Evaluation of Sensitivity Damage Degree of Sandstone Geothermal Reservoir in Lantian Bahe Formation in Guanzhong Area

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Abstract. Based on the petrology characteristics of the sandstone geothermal reservoirfrom Lantian Bahe Formation in the middle and deep layers, Guanzhong area, Shaanxi Province, natural core and artificial core models were used to quantitatively evaluate the damage of geothermal reservoir sensitivity. The results show that the conglomeratic sandstone and medium sandstone belong to medium to strong velocity sensitivity, and the fine sandstone belongs to strong velocity sensitivity. Particle migration is the most important damage type in the exploitation of geothermal reservoir. The conglomeratic sandstone has medium to strong water sensitivity, and the medium sandstone and fine sandstone have strong water sensitivity. Water sensitive damage is also the main type of reservoir damage. The conglomeratic and medium sandstone have strong stress sensitivity, and the fine sandstone has medium to high stress sensitivity. The stress sensitivity is also the main damage type of the reservoir. The acid sensitive damage of the reservoir is

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weak. The research results provide a theoretical basis for formulating reasonable reservoir protection technical countermeasures in the study area.

Keywords: Guanzhong area · Geothermal reservoir · Sensitive damage · Particle migration · Reservoir protection

1 Introduction

The Guanzhong area is rich in geothermal resources [1–3]. The development practice of medium and deep geothermal energy in Guanzhong area shows that the geothermal tail water reinjection of sandstone thermal reservoir is difficult, and it has long restricted the sustainable development of medium and deep geothermal resources.

For example, the decay rate of geothermal tail water reinjection is fast, and the reinjection well is blocked, far from reaching the level of balance between production and reinjection. The essence of the problem of geothermal tail water reinjection is the damage to thermal reservoirs, which is the result of a series of complex factors working together. The reasons for reservoir damage are related to the migration, blockage, stress changes, and chemical reactions of particles [4–6]. But so far, there has been very little research on damage assessment and protection techniques for thermal reservoirs in the Guanzhong area. The purpose of this study is to clarify the types and degrees of sandstone thermal reservoir damage in the Lantian Bahe Formation in the Guanzhong area, and to provide strong theoretical support for the formulation of reservoir protection technology measures in the study area.

The object of this study is the thermal reservoir of the Lantian Bahe Formation(N_2^{l+b}) in the Guanzhong Basin. The cores were taken from a geothermal development well. The well is located in Zhouzhi County, Xi'an City, Shaanxi Province, in the central part of the Guanzhong Basin. The geological stratification of the core well is shown in the table.

Table 1. Geological stratification in cored well

Geological stratification				vertical depth at bottom of formation (m)	Formation thickness (m)
Group	System	Series	Formation		
Cenozoic	Quaternary	Holocene/Pliocene	Q_{2-4}^{qc}	750.0	750.0
		Old pleistocene	Q_1^s	1150.0	400.0
	Tertiary	Pliocene	N_2^z	1900.0	750.0
			N_2^{l+b}	2800.0	900.0
		Miocene	N_1^{ls}	3600.0	800.0

2 Petrology Characteristics of Reservoir

According to lithology observation and thin section analysis results, the lithology of thermal reservoir mainly includes four categories, namely, glutenite, medium sandstone, fine sandstone and siltstone. Among them, glutenite particles are unevenly distributed, belonging to strong small power, rapid accumulation, weak diagenesis, rock consolidate is loose and fragile (Fig. 1). The clastic particles of medium sandstone are mainly rock debris, followed by quartz and a few feldspars. The fillings are mainly clay minerals and a few opaque minerals or siliceous materials. The rocks are loosely cemented (Fig. 2). The clastic particles are mainly sub angular or sub angular sub circular, with medium sorting degree. The contact relationship is mainly point contact. The clastic particles of fine sandstone are mainly quartz, followed by feldspar and a little rock debris. The fillings are mainly clay minerals, followed by calcite or opaque minerals, and occasionally siliceous (Fig. 3). The rock density is medium or loose. The clastic particles are mainly in secondary arris or secondary arris sub round shape, with medium sorting degree. The contact relationship is mainly point or point line contact. The clastic particles in siltstone are mainly quartz, a little feldspar and rock debris. The basement is mainly clay minerals, a little opaque minerals, and the density of rocks is medium (Fig. 4). The clastic particles are mainly sub angular or sub angular sub circular, with poor or medium sorting degree. The contact relationship is mainly suspended, and the cementation type is basement cementation, that is, the clastic particles float in the basement.

Fig. 1. Glutenite (ZZ1-2well, 2363.88–2364.19 m)

Fig. 2. Medium sandstone (ZZ1-2well, 2364.33–2364.58 m)

3 Reservoir Physical Property

A total of 93 rock samples were determined for physical properties in this study. The permeability of sandy conglomerate is mainly distributed between 194–1540 mD($\times 10^{-3}\mu m^2$), with an average of 689 mD($\times 10^{-3}\mu m^2$). The porosity is mainly distributed between 17.3% and 36.5%, with an average of 25.8%. The permeability of medium sandstone is mainly distributed in 105–1559.6 mD($\times 10^{-3}\mu m^2$), with an average of 755.7 mD($\times 10^{-3}\mu m^2$), and the porosity is distributed in 21.5%–27.8%, with an average of 25.1%. The permeability of fine sandstone is 4.2–73.6 mD($\times 10^{-3}\mu m^2$), with an average

Fig. 3. Fine sandstone (ZZ1-2well, 2363.24–2363.40 m)

Fig. 4. Siltstone (ZZ1-2well, 2227.38–2227.53 m)

of 23.7 mD($\times 10^{-3}\mu m^2$), and the porosity is 10.8%–19.5%, with an average of 16.4%. The permeability of siltstone is mainly distributed in 0.0348–2.74 mD($\times 10^{-3}\mu m^2$), with an average of 0.607 mD($\times 10^{-3}\mu m^2$), and the porosity is mainly distributed in 10.3%–19.0%, with an average of 14.0%.

In general, the distribution range of rock physical properties of thermal reservoir is wide, and the thermal reservoir physical properties of different lithology are very different (Fig. 5 and Fig. 6). The best physical property is glutenite, with the strongest fluid seepage capacity, followed by medium sandstone and fine sandstone, and siltstone has a very low contribution rate to the thermal reservoir seepage.

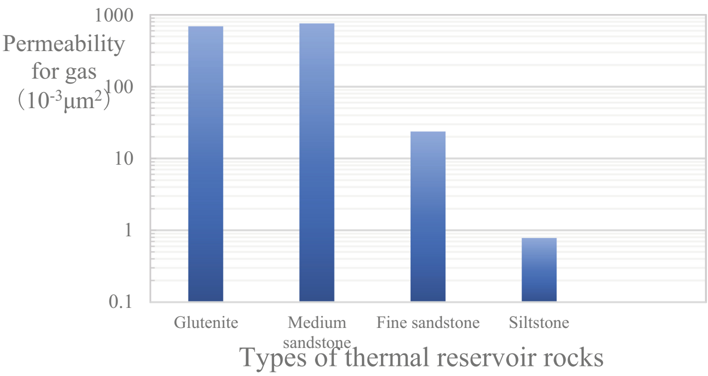

Fig. 5. Comparison of permeability of thermal reservoir rock samples with different lithology

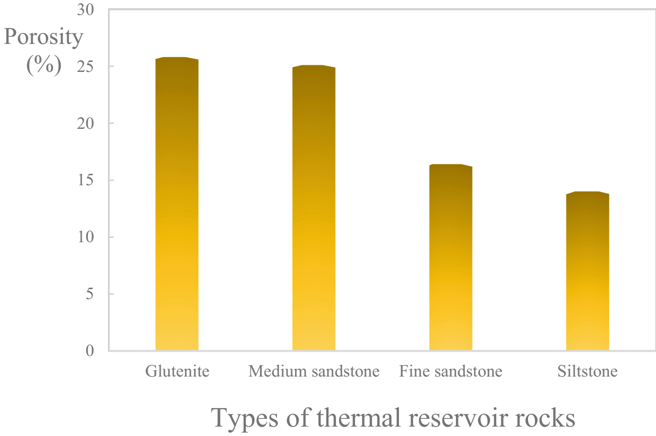

Fig. 6. Comparison of porosity of thermal reservoir rock samples with different lithology

4 Pore Types of Reservoirs

As shown in Fig. 7, the pore types of thermal reservoir rock samples are mainly intergranular pores, including rock cuttings, feldspar solution pores and intercrystalline pores. Among them, glutenite is mainly intergranular pores, medium sandstone and fine sandstone are mainly intergranular pores, with a small amount of solution pores, and siltstone is mainly intergranular pores and intercrystalline pores.

5 Reservoir Sensitivity Analysis

This study evaluated the velocity sensitivity, water sensitivity, acid sensitivity, and stress sensitivity of the sandstone thermal reservoir in the Lantian Bahe Formation of the research area. The experimental methods were based on the petroleum and natural gas industry standards and general practices in relevant literature [7–10].

5.1 Artificial Core Models and Core Protection

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(1) Production of artificial core models

For thermal reservoir rock samples with very loose, it is difficult to directly conduct core experimental analysis. Referring to reference [10] a sand filled tube core model was developed, and routine physical properties of the core were determined and subsequent experiments were conducted. When making a artificial core model, a plastic film is first used to make a cylindrical model. Then, a copper mesh is fixed at one end of the cylinder and the interface is sealed with AB glue. Then, unconsolidated rock sample particles are loaded into the cylinder from the other

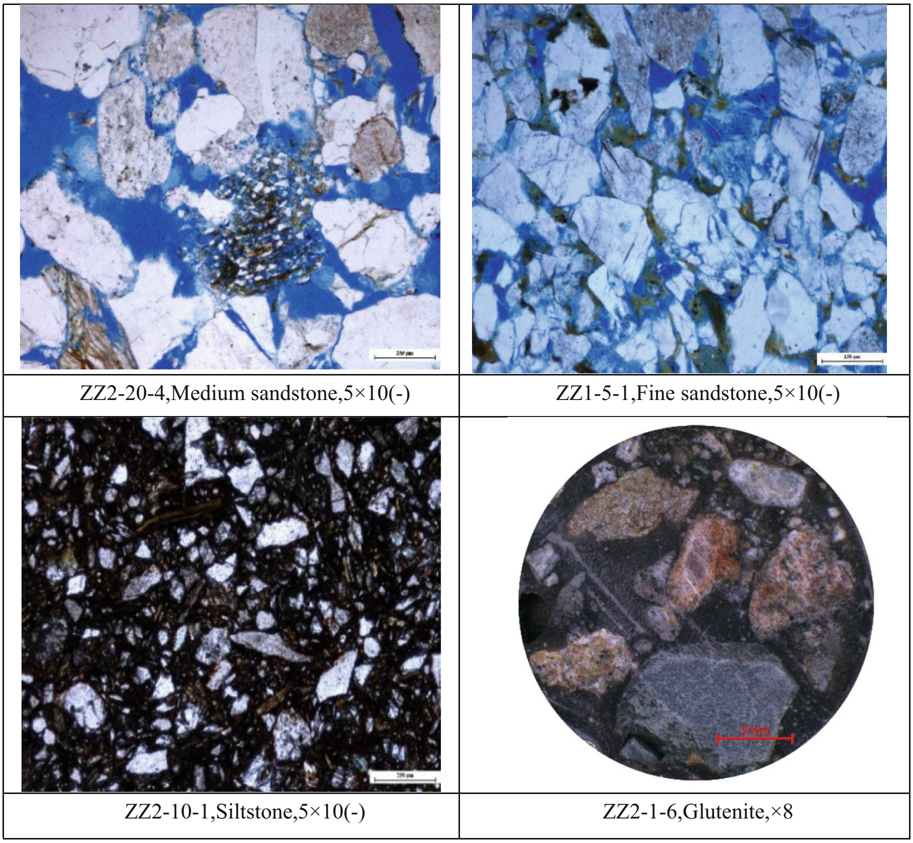

Fig. 7. Pore types of various thermal reservoirs in the research area

end, and the other end is sealed with a copper mesh. Finally, the rock sample is wrapped with a thermoplastic tube and placed in core holder for confining and shaping. All natural unconsolidated rock samples were used to fill the model, with a length of approximately 7 cm and a diameter of approximately 3 cm, as shown in Fig. 8.

Fig. 8. Unconsolidated core samples and artificial core models

(2) **Core Protection**

For rock samples with relatively good consolidation, such as fine sandstone and siltstone, generally complete rock sample columns can be obtained for routine physical property analysis, but rock samples are easily broken when saturated water is used to test water phase permeability in the later stage. Therefore, after gas permeability testing, a thermoplastic tube is used to encapsulate the rock sample. Due to the relatively rough surface of the rock samples and the large gap between the thermoplastic tube and the surface of the rock sample, the accuracy of the seepage test results of the rock sample has been affected. Therefore, the rock sample encapsulation method has been improved. Firstly, epoxy resin adhesive is evenly applied to the surface of the rock sample, and then the thermoplastic tube is quickly wrapped and heated for shaping. After 48 h, the rock sample can be used for experiments. The rock samples before and after encapsulation are shown in Fig. 9. The rock samples encapsulated in this way were not found to be broken in subsequent experiments.

Before rock sample encapsulation   Before rock sample encapsulation

Fig. 9. Comparison of rock samples before and after encapsulation

5.2 Velocity Sensitivity

The results of the velocity sensitivity experiment are shown in Table 2. The velocity sensitive damage ratio of glutenite is between 36.8%–124.5%, belonging to moderate to weak to strong velocity sensitivity. Its critical flow rate is 0.984–12.7 mL/min, which is converted into a flow ratio of 1.344–18.48 m^3/d/m per unit sand layer thickness in geothermal wells. The water phase permeability of medium sandstone shows a trend of first increasing and then gradually decreasing with the increase of flow rate. The velocity sensitive damage rate of medium sandstone is 50.5%, and the degree of velocity sensitive damage is middle to strong. The critical flow ratio is 0.894 mL/min, which is converted into a flow ratio of 1.392 m^3/d/m per unit sand layer thickness of geothermal wells. The water phase permeability of fine sandstone shows a significant change with flow rate, and its velocity sensitive damage rate is relatively high, ranging from 70.6% to 105.0%, belonging to strong velocity sensitivity. The critical flow rate is 0.03–0.49 mL/min, which is converted into a flow rate of 0.0672 to 1.128 m^3/d/m for unit sand layer thickness in geothermal wells. The water phase permeability of siltstone gradually decreases with the increase of flow rate. The velocity sensitivity damage rate of siltstone is also large, 68.6%, which is middle to strong. The critical flow rate is 0.01 mL/min, and the flow rate converted into unit sand layer thickness of geothermal well is 0.0226 m^3/d/m.

Table 2. Analysis data of reservoir velocity sensitivity experiment

Core number	Type of thermal reservoir	Porosity (%)	Gas permeability ($10^{-3}\mu m^2$)	Ratio of damage (%)	Critical flow rate (mL/min)	Flow rate of unit thickness in geothermal well (m^3/d/m)	Degree of damage
R2-19-2	Glutenite	23.2	353	47.7	12.7	18.48	Middle to week
R2-19-1	Glutenite	26.1	304	36.8	0.995	1.344	Middle to week
R1-18-1	Glutenite	29.0	542	63.2	0.994	1.584	Middle to strong
R1-18-2	Glutenite	22.3	360	124.5	0.984	1.584	Strong
R1-2-1	Medium sandstone	27.8	171	50.5	0.894	1.392	Middle to strong
ZZ1-8-6	Fine sandstone	14.7	25.6	88.3	0.49	1.128	Strong
ZZ1-15-4	Fine sandstone	18.5	12.2	105.0	0.03	0.0672	Strong
ZZ2-16-2	Fine sandstone	6.8	7.55	70.6	0.08	0.178	Strong
ZZ1-12-4	Siltstone	16.3	2.74	68.6	0.01	0.0226	Middle to strong

As can be seen from Fig. 10, the degree of velocity sensitivity damage of various thermal reservoir rocks ranges from fine sandstone>glutenite>medium sandstone, and the velocity sensitivity damage of fine sandstone is the most serious, mainly because the content of velocity sensitive minerals of fine sandstone is high. Under the effect of injected fluid, the migration of clay minerals such as illite and montmorillonite mixed layer and illite is easy to affect the permeability of thermal reservoir, so that the thermal reservoir shows strong velocity sensitivity. Although the content of clay minerals in the filling material of sandy conglomerate is not as high as that of fine sandstone and medium sandstone, its consolidation is very loose, so the internal velocity sensitive mineral particles are easy to migrate under the action of fluids, which can also cause certain velocity sensitive damage. Due to factors such as the degree of velocity sensitive minerals and the degree of consolidation, the degree of damage to various types of

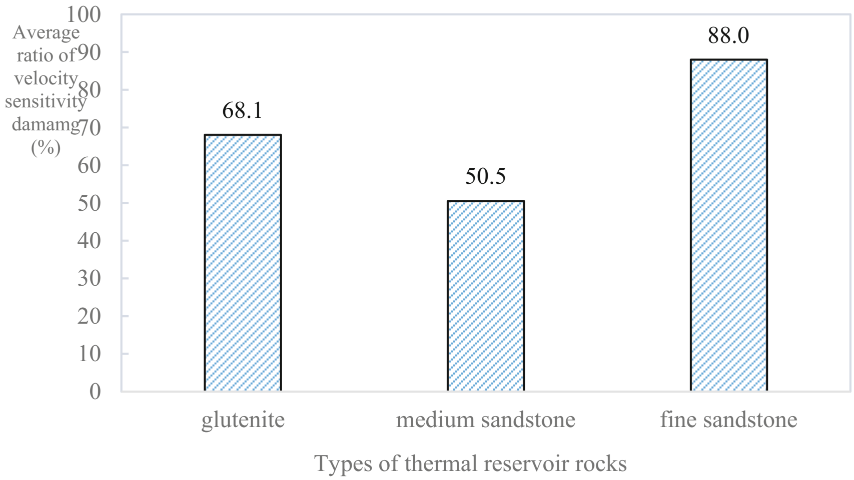

Fig. 10. Comparison of average velocity sensitive damage ratio of various thermal reservior rock samples

thermal reservoir velocity sensitivity varies. Therefore, from the perspective of thermal reservoir velocity sensitivity, when conducting tailwater reinjection, priority should be given to selecting medium sandstone and sandy conglomerate thermal reservoirs for reinjection under conditions below the critical flow rate.

5.3 Water Sensitivity

From Fig. 11 and Table 3, it can be seen that the water sensitivity damage ratio of thermal storage rock samples ranges from 57.4% to 98.2%, and the water sensitivity damage rate is in descending order: fine sandstone > medium sandstone > glutenite (Fig. 8). Compared to the results of this experiment, the water sensitivity damage ratio of glutenite is 57.4%–65.3%, with an average of 61.3%, indicating a middle to strong degree of damage. The damage ratio of medium sandstone is 91.6%, and the average water sensitivity damage ratio of fine sandstone is 97.7%. The degree of water sensitive clay minerals in glutenite is low, and the pore throat radius is large, so the damage rate is low. The degree of water sensitive minerals in fine sandstone and medium sandstone is high. Water sensitive minerals, such as montmorillonite, illite and montmorillonite mixed layer, will be hydrated, expanded and dispersed under low salinity conditions, resulting in a decline in permeability.

5.4 Stress Sensitivity

The results of stress sensitivity experiments are shown in Table 4 and Fig. 12. The permeability damage ratio of glutenite is 78.6%–96.9%, with an average of 88%. The irreversible stress sensitivity damage rate is 73.8%–94.3%, with an average of 83.3%.Glutenite is formed by rapid accumulation with weak diagenesis and good compressibility. Under the effect of effective stress, the debris particles are further compacted

Table 3. Results of water sensitivity experiment in the research area

Core number	Type of thermal reservoir	Porosity (%)	Gas permeability ($10^{-3}\mu m^2$)	Simulate formation water permeability ($10^{-3}\mu m^2$)	1/2 formation water permeability ($10^{-3}\mu m^2$)	Distilled water permeability ($10^{-3}\mu m^2$)	Ratio of water sensitivity damage (%)	Degree of water sensitivity damage
ZZ1-15-1	Fine sandstone	18.8	23.1	0.940	0.723	0.0168	98.2	Strong
ZZ1-5-4	Fine sandstone	15.3	11.9	0.0265	0.0122	0.000733	97.2	Strong
JM-3-2	Medium sandstone	26.9	1560	31.8	20.2	2.66	91.6	Strong
R2-18-2	Glutenite	17.3	879	6.84	6.69	2.91	57.4	Middle to strong
R1-2-8	Glutenite	23.1	945	216	186	74.8	65.3	Middle to strong

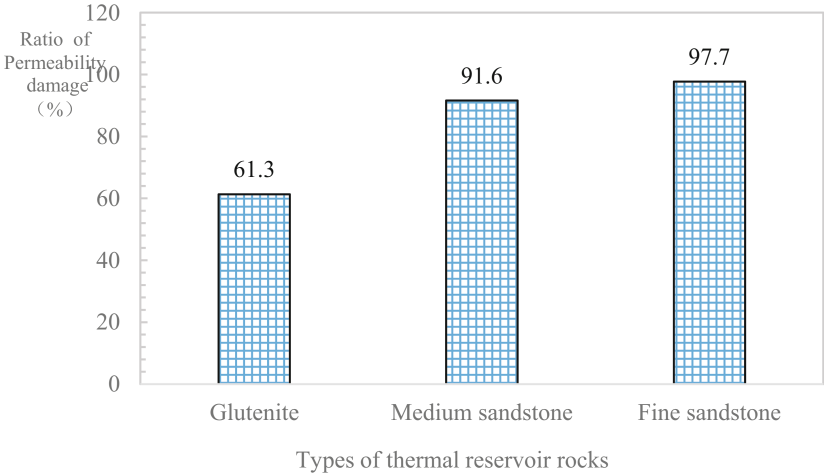

Fig. 11. Comparison of water sensitivity damage ratio for various types of thermal reservoir

and the seepage space is reduced, resulting in a large decline in permeability and a large damage rate of permeability, and it is difficult to recover after the stress sensitivity of the glutenite is damaged. The permeability of medium sandstone also significantly decreases with the increase of confining pressure, with a permeability damage ratio of 95.9% and an irreversible stress sensitivity damage ratio of 52.5%. Medium sandstone is argillaceous consolidated, easy to soften, and also has good compressibility. When effective stress increases, the arrangement of rock particles becomes tighter, the pore throat shrinks, and it also has strong stress sensitivity damage.

The permeability of fine sandstone decreases slower with confining pressure than that of medium sandstone and glutenite. The stress sensitivity permeability damage ratio of fine sandstone is 48.3%–87.2%, with an average of 61.6%. The irreversible stress sensitivity damage ratio is 33.5%–74.4%, with an average of 48.6%. The stress sensitivity of fine sandstone is relatively weak, mainly due to its relatively dense cementation. When subjected to effective stress, the pore throat is not easily deformed, resulting in a relatively low damage rate and relatively easy recovery of permeability. At the same time, there is a significant difference in the damage ratio of each fine sandstone, indicating that the degree of stress sensitivity damage may also be related to the pore structure and mineral composition of the rock.

The overall stress sensitivity of thermal reservoir rock samples is relatively strong (Fig. 12). As the main thermal reservoir, the medium sandstone and glutenite have a maximum permeability of only $41.5 \times 10^{-3} \mu m^2$ in the water phase at 30 MPa. Therefore, when extracting geothermal water in the research area, it is necessary to recharge it as soon as possible, and special attention should be paid to the stress sensitivity of medium sandstone and glutenite. Otherwise, it may lead to a rapid decrease in the permeability of the thermal reservoir, causing irreversible damage to the thermal reservoir.

Table 4. Results of stress sensitivity experiment in the research area

Core numbe	Type of Core	Types of thermal reservoir	Porosity (%)	Gas permeability ($10^{-3} \mu m^2$)	Ratio of stress sensitivity damage (%)	Ratio of irreversible stress sensitivity damage (%)	Degree of stress sensitivity damage
ZZ1-5-7	Natural core	Fine sandstone	14.8	19.1	49.2	37.9	Middle to week
ZZ2-17-6	Natural core	Fine sandstone	16.6	8.70	48.3	33.5	Middle to week
ZZ1-8-6	Natural core	Fine sandstone	14.7	25.6	87.2	74.4	Strong
R1-2-1	Artificial core	Medium sandstone	27.8	171	95.9	52.5	Strong
R1-18-2	Artificial core	Glutenite	22.3	360	89.7	88.8	Strong
R2-19-2	Artificial core	Glutenite	23.2	353	96.9	94.3	Strong
R1-18-1	Artificial core	Glutenite	29.0	542	90.2	73.8	Strong
R2-19-1	Artificial core	Glutenite	26.1	304	84.6	83.9	Strong
R2-18-1	Artificial core	Glutenite	18.8	874	78.6	75.5	Strong

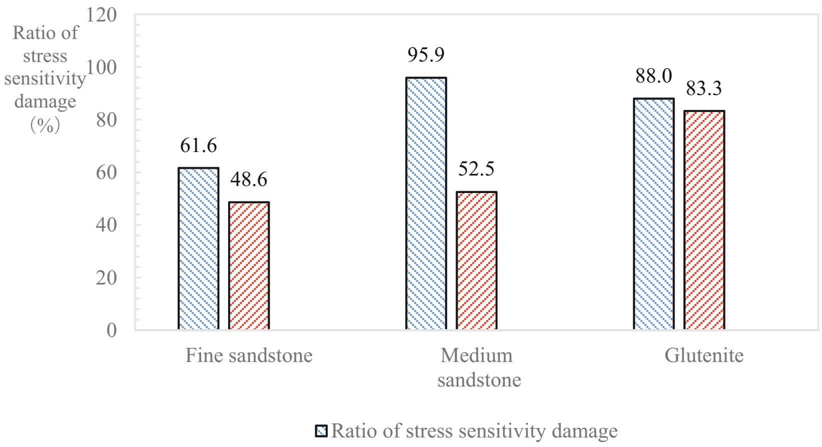

Fig. 12. Comparison of stress sensitivity damage of various types of thermal reservoir rock samples

5.5 Acid Sensitivity

This article conducted a total of 6 core samples for acid sensitivity evaluation experiments, and the experimental results are listed in Table 5 and Fig. 13. From the perspective of lithology, the acid sensitivity damage ratio of fine sandstone ranges from −68.8% to 34.8%, with an average of −14.3%. The acid sensitivity damage ratio of glutenite ranges from −16.8% to 8.9%, with an average of −3.95%. Overall, the acid sensitivity damage ratio of glutenite and fine sandstone is relatively small. From the perspective of the degree of acid sensitivity damage, they all show no acid sensitivity or weak acid sensitivity, that is, after injecting mud acid, the water phase permeability of the rock does not significantly decrease, and the permeability of some rocks still increases. This is mainly because there are acid sensitive chlorite, montmorillonite and other clay minerals (with an average relative content of 4.6%) and a small amount of carbonate cement and ash in the thermal reservoir. These substances are prone to chemical reactions with acid solution, changing the original pore structure through acid corrosion, and enhancing the permeability of the reservoir (Table 5).

Table 5. Acid sensitivity test results of thermal reservoir

Core number	Types of thermal reservoir	Porosity (%)	Gas permeability ($10^{-3}\mu m^2$)	Initial water phase permeability ($10^{-3}\mu m^2$)	Water phase permeability after damage ($10^{-3}\mu m^2$)	Ratio of acid sensitivity damage (%)	Degree of acid sensitivity damage
ZZ1-12-4	Fine sandstone	16.3	2.74	0.00287	0.00251	12.6	Weak
ZZ1-15-5	Fine sandstone	19.5	13.3	0.0731	0.123	−68.8	No
ZZ2-12-8	Fine sandstone	16.8	24.8	1.38	0.901	34.8	Middle to week
ZZ2-17-6	Fine sandstone	16.6	8.7	0.0712	0.0967	−35.8	No
R1-18-3	Glutenite	24.8	1017	443	518	−16.8	No
R2-18-2	Glutenite	17.3	879	125	114	8.9	Weak

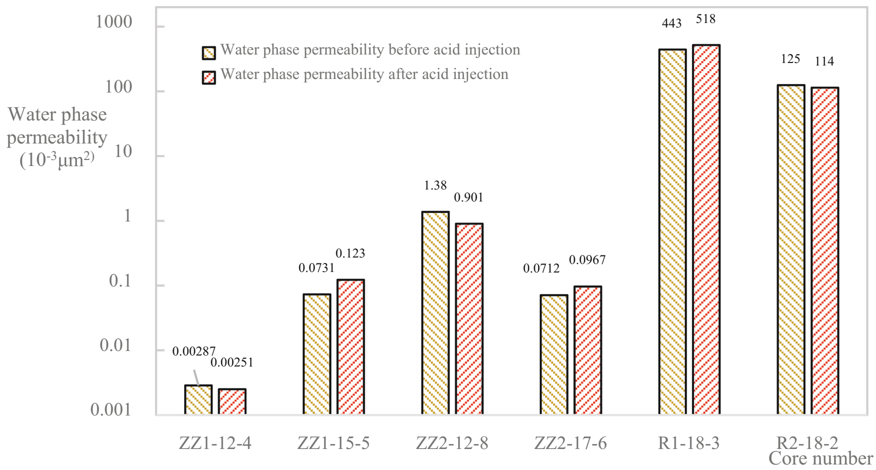

Fig. 13. Acid sensitivity test results of thermal reservoir

6 Conclusion

(1) According to lithology, sandstone thermal reservoir can be divided into glutenite, medium sandstone, fine sandstone and siltstone. Among them, the best physical property is glutenite, followed by medium sandstone and fine sandstone. siltstone has a very low contribution ratio to the seepage of thermal reservoir. Glutenite, medium sandstone, and fine sandstone are the main lithology of geothermal fluid production in thermal reservoirs, and are the focus of reservoir protection.

(2) Glutenite and medium sandstone belong to medium to strong velocity sensitivity, while fine sandstone belongs to strong velocity sensitivity. Therefore, particle migration is the main type of damage in thermal reservoir mining; Water sensitive damage

and stress sensitive damage are also the main types of reservoir damage; the acid sensitivity damage of the reservoir is weak.

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