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The Subsurface structure and stratigraphic architecture of rift-related units
in the Lishu Depression of the Songliao Basin, China

Hongyu Wang\textsuperscript{1,2}   Tailiang Fan\textsuperscript{1}   Yue Wu\textsuperscript{1}

1. China University of Geosciences, Beijing, 100083;
2.National Experimental Teaching Center of Geological Resources Exploration, Beijing, 100083;

Wang Hongyu, E-mail: wanghy@cugb.edu.cn, T:+861082323082
Fan Tailiang, E-mail: fantl@cugb.edu.cn, T: +861082321559
Yue Wu, E-mail: wuyue0906@gmail.com
Abstract: This contribution reports the basin configuration feature, stratigraphy and sedimentary architecture of the Lishu Depression in the Songliao Basin, China. The activity rate, distribution and style of local faulting demonstrate the timing and extent of regional rifting. Distinct episodes of compressional tectonic activity caused uplift and exposure of strata evident as the traditional syn- and post-rift stages of basin evolution. These episodes led to the sequential denudation of the Upper Jurassic Huoshiling Formation, Lower Cretaceous Yingcheng and Denglouku Formations, and corresponding regional unconformities. Acting in tandem with regional compression, activity along the major boundary faults influenced the evolving basin configuration, as well as seismic sequences and sedimentary patterns. Seismic, well log and drill core data described here show subdivision sections of the Lishu Depression strata according to discrete phases of the traditional syn-rift stage of deposition. We refer to these sub-stages as the initial rifting, the intensive rifting and the recession phases. The basin configuration shifted from a graben / half-graben configuration during the initial rifting phase, to a dustpan-shaped half-graben pattern during the subsequent phase of intensive rifting, and finally into a gentle sedimentary basin during the final recession phase. The early seismic sequence divides into a lowstand systems tract (LST), transgressive systems tract (TST) and highstand systems tract (HST). Evidence of the LST within the seismic sequence becomes less apparent with the intensive rifting phase, while the HST occupied an increasing proportion of the section. The shallow water depositional fill formed during the final recession phase consists only of TST and HST components. Depositional environment then shifts from alluvial fan and shallow lacustrine systems to fan delta, braided delta – lake, and finally to a braided fluvial setting. The vertical stacking pattern shifts from retrogradational, to progradational, to aggradational. Identification of sub-structural units and interpretation of their genetic relationships helps clarify basin evolution, and thus serves larger-scale continental basin analysis.

Keywords: Songliao basin, basin configuration, rift-related unit, stratigraphic architecture, the systems tract, sediment stacking pattern.
Introduction

Research concerning the tectonostratigraphic evolution of rift basins typically divides basin development processes into pre-, syn- and post-rift stages (e.g. Bosworth, 1985; Cohen, 1990; Bois, 1993; Nøttvedt et al., 1995; Cloetingh et al., 1997; Gawthorpe & Leeder, 2000; Martins-Neto, 2000; Arabi et al., 2003; Alves et al., 2003; Garcia et al., 2008; Baudon et al., 2009). A single model is typically used to describe the unique tectonic and sedimentary conditions operating during a given stage, even though each stage may consist of several phases of activity. Previous studies addressing the stratigraphic and sedimentary architecture of rift basins have focused on lithofacies properties and sedimentary facies stacking patterns (Rosendahl, 1987; Lambiase, 1990; Frostick & Reid, 1990; Papatheodorou & Fdrenttnos, 1993; Nøttvedt et al., 1995; Ravnås et al., 1997; Leeder, 2011) as well as the effects of tectonism, sea-level change and sediment supply rate on sedimentary architecture (Prosser, 1993; Howell & Flint, 1994; Gawthorpe et al., 1997; Ter Voorde et al., 1997; Ravnås & Steel, 1998; Gupta et al., 1999; Gawthorpe & Leeder, 2000; Yong et al., 2002; Gawthorpe et al., 2003). Few studies have addressed stratal geometry and sedimentary sequence stacking pattern that differentiate each phase of basin rifting. Systematic description of relationships between basin configuration, sequence stratigraphy and other sedimentary characteristics suggest
that classic rift stages can be further subdivided into discrete phases according to unique sedimentary conditions operating during these phases.

This paper describes the subsurface structure and stratigraphic architecture of strata formed during rifting of the Lishu Depression in the Songliao Basin (Fig. 1). The study used 3-D seismic imaging and data from numerous wells in the study area. We interpret fault activity, basin configuration, seismic stratigraphy and sedimentary features of traditional syn- and post-rift stages, focusing particularly on unique phases of the syn-rift stage. In Section 3, we describe major faults to introduce the overall basin structure. Using this structural background and other information from seismic images, Section 4 interprets the basin’s syn- and post-rift evolution. Section 5 describes detailed characteristics of the three discrete phases of the syn-rift stage, referred to as the rift initiation phase, the intensive rifting phase and the rift recession phase. This study provides a critical and high-resolution tectonostratigraphic perspective on the evolution of a continental rift basin.

1 Geologic setting

Located in northeast China, the Songliao Basin is a relatively large continental sedimentary basin that formed from Late Jurassic to Neogene time. The basin is divided into six structural units: the northern plunge, the central downwarp, the northeastern uplift, the southeastern uplift, the southwestern uplift and the western slope (Yu et al., 2001; Ren et al., 2002; Ge et al., 2010; Feng et al., 2010) (Fig. 1). The Lishu Depression, located in
the area referred to as the southeastern uplift, abuts the Yang uplift to the north, the Shenyang uplift to the west, and Gongzhuling uplift to the southeast. The Lishu Depression includes an independent hydrocarbon generation center covering an area of approximately 2350 km$^2$. According to its present structural layout, the depression divides into five secondary structural areas: the Sangshutai sag, the Central uplift, the Qikeshu syncline, the Northern slope and the Southeastern slope (Fig. 1) (Yu et al., 2000).

The Songliao Basin experienced three major tectonic episodes that differentiated its sediments into rift, depression and final structural inversion sequences (Fig. 2). Sediments in the Lishu Depression reflect only rift and subsidence-related deposition (Figs. 2, 3), as the depression does not include overlying structural inversion sequences associated with the larger Songliao Basin (Song, 1997; Yu et al., 2000; Zhao, 2008). The rift-related sequence in Lishu Depression, described in detail below, consists of the Upper Jurassic Huoshiling Formation (J$_2$h) overlain by the Lower Cretaceous Shahezi (K$_1$sh), Yingcheng (K$_1$y) and Denglouku Formations (K$_1$d). The depression-related sequence in Lishu Depression consists of the Lower Cretaceous Quantou Formation (K$_1$q) overlain by the Upper Cretaceous Qingshankou (K$_2$qn), Yaojia (K$_2$y) and Nenjiang Formations (K$_2$n). The Sifangtai (K$_2$s) and Mingshui Formations (K$_2$m) of the Upper Cretaceous, Paleogene and Neogene are missing in Lishu Depression.

The Lishu Depression shows the distributional and structural patterns of a typical rift basin. The rift strata are distinguished by faulting in the western part of the depression and thinning to the east (described below) (Fig.3). The overlap thinning extends
southeastward from the Sangshutai sag. Most rift strata near the Yang uplift have been exposed and eroded (Yu, et al., 2000; Huang & Shen, 2007; Zhang & Ren, 2008; Zhao, 2008). Overlying post-rift (subsidence) strata are extensively distributed throughout the Lishu Depression (Fig.3). Their lateral distribution exceeds that of the earlier rift-related units and stratigraphically connects to coeval strata in the Songliao Basin. The lateral thickness of the strata does not vary significantly in central parts of either the Changling or Lishu Depression (Fig.3).

2 Data

Over the last 40 years, 2-D and 3-D seismic surveys have been specifically conducted to investigate the deep structure and stratigraphy of the Lishu Depression. The dataset now includes over 6000 km of 2-D seismic lines covering the entire Lishu Depression with a 2.0×4.0 km cell grid. The 3-D seismic data coverage area has reached 1500 km$^2$ with an inline and cross-line spacing of 25 m, covering most of the region (Fig. 1). By 2011, around 190 exploratory wells had been drilled throughout the depression. Most of these wells yielded gamma-ray, sonic, spontaneous potential, resistivity and density log data. Cores or sidewall materials have been recovered from about 50 wells within rift-related strata.

In addition to the 3-D seismic data covering 1500 km$^2$ of the study area, this study also refers to data from 2000 km of 2-D seismic lines (grid in Fig. 1) as well as well log and drill core data. Calibrated sonic and density logs helped verify sequences interpreted
from seismic data. Stratigraphic features were interpreted to correlate with the lithostratigraphic framework established for the Songliao Basin by Yu et al. (2000), Ren (2002), Ge et al. (2010) and Feng et al. (2010). Gamma ray and spontaneous potential logs and core material provided specific constraints on lithofacies and seismic facies.

3 Regional fault features

Regional seismic profiles show that the Sangshutai Fault is a major structural feature that binds the Lishu Depression along its southwestern margin (Fig. 1) and extends to depth, affecting the lowermost units of the section (Figs. 3, 4). This normal fault affects Mesozoic basement units in the deepest part of the basin and extends upwards into the Cretaceous Qingshankou Formation. The distribution of fault indicates that offset began in the latest Jurassic and continued into the early Albian (Fig. 5-A). Fault activity peaked during the Barremian.

Stratigraphic deformation and contrasts in contacts on opposing sides of the fault indicate that regional structures such as the Pijia, Xiaokuan, Qinjiatun, Qindong and Jinshan Faults developed during discrete periods of tectonic activity, in spite of their aerial extent (Fig. 1). The Pijia, Xiaokuan and Qinjiatun Faults exhibit evidence of left-lateral strike-slip movement (Yu, et al., 2000; Zhang & Ren, 2008). These structures formed at the end of the Barremian and were reactivated at the end of the Aptian. The Qindong and Jing-gang Faults only affect the Upper Jurassic Huoshiling Formation.
(Fig.5-B, C). These small structures thus exerted only limited influence on sediment distribution and stratigraphy of the basin.

4 Basin evolution

We interpret Lishu Depression structure and sedimentary features in terms of Late Jurassic to Neogene rifting, post-rifting thermal subsidence and tectonic inversion phases that affected the larger Songliao Basin (Yu et al., 2000; Zhao, 2008; Ge et al., 2010; Feng et al., 2010; Wei et al., 2010). The entire rifting –thermal subsidence – uplifting process began at the end of the Jurassic and occurred episodically up to the end of Barremian, Aptian, Santonian and Maastrichtian.

Fault development features, regional unconformities, deposition rates and lithofacies characteristics of Lishu Depression sediments indicate that rifting events consisted of three sub-stages: a rift initiation phase, an intensive rifting phase and a final recession phase. Below we describe each of the major stages, along with the three sub-stages (phases) of rifting in terms of regional tectonics and their influence on basin configuration and stratigraphic architecture.

4.1 Rifting stage

4.1.1 Initial-rifting phase

During the Late Jurassic, extensional tectonism thinned the crust of northeastern China along a series of north-northeast-striking normal faults that developed in the Songliao Basin (Watson et al., 1987; Yu et al., 2001; Ren et al., 2002; Johnson, 2004; Stepashko,
Large-scale faults in the study area include the Sangshutai, Jin-gang and Qindong Faults. These high angle faults formed numerous NNE striking graben and half-graben structures (Figs.6, 7, 8-I, 9). Each graben includes sedimentary fill consisting of interbedded clastic and volcanic rocks assigned to the Huoshiling Formation (Fig.4). Deposition rates reached 250 m/Ma within the Sangshutai half-graben (Fig.5-A), and exceeded 300 m/Ma in the Jin-Gang graben (Fig.5-C).

In the late Tithonian, regional uplift and tilting caused denudation of the Houshiling Formation in most regions. A regional unconformity (T42 interface) formed between Upper Jurassic and Lower Cretaceous units. On the seismic profiles of most regions, the T42 seismic reflector occurs as an angular unconformity with onlap above the interface (Fig.6).

### 4.1.2 Intensive-rifting phase

During the Early Cretaceous, regional about E-W extensional stress influenced the Songliao Basin (Li et al., 1987; Stepashko, 2006; Feng et al., 2010). Continued displacement along the Sangshutai Fault caused widening of the Sangshutai half-graben. The cessation of activity along the Qindong and Jin-gang Faults also arrested the development of small grabens formed during the initial rifting phase (Fig.8-II). Extensional faulting exerted primary control on basin morphology and topography. From Berriasian to Barremian time, the Lishu Depression was a wedge-shaped, half-graben bound by the Sangshutai Fault along its western side, with overlapping layers extending to the east (Figs.8-II, 9). Basin fill consisted of fan delta, braided delta, lacustrine and
fluvial deposits (Zhao, 2008; Yang et al., 2013). The Sangshutai Fault activity and rates of deposition reached their maximum values during the Barremian (Fig.5-D). The Lishu Depression also reached maximal rates of extension during this intensive rifting phase.

4.1.3 Recession rifting phase

At the end of the Barremian, northeastern China experienced a transpressional tectonic movement (Yu et al., 2000; Ren, et al., 2002; Ge et al., 2010). The tectonic movement uplifted strata, caused the denudation of the Yingcheng Formation and formed the regional T4 disconformity (Fig.6). The tectonic event also formed several small-scale strike-slip faults including the Xiaokuan, Qinjiatun and Pijia Faults (Figs.1, 4).

During the subsequent Aptian, extension along the Sangshutai Fault waned and no longer exerted a strong influence on basin configuration (Figs.5-A, 9). Basin relief diminished while the lateral extent of deposition broadened and the horizontal thickness of units became more uniform across the basin. Rifting features within the basin were buried. Sedimentary systems in most areas of the Lishu Depression reflect fluvial and delta plain environments during this phase.

By the end of the Aptian, left-lateral transpressional strike-slip structures had formed throughout the Songliao Basin (Li and Li, 1999; Huang and Shen, 2007; Gan et al., 2011). This tectonic episode uplifted strata in the study area and contributed to the formation of a regional unconformity, the T3 interface, between the Denglouku and Quantou Formations (Yu et al., 2000; Ren et al., 2002). Stress fields reactivated the Pijia, Xiaokuan and
Qinjiautun Faults which became regional strike-slip systems with transpressional features along their margins (Figs.1, 8-III).

4.2 Post-rift subsidence stage

From Albian to Santonian, the Songliao Basin entered the post-rift, thermal subsidence stage. During this period, rifting ceased while deposition extended over a greater area and occurred with more uniform thickness (Fig.8-IV). Smaller depressions developed into a larger basin which filled with fluvial, deltaic and lacustrine sediments. At the end of the Santonian, regional tectonism uplifted the Lishu Depression, precluding deposition of the Sifangtai and Mingshui Formations.

4.3 Structural inversion stage

During the late Maastrichtian, the Songliao Basin entered the structural inversion stage (Song, 1997; Yu et al., 2001; Fang et al., 2003; Stepashko, 2006; Ge et al., 2010) which uplifted and folded the entire Lishu Depression section (Fig.3). As a consequence, deposition did not occur in the Lishu Depression during the Paleogene and Neogene. Instead, strata were severely folded into a large-scale, NNE-trending faulted-anticline. Older, deeper faults were reactivated and connected with younger structures that cut younger units in the depression. Older structures were also further folded (Figs.3, 4, 8-V). The current structural framework of the Lishu Depression was thus finalized during the late Maastrichtian (Yu et al., 2001).

5 Stratigraphic architecture of the rift sub-stratigraphic unit
The Lishu Depression consists of two megasequences (Fig.2). This paper focuses on the rift-related megasequence formed from Kimmeridgian to Aptian time. Using seismic stratigraphy and classic sequence division methods (Mitchum et al., 1977; Vail et al., 1977; Vail, 1987; Vail, 1991), we identified five seismic sequences within this tectonostratigraphic unit (Fig.10). The stratigraphic and sedimentary architecture show changes in the seismic sequences that correspond to different rift phases (Fig.11).

5.1 Rift-initiation stratigraphic unit (SQ1)

The Huoshiling Formation records the initial rifting phase. This unit occurs at the base of early, small-scale, NNE-trending graben or half-graben structures (Figs.7, 8-I, 9) that range in thickness from 0 – 2500 m.

Seismic facies, well logs and drill core data

The bottom interface of SQ1 is a non-conformable contact with the Paleozoic metamorphic basement (Figs.10, 12). The T5 seismic reflector from this surface correspondingly shows high amplitudes and medium continuity. The T42 seismic reflection interface forms the SQ1 top surface. In most regions of the depression, T42 shows features typical of an angular unconformity, including truncation below the interface and overlap above the interface (Figs.6, 10, 12-A). Deposition of this sequence is confined to grabens and half-grabens and shows apparent onlap and bi-directional onlap. Seismic facies within the strata divide into two sets. Some wave groups show high amplitude, medium to low continuity and chaotic to sub-parallel seismic reflection
patterns. Other wave groups show medium to high amplitude, low frequency, variable continuity, and parallel to divergent seismic reflection patterns (Figs.6, 12-B).

Drill cores from this sequence exhibit interlayered volcanic material, coarse-grained clastic rock and mudstone (Fig.13). Volcanic material is also evident from high amplitude responses in Resistivity Deep-lateral (RLLD) and irregular Gamma-Ray (GR) well log data. Most of the coarse-grained clastic rock layers show high amplitude responses with box or bell motifs on GR and RLLD log curves.

Comparison of well log, drill core and seismic data demonstrates consistent relationships between lithofacies and seismic facies. Areas of the section that include volcanic material usually show high amplitude, medium to low continuity and chaotic to sub-parallel seismic reflection configuration. Seismic data for areas of the section that consist primarily of sedimentary rocks show medium amplitude, medium to good continuity and sub-parallel to slightly divergent seismic reflection patterns.

**Sedimentary facies and sequence stratigraphic characteristics**

Both seismic and drill core data indicate a mixed sedimentary system that includes alluvial fan, subaqueous fan, fan delta, lacustrine and volcanic depositional environments (Fig.12-C). Multilayered volcanic deposition occurred throughout the graben and a series of fan-shaped sedimentary bodies developed along its faults. The alluvial fans include variegated breccia and conglomeratic sandstone with abrupt upper and lower boundaries. The fan delta sandstones have erosional contacts at their base and exhibit fining-upward cycles wherein pebble sized clasts grade upward into cross-bedded sands at the top. The
subaqueous fans are characterized by interbedded conglomeratic sandstones and dark mudstone layers.

This sequence shows signs of rapid sedimentation including abrupt shifts in sedimentary facies and irregular distribution of volcanic horizons. The strata may also have experienced episodes of post-depositional tectonic movement. Thus, subordinate seismic sequence and system tracts cannot be easily subdivided according to classic sequence stratigraphic criteria (Mitchum et al., 1977; Vail, 1987; Van Wagoner et al., 1990). Lithostratigraphy offers a more consistent interpretation of stratigraphic features for SQ1.

5.2 Intensive rifting units (SQ2, SQ3 and SQ4)

Intensification of movement on the Sangshutai Fault transformed the basin configuration into a dustpan-shaped half-graben, with the Sangshutai Fault as its western boundary. Overlapping deposition extended eastward (Figs.8-II, 9) to form the Shahezi (SQ2, SQ3) and Yingcheng Formations (SQ4).

Seismic facies, well logs and drill core data

The upper boundary of the SQ2 sequence is a high amplitude reflector characterized by baselap of the overlying reflections (Figs.10, 14-A). Its lower boundary coincides with a high amplitude reflector that also shows marked baselap (T42). The lower part of the sequence shows obvious mound and imbricate reflection patterns. The upper parts include 2-3 medium to high amplitude, sub-parallel continuous reflections. The sequence is only
visible in the Sangshutai Sag, which is adjacent to the Sangshutai Fault and has not been accessed by wells.

The SQ3 sequence reaches thicknesses of more than 700 ms TWT in basinal areas and is composed of three distinct seismic facies (Figs.10, 14-A). The lowermost facies exhibits medium amplitude, typical mound and imbricate reflection patterns. In terms of distribution, this facies is confined to the Sangshutai Sag area. The middle seismic facies includes continuous, medium to high amplitude, sub-parallel to parallel reflections of moderate frequency. This facies is more widely distributed. The uppermost seismic facies contains continuous, moderate amplitude, sub-parallel reflections with low frequency. About 50 exploratory wells were drilled into this sequence in the eastern region of the Lishu Depression. Most wells displayed interbedded gray conglomeratic sandstone, fine-to medium-grained sandstone and dark gray mudstone. GR and RLLD well log curves usually show high amplitude responses with bell or finger motifs. The lithofacies assemblage consists of cyclic sandstone- mudstone-sandstone interbeds.

The upper boundary of the SQ4 sequence is marked by erosional truncation in the areas around the eastern margin of the basin. The base of the sequence is marked by a moderate amplitude surface showing baselap. The sequence consists of high to very high amplitude, sub-parallel continuous reflections throughout most of the basin. In northeastern and southeastern regions of the basin, the upper facies includes distinctive progradational reflection patterns (Figs.10, 14-A). More than 100 exploratory wells have been drilled in this sequence. Well logs and drill cores indicate greater proportions of
interbedded sandstone and mudstone than those observed in SQ3. From the base of SQ4, the depositional stacking pattern shifts from retrogradation to progradation, and then to aggradation (Fig.15).

**Sedimentary facies and sequence stratigraphic characteristics**

Analysis of well logs, drill cores and seismic data indicate basin infilling by braided delta, lacustrine, nearshore subaqueous fan and lowstand fan environments (Figs.14-B, 15). Sediments reflecting braided delta environments dominate the gentle slope areas of the down-dropped block of the Sangshutai Fault. A series of near-shore subaqueous fans developed along steeper fault scarps. In central areas of the basin, the basal areas of SQ3 and SQ4 show incision by lowstand fans. Basin infill show frequently alternating braided delta and lacustrine facies.

Sequences SQ2, SQ3 and SQ4 show significant variation in their seismic stratigraphic patterns. SQ2 and SQ3 include three distinctive sections: a low-stand systems tract (LST), a transgressive systems tract (TST) and a high-stand systems tract (HST). The LST reflection configuration is readily apparent due to its considerable thickness, especially in the Sangshutai sag zone (Figs.10, 14, 16). Following development of the TST and HST, deposition extends over a wider area and lateral thickness becomes more uniform.

The LST of sequence SQ4 did not accumulate with the same thickness as that of earlier sequences and is thus difficult to discern in seismic profiles. The SQ4 TST developed in thicker proportions with strata forming on gentle slopes. The HST is relatively thick and exhibits progradational features (Figs.10, 14, 15).
5.3 Recession-rifting stratigraphic unit (SQ5)

Seismic facies, well log and drill core data

The lower boundary of the final recession-rifting sequence appears as the T4 reflector in seismic profiles. This boundary marks the contact between the Denglouku (younger) and Yingcheng (older) Formations, which is a disconformable surface in most areas and an angular unconformity along the basin margins (Figs.10, 14, 15). The T3 reflector marks the upper boundary of the recession sequence and corresponds to a large regional unconformity occurring throughout the Songliao Basin (Yu et al, 2000; Ren et al., 2002). Seismic reflection data shows continuous, sub-parallel contacts among different reflectors. Layers are truncated in regions bordering the basin and seismic onlap, downlap and toplap phenomena are no longer apparent within the basin.

Drill core material shows lithologies dominated by light gray conglomeratic sandstone, medium- to coarse-grained sandstone and gray mudstone. Sandstone layers usually keep an abrupt contact with gray mudstone layers. GR and RLLD log curves reveal higher response amplitudes than those observed for SQ4 and SQ3, and show finger or bell motifs. The T3 and T4 unconformities appear as abrupt changes in lithofacies and log curve responses at the top and bottom of the section (Fig.15). The sandstone and mudstone beds indicate aggradational conditions in the sequence.

Sedimentary facies and sequence stratigraphic characteristics

Well logs, drill core and seismic data indicate widespread fluvial and delta plain depositional environments. Lacustrine deposition is confined to areas of the Sangshutai
Sag. SQ5’s aggradational features and shallow water environments contrast the prominent progradational and retrogradational features in SQ3 and SQ4. Strata in this recession sequence exhibit only minor lateral variations in thickness. Basin fill included shallow water sediments that do not meet LST criteria (Patterson et al., 1995; Darmadi et al., 2007). Subordinate seismic sequences and system tracts are difficult to identify.

6 Relationship between basin structure and stratigraphic architecture

Accommodation in marine rift basins is a function of tectonic subsidence, sediment supply rate, sea level change and climatic conditions (Vail et al., 1977; Ravnås & Steel, 1998; Gawthorpe et al., 2003). Accommodation space in turn controls stratigraphic and sedimentary architectures. The Lishu Depression is a relatively small-scale continental rift basin, whose configuration and stratigraphic architecture are influenced primarily by major fault displacement rates, regional tectonic events and sediment supply rates. (Figs.11, 17).

During the initial-rifting phase, rapid faulting formed a series of grabens and half-grabens having relatively high relief. Sediment supply rates could not keep up with displacement on faults and basin accommodation space increases. The igneous material formed by episodic volcanism compensated for some of the difference between accommodation space and sediment supply. Tectonic uplift at the end of Tithonian finalized this sedimentary sequence. Mixed deposition of volcanic and clastic rocks created somewhat chaotic seismic facies, making systems tracts difficult to identify.
Throughout the intensive-rift phase, the basin grew due to continuous movement on the Sangshutai Fault. The basin assumed a wedge-shaped half-graben form with the Sangshutai Fault as its western boundary, and overlapping layers towards the east. In the early intensive-rift phase, rapid downthrow and rotation of Sangshutai Fault blocks created abundant accommodation space. In the later intensive-rift phase, high sedimentary accumulation rates (Fig.5-A) gradually reduced the accommodation space. The Sangshutai Fault downthrow block defined most areas of basin, and transited from a high dip angle to a gentler angle later in this phase (Fig.17). The eastern slope of the basin resembled a passive continental margin setting at this point. Correspondingly, the seismic sequence pattern is similar to that of a passive continental margin with a readily apparent LST, TST and HST. As the basin surface features became more and more gentle, LST features became less apparent and are difficult to recognize in seismic profiles (Figs.15, 16). Well data also show changes in sedimentary stacking patterns. From SQ2 to SQ4, the retrogradation sequence occupies less and less space. The progradation sequence meanwhile assumes a larger proportion of the section.

Following regional transpression at the end of the Barremian, the displacement rate of Sangshutai Fault decreased. The sediment supply rate equaled the basin subsidence rate. The basin surface leveled off by the Aptian and no longer showed sedimentary response to the relief of previous rifting phases. The aggradation sequence formed, appearing in seismic reflection data as continuous, sub-parallel contacts among different reflections.
These final units exhibit bimodal TST and HST sequence structure, without an LST component.

7 Discussion

Above statements clearly reported the features of basin structure and stratigraphy architecture and their relationship in the three rifting sub-stages for Lishu Depression. The discussion part will be used as a supplement to illustrate the unique properties in the rifting stage of Lishu Depression and point out some questionable aspects in this study.

1) Extension of the Lishu Depression was not a uniform or continuous event, but rather consisted of several regional tectonic events. These events caused the uplift, deformation and denudation of strata, evident from several regional erosional unconformities. Unconformable surfaces form the boundaries of stratigraphic units that represent sub-stages of larger-scale rifting event. Rift-related structural characteristics tend to vary among different rift basins. The Northern Viking Graben (Ter Voorde et al., 1997), Suez Rift of Egypt (Gupta et al., 1999) and northern of the North Sea (Nøttvedt et al., 1995) for example show rotation of fault blocks with the growth of major listric normal faults. The tilt of fault blocks in turn caused local region denudation of areas in the fault’s footwall. Deposition in these basins was more uniform and does not show the same punctuated phases as those observed in the Lishu Depression. Their unconformities are also more localized and arise from different structural dynamics.
2) In the Lishu Depression, the development of major faults exerted a primary influence on basin geometry. The basin geometry and topography in turn influenced stratigraphic and sedimentary architecture. In fact, regional tectonic subsidence, lake level change and climatic conditions also are the important influence factors in basin evolution. Regional tectonic subsidence may influence the amount of accommodation space (Nøttvedt et al., 1995; Gawthorpe and Leeder, 2000). Climatic conditions usually have a significant influence on the sediment source (Ter Voorde et al., 1997; Ravnås and Steel, 1998). Lake level change reveals an important influence on depositional stacking pattern (Lambiase, 1990; Gawthorpe et al., 2003). The main purpose of this paper is to discuss rifting sub-stage’s structural and stratigraphic features and analysis the relationship between them. So these factors are thought as the stable background, not being discussed here in detail.

3) Different slope areas corresponding to different fault segments show variation in sequence stratigraphic style and sedimentary stacking pattern (Yong et al., 2002; Gawthorpe et al., 2003). Most stratigraphic features described above occur on the slope regions corresponding to the central part of Sangshutai Fault and occupy most of the basin. Regions to the north and south of the Sangshtai Fault are not described and may exhibit a different stratigraphic style and sedimentary pattern.

4) Classic sequence stratigraphic analysis derives from sedimentary sequence studies of passive margin settings (Vail et al., 1977; Van Wagoner et al., 1990; Gawthorpe et al., 1997). As a continental rift basin, the Lishu Depression exhibits classic triplets of LST,
TST and HST sequences only in the intensive rift sub-stratigraphic unit. The system tracts in the initial rift sub-stratigraphic units are not clear as those found in other rift basins (e.g. Prosser, 1993; Lambiase and Bosworth, 1995; Martins-Neto, 2000; Richardson and Underhill, 2002; Renato et al., 2009). The recession rift units show a HST and TST, but no clear LST. It also suggest that the stratigraphic division method of Classic Sequence Stratigraphy has some limitations in continental rift basin. To setup high resolution stratigraphic framework within initial rift and recession rift sub-stratigraphic units, more methodologies and additional well log, drill core and high-resolution seismic data are requisite (e.g. Henry et al., 1990; Cheng and You, 2001; Escalona & Mann, 2006; Neal and Abreu, 2009; Reigenstein et al., 2011).

8 Conclusion

From the Late Jurassic Kimmeridgian to the Cretaceous Aptian, the Lishu Depression experienced a punctuated and long-lived extensional event that consisted of three regional compressional tectonic movements. These caused uplift, denudation, deformation and corresponding development of unconformities within Lishu Depression sediments, and established three phases of sedimentation during the rift period. Development of major fault systems and changes in their rates of movement influenced basin configuration in its transition from a graben / half-graben configuration during the initial rifting phase, to a dustpan-shaped half-graben pattern during the subsequent phase of intensive rifting, and finally to a gently-sloping sedimentary basin during the final recession phase.
During the initial-rifting phase, discrete graben and half-graben structures were filled with volcanic material and clastic sediment. The seismic facies consist of medium to low continuity and chaotic to sub-parallel seismic reflection patterns. Seismic data from the initial rifting phase does not show clear systems tracts. The intensive-rifting phase was characterized by increasing accommodation space and protracted depositional cycles. Seismic data show obvious divisions among three different system tracts. Progressing downward from the top of the section, LST features became less apparent, whereas HST features occupy an increasing proportion of each sequence. Well logs and drill core data from basal units also show clear progradational features. In the final recession phase of rifting, deposition reflects shallow water aggradation with high frequency depositional cycles affecting an extensive area of the basin. Stratigraphy exhibits a bimodal sequence structure, consisting only of TST and HST components.

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References


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Figure 1 Index map showing the location, surface structural features, seismic and well data coverage of the study area, as well as the transect location of the cross-section shown in Fig. 3, and the transect locations for seismic profiles cited in the text. For the sake of clarity, only a subset of wells is shown.

Figure 2 Stratigraphy, tectonic setting and seismic features of Lishu Depression sediments.

Figure 3 Schematic two-dimensional representation of the Songliao Basin (Transect A-B in Fig. 1), showing tectonostratigraphic characteristics of the Lishu Depression (right).

Figure 4 Seismic profile showing faults and stratigraphy of the Lishu Depression (Transect a-a’ in Fig.1).
Figure 5 Histograms showing major normal fault activity (y-axis) and corresponding maximum accumulation rates within the Lishu Depression. A. Sangshutai Fault; B. Qindong Fault; C. Jin-gang Fault; D. the maximum accumulation rates for different sedimentary units in the Lishu Depression. Estimates assume continuous sedimentation for each depocenter. The depositional rates were obtained according to the ratios of strata thickness and corresponding accumulation time. In the Late Jurassic, the down-dropped region of the Jin-gang Fault exhibits maximum depositional thickness. In the Early Cretaceous, the Sangshutai Fault was continuously active. The depocenter shifted to the Sangshutai Sag adjacent to the Sangshutai Fault.

Figure 6 Seismic profile of the Jin-gang graben and Qinjiatun half-graben, which evolved in the Late Jurassic. Arrows indicate continuous erosional truncation features that overlie both grabens (Transect b-b' in Fig.1).

Figure 7 Major faults and grabens that evolved during the initial Late Jurassic rifting phase. The isolines indicate TWT thickness according to 3-D seismic images.

Figure 8 Regional cross-section showing the structural evolution of the Lishu Depression (Transect c-c' in Fig.1). Note that the rift stage has been sub-divided into initial, intensive and recession rifting phases.

Figure 9 Schematic diagram of how basin geometry evolved with different sub-stages (phases) of rifting. F1: Shangshutai Fault; F2: Qindong Fault; F3: Jin-gang Fault; “+” marks the basin depocenter.
Figure 10 Seismic profile (A) and sequence stratigraphic interpretation (B) of Transect d-d’. For location see Fig.1. Note that T5, T42, T41, T4 and T3 reflectors all are disconformities. Also note the obvious baselap reflection between SQ2 and SQ3.

Figure 11 Division of tectonic stages and sequences within the Lishu Depression. The lithofacies column also shows the sedimentary system cycles.

Figure 12 Characteristics of initial-rifting stratigraphic unit (SQ1) (Transect e-e’ in Fig.1).

A. Seismic reflection features; B. Stratigraphic filling pattern of units remaining after denudation caused by Late Jurassic tectonism; C. Depositional infilling of original strata before the tectonic movement.

Figure 13 Lithology, log data and well-site seismic reflection profile of Sequence SQ1 (Huoshiling Formation) from Well Y204. Well data records unconformities at the bottom and top of the sequence. Also note the igneous horizons in this unit.

Figure 14 Seismic stratigraphy patterns and depositional facies model of the intensive rifting stratigraphic unit (Transect d-d' in Fig.1). For seismic profile see Fig.10. Data from Well SW2 shown in Fig.15.

Figure 15 Lithology and well log data for SQ3, SQ4 and SQ5 sequences (Well SW2), showing the sedimentary facies, system tract features and stratigraphic stacking pattern. Well location is marked in Fig.1, Fig.10 and Fig 14. Note the abrupt log curve responses and lithofacies features at disconformities.
Figure 16 Isopach map showing low-stand systems tract distribution characteristics of the intensive-rifting stratigraphic unit. For sequences SQ2, SQ3 and SQ4, the aerial extent of LSTs broadened, while the lateral thickness variation diminished.

Figure 17 Schematic diagram of sequence stratigraphic configuration, sediment stacking pattern and key controlling factors of different sub-stages (phases) of rifting in the Lishu Depression.
<table>
<thead>
<tr>
<th>Tectonic stage</th>
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Highlights

1. Classic rift stages can be further subdivided into discrete phases on the basis of the variation of sedimentary conditions.
2. Lishu Depression has unique sequence stratigraphy architecture and sediment stacking patterns in each rifting sub-stage.
3. A critical and high-resolution tectonostratigraphic perspective on the evolution of a continental rift basin was provided.