); F3, Luonan-Luanchuan fault; F4, Northern boundary fault of Qinling Range; F5, Tanlu fault; F6, Jiangnan thrust fault; F7, Yangri fault; F8, Feizhong fault; F9, Liu'an fault; F10, Lower Detachment Zone; F11, Middle Detachment Zone; F12, Upper Detachment Zone; F13, Top Detachment Zone; F14, Tongcheng fault; F15, Jingmen fault; F16, Hanshui fault; F17, Honghu fault; F18, Tuanma fault; F19, Heshengqiao fault; F20, Xiaotian-Mozitan fault. Other abbreviations are as follows: CM, core complex zone; UHP, ultrahigh-pressure metamorphic unit; HP, high-pressure metamorphic unit; EB, epidote-blueschist metamorphic unit; DC, depositional cover. Map units follow the usage of Suo *et al.* [2000]. Inset map shows major faults and sutures of China from Liu *et al.* [1997].

Figure 2. Structural cross sections from the Dabieshan area. Location of sections A, B, C, D and E are shown in Figure 1. Sections show (a) the entire Dabieshan orogenic belt; (b) the North Yangtze fold-thrust belt (NYFB); (c) the northern margin of the Jiangnan fold-thrust belt; (d) the North Huaiyang fold-thrust belt (NHFB), modified from *Zhao et al.* [2000]; (e) the southern margin of the NHFB, modified from *Liu* [1998]. Ages of units shown are Ar₂, middle Archean; Pt₁₋₂, Early to Middle Proterozoic; Pt₃, Late Proterozoic; Z, Sinian (equivalent to Vendian); Pz₁, early Paleozoic; Pz₂, late Paleozoic; C, Cambrian; O, Ordovician; S, Silurian; D, Devonian; C, Carboniferous; P, Permian; T, Triassic; T₁, Early Triassic; T₂, Middle Triassic; T₃₋₄, Upper Triassic to Middle Jurassic; J₁, Lower Jurassic; J₂₋₃, Middle to Upper Jurassic; J_{3-K1}, Uppermost Jurassic to Lower Cretaceous; K₂, Upper Cretaceous to Tertiary; Q, Quaternary.

and 2e). At the southern end of the NHFB, rocks involved in thrusting include, from south to north: metamorphic rocks of the Dabieshan core; medium- to low-grade metamorphic rocks of Neoproterozoic to early Paleozoic age (Shangcheng and Meishan Groups) and early Paleozoic-Devonian age (Fuziling Group and Xinyang Group); and late Paleozoic sedimentary rocks (Nanwan Formation and Yangshan Group) [Liu *et al.*, 2001b] (Figure 2e). These units prove to be useful compositional indicators of source area evolution during foreland basin sedimentation.

2.3. Dabieshan Core Zone

[9] The central core of the Dabieshan includes a variety of high-pressure metamorphic rocks formed from various protoliths [e.g., Okay *et al.*, 1989; Xu *et al.*, 1992a, 1992b; Li *et al.*, 1993; Maruyama *et al.*, 1994; Liou *et al.*, 1996; Wang and Cong, 1997; Zhang *et al.*, 2000]. Included in the core are ultrahigh-pressure metamorphic rocks (UHP) ranging up to blueschist grade. These UHP rocks originally formed at 220–240 Myr ago at depths possibly in excess of 100 km [e.g., Hacker *et al.*, 1995; Cong and Wang, 1999] during subduction of the Yangtze block under the North China block. Geochronology, evidence of retrograde metamorphism and structural interpretation indicate later episodes of rock uplift took place episodically between Late Triassic (~230 Ma) and earliest Tertiary (~60 Ma) time [Wang and Cong, 1997; S. Li *et al.*, 2000; Chen *et al.*, 1995; Liu *et al.*, 2001a; Wang and Yang, 1998]. S. Li *et al.* [2000, 2002] found evidence for two episodes of rapid exhumation recorded in the UHP rocks and one episode of rapid doming recorded in the Dabieshan core. They suggested that the first exhumation event (226–219 Ma) brought UHP rocks to lower crustal depths possibly caused by compressional extrusion. The second exhumation event (180–170 Ma) brought the UHP rocks to the middle-upper crustal depths may have been related to extensional detachment. The final exhumation event (130–110 Ma) occurred during doming of the Dabieshan core. Suo *et al.* [2000] instead suggest one period of rapid extensional exhumation of these deep core rocks during Early to Middle Jurassic time (200–170 Ma), while foreland basin sedimentation took place adjacent to the Dabieshan. The entire Dabieshan core was thrust southward along the XGF during Late Jurassic to Early Cretaceous time over the NYFB.

2.4. Late-Stage Extension

[10] Superimposed across the entire orogen during the late stages of shortening, are a series of isolated extensional basins that overlie shortened basement. These basins locally contain more than 1 km of fluvial and lacustrine deposits. Structural studies suggest that primary extension directions varied from northeast-southwest during latest Jurassic and Cretaceous time to nearly east-west during early Tertiary time [Liu, 1997]. The early rift basins, seen on cross sections D-D' and E-E' (Figures 2d and 2e), are small, isolated features that developed along the northern part of the orogen core contemporaneous with continued thrusting along the flanks of the orogen. Later on rifting was

widespread and developed on top of the previously shortened thrust belt.

3. Basin-Filling Evolution

[11] Foreland basins on both sides of the Dabieshan orogen record Mesozoic deformation and denudation of the evolving source areas. To the south, the Middle Yangtze Basin developed from Late Triassic through Middle Jurassic time. To the north of the orogen lies the Hefei foreland basin (Jurassic). In addition, extensional basins described above began to develop locally within the orogen core during latest Jurassic time and orogen wide beginning in the Late Cretaceous and continuing through the early Tertiary (Figure 3). Age control in these basins is provided by the national stratigraphic study results in China finished in 1996 [Chen *et al.*, 1996; Chen and Wu, 1997; Li and Jiang, 1997].

3.1. Middle Yangtze Foreland Basin

[12] The foreland basin south of the Dabieshan received sediment from the orogen core from Late Triassic through Middle Jurassic time. These deposits are primarily fluvial in origin with southerly paleoflow orientations. The basin was later incorporated into the southward advancing thrust belt and so has been locally structurally disrupted. This basin is further subdivided into two subbasins, the Dangyang Basin to the west and the Southeast Hubei Basin to the east (Figure 1a), as a younger basin, the Jiangnan Basin (Cretaceous to early Tertiary) overlies and separates the two areas. Because later thrusting buried the northern part of the Southeast Hubei Basin, only the most distal basin deposits are exposed there. As a result we concentrate here on the Dangyang Basin, which is better exposed and contains a more complete record of proximal foreland basin sedimentation.

[13] A long, continuous stratigraphic section exposed northeast of Yichang (S-1, Figure 1a) provides a representative record of Late Triassic sedimentation (Figure 4). Early Jurassic deposits are represented by another section measured nearby (Figure 5). The basal part of the foreland basin fill rests unconformably upon an older, Middle Triassic, shallow marine sequence (the Badong Formation) that formed prior to initiation of exhumation in the Dabieshan. The Dangyang Basin sequence consists of six depositional phases. Above the basal unconformity is a conglomeratic channel fill sequence (1 m) that fines upward into tabular cross bedded sandstones (16 m). This channel deposit can be found regionally and likely records transient sedimentation as thrust belt deformation began. Immediately above the basal conglomerate is 70 m of the Jiuligang Formation (Figure 4). This section is mostly massive bioturbated siltstones with carbonate nodules. The overall lithologic similarity with the underlying Badong Formation, widely thought to be tidal in origin [Wang *et al.*, 1993], possibly suggests a similar depositional setting.

[14] The second depositional phase is a section about 370 m thick consisting of the upper Jiuligang Formation (Figure 4). This unit consists of a series of fining upward sequences that is interpreted to record meandering stream/floodplain sedimentation. Sand bodies represent channel

Figure 3. Upper Triassic through Lower Tertiary unit names for foreland and rift basins, age data for ultrahigh-pressure (UHP) rocks [Cong, 1997; Suo et al., 2000; Li et al., 2002], and formation and rapid exhumation episodes of UHP rocks and rapid doming episode of Dabieshan core [S. Li et al., 2000; Li et al., 2002]. Ruled pattern represents hiatuses; dark shading highlights times of compressional deformation. Timescale is from Remane [2000].

belts and adjacent mudstones are overbank deposits, including levee deposits and floodplain lakes (Figure 4).

[15] The third phase of sedimentation is found in the Wanglongtan Formation (Figure 4) that is dominantly composed of nested channel filling medium-grained sandstones. The unit is 845 m thick. We interpret these deposits as laid down by braided streams. Paleocurrent indicators (cross beds) suggest paleoflow was to the west-southwest (Figure 4). The braided stream sequence is broken up by three thick intervals of mudstone 12- to 50-m thick, which may represent intervals of lake formation.

[16] The upper part of the Danyang Basin fill is best exposed in section S-2 (Figures 1a and 5) to the southeast of the first section. This section, composed of the Tongzhuyuan Formation, is broken into two phases of deposition. The base of the fourth phase everywhere contains a thick conglomeratic, fining upward channel sequence, reaching up to 40 m thick. The next 250 m of the phase contains two cycles of overall coarsening and thickening upward deltaic deposits. This entire interval of deltaic deposits likely formed along the shores of isolated, small lakes that are typical in this part of China in Early Jurassic time [Chen et al., 1996].

[17] The last (fifth) phase of basin filling in the Danyang foreland consists of a thick interval (460 m) of channel-filling sandstones, conglomeratic toward the base. Channels are

most abundant in the lower 120 m and upper 50 m of the interval. The middle part is finer grained, dominantly mudstone with some isolated fining upward channel sand bodies. Paleoflow, based on cross bed foresets, was to the south-southeast (Figure 5).

[18] Middle Jurassic deposits overlie these deposits in the Danyang Basin but are very poorly exposed. Well log data indicate a thickness of at least 740 m for the entire interval. The interval reaches 1050 m in the nearby southeast Hubei Basin [Chen et al., 1996]. The Middle Jurassic consists of the Qianfuyan and overlying Shaximiao formations (Figure 3), which in the nearby Zigui Basin, to the west, is composed of various deltaic and lacustrine mudstones and sandstones. However, in the Zigui Basin the entire Middle Jurassic interval reaches about 2800 m thick.

3.2. Hefei Basin

[19] The Hefei Basin is mainly filled with coarse clastic rocks of the Fanghushan, Sanjianpu and Fenghuangtai formations (Figures 3 and 6). The basin deposits unconformably overlie Archean rocks of the Huoqiu Group of the North China basement. The Fanghushan Formation, not exposed at section S-3, is mainly composed of fluvial deposits, including conglomerate at its base and, in its upper

Figure 4. Stratigraphic section through Upper Triassic units measured along the road between the towns of Jiuligang and Xiaoping in Yuanan County, Dangyang Basin (location S-1 on Figure 1a). Interpreted depositional environments are shown. Depositional phases are described in text. Paleocurrent directions (n is number of measurements) are taken from foreset orientations.

Figure 5. Stratigraphic section through Lower Jurassic units measured along road between towns of Guodiken and Gaodaohang in Jinmen City, Dangyang Basin (location S-2 on Figure 1a). See explanation in Figure 4.

part, isolated channel belt sand bodies distributed among floodplain siltstones [Z. Li *et al.*, 2000]. The entire Fanghushan Formation is at most 400 m thick. The overlying Sanjianpu Formation, measured at location S-3 (Figure 1a) is about 1850 m thick and consists of mostly mass flow and braided stream conglomerate (Figure 6). The lower part of the unit is composed of massive pebble conglomerate with internal scour surfaces. The middle part of the Sanjianpu Formation is coarse to medium sandstone with local conglomerate lenses that are composed of large-scale planar tabular cross beds. The upper part of the Sanjianpu Formation is a generally fining upward megasequence (>1000 m thick) that is cobble conglomerate at its base to granule-pebble conglomerate toward the top. Paleocurrent indicators, from imbricated gravel and cross bedding orientations, are toward the north-northeast.

[20] The Fenghuangtai Formation is extremely thick (2400 m) and very coarse grained (boulder to cobble conglomerate) (Figure 6). The gravel sequence contains units consisting of grain-supported, imbricated, thick beds as well as units of massive, matrix-supported conglomerate. Paleoflow, determined from imbricated grains, is toward the northeast.

[21] The entire Hefei Basin section at S-3 (Figure 1a) is interpreted to record alluvial fan and braid plain sedimentation derived from the Dabieshan to the south. Conglomerate composition is dominantly medium to low-grade metamorphic and sedimentary rocks with a smaller amount of high-grade metamorphic clasts (Figure 6). The entire basin sequence is up to 6 km thick at the southern end of the basin. Toward the north in the Hefei Basin there is a gradual decrease in total fill thickness, maximum grain size, and abundance of mass flow deposits [Z. Li *et al.*, 2000]. Fossils, although present in the Early Jurassic Fanghushan Formation [Li and Jiang, 1997; Bureau of Geology and Mineral Resources of Anhui Province, 1987], are not found in the Sanjianpu and Fenghuangtai formations. However, ^{40}Ar - ^{39}Ar dates on four illite samples from mudstone in the Sanjianpu Formation gives plateau ages of 160–158 Ma [Wang *et al.*, 2000]. The Maotanchang Formation that unconformably overlies the Fenghuangtai Formation, contains fossils *Ferganoconcha lingyuanensis*, *Carbicula*, *Sphaerium jeholense* of bivalves, *Probaicalia* of gasteropod and *Eosuthoria* of estherians which represent Late Jurassic deposition [Li and Jiang, 1997]. Thus the entire interval shown on Figure 6 runs from the Middle Jurassic to Late Jurassic time.

3.3. Rift Basins

[22] In addition to the major times of foreland basin formation described above there were also three episodes of rift basin formation across the Dabieshan and on top of the adjacent fold-thrust belts. The interpretation of a rift origin for these basins hinges on their association with basin flanking normal faults (Figures 2a, 2b, 2d, and 2e). The first phase of rift basin development took place during latest Jurassic through Early Cretaceous time mainly along the northern flank of the Dabieshan core zone, between faults F1 and F20 (Figures 1a and 2e). These rift basins are composed of pyroclastic rocks, lacustrine mudstones and alluvial sand-

stones and conglomerate. The best defined of these small basins is the Xiaotian Basin (Figure 1a). Here the basin fill includes the Maotanchang Formation (Uppermost Jurassic) [Wang *et al.*, 2002], composed of various andesite and trachytic flows of calc-alkalic to alkalic composition interbedded with lacustrine mudstone. K-Ar dating [Wang *et al.*, 2002] of volcanics within the Maotanchang Formation yields an age range of 149–138 Ma. Overlying this unit is the Heishidu Formation that contains abundant conglomerate and sandstone of alluvial fan, braided stream and fan delta origin [Z. Li *et al.*, 2000]. This unit is capped by the Xiaotian Formation composed of lacustrine mudstones with increasing abundance of thin turbidite sandstones in the upper part. The Xiaotian Formation contains the fossils *Nakamuranaia* of bivalves, *Yanjiestheria* and *Neodiestheria* of estherians [Li and Jiang, 1997] representing Early Cretaceous deposition. Thus the entire basin fill forms an overall fining upward sequence, more than 2000 meters thick that formed during late Late Jurassic and Early Cretaceous time [Z. Li *et al.*, 2000]. The southern flank of the Xiaotian Basin is defined by the Xiaotian-Mozitan normal fault that trends WNW. The fault dips to the north at the angle of 50°–60° (Figure 2e), as determined by well and field data [Xu, 1994; Liu, 1998; Bureau of Geology and Mineral Resources of Anhui Province, 1987]. Basin fill coarsens toward this flanking fault with locally more than 2500 m of conglomerate and pyroclastic rocks. The juxtaposition indicates that normal faulting occurred during deposition.

[23] The second phase of rift basin development took place during Late Cretaceous time and was followed by a third phase during early Tertiary time. The phases are distinct in that the earlier phase developed elongate rift basins along and parallel to the orogenic belt, whereas the latter phase formed along faults that cut across the entire region at high angles to the orogenic belt. Basins of the second phase developed along the southern side of the Dabieshan and include the Yuanan, Luoxiangguan and Hanshui Subbasins in the northwestern part of the Jiangnan Basin, which are defined by northeast dipping normal faults (the Tongchenghe, Jingmen and Hanshui faults, respectively) (Figures 1a and 2a). The second phase of rift basins along the northern side of the Dabieshan mainly overlap the Jurassic foreland basin belt. These basins are mostly interpreted as rift related because they are bounded by south dipping normal faults (Figures 1a and 2d). Most of the normal faults defining the rift basins in both sides of the Dabieshan are the reactivated older thrust faults. Later-stage basins include the Nanyang, Macheng, and Jiangnan Basins, which are bounded by NNE trending normal faults (F17 and F18, Figure 1a). All of the basin-filling deposits are similar in that they initiate with relatively coarse-grained alluvial fan and/or deltaic deposits that overall fine upward into lacustrine mudstones [Dai *et al.*, 2000]. Phase two and three basin fills are quite thick ranging from 3350 m in the Yuanan Basin up to 9000 m in the Nanyang Basin.

4. Composition of Basin Fill

[24] The unroofing history recorded in gravel and sandstone composition of the Dangyang and Hefei Basins

provides a useful indicator of the rock uplift and erosional evolution of the adjacent orogenic belt. Dangyang Basin is dominated by sandstones, whereas the Hefei Basin contains abundant gravel. Therefore different techniques

were used to identify composition of these different grain sizes.

[25] Sandstone compositions were determined as follows. Hand samples were collected in the field. Roughly five

samples were collected at intervals of approximately 50 m where exposure was good and grain size was relatively coarse (medium- to coarse-grained sandstone). In areas of poor exposure and/or small grain size fewer samples were collected. Thin sections were made and 200 to 350 framework grains were counted per slide. Since the Dabieshan has a wide range of rock types exposed, lithic grain composition is the most useful indicator of source area. Thus we show only the results for lithic composition, which typically represents less than 15% of all the grains counted. However, studies have demonstrated that lithic grain abundance is, in part, a function of grain size [Suttner *et al.*, 1985]; thus although we show results as percentages, we realize that to some degree these reflect sandstone grain size. Nonetheless, given the general consistency of grain size we believe compositional percents are useful as qualitative source area indicators.

[26] In areas where gravels are abundant, particularly in the Hefei Basin, we collected both gravel clast data in the field and collected sandstones within the conglomerate. Sandstones were identified as described above. Gravel clasts were described at five locations in the Hefei Basin. In each case nearly every grain in an area of 2 m² was identified, typically 30 to 80 clasts.

[27] Results for composition of lithic grains are shown for the Hefei Basin (Figures 6 and 7) and Dangyang Basin (Figure 8). Percentages shown on Figures 7 and 8 are normalized percent of the total lithic content. The composition results in Figure 9a are shown as petrofacies consisting of groups of lithologies that are found together in different source regions (Figure 9b), thus defining distinctive provenance. Source areas along the northern part of the Dabieshan are designated with roman numerals, along the southern flank of the range the numerals are primed (e.g., I', II', etc.). Source areas with similar composition, regardless of whether found on the north or south flank of the range, have the same Roman numeral (Figure 9).

[28] Lithic petrofacies I and I' come from gneiss and migmatite source areas exposed along both sides of the Dabieshan core (labeled CM on Figure 1b). Petrofacies II and II' contain granite and diorite clasts. Late Triassic granite and diorite are locally exposed along the southern margin of the Qinling-Dabieshan [Li and Sun, 1996; W. Sun *et al.*, 2000]; however, today there is no outcrop of this source rock in the northern Dabieshan. Such northern source areas did exist during Mesozoic time [Liu *et al.*, 2001a]. Petrofacies III and III' contain medium- to low-grade metamorphic rocks including quartzites, quartz-schists, schists, phyllites, granulites and slates. To the north of the Dabieshan, this source includes the Luzhenguan, Meishan and Fuziling groups (Late Proterozoic to Devonian) as well as some reworked clasts derived from the

Yangshan Group (Late Devonian) exposed between faults F1 and F20 (Figure 1a). To the south of the Dabieshan, the source area for petrofacies III' includes Middle Proterozoic rocks distributed along the southern Dabieshan. However, there is never very much petrofacies III' material found, implying that this source area was not much exposed during deposition.

[29] Petrofacies IV and IV' includes reworked sandstone and mudstone clasts and low-grade metamorphic argillites and sandstones. The source for these grains along the northern side of the mountain belt is the Yangshan Group (Late Devonian to Carboniferous). Petrofacies IV', south of the mountain belt, also includes sericitic sedimentary fragments possibly derived from Silurian rocks of the Dabieshan core zone. Petrofacies V and V' include intermediate to siliceous volcanic rocks, probably derived from the arc volcanics. A possible source area along the southern side of Dabieshan is now buried rocks of the Mianlue suture. However, it is not clear what source provided these compositions to the north. Petrofacies VI' and VII', along the southern side of the range, contains abundant chert and limestone fragments, respectively. These compositions most likely were derived from Paleozoic to Triassic sedimentary units in the Mianlue suture.

4.1. Hefei Basin

[30] The results for section S-3 (Figures 6, 7, and 9), in the Hefei Basin, show input from six source areas. Igneous rocks both extrusive (trachyte, liparite and andesite; petrofacies V) and intrusive (granite and diorite; petrofacies II) are found in the orogen, however, all known exposures are of Latest Jurassic and Cretaceous ages so they could not be the source for lithic fragments and pebbles in Jurassic units. No rocks of suitable composition and age are known in the Dabieshan [Liu *et al.*, 2001a]. However, geochronology on these detrital grains (214 Ma, U-Pb zircon [Liu *et al.*, 2001a]) suggests that suitable sources were in existence during early Mesozoic time within the orogen. A minor amount of various other lithic compositions (VI) are also found.

[31] The lithic petrofacies for section S-3 suggests two distinct unroofing sequences (Figure 7). From the base of the Sanjianpu Formation to the lower part of the Fenghuangtai Formation there is a gradual change in composition. The basal rocks, lithofacies 1, mostly contain reworked sedimentary rocks derived from the most northern flanks of the orogen. The overlying deposits, lithofacies 2, show a marked increase in abundance of moderately high-grade metamorphic rocks from the orogen core. Lithofacies 3, at the top of this sequence, has an increase in medium- to low-grade metamorphic source rocks; therefore these deposits

Figure 6. (opposite) Middle-Upper Jurassic stratigraphic section measured on road between town of Liushudian to Dingbachong Village in Jinzhai County, Hefei Basin (location S-3 on Figure 1a, modified from Liu *et al.* [2001b]). Table shows normalized lithic composition from thin sections (asterisk) and gravel counts (number symbol) for various locations indicated by solid circles next to the stratigraphic column. Dashed values in composition table are less than 1%. Lithofacies are either debris flow deposits (DF) or braided river deposits (BCH). Maximum grain sizes are as follows: S, sand; G, granule; P, pebble; C, cobble; B, boulder. Compositional data are grouped together (A–G) and shown on Figure 7.

Figure 7. Lithic petrofacies summary from section S-3, Hefei Basin, grouped into five lithofacies discussed in text. Data come from Figure 6 (A–G).

contain a complete mix of compositions representing input from all source areas (i.e., polymict). The overlying middle to upper parts of the Fenghuangtai Formation contains a second unroofing sequence, again beginning with dominantly sedimentary clasts (lithofacies 4) shifting to a polymict composition with abundant medium- to low-grade metamorphic and sedimentary source rocks (lithofacies 5) at the top of the sequence.

[32] The first occurrence of relatively high-grade metamorphic rocks (lithofacies 2) as detrital grains in the Sanjianpu Formation indicates that the metamorphic core of the Dabieshan was exhumed and exposed during Middle-Late Jurassic time. This occurrence, along with detrital grains of UHP rocks derived from the Dabieshan core showing up in the Fenghuangtai Formation of the Hefei Basin [Wang *et al.*, 2001], indicates that significant rock unroofing of the deep core was complete by Late Jurassic time. This result is consistent with the timing (between 214 and 166 Ma), exhumation rates (0.08 to 0.4 km/Myr) and process (exhumation from middle crust to the surface) determined for the northern Dabieshan by other compositional unroofing studies [Liu *et al.*, 2001a].

[33] The fact that there are two unroofing cycles seen in the stratigraphic section of the Hefei Basin suggests that there were at least two episodes of rock uplift in the source area. In addition, the rapid transition between source areas of different metamorphic grade from lithofacies 3 to lithofacies 4 (Figure 7) suggests that unroofing within each cycle was also related to individual thrust events.

[34] It is interesting to note that the major change in depositional style of basin filling in Hefei Basin (Figure 6) indicated by the change from the Sanjianpu Formation coarse sandstone deposits to conglomerates of the Fenghuangtai Formation takes place when there is no change in source-area composition (lithofacies 3) (Figure 7). Detailed geological mapping found that Fenghuangtai Formation overlapped the different part of the Sanjianpu Formation with angular unconformity [Liu *et al.*, 2001b; Liu *et al.*, 1995] indicating deformation took place, but compositional changes did not show up at the same time.

4.2. Dangyang Basin

[35] Samples collected from the Dangyang Basin come from two measured sections (S-1 and S-2) and, for comparison, unpublished data from the Zigui Basin (Shaofeng Liu, 2001), a western continuation of the Dangyang foreland basin some 100 km west of the study area (Figure 8). Within the study area, at S-1 and S-2, compositions indicate an abundance of fine-grained sedimentary and low-grade metasedimentary rocks (petrofacies IV'). The source for these lithologies may be either Silurian age marine fine-grained units that are now only locally exposed within the southernmost Dabieshan core [Zhang *et al.*, 1992] or from more distal flysch deposits of late Middle Triassic age found along the southwestern Qinling Mianlue suture [Zhang *et al.*, 1992] (Figure 9a). The scarcity of medium-grade metamorphic rocks (petrofacies III') from the Middle Proterozoic basement of the Dabieshan core, indicates that these rocks were barely exposed during the Late Triassic

Figure 8. Lithic petrofacies summary from the Danyang Basin (data collected at locations S-1 and S-2, Figure 1a) and from the Zigui Basin, which is located about 100 km to the west of the Danyang Basin.

through Jurassic (Figure 9a). There is an abundance of chert fragments (petrofacies VI') in the Late Triassic through Jurassic deposits of the Danyang Basin (Figure 9a). There are two possible sources for these grains. There are abundant chert beds intercalated with limestones of Permian to Early Triassic age exposed in the NYFB. However, if this were the source we would expect to find at least some detrital limestone grains in the deposits as well. There are no such grains found. In addition, uplift of Paleozoic rocks by the thrust belt did not take place until Late Jurassic time, after deposition of the Danyang deposits as evidence by an abundance of limestone grains in the Penglaizhen Formation in the Zigui Basin (Figure 8). An alternate source area

may be the Mianlue suture belt, now buried by the XGF (Figure 9b). Although rocks of the suture are no longer exposed, it is possible that deepwater cherts, seafloor of the Mianlue Ocean, may be present. In some detrital chert pebbles we have found radiolarians, suggesting a deepwater source.

[36] The same age deposits exposed in the Zigui Basin, 100 km farther west, contain these compositions similar to the Dabieshan, but, additionally, the Middle Jurassic units include andesitic and more siliceous volcanic grains (petrofacies V') (Figures 8 and 9a). The source for any extrusive rocks is no longer found in the Dabieshan. However, much farther west, along the XGF fault in the

Figure 9. (a) Summary of lithic petrofacies in the Hefei Basin (north of Dabieshan) and the Dangyang and Zigui Basins (south of Dabieshan). Data are from Figures 7 and 8. The petrofacies assemblages are arranged in order of how the source areas are distributed from north to south across the Dabieshan. (b) Simplified map of source areas within Dabieshan (from Figure 1). Dashed line shows trace of the buried Mianlue suture that contains source rocks for petrofacies V' and VI'. Data for Cretaceous units at S-4 and S-5 in Figure 9b are our gravel counts.

western Qinling Range, there are limited exposures of arc volcanics of similar composition [Lai and Zhang, 2000], suggesting there were arc rocks of the Mianlue suture exposed to the north of the Zigui Basin, now mostly covered by thrust nappes (Figure 9b). This, in turn, suggests that subduction was occurring in this region by Jurassic time. Also in the Zigui Basin limestone clasts (petrofacies VII') show up in abundance by Late Jurassic time (Figure 9). The most obvious source area for this composition is the

late Paleozoic shelf limestones now seen throughout the NYFB (Figure 9b).

4.3. Rift Basin Compositions

[37] Rift basins developed along the flanks of the Dabieshan during Cretaceous time. The composition of lithic fragments in the Lower Cretaceous Heishidu Formation and Xiaotian Formation counted at four locations in rift

basins located along the northern flank of Dabieshan core zone (S-4 in Figure 9b) are mainly volcanic (39%), medium to low-grade metamorphic (43%), gneissic (11%) and reworked sedimentary rocks (7%). The volcanic rock fragments were derived from the underlying Maotancang Formation, and the medium- to low-grade metamorphic and gneissic rocks came from the nearby northern margin of the Dabieshan core zone (Figure 9a). Conglomerates in the Late Cretaceous rift basins of the southern Dabieshan and along the XGF (S-5 in Figure 9b) mainly include quartzite-schist (38%), gneiss (24%), limestone/dolomite (22%) and cherts (16%) counted at three locations along the southern margin of the Macheng Basin. Source areas for these fragments are the high-grade metamorphic rocks in the Dabieshan core zone and the Early Triassic and late Paleozoic carbonates and cherts in the NYFB (Figure 9). We conclude from rift basin compositions that metamorphic rocks of the northern Dabieshan reached the surface by Jurassic time, but similar rocks of the southern Dabieshan core were not exhumed until Cretaceous time.

4.4. Petrofacies Summary

[38] Petrofacies data from Mesozoic strata in basins north and south of the Dabieshan suggest the relative timing of unroofing of the mountain core (Figure 9). South of the range foreland sedimentation began during Late Triassic time (T_3). Source areas for these rocks include the sedimentary cover of the southern Dabieshan core and/or early Mesozoic flysch basin deposits. No high-grade metamorphic rocks from deeper crustal levels were delivered to basins south of the Dabieshan. The now buried Mianlue suture belt may have provided some detritus to this area, particularly chert fragments. Beginning in Middle Jurassic time (J_2) a volcanic source, possibly an arc, provided some detritus found along the westernmost part of the southern foreland basin belt (the Zigui subbasin). By Late Jurassic time limestones of late Paleozoic through Early Triassic age were being eroded along the NYFB and incorporated into the evolving foreland basin to the south.

[39] To the north of the Dabieshan, sediment delivered to the foreland basin during Middle-Late Jurassic time includes high-grade metamorphic rocks derived from the exhumed core of the range. Thus deep crustal levels had been exhumed along the northern flank of the Dabieshan by the Late Jurassic time whereas similar rock types never reached the surface in Mesozoic time in the southern part of the range. Therefore either exhumation rates were higher and/or the thickness of sedimentary cover rocks was less in the northern part of the Dabieshan than in the southern part of the range.

5. Paleogeographic Reconstructions of the Dabieshan

[40] On the basis of detrital compositions, distribution of lithofacies in basins surrounding the Dabieshan, and available mapping in the region, we have interpreted the paleogeographic history of the area shown as maps (Figure 10) and interpreted large-scale cross sections (Figure 11).

[41] Prior to Late Triassic time, the area underwent two major suturing events (Figures 11a and 11b). The major continental fragments that make up central China, from north to south the North China plate, Qinling/Dabieshan microplate, and Yangtze plate, owe their origins to two episodes of rifting during late Precambrian and Devonian time [Zhang *et al.*, 2001; Liu and Zhang, 1999]. The Shangdan and Mianlue Oceans separated these crustal fragments (Figure 11a). Closure of the Shangdan ocean lead to continent-continent collision beginning in late Paleozoic time [Zhang *et al.*, 2001; Liu and Zhang, 1999]. It is less clear when the Mianlue ocean began to close, because of the absence of preserved arc rocks; however, by Middle Triassic time continent-continent collision in this area had certainly begun (Figure 11b) [Zhang *et al.*, 2001; Liu and Zhang, 1999]. A key feature of the Shangdan suture beginning in Middle Triassic time (240–220 Ma) is the formation of unusually high-pressure (>4.7 GPa), high-temperature ($>820^\circ\text{C}$) metamorphic rocks along the subducting Qingling-Dabieshan continental fragment [Zhang *et al.*, 2000; S. Li *et al.*, 2000]. Structure shown on the Middle Triassic cross section (Figure 11b) within the Mianlue suture zone is not seen in the study area but is generalized from where it can be observed farther west along the Qinling Mountains [Zhang *et al.*, 2001].

5.1. Late Triassic Time (Figure 10a)

[42] During Late Triassic time a foreland basin began to develop along the southern flank of the Dabieshan. Paleocurrent and compositional data indicate sediment derived from the orogen was shed southward into the basin. At this time the source area only included the shallow, supracrustal, sedimentary part of the Dabieshan core zone including exhumed oceanic sedimentary rocks of the Mianlue suture.

[43] Isopachs of the Wanglongtan Formation (late Late Triassic; Figure 10a) [Chen *et al.*, 1996] show a gradual decrease in thickness toward the south with maximum thickness in excess of 1 km, delineating the geometry of the foreland basin. Lithofacies show coarsening toward the mountain front, where braided streams dominated. Elsewhere fluvial deposits fill the exposed parts of the Middle Yangtze foreland basin.

[44] Much of the eastern part of the foreland basin during this time was subsequently overthrust and is not exposed. Both the facies belts and isopach data, where seen, have roughly east-west trends that are abruptly cut off by thrust older rocks. It is during this time (226–219 Ma) that ultrahigh-pressure rocks in the Dabieshan core began to rapidly exhume [S. Li *et al.*, 2000] (Figures 3 and 11c), albeit not to the surface, probably related to continued shortening and crustal thickening during this time.

5.2. Middle Jurassic Time (Figure 10b)

[45] Jurassic was a time of the second rapid exhumation event (180–170 Ma) (Figure 3) [S. Li *et al.*, 2000] in the Dabieshan core and shortening along the north and south flanks of the range. Basin filling in both the Hefei Basin, to the north, and the Middle Yangtze Basin to the south occurred throughout Early and Middle Jurassic time. Although Upper Jurassic rocks may be present in the Hefei

Basin [Liu *et al.*, 2001b], they are absent south of the Dabieshan. The Hefei Basin contains a range of petrofacies suggesting repeated episodes of unroofing, including initial exposure of high-grade metamorphic core rocks, in the northern part of the Dabieshan. An abundance of coarse-grained, fluvial deposits suggest significant relief was developed in the northern core with likely alluvial fan development along the Shangdan suture (Xinyang-Shucheng Fault) (F1). The dominance of coarse-grained fluvial deposits forming successions up to 6 km thick suggests that while subsidence rates were high, so too was the abundance of coarse sediment supplied off of the eroding northern margin of the Dabieshan.

[46] There are those who suggest that Hefei Basin formed by rifting [Wang *et al.*, 1997; Wang and Cong, 1999]; however, interpretation of seismic data [Zhao *et al.*, 2000] shows pervasive reverse faults interfingering with Early and Middle Jurassic deposits in the basin. In addition, the basin shows a simple asymmetric geometry consistent with flexural subsidence and the basin bounding fault, the Xinyang-Shucheng Fault, shows an older-over-younger relationship indicating reverse motion, although this structure may not have been active during deposition.

[47] To the south of the Dabieshan core, the Middle Yangtze Basin contains an overall much finer-grained basin fill than seen to the north. Braid plain deposits are found along the northern parts of the basin and lacustrine deposits fill the distal basin (Figure 10b). The comparatively fine-grained nature of foreland basin fill along the southern flank of the range indicates an underfilled basin, suggesting that sediment supply off of the source area was less copious relative to local subsidence rates than seen at the same time to the north of the orogen. Total sediment thickness during this time in the Middle Yangtze Basin was about 1 km, much less than observed in the Hefei Basin to the north of the orogen.

[48] Composition of basin fill in the Middle Yangtze Basin at this time is still dominated by supracrustal rocks, indicating that the basement core of the southern Dabieshan had not yet reached the surface. While we assume that the Middle Yangtze Basin formed in a foreland setting based on basin geometry and overall coarsening upward fill, we cannot unequivocally demonstrate thrust faults were active during deposition. Farther west, along the flanks of the Qinling Mountains, deposits of this age are well exposed and show an even more strongly developed asymmetry (reaching up to 3 km thick).

[49] Although the flanking basins appear to record overall shortening along the margins of the Dabieshan, deformation within the range core suggests significant extension, and geochemistry of UHP rocks represents a second rapid extensional exhumation at the same time [S. Li *et al.*, 2000]. Overall, the geodynamic driving forces for shortening in this region are a series of long-lived continent-continent collisions that began with the Shangdan suture

(late Paleozoic through Middle Triassic), stepped southward into the Mianlue suture (Middle Triassic through Early Cretaceous) and may include intracontinental subduction of the North China plate along the Northern Boundary Fault of Qinling Range (F4) (Figures 1a, 2a, and 2d) during Cretaceous time [Zhang *et al.*, 1997]. Extension may be the supracrustal response to continued shortening, crustal thickening and isostatic. Unroofing sequences in the flanking basins suggest that exhumation of the core was greatest along the northern Dabieshan. In fact, today, the deepest crustal levels are exposed primarily in the northern part of the range (Figure 10b).

5.3. Late Jurassic-Early Cretaceous Time (Figure 10c)

[50] Relatively little sedimentary record from this time is found in limited areas north and south of the Dabieshan core. Along the north flank of the range, thrusting continued to step basinward (northward) over time. Limited exposure of lacustrine and fan-delta deposition indicate source areas to the south [J. Sun *et al.*, 2000]. Some have suggested that during late Early Cretaceous time intracontinental underthrusting of the North China plate southward beneath the Dabieshan took place (Figures 2a and 2e) [Zhang *et al.*, 1997]. This interpretation is based primarily on seismic evidence of a steep reverse fault offsetting the Moho [Zhang *et al.*, 1996]. South of the active part of the thrust belt between faults of F1 and F20, a series of isolated rift basins developed within the study area and farther west. These basins are bounded by normal faults along their southern margins (Figure 1a and 2e). The most complete rift basin sequence of this time is found near Jinzai (Figure 1a), where the latest Jurassic deposits include pyroclastic units and volcanic flows. Above this sequence is an Early Cretaceous sequence of lacustrine and deltaic units that include sandstones that contain fragments of high-grade metamorphic rocks derived from the core of the range. Geochemistry of the volcanic rocks in the basins and mafic-ultramafic intrusions of the same age in the Dabieshan core suggest derivation in an extensional setting from sources that include mantle and lower crustal sources [Xu, 1994; Li *et al.*, 2002; Wang *et al.*, 2002].

[51] South of the Dabieshan, foreland sedimentation was centered to the west of the study area, into the Zigui Basin, during Late Jurassic and Early Cretaceous time. Within the study area, small basin remnants are found near Yichang (Figure 1a). Thrusting continued along the south flank of the range, and deformed the formerly developed foreland basin deposits in the Late Triassic and Early Middle Jurassic (Figure 2a) and possibly continued motion on the XGF.

[52] Thus thrust deformation continued along both flanks of the range while extension dominated the range core. Rift basins began to form along the north side of the range as well as extensional, primarily as low-angle, detachment

Figure 10. (opposite) Tectonic paleogeographic maps of Dabieshan and adjacent regions for (a) Late Triassic; (b) Middle Jurassic; (c) Late Jurassic; (d) Late Cretaceous; and (e) early Tertiary time. Position of units is not palinspastically restored. Basement symbols and abbreviations are from Figure 1. Isopachs of the Wanglongtan Formation, late Late Triassic, in the Middle Yangtze foreland basin are shown in Figure 10a. Area of each map is identical to that shown in Figure 1.

faults continued to develop in the metamorphic core zone [Suo *et al.*, 2000]. Extension was penecontemporaneous with the last episode of rapid exhumation recorded in the Dabieshan core (130–110 Ma, Figure 3) [Li *et al.*, 2002].

5.4. Late Cretaceous to Early Tertiary (Figures 10d and 10e)

[53] Shortening across the orogen all but stopped by Late Cretaceous time, but extension, seen by the development of rift basins, continued into the early Tertiary. The area over which extension took place increased with time, eventually involving the entire orogen. There was a change, however, in rift fault orientation between Late Cretaceous and early Tertiary time. The major Late Cretaceous faults trend parallel to the orogen, with subsidiary cross faults at right angles (Figure 10d). In early Tertiary time the main basin bounding faults were transverse to the orogen (Figure 10e). These transverse structures controlled late stage exhumation of the Dabieshan core, resulting in abrupt, stepwise changes in depth of crustal levels exposed along the range. To the east, the deepest crustal levels are exposed, including the ultrahigh-pressure rocks and structural windows into high-grade metamorphic rocks of the Yangtze basement. To the west, across fault F18 (Figure 1a), there is limited exposure of deep basement rocks and more preserved Paleozoic cover rocks are found. This region extends westward to the Nanyang Basin, an early Tertiary rift basin. Farther west along the Qinling Mountains even more Paleozoic cover rocks are preserved.

[54] The composition of rift basin sandstones and conglomerates all across the range and flanking areas show that deep crustal levels were exposed across the entire Dabieshan by Late Cretaceous time. Prior to this time high-grade metamorphic basement source areas were only found along the north side of the range.

6. Shortening Versus Extension Across the Dabieshan

[55] As seen in the paleogeographic maps, the time of extension in the Dabieshan overlaps, in part, the period of continued shortening across the range. Shortening in the Dabieshan was nearly continuous from late Paleozoic time, when the Shangdan suture formed by continent collision, through Middle Triassic time, when the Mianlue collisional

suture formed, on into Cretaceous time. In fact, the Early Cretaceous may have been the time of most severe shortening, as seen by the underthrusting of the North China plate along the Northern Boundary Fault of the Qinling Range and the thrust of the Dabieshan core zone along the XGF.

[56] Meanwhile extension across the range seems to have occurred, at least episodically, as shortening continued elsewhere in the range. Suo *et al.* [2000] has dated detachment faulting in the Dabieshan core as beginning around 200 Ma (Early Jurassic). Rift basins began to form locally along the north side of the core zone in latest Jurassic time (Figure 10c) and became increasingly pervasive during Cretaceous into early Tertiary time (Figures 10d and 10e). Thus it would appear that compression and extension took place at the same time, although not necessarily at the same crustal level, in the region. Alternatively, stress fields repeatedly fluctuated over time between compression and extension throughout this period. Regardless, overall the orogen changed from dominantly shortening in early Mesozoic time to dominantly extensional in late Mesozoic to early Cenozoic time.

[57] The cause of extension is not clear. The region had undergone a long history of collision and shortening, including possible initiation of intracontinental underthrusting [Liu, 1997] that likely built a thick crustal root. Isostatic response to crustal thickening may have led to rock uplift and extension in shallow crustal levels. As such this process may have played a role in exhumation of ultrahigh-pressure metamorphic rocks in the core zone [Suo *et al.*, 2000]. However, isostatic response to crustal thickening alone seems insufficient to explain more than 100 km of exhumation needed to unroof these UHP rocks from their likely depth of formation [Hacker *et al.*, 1995]. Nonetheless, it seems likely to us that prolonged shortening along two closely spaced collision zones (the Shangdan and Mianlue suture zones are within ~100 km of each other today) coupled with evidence of extension at supracrustal levels may have played some role in exhuming UHP rocks in the core of the Dabieshan during Mesozoic time.

7. Conclusions

[58] The Dabieshan, in central China, records a prolonged period of continental collision, shortening, foreland basin formation and penecontemporaneous extension at shallow

Figure 11. (opposite) Interpreted cross section showing evolution of Dabieshan from late Paleozoic through early Tertiary time. (a) Late Paleozoic, showing the major plates and intervening oceans. (b) Early Middle Triassic, showing plate collision and formation of the Mianlue and Shangdan suture belts. Cross-hatch pattern shows burial and formation of ultrahigh-pressure (UHP) metamorphic rocks of the Dabieshan core. (c) Late Triassic, showing continued shortening across Dabieshan, extrusion of UHP rocks, and early development of the Northern Middle Yangtze foreland basin. (d) Jurassic, showing onset of extension and exhumation of UHP rocks in the Dabieshan core while shortening continues along the flanks of the range. The Hefei foreland basin forms north of the Dabieshan. (e) Latest Jurassic to Early Cretaceous, showing continued extensional exhumation of the UHP in the core zone while shortening continues along the range flanks. Rifting of the northern part of the Dabieshan begins. Underthrusting of the North China plate beneath the Dabieshan (along the Northern Boundary Fault of Qinling Range) takes place during this time. (f) Late Cretaceous through early Tertiary, showing regional extension across the entire Dabieshan. Underthrusting of the North China plate ceases during this time. Abbreviations are as follows: YZ, Yangtze plate; QD, Qinling-Dabieshan plate; NC, North China plate; SDB, southern Dabieshan; NDB, northern Dabieshan. Cross sections incorporate those shown by Zhang *et al.* [2001] and Suo *et al.* [2000].

crustal levels during Mesozoic time. The timing and style of tectonism in the region is aided by interpretation of preserved basin deposits atop, and adjacent to, the orogen. This basin-filling history, along with constraints placed by regional structural and petrologic studies, provides the basis for paleogeographic reconstruction of the area.

[59] Lithic composition of basin clastics records unroofing of the Dabieshan core suggesting asymmetry of exhumation across the range. To the north of the orogen, a foreland basin developed in Early Jurassic time, the Hefei Basin, that tapped source areas in the high-grade metamorphic rocks of the northern part of the Dabieshan core. By latest Jurassic time, foreland deformation migrated to the north of the Hefei Basin.

[60] Along the southern margin of the Dabieshan, foreland basin sedimentation of the Middle Yangtze Basin (exposed today as two subbasins the Dangyang and Southeast Hubei Basins) began in Late Triassic time and continued through Middle Jurassic time. By Late Jurassic time, foreland sedimentation had mostly shifted farther west along the southern Qinling-Dabie orogen. From Late Jurassic through Early Cretaceous only local sedimentation occurred as thrust faults continued to deform earlier foreland basin deposits. Unroofing history indicates that only shallow crustal levels in the Dabieshan and its subjacent (i.e. subsequently overthrust) Mianlue suture belt core were exposed during Jurassic time.

[61] Beginning in latest Jurassic time, and continuing through the early Tertiary, rift basins developed, first locally

along the northern side of the orogen and then increasingly pervasive across the entire belt. Lithic composition in rift basins show that by Late Cretaceous time deep crustal levels are exposed at the surface across the entire orogen core. In the core zone, rift basin formation began a long time after the earliest evidence of extension (~ 200 Ma) [Suo *et al.*, 2000]. This time lag suggests that although extension may have developed early in the shortening history of the Dabieshan, it became increasing common as the orogen continued to grow. Thus the Dabieshan is an example of an orogen that has undergone a long, sustained period of shortening (from ~ 230 to 100 Ma), crustal thickening, isostatic rebound possibly leading to shallow-level extension across the exhumed tectonic welt. We suspect that the combination of prolonged shortening across the two nearby suture belts (Shangdan and Mianlue) played some role in the exhumation of ultrahigh-pressure rocks from beneath the Dabieshan.

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