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Mesozoic basin development and its indication of collisional orogeny in the Dabie orogen

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The Dabie orogen underwent deep continental subduction, rapid exhumation, and the huge amount of erosion during the Mesozoic. Its tectonic evolution, especially how its evolution was recorded by sedimentary basins at the flanks of the Dabie orogen is one of the most important issues of the world's attention. These years, newly studies of basin sedimentology, combined with structural geology, have shown a fundamental progress. The overall distribution of different basin types in the orogen indicates that shortening and thrusting at the margins of the orogen from the Late Triassic to the Early Cretaceous controlled the foreland basins, and extension, doming and rifting were initiated in the core of the orogen from the Jurassic to the Early Cretaceous and were expanded to the whole orogen after the Late Cretaceous. Therefore, The Dabie orogen records gradual transition from overall shortening and thrusting to dominantly extension and rift basin formation expanded from its core to its margins, although these shortening and extension overlapped in time from the Jurassic through Early Cretaceous at crustal levels. The unroofing ages of the ultra-high pressure (UHP) metamorphic rocks in the Dabie orogen change from Early Jurassic to Late Jurassic westward. The depth of exhumation increases eastwards. The sediment sources for the Hefei basin are mostly composed of the deeply exhumed, axial Dabie metamorphic complex, and the sediment sources for the Middle Yangtze basin are mostly from cover strata in the southern orogen and related strata with subjacent (i.e. subsequently overthrusted) Mianlue suture belt. Geodynamic analysis represents that continental collision between the North China Block and the South China Block along the Shangdan and Mianlue sutures, subsequently northwestward progradation of the Jiangnan fold and thrust belt, and the underthrusting of the North China Block along the Northern Boundary Fault of Qinling Range led to crustal thickening, gravitational spreading and balanced rebound of the resultant thick crustal welt, and multi-episodic exhumation of the HP/UHP metamorphic rocks. The future studies by the methods of tracing the Dabie orogeny through deposition in the marginal basins should focus on eastward extension of the Mianlue suture, thrust and overlap of the Dabie HP/UHP metamorphic block on different lithotectonic zones and basins along the northern South China Block, the structural framework of the source area of the basins in the syn-depositional stage, the basin lateral extension, huge amount of erosion and sediment transportation from the Dabie blanket and basement rocks, and recovery of subducted and removed structural units within the Dabie orogen, etc.

Dabie orogen, sedimentary basin, evolution of basin/mountain system, HP/UHP metamorphic rocks, provenance analysis, exhumation process, depositional paleogeography

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Deep subduction of continental crust and rapid exhumation of ultrahigh-pressure metamorphic rocks, and its mechanism have been one of the most important issues of the world's attention in the Dabie orogen. The studies on high-pressure (HP)/ultrahigh-pressure metamorphism (UHP) and its geochronology in the process of continental collision and deep subduction have been getting important progress [1]. But these researches are primarily constrained by petrologic studies of HP/UHP rocks, and are short of multistage reconstruction of structural framework on the scale of regional orogen. Because of structural overlapping, long-distance thrusting, and huge amount of erosion from the Dabie blan-

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ket and basement rocks, structural deformation at the early stage in the Dabie orogen was changed and is not easy to identify now, and some geological zones and blocks were disappeared through subduction or erosion after exhumed. All these tectonic results led to difficulties in structural reconstruction and orogenic studies. Since the end of last century and the early of this century, scientists have been realizing that basin strata at the margins of the Dabie orogen include information of orogeny, basin development is coupled with orogeny, and basin tectono-stratigraphic analysis and detrital compositional analysis of the sediments are able to trace orogeny [2–10].

The Dabie orogen underwent a process from oceanic plate subduction to continental collision and from collisional orogeny to extensional collapse since Late Paleozoic. The HP/UHP terranes formed by continental subduction were episodically exhumed [1,11]. Postorogenic erosion has removed many of the supracrustal units and structural deformation zones, limiting structural reconstructions of this area. However, sedimentation into adjacent basins provides another constraint on orogeny [12], and the detrital composition of the sediments in the basins records the structural frameworks, the spatial and temporal patterns of exhumation of the different rock units in the Dabie orogen and their contribution to basin sediments, and the initial unroofing age of the UHP complex [13]. Based on the newly research results on basin development and its indication of orogeny in the Dabie orogen, this paper is intended to synthetically introduce the structural deformation, basin-filling sequence, provenance of basin sediments, evolution of the basin/mountain system, and its coupling relationship, aiming to provide a reference for the study on the geodynamics of basin/mountain system in the Dabie orogen or the other orogen.

1 Structural framework of the Dabie orogen

The Dabie orogen is linked westward with the East Qinling orogen across the Nanyang basin, and is connected eastward with the Sulu orogen across the Tanlu fault. They constitute a gigantic Qinling-Dabie-Sulu orogen together [14–18]. But if and how the Shangdan and Mianlue sutures in the Qinling orogen extend eastward to the Dabie orogen are controversial issues [14–21]. According to recent researches of ours and the others, we initially think that the two main suture belts bounding the Qinling Range, the Shangdan and Mianlue belts, are exposed, respectively, in the northern Dabie range, along the Xinyang-Shucheng fault [14–18,21], and in the southern Dabie range, along the Xiangfan-Guangji fault [14,15,17,18]. The Mianlue suture was mostly overprinted by a south-directed overthrust of the Xiangfan-Guangji fault but some ophiolite remnants, to the south of the Tongbai range, were reported in Dahongshan and Xishui areas [22,23]. Therefore, the Xiangfan-Guangji fault is the Earth's surface structural belt of the overlapped Mianlue suture formed during the subduction stage. Zhang et al. [24] defined it as a component of the Mianlue structural belt. Bounded by the Shangdan suture, the Qinling-Dabie orogen is divided into the North China Block and the South China Block. The Mianlue suture zone separates the Qinling microcontinent from the northern part of the South China Block in Devonian to Mid-Triassic times [14], and the basement property of the Qinling microcontinent is the same as that of the South China Block [1,16]. In addition, the Dabie orogen can be broken into three generalized structural units: the northern Yangtze fold and thrust belt (NYFB) along the southern margin; the North Huaiyang fold and thrust belt (NHFB) along the northern margin; and the axial Dabie structural belt [14] (Figures 1 and 2).

1.1 Northern Yangtze fold and thrust belt (NYFB)

The NYFB is discontinuously exposed to the south of the Xiangfan-Guangji fault (Figure 1). The Xiangfan-Guangji fault locally buries older deformation including the Mianlue suture [14,25,26]. The middle part of the NYFB is also unconformably overlapped by Cretaceous to early Tertiary deposits of the Jianghan basin, formed during later rifting. The thrust belt is narrow to the west along a basement high, the Huangling dome, and pinches out to the east at Wuxue City [14]. The NYFB thrust southwards and the Jiangnan fold and thrust belt (JNFB) expanded northwestwards, the two belts joining together and overlapping each other [26]. Based on the deep seismic profile across the Dabie orogen, the Xiangfan-Guangji fault can be traced from the surface to the Moho in a zone dipping north, the Dabie metamorphic terrane thrusts southward, and both of JNFB and NYFB converge and central-vergently thrust [25,27].

The NYFB is characterized by tight and overturned folds and thrusts involved with the Proterozoic and Early Paleozoic strata along Baokang-Dahongshan area in the north, and lineation folds and thrusts involved with Silurian-Triassic strata along Jingshan-Wuhan area in the south [28]. The Late Triassic-Middle Jurassic foreland basin was developed along the Dangyang-Daye area, and was involved in deformation at the later stage (J_3-K_1) with a southern frontal thrust fault [28] (Figure 2(a)). The Xiangfan-Guangji fault, as a main controlling fault in the NYFB, developed as a thrust during collision [14,25,26], and acted as a sinistral transtensional fault during Cretaceous exhumation of the HP rocks [29]. Field observations indicate that at an earlier stage this fault behaved as a south-directed flat thrust and tight fold of Cambrian-Silurian strata which were overlapped by HP metamorphic rocks. Its original location is the northern border fault of the obducted horst part of Sinian-Cambrian sedimentary rocks, which was thrust upwards from the footwall of the subducted South China Block [25]. The deep seismic profile shows that the stacked small slices underthrust the Dabie HP/UHP terrane. These slices can be

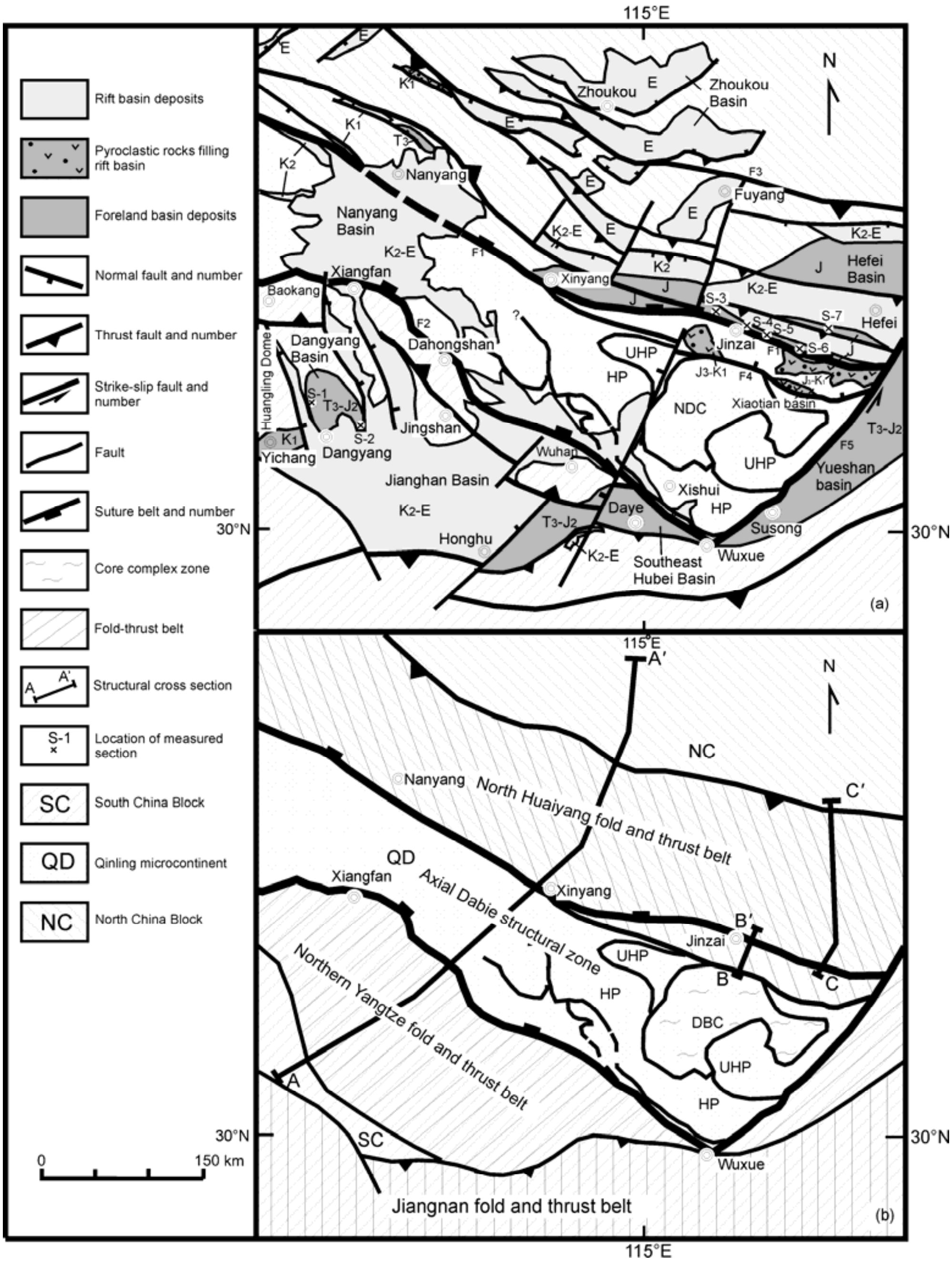

Figure 1 Tectonic framework of basins and orogen in the Dabie orogen and adjacent region. (a) Map showing distribution of basins, sutures and major faults; (b) simplified map of major structural belts and the location of cross sections in Figure 2. F1, Shangdan suture (Xinyang-Shucheng fault); F2, Xiangfan-Guangji fault (which buried the Mianlue suture); F3, Northern Boundary Fault of Qinling Range; F4, Xiaotian-Mozitan fault; F5, Tanlu fault; NDC-North Dabie core complex zone; UHP, ultrahigh-pressure metamorphic unit; HP, high-pressure metamorphic unit; S-1, Late Triassic stratigraphic section in Dangyang basin; S-2, Early Jurassic stratigraphic section in Dangyang basin; S-3, Wumiao section; S-4, Jinzhai section; S-5, Dushan section; S-6, Huoshan section; S-7, Feixi section. Modified from Liu et al. [14] and Suo et al. [30].

interpreted as subducted Paleozoic-early Mesozoic strata [25,31]. The south-directed thrusting of the XGF at the southern end of the Dabie range resulted in forming a structural zone in the NYFB which was cut and covered by the axial Dabie HP/UHP terranes at Wuxue City [14,25]. Based on the structural analysis at the Wuxue City by Li et al. [25], the three stages of structural events were indentified. The first two phases of deformation (D1 and D2) mainly include ductile shearing, overturned and recumbent folds, and thrusts with southeastern vergence, coeval with the subduction of the northern South China Block and the early stage of exhumation of the HP/UHP rocks in the Middle-Late Triassic, and the third phase of deformation (D3), belong to the later deformation phase of collisional orogeny in the Early and Middle Jurassic, includes southwest-vergent open folds. In Susong City to the east of the Tanlu fault,

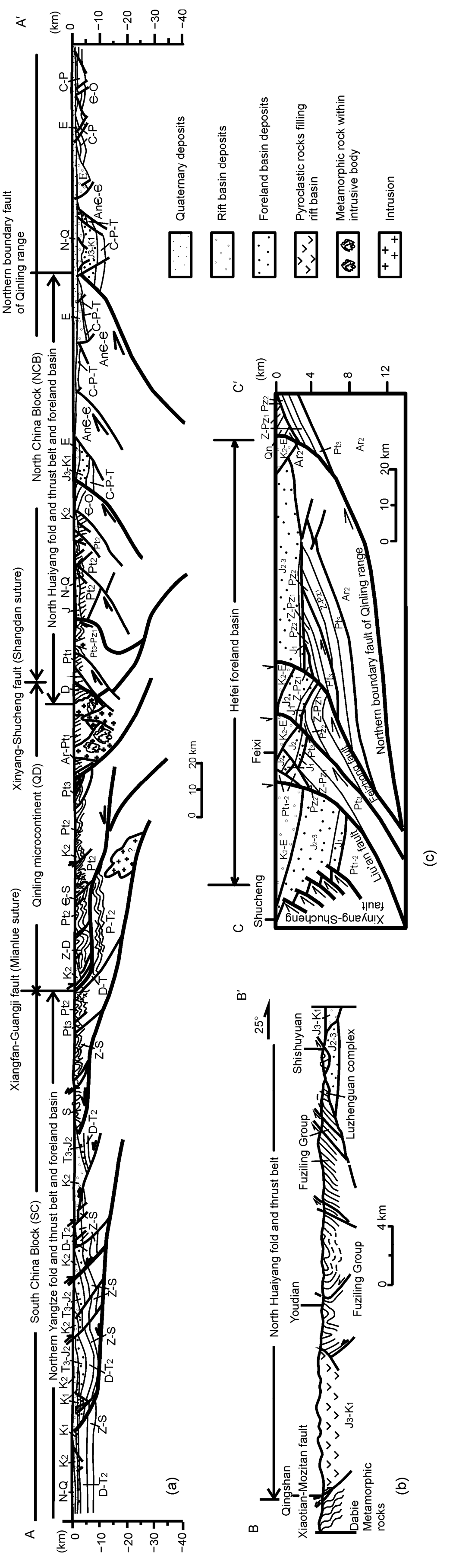

Figure 2 Structural cross sections from the Dabie orogen. (a) The entire Dabie orogen; (b) the North Huaiyang fold and thrust belt; (c) Xinyang-Shucheng fault and Hefei basin. Location of sections A–A′, B–B′, and C–C′ is shown in Figure 1(b). (a) and (b) were modified from Liu et al. [13]; (c) was modified from Zhao et al. [32].

the Lower Jurassic strata, which overlie the Silurian with an angular unconformity, were involved in south-directed thrusting, and were cut by late stage normal fault. It also suggests that the shortening deformation in the NYFB was mainly formed during the Triassic-Jurassic time [25].

1.2 North Huaiyang Fold-Thrust Belt (NHFB)

The NHFB is found north of the axial Dabie structural belt, and extends over 100 km northward from the Xiaotian-Mozitan fault (Figure 1). At the southern NHFB, rocks involved in thrusting include, from south to north: medium- to low-grade metamorphic rocks of Neoproterozoic to early Paleozoic age (Luzhenguan Group for example) and early Paleozoic-Devonian age (Fuziling Group and Xinyang Group); and late Paleozoic sedimentary rocks (Nanwan Formation and Yangshan Group). Zheng et al. [16,33] defined a set of Greenschist-facies metasedimentary and meta-igneous rocks occurring between the Xiaotian-Mozitan and Xinyang-Shucheng faults as the North Huaiyang low-pressure/low-temperature greenschist-facies metamorphic zone, and believed that this zone, composed of sedimentary rocks on the passive continental margin and their underlying basement rocks, was scraped off from the subducting northern South China Block during Triassic collision, and thus correspond to the accretionary wedge of the continent subduction. The structural deformation in this metamorphic zone is characterized by double-vergent folds and thrusts (Figure 2(a) and (b)). Interpretation of seismic data shows that the Jurassic foreland basin unconformably covers on the fold and thrust belt formed in the early stage, and the Xinyang-Shucheng reverse faults in the trailing edge of the basin interfinger with the Jurassic deposits. The Xinyang-Shucheng fault, with an older-over-younger relationship, indicates reverse motion, controlling the deposition of the basin. In addition, the Liu'an fault and Feizhong fault acted as extensional deformation in Late Cretaceous-Neogene, and controlled development of rift basins (Figure 2(c)) [14,32,34].

The NHFB is bounded by the Xiao-Mozitan fault and the Northern Boundary Fault of Qinling Range, which behaved as different deformation in the Late Jurassic (?)-Early Cretaceous, the extensional deformation of the former and the shortening of the later. The southern flank of the Xiaotian basin is defined and controlled by the Xiaotian-Mozitan normal fault that trends WNW. The fault dips to the north at the angle of 50°–60°[14]. Beside its brittle deformation, this fault also acted ductile shearing. Study on the ductile shearing deformation by Wang et al. [35] shows that the Xiaotian-Mozitan shear zone and the shearing zone at the southern North Dabie core (NDC) were originally a single connected, more flat-lying zone. The kinematics of the zone was interpreted to be that the ductile crust and possibly part of the lithospheric mantle in the eastern Dabie orogen underwent pervasive orogen-parallel and ESE-ward extension at ca. 142 Ma. Doming of the NDC modified the flat-lying zone into an antiformal shape at ca. 132–127 Ma. Subsequently erosional removal of the hanging wall in the broad hinge area of this dome led to the separation of the zone into two separate zones as we observe today. The Xiaotian-Mozitan fault gradually was changed into brittle deformation, and controlled formation of the Xiaotian basin. The Northern Boundary Fault of Qinling Range extends from Fuyang City, southern margin of Zhoukou basin in the east to Baji City in the west. Based on exposed geological structures and deep seismic profiles, Zhang et al. [36] regarded it as a gigantic thrust fault in the Cretaceous that was traced to the Moho, and was marked by underthrust of the southern North China block. This fault controlled the subsidence and deposition of the southern margin of the Zhoukou basin in the Early Cretaceous [36,37]. Therefore, the NHFB underwent a prolonged history of shortening and thrusting (Triassic to early Cretaceous), and the thrust front migrated northwards. In addition, the rift deformation expanded northwards from the Early Cretaceous (or latest Jurassic (?)) to Tertiary [5,14].

1.3 Axial Dabie structural belt

The axial Dabie structural belt is further divided into North Dabie core complex zone (NDC), ultrahigh-pressure metamorphic complex zone (UHP), and high-pressure metamorphic complex zone (HP) [1,16,21,33,38] (Figure 1). The NDC includes the Luotian and Yuexi domes that lie in the footwall of the Dabie orogen [38,39]. The domes have similar lithologic features; they are composed of amphibolite- and granulite-facies felsic gneisses (mainly tonalitic gneisses) (75% of the total area), a supracrustal sequence (24%), and metamafic-ultramafic rocks (<1%). The supracrustal sequence is made up of metavolcanic amphibolebiotite gneiss, amphibolite, and a small proportion of marble and magnetite-bearing quartzite [40]. The radial dips of foliation and predominant NW and SE plunges of mineral lineations outline the structural character of both domes [38]. Xu et al. [41] and Liu et al. [42] found several fresh eclogite outcrops in the NDC and inferred that they were subjected to deep continental subduction [43] and UHP metamorphism in the northern Dabie orogen. Zheng et al. [16,33] defined this zone as the North Dabie UHP/HT migmatitic zone.

The UHP/HP zone in the Dabie orogen consists chiefly of amphibolite felsic gneisses (mainly granitic gneisses) with minor amphibolite, garnet-bearing peridotite, jadeite quartzite and marble, low-grade metamorphic basement-cover sequences (including metasediments and metavolcanics), and eclogites [44–46]. Eclogite-facies parageneses in the gneisses and the basement cover units, along with P-T data demonstrate regional UHP metamorphism in the UHP/HP zone [46]. Zheng et al. [16,33] further differentiated the UHP zone into two subzones with different pressure-temperature (P-T) regimes: a Middle Dabie ultrahigh-pressure/mid-temperature and South Dabie ultrahigh-pressure/low-temperature eclogite-facies zones, and the HP zone into Susong high-pressure/low-temperature blueschist-facies zone. The different pressure-temperature zones in the axial Dabie structural belt and NHFB were the products of exhumation and unroofing of the north-vergent subducted South China block under the North China block with a different depth [1,16,47,48]. The timing of the final collision has been constrained at ca. 244–236 Ma [49,50] and ca. 230–220 Ma [51,52] by several radiometric studies. The two groups of ages may indicate a succession from the onset of HP-UHP metamorphism to peak UHP conditions, respectively, during ultra-deep subduction [1,33,47,48].

The orogen-scale structure of the axial Dabie structural belt is an antiform [53]. The north limb has north dipping foliation, north plunging lineation, and top-north shear sense formed as the footwall UHP-HP rocks were drawn southeastward out from beneath the low-grade hanging wall. The south limb carries similar structures that have been rotated through horizontal to southward inclinations [53]. Based on the study in the western part of the Dabie orogen, Li et al. [54] found that rocks of this orogen have been subjected to pervasive ductile deformation, and formed as asymmetric “antiform” around the core of the Xinxian UHP eclogite-facies zone. The asymmetry of structural patterns consistently indicates top-to-the-southeast thrusting across the orogen in early structural stages. Later stages of deformation show different senses of movement in northern and southern parts of the orogen, with top-to-the northwest sinistral shearing recorded in rocks north of the Xinxian HP-UHP eclogite-facies belt, and top-to-the southeast dextral shearing south of the same unit. Li et al. [54] concluded that the polyphase evolution of the western part of the Dabie orogen includes vertical or upward extrusion of HP/UHP zones at the early stage from 241 to 231 Ma and orogen-parallel eastward extrusion and local extension of the orogen-core at the later stage from 200 to 184 Ma. These two extrusions are correlative with two stages of rapid exhumation of the Dabie HP-UHP rocks (i.e. early stage of shortening exhumation and later stage of local extensional exhumation under a regional shortening setting), respectively [11,30,55] (Figure 3), which belong to the syn-collisional deformation and its later stage deformation of the Dabie orogen, developed right after the continental subduction in the Early and Middle Triassic. Superimposed across the entire orogen during the post-collisional deformation stage, are a series of isolated extensional basins that overlie shortened basement, and the shearing zones and normal faults in the orogen-core and margins in the latest Jurassic (?)-Early Cretaceous, or even later time (Figure 2(a)) [14,29,35].

2 Basin-filling sequence and its multi-episodically tectonic control

The Qinling-Dabie orogen underwent a multi-episodic evo-

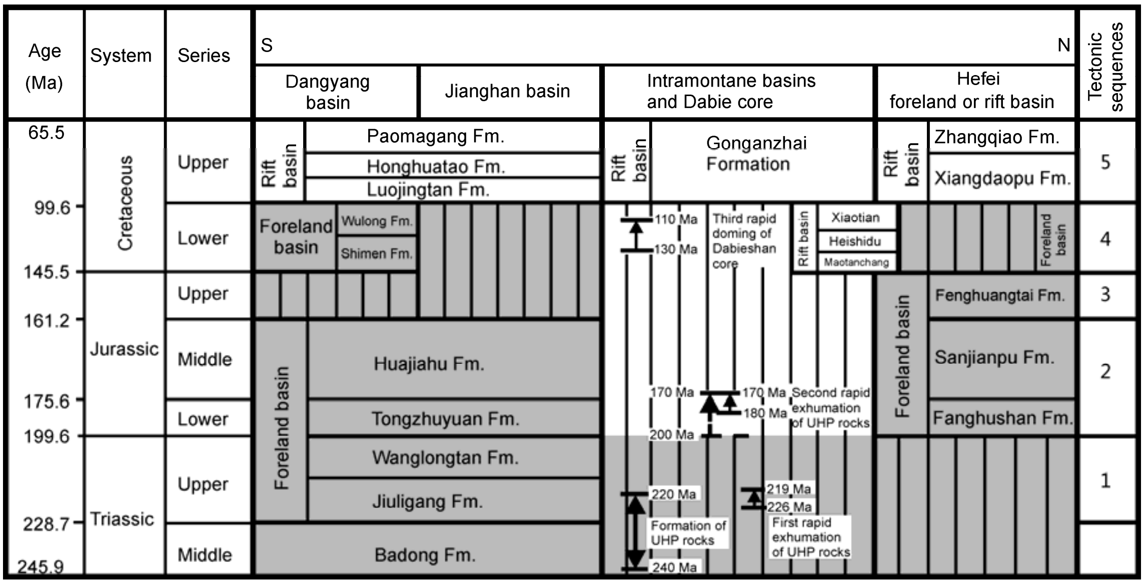

Figure 3 Division of stratigraphic units and tectonic sequences for basins in the Dabie orogen, age data for formation and rapid exhumation episodes of UHP rocks and rapid doming episode of Dabie core [11,30,55]. Dark shading highlights times of compressional deformation; ruled pattern represents hiatuses. Modified from Liu et al. [14].

lution of continental collision of the North China Block and South China Block in the Middle and Late Triassic, Jurassic continuous shortening of the orogenic margins and initial doming and local extension of the orogenic core, Early Cretaceous rift of the orogenic core, and Late Cretaceous rift of the whole orogen [14]. Corresponding to these tectonic events, the Mesozoic strata of the basins in the orogen and its flanks can be divided into 5 unconformity or disconformity-bounded tectonic sequences (Figure 3), which are the depositional response to collisional orogeny and post-orogeny. To the south of the Qinling-Dabie orogen, the Dangyang basin and Southeast Hubei basin were developed from Late Triassic through Middle Jurassic time. To the north of the orogen lies the Hefei basin (Jurassic) and Zhoukou basin (Early Cretaceous). In addition, extensional Xiaotian basin began to develop locally within the orogen core during latest Jurassic time, and the Jianghan basin in the southern orogen in the Late Cretaceous (Figure 1).

2.1 Late Triassic tectonic sequence

The Late Triassic strata are mostly developed in the southern margin of the Dabie orogen. The Dangyang basin is better exposed and contains a more complete record of foreland basin molasse sedimentation, which includes the Jiuligang (ca. 457 m thick) and Wanglongtan (ca. 845 m thick) formations [14,26] (Figures 3 and 4(a)). Above the unconformity between the Badong and Jiuligang Formations are channelized conglomerates (1 m) that fine upwards into tabular cross stratified sandstones (16 m). The channel deposits occur regionally and probably record the initial low-stand sedimentation of meandering channel. Immediately above the basal conglomerate is 70 m of the Jiuligang Formation. This section consists mostly of bioturbated siltstone with carbonate nodules. However, there are intervals of lenticular sandstone and conglomerate with limestone gravels [14,26]. The overall lithologic similarity with the underlying Badong Formation, widely thought to be tidal in origin, possibly suggests a similar depositional setting. Based on the depositional environments, these parts of sequences are interpreted to be the filling of backbulge depozone in the foreland basin system. The upper Jiuligang Formation consists of a series of upward-fining units, each of which typically begins with a scoured channel base overlain by 5–10 m of fine-grained sandstone with well developed tabular cross strata or, in places, lateral accretion bedding. The whole sequence is coarsening upwards, and the paleocurrent indicators (tabular cross strata) suggest paleoflow mainly to the northeast or east. This succession is interpreted to record meandering stream/flood-plain sedimentation, filled in the southern distal part of the foredeep depozone. Wanglongtan Formation is composed mainly of 845 m thick, vertically nested channel-filling sandstones. A clear, basin-wide, and isochronous facies transition surface was developed between the Wanglongtan and Jiuligang Formations. Nested channel deposits are composed, on a scale of several meters, of massive or plan-parallel laminated medium sandstones overlain by trough and planar cross stratified sandstones of similar grain size. Paleocurrent indicators (planar cross strata and trough axes) suggest paleoflow was to the west-southwest. We interpret these deposits to represent channel fill overlain by medial or transverse bars in braided rivers. The braided stream deposits are interrupted up by three, 12–50 m-thick intervals of mudstone which may represent intervals of lake formation on the braidplain. The Wanglongtan Formation may repre-

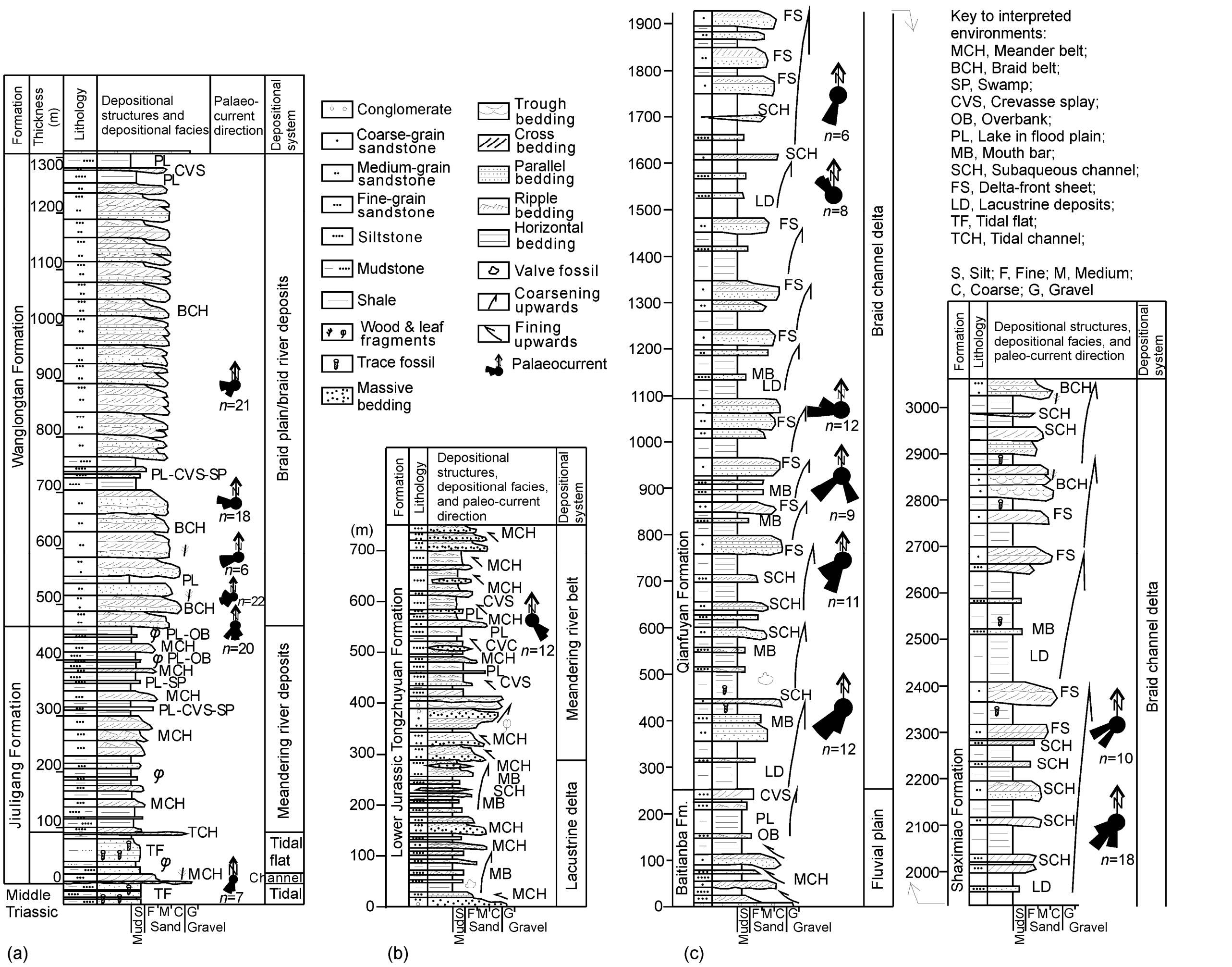

Figure 4 Stratigraphic sections through Upper Triassic succession ((a) S-1), through the Lower Jurassic succession ((b) S-2), and through the Early and Middle Jurassic succession. Location of sections (a) and (b) is shown in Figure 1(a), and (c) was measured in Daxiakou, Xinshan County, Zigui basin, to the West of the Huangling Dome. Modified from Liu et al. [26].

sent the deposits of foredeep depozone. As a whole, the Upper Triassic in the Dangyang basin is coarsening-upward sequence, which indicates the evolution from the distal backbulge deposition to foredeep deposition with the south or southwest-vergent progradation of the foreland fold and thrust belt. The Late Triassic tectonic sequence was the depositional response to the first episodic thrusting in the Dabie range, formed at the stage of the initial extrusion and exhumation of the HP/UHP rocks in the axial Dabie belt [54] and the first two phases (D1 and D2) of deformation in the NYFB [25].

2.2 Early-Middle Jurassic tectonic sequence

The Early and Middle Jurassic deposits crop out along the southern and northern flanks of the Dabie orogen. These rocks are stratigraphically subdivided into the Tongzhuyuan Formation (or Baitianba Formation, Wuchang Group) and Huajiahu Formation (or Qianfoya and Shaximiao Formations) in the Southeast Hubei basin, Dangyang basin, and Zigui basin of the southern flank [26], and Fanghushan Formation and Sanjianpu Formation (or Zhuji Formation, Yuantongshan Formation) in the Hefei basin of the northern flank [13] (Figures 1 and 3).

The Early Jurassic section (Figure 4(b)) in the Dangyang basin at the southern flank of the Dabie orogen, is composed of the Tongzhuyuan Formation. The base of the formation everywhere contains thick conglomeratic, fining upward meandering channel sequence, reaching up to 40 m thick. This channel sequence unconformably covers on the fluvial plain deposits of the Upper Triassic with an undulated scour surface. The next 250 m of the phase contains two cycles of overall coarsening and thickening upward deltaic deposits. Mudstones between the sand bodies contain coal, shale and oxidized paleosol horizons suggesting that the entire interval was deposited along the shores of isolated, small lakes on an alluvial or deltaic plain. The last phase of basin filling in the Dangyang basin consists of a thick interval (460 m) of channel-filling sandstone that is conglomeratic towards the base. Paleoflow, based on tabular cross sets, was to the south or the south-southeast. The Fanghushan Formation, filled in the Hefei basin at the northern flank of the Dabie orogen, is composed mainly of alluvial fan and meandering channel deposits, including massive and laminated conglomerate at its base and isolated channel-belt sand bodies with cross bedding distributed among flood-plain siltstones in its upper part [12,13] (Figure 5). Therefore, the Early Jurassic deposits were the depositional response to the initial thrusting of the second episodic tectonism at the foreland and hinterland of the Dabie orogen. The conglomerate at the base of the Lower Jurassic in the southern flank of the Dabie range can be traced to the northern Sichuan basin, which unconformably covers on the Triassic or Paleozoic strata.

Middle Jurassic deposits in the Dangyang basin at the southern flank of the Dabie range are poorly exposed. The interval reaches 1050 m in the nearby Southeast Hubei basin. In the Zigui basin to the west of the study area the entire Middle Jurassic interval reaches about 2810 m thick [26]. The Qianfoya Formation, 850 m in thickness, consists mainly of mudstone passing upward to an upward-coarsening sandstone succession. The mudstones are parallel- or ripple laminated or are simply massive, and the siltstone intervals developed massive beds and ripple lamination, interpreted to be lake deposits. The Shaximiao Formation consists of several coarsening-upward depositional cycles. Each one is about 100–300 m in thickness. Mudstones and about 0.5 m thick, massive or ripple siltstone intervals are developed at the lower part of the cycles. Two kinds of lithofacies are developed at the upper part. One is about 20–80 m thick, and contains vertically stacked, laterally extensive, medium to coarse-grained sand bodies with massive, parallel laminated or cross stratified beds, in which scour contacts and lag deposits are developed. The other is

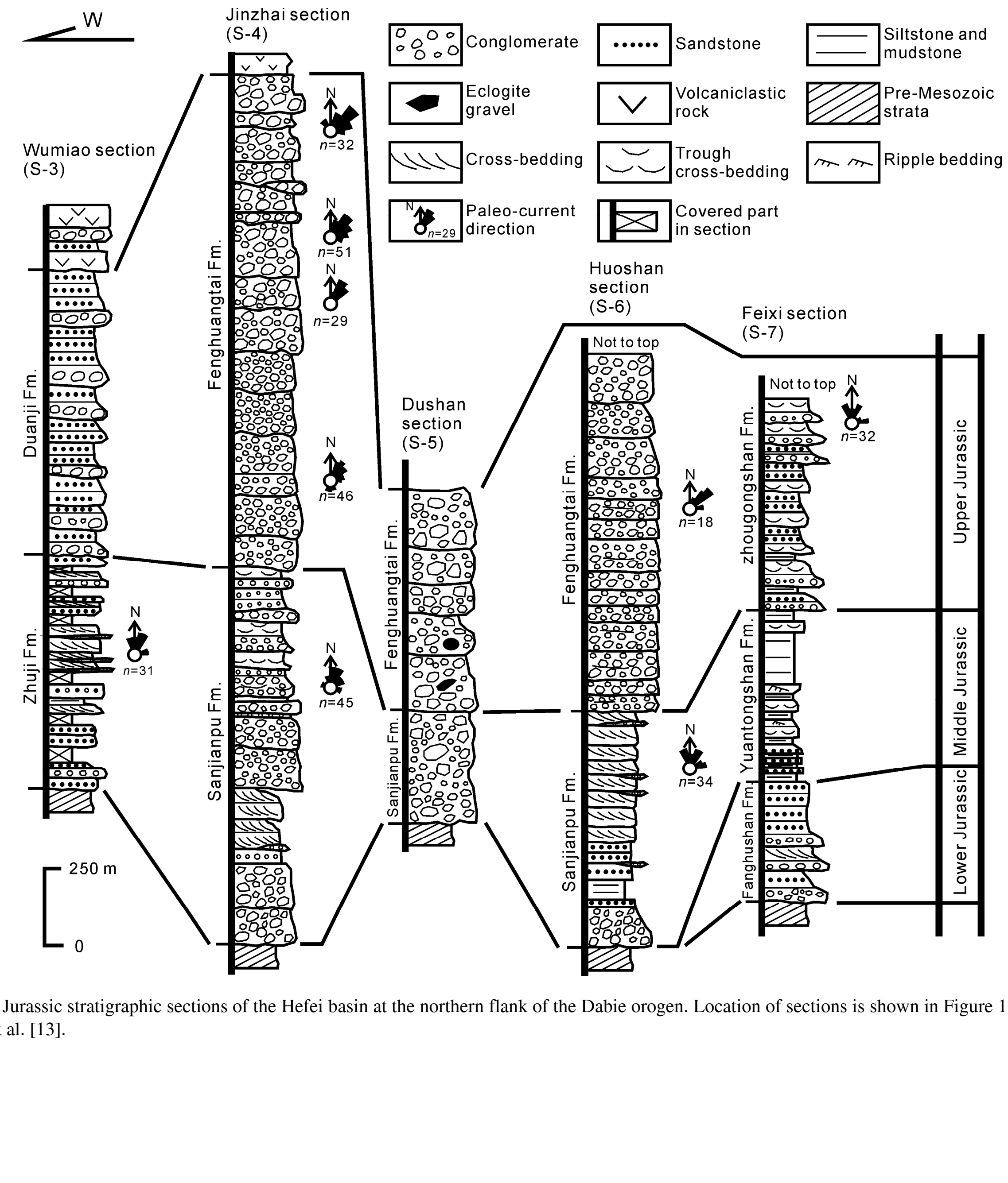

Figure 5 Jurassic stratigraphic sections of the Hefei basin at the northern flank of the Dabie orogen. Location of sections is shown in Figure 1(a). Modified from Liu et al. [13].

ca. 15 m thick, lenticular, coarse sandstone with cross bedding and basal scour surface. We interpret these lithofacies of the Shaximiao Formation as lake mudstones and braided channel-delta systems. The Sanjianpu Formation, as a typical example of the Middle Jurassic, measured along the Jinzhai section at the northern flank of the Dabie orogen, is ca. 1850 m thick (Figure 5). The lower part of the unit is composed of massive pebble conglomerate with internal scour surfaces. The middle part of the Sanjianpu Formation consists of coarse- to medium-grained sandstone with local conglomerate lenses that are composed of tabular, large-scale, planar cross beds. The upper part of the Sanjianpu Formation is fining upward, and is composed of cobble conglomerate at its base that fines to granule-rich pebble conglomerate toward the top. Paleocurrent indicators from imbricated gravel and cross stratification show flow that is directed toward the present-day north-northeast. The Sanjianpu Formation is interpreted to have been deposited by braided channel systems [13]. Corresponding to the Sanjianpu Formation, the Zhuji Formation at Wumiao section is interpreted to record a braided, channel-plain depositional system with some fine-grained overbank deposits. The Yuantongshan Formation at Feixi section is interpreted to represent a fluvial plain environment with some small lakes (Figure 5) [13]. Therefore, the Early and Middle Jurassic deposits along the flanks of the Dabie orogen are coarsening-upward sequences composed of fluvial plain-braid channel delta depositional system in the southern flank and alluvial fan-braid channel plain system in the northern flank, which were deposited at the stage of the second exhumation of HP/UHP rocks and the third phase of deformation (D3) of the southern NYFB [11,14,25]. This Early and Middle Jurassic tectonic sequence was the depositional response to the second episodic thrusting in the Dabie orogen [7,14].

2.3 Late Jurassic tectonic sequence

During the Late Jurassic, the basin at the southern flank of the Dabie orogen migrated from the east to the west controlled by intracontinental deformation. The NYFB thrust southwards, and the JNFB expanded northwestwards, the two belts joining together at the east. Thus the early basin in turn became involved in deformation in the Late Jurassic. The depocenter migrated to the Zigui basin, and even western area [26]. In the Zigui basin, the Late Jurassic consists of the Suining and Penglaizhen Formations, which constitute a coarsening-upward sequence. The Suining Formation (750–950 m thick) unconformably covers the Middle Jurassic Shaximiao Formation with an erosion surface at the base, and consists mainly of fine-grained sandstone, siltstone and mudstone of meandering channel plain and shallow lake or lacustrine delta depositional systems. These strata contain accretional, tabular cross bedded, and ripple-laminated, lenticular sandstone intervals, and horizontal or ripple-laminated mudstones and siltstones, and constitute several fining-upward and coarsening-upward sequences. The Penglaizhen Formation (above the Suining Formation with a regional erosional unconformable surface) is ca. 1060–1400 m thick, and is composed dominantly of gravel coarse sandstone, gravel conglomerate, coarse and medium-grained sandstone, fine-very fine grained sandstone, and mudstone which constitute fining-upward sequences. Massive, trough, and planar cross beddings are developed in sand bodies, and scour surfaces define sandstone margins. This formation is interpreted to represent braided channel and flood-plain deposition, which is different from depositional systems of the underlying Suining Formation. The sediment supply rate of the Penglaizhen Formation is much bigger than the subsidence rate. The Fenghuangtai Formation (or Duanji Formation, Zhougongshan Formation) in the Hefei basin at the northern flank of the Dabie orogen is extremely thick and very coarse grained (boulder to cobble conglomerate) (Figure 5). The conglomerate sequence in Jinzhai section contains units (ca. 2400 m thick) consisting of grain-supported, imbricated, thick beds as well as units of massive, matrix-supported conglomerate. These units are interpreted to be the deposits of a gravel alluvial fan system. Paleoflow, determined from imbricated grains, is toward the north-northeast or northeast. It is necessary to note that the major change in depositional style of basin filling in the Hefei basin indicated by the change from the Sanjianpu Formation coarse sandstone deposits to conglomerates of the Fenghuangtai Formation takes place. Detailed geological mapping found that Fenghuangtai Formation overlapped the different part of the Sanjianpu Formation with angular unconformity [56]. Structural analysis shows that deformation in the Dabie orogen is characterized by south-vergent progradating of the YZFB, uplifting and exhumation of the HP/UHP rocks [13], and thrusting of the NHFB [14]. As for the difference of the structural deformation at the both flanks of the orogen, the Late Jurassic tectonic sequence was formed at the northern Dabie flank, which was the response to the third episodic thrusting [7,14].

2.4 (Latest Late Jurassic (?) to) Early Cretaceous tectonic sequence

Totally different kinds of Early Cretaceous tectonic sequences, the normal fault controlled-rift basin-filling sequence and thrust fault-controlled flexural basin-filling sequence, are developed at the southern and northern flanks of the Dabie orogen (Figure 3). These sequences unconformably overlie on the Paleozoic, metamorphic basement, and Upper Jurassic strata.

Normal fault-controlled rift basin sequence was deposited along the northern flank of the NDC zone, to the north of the Xiaotian-Mozitan fault. The basin fill includes the Maotanchang Formation, Heishidu Formation, and Xiaotian Formation (some experts defined the latter as the upper part of the Heishidu Formation [12]) (Figures 1, 2(b), and 3).

The Maotanchang Formation is composed of various andesite and trachytic flows of calc-alkalic to alkalic composition interbedded with lacustrine mudstone. K-Ar dating of volcanics within the Maotanchang Formation yields an age range of 149–138 Ma [57], and it suggests that the Maotanchang Formation may extend to the latest Jurassic. Overlying this unit is the Heishidu Formation that contains abundant conglomerate and sandstone of alluvial fan, braided stream and fan delta origin. This unit is capped by the Xiaotian Formation composed of lacustrine mudstones with increasing abundance of thin turbidite sandstones in the upper part. Thus the entire basin fill forms an overall fining upward sequence, more than 2000 m thick [5,12,14]. Basin fill coarsens and thickens toward the Xiaotian-Mozitan flanking fault. The juxtaposition indicates that the normal faulting occurred during deposition.

Thrust fault-controlled flexural basin sequences are locally located in the Zhoukou basin in the northern flank and the Yichang basin in the southern flank, which indicate that the thrusting was prograded from the orogenic core to the margins. Sedimentology (including provenance and paleocurrent analyses) and structural geology studies represent that the Cretaceous strata in the Yichang basin include the Early Cretaceous flexural sequence of the Shimen and Wulong Formations and the overlying Late Cretaceous rift sequence [31]. The Shimen Formation, ca. 240 m thick, consists of massive or locally imbricate, grain-supported conglomerate in which the gravels range in size from ca. 8 to 20 cm. The lower part of the Wulong Formation is composed of ca. 120 m thick, purple-coloured mudstone and siltstone of floodplain origin, and the upper part is composed of ca. 1750 m thick, pebbly median to coarse-grained sandstone, conglomerate, fine-grained sandstone, and siltstone of braid channel plain origin. The thick, and vertically stacked, median to coarse-grained sand bodies and conglomerate develop trough and cross beddings, and basal scour surface, and the thin fine-grained sandstone and siltstone layers develop horizontal, ripple, and massive beddings. Both of them are interpreted to be braid channel and flood plain deposits, respectively. The whole Wulong Formation is characterized by a coarsening-upward sequence. Therefore, the Early Cretaceous tectonic sequences in the core and the flanks of the orogen were controlled by normal faulting and thrust faulting, respectively (Figure 2(a) and (b)). This tectonic sequence is the product of the fourth episodic tectonism [14], in which the flexural sequence and the rift sequence are overlapped in time.

2.5 Late Cretaceous tectonic sequence

The Late Cretaceous deposits extended from the Dabie margins to the Dabie core (Figures 2(a), (c), and 3). This tectonic sequence was filled in the basins along the southern side of the Dabie range, including the Yuanan, Jinmen, and Hanshui grabens and half-grabens in the northwestern part of the Jianghan basin (Figures 1 and 2(a)). The Hefei grabens and half-grabens filled with the Late Cretaceous along the northern side of the Dabie range mainly overlap the Jurassic foreland basin belt (Figure 2(c)). All of the basin-filling deposits are similar in that they initiate with relatively coarsegrained alluvial fan and/or deltaic deposits that overall fine upward into lacustrine mudstones, and the thickness of this sequence is ca. 3350 m in the Yuanan graben. Therefore, the Late Cretaceous tectonic sequence is the products of the fifth episodic extension in the Dabie orogen [14].

3 Provenance of sediments and exhumation of HP/UHP rocks in the source areas

Basin sediments are a ‘link’ between basin and orogen. Tracing the unroofing history of the orogen and paleotectonic framework by detrital composition analyses is an important and generally-concerned scientific issue [58]. Since HP and UHP rocks are largely exposed in the Dabie orogen, the provenance of the basin sediments must record their exhumation process. Facies changes and paleocurrent indicators consistently demonstrate that sediments for the marginal alluvial-fan and braided stream depositional systems in the Dangyang and Hefei basins were derived from the adjacent Dabie range (Figures 4 and 5) [5,6,12,14,26]. As the Dabie orogen has a wide range of exposed rocks with different ages, detrital grain compositions and ages are good indicators of the sediment source. Currently, provenance analyses of basin sediments in the flanks of the Dabie orogen mainly include detrital composition analysis, isotopic chronology analysis, and geochemical analysis.

3.1 Detrital composition analysis

(i) Methodology. The basins at the flanks of the Dabie orogen are dominated by different grain-sized clastic rocks, thus different techniques were used to identify the compositions of these different grain sizes. Sandstone compositions were determined by counting 500–560 framework grains per thin section. The point-count results, using the Gazzi-Dickinson method [59], were plotted on Qm-F-Lt and Qm-P-K ternary diagrams to provide insight into the tectonic setting of the source areas and were plotted along side of the measured sections to show the changes in detrital composition, structural setting, and provenance with time. The main advantage of this method is to remove the influences of grain-size changes on contents of detrital composition. Because the Dabie orogen has a wide range of exposed rock types, lithic grain compositions are considered to be the most useful indicator of source area. In order to link rock fragments to specific protoliths, we also determined sandstone compositions by traditional point counting, in which all polycrystalline grains were counted as rock fragments, including coarsely crystalline (e.g. individual sand-size crystals within a rock fragment were counted as that rock fragment) [14]. Similarity, 500–560 framework grains were measured for each thin section. We calculated the contents of different fragments and showed the results for rock detrital composition, referred to as model content, which typically represents more than 15% of all the counted grains. Where conglomerates were abundant, we collected both gravel clast data and sandstone samples within the conglomerate in the field. Clasts, typically 100–180 or more in number at each conglomerate station of ca. 2 m^2, were identified; sandstone compositions were identified by the point-counting method that is described above.

(ii) Ternary plots for sandstone compositional data. As a whole, Late Triassic-Jurassic sandstones from the northern Yangtze are lithic rich and dominated by chert and sedimentary-rock fragments [26]. Most samples fall in the area of recycled orogen provenances in Qm-F-Lt and Qt-F-L ternary diagrams, and some of the Middle Jurassic samples (sandstones in Zigui basin as an example) fall in the areas of the arc orogen sources and mixed orogenic sands in the Qp-Lv-Ls ternary diagram. We think that the source areas of the Late Triassic and Jurassic foreland basins are mostly the foreland fold and thrust belt and the consumed island-arc belt of the Mianlue ocean [14,26].

The Jurassic sandstones from the Hefei basin are lithic poor (most <5% Lt) and dominated by quartz and feldspar fragments based on the Gazzi-Dickinson method of point counting. The modal data can be divided into three groups [13], based primarily on detrital composition content (Figure 6). Group 1 samples are composed of 65%–80% quartz fragments and less than 5% lithic fragments in the plot of Qm-F-Lt, and 65%–80% quartz fragments and 2%–25% potassium feldspar fragments in the plot of Qm-P-K. This group most commonly represents samples from the Zhuji Formation in the western part of the Hefei basin (Wumiao section) and the Sanjianpu Formation in the middle part (Jinzhai section). Group 2 samples are composed of ca. 50%–65% quartz fragments and less than 5% lithic fragments in the plot of Qm-F-Lt. This group is representative of samples from the Sanjianpu Formation located in the eastern part of the Hefei basin (Huoshan section). Group 3 samples contain ca. 30%–50% quartz fragments and less than 10% lithic fragments in the plot of Qm-F-Lt, and 30%–50% quartz fragments and 35%–50% potassium feldspar fragments in the plot of Qm-P-K. This group represents samples from the Fenghuangtai Formation (upper Huoshan section). As an indicator of compositional maturity, the Qm-F-Lt diagram distinguishes Group 1 samples from those of Groups 2 and 3 that contain less stable minerals and more feldspar, mostly potassium feldspar, as shown in the plot of Qm-P-K. This indicates that Groups 2 and 3, especially Group 3, are derived from source terranes with more granitic rocks. The Sanjianpu Formation in the Jinzhai section contains more potassium feldspar than the Zhuji Formation in the Wumiao section, suggesting that the former was derived from a source with a higher percentage of granite. The modal contents of Groups 1, 2, and 3 (e.g. 2%–25%, 10%–50%, and 35%–50% potassium feldspar fragments in Groups 1, 2, and 3 in the plot of Qm-P-K, respectively) suggests stronger tectonism and more rapid exhumation of the Dabie range from the west to the east and from the Middle Jurassic to Late Jurassic. Although almost all samples plot in the continental block provenance in the Dickinson model [60], which does not mean that the source area, the Dabie range, was a stable craton, which represents the limitations of this plot in differentiation of tectonic setting.

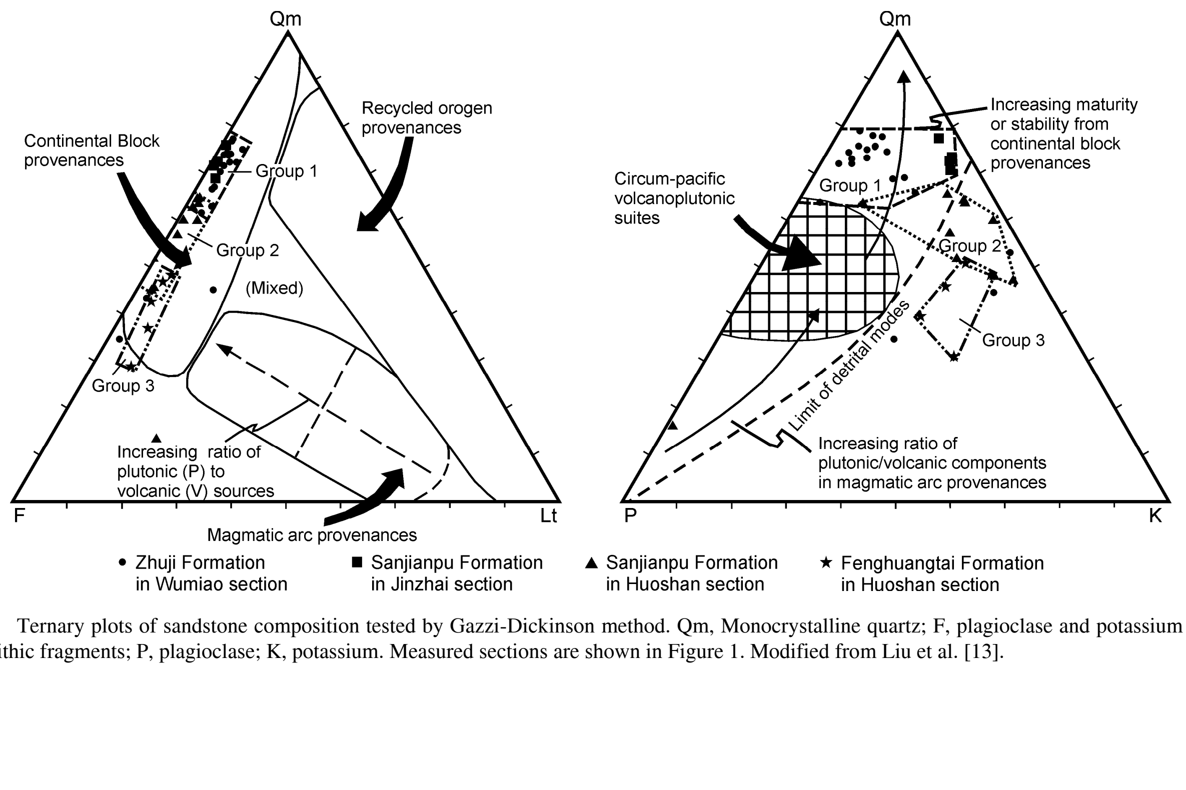

Figure 6 Ternary plots of sandstone composition tested by Gazzi-Dickinson method. Qm, Monocrystalline quartz; F, plagioclase and potassium feldspar; Lt, total lithic fragments; P, plagioclase; K, potassium. Measured sections are shown in Figure 1. Modified from Liu et al. [13].

(iii) Lithic petrofacies analyses. Detailed comparison between the source rocks and lithic fragments, especially lithic petrofacies, is an effective method of source-area analyses [7,13,14,26]. Percentages of lithic grains, normalized as percentages of the total lithic content, are calculated for each sample after point-count measurement. Liu et al. [13] expressed these detrital fragments as lithic petrofacies (petrofacies in short) consisting of groups of lithic fragments with similar lithologies that are found together, defining distinctive provenance terranes. In some measured sections the lithic petrofacies are further classified into some subtypes according to their specific lithic types. Various kinds of lithic petrofacies with distinctive lithic composition at the different parts of the sections are expressed as petrofacies assemblages [13], which represent the exposed rock types and tectonic setting of the source area in the source-area during the syndepositional stage [13].

According to the detrital composition of the basin sediments in the southern margin of the Dabie orogen and the rock types of the Qinling-Dabie source area, Liu et al. [14] divided the lithic petrofacies of the Late Triassic-Jurassic sediments in the Dangyang and Zigui (to the west of the study area) basins into 6 types (Figure 7). Lithic Petrofacies II′ contains granite and diorite clasts. There is no outcrop of this source rock (pre-Late Triassic granite) in the Dabie source area. Petrofacies III’ contains medium- to low-grade metamorphic rocks including quartzites, quartz-schists, and schists. The source area for Petrofacies III′ includes Middle Proterozoic rocks distributed along the southern Qinling-Dabie orogen. Petrofacies IV′ includes mainly sericitic sedimentary fragments and slates possibly derived from Silurian rocks of the southern Qinling-Dabie range. Petrofacies V′ includes intermediate to siliceous volcanic rocks and volcanic tuff probably derived from the arc volcanics. A possible source area along the southern side of Qinling-Dabie is the presently-buried rocks of the Mianlue suture. Petrofacies VI′ and VII′ contain abundant chert and limestone fragments, respectively. These grain types most likely were derived from Paleozoic to Triassic marine sedimentary units in the Mianlue suture. Samples collected from the Zigui basin and Dangyang basin indicate an abundance of fine-grained sedimentary and low grade metasedimentary rocks (Petrofacies IV′). The source for these lithologies may be either marine, Silurian fine-grained units that are now only locally exposed within the southernmost Qinling microcontinent or from more distal flysch deposits of late Middle-Late Triassic age found along the southwestern Qinling Mianlue suture (the Songpan area). The scarcity of medium-grade metamorphic rocks (Petrofacies III′) from the Middle Proterozoic basement of the Qinling-Dabie core indicates that these rocks were barely exposed during the Late Triassic through Jurassic. There is an abundance of chert fragments (Petrofacies IV′) in the late Triassic through Jurassic deposits of the basins, and no limestone fragments (VII′) but in the Penglaizhen Formation in the Zigui basin. Therefore, the source area of the chert lithic fragments may be the Mianlue suture belt, now buried by the Xiangfan-Guangji fault (Figure 8(b)). Although rocks of the suture are no longer exposed, it is possible that deepwater chert (seafloor of the Mianlue ocean) may have been present. Uplift of the Paleozoic-Early Triassic rocks by the thrust belt did not take place until Late Jurassic time, after deposition of the Late Triassic through the Middle Jurassic deposits as suggested by abundant limestone lithic sands and pebbles in the Penglaizhen Formation in the Zigui basin. Middle Jurassic deposits exposed in the Zigui basin also contain andesitic and siliceous volcanic grains, and volcanic tuff (V′). The source for these fragments may be arc rocks of the Mianlue suture, now covered by thrust nappes. The petrofacies data from Triassic through Jurassic strata along the southern flank of the Qinling-Dabie suggest the relative timing of uplift of the mountain. Source areas for the Late Triassic foreland basins were the sedimentary cover of the southern Qinling-Dabie and/or early Mesozoic flysch basin deposits. No high-grade metamorphic rocks from deeper levels were exposed. The Mianlue suture belt may also have provided some of the detritus to this area, particularly chert fragments. Beginning in Middle Jurassic time (J_2), a volcanic arc source area provided some detritus along the southern foreland basin belt.

According to detrital composition of the Hefei basin sediments and the source rocks in the Dabie orogen, Liu et al. [13] divided the lithic petrofacies of the sediments into 7 types (Figure 8). Petrofacies I is derived from granitic gneiss (Petrofacies I-1), plagiogneiss (Petrofacies I-2), and marble (Petrofacies I-3) source areas exposed along the NDC and UHP/HP zones, as well as from the Late Proterozoic Luzhenguan complex [40,44–46]. In addition, felsic fragments are common in many slides. Although it is difficult to confirm their exact origin, they likely derived from the granitoid rocks and gneisses, defined as Petrofacies I-4. Petrofacies II contains white metagranite (Petrofacies II-1), red granite, metagranite, and granite gneiss (Petrofacies II-2), and metadiorite and tonalite (Petrofacies II-3) clasts, in which the red granite, metagranite, and granite gneiss came from the Luzhenguyan Group, and the white metagranite, metadiorite, and tonalite came from the axial Dabie metamorphic complex. Petrofacies III contains quartzites, quartz schists, chlorite schists, and schists. Petrofacies IV contains phyllites, granulites, and slates. Sources to the north of the axial Dabie complex for these two groups include the Luzhenguan complex and Fuziling Group in the east, and the Luzhenguan complex, Guishan, Dingyuan, and Nanwan groups in the west. These two petrofacies also contain a few clasts derived from the NDC and UHP/HP zones [16,44]. Petrofacies V includes low-grade metamorphic argillites and sandstones (V-1), and reworked sandstone and mudstone clasts, all of which were derived from the Yangshan Group, and parts of the Nanwan Formation and Foziling Group. Petrofacies VI includes altered rocks

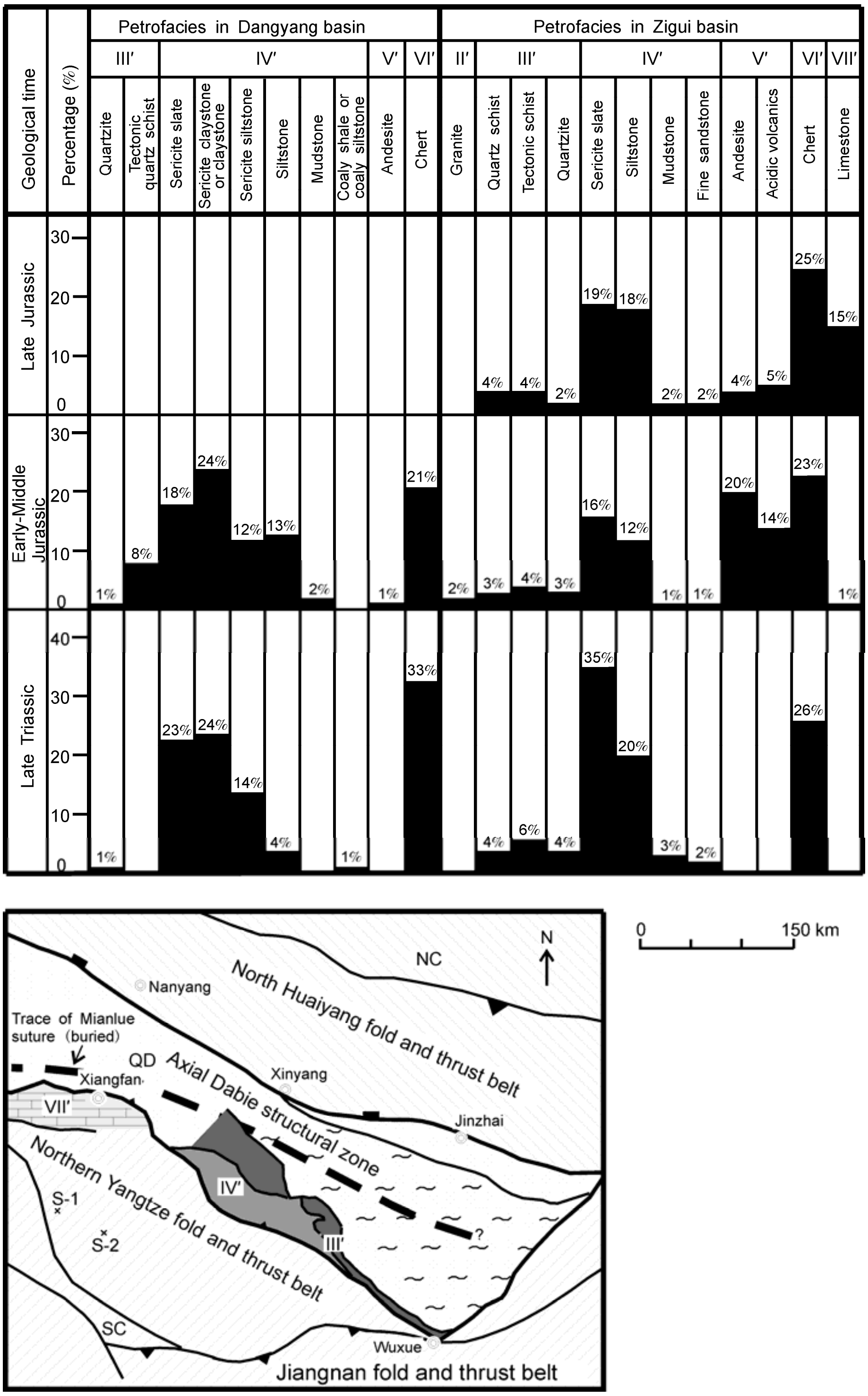

Figure 7 Summary of lithic petrofacies in the Dangyang basin (S-1 and S-2 in the inset map) and Zigui basin (ca. 100 km away from the Dangyang basin to the west). The inset map shows the source rocks in the Dabie orogen for the lithic petrofacies of basin sediments. Dashed line shows trace of the buried Mianlue suture that contains source rocks for petrofacies V′ and VI′. See explanation in Figure 1. Modified from Liu et al. [14].

and felsic to mafic metavolcanic rocks, probably derived from arc volcanics in the Dingyuan and Guishan Formations in the North Huaiyang zone [61]. Petrofacies VII only contains a small amount of chert clasts.

The modal data of sandstone samples generated by point counting from the Zhuji Formation in the Wumiao section show that the lithic fragments are mainly granite and metagranite (Petrofacies II-2), quartzite and schists (Petrofacies III), phyllite, granulite, and slate (Petrofacies IV), metasandstone (Petrofacies V), altered rock and rhyolite

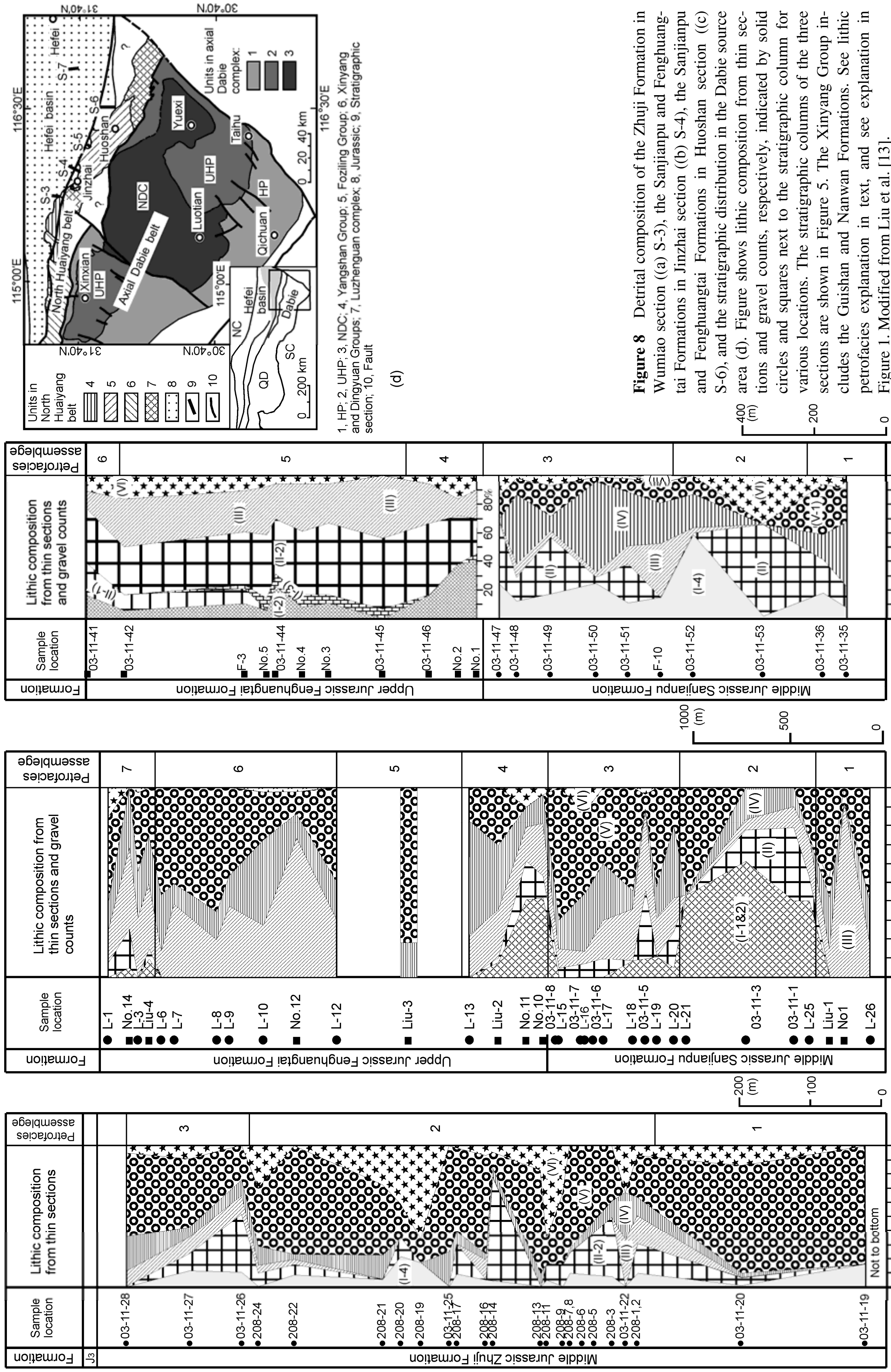

Figure 8 Detrital composition of the Zhuji Formation in Wumiao section ((a) S-3), the Sanjianpu and Fenghuangtai Formations in Jinzhai section ((b) S-4), the Sanjianpu and Fenghuangtai Formations in Huoshan section ((c) S-6), and the stratigraphic distribution in the Dabie source area (d). Figure shows lithic composition from thin sections and gravel counts, respectively, indicated by solid circles and squares next to the stratigraphic column for various locations. The stratigraphic columns of the three sections are shown in Figure 5. The Xinyang Group includes the Guishan and Nanwan Formations. See lithic petrofacies explanation in text, and see explanation in Figure 1. Modified from Liu et al. [13].

(Petrofacies VI), and felsic fragments (Petrofacies I-4) (Figure 8(a)). This analysis of the lithic portions of the petrofacies shows that sediment in the Zhuji Formation was derived from the Luzhenguan complex, the Nanwan, Guishan, and Dingyuan Formations, and the Yangshan Group in North Huaiyang (Figure 8(d)). The lithic petrofacies for Wumiao section constitute three petrofacies assemblages. The basal rocks, Petrofacies Assemblage 1, mostly contain reworked sedimentary rocks, Petrofacies V (76.4%–83.9%), derived from the Yangshan Group and the Nanwan Formation, the basement cover rocks in North Huaiyang zone. The middle part of the section, Petrofacies Assemblage 2, shows an increase in abundance of granite and granitic gneiss (Petrofacies II, mostly 10%–22% or more) and volcanic rocks (Petrofacies VI, 17%–67% in some parts) from the Luzhenguan complex, the basement rocks, and the Dingyuan and Guishan Formations of North Huaiyang zone. Petrofacies Assemblage 3, at the top of the section, shows an increase in content of medium- to low-grade metamorphic source (Petrofacies III and IV, 18.5%–35.9%) and reworked sedimentary rock source (Petrofacies V, 23.8%–59%). The first two petrofacies assemblages approximately record an unroofing event from cover strata to Luzhenguan basement, and the third one records a beginning of another unroofing event from cover strata in North Huaiyang.

The modal data generated by point counting and clast counting from sedimentary strata in the Jinzhai section show input from six petrofacies sources (Petrofacies I to VI) [13]. The lithic petrofacies for this section recorded seven petrofacies assemblages (Figures 8(b) and (d)). Petrofacies Assemblage 1 is composed mostly of medium- to low-grade quartz schist, quartzite, chlorite schist, phyllite, and slate rocks (Petrofacies III, 15%–92.2%; IV, mostly 21.8%–27%; and V, 7.8%–63.2%) derived from the Foziling Group on the northern flank of the orogen. The overlying deposits, which comprise Petrofacies Assemblage 2, show a marked increase in the abundance of moderately high-grade granitic gneiss and plagiogneiss rocks (Petrofacies I, 40%–61.1%), granite and metadiorite rocks (Petrofacies II, mostly 13%–38.8%) from the orogen core and the Luzhenguan complex. The high-grade plagiogneiss and metadiorite rocks are mostly sourced from the axial Dabie complex. Assemblages 1 and 2 correspond to the first unroofing event. Petrofacies Assemblage 3, located at the top of the Sanjianpu Formation, has an increase in medium- to low-grade metamorphic source rocks (Petrofacies III, 7%–41.7%; VI, 1.7%–38%; V, 6.6%–70%) derived from the Foziling Group. Petrofacies Assemblage 4, located at the base of the Fenghuangtai Formation, contains a mixture of compositions transported from all source areas (i.e. polymict) in which gneiss gravels (Petrofacies I, mostly 8%–42.1%) from a high-grade metamorphic source in the axial Dabie complex are increased. The second unroofing sequence is represented by Petrofacies Assemblages 3 and 4. The overlying middle to upper parts of the Fenghuangtai Formation, correspond to a third unroofing sequence. This part begins with dominantly reworked sandstone and mudstone clasts (Petrofacies V, 81.9%) sourced from the Yangshan Groups (Petrofacies Assemblage 5), and then shifts to a detrital composition composed of abundant medium- to low-grade metamorphic rocks, e.g. quartzites, quartz schists, phyllites, slates, and metamorphic argillites (Petrofacies III, 14%–73.7%; IV, 11.5%–45.3%; V, 10.5%–65.3%) (Petrofacies Assemblage 6), mostly from the Foziling Group. A further shift in detrital composition to an atypical polymict with a lower content of gneiss (Petrofacies I, 0–10%) and granite (Petrofacies II, 0–21.1%) and a metabasalt (Petrofacies VI, 0–15%) (Petrofacies Assemblage 7) transported from the North Huaiyang was observed at the top of the sequence. The evidence for three unroofing cycles in the stratigraphic section suggests that there were at least three episodes of uplift and exhumation in the source area. The rapid transition between source areas of different metamorphic grade may suggest that unroofing within each cycle was also related to individual structural events [7]. The major change in depositional style of the basin fill in the Hefei basin, indicated by the change from the Sanjianpu Formation coarse sandstone deposits to conglomerates of the Fenghuangtai Formation, is accompanied by a significant change in source-area composition from Petrofacies Assemblage 3 to 4, and represents a prominent period of unroofing and deformation. The first occurrence of relatively high-grade metamorphic rocks (Petrofacies Assemblage 2) as detrital grains in the Sanjianpu Formation in the Jinzhai section indicates that the UHP and HP metamorphic rocks of the Dabie orogen were exhumed and exposed during Middle Jurassic time. This occurrence, along with detrital grains of UHP rocks derived from the Dabie orogen appearing in the Fenghuangtai Formation of the Hefei basin [9] (Figure 5), indicates that significant unroofing of the deep core was complete by Late Jurassic time.

The modal data generated by point counting for the Sanjianpu Formation (J_2) and clast counting for the Fenghuangtai Formation (J_3) in Huoshan section reveal the presence of all seven lithic petrofacies derived from the NDC and UHP/HP zones, the Luzhenguan complex, and Foziling Group (Figure 8(c)) [13]. The lithic petrofacies in the section are classified into six petrofacies assemblages. The lower four assemblages in the Sanjianpu and the base of the Fenghuangtai Formation display two unroofing cycles of the basement rocks in the axial Dabie complex and the Luzhenguan complex. The upper two assemblages in the Fenghuangtai Formation, conglomerate deposited in an environment clearly different from that of the Sanjianpu Formation, was mostly shed from the proximal North Huaiyang area, but was derived more from the axial Dabie complex at the top of the Huoshan section, which probably represents another unroofing cycle. The petrofacies I and II were developed at the base of the Sanjianpu Formation, which represents the Dabie HP/UHP rocks in the source area unroofed at the Early Jurassic. Therefore, the provenance analyses of these depositional sections from the west to the east show that the unroofing ages of the HP/UHP rocks were late at the west and early at the east, and the source of the Wumiao section in the Middle Jurassic was the blanket rocks in the North Huaiyang [13].

Petrofacies data from Mesozoic strata in basins north and south of the Dabie range suggest HP/UHP rocks had been exhumed along the northern flank of the Dabie range by the Jurassic time whereas similar rock types never reached the Dangyang basin in the southern part of the range. Source areas for the Dangyang basin include the sedimentary cover of the southern Dabie core and/or buried, early Mesozoic flysch basin deposits and related strata with the Mianlue suture. The unroofed HP/UHP rocks in the Dabie range were far from the southern foreland basin, and located to the north of the division of the mountain.

3.2 Isotopic geochemical analysis

Because of variety, complexity, and contribution differences of sediment provenances, and differentiation of sediments under transportation, detrital composition and heavy mineral analyses are not enough to investigate lithic fragment disperse pattern and sediment provenance. Recently the methods of petrology, isotopic geochemistry, and isotopic chronology are used in analyses of basin sediments, tracing orogeny, and rock composition and unroofing of the source orogen. Scientists have carried on different kinds of geochemistry analyses on sedimentary rocks and gravels in the Hefei basin, and successfully revealed their provenances [4,62,63]. Here we introduce the results of Nd isotopic constraints on sources of basin fill [13]. Nd isotopic composition of the detrital sediments is assumed to result from mechanical mixing between old eroded crust and more recent detrital input [64,65]. Therefore, Nd isotope analysis, combined with detrital composition analysis, can identify and quantify erosion of the Dabie range.

(i) Nd composition of the basin sediments. Nd composition analysis results of the Jurassic stratigraphic sections at Wumiao, Jinzhai, and Huoshan in the Hefei basin are shown in Figure 9. The Nd composition in the Zhuji Formation in the Wumiao section is characterized by the highest $\varepsilon_{\mathrm{Nd}}$ values, ranging from –13.8 to –11.3, and the lowest ^{143}Nd/^{144}Nd values, ranging from 0.511829 to 0.511966, in the three sections (Figure 9). These values are clearly distinguishable from those of other sections and they suggest the sediments were derived from different sources. The T_{DM} values of this formation are relatively low, ranging from 1.7 Ga to 2.0 Ga. The Nd isotopic values do not exhibit any clear trends, but they can be conveniently divided into three parts (corresponding to Petrofacies Assemblages 1–3), which also represent the unroofing cycles of the source rocks [13].

Three sandstone samples of the Sanjianpu Formation were tested for the Nd composition in the Jinzhai section. The samples have the highest ^{147}Sm/^{144}Nd values, ranging from 0.1168 to 0.1266, of all of the basin sediments and lower $\varepsilon_{\mathrm{Nd}}$ values, ranging from –15.0 to –14.5, than those in the Wumiao section (Figure 9). This suggests that the sediments of the Sanjianpu Formation were derived from a mixed axial Dabie complex and North Huaiyang origin, including eclogite from the UHP/HP zone whose ^{147}Sm/^{144}Nd value is high [13].

Samples from the Huoshan section are characterized by the lowest $\varepsilon_{\mathrm{Nd}}$ values in the Hefei basin, which range from –22.0 to –14.6 (Figure 9), indicative of sediments largely sourced from the basement of the axial Dabie complex. The Nd isotopic composition regularly changes vertically along this section. The lower four assemblages (from Petrofacies Assemblages 1–4) at the Sanjianpu Formation and the lower part of the Fenghuangtai Formation record the first unroofing process from cover strata in North Huaiyang to the basement in the axial Dabie complex. The Petrofacies Assemblages 5–6 in Fenghuangtai Formation represent the second unroofing event of the medium- to low-grade metamorphic rocks and Luzhenguan granites [13].

(ii) End members of source rocks and their contribution to basin filling. The plot of $\varepsilon_{\mathrm{Nd}}$ values as a function of ^{147}Sm/^{144}Nd ratios indicates that plotted points for each section are relatively centralized, and that the $\varepsilon_{\mathrm{Nd}}$ values of the sediments for all sections generally decrease from the western Wumiao section to the eastern Huoshan section. The regular variations in the Nd isotopic composition suggest that sediments in each section were derived from a variety of source rocks. Therefore it is necessary to determine the end-member source rocks for each section and calculate their contribution to the basin sediments.

The plot of $\varepsilon_{\mathrm{Nd}}$ versus ^{147}Sm/^{144}Nd ratios (Figure 9(b)) for the Zhuji Formation and the presumed source rocks suggests that at least three end members are needed to explain the range of the data, which are (A) argillaceous sandstone of the Yangshan Group; (B) slate, phyllite, and chlorite schist of the Nanwan and Guishan Formations and metavolcanic rocks of the Dingyuan Formation; and (C) granite of the Luzhenguan complex. Presumed three end-members for the Jinzhai section in the middle part of the Hefei basin include the Luzhenguan granite (C), the medium- and low-grade metamorphic rocks, quartz schist, and quartzite in the Foziling Group (D), and felsic gneiss and eclogite in UHP/HP zone (E). The end-members for the sediments of the Sanjianpu and Fenghuangtai Formations in the Huoshan section are granite in Luzhenguan complex and metamagmatite in UHP/HP zone (end-member C′), quartz schist and quartzite in Foziling Group (D), and Gneiss and granulite in NDC (the metamorphic basement of the South China Block) and metapelite in UHP/HP zone (F) [13].

The end-member composition is taken as the average of the published data (see references in Liu et al. [13]), which includes $\varepsilon_{\mathrm{Nd}}$ value and ^{147}Sm/^{144}Nd ratio of the each end-

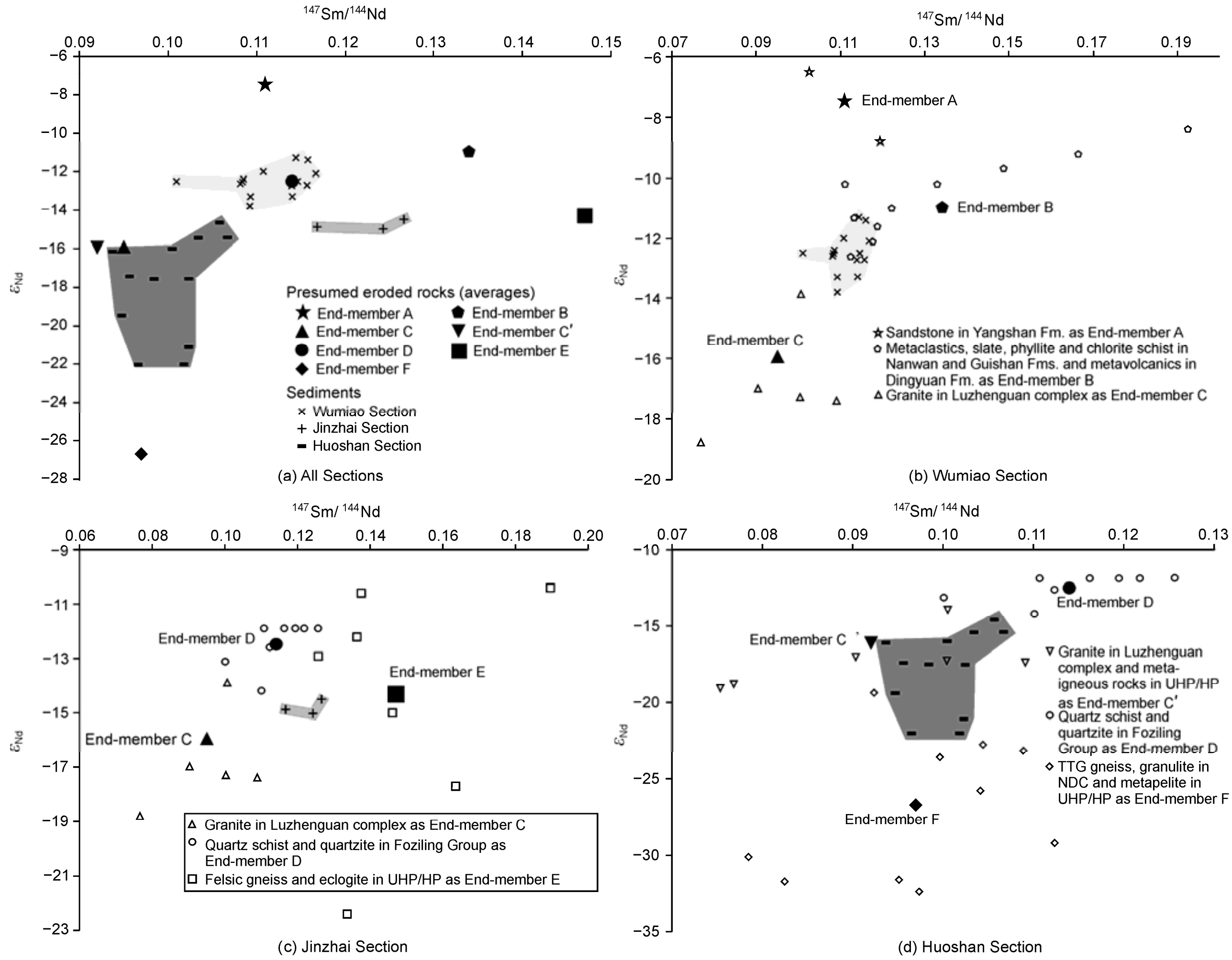

Figure 9 ε_{Nd} versus $^{147}Sm/^{144}Nd$. This diagram illustrates ε_{Nd} values and $^{147}Sm/^{144}Nd$ ratios obtained for the basin sediments in the sections of the Hefei basin and those for end members that were calculated by published data. See Liu et al. [13] for their references. Modified from Liu et al. [13].

member (Figure 9). The presumed end members can explain the isotopic character of the Jurassic sediments, and encompass all the data of each section in the coordinate systems of ε_{Nd} value and $^{147}Sm/^{144}Nd$ ratio (Figure 9), suggesting that the sediments were predominantly derived from the end-member source rocks and the presumed end-members are correct.

Having characterized the different end members, we can quantify the erosion of the Dabie orogen by calculating the relative contribution of each end member for different sections and different stratigraphic levels [66]. Figure 10 shows the relative contribution of each source area, calculated for each sample in all sections. (1) In the Zhuji Formation in the Wumiao section, the sources of the sediments were from the Yangshan Group, Nanwan and Guishan Formation of Paleozoic sedimentary sequence and Late Proterozoic granite in the North Huaiyang. According to variations in the relative proportions of the end members, three parts, which are the three Petrofacies Assemblages, are observed. The contribution of the Luzhenguan granite shows a system change within the range of 30 wt% to 60 wt% along the section. (2) The sources for the Sanjianpu Formation in the Jinzhai section contain detritus derived from the felsic gneiss and eclogite of the UHP/HP zone (end-member E), and its contribution is among 29 wt% to 50 wt%. (3) The sources of the sediments in the Sanjianpu and Fenghuangtai Formations in the Huoshan section were mainly from the axial Dabie complex (mainly NDC complex), and the Foziling and Luzhenguan Groups of the North Huaiyang. The contribution of end-member F (basement gneiss in NDC zone mainly) increases from 7 wt% to 59 wt% in Petrofacies Assemblages 2, 3, and 4, ranges among 12 wt% to 3 wt% at Petrofacies Assemblage 5, and then increases to 22 wt% at Petrofacies Assemblage 6 [13]. (4) The source rocks filling in the Jurassic Hefei basin in the northern margin of the Dabie orogen includes the HP/UHP rocks from the axial Dabie structural belt, the NDC complex of the basement of the South China block, and strata of the North Huaiyang. The unroofing of the Dabie orogen increased in depth eastwards, and the NDC complex located

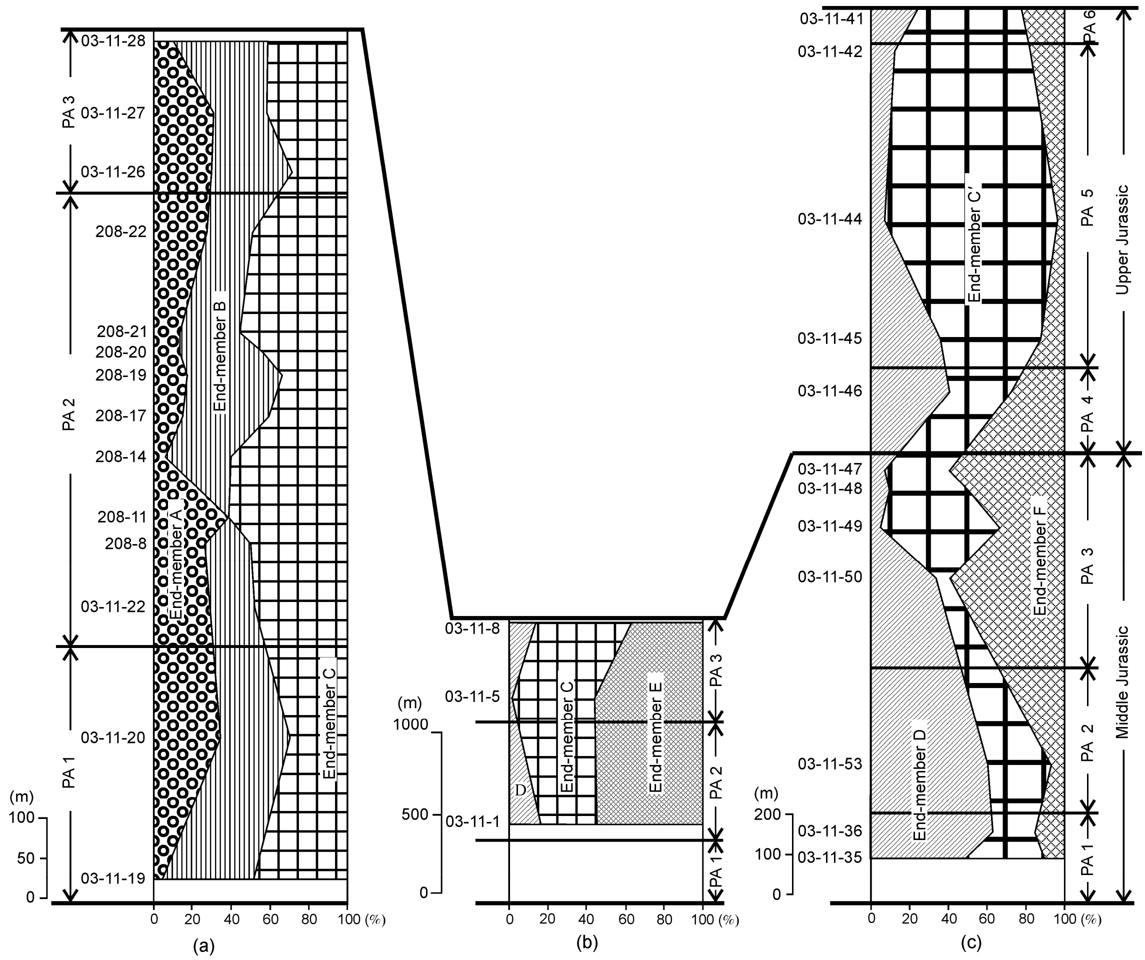

Figure 10 Contribution of end-members to the sediments in Wumiao (a), Jinzhai (b), and Huoshan (c) sections. See explanation in text. Modified from Liu et al. [13].

under UHP rocks was unroofed at the middle Jurassic in the eastern part of the Dabie orogen. The unroofing ages of the UHP and HP metamorphic rocks are changed younger westward.

3.3 Isotopic chronology analysis

The isotope chronology methods applied in the sediment tracing studies in the marginal basins of the Dabie orogen mainly include two categories. One is detrital zircon U-Pb (and detrital mica Ar-Ar) dating to obtain U-Pb and Ar-Ar geochronological spectra of basin sedimentary rocks, and trace source rock types and their changes in different stages. The other is the thermal chronological dating of zircon, mica, and potassium minerals picked out from granite gravels to investigate the history of uplift and exhumation of the intrusive granite in the source area, constrained by the age of strata that contain the gravels.

Recently some scientists obtained the U-Pb zircon age spectra from the Late Triassic and Early-Middle Jurassic strata in the Southeast Hubei basin in the southern Dabie range and Yueshan basin to the east of the Dabie range. For the upper Triassic sandstone from Qizhou, the U-Pb age clusters of these zircons are characterized by 28% of ca. 750–820 Ma, 29 % of ca. 2500 Ma, 12% of 420–450 Ma, 21% of 1050–1200 Ma, minor 1700–2000 Ma components, and no ca. 200–240 Ma grains [67]. The zircon ages of the Early Jurassic sandstones from Xianning area and drill cores of the Jianghan basin are dominated by 46% of ca. 1700–2000 Ma with less ca. 2500 Ma (ca. 19%), 750–820 Ma (10%), 220–260 Ma (10%), and 2160 Ma (9%) ages [67]. The Middle Jurassic sandstones from the northwestern Huangshi and drill cores of the Jianghan basin exhibit the similar age spectra to those of the Early Jurassic, that is, the four zircon age populations of ca. 1750–2000 Ma, 2500 Ma, 750–820 Ma, and 220–260 Ma with proportions of ca. 41%, 14%, 14%, and 13%, respectively, and minor populations of ca. 400–500 Ma and 1050–1250 Ma [67]. Yang et al. [68] obtained the similar zircon age spectra in the Early and Middle Jurassic sandstones from Huangshi, but the Early Jurassic sandstones exhibit no 200–300 Ma grain and a few of 400–500 Ma grains. The test results in Yueshan basin by Grimmer et al. [69] also show that the Early Jurassic sandstones exhibit very few 200–300 Ma grains and no 2400–

2500 Ma grain. Based on the above detrital zircon dating results and Ar-Ar chronological and geochemical analyses of white mica and high-Si-white mica, the scientists [67,69] thought that the Jurassic basin at the southern margin of the Dabie range had two source areas, that is, the main Dabie orogen source in the north and the JNFB source in the south [67–69]. According to the zircon and high-Si-white mica grains of 200–300 Ma exhibiting in the Early and Middle Jurassic strata, they also concluded that the HP/UHP rocks were unroofed and transported into the Southeast Hubei basin in the Early Jurassic [67,69]. As for no 200–300 Ma zircon and high-Si-white mica grains in the Late Triassic strata, some people identified that the sediment sources were mainly from the JNFB [67].

Generally, the isotope chronology research results on the basin sediments conform to those of the lithic petrofacies analyses, but some questions need to be further deliberated. (1) The Dabie orogen thrust southwards with a long-distance since the Middle Triassic, and its southern part converged with the JNFB. The Late Triassic and Jurassic basin (especially the Late Triassic foreland basin) in the southern margin of the Dabie range was almost overlapped by thrust nappe, and the Late Triassic Jigongshan Formation of the Southeast Hubei basin was not the deposits in the foredeep in front of the foreland fold and thrust belt at the syn-depositional stage. Even the lower part of the Jiuligang Formation also belonged to the deposits in the backbulge depozone. Therefore, the sediments of the Late Triassic Jigongshan Formation at the Southeast Hubei basin were lack of 200–300 Ma zircon grains, which do not suggest that the sediments of the whole foreland basin at the southern Dabie orogen were not transported from the north. (2) In the Early Mesozoic a wide foreland fold and thrust belt was developed at the southern margin of the Dabie orogen. The Mianlue suture was located between the UHP metamorphic terrane and the foreland. 200–300 Ma magmatic zircon and high-Si-white mica grains exhibited in sediments of the basins at the southern margin of the Dabie range were originated from the Mianlue collisional belt or volcanic arc. If these zircons had been eroded from Dabie HP/UHP rocks, the major zircon age population would have been 200–300 Ma and 700–800 Ma, otherwise the zircon age population of ca. 1750–2000 Ma sourced from the northern South China (The Three Gorges area of the Yangtze, for example) [70] because this zircon population does not largely exist in the HP/UHP terranes of the axial Dabie belt.

The dating of the detrital zircon and high-Si-white mica grains in the Hefei basin at the northern Dabie orogen [71], similar to the lithic petrofacies analysis, consistently represents the unroofing age of the HP/UHP rocks. According to the detrital zircon age spectra of the Fanghushan and Zhougongshan Formations in the Feixi section (Figure 5(b)) of the Hefei basin, Li et al. [72] concluded that the HP/UHP rocks in the Dabie orogen supplied source sediments (Triassic zircons) for the eastern part of the Hefei basin in the Early Jurassic, for the western part of the basin in the Late Jurassic, and were totally exposed at the Earth's surface in the Late Jurassic. Neoproterozoic zircons as the major component in the Jurassic sediments indicate that the source rocks were mainly derived from the exhumed South China basement rocks in the axial Dabie structural belt.

The thermal chronological analysis on the sedimentary gravels sourced from the Dabie range is another efficient method to reveal source rock uplift and exhumation. Lithochemical and isotope chronological analyses on the granite gravel in the Sanjianpu Formation and the Fenghuangtai Formation in Jinzhai prove that post-orogenic granite was developed in the major provenance of the Hefei basin; that is, Dabie orogen or North Huaiyang [73]. Discordant lower intersection point age of zircon U-Pb of granite gravel is about 214 Ma, and $^{40}Ar/^{39}Ar$ age of muscovite about 196 Ma, K-Ar age of K-spar about 181 Ma. The former is the diagenetic age of the sample, and the latter two represent the sealed ages of muscovite and K-spar respectively. The age of sedimentary rocks in which a lot of granite gravels appear in the sedimentary section may represent the newest age of the exhumation of the granite body, so the age is 166 Ma. Therefore, calculated uplift rates of the granite body from Late Triassic to early Middle Jurassic are ca. 0.08 km/Ma and 0.4–0.3 km/Ma in the early slowly uplifting stage and later fast uplifting stage, respectively, after the formation of the body at 214 Ma [8]. These results supplied a new evidence for revealing the uplift of the Dabie UHP and the NHFB. But we have not found any syn-collisional granite or granite gravel, and the calculated uplift rates are less than the exhumation rates of the HP/UHP rocks in the axial Dabie belt, obtained by other calculation methods [1,13].

4 Evolution of basin/mountain system

Qinling-Dabie orogen was formed by two times of oceanic basin closure and collision along the Shangdan suture at the north and Mianlue suture at the south during the Late Paleozoic and the early Mesozoic, respectively. The closure of the Shangdan ocean at the earliest Late Paleozoic led to the collision of the South China and North China Blocks. Afterwards the Mianlue ocean began to close since the Middle Triassic, which resulted in overall collisional orogeny of the Qinling-Dabie belt and the following intracontinental orogeny [74,75]. The collisional orogeny and the highly shortening deformation in the Dabie orogen underthrust, transformed, and eroded some structural zones. Therefore, revealing the tectonic evolution of the Dabie orogen largely depends on the reconstruction of the basin/mountain system and depositional paleogeography. The Mesozoic basins at the flanks of the Dabie orogen underwent the transformation from the foreland basin system to rift basin system (Figures 11 and 12).

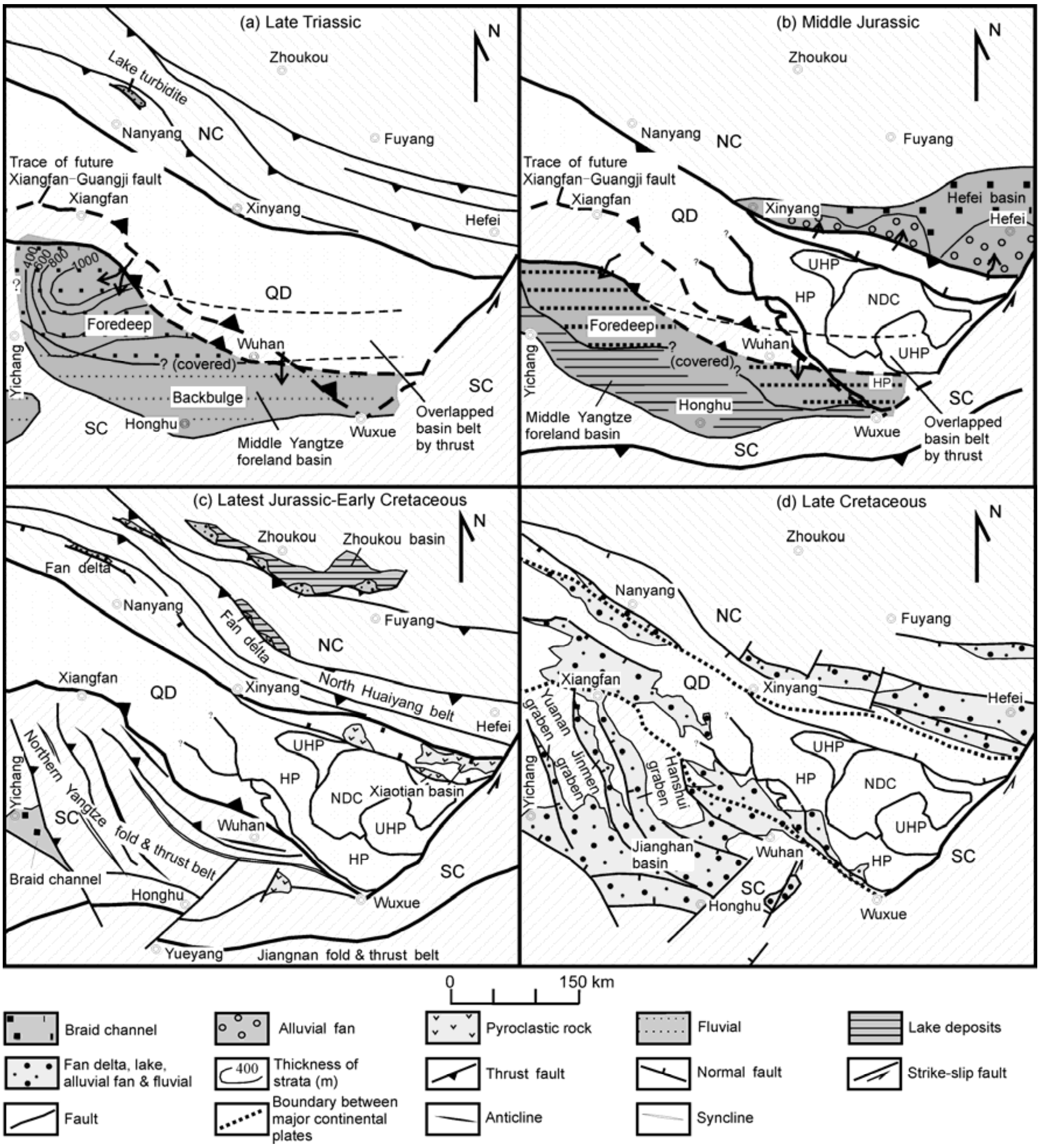

Figure 11 Tectonic paleogeographic maps of Dabie orogen and its adjacent regions. Position of units is not palinspastically restored. Basement symbols and abbreviations are from Figure 1. Modified from Liu et al. [14].

4.1 Late Triassic syn-collisional peripheral foreland basin system

During the Late Triassic time, the foreland basin in the southern Dabie orogen, called the Middle Yangtze foreland basin (including Dangyang and Southeast Hubei basins), began to develop upon the passive continental margin (Figure 11(a)). Palaeocurrent and composition data indicate that sediments derived from the orogen were shed southward into the basin. At this time, the source area included only the shallow, supracrustal, sedimentary part of the axial Dabie zone, including uplifted oceanic sedimentary rocks of the Mianlue suture. The Late Triassic lithofacies coarsen towards the mountain front, where braided streams dominated. The stratigraphic thickness is increased towards the north. Paleogeographic reconstruction shows that the eastern part of the foreland basin during this time was subsequently overthrust and is not exposed. In the Southeast Hubei basin near to the HP/UHP terranes, the only 50 m thick Jigongshan Formation, consists of Meandering channel plain deposits, was located in the backbulge depozone. The foreland deformation, formed at the syn-collisional stage and accompanied with foreland basin, only locally remained in Dahongshan-Baokang, and extended to Fangxian out of the study area. Therefore, the Dabie block thrust southward along the Xiangfan-Guangji fault with a long distance in the

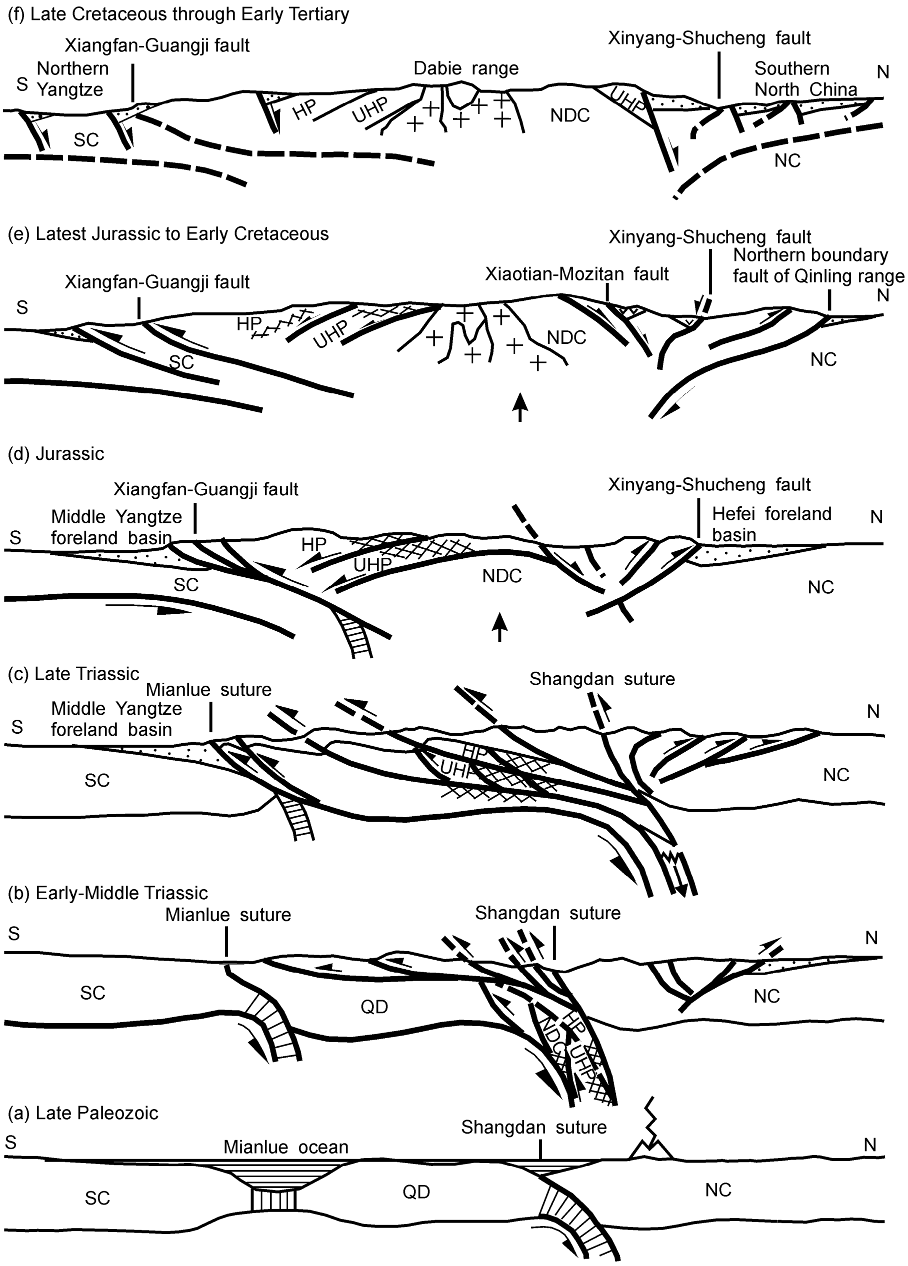

Figure 12 Interpreted cross section showing evolution of Dabie orogen from Late Paleozoic through Early Tertiary time. Modified from Liu et al. [14].

Late Triassic, and the Dabie HP/UHP rocks underwent their first time of thrust exhumation, but did not exposed to the Earth's surface (Figures 3 and 12(c)) [11]. The tectonism of the whole orogen behaved crustal shortening and thickening. As for the western extension of the Middle Yangtze basin and its connection with the Sichuan basin in the west, we need to do further investigation.

4.2 Jurassic and Early Cretaceous intracontinental foreland basin system

(i) Jurassic. The Dabie orogen was transformed into intracontinental deformation stage in the Jurassic. The orogen underwent strong shortening along the north and south flanks, and the axial HP/UHP rocks underwent a time of the second rapid exhumation [11,54]. 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 (Figures 11(b) and 12(d)). Although Upper Jurassic rocks are present in the Hefei basin, they are absent south of the Dabie range. The Late Jurassic basin belt was migrated to the Zigui area and its west. The Hefei basin contains a range of petrofacies suggesting repeated episodes of unroofing and thrusting. The provenance analysis of the Jinzhai and Huoshan sections in the Hefei basin represents initial unroofing of high-grade metamorphic core rocks in the Middle Jurassic, and then exposure of the blanket strata in the NHFB in the Late Jurassic, which were the products of northward progradation of the thrust belt in the northern Dabie range [7]. 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). 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 Dabie range.

To the south of the Dabie 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. 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. Composition of basin fill in the Middle Yangtze basin at this time is still dominated by supracrustal rocks. The depositional sequence of the Middle Yangtze basin is similar to that of the northern Sichuan basin, and the both were a united foreland basin filling. The deposits of this age in the Sichuan basin are well exposed and show a strongly developed asymmetry (reaching up to 3 km thick). Late Jurassic thrusting continued along the south flank of the Dabie range. The Late Triassic through Middle Jurassic strata were involved in the deformation. Meanwhile the axial Dabie structural belt began to thrust southward or southeastward since the Late Jurassic, and overlapped the early-formed foreland fold and thrust belt and foreland basin belt. The JNFB thrust and progradated northward or northwestward, and converged with the NYFB at the flank of the Dabie range. This tectonic process led to the foreland basin depocenter at this time began to move to the west and into the Zigui basin.

Although the flanking basins appear to record overall shortening along the margins of the Dabie range, deformation within the range core suggests significant local extension [54], and geochemistry of UHP rocks represents a second rapid extensional exhumation at the same time (Figure 3) [11]. 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), stepped southward into the Mianlue suture (Triassic through Jurassic) and may include intracontinental subduction of the North China Block along the Northern Boundary Fault of Qinling Range during Cretaceous time [36]. Extension may be the supracrustal response to continued shortening, underthrusting of Xiangfan-Guangji and Xinyang-Shucheng faults, crustal thickening and isostatic rebound. This tectonism induced uplift of the Dabie core HP/UHP rocks (Figure 12(d)). Unroofing sequences in the flanking basins suggest that exhumation of the core was greatest along the northern Dabie range. In fact, today, the deepest crustal levels are exposed primarily in the northern part of the range.

(ii) (Latest Late Jurassic and) Early Cretaceous. Relatively little sedimentary record from this time is found in limited areas north and south of the Dabie range. Along the north flank of the range, thrusting continued to step basinward (northward) over time into Zhoukou. Limited exposure of lacustrine and fan-delta deposition indicates source areas to the south [37]. Zhang et al. [36] have suggested that during late Early Cretaceous time intracontinental underthrusting of the North China Block southward beneath the Dabie range took place. South of the active part of the thrust belt, a series of isolated rift basins developed at the southern margin of the NHFB and farther west. These basins are bounded by the Xiaotian-Mozitan normal fault along their southern margins. The most complete rift basin sequence of this time includes volcanic flows, pyroclastic units, deltaic units, and lacustrine (Figures 11(c) and 12(e)). Besides, there were the Early Cretaceous intrusions from the mantle and lower crust in the Dabie range. South of the Dabie range, foreland sedimentation was centered to the west of the study area, into the western Sichuan, during Early Cretaceous time. Within the study area, small basin remnants, consisting of alluvial fan and braid channel plain coarse-grained clastic rocks, are found near Yichang.

Thus thrust deformation continued along both flanks of the range, and the northern South China and southern North China Blocks subducted along the Xiangfan-Guangji and the Northern Boundary Fault of Qinling Range, respectively. The orogen underplating, crustal isostatic adjustment further induced extension and collapse. Rift basins began to form along the north side of the Dabie range as well as extensional, primarily as low-angle, detachment faults continued to develop in the metamorphic core zone. Extension was penecontemporaneous with the third episode of rapid exhumation recorded in the axial Dabie range (Figures 3 and 12(e)) [11,55].

4.3 Late Cretaceous rift basin system

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 from the flanks to the core with time, eventually involving the entire orogen. The major Late Cretaceous rift basins and normal faults trend parallel to the orogen (Figures 11(d) and 12(f)) [14]. 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 Dabie range by Late Cretaceous time. Prior to this time high-grade metamorphic basement source areas were only found along the north side of the range [13,14,26].

5 Analysis of geodynamics

The collisional orogeny of the Dabie range is an important issue related with closure of northeastern branch of Paleo-Tethys ocean. Paleo-geomagnetism research results represent that there was a paleo-ocean open to the west between the North China and South China Blocks in the Late Paleozoic [76], which was so called Mianlue ocean located at the southern of the Dabie range otherwise the Shangdan paleo-ocean closed at the Late Paleozoic. Because of overlapping and transformation of the thrust at the southern flank of the Dabie range, the remnant basin sediments help to reveal the geodynamics of the basin/mountain system.

Liu et al. [26] initially put forward northwestward, oblique subduction model of the South China Block under the North China from Middle Triassic to Late Triassic, based on geological evidences below. From late Middle Triassic to Late Triassic, a thick foredeep flysch developed in the Songpan in the western part of the northern South China Block, and was the deposits at the initial stage of the ocean closure. This foredeep is not present along its strike to the east, and replaced by shallow marine basin at the northwestern Sichuan, and continental basins at the northeastern Sichuan and the Middle Yangtze. Thus the Mianlue ocean closed from east to west, which induced a continuous shortening and thrusting at the southern flank of the Dabie range. The collision along the Mianlue ocean began at its east, causing deep subduction of the Dabie-Sulu orogen, formation of the HP/UHP rocks, and their later rapid exhumation by thrust [54]. Zhu et al. [77] also concluded that the Tanlu fault, located between the Dabie-Sulu orogen, underwent a northwest-vergent, strike-slipping subduction and collision in the Late Triassic.

The conglomerate at the base of Jurassic and its unconformity with the underlying strata mark the collision between the South China and North China Blocks, and stepping into the stage of intracontinental evolution. A united, nearly E-W trending northern Yangtze foredeep (at the southern flank of the Qinling-Dabie range) was not formed until Middle Jurassic. The integration of the foreland basin system represents the complete amalgamation of the South China and North China Blocks, and face-to-face shortening and thrusting [26]. Prototype basin reconstruction shows that the northern Yangtze basin belt is lack of northern marginal zone at its eastern part, and extends eastward across the southern Dabie range to connect with Yueshan basin [28]. This geological evidence proves that the Dabie HP/UHP terranes thrust southwards for a long distance after the Middel Jurassic. During Late Jurassic, the NYFB thrust southwards and the JNFB expanded northwestwards, the two belts joining together and the early foreland basin in turn became involved in deformation. The depocenter migrated to the Zigui Basin. Meanwhile, the NHFB and Jurassic Hefei foreland basin were developed at the northern flank of the Dabie range. Thus, shortening deformation and two-sided thrust continued along both flanks of the range, which induced rapid exhumation of the HP/UHP rocks. This exhumation mechanism may be related with thickening and doming of the orogen core [14]. Some thought that this stage of exhumation was related with eastward extrusion [52,17], but Li et al. [17] proved that this eastward extrusion induced the extension of the Dabie core. Based on provenance analysis of the Hefei basin sediments, Liu et al. [13] demonstrated that unroofing depth of the Dabie orogen was increased eastwards, the unroofing ages of the UHP and HP metamorphic rocks changed from Early Jurassic to Late Jurassic westward, and the exhumation rate during the Late Triassic and Jurassic was inferred to have increased eastward from ca. 1.4 mm/a to ca. 2.5 mm/a on average (Figure 13). The difference in unroofing ages and exhumation rates may be related with shortening deformation generated early

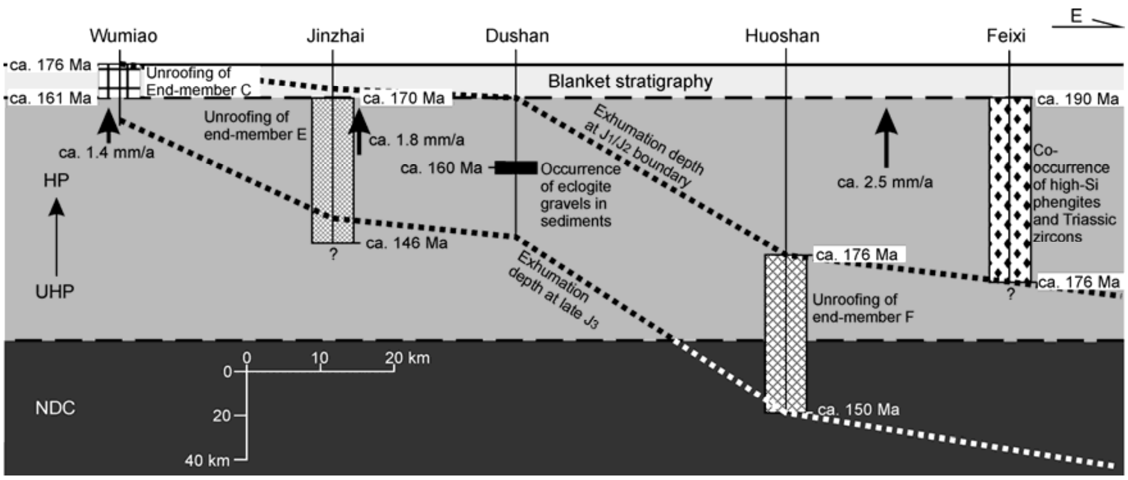

Figure 13 Simplified map showing the spatial distribution of the representative end member or eclogite gravels, high-Si phengites, and Triassic zircons that were exhumated in the source area. This map was organized according to provenance analysis results of stratigraphic sections in the Hefei basin [9,13,71], which demonstrate the depth of exhumation increasing from west to east, the unroofing ages of the UHP and HP metamorphic rocks changing from Early Jurassic to Late Jurassic westward, and eastward increasing exhumation rate in the Dabie orogen during the Jurassic. The vertical lines show location of the sections. Arrows indicate exhumation rate. See explanation in Figure 1. Location of the sections is shown in Figure 1(a). Modified from Liu et al. [13].

at the east and later at the west, which was induced by oblique subduction during the Middle and Late Triassic time.

During the Early Cretaceous, thrust deformation continued along both flanks of the range, and controlled the local foredeep subsidence at the outer edges. Local rift dominated the range core. The NYFB and the JNFB were overlapped and converged, and the joint front continuously migrated westwards. Under this tectonic control, the depocenter continuously moved to the west into the western Sichuan. Regionally, the structural framework in the Early Cretaceous was characterized by sinistral strike-slipping thrust along the Longmen Mountains at the western South China, northward extrusion of the Micangshan-Hannan block, sinistral strike-slipping in the JNFB, turning to NEE trending of the northern East Sichuan fold belt, and extensional rifting to the east of Zhangjiajie-Wuxue [28]. This structural setting represents that the South China block clockwise rotated relative to the North China-Qinling-Dabie block during their oblique convergence, and the East China began to spread due to paleo-Pacific subduction.

During the Late Cretaceous and its later, the Dabie orogen was characterized by a basin/mountain framework of extension and collapse. Regionally the boundary of structural differentiation between the east and the west in the South China migrated to Ansi-Fangxian, with extension to its east and shortening to its west. This tectonic situation may be caused by a combination of the plate collisional orogeny in the western Tethys domain and the tectonism in the eastern circum-Pacific domain.

Therefore, the Dabie range, in central China, records a prolonged period of shortening since the Middle Triassic 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 crustal levels. Penecontemporaneous compression and extension across the orogen may reflect long-term (>100 Ma) shortening [78] and continental crustal thrusting and thickening leading to gravitational spreading and isostatic rebound of the resultant thick crustal welt, and exhumation of the HP/UHP rocks. The development of these basin/mountain systems was the Earth's surface response to lateral accretion of the orogen, vertical thickening of the continental crust, uplift and exhumation of the basement, and deep mantle tectonic process during continental collision orogeny.

6 Conclusions and perspectives

(1) The Dabie orogen records a tectonic history of shortening and thrust from the Middle Triassic to Early Cretaceous which controlled the outer marginal foreland basin formation, gradually doming and local rifting at the core from Jurassic to early Cretaceous, and then overall collapse of the whole orogen after the Late Cretaceous.

(2) The depth of exhumation in the axial Dabie complex and the North Huaiyang increased from west to east, and the unroofing ages of the UHP and HP metamorphic rocks in the Dabie orogen vary from Early Jurassic to Late Jurassic westward. The sediment source areas for the Hefei basin are composed of the deeply exhumed, axial Dabie metamorphic complex, and the sediment sources for the Middle Yangtze basin are mostly from cover strata in the southern Qinling-Tongbai orogen and related strata with subjacent (i.e. subsequently overthrusted) Mianlue suture belt.

(3) Continental collision between the North China Block and the South China Block along the Shangdan and Mianlue sutures, subsequently northwestward progradation of the JNFB, and underthrusting of the North China Block along the Northern Boundary Fault of Qinling Range led to a prolonged period of shortening (>100 Ma) and crustal thickening, subsequently gravitational spreading, balanced uplifting, and exhumation of the HP/UHP rocks. This tectonism fully reflects the response of the Earth's surface basin/mountain systems to lateral accretion of the orogen, vertical thickening of the continental crust, uplift and exhumation of the basement, and deep mantle tectonic process during continental collision orogeny.

The Dabie orogen develops broad exposed HP/UHP rocks, which are infrequent in the world. The exhumation of the HP/UHP rocks and the eroded material transportation directions are still closely-concerned scientific issues. Most scientists have realized that the eroded materials from the Dabie range were transported to the Middle and Late Triassic Songpan basin so far, but they did not find enough evidences for transportation channels and structural framework. The point of view that the source area for 200–300 Ma detrital zircons in the Mesozoic northern Yangtze basin was defined to be the HP/UHP rocks in the Dabie range needs further study. The future studies also include eastward extension of the Mianlue suture, the tectonism of the Tanlu fault during the Early Mesozoic, subducted and removed structural zones at the flanks of the Dabie UHP terranes, especially southward-overlapped zones, and their relationship with the zones in the Qinling-Tongbai orogen. Because of the subduction, overlapping, and erosion coursed by the highly shortening in the Dabie orogen, some structural zones disappeared or unexposed on the Earth's surface. Therefore, the basin stratigraphy at the flanks of the range recorded the tectonism since the Mesozoic, and the marginal sedimentary basins are the important 'window' to reveal the above issues.

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1 Zheng Y F. A perspective view on ultrahigh-pressure metamorphism and continental collision in the Dabie-Sulu orogenic belt. Chin Sci

Bull, 2008, 53: 3081–3104
2 Liu S F, Zhang G W, Cheng X Y, et al. Evolution of flexural basins and process of collision orogeny in East Qinling-Dabie Shan and its adjacent regions (in Chinese). Sci Geol Sin, 1999, 34: 336–346
3 Liu S F, Zhang G W, Cheng X Y, et al. Basin evolution and deep tectonism in the East Qinling-Dabie orogenic belt and its adjacent regions. In: Li S T, Wang H, Lu F X, eds. Basin Geodynamics—Fundamental Idea and Some Approaches (in Chinese). Wuhan: China University of Geosciences Press, 1999. 130–145
4 Li R W, Jiang M S, Li Z, et al. Carbon and oxygen isotopic compositions of the marble conglomerates of Jurassic age in the northern margin of Dabie Mountains, China (in Chinese). Acta Petrol Sin, 1999, 15: 623–629
5 Li Z, Sun S, Li R W, et al. Mesozoic fill-sequences in Hefei Basin: Implication for Dabie Orogenesis, central China. Sci China Ser D-Earth Sci, 2001, 44: 52–63
6 Li Z, Li R W, Sun S, et al. Mesozoic basin-fill records in south foot of the Dabie Mountains: Implication for Dabie Orogenic attributes. Sci China Ser D-Earth Sci, 2003, 46: 217–230
7 Liu S F, Liu W C, Dai S W, et al. Thrust and exhumation processes of bounding mountain belt: Constrained from sediment provenance analysis of Hefei Basin, China. Acta Geol Sin, 2001, 75: 144–150
8 Liu S F, Zhang G W, Zhang Z Q, et al. Isotope chronological trace of granite gravel in Hefei Basin. Chin Sci Bull, 2001, 46: 1716–1721
9 Wang D, Liu Y, Li S, et al. Lower time limit on the UHPM rock exhumation: Discovery of eclogite pebbles in the Late Jurassic conglomerates from the northern foot of the Dabie Mountain, eastern China. Chin Sci Bull, 2002, 47: 231–235
10 Li S Y, Yue S C, Wang D X, et al. Stratigraphic evidence of the exhumation and uplift of ultrahigh-pressure metamorphic rocks in the Dabie orogenic belt: Enlightenment from eclogite gravels in the Maotanchang Formation (in Chinese). Geol Rev, 2002, 48: 345–353
11 Li S, Jagoutz E, Chen Y, et al. Sm-Nd and Rb-Sr isotopic chronology and cooling history of ultrahigh pressure metamorphic rocks and their country rocks at Shuanghe in the Dabie Mountains, central China. Geochim Cosmochim Acta, 2000, 64: 1077–1093
12 Meng Q R, Li S Y, Li R W. Mesozoic evolution of the Hefei basin in eastern China: Sedimentary response to deformations in the adjacent Dabieshan and along the Tanlu fault. Geol Soc Amer Bull, 2007, 119: 897–916
13 Liu S F, Zhang G W, Ritts B, et al. Tracing exhumation of the Dabie Shan UHP metamorphic complex using the sedimentary record in the Hefei basin, China. Geol Soc Amer Bull, 2010, 122: 198–218
14 Liu S F, Heller L P, Zhang G W. Mesozoic basin development and tectonic evolution of the Dabieshan orogenic belt, central China. Tectonics, 2003, 22: 1038
15 Zhang G W, Zhang B R, Yuan X C, et al. Qinling Orogenic Belt and Continental Dynamics (in Chinese). Beijing: Science Press, 2001. 1–855
16 Zheng Y F, Zhou J B, Wu Y B, et al. Low-grade metamorphic rocks in the Dabie-Sulu orogenic belt: A passive-margin accretionary wedge deformed during continent subduction. Int Geol Rev, 2005, 47: 851–871
17 Li S Z, Kusky T M, Zhao G C, et al. Thermochronological constraints on two-stage extrusion of HP/UHP terranes in the Dabie-Sulu orogen, east-central China. Tectonophysics, 2011, 504: 25–42
18 Dong Y P, Zhang G W, Neubauer F, et al. Tectonic evolution of the Qinling orogen, China: Review and sythesis. J Asian Earth Sci, 2011, 41: 213–237
19 Cong B, Wang Q, Zhai M, et al. Ultra-high pressure metamorphic rocks in the Dabie-Sulu region, China: Their formation and exhumation. Island Arc, 1994, 3: 135–150
20 Li S G, Huang F, Nie Y H, et al. Geochemical and geochronological constraints on the suture location between the North and South China Blocks in the Dabie orogen, Central China. Phys Chem Earth, 2001, 26: 655–672
21 Hacker B R, Ratschbacher L, Webb L, et al. U/Pb zircon ages constrain the architecture of the ultrahigh-pressure Qinling-Dabie Orogen, China. Earth Planet Sci Lett, 1998, 161: 215–230
22 Dong Y P, Zhang G W, Lai S C, et al. An ophiolitic tectonic melange first discovered in Huashan area, south margin of Qinling orogenic belt, and its tectonic implications. Sci China Ser D-Earth Sci, 1999, 42: 292–301
23 Lai S C, Zhang G W, Dong Y P, et al. Geochemistry and regional distribution of ophiolites and associated volcanics in Mianlue suture, Qinling-Dabie Mountains. Sci China Ser D-Earth Sci, 2004, 47: 289–299
24 Zhang G W, Dong Y P, Lai S C, et al. Mianlue tectonic zone and Mianlue suture zone on southern margin of Qinling-Dabie orogenic belt. Sci China Ser D-Earth Sci, 2004, 47: 300–316
25 Li S Z, Zhao G C, Zhang G W, et al. Not all folds and thrusts in the Yangtze foreland thrust belt are related to the Dabie Orogen: Insights from Nesozoic deformation south of the Yangtze River. Geol J, 2010, 45: 650–663
26 Liu S F, Steel R, Zhang G W. Mesozoic sedimentary basin development and tectonic implication, northern Yangtze Block, eastern China: Record of continent-continent collision. J Asian Earth Sci, 2005, 25: 9–27
27 Dong S W, Gao R, Cong B, et al. Crustal structure of the southern Dabie ultrahigh-pressure orogen and Yangtze foreland from deep seismic reflection profiling. Terra Nova, 2004, 16: 319–324
28 Liu S F, Wang P, Hu M Q, et al. Evolution and geodynamic mechanism of basin-mountain systems in the northern margin of the Middle-Upper Yangtze. Earth Sci Front, 2010, 17: 14–26
29 Ratschbacher L, Hacker B R, Webb L E, et al. Exhumation of the ultrahigh pressure continental crust in east-central China: Cretaceous and Cenozoic unroofing and the Tan-Lu fault. J Geophys Res, 2000, 105: 13303–13338
30 Suo S, Zhong Z, You Z. Extensional deformation of post ultrahigh-pressure metamorphism and exhumation process of ultrahigh pressure metamorphic rocks in the Dabie massif, China. Sci China Ser D-Earth Sci, 2000, 43: 225–236
31 Liu S F, Yan D P, Yu B S, et al. Mesozoic-Cenozoic Structural Evolution and Upper Group Studies in the Middle-Upper Yangtze. Research Report of Sinopec, 2009
32 Zhao Z, Yang S, Chen H, et al. Sedimentary environment of Carboniferous system in Shangcheng-Gushi area, Henan Province and its tectonic implications (in Chinese). Geol Rev, 2000, 46: 407–416
33 Zheng Y F, Gao X Y, Chen R X, et al. Zr-in-rutile thermometry of eclogite in the Dabie orogen: Constraints on rutile growth during continental subduction-zone metamorphism. J Asian Earth Sci, 2011, 40: 427–451
34 Wang Q C, Cong B L, Ma L. Structural coupling of the Dabie orogen with Hefei basin. Chin Sci Bull, 1997, 42: 1566–1572
35 Wang Y S, Xiang B W, Zhu G, et al. Structural and geochronological evidence for Early Cretaceous orogen-parallel extension of the ductile lithosphere in the northern Dabie orogenic belt, East China. J Struct Geol, 2011, 33: 362–380
36 Zhang G, Meng Q, Liu S, et al. A giant intracontinental subduction belt in the southern Huabei block and present 3-D lithospherical structure of Qinling orogenic belt (in Chinese). Geol J Chin Univ, 1997, 3: 129–143
37 Sun J, Yang X, Qiu R, et al. Dynamic settings and interactions between basin subsidence and orogeny in Zhoukou Depression and Dabie orogenic belt. J Chin Univ Geosci, 2000, 11: 369–371
38 Wang X D, Neubauer F, Genser J, et al. The Dabie UHP unit, central China: A Cretaceous extensional allochthon superposed on a Triassic orogen. Terra Nova, 1998, 10: 260–267
39 Liu X C, Jahn B M, Liu D Y, et al. SHRIMP U-Pb zircon dating of a metagabbro and eclogites from western Dabieshan (Hong'an Block), China, and its tectonic implications. Tectonophysics, 2004, 394: 171–192
40 You Z, Han Y, Yang W, et al. The High-Pressure and Ultra-High Pressure Metamorphic Belt in the East Qinling and Dabie Mountains, China (in Chinese). Wuhan: China University of Geosciences Press, 1996. 1–150
41 Xu B, Grove M, Wang C, et al. ^{40}Ar/^{39}Ar thermochronology from the northwestern Dabie Shan: Constraints on the evolution of Qinling-

Dabie orogenic belt, east-central China. Tectonophysics, 2000, 322: 279–301
42 Liu Y C, Li S G, Xu S T, et al. Sm-Nd dating of eclogites from Northern Dabie Mountains and its constraints on the timing of granulite-facies retrogression (in Chinese). Geochimica, 2001, 30: 79–87
43 Xie Z, Gao T S, Chen J F. Multi-stage evolution of gneiss from North Dabie: Evidence from zircon U-Pb chronology. Chin Sci Bull, 2004, 49: 1963–1969
44 Dong S, Wang X, Huang D. Discovery and signifi cance of low-grade metamorphic rock slices in ultrahigh-pressure metamorphic belt in Dabieshan. Chin Sci Bull, 1996, 41: 815–820
45 Liou J G, Zhang R Y, Jahn B M, Petrology, geochemistry and isotope data on a ultrahigh-pressure jadeite quartzite from Shuanghe, Dabie Mountains, east-central China. Lithos, 1997, 41: 59–78
46 Schmid R, Romer R L, Franz L, et al. Basement-Cover Sequences within the UHP unit of the Dabie Shan. J Metamorph Geol, 2003, 21: 531–538
47 Liu D, Jian P, Kröner A, et al. Dating of prograde metamorphic events deciphered from episodic zircon growth in rocks of the Dabie-Sulu UHP complex, China. Earth Planet Sci Lett, 2006, 250: 650–666
48 Hacker B R, Simon R W, Lothar R, et al. High-temperature geochronology constraints on the tectonic history and architecture of the ultrahigh-pressure Dabie-Sulu Orogen. Tectonics, 2006, 25: TC5006
49 Li S, Xiao Y, Liou D, et al. Collision of the North China and Yangtze blocks and formation of coesite-bearing eclogites: Timing and processes. Chem Geol, 1993, 109: 89–111
50 Hacker B R, Ratschbacher L, Webb L, et al. U/Pb zircon ages constrain the architecture of the ultrahigh-pressure Qinling-Dabie Orogen, China. Earth Planet Sci Lett, 1998, 161: 215–230
51 Ames L, Tilton G R, Zhou G. Timing of collision of the Sino-Korean and Yangtze cratons: U-Pb zircon dating of coesite-bearing eclogites. Geology, 1993, 21: 339–342
52 Liu X C, Jahn B M, Liu D Y, et al. SHRIMP U-Pb zircon dating of a metagabbro and eclogites from western Dabieshan (Hong'an Block), China, and its tectonic implications. Tectonophysics, 2004, 394: 171–192
53 Hacker B R, Ratschbacher L, Webb L, et al. Exhumation of ultrahigh-pressure continental crust in east central China: Late Triassic-Early Jurassic tectonic unroofing. J Geophys Res, 2000, 105: 13339–13364
54 Li S Z, Kusky T M, Liu X C, et al. Two-stage collision-related extrusion of the western Dabie HP-UHP metamorphic terranes, central China: Evidence from quartz c-axis fabrics and structures. Gondwana Res, 2009, 16: 294–309
55 Li S, Huang F, Li H. Post-collosional lithosphere delamination of the Dabie-Sulu orogen. Chin Sci Bull, 2002, 47: 259–263
56 Liu W C, Ma W P, Tan Y J. Regional Geological Report (Suxianshi and Jinzhai) (1:50000). Hefei: Geological and Mineral Bureau of Anhui Province, 1995. 1–194
57 Wang Y, Fan W, Guo F. K-Ar dating of late Mesozoic volcanism and geochemistry of volcanic gravels in the North Huaiyang Belt, Dabie orogen: Constraints on the stratigraphic framework and exhumation of the northern Dabie orthogneiss complex. Chin Sci Bull, 2002, 47: 1688–1695
58 Liu S F, Zhang G W. Fundamental ideas, contents and methods in study of basin and mountain relationships. Earth Sci Front, 2005, 12: 101–111
59 Ingersoll RV, Bullard T F, Ford R L, et al. The effect of grain size on detrital modes: A test of the Gazzi-Dickinson point-counting method. J Sediment Petrol, 1984, 54: 103–116
60 Dickinson W R, Beard L S, Brackenridge G R, et al. Provenance of North American Phanerozoic sandstones in relation to tectonic setting. Geol Soc Amer Bull, 1983, 94: 222–235
61 Liu Y C, Liu L X, Gu X F, et al. Occurrence of Neoproterozoic low-grade metagranite in the western Beihuaiyang zone, the Dabie orogen. Chin Sci Bull, 2010, 55: 3490–3498
62 Li S Y, Li R W, Yue S C, et al. Geochemistry of Mesozoic detrital rocks and its constraints on provenance in Feixi area, Anhui Province. Acta Petrol Sin, 2004, 20: 667–676
63 Li S Y, Li R W, Meng Q R, et al. Geochemistry of the Mesozoic and Cenozoic detrital rocks and its constraints on provenance in the southeast foot of Dabie Mountains. Acta Petrol Sin, 2005, 21: 1157–1166
64 Henry P, Deloule E, Michard A. The erosion of he Alps: Nd isotopic and geochemical constraints on the sources of the peri-Alpine molasse sediments. Earth Planet Sci Lett, 1997, 146: 627–644
65 Clift P D, Shimizu N, Layne G D, et al. Development of the Indus Fan and its signifi cance for the erosional history of the Western Himalaya and Karakoram. Geol Soc Amer Bull, 2001, 113: 1039–1051
66 Faure G. Principles of Isotope Geology. 2nd ed. New York: Wiley, 1986. 1–589
67 Wang Y J, Zhao G C, Xia X P, et al. Early Mesozoic unroofing pattern of the Dabie Mountains (China): Constraints from the U-Pb detrital zircon geochronology and Si-in-white mica analysis of synorogenic sediments in the Jianghan Basin. Chem Geol, 2009, 266: 231–241
68 Yang J H, Cawood P A, Du Y S. Detrital record of mountain building: Provenance of Jurassic foreland basin to the Dabie Mountains. Tectonics, 2010, 29: TC4011
69 Grimmer J C, Ratschbacher L, McWilliams M O, et al. When did the UHP rocks reach the surface?: A ^{207}Pb/^{206}Pb zircon, ^{40}Ar/^{39}Ar white mica, Si-in-white mica single-grain provenance study of Dabie Shan synorogenic foreland sediments. Chem Geol, 2003, 141: 1–34
70 Zheng Y F, Zhang S B. Formation and evolution of Precambrian continental crust in South China. Chin Sci Bull, 2007, 52: 1–12
71 Li R W, Sang H Q, Zhang R H, et al. Geochronology of source materials from high-pressure and ultrahigh-pressure metamorphic rocks in Jurassic sedimentary rocks of Hefei Basin. Chin Sci Bull, 2003, 48: 605–610
72 Li R, Wan Y, Cheng Z, et al. Provenance of Jurassic sediments in the Hefei Basin, east-central China and the contribution of high-pressure and ultrahighpressure metamorphic rocks from the Dabie Shan. Earth Planet Sci Lett, 2005, 231: 279–294
73 Lu X P, Wu F Y, Zhao C B, et al. Triassic U-Pb age for zircon from granites in the Tonghua area and its response to the Dabie-Sulu ultrahigh-pressure collisional orogenesis. Chin Sci Bull, 2003, 48: 1616–1623
74 Liu S F, Zhang G W. Process of rifting and collision along plate margins of the Qinling orogenic belt and its geodynamics. Acta Geol Sin, 1999, 73: 275–288
75 Zheng Y F. Metamorphic chemical geodynamics in continental subduction zones. Chem Geol, 2012, doi: 10.1016/j.chemgeo.2012.02.005
76 Zhao X X, Coe S R. Palaeomagnetic constraints on collision and rotation of North and South China. Nature, 1987, 327: 141–144
77 Zhu G, Liu S W, Niu M L, et al. Syn-collisional transform faulting of the Tan-Lu fault zone, East China. Int J Earth Sci (Geol Rundsch), 2009, 98: 135–155
78 Wu Y B. Multistage evolution of continental collision orogen: A case study for western Dabie orogen. Chin Sci Bull, 2009, 54: 2568–2579