Practice and recognition of low permeability tight gas development in West Sichuan

-taking Xinchang JS_2 gas reservoir as an example

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Abstract. Although the low-permeability tight gas reservoirs in western Sichuan are widely distributed, of varied types, complex geological characteristics and difficult development, the reserves are of large scale and there is great potential for development. With the technology research breakthroughs of geography, development and production increase technology, this kind of gas reservoir can be developed in large scale, but at different development stages there are different challenges. In this paper, take the core technology challenges for Xinchang JS_2 gas reservoir as the representative of low permeability tight gas reservoir, solution is given in aspect of geology, and development and yield increase process technology, three leaps are achieved from scattered distribution for storage permeability body to area distribution of favorable storage; three breakthroughs of yield increase process from straight well multilayer fracturing to horizontal well segment fracturing. In addition, large-scale yield and 9 years of high and stable yield are achieved, and the inherent awareness of people that tight gas reservoir has low rate of recovery rate (30%~ 50%) is revised. The recovery rate is expected to be above 55%, providing a reference for similar gas reservoir development experience and technology.

Introduction

Natural gas in West Sichuan mountain depression are of low permeability tight sandstone gas reservoir, with "low, small, scattered and poor" geological features, i.e. reserves are low quality, single sand body control reserves are in small scale, reserves space is dispersed and connectivity of sand is bad [1]. Up to December, 2011, reserves of natural gas of $2911.11\text{x}10^8$ m is discovered, including undeveloped reserves of $1832.66\text{x}10^8$m, by 63%, and most of them belong to the low permeability tight reserves which is difficult to recover. If the gas production rate of 1% is used to the development of such reserves, it will increase the annual gas production capacity by $18\text{x}10^8$m. To a certain extent, this can relieve the situation of inadequate reserves and production tension in Western Sichuan.

Although low permeability tight gas reservoir has development features of "low, fast, short, and big", that is low single well production, fast production and pressure decline, short gas reservoir stable period, and big development difficulty; but in recent years, difficulties in of yield process technology [2-3] and geological and development [4-5] research for this class of gas reservoir are overcame, reserves use rate and single well capacity is improved, continuous and stable yield of gas reservoir is recovery rate improved, large scale development is realized, making this class gas reservoir of large development potential. The geological features and development characteristics of tight gas reservoirs is a typical low permeability gas reservoir, therefore, it is very important to summarize such experience and knowledge of similar low permeability tight gas reservoir in west Sichuan represented by Xinchang JS_2 gas reservoir.

Features of low permeability tight gas realized in west Sichuan

(1) Low permeability tight gas reservoirs in West Sichuan depression is widespread and varied

Sichuan depression has the structure pattern of three peaks and two concaves. Since 1980s, 7 gas fields have been found, mostly are low permeability tight gas realized (low permeability: effective permeability is 0.1~5md, tight: effective permeability <0.1md), widely distributed horizontally and vertically, and differs in different region and different layers and different layered features of gas reservoir. As seen from the developed gas field, vertical difference is larger than horizontal difference. From shallow to deep are a thin layer of low permeability sandstone gas reservoirs (Xinchang JP_2), tight sandstone gas reservoir in thin alternating layers (Xindu JSN), layer of tight sandstone gas reservoir (Xinchang JS_2), massive super tight fractured gas reservoir (Xinchang TX_2) and so on.

(2) Complex gas reservoir characteristics and difficult development

Due to variety complex factors interwoven of tight storage layer, water, crack and multilayer stack and huge difference (normal pressure ---extreme high pressure) of layer pressure in vertical and horizontal directions, Sichuan depression gas reservoir has complex features (refer with: Table 1); and the gas capacity is low, and distribution difference is big, and technology bottleneck exists for formation water distribution, capacity evaluation and dynamic law, so it is extreme difficult for large-scale and effective development rare.

Table 1 Basic geological parameters of the gas field in West Sichuan

Field	Layer	Sand thick(m)	Reservoir type	Reservoir							
				Abundance ($10^8m^3/km^2$)	Depth (m)	Effective thickness (m)	Original formation pressure (MPa)	Pressure coefficient (f)	Porosity (%)	permeability (mD)	Original gas saturation (%)
Xianchang	TX	30~100	Fractured, pore-fractured	6.41	4800-5300	71.1	70	1.7	3.36	0.064	50
	JP_1	3~15	Pored	1.77	588-818	6.91	10.4	1.34	12.759	3.81	60.1
	JP_2	3~20	Pored	1.63	993-1092	7.83	15.4	1.5	12.31	0.91	60.429
	JP_3	3~12	Pored	1.04	1200-1400	6.7	22	1.6	10	0.2	63
	JS_2	5~30	Pored	2.91	2099-2449	13	45.3	2	11.2	0.24	49
	JS_3	3~30	Pored	2.88	2496-2586	11.7	46.26	1.91	10.7	0.36	62
Luodai	JP	3~20	Pored	1.74	450-1200	12.17	9.77	1.03	12.36	1.8	59.18
	JSN	1~15	Pored, fracture-pored	1.32	1480－1760	15.1	17.9	1.1	6.5	0.4	60
Xiaoquan	JP_2	3~15	Pored	0.88	949.69-995.88	6.83	16.5	1.48	10.3	0.3	55
	JS	3~20	Pored, fracture-pored	1.15	2000	8.9	34.3	1.7	5.84	0.065	55.3
Hexingchang	JP_2	5~20	Pored	1.25	828-1038	8.5	18	1.7	12.26	1.1	63.4
	T_3X_2	30~100	Fractured, pore-fractured	2.8	4610-4615	34.1	71.3	1.7	4.1	0.95	61
Majing	JP_2	3~20	Pored	0.87	1438	6.6	22.51	1.56	10.75	1.03	49.7
	JP_3	3~15	Pored	1.1	1850	6.9	30.65	1.6	9.31	1.03	51.95
	JS	5~30	Pored	3.41	3100	13.65	51.9	1.7	14	0.7	58
Xindu	JP	3~20	Pored	1.2	900-1400	9.03	13.2	1.04	10.7	0.838	57.2
	JSN	1~15	Pored, fracture-pored	0.78	1700-2000	12.1	24.6	1.22	5.6	0.05	50.7

Western Sichuan depression witnessed nearly 30 years of continuous research and technological innovation, especially for breakthroughs and change of development ideas for reservoir prediction technology and reservoir refore technology of gas reservoirs of Penglai Town and Shaximiao Town. 300 billion cubic meters of reserves in scale development of low-permeability tight sandstone gas reservoir in Western Sichuan is realized, and the annual gas production capacity reaches to 3 billion cubic meters.

Practice and realization of development – with the Xinchang JS_2 gas reservoir as an example

Xinchang JS_2 gas reservoir is of flat nasal-like structure almost east to west (refer with: Figure 1), buried 2120-2560 meters deep, the single sand body is Delta plain shunt river overlay deposition, distributed in a blanket-like way (width 5-12km, thickness 16-30m); vertically there are 4 sets sand sand group (JS_2^1~JS_2^4) with high overlap level (refer with: Figure 2); average porosity 9.7%, air permeability 0.16mD, is of typical tight storage layer (refer with: Table 2). Vertically physical property of JS_2^2 and JS_2^4 is better than that of JS_2^1, JS_2^3 (JS_2^1 and JS_2^3 are defined as difficult reserves due to its lower reservoir physical properties and heterogeneity); the ground pressure coefficient is

1.92, and there is local edge water but not active; the proven reserves is 53.4 billion cubic meters; it is large bulk tight porous and extreme high pressure, structural lithology reservoir[6].

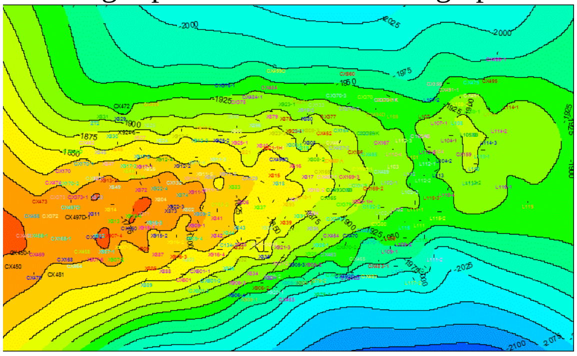

Figure 1 Top structure map for Xinchang JS_2 gas reservoir

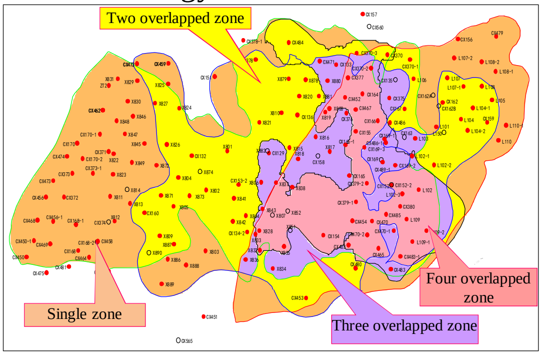

Figure 2 Overlapped gas area ofXinchang JS_2 gas reservoir

Table 2 Reservoir parameter table for Xinchang JS_2 gas reservoir

Layer	Porosity (%)			Permeability (mD)		
	Max	Min	Average	Max	Min	Average
JS_2^1	14.7	1.66	9.39	0.844	0.01	0.143
JS_2^2	15.71	3.87	10.33	0.47	0.033	0.191
JS_2^3	15.43	1.08	9.38	0.92	0.018	0.136
JS_2^4	17.07	1.87	10.35	0.98	0.022	0.238
Total	17.07	1.08	9.69	0.98	0.003	0.161

The Xinchang JS_2 gas reservoir was discovered in 1990, is currently in a period of stability. It has gone through three development methods of vertical single-layer fracture, multi-layer fracturing production segment and horizontal well segment fracturing (refer with: Figure 3). The production stage of straight well fracturing (2000~2005) is mainly for sand fracturing development of JS_2^2 and JS_2^4 gas layers, making the gas reservoir production scale reaching 2.5 million m^3/day; in the stable multilayer fracturing mining stage (2006~2009), multilayer fracturing mining technology is used and the development strategy of "excellent leading the poor" is used to improve the recovery rate of main layer (JS_2^2, JS_2^4), while the difficult mining layer reserves also counts, making gas reservoir production to 3 million m^3/days. Horizontal well segment fracturing stable phase (2010~ present) mainly uses segmented fracturing technology in horizontal wells to improve the utility of difficult mining layer (JS_2^1, JS_2^3) reserves, so that large scale of succession is realized and continued stable production of gas reservoir is kept (refer with: Figure 4).

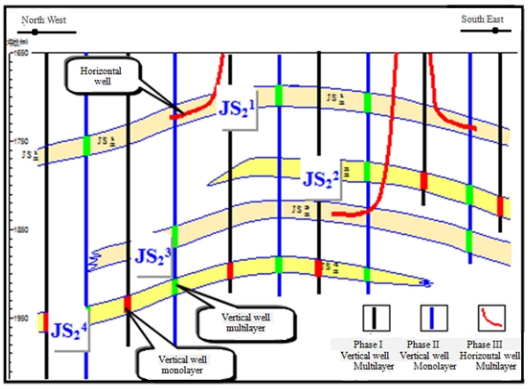

Figure 3 Different develop methods of JS_2 gas reservoir

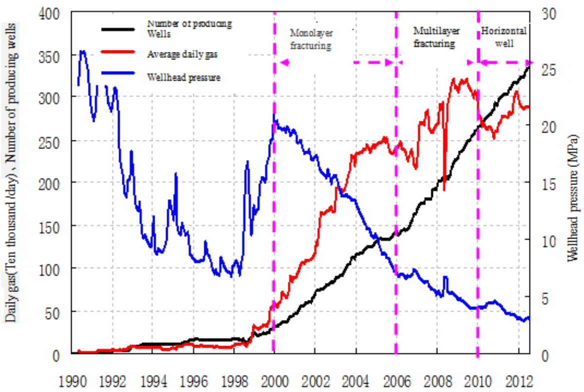

Figure 4 Development process of JS_2 gas reservoir

For the features of JS2 reservoir overpressure, low permeability tight and difficult to use, the key problems are tackled in the aspects of geology and reservoir engineering at different stages of development, in order to increase the utility of reserves and single well production, by continuous development and successive production, finally large-scale production of gas reservoir is realized.

(1) Break the bottleneck, increase reserves and production scale-- single layer sand fracturing production

From after Xinchang JS_2 gas reservoir is discovered by CX129 to 1996, more than 10 wells are drilled。The single well productivity is low and average single well perforating yield is 5,000 m^3/day, and yields most well are below economic limit production (10,000 m^3/day), so it is unable to develop the gas reservoirs. The technical bottleneck for this stage is how to improve single well productivity.

① Research sand fracturing technology and breakthrough is obtained for single-layer fracturing and production increases a lot.

In 1997-1998, single layer sand fracturing test (sand volume around 20m^3) were carried out several wells (X808, CX160, X804 and CX167, etc.) then X804 well in JS_2^4 made breakthrough (open flow 172,800 m^3/day), CX167 in JS_2^2 made breakthrough (open flow 37,800 m^3/day) (refer with: Figure 5); but difficult mining layer JS_2^1 and JS_2^3 has effect poor (below economic limit production). Then sand fracturing of JS_2^2 and JS_2^4 for 10 wells were successful, and the average single well tests yield 50,000/day on average, about 7 times that of before pressure (refer with: Figure 6).

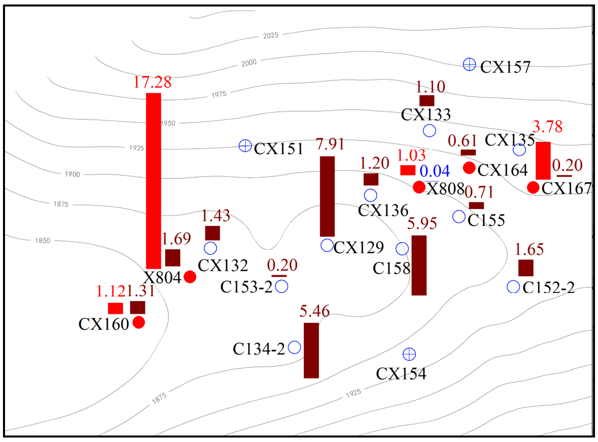

Figure 5 Open flow profile for early test drilling of JS_2 gas reservoirs

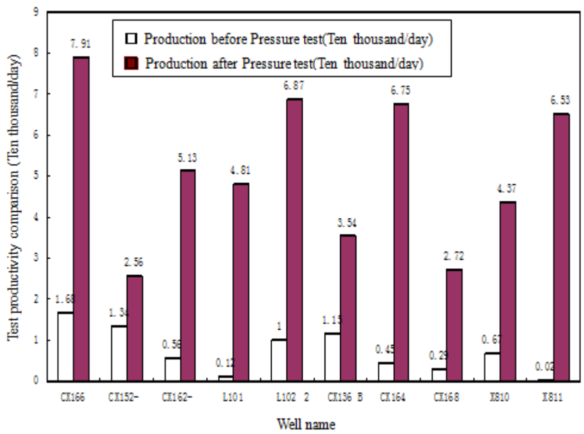

Figure 6 Comparison of yields before and after the test for early stage fractured well in JS_2 gas reservoir

② More geological knowledge and further identification of reserves.

Through multi-discipline of geology, logging and geophysical exploration, the sand body distribution range is decided and the distribution of high permeability region is definite. In this stage, based on description of river in 1994 (river is distributed in a band-like way), three dimensional earthquake information is used for gas reservoir description in 1997, and sand body distributed of band-like is clear, and "storage permeability body" is put forward (high penetration body: can naturally be put into production, but within limited area). Through static and dynamic combined method, storage layer distribution and reserves scale of Class I and II (poor band structure and limited distribution) available for production in scale is clear. On the basis described in early 1999, combined with the new well test data, reservoir classification and evaluation carried out according to the JS_2^2 and JS_2^4, it is clear that reservoir is big and of continuous distribution of Class I, II. The structural body part can be built (high production in test for several wells of Category II area), and further increased the size of proven reserves.

③ Development technique policy is clear on the basis of pilot test, and further optimization is done through numerical simulation technology.

In this stage, pilot test well district in local is selected for tight storage layer sand fracturing development (CX163 well district), development technology policies such as layer division (a set of layers, purpose layer: JS_2^2, JS_2^4; replaced layer: JS_2^1 and JS_2^3) an development well network (a set of wells, uniform well distribution, and well distance 700m) are clear for this tight gas reservoir preliminarily ; in design of development, multilayer fracturing mining test is carried out for the overlapped area.

④Effect analysis

In this stage, promoted by research on gas reservoir reserves foundation, yield increase and development technology policy, gas reservoir came into a stable stage of fast production in large scale, realizing the use and mass production of relative high quality reserves of main layers JS_2^2 and JS_2^4 (including extension reserves); to the end of 2005, reserves of 28 billion cubic meters are used with a daily production of 2.5 m^3/days (Figure 5), and the mining gas speed is close to 3.3%. Extension increase is nearly 16 billion and the results are obvious.

(2) Excellent leading the poor to boost multi-layer co-production----multi-layer sand fracturing stable production

After the first few years of fast and high speed mining, single-layer development well net has basically taken shape, and there is few room for deployment, and the single-layer fracturing effect for replacement layer (JS_2^1, JS_2^3) is still poor; gas production is in a decreasing trend and it is difficult for stable production (Figure 4). The core issue for this stage is: how to improve reservoir recovery and utility of reserves?

① More mature multi-layer fracturing production processes.

Multi-layer fracturing co-production have been carried out for test since the production stage, including two-layer, three-layer (refer with: Figure 7), and four-layer tests. Through conclusion of experience of nearly 30 wells, to 2006, double-layer and three-layer fracturing has become more mature and applied.

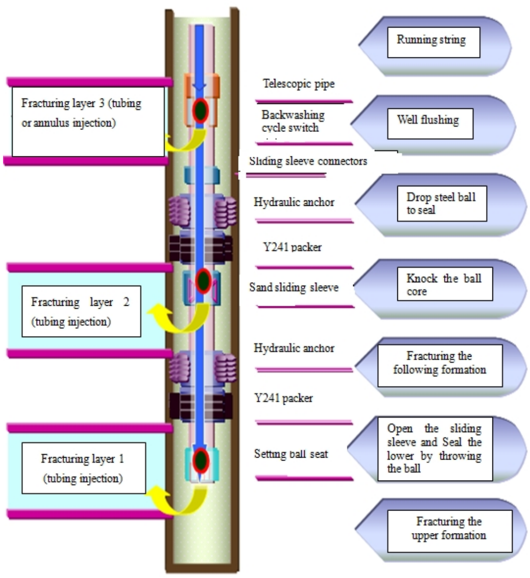

Figure 7 3-layer fracturing pipe results

② Geological knowledge was deepened relying on fine reservoir description.

On one hand, based on previous studies and new drilling files, refined reservoir classification and evaluation are carried out, reservoir development and distribution are clear. As shown in the description before and after, all kinds of reservoir distribution patterns are similar, but after refined description, the reservoir is divided into four categories, small changes of reservoir are more clear (refer with: Figure 8).

On the other hand, use refined numerical simulation technology for graph of parameters such as formation pressure (refer with: Figure 9) and gas saturation and make clear the unused reserves and remain reserves. The utility rate (70%) of main production layer JS_2^2 and $JS_2^4$is high, but still some part of high quality reserves is not use; the used area is still of local high pressure; the use rate of difficult mining layer JS_2^1 and JS_2^3 is low (18%), and the unused reserves is 8.5 m^3, mainly are low grade reserves. Generally, main production layer has not much unused reserves and the undeveloped reservoir are unevenly distributed; the replaced layer reserves are basically not use.

In addition, reserves are evaluates, the spatial overlap relations for different types of reserves are clear; high quality reserves (JS_2^2, JS_2^4) and inefficient reserves are highly stacked vertically and are available for multi-layer fracture and co-production process.

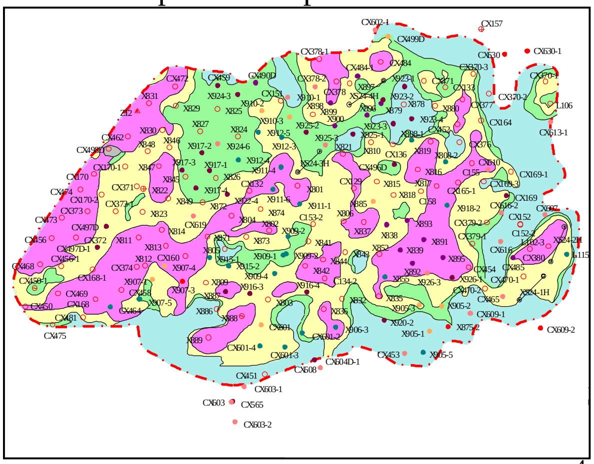

Figure 8 Classification evaluation for Xinchang JS_2^4reserve

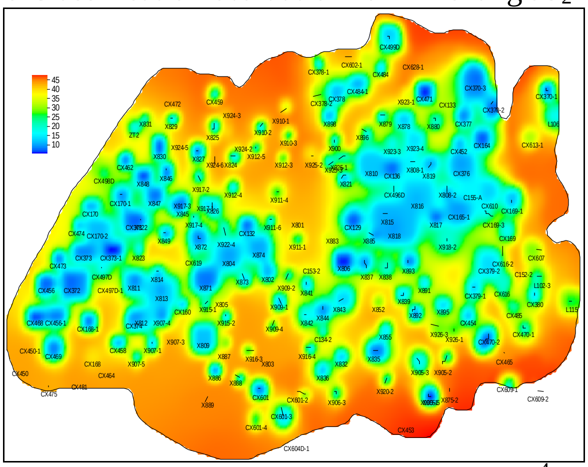

Figure 9 Local pressure plan for Xinchang JS_2^4reserve

③ Using "the excellent leading the poor" strategy, through multi-layer fracturing production , the perfection and encryption for main production layers JS_2^2, JS_2^4 are realized, also difficult mining layer is used.

Rely on refined description results and multilayer co-production test. Firstly, the Class I and II reserves of main layers have been developed and there is little room for increase of density. As shown in the single well and well area numerical simulation research results, there is no condition for single layer mass density increase for exceeded the lowest limitation of production. However, after co-production with the difficult mining layer, economic benefits can be made from area with larger well distance, and interference between layers is small after multilayer co-production. Secondly, for low permeability tight gas reservoirs such as Xinchang JS_2 gas reservoir, the production pressure difference is large, the pressure of abandoned layer is high and the proper well distance decreases along with the increase of gas price. Thirdly, for major layers, high quality reserves overlap mostly with the that of the difficult mining layer (Type I, II). The effect is better after co-production.

④Effect analysis

On the base of integrated geological research, combined with numerical simulation forecast results, taking Class I and II of major layers as the base and considering the difficult mining layer, in this stage, totally 132 adjustment wells (within which there are 108 multilayer fracturing collection mining wells and 24 single layer wells) are developed. Significantly effect is obtained and the yield is basically stable with some improvement (Figure 4). Recovery rate of major layer is improved and 7.732 billion cubic meters of reserves from difficult mining layer is used.

(3) Selecting excellent from the poor, realizing "pumping out"----- continuous and stable production of horizontal segment well fracturing

After 6 years of stable production for Xinchang JS_2 reservoir, there is no space for density increase for the major layers (JS_2^2 and JS_2^4). The use rate of difficult layers (JS_2^1 and JS_2^3) and recovery rate is low (30%), and gas production declines. Core problem for this phase is: how to improve the use rate of difficult mining layer reserves and maintain a continuous stable gas reservoir recovery?

① Based on the pilot test of horizontal well, optimize horizontal segment fracturing technology and maximize gas discharge area to improve single well productivity.

Because of very poor physical property of difficult mining layer reservoir, it is not able to be effectively used through vertical wells monolayer or multilayer co-production, so horizontal wells are used for drilling. Three horizontal well test is carried out in year of 2007-2008 to explore different well compeletion (underbalanced drilling, and naked finished well, and casing finished well,) and the storage layer transformation processes (acid pressure, and general sand fracturing, and segment sand fracturing) adaptability. In 2009-2010, horizontal well segment fracturing process technology is gradually completed, and the 10 wells with this technology applied made significantly yield effect (2~3 times), and the technology is completely promoted and executed in 2011.

②Further improve the refined description on difficult mining layer, make water and gas distribution clear, provide geological basis for optimization deployments of horizontal wells.

Through refined description, difficult mining layers JS_2^1 and JS_2^3 of JS_2 gas reservoir are mainly of Type II, and III. mainly (refer with: Figure 10), low and side parts of structure containing water of high saturated degrees (refer with: Figure 11), but no obviously gas water interface; horizontal wells are deployed high saturated area of Type II and IIIa to reduce the effect of water on capacity after horizontal segment.

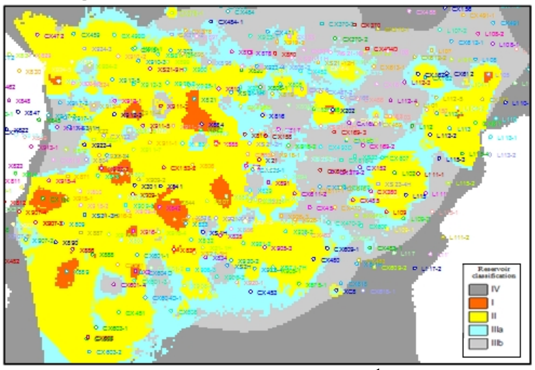

Figure 10 Type evaluation of JS_2^1 gas reservoir

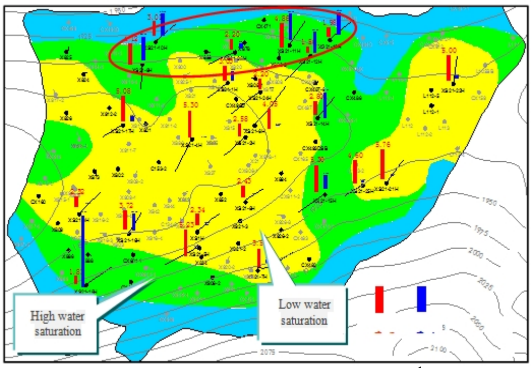

Figure 11 initial production of JS_2^1 layer horizontal well

③ Create optimization design technology for key parameters of horizontal wells, instructing reasonable development of gas reservoir using horizontal well.

Around the problem of extend the discharge area as much as possible for tight gas reservoir, horizontal plane mainly extends to the direction perpendicular to the largest principal stress so as to form horizontal cut for fracturing. For Xinchang JS_2 reservoir it is between NE30 °-60 °. For well net, parallel staggered well net is mainly considered to control gas reserves as much as possible. For well space, it is determined by combined factors dynamics research results of fracture length and gas discharge radius and economic benefits. For Type IIIa of Xinchang JS_2 reservoir or above with good water content, horizontal well distance is about 500m, around 300m from the vertical well. The vertical location of horizontal section into the layer of good physical properties is determined by well test description results and numerical simulation. For Xinchang JS_2 reservoir, the horizontal section should be deployed in the lower part of gas layer so as to get longer stable production period. The length of horizontal section shall be determined by reservoir classification evaluation results, numerical simulation and economic and technological boundaries. For I+II reserve of Xinchang JS_2 reservoir, the proper length is 600-800m, IIIa+IIIb reservoir 800-1000m. In addition, economic and technological boundaries are used to determine the initial production limitation of horizontal wells (Xinchang JS_2 gas reservoirs: 16,000-20,000 m^3/day) and economic limit reserves (Xinchang JS_2 gas reservoirs: 44-54 million m^3/day).

④ Effect analysis

Difficult reserve of Xinchang JS_2 gas reservoir effectively uses the difficult reserve, realized the production of difficult mining layer, and gas reservoir recovery is improved (as predicted, the gas reservoir recovery rat will reach 56.2%, increase by 7.6%).

Generally, from being difficult to be developed to efficient production of Xinchang JS_2 gas reservoir, mainly due to three leaps of geological understanding and three breakthroughs of yield-increasing techniques (refer with: Figure 12). The close combination of geology and engineering makes JS_2 gas reservoir a model of efficient development of tight gas reservoirs with big paradigm.

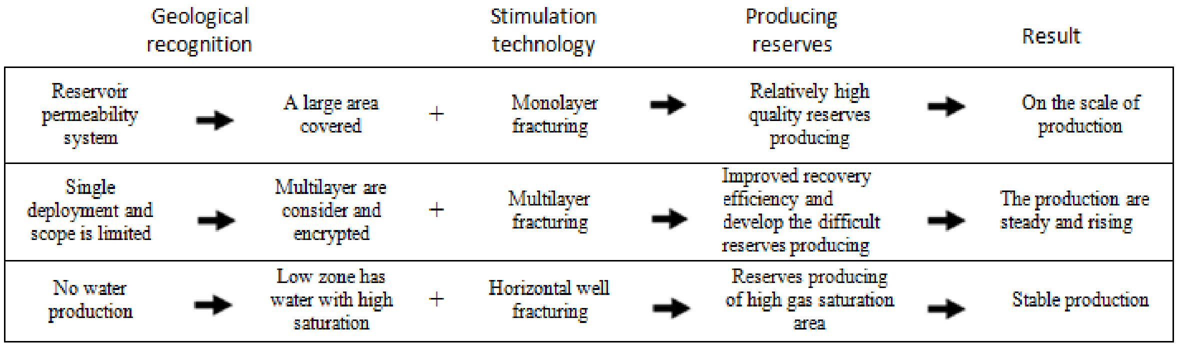

Figure 12 Geographic description and yield-increase process research of Xinchang JS_2 reservoir

Conclusions

(1) The foundation is to improve the development effect of low permeability tight gas in west Sichuan and deepen geologic understanding (continuous refined reservoir description). The key is to research engineering technology (continuous research on yield-increasing techniques). The core is to transfer development ideas (optimize and adjustment development technique policy in time).

(2) For tight oil reservoir, the recovery rate is low and the remaining reserve is large. With scientific and orderly density adjustment, sustainable and stable production can be realized and recovery rate can be maximized.

(3) For multi-layer tight gas reservoir, the combination engineering technics of vertical and horizontal wells, and the combination of single-layer large fracturing and multi-layer separate fracturing co-production can be applied, to achieve stereoscopic and effective development of economic reserves and secondary economic reserves.

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