Early–Middle Jurassic evolution of the northern Yangtze foreland basin: a record of uplift following Triassic continent–continent collision to form the Qinling–Dabieshan orogenic belt

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Early–Middle Jurassic evolution of the northern Yangtze foreland basin: a record of uplift following Triassic continent–continent collision to form the Qinling–Dabieshan orogenic belt

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The northern Yangtze foreland basin system was formed during the Mesozoic continental collision between the North and South China plates along the Mianlue suture. In response to the later phase of intra-continental thrust deformation, an extensive E–W-trending molasse basin with river, deltaic, and lake deposits was produced in front of the southern Qinling–Dabieshan foreland fold-and-thrust belt during the Early–Middle Jurassic (201–163 Ma). The basin originated during the Early Jurassic (201–174 Ma) and substantially subsided during the Middle Jurassic (174–163 Ma). A gravelly alluvial depositional system developed in the lower part of the Baitianba Formation (Lower Jurassic) and progressively evolved into a meandering river fluvial plain and lake systems to the south. The alluvial fan conglomerates responded to the initial uplift of the southern Qinling–Dabieshan foreland fold-and-thrust belt after the oblique collision between the Yangtze and North China plates during the Late Triassic. The Qianfoya Formation (lower Middle Jurassic) mainly developed from shore-shallow lacustrine depositional systems. The Shaximiao Formation (upper Middle Jurassic) predominantly consists of thick-bedded braided river delta successions that served as the main body of the basin-filling sequences. The upward-coarsening succession of the Shaximiao Formation was controlled by intensive thrusting in the southern Qinling–Dabieshan fold-and-thrust belt. Palaeogeographic reconstructions indicated an extensive E–W foredeep depozone along the fold-and-thrust belt during the Middle Jurassic (174–163 Ma) that was nearly 150 km wide. The depozone extended westward to the Longmenshan and further east to the northern middle Yangtze plate. The northern Yangtze foreland basin was almost completely buried or modified by the subsequent differential thrusting of Dabashan and its eastern regions (Late Jurassic to Cenozoic).

Keywords: northern Yangtze plate; foreland basin; Early–Middle Jurassic; sedimentation; south-vergent thrust

1. Introduction

In central China, the tectonic framework of the Qinling–Dabieshan orogenic belt is characterized by three plates and two sutures. From north to south, these three plates are referred to as the North China plate, the Qinling–Dabieshan microplate, and the Yangtze plate and are bounded by the Shangdan suture to the north and the Mianlue suture to the south (Zhang et al. 2001) (Figure 1). These three plates and two sutures have undergone prolonged tectonic evolution since the Palaeozoic (Liu and Zhang 1999; Liu et al. 2003, 2013). Amalgamation of the Yangtze and North China–Qinling-Dabie complex plates resulted in a continent–continent collision during the Middle to Late Triassic. During the Late Triassic through Early–Middle Jurassic collision-induced orogenesis, marine sedimentation in the Mianlue suture (northern Yangtze plate) ceased and the Mianlue oceanic basin evolved into a peripheral foreland basin (Liu et al. 2005). Several geodynamic models have been proposed based on the collision of the Yangtze and North China plates during the Middle to Late Triassic. These models include rotation (Zhao and Coe 1987; Eide et al. 1993; Gilder et al. 1999; Wang and Meng 2008), oblique (Liu et al. 2005; Zhu et al. 2009), wedging (Yin and Nie 1993), and face-to-face (Okay and Čelal Şengör 1992) models. However, whether the Early–Middle Jurassic amalgamation continued as oblique subduction or transitioned to face-to-face intra-continental thrusting and uplifting following the Triassic continent–continent collision has not been resolved. Recent research has been conducted on stratigraphic sequences, sediment source areas, and basin–mountain coupling relationships in the northern Yangtze foreland basin (Liu et al. 2003; Deng et al. 2012; Liu and Zhang 2013). However, despite these recent studies, the geodynamic mechanisms, the proto-basin architecture, and the sedimentary response to the southern Qinling–Dabieshan fold-and-thrust belt remain unclear. When considered as a basic tectonic unit, the sedimentary basin can effectively reflect the deformation processes of its peripheral orogenic belt. Formed by overloading along the southern Qinling–Dabieshan fold-and-thrust belt, the stratigraphy of the foreland basins in the northern Yangtze plate may have
documented the thrusting and uplifting of the Qinling–Dabieshan fold-and-thrust belt. Thus, in this study, we focus on the northern Sichuan and Zigui basins and describe the Lower–Middle Jurassic basin-filling sequence, stratigraphic frameworks, and palaeogeographic reconstructions to restore the Early–Middle Jurassic thrusting and uplifting of the Qinling–Dabieshan orogenic belt and evolution of the northern Yangtze foreland basin following Triassic continent–continent collision.

2. The southern Qinling-Dabieshan foreland fold-and-thrust belt

The northern Yangtze foreland basin was a peripheral foreland basin superposed on the passive continental margin of the southern Mianlue Ocean (Liu et al. 2005). The basin is surrounded by the southern Qinling–Dabieshan fold-and-thrust belt to the north, the Longmenshan orogenic belt to the west, and the southern Dabieshan to the east. The
2.1. **The arcuate Dabashan fold-and-thrust belt**

The SW-dipping Dabashan (Figure 1A) can be divided into the North Dabashan thrust-nappe belt, South Dabashan foreland fold belt, and Sichuan basin foreland depression belt (Figure 2) (Dong et al. 2010). The three belts are bounded by the Ankang fault, Chengkou fault, and Tiexi–Wuxi blind fault from north to south (Zhang et al. 2001). The foreland depression belt is predominantly composed of weakly deformed Jurassic to Lower Cretaceous successions. A structural analysis indicated that the North Dabashan belt underwent NE–SW shortening and formed NW–SE-trending structures during the Late Triassic to Early Jurassic in response to the continental collision between the Yangtze and North China plates (Zhao and Coe 1987; Nie et al. 1994). The tectonic deformation of the Micangshan (J3) occurred earlier than that of the South Dabashan (J3/K1) (Pei et al. 2009). Alternatively, the western part of the South Dabashan truncated the eastern Micangshan. This truncation indicated that the South Dabashan experienced thrusting after the Cretaceous.

2.2. **The Micangshan fold-and-thrust belt**

The Micangshan fold-and-thrust belt is adjacent to the Dabashan to the east and Longmenshan orogenic belt to the west (Figure 1A). The Hannan dome (basement uplift: Proterozoic) consists of well-exposed Neoarchean–Proterozoic metamorphic rocks and is characterized by large-scale basement-involved anticlinal structures (Wu et al. 2011). Corresponding to the diachronous collision between the Yangtze and North China plates, the Hannan dome was rapidly exhumed and intensively deformed after the Late Triassic (Tian et al. 2012). The frontal Micangshan areas developed widely spaced anticlines during the late Palaeozoic to Early–Middle Triassic. The rear regions developed imbricated thrust faults involving Palaeozoic strata (Figure 2). The Micangshan experienced a moderate phase of denudation during the Cenozoic (Tian et al. 2012).

2.3. **The Longmenshan fold-and-thrust belt**

The NE–SW-dipping Longmenshan fold-and-thrust belt is defined by three thrust faults. From foreland to hinterland, these faults are ordered as follows: Guanxian–Anxian (foreground fault), which is composed of three segments (northern (Figure 2), central, and southern) (Chen et al. 2011)); Yingxiu-Beichuan (principal fault); and...
3. Stratigraphic successions of the foreland basin

During the late Neoproterozoic and Early–Middle Triassic, a thick succession of platform and continent marginal facies were deposited on the Yangtze plate. In response to the Yangtze and North China collision, the Sichuan and Zigui basins, which are located in the northwestern part of the Yangtze plate, were inverted to a foreland basin in the Middle Triassic (Liu et al. 2005). In the following sections, we focus on the Lower–Middle Jurassic stratigraphy of these basins, where the successions of the Baitianba (J₁,b) (Lower Jurassic), Qianfoya (J₂,b), and Shaximiao (J₂,s) Formations (Middle Jurassic) are well exposed.

3.1. The Baitianba Formation succession of the Lower Jurassic

The thickness of the Baitianba Formation varies from tens of to five hundred metres and features basal conglomerate (Figure 3A). The marginal Baitianba Formation occurs above an angular unconformity that separates it from the Upper Triassic Xujiahe Formation. This contact evolves into a parallel unconformity toward the distal basin (Bureau of Geology and Mineral Resources of Sichuan 1991); this unconformity boundary formed in response to a late episode of Indosinian movement (Ma et al. 2009).

The Baitianba Formation (Figure 3A) is approximately 320 m thick near Guling (Figure 1A), which is located in the northern Sichuan basin. The formation resulted in a third-order stratigraphic sequence composed of fining-upward successions. The basal portion of the formation is approximately 3 m thick and consists of massive, grey-black, grain-supported conglomerate that is rich in moderately to poorly sorted granules (2–4 mm) and pebbles (4–64 mm), which are mainly composed of sub-angular to sub-rounded chert gravels, followed by quartz sandstone, minor quartzite, and mudstone gravels (Figure 4A). We interpret this conglomerate as a lag deposit of a meandering riverbed (Allen 1978).

Medium- to coarse-grained quartz sandstone with massive bedding, tree trunks, and coal fragments occurs above...
conglomerate. Capping the sand bodies are pebbly sandstone and thickly bedded coarse-grained quartz sandstone with massive and/or lateral accretion bedding along with abundant coal fragments. Alternating thickly bedded fine-grained sandstone, laminated siltstone, and mudstone overlie the sand bodies with top coal seams that are interlayered with thin beds (<1 m thick) of medium-grained sandstone containing siderite nodules. This succession records the meandering stream/floodplain sedimentation (Miall 1996). The coarser sand bodies represent channels, channel belts, and amalgamated channel belts. The finer-grained units probably represent over-bank deposits or swamp and floodplain lake deposits (Kraus and Bown 1993). According to the lithofacies, sedimentary structures, and fossils, the overall successions are mainly organized into a meandering river depositional system.

3.2. The Qianfoya Formation succession of the lower Middle Jurassic

The lower Middle Jurassic is composed of the Qianfoya Formation (Figure 3A), the base which contains thin beds...
of conglomerate or coarse-grained conglomeratic sandstone, each of which begins with a scoured channel base. The Qianfoya Formation constitutes a third-order sequence with an erosion surface at its base. The formation of the northeastern Sichuan basin reaches a thickness of 450 m and is composed of two depositional cycles. For example, the lower succession begins with a 1 m-thick conglomerate and thinly bedded medium-grained sandstone that is overlain by thick rhythmic layers composed of fine-grained sandstone, siltstone with well-developed parallel laminations (Figure 4B), and mudstone intervals of lenticular coarse-grained sandstone. The upper cycle consists of a 0.5 m-thick coarse-grained basal conglomeratic sandstone with tabular cross-stratification. Upward, this sandstone transitions to thick rhythmic layers composed of parallel laminated fine-grained sandstone, siltstone, silty mudstone, and mudstone interbedded with repeated lenticular sandstone. Abundant leaf fragments (Figure 4C) and non-marine bivalve fossils (Figure 4D) (Chen et al. 1996; Guo et al. 1996) occur in the finer sediments. We interpret these sediments as shore and shallow lacustrine successions (Liu et al. 2005).

3.3. The Shaximiao Formation succession of the upper Middle Jurassic

The thick succession of the Shaximiao Formation filled most of the foreland basin in the late Middle Jurassic (Figure 3B and C). The Shaximiao Formation succession consists of five third-order sequences. The lower and upper sequence boundaries are the lithological and lithofacies transitional surfaces. In addition, the lower and upper sequence boundaries of the top sequence are lithological and lithofacies transitional surfaces and a regional unconformity contact, corresponding to the second episode of the Yanshan movement (Ma et al. 2009).

The Shaximiao Formation primarily consists of accumulated pinkish-red siltstone, silty mudstone and mudstone, as well as pale-green coarse- to medium-grained sandstone. This formation is composed of several coarsening-upward depositional cycle intervals with localized fining-upward units. All cycles share nearly the same characteristics. The lower part of a cycle contains thick-bedded interlayered siltstone, silty mudstone, and mudstone with flaser-wavy-lenticular bedding (Figure 4E), which probably indicates dual-directional palaeocurrents. Within the sand bodies, the presence of a delta front environment (Jiang 2010) within the successions is inferred based on the presence of trace fossils and bioturbation structures (Figure 4F). Thinly bedded medium- to fine-grained sandstone with well-developed parallel and/or horizontal lamination intervals of the siltstone and mudstone are interpreted as delta front sheet deposits formed when the delta flowed into the water bodies (Liu and Yang 2000). Coarsening, upward successions composed of mudstone, siltstone, and fine-grained sandstone with parallel and small-scale cross-beds cap the sandstone sheets; these successions are interpreted as mouth bar deposits at the front of the delta (Liu et al. 2005). Sandstone lenses within the siltstone and mudstone bodies extend several metres laterally before pinching out or developing into thin-bedded sandstone layers (Figure 4G). These successions probably represent the inter-distributary channel deposits of a delta front (Jiang 2010). Medium- to fine-grained sandstone with well-developed tabular, trough, wedge, and parallel cross-stratification with local scour-filling surfaces overlies this unit and may represent an underwater distributary channel deposit (Liu et al. 2005; Jiang 2010). The upper part of this cycle is coarse- to medium-grained sandstone or conglomeratic sandstone, with a thickness of 10–35 m; it is composed of massive bedding and large-scale trough, tabular, and wedge cross-stratifications (Figure 4H, I, and J) with embedded tree trunks (Figure 4K). The bases of most sandstone beds consist of sharp, undulate scour surfaces (Figure 4L) with clasts of underlying units (Figure 4M) that define the channel margin. These sandstone bodies probably represent braided river delta plain deposits (Miall 1978; Liu and Yang 2000). The interlayered siltstone and mudstone intervals of the thick-bedded, channelized sandstone are probably over-bank deposits (Liu et al. 2005). In contrast to the thin-bedded channel sandstone and thick-bedded floodplain/swamp deposits of the meandering stream, the braided river is characterized by thick-bedded channel sandstone bodies and thin-bedded over-bank deposits. Therefore, we interpret the Shaximiao Formation successions as the product of a multi-channel braided stream delta depositional system (McPherson et al. 1987). No pro-delta deposits were observed in these successions. Based on the tabular crosssets, the palaeoflow was directed to the W, NW, and NE (Figure 3B and C).

4. Stratigraphic correlation

We correlated the stratigraphic units and analysed each unit in terms of its distribution and feature variations to reveal their spatial architectures. Several stratigraphic correlation sections (Figures 5–7) clearly display the asymmetric wedge-stacked architecture of the foredeep depozone from the Early–Middle Jurassic. The section located near Longmenshan (Figure 5) decreases from approximately 1900 to 750 m to the SW. The central basin section ranges from 2600 m at Nanjiang to 1400 m at well NJJ (Figure 6). However, the section near the Dabashan front varies in thickness between 2600 and 3000 m, and a thinning trend does not occur toward the SE (Figure 7).
4.1. Basal conglomerate at the basin margin

In the northern segment of Longmenshan, the frontal Micangshan, and Dabashan, conglomerates were widely deposited at the base of the Baitianba Formation, marking the Lower Jurassic succession. According to different depositional features, the conglomerates can be divided into three belts: Micangshan conglomerate belt (S-A), western segment of the Dabashan conglomerate belt (S-B), and eastern segment of the Dabashan conglomerate belt (S-C) (Figure 1A).

The S-A outcrops near the front of the Micangshan fold-and-thrust belt (Figure 8). The conglomerate units vary in thickness among the different localities from tens of to one hundred metres. At Baolun (1) the thickness reaches 110 m, whereas at Wangcang (3) it decreases to approximately 25 m. The conglomerates are generally grey and massive, exhibiting localized graded bedding. In the Baolun (1) section, pebbles account for more than 50% of the grains whereas at Baishui (2) they account for 90%. The maximum length of the a-axis is 50 cm (Figure 10A). The clasts in the conglomerate mainly consist of sub-angular to sub-rounded quartzite, followed by sub-angular chert and minor amounts of mudstone, limestone, and other materials. No preferred orientation appears in the largest flat surfaces of the gravels. The succession is mainly composed of thick-bedded conglomerate containing sandstone lenses or beds, interbedded sheet flood siltstone, and fine-grained sandstone with parallel bedding. No fossils have been observed in this succession. We interpret the Baolun (1) and Baishui (2) sections as an
alluvial fan depositional system which probably represents proximal fan deposits. The conglomerate outcropping at Wangcang (3) is clast supported, with dominant moderately sorted pebbles and granules (2–4 mm). The composition is polymictic, containing 65% quartzite, 25% chert, and other rocks. Parallel laminated siltstone, fine-grained sandstone, and mudstone cap the conglomerates. Thus, the Wangcang (3) section probably developed in the proximal fan environment. Continuing eastward, the conglomerates of the Puji (4), Sanjiang (5), Jinx (6) (Figure 10B), and Nanjiang (7) sections varied from 50 to 65 m in thickness. The Puji (4) conglomerate is composed of approximately 70% cobbles (Figure 10C) rich in quartzite gravels (90%), with a small amount of chert and quartz sandstone. However, the Sanjiang (5), Jinx (6), and Nanjiang (7) sections are mostly composed of pebbles with a volume
of up to 50% quartzite gravel. Additional minor components include chert and quartz sandstone. Within the conglomerate bodies, intervals of thin beds or lenticular fine-grained sandstone with parallel bedding exist. According to the poorly sorted gravels, lack of imbrication, and scarcity of fossils, we speculated that these four sections (4–7) are deposits of the alluvial fan system. To the east, the thickness of the conglomerates decreases significantly (only 12–25 m thick in the Pingxi (8) and Lianghekou (9) sections). The gravels were mainly pebble grade (65–90%) (Figure 10D) with quartz sandstone (50–75%). The basal conglomerates are interbedded with medium- to coarse-grained sandstone of sheet flood deposits. These conglomerates are overlain by thick-beded cross-stratified medium- to fine-grained sandstone containing leaf fragments which transition upward to siltstone and mudstone with local coal seams. Sections 8 and 9 possibly represent deposits between portions of the two alluvial fans.

The S-B continues NW–SE to the Gujun areas (14) (Figure 9). Field observations show that the thickness of conglomerates in the Huangzhong (12) and Jiuyuan (13) sections reaches 85 m but decreases to 12 m in Zhuyu. Erosion surfaces can be found in the lower portions of the Jiuyuan (13) conglomerates; the underlying medium- to coarse-grained sandstone is scoured. The Tiexi (10) conglomerates are composed of pebbles (>75%) with approximately 17% cobbles. However, the Huangzhong (12) and Gujun (14) conglomerates are mainly composed of pebbles and cobbles (60 and 40%, respectively). The Jiuyuan (13) conglomerates are composed of more than 78% cobbles. The clasts in the conglomerates mainly consist of sub-rounded to rounded quartzite (70-92%), with minor sub-angular chert and quartz sandstone. Pebbles and cobbles outcrop at Huangzhong (12) and show a preferred orientation (Figure 10E). The four measured sections (10, 12, 13, and 14) have depositional characteristics similar to those of the S-A, which may have resulted from the alluvial proximal or middle fan. Grain-supported sandy conglomerate outcroppings at Zhuyu consist of granules (65%) composed of moderately to poorly sorted quartzite (90%) and chert gravels (Figure 10F). Here, the conglomerates are capped by a massive thick-beded medium-grained sandstone that may represent the middle fan environment.

The S-C extends NW–SE to Xietan (21) in the Zigui basin (Figure 11). The belt is distinctly different than the former two belts. No conglomerate deposits occur in the lower parts of the Zishui (15), Qilixia (16), and Wenquan (17) successions. At the bottom of the Nanxi (18), Guling (20), and Xietan (21) sections, a 0.5–1.5 m-thick conglomerate occurs. The Nanxi (18) and Guling (20) conglomerates contain pebble gravels concentrated in the 15–45 mm size range, accounting for 95 and 89% of the gravels, respectively. The polymictic grain-supported conglomerates of the Nanxi (18) and Guling (20) sections are predominantly composed of sub-angular to sub-rounded chert (75–84%), followed by quartzite (~10%), mudstone, and other gravels. The conglomerate belt is interpreted as resulting from the lag deposits of a meandering river system based on the following facies indicators: thick-beded sandstone bodies with tree trunks, numerous types of sedimentary structures, leaf fragments, and coal seams.

4.2. Stratigraphic framework of the Baitianba Formation

On the AA’ section (Figure 5), the Baitianba Formation consists of one fining-upward unit. The basal section of the Baitianba Formation in the Wangcang region is a 15 m-thick proximal fan conglomerate that transitions upward to meandering channel fine- to medium-grained sandstone and is interbedded with mudstone (see above). The proximal fan conglomerate is pinched out until meeting the facies at well C40, where it transitions to a facies with few conglomerates rather than thick beds of medium- to fine-grained sandstone. The lithology and facies are easy to identify and are correlated in geophysical logs, particularly when using their gamma ray signatures in combination with natural potential and resistivity logs.
The formation at well C36 is characterized by a box-shaped signal with lower gamma ray signatures in the geophysical logs, reflecting environments with rapid accumulation, adequate sediment sources, and strong hydrodynamic conditions. The deposits at wells C91 and Pi4 show upward increases in gamma ray values that are related to a fining-upward succession in the core and outcrop. Consequently, a transition from dominantly coarse
(in the cores from well C36) to fine successions with basal thin-bedded sandstone (in wells C91 and Pi4) is interpreted as a change from alluvial fan to shore-shallow lake.

On the BB′ section (Figure 6), the Baitianba Formation mainly consists of one to two fining-upward successions. The lower part of the formation in the Nanjiang area consists of proximal or middle fan conglomerates (see above) capped by thick-bedded fine-grained sandstone and siltstone. Immediately above the finer units, thick conglomerate beds are present that transition upward to fine-grained sandstone with parallel stratification. The thickness of the alluvial fan successions decreases southward. Wells 17 and C55 are characterized by increased gamma ray values from bottom to top, which is consistent with coarser to finer sediments. In addition, the gamma ray values have lateral continuity allowing for reasonably good correlations at the sub-surface. Alluvial fan conglomerates pinch out near wells Y3 and C55 and change facies, first to a meandering river depositional system and then to shore-shallow lakes at well NJJ.

On the CC′ section (Figure 7), alluvial fan conglomerates are deposited in the Lianghekou area and are capped by thick-bedded siltstone and fine-grained sandstone. Passing upward to the next cycle, the succession consists of medium-grained sandstone with massive bedding and thick rhythmic alternating siltstone and mudstone with parallel lamination. To the south, the Baitianba Formation is mainly composed of one to two fining-upward retrograding and deepening successions, which are characteristic of a meandering fluvial plain.

The coarser clastic units constitute the low-stand systems tract (LST) of sequence Sq1, and the overlying medium- to fine-grained sandstone, siltstone, and clay deposited by a meandering stream constitute a transgressive systems tract (TST). However, a hiatus of high systems tract (HST) deposits represented by thick-bedded siltstone and mudstone is observed at the top of the TST. Extending westward to the northern segment of Longmenshan and eastward to the middle Yangtze regions, Sq1 primarily consists of a thin-bedded TST and thick beds with HST of lake/swamp siltstone and mudstone.

4.3. Stratigraphic framework of the Qianfoya Formation

The Qianfoya Formation slightly decreases in thickness toward the south (Figures 5–7) and is composed of one to two fining-upward and retrograding units that are integrated into a third-order sequence Sq2. Two fining-upward cycles in the Wangcang and well Y1 areas are present on the AA′ section (Figure 5). The lower portion begins with a thin-bedded, massive, or cross-stratified medium- to coarse-grained sandstone that is characteristic of a meandering channel and is capped by fine-grained sandstone with parallel lamination and thick-bedded siltstone with horizontal bedding and mudstone intervals with sandstone lenses. However, the formation around well C36 is composed of alluvial proximal fan deposits with lower gamma ray values from the geophysical logs. This difference may indicate localized tectonic activity at Longmenshan.

Southward from well C91, the entire formation consists of a shore-shallow lake depositional system.

On the BB′ section (Figure 6), from the Nanjiang areas to well C55, the formation consists of lower meandering and channelized medium-grained sandstone with massive bedding and upper alternating siltstone and mudstone from a flood plain. Southward from well NJJ, the unit is completely composed of lacustrine successions.

On the CC′ section (Figure 7), the Lianghekou areas begin with thinly bedded basal conglomerate and medium-grained sandstone and are capped by thick beds of siltstone and mudstone. These units are considered the product of a meandering river system. The facies change to lacustrine sedimentation, as evidenced by the lower proportion of conglomerates consisting of medium-grained sandstone in thin beds and an upper layer of siltstone, silty mudstone, and clay in thick beds.

Overall, the Qianfoya Formation is composed of a TST, which is represented by meandering channelized conglomeratic sandstone or medium- to coarse-grained sandstone, and a HST, which is represented by thick rhythmic siltstone and mudstone. However, the LST unit is absent.

4.4. Stratigraphic framework of the Shaximiao Formation

The Shaximiao Formation is characterized by the progradation of vertically stacked coarsening-upward braided delta units and can be divided into five third-order sequences: Sq3, Sq4, Sq5, Sq6, and Sq7. The lithologic and lithofacies contacts are generally identifiable and can be correlated due to lithology changes in the outcrops and abrupt changes in the geophysical logs. Deltaic deposits generally show an upward decrease in gamma ray values and good lateral continuity, which allows for reasonably good correlations at the surface.

On the AA′ section (Figure 5), the thickness of the Shaximiao Formation decreases to the southwest, which primarily resulted from depositional thinning within the foreland basin and away from the thrust belt. This formation is defined as sediments that accumulate in a braided river delta setting. These deposits are recognized in the geophysical logs as having decreasing-upward gamma ray signatures that are related to the coarsening-upward successions in the outcrop. Generally, these log signatures can be traced between wells that are several to hundreds of metres apart. In the Wangcang areas, each sequence consists of thick beds of alternating siltstone and mudrock that are interbedded with thin-bedded medium- to fine-grained
sandstone, indicating delta front facies associations. In addition, this sequence consists of thick-bedded conglomeratic or medium- to coarse-grained sandstone with tabular–trough–wedge–parallel bedding that indicates braided channel deposits on the delta plain. Distributed from wells Y1 to Pi4, these successions are similarly characterized by high gamma ray values related to finer sediments and low gamma ray values related to coarser sandstone signatures, according to the geophysical logs. The sequence Sq7 constitutes two parts, which are referred to as coarsening-upward and fining-upward successions that can be indicative of deeper and shallower environments, respectively.

In the Nanjiang outcrop of the BB’ section (Figure 6), each of the five sequences is composed of a lower, thick, alternating sequence of siltstone and mudrock interbedded with thin-bedded medium- to fine-grained sandstone, indicating delta front facies associations and an upper thick-bedded conglomeratic or medium- to coarse-grained sandstone that resulted from braided channel deposits on the delta plain. Each third-order sequence between wells L17 and C55 is characterized by high gamma ray values that subsequently decrease upward with the coarsening-upward succession in the outcrop. Compared with section AA’, this unit includes facies that change from dominantly braided delta to shore-shallow lake environments at well NJJ.

The CC’ section (Figure 7) is represented by field outcrops and well P4. Each sequence consists of two parts: the delta front and delta plain of a braided delta succession. The delta front deposits are represented by burrowed to bioturbated siltstone, silty mudstone, and clay intervals of thin-bedded medium- to fine-grained sandstone, which constitutes the TST. The delta plain deposits contain thick beds of channelized medium- to coarse-grained or conglomeratic sandstone with varied high-angle cross-lamination and tree trunks, which constituted the HST when the braided river flowed into the lake as the base level decreased. Similarly, the LST deposits were absent, and the braided river delta facies change to a shore-shallow lake depositional system toward the basin interior.

5. Palaeogeographic reconstructions of the foreland basin

We determined the palaeogeographic history of the area during the Early–Middle Jurassic using the distributions of the lithofacies and features of the basin-filling sequence in the foreland basin belt (Figure 12). The architectural styles in each stage were used to document the sedimentary responses to tectonic deformation and to develop the foreland basin system.

During the deposition of the Baitianba Formation (Figure 12A), the foreland basin, which superposed the Middle–Late Triassic continental molasse foreland basin, was initiated. An extensive E–W alluvial fan depositional system developed along the Micangshan fold-and-thrust belt, which was continuously exposed to the Xiangfan
area. The conglomerate belt was truncated by the arc-shaped Dabashan. The alluvial fan system changed facies to extensive meandering fluvial plains in the areas around wells C36 Y6 and Lianghekou, and the system further changed to a shore-shallow lacustrine system to the southwest. The mapped isopach variations revealed two 600 m-deep depocentres located on the front of the Micangshan fold-and-thrust belt and in the Wanyuan area.

During the deposition of the Qianfoya Formation (Figure 12B), meandering fluvial plain and lake deposits accumulated. However, a small-scale alluvial fan conglomerate occurred around well C36. Isopachs show a gradual increase in thickness toward the east to Nanxi, with a maximum thickness in excess of 500 m that delineates the geometry of the foreland basin. The architecture of the Qianfoya Formation indicates that the thrust belts of the peripheral basin did not create a large tectonic load that contributed to subsidence. Instead, an insufficient sediment supply resulted in widespread thick-bedded siltstone and mudrock units. Thus, the entire northern Yangtze foreland basin developed from under-compensation during the filling stage.

The foreland basin was filled with 600–2500 m of braided delta successions that were distributed along the southern Qinling–Dabieshan fold-and-thrust belt during the deposition of the Shaximiao Formation (Figure 12C). The lithofacies become finer toward the basin interior around well C100 and Qilixia, where a shore-shallow lake dominated. Braided channel deposits are mainly derived from the northern and eastern regions according to the two types of palaeoflow typical of the southern Qinling–Dabieshan fold-and-thrust belt (Figure 12C). The isopach map reveals that one depocentre had a depth of 2500 m and developed around the Wenquan area. The isopach variation and depocentre development indicate that the strong tectonic activity of the orogenic belts contributed to flexural subsidence and provided sufficient accommodations. Furthermore, the orogeny experienced exhumation and provided abundant sediments to the basin. The deposition of the Shaximiao Formation (late Middle Jurassic) is the main period of basin formation and responded to intense thrusting in the southern Qinling–Dabieshan fold-and-thrust belt.

6. Discussion

The foreland basin system of the northern Yangtze plate during the Early–Middle Jurassic records the intra-continen
tal tectonic deformation after the Late Triassic oblique amalgamation of the Yangtze and North China-Qinling-
Dabieshan complex plates. The northern Sichuan and Zigui basins were filled by the same depositional system. Thus, the two basins probably belonged to the same foreland belt. An extensive E–W conglomerate belt of gravelly alluvial fan deposits is distributed along the Micangshan fold-and-thrust belt and extends to the western segment of the Dabashan. Syndepositional conglomerates may extend further E to the middle Yangtze plate. The conglomerate belt records evidence that the South Dabashan was uplifted after the Early–Middle Jurassic. Previous deposits of alluvial fan conglomerates have been covered or modified by the subsequent uplift of the Dabashan (Late Jurassic to Cenozoic). The lithofacies and palaeocurrent distributions suggest that the conglomerate development was controlled by the southern Qinling–Dabieshan fold-and-thrust belt. A small-scale conglomerate was deposited on the northern segment of the Longmenshan and pinched out to the southwest, implying limited thrust tectonism of the northern segment of the Longmenshan during the Early–Middle Jurassic. The stratigraphic frameworks demonstrate a well-developed wedged asymmetry that is typical of foreland basin geometry, where successions become thinner from the northern fold-and-thrust belts toward the basin interior. Isopach and depositional systems cut each other and are truncated by the Dabasha, which also implies that the Dabashan did not undergo thrusting and deformation during the Early–Middle Jurassic. The syndepositional depocentre may have continually migrated eastward. Therefore, the current residual depocentre was buried or modified by the South Dabashan that formed after the Early Jurassic (201–174 Ma). Basin-filling features, stratigraphic frameworks, and palaeogeographic reconstructions fully show that the integrated extensive E–W-trending foreland basin system and almost 150 km-wide foredeep depozone were formed during the Middle Jurassic along the southern Qinling–Dabieshan fold-and-thrust belt. The foreland basin was nearly completely buried or modified by the subsequent differential thrust tectonism of the Dabashan and its eastern regions (Late Jurassic to Cenozoic). The covered or modified extent of the upper Yangtze foreland basin was relatively small compared with the middle Yangtze foreland basin, which resulted in the residual architecture of the foredeep depozone, where the preserved strata in the west are wider and the eastern portion is narrower. The development of the extensive E–W foreland basin denotes that the Qinling–Dabieshan fold-and-thrust belt underwent nearly N–S compression during the Early–Middle Jurassic following the Triassic continent–continent collision.

7. Conclusions

(1) The northern gravelly conglomerate belts of the Baitianba Formation responded to the initial limited thrusting of the southern Qinling–Dabieshan fold-and-thrust belt. During the deposition of the Shaximiao Formation, the intense tectonic activity in the southern Qinling–Dabieshan fold-and-thrust belt created loading-related subsidence that contributed to the formation of the foreland basin.
(2) The Lower–Middle Jurassic successions can be divided into seven third-order sequences. The Baitianba and Qianfoya formations constitute Sq1 and Sq2, respectively. The Shaximiao Formation consists of five third-order sequences, Sq3–Sq7. The stratigraphic frameworks demonstrated a well-developed Wedge asymmetry that was typical of foreland basin geometry.

(3) The Early–Middle Jurassic foreland basin of the northern Yangtze plate recorded the intra-continental thrust tectonism of the southern Qinling–Dabieshan fold-and-thrust belt following the oblique amalgamation of the Yangtze and North China plates in the Middle–Late Triassic. The tectonic process governed the ~150 km-wide E–W foredeep on the northern Yangtze plate. The synedepozone could extend to the Longmenshan westward and further E to the northern middle Yangtze plate. The extensive E–W foreland basin of the northern Yangtze plate demonstrated that the Qinling–Dabieshan fold-and-thrust belt underwent a south-vergent thrusting during the Early–Middle Jurassic.

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