Jia'en Lin *Editor*

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Static and Dynamic Reservoir Evaluation and Management in E&P

Application of Prestack Wide-Azimuth Coherence Technique in Complex Fault Area

Min Xu[1(✉)], Jing Luo[1], Hong Liang[1], Rong-rong Yang[1], Ying Deng[1], Fan Yang[1], Yue-zong Zhou[1], and Li-feng Gao[2]

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Abstract. The Permian in the northwest of Sichuan Basin is buried deep (more than 6000 m), and a large number of small Fault Horst structures are developed. The fracture system is very well developed, which leads to multiple solutions of prediction results, and the effect of various prediction techniques is very poor. Using the characteristics that P-wave propagates in parallel or vertical fractures in anisotropic media, the properties of seismic reflection data are studied, and the seismic information is mined to guide the study of fracture development law. Based on the seismic data of "two widths and one height", the prestack wide-azimuth coherent fracture prediction technology is studied. First of all, according to the post stack coherent attributes to find the general law of fault system development, then, the wide-azimuth data are divided into azimuth and angle. On the partial stack data volume with azimuth, the azimuth coherence volume is calculated by using the characteristics of seismic amplitude changing with azimuth, so as to predict the development characteristics of faults and fractures.

Prestack wide-azimuth coherence technique is more close to the actual geological phenomenon in describing the fault development zone and the morphological characteristics of fault and fracture cavity, which is helpful to the selection of drilling well location target. Compared with the conventional post stack coherence technology, it not only reduces the multi solution, but also can predict relatively small-scale fractures. At the same time, it has the anti-interference ability of post stack coherence, and has the characteristics of fast and efficient prediction, which is suitable for rapid and efficient exploration and development stage.

Keywords: Wide-azimuth · Fault system · Fracture prediction · Azimuth · Coherence

1 Introduction

The study area is located in the footwall of the nappe structural belt of LM Mountain Piedmont belt in the northwest of Sichuan Basin (Fig. 1). Affected by structure of many times activity, the hinterland structural fold has a huge range, which is a fault fold belt with developed faults, and the small faults are very developed. The buried depth of the

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Permian Maokou Formation is more than 6000 m. The overlying strata and the underlying strata have a large set of kneading gypsum strata. There are few upward and downward faults, and a large number of small fault Horst structures are developed (Fig. 2). The lithology is mainly marine carbonate rocks, and a large number of dissolution pores and fractures are the effective space for oil and gas accumulation. According to the analysis of drilling results, the main reservoir type is fractured-porosity type. Fracture is the main channel and reservoir, which is one of the main factors for high production. The corrosion holes and fractures can be seen on the electrical imaging logging map. The fracture strike is mainly NW-SE, the dip angle changes greatly, and the local fracture is mainly medium high angle fracture.

Because the resolution of seismic exploration is only a few meters to tens of meters, it is easy to detect the fracture cave system or development zone composed of many small fractures and caves, but it is unable to identify single or small fractures and caves. A variety of fracture prediction techniques have also been studied in this area. However, with the increase and acceleration of exploration and development, the requirements for fracture prediction are higher and higher. The limitations of seismic data obtained by conventional seismic exploration are gradually obvious, especially the problems of narrow azimuth and low spatial resolution, which seriously affect the identification of fractured vuggy gas reservoirs in this area. Prestack fracture detection technology can detect high angle fracture development zone, and exploring a new fast high-resolution fracture prediction technology based on prestack seismic data is the key to the study area.

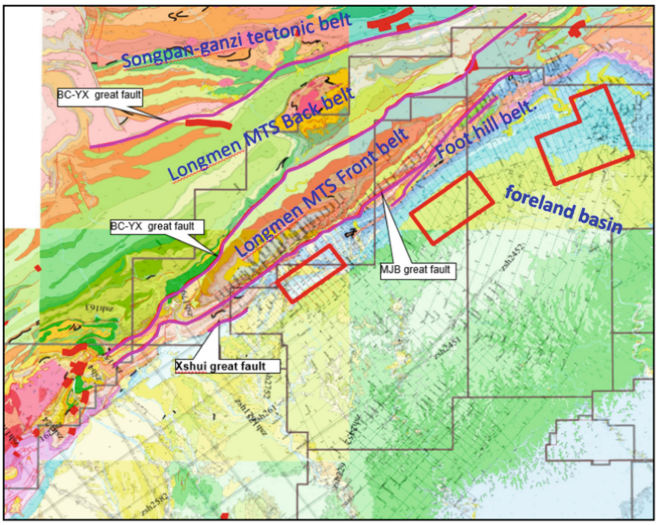


Fig. 1. Geological plan of study area.

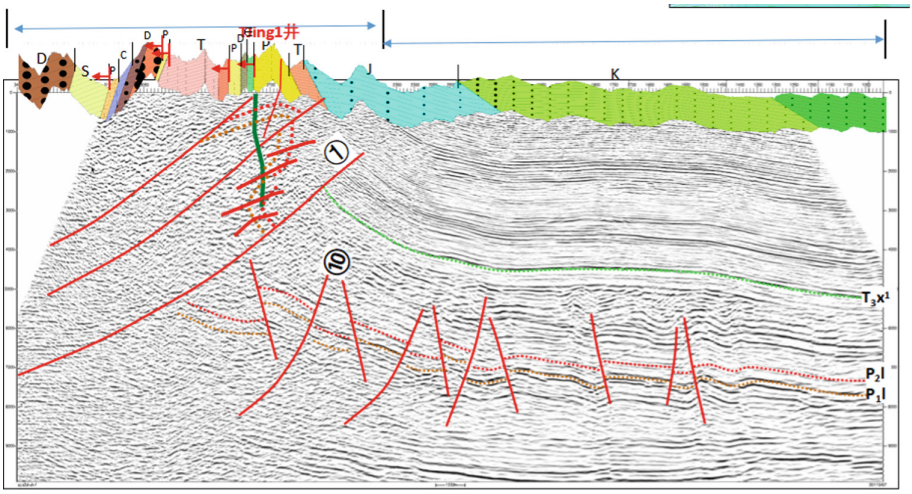


Fig. 2. Seismic section.

2 Prestack Wide-Azimuth Coherence Cube Technique

2.1 Principle of Prestack Wide-Azimuth Coherence Cube Technique

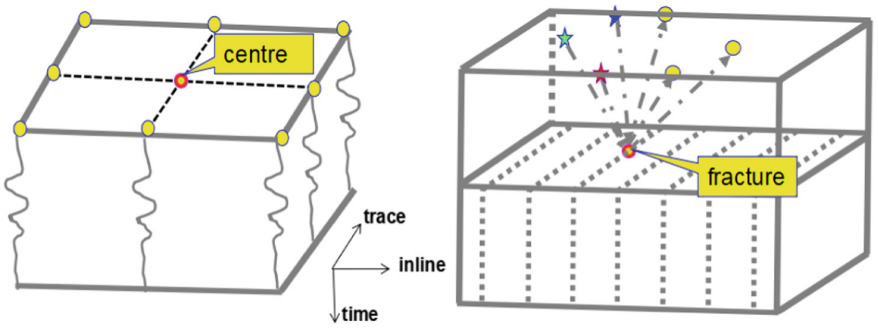
This method can predict relatively small-scale fractures by using the characteristics of seismic amplitude changing with azimuth, which provides a new idea and method for fracture detection and reservoir prediction.

Coherence technology is a technology that uses correlation principle to highlight the non similarity of seismic signals between adjacent traces, so as to detect faults and reflect the distribution of geological anomaly characteristics. According to the spatial variation of high and low coherence values, faults can be identified quickly, even small faults and small distortions that are difficult to be identified in conventional interpretation can be identified. Therefore, the magnitude of signal coherence between seismic traces is an important indicator to judge the existence of faults or fractures [1–4]. The stronger the coherence, the more continuous the formation.

Wide-azimuth data refers to the seismic data obtained by wide-azimuth seismic exploration acquisition technology. Because of the full azimuth distribution, reasonable offset and coverage times distribution, it is more conducive to the correct imaging of complex geological bodies in underground structure, and has high resolution. wide-azimuth seismic data contains more abundant information, which is helpful to identify micro structures, small faults and high angle fractures. Therefore, more seismic attribute information can be obtained by using wide-azimuth data for fracture detection in deep structural complex areas.

Wide-azimuth coherency is that the wide-azimuth data is stacked by azimuth, and then the coherence calculation is realized based on the characteristics of amplitude changing with azimuth on the azimuth data volume. It is based on the discontinuous information changing with spatial azimuth, which eliminates the multi solution caused by lithology change, and can also predict the small-scale fracture development zone.

However, the post stack coherent fracture prediction technology in conventional oil and gas exploration is only based on the reflection amplitude difference between each point in space and the surrounding points, which can not avoid the waveform change caused by lithology change. The schematic diagram of the two is shown in Fig. 3.



a Conventional Post stack coherence b wide azimuth coherence

Fig. 3. Difference between conventional coherence and wide-azimuth coherence.

2.2 Prestack Wide-Azimuth Coherent Calculation Flow (Algorithm and Flow)

Compared with conventional post stack coherence, the wide-azimuth high-precision coherence technology increases the azimuth processing of seismic data first, which reduces the multi solution of prediction, and can predict relatively small-scale fractures, so as to realize the synchronization of large-scale and small-scale fractures, and the accuracy is higher.

The calculation process of wide-azimuth coherence technique is as follows:

1) Read N original wide-azimuth seismic data (n is greater than or equal to 3);
2) Construction of covariance matrix: according to the inline and Xline cycles, taking a certain time point of the seismic data as the center of the sliding time window, take out the seismic trace data with the length of the coherent time window, construct the matrix trace of 6 times the length of the coherent time window, and then multiply the transpose of the matrix trace by the matrix trace to obtain the covariance matrix C.
3) The covariance matrix C is decomposed into eigenvalues, and the maximum eigenvalue is divided by the sum of all eigenvalues to get the coherence value of the point. The algorithm flow is shown in Fig. 4.

Combined with logging and forward modeling information, on the basis of logging data calibration, for the same grid, the dissolution holes and fractures are merged into a geometric structure geological model. Through the production dynamic data, the wave impedance/porosity threshold value is determined to filter the surrounding rock, and finally the effective three-dimensional geometric structure model is obtained. On this

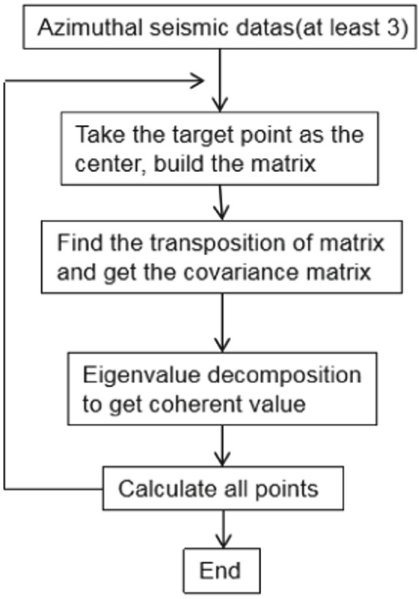


Fig. 4. Wide-azimuth and high precision coherent flow chart.

basis, the fracture cavity zone/system/unit division analysis can be carried out in combination with the production dynamic data. In addition, when merging, the threshold fusion method can be used to carry out the comprehensive prediction of fractures and holes, and then the 3D carving based on the boundary constraints can be carried out to study the development of fractures and holes.

2.3 Characteristics and Key Technologies of Wide-Azimuth Coherence Cube

Wide-azimuth coherence technology is based on wide-azimuth data volume, introduces the traditional coherence calculation method, and then realizes high-precision coherence attribute calculation. The key technology is the azimuth division of wide-azimuth seismic data. The principle is to effectively meet the uniform coverage times of each azimuth, which can effectively improve the fracture identification. The basis of division is to extract coherence slice from post-stack seismic data or along layer coherence attribute, find the general orientation of fault system and fracture development in the study area [5, 6], and then stack the divided gather data; the second is to select the time point of seismic data and the time window length when constructing the covariance matrix, and determine the time window according to the general reflection time of the target horizon. The time window is too long, it contains many in-phase axes, the coherence volume can not accurately reflect the characteristics of the fault; the time window is too small, it can not contain a complete waveform, the coherence volume data is unreliable, usually greater than t/2 and less than 3t/2, t is the period of seismic wave reflection; finally, the eigenvalue decomposition, select the eigenvalue representing fracture development,

remove the noise interference eigenvalue, can be used in order to improve the resolution of coherent volume calculation.

3 Application Effect Analysis

Well ST1, well ST3 and well SY001-X1 in the study area have achieved high production, and the fracture cavity is of great significance for the improvement of reservoir. In the study area, "two wide and one high" (wide-azimuth, wide frequency band, high density) high-precision seismic acquisition technology (the number of coverage is 10 * 10, and the transverse longitudinal ratio is 0.85) is used to obtain seismic data. The wide-band signal source and vibroseis can obtain more azimuth information, which can realize the flexible division of azimuth and provide reliable seismic data for fine fracture prediction.

The prestack wide-azimuth coherence technique is used to study the fractures in this area. The main processing flow of pre-stack fracture detection is dividing azimuth, and the general direction of fracture azimuth in the study area can be found from the post stack coherent slices. The study area is cut by many NE trending faults, which are obviously controlled by faults. The structures are long strip-shaped anticline, fault anticline, a small number of fault nose and fault block structures in NE direction. The fault system is distributed in NE direction, and the fractures are mainly developed along the direction of the fault system. However, there are many groups of fractures in multiple directions between the major fault systems (Fig. 5), so the fractures are fully considered in order to improve the identification ability of fractures and meet the principle of uniform coverage times in each direction, six directions are divided (Table 1).

Table1. Azimuth division.

Central azimuth (°)	6	36	66	96	126	156
Azimuth range (°)	−9–21	21–51	51–81	81–111	111–141	141–171

Omni directional angle domain imaging is a full wave field multi-path migration imaging technology based on ray theory. In different azimuth migration profiles, the anisotropy characteristics of fracture development are obvious [7–9]. From the section (Fig. 6), the characteristics of seismic reflection waves in various directions are similar, but more different. The blue arrow mark is about 10–20 ms down from the top boundary of Maokou Formation, indicating the position of fracture development section. When extracting the wide-azimuth coherent attribute, the window is set as 20 ms down from the target horizon. Through the analysis of different azimuthal stack sections, it is found that the energy of in-phase axis changes at different azimuths, showing strong anisotropy. The characterization of fractures on stack sections of 51°–81°, 81°–111° and 111°–141° is clearer. Therefore, the coherence attribute analysis is selected on these three stack sections to predict the distribution characteristics of fractures in the study area.

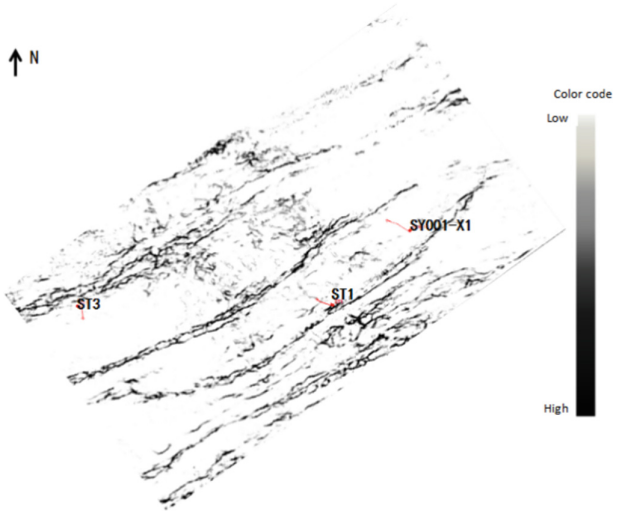


Fig. 5. Post stack coherence slice.

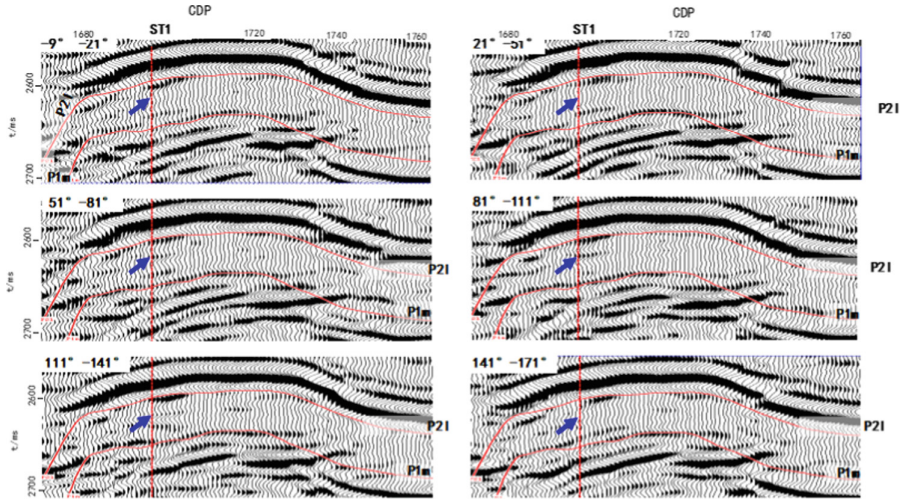
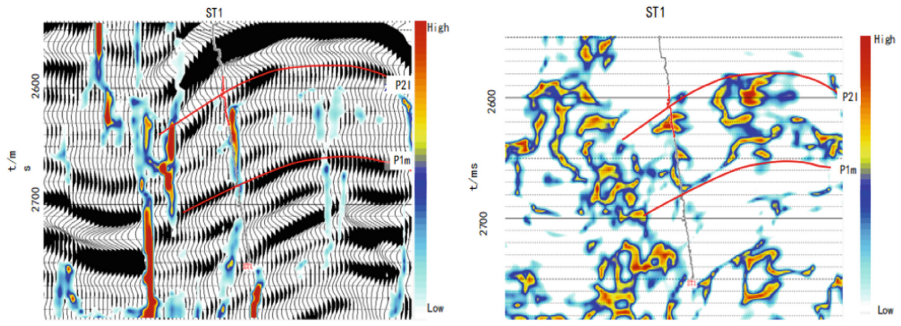


Fig. 6. Different azimuth migration sections.

On the basis of optimizing azimuth migration data, seismic attribute analysis is carried ou. It can depict large-scale fractures, but there are multiple solutions [10–12]. For example, in the lower Maokou Formation, there is obvious high coherence anomaly along the track of well ST1 in conventional coherence, but in fact, the anomaly is only caused by the waveform change caused by the change of sedimentary environment, not the fault. The wide-azimuth coherence has a certain ability to depict large-scale faults and microfractures, and can better characterize the azimuth anisotropyt (Fig. 7). In Maokou Formation, there are two microfractures along the well trajectory of well ST1, which

correspond to each other on the anisotropic section. Well ST1 obviously encounters microfracture development zone, which is consistent with the actual drilling and logging results. In addition, the fracture zone on the left side of well ST1 is characterized by high coherence and disordered anomaly on conventional coherence section, but different on wide-azimuth coherence section. The characterization of fracture zone by wide-azimuth coherence is consistent with the actual seismic data, and more consistent with the geological characteristics of small fault barrier development in this area.



a conventional coherent section b Wide-azimuth coherent section

Fig. 7. Comparison of conventional and wide azimuth coherence sections.

By extracting the 10 ms wide-azimuth coherence slice downward from the top boundary of Maokou Formation and superposing with fault interpretation, it can be found (Fig. 8) that there is a certain associated relationship between microfracture and fault.

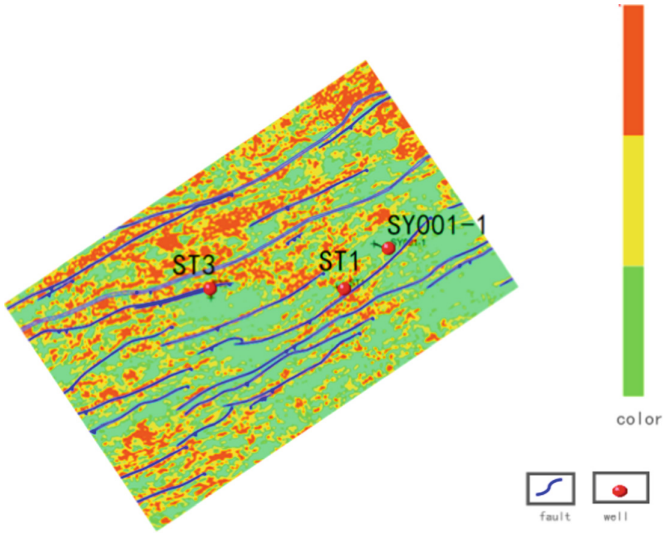


Fig. 8. Wide-azimuth coherent slice and fault superposition plan.

In the middle and north part of the work area (north of well ST1), microfracture is relatively more developed, and the northern structural position is relatively high, which is a favorable area for oil and gas exploration. In the later drilling, well ST3 encountered fractures and obtained more than 80×10^4 m^3/d of industrial gas. The reliability of the results has been proved.

4 Conclusion

1) The wide-azimuth seismic data can provide more azimuth information and realize the flexible division of azimuth. On this basis, the azimuth coherent technology can carry out the fine prediction of fractures.
2) The coherence attribute based on wide-azimuth seismic data is closer to the actual geological phenomenon in describing fault development zone and fracture cavity morphology, which is helpful to the selection of drilling well location target.
3) The waveform discontinuity of different azimuth migration data indicates the anisotropy of azimuth. The wide-azimuth coherence technology combines the advantages of strong ability of anti-noise and high efficiency of post stack coherence technique, and has the characteristics of low multi-resolution pre-stack fracture prediction technology. It can simultaneously predict multi-scale fractures, and realize the rapid and efficient geophysical exploration ability.

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Multiple Hydraulic Fractured Vertical Wells in Gas Condensate Reservoirs

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Abstract. Gas reservoirs can be classified into dry gas reservoirs, wet gas reservoirs and Gas condensate reservoirs. In gas condensate reservoirs, the reservoir temperature lies between the critical temperature and the cricondentherm. The gas will drop out liquid by retrograde condensation in the reservoir, when the pressure falls below the dew point. This heavy part of the gas has found many application in industry and also in daily life and by remaining in reservoir not only this valuable liquid is lost but also its accumulation will result in forming a condensate bank near the well bore region which makes a considerable reduction in well productivity. This highlights the need to find an economical way to increase the condensate recovery from these reservoirs. Wells in gas condensate reservoirs usually exhibit complex behaviors due to condensate deposition as the bottom hole pressure drops below the dew point. Formation of this liquid saturation results in reduced gas relative permeability around the well bore and a loss of gas productivity. One of the several ways of minimizing the pressure drop in order to reduce liquid drop-out is hydraulic fracturing before or after the development of the condensate bank. The pressure transients are often used as a reliable evaluation of stimulation performance for field development planning. It has been shown that condensate deposits effects can be identified and quantified by well test analysis dealing with a well test composite behavior; which, in presence of hydraulic fractures becomes much more complex. But the various impacting factors of stimulation; such as fracture length, conductivity, orientation, etc. can also be observed and defined in these analyses. In this paper, modeling and interpretation of pressure transient responses of multiple hydraulic fractured horizontal wells using a numerical reservoir model has been investigated.

1 Introduction

The first step in studying the gas condensate reservoirs is to characterize the reservoir fluid. It has been found that characterization of the gas condensate fluid is strongly influenced by some main factors such as hold up of retrograde condensate in the formation resulting in excessive producing gas to liquid ratio (GLR). Figure 1 shows a common characteristic of gas condensate fluids. The liquid drop out reaches a maximum and then decreases by vaporization during pressure depletion. This behavior may imply that when the reservoir pressure decreases sufficiently, the condensate will be recovered by re-vaporization. However, by the time pressure falls below the dew point, the original

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phase diagram is no longer valid as the system composition changes during the production period. The compositional analysis of gas condensate fluids is conducted generally in more details than that of oil. The compositional data are used often in phase behavior models, particularly in reservoir simulation. The fluid is commonly analyzed by flashing it at the atmospheric pressure and measuring the composition of the stabilized gas and liquid phases. The fluid heavy fraction is analyzes to identify major components, and also characterize it by extended carbon groups, as the results of phase behavior models are very sensitive to the heavy end description of gas condensate systems.

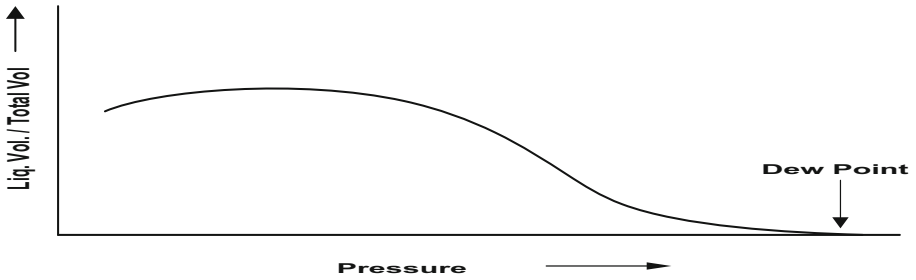

Fig. 1. Liquid drop out of gas condesate

Figure 2 shows pressure temperature relationship for gas condensate fluid with constant composition. Figure 3 shows effect of composition change on phase envelope.

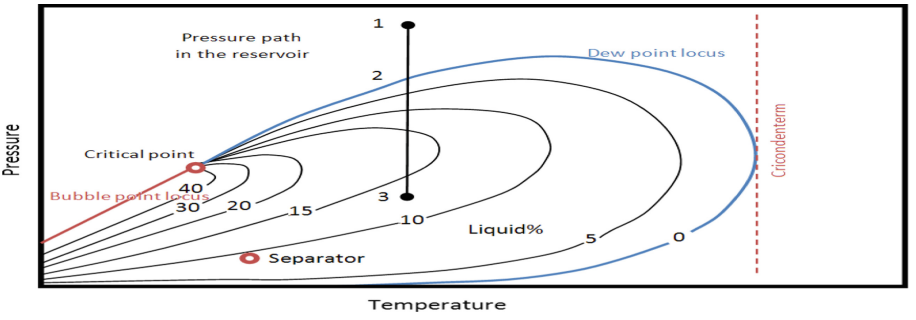

Fig. 2. Pressure – temperature curve for gas condensate with constant composition

In gas condensate reservoirs, gas injection and gas recycling are practices applied to reduce the drop out of the condensate in the reservoir. Gas injection can be implemented at the initial reservoir pressure to maintain the pressure above the dew point (full pressure maintenance), or after the reservoir pressure falls below the dew point (partial pressure maintenance) in which injection gas vaporizes the condensate and reduces the condensate accumulation in the reservoir. Gas recycling has been implemented in gas condensate reservoir for many years, but the increasing application of the reservoir gas and as a result its price made the engineers find an appropriate replace for it. N_2 and CO_2 were suggested

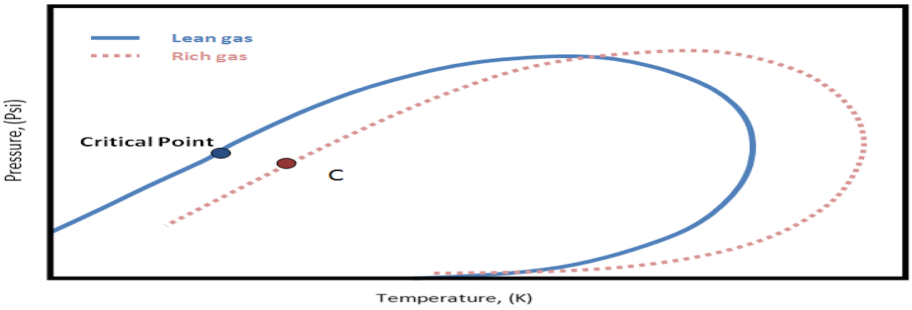

Fig. 3. Effect of composition change on phase envelope

as two alternatives which are now applied in some reservoirs. Nitrogen injection is not as effective as CH_4 and CO_2 injection, but as it is available and non-corrosive it can be properly applied for this purpose. Figure 4 shows condensate saturation in reservoir and Fig. 5 shows gas saturation versus relative permeability.

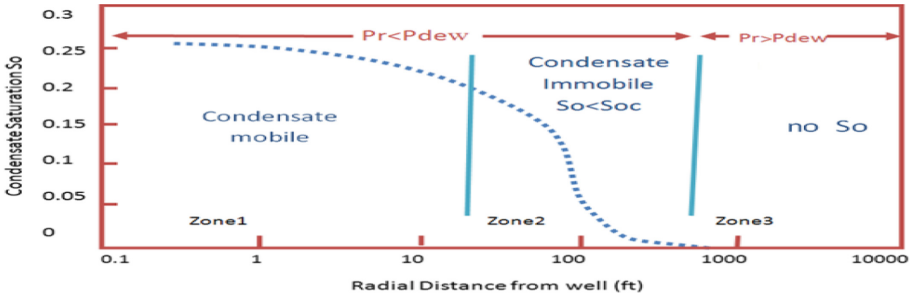

Fig. 4. Condensate saturation in reservoir

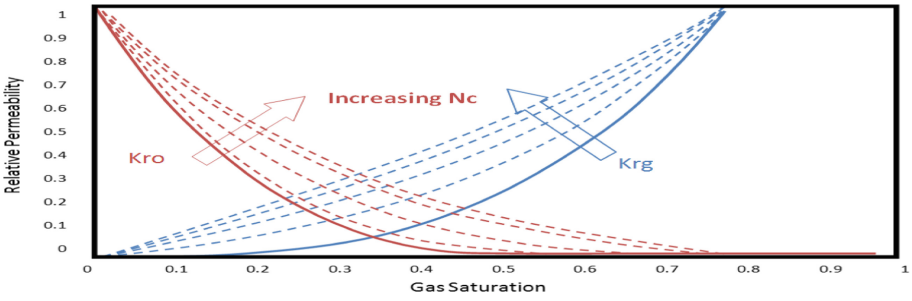

Fig. 5. Gas saturation versus relative permeability

2 Purpose of Study

This work investigates the modeling and interpretation of pressure transient response of multiple hydraulic fractured vertical wells in gas condensate reservoirs, using a fully compositional numerical reservoir model. After validating the numerical model using an analytical solution applied to a simpler reservoir/well model, complex reservoirs using the condensate PVT data are simulated and pressure transient response signatures obtained. Sensitivities of key reservoir/well/fracture properties are investigated and a result of each case is presented.

3 Methodology

The main aim of this investigation is to know fractured vertical wells behavior in a gas condensate reservoir. For this purpose, we use a compositional numerical model with one well to be able to predict derivative curves for fractured vertical wells with a pressure below dew point pressure. We use ECLIPSE 300 software which is compositional software. First, input data for numerical simulated model, fluids properties and initial reservoir parameters will be introduced. Then, three dimensional compositional models including one well with numbers of hydraulic fractures will be built. Finally, the results of this study will be discussed.

4 Cylindrical Compositional Model and Hydraulic Fracturing in Gas Condensate Reservoirs

Figure 6 shows a general pseudo- pressure logarithmic plot and its derivative plots for a vertical well in a two phase gas condensate reservoir. Figure 7 shows a fracture in a reservoir. Figure 8 shows effective well radius for a fracture with infinite conductivity. Figure 9 shows that slope 0.5 is a character for characterization fracture with infinite conductivity. Figure 10 shows that there is a little difference between steady state and non-steady state hydraulic fracture.

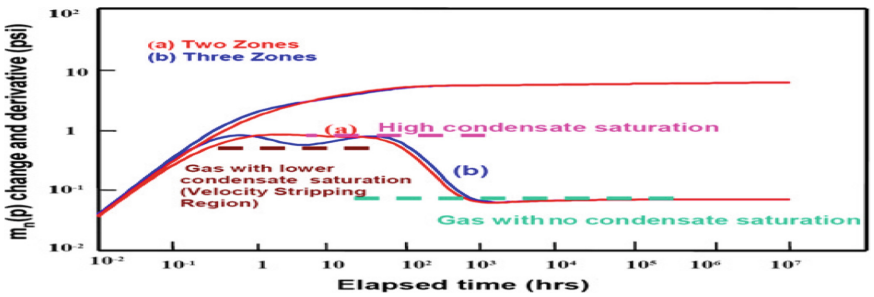

Fig. 6. Models for a well with two or three cylindrical compositional regions

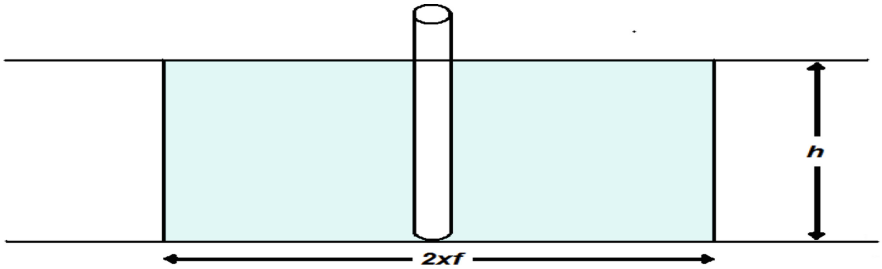

Fig. 7. Fracture in a reservoir

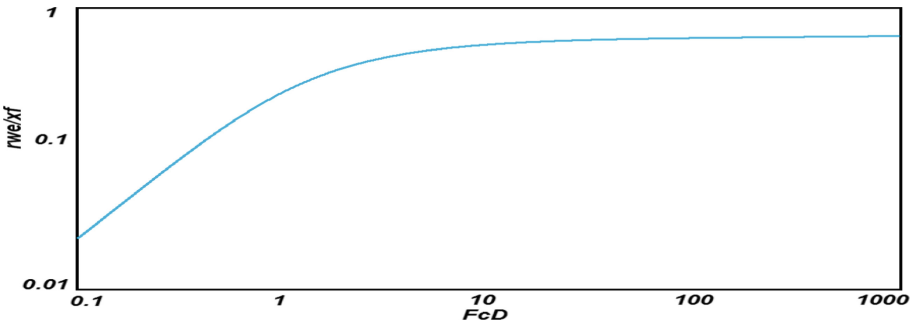

Fig. 8. Effective well radius for a fracture with infinite conductivity

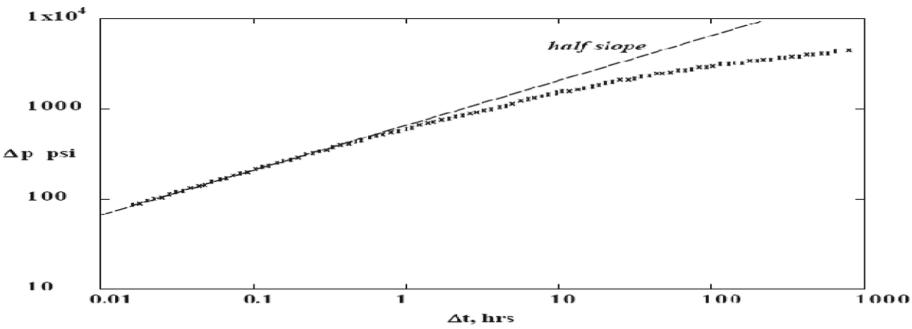

Fig. 9. Slope 0.5 is a character for characterization fracture with infinite conductivity

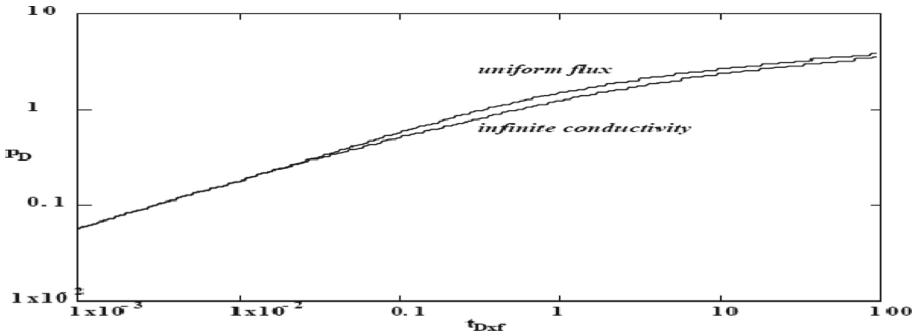

Fig. 10. A little difference between steady state and non-steady state hydraulic fracture

5 Fluid Properties Modeling

The main part of gas condensate reservoir modeling is finding a suitable fluid model. As fluid modeling and model optimization using laboratory data of fluid was not our purpose in this study, we use a prepared simulated fluid from a gas condensate reservoir and its properties as input data for simulation software. The composition of this fluid is shown in Table 1.

Table 1. Composition of fluid which was used in simulation

Mole%	Component	Number
0/0046	*N2*	1
0/0061	CO2	2
0/0	H2S	3
0/6864	C1	4
0/139	C2	5
0/0689	C3	6
0/0066	iC4	7
0/0266	nC4	8
0/0062	iC5	9
0/0094	nC5	10
0/014	C6	11
0/0348	C7 +	12
Sum		1

6 Building Numerical Model for Simulation

A three dimensional model with one vertical well was built by ECLIPSE 300 software. For this simulation, we used a reservoir with thickness of 100 foot and length of 450 foot along Cartesian X-Y axes. In this model, we ignored wellbore storage effect and skin factor. Initial reservoir, rock and fluid properties are summarized in Table 2.

Table 2. Initial reservoir, rock and fluid properties which was used in model

Porosity	0.2
Initial water saturation	0.349
Well radius	0.3 foot
Isothermal rock compressibility coefficient	0.000004 1/psi
Total length of reservoir	17800 foot
Total width of reservoir	16100 foot
Horizontal permeability	10 md
Vertical permeability	1 md

7 Numerical Gridding Analyzing

Sizes of grids especially near well bore are very important because of its effects on fluid saturation and pressure of each block. Therefore, we must optimize lengths of grids in each direction. To do this, several model with different number of grids, 4669 ($7 \times 23 \times 29$), 5887 ($7 \times 29 \times 29$), 10933 ($13 \times 29 \times 29$), 20787 ($13 \times 39 \times 41$), and 31447 ($13 \times 59 \times 41$) were tested. To study and understand gas condensate behavior near well bore clearly, we used small grid sizes around well bore and bigger grid sizes for grids which are far from well bore. Outer layers are selected with so big sizes that boundary effects on well test results can be ignored. The main purpose of selection this type of gridding was to be able to study flow regimes and accumulated condensate distribution during production or well test period more clearly and carefully. Finally, the model with 20787 ($13 \times 39 \times 41$) was selected as the best model. Gridding system used for this model was shown in Fig. 11 and its grid sizes are shown in Table 3.

There are two methods to design grids sizes and grid refinement around well bore using ECLIPSE300 software which are Near Wellbore Module (NWM) and Template (Fig. 12).

One of the advantages of NWM model is that numbers of grids in a reservoir are less than a case which total reservoir is divided into smaller grids. But, as larger grids are located along side small grids, its calculation error will be increased. To use this model, first, that part of the reservoir which include well and hydraulic fractures must be departed from total reservoir, then, by selecting type of refined grids and based on local grid refinement theory, smaller grids around wellbore and fractures will be built.

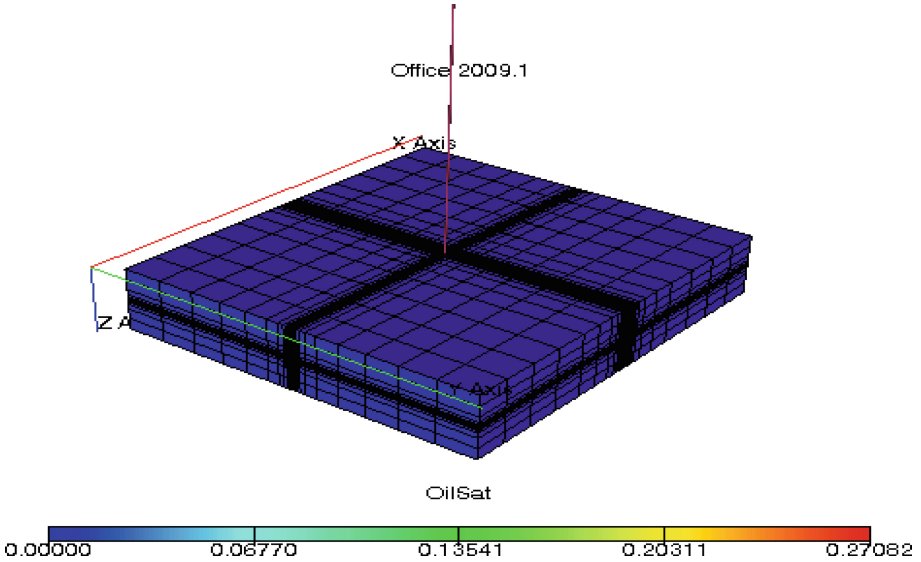

Fig. 11. Cartesian grid system for simulated model

Table 3. Grid sizes used for simulated model

i	*Dx*	*i*	*Dx*	*j*	*Dy*	*j*	*Dy*	*k*	*Dz*
1	1500	21	35	1	1500	21	0.25	1	17.8888
2	1500	22	35	2	1500	22	0.25	2	16
3	1500	23	35	3	1500	23	0.45	3	8
4	1500	24	35	4	1500	24	.8	4	4
5	1000	25	35	5	1014	25	1.4	5	2
6	800	62	35	6	512	62	2.5	6	2
7	400	27	35	7	256	27	5	7	1
8	200	28	35	8	128	28	10	8	2
9	88	29	35	9	64	29	20	9	2
10	45	30	35	10	35	30	35	10	4
11	35	31	45	11	20	31	64	11	8
12	35	32	88	12	10	32	128	12	16
13	35	33	200	13	5	33	256	13	17.88
14	35	34	400	14	2.5	34	512		
15	35	35	800	15	1.4	35	1014		
16	35	36	1000	16	0.8	36	1500		
17	35	37	1500	17	0.45	37	1500		
18	35	38	1500	18	0.25	38	1500		
19	35	39	1500	19	0.25	39	1500		
20	35	40	1500	20	0.25	40			