Study on the Variogram Analysis Methods of 3D Geological Modeling for Sandstone Reservoirs

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Abstract: Variogram analysis is a necessary step for 3D stochastic modeling. Different variogram settings will directly affect the final distribution characteristics of model attributes. Setting the variogram parameters on the optimization results of sedimentary types of sub-units has become a key step in geological modeling. In this paper, the influence of variogram parameters on the simulation results of reservoir properties is studied to improve the analysis method of the variogram. This paper is for typical river-delta sedimentary reservoirs, specifically taking the SII7+8 layers as the research object. Multiple sedimentary microfacies types, including river, abandoned river, floodplain, natural dyke, coexist and show highly heterogeneous in the SII7+8 layers. On this basis, the reservoir is divided into 3 types of sand bodies and 11 kinds of sedimentary microfacies according to the effective thickness, sedimentary conditions, scale and shape of main sand bodies to study the distribution characteristics and extension scale of different sedimentary types in plane, so as to determine the variogram parameters of different sand body types, and accurately simulate the reservoir property distributions. The process in variogram analysis methods can further improving the accuracy of 3D geological modeling.

1. Introduction
Sa, Pu, and Gao are three sets of oil layers developed in A Oilfield. These oil layers can divide into 3 types of sand bodies and 11 kinds of sedimentary microfacies. The 3D facies-controlled stochastic geological modeling method is adapted for the 3D spatial characterization of reservoir attribute parameters. However, there are still large uncertainties in the reservoir parameter prediction. To reduce this uncertainty during reservoir property prediction, the variogram parameters should be optimized according to the microfacies types, and further improve the accuracy of 3D geological modeling.

2. Variogram Settings
The variogram parameters can be obtained by setting the main, secondary and vertical direction, bandwidth, search radius, step size, tolerance and other parameters during variogram analysis. The variogram parameters include sill, nugget value, and range. Sill describes the difference between two irrelevant data samples, indicating the spatial variation trend of parameters. Sill after normal transformation is 1±0.3. Nugget value (C0) reflects the parameter randomness, and the larger the nugget value is, the greater the randomness of parameter distribution will be. Range (α) describes the spatial correlation of data. Sample data within the range are correlated, while those outside the range are not correlated. Since normal transformation is a general step for data analysis, nugget value and range have direct influence on the simulation results during variogram analysis[1].

In order to analyze the influencing factors of nugget value and range and their effects on simulation
results, the spherical model and sequential Gauss simulation algorithm are used to improve the variogram analysis method. The permeability parameters of the typical SII7+8b layer are selected as a case study.

2.1 The influence of variogram parameters on simulation results

With the main direction, tolerance, bandwidth and other parameters unchanged, the variogram analysis and simulation results with search range are shown in Table 1. (Property coefficient \( Q = \frac{C0}{C+C0} \) expresses the distribution characteristics of parameters with a certain variogram setting. The coefficient less than 0.5 is mainly structural, while that larger than 0.5 is mainly random.)

The results show that the nugget constants, range, and property coefficient of the main direction increase with the search range, but the simulation results are not the same. The simulation results with a search range of 500m below and 1500m above can only distinguish the general trend of parameter distribution. No better simulation results can be obtained with larger or smaller range. The best simulation results occur with a range of 233 m, a search radius of 750 m, and a reservoir property coefficient of 0.69. Under such parameter settings, the parameter distribution is mainly random, and the search radius is consistent with the main strip size of the parameter distribution[2].

| Search Radius (m) | Variogram Parameters in the Main Direction | Analysis of Simulation Results |
|-------------------|------------------------------------------|-------------------------------|
|                   | Nugget (constant) | Sill | Property Coefficient | Range (m) | |
| 200               | 0.21            | 0.87 | 0.24                | 62.2      | The parameters are randomly distributed and irregular. Direction and trend of provenance cannot be distinguished. |
| 300               | 0.37            | 0.87 | 0.43                | 86.3      | The general trend of parameters along the main channel sand can be distinguished, the continuous type is poor, and the distribution of parameters of non-main channel sand is irregular. |
| 500               | 0.49            | 0.87 | 0.57                | 113       | The main, non-main and extreme zones can be identified, but the simulation effect is the best when the search range is 750m and the range is 233m, and the distribution of parameters coincides best with the distribution of sedimentary microfacies and hypertonic zones. |
| 750               | 0.62            | 0.90 | 0.69                | 233       | |
| 1000              | 0.75            | 0.96 | 0.78                | 833       | The general trend of parameters along the main channel sand can be distinguished, while the distribution of parameters along the non-main channel is irregular. |
| 1500              | 0.75            | 1.07 | 0.70                | 1400      | |
| 2000              | 0.77            | 1.12 | 0.69                | 1818      | The parameter distribution has strong randomness and can only distinguish the main band. |

2.2 Influencing factors of the variogram function parameters

The parameters that can be set during variogram analysis include the main direction, bandwidth, search radius, tolerance and so on. In order to understand the influence of these parameters on variogram function parameters, the permeability parameters of SII7+8b sedimentary unit were taken as a case, and the effects of these parameters on the values of \( a \) and \( C0 \) were analyzed. Heterogeneity coefficient \( p = 10 \times \frac{\sqrt{C_0}}{a(C+C_0)} \) is introduced to evaluate the distribution characteristics of parameters. The smaller the heterogeneity coefficient is, the weaker the homogeneity will be.
Table 2 Effect of Main Direction and Tolerance on Analysis Results of Variance Function

| Main Direction (°) | Nugget (constant) | Sill | Range (m) | Property Coefficient | Heterogeneity coefficient |
|-------------------|------------------|------|-----------|----------------------|--------------------------|
| 0                 | 0.38             | 0.93 | 156       | 0.41                 | 0.51                     |
| 30                | 0.7              | 0.95 | 579       | 0.74                 | 0.36                     |
| 40                | 0.62             | 0.90 | 233       | 0.69                 | 0.55                     |
| 60                | 0.62             | 0.91 | 233       | 0.68                 | 0.54                     |
| 90                | 0.3              | 0.96 | 174       | 0.32                 | 0.43                     |
| 120               | 0.51             | 0.97 | 244       | 0.52                 | 0.46                     |
| 150               | 0.46             | 0.92 | 162       | 0.50                 | 0.56                     |

| Tolerance | Nugget (constant) | Sill | Range (m) | Property Coefficient | Heterogeneity coefficient |
|-----------|------------------|------|-----------|----------------------|--------------------------|
| 20        | 0.20             | 0.89 | 128       | 0.22                 | 0.42                     |
| 30        | 0.41             | 0.90 | 123       | 0.45                 | 0.61                     |
| 40        | 0.71             | 0.93 | 544       | 0.77                 | 0.38                     |
| 50        | 0.62             | 0.90 | 233       | 0.69                 | 0.55                     |
| 60        | 0.61             | 0.90 | 190       | 0.67                 | 0.60                     |
| 70        | 0.61             | 0.91 | 233       | 0.67                 | 0.54                     |
| 80        | 0.61             | 0.90 | 233       | 0.68                 | 0.54                     |

Variogram analysis results with the main direction while the other parameters unchanged are shown in Table 2. The results show that the property coefficients of parameter distribution vary greatly with the main direction, ranging from 156m to 579m, and the results of 40 and 60 are close. The distribution map of sedimentary microfacies shows that the extension direction of the high permeability band is about 45°. Therefore, the setting of main direction should be on the basis of the extension direction of the high permeability band.

Bandwidth is the maximum cutting width set to prevent the search area from being too large. It should not be too large or too small, and should be consistent with the distribution range of the main hypertonic strip. Since the size of hypertonic strip in SII7+8b sedimentary unit is 500-1500m, better analysis result will be obtained when the bandwidth is about 200 (Table 3).

Table 1 shows that the characteristic parameters of the variogram function increase gradually with the search range, but the simulation results show that the best results is obtained when the search range is consistent with the main sand and high permeability strip size.

Table 3 Effect of Bandwidth on Analysis Results of Variance Function

| Bandwidth (m) | Nugget (constant) | Sill | Range (m) | Property Coefficient | Heterogeneity coefficient |
|---------------|------------------|------|-----------|----------------------|--------------------------|
| 40            | 0.742            | 0.91 | 544       | 0.815                | 0.387                    |
| 50            | 0.592            | 0.88 | 156       | 0.673                | 0.657                    |
| 100           | 0.603            | 0.888| 174       | 0.679                | 0.625                    |
| 200           | 0.623            | 0.9  | 233       | 0.692                | 0.545                    |
| 300           | 0.652            | 0.916| 311       | 0.712                | 0.478                    |
| 400           | 0.654            | 0.929| 389       | 0.704                | 0.425                    |

In general, the variogram function should be set on the basis of the distribution characteristics of
reservoir parameters. The accurate 3D geological model be obtained when the variogram parameters are consistent with the parameter distribution by setting the variogram function according to the scale and extension direction of the main parameter distribution.

3. Variogram Function Setting Method for Sand Bodies with Different Sedimentary Types
M development zone is located in the western part of A Oilfield and controlled by Laxi River system. According to the different sedimentary environment, sand body development degree, scale and distribution characteristics, the single sand layers in 91 sedimentary units can be divided into three group, including channel sand body, delta inner front sand body and delta outer front sedimentary sand body\cite{3}. These sand layers can be also divided into 11 sand body sedimentary types, as shown in Table 4. The characteristics of various types of sand bodies are dissected in detail. The main parameters of variogram function are set according to the sedimentary characteristics of various reservoirs, and then reservoir property modeling is carried out.

Table 4 Reservoir Classification Characteristic Description and Main Parameter Setting of Variance Function in M Development Area

| Sedimentary Types | Sedimentary Characteristics | Layer | Variable main direction (°) | Variable search range (m) |
|-------------------|-----------------------------|-------|-----------------------------|---------------------------|
| Large-Medium Channel Sand Body | The channel has a large scale, thick reservoir, and high permeability. The width is 3-4 km, the thickness is 5-9 m, the width-thickness ratio is more than 400, and the permeability is between 500-1200×10^{-3}μm². The continuity of the channel is excellent. | PL2 of 9 sedimentary units is typical | 0-30 | River Channel: 2000 Interfluve: 500 |
| Small Channel Sand Body | The scale of single channel sand body is narrow, the plane is curved strip, the width is 500-1000m, the thickness is 3-6m, and there are many pinch-out areas. The channel sand body has good continuity, strong directivity and high permeability. | PL4 of 3 sedimentary units is typical | 0-30 | River Channel: 500 Non-river-channel: 500 |
| Branched Delta Sand Body | The channel is irregular strip-like and intermittent distribution. The channel is small in scale, and its width is more than 500-600 M. The thickness of single sand body in the channel is 2-5 m, and the average permeability is 300-500×10^{-3}μm². | SIII8 of 12 sedimentary units is typical | 0-40 | River Channel: 500-800 Non-river-channel: 500-800 |
| Branch-tuck Transitional Sand Body | The channel sand bodies are narrower in shape, with relatively small size and thickness. 90% of the underwater channel sand bodies are less than 120m in width and 1.5m-2.5m in thickness. | PIII3a of 26 sedimentary units is typical | 0-30 | River Channel: 500 Non-river-channel: 600-1000 |
| Tubular Delta Sand Body | The continuity of sand body is poor, and irregular thick sand dunes are scattered in sheet sand. The width of channel sand is small, more than 50% is less than 180 m, the thickness is about 1-2 m, and the average permeability is between 300-800×10^{-3}μm². | GII9 of 3 sedimentary units is typical | 0-30 | River Channel: 200-500 Non-river-channel: 800-1000 |
| Delta Outer Front Sedimentary Sand Body | Thick and Stable Type | The main sheet sand with stable distribution is dominant, and the drilling rate of the main sheet sand (effective thickness $\geq 0.5$ m) is more than 40%. The main belt has obvious north-south direction and extends far. |
| Thin and Stable Type | The main part is the inner sheet sand. The drilling rate of the non-main sheet sand (effective thickness is 0.2-0.4 m) is more than 40%. |
| Differential and Stable Type | The main part is sheet sand with poor physical properties. |
| Thick and Unstable Type | The main part is sheet sand in the table, which is unstable laterally and has poor connectivity. |
| Thin and Unstable Type | The main part is composed of off-surface reservoirs with poor physical properties. The sheet sand is unstable laterally, and most of the lateral extensions are less than 200 m. |
| Sporadic Type | Muddy deposits are widely distributed in the whole area, with pinch-out wells up to 70% and thin sand scattered outside. |

| | SI4+5a of 18 sedimentary units is typical | 0-30 | Subject: 500-1000 Non-subject: 300-800 |
| | GI18 of 4 sedimentary units is typical | 0-30 | Subject: 300-800 Non-subject: 500-1000 |
| | GI13 of 8 sedimentary units is typical | 0-30 | Subject: 500-1000 Non-subject: 300-800 |
| | SI2 of 1 sedimentary units is typical | 0-30 | Subject: 300-800 Non-subject: 300-800 |
| | GI17 of 5 sedimentary units is typical | 0-30 | Subject: 100-300 Non-subject: 200-500 |
| | G24 of 2 sedimentary units is typical | 0 | Off-balance-sheet: 200-300 |

4. Model evaluation

![Fitting Curve of Water Content in Block of North Erxi Team 1 Area](image)

The above 3D geological model of M development area is roughened out and output, and then the model evaluation and dynamic history fitting are carried out by Eclipse software. The water cut curve calculated after the first fitting shows good agreement with the actual water cut curve (Fig. 1). The fitting results are obviously better than that of the multidisciplinary research block N (Fig. 2). The results show that the 3D geological model developed is more in line with the actual development of reservoirs, and the accuracy of the geological model meets the requirements of fine numerical simulation.
5. Conclusions

5.1 The distribution of reservoir property parameters is controlled by sedimentary microfacies. Within the control range of sedimentary microfacies, the distribution of parameters is mainly structural, and the randomness of parameter distribution increases with variogram search range.

5.2 Random simulation results of typical layers with different ranges show that the variation is the main factor affecting the simulation results, but the simulation results do not change with the variation. The simulation effect is the best only when the variogram function is set in accordance with the scale of the main band of the parameter distribution.

5.3 During the setting of variogram function, the determination of main direction, bandwidth, search radius, tolerance and other parameters must base on the study of reservoir sedimentary characteristics.

5.4 Reservoir sedimentary characteristics and variogram function characteristics are the premise of 3D geological modeling. It is a fast and effective variogram function method to describe reservoir sedimentary characteristics according to reservoir development thickness, sedimentary facies, and main belt sand body characteristics. The numerical simulation results also show that the developed model shows good agreement with reservoir properties.

Reference

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