Advanced Reservoir Engineering

Wu Zhengbin

Department of petroleum engineering, China University of Geosciences

Chapter 9 Case study of complex reservoir development

Section 1 Well Pattern Design of Huff and Puff in Miqian10 Block

Section 2 Development Adjustment Design of Gudong 18-7 Fault Block Reservoir

Section 3 Development Adjustment Design of Low Permeability Reservoir in Baima Area, Xifeng Oilfield

Section 4 Xinggu Buried Hill Reservoir Development Design in Xinglongtai Oilfield

Section 1 Well Pattern Design of Huff and Puff in Miqian10 Block

1. Reservoir Geology and Development

Basic Reservoir Characteristics

- Shallow, long section of oil well;
- Thin, longitudinal distribution scattered;
- loose cementation, good physical properties, high oil saturation;
- Low reservoir pressure and temperature;
- High oil viscosity.

1. Reservoir Geology and Development

Reservoir Development History

- **Oil-bearing area: 1.4 km^2**
- **OOIP: 567×10^4 t**
- **Reservoir depth: 156.0~503.8m**
- **Thickness: < 10m**
- **Target layer: IV9**
- **Well pattern type: 70×100m, inverse nine-spot pattern**

2. Residual Oil Distribution Characteristics

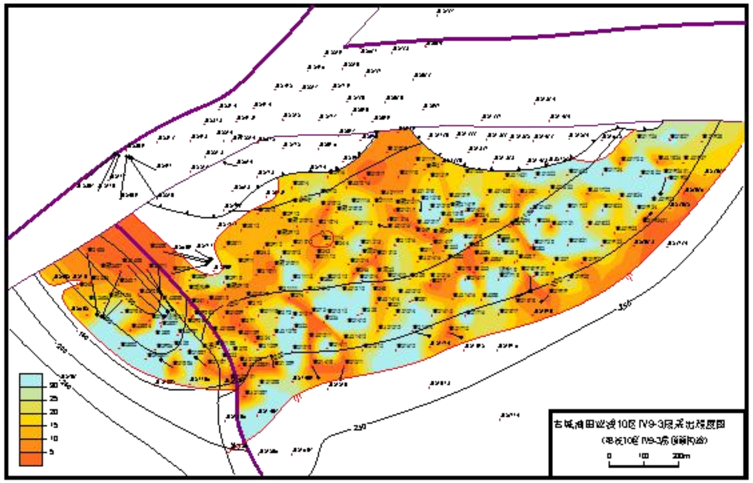
Plane Residual Oil Distribution

The distribution of remaining oil reserves is of great significance to the adjustment of well pattern in later period. Due to the imperfect well pattern and the difference of production system, there are many remaining oil in the reservoir.

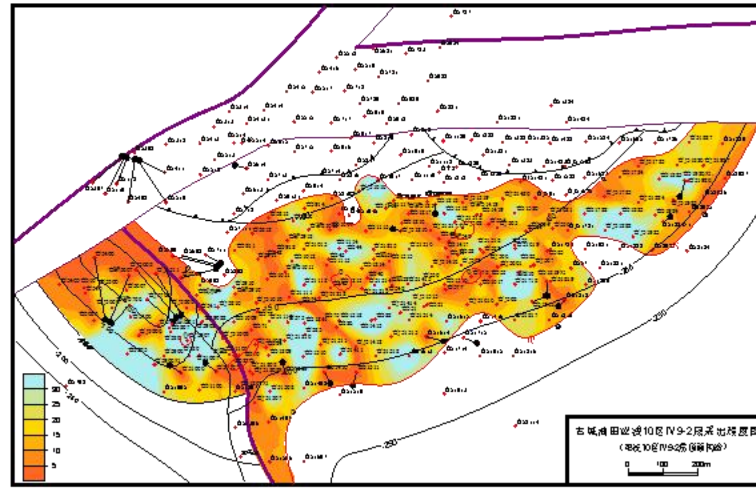
- ✓**Southern edge water area, the northern pinchout zone**
- ✓**Remaining oil is irregularly distributed in the middle of the reservoir**
- ✓**Both sides of the fault**

By comparing the distribution of original oil saturation abundance and residual oil abundance, the difference of production status between different IV9 layers was determined.

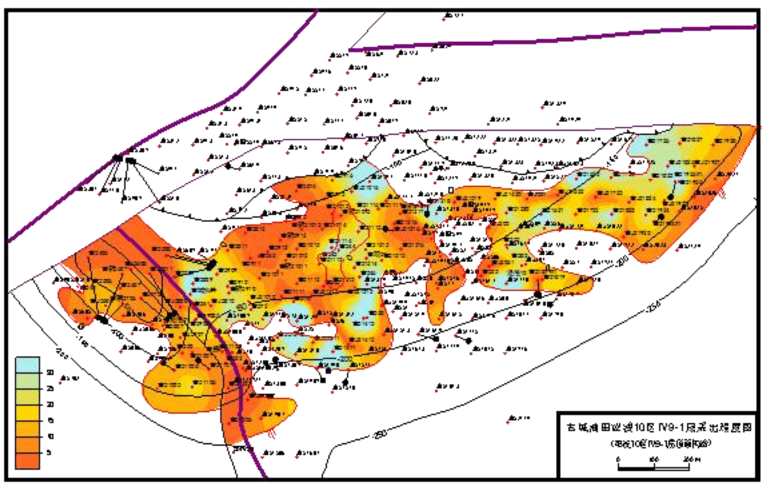
Plane Residual Oil Distribution



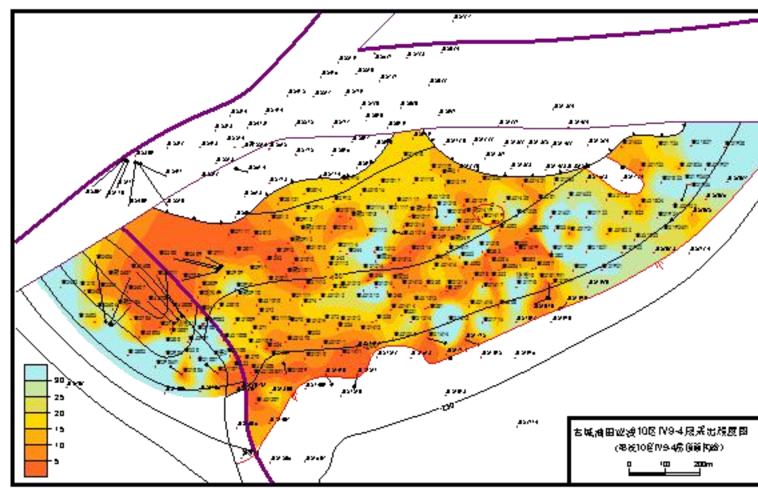
Ⅳ9^{1} layer



Ⅳ9^{2} layer



Ⅳ9^{3} layer



Ⅳ9^{4} layer

Plane Residual Oil Distribution

According to reservoir engineering methods:

$$V_{\mathrm{orj}} = \left(V\phi\right)_j \rho_{\mathrm{osc}} S_{\mathrm{oi}} - N_{\mathrm{oi}}$$

Where:

V_{orj} **— Residual oil reserves per layer, 10^4t;**

$(V\varphi)_j$ **— Pore volume per layer, $10^4 m^3$;**

S_{oi} **— Initial oil saturation, decimal;**

N_{oi} **— Cumulative oil production per layer, 10^4t.**

Plane Residual Oil Distribution

After several cycles of steam huff and puff, the remaining oil saturation of each layer varies greatly. Ⅳ 91 layer and Ⅳ 94 belong to thin layer, a large amount of heat is absorbed by the interlayer insulation, leading to poor reservoir performance and high residual oil content.

Remaining oil reserves of each layer of Ⅳ9 strata

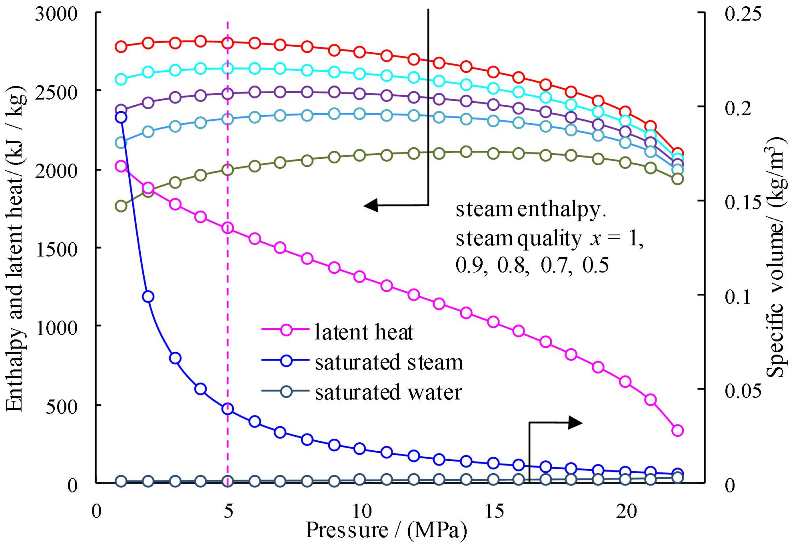
Layer	Pore volume $10^4 m^3$	Initial oil saturation %	OOIP $10^4 t$	Cumulative oil production $10^4 t$	Remaining oil reserves $10^4 t$
$Ⅳ9^1$	46.07	0.7	25.65	6.7084	18.9416
$Ⅳ9^2$	67.35	0.7	55.1	14.5436	10.5564
$Ⅳ9^3$	116.22	0.7	78.85	23.6218	55.2282
$Ⅳ9^4$	49.93	0.7	20.9	5.2671	15.6329
Ⅳ9	279.57	0.7	180.5	50.1409	130.3591

Vertical recovery status

Oil recovery percentage of each layer of Ⅳ9 strata

Layer	OOIP 10^4t	Cumulative oil production 10^4t	Oil recovery percentage 10^4t
$Ⅳ9^1$	25.65	6.7084	26.2
$Ⅳ9^2$	55.1	14.5436	26.4
$Ⅳ9^3$	78.85	23.6218	30.0
$Ⅳ9^4$	20.9	5.2671	25.2
Ⅳ9	180.5	50.1409	27.8

Converting time for steam flooding



oil saturation → 40%~50%

pressure → Maintain steam physical properties

temperature → > inflection point temperature

steam drive area selection after huff and puff

Empirical formula for inflection point temperature

$$T_c = \left(21.468 - 2.552 \ln K\right) \mu_{o50}^{0.139}$$

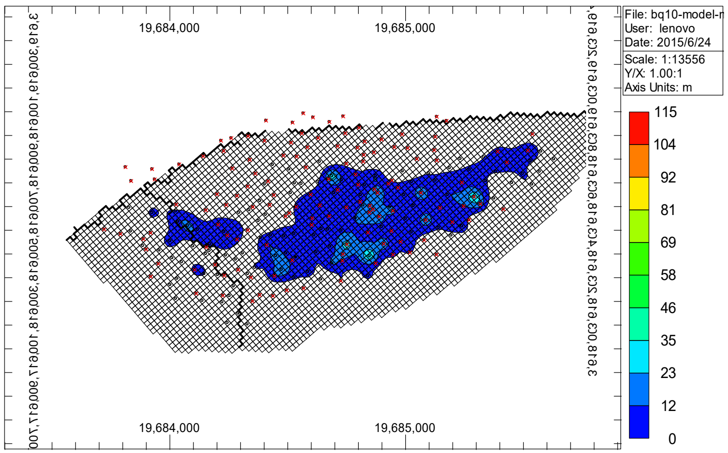
Where:

T_c — Crude oil inflection point temperature, ℃;

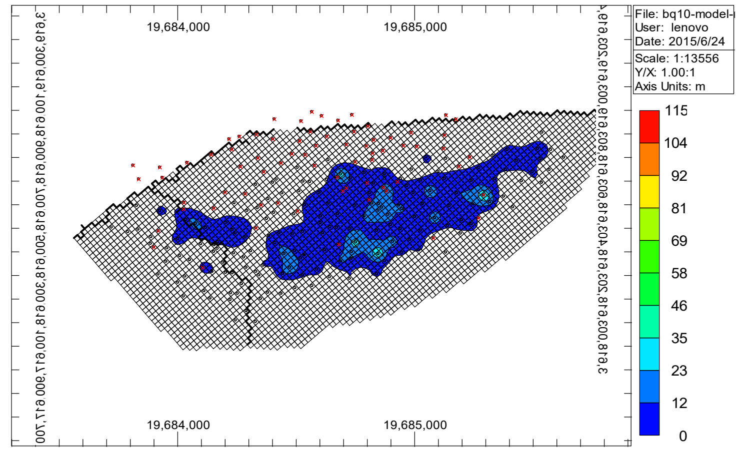
K — permeability， μm^2;

μ_{o50} — Oil viscosity @ 50 ℃, mPa·s。

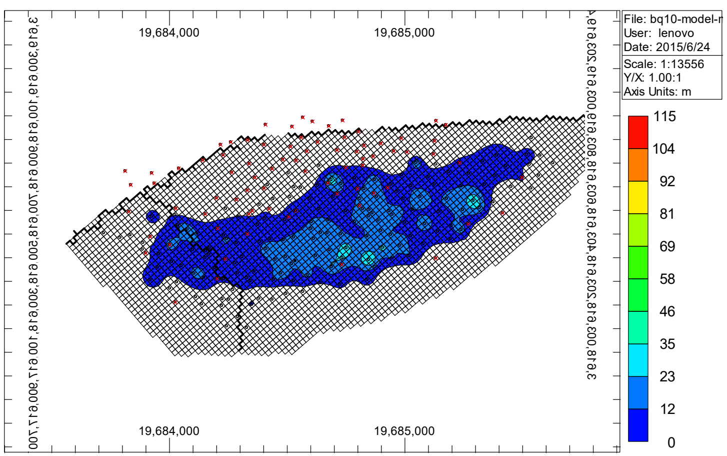
steam drive area selection after huff and puff



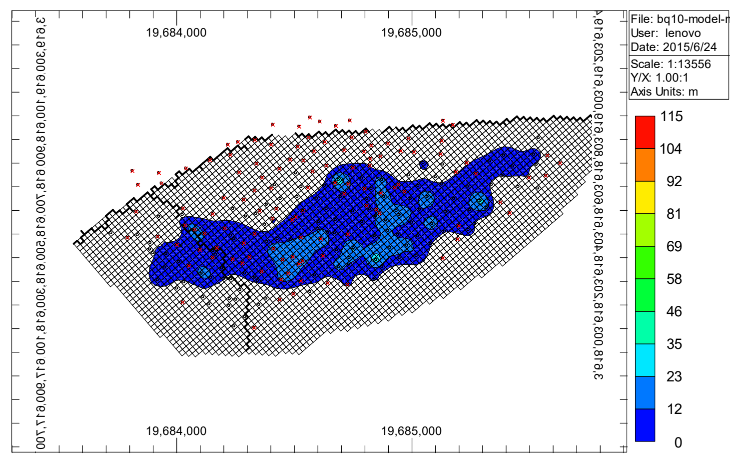
Ⅳ9¹ layer



Ⅳ9² layer



Ⅳ9³ layer



Ⅳ9⁴ layer

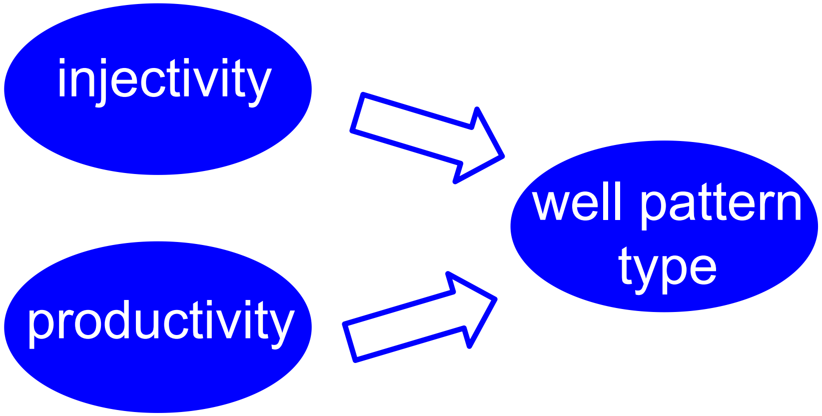
Well pattern adjustment design

- **Limits of steam flooding parameters**

Steam quality ⇨	**> 40% at wellbore**
Production-injection ratio ⇨	**> 1.2**
Steam injection rate ⇨	**> 1. 6 t/(d · ha · m)**

Well pattern adjustment design

- **Parameter optimization of steam flooding**



Parameters of the model

Well pattern type	α	β
reverse five-spot	100	10^{-4}
reverse seven-spot	87.7	2.6×10^{-4}
reverse nine-spot	86.6	4×10^{-4}

Well pattern adjustment design

➢ **Parameter optimization of steam flooding**

$$d = \alpha \sqrt{\frac{q_1}{Q_s h_o R_{PI}}}$$

$$q_s = \beta Q_s h_o d^2$$

Where:

d — well spacing, m;

q_l — average maximum fluid production per well, m^3/d;

Q_s — injection rate per unit reservoir volume of a well group, 8t/(d·ha·m)

h_o — effective thickness of the pay, m;

R_{PI} — production injection ratio;

q_s — steam injection rate per well, t/d.

Well pattern adjustment design

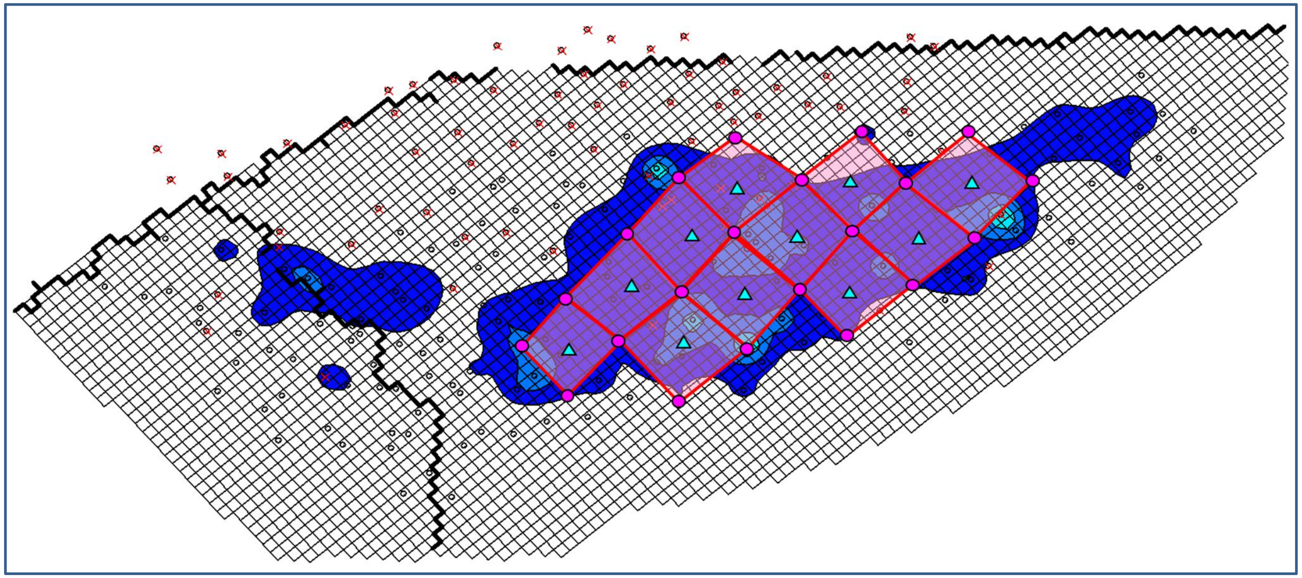
➢ Parameter optimization of steam flooding

Steam injection volume design

Well pattern type	Steam injection volume/ (t/d)
reverse five-spot	27.85
reverse seven-spot	85.33
reverse nine-spot	85.33

4. Well pattern optimization

➢ **Reverse five-spot**



well distribution

4. Well pattern optimization

➢ **Reverse five-spot**

steam injection volume design

well name	well type	thickness (m)	control area （ha）	injection volume (m^3/d)	P-I ratio	fluid production (m^3/d)	Control thickness (m)
G51312	injector	8.7	1.96	30.85	1.2	37.02	40.1
G51314	injector	11.3	2.56	52.05	1.2	62.46	43.0
G51316	injector	10.5	2.56	48.52	1.2	58.23	43.6
G51318	injector	9.4	2.56	43.54	1.2	52.24	40.3
G51514	injector	7.5	3.06	41.37	1.2	49.64	34.1
G51516	injector	11.9	2.56	54.86	1.2	65.83	43.3
G51518	injector	12.6	2.88	65.15	1.2	78.19	47.3
G51520	injector	11.0	2.24	44.48	1.2	53.37	45.2
G51718	injector	12.9	2.24	51.84	1.2	62.21	47.6
G51720	injector	12.9	2.24	51.96	1.2	62.35	48.3
G51722	injector	8.9	2.72	43.69	1.2	52.43	44.6

4. Well pattern optimization

➢ **Reverse five-spot**

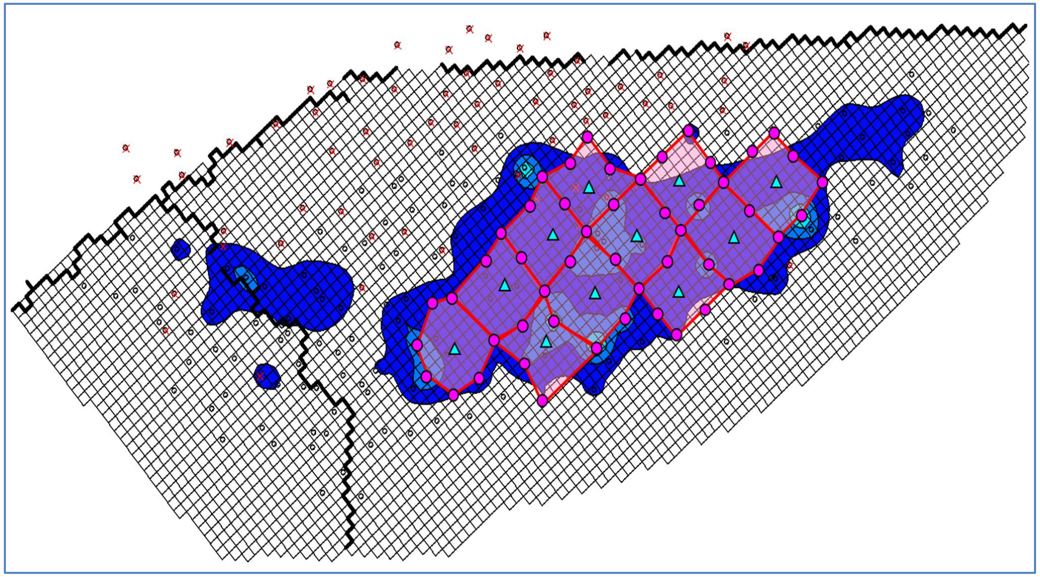
fluid production design

well name	well type	thickness (m)	fluid production (m^3/d)	well name	well type	thickness (m)	fluid production (m^3/d)
G51211	producer	10.1	9.30	G51613	producer	7.26	10.55
G51213	producer	14.7	34.81	G51615	producer	8.93	26.58
G51215	producer	10.4	28.94	G51617	producer	12.37	55.46
G51217	producer	11.3	29.74	G51619	producer	13.72	74.53
G51219	producer	7.8	10.09	G51621	producer	10.73	39.14
G51411	producer	7.1	6.53	G51623	producer	10.18	11.97
G51413	producer	8.3	31.85	G51817	producer	9.58	12.52
G51415	producer	9.6	55.51	G51819	producer	11.91	30.93
G51417	producer	12.3	71.60	G51821	producer	11.98	29.54
…	…	…	…	…	…	…	…

Production time: 18.8a; cumulative oil production: 77.0031×$10^4 m^3$; oil recovery: 45.40%.

4. Well pattern optimization

➢ **Reverse nine-spot well pattern**



well distribution

4. Well pattern optimization

➢ **Reverse nine-spot well pattern**

steam injection volume design

well name	well type	thickness (m)	control area （ha）	injection volume (m^3/d)	P-I ratio	fluid production (m^3/d)	Control thickness (m)
G51312	injector	8.7	2.16	34.00	1.2	40.80	72.5
G51314	injector	11.3	2.60	52.86	1.2	63.43	72.3
G51316	injector	10.5	2.56	48.52	1.2	58.23	84.5
G51318	injector	9.4	2.24	38.09	1.2	45.71	77.4
G51514	injector	7.5	2.40	32.44	1.2	38.93	58.9
G51516	injector	11.9	3.16	67.72	1.2	81.26	83.6
G51518	injector	12.6	2.88	65.15	1.2	78.19	94.9
G51520	injector	11.0	2.28	45.27	1.2	54.32	86.3
G51718	injector	12.9	2.40	55.54	1.2	66.65	97.9
G51720	injector	12.9	2.88	66.80	1.2	80.16	99.9
G51722	injector	8.9	2.72	43.69	1.2	52.43	85.5

4. Well pattern optimization

➢ **Reverse nine-spot well pattern**

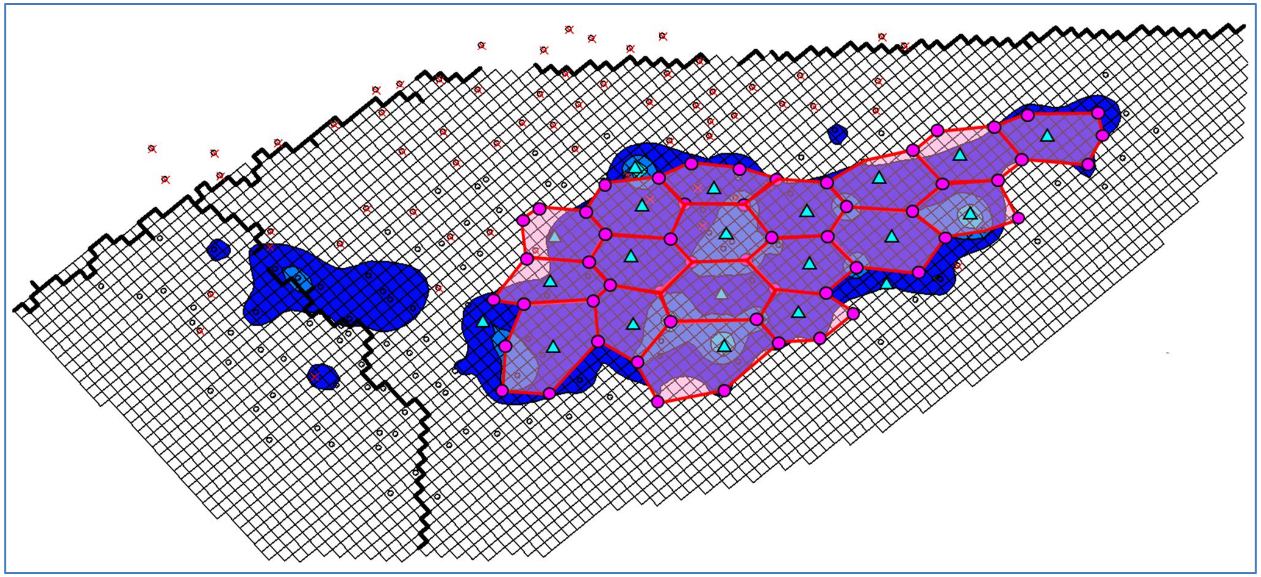
fluid production design

well name	well type	thickness (m)	fluid production (m^3/d)	well name	well type	thickness (m)	fluid production (m^3/d)
G51211	producer	10.0	5.67	GJ51412	producer	8.9	5.04
GJ51212	producer	14.3	8.09	G51413	producer	8.3	17.48
G51213	producer	14.6	21.11	GJ51414	producer	9.3	14.35
G51214	producer	10.3	9.11	G51415	producer	9.6	30.82
G51215	producer	10.3	16.27	GJ51416	producer	10.7	17.84
G51216	producer	10.5	7.26	G51417	producer	12.3	37.92
G51217	producer	11.2	14.46	G51419	producer	8.8	18.10
GJ51218	producer	8.1	4.81	GJ51420	producer	9.0	5.73
G51219	producer	7.7	4.59	G51411	producer	7.0	3.99
…	…	…	…	…	…	…	…

Production time: 16.2a; cumulative oil production: 75.1309×$10^4 m^3$; oil recovery: 44.29%.

4. Well pattern optimization

➢ **Reverse seven-spot well pattern**



well distribution

4. Well pattern optimization

➢ **Reverse seven-spot well pattern**

steam injection volume design

well name	well type	thickness (m)	control area (ha)	injection volume (m^3/d)	P-I ratio	fluid production (m^3/d)	Control thickness (m)
G51312	injector	8.7	2.40	37.78	1.2	45.33	60.21
G51825	injector	10.1	1.60	28.97	1.2	34.76	68.86
G51114	injector	11.9	1.60	34.31	1.2	41.18	68.42
GJ51414	injector	9.3	1.60	26.86	1.2	32.23	56.29
G51315	injector	9.6	1.84	31.73	1.2	38.08	62.96
GJ51216	injector	10.8	1.80	35.11	1.2	42.13	67.03
G51615	injector	8.9	3.08	49.53	1.2	59.44	48.80
G51516	injector	11.9	2.32	49.71	1.2	59.66	62.34
GX549	injector	12.9	1.96	45.69	1.2	54.82	67.57
G51318	injector	9.4	1.44	24.49	1.2	29.39	58.08
GJ508	injector	10.3	1.44	26.78	1.2	32.13	66.16

4. Well pattern optimization

➢ Reverse seven-spot well pattern

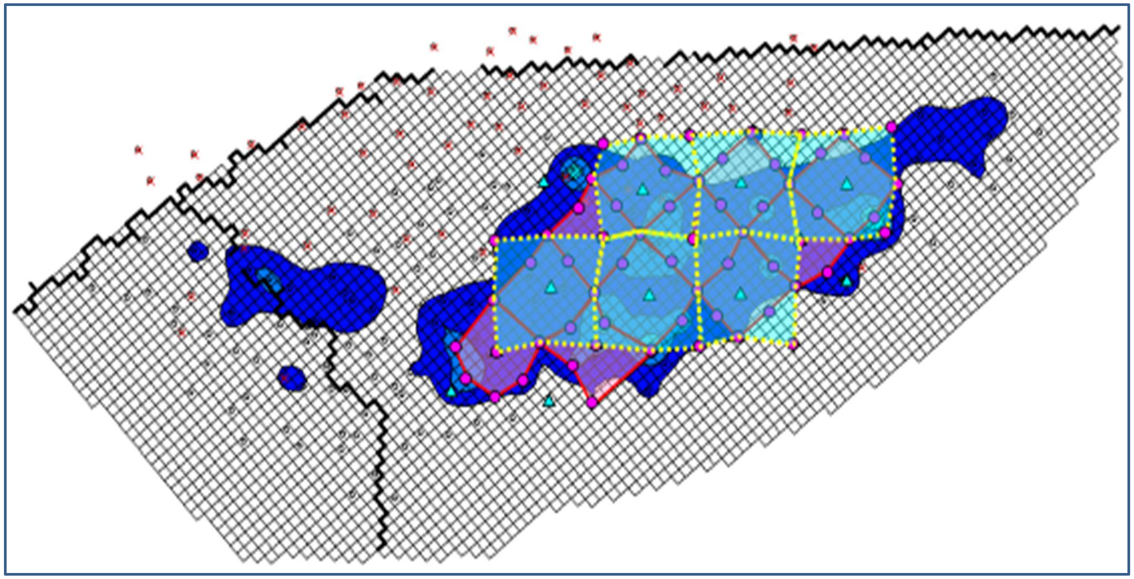
fluid production design

well name	well type	thickness (m)	fluid production (m^3/d)	well name	well type	thickness (m)	fluid production (m^3/d)
G51310	producer	8.8	14.09	G51116	producer	11.4	20.46
GJ51313	producer	11.6	22.73	G51217	producer	11.3	26.05
G51211	producer	10.1	16.15	G51613	producer	7.3	8.84
GJ51212	producer	14.4	32.20	G51316	producer	10.5	21.53
G51413	producer	8.3	11.02	GJ51416	producer	10.7	25.48
G51411	producer	7.1	5.33	G51415	producer	9.6	20.56
G51112	producer	14.5	21.58	GJ51515	producer	7.7	21.07
G51113	producer	12.9	15.96	GJ51513	producer	7.8	13.97
G51310	producer	8.8	14.09	G51116	producer	11.4	20.46
…	…	…	…	…	…	…	…

Production time: 8.4a; cumulative oil production: 72.8679×$10^4 m^3$; oil recovery: 42.96%.

4. Well pattern optimization

➢ **Reverse nine-spot diluting well pattern**



well distribution

4. Well pattern optimization

➢ **Reverse nine-spot diluting well pattern**

steam injection volume design

well name	well type	thickness (m)	injection volume (m^3/d)	P-I ratio	fluid production (m^3/d)
G51722	injector	8.9	46.33	1.2	55.60
G51718	injector	12.9	66.75	1.2	80.10
G51520	injector	11.0	57.27	1.2	68.72
G51516	injector	11.9	61.81	1.2	74.17
G51318	injector	9.4	49.05	1.2	58.86
G51314	injector	11.3	58.64	1.2	70.37
G51310	injector	8.8	45.64	1.2	54.77
G51116	injector	11.4	59.06	1.2	70.87
G51512	injector	8.1	42.09	1.2	50.51
G51920	injector	12.2	63.45	1.2	76.14
G51722	injector	8.9	46.33	1.2	55.60

4. Well pattern optimization

- **Reverse nine-spot diluting well pattern**

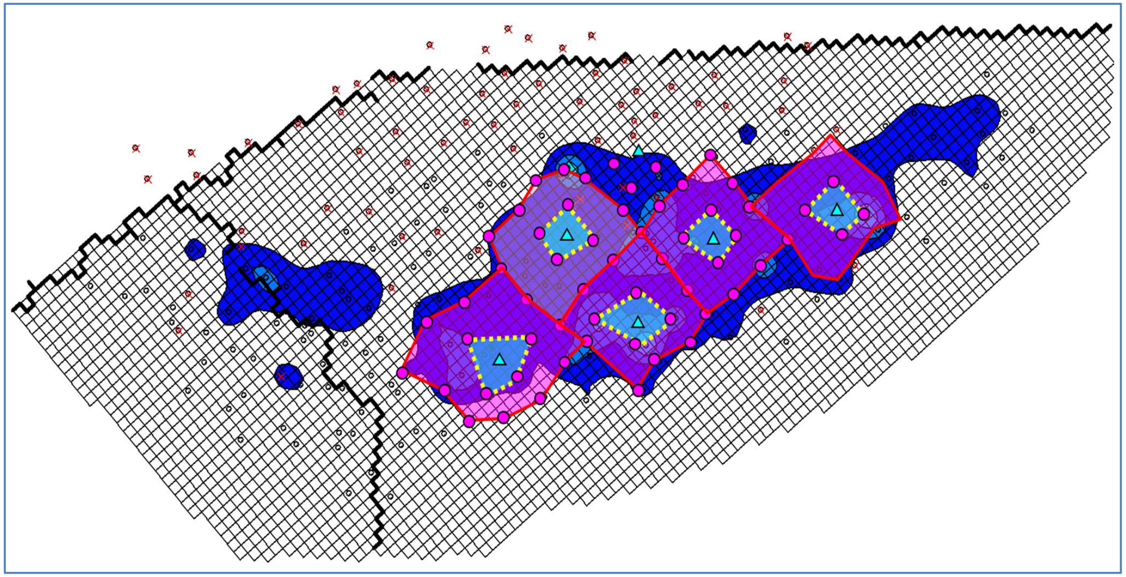
fluid production design

well name	well type	thickness (m)	fluid production (m^3/d)	well name	well type	thickness (m)	fluid production (m^3/d)
G51114	producer	11.9	12.58	G51419	producer	8.9	9.35
G51118	producer	9.0	9.51	G51411	producer	7.1	7.48
G51214	producer	9.7	10.24	GJ51414	producer	9.3	9.85
G51215	producer	9.5	10.05	G51415	producer	9.6	10.17
G51716	producer	10.5	11.09	G51922	producer	9.8	10.36
G51623	producer	10.2	10.75	G51918	producer	8.4	8.84
GJ51216	producer	8.4	8.84	GJ51416	producer	10.7	11.34
G51217	producer	11.3	11.93	G51417	producer	12.3	13.02
GJ51218	producer	8.1	8.60	GJ502	producer	10.8	11.41
…	…	…	…	…	…	…	…

Production time: 8.8a; cumulative oil production: $66.7402\times10^4 m^3$; oil recovery: 39.35%.

4. Well pattern optimization

➢ **Small return well pattern**



well distribution

4. Well pattern optimization

➢ **Small return well pattern**

steam injection volume design

well name	well type	thickness (m)	control area (ha)	injection volume (m^3/d)	P-I ratio	fluid production (m^3/d)	Control thickness (m)
GQI1(35,54)	injector	10.2	6.44	109.24	1.2	131.08	152.36
GQI2(48,50)	injector	11.9	5.64	111.29	1.2	133.55	178.45
GQI3(48,61)	injector	8.8	5.04	73.68	1.2	88.42	148.82
GQI4(59,60)	injector	12.7	5.24	110.23	1.2	132.27	191.69
GQI5(70,66)	injector	9.6	5.04	80.28	1.2	96.33	176.73
GQI6(58,49)	injector	7.2	5.48	65.38	1.2	78.46	100.97

4. Well pattern optimization

➢ **Small return well pattern**

fluid production design

well name	well type	thickness (m)	fluid production (m^3/d)	well name	well type	thickness (m)	fluid production (m^3/d)
GJ51210	producer	13.3	12.23	GJ505	producer	12.1	11.17
G574	producer	12.0	11.10	GX549	producer	12.9	11.93
G51714	producer	5.8	5.32	G51415	producer	9.6	8.88
G51310	producer	8.8	8.10	G51114	producer	11.9	10.98
G51410	producer	6.5	5.94	G51115	producer	12.6	11.64
G51511	producer	5.9	5.45	G51116	producer	11.4	10.48
G51512	producer	8.1	7.47	G51117	producer	11.4	10.46
GJ51513	producer	7.8	7.19	G51217	producer	11.3	10.41
…	…	…	…	…	…	…	…

Production time: 13.5a; cumulative oil production: $77.5727 \times 10^4 m^3$; oil recovery: 45.73%.

4. Well pattern optimization

Comparison of different schemes

layer	scheme	date	Cumulative oil production (10^4m^3)	Water cut (%)	Oil recovery (%)	producer	injector	Cumulative steam injection (10^4m^3)
IV9	Five-spot	2032.1	77.0031	91.4	45.40	21	11	348.4
	Nine-spot	2030.3	75.1309	91.0	44.29	50	11	325.9
	Reverse nine-spot diluting	2022.11	66.7402	90.2	39.35	62	10	212.5
	Small return	2027.7	77.5727	91.2	45.73	68	6	272.5
	Reverse seven-spot	2022.6	72.8679	91.6	42.96	56	21	234.6

Chapter 9 Case study of complex reservoir development

Section 2 Development Adjustment Design of Gudong 18-7 Fault Block Reservoir

Geological features

current problems

Serious interlayer interference

Well pattern imperfect

Poor reserve control

Low water drive control

physical property

Strong heterogeneity

Permeability variation coefficient: 1.84

Dash coefficient: 7.47

Reservoir evaluation and classification

- **Reserve calculation and evaluation**

layer	Oil-bearing area, km^2	Effective thickness, m	Unit reserve factor, $10^4 t/(m \cdot km^2)$	OOIP, $10^4 t$
Shaer top	0.44	6.66	10.30	30.20
Shaer bottom	0.53	11.54	10.30	63.02
Shasan top	0.52	30.90	8.60	138.26
Shasan middle	0.32	5.68	8.60	15.63
Total	0.82	27.90	9.11	247.11

Reservoir evaluation and classification

➢ Reservoir classification and evaluation

Order	Well	Layer	Oil-bearing area, km^2	OOIP, 10^4t	Fault block classification
1	18-16	S2-S3S4	0.05	13.86	quadrangle
2	18-48	S2-S3S4	0.08	12.19	strip
3	18-15	S2-S3S4	0.11	18.1	triangle
4	18-18	S2-S3S4	0.26	42.79	quadrangle
5	18-K11	S2-S3S4	0.28	74.59	triangle
6	18-12	S2-S3S4	0.16	13.61	quadrangle
7	18-17	S2-S3S4	0.03	2.65	micro block
8	18-27	S2-S3S4	0.01	0.91	micro block
9	82-X3	S2-S3S4	0.05	4.24	quadrangle
10	18-16	S2-S3Z7	0.06	6.49	quadrangle
11	18-48	S2-S3Z7	0.01	0.24	micro block
…	…	…	…	…	…

2. Main geological properties

Layers

Layer series	1	2	3
Layer	Shaer	Shasan3-4	Shasan5-7
Main pay zone	S_2S2、SX1、S_2X2	S_33^3、$S4^4$	S_35^9
Oil-bearing area, km^2	0.66	0.42	0.47
OOIP， 10^4t	93.2	88.9	65
Residual OOIP, 10^4t	21.6	13.2	17.1
Main zone thickness, m	11.8	13.6	7

2. Main geological properties

Well pattern and well spacing

➢ Well pattern optimization principle

According to the optimization technology of rational injection-production well pattern for complex fault blocks, the injection-production well pattern can be improved by fault form, area, remaining oil enrichment scale, so as to improve the degree of reserves control and water-driven use of well pattern.

The spacing of well pattern is optimized by taking into account many factors, such as water energy, structural style, formation dip angle and reservoir property.

Under the precondition of making full use of the old well, the new well should be arranged as close as possible to the fault to improve the reserve control.

2. Main geological properties

Well pattern and well spacing

- **Economical and reasonable well pattern density and spacing**

Layer	1	2	3
Oil-bearing area, km^2	0.7	0.42	0.47
Well density, $/km^2$	20.2	23.5	19.9
Well number	14	10	10
Well spacing, m	239	221	240

3. Program design of well pattern improvement

Program design principles

- According to the result of well pattern optimization, the fault block is improved and the producing reserves are increased.
- The maximization principle of reserve control degree and water drive degree;
- Ensure the development effect under the premise of economic optimization principle.

3. Program design of well pattern improvement

Program design process

Program design process can be divided into four steps:

- **Layer by layer, block by block potential design;**
- **Design of injection-production well pattern with layer-by-layer block system;**
- **Well pattern spacing optimization;**
- **Solid combination optimization of injection and production.**

3. Program design of well pattern improvement

Plan implementation

Through the combination of stratification system and fracturing block injection and production well pattern, the total number of wells designed is 35 (21 oil wells and 14 water wells), including 22 new wells (12 oil wells and 10 water wells), 3 side wells (all oil wells), 3 diversion wells and 10 old wells. Single well control recoverable reserves are 2.4×10^{4}t, reserves control degree is 93.2%, water drive control degree is 89.8%.

It is estimated that the post-implementation capacity will be 2.5×10^{4}t, the recoverable reserves will be increased by 27.3×10^{4}t, and the recovery rate will be increased by 11.0%.

3. Program design of well pattern improvement

Plan implementation

Layer	Oil well		Water well		Reserve control degree, %	Water drive degree %	Single well control of remaining recoverable reserves, 10^4 t
	Total	Turn to oil well	Total	Turn injection			
Shaer	14	0	8	3	89.3	86.1	2.2
Shasan3-4	10	0	7	1	95.9	92.3	2.0
Shasan5-7	7	0	4	0	94.7	90.2	2.1

3. Program design of well pattern improvement

Plan implementation

Project	Total well	Oil well	Water well	Current production (10^4t)	Average production in the first three years(10^4t)	15-year target			Single well control reserve (10^4t)	Oil production rate (%)
						Cumulative oil production (10^4t)	Oil recovery (%)	Water cut (%)		
Base scheme	13	13	0	1	0.93	46.83	19.0	90.2	19.0	0.4
Adjustment scheme	35	23	12	3.57	3.46	74.17	30.0	96.2	7.1	1.4
Comparison	22	10	12	2.57	2.50	27.3	11.0	6	-11. 9	1.0

Chapter 9 Case study of complex reservoir development

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Section 3 Development Adjustment Design of Low Permeability Reservoir in Baima Area, Xifeng Oilfield

1. Geological background

Relationship between permeability and oil production

Permeability/ ($\times 10^{-3} \mu m^2$)	Oil production/ (t/d)
> 2.0	> 10
1.0~2.0	10~5.0
< 0.8	< 5

2. Reservoir classification based on single well productivity

geological characteristics based on single well productivity

Well type	Sandstone thickness	Effective thickness	Porosity	Permeability/ $(10^{-3}\mu m^2)$	Oil-bearing area/ (km^2)	OOIP /(10^4t)	reserve abundance /$(10^4t/km^2)$
I	14.17	13.02	11.16	3.35	4.00	251.61	62.90
Il	15.58	11.71	10.97	1.73	8.82	495.92	56.23
Ill	14.97	9.69	10.76	1.69	4.83	219.74	45.50
IV	13.20	5.26	10.13	1.027	0.94	36.73	39.07
Average	14.48	9.92	10.76	1.95	18.59	1004.00	50.92

2. Reservoir classification based on single well productivity

Reservoir geological conditions are the internal factors for the development effect of an oilfield, and the comprehensive classification and evaluation of the study area are made by integrating reservoir geology, development level, development degree, comprehensive water cut and other factors.

Comprehensive reservoir evaluation of four types of wells

Well type	Effective thickness	Porosity	permeability $10^{-3}\mu m^2$	OOIP 10^4t	Cumulative oil production 10^4t	Oil recovery %	Water cut %
I	13.02	11.16	3.35	251.61	32.29	12.83	17.78
Il	11.71	10.97	1.73	495.92	30.49	6.15	28.30
Ill	9.69	10.76	1.69	219.74	18.81	8.56	46.49
IV	5.26	10.13	1.027	36.73	1.68	4.57	75.53
Average	9.92	10.76	1.95	1004.0	83.27	8.29	42.03

2. Reservoir classification based on single well productivity

In general, type I wells have high degree of production and low water cut, and their development level is the best. For I wells, the recovery degree is relatively high, but the water content is relatively high. Therefore, for Ill wells, the rise of water cut should be controlled while the degree of water drive control is improved. Il wells account for the largest geological reserves, but the recovery degree is relatively low, and the comprehensive water cut is not high. Therefore, Il wells are the main targets for stimulation and exploration in the future. For type IV wells, due to their thin oil layers, poor reservoir properties, and low geological reserves and reserves abundance, the potential of such Wells is not great. For high water cut wells, shut-in or diversion can be considered.

3. Well pattern adaptability analysis

(1) Effective drive distance

The effective injection-production relationship can only be established when the displacement pressure gradient between injection-production Wells completely overcomes the threshold pressure gradient in the case of low permeability reservoir waterflooding.

The relation between threshold pressure gradient and permeability is:

$$\lambda = 0.0608 K^{-1.1522}$$

So

$$\frac{p_{\mathrm{inj}} - p_{\mathrm{pr}}}{\ln \dfrac{r}{r_{\mathrm{w}}}} \frac{2}{r} = 0.0608 K^{-1.1522}$$

(2) Well pattern density evaluation

- **Pattern density based on single well productivity**

$$S = 1000 \frac{N_{\upsilon_o}}{365 A q_o E_y R_{no}}$$

Where:

S — well density, /km^2;

N — OOIP, 10^{4}t;

v_o — oil production rate;

A — oil-bearing area, km^2;

q_o — single well production, t/d;

E_y — well comprehensive utility, 0.95;

R_{no} — ratio between oil well and total well, 0.6648.

(2) Well pattern density evaluation

- **Reasonable well density**

After acquiring the optimized well density f_{opt}, the optimized control area of a single well is:

$$A_{opt} = \frac{1}{f_{opt}} = d_x d_y$$

The adjustment principle of well spacing and row spacing in anisotropic strata is as follows:

$$\frac{d_x}{d_y} = \sqrt{\frac{K_x}{K_y}}$$

Where :

d_x、d_y — well spacing of the x and y direction, m;

K_x、K_y — permeability of the x and y direction, $10^{-3}\mu m^2$;

(3) Adaptability analysis of waterflood development

- The reservoir permeability is low, the limit injection-production well spacing is small, and the current injection-production well spacing is large.
- Narrow strip channel sand body has small size and poor reservoir property.
- In general, the original well pattern can establish an effective driving system for the fractured block, but the Wells in the fractured block are prone to flooding, while the blocks with poor fracture development do not have enough driving force.
- Some effective thickness of original well pattern is difficult to drive effectively.

(3) Adaptability analysis of waterflood development

- I: The water injection system is basically adapted to the well pattern, and the degree of recovery can be further improved by infilling
- Il: The injection-production system and well pattern are not suitable
- Ill: The injection-production system and well pattern are not suitable。
- IV: The injection-production system and well pattern are not suitable for infilling and adjustment。

4. Well pattern adjustment and optimization

(1) Well pattern optimization

The original well network is a diamond inverse nine-spot well network with a spacing of 520m and 180m. The rectangular well pattern can be obtained by shut-in the wells in the original rhomboid pattern of injection Wells. The design transforms the original well pattern into rectangular well pattern and staggered row well pattern.

4. Well pattern adjustment and optimization

(1) Well pattern optimization

Comparison of main indexes of different well patterns

Well pattern type	Original diamond pattern	Rectangular well pattern	Staggered row pattern
Oil recovery after 10 years of development η, %	18.58	19.49	15.29
Water cut after 10 years of development f_w, %	78.99	76.85	72.87
Oil recovery after 20 years of development η, %	22.80	23.70	19.44
Water cut after 20 years of development f_w, %	88.32	88.07	83.36
Oil recovery after 50 years of development η, %	29.06	29.12	26.01
Water cut after 50 years of development f_w, %	95.03	95.28	92.43

4. Well pattern adjustment and optimization

(2) Encryption adjustment scheme design

The development well network in the research area is a rhomboid inverse nine-spot well network, with a well spacing of 520m and a row spacing of 180m. The remaining oil is mainly distributed where the injected water in the rhomboid inverse nine-spot well network is not affected. The remaining oil abundance is mainly concentrated in the zone with **large reservoir thickness** and **relatively high productivity**.

4. Well pattern adjustment and optimization

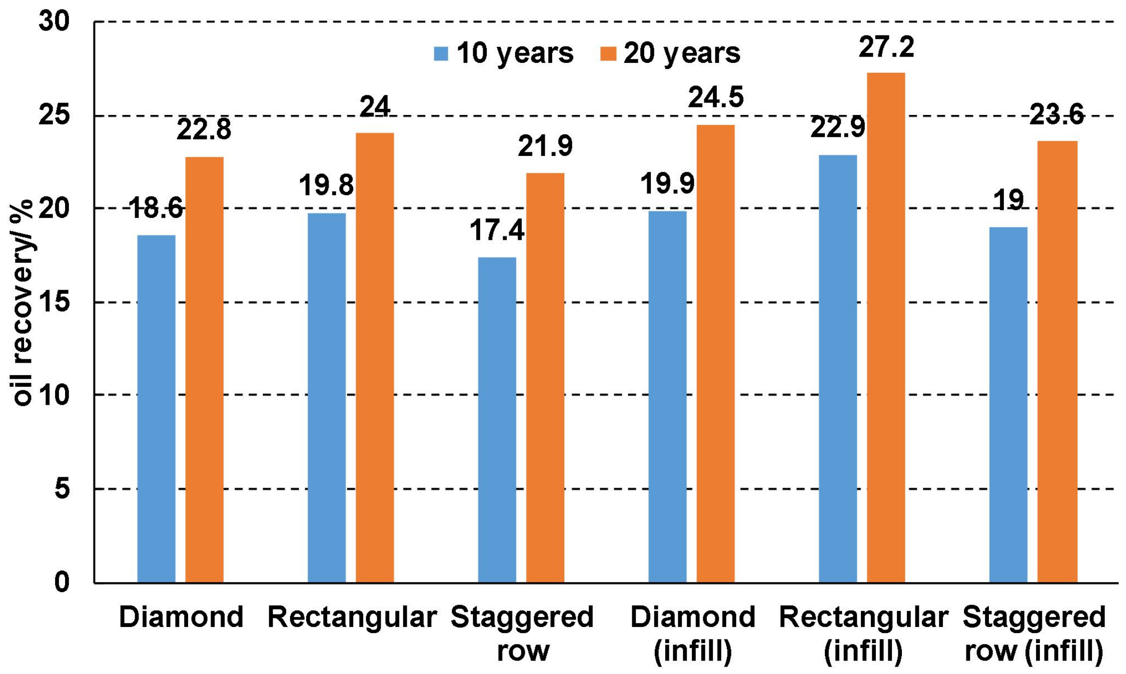
(2) Encryption adjustment scheme design

Comparison of effects before and after infilling of three well patterns

Year	Increased oil recovery, %			Average incremental oil production increment per, t		
	Original diamond	Rectangular	Staggered row	Original diamond	Rectangular	Staggered row
10	l. 32	3.03	1.54	6024	13827.81	7028
20	1.68	3.15	1.74	7666.91	14375.45	794.72

4. Well pattern adjustment and optimization

(2) Encryption adjustment scheme design



Comparison of oil recovery before and after infilling of three well patterns

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1. Reservoir geology

Fundamental physical property

Property	Porosity			Permeability($10^{-3}\mu m^2$)		Depth(m)
	Total	Matrix	Crack	Matrix	Crack	2355~4680
Value	0.05	0.043	0.007	<1	161	

Fluid property

Property	Oil density (g/cm^3)	Oil viscosity (mPa·s)	Gas density (g/cm^3)
Value	0.824	3.52	0.736

2. Characteristics of oil test and production test

- **Reservoir property**

The plane is full of oil.

The buried hill reservoir is divided into four sections vertically on the main body of xinggu buried hill.

Strong heterogeneity and great productivity difference.

Buried hill has certain energy of bottom water.

Reservoir has certain elasticity, dissolved gas energy, natural energy is not enough.

The main performance is:

The decline trend of production index

Most wells show an upward trend in gas-oil ratio

Formation pressure drop

The flow pressure of horizontal Wells has shown a downward trend

2. Characteristics of oil test and production test

- **Well production characteristics**
- ✓ **Horizontal Wells increase the rate of fracture penetration and the thickness of reservoir penetration.**
- ✓ **Horizontal Wells are conducive to high-speed and efficient development.**
- ✓ **Production data and pressure test analysis, well interference is not obvious.**
- ✓ **The reservoir has certain water absorption capacity.**
- ✓ **The reservoir is polluted to some extent, which affects the productivity of oil well.**

3. Pilot test development features

➢ **Development test design**

Selection of test area:

◆the thickness of oil layer is the largest and the development is difficult.

◆Discover time is early, geological understanding degree is high;

◆It has a certain area, reserves and strong representativeness;

◆It is beneficial to study well type, well pattern and development mode step by step.

The main contents of development test

◆Well type optimization

◆Reasonable well pattern study

◆Reasonable well spacing and reasonable development mode determination, providing reliable data for other reservoir engineering and production engineering.

3. Pilot test development features

- **Development test design**

The principles of development and design of the test area:

- reasonable, efficient and sustainable development;
- Take active action to collect static data, analyze and evaluate the natural energy of reservoir, and determine reasonable development mode, well pattern and spacing;
- On the basis of controlling large spacing vertical Wells, recognizing oil layers and reducing development risks, the new technology should be fully applied to realize less Wells and higher production, further understand production rules of metamorphic buried hill reservoirs, and determine reasonable working system.

3. Pilot test development features

- **Test results**
- The number of horizontal Wells and complex structural Wells decreased by more than 61% due to the increase of single control reserves, and higher production capacity was obtained, thus increasing the output of single Wells.
- Obtain better economic benefits;
- Seven horizontal Wells can realize overall development quickly;
- Compared with vertical Wells, the number of Wells is greatly reduced and the proportion of inefficient Wells is reduced.

4. Reservoir engineering design

(1) development layer series

- **Development principle**
- **Adhere to scientific, effective, sustainable development;**
- **Economic benefits as the center;**
- **Mfull use of new technologies to increase the production of oil reserves;**
- **Rational use of natural energy, timely artificial energy supplement;**
- **Optimize the design of plane, longitudinal well spacing, well pattern and well type, and improve the development level;**
- **Establish and improve the dynamic monitoring system, master the reservoir development dynamics, facilitate development and adjustment;**
- **To meet the requirements of oilfield development stage, the development of supporting drilling, oil production, surface engineering design and technology series.**

4. Reservoir engineering design

(2) Water injection

Although xinglongtai buried hill oil well has the ability of self-flowing at the initial stage, its natural energy is insufficient. The decrease of pressure in fractured buried hill reservoir will result in the decrease of fracture width or closure, the decrease or even sharp decrease of permeability, the loss of flow capacity, and the decrease of oil well production. The formation pressure drops, resulting in a large amount of degasification in the reservoir, and the oil viscosity will increase sharply. After waterflood development, water injection will be injected into the reservoir, which will seriously affect the oil recovery.

4. Reservoir engineering design

(3) Parameters of well type and horizontal well

➢**Well type**

◆Vertical wells are mainly used for reservoir rock recognition and control, reduce the risk of horizontal well deployment

◆Highly deviated horizontal wells are used to improve oil recovery rate and recovery rate and ensure high productivity.

◆Fishbone wells are conducive to improving the swept coefficient of water injection

4. Reservoir engineering design

(3) Parameters of well type and horizontal well

- **Main parameters of horizontal wells**
  - ✓ Length of main well section
  - ✓ Endpoint position relation
  - ✓ Branch number and branch clip

4. Reservoir engineering design

(4) Well pattern and well spacing

➢**Plan well spacing**

According to the reservoir physical parameters, when the oil price is 2039 yuan/t, the reasonable well spacing is 295m and the economic limit well spacing is 135m. According to the analysis of reasonable well pattern density, if all vertical wells are adopted, the reasonable well spacing should be between 350 and 400m, and the top should be closer. However, the well spacing can be larger simply for the purpose of controlling and recognizing the reservoir. The result of numerical simulation shows that the horizontal well spacing is around 300m and the reservoir is fully used.

4. Reservoir engineering design

(4) Well pattern and well spacing

➢**Vertical well spacing**

The deployment mode of multi-layered horizontal Wells is adopted for huge thick block reservoirs, and the main basis is as follows:

✓In line with the overall evaluation, the overall development requirements, to meet the needs of improving oil recovery speed;

✓The reservoir is thick;

✓Reservoir development is heterogeneous, especially in the longitudinal direction;

✓The development method is reasonable.

4. Reservoir engineering design

(4) Well pattern and well spacing

- **Vertical well spacing**

Gravity plays an important role in water injection in fractured reservoirs, and capillary pressure can be neglected. The flow conditions conform to darcy's law, which is a bottom-up gravity expulsion process. With multi-layer deployment, the injected water can be gradually carried upward from bottom to top, which reduces the injection and production pressure difference and is conducive to controlling the height of water cone. It will greatly improve the sweep coefficient of water flooding, increase the degree of reserves control and production, and improve the water flooding recovery.

5. Program deployment and key indicators

(1) Principle of program deployment

Give priority to the implementation of reserves, production capacity and benefits. We should give priority to the deployment and implementation of reservoirs with clear geological bodies and high reserves, with Xinggu buried hill as the main body and Chengu buried hill, Magu buried hill and Xingma Mesozoic as effective replacements, so as to maintain a long period of stable production. Horizontal wells with single controlled reserves greater than 20×10^4t and vertical Wells greater than 20×10^4t ensure that the scheme has good economic benefits. It can meet the requirements of development mode and other engineering design and dynamic monitoring.

5. Program deployment and key indicators

(2) Program design and optimization

Scheme	Horizontal well number	Vertical well number	Single well control reserve, 10^4t		Producing reserve, 10^4t	Initial oil production per year, 10^4t	Stable production time, a	Cumulative oil production of 10 years, 10^4t	Oil recovery of 10 years, %
			Horizontal	Vertical					
1	71	17	55.3	20	4268	76.6	3	674.2	15.8
2	86	20	45.0	20	4268	76.6	3	695.0	16.3
3	58	11	69.8	20	4268	57.4	3	477.9	11.2
4	34	17	115.5	20	4268	48.9	3	422.4	9.9

5. Program deployment and key indicators

(3) Development indicator prediction

➢ **Single well proration**

Section	Well name	well section, m	Oil testing			
			Pressure drop, MPa	Oil production, t/d	Effective thickness, m	Specific production index, t/(d·MPa·m)
I	XG8	3719.1~3733.1	17.8	5.83	10	0.033
Il	XG7	3653.5~3592.0	15.1	40.1	43.2	0.061
III	XG7	4014.5~3978.2	22.9	10.19	15.3	0.029
IV	XG7-10	4586.0~4633.7	3.23	22	48	0.142
Average			14.8	19.53	29.1	0.066

5. Program deployment and key indicators

(3) Development indicator prediction

➢ development index

According to reservoir engineering design for development and deployment, XG 7 and XG 7 north (Ar) plan is expected to implement 84 wells of various types, among which 10 wells are used for water injection and dynamic monitoring. There are 74 development wells (68 horizontal wells and 6 vertical wells), 29 horizontal wells (5 vertical wells and 24 horizontal wells) have been drilled, and 45 are to be drilled, all of which will be implemented within 3 years. The cumulative production capacity of the whole region is 123.7×10^4t, and the stable production period of each new well drilled is 3 years. In 2012, horizontal well test water injection was carried out, and the highest oil recovery rate reached 1.8% in the same year. The stable production time of the block is predicted to be 7 years. By 2019, the annual oil production of the whole block will be 50.2×10^4t, the oil recovery rate will be 1.0%, and the recovery degree will be 16.1%.