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Syn-depositional fault control on hydrocarbon migration and accumulation pattern: a case study from Tangbei Area, Bohai Bay Basin, NE China

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Abstract

Tangbei Area, a complex syn-depositional fault development area, is located in petroliferous Bohai Bay Basin with abundant petroleum resources in the Paleogene. The way to figure out possible migration pathways and potential accumulation accommodation controlled by syn-depositional faults has become a key issue for predicting favorable reservoirs. Based on seismic volume and wireline logs, we carried out fine seismic interpretation, document the faults and their combinations in plane view and section view, and reveal its influence on hydrocarbon migration and accumulation. The results indicate that fine seismic interpretation in the study area provides the distribution and characteristics of syn-depositional faults generated by regional tectonic activities. In addition, syn-depositional faults play an important influence on basin structure and the pathways and traps for hydrocarbon migration and accumulation. Three types of syn-depositional faults are divided based on their locations. It is found that syn-depositional faults in steep slope zone are much favorable for hydrocarbon migration and accumulation. Syn-depositional faults in different depositional periods throughout basin evolution act as pathways for hydrocarbon migration, as well as act as seals, which depend on surrounding lithology associations and sealing or leaking properties through time.

Keywords Syn-depositional fault · Hydrocarbon migration and accumulation pattern · Fine seismic interpretation · Bohai Bay Basin

Introduction

The analysis of controlling factors on hydrocarbon migration and accumulation in rift basins has long been of great scientific interest in the last few decades (Magoon and Dow 1994; Lin et al. 2003, 2005; Escalona and Mann 2006; Allen and Allen 2013; Bell et al. 2018). Hydrocarbon migration and accumulation can be influenced by overlapping effects of multiple factors in tectonically active basins (Cong and Zhou 1998; Chen et al. 2006; Deng et al. 2017). However, the

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factors driving the migration and accumulation of hydrocarbon, including fault activities and tectonic subsidence, are integrative and complex (Feng et al. 2000; Lin et al. 2005; Xu 2013; Duffy et al. 2017). The interaction of these factors in different rift basins or at different tectonic evolution stages contains various importance and provides various pathways/traps for hydrocarbon migration and accumulation (Morley et al. 1990; Morley 1995; Lin et al. 2005; Li et al. 2009; Qi et al. 2011; Gawthorpe et al. 2018; Li et al. 2018). Previous studies have demonstrated that syn-depositional fault activities predominantly play an essential role in controlling hydrocarbon migration and accumulation (Morley et al. 1990; Morley 1995; Zhang 2006; Qi et al. 2011; Wang et al. 2013; Zhang et al. 2015; Tarabees and Azam 2016; Zheng et al. 2018). Understanding the genetic relationship between fault activities and hydrocarbon migration and accumulation can provide insights for hydrocarbon exploration in rift basins.

The Bohai Bay Basin is a large petroliferous basin in the Cenozoic in northeast China (Qi and Yang 2010; Qi et al. 2010). It has undergone long-term tectonic evolution and corresponding deformations from pre-Cenozoic to present day (Ren et al. 2002; Xia et al. 2018, 2020). Qikou Sag, located in the east of Huanghua Depression, a tectonic unit in the Bohai Bay Basin, contains significant petroleum reserves that are confirmed by hydrocarbon discoveries (Chen et al. 2006; Zhang, et al., 2006; Miao et al. 2007; Wu et al. 2010; Meng et al. 2011; Qi et al. 2011) (Fig. 1a). The Tangbei Area, located between the Qibei and Banqiao sub-sags in the Qikou Sag, has been in the super-high water cut phase, and, as a result, the distribution of remaining oil has become more and more complex. The effective prediction of hydrocarbon migration and

accumulation has become an urgent issue in enhanced oil recovery (EOR).

Over the last decades, extensive hydrocarbon exploration and development in Tangbei Area have acquired a bunch of seismic and well data. These geological and geophysical datasets provide the basis for systematic study on hydrocarbon migration and accumulation. This study is focusing on how syn-depositional fault controls hydrocarbon migration and accumulation. The results are expected to serve decision-making on adding petroleum reserves.

Geological Background

Tectonic setting

The Bohai Bay Basin developed as back-arc basin during the Mesozoic and evolved into intra-cratonic rift basin during the Cenozoic in northeast China (Ren et al. 2002; Hsiao et al. 2004, 2010; Li et al. 2010; Qi and Yang 2010; Qi et al. 2010). It is located among northern Yanshan Massif, eastern Liaodong Massif, and Luxi Massif (Hsiao et al. 2004) (Fig. 1a). It shows an "S" shape and covers an area of about 30,000 km² with an NE strike. It is separated by several regional uplifts and depressions (Hsiao et al. 2004; Xia et al. 2018, 2020). The basin resulted from complex polyextension-phase tectonic history that is further divided into three periods (Cong and Zhou 1998; Zhao and Zheng 2005) (Fig. 3): (1) During early syn-rift stage, a number of small isolated basins developed along major faults with NW and NE strikes from the late Mesozoic to the Paleocene (Wang et al. 2013).
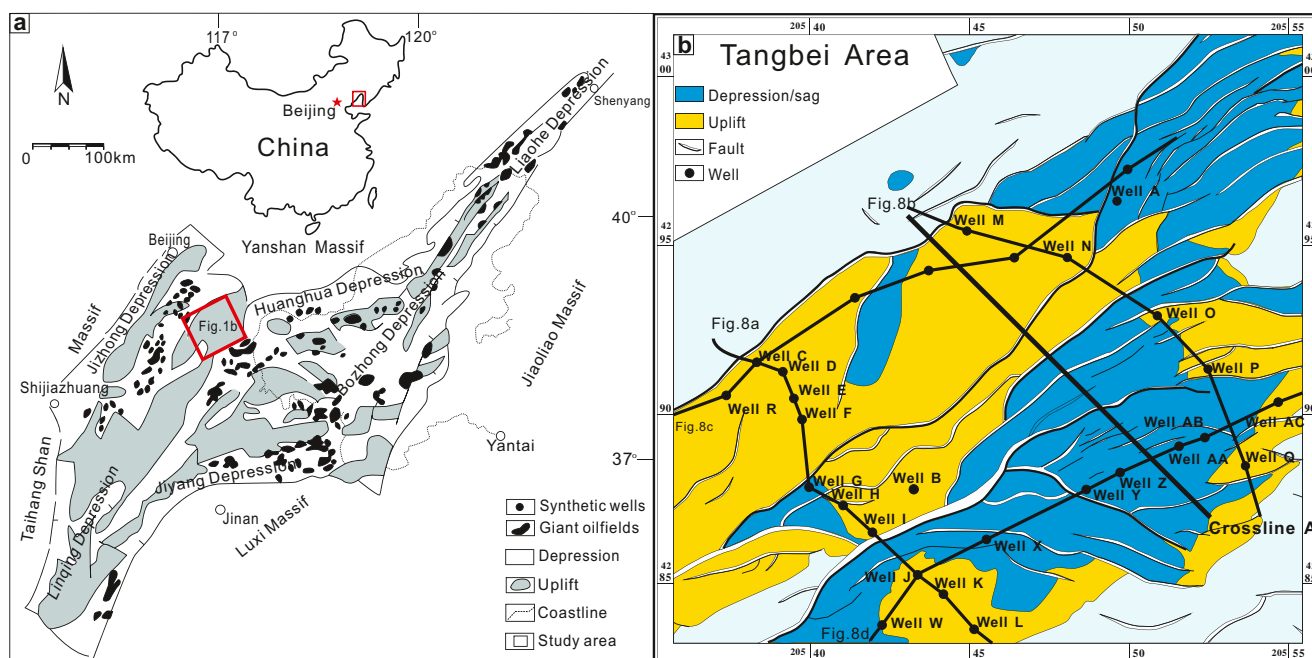
Fig. 1 Location map and fault distribution of study area

Potential source rocks and reservoirs were generated in a few isolated basins/depressions during the late period of this stage, which is depositional period of the Kongdian Formation (Ren et al. 2002); (2) during syn-rift climax stage, from the Eocene to the Oligocene (65.0-24.6 Ma), most grabens were isolated and separated. However, there were some local connections of adjacent grabens (Hsiao et al. 2004; Zhang et al. 2015). These grabens were characterized by significant fault movement, high sedimentation, and subsidence rates (Fig. 2). During this period, more than 40 sub-basins can be identified that were mostly controlled by uplift and subsidence resulted from fault movement (Hsiao et al. 2010). The Shahejie (E_2s) and Dongying (E_3d) formations with significant hydrocarbon generation and accumulation were formed during this stage (Zhao and Zheng 2005; Xia et al. 2018, 2020). (3) During late syn-rift stage, from the Neogene (24.6 Ma) to present day, it represents a status of thermal subsidence when syn-rift tended to cease gradually. Most depressions were connected with a few exposed structural highs, which allowed the sub-division of six superimposed sub-basins (Hsiao et al. 2004, 2010; Qi and Yang 2010; Qi et al. 2010). The Guantao and Minghuazhen formations were deposited during this stage. With all respects to stratigraphic evolution and depositional process of the Bohai Bay Basin, periods of (2) and (3) were considered to be major tectonic evolution stages (Ren et al. 2002). The sediments of in periods (1) and (2) were mainly deposited in lacustrine environments. The sediments in periods (1) and (2) were characterized by fluvial-deltaic deposits and distributed widely (Qi and Yang 2010, Qi et al. 2010).

Qikou Sag, as part of the Cenozoic intra-continental rift basin, is composed of one several sub-sags (including the Qikou, Banqiao, Qibei and Qinan sub-sags) with an NE strike that was resulted from extensional movements (Wang et al. 2013; Zhang et al. 2015). Influenced by continuous and strong subsidence of the Qikou sub-sag, the rest sub-sags lean toward the central sag (Wang et al. 2011; Zhang et al. 2015). The influence resulted in structural characteristics, such as small-scale uplifts, large-quantity sub-sags, and widespread slopes (Li et al. 2009; Wang et al. 2011). The geological framework

and structural characteristics vary significantly from that of classical rift basins (Zhu et al. 2015).

Tangbei Area is located between the Qibei and Banqiao sub-sags (Song et al. 2015) (Fig. 1b). It covers an area of roughly 100 km^2 with more than 120 wells drilled.
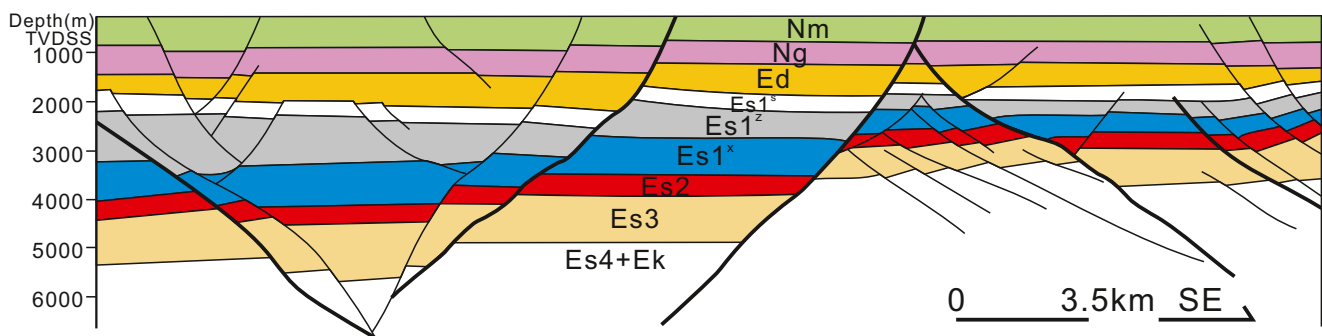
Stratigraphy

The Cenozoic strata are relatively well-preserved in the study area. Their stratigraphic characteristics are summarized as follows (Fig. 3):

(1) Kongdian Formation (E_1k)

The deposition of Kongdian Formation is occasionally distributed in the study area due to fault activity and geomorphology. It shows unconformities with underlying strata (Li et al. 2009; Zhang et al. 2015). Penetrated wells reveal up to 640 m of thickness in the formation. The Kongdian Formation is dominated by purplish mudstone interbedded with thin-layer grayish sandstone and glutenite. Grayish green and brownish-red mudstone was developed in the lower part. In contrast, the upper part is dominated by dark gray mudstone interbedded with thin limestone, dolomite, purplish-red mudstone, and grey sandstone and conglomerate.
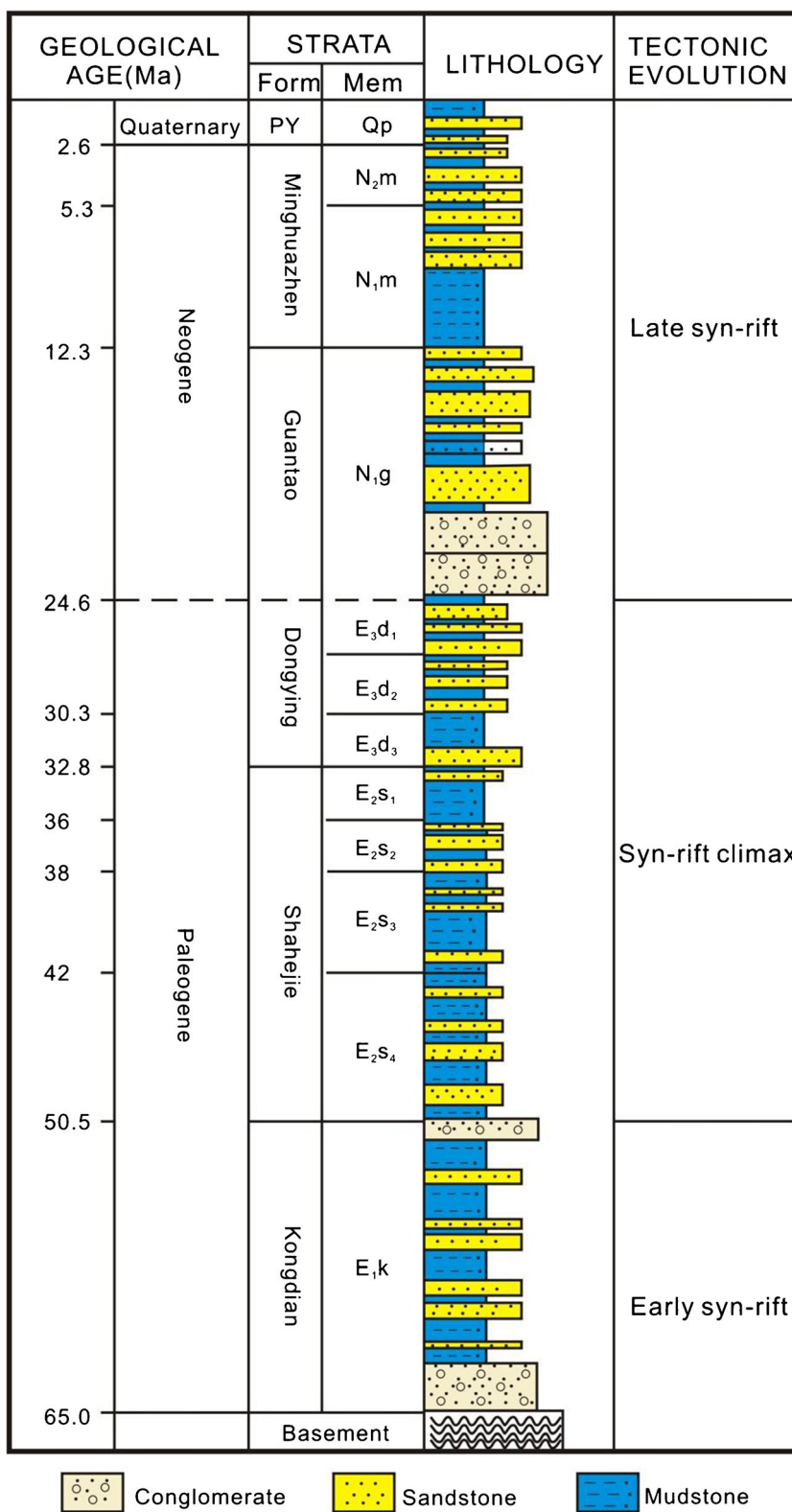
(2) Shahejie Formation (E_2s)

The Shahejie Formation can be further divided into four members in the study area (Fig. 3). However, controversy remains in the existence of the fourth member of Shahejie Formation (E_2s_4) (Zhang 2006; Wu et al. 2010). Determining the boundary between Kongdian Formation and the fourth Shahejie member (E_2s_4) is not easy. Therefore, in seismic interpretation, it is grouped with the underlying Kongdian Formation (Fig. 2) and is composed of limestone, dolomite, dark grey mudstone, dark green sandstone, and gypsum.

Fig. 2 Cross-section showing regional structural and formations. Section location is shown in Fig. 1 as "crossline A". Modified from Song et al. (2015)

Fig. 3 Stratigraphic chart showing the Cenozoic stratigraphic units, lithology, and tectonic evolution in Tangbei Area, Bohai Bay Basin

The third member of the Shahejie Formation (E_2s_3) was developed in responses to intense rifting stage featured by strong tectonic subsidence and increasing water depth (Wang et al. 2011). The depositional systems consist of fan deltas, shallow lacustrine, and deep lacustrine facies. It is characterized by grayish-brown mudstone interbedded with sandstone and sandy conglomerate in the upper part dark mudstone and oil shale in the middle part and coarse-grain sandstone,

conglomerate, in the lower part (Miao et al. 2007). In general, the member shows complete fining-up to coarsening-up cycle indicating water depth changes.

The second member of the Shahejie Formation (E_2s_2) is widely distributed in the study area. It displays unconformities with underlying strata along the slope/margin and in the central depression (Meng et al. 2011). The lithological facies are composed of light gray sandstone and pebbly sandstone interbedded with dark gray mudstone in the lower part. By contrast, the middle and lower part consist of thin oil shale and occasional dolomite. The member shows a fining upward trend (Meng et al. 2011).

The first member of the Shahejie Formation (E_2s_1) is distributed in the whole study area. It is characterized by special lithological facies (Meng et al. 2011). It is composed of dark gray mudstone interbedded with yellow-brown dolomite in the upper part, while in the middle part, it consists of thick grayish-white sandstone interbedded with dark gray mudstone, oil shale, or dolomite. Bioclastic limestone, dolomite, and oolitic limestone are widely and stably distributed. The lower part is dominated by grayish-white and light gray sandstone interbedded with light green mudstone (Miao et al. 2007; Meng et al. 2011).

(3)   Dongying Formation (E_3d)

The Dongying Formation is widely distributed in the study area overlying the Shahejie Formation or pre-Paleogene units (Chen et al. 2006; Miao et al. 2007). The boundary between the Shahejie and Dongying formations is conformities which are comfortable contact of different lithological associations. On the top, it is bounded by a major unconformity with overlying Guantao Formation (Chen et al. 2006).

The Dongying Formation on the top can be generally further divided into three members (Fig. 3).

The third member of the Dongying Formation (E_3d_3) was deposited during the time when the basin further continued to expand and deepen. It mainly developed deep lacustrine deposits (Chen et al. 2006; Miao et al. 2007). The lithological facies is dominated by dark grey and grayish-black mudstone with pure texture, grey siltstone, and sandstone (Miao et al. 2007). The second member of Dongying Formation (E_3d_2) is characterized by interbedded dark grey mudstone, grayish-white sandstone, and siltstone in the lower part and dark grey, grayish-green mudstone, and grayish-white sandstone in the upper part with varied thickness that resulted from fluvial-deltaic deposition (Chen et al. 2006). The first member of the Dongying Formation (E_3d_1) was partially denuded. It is dominated by fluvial-alluvial deposits. Interbedded grey mudstone and sandstone in the member mainly shows a coarsening-upward cycle (Chen et al. 2006).

(4)   Guantao Formation (N_1g)

The Guantao Formation is characterized by thick massive sandstone and conglomerate interbedded with mudstone (Fig. 3). The lithological facies is composed of brownish-red mudstone interbedded with grayish-green and grayish-white sandstone in the upper part. The bottom mainly includes glutenite with component of quartz and flint (Chen et al. 2006; Zhang 2006).

(5)   Minghuazhen Formation (N_1m)

The Minghuazhen Formation was well-developed in the whole basin. The upper part is characterized by grayish-green, brownish-red mudstone interbedded with grayish-green sandstone and gravelly sandstone (Fig. 3). In contrast, the lower part is characterized by grayish-green, brownish-red, and purplish-red mudstone interbedded with sandstone (Zhang 2006; Miao et al. 2007). In general, it presents an overall coarsening-up cycle in ascending order with varied thickness (Fig. 3).

Database and Workflow

The database used in this study predominantly consists of seismic volume and wireline logs. The seismic volume includes a 100km^2 post-stack, time-migrated 3D cube, with a bin spacing of 25 × 25 m and a two-way travel time trace length of 5 s. Data quality within seismic survey at target intervals (Cenozoic strata) is excellent with 40 Hz in the dominant frequency width. In addition, the seismic volume is zero-phase processed with normal polarity. As such, a positive seismic event represents an increase in acoustic impedance with depth. The wireline logs from boreholes include, but not limited to, the Gamma Ray, Spontaneous, Density, Acoustic and Resistivity logs.

The workflow of structural interpretation was used to derive geological insights from 3D seismic interpretation calibrated by wireline log analysis. Firstly, 3D seismic volume was quickly scanned along both inline- and crossline-directions in time domain to obtain a general understanding of structural frameworks (Xia et al. 2015). Next, synthetic seismograms were generated as the basis of structural interpretation (both faults and horizons picking), velocity analysis (including velocity spectrum crossplot analysis, examination, and calibration of spatial velocity field), and visualization validation (Box et al. 2004; Xia et al. 2015). Finally, the control as the basis of syn-depositional faults on hydrocarbon migration and accumulation was analyzed, especially pathway and seal.

Result and Interpretation

Seismic Interpretation

Synthetic seismograms were generated by taking key beds, dominant frequency, and polarity into considerations based on seismic volumes and wireline logs. The synthetic seismogram shows a satisfactory match between seismic reflectors and formation tops which allows time-depth domain conversion between seismic data and wells (Fig. 4). However, there are some shift inaccuracies on minor seismic events (Stewart and Reeds 2003; Lomask et al. 2009).

The time-depth relationship for key wells was calculated to generate velocity curve. In order to check the accuracy of time-depth relationship among key wells, velocity cross plots of key wells are presented (Fig. 5). It shows that the velocity curves from wells A and B generally match regional North China Velocity (NCVS) (Fig. 5a, b). The velocity curves of well A and well B are closely similar. The reason why this study is compared with the NCVS is because it usually acts as standard strata velocity for the sedimentary basins located in North China (including Bohai Bay Basin). Note that well A and well B are located in different locations of the study area (Fig. 1b); similar velocity trends indicate that generated velocity is reliable in the study area.

The gradient of average velocity below 1000 ms in time domain equals 1 more or less, which means two-way-time values equal to absolute true vertical depth (Fig. 5c, d). The average velocity in the southern area is 2000 m/s. In contrast, the average velocity in the northern area is 2400 m/s. However, there are some abnormal velocity points (Fig. 5c), which may lead to abnormality in 3D Depth-Team Module when more abnormal

velocities from individual wells are gathered together (Fig. 6a). After careful calibration, the velocity trend was recovered (Fig. 5d) as shown in 3D Depth-Team Module (Fig. 6b).

Velocity analysis not only provides us accurate subsurface structural feature, but also it gives us some robust insights on subsurface geology. After synthetic seismogram generation and velocity analysis, time slice analysis of cohere volume and amplitude volumes were employed to determine the dip and strike of faults and horizons during structural interpretation. Faults and horizons were interpreted and quality control was performed in 3D visualization (Fig. 7).

Syn-depositional faults

The rationality of structural interpretation can be checked through arbitrary lines throughout seismic survey. Seismic profiles along arbitrary lines show the configuration between faults and key horizons (Fig. 8). The strata below the Dongying Formation are thicker below Dongying Formation than those in the Shahejie Formation in the northwestern and southeastern parts is much thicker indicating probable large-scale fault activities that led to large fault throws (Fig. 8). In contrast, the strata above the Dongying Formation show an extensively equal thickness (Fig. 8). The faults developed in the study area are characterized by normal faults with various fault throws. The faults developed below the Dongying Formation commonly show larger fault throws than those developed above the Dongying Formation (Fig. 8). Some normal faults show a listric manner in the deeply buried strata below Dongying Formation (Fig. 8).

More than 50 normal faults with various scales are interpreted from the Shahejie Formation (E_2s) to the
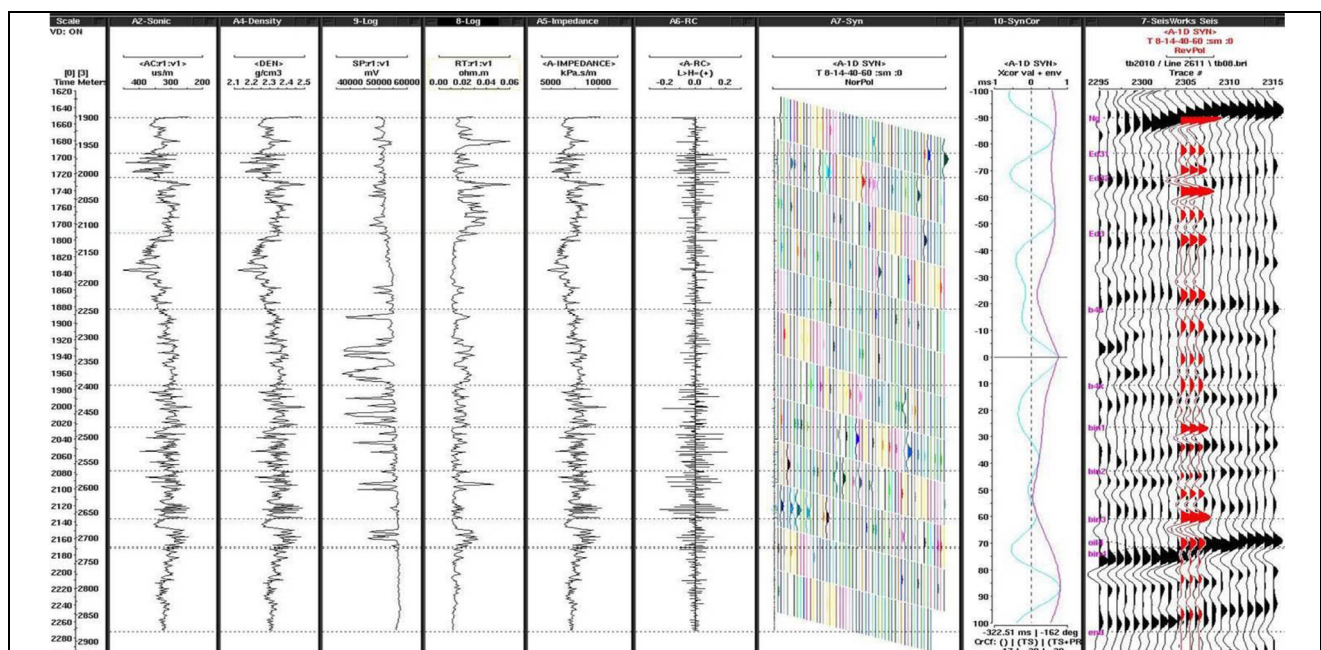

Fig. 4 Synthetic seismogram generation based on sonic logs, density logs, and wavelet extracted from seismic volume near well Z

Fig. 5 Velocity analysis of two key wells and multiple-well velocity cross-plot. **a** velocity profile of well A compared with North China velocity; **b** velocity profile of well B compared with North China velocity; **c** multiple-well velocity cross-plot before adjustment; **d** multiple-well velocity cross-plot after adjustment
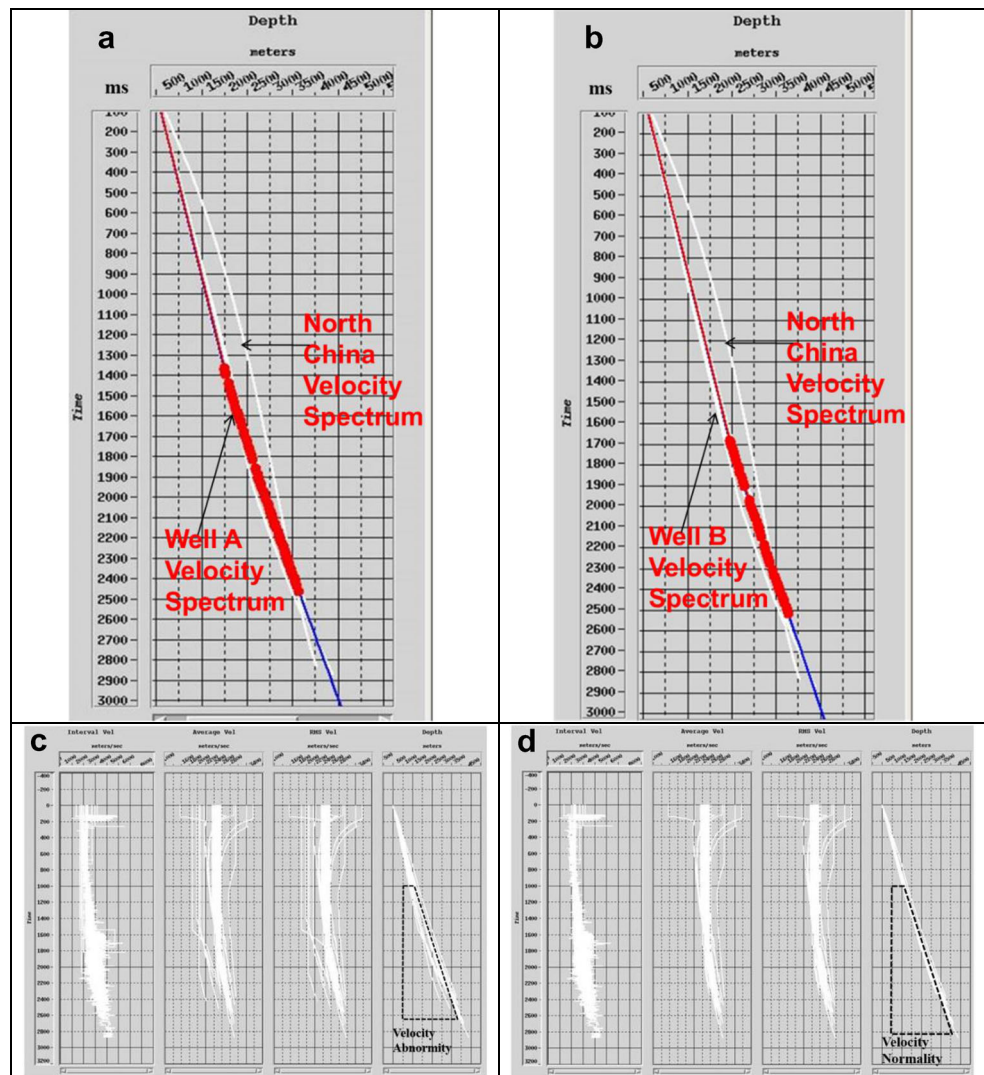
Minghuazhen Formation (N_1m). The faults are dominated by an NE strike (Fig. 9). Previous studies classified these faults into two types in the Paleogene based on faulting mechanism during basin evolution (Miao et al. 2007; Wu et al. 2010; Meng et al. 2011; Song et al. 2015; Zhang et al. 2015). The 1st-order faults refer to the boundary faults which control basin-scale evolution with an overall NE strike. In contrast, the 2nd-order faults refer to those attached to the 1st-order

Fig. 6 Analysis of **a** abnormal and **b** normal velocity field of seismic volume in the study area
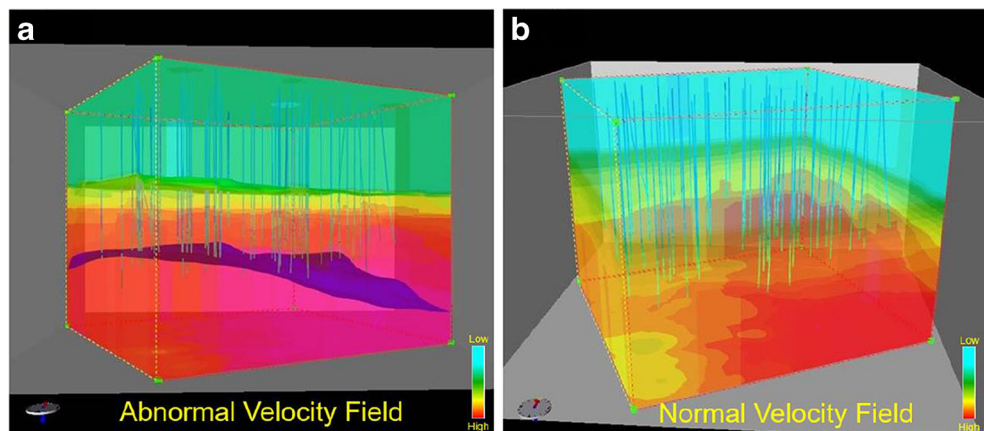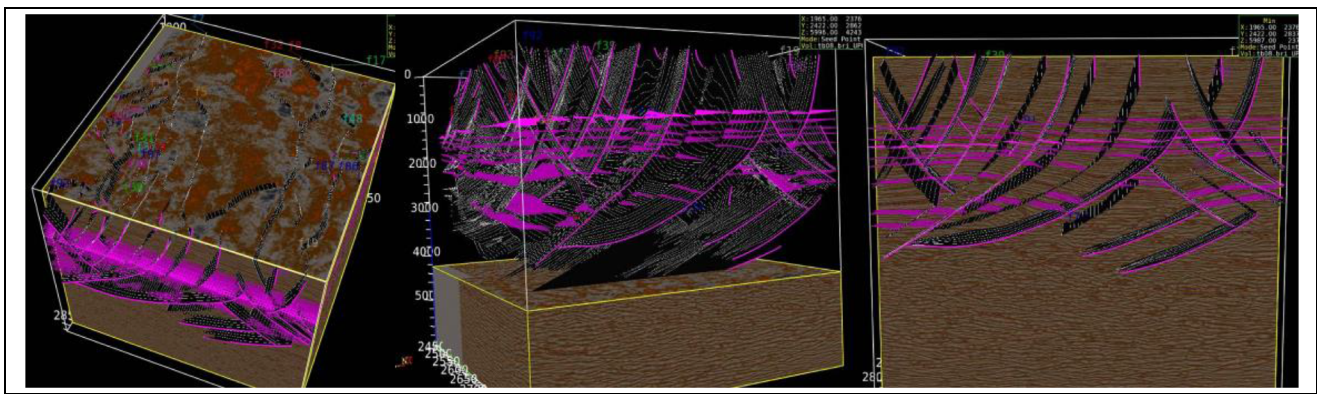
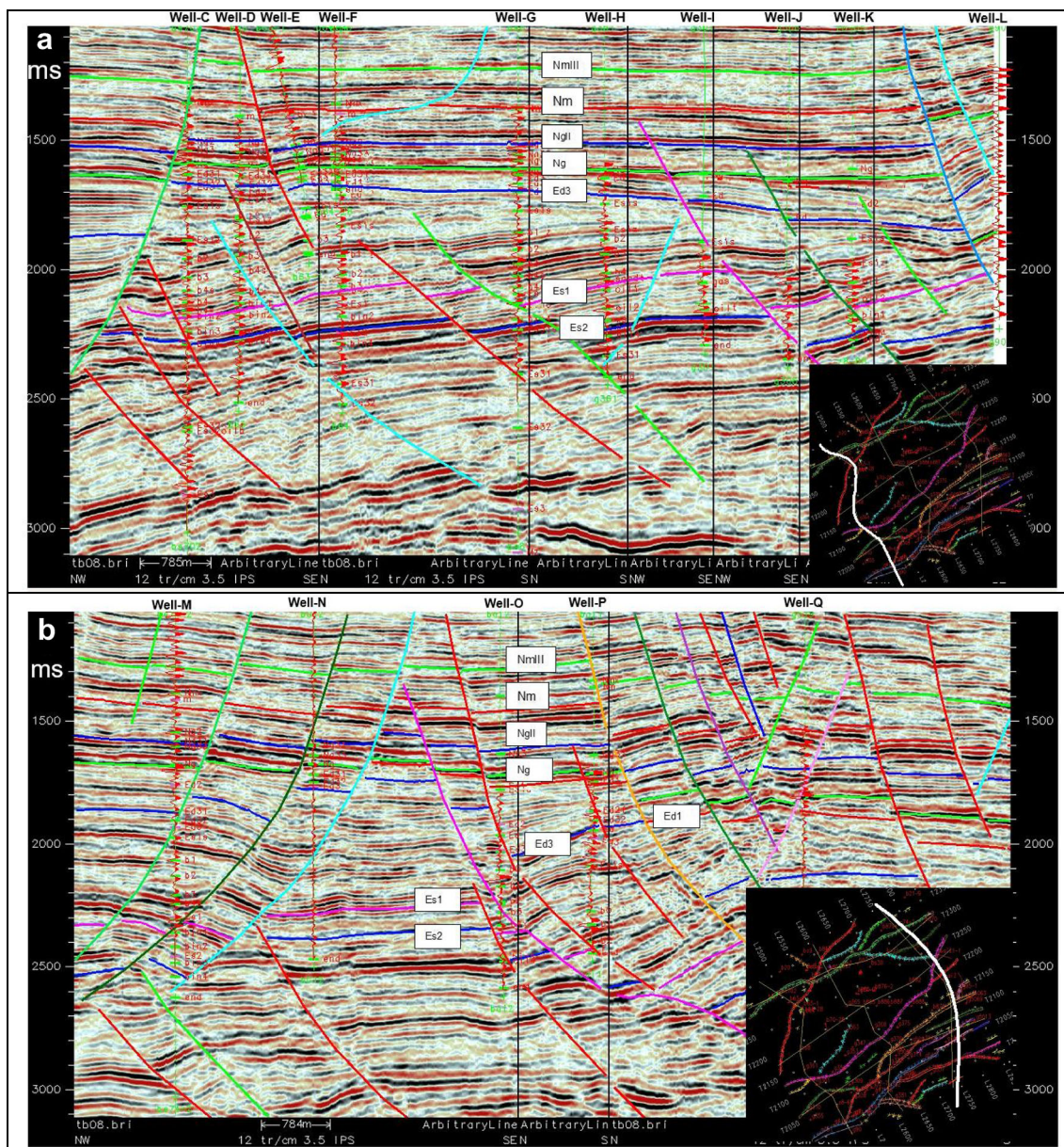**Fig. 7** Fault interpretation in visualization module

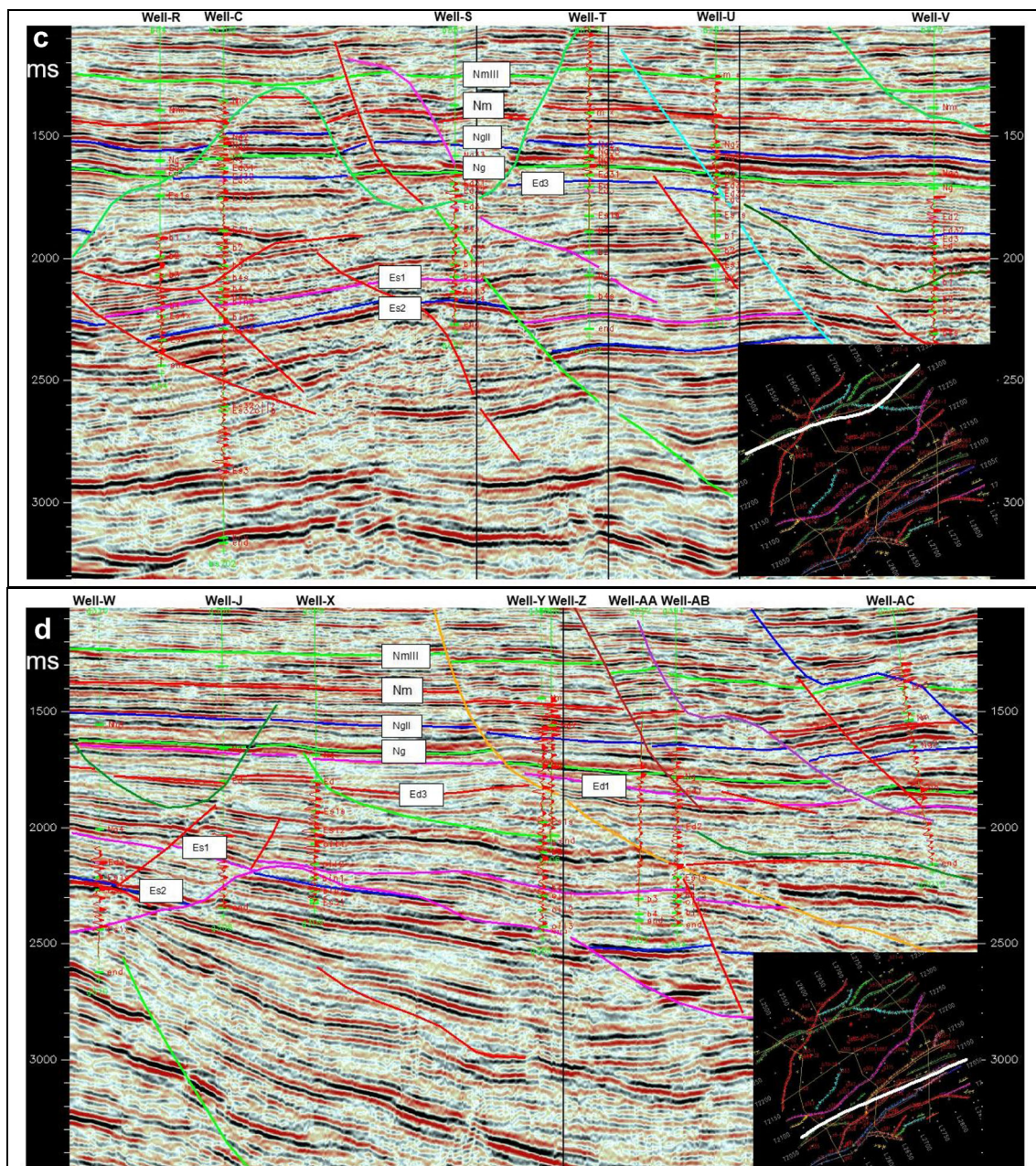**Fig. 8** The interpretation of horizon and fault in arbitrary lines

Fig. 8 (continued)

faults with NNE or NEE strikes which controlled localized tectonic evolution. The 1st-order faults commonly penetrate into deeply buried source-rock strata and provided pathway for hydrocarbon migration. Whereas the 2nd-order fault usually acts as lateral seal combined with fault-related structures (Yu et al. 2011). There is a significant inheritance in fault combination from the Shahejie Formation to the Minghuazhen Formation. In addition, fault throws decrease upwards associated with gradual increase in the number and extension range of faults (Fig. 9).

Discussions

Cenozoic petroleum system

Based on the concept of petroleum system (cf. Magoon and Dow 1994), the Tangbei area consists of multiple petroleum systems. The distribution of source rocks varies from place to place in gentle slope zone, steep slope zone, and central sag. These source rocks are mainly from the third member of the Shahejie Formation and Dongying Formation, where deep
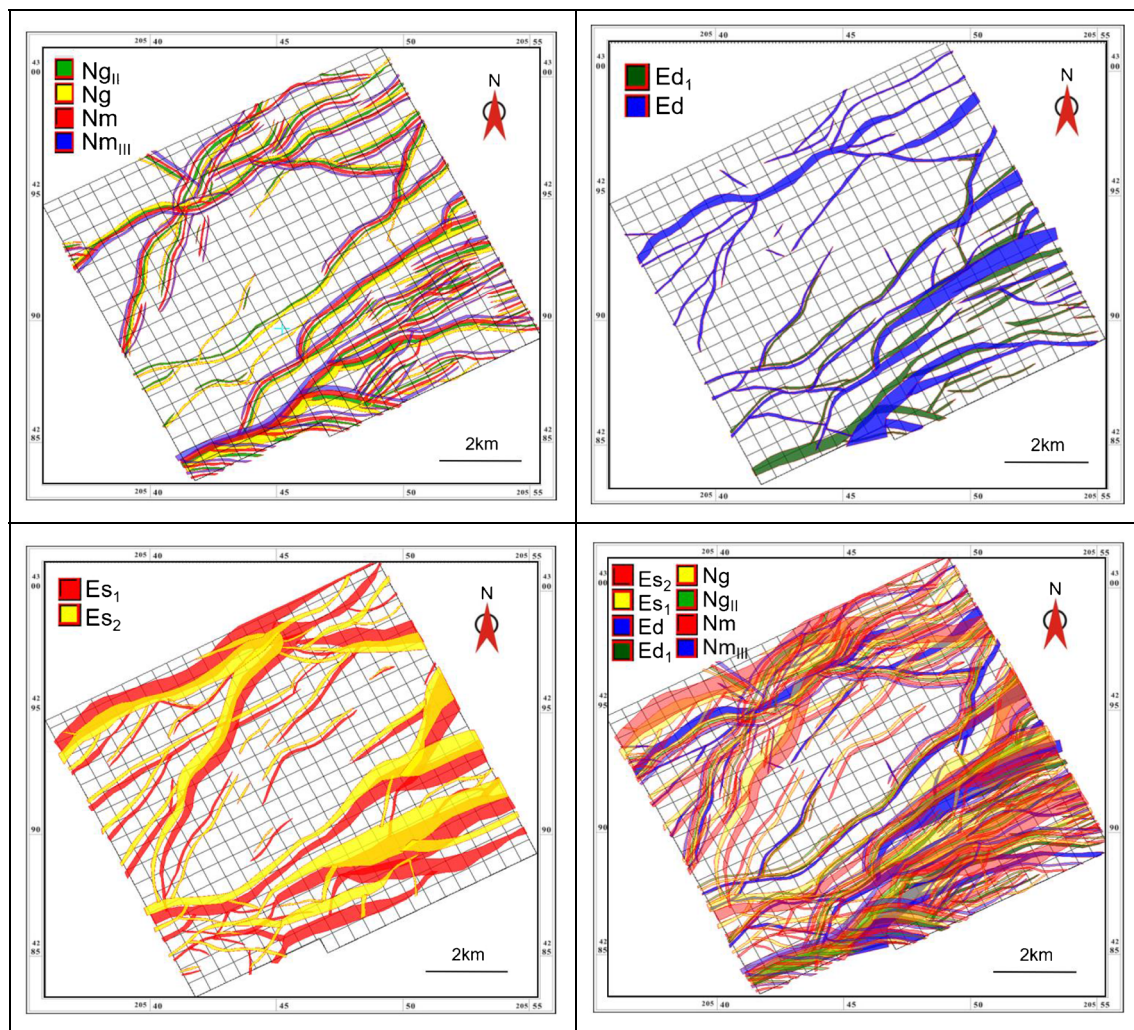
**Fig. 9** Fault superimposition in different depositional periods

lacustrine deposits with rich organic matters were developed (Miao et al. 2007; Qi et al. 2011; Song et al. 2015). Reservoir rocks are sandstone with various grain sizes, sandy conglomerates, and glutenite in fluvial-deltaic environments (Meng et al. 2011; Wang et al. 2013; Zhang et al. 2015). Widespread mudstone in the third member of the Dongying Formation and the first member of Shahejie Formation acts as regional seals (cf. Qi et al. 2011; Zhang et al. 2015). Both source rocks and reservoirs are distributed unevenly throughout the study area, as a result, the distribution of possible migration pathways and entrapments is complex. Stratigraphic pathways, for example, sandy and conglomeratic facies, are mainly located in steep-slope zone, where porous sediments provided possible migration pathways or host accumulation for hydrocarbon. Silty and shaly clastic rocks mainly act as lateral or vertical seal. In central sag, both sandy and silty facies are interpreted to have contributed to working petroleum systems. Normal faults, another important pathway for hydrocarbon migration, are active at different geological periods throughout basin evolution.

Syn-depositional fault control on hydrocarbon migration

The controls of syn-depositional faults on hydrocarbon migration and accumulation are addressed as follows (Fig. 10):

(1) The syn-depositional faults in steep-slope zone

Normal faults in steep-slope zone commonly control the structural framework during basin evolution. They are long-term active and make it possible to communicate the source kitchen and allow upward migration. Besides, the activity of these faults influenced the distribution of depositional systems such as alluvial fans, fan deltas, and few braided-river deltas. These sandy deposits are the source of reservoirs. Structural traps were developed in the zone, including concentrated faulted closures and occasional rollover anticlines. Syn-depositional faults penetrated into deep part of the sag and allow upward hydrocarbon migration and accumulation into these traps, which makes
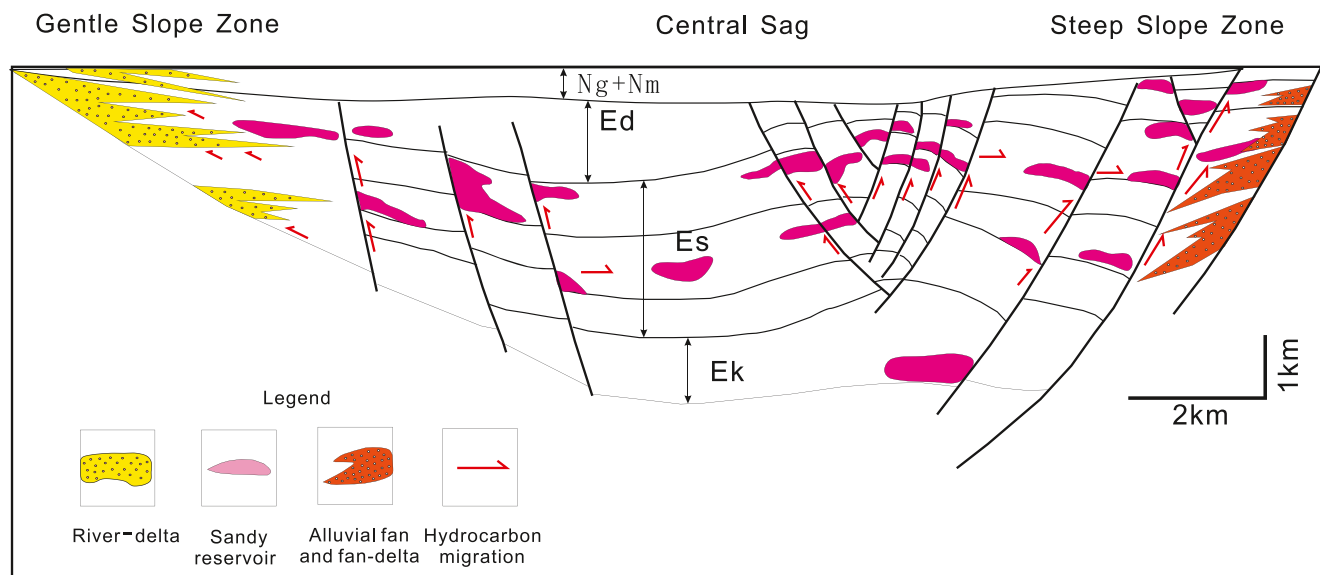
Fig. 10 Conceptual model showing syn-depositional fault control on hydrocarbon migration and accumulation in the study area

the steep = slope zone the most beneficial for hydrocarbon migration and accumulation.

(2)   The syn-depositional faults in gentle-slope zone

The faults in gentle-slope zone are less active than those in the steep-slope zone. Therefore, their impacts on facies distribution are limited. The depositional systems are dominated by braided-river deltas and occasional fan deltas. The sandy deposits are widely distributed. Due to limited fault activities, the seals are contributed by mudstone from delta front and pro-delta (cf. Li et al. 2009; 2018). Hydrocarbon migration is featured by fluid flow laterally through porous carrier beds or, in some cases, vertically through faults.

(3)   The syn-depositional faults in central sag

The faults in central sag contain the most variation in controlling the hydrocarbon migration and accumulation. In most cases, they did not penetrate into source rocks except strike-slip faults (Hsiao et al. 2010). Therefore, hydrocarbon is proposed to come from either gentle- or steep-slope zones. Flower-like faults usually were developed in shallow strata and controlled axial facies distribution. Reservoirs are derived from meandering river delta and sub-lacustrine fans (cf. Zhang 2006). The seal depends mostly on surrounding lithology, (especially mudstone). Hydrocarbon migration is featured by fluid flow vertically through faults.

Erosion and deposition influenced by multiple factors (mainly syn-depositional fault)

It has been universally accepted that global sea/lake level fluctuation, tectonic subsidence, climate change, and sediment supply are key factors in controlling the occurrence of erosion and deposition. Especially in tectonically active rift lacustrine basin, the strength and timing of tectonic activities exert strong influences on the depositional pattern of basin fills. With no doubt, the development of syn-depositional faults generated by regional tectonic activity will constrain hydrocarbon migration and accumulation with regard to source rocks, reservoirs, seals, pathways, and traps. When tectonic activities strengthen, one might argue for syn-depositional faults being active during hydrocarbon migration, there will be intermittent short periods where their porosity, permeability, saturation, and capillary structure will be enhanced. The activation of syn-depositional faults may provide pathway for hydrocarbon to migrate from high potential field to low potential field. In the meantime, the uplift side of syn-depositional faults can form a lateral-pinch out trap for hydrocarbon accumulation. Here is the question: is there a general pattern of syn-depositional fault controlling hydrocarbon migration and accumulation in different stages of tectonically active rift lacustrine basin?

Conclusions

(1)   The fine seismic interpretation in tectonically active Tangbei area makes it possible to get better insights about the distribution of syn-depositional faults generated by regional tectonic activities.
(2)   Syn-depositional faults map exert impact on basin structure and controls the pathways and traps, and therefore determine hydrocarbon migration and accumulation in tectonically active areas.

(3) Syn-depositional faults in different structural locations have proposed to be key factors for controlling hydrocarbon migration and accumulation. The syn-depositional fault in steep slope zone is much better for hydrocarbon migration and accumulation in terms of source rocks, reservoir, seals, traps, and pathways.

(4) The paper outlines an effective method for studying hydrocarbon migration and accumulation controlled by syn-depositional faults through fine seismic interpretation process. The process is expected to aid the understanding of a prospect area, to help gain more insights into future exploration tasks, and ultimately to support business decisions.

Compliance with ethical standards

Conflict of interest   The authors declare that they have no conflict of interest.

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