Preliminary Understanding of Complex Reservoirs by Multidisciplinary Integration: A Case Study of Well X-5 with "the Four High and One Ultra"

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Abstract. For high temperature, high pressure, high salinity, high drilling loss and ultra-deep well X-5 well testing, the causes of water production are unknown, and the problems of the productivity contradiction and the high risk of engineering operation are studied. Based on the integrated analysis of dynamic and static data such as well testing, wireline logging, mud logging, drilling, seismic, and coring, reservoir characteristics, faults sealing and the causes of water production are analyzed from multidisciplinary integration aspects, and a water source analysis schematic diagram is established correspondingly. Studies show that a large amount of water from T6 and T4 zone tested for the first time of the whole oilfield with poor formation petrophysical properties is from the upper water flooded zone T2, and water flows into the lower tested zones through the major fault channel with high conductivity. It was recommended to timely adjust the well testing design for subsequent T3 zone without wireline logging and mud logging show, and remove the packer to reduce the risk of a large number of salt crystallization blocking pipe string. The contradictions between liquid type, productivity and pre-test predictions of the DST4 (drill stem testing) and DST5 zone is clearly understood and verified further by the actual well testing results of DST6. Liquid type, formation pressure, and productivity of the DST6 zone were predicted accurately. The DST4, DST5 and DST6 zones belong to the same pressure system. Faults sealing was accurately identified and operations safety of well testing was ensured by the integrated analysis of multi-disciplinary data. Furthermore, the preliminary understanding of complex reservoirs is improved.

Keywords: Multidisciplinary · Faults sealing · Connection · Water production · Well testing · Pre-test prediction

1 Introduction

Currently, the integrated research on both well testing and static data is uncommon for complex reservoirs because they are characterized by different research content

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and aspects. Well testing technology is an important method to directly understand the reservoir [1], and it plays an important role in the early stage of exploration by analyzing reservoir characteristics from a dynamic perspective. X-5 well, an important well of CNPC, located in the oilfield in Central Asia with high temperature, high pressure, high salinity, high drilling loss and ultra-deep. The engineering and geological problems are extremely complex. Three-zone DST (drill stem testing) have been carried out, which poses severe challenges to the well testing operation. High temperature affects the performance of rubber sealing and perforation. The temperature field changes during the test flow and shut-in period resulting in greater test string stress and bending, deformation and fracture of the test string [2]. High pressure weakens the sealing performance of the test string. The packer is easy to lose sealing, and the wellhead is prone to loss of control, which can easily cause well testing failure, personal injury and equipment damage [3].

Salt plugging. During the test, as formation water with high salinity continue to flow into the wellbore, salt deposition is prone to occur in the wellbore with the decreasing temperature and pressure, causing the downhole pipe string to be blocked by salt grains. At this time, not only the flow channel is blocked, which affects the acquisition of test data, but also the pipe string cannot be lifted, resulting in major accidents in the well testing operation, and even abandonment of the well [4]. If the test pressure difference is large, the possibility of salt deposition near the wellbore cannot be excluded [5]. A certain well [6] has a salinity as high as 42.4×10^4 mg/L**,** and the diameter of crystal grains is mostly 1–3 mm. Considering that the crystal grain size may be greater than 3 mm, in order to ensure the open flow of the test string and avoid salt crystal subsidence blocking the string, the wellhead flow rate should not be less than 200 m^3/d for the inner diameter of the tubing of 62 mm.

T6 (DST4), T4 (DST5) and T3 (DST6) zone of well X-5, which have never been tested before for the corresponding zone in the entire oilfield, the characteristics of the reservoir are not clear. The main problems before well testing are unknown liquid properties, unknown productivity and high engineering operation risk. Static data show that the porosity of T6 and T4 zone are low and the productivity are poor, but why a large amount of water were both produced after well testing? Wireline logging and mud logging have no show for T3 zone, and no valid zone was identified. According to the well testing results of DST4 and DST5, how should the DST6 well testing design be optimized? How to ensure the operation safety of DST6 under the premise that a large number of salt crystals occurred in DST4 and DST5? In this paper, the dynamic and static data of well testing, wireline logging, mud logging, drilling, seismic and coring are integrated utilized to analyze the reservoir characteristics and deepen the preliminary understanding of complex reservoirs. At the same time, the DST6 well testing results were predicted, which is more challenging, and reasonable suggestions were provided for the improvement of subsequent well testing design and the guarantee of operation safety. This study is conducted to determine the water production of the DST4 and DST5 zone was from the upper water flooded zone through the fault channel and the fractures in the tested zone, and the knowledge is supported by the well testing results of the follow-up DST6.

2 Brief Introduction of the Tested Well

The key well X-5 is an exploration evaluation well. The Well depth is 5918 m, the maximum temperature is 152.1 °C, the maximum formation pressure is 111.4 MPa, the maximum formation water chloride concentration is 21.50 × 10^4 mg/L, and total drilling loss is 1010.9 m^3. The specific gravity of the drilling fluid is 2.22, and the highest formation pressure coefficient is 2.13. The drilling purpose of this well is to evaluate the oil and gas properties of related reservoirs, determine reserves and productivity, and study reservoir characteristics and oil-water relationship. According to the requirements of geological design, the zone-by-zone up-and-back well testing process is adopted to test the three zones of T6, T4 and T3 in turn, so as to determine the oil and gas production capacity, obtain oil, gas and water samples, provide data for reserves calculation and development, and provide data support for large-scale development of oilfields.

The reservoir is the Upper Tertiary, and the lithology is dominated by mainly sandstone and mudstone. Wireline logging interpretation results (Fig. 1) show that the T2 zone of X-5 well 5226.6–5231.3 m is the main reservoir of the well and it is a water flooded zone because of long production history of the adjacent wells. T2 zone has good petrophysical properties with porosity of 23.4%. Water zone characteristics are not obvious except T2 zone in the whole well section. The wireline logging interpretation results of the DST4 and DST5 zone are inconsistent with the well testing results and a large number of salt crystals occurred in the wellbore (Table 1). Before DST6 operation, it is necessary to combine the well testing results of DST4 and DST5 with other subject data to study the complexity of reservoir characteristics and explore the causes of water production in DST4 and DST5. At the same time, DST6 operation risk should be fully assessed and specific countermeasures should be proposed.

Table 1. The comparison table of the three-zone wireline logging interpretation results and well testing results of well X-5.

Zone	WT Date	Testing No.	WT interval (mKB)	Porosity (%)	Net pay thickness (m)	WL interpretation results	Liquid property of WT	Production rate (m^3/d)	Drilling loss, (m^3)
T6	2018.12	DST4	5363~5376	7	5.5	Oil	Water	195	67.6
T4	2019.1	DST5	5286~5315	12.7	5.5	Oil	Water	228	552.8
T3	2019.4	DST6	5256~5270	/	0	Non-reservoir	Water	394	47.5

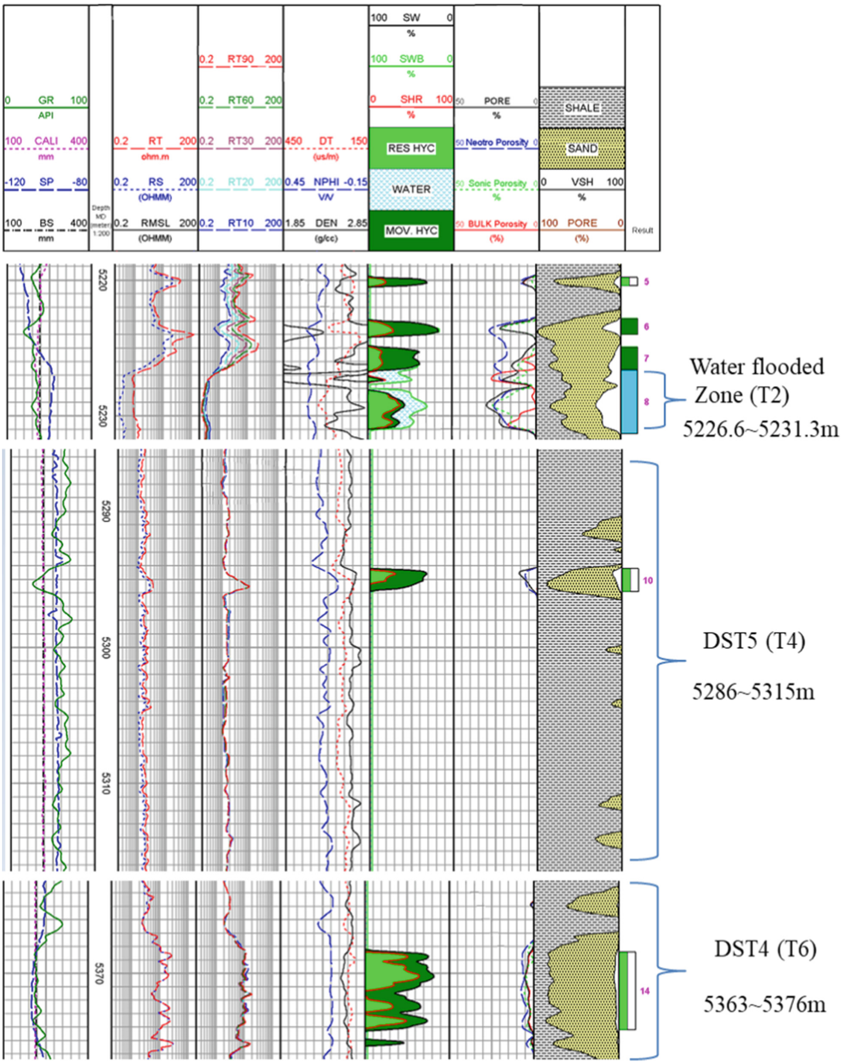

Fig. 1. The wireline logging interpretation plot of the DST4 and DST5 zone and the upper water flooded zone

3 Multidisciplinary Integration Analysis of Water Source, Reservoir Characteristics and Evaluation of Faults Sealing

3.1 Cause Analysis of Water Production of the DST4 and DST5 Zone

A large amount of water was produced during the DST4 and DST5 test (Table 1). The wireline logging data show that the cementing quality of the well interval of 5384.60–5873.00 m was good, and the pressure test was completed with clean water at 69 MPa, and the test pressure is qualified. Mud logging data show that cuttings gas survey of the two zones show is weak and the lithology are mudstone and silty mudstone. According to wireline logging data, a large amount of water in the tested zone is not from the inner zone of the DST4 and DST5. The existence of bottom water is not supported by the wireline logging information and the existence of edge water is also not supported by the wells correlation profile.

Wireline logging information shows that the petrophysical properties of the DST4 and DST5 do not match the productivity achieved by the well testing (Fig. 1, Table 2). The porosity of the DST4 zone is 7% with net pay thickness of 5.5 m and the porosity of the DST5 zone is 12.7% with net pay thickness of 5.5 m from the wireline logging interpretation results. The productivity of well testing results are high without stimulation for DST4 and DST5 (Table 2).

Table 2. The well testing results of DST4 and DST5.

Testing No.	Zone	Well testing interval (mKB)	Liquid property of WT	Production rate (m^3/d)	P.C.	Density (g/cm^3)	Cl^- (ppm)	Production index ($m^3/d/MPa$)
DST5	T4	5286~5315	water	228	2.13	1.2	200,000	1763
DST4	T6	5363~5376	water	195	2.12	1.2	190,000	16.2

The DST4 and DST5 zones are not good reservoirs according to the wireline logging and mud logging information. The main basis for well testing is that there is drilling loss in the tested interval (Table 2). The following integrated analysis shows that the water production of DST4 and DST5 was not from its own zone but the water flooded zone of 5226.6–5231.3 m in the upper T2 zone (Fig. 1), which is the only established water zone in the whole well section from the wireline logging information.

3.2 Analysis of Water Source Channel and Evaluation of Faults Sealing

Faults are developed and strata is broken for well X-5 with complex geological conditions.

The seismic and coring data from adjacent wells indicate that the T6 and T4 zone may be connected with the upper T2 zone through the fault fracture zone.

Seismic. The seismic section (Fig. 2) shows that there is a major fault near well X-5, and the seismic event of T6 and T4 zone are discontinuous, indicating that these two zones may be laterally separated by minor fault. Well X-5 is located in the high position of the structure with concentrated stress and it is close to the major fault.

The predecessors [7–9] believes that the fault zone is composed of shattered zone and induced fracture zone, and believes that the shattered fault zone is mainly characterized by fault rock and associated fracture development. Jin Qiang et al. [10] propose that the shattered fault zone is composed of cross-section fillings and derived fractures based on the observation results of the outcrop. Li Shaohua et al. [11] believe that shattered fault zone play an important role in controlling the flow path of fluid in the reservoir. Therefore, the shattered fault zone may provide a flow channel for T4 and T6 zone to connect the water source of the upper T2 water flooded zone.

Coring. The coring information shows that the fractures in the sandstone are filled with salt in the No. 37 sample (5248.2–5253.2 m) of the adjacent well X-3 (Fig. 3), indicating that the fractures may develop near the corresponding zone of the well X-5, which may provide a flowing channel for T6 and T4 zone to connect the water source of T2 zone.

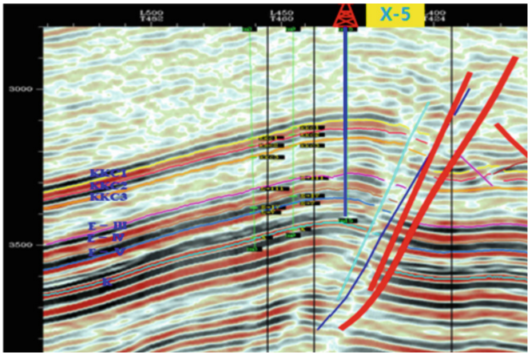

Fig. 2. The seismic section of well X-5.

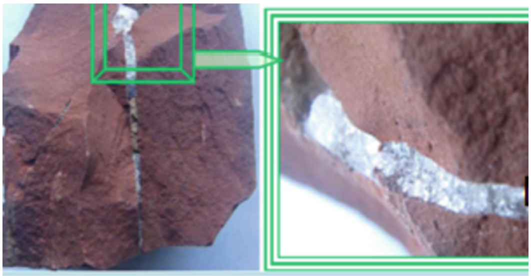

Fig. 3. The no. 37 coring sample of well X-3.

Drilling. Previous study believe that the difference between the pore pressure and the fracture pressure in the abnormally high temperature and high pressure reservoir is little [12], and the safety density window of the drilling fluid is narrow, which is prone to leakage and overflow almost simultaneously [13, 14]. It is difficult to predict formation pressure. The well-developed pores can easily cause oil and gas replacement in the reservoir which leads to leakage. Xu Tongtai [15] et al. (1997) believe that three conditions must be met for lost circulation: first, the pressure of the wellbore working fluid must be greater than the pore pressure of the formation; second, there is a leakage channel in the formation and enough space for the formation to hold the liquid; third, the opening size of the leakage channel should be greater than the particle size of the solid phase in the working fluid. But replacement leakage does not necessarily have a positive pressure difference. Most of the leakage channels in nonmarine depositional formation are fractures [15].

Drilling information show that there are drilling loss for the tested zones of DST4 and DST5 and the upper T2 water flooded zone (Fig. 4). The determination of the tested interval depth mainly refers to the drilling loss depth. The drilling loss is 343 m^3 at 5226.6–5231.3 m of T2 zone, 552.8 m^3 in the DST5 interval, and 67.6 m^3 in the DST4 interval. The magnitude of loss may reflect the fracture development degree in the tested zone. After the water in the water flooded zone flowed into the lower tested zone through the shattered fault zone, the developed fractures in the tested zone provide a flow channel for the water to flow into the wellbore.

3.3 Water Source Direction Analysis by the WT Data

The dynamic data from well testing shows that the water density and the pressure coefficient of the DST4 and DST5 zone are the same respectively, and the concentration of chloride is close (Table 2). They may come from the same water source and the DST4 and DST5 zone belong to the same pressure system connected to each other. If the two zones are connected by the major fault, the difference of calculated formation pressure should be 0.5–1.06 MPa. The difference of actual formation pressure is 0.9 MPa, which further increases the possibility of the two zones being connected.

The water production index of DST5 is 109 times that of DST4, indicating that the water energy of DST5 is stronger and the DST5 zone may be closer to the water source than that of DST4 (Table 2). The middle depth of the upper water-flooded zone is 71.15 m from the middle depth of DST5 interval, and 140.15 m from the middle depth of DST4 interval. T4 zone is closer to the upper water flooded zone, which is consistent with the change trend of production index. The water source should be located in the upper part of T4 zone rather than the lower part of T6 zone.

3.4 Water Properties of T6 and T4 Zone are Consistent with the Upper Water Flooded Zone

Well testing samples confirmed that the chloride concentration of T6 and T4 zone was consistent with the upper T2 water-flooded zone (200,000 ppm) and the pressure coefficient (2.12) was also consistent (Table 2).

4 Establishing a Water Source Analysis Schematic Diagram, Guiding Engineering Operation and Reducing Operation Risk

4.1 Establishing a Water Source Analysis Schematic Diagram

Based on dynamic and static data such as well testing (Tables 1 and 2), wireline logging (Fig. 1), mud logging, drilling (Table 1), seismic (Fig. 2) and coring (Fig. 3), multidisciplinary analysis was carried out, and a schematic diagram of water source analysis of DST4 and DST5 was established as Fig. 4. The major fault (the red one in Fig. 2) was simulated by the fault (Fig. 4) connecting T2, T3, T4 and T6 zone.

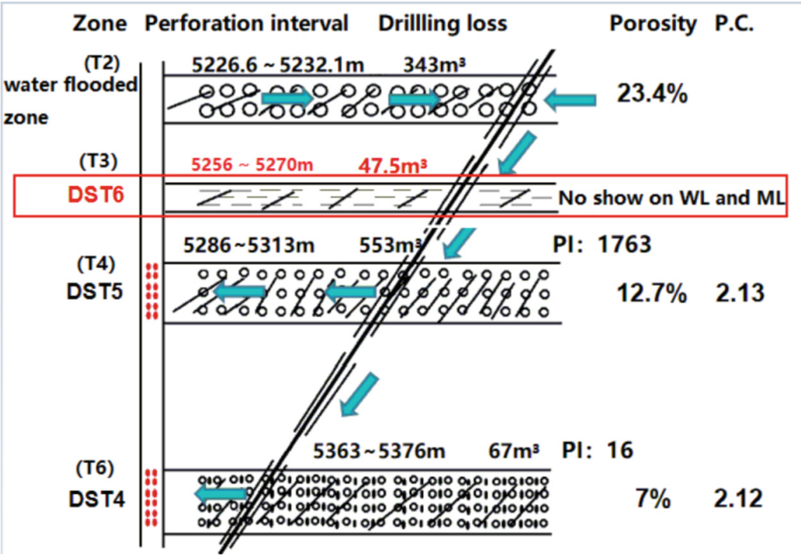

Fig. 4. The schematic diagram of water source analysis of well X-5.

A large amount of water flowed from the upper water flooded zone of 5226.6–5231.3 m to the tested zones of DST4 and DST5 through the shattered fault zone during the well testing period (Fig. 4), resulting in the well testing productivity of the two zones significantly exceeds the productivity represented by the petrophysical properties reflected by the wireline logging and mud logging data.

4.2 Prediction of DST6 Well Testing Results

The rock debris of mud logging of the DST6 interval is mudstone, which is consistent with the wireline logging show (Fig. 5). The zone of the tested DST6 interval is considered an invade reservoir, and it had not been tested before in the whole oilfield. The drilling loss of this zone is 47.5 m^3. Combined with the similar geological characteristics and the study of water production mechanism of DST4 and DST5, the zones of DST6, DST5 and DST4 should be connected with the upper water flooded zone through the shattered fault zone with high permeability, belonging to the same pressure system, and the pressure coefficient should be consistent. Therefore, the DST6 zone was predicted to produce water with high salinity, and the pressure coefficient should be 2.12–2.13, as shown in Table 3.

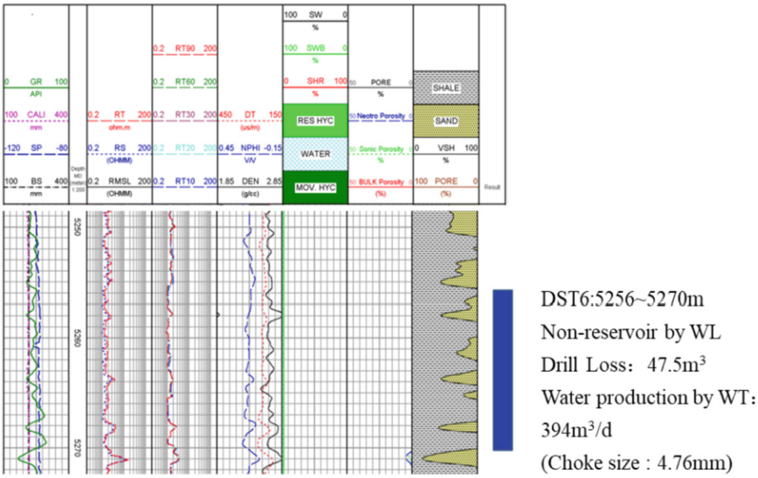

Fig. 5. The wireline logging interpretation results plot of the DST6 interval of well X-5.

4.3 Adjustment of the DST6 Well Testing Design

Due to the high salinity of formation water, salt crystals can easily cause engineering accidents when the testing string is blocked. In order to ensure the safety of operation, different from the previous DST4 and DST5, DST6 testing design was changed to blank tubing test removing the packer to minimize the complexity of downhole tools, which can effectively reduce the risk of buried stuck after salt crystallization plugging string. Well testing duration should be shorten and measure the chloride concentration of the produced liquid every 15 min to judge the possibility of salt plugging. When the chloride concentration reaches 18.00×10^4 mg/L or more, it should be noted that salt plugging may occur. The perforation operation design also refers to the predicted formation pressure.

4.4 Verification of the DST6 Well Testing Results

The DST6 zone produced is 394 m^3/d of water with the density of 1.2 g/cm^3 and the chlorine concentration of 21.5×10^4 ppm. It is an obvious formation water zone, which is consistent with the prediction before the well testing (Table 3). It is further verified that the formation water come from the upper T2 water flooded zone (Figs. 1, 4 and 5). The fractures shown by coring, seismic and drilling loss provide a flow channel for the water from the upper water flooded zone to flow into the lower non-reservoir tested zone (Fig. 4).

Table 3. The comparison table of the DST6 prediction and actual well testing results.

	Predicted	Actual
Liquid·property	water	water
Production rate（m^3/d）	200-400	394
Chloride concentration（×10^4 ppm）	slightly higher than 20	21.5
Pressure coefficient	2.12~2.13	2.13

5 Conclusions

The water of the upper T2 water flooded zone was confirmed to flow into the lower T6, T4 and T3 tested zones through the major fault. They have almost the same water properties and pressure coefficient. The major fault should not be sealed. The drilling loss information of T6, T4 and T3 zones show the developed fractures, providing a channel for the water to flow into the wellbore from the formation. The zones of T6, T4, T3 and the upper water-flooded zone belong to the same pressure system, connected by the major fault.

Based on the research results, the liquid properties, formation pressure and productivity of the DST6 zone were predicted accurately, and the well testing design was optimized in time to reduce the engineering operation risk. The knowledge of the study is supported by the actual well testing results of DST6, and the production operation is guided scientifically and finished successfully. The research results are helpful for the integrated application of reservoir, geology and engineering.

For complex reservoirs with high temperature, high pressure, high salinity, faults development and serious drilling loss, multidisciplinary data of well testing, wireline logging, mud logging, drilling, seismic and coring should be integrated to deepen the preliminary understanding of reservoirs from dynamic and static perspectives, so as to improve the safety of production operations and provide scientific basis for subsequent exploration and development.

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