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Cenozoic Tectonic Characteristics, Evolution and Geodynamics of Dongpu Sag, Bohai Bay Basin, China

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1. Introduction

The Dongpu Sag is located at the southwest of the Bohai Bay basin (Fig. 1), east China. Some 5300 km^2 in size it forms 2 % of the area of the Bohai Bay basin. The Dongpu Sag is rich in oil and gas, with petroleum exploration history over 50 years long. Over 4,000 km of two dimensional and 4173km^2 of three dimensional seismic data have been acquired in the basin, covering the main tectonic units. Over a thousand exploration wells have been drilled, with a total drilling footage of almost 4 million meters. Twenty one oil and gas fields have been found. The proven reserve of oil and gas are $18 \times 10^8 t$ and $515.1 \times 10^8 m^3$, respectively.

Ongoing petroleum exploration has resulted in significant increase in information relevant to the structure and tectonic evolution of the Dongpu Sag (Sun, et al., 2003a, b; Xu & Zhou, 2003, 2005; Xu et al, 2003, 2004; Chen et al, 2006, 2007a, b; Qi et al., 2006; Zhang et al., 2007), including salt tectonics (Xu, 1988; Ge et al., 1997; He et al., 2003; Chen, et al., 2007a). However, these researches addressed either only one structure or one sedimentary layer, and a comprehensive analysis of the tectonic styles of the Dongpu sag is seldom reported. Also, the Dongpu sag underwent complex dynamic regimes, extension and wrench (Allen, M.B. et al., 1997, 1998; Qi 2004; Qi & Yang, 2010). Various kinds of rocks were involved in deformation, including clastic rocks and salt rock (Chen et al., 2007b). Little work has been done on the space-time relationships among the extensional, wrench and salt tectonics.

The data from petroleum exploration in the Dongpu Sag can help to understand the formation and evolution of the Bohai Bay Basin. Several researchers have addressed the dynamic factors controlling the Bohai Bay Basin (Lu & Qi, 1997; Zhang, 1995; Qi, 2004), but three different models for the kinematics of the basin have emerged: (1) WNW-ESE extension (Ma, et al., 1983; Lu & Qi, 1997; Ren et al, 2002), (2) Pull-apart (Jolivet, 1987; Chen & Nabelek, 1988), or, WNW-ESE extension with NNE dextral strike-slip faulting

superimposed the transtensional model proposed by Hu (1982) and Qi et al., (1995), and (3) N-S extension (Zhou & Zhou, 2006).
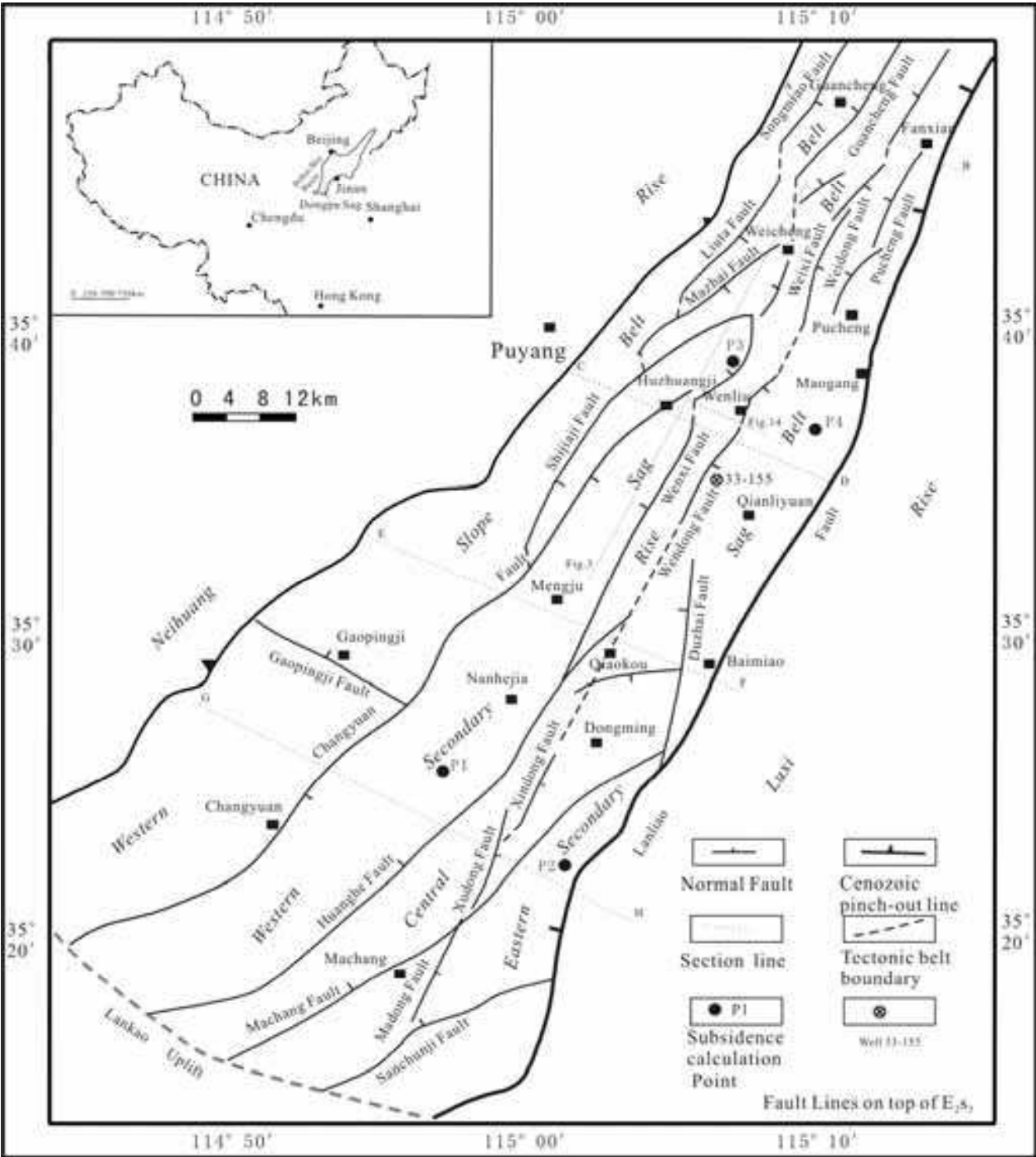

Fig. 1. Tectonic units and main faults of the Dongpu Sag

Based on the interpretation of seismic data and integrating the well drilling and well logging data, this paper will demonstrate the tectonic styles and their space-time distribution in the Dongpu sag. The tectonic evolution and dynamics of the sag will be discussed as well.

| Stratum system | | | | | Thickness (m) | Lithologic Section | Lithology and Sedimentary facies |
Erathem	System	Series	Formation	Member	Sub-member			
Cenozoic	Neocene	Pleistocene-Holocene	Pingyuan			150-230		Clay,slit,sand,gravel layer
		Pliocene	Minghuazhen	N_2m		100-1250		Fluvial mudstone,slitstone,sandstone,conglomerate
		Miocene	Guantao	N_1g		200-600		Fluvial sandstone,mudstone,conglomerate
	Paleogene	Oligocene	Dongying	E_3d		400-1400		River-flood plain mudstone,sandstone
			Shahejie	E_3s_1	$E_3s_1^1$	120-260		Mudstone,biogenic limestone interbeds, sandstone. Shallow-semideep lake,delta
					$E_3s_1^2$	50-250		Salt rock and mudstone in the north,mudstone, marl,and siltstone in the south. Shallow-semideep lake,delta
				E_3s_2	$E_3s_2^1$	250-550		Mudstone,shale gypsum,salt rock and sandatone. Perilow lake,fan delta
					$E_3s_2^2$	250-650		Interbeds of mudstone and sandstone. River-flood plain,sheet lake
		Eocene		E_2s_3	$E_2s_3^1$	150-500		Mudstone, oil shale,siltstone,sandstone. Semideep lake-deep salt lake,delta ,turbidite,fan delta
					$E_2s_3^2$	130-500		Salt rock and mudstone assemblage in north, mudstone and sandstone assemblage in south. Semideep lake-deep salt lake,delta ,turbidite,fan delta
					$E_2s_3^3$	170-600		Salt rock and mudstone in north,mudstone and sandstone in south. Semideep lake-deep salt lake,delta ,turbidite,fan delta
					$E_2s_3^4$	500-2000		Salt rock and mudstone in north,interbeds of mudstone and sandstone in south. Semideep lake-deep salt lake,delta ,turbidite,fan delta
				E_2s_4		0-400		Mudstone,siltstone,sandstone. Sheet lake,turbidite,fluvial
		Paleocene	Kongdian	E_1k				(Absent)
Mesozoic	Triassic							Interbeds of sandstone and mudstone. Fluvial, lake

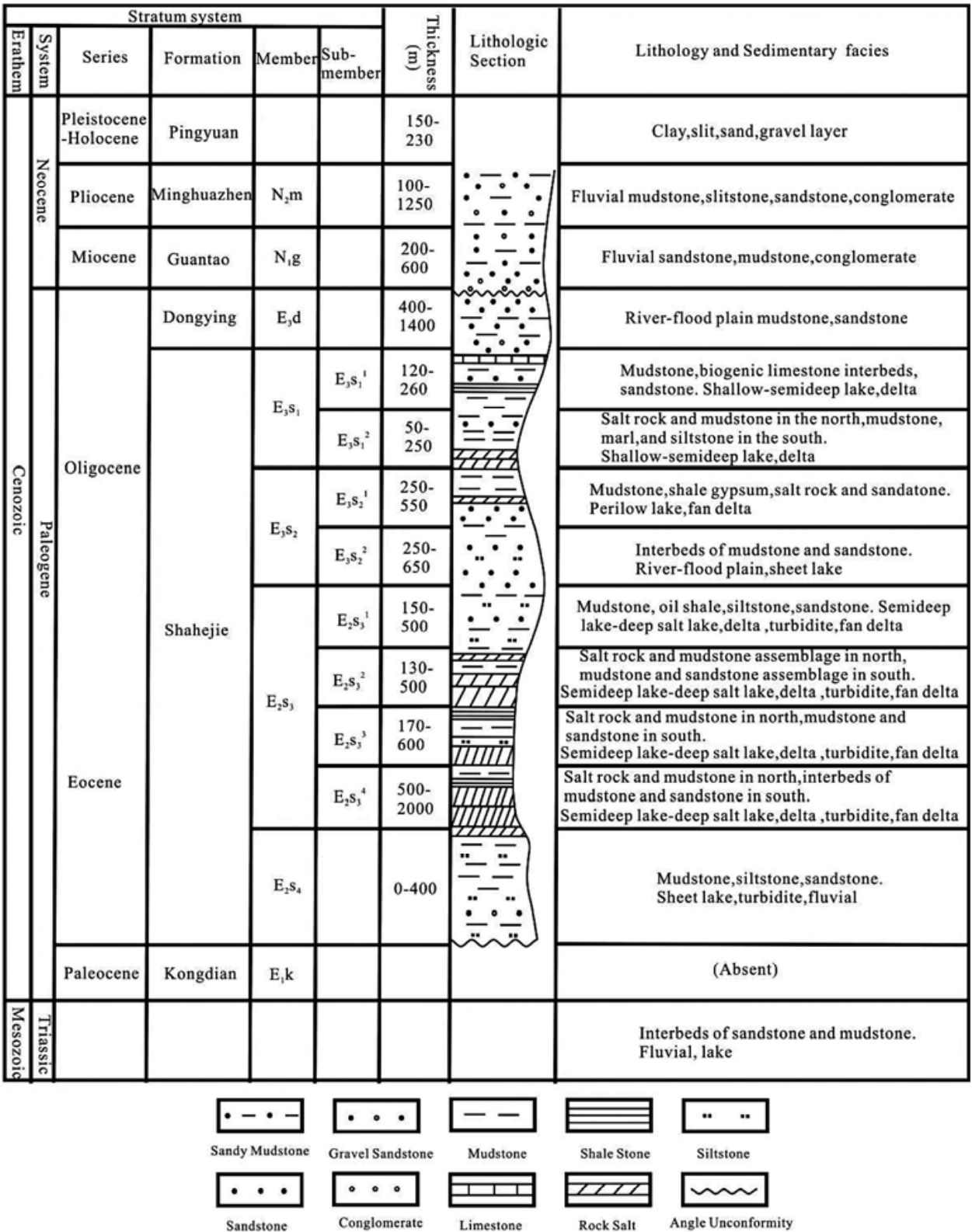|				
Sandy Mudstone	Gravel Sandstone	Mudstone	Shale Stone	Siltstone
Sandstone	Conglomerate	Limestone	Rock Salt	Angle Unconformity

Fig. 2. Cenozoic basin fill of the Dongpu sag

2. Geological setting

2.1 Basin fill

The Dongpu sag trends in a northeast direction and abuts the Neihuang rise on west and the Luxi rise on east, with internal northeast-southwest striking faults (Fig.1). It is a Cenozoic sedimentary basin, and the underlying strata are Paleozoic and Lower to Middle Triassic. The Cenozoic basin fill developed from the Eocene to the Holocene (Fig. 2). In terms of lithology, the basin was filled mainly by terrestrial clastic rocks, while some salt rocks and volcanic rocks occurred.

Salt layers existed in some intervals (Gu, 1986; Huang, et al., 2007), such as E_2S_3, E_3S_2 and E_3S_1, mainly distributed in the north of the sag. Salt layers of different time are not stacked vertically (Fig. 3). The salt layers consisted of salt rhythms, each of which was composed by thick mudstones, salt rocks and gypsums or alternating layers of gypsum-salt rocks, oil shalestones and mudstones. These salt layers played important roles both in reservoir formations and in structures, but the basin is not characterized by salt diapirism as the thickness of an individual pure salt layers is not large (Ge et al., 1997; Wang et al., 2002; Xu & Zhou, 2003; Chen et al., 2007a,b).
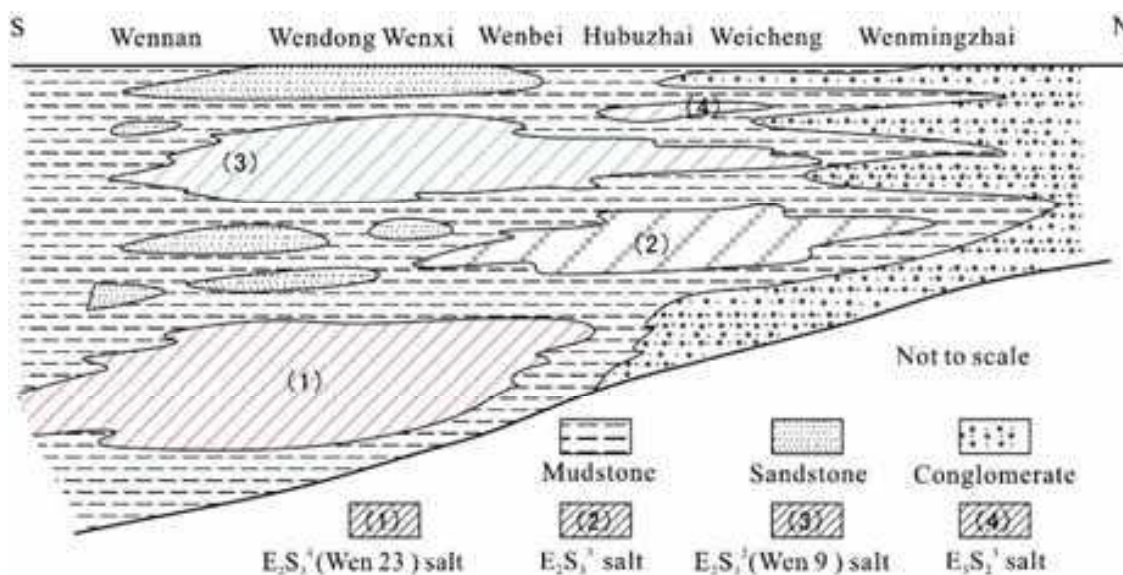
Fig. 3. Salt distribution in the northern Dongpu sag (see Fig. 1 for location)

2.2 Magmatic activity

The Dongpu Sag experienced multiple phases of magmatic activity during Paleogene, which varied not only in volume but also in aerial distribution with time (Fig. 4). During the deposition of E_2S_4, basaltic eruptions were concentrated in Zhaoying and Machang of the south of the sag, and migrated during the deposition of E_2S_3, northward to Qiaokou and to the west of Dongming. The E_3S_2 related magmatism was distributed similarly to that of E_2S_3, but the area of magmatic rocks became narrowed. By E_3S_1 time, volcanism again became widely distributed, with not only extrusive basalts but also intrusive diabase. Finally, during the deposition of E_3d, the distribution of the volcanic rocks was adjacent to those deposited during E_3S_1, with basalts deposited in the vicinity of Qiaokou, Dongming and Xuji.

2.3 Basin subsidence

Applying the back-stripping analysis method of Allen, P.A. and Allen, J.R. (1990), basin subsidence of the Dongpu Sag was calculated and basin subsidence were generated (Fig. 5). A porosity-depth relation (Equation 1) for clastic rocks from eight wells in the Dongpu Sag was used to decompact
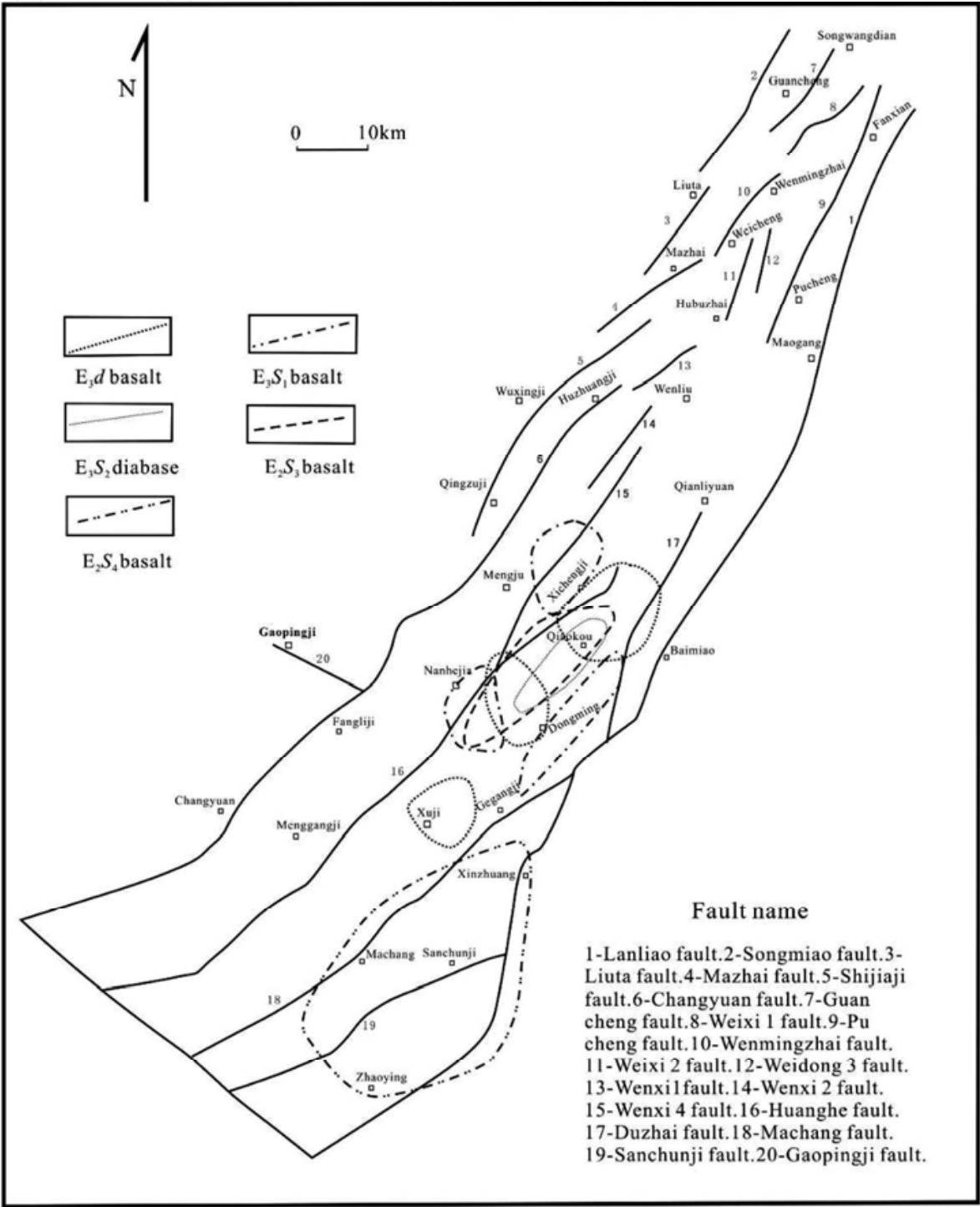
$$\Phi_z = 50.0\exp(-0.000433z) \tag{1}$$

Fig. 4. Distribution of magmatic rocks formed in Paleogene time in the Dongpu Sag

where Φ_z is porosity (%), z is depth (m), salt rocks and limestones constant. The results indicate that the subsidence history of the Dongpu Sag was composed of two-stages; an early rapid period of subsidence from 45 to 37Ma (E_2), followed by a later period of slower subsidence from 37 Ma to present. The shapes of the subsidence curves within the Dongpu Sag are typical of those in a rift basin (Allen, P. A. & Allen, J. R., 1990). If the whole Bohai Bay Basin was rifting at a fairly stable rate during the Paleogene, the subsidence curves for each epoch within the Paleogene should be quite similar. The subsidence rate curve becoming gentle at 37Ma is interpreted to represent a decrease in extension and an increase in strike-slip deformation.

3. Basin architecture

In terms of structural features, the Dongpu Sag can be divided into different belts in the west-east direction and different sections in the north-south direction.
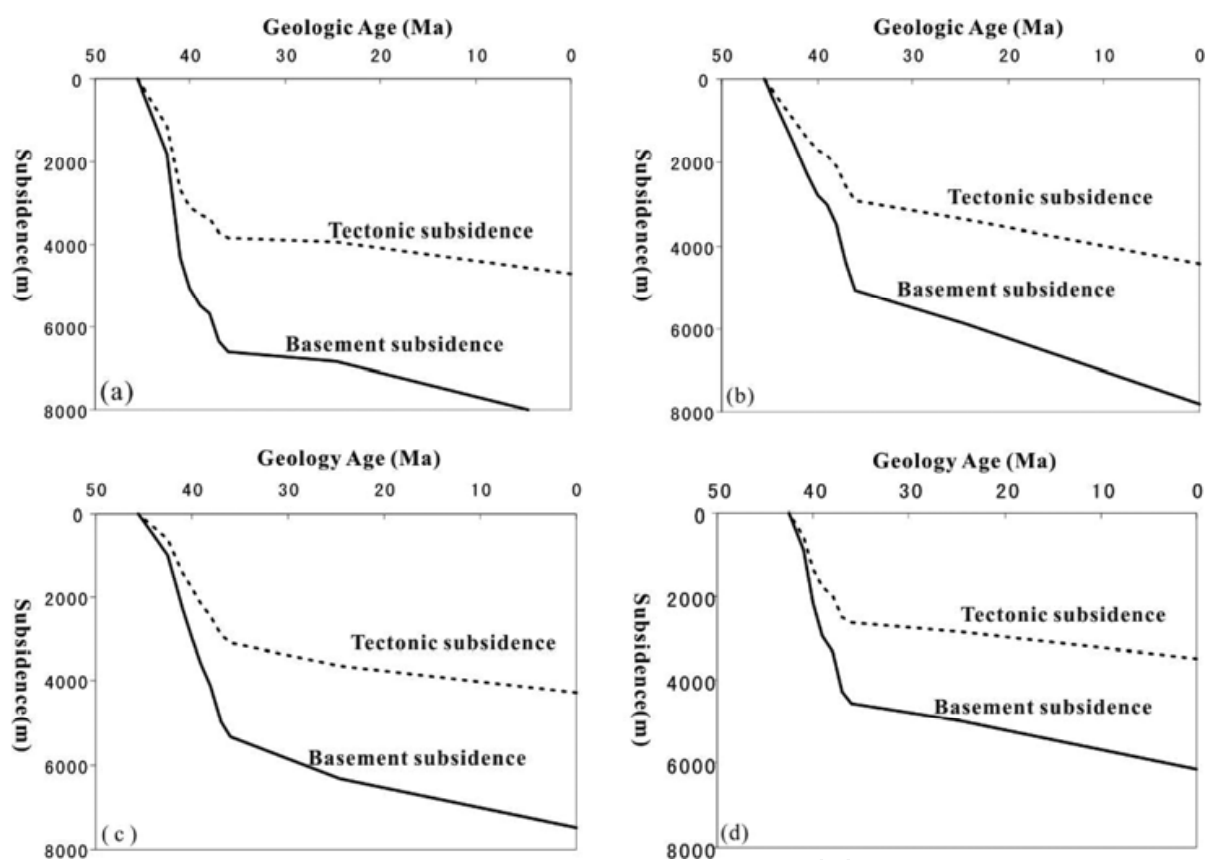
Fig. 5. Typical basin subsidence curves in the Dongpu Sag. a-the southern part of the west secondary sag belt (see P1 in Fig. 1 for location); b-the southern part of the east secondary sag belt (see P2 in Fig. 1 for location). c-the northern part of the west secondary sag belt (see P3 in Fig. 1 for location). d-the northern part of the east secondary sag belt (see P4 in Fig. 1 for location). Tectonic subsidence was caused by crust sketching due to mantle upwelling. Basement subsidence is the total subsidence including tectonic subsidence and sediment load subsidence

The Dongpu Sag is a half-graben controlled by the master fault on the east side, the Lanliao fault (Fig. 1, Fig. 6, Fig. 7, Fig. 8, and Fig. 9). This graben is cut by other ENE-trending faults,

such as Huanghe, Changyuan, Wenxi, and Wendong faults, dividing the Dongpu Sag into several secondary tectonic units. From east to west, the units are the eastern secondary sag belt, the central rise belt, the western secondary sag belt and the western slope belt. The so-called eastern secondary sag and western secondary sag belts can be regarded as two secondary grabens within the main graben.
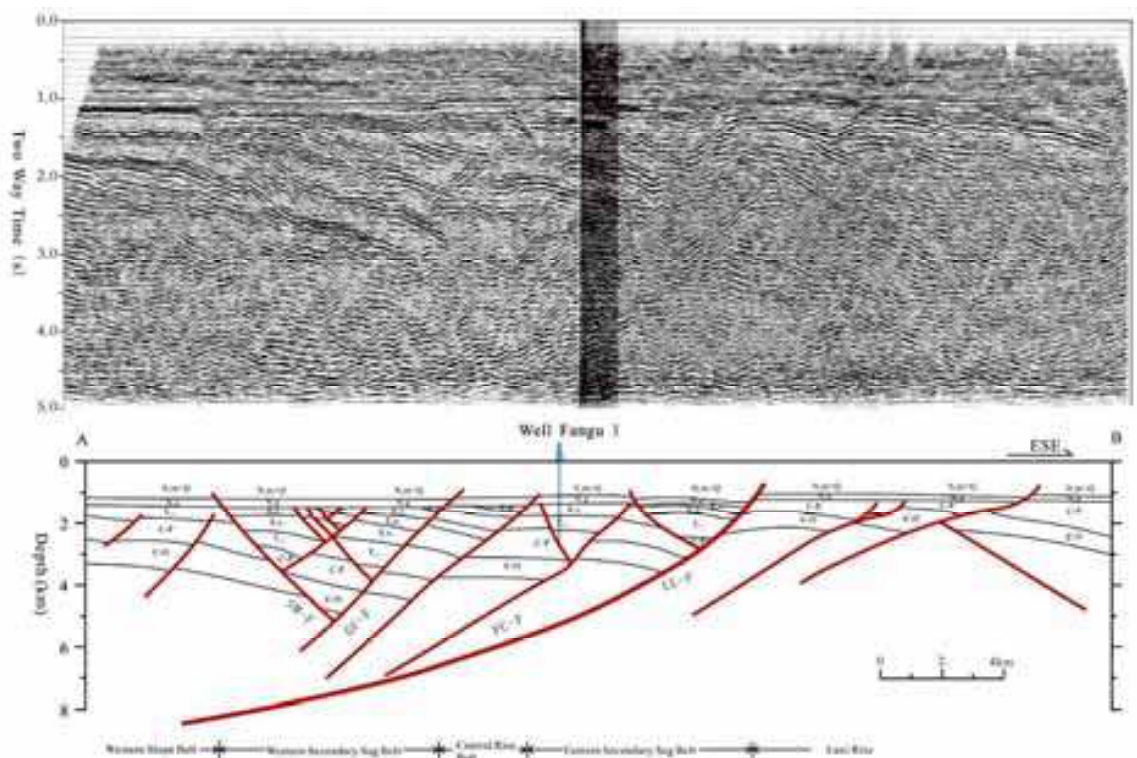

Fig. 6. Guancheng-Fanxian section of the north of Dongpu Sag (see A-B in Fig. 1 for location). SM-F: Songmiao fault, GC-F: Guancheng fault, PC-F: Pucheng fault, LL-F: Lanliao fault. T_{1-2}: Middle-Upper Triassic, C-P: Carboniferous-Permian, Є-O: Cambrian-Ordovician, Refer to Fig. 2 for other formation markers. Lanliao fault is the master fault and it soles out in the detachment surface of 9-12 km deep

In the north-south direction, the Dongpu Sag is divided into three segments by NW-striking transfer zones in the vicinities of Maogang and Qiaokou (Fig. 1). (1) North of Maogang, the Dongpu Sag is characterized by west-dipping domino-style faults within the half-graben (Fig. 6), but several smaller faults occur outside the main half graben to the east. (2)In the middle section between Maogang and Qiaokou, the Lanliao fault controlled deposition, and a prominent central horst (the central rise) appears. The basin structure is a rollover half-graben controlled by the Lanliao listric fault, and a secondary full graben west of the rise formed by other faults, like the Shijiaji and Wenxi faults, accommodates considerable sedimentation (Fig. 7). In Fig. 7, fault F_1 was active during the depositional time from the E_2s_4-$E_2s_3{}^3$ and its dip angle increased with the rollover of hanging wall of Shijiaji fault. From the depositional time of $E_2s_3{}^2$, the fault F1 stopped acting, and the displacement was transferred to Wenxi fault. Faults F_2 and F_3 were related to the bending of the layers. Lanliao fault soles out in the detachment surface of 14-16 km deep. In the southern portion of the middle section, that western full graben is dominated by rollover to the west and the central rise is subdued (Fig. 8). (3)In the southernmost part of the Dongpu Sag, the basin structure is a

product of the half-graben controlled by the Lanliao fault and the graben bounded by the Changyuan fault and Huanghe fault (Fig. 9). In this region, rollover is exclusively to the east.
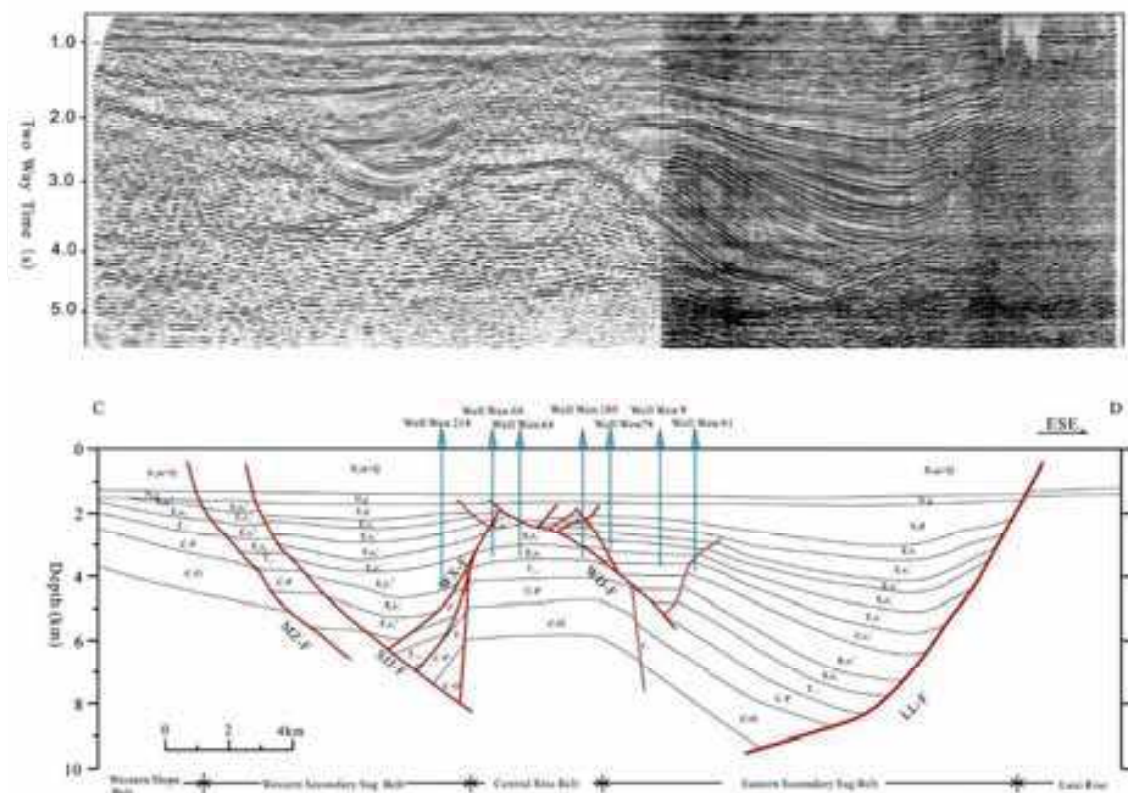

Fig. 7. Wenliu section of the middle of the Dongpu Sag (see C-D in Fig. 1 for location).
MZ-F: Mazhai fault, SJJ-F: Shijiaji fault, WX-F: Wenxi fault, WD-F: Wendong fault,
LL-F: Lanliao fault

The Lanliao fault is the master or controlling fault of the Dongpu Sag. The change of the basin structure is relevant to the geometry of the Lanliao fault and the depth and shape of its relative detachment surface (Fig. 10). To the north of Maogang, the Lanliao fault dips gently west to depths in excess of 8 km. From Maogang to Qiaokou, the Lanliao fault dips relatively steeply to depth of 8 km, and flattens under the central rise to the detachment surface at about 14-16km. In the south, the Lanliao fault develops a ramp-flat geometry at depth. The depth of the detachment plane in the eastern secondary sag belt is about 8-10km, and the depth in the western secondary sag is about 11-13km.

Research indicates that there are low velocity layers under the Lanliao fault (Fig. 11). It is interpreted from this data that the Lanliao fault may have two branches in the deep, one soling out in this low velocity layer and the other may cut through the upper mantle. That the controlling boundary faults sole out in a detachment surface at depth is common in extensional rift basins.

4. Tectonic style

Due to the various tectonic regimes, extensional and strike-slip tectonic styles formed in Dongpu sag. The extensional tectonic style is dominated. Also, since there are salt layers, salt structures exist.
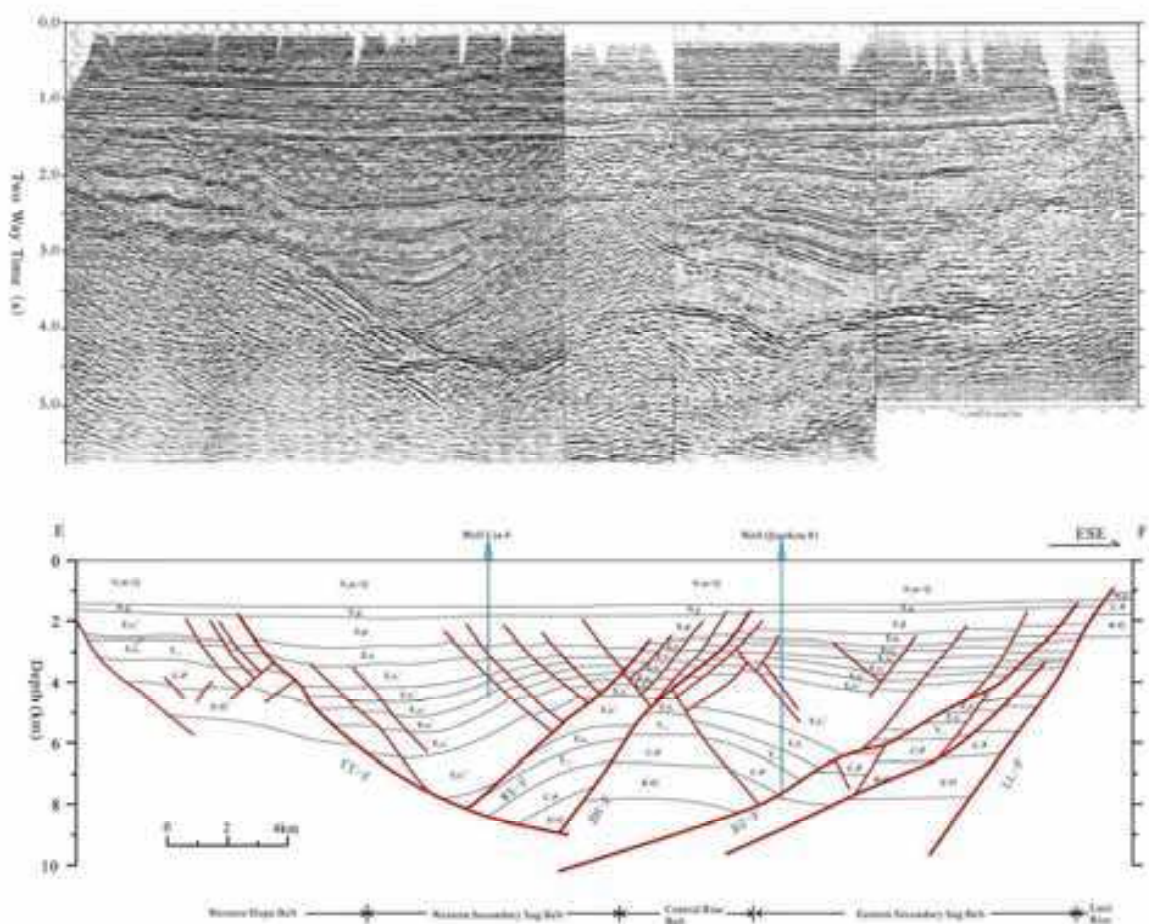
Fig. 8. Qiaokou section of the middle of the Dongpu Sag (see E-F in Fig. 1 for location).
CY-F: Changyuan fault, HH-F: Huanghe fault, DZ-F: Duzhai fault, LL-F: Lanliao fault,
WX-F: Wenxi fault. Lanliao fault soles out in the detachment surface of 14-16 km deep

4.1 Extensional structure

Extensional structures are dominated tectonic styles in the Dongpu sag, including
extensional fault assemblages, extensional folds and detachment faults (Fig. 12).

The parallel faults assemblage fault steps (Fig. 12a), mainly existing in the north part of the
Dongpu sag, and the north part of the western slope belt. X-type faults were resulted from
either conjugate faults forming in identical time or the superimposition of anti-dip faults
forming in different times (Fig. 12b), which are significant tectonic style in the Dongpu sag
and mainly distributed in the central rise belt (Fig. 8). Y-type faults (Fig.12c) are composed
by a listric master fault and hanging wall antithetic faults, and anti-y-type faults (Fig. 12d)
consists of a listric master fault and hanging wall synthetic faults. These two kinds of fault
assemblages distributed in the east and west of the central rise and east of the western slope
belt. Fan-type faults (Fig. 12e) are similar with crest collapse faults, and are composed by
anti-dip faults, which often accompany with rollovers in the middle central rise belt between
Mengju and Wenliu and in the east limb of the central rise belt. Horse tail faults(Fig.12f),
mainly distributing in the east limb of the central rise belt, resulted from the upward
propagation of a master fault, and were related to multi-phase actions of the master fault.
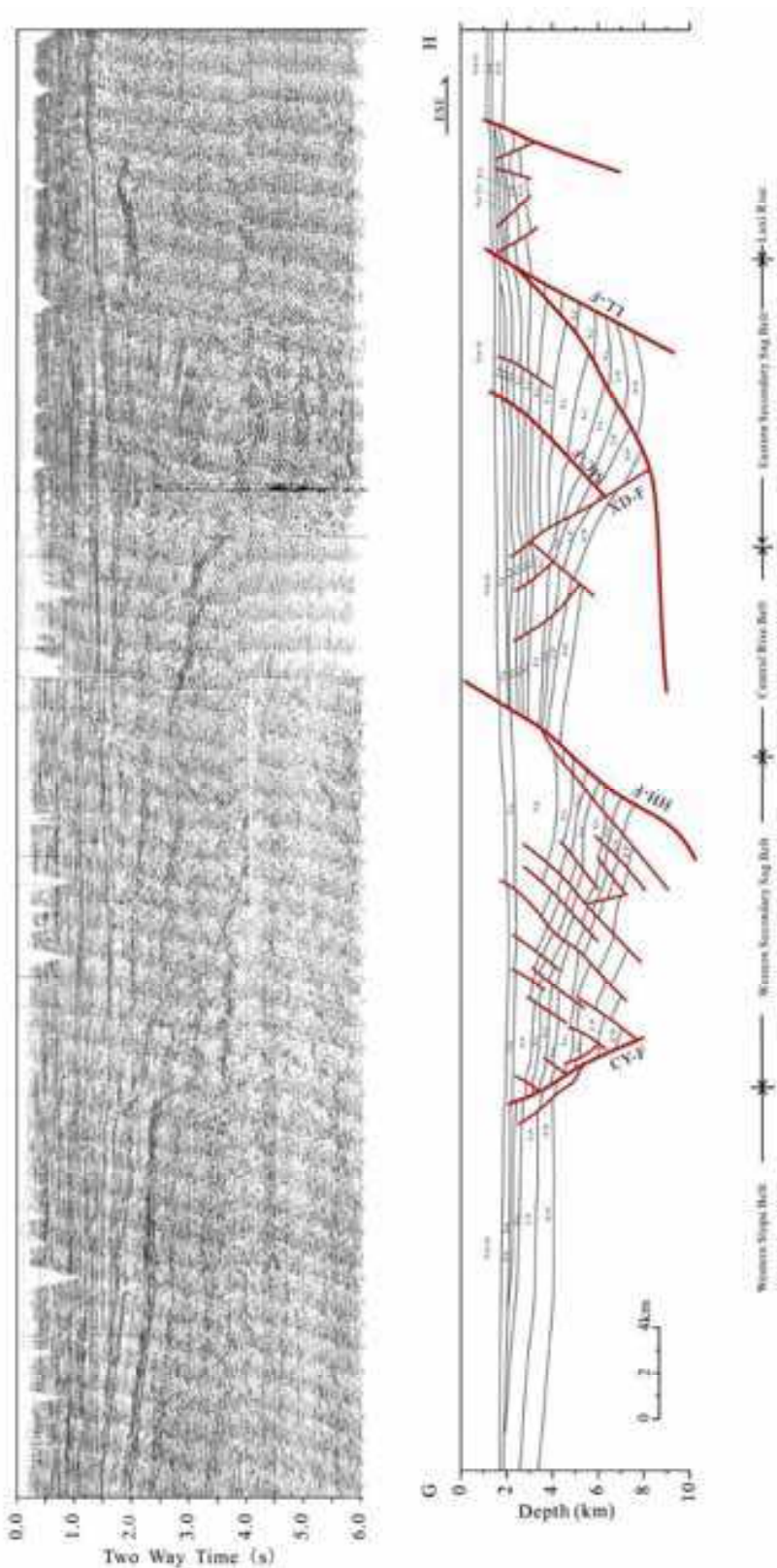
Fig. 9. Changyuan section of the south of the Dongpu Sag (see G-H in Fig. 1 for location).
CY-F: Changyuan fault, HH-F: Huanghe fault, MC-F: Machang fault, LL-F: Lanliao fault,
XD-F: Xudong Fault. The depth of detachment surface is 8-10km in the east of Huanghe
fault and 11-13 km in the west of Huanghe fault

Extensional folds in the Dongpu sag are rollovers and extensional forced folds. The rollovers are related to the hanging wall deformation of a listric fault and the latter to salt. The rollovers are common in the middle part and in the east limb of the central rise belt. Only one extensional forced fold has been found in north of Pucheng, where a thick salt layer existed.

The detachment faults are related to salt and mudstone in Paleogene, and coals in Carboniferous and Permian, mostly along salt. Detachment faults are common in the north part and in the east limb of the central rise belt.

The development of extensional structures is through the Dongpu sag evolution from Eocene to early Neogene.

4.2 Strike-slip structure

Many strike-slip structures occurred in Dongpu sag (Fig.13). Feather faults are composed by a master strike-slip fault and its related normal faults (Fig. 13a), mainly distributing in the north part of the western slope belt. En echelon faults (Fig. 13b) consist of R-shears (Davis et al., 1999), mainly distributing in the central rise belt from Qiaokou toward north. En echelon folds (Fig. 13c) occurred in the central rise belt, and there are two anticlines and one syncline. Mini-pull-apart basins (Fig. 13d) occurred in the north part of the western secondary sag belt, where the NNE-trending small depressions in E_2s_3 became NE-trending in E_3s_1, indicating that the NWW-SEE extension were superimposed by NNW-SEE pull-apart. Flower structures (Fig.13e, f) occurred mainly in the middle part of the central rise belt from Qiaokou to Wenliu.

Almost all of the strike-slip structures occurred in the middle part of the Dongpu sag from Qiaokou to Weicheng, and they indicated a right-hand strike-slip function. In terms of the trend change of the mini-pull-apart basins, the strata cut by faults and the change of subsidence, it can be reached that the strike-slip function mainly occurred in Oligocene.

4.3 Salt structure

Due to thin thickness of an individual pure salt layer, salt diapirisms are seldom in the Dongpu sag. The salt structures are salt domes, salt-related faults and folds, salt welds and mini-basins. Salt domes exist in the middle part of the central rise belt from Qiaokou to Wenliu, accompanied by secondary faults (Fig. 14). Other salt-related faults are detachment faults like those shown in the right of the Fig. 12i and Fig. 14. A salt-related fold, namely the forced fold (Fig. 12h) is in the north of Pucheng area. It is related to the action of the Pucheng fault, which has a large throw in the substrate of salt layer and a small throw in the overburden. While the faulting occurred in the substrate, the folding made the overburden bend to form the anticline. The anticline was enhanced by the slipping of the hangingwall of the Weidong fault along the $E_2s_3{}^4$ salt layer.

The salt-related sag, mini-basin, formed in Xulou area in the Dongpu depression. In the Fig. 14, the Xulou fault became gentle toward the deep and slip along the $E_2s_3{}^2$ salt layer. The $E_2s_3{}^2$ salt layer thinned obviously. The heave of the bottom horizon of the $E_2s_3{}^2$ is up to 2000m and the thickness of the E_3s_2 in the hangingwall is greatly larger than that in the footwall. The phenomena could not be explained only based on the slipping of the Xulou fault. The salt flowage must have played an important role. It can be inferred that the salt flowage occurred in the depositing period of the E_3s_2 in terms of the thickness of the strata in the hangingwall and in the footwall of the Xulou fault. The withdrawal of the $E_2s_3{}^2$ salt layer led the E_3s_2 to connect with the $E_2s_3{}^2$ to form a salt weld.
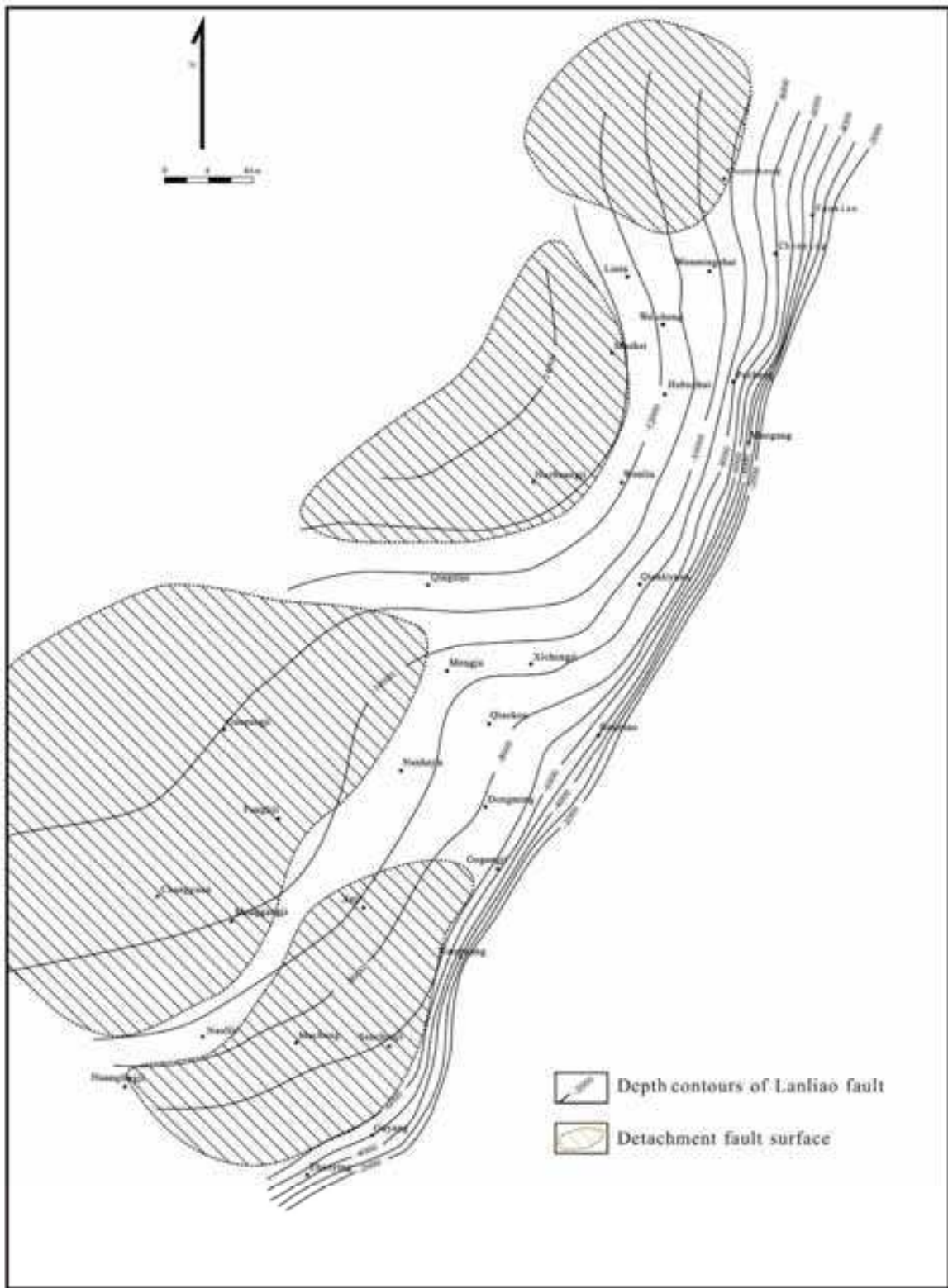
Fig. 10. Depth of the Lanliao fault and its related detachment surface. Twenty eight seismic lines were used. The geometry of Lanliao fault shallower than 8000m depth is based on seismic interpretation and that deeper than 8000m depth was based on the area-balance work, which is got from the section area of sediments and horizontal stretching amount (Modified after Qi et al., 2006)
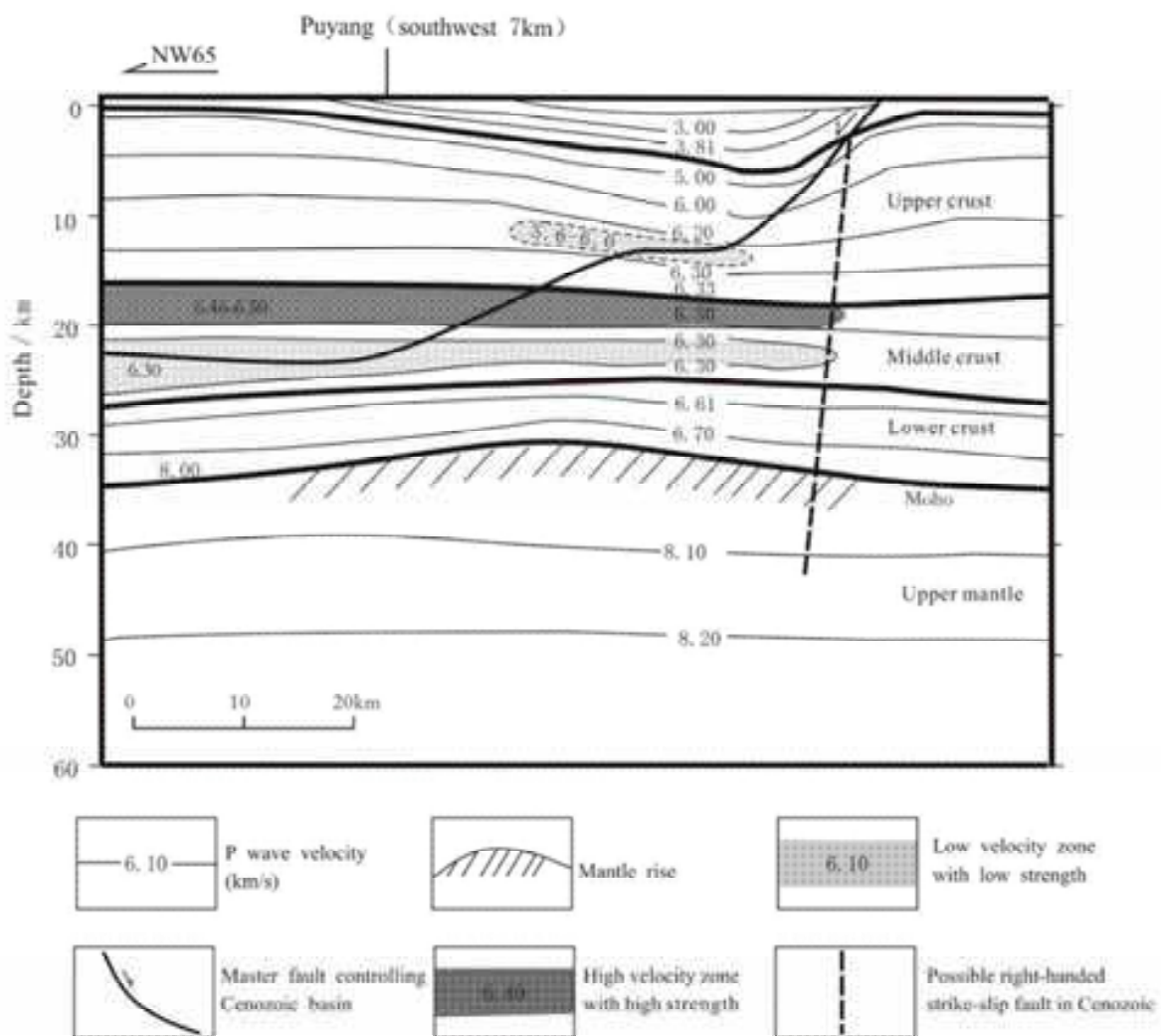
Fig. 11. Two dimensional seismic velocity cross section in the Dongpu Sag. Under the Dongpu Sag, there are two low velocity layers. The upper one is at the depths of 10-15km with P-wave velocities of 5.6-6.0 km/s, and the lower one is at the depths of 22-24 km with P-wave velocity of 6.3 km/s. (Modified after Qi et al., 2006)

The salt tectonic evolution in the Dongpu sag in the Paleogene can be divided into three stages including the pre-salt tectonic stage in the period of the E_2s_4-E_2s_3, the salt tectonic stage I in the period of the E_3s_2- E_3s_1, and the salt tectonic stage II in the period of the E_3d. In the pre-salt tectonics stage, the $E_2s_3{}^4$ and the $E_2s_3{}^2$ salt rhythms deposited. In the stage I, the salt tectonics was characterized by structures associated with the overburden slippage along the salt layers and the salt flowage. During the period of the E_3s_2, the salt flowage formed the salt-related basin (Fig. 14). The salt might rose above sedimentary datum to make the E_3s_1 overlie the $E_2s_3{}^4$ salt layer directly to form salt meld. The Pucheng forced fold began to develop. In the period II, the salt tectonics was characterized by structures associated with the overburden slippage along the salt layers, such as detachment folds and the secondary faults in the hangingwalls. Salt domes occurred in some areas and the Pucheng forced fold was enhanced in this period. It can be reached that the salt tectonics in Dongpu depression were stirred by extensions and was mainly related to the $E_2s_3{}^4$ and the $E_2s_3{}^2$ salt rhythms.
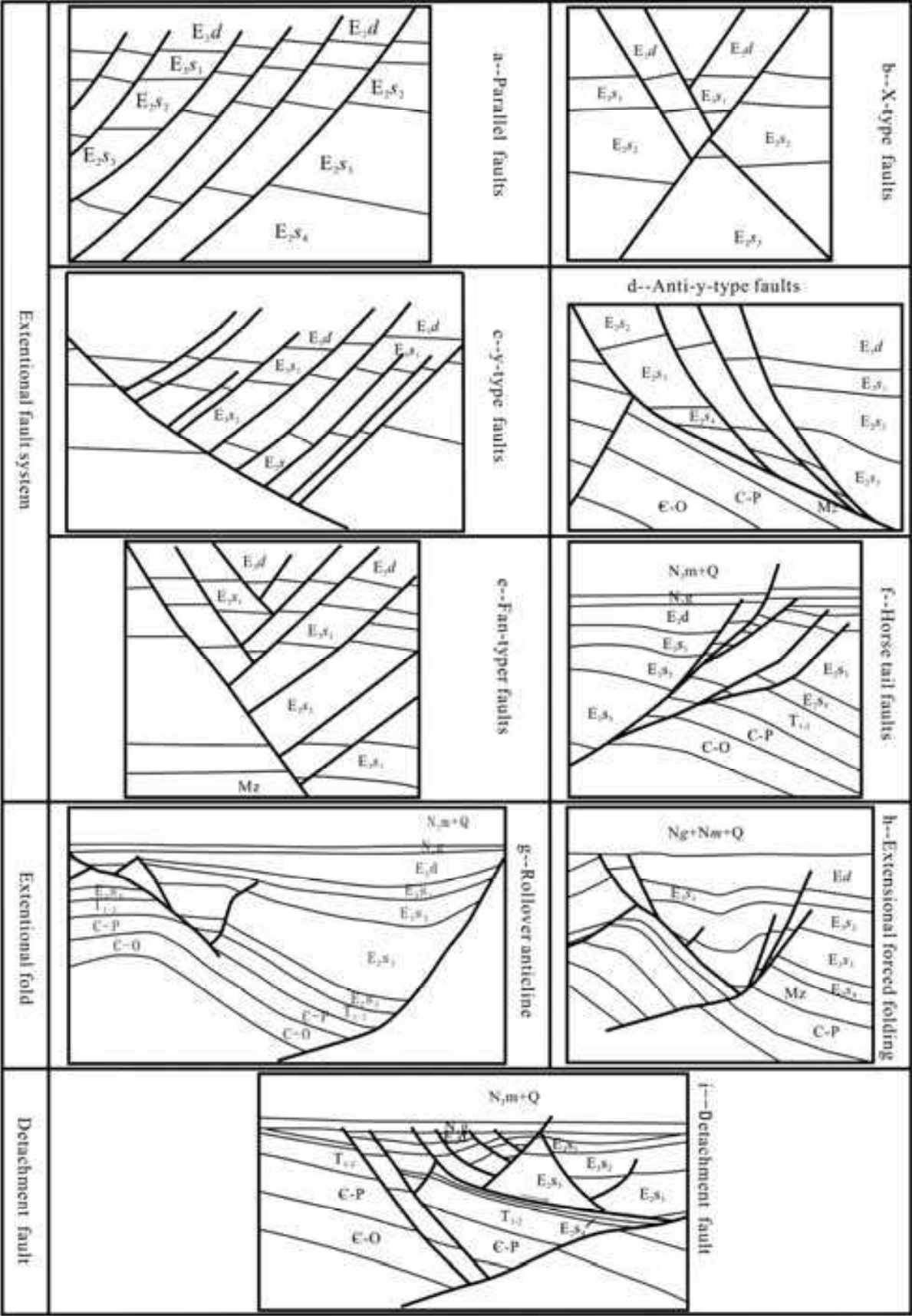
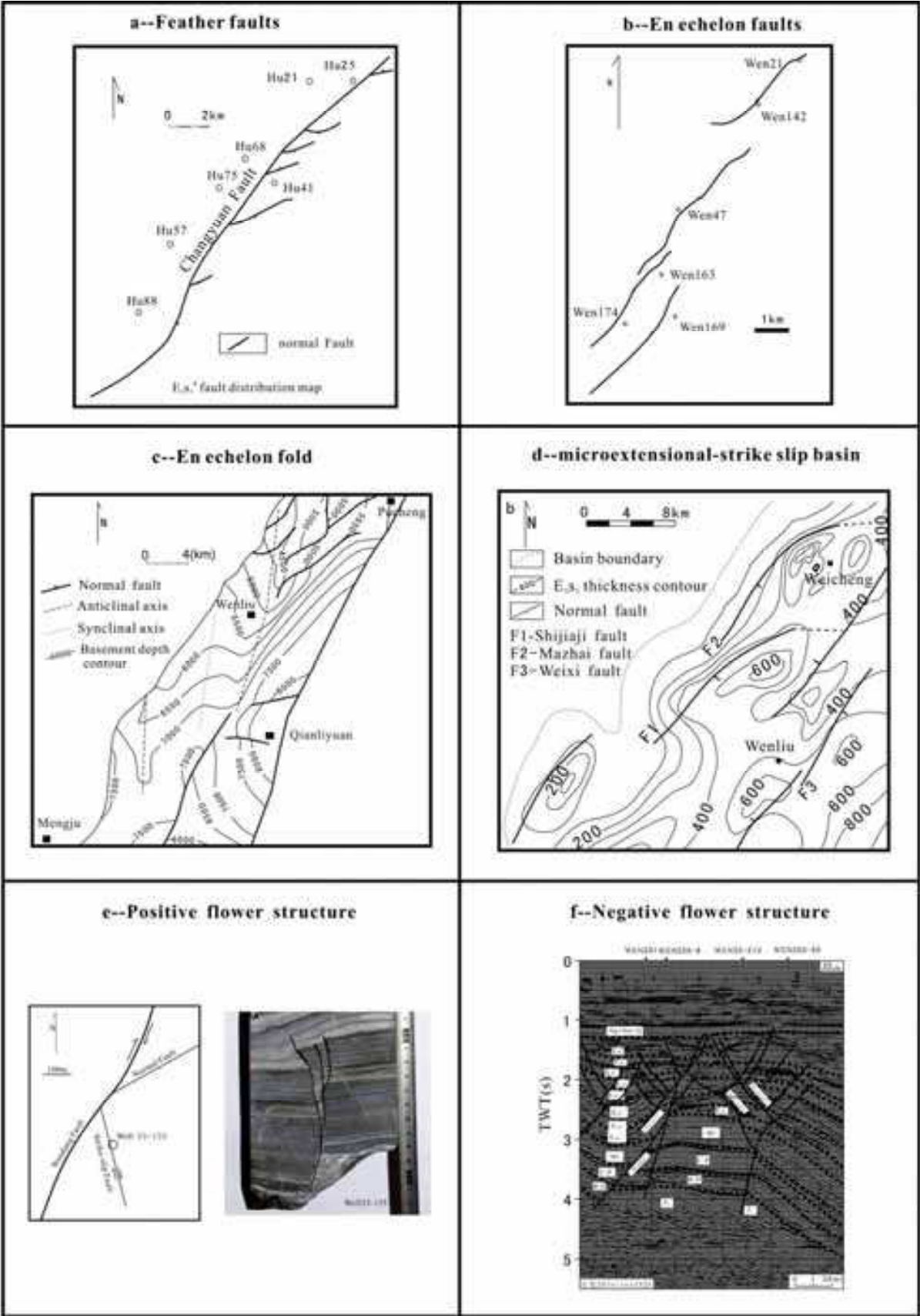Fig. 12. Extensional tectonic styles in the Dongpu sag

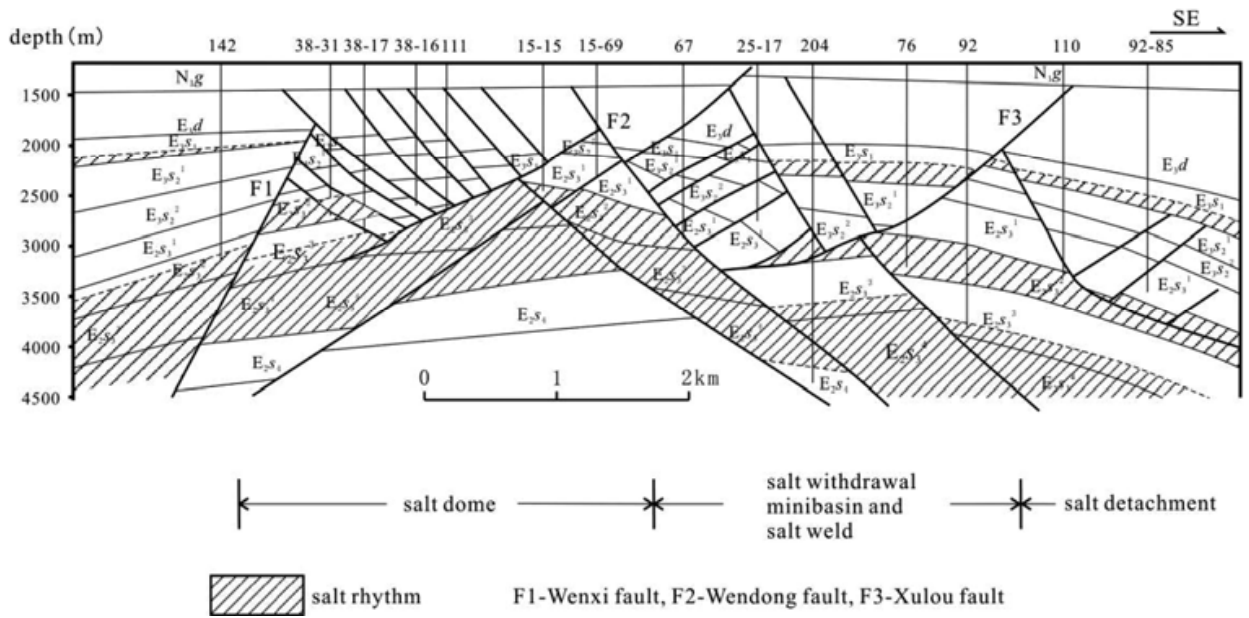Fig. 13. Strike-slip structures in Dongpu sag

Fig. 14. Salt structures in the cross section from Well Wen 142 to Well Wen 92-85

5. Tectonic evolution

5.1 Fault linkage and progressive deformation

The faults in the Dongpu sag can be divided to four fault systems (Fig.1): 1) the Lanliao fault system, 2) the eastern central rise fault system including the Xudong fault, the Xindong fault, the Wendong fault and the Weidong fault, 3) the western central rise fault system including the Huanghe fault, the Wenxi fault and the Weixi fault, and 4) the western fault system including the Changyuan fault, the Shijiaji fault, the Mazhai fault, the Liuta fault and the Songmiao fault. The fault evolution has formed linked fault systems. These fault systems are parts of the linked fault system taking the Lanliao fault as the master faults.

Based on the calculated fault activity speed, the evolution of faults in the Dongpu sag can be divided into three cycles (Table 1), namely E_2S_4, E_2S_3, and E_3S_2-E_3d.

During the deposition of E_2S_4 in the Eocene, a lot of small-scale normal faults striking to the NNE formed, with small displacement and weak activity. These faults were not linked together; the Lanliao, the Machang, and the Sanchunji faults may have followed the paths of the faults existing before the Paleogene. Some faults in the four fault systems started to develop, but were not joined together in plane or cross-sectional view (Fig. 15).

During the deposition of E_2S_3, the Lanliao fault was very active, with a maximal activity rate of 1800m/m.y., and was linked to the detachment plane. Other faults developed and were linked together by the detachment fault. Laterally, the faults at the same structural sites propagated to connect with each other. The extensional link fault systems controlling the evolution of the Dongpu sag thus were built and the graben-horst-graben basin tectonic framework was formed. During this period, the western slope fault system began to form, the western central rise fault system, and the Lanliao fault system were formed. Meanwhile, the eastern central rise fault system started to develop, which, together with the western central rise fault system, made the central rise develop.

During the deposition of Oligocene E_3S_2 to E_3d, the shallow antithetic normal faults propagated downward and sole out in the detachment plane or in the weak layers in the tilted blocks. They link with the Lanliao fault or the detachment surface finally. The maximum fault activity rate is 1400m/m.y. During this period, some key basement faults that were intensely active in E_2S_4 and E_2S_3 became inactive, even being cut by the shallow normal faults, such as the Machang fault, the Duzhai fault, and the Gaopingji fault. Also, during this period, the north part of the Lanliao fault, the Huanghe fault, the north part of the Changyuan fault, the Wendong fault, and the Weidong fault were very active, settling the tectonic framework of the Dongpu sag and the four fault systems. Under the right-handed wrench, some en echelon faults formed.

During Neogene-Quaternary (Pleistocene and Holocene), the all of the Dongpu sag subsided. The faults of the extensional link fault systems essentially stopped acting, although some dominant faults kept moving. The fault activity basically did not control the deposition.

Stratum	E_2S_4	E_2S_3				E_3S_2	E_3S_1	E_3d
		$E_2s_3^4$	$E_2s_3^3$	$E_2s_3^2$	$E_2s_3^1$			
Time (Ma)	45.5-2.5	42.5-1.0	41.0-0	40.0-9.0	39.0-8.0	38.0-7.0	37.0-6.0	36.0-4.6
Active rate (m/Ma)	230	1800	1200	800	600	1400	700	100
Active cycle	I	II				III		

*fault activity rate =Horizontal displacement of a fault in certain period/duration time

Table 1. Fault activity rate* in Dongpu sag in Paleogene

5.2 Basin evolution

For the basin evolution of the Dongpu Sag, two basin-forming periods can be recognized during the Cenozoic, the Paleogene rifting and Neogene thermal cooling and subsidence. Based upon changes in fault activity, the rifting period in the Paleogene can be divided into three stages:

(1) the initial rifting during deposition of E_2S_4 when the fault activity was not yet linked, and the basin underwent its initial stages of northwest-southeast extension (Fig.16a). The thickness of sediments accumulated at that time was small, and there were no obvious subsidence centers.

(2) the intensive rifting stage during the deposition of E_2S_3, when wedge-shaped sediment bodies grew, and the small-scale faults began to connect to form large ones. At this time, while the basin underwent extension in a northwest-southeast direction, it may have been affected by dextral wrench motion (Fig.16b). During this stage, areas of high subsidence were located along the Lanliao fault and in the middle of the Dongpu Sag.

(3) the later rifting stage during the deposition of E_3S_2-E_3d, when the fault activity progressively weaken. During this stage, the loci of high subsidence migrated to the south of the western secondary belt, and structures were further affected by dextral wrench motion with some strike-slip faults (Fig.16c). Also during the deposition of E_3S_2-E_3d, main salt structures formed.
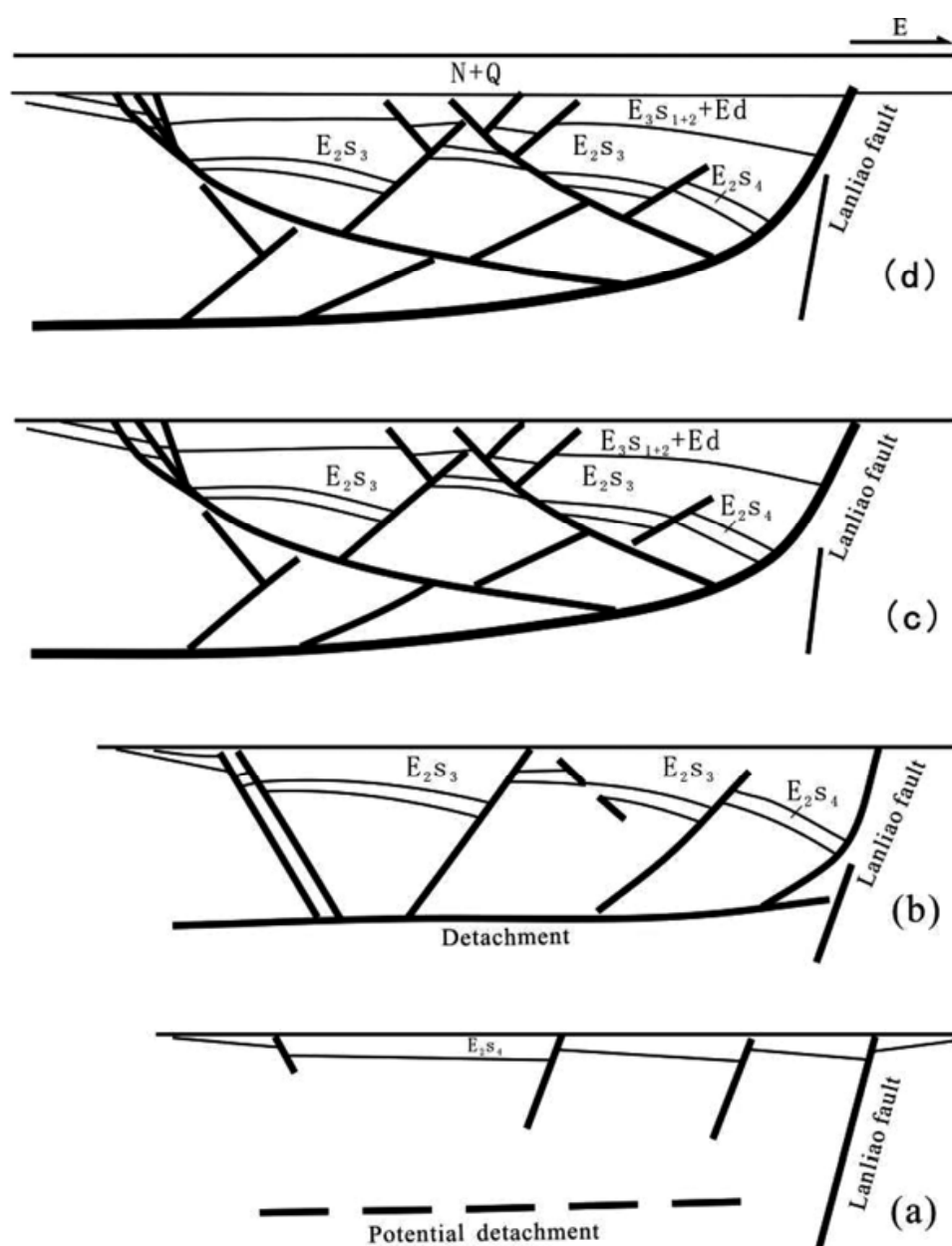
Fig. 15. Evolution of extension linked fault system in the Dongpu sag

6. Discussion

6.1 Plate tectonic setting

The regional plate tectonic picture can be related to the evolution of the Dongpu Sag. Throughout the Cenozoic Era, the China plate has been located at the junction of the Eurasian, the Indian, and the Pacific plates (Fig. 17). During the early Eocene time, the Pacific plate subducted in a nearly north direction (Chen, 1990; Zhang, 1995), but shifted to a west-northwest and westerly direction of subduction during the middle Eocene to Oligocene at rates of 4-7.7cm/yr. In the late Oligocene, the rate of Pacific plate subduction increased (Lee & Lawver, 1995), and two trenches were formed, the west Taiwan-

Philippines trench and the east Japan-Mariana trench. In Oligocene, the sea of Japan opened and gave the China plate a SW push (Allen, M.B., et al., 1997). During the Neogene, the Pacific plate subducted to the W-WNW at a rate of 6.9-10.6 cm/yr and the Philippines plate moved toward the north (Wan, 2004; Zhang, 1995).
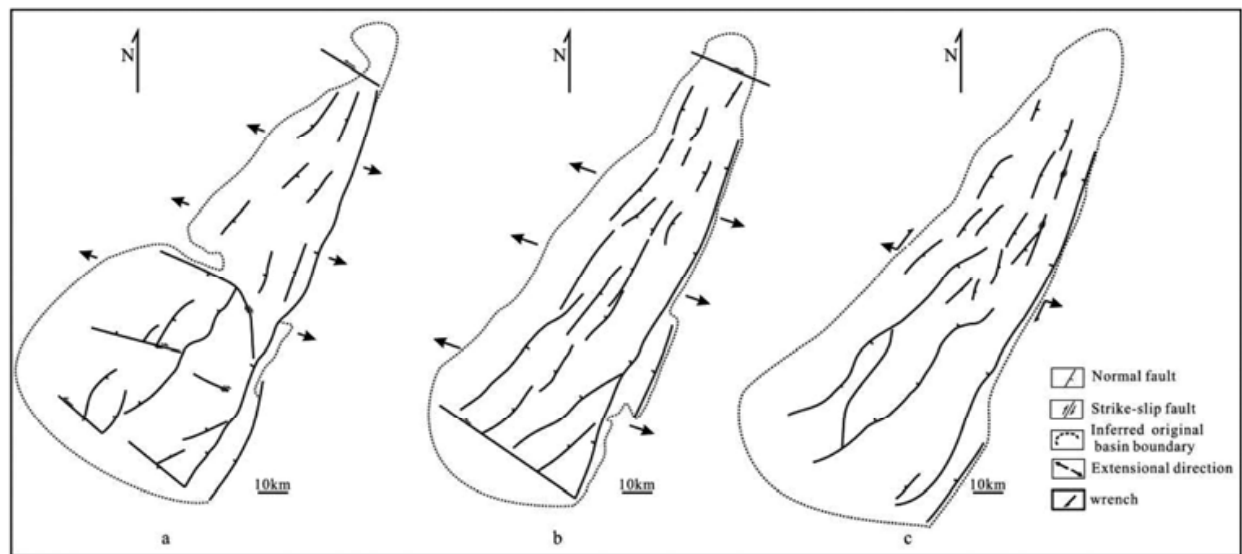

Fig. 16. Distributions and tectonic stress fields of Dongpu sag in Paleogene. (a) Fault distribution in E_2s_4. (b) Fault distribution in E_2s_3. (c) Fault distribution in Oligocene (E_3)

In the west, the China plate was mainly influenced by the collision of the Indian continental block with Asia beginning about 45Ma (Hendrix et al., 1992; Graham et al., 1993). During the Paleocene to the early Eocene, the Indian plate subducted under China in a north/northeast direction at a rate of 17cm/yr (Lee and Lawver, 1995). During the middle Eocene to early Oligocene, the Indian plate slowed to 5.6cm/a (early) and 4cm/a (later) as a result of the continental collision, later to speed up in the Neogene to Quaternary to 4.5-5.6 cm/yr. The far-field effect of the collision between the Indian plate and the China plate has often been linked to the tectonic evolution of east China (Molnar & Tapponnier, 1975; Tapponnier et al., 1982; Burchfiel & Royden, 1991; Guo et al., 1992; Avouac & Tapponnier, 1993; Allen, M.B., et al., 1997; Yin & Harrison , 2000; Wan & Zhao, 2002; Zhang et al, 2008; Qi & Yang, 2010).

It is arguable from timing considerations that these changes in the plate tectonic environment controlled, and are reflected in, the structural evolution of the Dongpu Sag. At the end of the middle Triassic, the early Indosinian movement caused the area of the Bohai Bay Basin and its adjacent rise to be eroded. At the beginning of the Eocene, with the subduction of the Pacific plate, mantle upwelling in the back arc opened the rifting prelude to the creation of the Dongpu Sag. In the Oligocene, while the Dongpu Sag underwent rifting, the right lateral wrench related to both the movement of the Indian plate and the open of Sea of Japan was enhanced. In the Neogene, with both the Pacific plate subduction under the China plate with a high angle at a fast rate, and the Philippines plate formation, the previous dynamic condition changed, and the basin entered the thermal-cooling depression stage. For the whole Bohai Bay Basin, including the Dongpu sag, the tectonic activity was weak with a few large-scale faults controlling deposition during the Neogene.
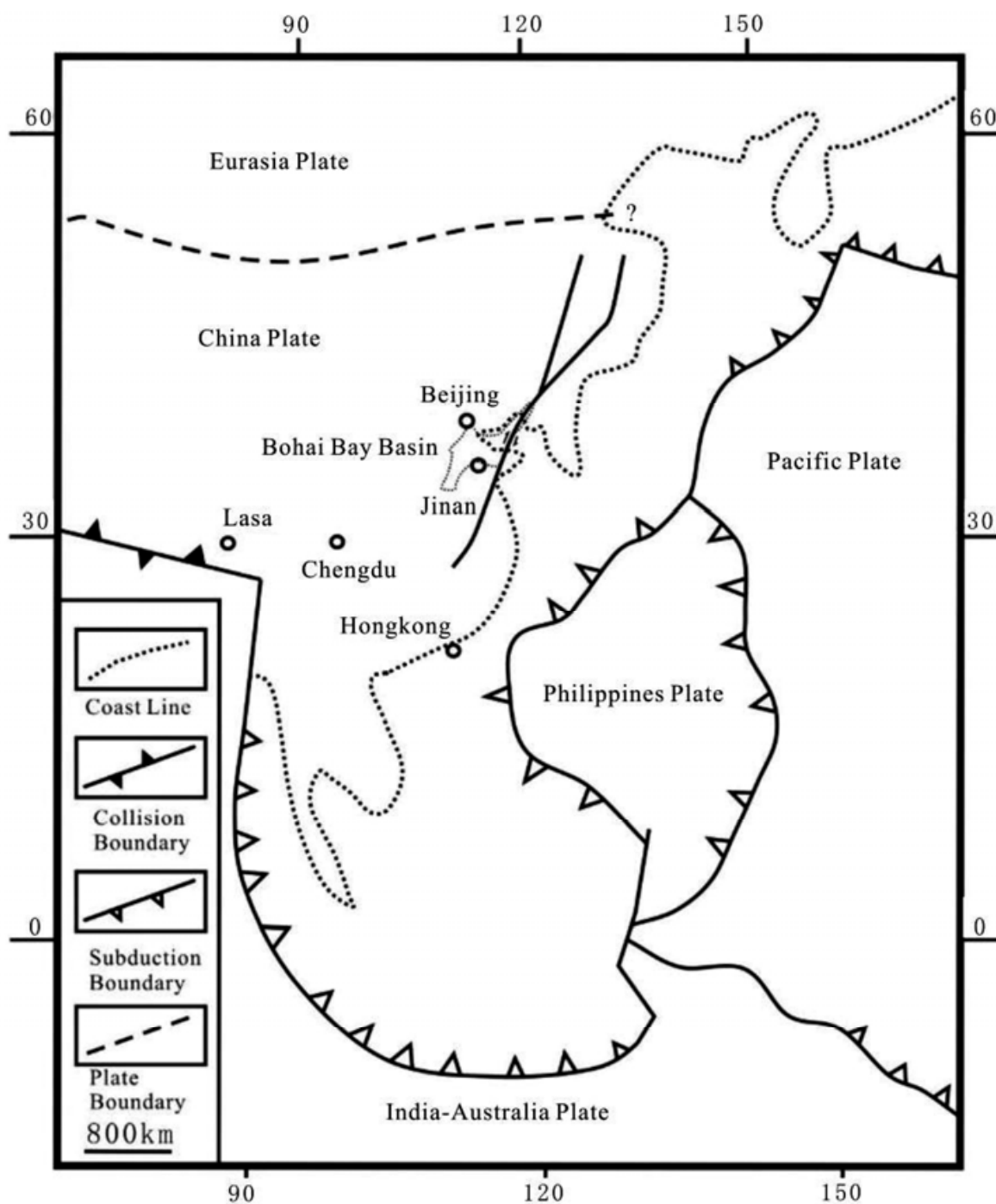
Fig. 17. Plate tectonic settings of east China area in the Cenozoic (Adapted after Chen, 1990; Cheng, 1994; Zhang, 1995; Lu et al., 2003)

6.2 Dynamic model

The patterns of sedimentation, magmatic activity, basin subsidence, and faulting in the Dongpu Sag indicate that the fundamental history was one of rifting and crustal extension. There is some evidence that a wrench component of deformation was superimposed on the rift. Evidence such as the en echelon faults, the migration of the depocenters, and the

positive flower structures are indicative of a right-lateral wrench component of deformation. The changes in subsidence rate and stratum thicknesses indicate the wrench action beginning in the late Eocene and lasting through the Oligocene. Salt tectonics, starting from the late Eocene, enhanced the structures of the Dongpu sag. Mostly, the salt layers were detachments.

A conceptual model of this tectonic environment is shown in Fig. 17. In the Paleogene, the listric faults developed accompanied by magmatic activity and northwest-southeast extension. The faults exerted obvious control on deposition, and the basin had high subsidence rates.

In the beginning of the Dongpu sag in $E_2s_3^4$, NW-dipping faults were dominated. The crust extension was simple shear. In this time, the mantle upwell was not significant and mantle flowage toward east controlled the initial development of the sag. This eastward mantle flowage was caused by a large convection circle, which resulted from the Pacific plate subduction. From late Eocene to Oligocene, the mantle upwelling increasingly controlled the middle part of the Dongpu sag, where the crust extension was simple shear and volcanic activity was intensive. The north and south sections of the sag still behave simple shear crust extension. Seismic velocity data show a mantle high under the Dongpu Sag (Fig. 11). The crustal thickness in the sag is 28-30 km, while the crust thickness in the eastern Luxi rise and in the western Neihuang rise is 34 km.
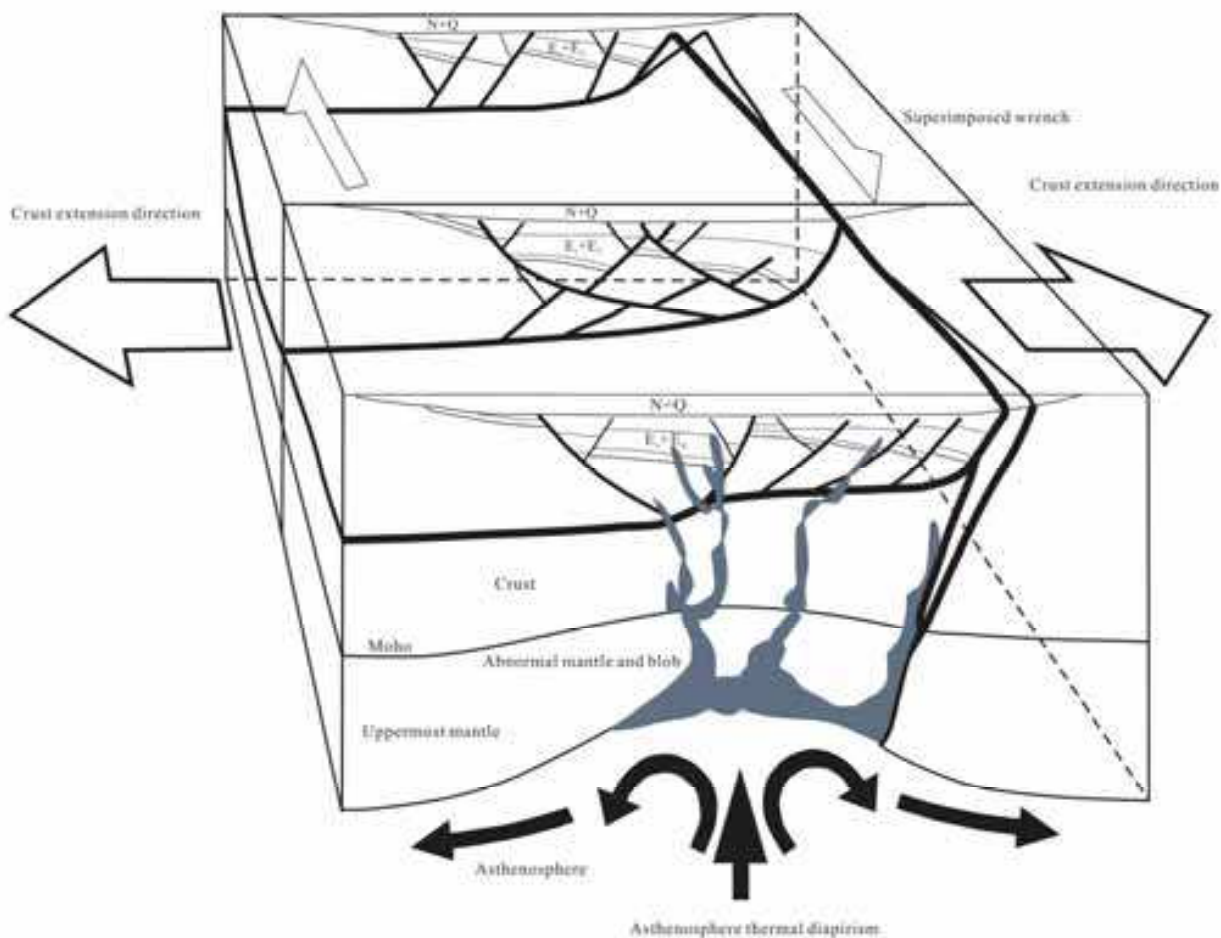

Fig. 18. Cenozoic dynamic model of Dongpu sag

A major unconformity lies between the Neogene and the Paleogene, marking the change from rifting associated with mantle upwelling to subsidence caused by thermal cooling. In the Neogene, the faults were relatively quiescent, and the basin was dish-like with a low subsidence rate; Magmatic activity was absent.

7. Conclusions

The structures, basin subsidence history and magmatic activity indicated that the Dongpu Sag is rift basin, being enhanced by right-handed strike-slip and salt tectonics in late Eocene and Oligocene.

The structural framework and sediment deposition in the Dongpu Sag were controlled by the Lanliao fault and its related detachment surface. The structural style of the Dongpu Sag, as a whole, is a half-graben with hanging wall rollover into the Lanliao fault. This half-graben was cut by other large scale faults to divide the basin, from west to east, into a slope, graben, horst, and graben succession. The structural style varies in the strike direction along the Lanliao fault, which links at different depths to the detachment surface.

The tectonic styles include extensional, strike-slip, and salt structures. The extensional faults are step faults, x-type faults, y-type faults, fan faults and horse-tail faults, and the extensional folds are rollover anticlines and extensional forced folds. The strike-slip structures are en echelon faults, en echelon folds, mini-pull-apart basins and flower structures, demonstrating a right-handed wrench. The salt structures are salt domes, salt welds and mini-basins. The extensional structures, developing from the Eocene to early Neogene, are dominated tectonic styles of the Dongpu sag. The strike-slip structures and salt structures occurred from late Eocene to Oligocene.

The Dongpu rift sag underwent two evolutionary stages, the rift period with intensive faulting in Paleogene and the post-rift depression period with simple structures in Neogene and Quaternary. The maximum extension occurred during the deposition of the third member of Shahejie formation (E_2s_3) with intensive fault block rotation. The maximum extensional speed occurred during the deposition of the second member of Shahejie formation (E_3s_2) with most secondary, eastern dipping faults. The period of deposition from the fourth member to the first member (E_2s_4-E_3s_1) of the Shahejie formation was of high subsidence rate, and the period of deposition from Dongying formation (E_3d) to present was of low subsidence rate. A right-handed wrench occurred in Oligocene and affected the basin tectonic frame and structures to a certain extent.

The Dongpu sag is resulted from the evolutions of the Lanliao fault-related linked fault systems. During the deposition of E_2S_4 in the early Eocene, the Dongpu sag was faulting within the context of regional uplift. A lot of small-scale normal faults striking to the NNE direction formed, with small displacement, and weak linkage. During the deposition of E_2S_3, the Lanliao fault was very active, and was linked to the detachment surface. Other faults developed and were linked together by the detachment fault. The extensional linked fault systems controlling the evolution of the Dongpu sag thus were built, and the slope-graben-horst-graben framework began to form. During the Oligocene, from deposition of E_3S_2 to that of E_3d, the shallow eastern dipping antithetic normal faults propagated downward and eventually linked with the Lanliao fault or the detachment surface. The basin frame and the fault systems were established. Strike-slip structures formed under the right-handed wrench in this period. During Neogene-Quaternary (Pleistocene and Holocene), the all of the Dongpu sag subsided. Activity on the faults of the extensional systems essentially ceased.

The properties and assemblages of the faults indicate that the Dongpu sag underwent stretching in a northwest to southeast direction in the Eocene, and while still extending NW-SE, a right-handed strike-slip wrench was superimposed in the Oligocene. The stretching was caused by the creep and upwelling of the mantle due to the subduction of the Pacific plate beneath the Eurasian plate. An early (E_2s_4) mantle creep eastward led a simple shear crust stretching with westward dipping faults, and a late (E_2s_3-E_3d) mantle upwelling led a pure shear crust stretching with symmetric faults. The interaction of the northward motion of Indian plate, the opening of the Sea of Japan and the change of the Pacific plate subduction direction led the right-handed strike-slip.

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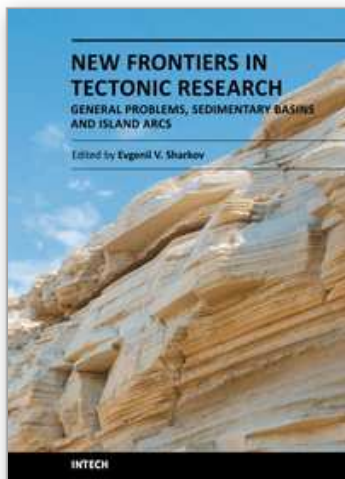
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