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Research Article

Experimental and Statistical Study on Wellbore Scaling Mechanisms and Characteristics for Huanjiang Oilfield

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Wellbore scaling is a complex and one of the common problems encountered during the depletion of an oilfield. Many studies have been conducted on general scale mechanisms, scale predictions, and removal measurements. However, the detailed study of the scaling characteristics and mechanisms in Huanjiang oilfield is limited. The objective of this work is to investigate the scaling mechanisms and characteristics to provide guidance for scale inhibitor selection, synthesis, and testing in the Huanjiang oilfield. Ion chromatography (IC) was used to test the composition of 100 water samples, and energy dispersive spectroscopy (EDS), scanning electron microscope (SEM), and X-ray diffraction (XRD) were utilized to analyze the composition of 120 wellbore scale samples that were collected from the Huanjiang oilfield. The results show that the water types of formation and groundwater are $CaCl_2$ and Na_2SO_4, respectively. The oil wells produced from Chang 4 + 5, Chang 6, and Chang 8 reservoir layers in the development of Yanchang group are mainly calcium-based scale ($CaCO_3$ and $CaSO_4$), supplemented by wax deposition scale, corrosion scale, and NaCl and KCl crystal scale. In contrast, the oil wells in Yan'an group (Yan 6, Yan 7, Yan 8, Yan 9, and Yan 10 reservoir layers) are mainly wax deposition scale and corrosion scale.

1. Introduction

Water injection is a mature and effective technology which has been successfully implemented worldwide. Although many oilfields have entered the tertiary oil recovery (EOR) stage, water injection to supplement formation energy and maintain formation pressure is still one of the basic measures for worldwide oilfields to ensure long-term stable production and improve oilfield development efficiency [1–3]. However, a series of production problems have been induced during the water injection process [4]. For example, with the injection of water, the production of oil is often accompanied by a large volume of produced water. In the United States, seven barrels of water are produced with one barrel of oil production [5]. The produced water from the reservoir normally has high salinity and dissolves hydrogen sulfide, carbon dioxide, oxygen, and other gases, which could not only corrode pipelines (may even lead to pipeline "perforation") but also lead to severe environmental pollution [6, 7]. On the other hand, produced water from the reservoir is often reinjected into wells for environmental concerns and to provide a large and sustainable water source. Due to thermodynamic instability and chemical incompatibility of water, the solubility of a large amount of scaling salt (calcium carbonate, magnesium carbonate, calcium sulfate, magnesium sulfate, etc.) in reinjection water changes with temperature and pressure during the injection process. The mixture of reinjection water, fresh water, and formation water with different compatibility will cause scaling and clogging in the wellbore and surface transportation system, which will seriously affect the oilfield production efficiency.

Scaling is one of the most serious problems encountered in the water quality control of oilfields, which usually refers to inorganic salts with small solubility products that are separated and precipitated from the water under certain conditions [8, 9]. Scaling may occur at any position of the oilfield water system, such as the underground reservoir, the pump head, the wellbore of the oil production well, and the pipelines of the surface oil and gas gathering and transmission equipment [10]. The scaling of oil wells will make the working efficiency of mechanical devices such as oil pumps drop sharply and even lead to accidents such as pump jamming, leakage, and corrosion of pipes and rods. More importantly, the reservoir will also be damaged by scaling to varying degrees when the oil/water wellbore is scaling. Once the formation has favorable geological conditions (pores of the formation, rock mineral composition, properties of formation water, etc.) for scaling of reinjection water, microcrystals will be generated and lead to formation scaling. The scale will block the pore system of the formation, damage the payzone, reduce the effective permeability of the formation, increase the injection pressure of the injection well, reduce the formation water absorption index and injection volume, and eventually affect the oil production efficiency.

Many researchers have conducted research on scaling mechanisms, prediction of scale under different conditions, and the methodologies to remove/mitigate scales. On the one hand, Deng et al. [11] analyzed the calcium carbonate scaling mechanism and characteristics of a double-defect screen in Hafaya oilfield, and the results found that the defect size is the dominating factor that affects the scaling [11]. Antony et al. [12] reviewed that crystallization and transportation are the main mechanisms for scaling when the solution becomes supersaturated [12]. Kumar et al. [13] illustrated that surface and bulk crystallization is the main mechanism for the generation of scale in oilfields [13–15]. On the other hand, Shokrollahi et al. [16] summarize the main existing experimental studies on scale formation that were published before 2015 and established a Least-Squares Support Vector Machine and Coupled Simulated Annealing (LSSVM-CSA) hybrid model to describe the permeability reduction by scale deposition [16]. Yang et al. [17] developed a scaling prediction software for water injection well in Shengli oilfield based on the calculation of deposition and removal mass rates [17]. Zolfagharroshan and Khamehchi [18] built a geothermal wellbore simulator to predict the scale precipitation and deposition during the drilling process [18]. In addition, Pu et al. [19] and Zhang et al. [20] proposed to remove the near wellbore inorganic scale by using high-power ultrasonic treatment [19, 20]. Vazquez et al. [21] compared the nonaqueous and aqueous overflush scale inhibitor squeeze treatment to mitigate barium sulphate scale by building a reservoir simulation model based on a Norway offshore oilfield [21]. Shi et al. [22] present a comprehensive literature review for wellbore scale types, mechanisms, and treatments [22].

Existing experimental and literature studies have demonstrated that carbonate and sulfate are the main scales in oil reservoirs [23–26]. The carbonate scale is related to the change of pressure and pH value of production fluid while the sulfate scale is mainly caused by the mixing of incompatible water, that is, the mixing of injection water and formation water, and calcium carbonate is the most common scaling mineral

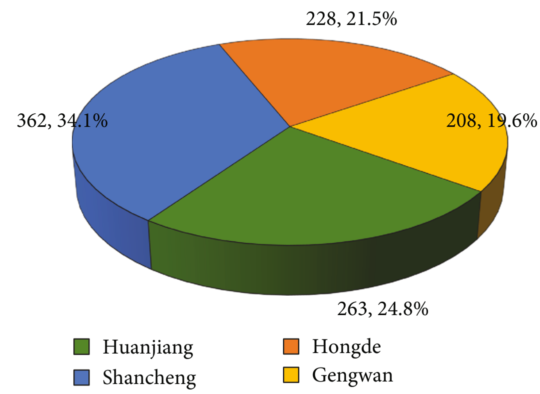


Figure 1: Number/proportion of scaling wells in different operation areas.

in formation scale [27, 28]. However, a limited study has been conducted to investigate the scale types, scale mechanisms, and the scale characteristics at Huanjiang oilfield. At present, 1471 scaling oil wells have been found in the Huanjiang oilfield, accounting for 34.1% of the total number of wells. The most serious scaling is in Shancheng operation area, with 362 scaling wells. The scaling oil wells are mainly distributed in Chang 8, Chang 6, and Jurassic systems, among which the number of scaling wells in Chang 8 is the largest (474 in total). The wellbore scaling of oil wells can easily cause the wellbore failures such as pump valve leakage and stuck pump, resulting in an increase in the maintenance workload and the number of pipe rod replacements and an increase in the production cost of 37.06 million yuan per year, which has seriously affected the economic benefits of the development of the Huanjiang oilfield.

Aiming at the serious scaling problem in the production process of oil and water wells in the Huanjiang oilfield, this research work investigates the current situation of scaling and clarifies the characteristics and mechanisms of scaling by combining the analysis of water quality and scale samples. The outcome of this research could provide guidance for antiscaling technical measures and suggestions for the Huanjiang oilfield and carries out field application and effect evaluation, in order to provide a certain guarantee for the normal production of the Huanjiang oilfield and improve the comprehensive benefits of oilfield development.

2. Huanjiang Oilfield Description

The Huanjiang oilfield is located in Huanxian County, Gansu Province. The work area starts from the west of Shancheng and ends at Qiaochuan in the east, and the area is about 3400 km [2]. The proven geological reserves are 335 million tons, and the geological reserves are 283 million tons. The surface of the area belongs to a typical loess source landform, with undulating terrain. The ground elevation is 1350 m to 1750 m, and the relative height difference is about 400 m. The main oil-bearing layers are the Jurassic Yan'an formation and the Triassic Yanchang formation. The Triassic Yanchang formation is a set of inland lake delta deposits, mainly composed of clastic rocks. The estuary bar sand and

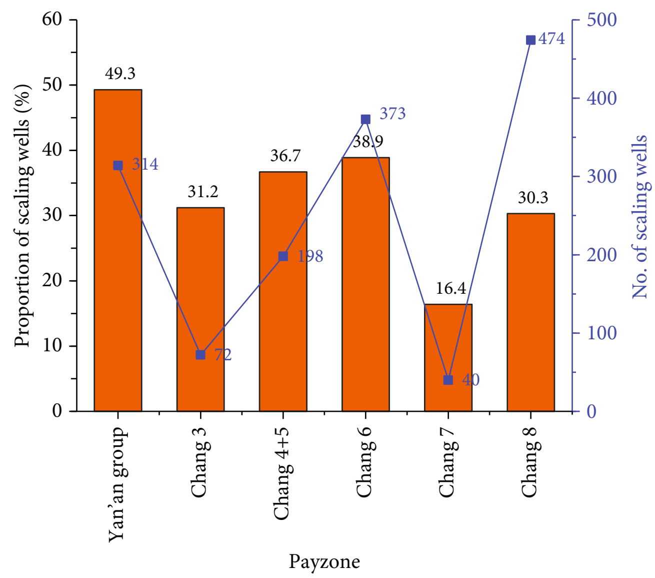


Figure 2: Number/proportion of scaling wells in the Huanjiang oilfield by payzones.

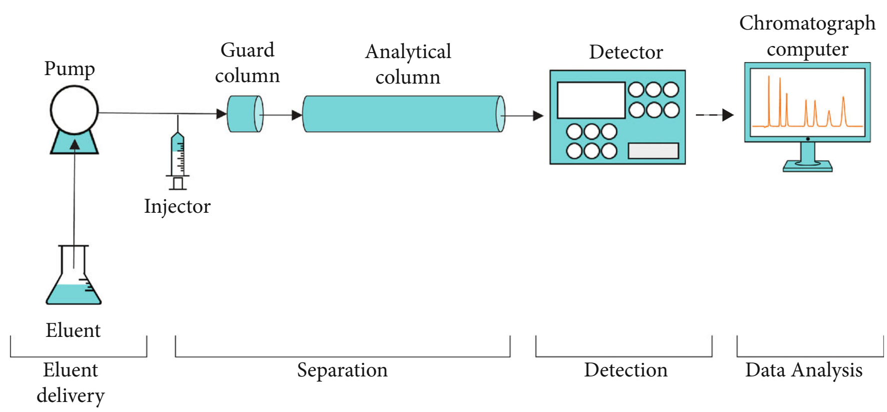


Figure 3: Ion chromatograph flowchart.

delta distributary channel sand bodies have rich oil and gas reserves. The top structure of Yanchang formation in the study area is generally a west-dipping monocline, rising from the west to the east, and the nose bulge is developed from the south to the north. The nose bulge runs through the whole area, and the width and amplitude of the nose bulge are about 2 to 5 km and 10 to 20 m wide, respectively.

The oil exploration in the Huanjiang area began in the early stage of the battle of Changqing oilfield in the 1970s. The exploration has roughly gone through three stages: the first stage (1967-1993) is mainly the discovery stage of Yan'an formation and the number of Jurassic oilfields in the south slope of Jiyuan. The second stage (1997-2003) mainly focused on the exploration of the upper oil layer of Yanchang formation which was discovered in the exploration of Chang 3. In the third stage (from 2003 to now), the exploration of oil-bearing series in the lower part of Yanchang formation has been increased and a great breakthrough has been made. In 2004, well Geng 73 was drilled to the Chang 8 layer and the pilot wells successfully produced 31.45 t/d, which opened the prelude to the exploration of the Chang 8 layer in Huanjiang area. In 2007, well Luo 38 was first drilled to the Chang 8 layer and the production rate of pilot wells is 10.8 t/d, which made another favorable oil-bearing area of Chang 8 discovered in the south of the area. In recent years, through exploration and evaluation, Chang8 oil-rich area of Geng 73-Luo 38 well has been further identified. There are 13 industrial oil flow wells in this area, with an average production rate of 14.0 t/d. At the same time, the exploration was actively carried out to look for new oil-rich areas, Luo 73 and Huan 37 were discovered in the Chang 8 layer with the industrial oil flow rate of 14.20 t/d and 10.29 t/d, respectively. In addition, well Bai 38 (Chang 8) recently completed the pilot test in the east of well Luo 38 and obtained 21.08 t/d of oil flow rate. Well Bai 6 and well Luo 72 (Chang 8) have the payzone thickness of 9.1 m to 9.3 m which further expanded the oil-bearing surface of Chang 8 reservoir in Huanjiang area. At present, the favorable oil-bearing area of Chang 8 in this area is about 300 km [2], and the reserve is about 100 million tons which shows great exploration and development potential. While exploring Chang 8 oil reservoir, in recent years, according

Figure 4: Composition analysis for scale samples: (a) energy dispersive spectroscopy (EDS); (b) X-ray diffraction (XRD); (c) scale sample preparation for EDS; (d) scale sample preparation for XRD.

to the principle of centralized exploration and implementation of oil-bearing enrichment areas and actively putting aside the search for new discoveries, important progress has been made in Yanchang Chang 6, Chang 4 + 5, Chang 3, and Jurassic oil reservoirs, and new oil-bearing enrichment areas have been initially formed. The Chang 6 oil layer in Huanjiang area is vertically adjacent to the Chang 7 source rock. The delta front sand body is developed with good physical properties and good exploration potential. In 2009, well Hu 2 in this area obtained 23.04 t/d flow rate in Chang 6_3 pilot test, thus making a breakthrough in the exploration of the Chang 6 oil layer and discovering a new oil-bearing sand belt. Currently, there are 8 industrial oil flow wells in this sand belt, with an average production rate of 10.82003 t/d, the favorable oil-bearing area is about 240 km [2], and an estimated reserve scale is about 6000×10^4 t.

At present, there are 7109 oil and water wells in the Huanjiang oilfield, including 5201 oil wells (4322 active wells) and 1908 water injection wells (1610 active wells), which are mainly distributed in Shancheng, Gengwan, Hongde, and Huanjiang operation areas. 1471 scaling oil wells have been identified in the Huanjiang oilfield, accounting for 34.1% of the total number of wells opened in the Huanjiang oilfield. Among them, there were 1061 wells in the Huanjiang oilfield, accounting for 72% of the total scale wells. Figure 1 shows the current scaling distribution in four operation areas. The number of scaling wells in Shancheng, Gengwan, Hongde, and Huanjiang is 362, 208, 228, and 263, respectively. Figure 2 indicates the number and proportion of scaling wells in the Huanjiang oilfield by payzones, which are mainly distributed in Luo 228, Luo 38, Bai 168, Bai 157, and Bai 155 blocks. Scaling has caused a serious of operational problems in the Huanjiang oilfield such as leakage, jamming, and pipe rod damage of oil well pump valves and has increased the annual maintenance cost by 30 million yuan, which significantly restricts the economic benefits of the oilfield development.

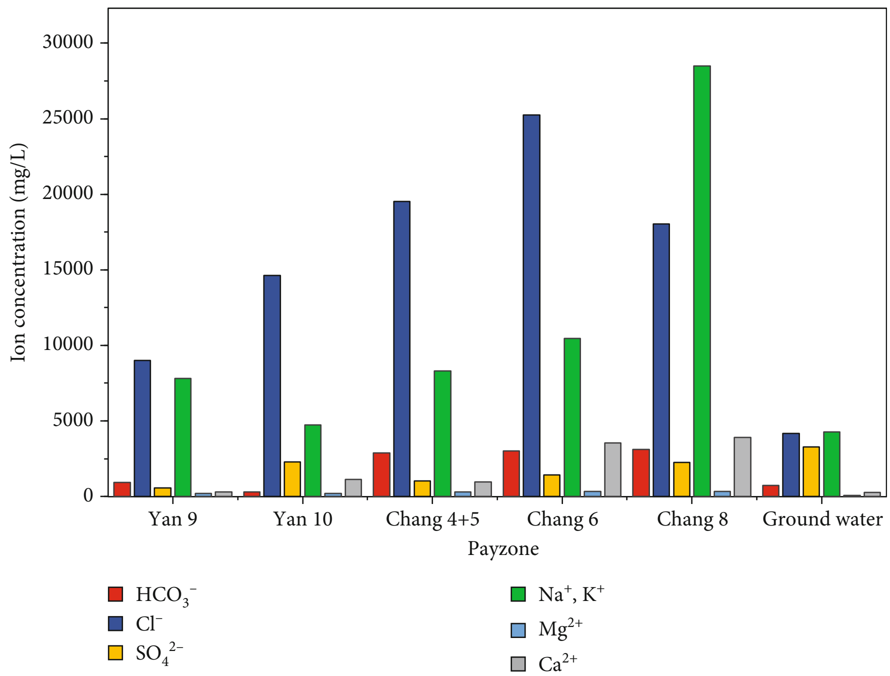


Figure 5: Ion concentrations of water samples by payzones.

3. Materials and Methods

3.1. Materials. Formation and injection waters from 100 wells were sampled from the Huanjiang oilfield, where the number of injection and production wells is 38 and 62, respectively. Scale samples of 120 wells were extracted from eight payzones in the Huanjiang oilfield. All samples were provided by Changqing oilfield.

3.2. Composition Analysis of Injection/Formation Water for the Huanjiang Oilfield. According to the water quality of formation water, the scaling trend of oil wells can be predicted. In this work, the composition of injection and formation water samples was determined by the oilfield water analysis method (SY/T 5523-2016, SY/T 5329-2012).

The classification method of formation water used in this research is mainly based on the Sulin water classification method. According to the Sulin classification method [29, 30], the chemical composition of groundwater can be linked with its natural environmental conditions, and different geological environments can be represented by different water types [31, 32].

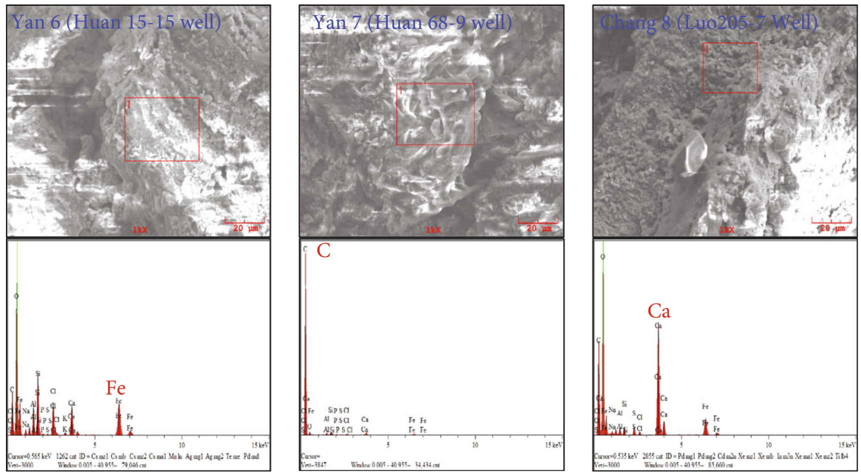
Ion chromatography (IC, from Thermo Fisher) was used to test the water quality in this research work. IC is a new type of liquid chromatographic analysis technology, which realizes separation based on the difference of reversible ion exchange ability between each ionic component in ionic compound and the charged group on the surface of stationary phase. Since its appearance in 1975 by H. Small, IC has developed rapidly. At first, IC was mainly used for the analysis of anions. Now, ion chromatography is used not only for the analysis of common anions and cations but also for the determination of amines, sugars, amino acids, proteins, and other biological molecules. It has developed into an indispensable rapid detection method in the analytical chemistry field which has the advantages of good selectivity, high sensitivity, fast separation speed, and simplicity and has been widely used in food, environment, agriculture, medicine chemical industry, and other fields [33–36]. The experimental process is shown in Figure 3.

Table 1: Water sample analysis results by payzones.

Payzone	Average depth (m)	Water type	Average salinity (mg/L)	pH
Yan 9	1975	$CaCl_2$	19306	6.8
Yan 10	2070	$CaCl_2$	28054	7.0
Chang 4 + 5	2276	$CaCl_2$	33929	6.1
Chang 6	2465	$CaCl_2$	43745	6.0
Chang 8	2611	$CaCl_2$	55338	6.3
Groundwater	1200	Na_2SO_4	12789	6.6

3.3. Composition Analysis of Scale Samples for the Huanjiang Oilfield. Scaling usually refers to some salts that are supersaturated in the aqueous phase under certain specific conditions and then begin to slowly precipitate and gradually deposit in the aqueous phase. The solid salts formed by deposition are often called scales, mainly calcium and inorganic salts with small solubility. In the process of putting the oil field into production, once the scale is formed, it will cause many adverse effects on the production and scale cleaning must be carried out.

In this study, energy dispersive spectroscopy (EDS, from HITACHI) and a scanning electron microscope (SEM, from FEI) were utilized to analyze the composition



(a) (b) (c)

FIGURE 6: Test results of typical scale samples from different wells.

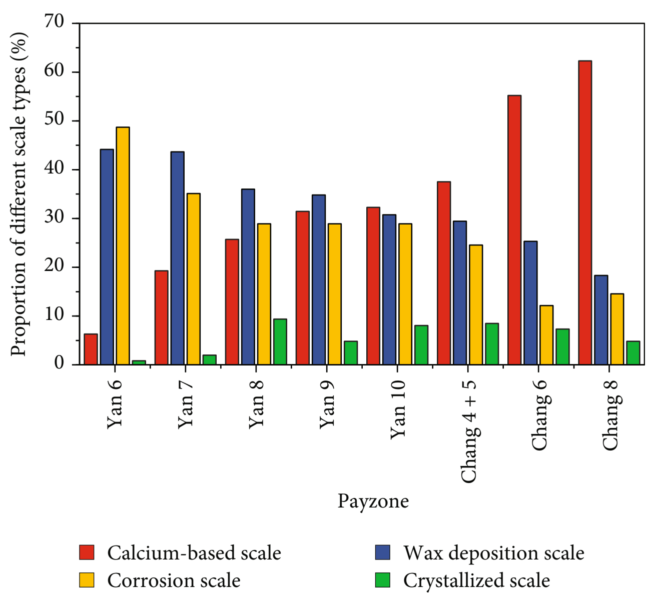


FIGURE 7: Scale type distribution by payzones.

and content of scales, and the test results were further confirmed by X-ray diffraction (XRD, from Rigaku). 120 scale samples were taken from 8 payzones, which include Yan 6, Yan 7, Yan 8, Yan 9, Yan 10, Chang 4 + 5, Chang 6, and Chang 8. The scale types of oil wells in different payzones/locations were determined through scale sample detection. Figure 4 presents the scale sample preparations for EDS and XRD tests.

4. Results and Discussions

4.1. Composition of Injection/Formation Water Samples. Water samples from 100 wells in the Huanjiang oilfield were collected. Water quality component analysis was carried out on 100 water samples, and it was determined that the water quality ion detection results of different development layers are shown in Figure 5.

It can be seen from Figure 5 that with the increase of formation burial depth, the calcium ion concentration increases, in which the calcium ion concentration of Chang 8 is 12 times higher than that of Yan 9, and the concentration of scaling anions is also larger, with a stronger scaling tendency. Table 1 illustrates the analysis results of injection and formation water samples based on IC and Sulin classification. The results demonstrate that the water type for the injected groundwater (from Luohe formation) is Na_2SO_4, and the water type in Yan 9, Yan 10, Chang 4 + 5, Chang 6, and Chang 8 is $CaCl_2$. The main reason for the water type and salinity difference is normally caused by the burial depth of the formation.

Based on the experimental results from Table 1, the following conclusions can be drawn [1]: The formation water of deep Yanchang formation has a high content of scaling anions (HCO_3^-) and scaling cations (Ca^{2+}). During the uplifting process in oil depletion, the reduction of

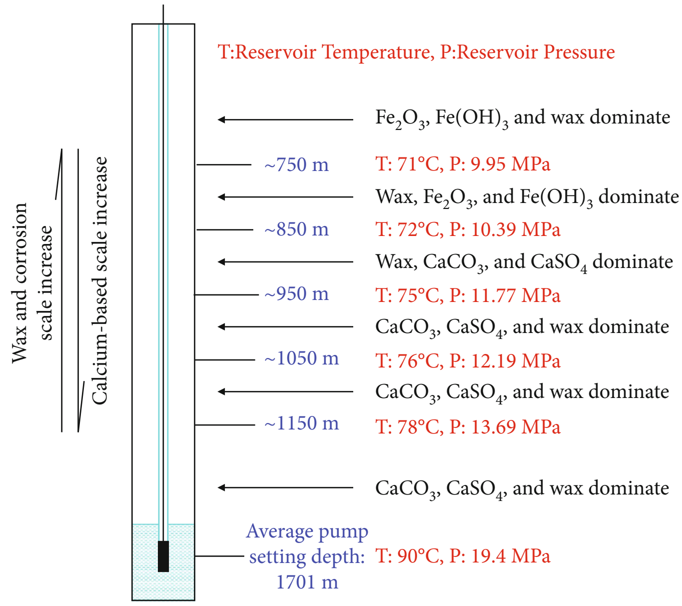


Figure 8: Wellbore scaling characteristics for Chang 8 payzone.

temperature and pressure leads to a large trend of inorganic scaling ($CaCO_3$) [2]. Each payzone contains a large amount of Na^+, K^+, and Cl^-, which induces the crystallization of NaCl and KCl during the uplifting process and gradually forms the crystal scale on the wellbore [3]. The water type difference between the injected water (groundwater) and the formation water implies the incompatibility of fluids and proves one of the reasons why $CaSO_4$ scale could be formed.

4.2. Composition of Wellbore Scale Samples. Figure 6 presents the typical test results for scale samples based on EDS and SEM, where the weight or concentration of elements could be easily identified. Figure 7 shows the statistical analysis results based on scale sample tests in different payzones. It can be seen that the oil wells in Yanchang group are mainly calcium scale, supplemented by wax deposition scale, corrosion scale, and NaCl and KCl crystal scale that were precipitated by supersaturation due to temperature and pressure changes. The oil wells developed in Yan'an group are mainly wax deposition scale and corrosion scale, and the calcium-based scale is greatly reduced compared with that in the Yanchang group.

4.3. Wellbore Scale Characteristics. On the basis of the test results of oil well scale samples in different payzones, the scaling characteristics of the wellbore are further studied. Figure 8 indicates the scaling characteristics (scale type, temperature, pressure, and depth) of 69 scale wells from the Chang 9 layer based on statistical analysis; the depth interval was determined based on the location/depth of the scale samples that were extracted. It can be seen that during the uplifting process, with the decrease of temperature and pressure, the solubility of calcium scale increases and the solubility of gas decreases, resulting in the slowdown of the tendency of calcium-based scale formation, while the tendency of wax deposition scale and corrosion scale formation increases. Figure 9 presents the scale types at different depths of the wellbore.

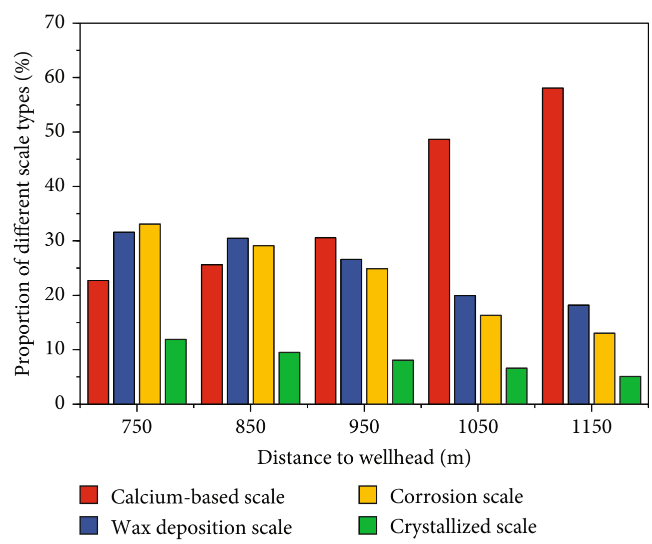


Figure 9: Distribution of scale types for Chang 8 payzone.

The results from Figures 8 and 9 show that wax deposition scale and corrosion scale are easy to form in the upper part of the wellbore (less than 850 m from the wellhead), and calcium scale is easy to form in the lower part of the wellbore (more than 950 m from the wellhead). In addition, crystallized scales such as NaCl and KCl exist at all positions of the wellbore. According to the above analysis results, it can be concluded that the scaling characteristics of oil wells in the Huanjiang oilfield in different payzones are as follows [1]: the oil wells (Chang 4 + 5, Chang 6, and Chang 8) in the development of the Yanchang group are mainly calcium-based scale ($CaCO_3$ and $CaSO_4$), supplemented by wax

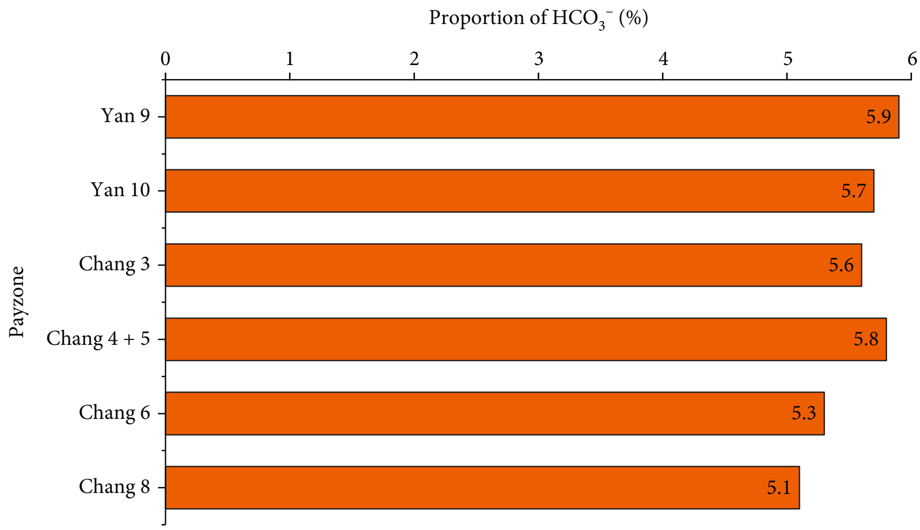


FIGURE 10: Proportion of HCO_3 concentration of the Huanjiang oilfield by payzones.

deposition scale, corrosion scale, and NaCl and KCl crystal scale [2]. The oil wells in the Yan'an group (Yan 6, Yan 7, Yan 8, Yan 9, and Yan 10) are mainly wax deposition scale and corrosion scale, and the calcium-based scale is greatly reduced compared with that in the Yanchang group.

4.4. Scaling Mechanisms. Through the analysis of the scale samples taken in the Huanjiang oilfield, it is found that wax was formed by asphaltene accumulation, $FeCO_3$ and Fe_2O_3 were formed by pipe corrosion, and $CaCO_3$, $BaCO_3$, and sand particles were produced due to the incompatibility between formation water and injection water. These results indicate that the scaling, waxing, and corrosion in the wellbore do not act alone, but synergistically.

Figure 10 illustrates the HCO_3 ion concentration in different layers of the Huanjiang oilfield. Comparing the HCO_3 ion concentration with a typical Changqing No. 9 Oil Production Plant (about 1.23% to 1.44%) [37], the HCO_3 ion concentration in Huanjiang is significantly higher. During the uplifting process, the solubility of CO_2 and O_2 decreases with the decrease of temperature and pressure and escapes from the liquid. At the same time, HCO_3 dissociates to produce H^+ and CO_3^{2}. H^+ can reduce the pH of water, form a strong corrosive medium environment, and react with Fe to cause metal corrosion and generate ferrous carbonate. Due to the instability of ferrous carbonate, the Fe_2O_3 scale is finally formed. The free iron ions in the water will react with CO_3^{2} to form the precipitation of scaling products; therefore, the corrosion and scale appeared synergistically. The specific CO_2 corrosion mechanism is as follows:

$$\begin{aligned} &\text{Anodic reaction}: Fe - 2e \longrightarrow Fe^{2+} \\ &\text{Cathodic reaction}: H_2O + CO_2 \longrightarrow H_2CO_3 = 2H^+ + HCO_3^- \\ &HCO_3^- \longrightarrow H^+ + CO_3^{2-} \end{aligned} \quad (1)$$

wherein the reaction control step is

$$Fe + H_2O + CO_2 \longrightarrow FeCO_3 + H_2\uparrow \quad (2)$$

On the other hand, during the process of lifting crude oil from the formation to the wellhead, the wax deposition is caused by the decrease of pressure and temperature. Wax deposition will reduce the inner diameter of the tubing, cause blockage, increase the flow resistance of the fluid, and make the inorganic scale particles easy to accumulate on the pipe wall, thus intensifying the scaling. At the same time, the corrosion of the tubing string will also increase the roughness of the tubing surface, provide convenience for the adsorption of wax crystals and the deposition of inorganic scale, and intensify wax and scale formation.

In a word, the scaling, waxing, and corrosion of oil wells affect the normal production of oil wells synergistically. It is difficult for a single prevention and treatment measure to achieve effective improvement. Only by preventing and treating the three at the same time can the long-term and stable production of oil wells be ensured.

5. Conclusions

(i) The formation water of the deep Yanchang group has a high content of scaling cation (Ca^{2+}), the oil wells in the Yan'an group (Yan 6, Yan 7, Yan 8, Yan 9, and Yan 10) are mainly wax deposition scale and corrosion scale, and the calcium-based scale is greatly reduced compared with that in the Yanchang group

(ii) The content of HCO_3 in the formation water of the shallow Yan'an formation is higher, which makes it easier to form corrosion scale

(iii) Each payzone at the Yanchang group contains a large amount of Na^+, K^+, and Cl^-. During the uplifting process, the temperature and pressure decrease, resulting in the crystallization of NaCl and KCl scale on the wellbore

(iv) The water type of formation water in Yan 9 to Chang 8 is $CaCl_2$ type, and the water type of injected water (groundwater) is Na_2SO_4 type. The incompatibility of fluids leads to a large tendency of $CaSO_4$ scaling

(v) Waxing, corrosion, and scaling of oil wells in the Huanjiang oilfield have synergistic effects. In the process of wellbore protection, the original "scale prevention" should be changed into the "three prevention measures" of "wax prevention, corrosion prevention, and scale prevention"

Data Availability

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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