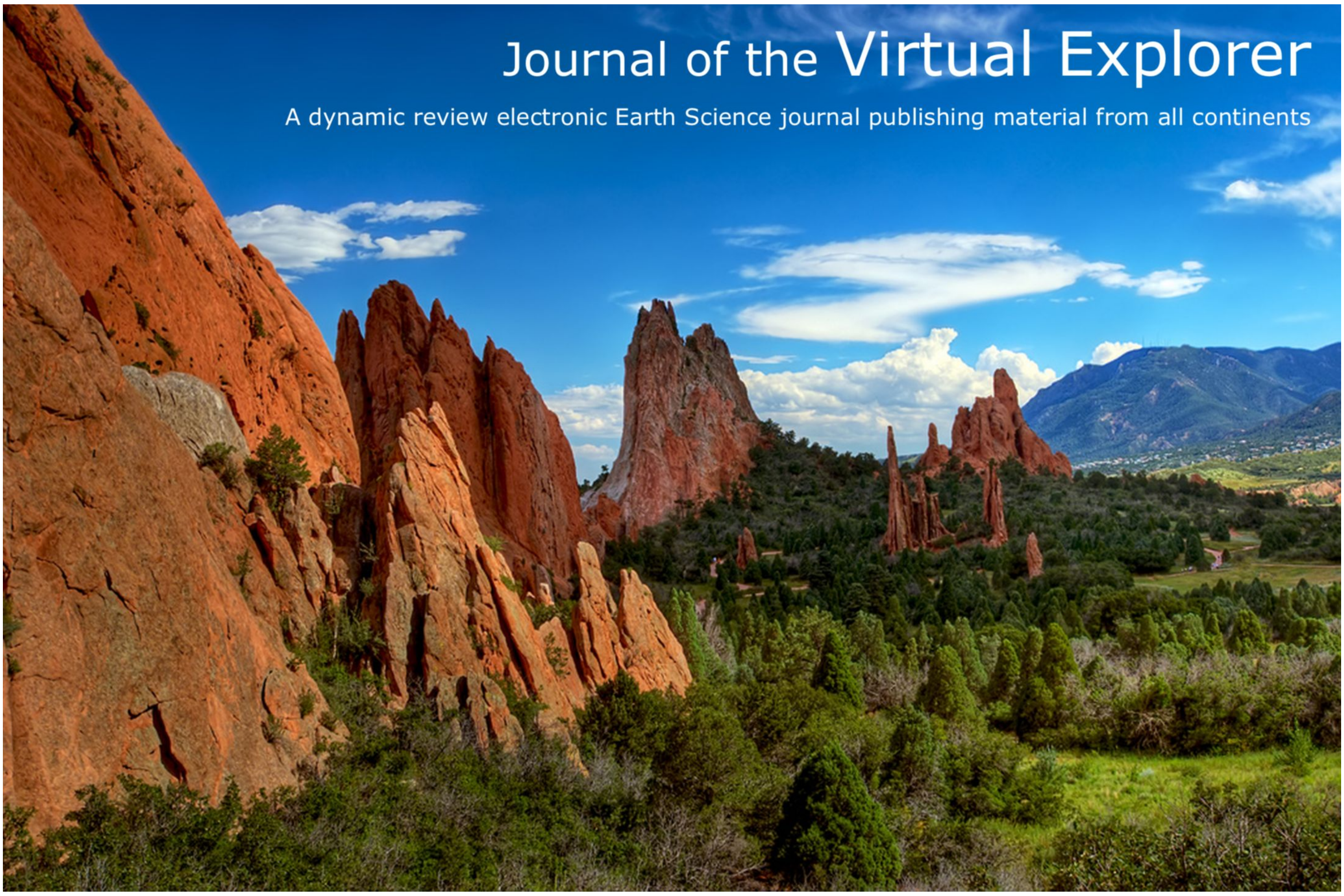

Prediction of Structural Fractures in Olituoz Volcanic Rocks, Liaohe Field, Northeast China

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Abstract: The key point to study and explore fracture-related reservoirs lies on awareness of fracture development. Prediction of structural fractures based on Finite Element Method (FEM) sheds new light on this tricky problem and this method is applied to Eocene Olituoz volcanic rocks, Liaohe Field, northeastern China. Fracture value is calculated, which is the common method, based on simulated stress field of Olituoz area, rock strength value and fracture criteria. Meanwhile, strain energy related to fracture initiation is also calculated, which is defined as energy value. However, both values do not fit well with the statistical density of structural fractures from the core rock samples available. Because in reality both the two factors--stress and strain energy, are involved in the forming process of fractures. Hence, a method named "Bio-Factor Method" which concerns both stress and strain is adopted here and the simulation data fits the statistic data fairly better. Development and distribution of structural fractures is controlled or strongly affected by the pre-existing fault system in the region. Based on the prediction results, several areas with high potential of structural fracture development are recommended for petroleum exploration.

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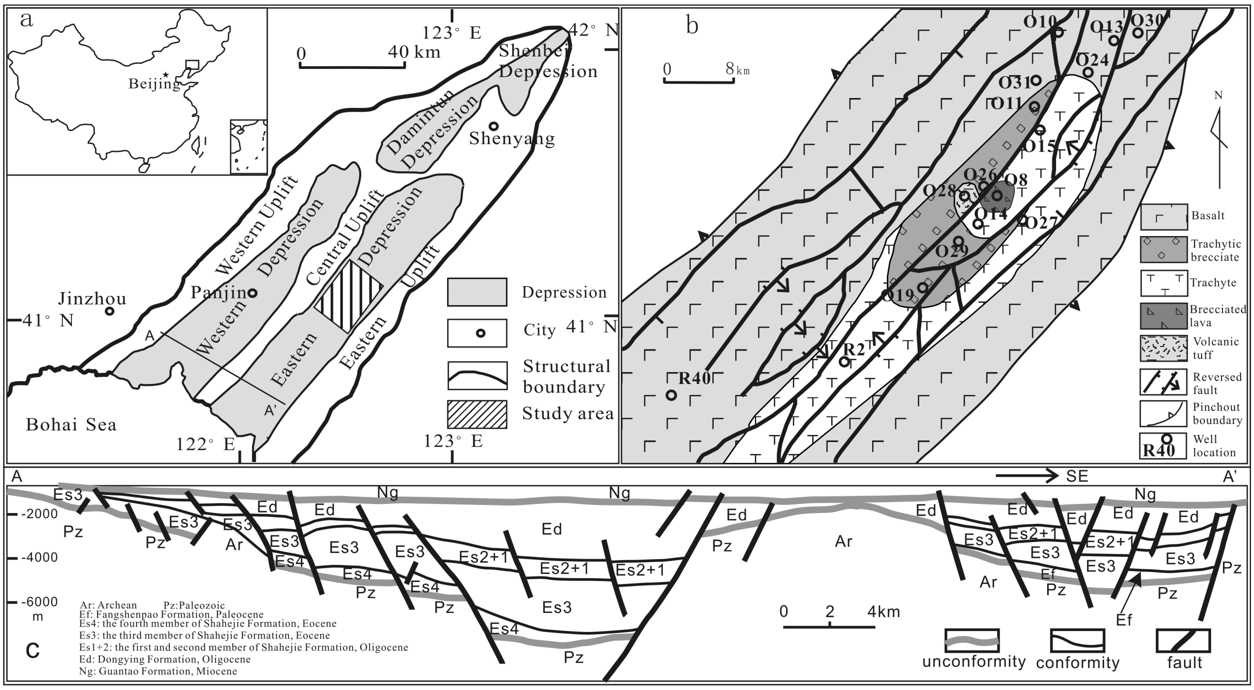
Introduction

Structural fractures play an important role in developing trap space or/and conduit channels for hydrocarbon in reservoir rocks (Cao, *et al.*, 1999; Wu, *et al.*, 2006), as well as enlarging and/or connecting the pre-existing fissures and cracks to improve both the porosity and the permeability of the rocks (Zeng, *et al.*, 2007). According to many researchers (e.g. Chen *et al.*,2001), oil and gas from fracture-related reservoirs account for over 50% of the total hydrocarbon production in the world. Thus, more attention should be paid to fracture-related reservoirs in petroleum exploration.

Figure 1. Structural units of the Liaohe basin



a. Structural units of the Liaohe basin and the location of the study area (Modified after Gu, et al. 2002); b. Distribution and lithology of the volcanic rocks (Es3) in the study area (derived from well data and seismic interpretation from Liaohe Petroleum Company, unpublished data). O8 is the crater of the volcanic eruptions during the period of Es3-the third member of Shahejie Formation, Eocence. Trachyte is the main rock type that bears the potential to be reservoir.

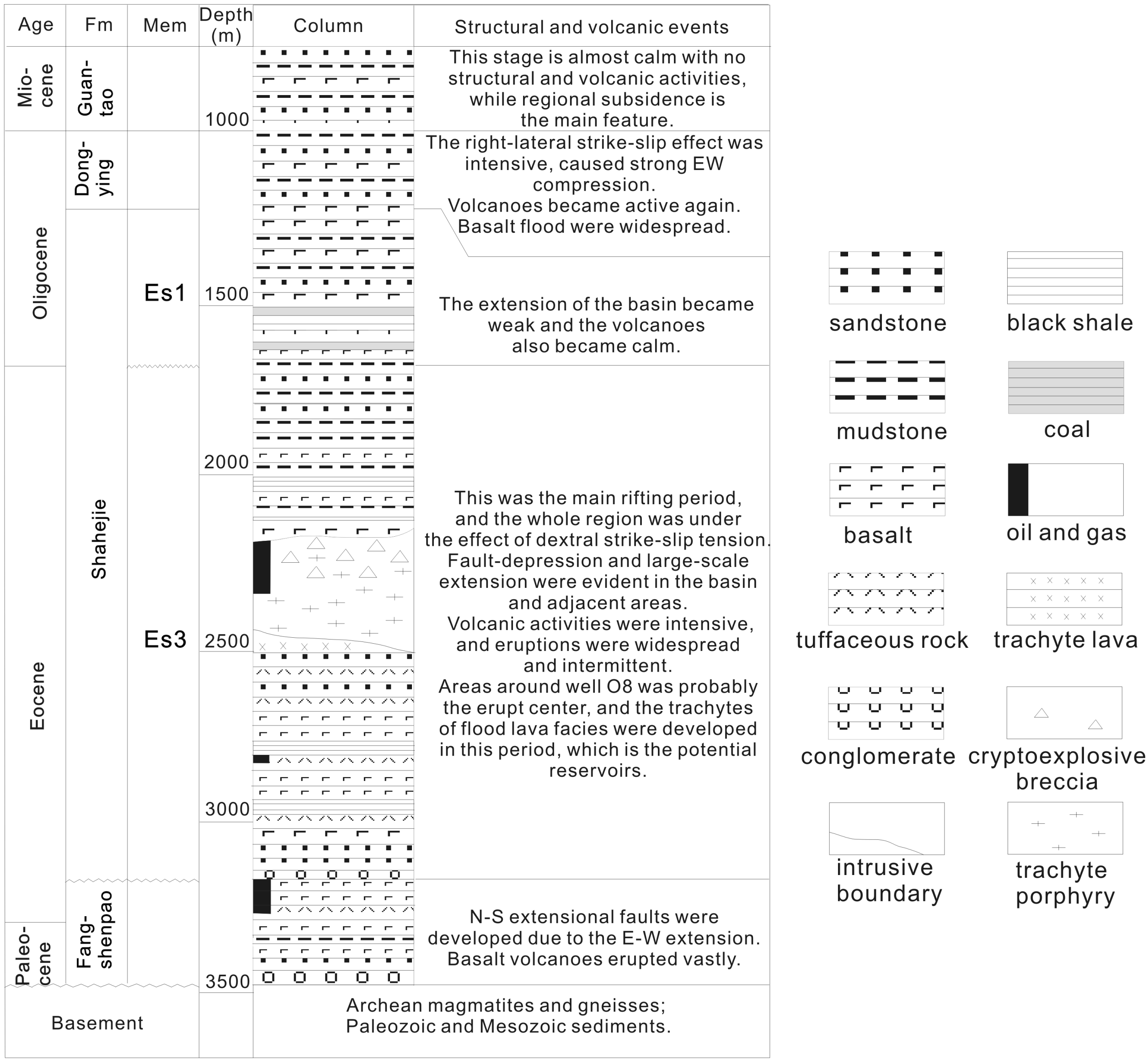
Extensive work has been done by employing finite element methods (FEM) to simulate the stress field and predicted fracture development [*e.g.* Wang *et al.* (1999), Maerten L. and Maerten F. (2006), and Maerten *et al.* (2006)], unfortunately forgetting the fact that strain energy also plays a significant role in producing fractures. A very few of researchers [*e.g.* Tromans (2008)] discussed the strain energy required to produce new fracture. Wang *et al.* (1999) proposed that "Crack initiation from a flow occurs when both stress and energy criteria are fulfilled simultaneously," which is better because both the two factors (stress and strain energy) are taken into account. Bio-Factor Method is just based on this concept and is employed to predict structural fractures in volcanic rocks in Olituoz area, Liaohe Oilfield, Northeast China.

The traditional concept of the reservoir has been challenged by the discovery of fracture related volcanic reservoir in Olituoz in 1997 when well O26 started producing oil at a rate of 150 t/day (Zhang *et al.*, 2005). Many researchers have studied the formation mechanism of this unusual reservoirs (Gu *et al.*, 2002; Wu *et al.*,2006). According to them, the hydrocarbon occupies mainly in trachyte porphyry of Es3 Formation (the third member of Shahejie Formation, Eocene), and the trapping spaces are with fractures, such as cryptoexplosive breccia, structural fractures and primary fractures. Among these fractures, structural fractures play a key role. It is meaningful and helpful to predict structural fractures in volcanic trachyte reservoirs (Es3) of the Olituoz area, for the exploration of the volcanic reservoirs.

Geological Setting

Liaohe Basin in Northeast China has been divided into several depressions (Wang & Wang, 1988; Hu, *et al.*, 2005) and Olituoz of Liaohe Oilfield resides in the middle segment of Eastern Depression (Fig.1a). Liaohe basin is a Cenozoic rift basin which experienced pre-rift in Paleocene, chief rift stage in Eocene, and post-rift subsidence stage since Miocene (Fig.1c and Fig.2). Shahejie formation of Eocene was the main strata in the region (Fig.1c and Fig.2) and was subdivided into 4 members - Es1 to Es4. Es4 is absent in the region, while Es2 is narrowly distributed in Olituoz block. Es3 is most important strata in the region and the target layer for oil exploration. Volcanic activities were intensive and widespread in the region during the phase of rifting (Fig1.b) and many episodes could be recognized.

Figure 2. Stratigraphy of Olituoz area.



Three stages of volcanic activities are shown, with each stage data after Sun (1999). Es4 is absent in the region, while Es2 is narrowly distributed.

Tan-Lu Fault system plays a key role in the evolution of the area. The strike-slip motion of Tan-Lu Fault Zone transferred from dextral strike slip to left-lateral strike slip at 42 Ma is a key turning point for the region (Hou, *et al.*, 1998; Hou *et al.*, 2001). Detail structural and volcanic events are presented in Fig. 2.

Research has proved that the trachyte of Es3 is the main reservoir layer in Olituoz area (Gu, *et al.*,2002). Judging from structural evolution, these volcanic rocks only experienced the structural events of Dongying Formation time (Ed). And their development of structural fractures should be chiefly controlled by the stress field in Ed stage.

Elastic rock properties

The main reservoir strata of Olituoz area was originally formed at the surface or near surface (less than 1km, Gu, *et al.*, 2002) during Es3, Which later on were overlaid by Dongying Formation and the up-layers. Thus the up-layers were peeled in order to obtain the corrected depth for these strata till the end of Dongying Formation time with normal temperature conditions. After depth calculation, rock samples collected from the intact well cores are subjected to tri-axial compression tests to gain the mechanical parameters of these rocks (Table 1 and Table 2) for the simulation of stress field and prediction of fractures.

Table 1. Rock Mechanic Parameters Obtained Through Triaxial Compression Tests

Sample Number	**Lithology**	**Depth (m)**	**Diameter (mm)**	**Height (mm)**	**Confining Pressure σ_3(Mpa)**	**Axial Crack Stress σ_1(Mpa)**	**Young's Modulus E (GPa)**	**Poisson's Ratio ν**	**Form of Crack**
O11-1	Basalt	2411.4	25	50	31.52	244.34	28.73	0.232	Tension
O15-1	Trachyte	2303.7	25	50	26.1	167.52	18.78	0.252	Shear
O15-4	Trachyte	2313.1	25	50	26.33	176	41.09	0.189	Shear
O15-8	Trachyte	2405.6	25	50	28.6	302.51	37.17	0.33	Shear
O19-4	Trachybreccia	2369.1	25	50	25.95	141.28	15.58	0.143	Tension
O27-1	Trachyte	2401.1	25	50	28.2	153.83	20.58	0.206	Shear
O27-4	Trachyte	2525.3	25	50	31.24	233.76	37.47	0.253	Shear
O28-2	Tuff	2341.2	25	50	26	93.82	10.41	0.232	Shear
O29-4	Trachybreccia	2218.5	25	50	23.48	115.47	16.88	0.268	Shear
O29-5	Trachybreccia	2223	25	50	23.52	151.9	20.35	0.23	Shear
O30-1	Basalt	2515.4	25	50	29.41	111.79	45.57	0.179	Tension

Table 2. Evaluation of Shear Strength Parameters Based on Triaxial Compression Tests

Number	**Sample Number**	**Lithology**	**σ_0(MPa)**	**K**	**C(MPa)**	**φ(°)**
1	O11-1	Basalt	92.83	4.807	21.17	40.96
2	O15-1	Trachyte	67.61	3.828	17.28	35.86
3	O15-4	Trachyte	81.56	3.587	21.53	34.33
4	O15-8	Trachyte	61.91	8.413	10.67	51.95
5	O19-4	Trachybreccia	68.22	2.815	20.33	28.41

Number	Sample Number	Lithology	σ_0(MPa)	K	C(MPa)	φ(°)
6	O27-1	Trachyte	66.37	3.101	18.84	30.82
7	O27-4	Trachyte	38.1	6.263	7.61	46.44
8	O28-2	Tuff	24.95	2.649	7.67	26.86
9	O29-4	Trachybreccia	49.1	2.827	14.6	28.51
10	O29-5	Trachybreccia	38.9	4.804	8.87	40.95
11	O30-1	Basalt	72.17	1.347	31.09	8.51

Observation and Statistics of Structural Fractures

It is a meaningful and indispensable step for quantitative prediction of fractures to make statistics of the structural fractures on the core-rock samples. They will serve as the check data for the final result. The method employed to count fractures is as follows: fracture density refers to the total length of fractures on each unit of surface area for the core-rock, that is,

$$D = \frac{\sum Li}{S}$$

where D = fracture density.

?Li is the total length of structural fractures on the surface area of the core-rock. S is the surface area of the core-rock:

$$S = 2\pi r Lc + 2\pi r^2 = 6.3r(r + Lc)cm^2$$

r stands for the radius of the core column; and L_C is the length of the core for statistics.

For those cracked core-rocks, we employed the method of Van Golf-Racht (1982) to get the volume fracture density:

$$D_v = \frac{6d^2}{d^3} = \frac{6}{d}$$

d is the mean diameter of the core cracked rocks, that is d= (a+b+c)/3, while a, b, c stand for the long, middle and short axial of the samples respectively.

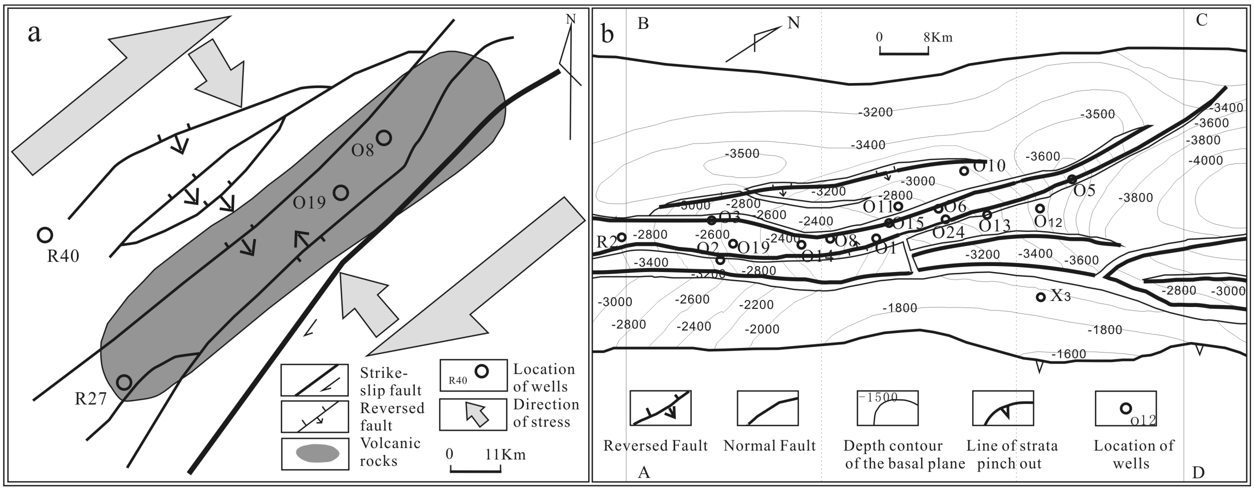
Generally, 3 to 5 core samples for each well are selected from different depths and the results shown in the sixth column of Table 4 are the results of weighted mean for these samples.

As revealed from the observation and statistics of the core-rocks, tensional-cracking is the dominant type, while the shear cracking is the secondary one. Based on statistic data, four areas of high fracture density are apparent: area around O8 and O26, area around O11, area around O5, and area around X3 (well locations shown in Fig.1b and Fig.3b). The distribution of the four areas trends NNE-SSW in a right-lateral echelon form, closely parallel to the fault system in the region. On the other hand, the low density areas are mainly located around O12 and around O30, with the lowest density of 0.0235/cm.

Petroleum exploration and production proved that the four high density areas are the main hydrocarbon productive zones, reinforcing the necessity for the prediction of the structural fractures in Olituoz area.

Numerical simulation of structural stress field for Dongying Formation in Olituoz area

Figure 3. Mechanic model of Dongying Formation



a. Mechanic model of the study area at the end of Dongying Formation time, which is used in the simulation of the Stress field for the preparation of quantitative predicion; b. The bottom structural contour map of Es3 for the study area, which also serves as the geometric model for pre-existing fault system that strongly influences the development of structural fractures. ABCD is the simulation area of structural fractures, shown in Fig.4.

Table 3. Material Parameters for Simulation of Stress Field

Material	**Density ρ(kg/m^3)**	**Young's Modulus E(GPa)**	**Poisson's Ratio ν**	**Cohesive Force C(Mpa)**	**Angle of Internal Friction φ(°)**	**Tensile Strength σ_0(MPa)**
Trachyte	2500	30	0.22	15.5	41.3	6.68
Basalt	2700	35	0.22	31	25	10
Lava Breccia	2500	30	0.25	20	30	4.04
Laval Trachy-Breccia	2500	28	0.22	30	40	8
Tuff	2400	20	0.26	7.7	26.9	5
Alternation of Sand and shale	2400	30	0.25	15	30	7
Sandybreccia	2500	30	0.22	30	40	7
Shale	2400	25	0.25	20	40	8
Fault	2300	14	0.18	10	36	Null

Before quantitative prediction for structural fractures, simulation of stress field for Dongying Formation (Ed) time is fulfilled through ANSYS 7.0 University software (University Version). The geological model as well as mechanical model (Fig.3a) have been derived from the above study of stratigraphy and structural evolution along with the structural contour map shown in Fig.3b. The boundary conditions on the Olituoz area is the deviatoric compressive stress induced by the right-lateral strike-slip motion of Tanlu Fault system from Es3 to Ed time.

Materials of each unit for simulation are assumed to be elastic, based on the fact that the structural fractures are usually produced by brittle crack. Rock mechanical properties for simulation (Table 3) are derived from Lithomechanic measurement. As the rock samples for the whole area are limited, we have to take the data as references from previous studies (e.g. Jaeger and Cook, 1979; Sun, 1988) to provide the rock mechanical properties for the calculation. Furthermore, due to lack of data for the faults in the region, the faults are assumed to be the most common materials bearing common properties.

A more detailed description of the linear elastic finite element simulation technique can be found elsewhere (Hou *et al.*, 2006). The results of the stress field for Es3 Formation in the Olituoz at Ed time were calculated to predict the fracture value and energy value of structural fractures for the prediction of fracture density.

Bio-Factor Method for prediction of structural fractures

The Bio-Factor Method employed here was originally developed by Ding, *et al.* (1998), in which the two factors refer to Fracture Value derived from stress-related Fracture Laws and Energy Value obtained from strain energy. The combination of these two factors is realized through the simulation formula of Bio-Factor, which requires a large number of trials to obtain the coefficients in the formula by the fitness between the calculated fracture density and the statistic fracture density.

The most common prediction method for structural fractures is based on stress, rock strength and rock fracture criteria, such as Mohr-Coulomb criterion. In this study Fracture value (Fv) is redefined (Wang, *et al.*, 1980):

$$Fv = \frac{\tau_n}{[\tau]}$$

σ_n is the shear stress on the shear-crack plane, while [σ] is shear strength. Fv<1 at a certain point indicates unfractured, while Fv=1 fractured. Furthermore, if Fv>>1 at a certain point, it indicates the rock has fractured long before and Fv<<1 indicates that the rock is far from fracturing.Thus the results are more quantitative rather than just predicting whether the rock has fractured or not.

For tensile fracture, we employ the formula:

$$Fv = \frac{\sigma_1}{T_0}$$

Where s_1 is the maximum of the tension force, and T_0 is tensile strength.

A close perusal of the Table 4 indicates that the co-efficient between Fv and Fd is very weak (*e.g.* Fv at O5, O11, and O26) and so a better method is needed for the predictions, taking into account of the strain energy also.

The elastic strain energy in each unit is used to define Energy Value (Eg), which can be calculated based on the results of stress field through the following formula:

$$Eg = \frac{[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1)]}{2E}$$

Where σ_1, σ_2 and σ_3 are the three principal stresses, E and ν are Young's Modulus and Poisson's Ratio respectively which can be obtained from rock mechanical properties (Table 3). The Strain Energy at a particular point can be calculated from the three principle stresses at that point. Once more, it turned out to be that the coefficient between Eg and statistic Fd is also weak (Table 4, Column 5).

As there is no fit between Fv and Fd, as well as between Eg and Fd, another method X^2 has to be employed for solving the problem.

Table 4. Data from Statistics and Predictions of Es3 for Each Well in the Study Area

Well	X-axis	Y-axis	Fracture Value Fv	Energy Value Eg	Statistic Fracture Density Fd	Predicted Fracture Density Fd	Absolute Error (1/cm)	Relative Error (%)
O1	27.9	16.2	1	10.69	No Core	0.3883	Null	Null
O2	16.6	15	0.9	5.03	No Core	0.1551	Null	Null
O3	16	17.7	0.99	9.73	No Core	0.3481	Null	Null
O5	41.7	19.7	1.06	19.12	0.79	0.7548	-0.0352	4.5
O6	32.5	18.3	1.01	6.09	No Core	0.2194	Null	Null
O7	26.8	18.6	1.02	0.47	No Core	0.0074	Null	Null

Well	X-axis	Y-axis	Fracture Value Fv	Energy Value Eg	Statistic Fracture Density Fd	Predicted Fracture Density Fd	Absolute Error (1/cm)	Relative Error (%)
O8	24.2	16.4	0.99	8.19	0.2968	0.2914	-0.0054	1.8
O10	34.2	20.5	1.25	1	No Core	0.0358	Null	Null
O11	29.5	18.3	1.02	10.64	0.4245	0.396	-0.0285	6.7
O12	39.4	18	1.03	0.98	0.0235	0.0272	0.0037	15.8
O13	35.7	17.8	0.98	15.74	No Core	0.5623	Null	Null
O14	22.3	15.9	1	5.13	0.1358	0.1809	0.0451	33.2
O15	28.5	17.3	1	2.88	0.0874	0.097	0.0096	11
O19	17.6	16.1	0.64	5.61	0.1076	0.1096	0.002	1.9
O24	33	17.3	0.97	6.71	No Core	0.2309	Null	Null
O26	24.2	17.3	1.11	14.28	0.5888	0.5933	0.0045	0.8
O27	24.2	14.1	1.02	2.88	0.0968	0.0995	0.0027	2.7
O28	23.1	17.8	1.26	3.12	0.1164	0.1406	0.0242	20.8
O29	21.2	15.4	0.9	6.68	0.2084	0.209	0.0006	0.3
O30	37.2	17.3	1.08	1.78	0.0708	0.0617	-0.0091	12.8
L10	26.8	15.9	1.02	12.14	No Core	0.4533	Null	Null
L12	15.4	16.2	0.97	5.5	No Core	0.1874	Null	Null
X3	39.5	12.3	0.93	11.61	0.4065	0.3859	-0.0206	5.1
J1	39.9	6.1	0.77	0.35	No Core	0.0014	Null	Null
J4	49	6.8	0.81	0.95	No Core	0.0187	Null	Null
J12	35.7	6.7	0.79	0.39	No Core	0.0026	Null	Null

Unit Note: Eg: J×10^4/m^3; Fd: 1/cm.

Bio-factor Method

Bio-Factor Method in the form of polynome yielded by a large number of tests is as follows:

$$Fd = a_1 Fv + a_2 Eg + a_3 Fv \times Eg$$

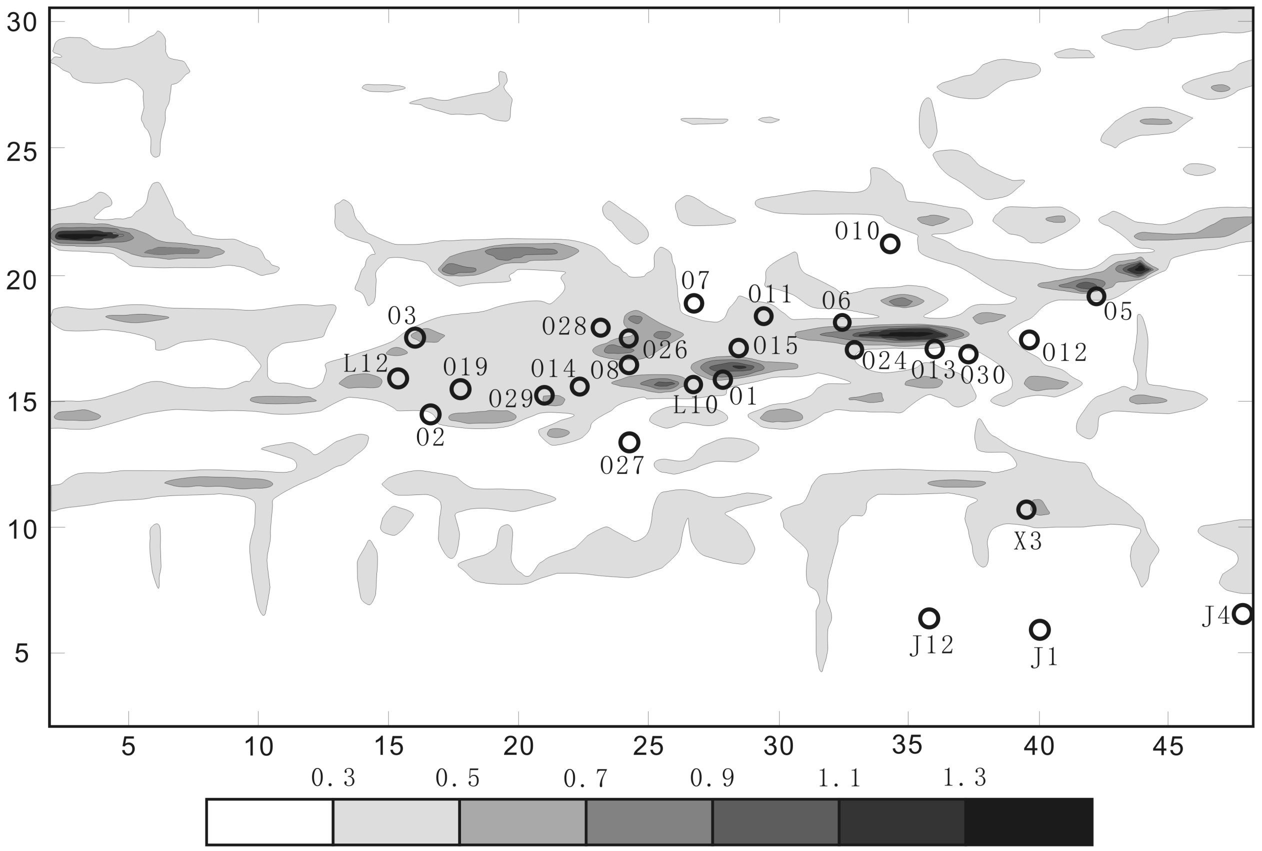
From Fv, Eg, and Fd (Table 4, Column 6) , the obtained coefficients are as follows:

$$a_1 = -0.01040, a_2 = -0.00872, a_3 = 0.04600$$

The Bio-Factor Simulation Formula for Olituoz area employed here to predict the fracture density (Table 4, Column 7) is flexible by changing the coefficients in the formulae. The predicted results around the boundaries (the boundaries of the predicted area shown in Fig.4) are not reliable due to the boundary effect of calculation, especially the high values near the left boundary in Fig.4.

The calculated results are checked by comparing to the statistic data, and the errors are given in Table 4. The result is highly accurate and credible: of the total 13 wells, the errors of 10 wells are less than 15%, 8 are less than 7%. However, there are some unexpected results. The reasons and solutions for the high error data around well 028 and well 014 are to be studied further and need more future research.

Figure 4. Quantitative prediction result map derived from Bio-Factor Method



The prediction area are shown in Fig.3b as the ABCD. The contour lines stands for the Predicted Fracture Density.

Based on quantitative prediction, the areas with high density of structural fractures are demarcated (the region surrounded by O26, O8, L10, O1 and O15, areas around O5, northwest of O28, and the region surrounded by O11, O6, O13 and O24) (Fig. 4). These areas with Fd>0.9 are with high probabilities of forming fracture reservoir, which are the potential areas of drilling for oil.

In comparison to the faults (Fig. 3b), the main areas with high density of structural fractures are consistent with the NE-NNE trending faults in Olituoz area. Another evident feature is that the distribution of high density is arranged in left-en-echelon which resulted from dextral shearing.

These features compelled us to pay attention to the pre-existing faults in the region. According to Tuckwell *et al.* (2003) and Zeng *et al.*(2007), the pre-existing long fractures would dominate the local stress field and the stress are concentrated near the former faults, giving rise to intensive fractures. At the same time, the strain energy influenced by the pre-existing faults or fractures, triggers an additional strain energy (Li & Liu, 2008). Overall, the fracture development and distribution is controlled or strongly affected by the former fault system in the region.

Conclusions

Structural fractures play significant roles in the reservoirs lacking porous and permeable channels, like the volcanic/subvolcanic rocks. Hence, prediction of fractures plays a key role in the exploring and producing hydrocarbon in these kind of rocks.

Both stress and strain energy are involved and both should be taken into consideration when structural fractures are formed. As am improved method, Bio-factor Method employs both stress and strain energy for the fraction predictions.

The results of predicted fracture density derived from Bio-Factor Method are more accurate than the fracture value and strain energy value. Areas with high potential of structural fractures are blocked out and recommended for petroleum exploration.

Pre-existing fault system dominantly influences the stress field and strain energy condition which sequentially controls the distribution and development of structural fractures.

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