Geoscience Frontiers 14 (2023) 101527

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Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research Paper

From foredeep to orogenic wedge-top: The Cretaceous Songliao retroforeland basin, China

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ARTICLE INFO

Article history:
Received 14 October 2022
Revised 30 November 2022
Accepted 8 December 2022
Available online 15 December 2022
Handling Editor: M. Santosh

Keywords:
Retroforeland basin
Intracontinental basin
Seismic reflection and borehole data
Lithospheric plate dynamics
Songliao basin

ABSTRACT

Songliao Basin, the largest Mesozoic intracontinental nonmarine basin in eastern China, initiated during the latest Jurassic as a backarc extensional basin; rifting failed and thermal cooling controlled subsidence through the early Late Cretaceous. Integrating 2-D and 3D reflection seismic and borehole data with regional geological studies, we interpret sedimentary sequence and structural patterns of the Coniacian-Maastrichtian fill of Songliao Basin as defining a retroforeland basin system developed after 88 Ma (marked by the T11 unconformity in the basin), including (1) significant increase in the thickness of the Nenjiang Formation eastward towards orogenic highlands of the Zhangguangcai Range and the convergent continental margin; (2) a shift of detrital provenance in the basin from north to southeast; and (3) propagation of E-W shortened structures, increasing eastward in amplitude, frequency, and degree of inversion toward the orogen. During latest Cretaceous, foreland basin fill progressively deformed, as the foredeep evolved to a wedge-top tectonic setting, marked by the basin-wide T04 unconformity within the upper Nenjiang Formation at 81.6 Ma. Much of the basin was brought into the orogenic wedge and eroded by the end of the Cretaceous. Late Jurassic/Early Cretaceous backarc rifting of uncratonized basement comprised of accreted terranes likely facilitated and localized the foreland. Synrift normal faults reactivated and extensively inverted as thrust faults are prominent in the eastern 1/3 of the basin, whereas folds developed above detachments in shaley early post-rift strata dominate the western 2/3 of the basin. Songliao foreland development likely was driven by changing plate dynamics and collision along the Pacific margin after 88 Ma.

1. Introduction

The Songliao Basin is the largest non-marine intracontinental basin in eastern China. The NNE-SSW-trending basin is 750 km long, 330–370 km wide and occupies approximately 2.6×10^5 km^2 (Fig. 1). The 10,000 m-thick sedimentary fill of the largely subsurface basin is dominated by a nearly continuous Cretaceous section of nonmarine strata, capped by minor Cenozoic strata (Figs. 2 and 3). Correlation of basin stratigraphy (Figs. 2 and 3), gleaned from thousands of borehole logs and cores and extensive 2-D and 3-D seismic reflection data, as illustrated by informally named reflector numbers (e.g., T2, T02, etc.), is key to understanding basin history.

The basin initiated in latest Jurassic as an extensional basin which subsided and accumulated sediment until mid-Late Cretaceous in the backarc of the east Asian continental margin arc system (Figs. 1 and 2b). Best known for its vast petroleum resources of 136×10^8 t (Feng et al., 2010), for decades Songliao has been cited as a world-class example of a rift-sag basin nonmarine petroleum system (e.g., Demaison, 1984). Less discussed is the Late Cretaceous contractile tectonic event that significantly changed patterns of sedimentary filling, and eventually deformed and partly inverted the basin fill. In this paper, we argue that Songliao Basin evolved into a retroforeland basin system in the latter part of the Late Cretaceous, and transitioned from a foredeep depocenter, localized by earlier rifting of non-cratonized basement, to a foreland wedge-top basin. The basin lacks significant Cenozoic structural overprint and given the immense subsurface database, the Songliao Basin preserves an excellent record of the transition from extensional backarc basin to retroforeland basin to incorporation into the orogenic wedge.

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https://doi.org/10.1016/j.gsf.2022.101527

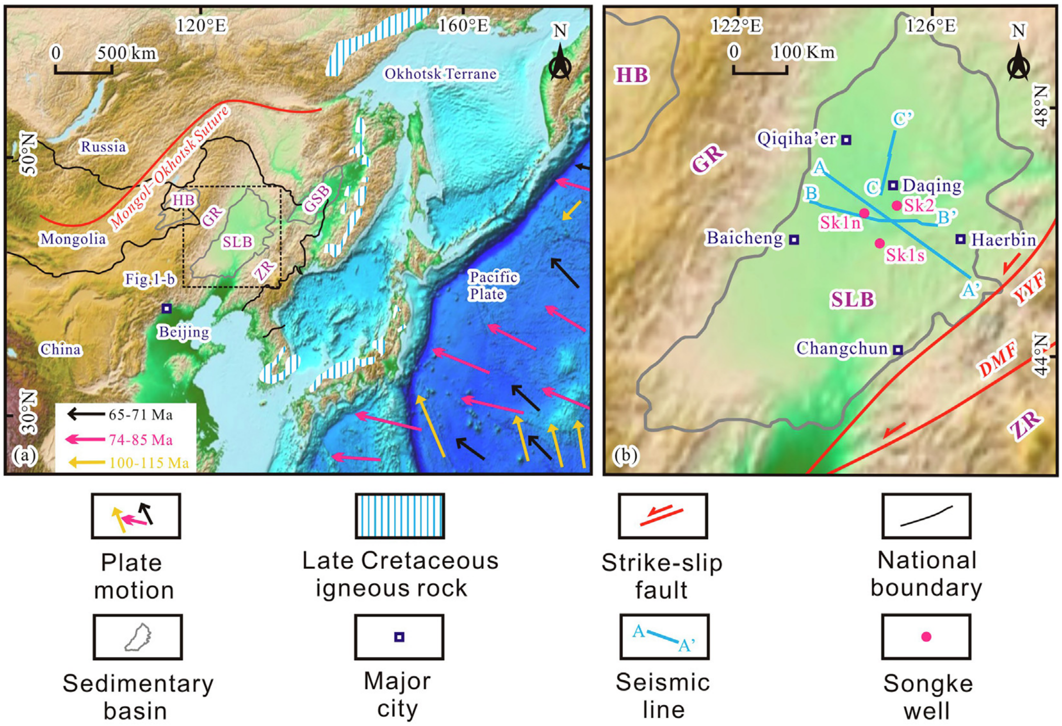

Fig. 1. (a) Simplified map of Cretaceous Pacific plate motion in later Cretaceous relative to position of the Eurasian plate (modified from Cox et al., 1989). Igneous rocks of the Jurassic-Cretaceous continental margin arc are shown in their current geographic positions, whereas the coeval subduction zone is shown in its approximate Cretaceous position (Zahirovic et al., 2014; Li et al., 2018, 2020). GR = Great Xing'an Range Mountains; GSB = Great Sanjiang Basin; HB = Hailar Basin; SLB = Songliao Basin; ZR = Zhangguangcai Range. (b) Location map of Songliao Basin. A-A' is Fig. 2A; B-B' is Fig. 5; C-C' is Fig. 7. Sk1s, Sk1n, Sk2 are locations of deep scientific boreholes (Wang et al., 2019).

2. Pre-foreland history as a backarc rift basin

The late Mesozoic Songliao Basin initiated as an extensional backarc basin, which passed through several stages of tectonic evolution including backarc rifting driven by slab rollback, followed by lithospheric thermal subsidence, then tectonic inversion late in its history (Li et al., 2012; Wang et al., 2015; Zhang et al., 2017a,b; Feng et al., 2018). The basement of the Songliao Basin and adjacent areas consists of Paleozoic meta-sedimentary rocks intruded by Paleozoic and early Mesozoic granitic plutons, reflecting tectonic blocks stitched together during accretionary construction of northern China (e.g., Li, 2006; Wang et al., 2016; Zhou et al., 2018). The history of Jurassic-Cretaceous arc plutonism east of Songliao Basin and the plate tectonics of the eastern Pacific Ocean basin establish the extensional backarc setting of Songliao (Fig. 1). The geology of the Berriasian-Santonian basin fill (colored red in Fig. 2a,b; Huoshiling-Shahzi-Yingcheng formations) is typical of terrestrial rift basins (cf. Lambiase, 1990), with the oldest fill consisting of alluvial and volcanic facies localized in small rift subbasins, overlain by more expansive and generally upward deepening lacustrine strata in the basin center (Fig. 3), which in turn shoal upward as subsidence slowed and was overtaken by sedimentation. The Moho lies at just 27 km (including its sedimentary fill) beneath the center of the basin (Wang et al., 2020a; Wang et al., 2020b), reflecting the magnitude of crustal thinning during the rift phase of basin history.

Tailing off of rift faulting and subsequent lithospheric cooling created accommodation in which the Denglouku-Quantou-Qingshankou fluvial-lacustrine formations accumulated in great thickness and lateral extent (colored pink in Figs. 2b and 3). For most of the Cretaceous, the basin center was occupied by a lake system that varied from profundal to ephemeral and was ringed by alluvial, fluvial and deltaic depositional systems, with longitudinal sediment fed from a northern fluvial-deltaic source dominating sediment supply (Fig. 4a) (Feng et al., 2010; Zhang et al., 2017b). The T11 unconformity (Fig. 2) beveled the Qingshankou Formation across the basin, hosts well-developed paleosol horizons (up to 15 m thick) indicative of extended exposure (Hou et al., 2009; Feng et al., 2010; Song et al., 2018), and reflects a reorganization of the basin heralding the transition to retroforeland basin, as discussed below.

3. Retroforeland evolution from foredeep to orogenic wedge and wedge-top

Numerous authors have noted that contractile inversion characterized Songliao Basin during Campanian and Maastrichtian (e.g., Wang et al., 2016), but the basin had not previously been recognized as evolving into a retroforeland basin. However, Zhang et al. (2017a) proposed that during the latest Cretaceous, a retroforeland system spanned across nearly the entirety of northeast China, with Songliao Basin as a foredeep, the Great Xing'an Range orogenic belt as a forebulge and the Hailar Basin as a back-bulge basin (Fig. 1b). We concur that the sedimentary sequence and structural patterns of the uppermost Cretaceous fill of the Songliao Basin are consistent with a foreland foredeep but propose that the Songliao foredeep evolved over time into a foreland wedge-top basin (cf. DeCelles and Giles, 1996).

In discussing retroarc foreland basins, Dickinson (1976) recognized (1) expansive foreland basins lacking fault involvement of the basement and (2) broken foreland basins, which occur as much smaller basins partitioned by topographically-expressed basement-block uplifts. Recently, Horton et al. (2022) tabulated the differences between what they termed broken foreland basins and contiguous (i.e., unbroken) foreland basins. How Songliao Basin fits in their classification is an interesting question. The

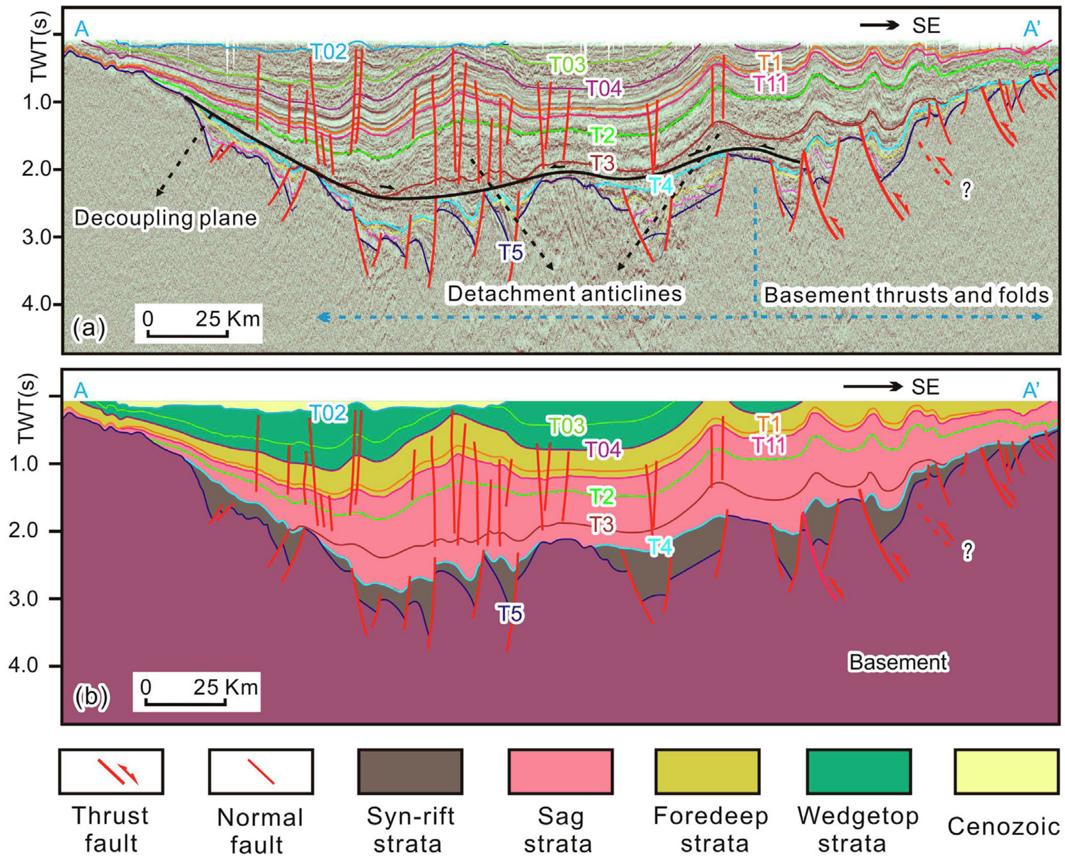

Fig. 2. (a) Regional seismic profile across Songliao Basin. Line is A-A' in Fig. 1b. Seismic correlation horizons labeled T1, T2, etc., correlate with the stratigraphic column in Fig. 3. Normal faults shown in red; double-headed arrows indicate rift normal faults reactivated as thrusts. Proposed black detachment fault(s) shown schematically. Line location is shown in Fig. 1b. Modified from Feng et al. (2010). (b) Major tectonostratigraphic elements of the Songliao Basin: undivided basement (purple); syn-rift strata (brown); thermal cooling sag strata (pink); retroforeland foredeep transition strata (yellow), retroforeland wedgetop (green), and post-tectonic strata (light yellow). Modified from Feng et al. (2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Zhuangguangcai Range is a basement uplift that separates the Songliao Basin from the Great Sanjiang Basin (Fig. 1), which Zhang et al. (2017a) identified as the easternmost element of the foreland system and where shortening deformation began earlier than in Songliao. In this view, Songliao and Great Sangjiang basins might be viewed as comprising a broken foreland system. However, at 750 km long and 330–370 km wide, the scale of the Songliao Basin falls in the typical range for contiguous foreland basins (Horton et al., 2022). Other features of the Songliao Basin (e.g., fill thickness, percent shortening, fault and fold geometries, involvement of basement) most closely resemble contiguous foreland basins, as summarized in table 1 of Horton et al. (2022). Thus, we conclude that the Songliao Basin is best characterized as a contiguous foreland basin in the scheme of Horton et al. (2022).

The basin's structural hinterland to the east, including the Zhangguangcai Range, is an amalgam of older accreted terranes (Zhang et al., 2017a,b). Reflection seismic profiling and geologic mapping of small subbasins in eastern Heilongjiang Province and adjacent to the Zhangguangcai Range reveal extensive folding and thrust faulting that places crystalline basement over Upper Cretaceous strata covered by undeformed Paleogene strata (fig. 6 of Zhang et al., 2017b). Shortening created orogenic highlands in the Songliao hinterland, based on thermochronologically determined exhumation of nearly 5 km in the Zhangguangcai Range (Zhou et al., 2022), which peaked at 90–88 Ma (Song et al., 2014). Coeval Late Cretaceous left-lateral strike-slip along several important continental margin-parallel hinterland faults (including the Yilan-Yitong and Dunhua-Mishan faults as the northerly extensions of the Tanlu fault) suggests a transpressional hinterland (e.g., Wei et al, 2010; Yang, 2013; Xu et al., 2017).

As noted above, the T11 unconformity signals an important point in the basin's evolution. Song et al. (2014, 2015, 2018) have extensively documented the nature of the T11 unconformity, noting that the unconformity reflects uplift and erosion over most of the basin except in its deepest part. Angularity of the unconformity is expressed on seismic reflection data across three large, gentle anticlines arrayed across the northern basin. Anticlines near the eastern and western basin margins are similarly eroded at their crests (Song et al., 2015). Song et al. (2014) bracketed the duration of the T11 unconformity as no older than 88 ± 0.3 Ma based on $^{40}Ar/^{39}Ar$ dating of feldspar from strata below the unconformity and no younger than ca. 86.2 Ma for strata above the unconformity based on downward linear interpolation from zircon ages from ashes above the unconformity. Noting contemporaneity of T11 with unconformities in other basins in eastern Asia, and plate interactions inferred from the Pacific Ocean basin, Song et al. (2014, 2018) concluded that Pacific plate re-organization was the far-field driver for the deformation recorded in T11, as the eastern Asian convergent margin changed from Western Pacific-type to Andean-type.

Following the Qingshankou unconformity (T11), Yaojia Formation deposition re-commenced and the Songliao lake rapidly re-expanded to an area of 2.0×10^5 km^2. The T07 reflector (early Campanian) corresponds to the largest flooding surface of Songliao Basin (Fig. 4b), so is used as a horizon for flattening seismic reflection data and correlating borehole logs (Fig. 5). The second and

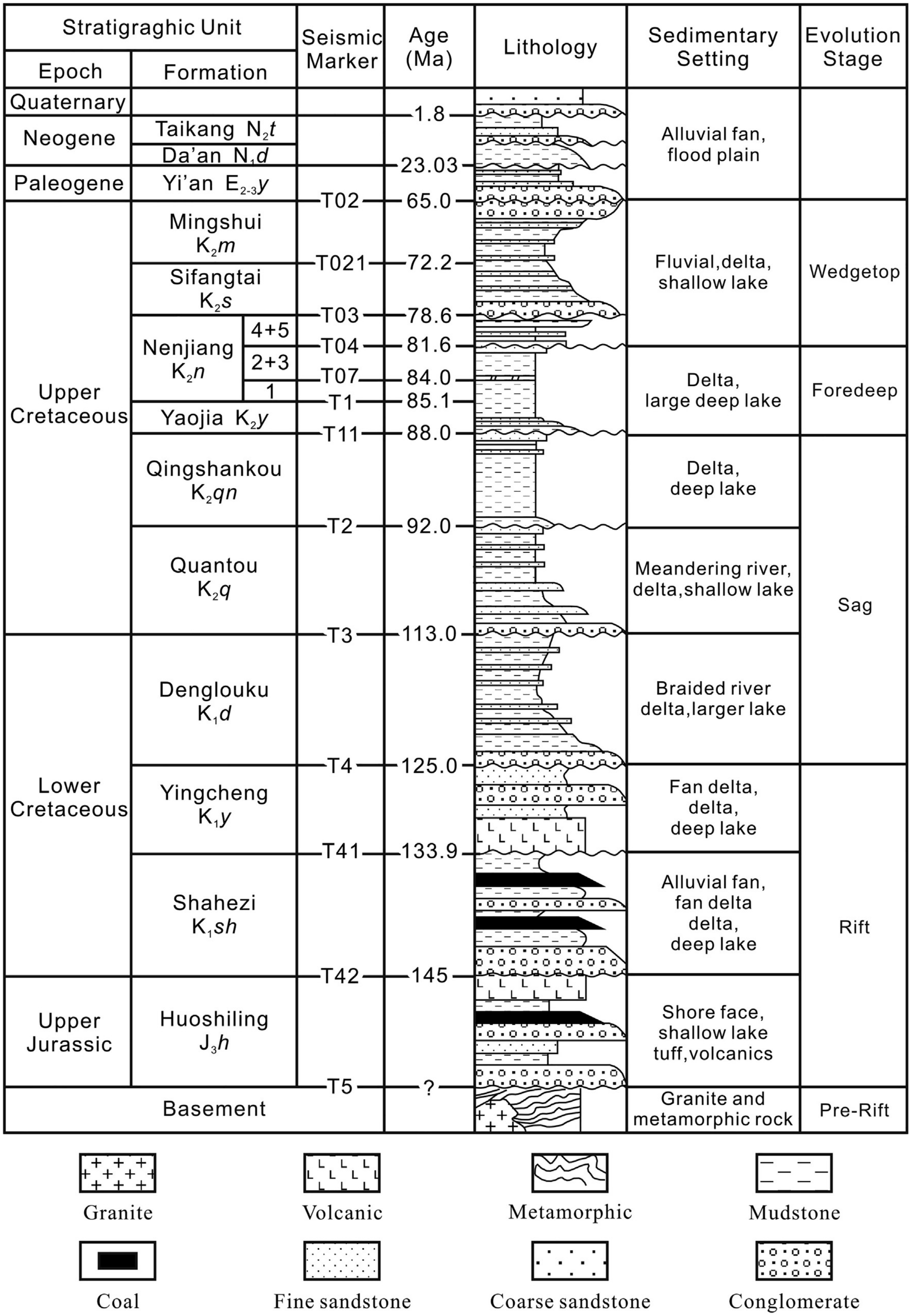

Fig. 3. Stratigraphy of the Songliao Basin showing formation names and ages, lithologies, depositional and tectonic settings. Modified from Feng et al. (2010). T5-top of basement; T4-top of rift megasequence; T11-top of sag megasequence; T04 -top of foredeep strata; T02-top of wedge-top and the entire retroforeland megasequence (top of Cretaceous). We note that recent work based on astronomical tuning proposes revision of Cretaceous formation boundaries in Songliao Basin (Wang et al, 2022; Wu et al., 2022). Specifically relevant to this paper are the Qingshankou/Yaojia (T11) at 86.303 ± 0.220 Ma and Yaojia/Nenjiang (T1) at 85.212 ± 0.220 formational boundaries; In this paper, we nevertheless elect to retain formation ages widely accepted over the past decade, based on conversations with a number of Songliao Basin experts.

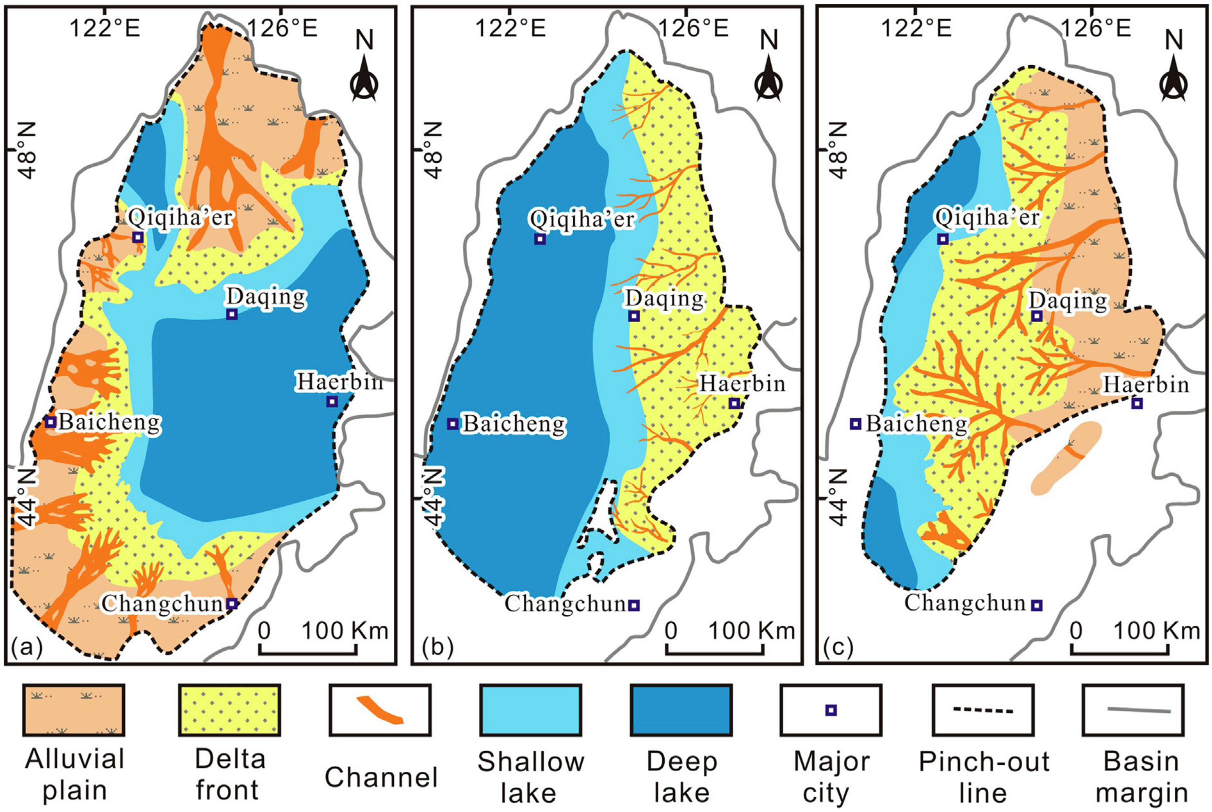

Fig. 4. Depositional facies maps of (a) the 1st Member of the Qingshankou Formation (K_2qn); (b) 2nd-3rd Member of the Nenjiang Formation; (c) 4th Member of the Nenjiang Formation (K_2n). Modified from Feng et al. (2010).

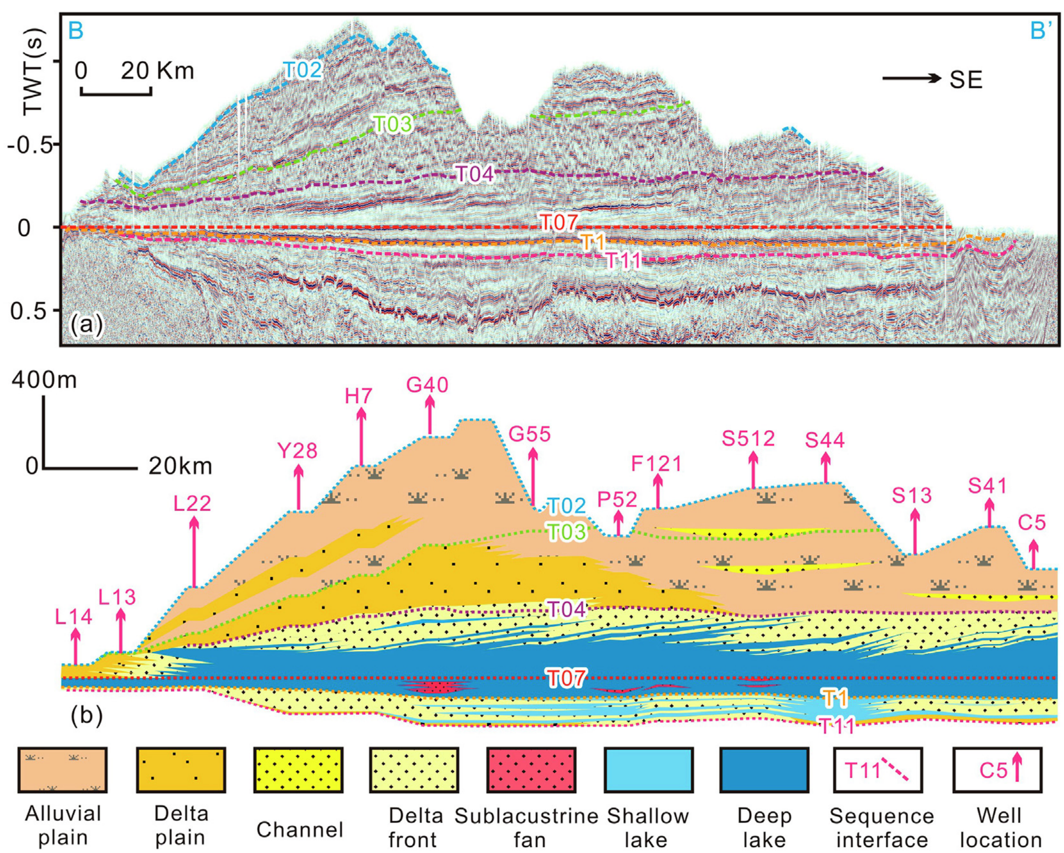

Fig. 5. (a) Seismic profile flattened on reflector T07. Seismic line is B-B′ in Fig. 1; (b) Facies interpretation profile of line B-B′ calibrated by wells. See Fig. 1 for line location and Fig. 3 for stratigraphic position of reflectors. T11 = unconformity atop Qingshankou Formation; T1 = top Yaojia Formation; T07 = top first member, Nenjiang Formation; T04 = top second and third members, Nenjiang Formation; T03 = top Nenjiang Formation; T02 = top of Cretaceous. Modified from Feng et al. (2010).

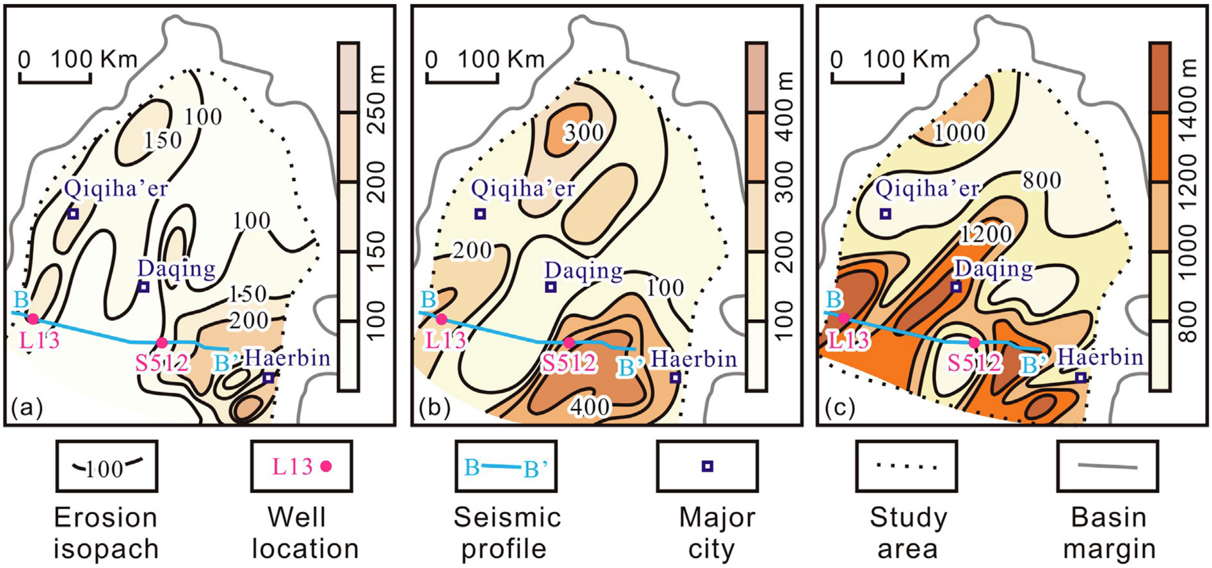

Fig. 6. Maps of the northern half of Songliao Basin showing magnitude of erosion in meters below unconformity surfaces important in evolution of the Songliao foreland, (a) T11, (b) T04, (c) T02. The maps reveal increasing magnitude of erosion as the basin evolved into the wedgetop after T04 during the Late Cretaceous. Erosional loss at each unconformity is based on discontinuities in 200 sonic well logs, as well as vitrinite and apatite fission track analysis from 36 wells. Figs. 2 and 3 illustrate the stratigraphic positions of the unconformities. Adapted from Ren et al. (2011).

third members of the Nenjiang Formation include voluminous deltaic deposits of the foredeep which were derived from beyond the eastern margin of the basin (Figs. 3 and 4c). Reflectors above T07 downlap from east to west on seismic and borehole correlation sections, evincing sedimentary progradation from an eastern sediment source area into the underfilled foredeep which we estimate housed water depths of 300–400 m (Fig. 5). Although the lower part of the Nenjiang Formation is a transgressive lacustrine sequence, the balance of the formation consists of several westward prograding upward-coarsening sequences. Erosion removed significant portions of the Nenjiang in the eastern part of basin (Figs. 2 and 5) as it entered the wedge-top element of the foreland basin system, described below, but preserved sedimentary thickness markedly increases from the western margin of the basin eastward into the foredeep adjacent to the orogenic hinterland in the Zhangguangcai Range (Fig. 5). Above the T04 unconformity, lacustrine facies along the section line in Fig. 5 are supplanted by delta plain and alluvial strata, demonstrating that the entirety of the Nenjiang Formation constitutes a grand upward shoaling and coarsening sequence, as is typical of foreland basins (DeCelles, 2012).

Pronounced westward sedimentary progradation during deposition of Nenjiang Formation signals a profound change in basin paleogeography. During the height of syn- to post-rift subsidence, coarse sediment entered the basin from fringing alluvial-fluvial sources ringing the basin, but especially from a major deltaic system fed longitudinally southward from the northern basin margin (Fig. 4a) (Feng et al., 2010). Seismic and borehole sections (Figs. 2 and 5) and paleogeographic reconstructions of the basin (Fig. 4) during Campanian (Nenjiang Fm.) (Feng et al., 2010) reveal a major change in dominant sediment supply to the basin, suggesting that the Zhangguangcai Range to the east served as a main source of sediments for the basin, as noted by Zhang et al. (2014) and Zhang et al. (2017a,b). This interpretation is supported by provenance studies which indicate that detrital zircon in the upper Nenjiang Formation was mainly derived from the Zhangguangcai Range and other areas SE of the basin, but perhaps also as far away as 300–400 km near the North Korean border and adjacent Russia (Zhao et al., 2013; Song et al., 2014; Zhang et al., 2017b). The rapid (>300 km in 5 Myr at the latitude of Harbin, China) westward advance of alluvial deposystems markedly pushed the locus of lacustrine deposition away from the basin center (compare Fig. 4b and c).

Songliao Basin became structurally asymmetric during early Campanian as it entered its retroforeland phase. Basin fill is extensively folded, reflecting NW-SE-directed shortening (Fig. 2). Folds generally verge to the west. In the eastern 1/3 of the basin, underlying basement-cutting rift faults were re-activated as reverse faults, whereas in the western 2/3 of the basin basement is much less involved (Fig. 2), although data from the recent Songke II deep borehole near the basin center (Fig. 1b) confirms that basement of Songliao Basin was shortened east-to-west (Wang et al., 2020a,b).

Recent work has recognized numerous thrust faults in the basin, many as re-activated rift faults (faults with double arrowheads in Fig. 2a) (Shan et al., 2013; Song et al., 2014, 2018; Yu et al., 2015; Zhao et al., 2018). These are much more numerous near the eastern basin margin (Fig. 2a), although Song (1997) noted that most NE-SW trending rift faults in the basin were later re-activated as reverse faults. Ideally, the faultfold pairs should young in age of formation westward away from the convergent margin; unfortunately, folds in the eastern part of the Songliao Basin are so deeply eroded and poorly studied that determining the relative ages and deformational younging trends is impossible at present.

Suo et al. (2020) expanded on the theme of contractile basin inversion in eastern China, noting that Late Cretaceous inversion in Songliao Basin ranged from mild in the western basin to total inversion in the southeast, where total inversion entails the total reversal of normal fault displacements by reverse-slip on the former normal faults. They noted that the magnitude and complexity of inversion decreases westward across the basin away from the orogenic hinterland of the Zhangguangcai Range. They concluded (their fig. 1) that NW-SE shortening across the basin decreased from about 40% in the eastern basin to 4% near the western basin margin, as is visually evident in our Fig. 2.

We suggest that folding and shortening of the post-rift basin-fill in the western 2/3 of the basin was accomplished by detachment in the shaley portions of the rift and thermal sag section (shown schematically in Fig. 2) (e.g., Song et al., 2018). This accounts for the high amplitude folds developed in the foredeep fill, in contrast to the limited structural involvement of basement and *syn*-rift strata/structures that lie below the proposed detachment(s), and results in stratal crowding and thickening in the cores of the anticlines just above the detachment(s).

Because southeastern edge of the basin was uplifted, inverted and extensively eroded by the end of the Cretaceous, the Yaojia Formation and younger strata are poorly preserved in that area (Figs. 2 and 5). Hence, the original thickness of foreland strata is unknown. Zhang et al. (2017b) factored in only 221 m of missing Cretaceous foredeep strata in their subsidence analysis from the Songke wells (their fig. 6), but by projecting the preserved T02 horizon (K-T boundary) eastward to the basin boundary and measuring against the T11 datum (Fig. 5), we estimate that about 3 km of foredeep and wedge-top strata originally existed in the eastern part of the basin.

As summarized by Suo et al. (2020), various authors have characterized the timing of inversion in the Songliao Basin as ranging from 88 to 65 Ma (Song et al., 2014; Song et al., 2015), to 84–65 Ma (Zhang et al., 2017a,b), or 82–65 Ma (Zhao et al., 2013), or 79.1–64 Ma (Wang et al., 2016). The oldest proposed date recognizes the T11 unconformity as the lower age limit for initiation of inversion. However, in this paper we emphasize the T04 unconformity as marking an important turning point in the involvement of basin fill in developing shortening structures. The T04 unconformity is basin-wide in its extent, and stratigraphic and structural relationships provide evidence that foredeep strata deposited prior to the T04 unconformity (81.6 Ma) became involved in the propagating foreland structural wedge after 81.6 Ma. T04 clearly marks the initial growth of the basin's major folds, based on lateral uniformity of stratal thickness below T04 compared to lateral thinning of strata onto the folds above T04 (e.g., Fig. 7).

We contend that post-T04 strata in the Songliao Basin comprise a foreland wedge-top depositional sequence. DeCelles and Giles (1996) described the wedge-top depozone as "the mass of sediment that accumulates on top of the frontal part of the orogenic wedge", which are "characterized by extreme coarseness, numerous tectonic unconformities and progressive deformation." Post-T04 strata fit that description. Conglomerate, absent in the pre-T04 foredeep fill, occurs within the coarser grained section above T04 (Fig. 3). Progressive deformation of the foredeep and evolution to a wedge-top basin during the Late Cretaceous is evident in the growth history of thrust-cored folds in the basin, discussed below.

Based on previously unpublished estimates of erosion across unconformities (Ren et al., 2011) observed from 200 borehole sonic logs, vitrinite reflection data, and apatite fission track data from 36 wells distributed across the northern half of the basin (Fig. 6), we infer that: (1) the T11 unconformity records initial rumpling of pre-T04 strata across the basin and modest erosion of folded areas, especially in the southeast adjacent to the orogen (Fig. 6a); (2) the T04 unconformity records the onset of wedge-top deposition with the initial growth of the Daqing anticline (Fig. 2a and 7), the dominant fold in the basin, and increasing uplift and erosion in excess of 400 m in the southeast and elsewhere (Fig. 6b), and (3) by the end of the Cretaceous (T02), erosion of the crests of anticlines in excess of 1400 m occurred on major structures across the entire basin (Fig. 6c). Stratal thinning onto the growing Daqing anticline from T04 to the end of the Cretaceous is evident on reflection seismic data (Fig. 7). While subaerial expression and erosion of the anticline is not evident on the seismic line in Fig. 7, erosion of the crest of Daqing up to 200 m at T04 is supported by Ren et al.'s (2011) analysis (Fig. 6b).

Pronounced structural growth of the basin's folds, evidenced by growth strata flanking folds, continued from T04 to T02. Additionally, as noted above, there is a marked contrast in depositional setting and average grain size above and below the T04 unconformity from principally fine-grained lacustrine and peri-lacustrine strata below to principally coarser grained fluvial and alluvial strata

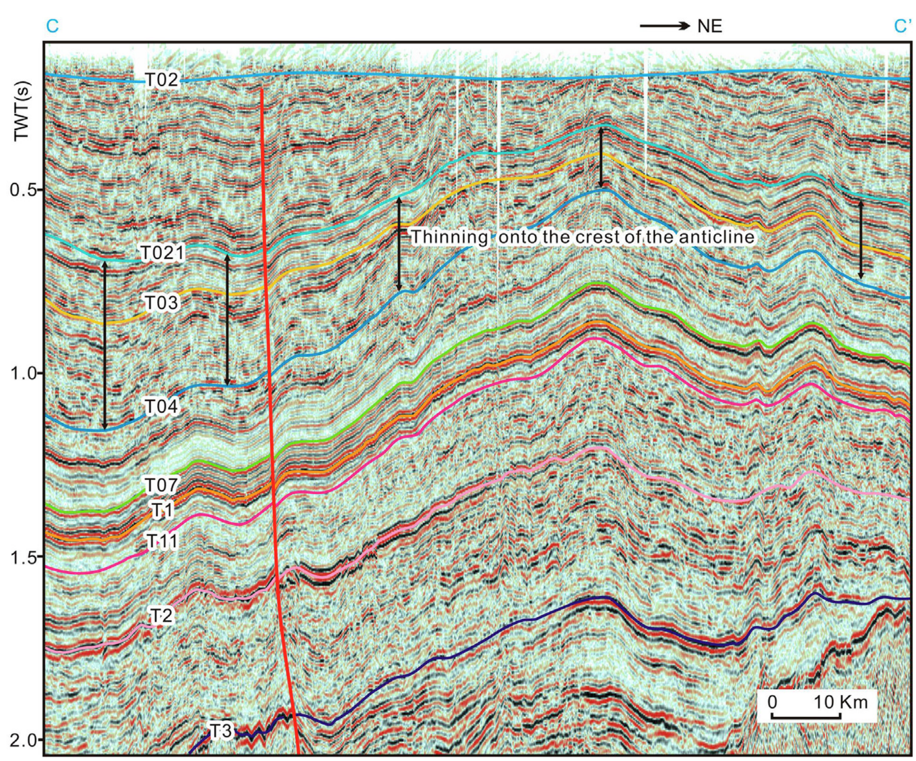

Fig. 7. Seismic line illustrating pronounced structural growth of Daqing anticline between T04 (dark blue) (81.6 Ma) and the base of the Mingshui Formation (T021, light blue) horizons, in contrast to pre-T04 strata which are much more uniform in thickness laterally. Stratal thinning onto the anticline is highlighted by the contrasting lengths of vertical black lines between the two reflector horizons. Note that the line, located on Fig. 1b, is highly oblique to the axis of Daqing anticline.

above, as is evident in the contrast in reflector continuity above and below T04 (Fig. 7). Song et al. (2018) presented the T03 unconformity, which they dated as ca. 75–79 Ma, as marking an important shortening pulse in the basin. In support of this notion, they noted stratal truncations beneath the T03 surface. We agree that stratal thinning and onlap occur above T03 as is evident on Fig. 7, but T03 is most important in the central and eastern part of the basin, whereas T04 is basin-wide in its extent.

The Sifangtai and Mingshui formations include conglomerate units (Fig. 3), consistent with a wedge-top setting. Isopach maps of the Sifangtai and Mingshui formations (Feng et al., 2010) reveal that their depositional footprint was vastly reduced compared to pre-T04 formations, and that areas of sediment accumulation were wrapped around growing anticlines, whose crests were in some instances were exposed and eroded (Figs. 6 and 7). Cretaceous stratal packages younger than T04 thin onto anticlines through the end of the Cretaceous, and unconformities such at T03 hint at episodicity in fold growth during the latest Cretaceous, although Horton (2022) recently noted that caution is appropriate in attributing tectonic drivers to unconformities on the flanks of foreland folds without additional information. In any event, the basin evolved rapidly from foredeep to wedge-top during the latest Cretaceous (81.6–65 Ma).

In sum, the Late Cretaceous Songliao Basin has many attributes common to other retroforeland basin systems (e.g., DeCelles and Giles, 1996; DeCelles, 2012): it features a cross-sectionally asymmetric fill, which thickens toward the continental margin arc and coarsens upward; syn-depositional contractile structures which become more numerous toward the arc; and basin fill uplifted and deeply eroded toward the deformed basin margin. Retroforeland basins typically display a spatio-temporal evolution from backbulge to forebulge to foredeep to wedgetop depozones (DeCelles and Giles, 1996), and the Songliao Basin has readily identifiable foredeep and wedge-top elements, as we have noted. The T11 unconformity with its associated low-angle beveling (Fig. 5) and paleosol deposits may represent an elastic flexural response to initial hinterland load. The original western limit of Songliao Basin is lost to erosion, because deep lake deposits of the 1st and 2nd Member of the Nenjiang Formation crop out at the current western edge of the basin (Fig. 4a), indicating that the foredeep once extended to this region (cf. Suo et al., 2020). Nevertheless, the western slope of the basin possibly preserves the basinward slope of a forebulge in onlap and thinning of the foreland strata (Fig. 2a).

4. Orogenic drivers for foreland evolution

The driver for contractile inversion of Songliao, hence foreland development and regional Cretaceous shortening, has been the subject of a number of recent papers. These focus on plate relations in the Pacific Ocean basin and its western margin and generally fit into one of two models. In one view, the sub-Yaojia unconformity (T11) may signal the onset of flexural uplift in the basin at onset of thrust belt loading in the Zhangguangcai Range, contemporaneous with reorganization of Pacific Ocean plate motion around 88 Ma following subduction of the Izanagi Plate beneath Eurasia and initial subduction of the Kula Plate; changes in subduction direction from oblique to orthogonal; and/or changes in subduction angle from high to low (Kravchinsky et al., 2002; Otofuji et al., 2003; Stepashko, 2006; Li et al., 2012, 2020; Zhang et al., 2015, 2017a, b; Wang et al., 2016; Zhu et al., 2020; Zhao et al., 2022) (Fig. 1).

Alternatively, oblique collision of terranes outboard of the Asian convergent margin has been suggested as a driver for Late Cretaceous contractile deformation in northeastern China and along the Pacific margin of Russia (e.g., Yang, 2013; Zhang et al., 2017a, b; Suo et al., 2020). Updating Yang (2013) and Zhang et al. (2017a, b), Suo et al. (2020) reconstructed the Okhotomorsk terrane as initially collided with the southeastern China margin around 115–110 Ma and subsequently slid transcurrently northward along the margin until from 100 Ma to 89 Ma, triggering contractile deformation in northeastern China. Perhaps consistent with this scenario, a major unconformity occurs in the Great Sanjiang Basin (GSB) outboard of the Songliao Basin after 100 Ma (Zhang et al., 2017b), whereas the T11 unconformity reflecting onset of foreland development in the Songliao Basin dates from ca. 88 Ma, a 12 Ma lag continentward, as is typical in foreland systems (e.g., DeCelles and Giles, 1996; DeCelles, 2012). Yang (2013) and Zhang et al. (2017a, b) proposed terminal collision of the Okhotomorsk terrane with the Sakhalin-Siberian margin of Russia at 70–65 Ma, forcing continued contractile deformation in Songliao Basin.

5. Conclusions

From 88 Ma to 65 Ma, Songliao Basin is best characterized as a retroforeland basin, based on its position relative to the continental margin arc; pronounced SE-NW asymmetry in sedimentary fill patterns and shortening structures; and proximal syn-shortening strata removed by erosion. The foreland basin was built atop a Late Jurassic-early Late Cretaceous rift-sag basin after ca. 88 Ma, signaled by the basin-wide T11 unconformity, which we take as the initial flexural response to orogenic compressional loading. With increasing prograde shortening, the foreland foredeep evolved to a wedgetop basin after about 81.6 Ma, marked by the T04 unconformity and the growth of major anticlines in the basin. The foreland phase ended after the Cretaceous-Tertiary boundary, as demonstrated by modestly deformed Paleogene strata which overlie the Upper Cretaceous strata with angularity.

The character of the Songliao foreland basin was shaped by the structure of its uncratonized accreted terrane basement and the distribution of crustal thinning and rifted basement structures developed just a few tens of millions of years earlier during the basin's backarc extensional phase, with many rift normal faults reactivated as shortening structures during foreland evolution. Over its relatively brief lifespan as a foreland basin system, Songliao Basin evolved from foredeep to wedge-top as it became part of the orogenic wedge. The retroforeland phase of Songliao Basin history perhaps was initiated by the combined agencies of a change in Pacific basin plate trajectories and collision of an outboard terrane.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We gratefully acknowledge Peter DeCelles and Shufeng Yang for constructive reviews of an early version of this paper and valuable reviews of the submitted manuscript by Brian Horton and an anonymous reviewer and Geoscience Frontiers Editor M. Santosh. We thank Gaokui Wu, Li Dong, Shun Zhang, Shumin Chen and Zihui Feng for assistance in manuscript preparation. We thank Daqing Oilfield Ltd for permission to publish Figs. 6 and 7. Zhiqiang Feng acknowledges support from the Innovative Research Group Project of the National Natural Science Foundation of China, Award Number 41790450.

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