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*Research Article*

# Microgravity Monitoring in Fractured-Vuggy Carbonate Reservoirs

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With the development of Tahe Oilfield entering the high water cut stage, gas channeling occurs in fractured-vuggy system during nitrogen injection, resulting in some inefficient wells. To improve the development effect of gas flooding, how to define the distribution of fracture, vuggy, and remaining oil has become one of the urgent problems to be solved at present. Microgravity monitoring technology uses high-quality data, the residual gravity anomaly of the target layer is obtained by depth recursion processing, the density distribution of the target layer is obtained by layer density inversion, and the fractured-vuggy distribution is depicted by edge detection. The results show that the lower part of the fractured-vuggy system in the north is connected to the middle, while the fractured-vuggy system in the south is directly connected to the middle, which leads to different effects of injected nitrogen. The early injected nitrogen in the SX area is mainly distributed in the north. Nitrogen injection in the north needs to reach a certain amount of gas before the middle can be effective. Nitrogen is injected in the south, and the central part is effective quickly. The research results provide a basis for adjusting injection-production scheme and improving reservoir development effect. Compared with the production performance and seismic interpretation results, it verifies the accuracy of ultradeep microgravity monitoring in depicting the development of fractured-vuggy system, which provides a new technology and idea for characterizing fractured-vuggy carbonate reservoirs.

## 1. Introduction

Fractured-vuggy carbonate reservoir has become an important target of petroleum exploration and development in the world [1–4]. This type of petroleum reservoir has been discovered in Tarim Basin, Ordos Basin, and Sichuan Basin in China [5–8]. Tahe Oilfield is the most typical karst fractured-vuggy reservoir, which is rich in petroleum resources [9]. Since the end of the 20th century, a large number of researches have been carried out on fractured-vuggy reservoirs in China. Although these reservoirs have played a lot of roles in petroleum production, there are still some problems such as unclear fractured-vuggy connection and difficult development adjustment in the later period [9, 10].

Microgravity monitoring technology is used mainly for monitoring water drive front, gas-water boundary and density dynamic change during material migration in reservoirs [11–18], and description of the development morphology and production performance of the steam chamber in thermal recovery of heavy oil [14].

SX area is an independent mobile unit in Tahe Oilfield, and the surrounding wells have been stopped. Taking the SX area of Tahe Oilfield as an example, this paper describes fractured-vuggy reservoir by using microgravity monitoring technology and compares it with production performance and seismic prediction, in order to add a methodology to characterize fractured-vuggy reservoir in paleokarst.

In this study, depth recursion and layer density inversion technology are used to obtain the residual gravity anomaly and layer density results of the target layer and then describe the change and difference of the target layer density. According to the results of layer density inversion boundary, the connectivity of three wells in the SX area is different at different depths, and the upper part of well A is not connected

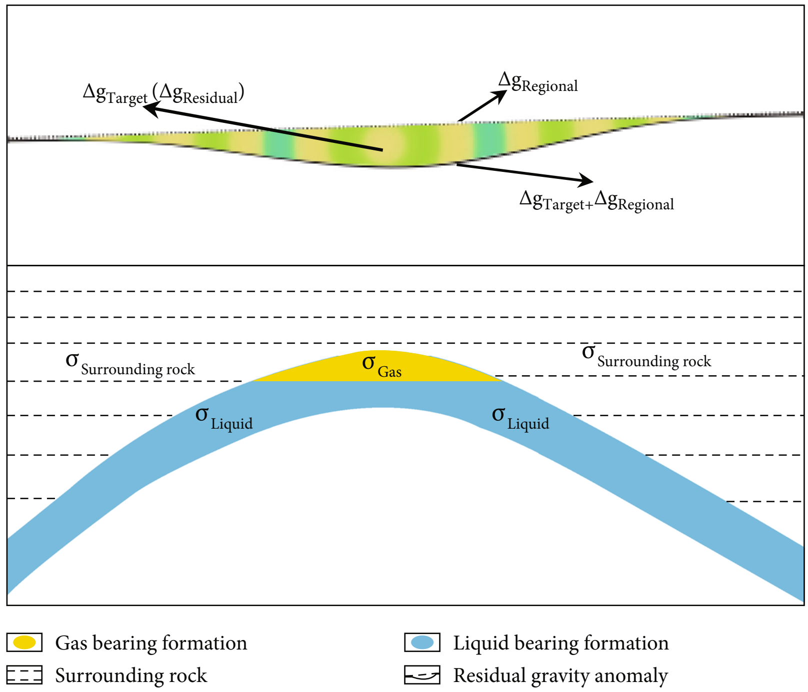


Figure 1: Schematic diagram of the gravity anomaly characteristics of gas-bearing formations.

with well B, but the lower part is connected. The nitrogen injection rate reaches a certain degree, and the oil production of well B increases. Wells C and B are in the same fractured-vuggy system. Once gas is injected, the production of well B will change. Production dynamics and seismic characterization results confirm the reliability and applicability of microgravity monitoring technology.

## 2. Principle of Microgravity Monitoring

Before the 1970s, gravity exploration was mainly used to predict oil exploration prospect areas. The technology was used in the general survey stage and achieved great success in studying the large-scale mass changes of the earth. The success rate of exploration wells can reach 20%~30%, but it is difficult to meet the needs of local geophysical events. Since the 1970s, with the advent of high-precision gravimeter and the improvement of field acquisition level, small-scale high-precision gravity exploration has appeared for the purpose of directly finding oil-producing structures. In the 21st century, with the appearance of CG-6 gravimeter and the improvement of processing and interpretation level, gravity monitoring has received more and more attention, which makes the application field of gravity from structural survey to detailed reservoir survey. Microgravity monitoring, on the one hand, means that the measurement accuracy can reach micro-Ga level, and on the other hand, it means that this measurement can be carried out between measuring points with small gravity difference.

As we all know, gravity anomaly is caused by the density difference between underground geological body and its surrounding rock (Figure 1). The low value of hydrocarbon gravity anomaly (load-bearing force effect) is caused by the negative residual density (or mass deficit) between hydrocarbon reservoir and surface relative to surrounding rock [16]. Gas injection production is equivalent to remigration, accumulation, and distribution of underground petroleum. In the gravity anomaly plane, the results always show the gravity anomaly characteristics of uplift-concave (or mirror image relationship) or abnormal isoline distorting upward regularly at slope position. From the angle of signal frequency, the gas gathering area shows high frequency (extreme value area), and the liquids show relatively low frequency (transition area) (Figure 1).

However, it is difficult to clearly distinguish the gas-water boundary, which is only a means in the initial stage of exploration, and it is difficult to provide better suggestions for petroleum companies in the later stage of petroleum exploration or development. Layer density inversion technology is used to transform the residual gravity anomaly into the density change difference of the target layer and clearly distinguish the density change of fluid or reservoir, which can distinguish oil, gas, water, and even reservoir changes more finely and provide more reference opinions for petroleum companies.

## 3. Interpretation of the Monitoring Results

*3.1. Data Acquisition and Processing.* Microgravity measurement is simple, the cost of data acquisition is low, and it has the characteristics of wide coverage, high speed, high efficiency, safety, and environmental protection.

According to the production and reservoir situation of the SX area, the gravity acquisition standard is strictly abided, and the microgravity monitoring design scheme is formed. The most advanced relative gravimeter CG-6 is used

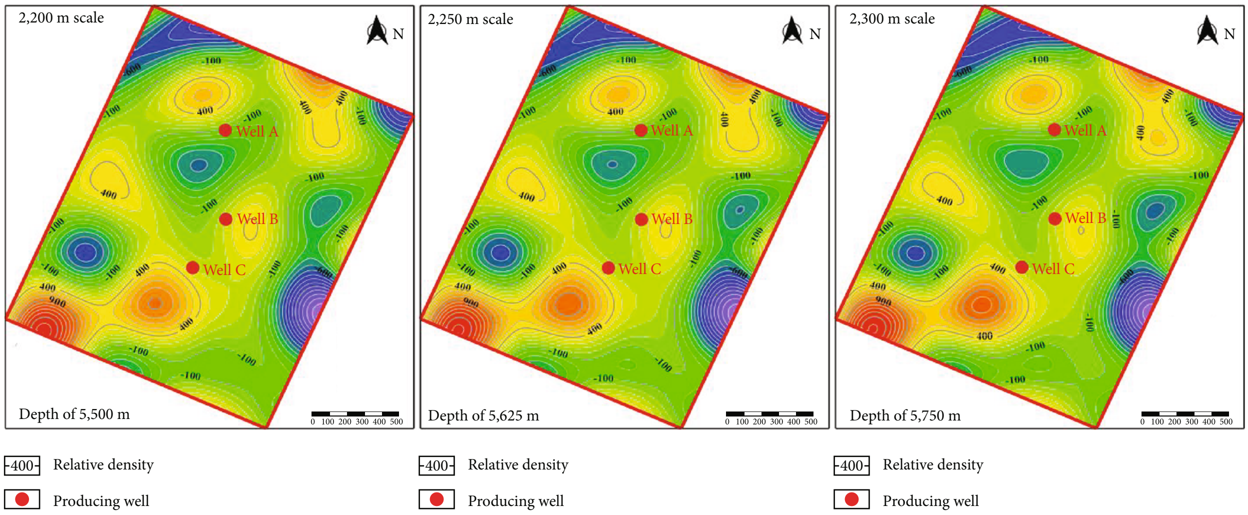


FIGURE 2: Density inversion map of the different scales in the SX area.

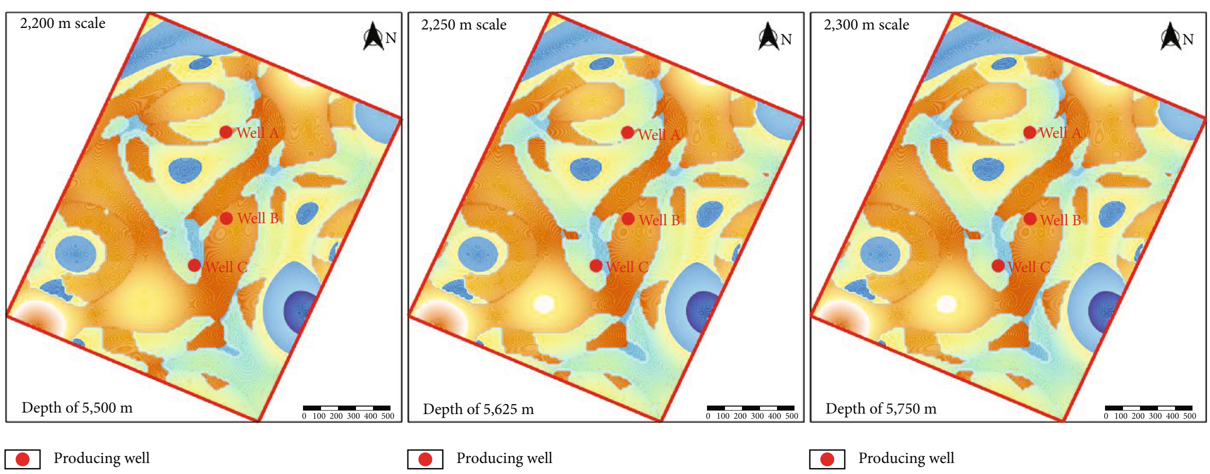


FIGURE 3: Schematic diagram of density inversion results at different scales.

to measure gravity acceleration, and the elevation is measured by the CHCNAV T7 series. The gravimeter is calibrated dynamically and statically to ensure the accuracy of the instrument and the measurement, which is consistent with the requirements of the gravity specification.

Under the condition of obtaining high-quality and high-precision original basic data, lattice value, solid tide, zero drift, terrain, middle layer, altitude, latitude, and Bouguer correction are completed, and Bouguer gravity anomaly in the work area is obtained.

Bouguer gravity anomaly is the result of superposition of many anomalies, which includes the gravity effect of residual density distribution on observation points from shallow to deep and can be decomposed into three parts: regional field, near-source field, and target field. Combined with the buried depth range of the SX area, the residual gravity anomaly of the target layer is extracted by the depth recursion method, and the layer density inversion and boundary characterization are carried out.

*3.2. Analysis of Treatment Results.* Because the buried depth is 5500 m at the top of the reservoir in the monitoring area, the relationship between extraction scale and depth is determined as $H \approx 2.5 \times \text{scale}$. In order to obtain the residual gravity anomalies in different depths, the regional fields separated by 2200 m, 2250 m, and 2300 m are subtracted from the Bouguer gravity anomaly field, respectively, and the residual gravity anomalies reflecting the depth of the target layer are obtained. Assuming that multiple scales correspond to depth separation anomalies and the density does not change with depth in a small range above and below the depth, then the relative density inversion maps of different scales can be obtained by inversion (Figure 2).

In Figure 2, the color difference reflects the relative density. The layer density varies greatly in different parts, and different colors represent an obvious difference in the layer density. The blue-purple (cool color) region represents the lowest density, while the yellow-red (warm color) region represents the highest density.

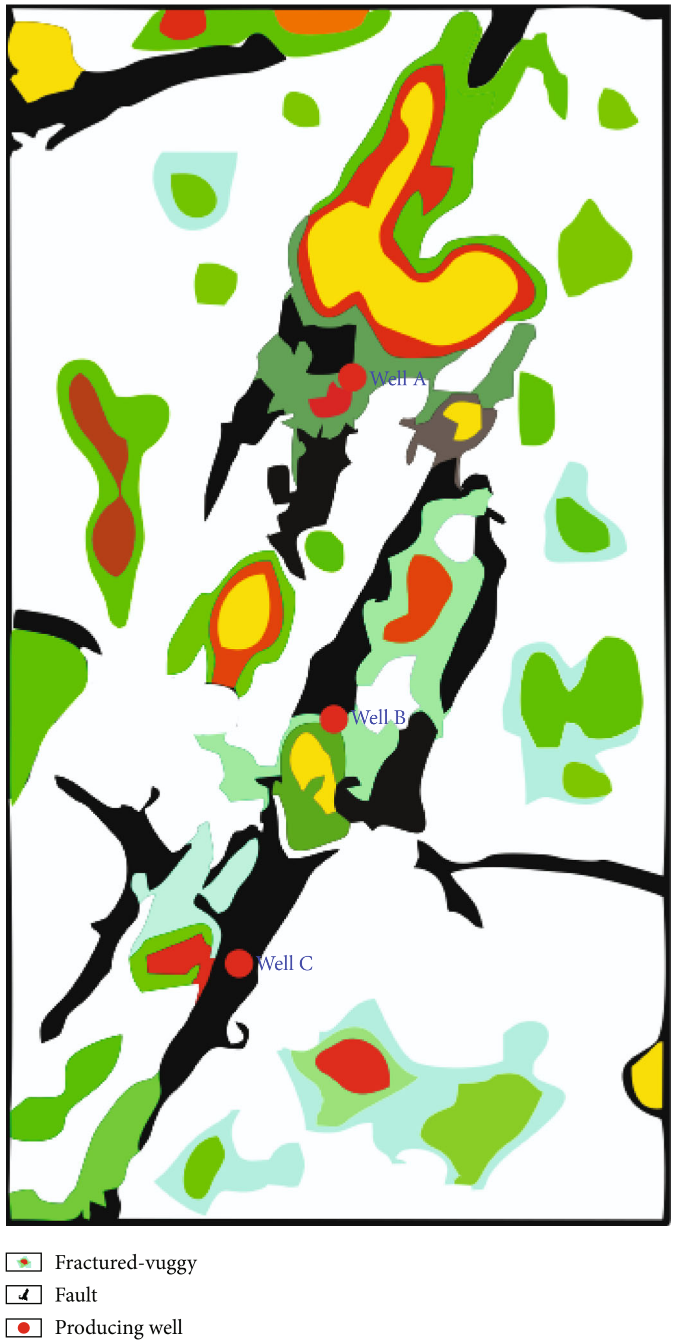


Figure 4: Spatial structure of the seismic characterization in the SX well area.

The cold color region is a fractured-vuggy development area and an oil-water enrichment area. Wells A, B, and C are located in the same density zone, indicating that the three wells are located in the same flow unit, and the connectivity between wells is predicted. At the same time, the density extreme area is between wells A and B, and the gas accumulates between wells A and B after gas injection (Figure 2).

There is a gradient and blurred transition zone in the change of layer density, which cannot reflect the specific fluid boundary or the clear change zone of reservoir physical properties. Therefore, this paper describes its boundary through forward simulation.

*3.3. Boundary Characterization of the Fracture and Vug.* Gas injection displaces oil and water. The density of gas is less than that of liquid, and a boundary characterization model is established for forward simulation, and the forward formula is as follows:

$$\Delta g = G\Delta\rho \cdot \left|\left|\left|(x-\xi)\ln\{(x-\eta)+R\} + (y-\eta)\ln\{(x-\eta)+R\} - (z-\zeta)\arcsin\frac{(y-\eta)^2+(z-\zeta)^2+(y-\eta)R}{\{(y-\eta)+R\}\cdot\sqrt{(y-\eta)^2+(z-\zeta)^2}}\right|_{\xi_1}^{\xi_2}\right|_{\eta_1}^{\eta_2}\right|_{\zeta_1}^{\zeta_2} \quad (1)$$

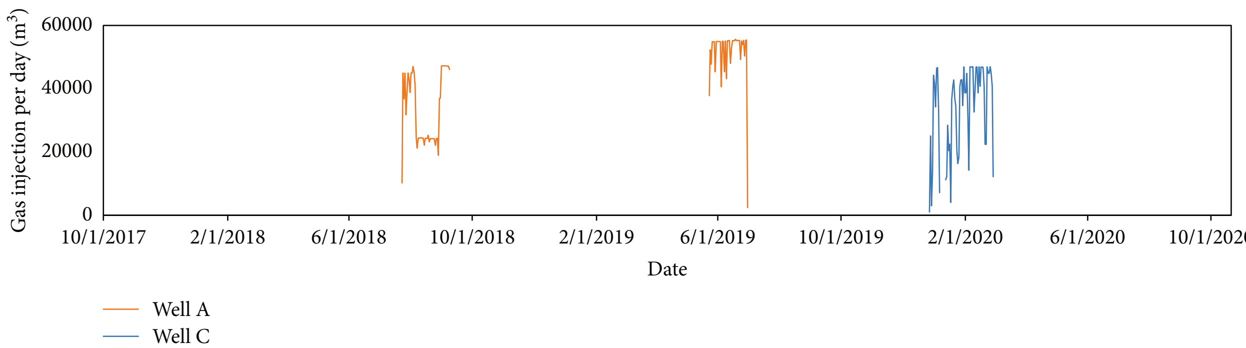


Figure 5: Gas injection curves of wells A and C.

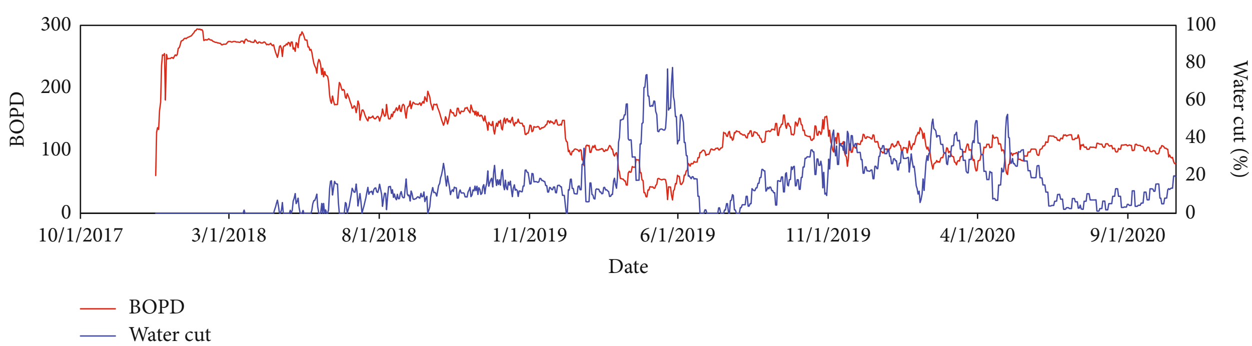


Figure 6: Schematic diagram of producing dynamic curve analysis in well B.

where $G$ represents the gravitational constant ($m^3/(kg{\cdot}s^2)$); $\rho$ represents the density of the field source density ($g/cm^3$); $(x, y, z)$ denotes the coordinates of the observation point (m); $(\xi, \eta, \zeta)$ denotes the coordinates of the source point in the target body field (m); and $R = \sqrt{(\xi - x)^2 + (\eta - y)^2 + (\zeta - z)^2}$, and its corresponding integral limit varies in the range of $(\xi_1, \xi_2)$, $(\eta_1, \eta_2)$, and $(\zeta_1, \zeta_2)$ (m).

It can be seen from the above formula that $\Delta g \propto \Delta\rho$ shows that the residual gravity anomaly produced by the model is proportional to the density value of the model itself.

According to the forward formula, gas saturation reaches 95%, the boundary characterization results are obtained and 65% of the abnormal extreme value is used as the threshold to characterize the fluid boundary. The warm color area of layer density is a reflection of dense carbonate rocks. Because layer density inversion is equivalent to the convolution of density and Green's function and the process of layer density inversion is deconvolution, while convolution is equivalent to filtering and removing background values, the density interface inversion results can more accurately describe the boundary range (Figure 3).

The blue is a low-density area, which is a nitrogen enrichment area. The light yellow part is a medium density area and a residual oil enrichment area. The deep yellow is a high-density area, which is an undeveloped area of fracture and vuggy (Figure 3). There is a strip-shaped occlusion zone in the south of well A, which is separated from the south at the depth of 5500 meters, and gradually narrows to the deep until it disappears, connecting with the south. In the south, wells C and B are always in light-colored areas and in the same fractured-vuggy system. It can be seen that wells A, B, and C are in the same fractured-vuggy system, there is connectivity between wells A and B in the lower part of the reservoir, and there is connectivity between wells C and B (Figure 3).

*3.4. Results of Seismic Characterization and Production.* The characterization technology of the fractured-vuggy spatial structure is based on geophysical methods, which characterizes the external contour, spatial position, volume, and internal structure of fractured-vuggy bodies; further clarifies the spatial position relationship of fracture-cave, cave-cave, and well-cave (Figure 4); and realizes the complete description of fracture-cave systems of different scales and types under different geological backgrounds [19]. It can be clearly seen that wells A, B, and C are in the same large fault system. Wells C and B are in the same small fracture system. It is consistent with microgravity monitoring results.

To further verify the results of the microgravity monitoring, the dynamic situation of the SX area is analyzed (Figures 5 and 6). Well B did not respond to the first gas injection in well A. When the water cut of the second gas injection decreased from 70% to 0 and oil production per day increased from 54 bbl to 127 bbl, the initial effect was achieved, which showed that the connection relationship between wells A and B had been established. When the gas injection volume of well A reached a certain level, it could affect well B, which was consistent with the lower connection of fractured-vuggy characterization. With gas injection in well C, the water cut of well B decreased from 50% to 3%, and oil production per day increased from 73 bbl to 110 bbl. In fact, gas injection in well C has a similar effect with well A. The nitrogen injection in well C is almost synchronized with the production change of well B. Wells C and B are in the same fractured-vuggy system and connected directly. From the dynamic analysis results of the above three well groups, it can be seen that the microgravity monitoring results are consistent with them.

## 4. Conclusions

After processing layer density inversion and edge detection, the following conclusions are obtained in this paper:

(1) The fractured-vuggy development edge is depicted, the connectivity between three wells is analyzed, the north is connected in the lower part of the oil layer, and the south is connected

(2) Three wells are located in the same fluid unit. The gas injection enrichment is in the low-density area between wells A and B

(3) By comparing the results of microgravity monitoring and seismic interpretation, it is verified that ultra-deep microgravity monitoring has good applicability in fractured-vuggy system characterization. Through the analysis of production dynamic data, the reliability of microgravity monitoring results to fractured-vuggy connectivity monitoring results is verified

In other words, microgravity monitoring technology has certain accuracy in characterizing the fractured-vuggy system of carbonate rocks, providing a basis for adjusting injection-production scheme and improving the effect of reservoir development. At the same time, it also opens up a new idea and finds a new direction for monitoring the fractured-vuggy system.

## Data Availability

Data is available in World Journal of Engineering and Technology, 2020, 8, 237-247 https://www.scirp.org/journal/wjet ISSN Online: 2331-4249 ISSN Print: 2331-4222.

## Conflicts of Interest

The authors declare no competing interest or conflict of interest.

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