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The fracture network model of Shen 229 block buried hill: A case study from Liaohe Basin, China

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Abstract: High oil production from the Proterozoic formation of Shen 229 block in Damingtun Depression, Liaohe Basin, China, indicates the presence of natural fractured reservoir whose production potential is dominated by the structural fracture. A consistent structural model and good knowledge of the fracture systems are therefore of key importance in reducing risk in the development strategies. So data from cores and image logs have been collected to account for the basic characteristics of fracture, and then the analyzed results were integrated with the structural model in order to restrict the fracture network development during the structural evolvement. The structural evolution of the Proterozoic reservoir with time forms the basis for understanding the development of the 3D fracture system. Seismic interpretation and formation correlation were used to build a 3D geological model. The fault blocks that compose the Proterozoic formation reservoir were subsequently restored to their pre-deformation. From here, the structures were kinematically modeled to simulate the structural evolution of the reservoirs. At each time step, the dilatational and cumulative strain was calculated throughout the modelling history. The total strain which records the total spatial variation in the reservoir due to its structural history, together with core data, well data and the lithology distribution, was used to simulate geologically realistic discrete fracture networks. The benefit of this technique over traditional curvature analysis is that the structural evolution is taken into account, a factor that mostly dominates fracture formation.

Key words: Buried hill, Fracture network, In-situ stress, Structural fracture
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INTRODUCTION

Several fields in Liaohe Basin are host to fractured hydrocarbon oil reservoir, fractures are considered to influence productivity significantly in these reservoirs, which not only form a large part of the overall porosity, but also are responsible for the potential reservoir volume. More importantly, the fracture system facilitates permeability and flow. Cemented and closed fractures act as barriers to flow, whereas open fractures intersected by the wellbore may increase the flow rates or result in early water breakthrough (McKeown *et al*., 2003; Smallshire *et al*., 2002), and open fracture networks may cause severe mud losses and well blowout during drilling. Thus understanding of the in-situ natural fracture network is of importance in the exploration and development of petroleum. An improved understanding of the fracture systems may help to explain well behavior and may help us to prevent some drilling hazards.

The aim of the present work is to describe the techniques for fracture network modelling, assessment, and application to the Proterozoic formation of Shen 229 buried hill. These techniques for fracture assessment can be summarized as follows: (1) Structural geological model building; (2) Fracture description; (3) Discrete Fracture Network simulation; (4) Assessing the relation between the fracture and in-situ stress.

GEOLOGICAL SETTING AND STRUCTURAL ANALYSIS

The study area is located in Damingtun Depression of Liaohe Basin in Northeast China (Fig.1). The

Proterozoic series consists of mudstones, sandstones and carbonates (Fig.2), some of the rock has metamorphed slightly. The series is subdivided in formations and members comprising distinctive facies associations, interpreted as the products of deposition in sea or lake environments. The base of the formation is marked by an unconformity with the underlying succession (base rock). The overlying Mesozoic igneous rock or mudstone form the reservoir seal, some mudstone can act as source rock.

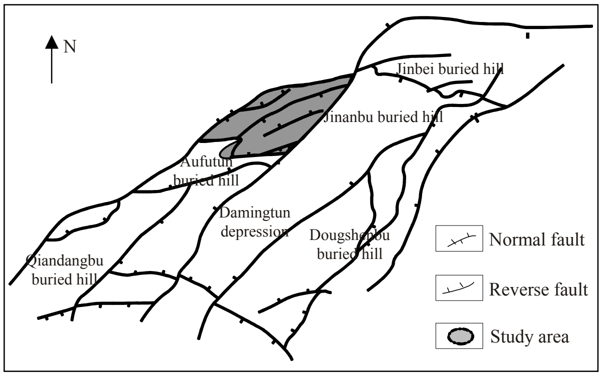

Fig.1 Location of about 20 km^2 study area

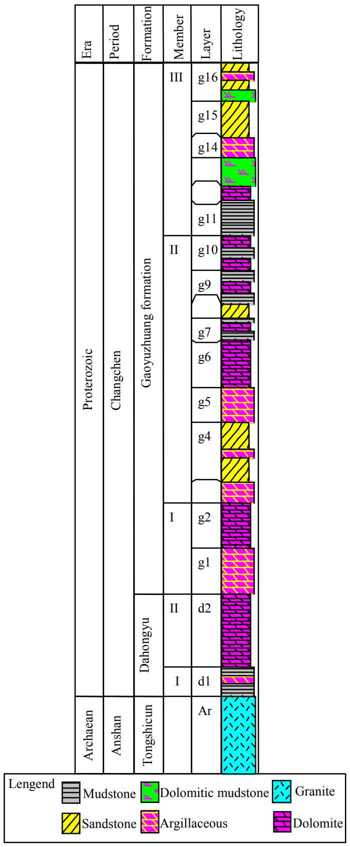

Fig.2 Stratigraphic column for study area

In order to predict regional fracture patterns, it is necessary to identify the main processes responsible for fracturing. No straightforward answer exists as different processes may be dominant in various geological settings and is highly dependent on the various phases and characteristics of the local geological history (Sanders *et al*., 2002), and fracturing also takes place in essentially undeformed regions (Price and Cosgrove, 1990) but this has a much more regional character and is strongly lithology related. With a 3D geological model we can study the geological history of the structure in an analytical way and identify the highly deformed regions. Though traditional curvature analysis has often been used for fracture assessment (Price and Cosgrove, 1990), curvature analysis on the present day geological model gives limited insight for fracture purposes as it only analyses the geometry on the present day model statically (Lisle, 1994). So the structural evolution does have a profound impact on the identification of highly deformed zones.

According to the result of previous study, the tectonic evolution of the area and its surroundings can be divided into the following four main phases (Shi, 1988):

(1) Archaean-Paleozoic: the area belongs to North China platform (relatively stable clastic and carbonate sedimentary architecture), during which period the main tectonic movement was upright or straight down, which led to the erosion of Palaeozoic formations.

(2) Early Mesozoic (Indo-Chinese epoch): The area suffered complex structural movement during this period, main tectonic movement was folding (especially vertical folding), and thus formed mostly NE transversal tensile fracture and NW or NE inclined shear fracture.

(3) Late Mesozoic (Yanshanian): Because of the NWW extension, the area was subjected to faulting movements along previous structure, resulting in block faulting with the structure axial direction turning from NW to NNE, which caused the shear fractures (NNE) and tensile fractures (NE and NNE).

GEOLOGICAL MODEL BUILDING

To constrain the parameters that can describe the observed fracture pattern, the fundament is a valid geological model. The data used to build the geological model consist of 3D seismic data, outcrop measurements, and well data (core and well logging data). The 3D seismic data show good controls on the top of the formation above the buried hill, but the Archeozoic formation is obscure. In order to build a valid geological model all data obtained was integrated. The structural profiles were constructed and subsequently balanced to check for their geological validation. In addition, kinematic restorations were carried out in order to constrain the shape of the Proterozoic formation top. As such, consistency of structural style is thought to reduce risk in geological interpretation.

The balanced profiles were subsequently inputted into 3D structural restoration software 3DMove, where the horizons of the individual profiles were connected to make a 3D geological model (Fig.3). Apart from the useful visualization, this also serves to test if the lateral variations in the interpretation are valid in the 3D space. Geological maps were used to track lateral trends. Finally, 3D seismic data were inputted to validate the constructed model.

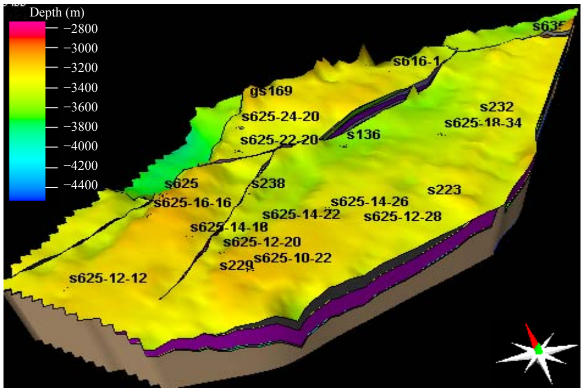

Fig.3 Geological model of the study area

FRACTURE DESCRIPTION

Among 69 wells distributed over the study area, 14 are core wells with core length of 108.2 m and 12 are FMI well across the field (Fig.4), more than 1700 fractures have been measured or analyzed using core and FMI well log data.

Geometrical parameters

The following three geometrical parameters are at least required for quantifying a fracture network: orientation, size and spacing (or frequency, which is 1/spacing).

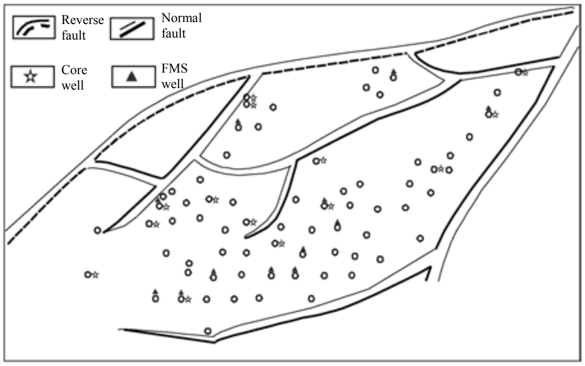

Fig.4 The FMI and core wells location on the study area

Orientation

An overview of the fracture trends identified in the Proterozoic formation and the result are shown in Fig.5. From the figure we can see the fractures orientations are relatively complex. Three main fracture trends prevailed: NE-NNE, NW-NNW, and E-W. In addition, the dominant fracture trend almost matches the orientation of the nearest seismically imaged fault trend namely NE-NNE, NW-NNW and E-W.

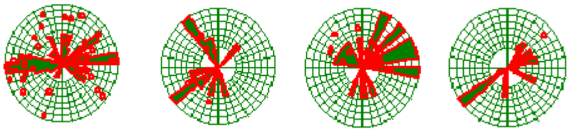

Fig.5 Fracture orientations (azimuth) of different wells at different location

Size (fracture extent)

Deterministic determination of the average size of fractures intersected by a simple core is practically impossible while it is reasonable in theory, because the probability of a core to intersect a fracture, and the chance of this intersected fracture to terminate in the core mainly depend on the fracture size and the borehole size. In order to estimate the fracture extent we used the method supposed by Gauthier *et al.*(2000). Though this approach cannot give absolutely accurate estimates of fracture size, the relative size of each fracture set can be assessed objectively. The result shows that fractures with N-W and W-E trends are relatively short, those with a NE-SW or NNE-SSW trend show a larger spread in size.

Fracture density

In the complete fracture network (comprising various sets) simulation, the estimation of the fracture density is required. In this study, determining the spacing distribution for each fracture set can be obtained from image log and core data.

Fracture spacing is the distance between the fracture planes. In order to obtain more accurate fracture density, we used the correction method proposed by Terzaghi (1965) to evaluate the error related to the orientation of the well trajectory with respect to the fracture set orientation. This method consists of weighting each directional data as a function of the cosines of the angle between the core axis and the fracture pole vector (Fig.6).

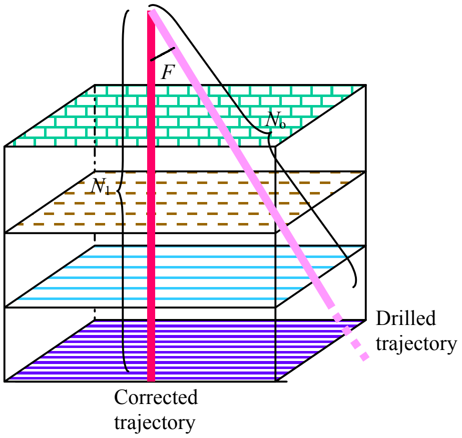

Fig.6 Effect of well-orientation correction on fracture density. N_o is the number of observed fracture; N_t is the number of corrected fracture. $N_t=N_o/\sin(\beta)$

From the statistical result combined with well location, it is obvious that fracture spacing is mainly controlled by lithology and structural position. Fig.7 shows average spacing values ranging from 1 cm to 9 cm. The fracture density increases with the shorter distance to fault (Table 1), the average fracture spacing is 2.3 cm in dolomite reservoir and 3.1 cm in sandstone reservoir, while there is almost no fracture in other layers.

Table 1 Fracture spacing variations with fault distance

Distance to the nearest fault (m)	Average fracture spacing (cm)
300	1.6
400	4.7
500	7.3
700	11.0

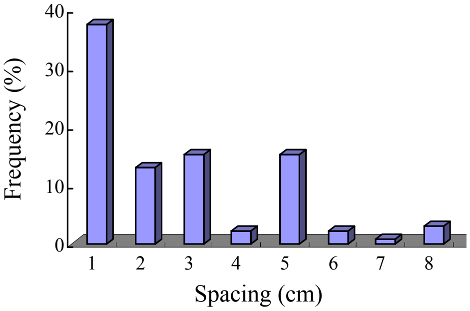

Fig.7 Fracture spacing distribution

GENETIC FRACTURE PARAMETERS

Fracture type

Fracture type can be classified according to mechanical origin which indicates the stress regime in which the fractures formed (Engelder, 1985) and is a key parameter to understand their impact on reservoir behaviour (Loosveld and Franssen, 1992). The following four mechanical origins are commonly distinguished in the study area.

(1) Tension fractures form perpendicular to σ_3 (smallest principal stress) and are characterized by movement perpendicular to the fracture plane. If not cemented, these fractures improve reservoir permeability and connectivity.

(2) Shear fractures form as conjugate sets of Coulomb slip planes oblique to σ_1 (largest principal stress), the intersection of the fracture planes is parallel to σ_2 (intermediate principal stress), this type of fracture is characterized by movement in the fracture plane. Generally, shear fractures result in permeability reduction.

(3) Dilational shear fractures have movement components in and perpendicular to the fracture planes. If uncemented, these fractures improve reservoir permeability and connectivity.

(4) Coring-induced fractures form in response to stress changes during the drilling and coring process.

Fracture infilling and effect on fluid flow

Three types of fracture planes (open, closed and cemented) are distinguished with respect to their effect on fluid flow.

From the table (Table 2) of fracture cement we can find that most fractures in this area are open, and some fractures are filled with calcite.

Table 2 Fracture characteristic of study area

Average fracture orientation	Type (open or cemented with)
NNE-SSW	Open
NW-SE	Open (some were filled with calcite)
E-W	Calcite, siderite

Timing

In order to assess the development of the fracture network and the relation of fracture formation to the structural evolution of the area, relative timing should be considered. The relative timing of fracture development can be established from abutting relationships (Engelder and Geiser, 1980). Joints tend to abut against any pre-existing plane of weakness (older fractures). The joints can therefore be assumed to be younger if a joint set systematically abuts against another set (Fig.8). From the figure we can see the oldest fracture is I set, the youngest fracture set is III.

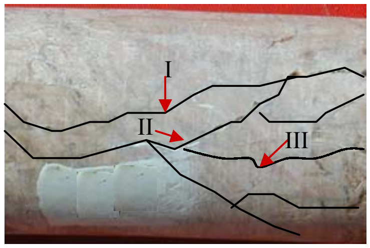

Fig.8 Different fracture sets

A more accurate timing method is to reveal the fracture's forming time by the isotopic signatures of the cements. Stable-isotope data (Table 3) combined with fluid-inclusion analyses of the matrix and fracture cements are used to determine the pore-water origin and paleotemperature during the period the cements precipitated. From the former result the fracture is formed mainly during the Indo-Chinese epoch (150 Ma) and Yanshanin (63.9 Ma).

Table 3 Isotopes data in cemented mineral

Early			Later		
Sample	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	Sample	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb
Y1	17.95	16.01	Y22	42.65	18.19
Y2	20.00	16.12	Y23	51.25	18.70
Y3	25.12	16.50	Y24	15.20	16.19
Y4	34.05	17.12	Y25	20.95	16.45
Y5	42.25	17.57	Y26	23.01	16.70
Y6	48.15	18.07	Y27	26.75	16.89

DISCRETE FRACTURE MODEL BUILDING

It is important to simulate fracture networks as they enable visualization and analysis of spatial variation in fracture intensity and orientation. At the same time we can understand the fracture observations obtained from wells and outcrop, and extrapolate fracture networks in areas where we have no data. So the fracture network model building should be geologically realistic, and its realizations should be controlled by geological rules, such as geological settings, lithology distribution and well data, not just a stochastic representation of a natural fracture network. Although cores and image logs are sparse and random, they can be a condition of the fracture model building; therefore, a systematic methodology needs to be applied to all available data.

Lithology influence on fracture growth is a very important factor for the formation of tectonic fracture sets in this case. Lithology distribution is obtained by seismic inversion combined with well logging (Fig.9).

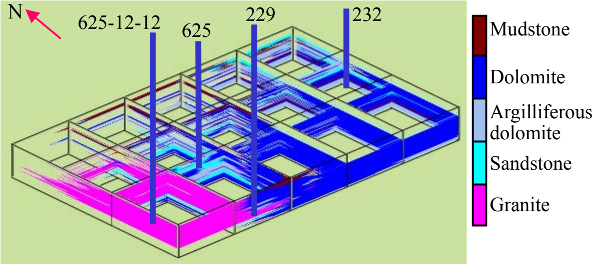

Fig.9 Lithology distribution of the study area

The workflow is as follow. In the 3D model, the fault blocks are restored kinematically by moving them over the fault surface, until footwall cut-off matches hanging wall cut-off along the fault (i.e. displacement is zero all along the fault), during restoration the rock volume is preserved, and then reversing the fault-block restoration in a number of time steps. At each time step the geometry of the last step is compared with the actual geometry, and the difference defines the local strain values. These strain values are added up at every time step in order to arrive at a cumulative strain value at the end of the forward modeling routine, i.e. the present day geometry.

After the restoration, we used a Fracture Generator module in the restoration software 3DMove to interactively control fracture density, length, orientation and fracture type of multiple simultaneous fracture sets. All characters are controlled by numerical attribute maps such as cumulative strain and lithology distribution map.

The fracture network model is shown in Fig.10. Dots represent oil wells, different colors of lines denote different fractures formed in different geological phases, the orientation of lines shows the fracture orientation and the density of lines denotes the fracture relative density.

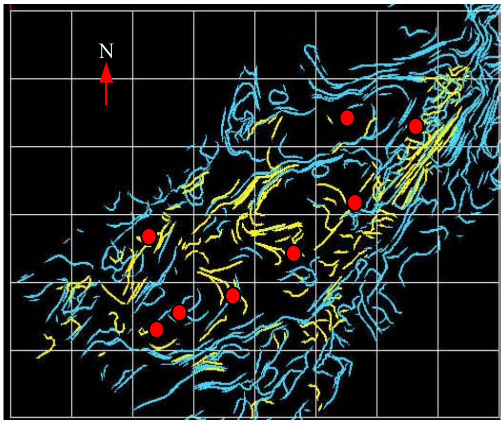

Fig.10 Fracture network of Proterozoic formation

From the result we can draw a conclusion that most fractures occur around the fault, and the fracture density decreases with the distance from the fault. At the same time, the fracture density is controlled by the lithology, in the dolomite distribution area, fractures are more developed than in any other places.

PRESENT STRESS ANALYSIS

As what is observed in fractured cores, a number of fracture sets tend to be closed while others tend to be open. Therefore it is important to have a good understanding of the fracture network in the early stage of the development of oil field, especially understanding which fractures are effective to fluid flow. This work can be done by analyzing its tendency to be opened or closed in a certain regional stress field to the fracture network.

The shear stress/normal stress ratios are analyzed in various ways to get the slip tendency, dilation tendency and leakage tendency of fracture networks in regional stress conditions. The stress directions and magnitudes were obtained by experiments. The dilation tendency can be viewed along with an equal area net view of the regional stresses. The effect of changes in the regional stress directions can be seen interactively with a map view of fracture. In this example, the regional tectonic stresses are primary factors in controlling the flow paths in fracture networks. And thus a rapid analysis of the stress ratio and various images can suggest the connectivity and flow paths in the fracture network (Fig.11).

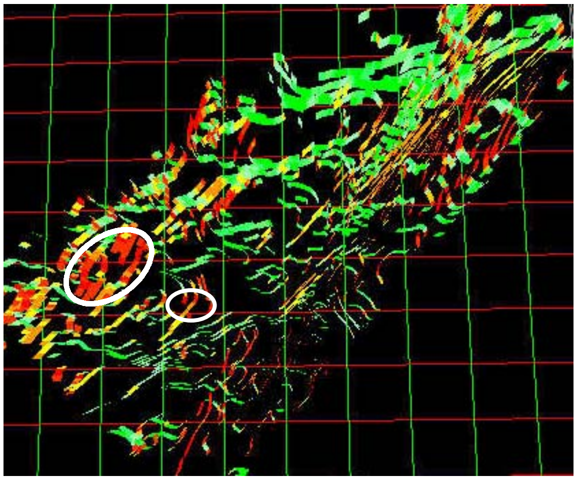

Fig.11 Leakage tendency of the fracture network

Fig.11 shows the leakage of the study area, the elliptic regions imply higher leakage tendency, while other regions imply lower leakage tendency.

APPLICATION OF FRACTURE NET WORK

The best way to validate the pattern is through well observations and production data. Wells drilled in several parts of the area seem to confirm the simulated fracture pattern, i.e. oil well in high fracture density area had high production at the beginning of the perforation.

According to the results and interpretations presented above we designed 8 horizon wells in intensive fracture zones, the wells have much greater production than any other wells of this area, the average production is 60 t/d while other wells is 10 t/d.

CONCLUSION

This study showed the workflow of fracture modeling and the application in a reservoir of buried hill using structural validation tools and interactive fracture simulations constrained with lithology, well log and core data.

The fracture network model can help us understand not only what a fractured reservoir looks like, but also how the existing fracture network behaves. The presented methods only show how we assess the fracture network in the study area (especially fractures of a buried hill), every geological setting has its own peculiarities and needs a proper approach. In any case, one needs to understand and constrain the geological history in 3D space in order to assess the fracture network properly.

It is essential to assume that the fracture network modeling is geologically realistic, and that is unreasonable only through some inadequate random data (such as log or core data) and through stochastic simulation. Alternative insight in the geology may result in a number of possible scenarios with final fracture patterns that may look remarkably different. Well and production data will help distinguish between the various scenarios. Once a good fit is found, the technical risk for the fractured reservoir is highly reduced and future well observations and performance are more predictable. The integration of the above-described analyses can help us to define new well trajectories or development strategies.

In this case the fracture density is highly controlled by the structural history of the area and the lithology. The reservoirs have good flow in the initial stages of production, but "shuts down" rapidly, this phenomenon is common and from the study we consider that the present stress distribution is one of the important factors. Another important factor is that all fractures are initially kept open by the fluid pressure, but the pressure declines during production, some fracture sets closed and disrupted the connectivity of the network.

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