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Prediction Methods of Key Development Indexes of Large Gas Fields Based on Big Data Analysis

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Abstract

Large gas fields play an important role in natural gas industry. Recovery rate, plateau duration, recovery at the end of plateau, decline rate and recovery factor are the key development indexes for dynamic performance analysis and development planning. Scientific prediction for those indexes can support gas development planning strongly.

Through mining statistical analysis of 150 large gas fields and numerical simulation analysis, 23 objective influencing factors which affect the development effect are studied. Gas fields are classified according to the main influencing factors, and then the distribution of development indexes are summarized. Finally, a series of prediction methods for key development indexes are established.

Based on the above work, it is found that matrix permeability, drive types, reservoir architecture and fluid type are the most sensitive factors among them. According to the most sensitive factors, gas fields should be divided into 4 categories, and 13 subcategories and the distributions rules of development indexes of all categories are presented. Then new prediction methods for development indexes are established, including linear empirical formula method, similarity analogy prediction method based on Euclidean theorems, and probabilistic values method. In this process, according to the characteristics of influencing factors, logarithmic and piecewise function methods are used for dimensionless treatment, and the prediction accuracy of the methods is improved. Finally, the expert system software is developed which can automatically predict the key development indexes. The prediction accuracy is over 80% which can satisfy the requirement of strategic planning.

The new methods have the characteristics of multiple methods, applicable to multiple gas field types and predicting multiple development indexes. Those methods can be applied to predict the development indexes of new fields and evaluate the development effects of matured gas fields in batch.

Introduction

The history of natural gas exploration and development shows that large gas fields play an irreplaceable role in natural gas industry. They are not only the main contribution of production, but also undertake the seasonal peak shaving and long-term strategic storage. Among all development indexes, recovery rate, plateau duration, recovery at the end of plateau, decline rate and recovery factor are the most direct parameters used in the gas field strategic planning. This paper focuses on the prediction method of these key development indexes.

Prediction methods for development indexes usually include mining statistical analysis (analogy method, empirical valuation method, and empirical formula method), experimental analysis, reservoir engineering, and numerical simulation analysis and so on. For the undeveloped gas fields with insufficiency of information, mining statistical analysis method is more realistic and effective. But there are the following problems of the mining statistical analysis.

1. Contradiction of gas field classification. Gas field type classification criteria are mainly based on single factor. Some standards use permeability, while others use drive type or lithology. Based on different standards, a gas field may be placed into different types. It is difficult to determine the final value because different classification methods recommend different values.
2. Subjectivity impact while indexes are recommended. Human subjectivity is greater when value is taken. The development indexes recommended by different scholar are always different.
3. Representativeness of gas field samples. Some recovery data are derived from calibration results rather than actual values. Practices show that development indexes understanding is constantly changing along with the advancement of gas filed development. The early recognition is highly uncertain, which usually differ from the final recognition. If these uncertain cases are used as analytical samples, the validity of these statistical results will be questioned.
4. Reliability of the empirical formula. Lack of necessary explanations and big data support, low coefficient correlation of empirical formula will affect the reliability of the empirical formula.

Through extensive investigation, 18000 gas fields are obtained with total recoverable reserves of 249.79 TCM. These gas fields can represent the current global situation. The declining or abandoned large gas fields, single gas field with recoverable reserves greater than 10 BCM, are further screened as analysis samples. Based on certain mathematical statistics method, the objective influencing factors of development index are analyzed. Gas fields are classified according to the main controlling factors and the development rules of each type are formed. Finally, new methods for forecasting development indexes are established.

Objective Influencing Factors of Development Indexes

In order to improve the comprehensiveness of analysis, 23 indicators were analyzed including drive types, aquifer types, matrix permeability, fracture types, porosity, water saturation, reservoir architecture, net to gross ratio(N/G ratio), No. of reservoir stratigraphic layers, hydrocarbon type, hydrocarbon content, oil to gas ratio, H_2S content, CO_2 content, geographic landform, buried depth, original volume in-place, reserve abundance, reservoir facies types, reservoir lithology, net reservoir thickness, pressure gradient, geothermal gradient. Considering the correlation between parameters, some related factors have not been analyzed, such as gross reservoir thickness which can be calculated by net reservoir thickness and net to gross ratio.

Based on the big data statistics, the mechanism of influencing factors is systematically and comprehensively analyzed.

Drive Types

Among the various controls on the recovery efficiency of gas reservoirs, aquifer drive type is identified as one of the most important factors. Figure 1 shows that the recovery factor presents a downward trend with the increase of aquifer energy. The average recovery factor of gas expansion gas fields is 77%. Recovery factor of weak and moderate aquifer drive fields are 70% and 59% respectively. Strong aquifer drive fields have the minimum value, averaging 49%.

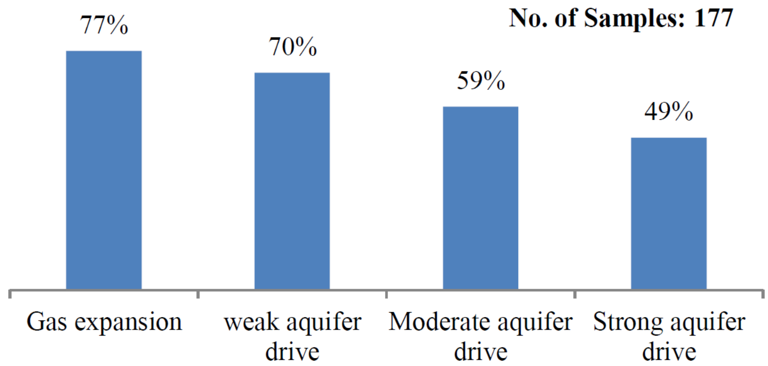


Figure 1—Average Recovery Factor of Different Drive Types

Recovery rate of aquifer drive fields is usually low and wide. Bottom aquifer invasion in irregular way usually lead to water influx and very low recovery factor. For example, Beaver River in Canada and Weiyuan in China, both of which featured by active bottom aquifer and fracture system. In the early production, due to high production rate and small interval between the completion interval and GWC, water influx occurred very early. The ultimate recovery factor of the above two fields were 12% and 37% respectively.

Water invasion which relate to aquifer distribution, reservoir characteristics, production rate, completion interval and well location, will brings the biggest risk for gas field development. It usually occurs in gas reservoir with dual porosity and active bottom aquifer. By measures of accurate production control, reasonable well spacing and completion interval control, water production can be decreased in minimum level. Early precaution is more important and effective than unloading liquid in late stage.

Matrix Permeability and Fracture Types

Seepage capacity has a great influence on development indexes. Gas recovery factor has positive correlation with matrix permeability obviously, and gas field recovery factor ascends with permeability increasing. High permeability gas fields usually get better recovery factor. Recovery factor of gas reservoirs with matrix permeability 0.1 to 1mD ranges from 30% to 60%, and that of 1 to 20mD gas fields ranges from 50% to 90%. When matrix permeability exceeds 20mD, recovery factors are often high but present a weak correlation with permeability which means no more the most important influencing factor determining the development indexes (Figure 2).

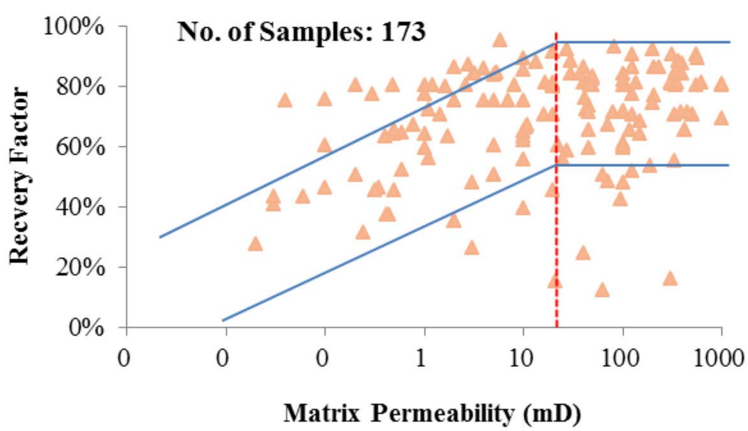


Figure 2—Relationship between Recovery Factor and Matrix Permeability

Natural fracture can increase effective permeability greatly especially in low permeability reservoir. Simulation method was taken to evaluate how fracture works. Three types of reservoirs are established: the first type is porous reservoir with matrix permeability 0.1mD; the second type is also porous reservoir with matrix permeability 8.6mD; the third type is dual-medium reservoir with matrix permeability 0.1mD, fracture permeability 10mD and effective permeability 8.6mD. Simulation results show that fracture can greatly improve gas reservoir performance. The recovery of first type is 42% and that of third type is 61%. The second type gas reservoir get a recovery of 98% which means fracture-porosity reservoirs perform not as well as porosity reservoir with same effective permeability. Therefore, development indexes of fractured gas reservoir cannot be simply analogous to porous gas reservoir with same effective permeability.

For low permeability gas reservoir, sparse well spacing cannot control all reserves considering its low seepage capacity, strong heterogeneity and poor connectivity. Infill drilling can greatly improve gas field performance. Moxa Frontier, Wattenberg, Jonah, Rulison, Pinedale and Su6 gas fields all experienced well infilling which expand reserve exploring and enhance recovery factor as showed in Figure 3.

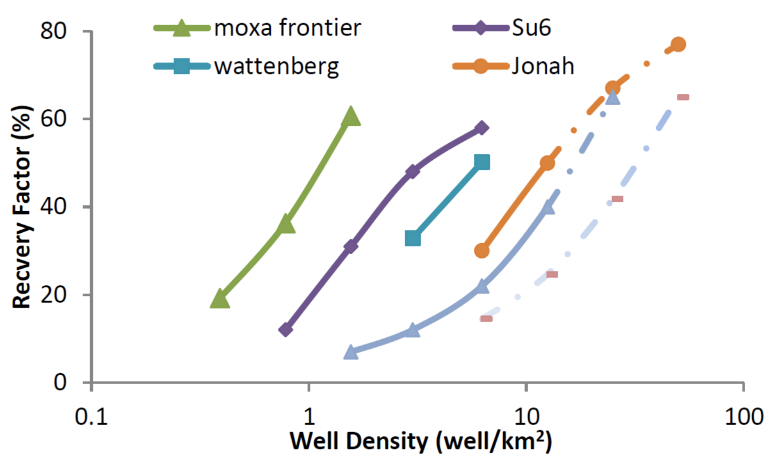


Figure 3—Relationship between Well Density and Recovery Factor

Reservoir Architecture

Large gas fields usually consist of multiple reservoirs which bring about more complex macro-features. The reservoir architecture determines the macro connectivity and complexity, further determine the degree of difficulty and effectiveness of development strategy. Block-integral and layered-integral fields have good connectivity and their recovery factors can reach to 72% on average. Layered multi-fault block and multi-layer with no main productive layer fields own less connectivity and their recovery factors fall into 69% and 60 relatively. Lenticular field presents that the worst connectivity and well spacing are limited by economic condition which leads to the lowest recovery factor, only 36% on average (Figure 4).

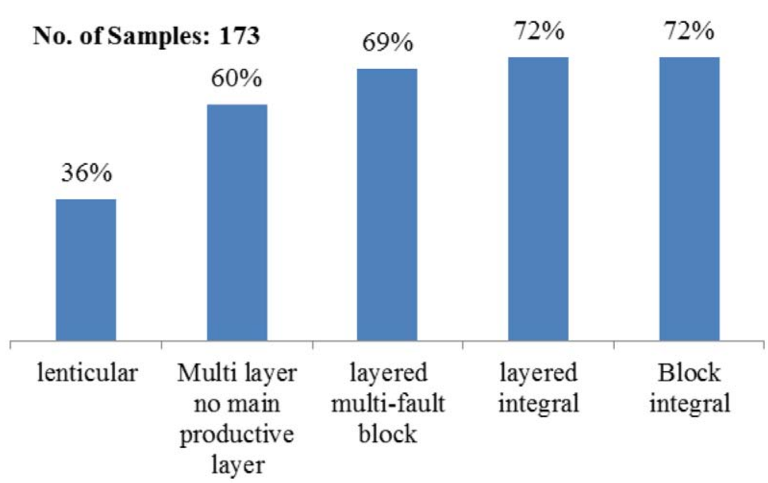
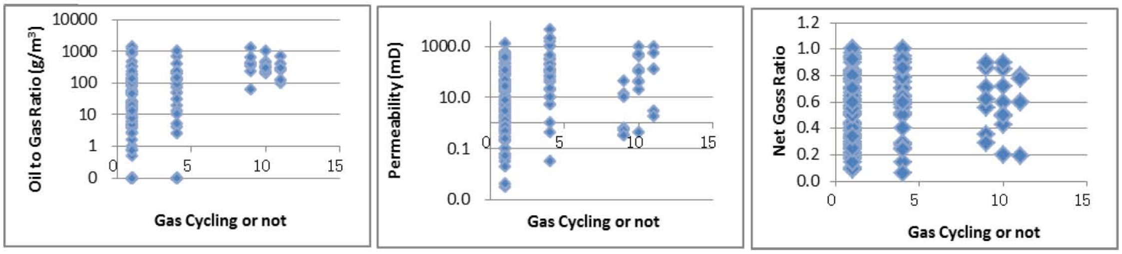


Figure 4—Average Recovery Factor of Different Reservoir Architecture

Fluid Properties

If the content of condensate oil is high, the method of reinjection will be introduced. Figure 5 shows that gas rejection is used in condensate fields which are high condensate content (oil/gas ratio more than 100g/ m^3), high permeability (more than 10mD), well connectivity (N/G more than 0.4). By this way, rejecting gas can maintain formation pressure to avoid two phases flow. The lower the abandonment pressure is, the higher the recovery factor of gas and condensate is.



Meaning of Ordinate Axis: 1-expansion & weak aquifer, 4-moderate&strong aquifer, 9-late reinjection, 10-reinjection with uncertain injection time, 11-early reinjection

Figure 5—Development Policy and Key Factors of Condense Gas Fields

Vice versa, the lower condense content is, the simpler the development method is, and the higher gas recovery factor is (Figure 6).

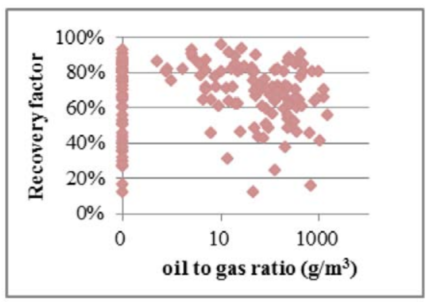


Figure 6—Relationship between Oil to Gas Ratio and Recovery Factor

When natural gas composition has high content of H_2S and CO_2, drill and production equipment are inclined to be corroded by carbonic or sulfuric acids, especially in high pressure and high temperature reservoir. Small amounts of H_2S and CO_2 will damage equipment seriously under high reservoir pressures and temperatures. Mending and renew equipment increase cost gradually, which leads to early abandonment of gas wells and worse development effect and less recovery.

Other Influencing Factors

Figure 7 shows that gas recovery factor is also correlated with other single influencing factors, but the correlation coefficient is low.

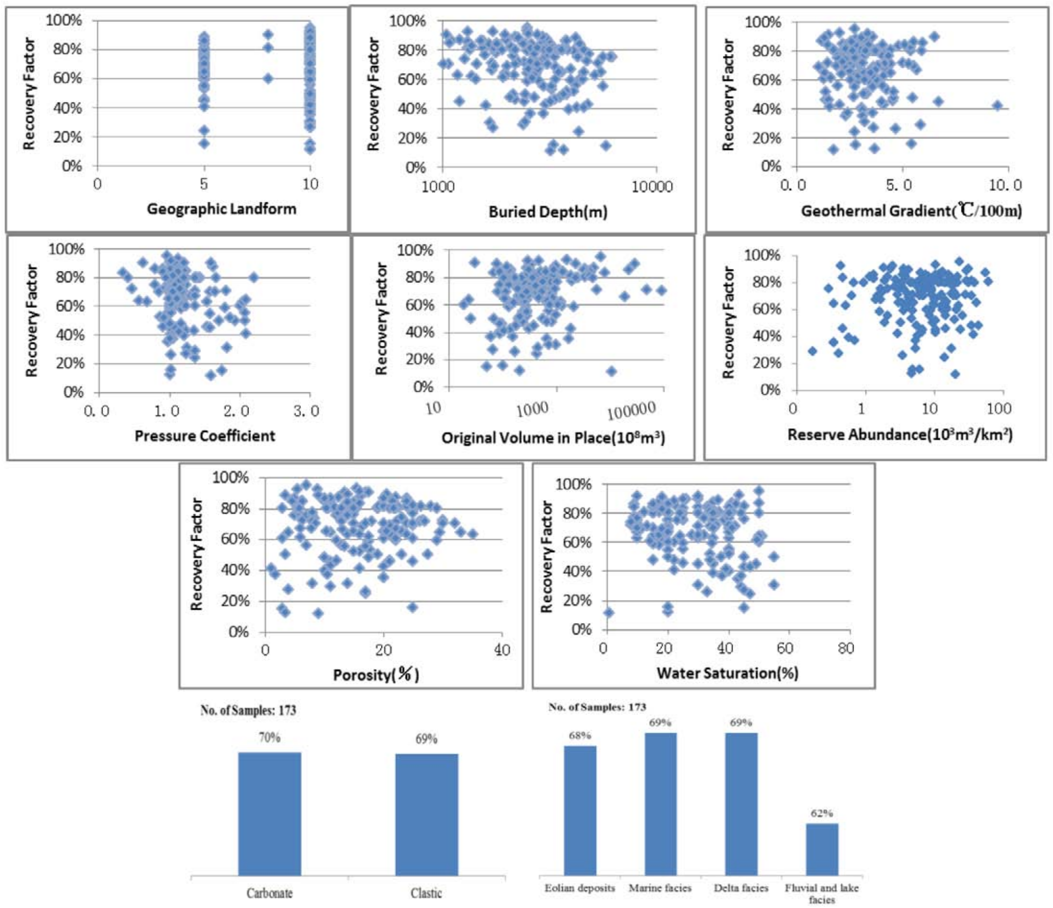


Figure 7—Relationship between Recovery Factor with Geographic Landform (5-onshore, 10-offshore), Buried Depth, Geothermal Gradient, Pressure Coefficient, Original Volume in-place, Reserve Abundance, Porosity, Water Saturation, Reservoir Lithology, Reservoir Facies Types

Deep buried depth, high temperature (geothermal gradient), high pressure (pressure coefficient) and offshore gas field need lots of capital investment which limit workload input to exploit more reserves.

Original volume and reserve abundance show a positive correlation with recovery factor.

Fluvial facies and lacustrine facies gas field get a low recovery. Delta facies, marine facies and eolian deposit gas field has the similar recovery.

Gas field with low N/G ratio, large number of reservoir stratigraphic layers, thin net reservoir thickness is more difficult to exploit them.

Porosity and water saturation show a weak correlation with recovery factor. Lithology also shows weak correlation with recovery factor.

Distributions of Development Indexes of Different Gas Fields

In order to reduce the prediction error, gas fields are divided into 4 categories and 13 subcategories, including medium-high permeability clastic gas fields (matrix permeability more than 10mD), low permeability clastic gas fields (matrix permeability between 0.1 and 10mD) and tight clastic gas fields (matrix permeability less than 0.1mD) and carbonate gas fields.

Medium-High Permeability Clastic Gas Fields

According to main influencing factors of development indexes, gas fields can be divided into several subcategories. As shown in the Table 1, development indexes of 79 medium-high permeability clastic gas fields are summarized. And it shows that onshore gas expansion fields own the highest recovery factor, in which dry gas fields are between 80% and 90%, averaging 86% and condensate gas fields are between75% and 83%, averaging 79%. Offshore gas expansion fields have relatively high recovery factor, with dry gas fields between 62% and 89%, averaging 75%, and condensate gas fields between 60% and 80%, averaging 70%. Moderate-strong aquifer drive gas fields also have high recovery factor, with edge aquifer drive gas fields between 78% and 84%, averaging 79% and bottom aquifer drive gas fields 70% and 80%, averaging 75%. In a word, under a situation of similar subjective factors, bottom aquifer drive gas fields' recovery factor is usually lower than edge aquifer drive gas fields' and gas expansion fields'; condensate fields lower than dry gas fields, and offshore fields lower than onshore fields.

Table 1—Development Indexes of Medium-High Permeability Clastic Gas Fields

Subcategories			No. of Samples	Recovery Rate (%)	Plateau Duration (years)	Decline Rate(%)	Recovery Factor(%)
Gas Expansion	Onshore	Dry Gas	17	2.2~9 (4.9)	3~21 (7.4)	8~29 (17.5)	80~92 (86)
		Cond.	12	3.1~5.4 (3.9)	1~16 (8.6)	4~23 (11.3)	75~83 (79)
	Offshore	Dry Gas	17	2~11.2 (6.2)	2~33 (11.1)	7~41 (13.5)	62~89 (75)
		Cond.	9	3~11 (6.8)	5~20 (9)	12~23 (15.4)	60~86 (70)
Medium-High Aquifer Drive	Edge water	Dry Gas	9	0.7~6.4 (3.8)	1~35 (12)	13~24 (18.2)	Integrated 78~84(79) Multi-layers 50~65(57)
	Bottom water	Dry Gas	6	2~8.9 (4.8)	5~13 (9)	6~41 (17.3)	Integrated 70~80 (75)
		Cond.	9	3~8.3(4.9)	6~17 (11)	12~64 (32.3)	53~75 (67)

Low Permeability Clastic Gas Fields

Considering reservoir architecture and drive types are the two most susceptible factors, medium-low permeability clastic gas reservoirs are divided into block gas expansion fields, layered gas expansion fields and layered aquifer drive fields. The statistic results are shown in Table 2. Block gas expansion fields present lower recovery rate between 3.1% and 5.2%, averaging 4%; plateau duration 10 to 17 years, averaging 14 years; recovery at the end of plateau 51% to 94%, averaging 76%; average decline rate 11%, thus it has relative high ultimate recovery factor 52% to 87%, averaging 73%. Layered gas expansion fields also have relative high recovery factor up to 71% with recovery rate 3.45% to 12%, averaging 5.6%, plateau duration averaging 10 years, and average decline rate 14.7%. Otherwise, layered aquifer drive fields' recovery factors are lower 54%, with its recovery rate 3.4% to 7.1%, averaging 4.9%, average plateau duration 5.8 years, average recovery at the end of plateau 47%, average decline rate 4.9%, average plateau duration 5.8 years and average decline rate 18.5%. To sum up, block gas expansion fields own the highest recovery factor, layered gas expansion fields have lower recovery factor and layered aquifer drive fields have the lowest recovery factor.

Table 2—Development Indexes of Low Permeability Clastic Gas Fields

Subcategories		No. of Samples	Recovery Rate (%)	Plateau Duration (years)	Recovery at End of Plateau (%)	Decline Rate (%)	Recovery Factor (%)
Reservoir Architecture	Drive Types						
Block	Gas Expansion	4	3.1~5.2 (4)	10~17(14.3)	51~94(75.8)	6.3~20 (11.1)	52~87 (73)
Layerd	Gas Expansion	10	3.4~12 (5.6)	2~14(10.1)	35~70(52.9)	10~21 (14.7)	60~83 (71)
	Water Drive	7	3~7.1 (4.9)	5~6 (5.8)	35~65(47.2)	13~22 (18.5)	37~70 (54)

Tight Clastic Gas Fields

Tight clastic gas fields are divided into two subcategories: lenticular gas fields and layered gas fields. The development indexes of worldwide tight clastic gas fields are shown in Table 3. It shows that the recovery rate of lenticular gas fields is from 1.5% to 6%, averaging 3.3%; plateau duration 3 to 32 years, averaging 12 years; recovery at the end of plateau from 15% to 68%, averaging 45%; decline rate from 5% to20%, averaging 10.5%; and ultimate recovery factor quietly low 20% to 75%, averaging 36%. Layered gas expansion fields' recovery rate is 1.5% to 3.4%, averaging 2.5%; plateau duration 7 to 26 years, averaging 18 years; recovery at the end of plateau 55% to 73%, averaging 63%; decline rate 7% to 11%, averaging 9% and recovery factor also low about 43% to 80%, averaging 58%.

Table 3—Development Indexes of Tight Clastic Gas Fields

Subcategories	No. of Samples	Recovery Rate (%)	Plateau Duration (years)	Recovery at End of Plateau (%)	Decline Rate (%)	Recovery Factor (%)
Lenticular	8	1.4~6.0(3.3)	3~32 (12)	15~68 (45)	5~20 (10.5)	20~75 (36)
Layered	4	1.5~3.4 (2.5)	7~26 (18)	55~73 (63)	7~11 (9)	43~80 (58)

Carbonate Gas Fields

The Carbonate gas fields are subdivided into four subcategories: gas expansion fields, pore aquifer drive gas fields, fractured edge aquifer drive fields and fractured bottom aquifer drive fields. The development indexes of different subcategories are illustrated in Table 4. Generally, gas expansion fields have longer plateau duration, averaging10 years, with high recovery at the end of plateau up to 55%. The pore aquifer drive gas fields' recovery factors are about 50% to 80%, averaging 71%. Compared to the fractured bottom water drive gas reservoir, the fractured edge water drive reservoir has relatively lower development risk and difficulty, especially moderate and weak edge water fractured fields, whose recovery factor is dominated by the reservoir management. In addition, the recovery factor of the fractured bottom aquifer drive fields is about 40% to 50%, averaging 45%, and it would be reduced to 10% to 30%, averaging 20%, caused by the improper measures which lead to water flooding.

Table 4—Development Indexes of Carbonate Gas Fields

Subcategories	No. of Samples	Recovery Rate (%)	Plateau Duration (years)	Recovery at End of Plateau (%)	Decline Rate (%)	Recovery Factor (%)
Gas Expansion	28	2~13.6 (5.1)	1~20 (10.1)	19~70 (54.8)	3.8~22 (10.2)	Pore fields: Medium to high permeability: 70%~90%,average 82% Low permeability: average 80% Fractured fields Low porosity and high permeability: 80%~90%,average87% Low porosity and low permeability: 60%~80%,average69% High porosity and low permeability:50%~60%,average 55%
Pore Aquifer Drive	7	2.8~4.9 (3.8)	5~18 (9.3)	28~31 (29.3)	5~19 (11.3)	Medium-high permeability: 50%~80%, average 71%
Fractured Edge Aquifer Drive	7	3.2~12.2 (7.7)	1~17 (7.8)	31.4~72.5 (54.4)	14~29 (21.4)	Moderate aquifer: 55%~75%,average 64%
Fractured Bottom Aquifer Drive	10	2.3~14.2 (8.8)	1~14 (3.7)	18.4~56.6 (40.1)	5.1~20.2 (14.5)	Effective stimulation 40%~50%,average 45%; aquifer flood: 10%~30%,average 20%

Prediction Methods of Development Indexes

Similarity Analogy Prediction Method

The exploiting experience of matured fields can provide useful references for those undeveloped fields. The most important thing is to find out the similar mature fields from big database. For this purpose, the similarity analogy prediction method is established. There are four steps for evaluating different fields' similarity

First, select evaluation parameters. It includes 23 parameters as below: drive types, aquifer types, matrix permeability, fracture types, porosity, water saturation, reservoir architecture, net to gross ratio, No. of reservoir stratigraphic layers, hydrocarbon type, hydrocarbon content, oil to gas ratio, H_2S content, CO_2 content, geographic landform, buried depth, original volume in-place, reserve abundance, reservoir facies types, reservoir lithology, net reservoir thickness, pressure gradient, geothermal gradient.

Second, quantify the evaluation parameters. The evaluation parameters are sorted into three groups according to these characteristics: qualitative parameters, quantitative parameters to be processed, quantitative parameters no to be processed.

Qualitative parameters include drive types, aquifer types, fracture types, hydrocarbon type, reservoir architecture, reservoir lithology, geographic landform, and reservoir facies types. These qualitative parameters need be quantified. Considering the comprehensive evaluation method is multivariate linear theory, quantitative results of above parameters need present features of nearly equal difference and uniform distribution. Combining with the correlation between influencing factors and recovery factor, the quantitative ceria is established shown as Table 5.

Quantitative parameters to be processed include matrix permeability, reserve abundance, oil to gas ratio, No. of reservoir stratigraphic layers, hydrocarbon content, net reservoir thickness. The characteristics of these evaluation parameters are non-uniform distribution. According to the different characteristics of parameters, different quantization methods are used for different parameters. Among them, matrix permeability, reserve abundance, oil to gas ratio are treated by logarithmic method considering that their distribution ranges vary by orders of magnitude. Besides, No. of reservoir stratigraphic layers, hydrocarbon content, net reservoir thickness are characterized by "extreme numbers". For example, some fields have only one layer, but others have up to 50 layers. The fitting coefficient will only represent the multi-layer fields instead of single layer ones. The treatment of piecewise function is performed on No. of reservoir stratigraphic layers, defining the No. of reservoir stratigraphic layers 10 even if the actual value is greater than 10. Similarly, defines net reservoir thickness is 350 m if the actual value is thicker than 350m, and defines hydrocarbon content is 60% if actual value is less than 60%

Table 5—Quantitative ceria of Qualitative Parameters

Qualitative Parameters	Feature Description	Quantitative Value
Reservoir Architecture	Block/integral	9
	Layered/integral	7
	Layered/ multi-fault block	5
	Multi-layers /no main productive layer	3
	Lenticular	1
Drive Types	Gas expansion	8
	Weak aquifer drive	6
	Moderate aquifer drive	4
	Strong aquifer drive	2
Aquifer Types	No aquifer	10
	Edge water dominated by stratigraphic traps	7
	Edge water dominated by structural traps	5
	Bottom water	1
Fracture Types	Low porosity, low permeability of matrix, fracture storage, fracture seepage	10
	Low porosity, low permeability of matrix, matrix storage, fracture seepage	8
	Low porosity, low permeability of matrix, matrix storage, fracture seepage	6
	matrix storage, matrix seepage	4
Reservoir Facies Types	Eolian deposits	8
	Marine facies	6
	Delta facies	4
	Fluvial and lake facies	2
Reservoir		
Lithology	Carbonate	10
Clastic	5	
Geographical Landform	Onshore	10
Offshore	5	
Hydrocarbon		
Types	Dry gas	10
	Condensate gas	5

Quantitative parameters no to be processed include buried depth, porosity, water saturation,H_2S content, CO_2 content, pressure gradient, geothermal gradient, net to gross ratio, original volume in-place. Those indexes could be used with no process considering these features of quantitation and evenly distribution.

Third, non-dimensionalize the evaluation parameters. Different parameters have different dimensions, so non-dimensionalization is needed. In general, taking the maximum and minimum values for references, the relative value is used to non-dimensionalize the parameters.

Fourth, compute comprehensive similarity. There are three typical ways for calculating the Euclidean distance of two fields in non-dimensional space, namely Manhattan distance method, Euclidean distance method and standardized Euclidean distance method. By using the weighted standard Euclidean distance and considering the sensitivities of the evaluation parameters of development indexes, a comprehensive similarity analogy prediction method is proposed. The similarity distance of two gas fields is as follows.

$$d_{12} = \sqrt{\sum_{k=1}^{n} \omega_k \cdot \left(x_{1k} - x_{2k}\right)^2}$$

Where x_{1k} and x_{2k} are the quantitative indices of the two gas fields respectively, and ω_k is the weight of the k-th quantitative parameter. It can be found that the more similar the two gas fields are, the smaller the distance d_{12} is. Therefore, d_{12} can be used for representing the similarity degree between two gas fields. When x_1 and x_2 are identical, d_{12} equals to zero.

The advantages of similarity analogy prediction method: the key influencing factors are comprehensively taken into account, avoiding one-sidedness in the screening process of gas field; this is a quick and effective method for screening similar gas fields from big database, which reduces the workload of typical gas field investigation.

Linear Empirical Formula Method

There are correlations among the five development indexes. For a specific gas field, when the gas recovery rate is constant, the plateau duration and the recovery at the end of the plateau are also determined. And if the decline rate is determined again, the recovery rate is basically the only one. Considering the above correlation, the recovery rate is taken as the input parameter, the recovery rate and the recovery at the end of plateau as the fitting parameter, and the other two are calculated theoretically according to the correlation.

The multiple linear regression analysis theory is applied to establish the relationship between development indexes and influencing factors. It is described that suppose X are independent variables (drive type, matrix permeability, etc), subjectively denoted by $X_1, X_2, \ldots, X_P$, P are number of independent variables including recovery rate when calculating the recovery at the end of plateau, and its dependent variables are Y (recovery factor and recovery at the end of plateau), with an assumption of linear correlation between independent variables and Y:

$$Y = \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_p X_p + \varepsilon$$

Where, ε is a constant term, both of $\beta_0, \beta_1, \beta_2, \ldots, \beta_p$ and $X_1, X_2, \ldots X_p$ are unknown parameters and unrelated to each other. The least-squares algorithm is applied to the solution of coefficient of β_0, β_1, $\beta_2, \ldots, \beta_p$

Referred to the actual development indexes of matured gas fields, empirical formulas of development indexes of different types are fitted. The fitting coefficient is shown in Table 6. Because the number of tight gas fields is too small (only 13), it is meanness to fit its formula.

Probabilistic Values Method

In general, the development indexes have asymmetric distribution characteristics. However, if the interval ranges are known, most decision makers will take the average of maximum and minimum values as the final recommendation. This average method is suitable for indicators with symmetrical distribution, but not for development indexes of gas fields.

Therefore, the cumulative probability distribution curves of development indexes are obtained based on a large number of statistical analyses. The recommendation of development indexes is determined based on different probabilities. Generally, the recommended value is the index size corresponding to 50% cumulative probability. This method can objectively evaluate the reasonable development indexes of new gas fields, and also provide a basis for evaluating the development effect of matured ones.

Table 6—Fitting Coefficient of Recovery Factor and Recovery at the end of Plateau

Influencing Factors	Carbonate fields		Medium-High Permeability Clastic Fields		Low Permeability Clastic Fields	
	Recovery Factor	$(1- V°T)^2$	Recovery Factor	$(1- V°T)^2$	Recovery Factor	$(1- V°T)^2$
constant term	−0.06480	−0.34692	0.08382	0.15261	−0.45109	−0.08045
original volume in place	−0.00001	0.00000	−0.00000076	0.00000	0.00016	−0.00021
reserve abundance	−0.00504	−0.06670	−0.00638	0.00396	−0.17844	0.09202
geographic landform	0.01844	0.01085	0.02261	0.01346	0.00366	−0.02729
buried depth	0.00003	0.00002	0.00000	0.00005	0.00019	−0.00021
reservoir architecture	0.03061	−0.01580	0.00908	−0.03795	0.02117	−0.00044
facies types	−0.04542	−0.02817	0.01359	−0.01746	−0.04882	0.05708
No. of reservoir stratigraphic layers	0.02734	−0.00566	−0.00199	−0.01697	−0.01909	0.01304
net-to-gross ratio	0.00108	−0.09089	0.05867	−0.05206	0.37371	−0.73419
lithology	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
matrix permeability	0.01429	0.00725	0.02074	0.02540	0.04612	0.11119
porosity	0.00355	0.00781	−0.00367	0.00044	0.02137	−0.07846
water saturation	0.00117	−0.00211	−0.00194	0.00695	0.00234	−0.00929
natural fracture types	−0.00947	0.02121	0.00196	0.00357	−0.04092	0.00092
drive types	0.05522	−0.01463	0.03566	−0.01082	−0.07483	0.13426
Aquifer types	0.01316	0.00470	0.01039	−0.03541	−0.00894	−0.03642
hydrocarbon type	0.02423	0.01799	0.00444	−0.00555	−0.02974	0.01277
hydrocarbon content	−0.00430	0.00872	0.00165	−0.00155	0.01749	−0.00706
H_2S content	0.01025	0.00422	0.00822	−0.00821	−0.04605	−0.13753
CO_2 content	0.00013	0.02974	0.01468	0.00230	−0.01182	0.03470
oil to gas ratio	0.01014	0.02599	−0.00786	−0.01113	0.00658	−0.01942
geothermal gradient	−0.01883	0.03956	0.02103	0.07368	0.13296	0.03224
pressure coefficient	−0.13747	−0.08254	−0.08413	−0.11626	−0.33664	0.66627
net reservoir thickness	−0.00021	0.00016	0.00019	0.00042	0.00121	−0.00053
recovery rate		1.47967		1.51396		−0.19199

Prediction System of Development Indexes of Gas Fields

With the help of Visual Studio compilation platform, the Prediction System of Development Indexes of Gas Fields (Figure 8) is compiled to facilitate the use and promotion of above new prediction methods.

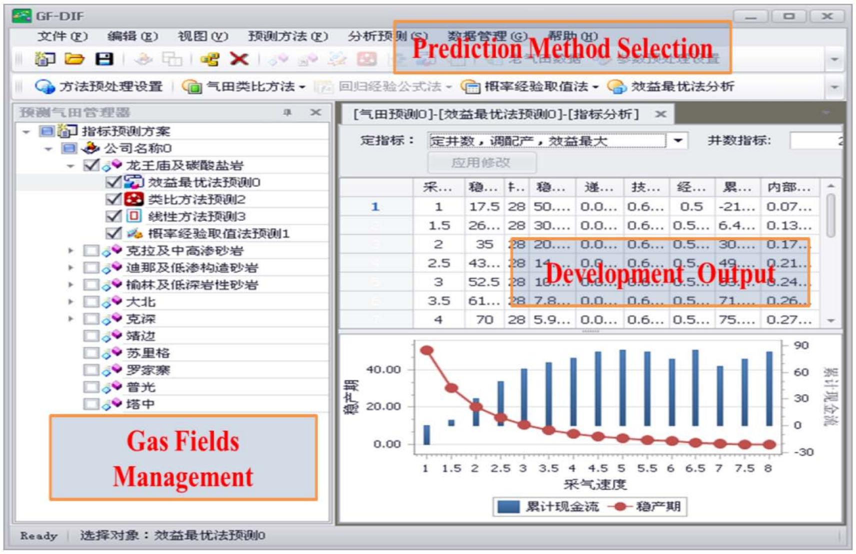


Figure 8—Interface of Prediction System of Development Indexes of Gas Field

The Prediction System of Development Indexes of Gas Fields can predict and analyze development indexes based on the basic data of gas field input by users. Its functional characteristics are as follows: (1) Multiple indexes. The predicted development indexes include recovery rate, plateau duration, recovery at the end of plateau, decline rate and recovery factor. (2) Multiple methods. The prediction system mainly includes linear empirical prediction method, similarity analogy prediction method, probabilistic value method, and neural network prediction method, and economic benefit optimization method. The software can evaluate the development indexes intelligently and automatically. (3) Multiple gas field types. The prediction system can evaluate the development indexes of 4 categories and 13 sub-categories. (4) Multiple purposes. It can be applied to optimize the development indexes and strategic planning of new gas fields, and also to evaluate the development effect of developed gas fields. (5) Higher prediction accuracy. Overall, the prediction system has a high fitting accuracy. Taking recovery factor prediction as example, the average fitting accuracy of all gas fields is 82%,that of carbonate gas fields 88%,that of medium-high permeability clastic gas fields is 87%, and that of low permeability clastic gas fields is 94% (Figure 9). That means the minimum prediction accuracy is over 80%.

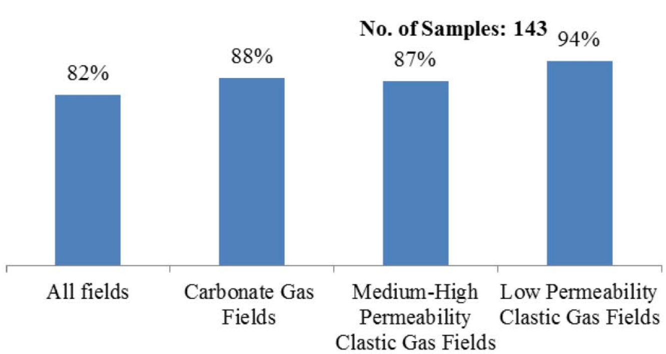


Figure 9—The Fitting Error of Recovery Factor

Furthermore, the gas fields are divided into two parts, the fitting samples and the testing sample, and the validity of the system is evaluated.

Conclusions

The relationship between development indexes and their influencing factors is systematically analyzed. Among them, matrix permeability, drive type, reservoir architecture and fluid type are the main controlling factors.

In order to predict development indexes effectively, gas fields should be divided into four categories, 13 subcategories according to the main influencing factors. The distribution of recovery rate, plateau duration, recovery at the end of plateau, decline rate and recovery factor are revealed.

Similarity analogy prediction method based on Euclidean theorems, linear empirical formula method, and probabilistic values method are established. This series of prediction methods are systematic, practical, and effective.

The prediction system software is developed which can quickly predict the development indexes of different gas field types based on their geological parameters. The fitting accuracy is over 80% which can satisfy the requirement of strategic planning.

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