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Syn-tectonic sedimentation and its linkage to fold-thrusting in the region of Zhangjiakou, North Hebei, China

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Abstract The timing of the "Yanshanian Movement" and the tectonic setting that controlled the Yanshan fold-and-thrust belt during Jurassic time in China are still matters of controversy. Sediments that filled the intramontane basins in the Yanshan belt perfectly record the history of "Yanshanian Movement" and the tectonic background of these basins. Recognizing syn-tectonic sedimentation, clarifying its relationship with structures, and accurately defining strata ages to build up a correct chronostratigraphic framework are the key points to further reveal the timing and kinematics of tectonic deformation in the Yanshan belt from the Jurassic to the Early Cretaceous. This paper applies both tectonic and sedimentary methods on the fold-and-thrust belt and intramontane basins in the Zhangjiakou area, which is located at the intersection between the western Yanshan and northern Taihangshan. Our work suggests that the pre-defined "Jurassic strata" should be re-dated and sub-divided into three strata units: a Late Triassic to Early Jurassic unit, a Middle Jurassic unit, and a Late Jurassic to early Early Cretaceous unit. Under the control of growth fold-and-thrust structures, five types of growth strata developed in different growth structures: fold-belt foredeep type, thrust-belt foredeep type, fault-propagation fold-thrust structure type, fault-bend fold-thrust structure type, and fault-bend fold-thrust plus fault-propagation fold composite type. The reconstructed "source-to-sink" systems of Late Triassic to Early Jurassic, Middle Jurassic and Late Jurassic to early Early Cretaceous times, which are composed of a fold-and-thrust belt and flexure basins, imply that the "Yanshanian Movement" in our study area started in theMiddle Jurassic. During Middle Jurassic to early Early Cretaceous times, there have been at least three stages of fold-thrust events that developed "Laramide-type" basement-involved fold-thrust structures and small-scale intramontane broken "axial basins". The westward migration of a "pair" of basement-involved fold-thrust belt and flexure basins might have been controlled by flat subduction of the western Paleo-Pacific slab from the Jurassic to the Early Cretaceous.

Keywords Yanshan-Taihangshan, Fold-and-thrust belt, Flexural basin, Growth strata, Source-to-sink system, Thick-skinned fold-and-thrust belt

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1. Introduction

The Yanshan are located in northern Hebei province and western Liaoning province, extending westwards to the Yinshan Mountains and southwestwards to the Taihangshan. They are characterized by development of fold-and-thrust structures and multiple angular unconformities above the upper depositional sequence of the North China Craton (the Jurassic formations). Wong (1927) advocated the concept of "Yanshanian movement" on the basis of these unconformities, and the timing of this major tectonic movement is limited to that between the Jiulongshan succession and the Tiaojishan succession. Since then, the majority of China geologists have accepted the concept of "Yanshanian

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movement" as a proxy for tectonism in the Mesozoic. Geologists have gradually identified the occurrence of three phases of tectonic events in the Mesozoic in the Yanshan and even in the whole of North China. The first stage started in the Middle and Late Jurassic (approximately 174–154 Ma), followed by the second stage in the Late Jurassic to Early Cretaceous (approximately 161–136 Ma), and the third stage in the Cretaceous (Zhang et al., 2002; Niu et al., 2003; Zhao et al., 2004a, 2004b; Liu et al., 2004a, 2004b; Davis, 2005; Zhang et al., 2005; Dong et al., 2007; Liu et al., 2007; Zhang et al., 2011; Wang et al., 2011; Liu et al., 2013; Zhang et al., 2014; Liu et al., 2015a). The North China Craton, which was stable in the Palaeozoic, has been considered to have experienced intense tectonic movement, lithospheric thinning and cratonic destruction since the Mesozoic (e.g., Fan and Menzies, 1992; Deng et al., 2007; Zhu et al., 2011).

However, there is still controversy over the main processes of the Yanshanian movement, including structural processes, deformation mechanisms and tectonic properties from the Jurassic to Cretaceous. Some scholars have argued that movements that occurred in the Middle-Late Jurassic and Late Jurassic-early Early Cretaceous generally developed within a contractional background and formed the intramontane flexure basins (Liu et al., 2007; Zhang et al., 2011; Wang et al., 2011; Liu et al., 2013; Zhang et al., 2014). In contrast other scholars contend that the thrust events of the Yanshanian movement were constrained to a short duration based on the development of unconformities and that the major tectonism of the Yanshanian movement occurred in extensional settings in the Middle Jurassic and Late Jurassic-Early Cretaceous and formed rift basins, which were modified by subsequent thrusting and resulted in basin inversion (Shao et al., 2003; Meng et al., 2014; Davis et al., 2009; Qi et al., 2015). The driving mechanisms of the Yanshanian movement and the Yanshan-Taihangshan thrust-and-fold belt developed in the interior of North China Craton, or the "intraplate orogenic belt" (Zhang, 1999), are still unclear. Davis et al. (2001) argued that the Yanshanian movement was the product of alternating southward extrusion from the closing of the Northern Mongolia-Okhotsk Ocea nand westward subduction of Pacific plate. Dong et al. (2007) thought that the Yanshanian movement was driven by multi-directional plate convergences with East Asia from the north, east and southwest, rather than the one-way convergence with the Pacific plate. Zhao et al. (2004a) emphasized that the Yanshanian movement resulted from a major tectonic transition from the Tethys tectonic domain to the Pacific tectonic and dynamic system. Zhu et al. (2012) regarded the westward subduction of the Pacific plate as the main driving force for destruction of the North China Craton in the Late Mesozoic.

To answer these questions and fully understand the deformation mechanism of the main Yanshanian movement, it is necessary to carefully analyse the deformation style of fold-and-thrust belts and the basin-filling style of intramontane basins developed in the North China Craton and to reveal the structural processes, coupling mechanism and possible dynamic setting of the basin-mountain system. In this study, detailed work has been conducted in basins located in the Zhangjiakou area of northern Hebei province, which is the junction between the western Yanshan and northern Taihan mountains, to re-determine the stratigraphic sequences from the Jurassic to the early Early Cretaceous, to ascertain the internal geometry of growth strata and its relationship to syn-depositional fold-and-thrust structures, and to decipher the source-to-sink routines between basins and mountains.

2. Regional tectonic settings

The E-W- to NE-SW-trending Mesozoic Yanshan fold-and-thrust tectonic belt (hereinafter referred to as the Yanshan tectonic belt) is located in the northern margin of the North China Block (NCB). To the north are the Late Palaeozoic-Mesozoic Central Asia orogenic belt (Yang et al., 2006) and the Late Mesozoic Mongolia-Okhotsk collisional orogenic belt (Zorin et al., 1995; Zorin, 1999); its eastern part is bounded by the Mesozoic-Cenozoic Tan-Lu strike-slip fault zone; the south of the belt is widely covered by the sediments of the Cenozoic Bohai Bay Basin; and to the southwest, it is connected with the Taihangshan tectonic belt (Figure 1). Since the Late Palaeozoic, the Yanshan tectonic belt has been subjected to multi-directional subduction and continental collisions of adjacent plates (Zhao, 1990; Cope et al., 2007; Liu et al., 2012; Li et al., 2016), including the closure of the Paleo-Asian ocean along the Solonker suture zone during the Permian-Triassic period (e.g., Xiao et al., 2003); the closure of the Mongolian-Okhotsk Ocean from the Jurassic to Early Cretaceous (e.g., Zorin, 1999); subduction of the Izanagi plate and the subsequent Pacific plate beneath the East Asian continental margins with subductional polarity to the northwest (Liu et al., 2013; Liu et al., 2017); and the collision between North China and South China during the Middle-Late Triassic to Jurassic along the Qinling-Dabie-Sulu orogenic belt (Liu et al., 2003; Liu et al., 2013). Thus, the Yanshan structural belt was formed within a complex tectonic framework and evolutionary history. Not only the typical fold-and-thrust structure (Liu et al., 2012; Zhang et al., 2014; Meng et al., 2014) but also widely distributed extensional structures and metamorphic core complexes were developed in this area. These complex structures are considered to be crucial geological evidence for the destruction of the North China Craton (Liu et al., 2013; Zhang et al., 2011; Zhang et al., 2014).

The Yanshan tectonic belt, as part of the North China craton, developed Archaean to Palaeoproterozoic meta-

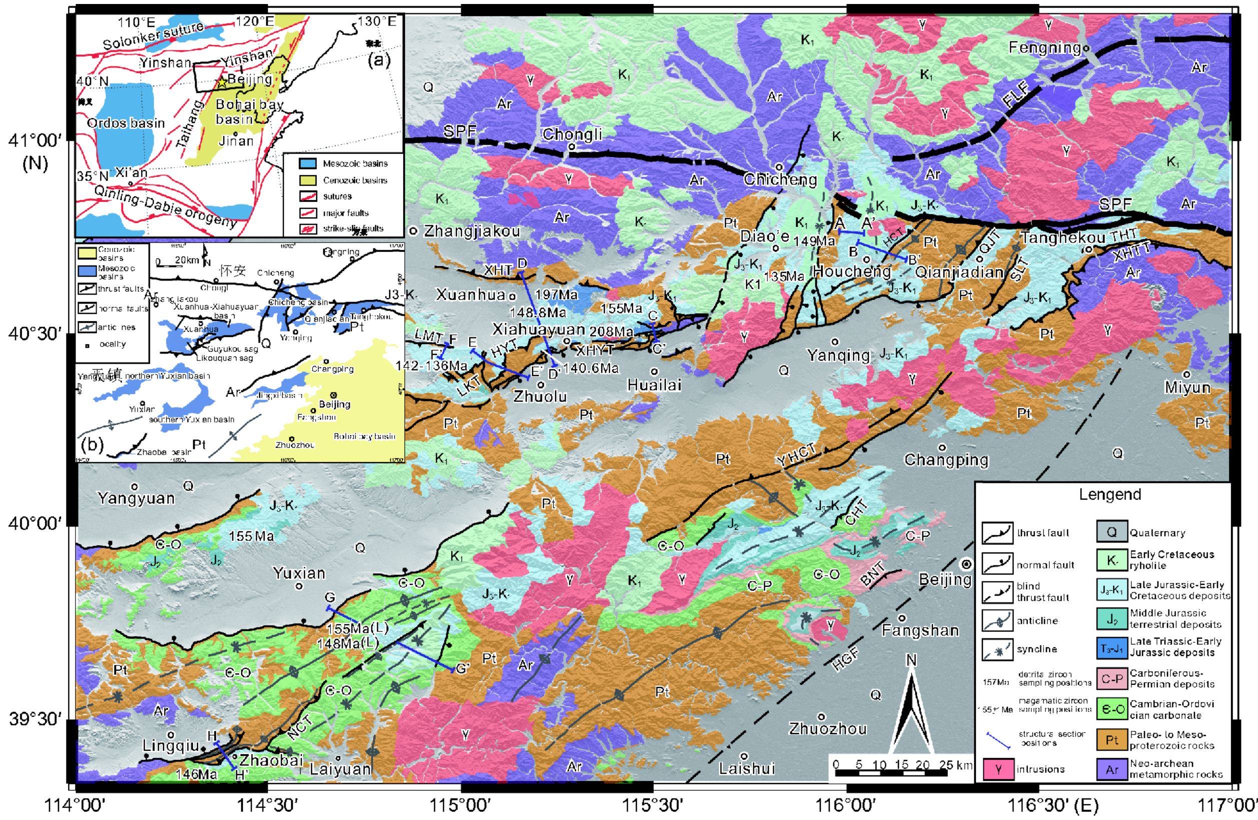

Figure 1 Schematic geological map of the Zhangjiakou area, northern Hebei province (modified from 1:200000 geological maps of Fengning, Chicheng, Xuanhua, Tianzhen, and Yuxian and the 1:250000 geological map of Yanqin). Location of the study area is shown in Figure 1a. The distribution of Mesozoic basins is shown in Figure 1b. Structural profiles: A-A′: Sanhe village profile; B-B′: Houcheng profile; C-C′: Huailai profile; D-D′: Xuanhua-Xiahuayuan profile; E-E′: Liukouquan-Zhuolu profile; F-F′: Longmenbu profile; G-G′: Southern Yuxian profile; H-H′: Zhaobai profile. Faults: BNT, Babaoshan-Nandazhai thrust fault; CHT, Caojiabu-Huangtuliang thrust fault; FLF, Fengning-Longhua fault; HGF, Huangzhuang-Gaoliying fault; HYT, Huangyangshan thrust fault; LKT, Likouquan thrust fault; LMT, Longmenbu thrust fault; NCT, Nanyangzhai-Chenjiazhuang thrust fault; QJT, Qianjiadian thrust fault; SLT, Shaliangzi thrust fault; SPF, Shangyi-Pingquan fault; THT, Tanghekou thrust fault; WJT, Wenjiadian thrust fault; XHT, Xuanhua thrust fault; XHTT, Xiaohuangtang thrust fault; XHYT, Xiahuayuan thrust fault; YHCT, Yanhecheng thrust fault.

morphic crystalline bases, Palaeo- to Mesoproterozoic shallow carbonate and clastic strata, Cambrian-Ordovician limestone strata, and Late Palaeozoic, Mesozoic, and Cenozoic clastic or volcanic debris rock formations. Mesozoic sedimentary basins in this tectonic belt are characterized by discrete distributions and are poorly connected to each other (Liu et al., 2004a, 2012). However, as these basins are located in similar structural and climatic backgrounds, stratigraphic division and comparison between basins are mainlybased on lithology and a few fossils. Analysis of detrital zircon geochronology and isotope chronology plays an important role in determining the stratigraphic chronology of Mesozoic terrestrial deposits in the Yanshan tectonic belt. Recent studies in the Xiabancheng Basin revealed the presence of the youngest zircon, with an age of 193±8 Ma, in conglomerates of the Xingshikou Formation and changed the geological age of this succession to Early Jurassic. A Moss $^{40}Ar/^{39}Ar$ age of 180±2 Ma has been yielded in the Nandaling Formation volcanic rocks (Davis et al., 2001). In the Xinglonggou Formation (equivalent to the Nandaling Formation) volcanic rocks, which developed in western Liaoning, the magmatic zircon U-Pb age is 176±3.5 Ma (Yang and Li, 2008). Therefore, the geological age of the Nandaling Formation is identified as late Early Jurassic. The Yaopo Formation (equivalent to the the Xiahuayuan Formation) in western Beijing is mainly a coal-bearing clastic succession with a weighted average age of 174±8 Ma from detrital zircon U-Pb dating (Yang et al., 2006). The weighted average U-Pb age of magmatic zircons from tuff in the Jiulongshan Formation of the Chengde Basin is 163.4±1.1 Ma (Chen et al., 2014). The Haifanggou Formation in western Liaoning province is composed of conglomerate, sandstone and mudstone, with andesite breccia and tuff interbeds. In the past, most scholars regarded the Haifanggou Formation as equivalent to the Jiulongshan Formation, but Huang (2015) thought it should be comparative to the Longmen conglomerate unit in western Beijing. Tuff interlayers of the Haifanggou Formation yield a $^{40}Ar/^{39}Ar$ Moss age of 166.7 Ma (Chang et al., 2014; Huang et al, 2015). The Tiaojishan Formation (equivalent to the Lanqi Formation), which unconformably overlies strata of the Jiulongshan Formation and the Xiahuayuan Formation, is mainly composed of andesitic and basaltic volcanic rocks, pyroclastic breccia, and tuff with clastic intercalations. The $^{40}Ar/^{39}Ar$ and U-Pb dating results for the Tiaojishan Formation yieldages of 161–152 Ma (Davis et al., 2001; Zhao et al., 2004b; Davis, 2005; Liu et al., 2007; Chang et al., 2014; Huang, 2015). The Tuchengzi Formation (or the Houcheng Formation) that covers the Tiaojishan Formation, is mainly composed of thick layers of conglomerate with intercalated mudstone beds, thin layers of gravelly sandstones, layered volcanic lava and pyroclastic breccia (Sun et al., 2007). The Tuchengzi Formation is overlain by rhyolites of the Zhangjiakou Formation (Liu et al., 2005). Published papers have presented $^{40}Ar/^{39}Ar$ and U-Pb ages of 153–137 Ma in the Tuchengzi Formation (Davis, 2005; Davis et al., 2001; Zhang et al., 2002; Liu et al., 2015a). The ages of rhyolite in the Zhangjiakou Formation are *ca*. 136–127 Ma (Swisher et al., 2002; Niu et al., 2003; Zhao et al., 2004b; Zhang et al., 2005). Based on these chronological data and stratigraphic contact relationships, the ages of the Xiahuayuan Formation and the Jiulongshan Formation are identified as Middle Jurassic to early Late Jurassic, and the Tiaojishan Formation and the Tuchengzi Formation are refined to Late Jurassic to early Early Cretaceous.

The Yanshan tectonic belt is characterized by the development of typical fold-and-thrust structures. A series of fold-thrust deformations in the plane shows the shape of a three-segment reversed “S” (Figure 1). The northern segment is generally located in western Liaoning Province, and its main deformations strike NE to NNE (Zhang et al., 2002); the middle segment is located in the Chengde-Luanping area of northern Hebei Province with major structures trending nearly E-W (Zhang et al., 2001; Liu et al., 2015a); the southwestern segment is located in the Zhangjiakou area of northern Hebei province and characterized by the coexistence of structures trending nearly E-W and trending NE-SW (Zhang et al., 2011). The Zhangjiakou area in northern Hebei Province, which is the study area for this paper, is located in the western part of the Yanshan tectonic belt. The major faults in this area include the Fenning-Longhua fault (FLF) and Shangyi-Pingquan fault (SPF) with nearly E-W strikes and the Zijingguan fault extending N-S. The FLF is mainly developed in the Archaean substrates and separates the Yanshan tectonic belt from the “Inner Mongolia axis” of Archaean highly metamorphosed crystalline basements to the north (Liu et al., 2004a, 2004b; Zhang et al., 2011; Liu et al., 2015a). The FLF is characterized by southward thrusting of the Archaean basements over the Mesoproterozoic strata in the south. The Cretaceous strata unconformably cover the fracture zones and the metamorphic basements in the hanging wall. The inclination of the present thrust fault at the surface is greater than 55° and up to 75°–85° in localities. Because the Proterozoic strata close to the fracture zone are very steep and the fault planes are parallel to the Mesoproterozoic bedding (Zhang et al., 2004), this fault is interpreted as a low-angle thrust fault pointing south. The steep fault plane responded to subsequent folding deformation. The vertical variety of clast compositions in Late Triassic to Early Jurassic conglomerates (from the Ermaying Formation to the Xingshikou Formation), which developed in the northern margin of Yanshan, records a gradual erosion process in hanging wall successions of the FLF and the Damiao thrust to its south (Liu et al., 2012). The FLF was interpreted to have been active in the Late Palaeozoic and the Mesozoic (Zhang et al., 2004; Liu et al., 2004b, 2015b; Li et al., 2016). In the Chicheng area, the SPF is characterized by Archaean gneiss thrusting southward at high angles over Proterozoic carbonate and Jurassic clastic sequences and is interpreted as a large-scale basement-involved thrust-nappe structure (Zhang et al., 2011). The SPF is a large continuous thrust fault developed in the Yanshan tectonic belt, and some scholars have identified this fault as the northern boundary of the outcropping Triassic deposits in the Yanshan area (Davis et al., 2001; Liu et al., 2012). In the middle of the Yanshan tectonic belt, the fault is commonly referred to as the Gubeikou-Pingquan fault. The internal structure of the SPF is complex, including the north-thrusting Chengde County thrust fault and the south-thrusting Dazhangzi thrust fault in sections. The Chengde County thrust fault separates the Triassic succession and the Lower Palaeozoic strata to its south in the Xiabancheng Basin and is characterized by the north-dipping steep Ordovician strata thrusting over the steep, even overturned, Triassic strata or by the Proterozoic strata thrusting atop the Palaeozoic or Triassic sequences. The Triassic and Jurassic strata located in the footwall of the thrust fault were deformed into an overturned closed syncline. According to the cross-cutting relationships between the faults and the intrusions in the fracture zone and between the fault zone and the Jurassic to Cretaceous strata, this fault is interpreted to have been active during the Early Jurassic to early Early Cretaceous period (Zhang et al., 2004; Liu et al., 2007). The Dazhangzi thrust fault is inclined toward the north and continuously extends in an E-W trend, forming the northern boundary of the Dazhangzi-Xinchengzi Basin. The results of syn-tectonic sedimentation studies from Zhang et al. (2004) and Liu et al. (2007) show that the thrusting of the Dazhangzi fault controlled sediment supply and basin deposition in the Dazhangzi-Xinchengzi Basin. Combining the controls of thrust faults on sedimentary stratigraphy and the emplacement of intrusions in the fault zone indicates that the Dazhangzi thrust fault may have been primarily activated from 148–132 Ma (Davis et al., 2001; Zhang et al., 2004; Liu et al., 2007). The Zijinguan fault extends from the north of Fengning to the south of Laishui and displays as normal faults that are tilted to the west in the Chicheng area. The footwall succession is composed of dolomite of the Wumishan Formation, and the hanging wall generally comprises terrestrial clastic deposits of the Tuchengzi Formation and acid volcanic rocks of the Zhangjiakou Formation. The Zijinuan fault clearly controlled the distribution of the Early Cretaceous Zhangjiakou Formation with thicker volcanic sequences in the hanging wall. Its active time may have been Early Cretaceous (Liu et al., 2004a). Some scholars have considered that the formation of the Chicheng Basin in the western part of the Yanshan tectonic belt was controlled by extensional structures represented by the Zijinguan fault on the basis of geochemical analysis and isotopic dating results of the volcanic interlayers within the Tuchengzi Formation, and they proposed that the activity of the Zijinguan fault was duringthe Late Jurassic to Early Cretaceous (Shao et al., 2003; Qi et al., 2015).

Basin margin faults in the study area include the Qianjiadian thrust fault (QJT), Shaliangzi thrust fault (SLT), Tanghekou thrust fault (THT), Xuanhua thrust fault (XHT), and Xiahuayuan-Huailai thrust fault (XHYT) (Figure 1). Their lateral extents are limited to less than 50 km. The QJT, SLT and THT, located in Qianjiadian town of the eastern Chicheng Basin, are characterized by NE-SW trend sand nearly parallel arrangement and are marginal faults of the Qianjiadian Basin and the Tanghekou Basin. The QJT and SLT are both northwest-dipping faults. The hanging wall succession of the Proterozoic to Archaean metamorphic basements form fault-propagation anticlines and thrust southeastward over the Mesozoic Tuchengzi Formation and Zhangjiakou Formation in the footwall. Meanwhile, the THT and the Xiaohuangtang fault (XHTT) to its east are southeast-dipping and may converge downward into the same detachment located in the basement of the basin. The QJT, SLT and THT all terminate northward in the SPF. The XHT and XHYT are the northern and southern boundary faults of the Xuanhua-Xiahuayuan Basin, respectively (Figure 1). The XHT, trending E-W, is the northern boundary of the basin and expresses southward thrusting at the surface as Proterozoic-Archaean hanging wall successions were thrust atop the Mesozoic basin fill. This fault laterally ends in Middle Jurassic granites to the east and is covered by Quaternary sediments to the west, with total surface extent of less than 40 km. The XHYT is located along the southern margin of the Xiahuayuan-Xuanhua Basin and is an imbricated thrust belt composed of a number of E-W-trending thrust faults. The hanging wall succession exposed on the east side of this fault belt is mainly composed of Neoarchaean gneisses with high-grade metamorphism and Proterozoic Wumishan Formation dolomites; to the west, the hanging wall succession is dominated by Proterozoic carbonate strata. Generally, the XHYT is characterized by westward, northwestward or northward thrusting of the Proterozoic-Archaean basement over the Mesozoic basin fill. In the western segment of the Xiahuayuan-Xuanhua Basin, the XHYT, HYT and Likouquan thrust fault (LKT) constitute a larger imbricated thrust system in which the Mesoproterozoic Wumishan Formation is displaced northwestward atop the Mesozoic Tiaojishan Formation and lower Tuchengzi Formation.

3. Basin stratigraphic age and stratigraphic sequence

Although Jurassic terrestrial basins in the study area are lithologically comparable to basins in other parts of the Yanshan tectonic belt, because of the lack of fossils in the strata of the Zhangjiakou area, a simple division of stratigraphic chronology on the basis of lithology leads to inevitable bias in lateral correlations of some strata. In comparison with the regional stratigraphy, the Jurassic strata in the study area are divided into the Xiahuayuan Formation (or Yaopo Formation and Longmen conglomerate unit), the Jiulongshan Formation, the Tiaojishan Formation and the Tuchengzi Formation (Bureau of Geology and Mineral Resources of Hebei Province, 1989; Chen and Wu, 1997). However, a comprehensive analysis of detrital zircon U-Pb dating and stratigraphic contact relationships suggests that the ages of some units in the study area are quite different from strata in the middle and eastern sections of the Yanshan tectonic belt, and thus, lateral correlation is impossible. To solve this problem, we re-establish the stratigraphic sequence of the Late Triassic through Early Cretaceous (Figure 2) by identifying the absolute ages of some strata in the study area.

The oldest Mesozoic strata in the study area comprise the “Xiahuayuan Formation” (Figure 3b) (Bureau of Geology and Mineral Resources of Hebei Province, 1989), distributed in both the southern and northern margins of the Xuanhua-Xiahuayuan Basin near the Xiahuayuan-Huailai area. This Mesozoic stratigraphy consists of two lithologic units: a coarse-grained unit composed of thick conglomerates and gravelly coarse sandstones (with basal mafic-to-intermediate volcanic rocks and breccia in northern Xiahuayuan town) distributed along basin margins and a fine-grained unit of fine sandstones, siltstones and mudstones interbedded with coal seams and cropping out near the central basin area. This succession unconformably overlies the Palaeo- and Mesoproterozoic strata on the margin of this basin. The thickness of the lower coarse-grained unit in the Huailai area is greater than 100 m, and the thickness of the upper fine-grained unit is greater than 200 m. Pyroclastic sediments of the Tiaojishan Formation unconformably overlie this succession. Detrital zircon U-Pb dating in the lower unit yields a youngest single detrital zircon grain age of 206 Ma, and the weighted mean ages of the youngest 3 and 5 grains are 206.7 ±3.8 Ma and 207.8±2.9 Ma, respectively. Based on the detrital zircon U-Pb ages, the maximum depositional age is determined to be 206 Ma (Figure 4a). Therefore, the so-called “Xiahuayuan Formation” in this area may be comparable to the Xingshikou Formation and its lower strata in

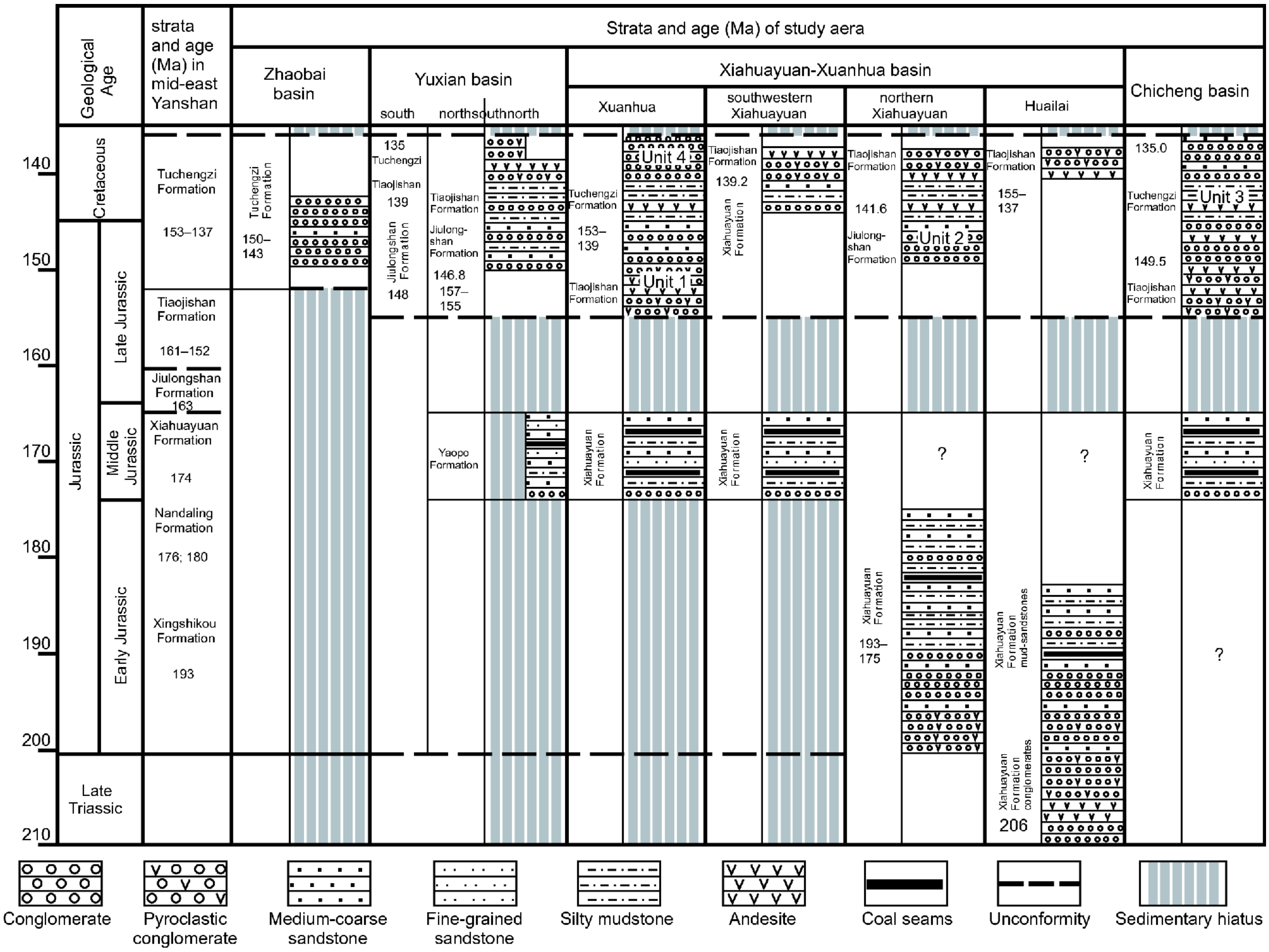

Figure 2 Late Triassic to Jurassic lithostratigraphic division, age correlations and stratigraphic sequences in the Zhangjiakou area, northern Hebei province. The sources of geochronological data are described in the text. Note: Names of the lithostratigraphy used in this table are the original names from previous regional geological surveys. Here, we do not modify these names on the basis of the newly reported U-Pb ages. Some of these lithostratigraphies cannot be correlated laterally with lithostratigraphies in the middle and eastern sections of the Yanshan belt.

terms of geochronology, belonging to the Late Triassic to Early Jurassic. The “Xiahuayuan” Formation in the northern part of Xiahuayuan town is approximately 90 metres thick and unconformably overlain by the “Jiulongshan” Formation. Zircon U-Pb dating is applied to this succession and yields a youngest magmatic zircon age of 175±3.5 Ma (Lin et al., 2018) and weighted mean ages of 192.9±3.3 Ma and 193.6±3.0 Ma from youngest clusters of 4 and 5 grains (with exception of the youngest single grain age of 175 Ma). Thus, the maximum deposition age of this “Xiahuayuan” Formation is constrained to be 193–175 Ma (Figure 4b). The stratum may share the same age with the Xingshikou Formation and the Nandaling Formation in the Chengde area of the middle Yanshan tectonic belt (Liu et al., 2012; Li et al., 2016) and belong to the Early Jurassic. The upper part of the “Xiahuayuan” Formation in northern Huailai and northern Xiahuayuan town chiefly consists of sandstone and mudstone assemblages with coal lines. Is it comparable to the standard Middle Jurassic Xiahuayuan Formation near Xiahuayuan town? To answer this question, further chronological analysis is required. The present data indicate that at least the age of the “Xiahuayuan” Formation in the northern part of the Xiahuayuan town is constrained to Early Jurassic. However, whether or not its sedimentation continued to the Middle Jurassic remains unclear and needs more detailed geochronological analysis. The existence of sedimentary discontinuities or unconformities within the “Xiahuayuan” Formation are also doubtful and require more sedimentary work.

The Middle Jurassic “Xiahuayuan” Formation (or Yaopo Formation) crops out mainly in the southern Xuanhua-Xiahuayuan Basin near Xiahuayuan town and Zhuolu town and in the northern part of the Yuxian Basin. In the Yuxian Basin, the “Yaopo” Formation unconformably overlies the Cambrian-Ordovician limestones (Figure 3a) with thickness of approximately 118 m and is mainly composed of siltstones and mudstones with coal beds, coal lines and fine sandstone. This fine-grained succession comprises numerous coarsen-

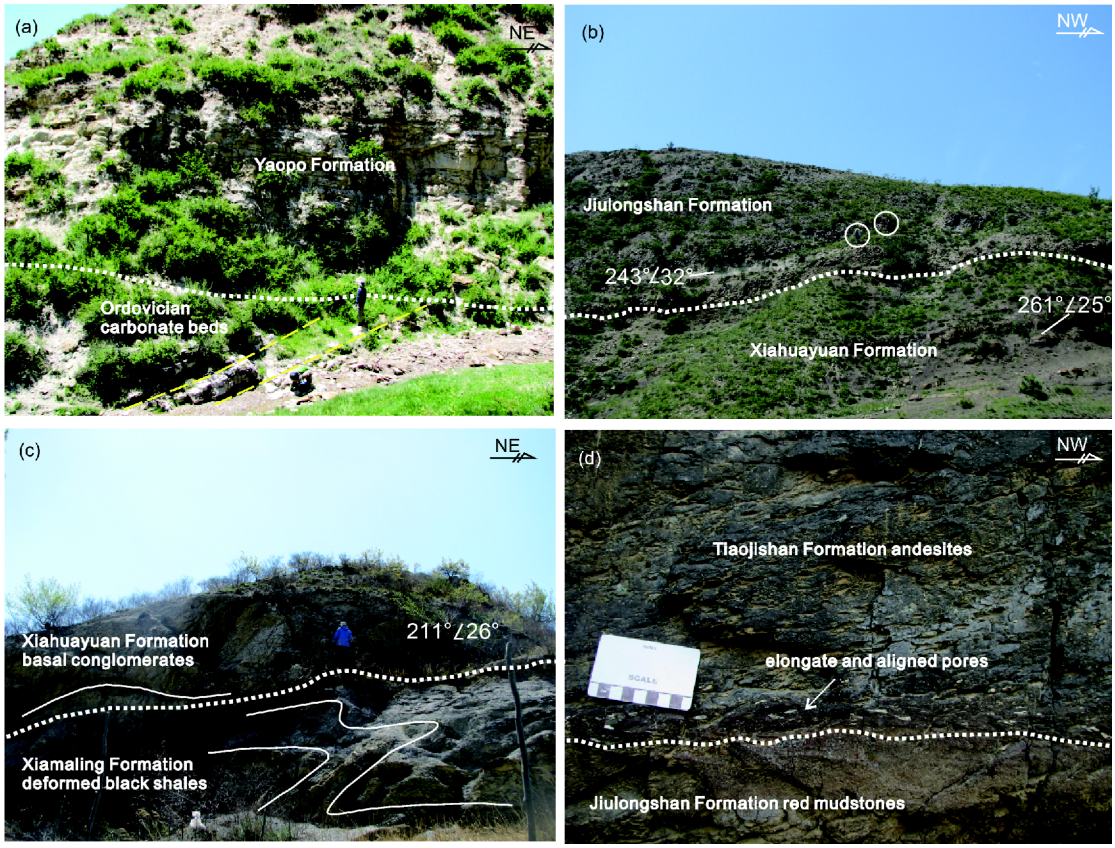

Figure 3 Field photographs of contact relationships between different strata. (a) Unconformity between the "Yaopo Formation" and the underlying Ordovician limestone in the Yuxian Basin; (b) unconformity between the "Jiulongshan Formation" and the underlying "Xiahuayuan Formation" in northern Xiahuayuan town; (c) unconformity between the "Xiahuayuan Formation" massive conglomerates and the underlying highly deformed Proterozoic "Xiamaling Formation" in southern Xiahuayuan town; (d) sedimentary interface between the "Tiaojishan Formation" andesite and underlying "Jiulongshan Formation" lacustrine mudstones in northern Xiahuayuan town.

ing-upward sequences, which start from basal conglomerate beds up to 20 m thick. The "Xiahuayuan" Formation near Zhuolu town unconformably overlies the Proterozoic Xiamaling Formation and is overlain by volcanic and pyroclastic rocks of the Tiaojishan Formation. No sound detrital zircon U-Pb age has been obtained from this so-called "Xiahuayuan Formation" in the study area. Here, we assign an age of Middle Jurassic to these successions based loosely on detrital zircon U-Pb ages reported from the Yaopo Formation in western Beijing (Yang et al., 2006). More work is required to determine whether the deposition of these successions started in Early Jurassic time.

The "Jiulongshan" Formation is distributed north of Xiahuayuan town in the Xuanhua-Xiahuayuan Basin and the Yuxian Basin (Bureau of Geology and Mineral Resources of Hebei Province, 1989). The "Jiulongshan" Formation north of Xiahuayuan town unconformably covers the Jurassic "Xiahuayuan Formation" lacustrine mudstones (Figure 3b). The lower part of the "Jiulongshan" Formation is an approximately160-m-thick layer and is mainly composed of conglomerates; the upper part, however, is dominated by red siltstones and mudstones up to 280 m thick with interbedded sandstones. Tuffaceous rhyolite and tuff beds, up to 25 m thick, are developed in the lower part of this succession. Zircon U-Pb dating of a tuff sample yields weighted mean ages of 141.6±4.7 Ma and 146.6±2.8 Ma (Figure 4c) from youngest clusters of 2 grains and 5 grains, respectively, which define the maximum deposition age at 141.6 Ma. Based on careful stratigraphic comparison in the field, the stratigraphic sequence of the "Jiulongshan" Formation, "Tiaojishan" Formation" and "Tuchengzi" Formation (Bureau of Geology and Mineral Resources of Hebei Province, 1989) in the south of the Yuxian Basinis subdivided into 4 stratigraphic units. The "Bottom unit" is equivalent to part of the so-called "Tuchengzi" Formation" of previous scholars. This unit, with thickness of 120–183 m, is composed of a lower part of purple red conglomerates and gravelly coarse sandstones and an upper part of purple red silty mudstones and siltstones with conglomerate interlayers. The "Jiulongshan" Formation, resting upon the bottom unit, is a group of thick conglomerates mainly consisting of pyroclastic material (particle size ranging from 10 to 30 cm) with development of an 18-m-thick tuff bed at the top. The overlying "Tiaojishan" Formation is mainly composed of pyroclastic

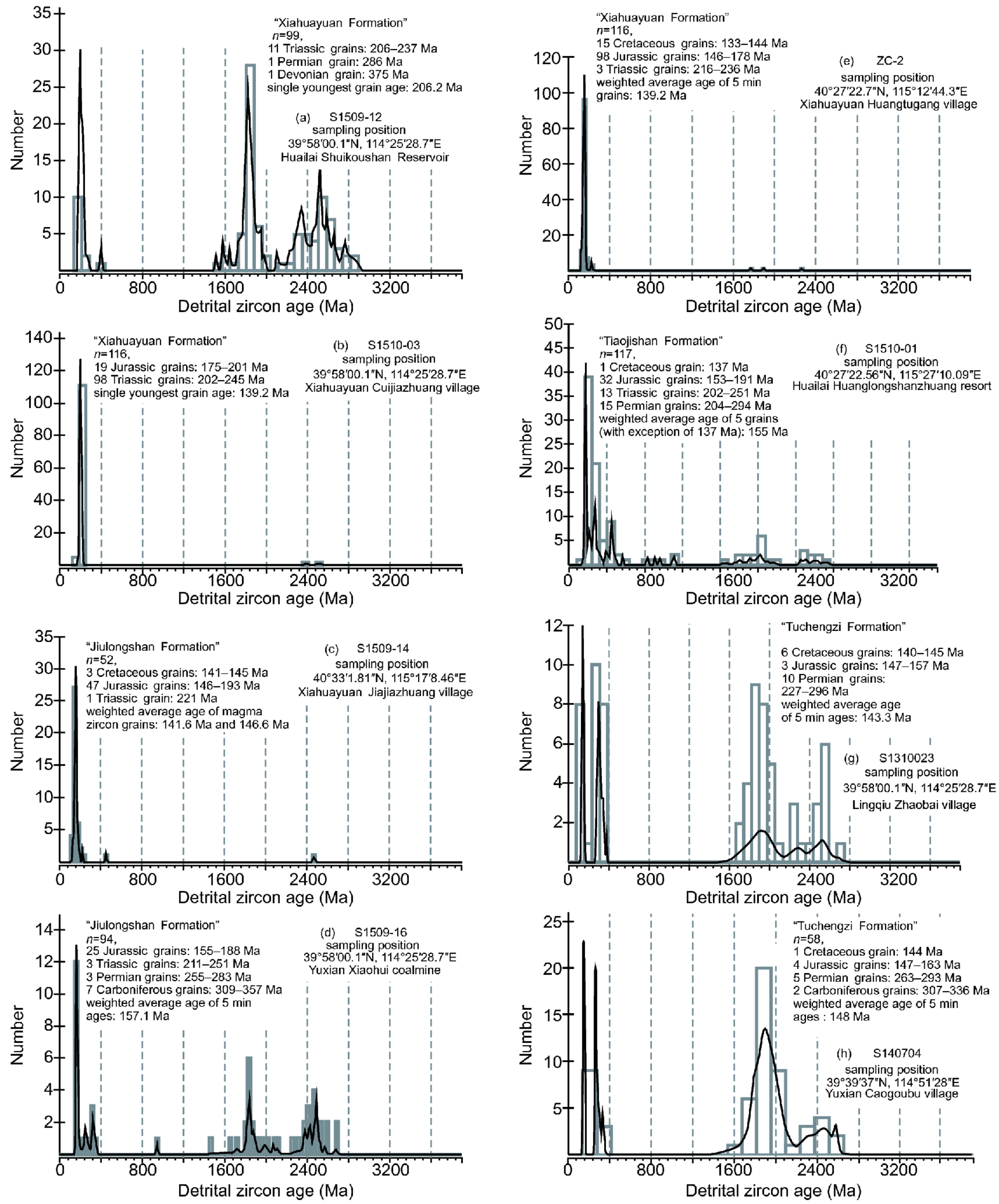

Figure 4 Early Mesozoic detrital zircon U-Pb age spectra. (a) Sample S1509-12 from the "Xiahuayuan Formation" coarse-grained sandstones in Huailai county; (b) sample S1510-03 from the "Xiahuayuan Formation" sandstones in northern Xiahuayuan town (Lin et al., 2018); (c) sample S1509-14 from the "Jiulongshan Formation" in northern Xiahuayuan town; (d) sample S1509-16 from the "Jiulongshan Formation" tuff beds in northern Yuxian county; (e) sample ZC-2 from the "Xiahuayuan Formation" medium-grained sandstones in southern Xiahuayuan town; (f) sample S1510-01 from the "Tiaojishan Formation" pyroclastic sandstones in Huanlongshanzhuang, north of Huailai county; (g) sample S1310023 from the "Tuchengzi Formation" coarse-grained sandstones in the Zhaobai Basin; h-sample S140704 from the bottom of the "Jiulongshan Formation-Tuchengzi Formation" in southern Yuxian Basin. For sampling locations and the identified maximum depositional ages, see Figure 1.

conglomerates and andesite up to 56 m thick, with minor tuffaceous gravelly coarse sandstone interlayers. The "Tuchengzi" Formation is the highest unit in the Mesozoic sequence of the southern Yuxian Basin and mainly comprises conglomerates, which chiefly consist of volcanic gravels with gravelly sandstone interbeds. Correspondingly, only two units are developed in the northern part of the Yuxian Basin: the "Jiulongshan" Formation in the lower part and the "Tiaojishan" Formation in the upper part. The "Jiulongshan" Formation may lithologically correspond to the "bottom unit" in the south of the Yuxian Basin and comprises gravelly coarse sandstone with siltstone and mudstone interbeddings, which fine upward into purple red lacustrine mudstones intercalated with calcite mudstones and are overlain by tuffaceous sandstones at the top. This unit is approximately 148–200 m thick. The "Tiaojishan" Formation in the north of the Yuxian Basin is mainly composed of pyroclastic conglomerates with interlayers of volcanic rocks. Detrital zircon U-Pb dating of the bottom unit in the south of the Yuxian Basin yields a weighted mean age of 148±11 Ma from a youngest cluster of 3 grains. Based on this minimum detrital zircon U-Pb age, the maximum deposition age of this unit is limited to 148 Ma (Figure 4h). A minimum detrital zircon U-Pb age of 146.8±3.9 Ma is used to constrain the maximum depositional age of the bottom unit of the "Jiulongshan" Formation in the northern part of Yuxian County. However, the U-Pb dating of the tuffaceous sandstone at the top of this "Jiulongshan" Formation yields a weighted mean age of 157.1±1.5 Ma from a youngest cluster of 4 minimum magmatic zircons (Lin et al., 2018). Therefore, the maximum deposition age of the "Jiulongshan" Formation is determined to be 157–155 Ma in the northern Yuxian Basin (Figure 4d). The zircon U-Pb dating of tuffs from the "Jiulongshan" Formation and the tuffaceous sandstone from the "Tiaojishan" Formation and the "Tuchengzi" Formation in the south of the Yuxian Basin obtains ages of 139 Ma, 135 Ma and 135 Ma, respectively, which are used to constrain the maximum deposition age. In addition, the previously defined "Xiahuayuan" Formation, which is distributedin southwestern Xiahuayuan town, is a succession of terrestrial deposits dominated by conglomerates and gravelly sandstones in the lower part and by purple red interbeddings of sandstones, siltstones and silty mudstones at the top (Bureau of Geology and Mineral Resources of Hebei Province, 1989). These strata are strongly deformed, forming closed overturned folds and thrust faults, and hence, the thickness is unclear. The bottom of the "Xiahuayuan" Formation unconformably overlies the Proterozoic Xiamaling Formation (Figure 3c), and the top is covered by the "Tiaojishan" Formation. The weighted mean age of the youngest cluster of 11 zircons is 139.2±2.6 Ma, which defines the maximum depositional age of 139.2 Ma (Figure 4e). Compared with the lithological and detrital zircon chronological characteristics in other parts of the Yanshan tectonic belt, the "Xiahuayuan" Formation in the study area is much younger and belongs to the Late Jurassic.

The "Tiaojishan" Formation is widely developed in the study area and mainly consists of a set of andesitic volcanic rocks, including layered andesitic lavas, volcanic breccia, pyroclastic conglomerates, tuffaceous sandstones and gravelly sandstones, with a handful of red mudstone interbeds. This volcanic succession is usually assigned to different stratigraphic positions based on the lithology of various andesitic volcanic rocks because of the lack of fine geochronological data. The "Tiaojishan" Formation in the Xiahuayuan area of the Xuanhua-Xiahuayuan Basin is defined as the andesitic volcanic rocks and pyroclastic conglomerates with thickness greater than 650 m, which conformably overlies the lacustrine mudstone-dominated top of the Jiulongshan Formation (Figure 3d). The "Tiaojishan" Formation in the Xuanhua area, however, is defined as a succession of volcanic lavas and pyroclastic conglomerates conformably overlain by the "Tuchengzi" Formation. The U-Pb dating of the tuffaceous sandstone at the bottom of the "Tiaojishan" Formation in the Huailai area yields a youngest single grain age of 136.7±5.9 Ma, and the weighted mean ages of youngest clusters of 3 and 5 zircons (except for the youngest single zircon age of 137 Ma) are 155.3±5.9 Ma and 156.2±4.5 Ma, respectively. These detrital zircon U-Pb ages help to constrain a maximum depositional age of 155–137 Ma (Figure 4f). The results of detrital zircon U-Pb dating of the tuffaceous coarse sandstone at the bottom of the "Tiaojishan" Formation in the south of Yuxian county are used to constrain a maximum depositional age of approximately 135 Ma. Therefore, the "Tiaojishan" Formation in the study area belongs to a different geochronological stratigraphy. However, in general, the so-called "Tiaojishan" Formation in the study area is roughly equivalent to volcanic lavas and pyroclastic conglomerates developed at the bottom or upper part of the "Tuchengzi" Formation in other parts of the Yanshan tectonic belt (Li et al., 2004; Liu et al., 2007) in which the stratigraphic age is Late Jurassic or Early Cretaceous.

The "Tuchengzi Formation" is well exposed in the Zhaobai Basin, the southern Yuxian Basin, the Xuanhua-Xiahuayuan Basin and the Chicheng Basin. In the Zhaobai Basin, this succession unconformably overlies the Ordovician limestone and is mainly composed of thick conglomerates consisting mostly of limestone detritus. The "Tuchengzi Formation" in the south of Yuxian county is in conformable contact with the underlying "Tiaojishan Formation" and is composed of vertical stacking of conglomerates, which consist of volcanic gravels and gravelly coarse sandstones. In the Xuanhua-Xiahuayuan Basin and the Chicheng Basin, this succession is better exposed and displays distinctively tripartite architecture: a lower part dominated by thick conglomerates with gravelly coarse sandstone interlayers; a middle part of purple red mudstone and silty mudstone with interlayers of conglomerates and gravelly sandstones; and an upper part that is composed of thick layers of conglomerate interbedded with thin layers of gravelly coarse sandstone (Liu et al., 2016). The "Tuchengzi Formation" is in conformable contact with the underlying "Tiaojishan Formation" in the Chicheng Basin. The "Tuchengzi Formation" in the Xuanhua-Xiahuayuan Basin is distributed only in the front of a thrust fault in the southern margin of the basin, with a thickness of approximately 700 m. However, the "Tuchengzi Formation" is widely distributed in the Chicheng Basin, covering almost the whole basin with thickness greater than 1200 m. Detrital zircon U-Pb dating for the "Tuchengzi Formation" in the Zhaobai Basin yields a youngest peak age of 150 Ma in an age histogram, and a weighted mean age of 143.3±3.1 Ma from the youngest cluster of five grains. The minimum detrital zircon U-Pb ages suggest a maximum depositional age of 150–143 Ma for this succession (Figure 4g). Detrital zircon U-Pb ages obtained from the tuffaceous sandstone in the lower part of the "Tuchengzi Formation" in the Xuanhua area constrain the maximum depositional age to 153–139 Ma. In the Chicheng Basin, the maximum depositional age at the bottom of the "Tuchengzi Formation" is approximately 149.5 Ma, and at the top, it is constrained to approximately 135 Ma. Therefore, the age of the "Tuchengzi Formation" in the study area is late Late Jurassic to early Early Cretaceous.

In summary, basin fill in the study area is assigned to three distinctive chronostratigraphic successions in ascending order: the Upper Triassic to Lower Jurassic (T_3-J_1), the Early to Middle Jurassic (J_1-J_2) and the Upper Jurassic to Lower Cretaceous (J_3-K_1) (Figure 2). Clearly, the Upper Triassic to Lower Jurassic (T_3-J_1) succession may be comparable to the Xingshikou Formation and its underlying strata developed in the eastern segment of the Yanshan tectonic belt. The differences between these two strata are that the upper part of this unit in the study area consists of greyish green mudstones with massive sandstone or gravelly sandstone interbeddings and the bottom is dominated by volcanic breccia, and it is unclear whether or not the upper strata of this succession extend to the Middle Jurassic. The Upper Jurassic to Lower Cretaceous (J_3-K_1) succession should be roughly equivalent to the Tuchengzi Formation in the central Yanshan area (such as the Chengde Basin). They have not only consistent stratigraphic ages but also similar lithostratigraphy. This succession (J_3-K_1) is generally composed of volcanic conglomerates at the bottom (unit 1), conglomerates in the lower part (unit 2), purple red mudstones and silty mudstone with thin conglomerate interlayers in the middle (unit 3), and conglomerates, volcanic conglomerates with volcanic lava interlayers and tuffaceous sandstone in the upper part (unit 4). This succession is laterally comparable in the entire western Yanshan tectonic belt, with the middle purple red lacustrine fine-grained sequence (unit 3) being the marker bed. The geochronological analysis discussed above indicates that the maximum depositional age of the sequences (units 1 and 2) underneath the red lacustrine mudstones (unit 3) are approximately157–150 Ma and 150–141 Ma, respectively. Further, the maximum depositional age of conglomerates (unit 4) above the lacustrine deposits (unit 3) is approximately 139–135 Ma. The maximum depositional age of the middle lacustrine mudstones (unit 3) is limited to approximately 141–139 Ma (Figure 2) on the basis of the age (141.6 Ma) of the "Jiulongshan Formation" tuff beds, which occur beneath the purple lacustrine mudstones in the northern part of Xiahuayuan town. Conglomerates in the Zhaobai Basin may correspond to unit 2 of the J_3-K_1 succession. The "bottom sequences" in the south of the Yuxian Basin are stratigraphically equivalent to units 2 and 3 of the J_3-K_1 succession, while the "Jiulongshan Formation", "Tiaojishan Formation" and "Tuchengzi Group" in the upper part correspond to unit 4 conglomerates. The "Jiulongshan Formation" in the northern part of the Yuxian Basin corresponds to units 2 and 3, and the "Tiaojishan Formation" in the upper part is equivalent to unit 4. The so-called "Xiahuayuan Formation" and "Tiaojishan Formation" developed in southwestern Xiahuayuan town in the Xuanhua-Xiahuayuan Basin should be equivalent to units 3 and 4 of the J_3-K_1 succession. In addition, the previously defined "Jiulongshan Formation" and "Tiaojishan Formation" in the northern part of Xiahuayuan town should correspond to units 2–4, respectively. The "Tiaojishan Formation" of the Huailai area is the same set of strata as that of the Xiahuayuan town area and belongs to unit 4. The "Tiaojishan Formation" in the Xuanhua area may correspond to unit 1, whereas the "Tuchengzi Formation" corresponds to units 2–4 of this succession (Figure 2).

4. Growth folds, growth thrust faults and growth strata

Folds or thrusts that develop at the edges of basins, and even within the basins, usually control sedimentary processes and form growth strata (or syn-tectonic deposits). Mesozoic sedimentary basins in the Zhangjiakou area of the Yanshan tectonic belt are under the control of fold-and-thrust activity and develop multiple types, typically fold- and thrust-controlled growth strata. According to their spatial and genetic relationships with fold-and-thrust structures, the growth strata developed in the study area are subdivided into four distinctive categories: fold front-type growth strata (e.g., the Yuxian Basin), thrust front-type growth strata (e.g., the Zhaobai Basin), fault-propagation fold-type growth strata (e.g., the Likouquan area of the Xuanhua-Xiahuayuan Basin) and fault-bend fold-type growth strata (e.g., the Chicheng Basin). Growth strata controlled by different growth folds and faults display correspondingly unique geometries and internal architectures and reliably record the timing and kinematic processes of growth structures (Suppe et al., 1997; Salvini and Storti, 2002; Poblet, 2012).

4.1 Fold front-type growth strata

These types of growth structure and growth strata typically develop in the Yuxian Basin. The Jurassic-Early Cretaceous Yuxian Basin has been subsequently superimposed and modified by Cenozoic rift basins and is spatially separated into the northern Yuxian Basin and the southern Yuxian Basin. The Middle Jurassic "Xiahuayuan Formation" is mainly distributed in the northern Yuxian Basin and unconformably overlies the Ordovician strata, forming small-scale sag deposits. The Early Jurassic-Early Cretaceous basin fillings, which unconformably rest on the Middle Jurassic strata, cover a larger area and are distributed in both the southern and northern Yuxian Basin. These basin successions are better exposed in the southern Yuxian Basin and are closer to marginal structures and source areas (Figure 5). Based on careful lateral correlations of the stratigraphy and its relationship with basin substrate strata and on analysis of the marginal structures in the field, this Mesozoic basin has been found to show the following main tectono-sedimentary characteristics:

(1) The Late Jurassic-Early Cretaceous succession in this area (Figure 2) was deposited in the Caogoubu depression, which is located in the western flank of the Motianling broad-and-gentle complex anticline composed of Archaean, Meso- to Neoproterozoic and Early Palaeozoic successions to the east, with unconformable contacts with underlying basements (Figure 5a and 5c). This stratigraphic sequence consists of purple red conglomerates mainly comprising clasts of limestone and dolomite in the lower part and of grey or greyish purple conglomerates with volcanic clasts in the upper part (equivalent to units 2 and 3 of the Late Jurassic to Early Cretaceous succession). Above this succession lies the Early Cretaceous rhyolite of the Donglingtai Formation with a prominent unconformity. The pyroclastic conglomerate in the upper part (equivalent to unit 4 of the Upper Jurassic to Lower Cretaceous strata) of the Late Jurassic-Early Cretaceous succession has developed tuff and andesite interlayers. These two conglomerate units have completely different clast compositions and a clear boundary between (Figure 5b). The Motianling anticline on the eastern side of the area is superimposed by the Dongtuanbu normal fault, which not only displaced the Proterozoic-Palaeozoic strata but also crosscut the Late Jurassic to Early Cretaceous succession. Therefore, this normal fault is a destructive structure that acted in a later stage of development of the Caogoubu Basin.

Faint parallel stratifications and massive bedding are generally developed in this succession. The clasts in conglomerates are crudely aligned. Conglomerates were deposited upon erosional surfaces with stable lateral extent. According to the sedimentary features described above, the conglomerate beds are interpreted to be deposits of stream flows in braided channels and debris flows. These coarse-grained sediments of braided rivers and debris flows indicate an environment of the proximal to median part of a large-scale alluvial fan. However, gravelly siltstones, silty mudstones and parallel-stratified or massive fine-grained sandstone intervals in the upper part of the lower succession may be turbidites in plain lakes or shallow lakes.

(2) The lower part of the Late Jurassic-Early Cretaceous succession covers the Ordovician limestone basement to the west with onlap contacts and wedges out to the east on the western flank of the Motianling anticline. Further, in most areas of the basin, only the purple gravelly sandstones in the mid-lower part of this succession have been preserved. This evidence suggests that the Late Jurassic-Early Cretaceous succession migrated away from the structural high and formed offlap contacts as the anticline structure was continuously uplifted. Therefore, the depocentre for the lower part of the succession is located in the Dataizi area. The same stratigraphic architecture is also developed in the upper part of this succession as strata retreated from the Motianling anticline and formed offlap contacts in the east but continuously migrated westward (up the Liangtianling complex anticline) and formed onlaps. During this strata migration, the depocentre also migrated westward to the western Caogoubu (Figure 5).

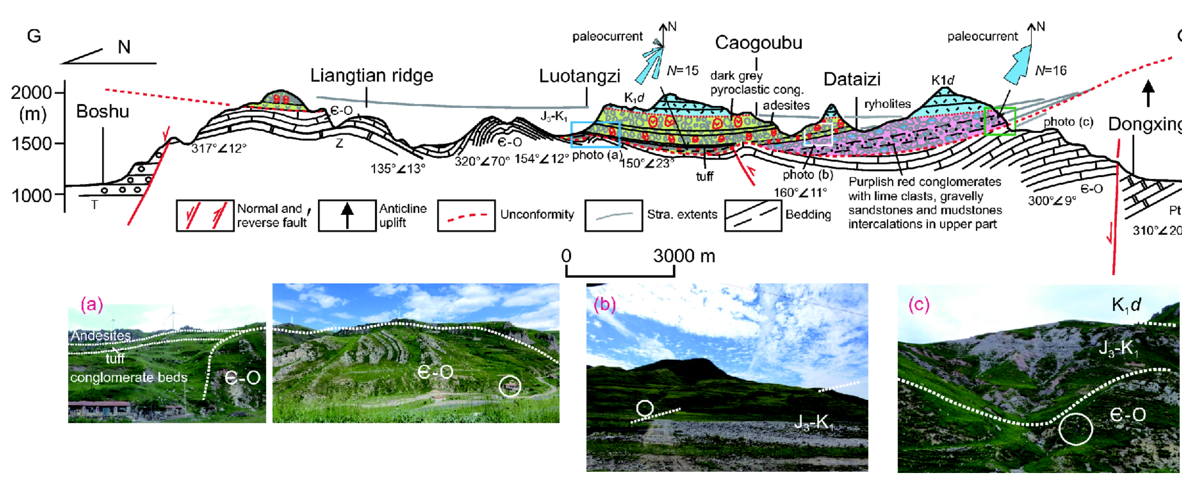

Figure 5 Structural profile (G-G′) of fold foredeep-type growth strata in southern Yuxian County. (a) Luotangzi growth anticline. Houses next to the road for scale; (b) interface of the upper and lower stratigraphic sequences of Late Jurassic-early Early Cretaceous in the Dataizi area. Off-road vehicle for scale; (c) unconformity between the underlying Ordovician limestones and the lower part of the Late Jurassic-early Early Cretaceous strata. Human for scale. For profile locations, see Figure 1.

(3) Many small anticline structures are developed in the basement of the Caogoubu synclinal basin, and local depocentres are situated in the frontal zones of these anticlines. Thick lenticular conglomerate beds were deposited in these depocentres. For example, two conglomeratic units, which are boulder conglomerates dominated by limestone clasts and volcanic clasts, were locally deposited on the west side of the Luotangzi anticline. The crest of this anticline is conformably overlain by rhyolites and higher strata (Figure 5a). The structural and sedimentary characteristics described above clearly indicate that uplift and erosion processes associated with the anticline structures directly controlled the simultaneous subsidence and sedimentation in their frontal zones.

(4) An analysis of clast composition shows that the basin source area should be the anticline structural zone to the east. The lower part of the basin-filling succession is dominated by limestone clasts with minor purple sandstone and mudstone clasts, and in the upper part, volcanic clasts prevail with minor limestone clasts. In some areas, palaeocurrent measurements from imbricated clasts indicate that the palaeo-flows of the Caogoubu Basin mainly routed to the SSW direction, which is parallel to the strikes of structures in this area.

In summary, continuous uplifting of the anticline structure to the east controlled the development of the Caogobu anticlinal basin. The depocentre, which is located in the frontal deep of the anticlines, gradually migrated westward as these anticline structures were forming. The migration of the depocentre, therefore, led to the formation and lateral migration of the basin-filling succession that comprises two vertically stacked stratigraphic wedges. The abrupt change in clast composition and the development of small-scale anticline-depression couplets in the basin basements indicate a two-stage uplift of the Motianling anticline. The times of these two uplifts are approximately 148 Ma and 139–135 Ma.

4.2 Thrust foredeep-type growth strata

The thrusting growth structure and growth strata are mainly developed in the Zhaobai Basin and the Xiahuayuan Basin. The Zhaobai Basin stretches in a nearly NE- to ENE-trend and displays a band-like outline in map view. Two high-angle thrust faults are developed in the northwest margin of this basin and are organized in an imbricated thrust belt. They are characterized by displacing the Mesoproterozoic Wumishan Formation of banded dolomites atop the Early Cambrian limestones, purple fine-grained sandstones and siltstone and the Tuchengzi Formation of conglomerates. The attitudes of thrust faults in the west and east are 324°∠80° and 310°∠50°, respectively. At the front edge of the western thrust fault, the Early Cambrian stratum forms close overturned folds with prevailing axial planes of 316°∠50° and indicates the southeastward thrusting of the hanging wall basement (Figure 6F). The high-angle eastern thrust fault is characterized by placing the Early Palaeozoic carbonate and Mesoproterozoic Wumishan Formation southwestward atop the Tuchengzi Formation. The Early Cambrian succession in the hanging wall develops typical fault-progradation fold structures (Figure 6F).

The Tuchengzi conglomerates with a thickness of approximately 881 to 0 m fill the Zhaobai Basin, located at the frontal edge of the imbricated thrust belt (Figure 6E). The conglomerate beds are nearly horizontal with attitudes of approximately 347°∠5°–11°. This conglomeratic succession thickens northwestward and tapers to the south. To the west, this succession has a prominent contact with the thrust fault but shows no interior deformation. It conformably overlies the Ordovician limestone beds with attitudes of 318°∠13°–28° and gradually pinches out toward the east. The conglomerate beds are roughly parallel stratified (Figure 6D). A single conglomerate layer that constitutes the cross-beddings is 16–100 cm thick and is normally or inversely graded. The conglomerates feature a sandy matrix material and poorly sorted angular gravels ranging in size from 4 to 70 cm. Some gravels show significant alignment. Conglomerate beds in this succession show strong correlation (with correlation index R^2 as high as 0.82) between maximum average particle size (MPS) and thickness (BTh) of the same bed (Figure 6A), which strongly suggests a gravity sediment-flow origin for the conglomerate deposits (Nemec and Steel, 1984). Therefore, it is reasonably inferred that the conglomerates at the frontal edge of the thrust belt represent deposits from gravity sediment-flows in a piedmont alluvial fan system. The clast composition in the conglomerates is mainly derived from dolomites, dolomitic limestone, (siliceous stripes) limestone, siliceous rocks, silicolites, purple red sandstones, and various limestone, including flat-pebble limestone, oolitic limestone, bioclastic limestone, striped limestone, and marlstones. In some segments of this conglomerate succession, the content of clasts of granular limestone, flat-pebble limestone and bioclastic limestone (Figure 6C) is up to 75%. It is obvious that the lithology of clasts in this conglomerate succession is consistent with that of the hanging wall successions (partially eroded) of the thrust belt to the west, suggesting that the basement rocks in the hanging wall may be the source regions for the conglomerates in the Zhaobai Basin. The statistical analysis of preferred orientations of 53 imbricated elongated clasts indicates that the palaeo-flow direction was towards the east (Figure 6B) during the deposition of the conglomerate succession. All of the above geological facts fully demonstratethat the conglomerates of the Tuchengzi Formation in the Zhaobai Basin represent deposits in a thrust foredeep, and the general timing of the syn-depositional thrusting is 150–143 Ma. The conglomerate succession thickens in the direction of the thrust belt and thins away

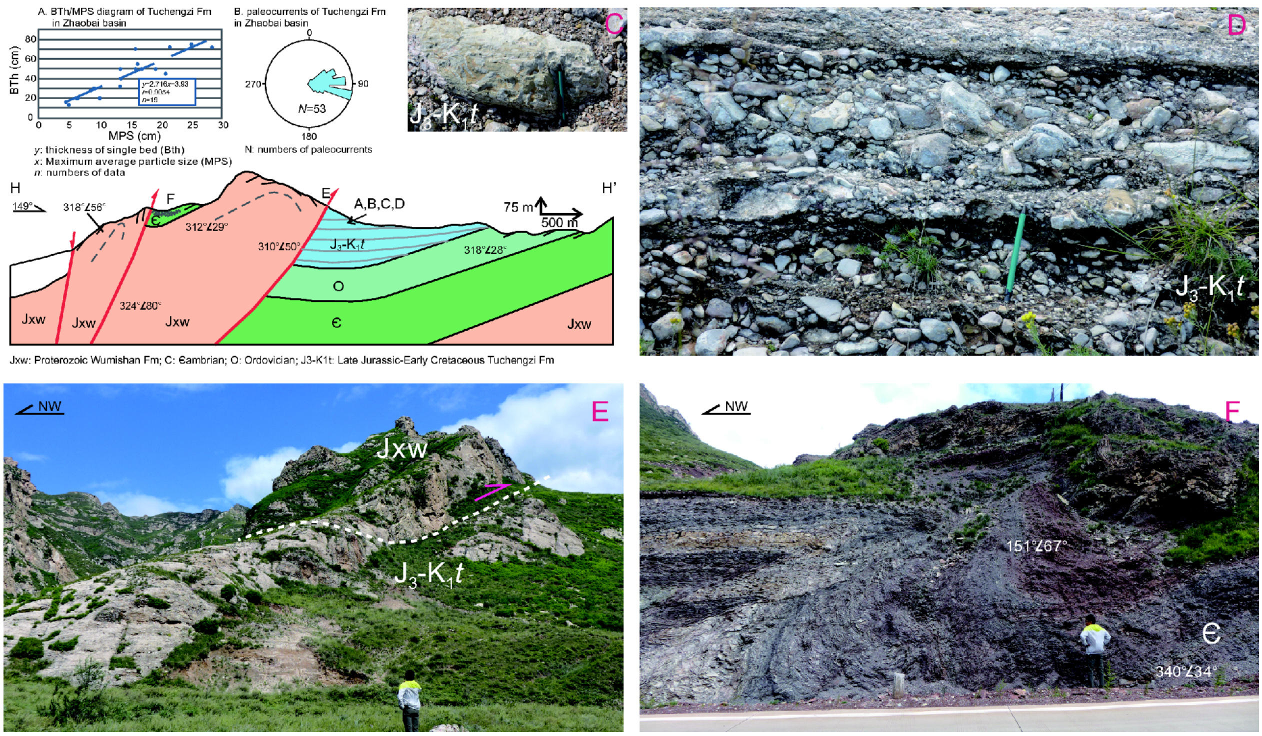

Figure 6 Structural profile (H-H′) of thrust foredeep-type growth strata in the Zhaobai Basin. For locations of outcrops in inset maps and photographs A–F, see the profile. For the profile position, see Figure 1.

from it and is deposited above an onlap contact with the underlying basement. These stratigraphic features define typical growth strata in a foredeep basin controlled by thrust faults. Based on the analysis of the thrust belt along the Zhaobai Basin, strata in this foredeep basin may have experienced early-stage growth under the control of the fault-related folds (similar to the fold foredeep-type growth strata described above). Then, a thrust fault cut through the flank sequences of the folds and early or quasi-synchronous foredeep-type growth strata and extended to the surface, forming a maximum accommodation space near the frontal edge of the thrust fault. The accommodation space laterally decreases with increasing distance to the fault. This tectonic process controls the formation of the thrust foredeep-type growth strata in the study area (Studnicki-Gizbert et al., 2008). This process may also be the reason why thrust foredeep-type growth strata bear no forced deformation. The tectono-stratigraphic characteristics of the "thrust belt and the small foreland basin couplet" are also typical in broken foreland basins of the Rocky Mountains, USA (Yonkee and Weil, 2015).

In the study area, the piggyback propagation of thrust belt results in the formation of numerous "thrust fault and small front depression" couplets. In addition, the early-formed front depressions evolve into piggyback basins with wedge-top deposits. A typical example is the Xiahuayuan-Huailai thrust belt along the southern margin of the Xiahuayuan Basin. This thrust belt consists of multiple (more than three) nearly E-W-trending, mainly N-directed thrust faults (Figure 7). The southernmost thrust in this thrust belt displaces the Wumishan Formation northward atop the shale of the Xiamaling Formation with a steep fault plane at the surface. The small crimple structures developed in the Xiamaling Formation shale indicate northward thrusting with a component of dextral strike-slip. The Late Triassic-Early Jurassic conglomerates, which are distributed along the frontal zone of the southernmost thrust fault, unconformably overlie the shale of the Xiamaling Formation and are covered unconformably by the andesite of the Late Jurassic Tiaojishan Formation. The clast composition at the bottom of the basal conglomerate unit is mainly composed of shale detritus from the Xiamaling Formation and limestone clasts of the Early Palaeozoic succession, with minor dolomite clasts. Moving upthe stratigraphy, the content of dolomite clasts gradually increases as limestone and shale clasts decrease. This vertical variation in clast composition is highly consistent with an unroofing denudation process in the source area. To the north, two thrust faults with opposite thrusting directions constitute a ramp structure. The southern thrust fault places the Cambrian limestone atop the Late Jurassic volcanic rocks, with tectonic slices of the Late Triassic-Early Jurassic conglomerate unit in the fracture zone; the N-directed fault displaces the Cambrian strata onto the basal conglomerate unit. The geological facts described above indicate that the timing of activity of this ramp structure is after the Late Jurassic. Meanwhile, the southernmost thrust fault may be a syn-depositional marginal structure that controlled the formation of the Late Triassic-Early Jurassic conglomerate unit (growth strata). As the thrust structures continuously advanced into the basin, the early deposits of the thrust foredeep basin were involved in the deformation of the thrust belt and became wedge-top sediments.

Similar but more typical wedge-top gravelly deposits of the thrust belt also developed in both the southern and northern margins of the Xuanhua-Xiahuayuan Basin, which are located in western Xiahuayuan town and northern Xuanhua town, respectively (Figure 7). However, the maximum depositional age obtained from detrital zircon dating of samples in southwestern Xiahuayuan town is 139.2 Ma (Figure 4e), which is significantly younger than the age (206 Ma) of the basal conglomerate in northern Huailai town (Figure 4a). Therefore, the thrust foredeep-type growth strata in southwestern Xiahuayuan town and northern Xuanhua town are syn-tectonic deposits of the late tectonic event, which is synchronous with the late tectonic event in the southern Yuxian Basin.

4.3 Fault-propagation fold-type growth strata

Fault-progradation fold-type growth strata are typically developed in the Guyukou, Likouquan (Figure 8) and Longmenbu areas (Figure 9) in the southern Xuanhua Basin. In the Likouquan-Guyukou area, the Guyukou sag located in the eastern part of the southern Xuanhua Basin and the Likouquan sag in the west are both subsidiary small-scale flexural basins, which developed under the control of the NEE-trending Huangyangshan thrust fault (HYT) and Likouquan thrust fault (LKT), respectively. These two NNW-vergent thrust faults together constitute a piggyback thrust belt that progrades basinward. The Mesoproterozoic Wumishan Formation is thrust northwestward atop the Jurassic-Early Cretaceous clastic succession by the Likouquan thrust fault. A distinctive "box-like" asymmetric anticline, with gently inclined crest, that developed at the top of the Wumishan Formation indicates the northwestward thrusting.

The thrust front basin (filled with Late Jurassic-Early Cretaceous units) contains the so-called "Tiaojishan Formation" volcanic rocks and pyroclastic rocks (equivalent to unit 1 of the Late Jurassic-Early Cretaceous succession) and the "Tuchengzi Formation" conglomerate in the upper part. Conglomerates of the "Tuchengzi Formation" are subdivided into three sequences: The lower sequence is approximately 300 m thick and is composed of cross-stratified purple conglomerate and gravelly sandstone beds, which intercalate

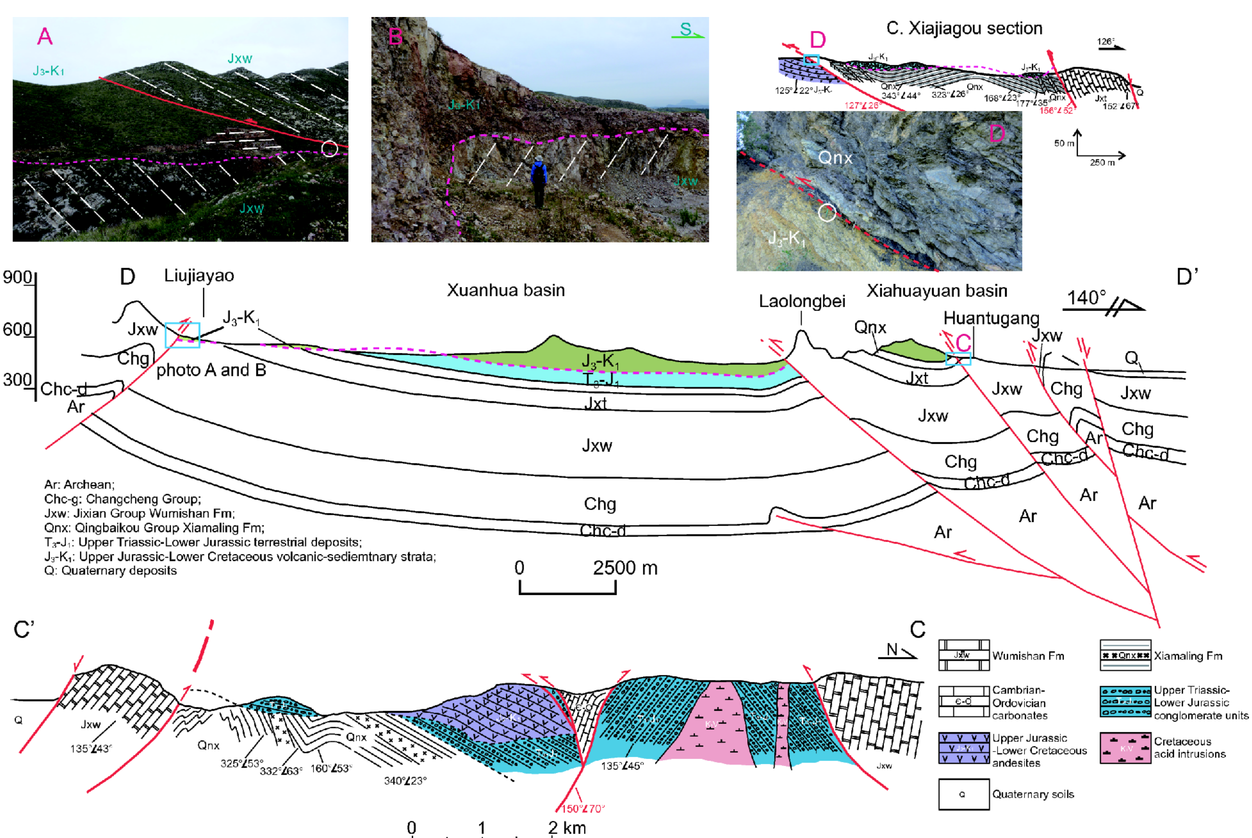

Figure 7 Structural profiles of piggyback basins in northern Huailai County (C-C′) and northern Xuanhua town of the Xuanhua-Xiahuayuan Basin (D-D′). For positions of photographs A and B and profile C, see D-D′ profile. For position of photograph D, see profile C. Human in photographs A and B and pencil in photograph D for scale. For positions of profile C-C′ and D-D′, see Figure 1.

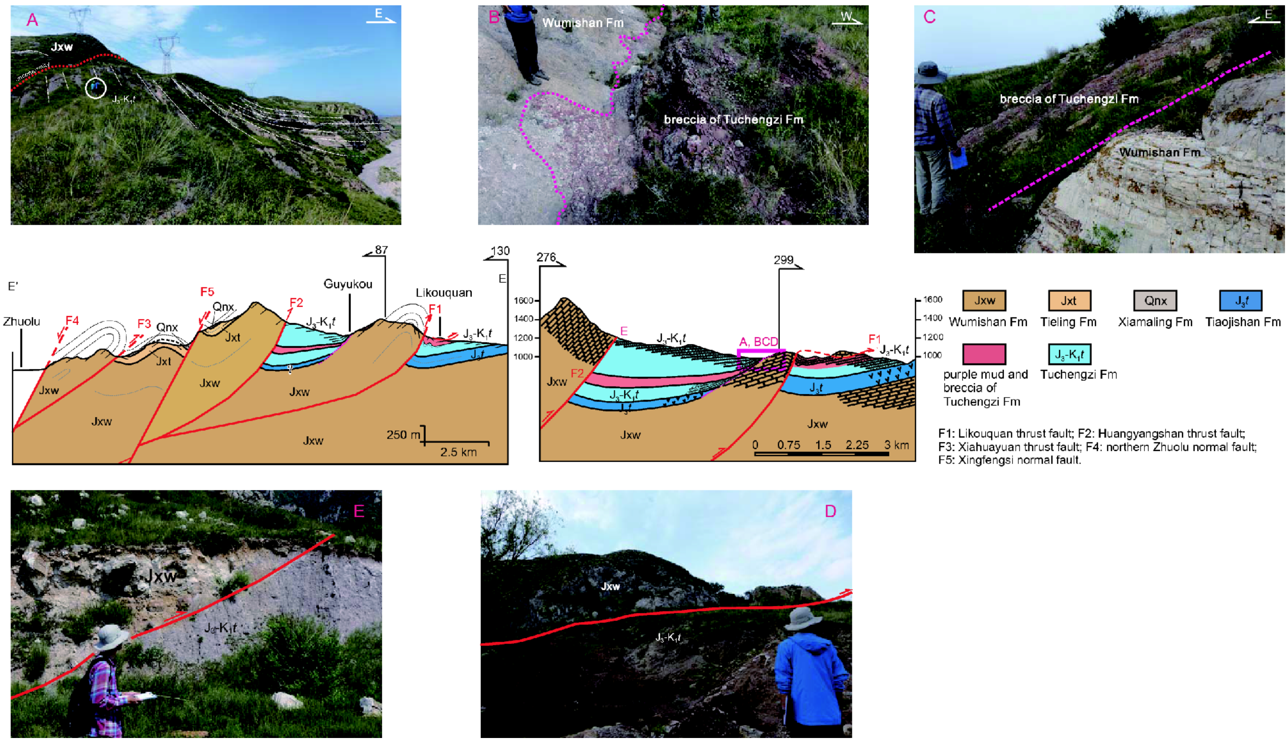

Figure 8 Likouquan regional structural profile (E-E′) and Guyukou-Likouquan growth strata profile in the southern Xuanhua Basin. Photographs A and B, Growth strata atback edge of the fault-progradation anticline near Guyukou village; C, growth strata on top of the fault-progradation anticline near Guyukou village; D, nappe structure of the Likouquan thrust fault; E, Huangyangshan thrust fault and deposit in frontal zone. For location of profile E-E′, see Figure 1.

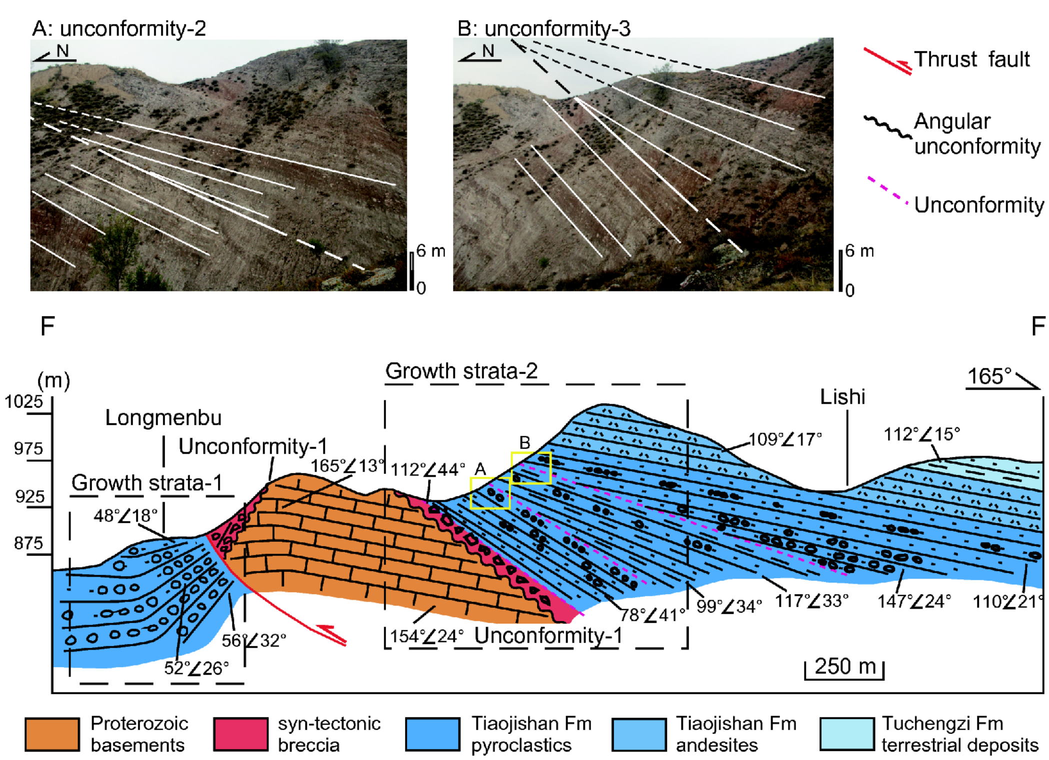

Figure 9 Structural profile (F-F′) of growth thrust fault, fault-progradation fold and growth strata in southern Longmenbu village. Growth strata develop in both the frontal zone of the thrust fault and the back edge of the fault-progradation fold. Photographs A and B represent the unconformities 2 and 3 of the growth strata in the back edge of the fault-progradation fold. See Figure 1 for the profile location.

with siltstones and silty mudstones. The thickness of the conglomerate bed is approximately 5–15 m with sharp laterally stable erosional bases, while the thickness of the structure-less siltstone unit is approximately 2–5 m. This lower sequence is interpreted as a set of braided river deposits in an alluvial plain environment (unit 2). The middle sequence is approximately 150–200 m thick and mainly comprises purple siltstones, silty mudstones with thin conglomerate and gravelly coarse-grained sandstone interlayers. Horizontal bedding is well developed in the mudstone beds. This sequence represents deposits of a floodplain, plain lake or shallow lake environment (unit 3). In addition, theupper sequence is a thick conglomerate-dominated unit, with thickness of 260–300 m, composed mainly of roughly parallel-bedded pebble-cobbles with thin gravelly sandstone interlayers (unit 4). The sedimentary characteristics of this upper sequence suggest that they are from stream flows of braided channels or of unchannelized debris-flows in an alluvial fan environment. The Likouquan sag, which is one of the secondary flexure basins in the Xuanhua-Xiahuayuan Basin, has developed only the "Tiaojishan Formation" and "Tuchengzi Formation" (units 1–3) of the Late Jurassic-Early Cretaceous succession. The dolomitic limestone and dolomite of the Wumishan Formation are placed atop the middle sequence purple red silty mudstones, which are distributed in the centre of the Likouquan sag by the Likouquan thrust fault to the east (Figure 8D). However, only part of the middle sequence (partial unit 3) and the entire upper sequence (unit 4) of the "Tuchengzi Formation" are exposed at the surface in the Guyukou sag. Further, more detailed work is needed to determine whether or not the lower parts of the Late Jurassic-Early Cretaceous succession exist in this basin. On the east side of the Guyukou sag, the Huangyangshan thrust fault places the strata of the Wumishan Formation on the upper conglomerate unit of the "Tuchengzi Formation" with a high-angle fault plane (Figure 8E). However, the conglomerates near the thrust fault show no significant deformation.

Growth strata in the Guyukou sag are developed at the back edge of a fault-propagation fold near Guyukou village, and the main characteristics are as follows: (1) Purple mudstone with scattered breccia or breccia in lacustrine deposits of the middle sequence of the "Tuchengzi Formation" unconformably overlie the Wumishan Formation at the back edge and the crest of the anticline structure, while the lower sequence and other strata in between are absent (Figure 8B and C). This stratigraphic architecture indicates that the anticline structure may have been uplifted in the early stage of the basin development and received no sediment. Therefore, the Wumishan Formation represents the pre-growth strata. (2) Breccia that developed just above the unconformity is composed of angular clasts and muddy matrix and is matrix-supported in texture. These angular clasts are products of an in situ erosional process from the exhumed Wumishan Formation, which is composed of dolomitic limestones and dolomites. The thin breccia bed changes upward into purple mudstones or gravelly mudstones with the rapid decrease in gravel content. (3) Purple mudstones or breccia layers cover the underlying Wumishan Formation with a low-angle unconformity at the back edge (east or southeast flank) of the fault-propagation fold and with a high-angle unconformity on the crest or west flank of the fold (Figure 8). This stratigraphic relationship indicates that the fold continuously grew and was buried by avalanching deposits in a subaqueous environment. (4) Conglomerates of the upper sequence of the "Tuchengzi Formation" overlie the purple mudstone with a conformable contact at the back edge (southeast flank) of the growth fold. As distance to the fold increases, the conglomerate beds become thicker, and their attitudes are gentler. The lateral variation in attitude and thickness of this conglomerate unit results in a fan-like strata assemblage (Poblet, 2012). The vertical variation in clast composition of the growth strata indicates the unroofing process in the hanging wall of the Likouquan thrust fault, with an upward decrease in the andesite clast content and an increase in the dolomite clast content from bottom to top. As a result, the pebbly purple mudstones and the overlying fan-like conglomerate beds are interpreted as growth strata. Compared with the results of the forward modelling in growth strata geometry by Poblet (2012), we infer that the deformation process of growth structure controlling the growth strata was fault-progradation folding by kink-band migration. This interpretation is consistent with the characteristics of the Likouquan thrust fault and with the deformation of successions in both the hanging wall and footwall in the field. Because the growth strata developed in the upper unit 3 and unit 4, the initiation of thrust faulting is limited to approximately 139–135 Ma (Late Jurassic-Early Cretaceous).

The Longmenbu thrust fault to the south of Longmenbu village in the southern Xuanhua Basin stretches with a nearly E-W trend and places dolomite beds of the Wumishan Formation northward atop the Late Jurassic volcanic conglomerates (equivalent to unit 1 of the Late Jurassic-Early Cretaceous succession). A typical asymmetric anticline develops in the hanging wall dolomites. Similar to the Likouquan thrust fault, this thrust fault is also characterized by avalanching breccia with a thickness of 15–30 m covering the back edge of a fault-related fold in its hanging wall. The breccias are mainly composed of dolomite clasts from the underlying Wumishan Formation, and the clasts are poorly sorted and angular in texture. The breccia bed is overlain by pyroclastic beds, which are covered by massive andesite and the so-called "Tuchengzi Formation" conglomerate (unit 2) at the top (Figure 9). The pyroclastic strata occurring along the frontal zone of the Longmenbu thrust fault show prominent deformation. The structures secondary to this fault, such as small fault-related folds and small fractures, are consistent with the thrusting direction of this thrust fault. The inclination of the breccia bed and pyroclastic strata in the back edge of the fault-progradation fold, which is located in the hanging wall of the Longmenbu thrust fault, is gradually decreasing upward without a prominent change in the bed strike. The thickness of a stratum increases in the direction opposite to the fold crest. Spatial variation in attitude and thickness of strata results in a fan-like geometry (Figure 9). Two sedimentary unconformities developed in the pyroclastic strata and strata above and below the interface show slight variations in attitude. The dip of the upper strata is significantly smaller than that of the lower strata, and this change in bed attitude indicates that the unconformity represents an offlap contact. These two offlap contacts suggest two small-scale thrusting events of the Longmenbu thrust fault during the formation of the pyroclastic strata. In addition, during exhumation of the hanging wall succession by thrusting, the deposition rate was far slower than the uplift rate of the basement (or the growth rate of the fault-progradation fold). Further, subsequent overlapping of the upper strata represents the end of thrusting activity, after which the deposition rate surpassed the uplift rate of the basement (Shaw et al., 2005). The field survey suggests that the massive andesite above the pyroclastic strata is consistent with the basal part of the "Tuchengzi Formation" in terms of strata attitude. It can be clearly seen that the breccia and pyroclastic strata are typical growth strata and the andesite and the basal part of the "Tuchengzi Formation" are post-growth strata. The former is the record of syn-depositional tectonic activity, while the latter indicates the end of structural activity. Combining the results of forward modeling by Poblet (2012) with the spatial relationship between the growth fault and the growth strata in Longmenbu village implies that the deformation of the Longmenbu growth strata was controlled by both the kink-band migration and limb rotation mechanisms in folding (Suppe et al., 2004). The internal architecture features of the Longmenbao growth strata clearly suggest thrusting events in the Late Jurassic-Early Cretaceous (approximately 157–150 Ma), and the basal avalanching breccia represents the initial thrusting.

4.4 Fault-bend fold-type growth strata

Fault-bend fold-type growth strata are developed in several localities in the Chicheng Basin, such as Wenjiadian village, Liangjiagou village, Sanhe village and Shenjiagou village. These examples of growth strata are all developed in the hanging wall successions of thrust faults, and the Wenjiadian thrust fault and the Sanhe thrust fault are the most typical growth structures that control the formation of these growth strata. The fault-bend fold-type growth strata have the following characteristics: (1) The thrust fault is characterized by the typical flat-ramp geometric structure. The fault plane on the surface trends NE-SW, and the stratigraphic sequences involved in deformation by thrusting are the Mesoproterozoic Xiamaling Formation and the Late Jurassic-Early Cretaceous "Tuchengzi Formation" (Figures 10 and 11). Among these growth structures, the Wenjiadian thrust is developed on the northwest flank of the Luotuoshan anticline, which is interpreted to be a fault-progradation fold near Houcheng town and may be genetically related to the uplifting and erosion of this anticline. The Wenjiadian thrust is characterized by southeastward thrusting and places the Xiamaling Formation shale and its overlying "Tuchengzi Formation" conglomerates (corresponding to the bottom of unit 2 of the Late Jurassic-Early Cretaceous succession) atop the lower part of the "Tuchengzi Formation". (2) The basal part of the "Tuchengzi Formation"in the hanging wall of the Sanhe thrust fault is covered unconformably by lower "Tuchengzi Formation" alluvial fan conglomerate (equivalent to the upper part of unit 2). The basal strata of unit 2 show no variation in bed inclination, but bed dips of the upper unit 2 that occur above the unconformity are gradually reduced from bottom to top, with the exception of the topmost strata. Therefore, the lower unit 2 strata are interpreted as the pre-growth strata, and the upper unit 2 strata above the unconformity are growth strata (Figure 10). At outcrops in Wenjiadian village, Liangjiagou village, Sanhe village and Shenjiagou village, the Xiamaling Formation is displaced atop a distinctive marker bed, which is characterized by grey and greyish green massive sandstones and laminated siltstones, as well as abundant plant-debris fossils, in the lower "Tuchengzi Formation" (unit 2). This stratigraphic configuration indicates that the thrusts that crop out in different sites all belong to the same thrust event and may even belong to the same fault, with discrete exposures in different locations. (3) Different contact relations of fault planes occur in different outcrops of the thrust fault: the fault plane displays as a fault-flat in both the hanging wall and footwall successions in outcrops near Wenjiadian village and Shenjiagou village (Figure 11); in outcrops near Sanhe village and Liangjiagou village, the fault plane represents a fault-flat in the hanging wall but a fault-ramp in the footwall (Figure 10). The geometries of growth strata developed in faults with different contact relationships are different: in outcrops where a fault-flat develops in both the hanging wall and footwall, growth strata show no prominent variation in bed attitude and thickness and are almost parallel to the fault plane; in outcrops where a fault-flat develops in the hanging wall and a fault-ramp develops in the footwall, growth strata of the "Tuchengzi Formation" in the hanging wall display significantly lateral variation in bed attitudes and thickness. This regular variation of attitudes and thickness results in a fan-like shape of the growth strata with numerous interior offlap and onlap sedimentary unconformities (Figure 10).

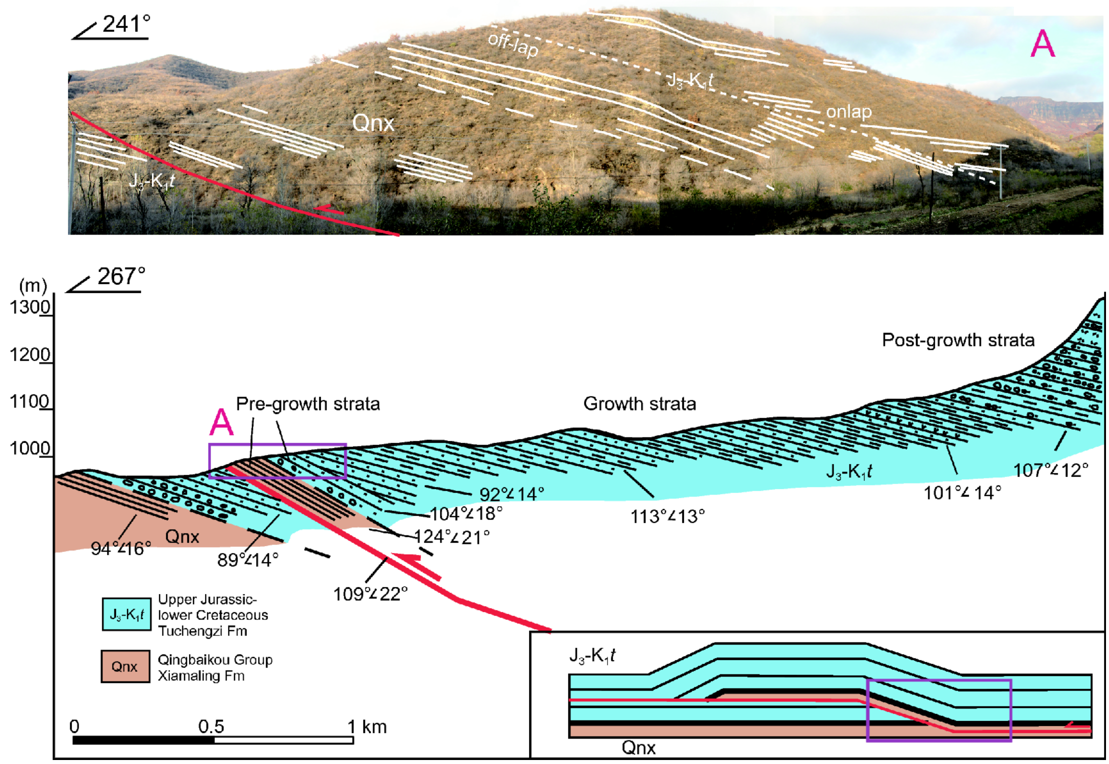

Figure 10 Structural profile (A-A′) of fault-bend fold-type growth strata in Sanhe village. A-field photographs of growth fault and growth strata; illustration in lower right shows the model of fault-bend fold-type growth strata. For profile position, see Figure 1.

The growth strata correspond to exhumation of the hanging wall succession by thrusting. Above the onlap contacts, the variation in strata gradually decreases, and finally, the attitudes and thickness of strata tend to remain unchanged, which represents the gradual ceasing of tectonic activity and indicates that the depositional rate in the basin is clearly larger than the growth rate of the fault-progradation fold (Shaw et al., 2005). The geometric and internal structural characteristics of these growth strata are consistent with the results of forward modelling on fault-progradation fold controlled growth strata by Poblet (2012), and the deformational mechanism is kink-band migration.

Therefore, the growth structure that controls the formation of this type of growth strata is a thrust fault with typical flat-ramp internal structure. The growth structures develop in the interior of the Houcheng Basin rather than in the marginal area. The thrusting direction, polarity of the flat-ramp thrust faults and their controls on the growth strata indicate that the Chicheng Basin was in a compressional setting with NW-SE contraction during the Late Jurassic-Early Cretaceous period. The shale beds of the Xiamaling Formation provided a weak zone for the development of detachment as the thrust fault prograded upward from strong basements. According to the stratigraphic position where the fault-progradation fold-type growth strata developed, the fold-and-thrust event in the Chicheng Basin is inferred to have occurred at 150–141 Ma.

4.5 Composite growth strata

This type of growth strata is developed in the Houcheng-Jijiayao area of the Chicheng Basin (Figure 11), and it is the Luotuoshan anticline with a nearly NE-SW trend that controls the formation of the growth strata (Figure 1). The axial plane of the Luotuoshan anticline points to the northwest, with a hinge plunging toward the northeast. The basement strata that are involved in folding include the Wumishan Formation, Hongshuizhuang Formation, Tieling Formation and Xiamaling Formation of the Mesoproterozoic Jixian Group. The Xiamaling Formation in the southeast flank of the Luotuoshan anticline is strongly deformed with the development of small folds and secondary thrust faults, which indicate contraction in the NW-SE direction. To the east of the Luotuoshan anticline, the Qianjiadian thrust fault, which is locatedin the western margin of the Qianjiadian Basin, has developed alarge-scale fault-progradation fold in the hanging wall. This fault-related fold deforms a basement composed of Palaeoproterozoic to Neoarchaean metamorphic rocks and thus has been interpreted as a classic thick-skinned structure. The Luotuoshan anticline is similar to the Qianjiadian thrust fault in aspects of geometry and kinematic sense. Therefore, it is reasonable to infer that the Luotuoshan anticline may belong to a fault-progradation fold controlled by a blind thrust fault beneath it. This blind fault, together with the

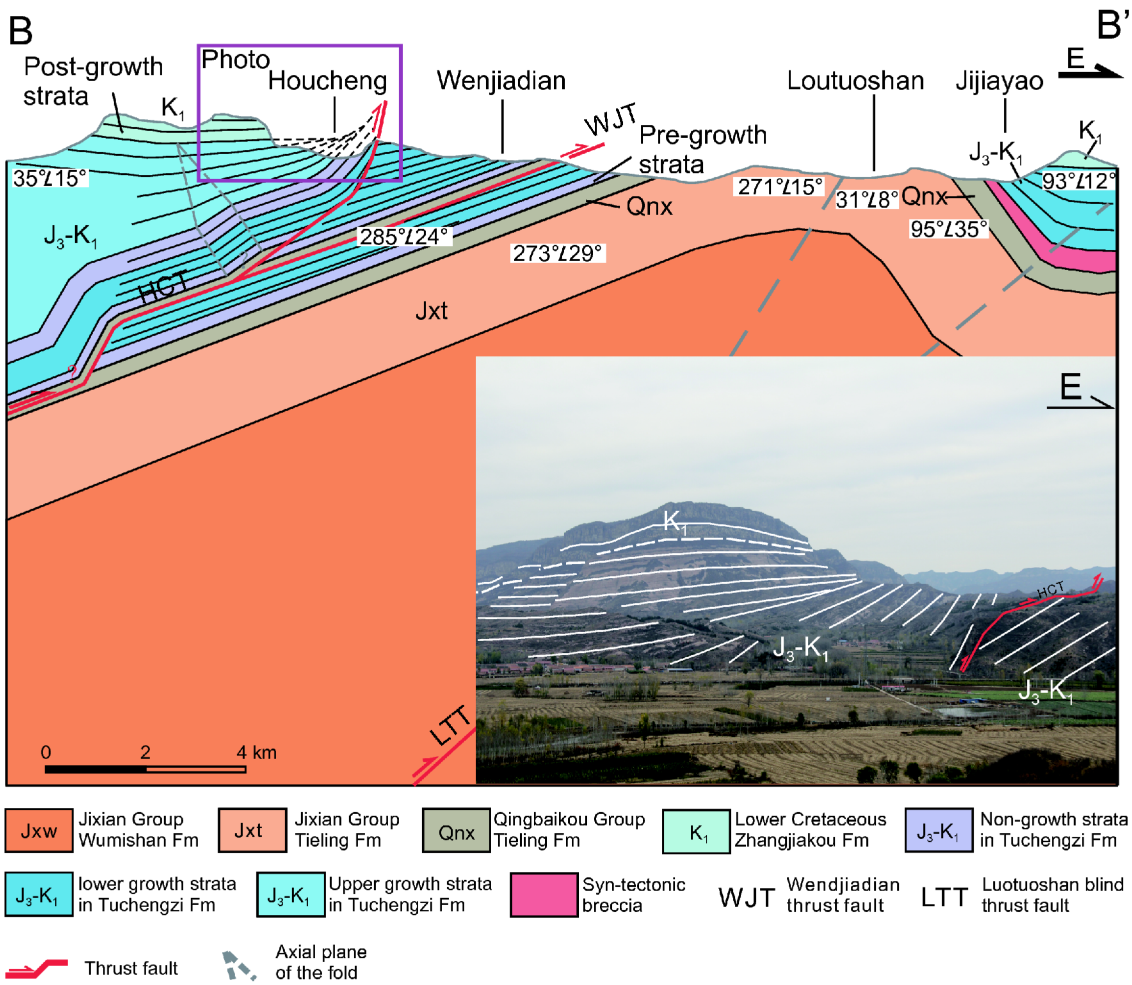

Figure 11 Growth folds, growth faults and growth strata in Houcheng town of Chicheng County (B-B′). The Late Jurassic-Early Cretaceous growth strata develop in both two flanks of the Luotuoshan fault-progradation fold. The illustration to the lower right is a photograph of the Houcheng thrust fault (HCT) and the Late Jurassic-Early Cretaceous growth strata. See Figure 1 for the profile location.

Qianjiadian thrust fault and the Tanghekou thrust fault, constitute a typical imbricate thrust system, which is rooted by a deep detachment surface within the basement. The Wenjiadian thrust fault and the Houcheng thrust fault are developed in the northwest flank of the Luotuoshan anticline. The Houcheng thrust fault is steeply dipping to the west at the surface and locally vertical. Both the hanging wall and footwall of this fault are composed of the "Tuchengzi Formation", and their contacts with the fault plane are all displayed as fault-ramps. According to the spatial relationship between the Houcheng thrust fault and the Wenjiadian thrust fault, it is inferred that the strata involved in the deformation by Houcheng thrust fault also include the Xiamaling Formation, and the Houcheng thrust fault is also characterized by a fault-ramp. It is concluded that the fold structures in the Houcheng area display a composite style of a fault-bend fold and a fault-propagation fold. Analysis of the tectonic relationships in profile suggests that the formation of the fault-bend fold is relatively earlier than the formation of the fault-progradation fold. In addition, the Houcheng thrust fault with flat-ramp geometry was active during the deformation of the Luotuoshan fault-progradation fold.

The growth strata of the "Tuchengzi Formation" are developed in both the southeast (near Jijiyao village) and northwest flanks (near Houcheng town) of the Luotuoshan fault-progradation fold and are overlain by nearly horizontal post-growth strata of the Early Cretaceous Zhangjiakou Formation rhyolite. The growth strata developed in opposite flanks of the anticline are very different in strata thickness, which is greater than 400 m in Houcheng town on the northwest flank but only 100 m in Jijiyao village on the southeast flank. The growth strata in Jijiayao village are composed of the "Tuchengzi Formation" with syn-tectonic breccia deposits in the basal part. The breccia bed with is 16 m thick and unconformably overlies the Xiamaling Formation shale. Two different breccias are seen in the field: (1) muddy matrix-supported breccia from subaqueous debris flows, with poorly sorted angular clasts that are mostly mottled shale detritus from the Xiamaling Formation, structure-less with thin, massive or laminated mudstones; and (2) large breccia units from tectonic-triggered collapses of the Xiamaling Formation shale. This breccia shows downslope slipping of large fragments from shale beds in a tectonically active subaqueous scarp and is generally encased within the matrix-supported breccia. The breccia deposits (upper unit 2) are conformably overlain by purple mudstone (unit 3), and this sedimentary contact between breccia and mudstone indicate continuous deposition in a subaqueous environment. There are many sandstone or conglomerate interlayers in mudstones of the "Tuchengzi Formation". The conglomerate interlayers are generally structure-less with poorly sorted clasts, and their clasts are mostly shale detritus from the Xiamaling Formation. The content of dolomite and chert clasts gradually increases upward. The clasts of gneiss, quartzite and granite, which represent a distant source area to the north of the Chicheng Basin, are discovered only in the topmost part of the "Tuchengzi Formation". Therefore, this provenance information suggests that the development of the "Tuchengzi Formation" in Jijiayao village was significantly controlled by the activity of the Luotuoshan anticline. In addition to the provenance aspect, the growth strata of the "Tuchengzi Formation" in Jijiayao village are also characterized by systematic changes in the attitudes and thickness. The dip angle of the stratum decreases upward, and the thickness of the stratum thickens in the direction opposite to the fold crest. The geometric characteristics of growth strata in Jijiayao village suggest that the deformation mechanism of the Luotuoshan fault-progradation fold was limb rotation (Poblet, 2012). On the basis of geochronological constraints from detrital zircon U-Pb dating of the "Tuchengzi Formation", this fault-progradation fold may have developed at 150–141 Ma. The growth strata in this area are deposited in synclinal depressions ahead of anticlines and are similar to the growth strata in the Yuxian Basin.

The most typical growth strata in the study area are developed in the "Tuchengzi Formation" on the northwest flank of the Luotuoshan anticline (Figure 11). At the bottom of the "Tuchengzi Formation", the hanging wall of the Houcheng thrust fault is composed of red lacustrine mudstones approximately 110 m thick (unit 3). The mudstone beds are steeply inclined and intersect with the fault plane at an acute angle. Although the mudstone beds near the Houcheng thrust are strongly deformed and have developed many secondary folds and small reverse faults, they show no significant variation in attitude and thickness and are interpreted as pre-growth strata. The strata that developed at the top of the "Tuchengzi Formation" and just beneath the overlying Early Cretaceous Zhangjiakou Formation rhyolite are mainly composed of conglomerates and gravelly sandstones from a subaqueous fan delta environment and occur as horizontal beds. The middle segment of the "Tuchengzi Formation" in between the basal lacustrine mudstones beds and the upper fan-delta coarse-grained sediments is dominated by interbeddings of gravelly and muddy deposits, and its inclination shows a decreasing-upward trend. This decreasing-upward inclination in the "Tuchengzi Formation" starts from the upper lacustrine mudstone beds with dips from 57° to 79° and ends in conglomerate beds beneath the rhyolite with dips of 2°–6°. This part of the "Tuchengzi Formation" is approximately 240 m thick, and the thickness of a single stratum within it gradually thickens in the direction away from the Houcheng thrust fault. The spatial variations in bed attitude and thickness result in a fan-like geometry of the gentling-upward strata sequence (Figure 11**)**. In addition, several offlap interfaces have developed in the gentling-upward sequence, and the onlap of overlying strata is developed just above these offlap interfaces. It is clear that this part (unit 4) of the "Tuchengzi Formation" consists of typical growth strata. Further, the "Tuchengzi Formation" located in the footwall of the Houcheng thrust fault contains monoclinic strata (unit 4) with dips pointing to the northwest and decreasing upward from 21°–25° in the basal breccia bed to 18°–22° in upper gravelly sandstones near Houcheng town. The 2-m-thick basal breccia of mass-flow origin unconformably overlies the Xiamaling Formation, and the angular clasts are all detritus from the Xiamaling Formation shale beds. This clast composition of the breccia clearly suggests that the dramatic uplifting of the Luotuoshan anticline controlledthe deposition of breccia. In contrast, the clast compositions of the "Tuchengzi Formation" conglomerates (unit 4) in the northwest flank of the anticline and in the hanging wall of the Houcheng thrust fault are dominated by gneiss, quartzite and granite debris, which represent the crystallized basement rocks to the north of the Chicheng Basin. The prominent variation in clast compositions of conglomerates in the "Tuchengzi Formation" suggests that the main source area changed from the uplifted Luotuoshan anticline to the crystallized basement.

On the basis of the above analysis, the upper part of the "Tuchengzi Formation" in Houcheng town is growth strata. The lower part (unit 2) of the "Tuchengzi Formation" in the footwall of the Houcheng thrust shows a significant change in attitude and thickness and represents continuous deposition on the pre-growth strata. Thus, this part of the "Tuchengzi Formation" is interpreted as early growth strata (unit 2 lower growth stratum; Figure 11). Correspondingly, the strata (unit 2) developed below the purple lacustrine mudstones (unit 3) in the hanging wall of the Houcheng thrust also show changes in attitudes, and their geometric characteristics suggest that the deformation of this late growth strata was under the control of the kink-band migration mechanism (Poblet, 2012). However, the growth strata developed above the purple lacustrine mudstones (unit 3; non-growth strata) belong to the late growth strata (unit 4; the upper growth strata in Figure 11), which was under the control of the limb rotation mechanism (Poblet, 2012). The present-day high-angle fault plane of the Houcheng thrust fault is obviously modified by the growth of the Luotuoshan anticline. According to the results of forward modelling of different growth structures by Poblet (2012), the deformational mechanism of fault-bend folds is generally kink-band migration, while the limb rotation mechanism controls the deformations of fault-progradation folds and detachment folds. Therefore, the early growth strata were controlled by fault-bend folding in the hanging wall of the Houcheng thrust fault (approximately 150–141 Ma), and the late growth strata were controlled by growth of the Luotuoshan fault-progradation folding (approximately 139–135 Ma). The "Tuchengzi Formation" in the Houcheng area represents composite growth strata under the control of both fault-bend and fault-progradation folding that were active in the Late Jurassic-early Early Cretaceous and Early Cretaceous, respectively. Similar growth strata are reported in the Sant Llorenc region of the Spanish Pyrenees Mts. (Erslev, 1991; Suppe et al., 1997).

5. The "source-to-sink" system

The "source-to-sink" system of a sedimentary basin reflects the control of tectonic activity in both the basin margins and the interior on basin sedimentation and records the history of tectonic belts and sedimentary basins. The growth strata described above indicate that the Late Triassic-Early Cretaceous sedimentary basins in the western Yanshan belt and northern Taihangshan belt are generally controlled by multiple stages of fold-and-thrust events, and strata formed under controls of different stages of tectonic activities are separated by unconformities. According to the maximum depositional age obtained from detrital zircons and the results of previous research on stratigraphy (Bureau of Geology and Mineral Resources of Hebei Province, 1989; Chen and Wu, 1997), sedimentary strata in the study area are subdivided into three distinctive stratigraphic units: the Late Triassic-early Early Jurassic unit (ca. 206 to 197–175 Ma (?)); the Early-Middle Jurassic unit (ca. 197–175 to 165 Ma); and Late Jurassic-early Early Cretaceous units (ca. 157–155 to 135 Ma). At present, these three stratigraphic units overlie the basin basements with angular unconformities. In addition, the Cretaceous volcanic rocks also overlie the Late Jurassic-Early Cretaceous and the Middle Jurassic strata with angular conformities. Detailed sedimentary facies analysis and palaeo-environment reconstruction, palaeo-flow statistics and petrological analysis in conglomerates and sandstones, combined with the characteristics of stratigraphy in the basement, allow us to reveal the sediment dispersal systems in different tectonic events and to reconstruct the relationship, or the "source-to-sink" system, between tectonic active regions (resource areas) and the depositional zone in the basin. These "source-to-sink" systems record the tectono-sedimentary processes in the basins of the western Yanshan belt and northern Taihangshan belt.

5.1 Late Triassic-early Early Jurassic "source-to-sink" system

The Late Triassic-early Early Jurassic unit is mainly distributed in the Xuanhua-Xiahuayuan Basin and extends eastward to the Chengde area (Liu et al., 2012). This unit in the Xuanhua-Xiahuayuan Basin consists of an alluvial fan-fan-delta-lacustrine facies belt. The alluvial fan deposits are developed in both the southern and northern margins of the basin and transition to a fan-delta sedimentary system and lacustrine sedimentary system in the central basin (Figure 12). In map view, the sedimentary facies belts in the basin are nearly E-W-trending and parallel to the fold-and-thrust belt along the basin margins. The palaeo-flow data also suggest that the source area is mainly to the east and northeast of the basin. The results of clast composition analysis in the marginal alluvial-fan conglomerates indicate that clasts in the northern part of the basin are dominated by debris from Mesoproterozoic dolomite and Upper Triassic andesite. The content of dolomite clasts gradually increases upward, and the content of andesite clasts decreases upward. The clast composition of conglomerates in the southern basin (i.e., conglomerates in northern Huailai County) is mainly dolomite debris from the Mesoproterozoic Jixian Group, mottled shale debris from the Qingbaikou Group and limestone debris from the Early Palaeozoic. Clasts of the basal conglomerate are mainly debris of limestones and volcanic rocks, and the content of limestone clasts decreases upward. The content of dolomite clasts, however, shows an increasing-upward trend. This regular variation of clast composition clearly constrains the location and lithology of the source region during deposition of marginal conglomerates and suggests a prominent unroofing process in the source area.

The sedimentary facies belt distribution and the sediment dispersal system of the Late Triassic-early Early Jurassic unit in the Xuanhua-Xiahuayuan Basin are significantly controlled by the E-W-trending Xuanhua thrust fault and Xiahuayuan thrust fault along the southern and northern margins, respectively. In the Huailai area of the southern part of the basin, wedge-top deposits in the fold-and-thrust belt are composed of Late Triassic-early Early Jurassic alluvial fan conglomerates (Figure 7) and clearly represent the Late Triassic-early Early Jurassic thrust foredeep-type growth strata, which are modified by subsequent fold-and-thrust deformation. In northern Xiahuayuan town in the northern part of the basin, the Xuanhua thrust fault controls the formation and southward (basinward) progradation of gravelly

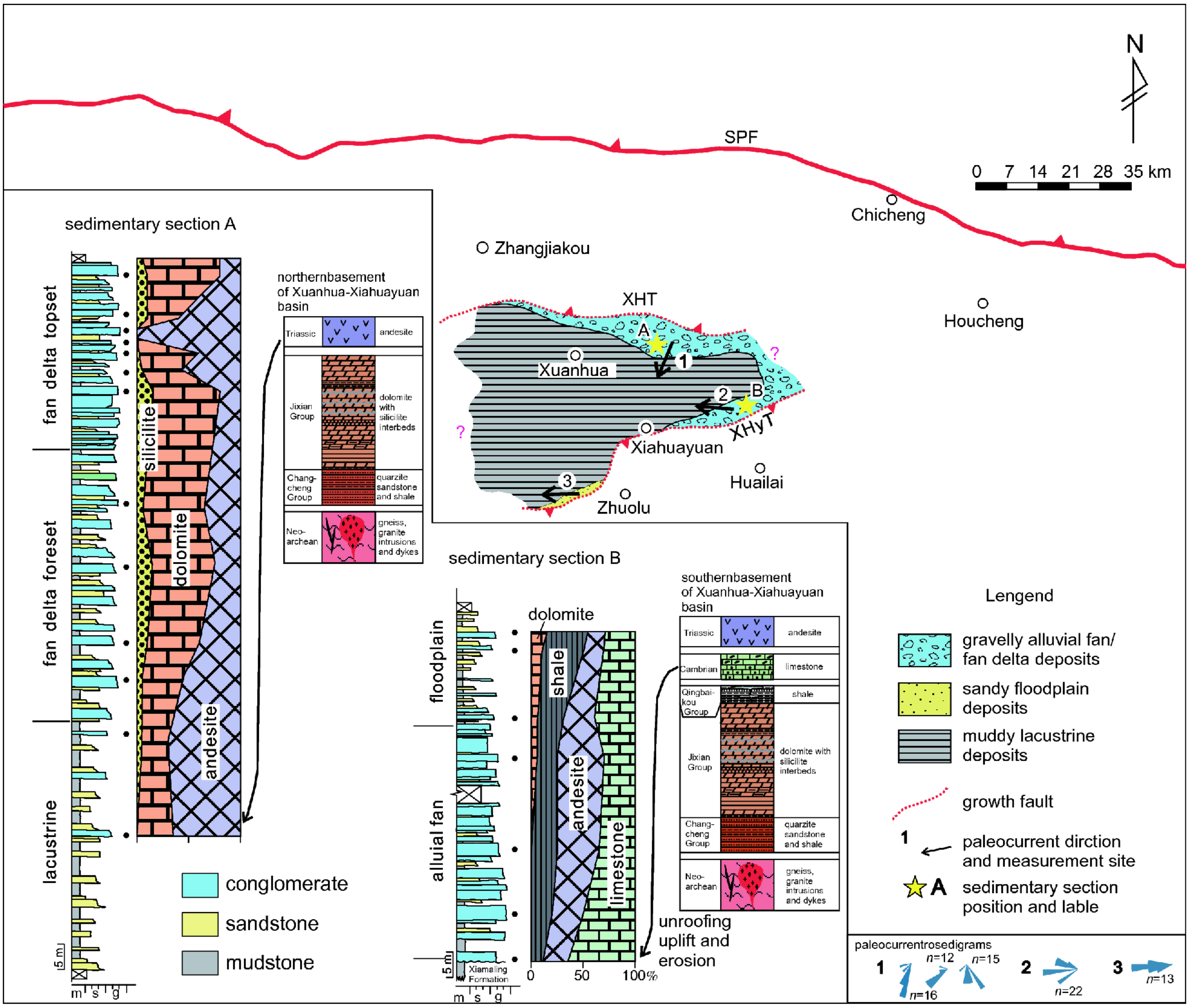

Figure 12 Changes in clast composition in sedimentary sections A and B and distributions of the source-to-sink system in the Late Triassic-early Early Jurassic (ca. 206 to 197–175 Ma). m: mud; s: sand; g: gravel.

alluvial fan–fan-delta wedges. The Late Triassic-Early Jurassic unit in this part of basin also shows the characteristics of incomplete thrust foredeep-type growth strata[1)]. Therefore, the E-W-trending Xuanhua thrust fault and Xiahuayuan thrust fault (thrust belt), together with the Xiahuayuan Basin (flexural basin), constitute the Late Triassic-early Early Jurassic "source-to-sink" system in the study area. This "source-to-sink" system is mainly controlled by regional compression in the N-S direction. Sediments in this system are delivered from thrust belts in northern and southern margins and from east of the basin to the central and western basin.

5.2 Early-Middle Jurassic "source-to-sink" system

The Early-Middle Jurassic unit is locally exposed only in the northern Yuxian Basin, Zhuolu County and Xiahuayuan town. Its "source-to-sink" system is fragmentarily developed. In the northern Yuxian Basin, the Middle Jurassic unit contacts the underlying Ordovician limestone strata and the overlying Cretaceous rhyolite with unconformities. The outcrop profile in Zhengjiayao village of Yuxian County shows that the basal part of this unit is dominated by a gravelly river depositional system and that the main sequence is composed of lacustrine and river delta deposits. Palaeo-flow measurements in these strata show that the source area is to the southeast of the southern Yuxian Basin. Near Baicao village, the Late Jurassic-early Early Cretaceous strata unconformably overlie the Middle Jurassic delta deposits. Clasts in the basal conglomerates of the Middle Jurassic unit are mainly Cambrian-Ordovician limestone and Mesoproterozoic dolomite debris. In addition, the upward decrease in limestone debris and the upward increase in dolomite debris reflect a process of uplift and erosion of deeper basement rocks in the source area from the Mesoproterozoic strata to the Upper Palaeozoic strata or even older strata.

In the study area, no thrust-controlled growth stratum has been observed in margins of this Middle Jurassic basin. Fold structures with NE to ENE trends are widely developed in the basements to the southeast of the basin, and the Middle Jurassic unit mainly occurs in these synclinal depressions. Thus, the uplifted anticlines and synclinal basin formed the "source-to-sink" system of Middle Jurassic age. Basement rocks in anticlines are uplifted and eroded and become the main sediment suppliers of the synclinal basins.

5.3 The Late Jurassic-early Early Cretaceous "source-to-sink" system

The Late Jurassic-early Early Cretaceous unit crops out widely in the study area and is mainly composed of volcanic rocks, pyroclastic rocks and terrestrial clastic rocks, with full thicknesses of approximately 300–1200 m. According to the maximum depositional ages from both detrital and magmatic zircon U-Pb dating and sedimentary characteristics of stratigraphy, the Late Jurassic-early Early Cretaceous unit in the study area issubdivided into four sequences: sequence 1 (ca. 157–155 to 150 Ma), sequence 2 (approximately 150–141 Ma), sequence 3 (approximately 141–139 Ma) and sequence 4 (approximately 139–135 Ma). All four sequences are developed in the Houcheng Basin and the Xuanhua-Xiahuayuan Basin. Only sequences 2–4 are developed in the southern Yuxian Basin, and only the lower sequence 2 develops (or remains) in the Zhaobai Basin.

Sequences 1–2 of the Late Jurassic-early Early Cretaceous unit are composed of alluvial fan-floodplain-lacustrine deposits, which crop out well in the Chicheng Basin and the Xuanhua Basin, and are dominated by gravelly alluvial fan deposits in the Zhaobai Basin. The marginal thrust belts and the flexural basins constitute complete "source-to-sink" systems. Although intensively modified by subsequent extensional structures, a relatively complete Late Jurassic-early Early Cretaceous "source-to-sink" system, comprising complex folds to the southeast and fold foredeep-type flexural basins filled with small-scale gravelly alluvial fan-meandering river-shallow lacustrine deposits to the northwest, is developed in the Yuxian Basin. The Zhaobai Basin represents a typical fold foredeep-type depression at asmall scale. In this small basin, the marginal thrust belt and the foredeep-type growth strata composed of gravelly alluvial fan deposits in its frontal zone constitute a simple complete "source-to-sink" system. Here, we highlight the "source-to-sink" system of units 1–2 in the Chicheng Basin and the southern Xuanhua-Xiahuayuan Basin (Figure 13). Sedimentary facies belts in these two basins trend EW-NE-NNE, and gravelly alluvial fan and braided river deposits are mainly distributed along the northern margins. Sequences 1–2 in the Chicheng Basin are mainly distributed to the south of the Shangyi-Pingquan fault (SPF), and the palaeo-current measurements in the gravelly alluvial fan deposits along the northern margin generally indicate a S- or SW-directed palaeo-flow system. The clast composition of these two sequences is dominated by biotite plagioclase gneiss and flesh-pink granite debris, which are consistent with the lithology of the Archaean crystalline basement largely exposed to the north of the basin. The SPF and Wenjiadian fault are thrust in "step-like" fault planes that develop in the weak layer of the Xiamaling Formation shale and place the Xiamaling Formation atop the Late Jurassic mudstones, forming fault-bend folds and corresponding growth strata in the hanging wall (Figures 10 and 11). The geological facts noted above indicate that the gravelly alluvial fan deposits in the northern part of the Chicheng Basin are generally from basement rocks to the north of the basin (Figure 13, sedimentary section A). During this early stage of basin development, the Chicheng Basin was under the control of the SPF and its secondary faults. Meanwhile, the analysis of palaeo-current data and clast components of deposits in the southern part shows that minor sediments were fed by a source area to the south of the basin (Figure 13, sedimentary profile B). Therefore, sediment supplies from both northern and southern provenance areas controlled the deposition of strata in the Chicheng Basin. Further, this bidirectional sediment disposal system resulted in a nearly E-W-trending depocentre belt in the central basin, which was dominated by a lacustrine depositional system. The spatial distribution of sedimentary facies trendsnearly E-W and parallel to the strike of the SPF. Although destroyed by subsequent rifting events, the Late Jurassic-early Early Cretaceous "source-to-sink" system in the Chicheng Basin is relatively complete. This basin is separated from the Qianjiaadian Basin and the Tanghekou Basin to the east by the NE-trending Qianjiadian thrust fault (QJT) and Tanghekou thrust fault (THT). The latter two basins together constitute a spatially and genetically independent "source-to-sink" system of a thrust belt and flexural basins couplet (Figure 13).

From the Late Jurassic to the Early Cretaceous, a typical alluvial fan system developed along the Xuanhua thrust fault in the northern part of the Xuanhua-Xiahuayuan Basin (Figure 13), and its deposits form thrust foredeep-type growth strata, which become piggyback deposits after involvement in a subsequent thrusting event in the Early Cretaceous (Figure 7). The measurements and statistical analyses of the preferred orientation of clast long axes in alluvial fan conglomerates show that the palaeo-currents in the northern part of the basin were generally directed SSW. The results of systematic clast composition analyses show that clasts in conglomerates are mainly from gneiss, granite, dolomites and andesite, which indicates that the main source area is the exposed basement rocks to the north of the basin. The western and southern parts of the basin developed an

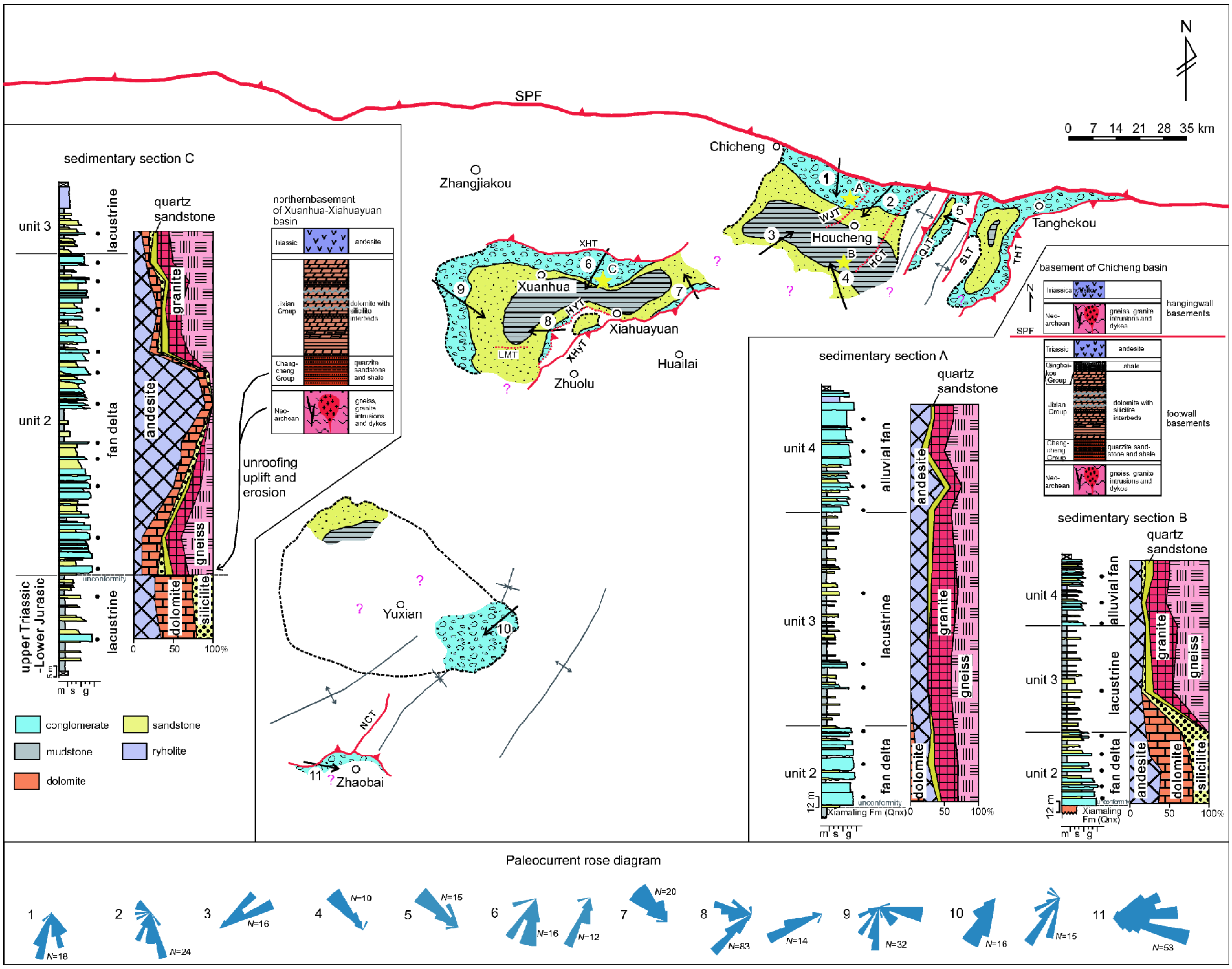

Figure 13 Changes in clast composition in sedimentary sections A–C and distribution of source-to-sink system in the late Late Jurassic-early Early Cretaceous (ca. 157–155 to 141 Ma). For legends and fault codes, see Figures 1 and 12.

alluvial fan system dominated by braided stream conglomerates, and palaeo-current data show that the source areas are located to the northwest and south of the basin. In the southern margin of the basin, the alluvial fan conglomerates are distributed along the marginal Huangyangshan thrust fault (HYT) and Longmenbu thrust fault (LMT), forming thrust foredeep-type growth strata and fault-progradation fold-type growth strata (Figures 8 and 9). The source areas of the conglomerates are the Mesoproterozoic Wumishan Formation and Xiamaling Formation in the hanging wall. Floodplain and shallow lake deposits generally occupy the middle and southern parts of the basin. The thrust belts along the northern and southern margins and the Xuanhua-Xiahuayuan Basin together constitute an independent "source-to-sink" system in the Late Jurassic-early Early Cretaceous period. Whether the basin connects westward with the Chicheng basin still lacks solid geological evidence.

In general, a number of independent "source-to-sink" systems developed in the study area from the Late Jurassic to early Early Cretaceous (ca. 157–155 to 141 Ma). Thrusting activities during this period mostly tookadvantage of pre-existing thrust faults, and therefore, the sedimentary facies belt in the northern part of the Chicheng Basin trendsnearly E-W. However, facies belts in the southern Xuanhua- Xiahuayuan Basin, Qianjiadian Basin, Tanghekou Basin, Yuxian Basin and Zhaobai Basin trend NE-SW. The Late Jurassic gravelly alluvial fan deposits in the Xuanhua-Xiahuayuan Basin are mainly distributed along the northern margin and are fed by sediments from the hanging wall successions of the nearly E-W-trending Xuanhuan thrust fault (XHT). In contrast, gravelly deposits in the southern margin are limited to a narrow belt with a NE-SW trend and derived from the erosion of hanging wall successions of the XHYT and HYT. Clearly, the deposition in the Chicheng Basin was controlled by the pre-existing SPF with an E-W trend, but the NE-SW-trending fault-bend fold-type growth structures developed in the lacustrine sediments strongly suggest that deposition in this basin was also under the control of SE-directed thrusting during the Late Jurassic-early Early Cretaceous. Investigations in the field find a large number of secondary small fold-and-thrust structures in the fracture belt of the SPF, and attitudes of the fold axial surfaces and hinges indicate a dextral slip component to the SPF. The deposition in Chicheng Basin is consistent with that in the Qianjiadian Basin and the Tanghekou Basin in terms of their relationship with marginal thrust faults, and this consistency clearly suggests that the western Yanshan belt has developed a NE-trending belt-flexural basin couplet and may connect with the Taihangshan belt to the south.

5.4 The Early Cretaceous "source-sink" system

Early Cretaceous (ca. 139–135 Ma) strata (unit 4) are a terrestrial succession composed of purple alluvial fan coarse-grained deposits that arecomparable to those in the Yanshan belt and are roughly equivalent to the upper part of the previously defined "Tuchengzi Formation", which developed in the Chicheng Basin, Xuanhua-Xiahuayuan Basin, Qianjiadian Basin, Tanghekou Basin and southern Yuxian Basin. They overlie the lacustrine and fluvial deposits or unconformably overlie the basement rocks (Figure 14), showing a coarsening-upward trend. The Early Cretaceous "source-to-sink" system in the study area shows different structures in source areas and different basin-filling architecture.

The structures of the source region and the catchment area of the Chicheng Basin in the Early Cretaceous experienced dramatic change. Alluvial fan conglomerates that cover the basin extend northward and overlie the (Shangyi-Pingquan fault) SPF, which is considered to be the northern margin of this basin in the Late Jurassic-early Early Cretaceous period. These marginal coarse-grained sediments display a wedge-like geometry with the thickest part occurring near the frontal zone of the Fengning-Longhua fault (FLF) and unconformably overlie the basements of Archaean metamorphic rocks. Alluvial fan sediments are thick and mainly composed of coarse-grained clasts from rapid dumping of debris-flows in a proximal alluvial fan environment. Alluvial

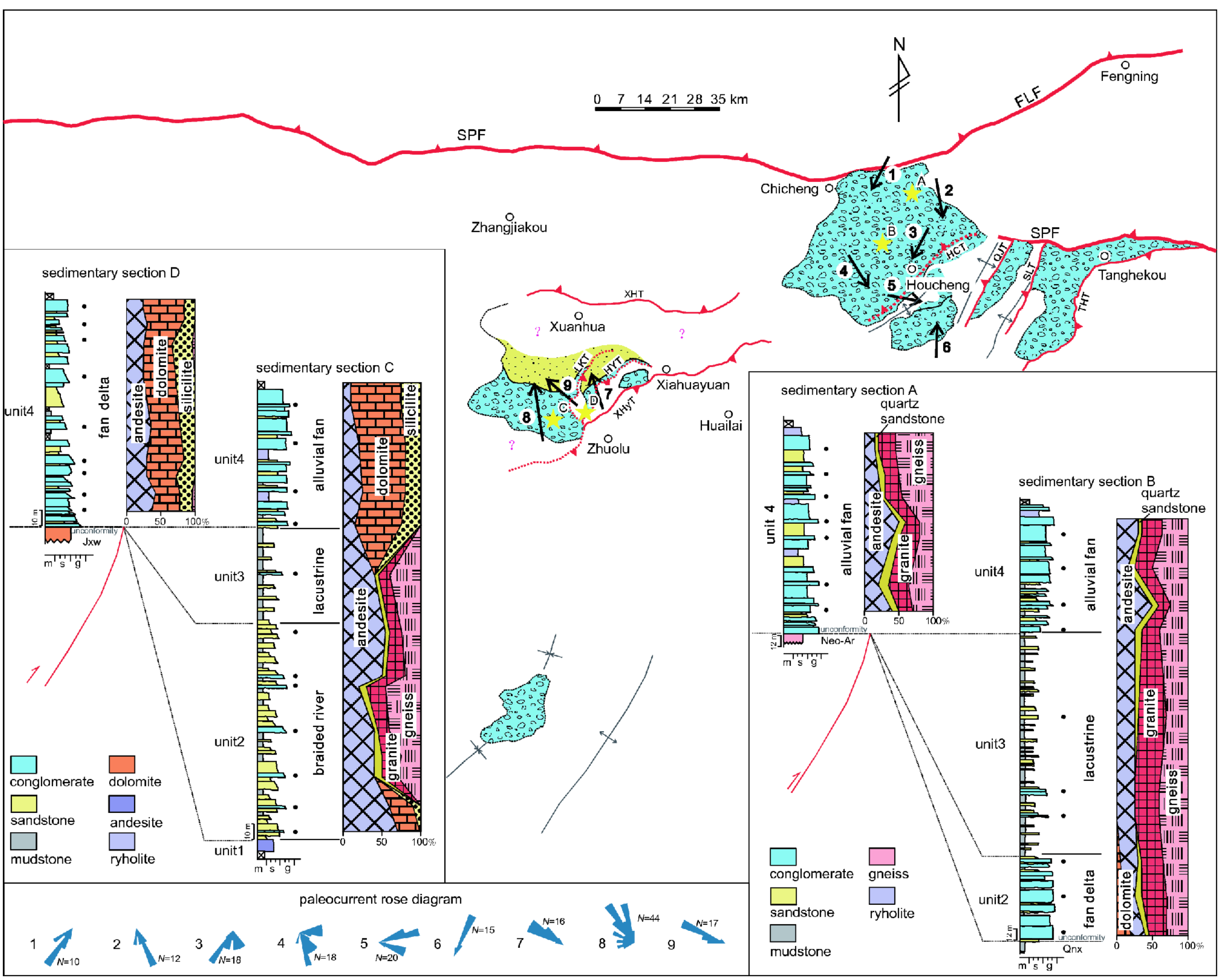

Figure 14 Changes in clast composition in sedimentary sections A–D and distribution of source-to-sink systems in Early Cretaceous (ca. 139–135 Ma). For legends and fault codes, see Figures 1 and 12.

fan deposits prograde southward across the SPF and directly overlie the lacustrine deposits (unit 3). The particle size and bed thickness of the alluvial fan deposits decrease and thinsouthward, respectively. In addition, thecontent of sandstones, gravelly coarse-grained sandstones and conglomerates from tractional deposition in the braided channel generally increase southward with the decrease in content of mass-flow deposits. Statistical analysis of clast composition in this conglomerate unit shows a provenance area composed mainly of gneiss, granitic gneiss and granites. Combining this information with the results of palaeo-current measurements, the source area for this conglomerate unit is the Archaean and Palaeoproterozoic strata exposed to the north of the Chicheng Basin. Thrusting activity of the NE-SW-trending FLF is inferred to have controlled the southward (basinward) progradation of alluvial fan coarse-grained sediments. Thrusting of the Houcheng thrust fault and fault-progradation folding of the Luotuoshan anticline together controlled the formation of growth strata in a distal alluvial fan–fan-delta system and the deposition of subaqueous avalanching and turbidity currents in an offshore environment (Figure 11). The characteristics of sedimentary strata, syn-depositional structures and growth strata in the northern and western parts of the Chicheng Basin show that the source areas of the basin are the hanging wall blocks of marginal thrust faults to the north and west of the basin, and the distribution of the basin's depocentre is limited to around Houcheng County. In the southeastern margin of the basin, palaeocurrent data and clast composition clearly show that the sediments were delivered to the basin from source areas to the south, but the structures in this area are inaccessible due to subsequent modification by the rifting event in the Cretaceous. Small-scale NE-trending "source-to-sink" systems controlled by the Qianjiadian thrust fault and Tanghekou thrust fault developed in basins to the east of the Chicheng Basin. Basin-mountain relationships in these basins clearly show that the NW-directed fold-and-thrust processes controlled these early Early Cretaceous "source-to-sink" systems in the region.

The early Early Cretaceous (ca. 139–135 Ma) unit in the Xuanhua-Xiahuayuan Basin shares the same stratigraphic architecture as that in the Chicheng Basin, as alluvial fan coarse-grained sediments developed directly above lacustrine-floodplain deposits and constitute a coarsening-upward sequence. The results of palaeo-current measurements indicate a northwest-directed sediment disposal system. The clast composition of the alluvial fan conglomerates is mainly dolomite debris from the Mesoproterozoic Wumishan Formation, which is located in the hanging wall block to the south of the basin. In the frontal zone of the Huangyangshan thrust fault and the back edge of the fault-progradation fold in Guyukou village, alluvial fan or braided river conglomerates form thrust foredeep-type growth strata and fault-progradation fold-type growth strata (Figure 8). These growth strata in the southern Xuanhua-Xiahuayuan Basin are the sedimentary response to the activity of the NE-SW-trending thrust along the southern margin. Similarly, source-to-sink systems composed of complex anticlines and flexural basins developed in the southern Yuxian Basin and generally dispersed sediment to the southwest (Figure 14).

6. Discussion

The start time, tectonic phase and age, structural nature and regional tectonic setting of the Yanshanian movement are key scientific issues that have drawn increasing interest in recent years. Previous studies tended to define the Yanshanian movement by an unconformity and expect to determine a solid consistent initiation age. However, tectonic activities are generally migratory, and it is hard to limit them in the time interval of an unconformity. Therefore, it is difficult to define the timing of the different phases of Yanshanian movement within the time intervals of unconformities in a large region, respectively. The tectono-sedimentary analyses of fold-and-thrust belt and flexural basins in the Zhangjiakou area provide windows for understanding the structural properties of the Yanshan tectonic belt and the "Yanshanian movement".

6.1 Tectonic evolution

The basin-mountain system in the Zhangjiakou area has experienced three stages of fold-and-thrust processes in the Late Triassic-early Early Jurassic, Early-Middle Jurassic and Late Jurassic-early Early Cretaceous and formed 3 distinctive stratigraphic units: a Late Triassic-early Early Jurassic unit, an Early-Middle Jurassic unit and a Late Jurassic-early Early Cretaceous unit. The Late Triassic-early Early Jurassic fold-and-thrust belt and flexural basin couplet is developed only in the Xuanhua-Xiahuayuan Basin, with a nearly E-W trend. The sediment dispersal system is mainly composed of alluvial fan-fan-delta-lacustrine sub-environments and disperses sediments westward into the basin area. This basin-mountain system, the Xiabancheng Basin-Pingquan-Gubeibei thrust belt couplet in the Chengde area and the Dengzhangzi Basin-Yangzhangzi-Wafangdian thrust belt couplet in western Liaoning province all developed along the northern margin of the Yanshan belt and were controlled by south- or southeast-dipping fold-and-thrust events. In view of plate tectonics, these basin-mountain systems in the northern Yanshan belt are located in the northern marginal slope of the Late Triassic "large" Ordos Basin in the North China Block (NCB) (Liu, 1998; Liu et al., 2013) and parallel to the Qinling-Dabie-Sulu-Japan Takayama collisional orogeny to the south and the Late Palaeozoic Suolun-Linxi orogenic belt to the north. To the south, the Qinling-Dabie-Sulu orogenic belt formed in the Late Triassic and developed Middle-Late Triassic foreland/hinterland fold-and-thrust belts and peripheral foreland basin/back-arc flexural basin systems at its southern and northern margins, respectively (Zhang et al., 2001; Liu and Yang, 2000; Liu et al., 2015b). To the north, Late Palaeozoic orogenic movements lasted through the Triassic to the early Early Jurassic and resulted in the E-W-trending south-dipping ductile shear deformation at a deep crust level and south-dipping asymmetrical folding in the shallow sedimentary cover. The high-grade metamorphic rocks along the northern margin of the Yanshan belt were exhumed and eroded during this time interval (Wang et al., 2013). Therefore, the Late Triassic-early Early Jurassic tectonic activities in the Yanshan belt and the whole of North China are related to the collisional orogeny in the Central Asian and Paleo-Tethys tectonic domain.

The Early-Middle Jurassic "source-to-sink" system in the study area is poorly developed. The typical fold-and-thrust belt and the flexure basin system of the Early-Middle Jurassic is the Beijing sag, which extends from western Beijing to the western margin of the Bohai Bay Basin, and the Daxing uplift, which is located in Xinglong County of the southern Yanshan belt. It is the W-directed NE-trending Huangzhuang thrust fault, Daxing thrust fault, Jurassic Taihangshan front thrust fault and Xinglong thrust fault (Zhang et al., 1997) that control the depositional process of flexural basins in the thrust front or in the back edge of fault-related folds of the hanging wall. The Longmen conglomerate unit represents rapid deposition of subaqueous mass-flows and is the sedimentary response to this thrusting event (Zhang et al., 2013). Therefore, unlike the pre-existing fold-and-thrust structures, the Yanshan tectonic belt extends to the west with one branch connecting to the NE-trending Taihangshan belt to the southwest. The thrust front of the Yanshan belt is located in the eastern margin of the Taihangshan, and its thrusting occurred in the late Middle Jurassic. The Late Jurassic-early Early Cretaceous "source-to-sink" systems are completely developed in the study area. We identified growth strata in stratigraphic units 1, 2 and 4 of the Late Jurassic-early Early Cretaceous rocks. The development of growth strata indicates that there were at least three fold-and-thrust events in the Late Jurassic-Early Cretaceous period. The thrust belt-flexure basin systems are generally ENE- to NE-trending. The thrust fronts migrated from the western margin of the Bohai Bay Basin in the early stage to the Likouquan thrust fault, Houcheng thrust fault, Xuanhua thrust fault and FLF in the Xuanhua-Xiahuayuan-Chicheng area. The SPF in the western extension of the Yanshan belt was gradually converted into a thrust fault with a dextral slip component and coordinated the displacement between the northern and southern blocks. Based on the analysis above, it is inferred that the western part of Yanshan and the northern part of the Taihangshan may have been chained together since the Middle Jurassic and may have started the contractional fold-and-thrust deformations of the Yanshanian movement in the eastern Taihangshan belt. This stage of deformation in eastern North China may have occurred earlier (approximately 180–175 Ma, Wang et al., 2017), but the determination of the particular timing requires further work. It was during the Late Jurassic-early Early Cretaceous (ca. 157 to 141 Ma) that the tectonic deformation of the Yanshanian movement began migrating to the study area, and the deformation extended into the early Early Cretaceous (ca. 135 Ma), forming a typical fold-and-thrust belt-flexural basin system and fold-thrust type growth strata.

6.2 Structural property

Similar to the tectonic deformations of the Laramide movement in the Rocky Mts. of western North America (Berg, 1962), the Yanshan-Taihangshan fold-and-thrust belt–small flexure basin systems also developed in the continental craton, which is more than 1000 km away from the plate edge, and developed an intracontinental belt with intense deformation. Thrust structures in the western Yanshan-northern Taihangshan belt are also characterized by simple steep fault planes that become gentler in the shallow crust and form fault-ramps or nappes. The basement-involved large-scale asymmetric anticlines (growth folds) indicate the development of thrust faults in the deep crust. The sedimentary strata in the synclinal basins (or small flexural basins) are weakly deformed and mostly occur as monoclinal strata dipping toward the fault. The flexural basins developed in the study area are similar to the "broken foreland basins" formed by the "Laramide movement", which are characterized by their small scale, association with fold-and-thrust structures, high relief in basin margins, elongate distribution, and development of basin-axial drainage systems (Dickinson et al., 2005). Therefore, the Yanshan-Taihangshan tectonic belt is composed of thick-skinned fold-and-thrust structures in basements and thinner sedimentary covers. Wide basins separate fold-and-thrust structures, which extend NE-ENE. The bending and distribution of tectonic deformation may be controlled by weak zones or pre-existing structures in the crustal basement.

6.3 Dynamic backgrounds

The Yanshan-Taihangshan fold-and-thrust belt of the Yanshanian period developed in the central part of the North China Craton. To the east, it may be widespread in the Mesozoic basements of the Bohai Bay Basin and in the eastern coastal area of the Tan-Lu fault. Previous studies have found that the western Pacific subduction belt developed along the Mudanjiang fault belt, central Japan Honshu Island, and the central uplift of the Donghai Basin. The accretion of the Jiamusi block of NE China, the Nadanhada block, abundant marine sediments in Honshu of Japan and Permian seamount fragments to the East Asia continental margin occurred along this subduction belt (Wu et al., 2007; Isozaki et al., 2010; Kemkin, 2012; Charvet, 2013; Ren et al., 2016). Residues of a calc-alkaline volcanic belt in NE China distributed parallel to the subduction belt (190–173 Ma; Xu et al., 2013) were developed in northeastern China. Therefore, the continental margin and accretion belt of East Asia and the western Pacific subduction belt together constitute acontinental marginal arc-type orogenic belt formed by ocean-continent (B-type) subduction during the Jurassic-Early Cretaceous period. The Yanshan-Taihangshan fold-and-thrust belt in the North China Craton represents the distal part of this orogenic belt. In this fold-and-thrust belt, the Chengde area in the middle segment and the western Liaoning area in the eastern segment may have been under the far-field effect from the collisional closure of the Mongol-Okhotsk Ocean and developed in the frontal convergence zone between the western Pacific orogenic belt at the east and Mongol-Okhotsk orogenic belt at the west. Eastern China in the continental back-arc area has undergone widespread shortening events during the Jurassic-Early Cretaceous period (Wang et al., 1992; Qi et al., 2003; Wang et al., 2017; Zhang et al., 2017). This tectonic setting of eastern China indicates the advancing subduction of the Izanagi plate in the western Pacific. The basement-involved fold-and-thrust belt-small flexural basin systems widely developed in the Yanshan-Taihangshan belt indicate that this subduction may have been a flat slab-type (Liu et al., 2013; Liu et al., 2017). The thinner Mesozoic and Palaeozoic sedimentary covers developed above the strong basements and mantle lithosphere, and their interactions with the subducted slab induced the transmission of stress and led to ruptures in the crustal basements (Dickinson et al., 2005; Yonkee and Weil, 2015).The leading edge of the subducted slab advancedtoward the interior of the East Asia continent, and its load in the deep mantle led to the subsidence and westward migration of the small catchment basin belts.

7. Conclusions

Based on new detrital zircon U-Pb ages, the Jurassic strata in the study area are subdivided into three units: the Late Triassic-early Early Jurassic unit, the Early-Middle Jurassic unit and the Late Jurassic-early Early Cretaceous unit. Under the control of the fold-thrust growth structures, the fold foredeep-type, thrust foredeep-type, fault-progradation fold-type, fault-bend fold-type, and composite-type growth strata are developed. Recognition of the growth structures and growth strata strongly demonstrates that the Yanshan belt is controlled by compressional structures that formed from frontal deflection in the Late Triassic-early Early Cretaceous. The analysis of "source-to-sink" systems suggests that the Late Triassic-early Early Jurassic nearly E-W-trending "source-sink" system is controlled by nearly N-S shortening and developed W-pointing sediment disposal systems; in the Early-Middle Jurassic and the Late Jurassic-early Early Cretaceous, however, NE-trending "source-to-sink" systems started to develop in basins under the control of NW-SE shortening and dispersed sediments, which originated from hanging wall blocks along basin margins, to the southwest. The changes in "source-to-sink" systems reflect that the Yanshanian movement in the study area started in the Middle Jurassic and perhaps earlier in the east; at least three fold-and-thrust events occurred in the Late Jurassic-early Early Cretaceous and formed basement-involved fold-and-thrust belts and small flexural basins. The formation and westward migration of the basement-involved fold-and-thrust belt–flexural basin systems may have been related to the "flat slab-type" advancing subduction of the Izanagi plate in the western Pacific. This basin-mountain system may be the distal part of a continental marginal arc-type orogenic belt formed by ocean-continent (B-type) subduction in the East Asia continental margin.

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