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Sensitivity Analysis of Offshore Sandstone Reservoir—A Case Study of an Oilfield in the Western Bohai Sea

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Abstract

X oilfield is located in the Western Bohai Sea. During the water injection development process, the oil well productivity continued to decline. The effect of water injection and oil increase is poor. This time, by analyzing the sensitivity of the reservoir, the damage mode of the reservoir is analyzed, the reasons for the poor water injection effect are obtained, because of strong water sensitivity, medium to strong stress sensitivity, and the corresponding measures and suggestions are put forward, such as greater than 4500 mg/l of the salinity of injected water, timely supplement formation energy. Provide basis for the development of similar oil fields.

Keywords

Sensitivity, Clay Minerals, Reservoir Damage, Experiment

1. Preface

The practice of oilfield development shows that the development process of the oilfield may damage the oil and gas reservoir, reduce the productivity of the reservoir, and even completely lose the production capacity of oil and gas wells [1]-[6]. It will also affect the discovery of new oil and gas reserves. It has caused great losses to oilfield development, so reservoir protection is a subject that must be studied in the oilfield, and the most important thing to protect the reservoir is to find out the possible types of damage to the reservoir and the degree of damage, so as to take corresponding countermeasures. In the study of reservoir damage evaluation, reservoir sensitivity evaluation is one of the most important means [7] [8] [9] [10] [11].

However, due to the complex nature of oil and gas reservoirs, the influencing factors often change. Therefore, there are still many problems that need to be further studied and solved. In order to ensure the effective development of the oilfield, a reasonable adjustment scheme, water injection scheme and measure direction are formulated, and the analysis and evaluation of reservoir sensitivity flow experiment are carried out.

2. Study on Reservoir Damage Mechanism

Sensitivity evaluation experiments are divided into single-phase velocity sensitivity evaluation experiment, water sensitivity evaluation experiment, acid sensitivity evaluation experiment, alkali sensitivity evaluation experiment, and stress sensitivity evaluation experiment.

Experimental water

Prepare simulated formation water according to formation water data, after standing for 1 day, after 0.22 μm microporous membrane filtration, standby.

Experimental conditions

The evaluation experiment is a core displacement experiment, which is carried out under normal temperature and pressure. According to the formation geothermal and pressure gradient, the formation temperature is 60 - 75 degrees, the formation pressure is 14.5 MPa. Normal temperature and pressure is 25 degrees and 1 MPa.

Evaluation method

The reservoir damage research methods mainly include the velocity sensitivity evaluation experiment, water sensitivity evaluation, and permeability damage experiment. The compatibility between fluid and rock is judged according to the experimental results.

2.1. Velocity Sensitivity Evaluation Experiment

Velocity sensitivity refers to particles in oil formation rocks that migrate and block the throat due to the change of fluid velocity, resulting in decreased permeability. The purpose of the velocity sensitivity evaluation experiment is to determine the relationship between fluid velocity change and permeability and determine the critical velocity as the index to evaluate the degree of velocity sensitivity.

The specific method is to vacuum the core and saturate the formation water. Under the condition of confining pressure of 2.5 MPa and formation temperature, first, drive it at the speed of 0.1 mL/min. After the pressure difference is stable, measure the liquid permeability at this flow rate; Then, the liquid permeability of the core is tested according to the displacement speed sequence of 0.25 mL/min, 0.5 mL/min, 1.0 mL/min, 1.5 mL/min, 2.0 mL/min, 3.0 mL/min, 4.0 mL/min, 5.0 mL/min and 6.0 mL/min. When the permeability change rate is greater than 20%, the velocity sensitivity occurs, and the displacement speed at the previous point of the velocity is determined as the critical velocity.

According to the standard SY/T 5358-2010 "evaluation method of reservoir sensitive flow experiment", the critical velocity and the damage degree of velocity sensitivity are determined according to the following methods.

Determination of critical velocity

With the flow velocity increase, the flow velocity at the previous point corresponding to the change rate of rock permeability DVN greater than 20% is critical.

Determination of seepage velocity

The formula for converting the flow velocity into seepage velocity is:

$$v = \frac{14.4Q}{A \times \varnothing} \tag{1}$$

where v is fluid seepage velocity, m/d. Q is the rate of flow, cm^3/min. A is the cross-sectional area of a rock sample, cm^2. $\varnothing$ is rock sample porosity, %.

Determination of damage degree of velocity sensitivity

The damage degree of velocity sensitivity shall be calculated according to the following formula:

$$D_v = \frac{K_i - K_n}{K_i} \times 100\% \tag{2}$$

where, D_v is velocity-sensitive damage rate, %. K_n is the permeability of rock sample (corresponding to brine with different salinity), mD. K_i is initial permeability, mD.

Evaluation index of velocity-sensitive damage degree

It can be seen from the three rock samples of reservoir velocity sensitivity that the velocity sensitivity of rock samples from strong to weak is the sample 2-007F, 1-013F, and 3-023F, and the overall damage degree is strong velocity sensitivity (see Table 1 and Figure 1).

2.2. Water Sensitivity Evaluation Experiment

Salinity sensitivity refers to the phenomenon that a series of mineralized injected water into the oil formation causes clay expansion, dispersion, and migration, resulting in the change of rock permeability. The primary reason for the salinity sensitivity of oil formation is that the clay minerals of oil formation are susceptible to the composition, ionic strength, and ionic type of injected water. The damage mechanism of salinity sensitivity is similar to that of water sensitivity, such as the expansion of montmorillonite, illite, and smectite mixed-layer minerals

Table 1. Evaluation index of velocity-sensitive damage degree.

Velocity-sensitive damage rate, %	Degree of damage
$D_v \le 5$	No
$5 < D_v \le 30$	Weak
$30 < D_v \le 50$	Moderate to weak
$50 < D_v \le 70$	Moderate to strong
$D_v > 70$	Strong

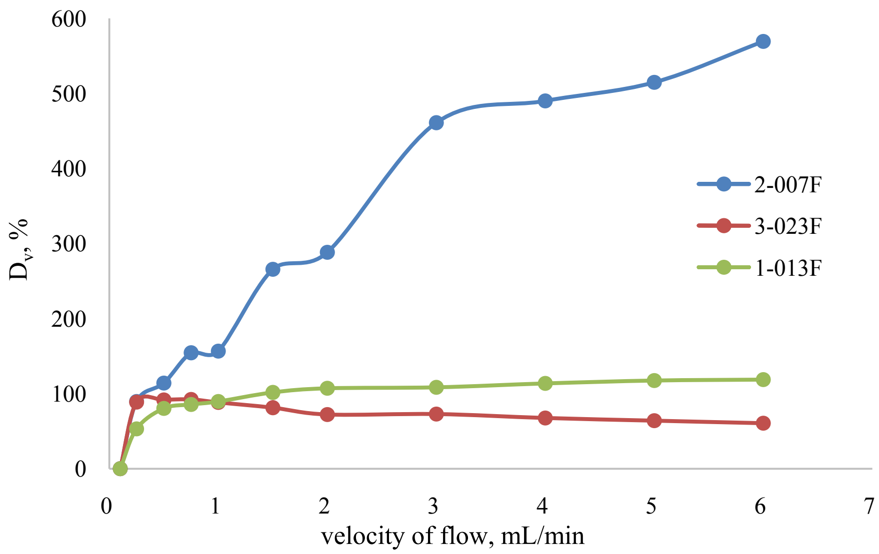


Figure 1. The 1-013F, 2-007F, and 3-023F speed-sensitive injury curves.

in contact with geological salinity fluid, diffusion, and migration kaolinite in case of the sudden change of ionic strength of oil formation fluid. The purpose of the salinity sensitivity evaluation experiment is to understand the change law of permeability of oil formation rocks when contacting fluids with different salinity.

The method of salinity reduction experiment is:

1) Core oil washing, salt washing, drying, vacuuming, and saturated formation water;

2) Measure the initial brine (formation water salinity) permeability of the core;

3) After measuring the initial brine permeability, use the intermediate test fluid (1/2 formation water salinity) to displace 10 - 15 times the core pore volume, keep the confining pressure and temperature unchanged, and make the brine fully react with rock minerals for more than 12 h;

4) Determine the permeability of the brine (1/2 formation water salinity) to the rock;

5) Repeat steps (3) and (4) to measure 1/4 formation water salinity, 1/8 formation water salinity, and the permeability of distilled water to rocks.

The permeability change rate of rock sample caused by salinity change is calculated according to the following formula:

$$D_{sn} = \frac{K_i - K_n}{K_i} \times 100\% \quad (3)$$

where, D_v is Permeability change rate of rock samples corresponding to brine with different salinity, %.

With the change of fluid salinity, when the change rate of rock permeability DSN is greater than 20%, the fluid mineralization at the previous point is the critical mineralization.

There are 3 samples of reservoir water sensitivity. The damage degree of 1-013H, 2-007H, and 3-023H are medium to strong water sensitivity. The critical mineralization corresponding to 1-013H water sensitivity is 2500 mg/L, the critical mineralization corresponding to 2-007H water sensitivity is 1600 mg/L, and the critical mineralization corresponding to 3-023H water sensitivity is 1500 mg/L (see Figure 2).

2.3. The Acid Sensitivity Evaluation Experiment

Acid sensitivity refers to the phenomenon that the acid fluid reacts with the acid-sensitive minerals and fluids of the oil formation after entering the oil formation to produce precipitation or release particles, which changes the permeability of the oil formation. There are two main types of damage caused by acid sensitivity: chemical precipitation or gel, which destroys the original structure of the rock and produces or aggravates the flow sensitivity.

The method is:

1) Core oil washing, salt washing, drying, vacuum pumping, and saturation of potassium chloride solution with the same salinity as formation water;

2) Selection of acid solution: if there are no special requirements for the experimental acid solution, 15% HCl or 12% HCl + 3% HF can be selected, and 15% HCl can be directly selected for carbonate oil formation;

3) It is used to measure the initial permeability of core with potassium chloride solution with the same salinity of formation water;

4) Sandstone samples are injected with 0.5 - 1 PV acid solution in reverse, and carbonate samples with 1.0 - 1.5 PV 15% HCl in reverse;

5) Stop displacement and close the inlet and outlet valves of the gripper. The reaction time between sandstone sample and acid is 1H, and that between carbonate sample and acid is 0.5 h;

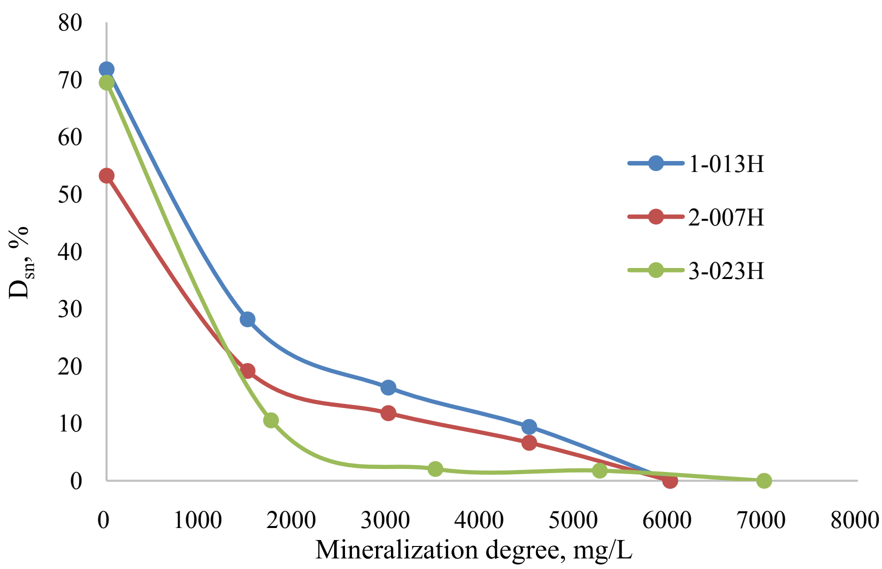


Figure 2. The 1-013H, 2-007H, and 3-023H water-sensitive injury curves.

6) Forward displacement of potassium chloride solution with the same salinity as formation water to determine the liquid permeability of rock sample after acid treatment.

Determine the degree of acid sensitivity damage according to the following methods.

Determination of acid-sensitive damage degree

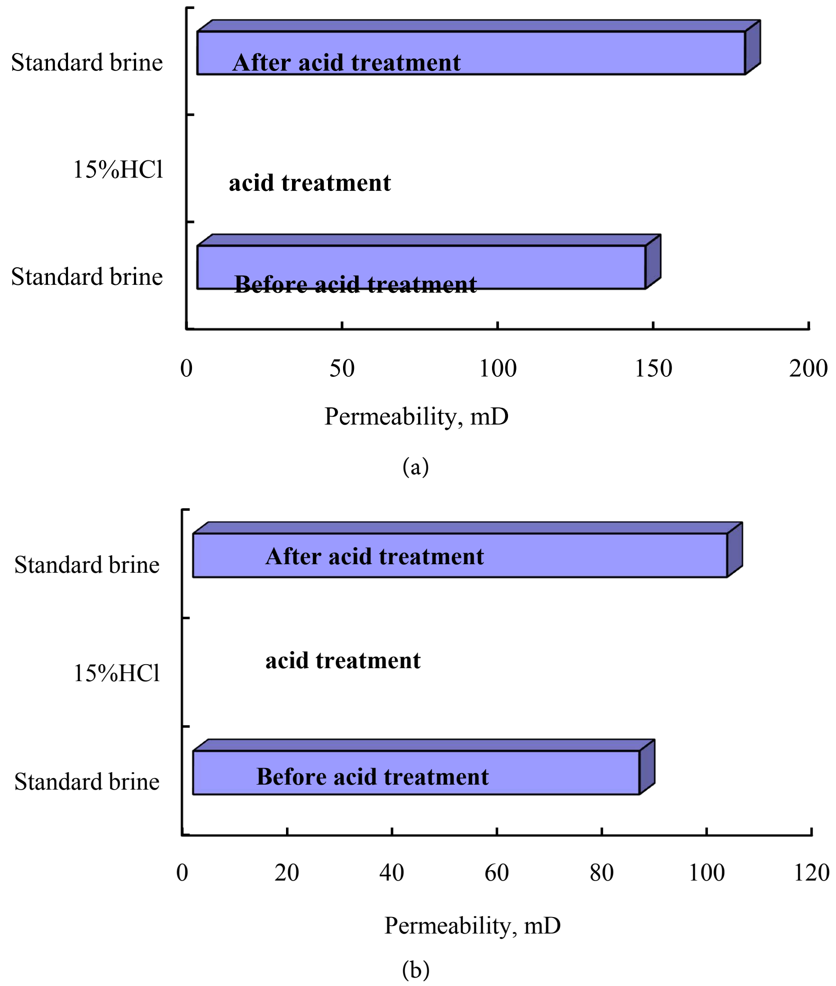
The acid-sensitive damage rate is calculated according to the following formula:

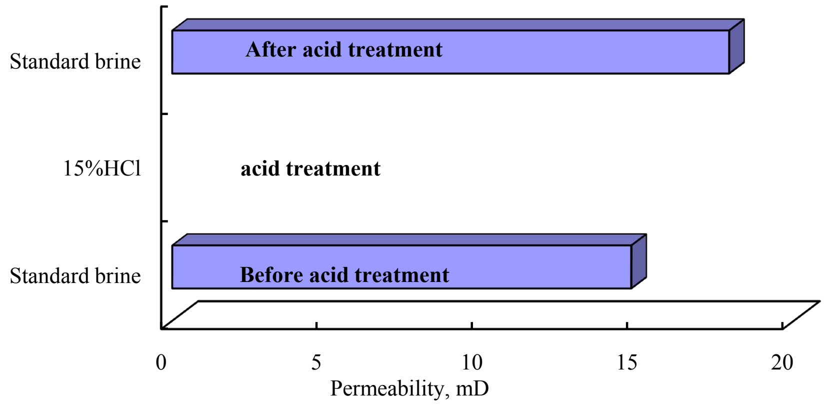
$$D_{ac} = \frac{K_i - K_{acad}}{K_i} \times 100\% \tag{4}$$

where, D_{acad} is acid-sensitive damage rate, %. K_{acad} is the permeability of rock sample corresponding to experimental fluid after acid treatment, mD.

Evaluation index of acid sensitivity damage

The acid sensitivity of 1-013D, 2-007D, and 3-023D reservoirs of rock samples is generally weak acid sensitivity, in which the acid-sensitive permeability damage of 1-013D is 22.93%, the permeability damage of 2-0007D is 19.61%, and the permeability damage of 3-023D is 21.32% (see Table 2 and Figure 3).





(c)

Figure 3. Acid sensitive damage curve of reservoir. (a) 1-013D; (b) 2-007D; (c) 3-023D.

Table 2. Evaluation index of acid-sensitive damage degree.

Acid sensitive damage rate, %	Degree of damage
$D_{ac} \le 5$	No
$5 < D_{ac} \le 30$	Weak
$30 < D_{ac} \le 50$	Moderate to weak
$50 < D_{ac} \le 70$	Moderate to strong
$D_{ac} > 70$	Strong

2.4. Alkali Sensitivity Evaluation Experiment

Alkali sensitivity refers to the phenomenon that the foreign alkaline liquid reacts with the minerals in the oil formation to disperse, fall off or generate new precipitates or colloidal substances, block the pore throat and cause the change of oil formation permeability. The pH value of the formation fluid is generally distributed in the range of 4 - 9. If the pH value of external fluid entering the oil formation is too high or too low, it would cause the incompatibility between external fluid and oil formation. The standard alkali-sensitive minerals are mainly cryptocrystalline quartz, carbonate, kaolinite, and montmorillonite in clay components. The purpose of the alkali-sensitivity evaluation experiment is to understand whether various alkali liquids are entering the well cause damage to the oil formation and the degree of damage.

The method is:

1) Core oil washing, salt washing, drying, vacuum pumping, and saturation of potassium chloride solution with the same salinity as formation water;

2) Alkali liquor preparation: take potassium chloride solution with the same salinity as formation water as the mother liquor, adjust the pH value of potassium chloride solution from 7.0, and increase the pH value of alkali liquor at an interval of 1 - 1.5 pH units until the pH value is 13.0;

3) It is used to measure the initial permeability of core with potassium chloride solution with the same salinity of formation water;

4) Inject alkali liquor with adjusted pH value into the rock sample, displace 10 - 15 times the pore volume of the rock sample, stop displacement, make the alkali liquor fully react with rock minerals for more than 12 h, and then displace with alkali liquor with pH value to measure the liquid permeability.

5) The alkali injection sequence is from pH 7.0 to 13.0, and repeat (4).

Determination of alkali sensitive damage degree

The alkali sensitive damage rate is calculated according to the following formula:

$$D_{aln} = \frac{K_i - K_{acad}}{K_i} \times 100\% \quad (5)$$

D_{aln} is the permeability change rate of the rock sample corresponding to alkali solution with different pH values, %.

Evaluation index of alkali sensitive damage degree

The reservoir alkali-sensitivity test results show that the whole is mainly reflected in medium-weak to strong alkali sensitivity, and the degree of alkali sensitivity damage varies greatly. The permeability damage of 1-013E is 71.2%, and the degree of alkali sensitivity damage is strong alkali sensitivity; The permeability damage of 2-013E is 54.6%, and the damage degree of alkali sensitivity is medium to strong alkali sensitivity; The permeability damage of 3-023E is 39.78%, and the damage degree of alkali sensitivity is medium to weak alkali sensitivity. When the change rate of rock permeability D_{aln} is greater than 20%, the pH value of the previous point is the critical pH value. The critical pH of 1-013E is 8.5, 2-0007E is 11, and 3-023E is 10.0 (see Table 3 and Figure 4).

2.5. Stress Sensitivity Evaluation Experiment

In the process of oil and gas reservoir exploitation, with fluid production in the reservoir, the reservoir pore pressure decreases, and the original stress balance of reservoir rock changes. The purpose of the stress sensitivity evaluation experiment is to understand the process of pore throat deformation, crack closure, or opening when the net overburden pressure changes and the degree of change in rock seepage capacity.

The method is:

1) Core oil washing, salt washing, drying, vacuum pumping, and saturation of potassium chloride solution with the same salinity as formation water;

Table 3. Evaluation index of alkali sensitive damage degree.

Alkali sensitive damage rate, %	Degree of damage
$D_{aln} \le 5$	No
$5 < D_{aln} \le 30$	Weak
$30 < D_{aln} \le 50$	Moderate to weak
$50 < D_{aln} \le 70$	Moderate to strong
$D_{aln} > 70$	Strong

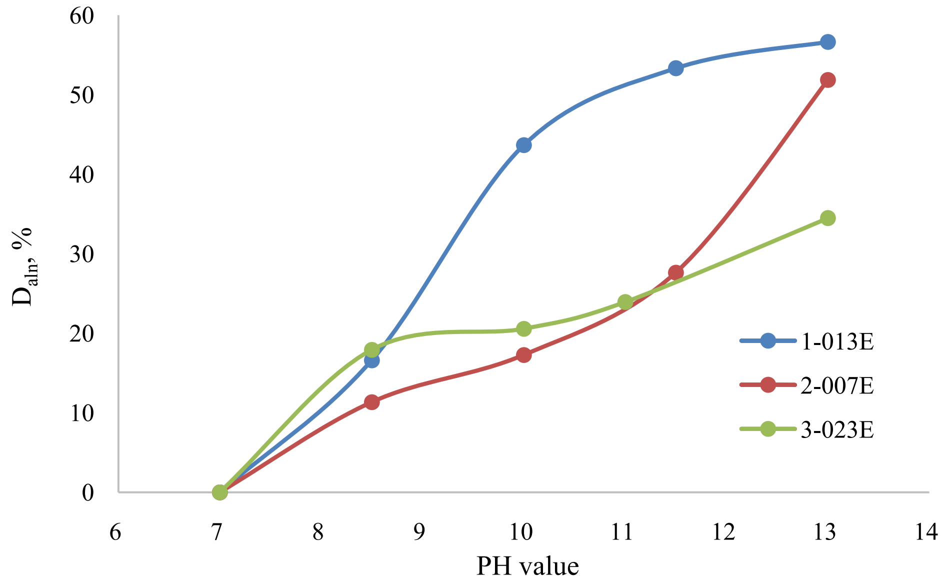


Figure 4. Alkali sensitive damage curve of the 1-013E, 2-007E, and 3-023E samples.

2) Calculate the net overburden pressure of the formation where the core is located;

3) Put in the core and slowly increase the confining pressure to 2 MPa;

4) Take the initial net stress as the starting point and slowly increase the net stress according to the set net stress value. When the net stress increases to the maximum net stress value, it stops increasing, and the interval is 2.5 MPa, 3.5 MPa, 5.0 MPa, 7.0 MPa, 9.0 MPa, 11.0 MPa, 15.0 MPa, and 20.0 MPa;

5) Keep each net stress point for more than 30 min, measure the pressure, flow, time, and temperature as required, and calculate the permeability;

6) After the net stress is added to the maximum net stress value, slowly reduce the net stress to the original net stress point according to the net stress interval set in the experiment, and each net stress pressure point shall be maintained for more than 1 h.

Determine the degree of stress-sensitive damage according to the following methods.

Determination of damage degree of stress sensitivity

The stress-sensitive damage rate is calculated according to the following formula:

$$D_{stn} = \frac{K_i - K_{acad}}{K_i} \times 100\% \tag{6}$$

where, D_{stn} is stress-sensitive damage rate, %.

Evaluation index of stress-sensitive damage degree

The experimental results of reservoir stress sensitivity show that the reservoir stress sensitivity is mainly reflected in medium to strong stress sensitivity. The permeability damage rate of 1-013C is 71.2%, 2-007C is 73.2%, and 3-023I is 52.8% (**Figure 5**).

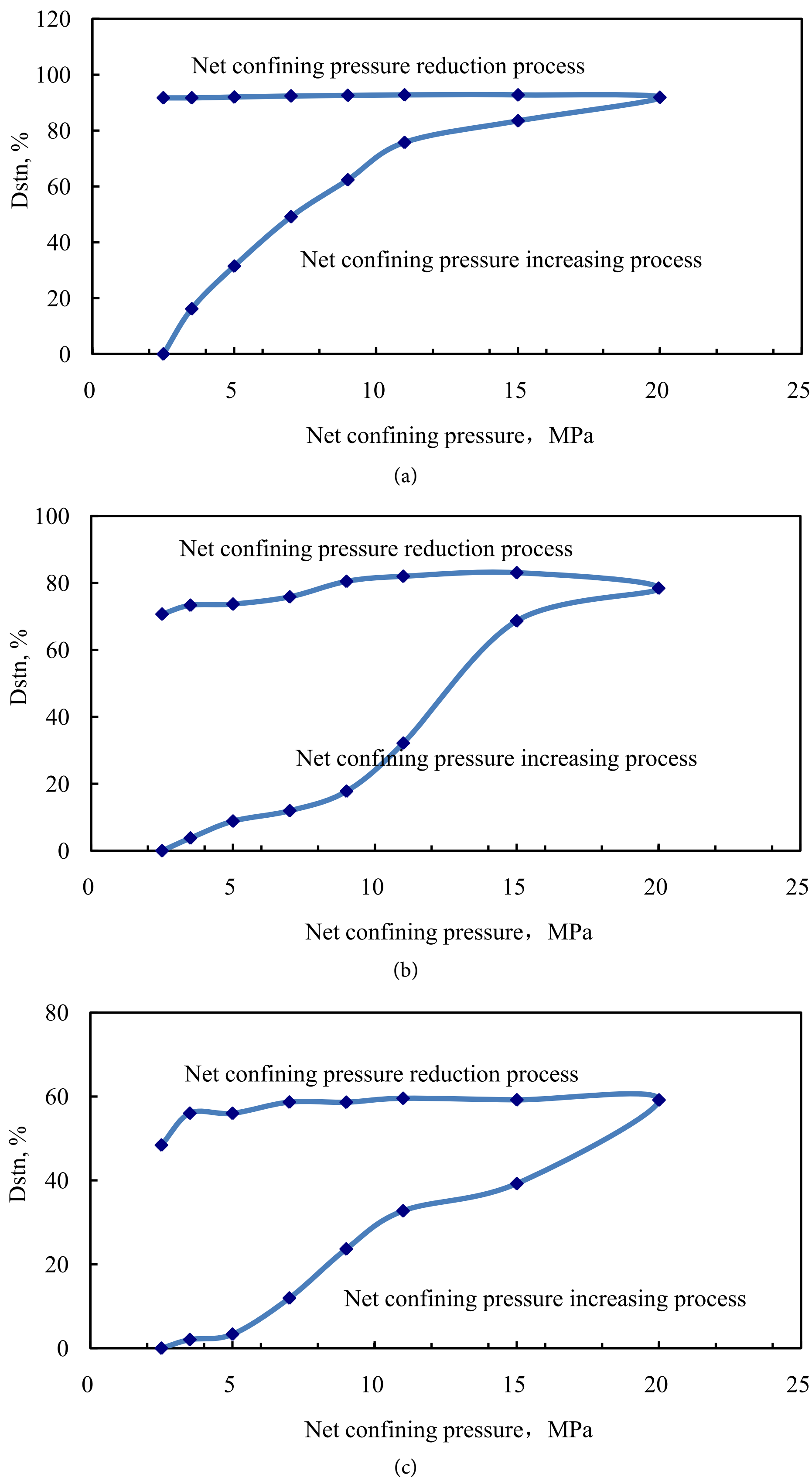


Figure 5. Stress sensitive damage curve of the reservoir. (a) 1-013C; (b) 2-007C; (c) 3-023I.

Table 4. Analysis results of the X oilfield reservoir sensitivity evaluation.

Analysis project	Sample No	Permeability damage rate %	Degree of damage	Empirical conclusion
Speed sensitivity	1-013F	118.8	strong	Critical velocity: 0.1 mL/min
	2-007F	569.31	strong	Critical velocity: 0.1 mL/min
	3-023F	60.6	Medium to strong	Critical velocity: 0.1 mL/min
Water sensitivity	1-013H	77.97	strong	Critical salinity: 2500 mg/L
	2-007H	63.47	Medium to strong	Critical salinity: 1600 mg/L
	3-023H	74.47	strong	Critical salinity: 1500 mg/L
Acid sensitivity	1-013D	22.93	weak	/
	2-007D	19.61	weak	/
	3-023D	21.32	weak	/
Alkali sensitivity	1-013E	71.2	strong	Critical pH: 8.5
	2-007E	54.6	Medium to strong	Critical pH: 11
	3-023E	39.78	Moderately weak	Critical pH: 10
Stress sensitivity	1-013C	91.7	strong	/
	2-007C	73.2	strong	/
	3-023I	52.8	Medium to strong	/

2.6. Summary of Sensitivity Evaluation

18 sensitive samples were analyzed, and the experimental results are shown in Table 4. Because the pore structure and rock minerals of different samples are different, the experimental results of sensitivity evaluation are slightly different.

3. Conclusions

1) The reservoir sensitivity research of X oilfield is carried out from five aspects: velocity sensitivity, water sensitivity, salt sensitivity, acid sensitivity, alkali sensitivity and stress sensitivity, the experimental results shows medium to strong velocity sensitivity, strong water sensitivity, weak acid sensitivity, medium to weak to very strong alkali sensitivity and medium to strong to strong stress sensitivity.

2) Due to the strong water sensitivity of the reservoir in X oilfield, during water injection production, the salinity of injected water should be controlled to be greater than 4500 mg/l, and the compatibility between injected water and formation and between injected water and formation water should be evaluated. The reservoir of X oilfield is weak acid sensitive, so acidizing operation can be considered. The stress sensitivity is medium to strong to strong. If the energy is not supplemented in time during oilfield development, the net overburden pressure will increase too much. At this time, energy supplementation will cause irreversible loss of permeability. Therefore, timely replenishment of formation energy will reduce formation damage.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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