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Characteristics and Numerical Simulation of Extensional Structure Since Late Mesozoic in Western Shandong, China

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Abstract

The extensional structure in western Shandong is composed of steep normal fault and décollement fault, which two together constitute a unique "extensional structure framework". With the regional geological survey of West Shandong Rise and seismic data from Jiyang Depression, we make comprehensive researches on extensional structural features in western Shandong. A number of NW-trending and NWW-trending normal faults, together with several NE-trending and nearly EW-trending faults, constitute a typical "fault-block style" all over the research area. In the steep normal fault zone, there are dynamic breccia, fault clay and scraping trace making up signs of faults activity. Low-angle décollement faults are mainly found at unconformity / lithologically abrupt interfaces or disconformity surfaces, of which the most outstanding in western Shandong occurred along unconformity surface between the Archean and Cambrian (Ar/∈), and the disconformity surface between the Ordovician and Carboniferous (O/C). Based on the finite element method, we use the software of Ansys12.0 to carry out tectonic stress field numerical simulation of the evolution in research area since late Mesozoic. The result indicates that the strength of the tectonic stress field has experienced a process from strong to weak since late Mesozoic. The evolution of extensional structures of western Shandong commenced in late Jurassic, with the direction of NE-SW. And the research area entered its first massive extended fault-depression phase in Late Jurassic-Early Cretaceous (140 - 65 Ma). Then the extension continued in Paleocene-Early Eocene (65 - 53 Ma) which was a transforming transitional period with its extending orientation transformed from NE-SW to SN. In Eocene-Oligocene (53 - 23.3 Ma) the extension met its large-scale extensional activity with the direction of NW-SE. As can be seen in the study, the essential dynamic origin is mainly influenced by the structural changes since late Mesozoic, and the chief factors leading to the tectonic stress field change are the subduction of the Pacific Plate and the strike slip motion of the boundary faults.

Key words: Numerical simulation; Extensional structures; Since late Mesozoic; Western Shandong

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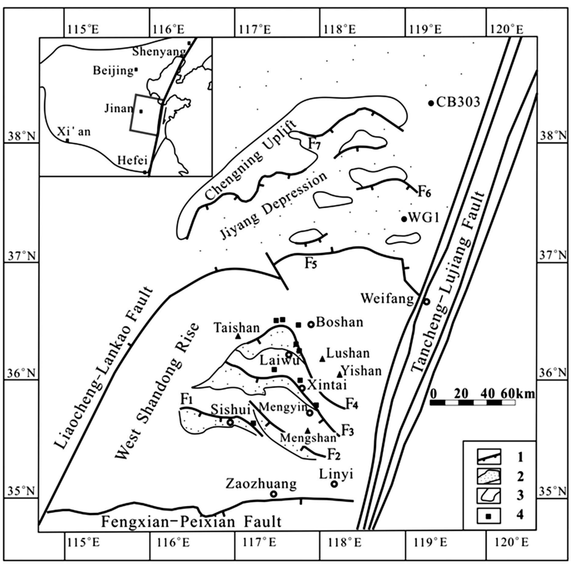
INTRODUCTION

Extensional structures are important geological features whose theoretical research system is developing rapidly. Since 1970s, geologists have achieved fruitful results of extensional structure such as geometry, kinematics and mechanism[1-5]. With the widely application of the quantitative analysis technology, the research of tectonic deformation has gradually realized an important change from qualitative to quantitative in recent years. It should be the first choice of the extensional structure research because of the unique regional geological background in western Shandong. Until now, the original work has been related to the characteristics and evolution of the extensional structures in West Shandong Rise and Jiyang Depression[6-9]. However, the systematical support of stress-strain has not been evaluated. Based on regional geological research in West Shandong Rise and seismic surveys in Jiyang Depression, combined with the tectonic stress field numerical simulation, we attempt to investigate the characteristics of the extensional structure and explore its evolution mechanism.

1. GEOLOGICAL SETTING

Taking Qihe-Guangrao Fault as the boundary, the western Shandong block contains two tectonic units of West Shandong Rise and Jiyang Depression. It is situated to the west of Tancheng-Lujing Fault, east of Cangdong-Lanliao Fault, south of Chengning Uplift, and north of Fengxian-Peixian Fault (Figure 1).

There is a typical North China Craton type formation, including the basement and cover rocks. Its basement is composed of Proterozoic-Archean rocks of the Taishan Group, tonalite-trondhjemite-granodiorite (TTG) and granite, while cover rocks comprise Sinian-Cenozoic strata. The Sinian is composed of marine rocks, limited in extent in both southern areas and adjacent to the TLF. Rocks of the lower Paleozoic constitute Cambrian Zhushadong Formation ($\in_{1zh}$), Mantou Formation ($\in_{1\text{-}2m}$), Chaomidian Formation ($\in_{3c}$), Ordovician Sanshanzi Formation (O_{1s}), and Majiagou Formation ($O_{1\text{-}2m}$). And rocks of the upper Paleozoic constitute Carboniferous Benxi Formation (C_{2b}), Taiyuan Formation (C_{2t}), Permian Shanxi Formation (P_{1s}) and Shihezi Formation (P_{2s}). The Mesozoic rocks comprise Jurassic and Cretaceous Formation, lacking of Triassic Formation. The Cenozoic rocks in Western Shandong constitute Paleogene, Neogene and Quaternary Formation. The basement in Western Shandong was formed in pre-Sinian, with vertical movement which controlled the Sinian-Permian geology. Fault-block movement had been the key tectonic movement since Late Mesozoic.



Note. 1-Extensional normal faults; 2-Depression; 3-Uplift; 4-Observation; F_1-Wensi Fault; F_2-Mengshan Fault; F_3-Xintai-Duozhuang Fault; F_4-Taishan-Tongyedian Fault; F_5-Qihe-Guangrao Fault; F_6-Chennan Fault; F_7-Chengnan Fault.

Figure 1
Regional Tectonic Location of Western Shandong

2. CHARACTERISTICS OF THE EXTENSIONAL STRUCTURE

The extensional structure in western Shandong is composed of steep normal fault and décollement fault, which two together constitute a unique "extensional structure framework"[10]. With large scales, the NW-trending and NWW-trending normal faults were developed from several NW-trending reverse faults affected by Indosinian movement[11]. Together with several NE-trending and nearly EW-trending faults, there was a typical "fault-block framework" all over the research area. Among them, the NW-trending and NWW-trending steep normal faults which developed earlier than the other controlled the sedimentary of the half-graben in Mesozoic-Cenozoic. Regional geological research and geophysical data show the existence of steep normal faults such as Wen-Si Fault, Mengshan Fault, Xintai-Duozhuang Fault, Taishan-Tongyedian Fault, Chennan Fault and Chengnan Fault (Figure 1). These structures which play a leading role for the regional extension in western Shandong are the main content of tectonic field numerical simulation below. Low-angle décollement faults are mainly found at unconformity / lithologically abrupt interfaces or disconformity surfaces, of which the most outstanding in western Shandong occurred along unconformity surface between the Archean and Cambrian (Ar/∈), and the disconformity surface between the Ordovician and Carboniferous (O/C). Furthermore, décollement faults are also discovered in the Cenozoic, Mesozoic and Ordovician in Jiyang Depression. Based on several times of fieldwork along the trending of steep normal faults and décollement faults, combined with geophysical data in Jiyang Depression, we attempt to give a comprehensive study of the extensional structure in western Shandong. The characteristics of these extensional structures are as follows.

2.1 Characteristics of Extensional Structures in West Shandong Rise

In the regional geological survey, we observe several steep normal faults (F_1-F_4) and two representative large décollement fault zones in West Shandong Rise (Figure 1). At Huacun Reservoir (35°41′43″N, 117°29′7″E) breccias are developed in the Wensi Fault zone whose attitude is 200°∠58° (Figure 2a) . At Fenghuangshan (35°48′26″N, 117°53′31″E), field survey indicates that the attitude of Xintai-Duozhuang Fault is 215°∠55°. The limestone of Zhangxia Formation is found in the fault's hanging wall, on which scratch is well developed (Figure 2b). Besides, amount of purple fault gouge is discovered close to the footwall of the fault (Figure 2c). At Pengshan (36°17′33″N, 117°43′6″E), the fault plane of Tanshan-Tongyedian Fault is well exposed (Figure 2d). And geological research has determined that the attitude of the fault is 240°∠76°. At Jindou (35°57′36″N1, 17°47′36″E), we observe a large décollement fault zone at the surface between the Archean and Cambrian along the footwall of Xintai-Duozhuang Fault. The cataclastic rock at the top of décollement zone constitutes mainly thin algae dolomite limestone (Figure 2e). The same tectonic situation is found at Litiao (36°5′55″N, 117°34′1″E). The décollement surface shows a small dip of 10° and its attitude is the same as the stratum attitude (Figure 2f). Another representative large décollement fault zone is observed at Nanluan and Xueye. At Nanluan (36°30′8″N, 117°35′24″E), an outcrop scale asymmetric fold is well developed in the thin limestone (Figure 2g), resulting from tectonic extrusion and gliding at the décollement surface. At Xueye (36°27′49″N, 117°28′17″E), the cataclastic rock in Ar/P_{z1} surface is ca. 40 cm in thickness, with a breccia mainly of Cambrian silicified limestone and some Archean granite gneiss (Figure 2h). All the situations mentioned here indicate that tectonic gliding modified the rocks beneath or above the décollement surface.

2.2 Characteristics of Extensional Structures in Jiyang Depression

Line 616 across the Dongying Sag which is in the eastern part of Jiyang Depression indicates that the Chennan Fault is steep inclined in the profile with a dip angle of 40°[12]. The formation in the hanging wall of Chennan Fault constitutes Palaeozoic and Cenozoic. While in the footwall it constitutes Quaternary and Neogene which directly covered on the Archean formation. Furthermore, it presents an arc distribution on the plane and steep inclined with a dip angle of 65° in the profile of Chengnan Fault which controlled the sedimentary of Chezhen Sag in Mesozoic-Cenozoic. Also, geophysical data confirmed the existence of the décollement fault in Jiyang Depression. In overlying areas it mostly occurred to the south and northeast of the Jiyang Depression. The drill core of well WG1 across the Wangjiagang area in Dongying Sag shows that the Paleozoic sequence is significantly thickened, while its attitude is the same as the regional stratum attitude. Assume that speed is constant, the thickness of the Paleozoic formation increases 1 times than that around (Figure 2i). The profile of CB302-CB303 across Chengdao area in northeast of Jiyang Depression shows that a shallow décollement fault at the surface between Archean and Paleozoic (Figure 2j). All the situations confirmed the existence of the shallow décollement fault resulting from the transfer of tectonic gliding.

All the information above shows that the extensional structures are well developed in western Shandong. The steep normal faults which are almost NW-trending and NWW-trending constitute a north protruding arc on the plane (Figure 1). With deep cutting, tendency of S-SW and 60° - 70° dip angles, the NW-trending and NWW-trending boundary extension faults which are parallel aligning from south to north in western Shandong, controlled the sedimentary of half grabens that had formed since late Mesozoic. The décollement faults which occurred at the surface between the Archean and Cambrian (Ar/∈), and the surface between the Ordovician and Carboniferous (O/C), are well developed all over the research area. Their gliding directions are to the NW and NE, and dip angles are 10° - 30°. In profile, the décollement faults, combined with the steep normal faults, constitute a “book oblique type” together.

3. TECTONIC STRESS FIELD NUMERICAL SIMULATION

It has experienced a series of extensional lacunae in western Shandong since Late Mesozoic. In this paper we develop the regional geological model as summarized the characteristics of extensional structures above. With the finite element method[13], we use the software called ANSYS12.0 to solve the stress-balance equations in order to simulate the distribution at a given time in western Shandong in Late Mesozoic-Paleogene. Here we just select a group of simulations which is most fitting to discuss.

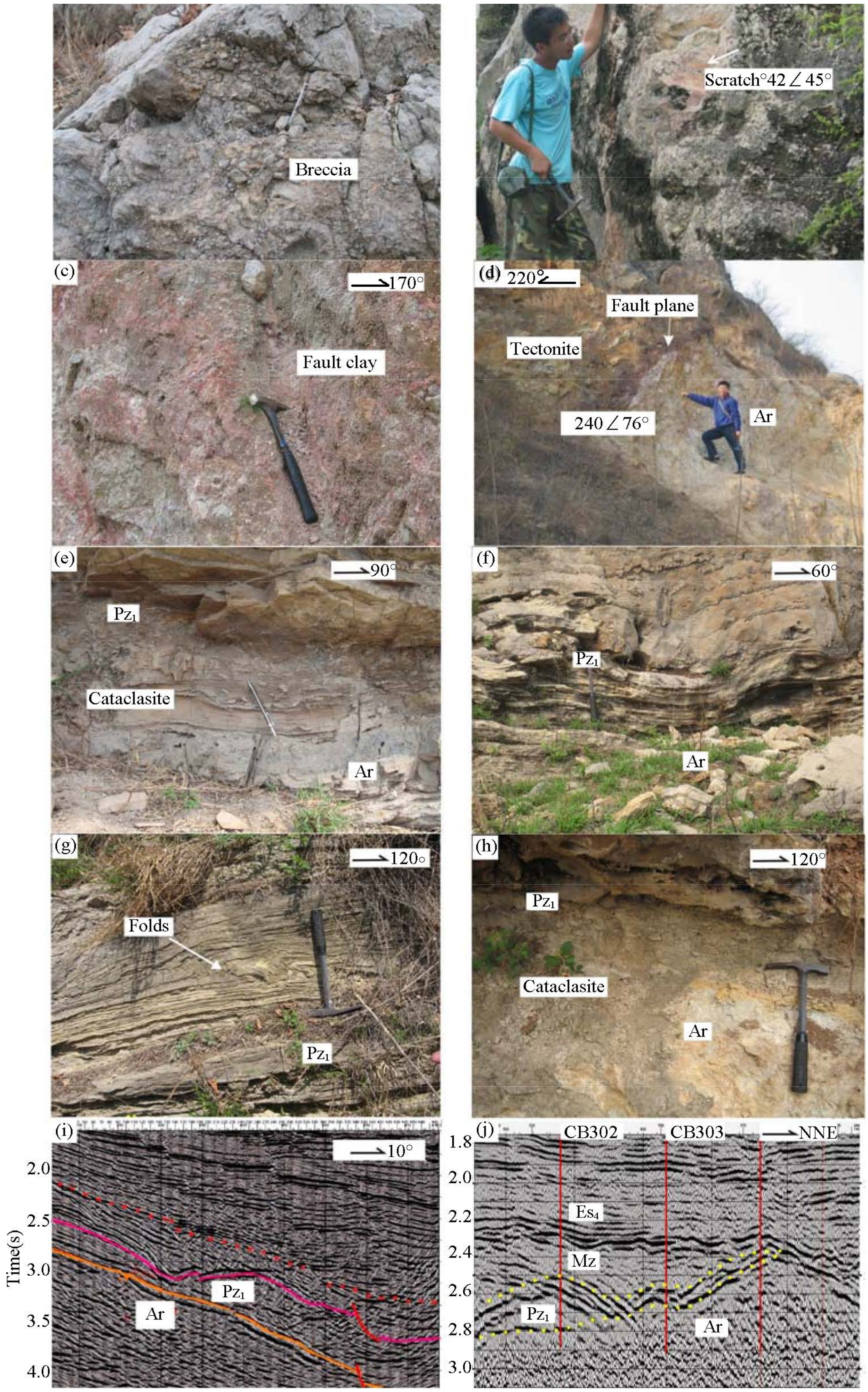
3.1 Geological Model, Mechanical Parameters and Boundary Conditions

3.1.1 Establishment of a Geological Model

Given the characteristics of the extensional structures above, and regarding West Shandong Rise and Jiyang Depression as a whole, we attempt to extract the main structures digitally in research area. We use the thin sheet model[14-15] to obtain the horizontal distribution of lithospheric deformation and tectonic stress field in numerical simulation of the western Shandong block since Late Mesozoic. Therefore, treated the Tancheng-Lujiang Fault as an eastern boundary, Cangdong-Lanliao Fault as an western boundary, Fengxian-Peixian Fault as an southern boundary, and north of Chengning Uplift as an northern boundary, we have established three stages of geological models which constitute Late Jurassic to Early Cretaceous (140 - 65 Ma), Paleocene to Early Eocene (65 - 53 Ma) and Middle Eocene to Oligocene (53 - 23.3 Ma).

3.1.2 Selection of Rock Mechanics Parameters

It depends on two factors in selecting mechanics parameters of rocks: firstly the rock fabric resulting from itself, and secondly a tectonic environment relating to the western Shandong block. Based on the establishment of geological models, we have a weighted average of the data that obtained through rock mechanics experiments, and ultimately determine the relevant mechanical parameters of the numerical simulation (Table 1).



(a) Breccia in the fault zone, Huacun (Hu et al., 2009); (b) Scratch developed on the fault's hanging wall, Fenghuangshan; (c) Fault clay in the fault zone, Fenghuangshan; (d) Fault plane, Pengshan; (e) Cataclasite in the décollement zone, Jindou; (f) Décollement surface between Paleozoic and Archean, Litiao; (g) Folds developed at the top of décollement zone, Nanluan; (h) Décollement surface between P_{z1}/Ar and cataclasite, Xueye; (i) Strata thickening and stacking in P_{z1}, WG1; (j) Décollement fault at the surface of P_{z1}/Ar, CB302-303.

Figure 2
Characteristics of the Extensional Structures in Western Shandong

Table 1
Rock Mechanics Parameters of Late Mesozoic-Paleogene Tectonic Stress Field Numerical Simulation in Western Shandong

Serial number	Medium type	Late Jurassic-Early Cretaceous		Paleocene-Early Eocene		Middle Eocene-Oligocen	
		Young Modulus *E*/GPa	Poisson ratio *μ*	Young Modulus *E*/GPa	Poisson ratio *μ*	Young Modulus *E*/GPa	Poisson ratio *μ*
1	Stratum	22.9	0.22	23.8	0.20	24.0	0.21
2	Faults	19.5	0.25	19.5	0.25	19.5	0.30
3	Uplifts	—	—	26.0	0.20	26.0	0.20
4	Auxiliary frame	15.0	0.20	15.0	0.22	15.0	0.21

3.1.3 Determination of Boundary Conditions

Our boundary conditions are based on the background of several tectonic evolution stages[16-17]. The NNW subduction of the paleo-Pacific Plate to the Eurasia at a speed of 30 cm/a in Late Jurassic resulting from the Pacific mantle plume[18-19], led to the Tancheng-Lujiang Fault's left translation and the Cangdong-Lanliao Fault's right translation[20]. Although the speed of subduction significantly decreased in Paleocene-Early Eocene, the Pacific Plate still made a NNW subduction at a speed of 7.8 cm/a to the Eurasia. This made western Shandong block situated in the clip limit of the Tancheng-Lujiang Fault, Cangdong-Lanliao Fault and Qinling-Dabie suture zone. Therefore, the main boundary strike-slip faults inherited their activities that in Late Mesozoic. In Middle Eocene-Oligocene, the collision of the Indo-European Plate and the Pacific Plate reached to a peak[21]. Besides, the subduction direction of the Pacific Plate transferred from NNW to NWW. And the speed of subduction reduced to 3.8 cm/a. All the conditions above led to the stop of Tancheng-Lujiang Fault's left translation, instead of right left translation[22].

Due to the tectonic background above, we attempt to determine the boundary conditions. In our simulations, we write calculation processing modules using APDL (Ansys Parametric Design Language), and then calculate several times. Ultimately, the mechanical boundary conditions, mentioned in 3.1, may be summarized as follows (Table 2):

a. For the model of Late Jurassic-Early Cretaceous, we apply extrusion force equal to 50 MPa on its northern border and tension force equal to 75 MPa on its eastern border, setting the NW-SE movement of its western border equal to 0, but allowing it to move northeast or southwest.

b. For the model of Paleocene-Early Eocene, we apply extrusion force equal to 38 MPa on its northern border and tension force equal to 56 MPa on its eastern border, setting the NW-SE movement of its western border equal to 0, but allowing it to move northeast or southwest.

c. For the model of Middle Eocene-Oligocen, we apply extrusion force equal to 29 MPa on its northern border and tension force equal to 37 MPa on its eastern border, setting the NW-SE movement of its western border equal to 0, but allowing it to move northeast or southwest.

Table 2
Mechanical Boundary Conditions for Three Stages of Tectonic Stress Field Numerical Simulation

Simulation stage	Mechanical boundary conditions / MPa	
	Extrusion force	Tension force
Late Jurassic-Early Cretaceous	50	75
Paleocene-Early Eocene	38	56
Middle Eocene-Oligocene	29	37

3.2 Results

The solutions for our simulations (with mechanical parameters and boundary conditions in Table 1 and Table 2) are shown as maps of horizontal distribution for the maximum principal stress (Figure 3). We first describe the result in Late Jurassic-Early Cretaceous. There are obvious stress gradient belts nearby a series of NW-trending and NWW-trending faults which are parallel aligning from south to north such as Wensi Fault, Mengshan Fault, Xintai-Duozhuang Fault, Taishan-Tongyedian Fault, eastern of Chennan Fault and Eastern of Chengnan Fault. The Maximum principal stress concentrates in a scope of 67.7 MPa to 82.1 MPa (Figure 3a), which leads to the activity of several extensional normal faults and indicates that western Shandong block experienced the first large-scale extension.

Result of the second stage of simulations fits well with the tectonic background. It shows that the maximum principal stress concentrates in a scope of 21.3 MPa to 57 MPa (Figure 3b) in Paleocene-Early Eocene, corresponding to the continuous activity of NW-trending and NWW-trending extensional faults above and the experience of some EW-trending and NE-trending extensional faults. Besides, the direction of principal extrusion force is oblique to the strike of NE-trending faults, which indicates that the NE-trending faults are both of extension faults and strike-slip faults. Compared with the first stage, the activities of extensional faults have begun their migration to Jiyang Depression. Therefore, the period from Paleocene to Early Eocene is a second important stage of extension.

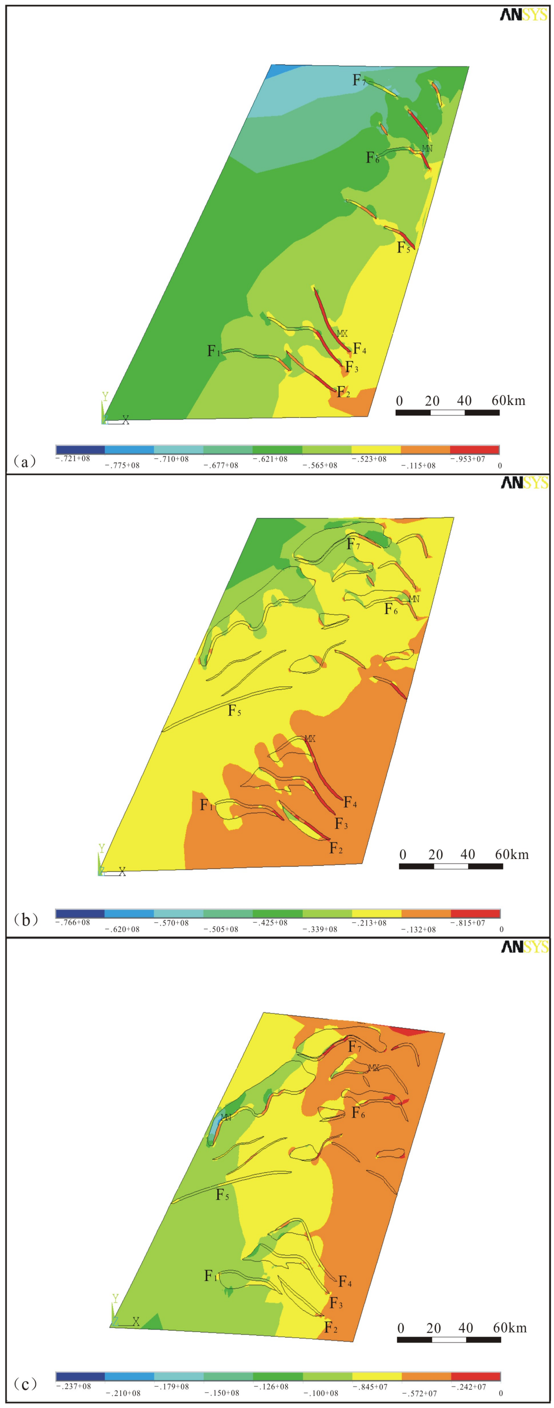
Result of the third stage of simulations is significant different from that of the second stage. It shows that the maximum principal stress concentrates in a scope of 12.6 MPa to 23.7 MPa (Figure 3c) in Middle Eocene-Oligocene, corresponding to the extremely weakness of NW-trending faults and activity of NE-trending faults, which indicates that the conversion of extension direction to NW-SE. All the situations mentioned above fit well with the characteristics of steep normal faults researched by Li[23]. Therefore, the period from Middle Eocene to Oligocene is a third important stage of extension.

Three stages of numerical simulation make us confirm that the extension since Late Mesozoic in western Shandong is triggered by two factors. Firstly the most important factor is the extrusion causing by subduction of the Pacific Plate further to the East. The calculation date from simulations above indicates that the extension strength is consistent of the Pacific Plate's subduction speed. Secondly another main factor is the tension derived from strike-slip of the boundary faults, of course, which is also caused by the subduction of the Pacific Plate fundamentally.

CONCLUSION

Depending on the regional geological survey in West Shandong Rise and seismic data of Jiyang Depression, we have explored the characteristics of extensional structures in western Shandong. The extensional structure in western Shandong is composed of steep normal fault and décollement fault, which two together constitute a unique "extensional structure framework". A number of NW-trending and NWW-trending normal faults, together with several NE-trending and nearly EW-trending faults, constitute a typical "fault-block style" all over the research area. In the steep normal fault zone, there are dynamic breccia, fault clay and scraping trace making up signs of faults activity. Low-angle décollement faults are mainly found at unconformity / lithologically abrupt interfaces or disconformity surfaces, of which the most outstanding in western Shandong occurred along unconformity surface between the Archean and Cambrian (Ar/∈), and the disconformity surface between the Ordovician and Carboniferous (O/C). Geological survey and seismic data indicate that the shallow décollement faults between the Archean and Cambrian are more common in western Shandong.

We have used the method of numerical simulation to represent the tectonic processes occurring in western Shandong during Late Jurassic to Early Cretaceous, followed by Paleocene to Early Eocene and Middle Eocene to Oligocene. In every stage, the western Shandong had experienced regional extension to varying degrees. The strength of the tectonic stress field has experienced a process from strong to weak since late Mesozoic, and the maximum principal stress has transferred from NW-SE to NE-SW. Three stages of numerical simulation indicate that the extension in western Shandong is triggered by structural change since Late Mesozoic, of which the subduction of the Pacific Plate the strike-slip of the boundary faults are the most important.



(a) Distribution of the maximum principal stress in Late Jurassic-Early Cretaceous; (b) Distribution of the maximum principal stress in Paleocene-Early Eocene; (c) Distribution of the maximum principal stress in Middle Eocene to Oligocene.

Figure 3
Results of Late Mesozoic-Paleogene Tectonic Stress Field Numerical Simulation in Western Shandong Rise and Jiyang Depression (Serial Number as for Figure 1)

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