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Neogene-Quaternary post-rift tectonic reactivation of the Bohai Bay Basin, eastern China

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ABSTRACT

The Bohai Bay Basin, located in the eastern China, is considered to be a Cenozoic rifted basin. The basin is atypical in terms of its Neogene-Quaternary post-rift subsidence history in that it experienced intensive tectonic reactivation, rather than the relative tectonic quiescence experienced during this stage by most rift basins. This Neogene-Quaternary tectonic reactivation arose principally in response to two tectonic events: (1) activity on a dense array of shallow faults and (2) accelerated tectonic subsidence that occurred during the post-rift stage; these two events were neither strictly temporally nor spatially equivalent. The dense array of shallow faults form a NW-SE trending belt in the central part of the basin, with displacement on them having been induced by the reactivation of older northeast- and northwest-trending basement faults and an associated substantial component of strike-slip displacement occurring after 5.3 Ma. The intense reactivation of these faults contributed to the atypical accelerated rate of post-rift tectonic subsidence of the basin, which commenced ~12 Ma. However, this was not the sole cause of this accelerated tectonic subsidence: a combination of geological activity at a deep level within the crust led to the build-up of intraplate stresses and this, combined with on-going thermal subsidence, acted as additional contributory factors that drove unusually high rates of subsidence for this basin. This episode of accelerated post-rift tectonic reactivation resulted in conditions favorable for hydrocarbon accumulation.

Keywords: *Bohai Bay Basin, Neogene, Quaternary, tectonic reactivation, shallow faults, post-rift tectonic subsidence, craton destruction*

INTRODUCTION

The majority of rifted basins evolve in two main stages: the rifting stage and post-rift subsidence stage. Post-rift subsidence is typically characterized by an episode of relative tectonic quiescence characterized by significantly reduced (or zero) fault activity and relatively slow rates of thermal subsidence (e.g. Anza rift in Kenya, Bosworth and Morley, 1994; the Atlantic continental margin, North Sea rift system, Bott, 1995; Sirt Basin of Libya, Abadi et al, 2008). Contrary to this usual behavior, the Bohai Bay Basin of eastern China, which evolved as a Cenozoic rift basin, experienced intense tectonic reactivation during the post-rift stage that was characterized by intense faulting and substantial rates of tectonically induced subsidence. This evolutionary characteristic of the Bohai Bay Basin has been noted previously (e.g., Hu et al, 2001; Gong and Wang, 2001; Gong, 2004a, 2004b; Hsiao et al, 2004; Gong et al, 2010). However, results from these earlier studies simply recognized the two tectonic events (strong faulting and anomalously high rates of tectonic subsidence) and noted their role in determining the hydrocarbon habitat of the basin. As a consequence, several significant issues relating to these tectonic events have not previously been thoroughly examined in detail, including the documentation and analysis of the specific characteristics relating to the distribution and development of post-rift renewed faulting, the timing and location of zones of accelerated subsidence across the basin, and the relationship of one to the other.

The aim of this study is to undertake a thorough investigation of the spatial and temporal characteristics of the mechanisms and style of tectonic reactivation in the Bohai Bay Basin, and to account for the specific characteristics and original relationships of two significant tectonic events: strong faulting and anomalously high rates of tectonic subsidence. This is achieved through analysis of a large and varied dataset derived from an extensive program of hydrocarbon exploration in the basin. Specific objectives of this study are to: (1) critically assess current models that account for the style of Neogene-Quaternary structural deformation in the Bohai Bay Basin; (2) discuss the influence of the post-rift tectonic reactivation on the structural evolution of the basin and its role in influencing hydrocarbon accumulation and habitat; (3) provide a novel case study for post-rift tectonic reactivation and evolutionary history of a rifted basin.

GEOLOGICAL SETTING OF THE BOHAI BAY BASIN

The Bohai Bay Basin is a major continental petroliferous basin located in eastern China; the entire basin occupies an area of ~200,000 km^2 (77,220 mi^2), of which the offshore part covers ~73,000 km^2 (28,185 mi^2). The basin is surrounded by uplifted Precambrian basement blocks: the Taihang Shan to its west, Yanshan to its north, Luxi to its south, and Jiaoliao to its east. Internally, the basin is characterized by several secondary structural units, such as sags and rises, giving it a 'basin-and-range' type of structural configuration (Figure 1). Previous studies have convincingly demonstrated the overall structural feature to be a rifted basin (e.g. Li, 1980; Ye et al, 1985; Yang and Xu, 2004； Zhu et al, 2009) that was locally influenced by strike-slip movement (Hu et al，2001; Huang et al, 2012b). The evolution of the basin can be clearly divided into two stages: the Paleogene rifting stage and Neogene-Quaternary post-rift stage. The Paleogene rifting stage is characterized by extension and rifting, tilting of fault blocks, half-graben development and filling, and is additionally associated with volcanic activity. By contrast, the Neogene-Quaternary post-rift stage is characterized by the accumulation of a thick succession of relatively uniform and nearly flat-lying strata that gently thickens toward the basin center, giving rise to a steer-head basin geometry (Figure 2).

The fill of the Paleogene rift stage of basin evolution consists of three sedimentary sequences represented by the Kongdian, Shahejie and Dongying formations, which collectively have a total thickness of 3,000 to 7,000m (9,842-22,965 ft) and which represent a succession of non-marine, clastic strata (Figure 3). By contrast, three sedimentary sequences record the Neogene-Quaternary post-rift fill of the basin and these are represented by the Neogene Guantao and Minghuzhen formations and the Quaternary Pingyuan Formation with a total thickness of 1,000 to 5,000m (3,281-16,404 ft), each also of mostly non-marine (fluvial) origin (Figure 3). The offshore part of the basin (called the Bozhong Depression), has a sedimentary fill of up to 4,000-5,000 m (13,123-16,403 ft) thick, and became a major depocenter in the basin during the post-rift stage.

Within the Bohai Bay Basin, three major groups of fault system are developed: NNE (or NE)-trending, NW-trending and east-west-trending. The majority of faults in these groups can be shown to have existed prior to the Cenozoic, and to have experienced repeated movement and displacement of different intensities during the Cenozoic (Li, 1980; Ye et al, 1985; Zhu et al, 2009). The NNE(or NE)-trending faults form the dominant group of structures present across the majority of the Bohai Bay Basin, and these experienced intense right-lateral motion during the Neogene-Quaternary; among them, the well-known Tan-Lu Fault Zone occupies a position close to the eastern edge of the basin and is considered to have exerted the most significant control on basin development (Klimetz, 1983; Chen and Nabelek, 1988; Allen et al, 1997, 1998; Hou et al, 1998; Gong et al, 2007, 2010; Zhu et al, 2009).

Additional NW-trending and east-west-trending faults are developed in the offshore portion of the basin. The NW-trending faults had a component of left-lateral motion during the Neogene-Quaternary. Within this group, the Zhangjiakou-Penglai Fault Zone, which runs through Bohai Bay, is especially significant since it is a very large and active, yet hidden, basement fault that behaves in a conjugate relationship with the Tan–Lu Fault Zone in terms of the sense of slip movement. This fault zone is associated with a presently active seismic zone from which many historical and recent earthquakes have been recorded (Liu, 1987; Fu et al, 2004; Figure 1).

MAIN MANIFESTATIONS OF NEOGENE-QUATERNARY TECTONIC REACTIVATION

During the Neogene-Quaternary post-rift subsidence stage, some regions in the Bohai Bay Basin experienced an anomalous tectonic evolutionary process marked by intensive tectonic reactivation, which is usually referred to as neotectonism in the existing literature (e.g. Zhu et al, 2009; Gong et al, 2010). The most notable manifestations of this are two tectonic events: (1) the development of a dense network of shallow faults and (2) accelerated rates of tectonic subsidence. These two events are best known because of their significant influence on the hydrocarbon habitat of the basin.

Numerous angular unconformities of regional extent are recognized in the Neogene-Quaternary sequence and these developed in response to deformation associated with compressional stress and tectonic uplift, and also indicate intensive tectonic reactivation during this period. Of these unconformities, the most obvious one is located at the base of the Quaternary succession and is characterized by truncation of a broad anticline in the underlying strata; this unconformity demonstrates that an intensive regional compressive tectonic event occurred at about 2.6 Ma (Huang et al, 2012a).

Investigations of a major river terrace that developed in response to tectonic activity around the Bohai Bay Basin demonstrate at least 3 phases (episodes) of tectonic activity during the Quaternary in the Bohai Sea, and these occurred in the late Eopleistocene (900-400 Ka), the late to middle Pleistocene (100-80 Ka) and the late Epipleistocene（10-8 Ka）(Xu et al, 2005; Gong, 2005; Gong et al, 2007).

Frequent historic and recent earthquakes also demonstrate intense tectonic activity in the Bohai Bay Basin (Chen and Nabelek, 1988; Hsiao et al, 2004; Fu et al, 2004; Zhu et al, 2009). The epicentres for these earthquakes describe a distinctive pattern of distribution (Figure 4): (1) they occurred along the NNE(or NE)-trending and NW-trending basement faults, and were characterized by focal points that were notably arranged into a dense cluster in the NW-trending middle segment of the basin, corresponding to the Zhangjiakou-Penglai Fault Zone (Fu et al, 2004); (2) statistical analysis has shown that most earthquakes greater than 6.0 Ms occurred in Tan–Lu Fault Zone and Zhangjiakou-Penglai Fault Zone, and most earthquakes greater than 7.0 Ms occurred at or close to the intersection of these two fault zones (Teng et al, 1997). The focal mechanism solutions for these earthquakes indicate NE-trending right lateral slip (Chen and Nabelek, 1988).

NEOGENE-QUATERNARY FAULTS

Geometrical Characteristics and Spatial Distribution

In the middle of the Offshore Bohai Sea (the Bozhong region), seismic data reveal two different sets of normal fault systems developed in Paleogene and Neogene-Quaternary strata; the sections and time slices from three-dimensional (3-D) seismic show the following characteristics for the Neogene-Quaternary faults:

(1) The pattern of arrangement of faults exhibits significantly greater density in Neogene-Quaternary strata compared to Paleogene strata, and the arrangement becomes progressively denser with decreasing depth. The density of the Neogene-Quaternary faults is apparently mostly controlled by the pre-existing palaeogeomorphology, being greater at the margin of the Paleogene half-grabens and grabens (Figs 5 & 6).

(2) Some of the Neogene-Quaternary faults were inherited from the NNE (or NE)-trending and NW-trending Paleogene or basement faults. However, many additional newly formed faults developed adjacent to these inherited faults during this time, and most of these extend downward to the top of the Dongying Formation and upward to the sea floor. The majority of these more recent faults (though not all) grew to a size where they became connected with the older, inherited faults (Figure 5).

(3) The pattern of arrangement of most faults gives rise to a “flower structure” in section view. This is characterized by an upward divergent pattern of faulting in Neogene-Quaternary strata and a merging of faults at depth with the basement faults (either sub-vertical strike-slip faults or listric normal faults) in Paleogene strata (Figure 5).

(4) Most of these faults trend either NE-SW or close to E-W, have a small size in plan-view, and are related to the large NNE (or NE)-trending and NW-trending basement faults (Figure 7).

(5) The distribution of faults becomes progressively denser with increasing proximity to basement faults, and most trend at an acute angle to the main basement faults, displaying

an *en-echelon* pattern in plan-view (Figure 6, 7).

Together, these characteristics indicate that the Neogene-Quaternary faults are mostly the subsidiary normal faults of NNE (or NE)-trending and NW-trending basement faults reactivated in strike-slip movement. Most of these basement faults are the boundary faults of the Paleogene half-grabens and grabens, thereby resulting in a denser arrangement of faults at the margin of the Paleogene half-grabens and grabens.

By contrast, the Liaodongwan region in the north of the offshore Bohai Sea has a markedly different style of Neogene-Quaternary fault development (Figure 6 and seismic line F in Figure 8): only a few faults are developed in the Neogene-Quaternary strata, far less than that in the Paleogene strata, and these become progressively more sparse with increasing proximity to the surface. Most of these Neogene-Quaternary faults were inherited from the older faults that controlled the development of Paleogene sags. More recently formed faults that can be shown not to have been inherited from the older faults are few in number, as are subsidiary faults related to the reactivation of the older faults during Neogene-Quaternary. The situation in the southern portion of the Bohai Bay Basin (the Jiyang Depression) is very similar to that in the Liaodongwan region: both regions are characterized by a relatively small number of Neogene-Quaternary faults (Figure 8). Furthermore, a similar pattern of Neogene-Quaternary fault development also exist in the western portion of the Bohai Bay Basin (the Jizhong and Huanghua Depressions) (Zhai, 1988; Editorial Committee of Petroleum Geology of Dagang Oil Field, 1991; Liang, 2001; Li et al, 2009; Ren et al, 2010).

The arrangement of Neogene-Quaternary faults into dense networks is therefore confined to a NW-trending belt with a width of about 200 km running through the Bohai Sea from east to west (as shown in Figure 1C). The boundary between the dense and sparse arrangements of Neogene-Quaternary faults can be reliably identified via analysis of hydrocarbon exploration data in the basin. For example, the boundary between the Liaodongwan and Bozhong regions is evident from and can be constrained by the shallow faults' distribution map and the 3-D seismic time slice (Figure 6A, C); two seismic sections located on either side of the boundary reveal differences in the style of Neogene-Quaternary faulting (Line D in Figure 5 versus Line F in Figure 8). The boundary between the middle and southern portions of the Bohai Bay Basin can also be identified from seismic data (Lines G and H in Figure 8).

Based on the above-mentioned investigations of Neogene-Quaternary faulting, the following conclusions can be reached: (1) the Bohai Bay Basin can be divided into northern, middle and southern segments (Figure 1C); (2) a dense arrangement of Neogene-Quaternary faults developed in the middle segment, whereas sparse arrangement of Neogene-Quaternary faults developed in the northern and southern segments.

Evolutionary History

In this study, reconstructed rates of active dip-slip faulting have been used to reveal the faults′ evolutionary history. This approach assumes that differences in the thickness of syn-kinematic strata between the hangingwall and footwall of individual fault planes are related to active periods of fault slip (cf. Maloney et al, 2012); thus, for any given stratal interval, the ratio of the thickness difference between the hangingwall and footwall and duration of the interval over which the body of strata accumulated can be used as an indicator of dip-slip faulting rate (for details of the method of calculation employed, see Fig. 9C). The assumption in this method requires that time-averaged sedimentation rate is equal to or greater than the rate of fault slip during synchronous periods of deposition and fault activity (Cartwright et al, 1998; Maloney et al, 2012). Sedimentation rates in the region where the investigated faults are located have been approximately determined from the ratio of the present stratal thickness and the relating sedimentary duration via seismic data. Results show that all the Neogene-Quaternary stratal intervals considered had sedimentation rates greater than rates of fault slip (>25 m/Myr for N_1g, >60 m/Myr for N_2m^L, >100 m/Myr for N_2m^U, and >150 m/Myr for Q_p); the assumption made in the method is therefore reasonable for this study.

Rates of active dip-slip fault displacement have been calculated for individual faults and average rates have additionally been calculated for groups of main faults in the southern part of the Offshore Bohai Bay Basin (Figure 9A and B). Results for individual faults show that the larger faults that controlled the development of Paleogene half-grabens had higher active rates of dip-slip during the Paleogene, whereas, for the majority of faults that did not penetrate the entire Paleogene succession, the rate of active dip-slip during the lower Paleogene was less (Fig. 5, F4 in Line B). In the post-rift stage, the majority of faults have a greater rate of fault movement during N_2m^u-Q_p deposition (5.3 Ma to the present day) compared to that experienced during N_2m^L-N_1g deposition (24.6 Ma to 5.3 Ma), and many faults apparently were not active during N_1g (24.6 Ma to 12 Ma) deposition (Figure 9A). Similar results relating to average active rates of fault movement also reveal more generally that the faults exhibited the highest rates of displacement during N_2m^u-Q_p deposition (5.3Ma to the present day) for the whole post-rift stage (Figure 9B).

Analysis of 3-D seismic data indicates that the Neogene-Quaternary faults in the middle segment of the basin were mainly developed after 5.3 Ma, which is supported by the following observations (Figure 10): (1) the number of faults present in the sequence that accumulated from 5.3 Ma to the present day is more than twice the number of faults present in the sequence that accumulated from 12 Ma to 5.3 Ma (Figure 10A); (2) the sequences that accumulated from 24.6 Ma to 5.3 Ma reveal no visible difference in thickness in the stratal packages present in the hangingwall and footwall of most Neogene-Quaternary faults, suggesting no syn-depositional fault activity for this period, despite many such faults having a throw of several hundreds of meters. This indicates that these faults were effectively inactive during this period (Figure 10B); (3) a large number of faults extend upward to the sea floor, demonstrating that they remain active to the present day. Given the above-mentioned frequent occurrence of historic and recent earthquakes in the Bohai Sea, this is to be expected. Indeed, the distribution of these earthquakes and focal-mechanism solutions demonstrate the close relationship between the Neogene-Quaternary faults and the strike-slip behavior of the Tan–Lu and Zhangjiakou-Penglai fault zones (Chen and Nabelek,1988; Hsiao et al, 2004; Fu et al, 2004; Zhu et al,2009).

Origin and Controls

The Neogene-Quaternary faults in the Bohai Bay Basin demonstrate that the NW-trending middle segment of the basin experienced intense faulting during the post-rift subsidence stage; this behavior is inconsistent with the style of evolution of typical rifted basins, which tend to be characterized by steady but generally weak faulting during the post-rift subsidence stage (Mckenzie, 1978; Ziegler and Cloetingh, 2004). Based on the geometrical characteristics and the distributions of the faults, it can be concluded that the faulting was closely associated with the NNE (or NE)-trending and NW-trending basement faults, and activity on these post-rift faults was mostly induced by the reactivation of these two major fault systems with a significant component of strike-slip movement during the Neogene and Quaternary. It is there therefore appropriate to refer to this phase of intense tectonic activity in the Bohai Bay Basin as Neogene-Quaternary tectonic reactivation.

The occurrence in the basin of a NW-trending belt characterized by dense, shallow faults implies that the NW-trending Zhangjiakou-Penglai Fault Zone played the most significant role. Noticeably, the NNE-trending Tan-Lu Fault Zone runs through the eastern part of the basin rather than the middle segment of the basin; the intensive faulting along this fault zone also occurred in the northern and southern segments of the basin during Neogene-Quaternary, and this was characterized by a single dominant fault that extended upward to a shallow level and even to the sea floor apparently without association to a dense network of subsidiary normal faults (Figure 6, Line F in Figure 8). Thus, it is worth discussing the likely conditions required to cause such differences in the overall spatial pattern of distribution of Neogene-Quaternary faults.

Analysis of the conditions required for the formation of Neogene-Quaternary faults demonstrates that both the density and pattern of these shallow faults were probably related to the thickness of Neogene-Quaternary strata. Considering this aspect, four types of behavior are envisaged to account for the development of shallow faults in the Bohai Bay Basin (Figure 11):

Type I: in areas characterized by a very thick accumulation of Neogene-Quaternary strata (equating to more than 2 seconds two-way travel time on the seismic profiles), such as the central portion of Bozhong sags and other deeper sags, the shallow faults are very densely packed, most were initiated during the Neogene-Quaternary, and a small number are not connect with the older faults either directly or indirectly (Figure 5: left part of Line A, right part of Line B and Line E). In this situation, one single old fault apparently induced the initiation and development of a wider network of Neogene-Quaternary faults.

Type II: in areas characterized by a moderate thickness of accumulation of Neogene-Quaternary strata (equating to about 1 to 2 seconds two-way travel time on seismic profiles), shallow faults are arranged into a very dense pattern; most were initiated during the Neogene-Quaternary, and nearly all connect with the older faults either directly or indirectly. In this situation, one single old fault, either a sub-vertical strike-slip fault or a listric normal fault, apparently induced a narrower network of Neogene-Quaternary faults than in the first situation (compare the left part and right part of Line A in figure 5).

Type III: in areas characterized by a very thin accumulation of Neogene-Quaternary strata (equating to less than 1 second two-way travel time on seismic profiles), such as the northern and southern segment of the basin, the shallow faults that elsewhere form dense networks are very sparse, and in places only the major Paleogene faults extend upward to the shallow level and even to the sea floor (Figure 8).

Type IV: elsewhere in the areas characterized by a very thin accumulation of Neogene-Quaternary strata (equating to less than 1 second two-way travel time on seismic profiles), denser arrangements of shallow faults may occur. This type of situation only occurs in eastern part of the middle segment of the basin where the NW-trending Zhangjiakou-Penglai Fault Zone and NNE-trending Tan-Lu Fault Zone intersect (right parts of geological section XX′ in Figure 2 and seismic line A in Figure 5).

Based on the above discussion, the origin of the dense Neogene-Quaternary faults in the middle segment of the basin arose mainly in response to two conditions: (1) the interaction between the NW-trending and NNE(or NE)-trending faults, and (2) the occurrence of a thicker developed succession of Neogene-Quaternary strata. Both of these conditions favor the occurrence of a greater number of subsidiary faults at relatively shallow levels.

The great majority of Neogene-Quaternary faults discussed above were induced by the reactivation of older faults; exceptions to this are a relatively small number of Neogene-Quaternary faults that were initiated by other conditions, including faults associated with igneous intrusions, as illustrated by seismic sections B and E (Figure 5).

ACCELERATED TECTONIC SUBSIDENCE

A second noteworthy characteristic of the Neogene-Quaternary evolution of the Bohai Bay Basin is a marked acceleration in the rate of tectonic subsidence that occurred at ~12 Ma. This event has been documented by the previous researchers (Hu et al, 2001; He and Wang, 2003; Xie et al, 2007) and has been interpreted as rapid tectonic subsidence that was considered to result from the dextral movement of the Tan-Lu Fault Zone. Further analysis and interpretation of this phenomenon is provided in this study.

The back-stripping method (Steckler and Watts, 1978) is herein used to quantify the rate and history of tectonic subsidence in the main structural units (including rises and sags) of the Bohai Bay Basin for the Cenozoic and Quaternary. Data from 120 wells have been analyzed. A correction for compaction has been applied using porosity-depth relationships based on the observed lithologies, and by using standard mean exponential relationships, and material parameters (cf. Sclater and Christie, 1980). Input data include lithology, age and paleo-water depth. Lithologies and stratal ages have been obtained from well data; the biostratigraphy of Neogene-Quaternary strata have been studied in detail for the offshore the Bohai Sea (e.g. Deng and Li, 2008; Zhu et al, 2009), such that data pertaining to lithology and stratal ages for all investigated wells are credible. Paleo-water depths are inferred from depositional environment; the water depths during Paleogene rifting stage are restricted to a narrow range of less than 50 m because most of the sediments were deposited in continental shallow lacustrine environments (Figure 3); by contrast, the water depths during Neogene-Quaternary post-rift stage are treated as zero because the great majority of the succession accumulated in a non-marine fluvial environment.

The wells used in this study are distributed in a non-uniform arrangement across both the rises and sags, through more are located on the rises. Despite this, because the Neogene-Quaternary strata are relatively uniform and near-flat-lying with only gradual thickening to the basin center, it can be demonstrated that the Paleogene topography exerted only a modest influence on the thickness of accumulation of the succession; thus, the pattern and history of Neogene-Quaternary subsidence revealed by the studied well data reflects the overall trends for the entire basin. Given that some wells in the basin have been drilled on Neogene structural highs, care is required to ensure that these wells do not bias results due to the occurrence of locally anomalous data; considering this aspect, data from these wells have been ignored to eliminate this risk in this study. Given that the analysis of Paleogene subsidence is not the focus of this study, the data obtained solely from wells located in sags are considered sufficient for this analysis.

Tectonic subsidence curves for the entire Cenozoic and Neogene-Quaternary post-rift stage are shown in Figure 12. The curves (Figure 12A) reveal an anomalous post-rift tectonic subsidence history that is characterized by a marked increase in subsidence rate. This differs significantly from the theoretical trend predicted by conventional post-rift subsidence models, which predict an exponentially decreasing rate of subsidence. This departure from the expected norm is demonstrated by comparison of subsidence curves from this study with theoretical post-rift tectonic subsidence curves arising from different stretching factors in a theoretical rift basin (cf. Baur et al, 2010) in Figure 12A.

To more fully describe and analyze the change in tectonic subsidence a distinction is here made between rapid tectonic subsidence and accelerated tectonic subsidence. Rapid tectonic subsidence refers to a change in total tectonic subsidence in space, whereas accelerated tectonic subsidence emphasizes a change in tectonic subsidence rate over time; in this study, the former term is reflected by the total tectonic subsidence of several sedimentary intervals (Ng, N_2m^L, N_2m^U, Q) (Figure 13), whereas the latter term is reflected by the accelerated rate of tectonic subsidence relative to the N_1g tectonic subsidence rate (accelerated intensity or AI for short, Figure 14); a steepening of the slope of the tectonic subsidence curve (distance/time) for a given point demonstrates accelerated subsidence (Figure 12B). For comparison, the contour maps in Figures 12 and 13 illustrate well the difference between the two terms: the area with greater total tectonic subsidence (i.e., rapid tectonic subsidence) may not necessarily experience an increase in the accelerated intensity of tectonic subsidence. The two terms have no strict inter-relationship or dependency (potential reasons for this are discussed below).

From this study, the following interpretations are made regarding the Neogene-Quaternary tectonic subsidence of the Bohai Bay Basin:

(1) Rapid tectonic subsidence occurred distinctly in the middle segment of the basin during the Neogene-Quaternary, and was characterized by increased total tectonic subsidence. It has a regular pattern such that the total tectonic subsidence is greatest in the Bozhong region (i.e., the Bozhong depression) during each sedimentary interval but gradually decreases with distance away from the center of this region. The Liaodongwan region, for example, experienced no deposition from 5.3-2.6 Ma and consequently had a zero tectonic subsidence during this interval (Figure 13).

(2) From the changes in the slope of the post-rift tectonic subsidence curve (Figure 12B), the following interpretations are made. The tectonic subsidence of the later post-rift subsidence stage (12-0 Ma) in the entire Bohai Bay Basin was clearly accelerated relative to that of the early post-rift subsidence stage (24.6-12 Ma) and this change is here defined as an accelerated tectonic subsidence event. Indeed, three phases of accelerated tectonic subsidence are recognized: 12-5.3 Ma, 5.3-2.6 Ma and 2.6-0 Ma. Most of the data reveal that the accelerated intensity of the three phases increased with time, with the exception of

data from the Liaodongwan region, which did not experience tectonic subsidence from 5.3-2.6 Ma. This phenomenon identified here is inconsistent with the theoretical understanding regarding a purely thermal subsidence history during the post-rift thermal subsidence stage of rifted basin evolution, which is characterized by an exponential reduction in the rate of subsidence over time (Mckenzie, 1978).

(3) Contour maps of the accelerated intensity (AI) based on analysis of well data reveal some detailed information about the nature of the accelerated tectonic subsidence (Figure 14): the entire configuration of the contours is similar with that of the contours of total tectonic subsidence in Figure 13, although it is important to note that the center of the Bozhong Depression, which has a greater total tectonic subsidence has a smaller accelerated intensity, whereas the area around the depression has a larger accelerated intensity. Also, the Liaodongwan region has a negative accelerated intensity during the period from 5.3-2.6 Ma due to the zero tectonic subsidence. The overall distribution of the contours is not strictly controlled by the location of the NE-trending Tan-Lu Fault Zone and this indicates that the dextral movement of this fault zone exerted only a weak influence on the accelerated tectonic subsidence.

(4) The rapid tectonic subsidence in the Bozhong region is characterized by a large total tectonic subsidence that was initiated during the N_1g deposition following the rifting stage of the whole basin (Figure 13). This is consistent with the location of the depocenter and subsidence center of the whole Paleogene rifting basin; it may therefore reflect a natural evolutionary process of the rifted basin. By contrast, the onset of accelerated tectonic subsidence at 12Ma, which occurred in the whole basin and even in the entire East Asia continental margin (Hu et al., 2001; Ren et al, 2002; Yang et al, 2004; Xie et al, 2006), may reflect a change of regional geodynamic setting. Significantly, the occurrence of similar accelerated tectonic subsidence events in other rifted basins during their post-rift subsidence stages are usually considered to have arisen as an effect of intraplate stresses (e.g. Southern North Sea, Kooi et al.,1991; Black Sea Basin, Cloetingh et al., 2003). Thus,

it is conceivable, and arguably likely, that the post-rift subsidence of the Bohai Bay Basin was markedly influenced by intraplate stresses.

(5) The final phase of accelerated tectonic subsidence (2.6 Ma to present) was most the intense and extensive (Figure 14B), implying that it arose in response to a dynamic setting that operated over a broad region. Noticeably, this phase of accelerated tectonic subsidence was more intense in some parts of the Liaodongwan region than in the other parts of the basin. By contrast, the Bozhong region, which experienced a greater total tectonic subsidence during the Quaternary and which is characterized by a relatively thick Neogene-Quaternary sedimentary succession, experienced weaker accelerated tectonic subsidence during this period (Figure14B).

DISCUSSION

Relationship between the Neogene-Quaternary Faults and Accelerated Tectonic Subsidence

The enhancement of the syn-depositional normal faulting is the usual mechanism that results in accelerated tectonic subsidence; the rifting stage with intense faulting would be expected to result in a faster rate of tectonic subsidence than the post-rift stage. However, during the post-rift stage of the Bohai Bay Basin, the faulting also caused accelerated tectonic subsidence, as illustrated by the horizon-flatted seismic section in Figure 10B, for example, where the hangingwall reveals a thicker accumulated succession, thereby demonstrating syn-depositional fault activity (5.3-0 Ma). Thus, the accelerated intensity of the tectonic subsidence rate around the Bozhong Depression is greater than in the center of the depression; this may be due to the development of the network of dense faults around the depression (Figure 14).

A significant question is to be resolved is whether all the accelerated subsidence of the Bohai Bay Basin occurred in response to the Neogene-Quaternary faulting. If this was the case then the accelerated subsidence would likely have occurred in the hangingwall only, whereas the footwall and areas where no active faulting was present would not have been subjected to accelerated subsidence. Following this reasoning, we use the Neogene-Quaternary tectonic subsidence history from two wells (Well-1 and Well-2), located on the hangingwall and footwall of a master fault, to reveal the relationship between tectonic subsidence and faulting intensity (Figure 15). The following observations are made. (1) During the N_1g deposition, the master fault ceased activity, whereas the footwall (Well-2) experienced more rapid tectonic subsidence than the hangingwall (Well-1); since that time, the master fault experienced intensive activity and tectonic subsidence in the hangingwall was substantially accelerated (especially during N_2m^u and Q); this demonstrates that the intense reactivity of the fault did indeed induce the accelerated subsidence. (2) for the same period, variation in the slopes of the two curves record that some accelerated subsidence occurred in *both* the hangingwall and the footwall; this trend implies that the accelerated subsidence is not entirely produced by the intense reactivity of the fault alone.

Furthermore, comparison of the distributions of the densely spaced faults and the region that experienced an accelerated intensity of tectonic subsidence (Figure 6, 14) reveals that the two tectonic events did not wholly temporally nor spatially overlap and intense reactivation of the faults was not alone responsible for generating the entire component of accelerated subsidence; there must, therefore, be additional factors that contributed to the accelerated subsidence.

Geodynamics

Previous studies show that the Bohai Sea is the location of the thinnest crust and lithosphere in northern China (Teng et al, 1997; Griffin et al 1998; Kusky et al, 2007; R.X. Zhu et al 2012). The broader region has been generally referred to as the site of craton destruction in the North China Craton, and is associated with widespread crustal extension and the formation of many rift basins (e.g. Wu et al., 2005; Zhai et al., 2007; Li et al, 2010; G. Zhu et al., 2012; R.X. Zhu et al., 2012; Figure.1A). Results from this study suggest that the post-rift accelerated tectonic subsidence in the Bohai Bay Basin is most likely the manifestation of the reduced thickness of lithosphere, and is therefore a probable indicator of craton destruction in the North China Craton. Although the latest occurrence of craton destruction proposed previously has been early Cenozoic (Xu et al, 2009; R.X. Zhu et al., 2012), this post-rift accelerated tectonic subsidence may indicate a new phase of craton destruction in the North China Craton, with an onset age of 12 Ma. Furthermore, the widespread occurrence of a similar accelerated tectonic subsidence event, also with an onset age of 12 Ma, in the East Asia continental margin (Hu et al., 2001; Ren et al, 2002; Yang, et al, 2004; Xie, et al, 2006) indicates that the geodynamics of this tectonic event may be related to the subduction of the Pacific Plate relative to the Eurasian Plate. This conclusion is consistent with recent insights into dominant geodynamic controls on craton destruction of the North China Craton (R.X. Zhu et al., 2012).

Recent GPS measurement and seismo-tectonic studies show that the eastward extrusion induced by India-Asia convergence is the dominant mode of block kinematics in north of China (Shen et al., 2000; Wang et al, 2001; Xie et al, 2004; Xu et al, 2008). It is therefore possible, and arguably probable, that India-Asia convergence is the driving force responsible for the widepsread development of the dense networks of shallow faults after 5.3 Ma. Specifically, the far-field effect of this convergence could be responsible for the lateral movements on the massifs around the Bohai Sea Basin, which induced the intense reactivation of the basement faults and produced the high density Neogene-Quaternary faults. This intense faulting would contribute to the accelerated tectonic subsidence. The post-rift accelerated tectonic subsidence in the Bohai Bay Basin may therefore have arisen as a result of deep geological function involving intraplate stresses, combined with rift-basin thermal subsidence.

Influence of Tectonic Reactivity on Hydrocarbon Accumulation

The significance of the Neogene-Quaternary post-rift tectonic reactivation in terms of petroleum geology is that it produced numerous structural traps as well as directly reforming the primary pressure and fluid fields of the basin; thus, it induced the redistribution and re-accumulation of hydrocarbons. The following discussion points arise:

(1) The accelerated tectonic subsidence occurring after 12 Ma in the Bohai Bay Basin buried the Paleogene source rocks of the basin deeper, resulting in a higher maturity. This is especially the case for the Bozhong depression, offshore the Bohai Sea, site of the shallowest viable source rocks accumulated during Paleogene rifting stage (i.e., the source rock for the lower part of Dongying Formation). This additional subsidence enabled the source rocks to reach maturity due to the emplacement of additional overburden (Gong et al, 2010). Furthermore, as a direct result of accelerated tectonic subsidence, the offshore Bohai Sea deposited shallow, argillaceous lacustrine successions, and these likely served to enable the juxtaposition of seal and reservoir rocks required for the development of viable hydrocarbon plays (Deng and Li, 2008).

(2) The networks of dense Neogene-Quaternary faults provided the most important pathway for vertical hydrocarbon migration from the Paleogene sequence to the Neogene sequence. Although some previous studies argue against the function of these shallow faults as conduits for the transport of hydrocarbons (e.g., Hao et al, 2007), statistical data analysed as part of this study relating to discovered reserves in the offshore Bohai Sea demonstrate that, in the middle segment (Bozhong region) of the Offshore Bohai Sea, 61% of the reserves are hosted in the Neogene sequence, suggesting that the existence of shallow faults connecting the Paleogene source rock with the Neogene reservoir rock has been critical for enabling hydrocarbon migration (Figure 16). By contrast, in the Liaodongwan region, where shallow faults are sparsely developed, shallow hydrocarbon reservoir are few in number. Thus, it is here suggested that these shallow faults played an active role in vertical hydrocarbon migration, and were the critical in enabling the charging of Neogene reservoirs in the Offshore Bohai Sea. Direct evidence to support this claim includes the occurrences of gas chimneys imaged on seismic data and gas vent

pits observed on the seafloor in the Offshore Bohai Sea, which indicates that faults that extend upward to the sea floor are highly efficient pathways for gas seepage to the sea floor (Deng and Li, 2008; Gong et al, 2010).

Furthermore, fault patterns may also influence hydrocarbon accumulation (Figure 16): the Type II and Type IV fault patterns (described above) are most favorable for hydrocarbon accumulation at shallow levels since they are characterized by large numbers of Neogene subsidiary faults that connect to older faults either directly or indirectly. By contrast, the Type III fault pattern is least favorable due the presence of fewer Neogene subsidiary faults. Similarly, the Type I fault pattern in which Neogene subsidiary faults do not connect to older faults is also unfavorable for hydrocarbon accumulation at shallow levels.

(3) Many Neogene structural traps were formed due to the influence of the post-rift tectonic reactivation in the Bohai Sea. Such traps are mostly associated with anticlines formed in response to regional compressional stress, many of which are affected by the normal faulting and strike-slip movement. Many of these structural traps have been discussed in the previous literature (e.g., Deng and Li, 2008; Zhu et al, 2009; Gong et al, 2010).

(4) Theoretically, hydrocarbon accumulation is dominantly controlled by the latest tectonic event. Therefore, the Neogene-Quaternary tectonic reactivation in the Bohai Bay Basin was the critical tectonic event for hydrocarbon accumulation in the region. The peak accumulation of hydrocarbons in the offshore Bohai Sea occurred after 5.3 Ma (Gong et al, 2010), and undoubtedly this was a direct result of this tectonic event: the accelerated tectonic subsidence after 12 Ma enabled the generation of abundant hydrocarbons and the associated faulting facilitated their migration to shallow reservoirs. The intensity and long-lived duration of tectonic activity produced a large number of shallow structural closures, and also reformed the primary pressure and fluid fields required to drive migration and charge reservoirs. Pre-existing older reservoirs were also deformed as a consequence of this process, resulting in further hydrocarbon migration from the deeper

reservoirs through the networks of dense, shallow faults to further contribute to the re-charging of the new closures.

CONCLUSIONS

The Bohai Bay Basin underwent intense post-rift tectonic reactivation, which was characterized by the development of a dense network of shallow faults and an anomalously high rate of post-rift tectonic subsidence. The following new insights regarding the structural deformation experienced in the Bohai Bay Basin during the Neogene-Quaternary have arisen as an outcome of this study:

(1) The dense network of shallow faults is located solely in a NW-trending belt of the basin where the Zhangjiakou-Penglai Fault Zone was developed. Activity on most of these faults, which developed mainly after 5.3 Ma, was induced by the reactivation of NNE (or NE)-trending and NW-trending basement faults, which themselves experienced a substantial component of strike-slip movement during the Neogene and Quaternary. The origin and pattern of the dense network of faults arose in response to two conditions: interaction in the zone of intersection between the NW-trending and NNE (or NE)-trending faults, and the occurrence of a thick succession of Neogene and Quaternary strata. The accelerated rate of post-rift tectonic subsidence was distributed across the whole Bohai Bay Basin, and was initiated by 12 Ma; it evolved in three phases (12-5.3 Ma, 5.3-2.6 Ma and 2.6-0 Ma) with each phase characterized by an increased rate of tectonic subsidence and a greater intensity of tectonic subsidence at the margin of the Bozhong Depression.

(2) Fault reactivation acted as a contributory factor that further enhanced the rate of post-rift subsidence, especially around the Bozhong Depression. However, inconsistencies in the timing and spatial location of the faulting and accelerated subsidence demonstrates that the intense faulting was not the sole cause of the accelerated tectonic subsidence. The post-rift accelerated subsidence may indicate a new phase of craton destruction of the North China Craton, possibly related to the build-up of intraplate stresses at great depth combined with the

effects of rift-basin thermal subsidence. Results from this study imply a weak link between the anomalously high rate of tectonic subsidence and the dextral motion of the Tan-Lu Fault Zone, which is contrary to most previous suggestions.

(3) This case study demonstrates that post-rift tectonic reactivation results in conditions that are favorable to hydrocarbon accumulation in a rift-basin setting. Post-rift tectonic reactivation in the Neogene-Quaternary resulted in the generation of a unique hydrocarbon habitat in the Bohai Bay Basin, whereby hydrocarbon formation, migration and accumulation within reservoirs occurred at a late and super-late stage, such that abundant shallow reservoirs exist in the NW-trending middle segment where the dense network of shallow faults that connect to the older faults (either directly or indirectly) are developed.

(4) This study provides a detailed case study for an unusual style of post-rift tectonic reactivation within a rift-basin setting. It indicates that structural deformation associated with post-rift tectonic reactivation has a different expression to that which occurred during the syn-rift stage: it is less intense overall, yet arose in response to a complex and dynamic formative mechanism. This post-rift structural deformation may comprise two parts: one requires the reactivation of the syn-rift structural elements (i.e., fault development), whereas the other develops in a manner unrelated to syn-rift structural deformation (i.e., anomalous tectonic subsidence).

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FIGURE CAPTIONS

Figure 1. (A) Regional location and (B) simplified structure of the Cenozoic Bohai Bay Basin. (C) Location of seismic and well data used in this study.

Figure 2. Geological section through the Bohai Bay Basin. See Figure 1(C) for location.

Figure 3. General stratigraphy of the offshore Bohai Bay Basin showing major tectonic and depositional events. Lacustrine source rocks are concentrated in the Dongying and Shahejie formations. Form. = Formation; RPW depth = relative paleowater depth. This stratigraphy is representative of all wells analyzed in this study.

Figure 4. Epicenter distribution of earthquakes (Ms≧5.0) in Bohai Bay Basin and adjacent areas for the period 1500 to 1999 (modified from Fu et al, 2004). The focal mechanism solutions are from Hsiao et al (2004).

Figure 5. Non-interpreted and interpreted seismic sections through the middle of the Offshore Bohai Sea showing a network of denser faults developed in Neogene-Quaternary strata. Note the presence of an anticline below the Quaternary sequence in seismic line A, indicating an intensive regional compressive tectonic event occurring at about 2.6 Ma. See Figure 1(C) for location.

Figure 6. The planimetric distribution of the faults at the bottom of Pliocene sequence (A, about 5.3 Ma) and Oligocene sequence (B, about 38 Ma), offshore the Bohai Sea. Map C is the 3-D seismic coherency time slice (800ms) within the Neogene sequence of the area marked in Map A.

Figure 7. 3-D coherency seismic time slices (600 ms) within the Neogene sequence showing the distribution of Neogene faults in the Offshore Bohai Sea (A). (B)-(E) show details of some local areas that contrast the style of development of Paleogene and Neogene faults. Time slices from 1000 ms and 2500 ms from within the Paleogene sequence and basement are

presented. The *en-echelon* pattern of the subsidiary faults indicates the strike-slip movement of the basement faults during Neogene-Quaternary. See Figure 1(C) for location.

Figure 8. Non-interpreted and interpreted seismic sections showing different styles of development of Neogene faults. See Figure 1C for location. See the text for further explanation.

Figure 9. (A) Rates of active dip-slip faulting from some of the main faults indicated by black lines on the seismic sections shown in Figures 5 and 10; the number behind the gray columns are the rates of active dip-slip of the faults (m/Myr); F1-F6 are marked on the seismic sections; note that for the analysis of F3, two parallel faults were treated as a whole. (B) Average rates of active dip-slip faulting of the main faults in the southern part of the Offshore Bohai Bay Basin. (C) Explanation of the methodology used for the calculation of the active rate of dip-slip faulting.

Figure 10. Seismic sections demonstrating that the Neogene-Quaternary faults were mainly developed after 5.3 Ma. (A) Two seismic sections show that most of the faults were developed in the N_2m^u and Q sequences (5.3-0 Ma). (B) Seismic Line B in Figure 5 without fault interpretation, and horizon-flatted sections from the base of the 5.3 Ma horizon and the 12 Ma horizon. Note the variety of the shaded areas between the hangingwall and footwall that show that notable differences in accumulated thicknesses caused by syn-depositional faulting between the hangingwall and footwall only occurred in the N_2m^u and Q sequences (5.3-0 Ma). See Figure 5 for fault interpretation of Line B. See Figure 1C for location.

Figure 11. Models describing the style of development of shallow faults in the Bohai Bay Basin. See the text for further explanation.

Figure 12. Back-stripping analysis of tectonic subsidence (m) using data from wells in the Bohai Bay Basin during the whole Cenozoic (A, 65-0 Ma) and Neogene-Quaternary post-rift stage (B, 24.6-0 Ma). The broad gray curves in (A) show the theoretical post-rift tectonic subsidence with different stretching factors for a standard rift basin (from a uniform Mckenzie model, modified from Baur et al, 2010). The curves reveal the marked anomalous post-rift tectonic subsidence history of the Bohai Bay Basin (characterized by increasing subsidence rate instead of the exponentially decreasing subsidence rate). See Figure 1C for well locations. All wells shown in Figure 1C are used in (B), whereas only those indicated as black dots in circle are used in (A).

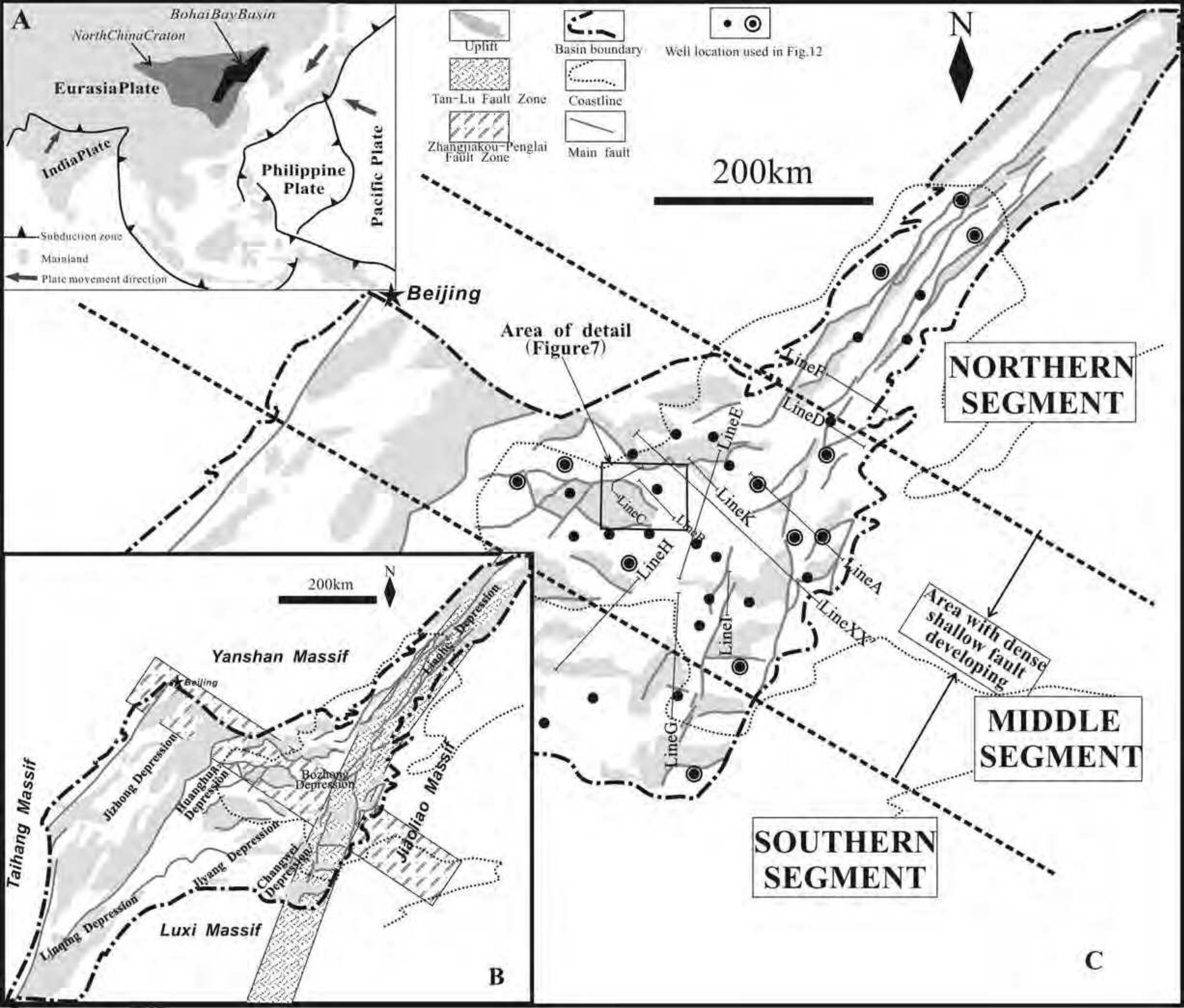
Figure 13 Contour maps of tectonic subsidence (m) of (A) Quaternary, 2.6-0 Ma; (B) N_2m^u, 5.3-2.6 Ma; (C) N_2m^L, 12-5.3 Ma; (D) N_1g, 24.6-12 Ma; (E) Neogene and Quaternary, 24.6-0 Ma. For comparison, the main faults at the bottom of the N_1g (indicated as red lines) are superimposed; location of analyzed wells are indicated by black dots.

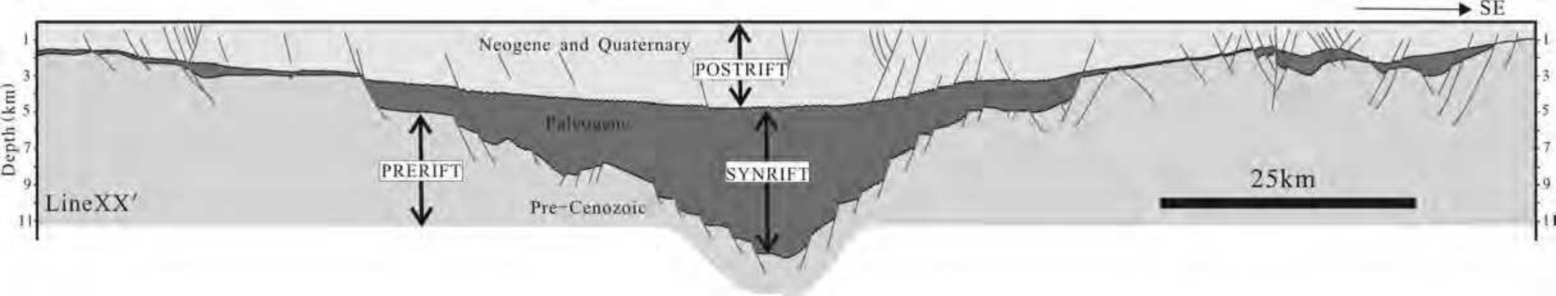
Figure 14. Contour maps of (A) tectonic subsidence rate (m/Myr) during N_1g deposition (24.6-12 Ma), and the accelerated intensity of the tectonic subsidence rate relative to the N_1g tectonic subsidence rate during (B) Quaternary, 2.6-0 Ma; (C) N_2m^u, 5.3-2.6 Ma; (D) N_2m^L, 12-5.3 Ma. The numbers in maps B, C, D are the accelerated intensity of the tectonic subsidence rate relative to the early post-rift tectonic subsidence rate, and are obtained by the equation $AI = (R_i - RN)/RN$, where AI is the accelerated intensity, R*i* and RN are the tectonic subsidence rates during the corresponding period (Quaternary, N_2m^u, N_2m^L) and the episode of N_1g deposition (24.6-12 Ma), respectively; location of the analyzed well is indicated by the black dot.

Figure 15. (A) Seismic section across the boundary fault of a Paleogene half-graben (indicated as black line), which underwent intensive reactivation during the

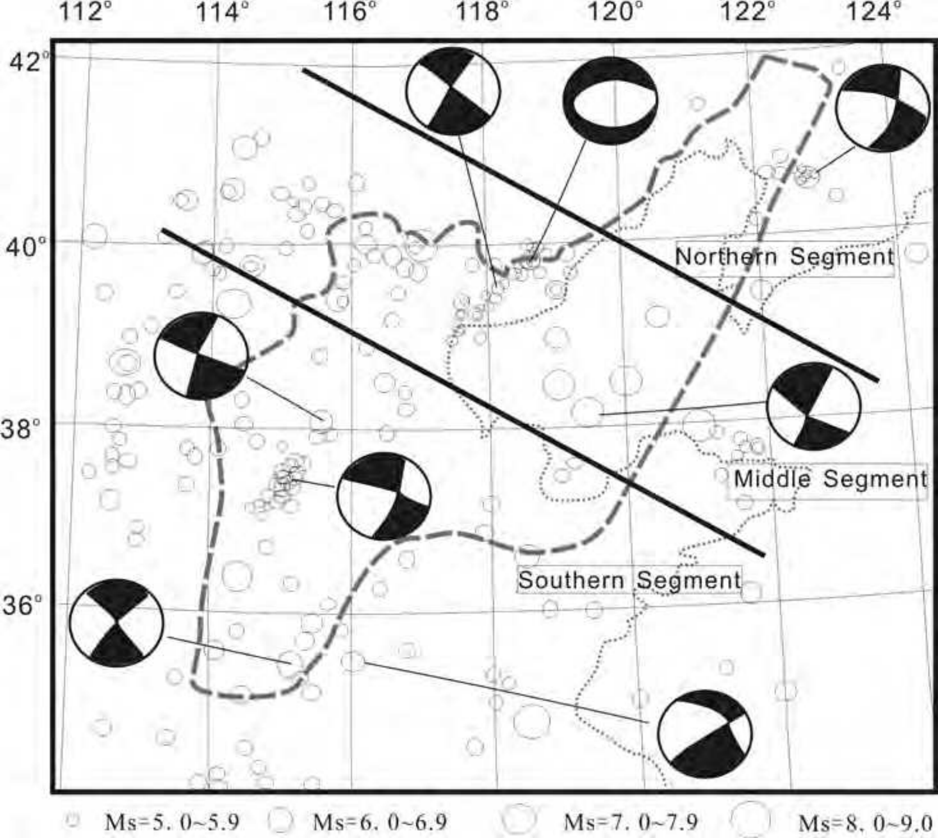
Neogene–Quaternary to produce many Neogene-Quaternary faults; (B) the active rate of tectonic subsidence (m/Myr) of this master fault. (C) tectonic subsidence curves of two wells located on the hangingwall and footwall of this master fault, respectively. They indicate the relationship between fault reactivation and accelerated subsidence during the Neogene-Quaternary. See the text for further explanation.

Figure 16. Schematic-cross-section of Neogene reservoirs in the Offshore Bohai Sea showing the relationship between hydrocarbon accumulation and Neogene-Quaternary faulting. In the area with sparse Neogene-Quaternary faults, there are no Neogene reservoirs; by contrast, in the area characterized by a network of dense Neogene-Quaternary faults, many Neogene reservoirs are documented and these are usually closely related to old (Paleogene) faults that have been continuously active and their Neogene subsidiary faults, which connect to the Paleogene faults either directly or indirectly. Type II and IV fault patterns are most favorable for hydrocarbon accumulation at shallow levels, whereas the Type III fault pattern is least favorable; the Type I fault pattern, in which Neogene subsidiary faults do not connect to the older faults, is also unfavorable for hydrocarbon accumulation at shallow levels.

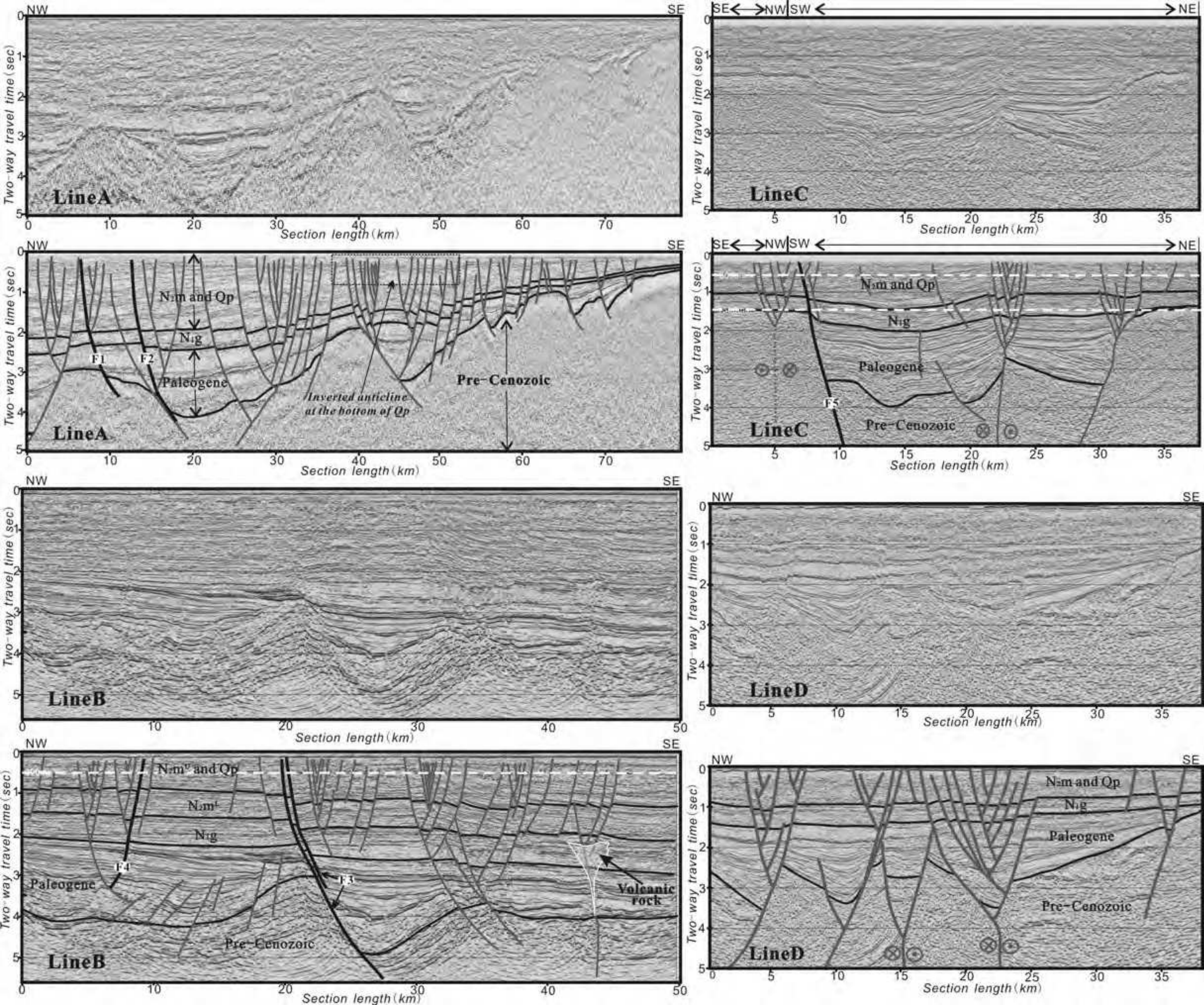

A
BohaiBayBasin
NorthChinaCraton
EurasiaPlate
IndiaPlate
Philippine Plate
Pacific Plate
Subduction zone
Mainland
Plate movement direction
Uplift
Basin boundary
Well location used in Fig.12
Tan-Lu Fault Zone
Coastline
Zhangjiakou-Penglai Fault Zone
Main fault
N
200km
Beijing
Area of detail (Figure7)
LineF
LineD
LineE
LineK
LineC
LineB
LineH
LineA
LineXX'
LineI
LineG
NORTHERN SEGMENT
Area with dense shallow fault developing
MIDDLE SEGMENT
SOUTHERN SEGMENT
200km
Yanshan Massif
Beijing
Liaohe Depression
Jizhong Depression
Huanghua Depression
Bozhong Depression
Jiyang Depression
Changwei Depression
Jiaoliao Massif
Taihang Massif
Linqing Depression
Luxi Massif
B
C

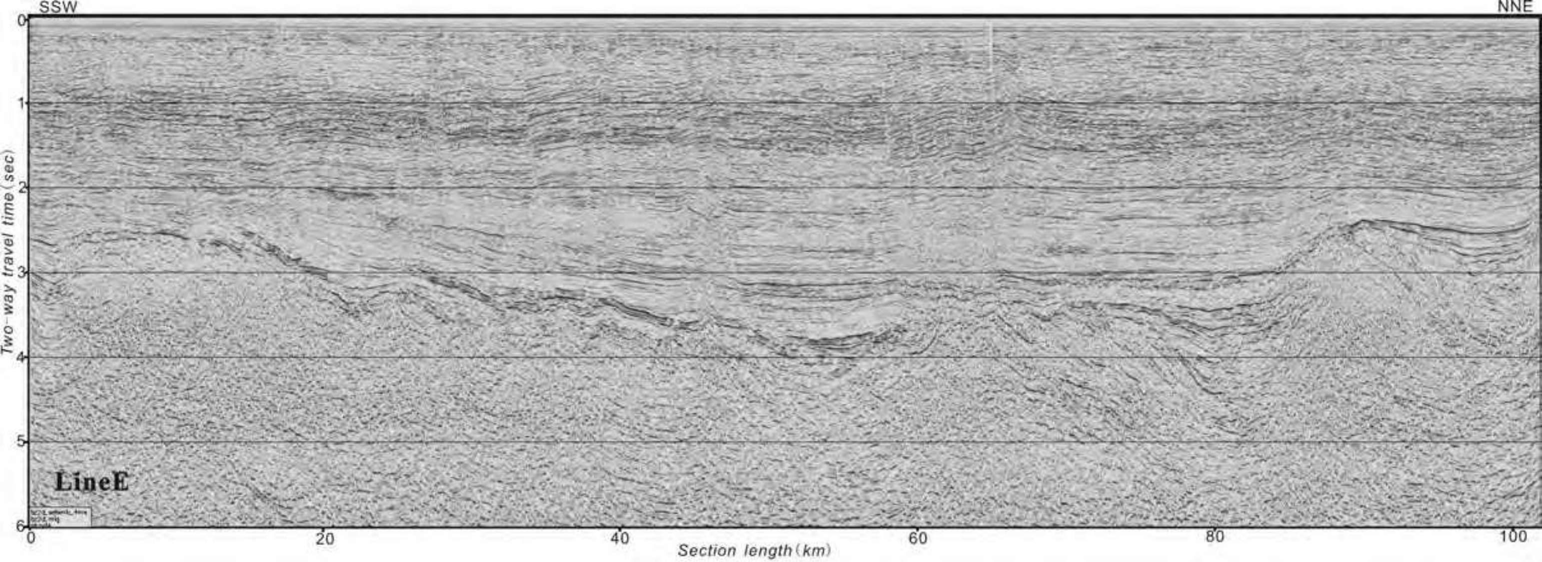

SE
Depth (km)
1
3
5
7
9
11
Neogene and Quaternary
POSTRIFT
PRERIFT
SYNRIFT
Pre-Cenozoic
LineXX′
25km

Geological Age (Ma)
Strata
Form.
Member
Symbol
Lithology
Sedimentary Face
RPW Depth
Tectonic Evolution
Quaternary
Qp
Shallow marine
Neotectonic stage
2.6
+
−
Neogene
Pliocene
Minghuazhen
Upper
N2mU
meandering river;
flood plain;
5.3
Lower
N2mL
meandering river;
shallow-water delta;
Miocene
post rift stage
12
Guantao
N1g
braided channel;
shallow lake;
24.6
Paleogene
Oligocene
Dongying
First
E3d1
alluvial facies (upper section);
delta (lower section);
Second
E3d2U
E3d2L
delta;
middle-deep lake;
30.3
Third
E3d3
32
Eocene
Shahejie
First
E2s1
carbonate platform;
shallow lake;
36
Second
E2s2
delta fan
38
synrift stage
Third
E2s3
middle-deep lake;
42
Forth
E2s4
deep lake (upper section);
evaporitic lake (meddle-lower section);
50.5
Kongdian
E2k
alluvial faces (upper section);
lake (meddle section);
alluvial/alluvial fan; (lower section)
65
Basement
mudstone
sandstone
conglomerate
oil shale
gypse

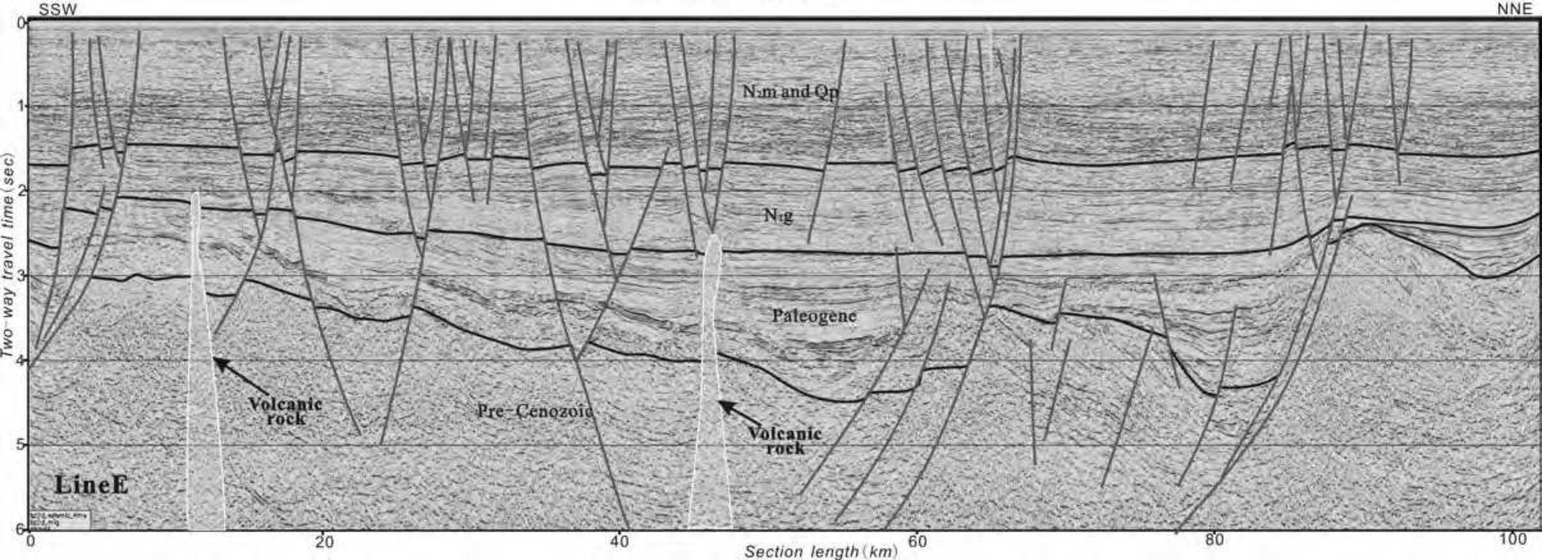


112°
114°
116°
118°
120°
122°
124°
42°
40°
38°
36°
Northern Segment
Middle Segment
Southern Segment
Ms=5. 0~5.9
Ms=6. 0~6.9
Ms=7. 0~7.9
Ms=8. 0~9.0

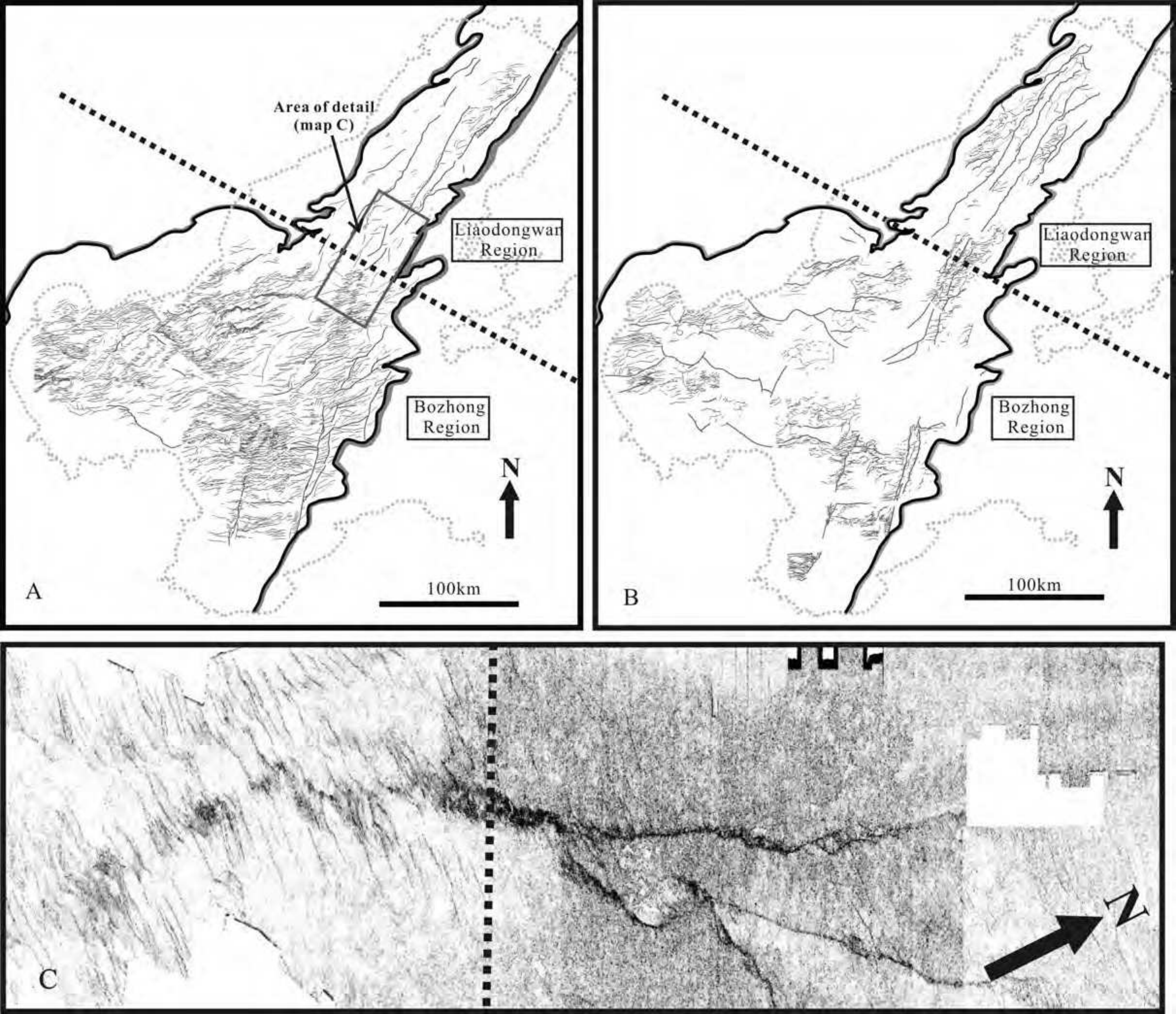

LineA
LineB
LineC
LineD
NW
SE
NE
SW
Two-way travel time (sec)
Section length (km)
N2m and Qp
N1g
Paleogene
Pre-Cenozoic
F1
F2
F3
F4
F5
Inverted anticline at the bottom of Qp
N2m^u and Qp
N2m^l
Volcanic rock

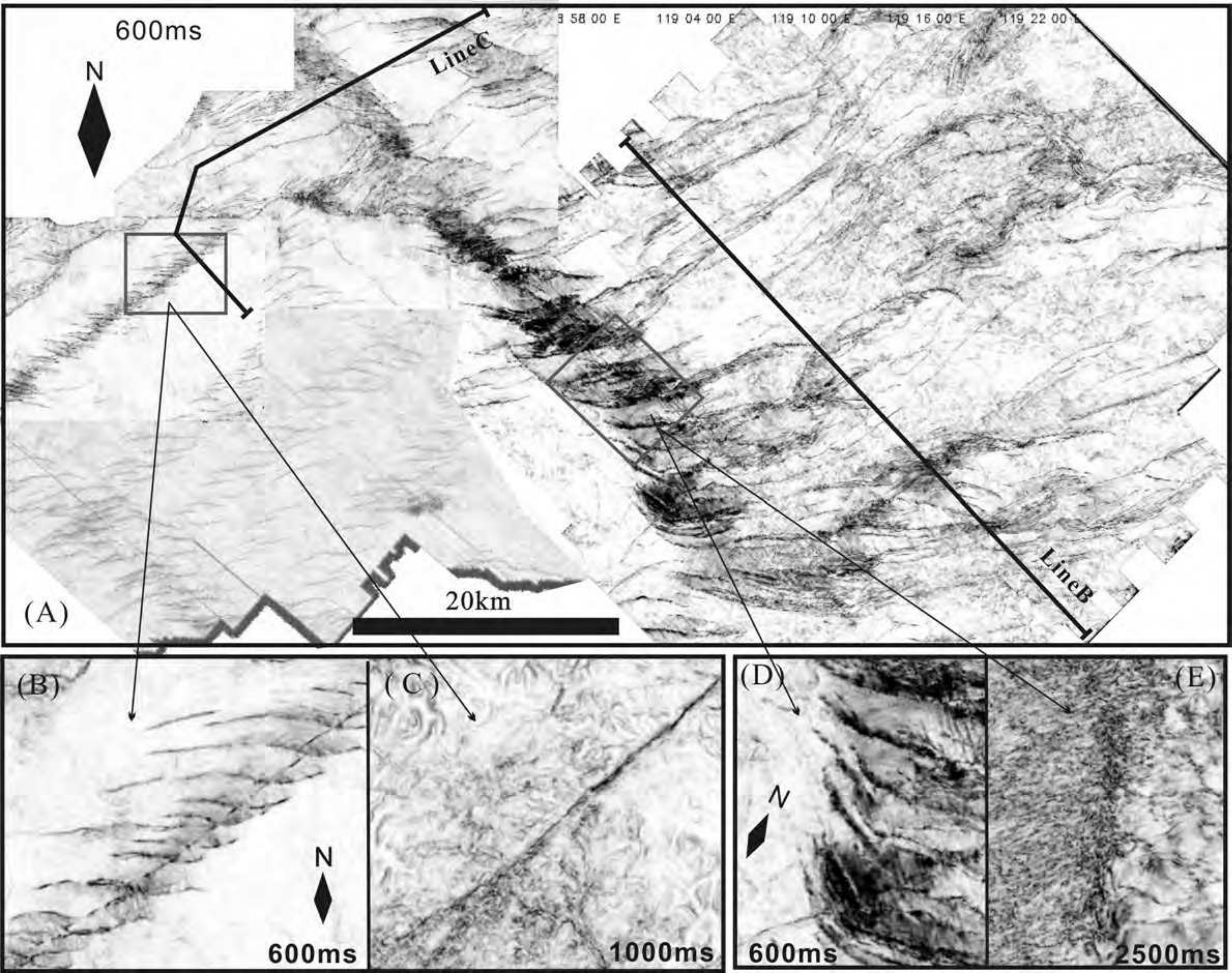


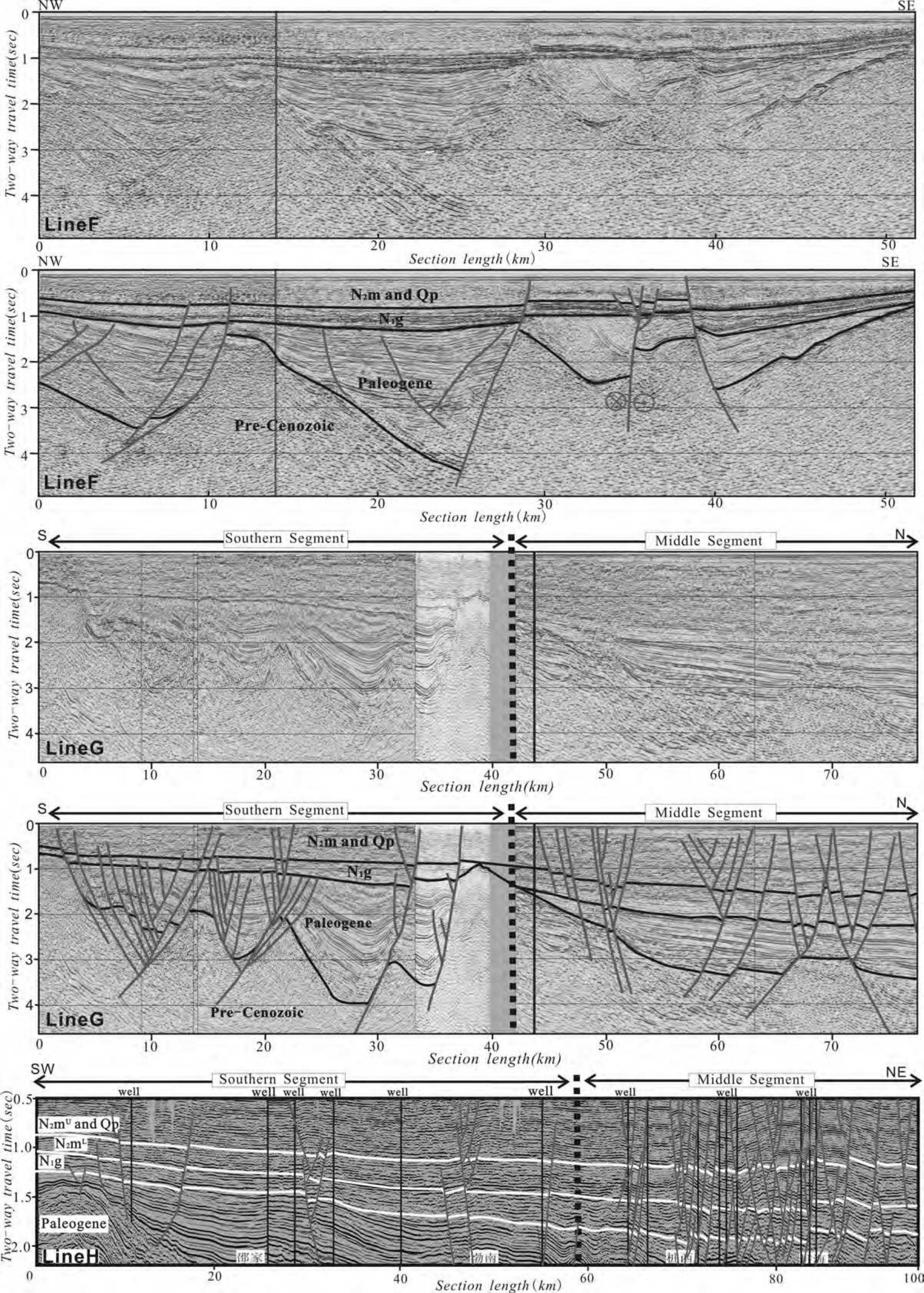
SSW
NNE
Two-way travel time (sec)
LineE
Section length (km)



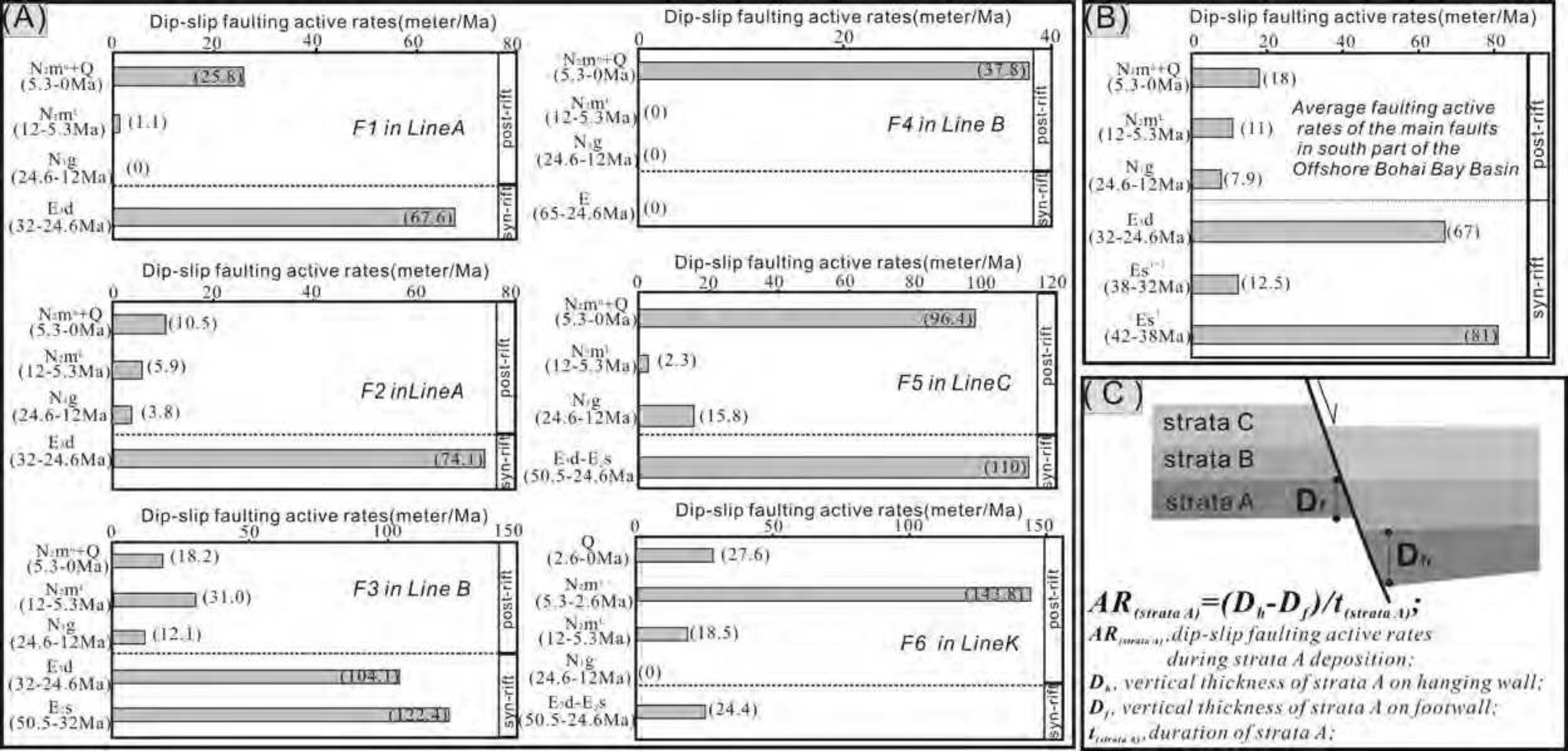
SSW
NNE
Two-way travel time (sec)
N2m and Qp
N1g
Paleogene
Pre-Cenozoic
Volcanic rock
Volcanic rock
LineE
Section length (km)


Area of detail
(map C)
Liaodongwan
Region
Bozhong
Region
N
100km
A
Liaodongwan
Region
Bozhong
Region
N
100km
B
C
N

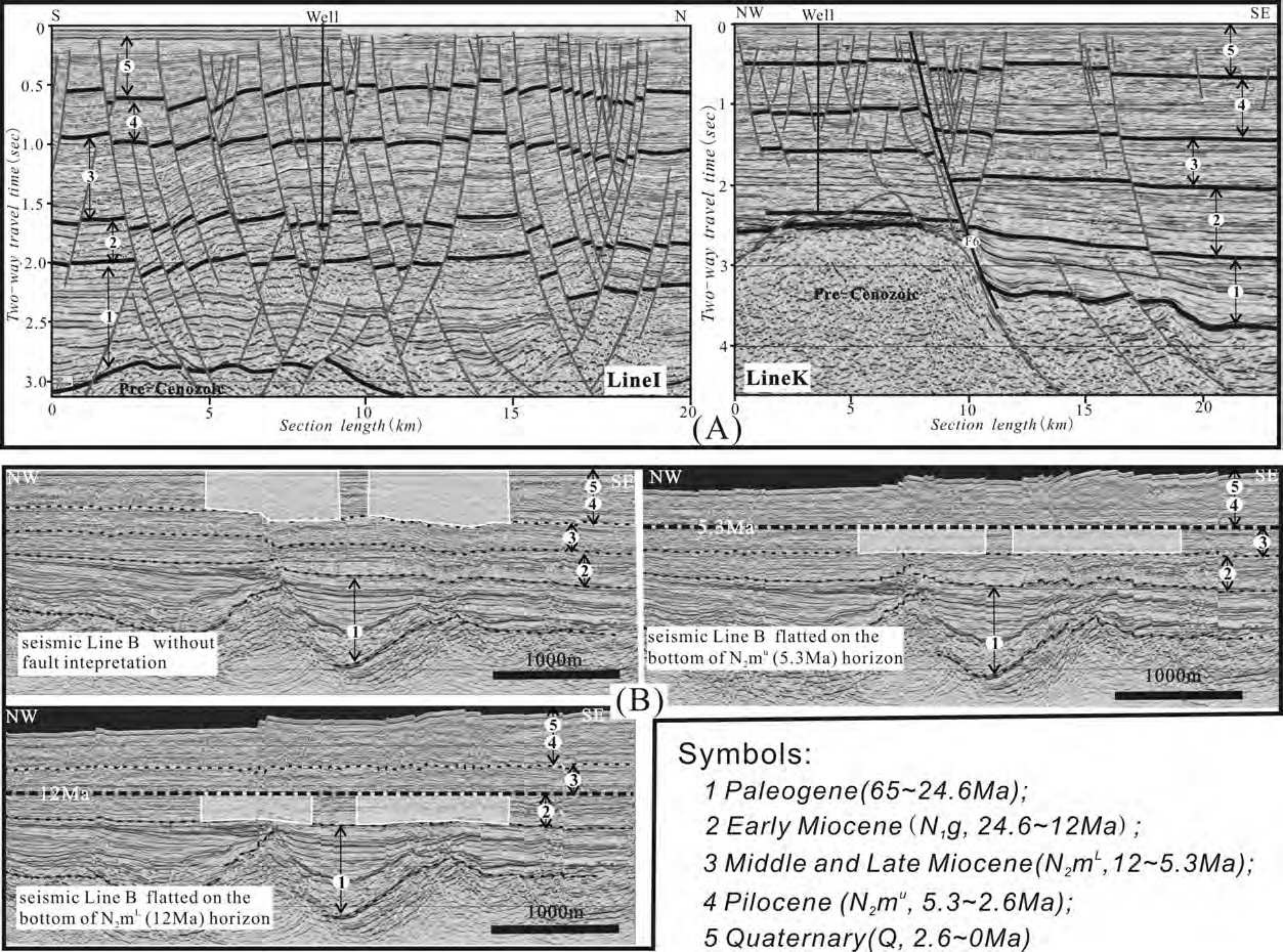

600ms
N
LineC
8 58 00 E
119 04 00 E
119 10 00 E
119 16 00 E
119 22 00 E
LineB
20km
(A)
(B)
600ms
(C)
1000ms
(D)
N
600ms
(E)
2500ms



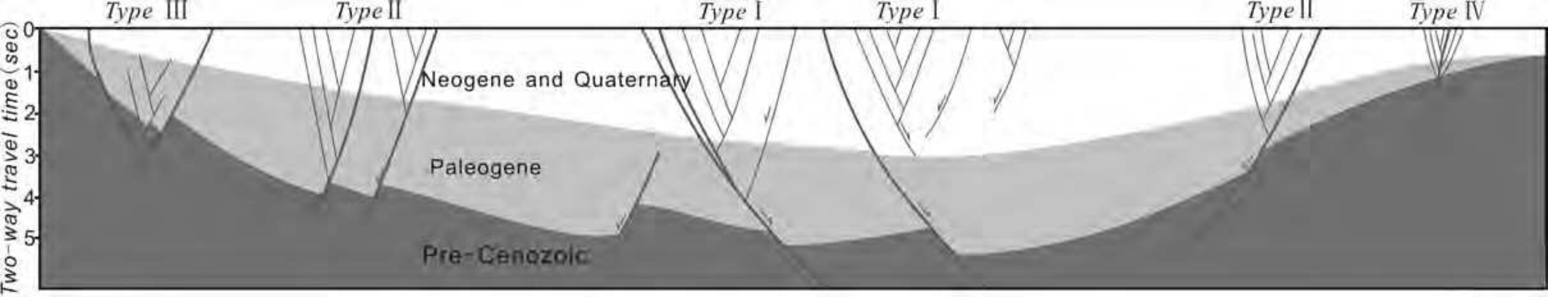
NW
SE
Two-way travel time(sec)
LineF
Section length (km)
N2m and Qp
N1g
Paleogene
Pre-Cenozoic
S
N
Southern Segment
Middle Segment
LineG
Section length(km)
SW
NE
well
N2mU and Qp
N2mL
N1g
Paleogene
LineH



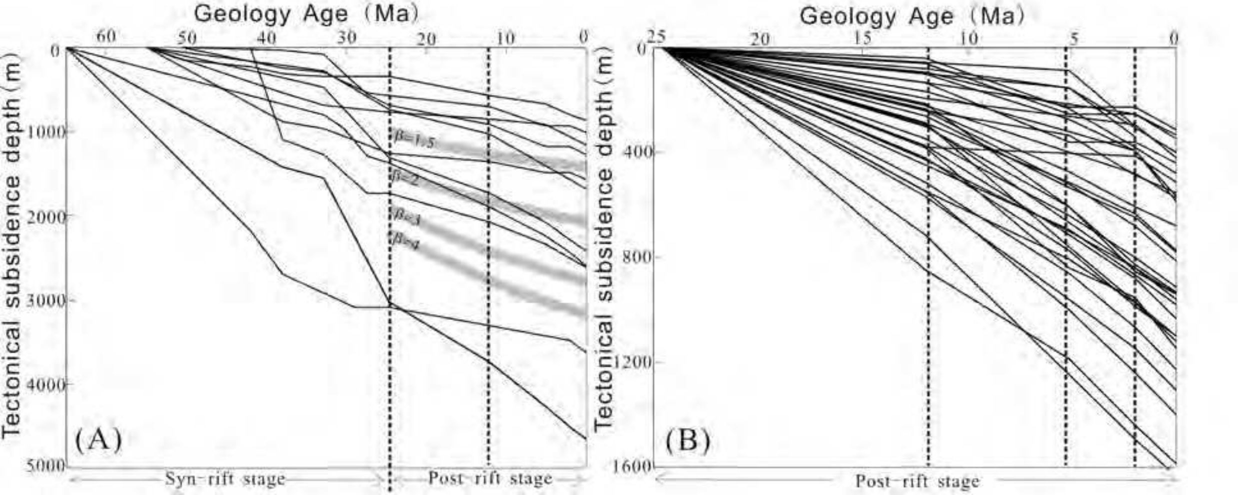
(A)
Dip-slip faulting active rates(meter/Ma)
F1 in LineA
F2 inLineA
F3 in Line B
F4 in Line B
F5 in LineC
F6 in LineK
post-rift
syn-rift
(B)
Average faulting active rates of the main faults in south part of the Offshore Bohai Bay Basin
(C)
strata C
strata B
strata A
$AR_{(strata\ A)}=(D_h-D_f)/t_{(strata\ A)}$;
$AR_{(strata\ A)}$, dip-slip faulting active rates during strata A deposition;
D_h, vertical thickness of strata A on hanging wall;
D_f, vertical thickness of strata A on footwall;
$t_{(strata\ A)}$, duration of strata A;

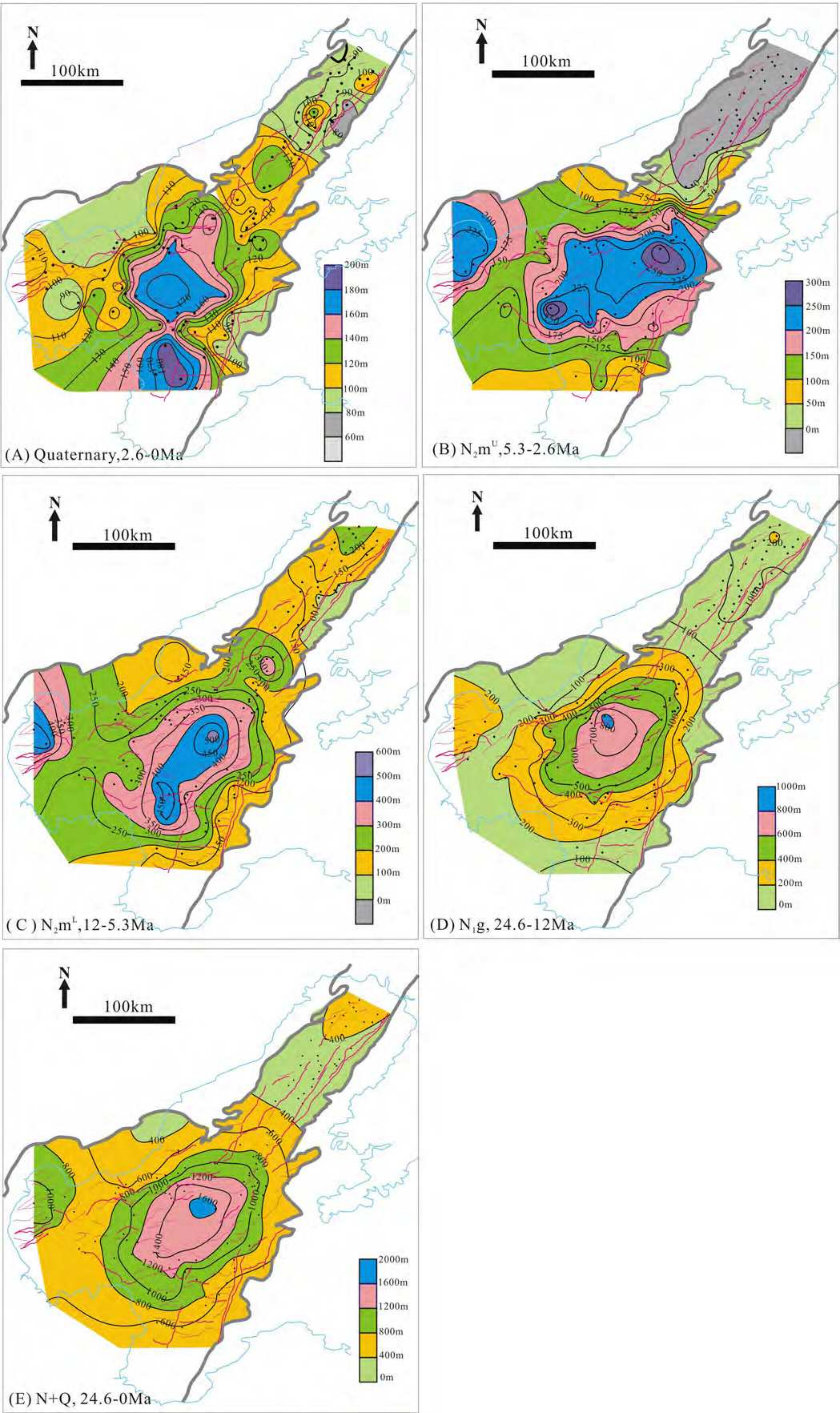


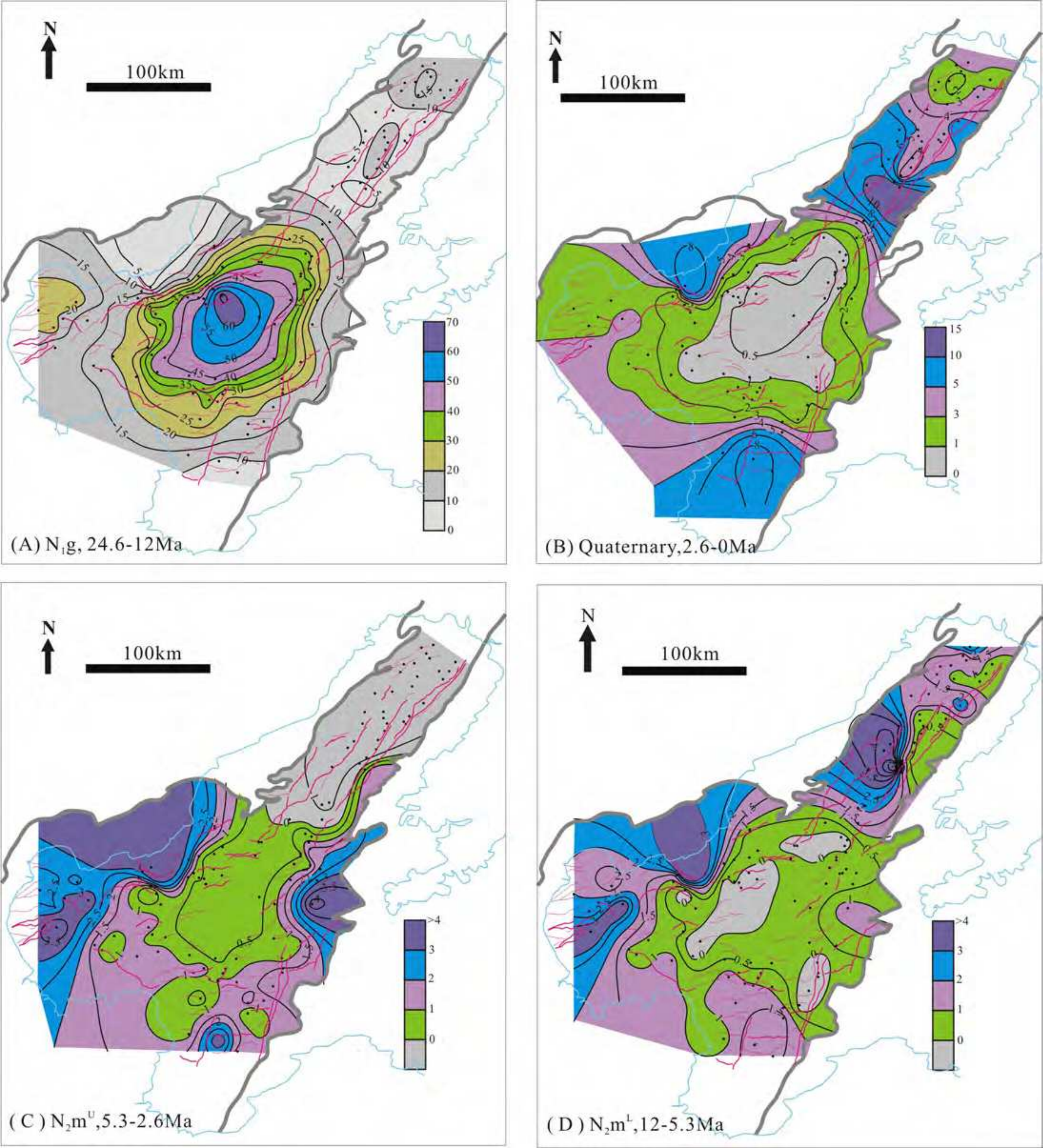
S
Well
N
Two-way travel time (sec)
Pre-Cenozoic
LineI
Section length (km)
NW
Well
SE
Pre-Cenozoic
F6
LineK
(A)
NW
SE
seismic Line B without fault intepretation
1000m
5.3Ma
seismic Line B flatted on the bottom of N_2m^u (5.3Ma) horizon
(B)
12Ma
seismic Line B flatted on the bottom of N_2m^L (12Ma) horizon
Symbols:
1 Paleogene(65~24.6Ma);
2 Early Miocene (N_1g, 24.6~12Ma);
3 Middle and Late Miocene(N_2m^L,12~5.3Ma);
4 Pilocene (N_2m^u, 5.3~2.6Ma);
5 Quaternary(Q, 2.6~0Ma)

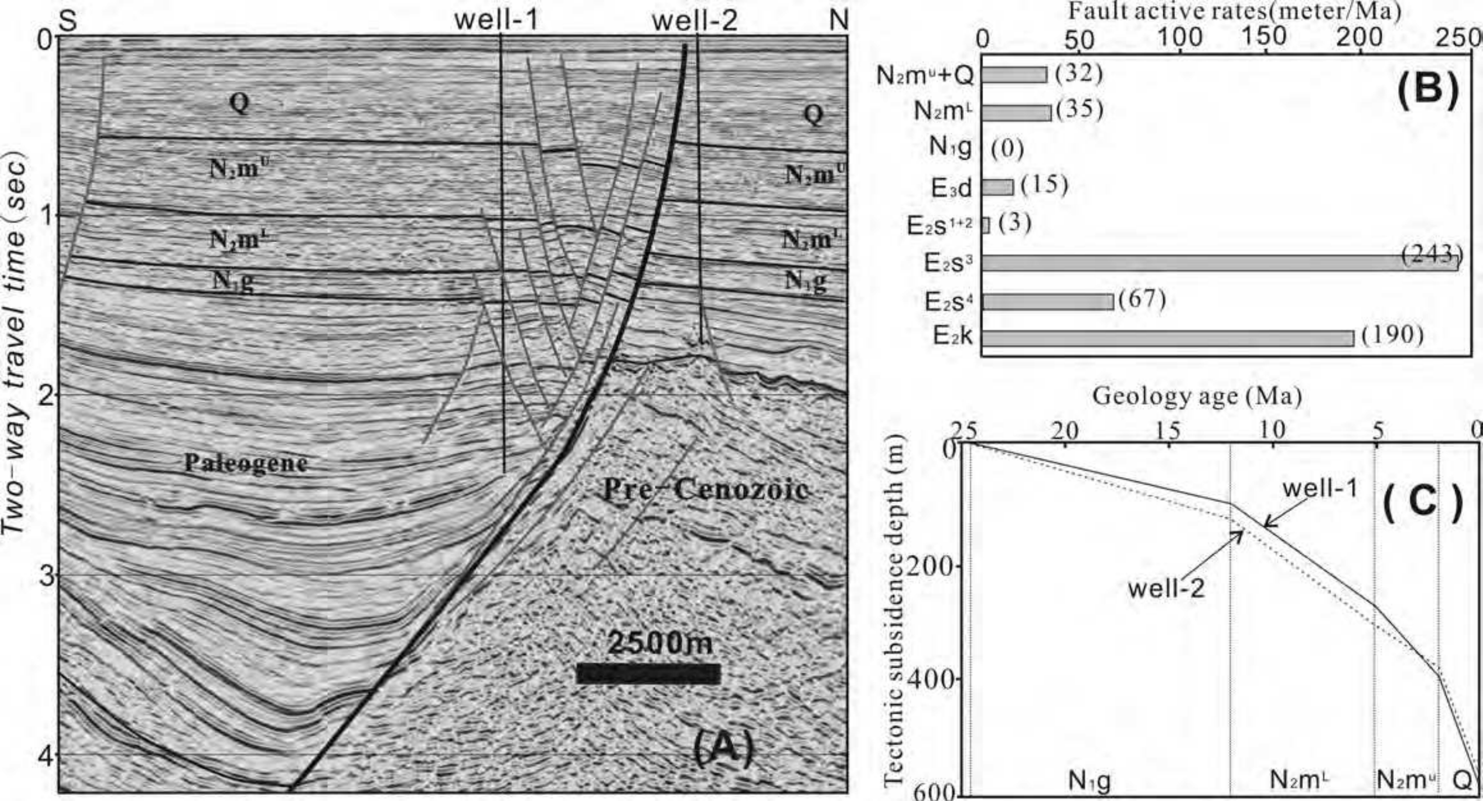


Type III
Type II
Type I
Type I
Type II
Type IV
Two-way travel time (sec)
0
1
2
3
4
5
Neogene and Quaternary
Paleogene
Pre-Cenozoic

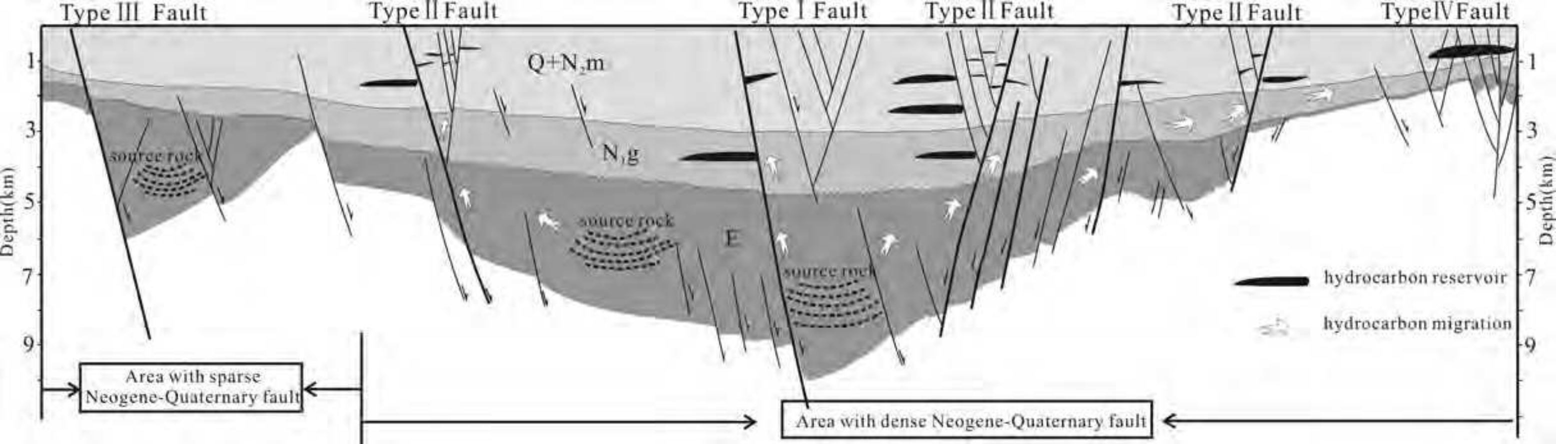

Geology Age (Ma)
60
50
40
30
20
10
0
Tectonical subsidence depth (m)
0
1000
2000
3000
4000
5000
β=1.5
β=2
β=3
β=4
(A)
Syn-rift stage
Post-rift stage
Geology Age (Ma)
25
20
15
10
5
0
Tectonical subsidence depth (m)
0
400
800
1200
1600
(B)
Post-rift stage


N
100km
200m
180m
160m
140m
120m
100m
80m
60m
(A) Quaternary,2.6-0Ma
N
100km
300m
250m
200m
150m
100m
50m
0m
(B) N_2m^U,5.3-2.6Ma
N
100km
600m
500m
400m
300m
200m
100m
0m
(C) N_2m^L,12-5.3Ma
N
100km
1000m
800m
600m
400m
200m
0m
(D) N_1g, 24.6-12Ma
N
100km
2000m
1600m
1200m
800m
400m
0m
(E) N+Q, 24.6-0Ma


N
100km
(A) N_1g, 24.6-12Ma
N
100km
(B) Quaternary,2.6-0Ma
N
100km
(C) N_2m^U,5.3-2.6Ma
N
100km
(D) N_2m^L,12-5.3Ma



S
well-1
well-2
N
Two-way travel time (sec)
0
1
2
3
4
Q
Q
N2mU
N2mU
N2mL
N2mL
N1g
N1g
Paleogene
Pre-Cenozoic
2500m
(A)
Fault active rates(meter/Ma)
0
50
100
150
200
250
(B)
N2mu+Q (32)
N2mL (35)
N1g (0)
E3d (15)
E2s1+2 (3)
E2s3 (243)
E2s4 (67)
E2k (190)
Geology age (Ma)
25
20
15
10
5
0
Tectonic subsidence depth (m)
0
200
400
600
well-1
well-2
(C)
N1g
N2mL
N2mu
Q



Type III Fault
Type II Fault
Type I Fault
Type II Fault
Type II Fault
Type IV Fault
$Q+N_2m$
N_1g
E
source rock
source rock
source rock
Depth(km)
Depth(km)
1
3
5
7
9
hydrocarbon reservoir
hydrocarbon migration
Area with sparse Neogene-Quaternary fault
Area with dense Neogene-Quaternary fault