



Old well sidetracking selection standards: Sulige low-permeability gas field, China

Yingzhong Yuan¹ · Zhilin Qi¹ · Wende Yan¹ · Ji Zhang² · Cen Chen¹

Received: 28 July 2019 / Accepted: 30 December 2019 / Published online: 22 January 2020
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Abstract

The old well sidetracking technology is an effective means to stabilize production and increase recovery in later stage of gas field development. Based on economical and reservoir geologic parameters of Sulige low-permeability gas field in China, method and procedure of old well sidetracking selection standards are established, which can effectively improve the sidetracking effect and adequately develop remaining gas. Comprehensively considering corresponding economic parameters including sidetracking drilling cost, operating cost, management cost, gas production rate and gas price, recoverable reserve standard of sidetracking well is determined first. According to gas recovery, gas-bearing area, porosity and gas saturation, standards of remaining geological reserve, reserve abundance and gas pay thickness of sidetracking well are obtained. According to extension direction and distribution characteristics of the sand body in research area, numerical simulation conceptual model of typical sidetracking horizontal well is established, and then standards of old gas well production rate and gas cumulative production rate for sidetracking are obtained. According to the standards, well Su 36-6-9CH is selected to be sidetracked as a horizontal well and its development effect is good. The method has important value of popularization and application in similar low-permeability gas reservoir.

Keywords Old well sidetracking · Horizontal well · Numerical simulation · Well selection standard · Sulige gas field

Introduction

Geological characteristics and distribution law of sand body in low-permeability gas reservoir are very complex (Hu et al. 2015). Initial development well cannot control all the reserves; therefore, many technical means are adopted to develop the residual gas in later stage of gas field development based on fine reservoir description (Wang et al. 2018). Among them, sidetracking has a unique advantage over the remaining gas in the interwell zone. It is an effective technology that allows increasing residual gas production and

recovering damaged wells (Koshovkin et al. 2008; Chuanzhi and Xiaoyan 2013). With the application of various drilling tools and instruments (Tybero et al. 1996; Qiu and Miska 1999; Pineda et al. 2013; Kong et al. 2017), the technology has been developed quickly, and it has obtained more obvious economic benefits than drilling a new vertical well. At present, sidetracking technology is very mature, not only the horizontal wells with various curvature radii can be completed in the sidetracking hole, but also the multi-branch wells can be sidetracked in a main wellbore (Yang et al. 2017; Yue et al. 2018).

Optimizing the trajectory is significant for sidetracking horizontal well. Many theories, methods and models have been used to optimize well trajectory (Sawaryn and Thoroughood 2005; Qi et al. 2014; Wang et al. 2016). Khosravian et al. (2018) used metaheuristic algorithms including genetic, ant colony, artificial bee colony and harmony search algorithms to optimize complex three-dimensional well-path length and minimize drilling cost. Manshad et al. (2019) considered the parameters in fishbone configuration well including length of main hole and side track, space between side tracks, number of side tracks, and angle between side

✉ Yingzhong Yuan
yuanyingzh0001@126.com

✉ Zhilin Qi
qizhilin76@sina.com

¹ Chongqing Key Laboratory of Complex Oil & Gas Fields Exploration and Development, Chongqing University of Science and Technology, Chongqing 401331, China

² Exploration and Development, Research Institute of Changqing Oilfield Company, PetroChina, Xi'an 710018, China

track and main hole to maximize the reservoir contact and well productivity. For the fields especially in the Middle East fields with good reservoir properties, the geological risks of oil/gas wells are small. The influences of reservoir geological conditions on sidetracking well trajectory are rarely considered in these studies (Khosravanian et al. 2018; Manshad et al. 2019). However, reservoir distribution and resource condition are the bases of sidetracking well location design and optimization, especially in low-permeability oil/gas field where the reservoir is discontinuous.

Sulige gas field in China is characterized by low porosity, low permeability and low reserve abundance (Xu et al. 2012; Ma et al. 2014; Ding et al. 2016). With the deepening of exploration and development, Sulige gas field has entered a long-term sustained and stable production period (Tan et al. 2016). Despite reserve resource in Sulige gas field is abundant and potential of stable production is great, there are many low production wells with big production decline rate because of tight reserve, thin lentic payzone, strong heterogeneity and low control reserve of single well (Lu et al. 2015; Luo et al. 2016). As development time going on, the wells with low production and low efficiency will increase gradually, the loss reserves of wells will continue to increase, and the development benefit will be further reduced. The old wells which are close to the limit of shut-in with low production and low efficiency, and those abandoned wells without production, can all be used to sidetrack horizontal well, develop the remaining reserve, increase the production rate of gas wells and increase the recovery factor. Based on economical and reservoir geologic parameters of Sulige low-permeability gas field, old well sidetracking selection standards are established, which provides a theoretical basis for efficient development of low permeability or tight sandstone gas reservoir in Sulige and other similar gas field.

The method of establishing sidetracking well selection standards

Old well sidetracking technology is very difficult to be implemented because of thin lentic payzone and strong heterogeneity in Sulige gas field. In order to improve reserve utilization degree and enhance economic benefits of gas reservoir development, it is essential to establish old well sidetracking selection standards in Sulige gas field.

Remaining recoverable reserve and economic benefits must be considered to overcome the risks of sidetracking (Lerche and Mudford 2001; Orodu et al. 2013). Based on fine description of reservoir in the interwell zone and the study of residual gas distribution, we selected sidetracking well location in the area with relative abundance of residual gas.

Method and flowchart of establishing sidetracking well selection standards are shown in Fig. 1. At first, according to corresponding economic parameters including sidetracking drilling cost, operating cost, management cost and gas price, the net present value (NPV) under different gas production rate is calculated. The value of NPV decreases as gas production rate decreases. When NPV equals to 0, the minimum gas cumulative production rate of sidetracking well can be determined. According to gas recovery, gas-bearing area, porosity and gas saturation, the standards of remaining geological reserve, remaining reserve abundance and thickness of gas pay around the old well for sidetracking are determined. According to extension direction and distribution characteristics of the sand body in research area, numerical simulation conceptual model of typical sidetracking horizontal well is established. Sidetracking well is designed and put into production under different development indexes of old wells, then gas production rate is forecasted with the conceptual model. If forecasted gas cumulative production rate of sidetracking well reaches up to required minimum gas cumulative production rate, the standards of old well condition, old gas well production rate and old gas well cumulative production rate can be known.

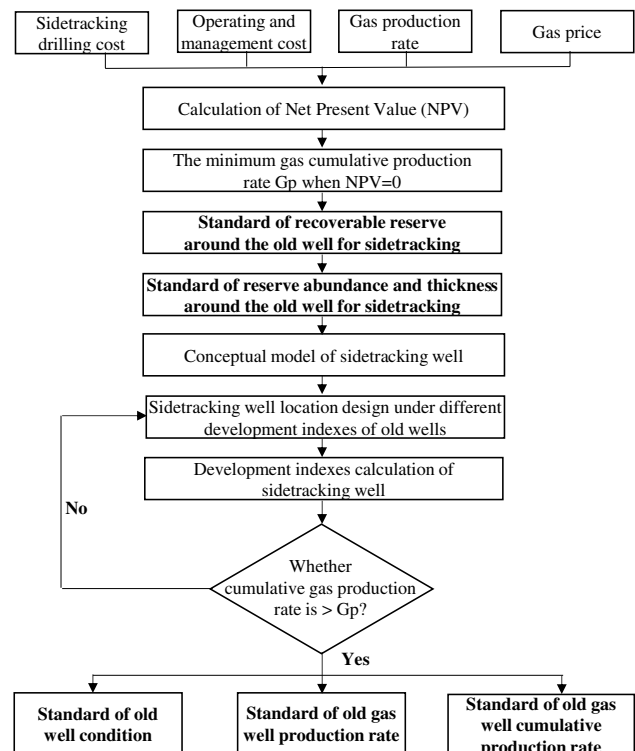


Fig. 1 Method and flowchart of establishing sidetracking well selection standards

Establishment of old well sidetracking selection standards

Standard of old well condition

Sidetracking horizontal well from old well (small hole) is a comprehensive drilling technology developed from directional, horizontal and small hole drilling technology. Using unbroken ground equipment and part wellbore of low production and low efficiency well or casing deformation well, a horizontal well after sidetracking and kicking off is drilled at an appropriate location in the upper casing of old well (Stokley and Seale 2000).

Production casing diameter of vertical well in Block Su 14 is 139.7 mm. The horizontal well has 177.8 mm of intermediate casing diameter plus 114.3 mm of liner diameter. Sidetracking in the casing with diameter of 139.7 mm belongs to small hole drilling, which has been widely used in Liaohe, Daqing, Shengli and Zhongyuan oil field of China. Sidetracking horizontal well has also been applied in Block S10 and S36 of Sulige gas field, with good experiment effects.

Summarizing the experience and lessons of sidetracking in Sulige gas field and other similar gas fields in China, sidetracking standard of old well condition is as follows. Well condition and cementing quality within 500 m above gas pay is good. In order to accord with engineering implementation condition, it is needed that there are no perforation or serious casing damage and deformed well section above the sidetracking section.

Standard of recoverable reserve

Standard of recoverable reserve for sidetracking well selection is determined with economic method. The net present value (NPV) is the cumulative present value calculated from all years in the life cycle of an investment project to the base year (usually the beginning of the investment) under a given discount rate (benchmark rate of return).

Calculation formula of the NPV is as follows:

$$NPV = \sum_{t=0}^n \frac{(CI - CO)_t}{(1 + i_0)^t} \tag{1}$$

or

$$NPV = \sum_{t=0}^n \frac{CI_t}{(1 + i_0)^t} - \sum_{t=0}^n \frac{CO_t}{(1 + i_0)^t} \tag{2}$$

where CI is net cash inflow, ¥ yuan; CO is net cash outflow, ¥ yuan; i_0 is benchmark rate of return, percentage. The internal rate of return is the discount rate at which the present

value of net cash flow for each year of the project is equal to 0 in the calculated period, which is expressed with IRR. The calculation formula is as follows:

$$\sum_{t=0}^n \frac{(CI - CO)_t}{(1 + IRR)^t} = 0 \tag{3}$$

where CI = annual gas production rate × price P. Economic meaning of IRR is that the investment is just fully recovered calculated at interest rate $i = IRR$ at the end of the life cycle of the project.

According to corresponding economic parameters, total cost of sidetracking well is ¥10,000 thousand yuan, gas price is ¥ 1.1 yuan/m³, unit operating cost is ¥ 0.14 yuan/m³ and unit management cost is ¥ 0.18 yuan/m³. Annual decline rate of gas production rate is 0.21 according to actual decline analysis results, and the IRR is calculated with 8%. Suppose different gas production rate to calculate the NPV until it is equal to 0 in the calculated period, then corresponding cumulative gas production rate is the required minimum economic remaining recoverable reserve. According to this method, the standard of remaining recoverable reserve for sidetracking well is that it must be higher than 1770×10^4 m³ (Figs. 2 and 3).

As increase in recoverable reserve of sidetracking well, the NPV in the prediction period will further increase. When remaining recoverable reserves for sidetracking well are 2000×10^4 m³, 3000×10^4 m³ and 4000×10^4 m³, the NPV is ¥1304 thousand yuan, ¥6956 thousand yuan and ¥12,608 thousand yuan, separately.

Geologic reserve standard of sidetracking well

According to recovery of Sulige gas field (40%) and the minimum standard of cumulative gas production, the standard

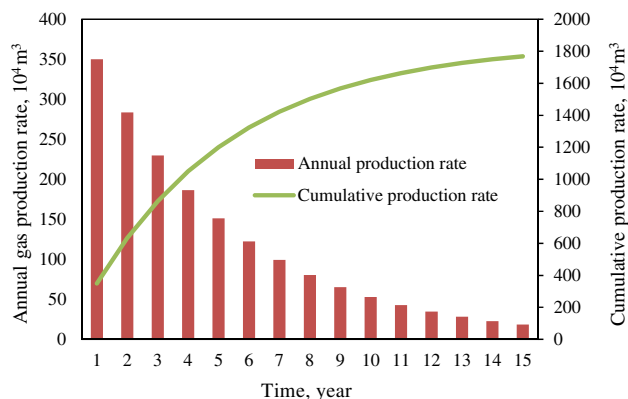


Fig. 2 Prediction of sidetracking well production and cumulative production

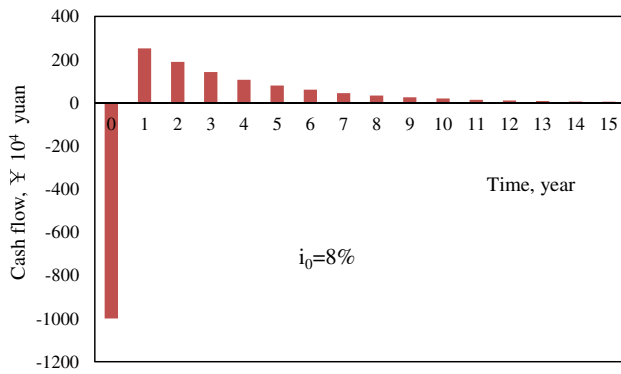


Fig. 3 Net cash flow chart with the internal rate of 8% return

of the minimum remaining geologic reserve of sidetracking well is

$$G = G_p/R = 1770 \times 10^4 \text{ m}^3 / 0.4 = 4425 \times 10^4 \text{ m}^3 \quad (4)$$

where G_p is gas cumulative production rate, 10^4 m^3 , G is geologic reserve, 10^4 m^3 , R is gas recovery, fraction. It is calculated that the remaining geologic reserve of sidetracking well should be higher than $4425 \times 10^4 \text{ m}^3$.

Reserve abundance standard of sidetracking well

At present, average distance before the target of sidetracking horizontal well in Sulige gas field is 450 m. Average length of horizontal well section is 700 m. The minimum distance to the end of horizontal well section is 500 m. The distance between horizontal wells is 500 m.

Gas-bearing area of sidetracking horizontal well is

$$A = (450 + 700 + 500) \text{ m} \times 500 \text{ m} = 0.825 \text{ km}^2 \quad (5)$$

Reserve abundance of sidetracking horizontal well is

$$\Omega = G/A = 0.54 \times 10^8 \text{ m}^3/\text{km}^2 \quad (6)$$

Therefore, reserve abundance standard of sidetracking well is that it should be higher than $0.54 \times 10^8 \text{ m}^3/\text{km}^2$.

Gas pay thickness standard of sidetracking well

Volume method of geological reserve calculation is

$$G = 0.01 Ah\phi S_g \frac{PT_{sc}}{ZP_{sc}T} = 2.37 Ah\phi S_g \quad (7)$$

where h is thickness of gas pay, m; P is formation pressure, MPa; P_{sc} is standard surface pressure, MPa; S_g is gas saturation, fraction; T is formation temperature, K; T_{sc} is standard surface temperature, K; ϕ is porosity, fraction. According to

Table 1 Formation and fluid parameters

Formation	HE ₈	SHAN ₁
Original formation pressure P (MPa)	29.91	32.64
Standard surface temperature T_{sc} (K)	293	293
Standard surface pressure P_{sc} (MPa)	0.1	0.1
Average formation temperature T (K)	381	384
Original gas Z-factor	0.966	1.054

corresponding parameters (Table 1), average value of $0.01 \frac{PT_{sc}}{ZP_{sc}T}$ is equal to 2.37.

Then, thickness of gas pay is

$$h = \frac{G}{2.37 A\phi S_g} = \frac{\Omega}{2.37 \phi S_g} \quad (8)$$

Substitute average porosity $\phi = 7.2\%$ and average gas saturation $S_g = 63.1\%$ of Block Su 14 in Sulige gas field into Eq. (8), calculated gas pay thickness of sidetracking well is about 5.0 m.

Economic parameters have important influences on calculation results. Geological selection standards for old well sidetracking under changing gas price are shown in Table 2.

For a known gas field, drilling, operation and management costs are relatively fixed, but gas price is unpredictable. Calculation results indicate that as the increase in gas price, old well sidetracking selection standards will decrease. On the contrary, the standards will increase. In the process of practical application, the standards should meet the requirements of predicted minimum gas price as much as possible.

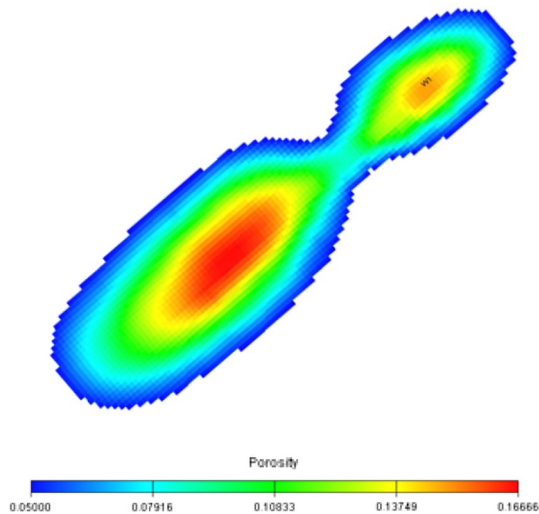
Standard of old gas well production rate

The remaining recoverable reserve of old well increases as the old gas well production rate increases. Because borehole of the old well will be plugged through cementing in the process of sidetracking, the loss of recoverable reserve will be high if the old well with high production rate is sidetracked, which is not favorable for enhancing gas reservoir recovery. If the old well with low production rate is sidetracked, the loss of recoverable reserve will be low, but the time with low production efficiency is long, which is not favorable for enhancing economic benefits of gas reservoir. Therefore, there is a reasonable production rate for old well when sidetracking.

According to extension direction and distribution characteristics of the sand body in research area, a conceptual model is established with average parameters of typical well groups in Block Su 14 (Fig. 4). The old well is located in the northeast, where the reserve is small. It will be sidetracked toward the southwest, where the remaining reserve is more abundant. Top depth of the model is

Table 2 Geological selection standards for old well sidetracking under changing gas price

Gas price, ¥yuan/m ³	0.9	1.1	1.3
Remaining geological reserve of sidetracking well, 10 ⁴ m ³	> 5950	> 4425	> 3520
Remaining reserve abundance, 10 ⁴ m ³ /km ²	> 7212	> 5400	> 4267
Cumulative thickness of gas pay, m	> 6.7	> 5.0	> 4.0
Remaining recoverable reserve of sidetracking well, 10 ⁴ m ³	> 2380	> 1770	> 1408

**Fig. 4** Establishment of conceptual model for sidetracking

3500 m. The length of long axis and short axis are 2200 m and 600 m. Effective thickness of gas pay and average porosity is 10 m and 8.0%. The reserve is 1.61×10^8 m³.

Suppose the old well is sidetracked under different gas production rate; then calculate gas cumulative production rate and the loss percentage. Research results (Table 3) indicate that when the old well is sidetracked with production rate lower than 0.2×10^4 m³/d, loss percentage of cumulative production rate is lower than 10% (Fig. 5 and Fig. 6), which is reasonable gas well production rate standard for sidetracking.

Table 3 Effect of different sidetracked old gas well production rate on gas cumulative production rate

Old gas well production rate when sidetracking (10 ⁴ m ³)	Gas cumulative production rate (10 ⁴ m ³)	Loss percentage of gas cumulative production rate (%)
0.40	1027.3	31.70
0.30	1173.7	21.96
0.25	1256.9	16.44
0.20	1358.4	9.69
0.18	1398.4	7.03
0.14	1504.1	0.00

Standard of old gas well cumulative production rate

Gas cumulative production rate of old well is related to its reservoir development condition and pressure conformance area. If reservoir of old gas well is not developed, gas cumulative production rate is low and the pressure conformance area is small. Under the condition that the reservoir in the sidetracking area meets the standards, it is suitable for sidetracking only when old well does not greatly develop the reserve in sidetracking area because of low old gas well cumulative production rate. Otherwise, there is no need for sidetracking because of good production status of old gas well.

Under different gas cumulative production rate of the old well, simulation results of pressure conformance condition and development effect of sidetracking well are shown in Figs. 7 and 8. It is indicated that under certain reserve condition, bigger old gas well cumulative production rate results in smaller sidetracking well cumulative production rate. When cumulative production rate of the old well is smaller than 1200×10^4 m³, sidetracking well cumulative production rate is bigger than 2055.7×10^4 m³. When cumulative production rate of the old well is smaller than 1570×10^4 m³, sidetracking well cumulative production rate is bigger than 1770×10^4 m³, which can meet the standard of the minimum recoverable reserve for sidetracking well. According to prediction results of sidetracking well cumulative production rate under different old well cumulative production rate (Fig. 9 and Table 4), sidetracking standard of gas well cumulative production rate of the old well is that it should be lower than 1570×10^4 m³.

In the process of actual application, under the condition that geological reserve and recoverable reserve of

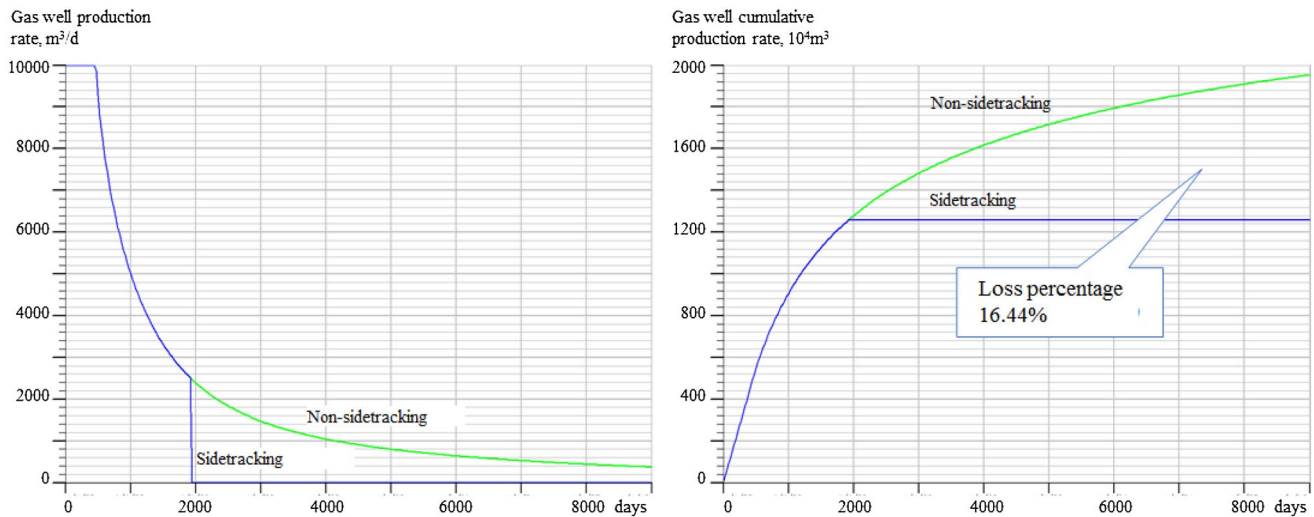


Fig. 5 Comparison of production curves between sidetracking and non-sidetracking in 2500 m³/d

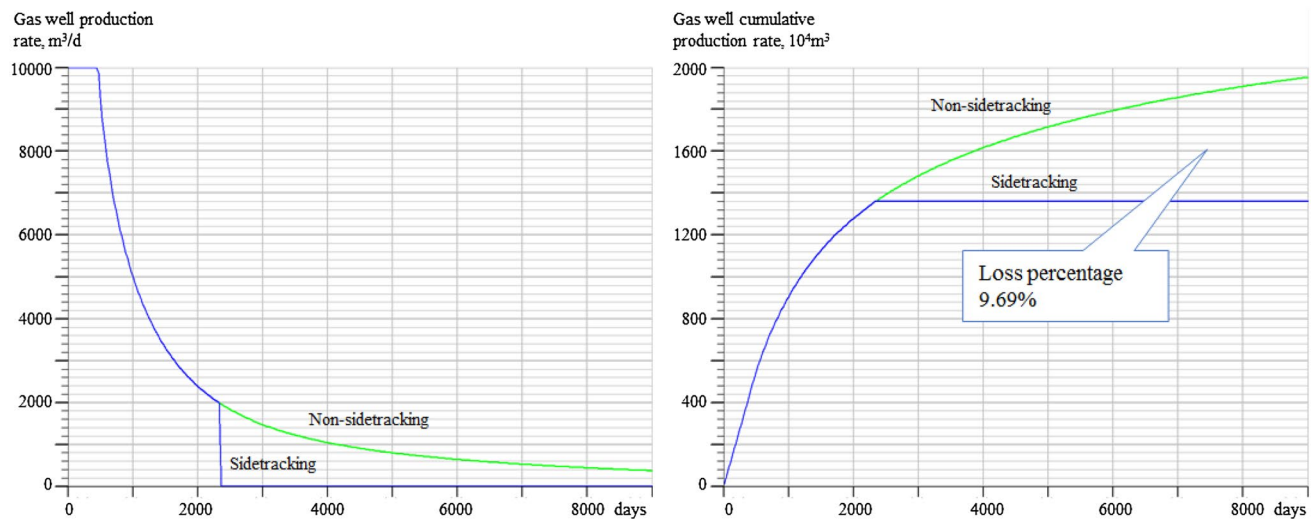


Fig. 6 Comparison of production curves between sidetracking and non-sidetracking in 2000 m³/d

sidetracking horizontal well meet the requirements, selection standards for gas production rate and cumulative production rate of the old well can be flexible to some extent. As a reminder, if gas well production rate and cumulative production rate are high, often remaining geological reserve around the old well is insufficient for sidetracking horizontal well.

Comprehensive standards of old well sidetracking selection

According to above researches, comprehensive well selection standards of sidetracking horizontal well from old well in Sulige gas field are as follows.

- (1) The distance from sidetracking old well to the neighboring well should be bigger than 1600 m.
- (2) Comprehensively considering sidetracking drilling cost, operating cost, management cost, gas production rate and gas price, in order to satisfy IRR of 8%, remaining recoverable reserve of sidetracking well should be higher than $1770 \times 10^4 \text{ m}^3$.
- (3) Remaining geological reserve of sidetracking well should be higher than $4425 \times 10^4 \text{ m}^3$, whose lower limit of remaining reserve abundance should be higher than $0.54 \times 10^8 \text{ m}^3/\text{km}^2$. Cumulative thickness of gas pay should be higher than 5.0 m.
- (4) Daily gas production rate of the old well is lower than $0.2 \times 10^4 \text{ m}^3/\text{d}$, and gas cumulative production rate of the old well is lower than $1570 \times 10^4 \text{ m}^3$. Production

Fig. 7 Pressure conformance status before and after sidetracking (old gas well cumulative production rate when sidetracked is $800 \times 10^4 \text{ m}^3$)

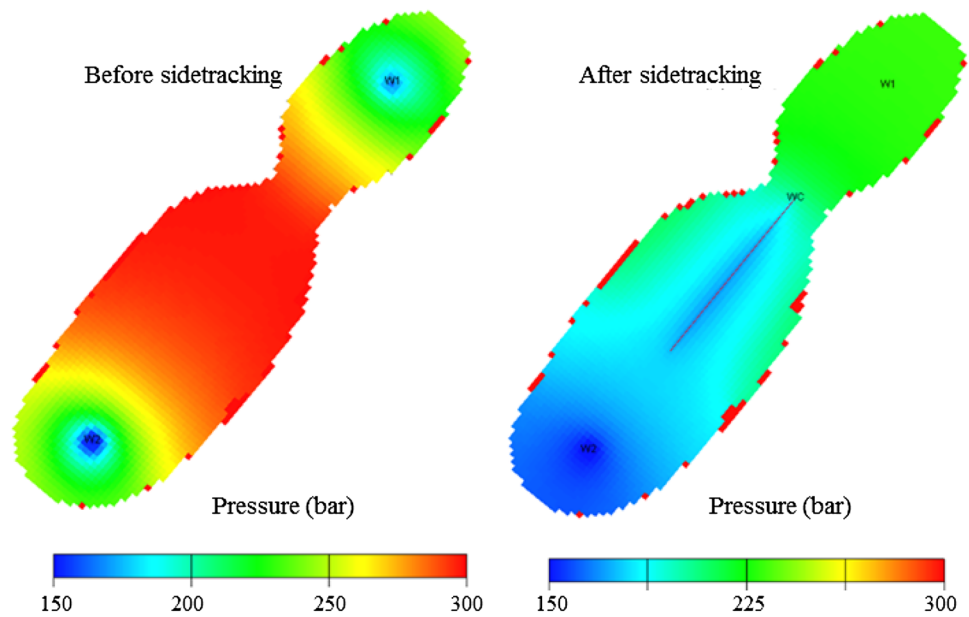
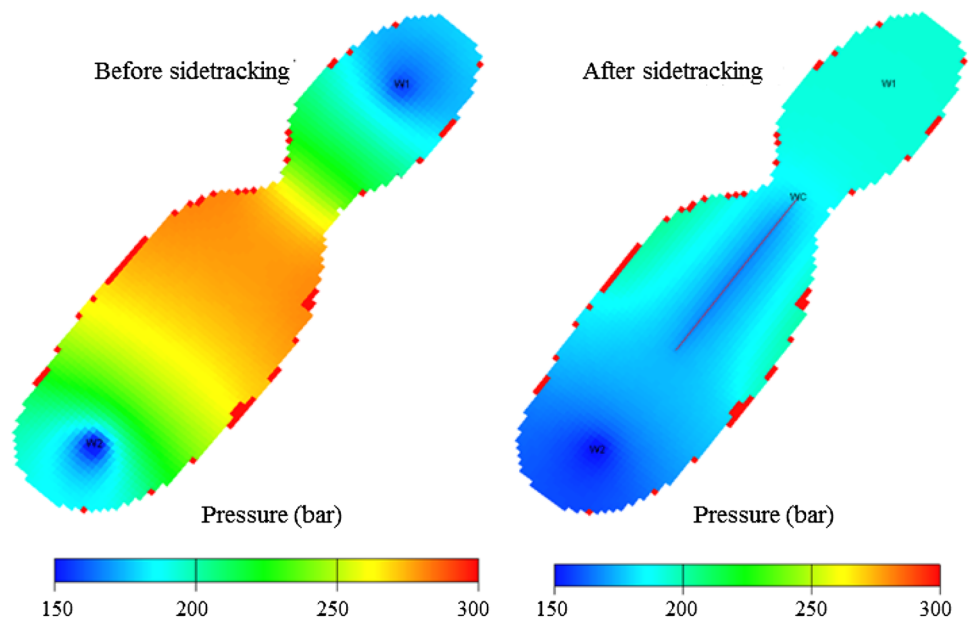


Fig. 8 Pressure conformance status before and after sidetracking (old gas well cumulative production rate when sidetracked is $1500 \times 10^4 \text{ m}^3$)



dynamics of the neighboring well is good, which indicates that the reservoir in the sidetracking area is good.

(5) Gas-bearing series including HE_8 and SHAN_1 in the neighboring well are concentrated and developed, which are beneficial to sidetrack high slope horizontal well.

Analysis on the effect of sidetracking well in Sulige gas field

At present, there are seven sidetracking horizontal wells in Sulige gas field, and all of them have been put into

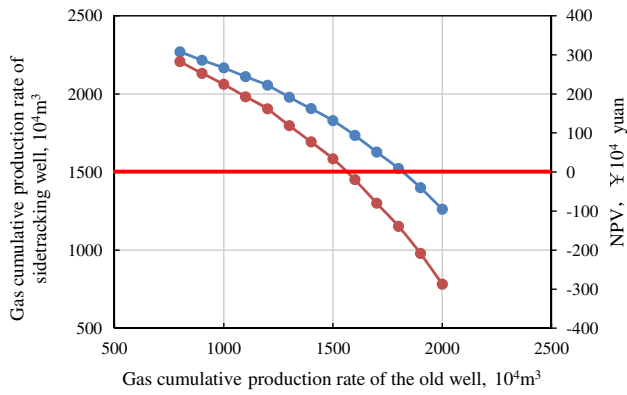


Fig. 9 Prediction of sidetracking well accumulative production rate under different old gas well cumulative production rate

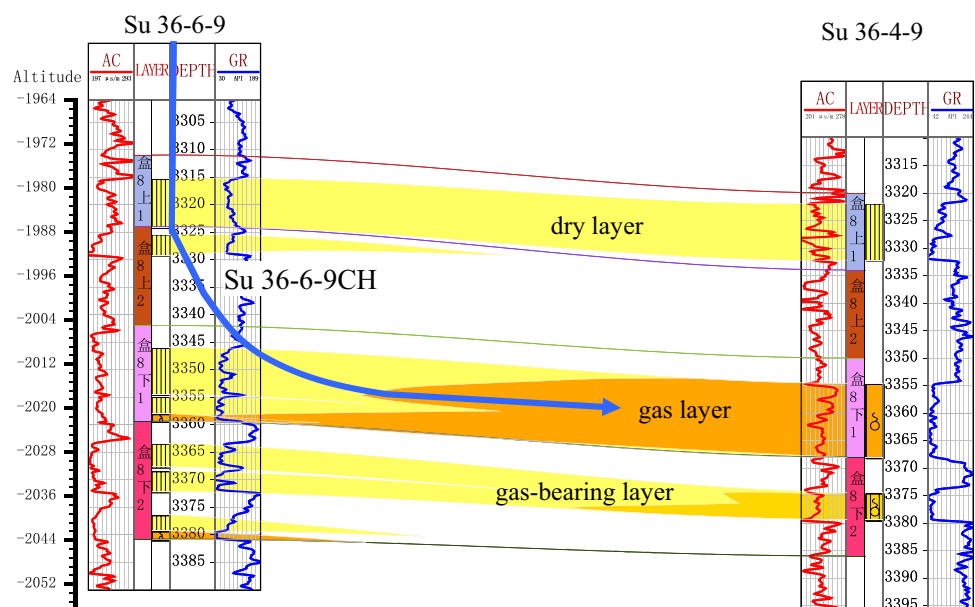
production. Initial and present average daily gas production rates after sidetracking are $3.9 \times 10^4 \text{ m}^3/\text{d}$ and $1.4 \times 10^4 \text{ m}^3/\text{d}$. Average increase in cumulative gas production rate in single well is $1554.2 \times 10^4 \text{ m}^3$. Overall effect of sidetracking well in Sulige gas field is good.

Take well Su 36-6-9 as an example. Sand thickness of well Su 36-6-9 in HE_8 is 25.6 m, and effective thickness of gas pay is 2.9 m according to well logging interpretation. Sand thickness in SHAN_1 is 25.0 m and effective thickness of gas pay is 5.8 m. Total thickness of gas pay is 8.7 m. There are three perforation intervals including 3357.0~3360.0 m and 3378.0~3381.0 m in HE_8 , 3416.0~3420.0 m in SHAN_1 . Tested absolute open flow is $1.1875 \times 10^4 \text{ m}^3/\text{d}$.

Table 4 Prediction of gas accumulative production rate of sidetracking well under different old gas well cumulative production rate

Cumulative production rate of the old well (10^4 m^3)	Cumulative production rate of the sidetracking well (10^4 m^3)	NPV ($\text{¥ } 10^4 \text{ yuan}$)
800	2268.9	282.5
900	2216.4	252.8
1000	2166.6	224.7
1100	2110.5	192.9
1200	2055.7	162
1300	1978.6	118.4
1400	1905.5	77.1
1500	1828.7	33.7
1570	1770.0	0
1600	1734.6	-19.5
1700	1627.5	-80
1800	1523.1	-139
1900	1400	-208.6
2000	1261.4	-286.9

Fig. 10 Profile of well Su 36-6-9–Su 36-4-9



Effective reserve of sidetracking well Su 36-6-9CH in HE_8 is developed, and reserve distribution in the plane and the vertical is stable (Fig. 10). Average thicknesses of sand body and gas pay are 9.2 m and 5.5 m. The old well Su 36-6-9 does not fully develop the reservoir. Considering the requirements of well spacing along sidetracking direction, azimuth of the sidetracking well Su 36-6-9CH is designed to be 10° , with horizontal well section length of about 700 m.

Well Su 36-6-9CH was spudded on October 18, 2012, and completed on November 24 with depth of 4236.0 m and horizontal well section length of 641 m. Length of drilled sandstone is 641 m. According to results of well logging interpretation, length of gas pay is 321 m, with drilling rate of 50%.

20-mm orifice flow meter is used to test the well. Tested stable tubing and casing pressure is 16.7/17.5 MPa. Daily gas production rate is $6.3529 \times 10^4 \text{ m}^3$. Static pressure and flowing pressure are 24.60 MPa and 22.35 MPa. Tested absolute open flow (AOF) is $34.0898 \times 10^4 \text{ m}^3/\text{d}$, which is 28.7 times of AOF of old well Su 36-6-9.

Sidetracking well Su 36-6-9CH was put into production on June 17, 2014. Average daily gas production rate is $2.3 \times 10^4 \text{ m}^3/\text{d}$. Up to now, cumulative production is $3633.5 \times 10^4 \text{ m}^3$ (Fig. 11). Dynamic reserve of original old well Su 36-6-9 and sidetracking well Su 36-6-9CH is $1702.55 \times 10^4 \text{ m}^3$ and $8555.1 \times 10^4 \text{ m}^3$, with increase in $6852.6 \times 10^4 \text{ m}^3$.

Generally speaking, production effect of sidetracking well 36-6-9CH is good because of developed sand body and

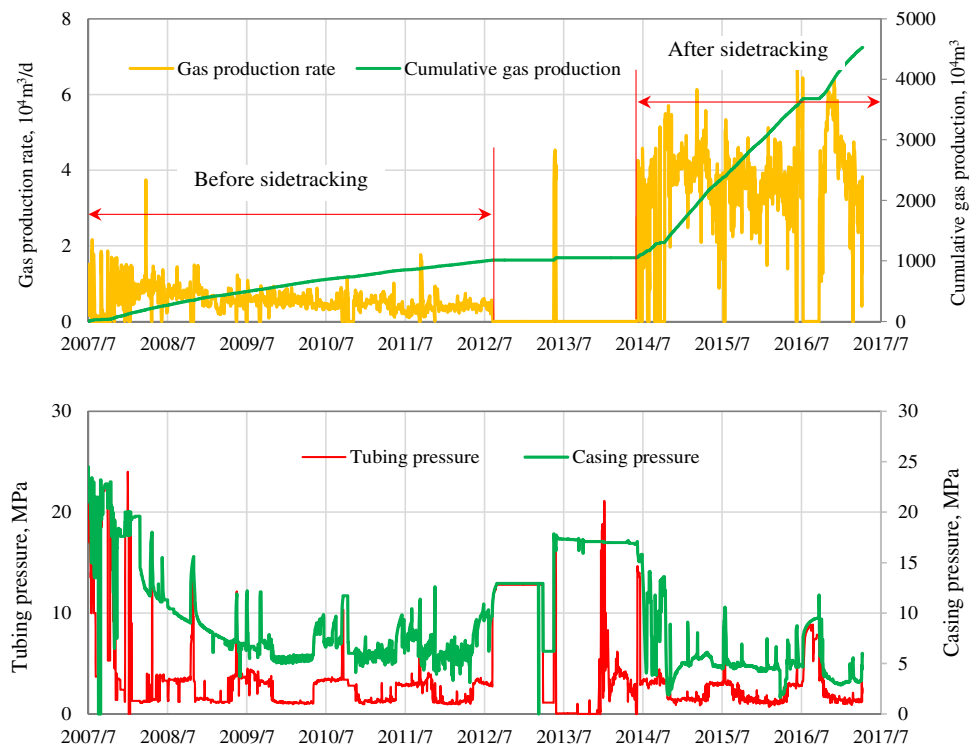
stably distributed reserve in layer system of HE_8 . Through horizontal well sidetracking and fracturing stimulation, the undeveloped reserve of this layer is fully utilized, and the well control range is enlarged.

In summary, sidetracking horizontal well is suitable for the reservoir region where remaining geologic reserve is abundant but the old well cannot effectively control it. Because different fields have different geological characteristics and different economical costs, the specific standards for old well sidetracking selection in different fields are different. The case study results on Sulige low-permeability gas field cannot be simply expanded to other fields, but the method shown in Fig. 1 is universal, and it is still applicable in other fields. Once corresponding economical parameters and reservoir geologic parameters are known, old well sidetracking selection standards can be established according to the method proposed in this paper.

Conclusions

1. Sidetracking horizontal well can effectively develop remaining gas resources around the old wells. Quantization standards of old well sidetracking selection are difficult to determine in field application. Based on economical and reservoir geologic parameters of Sulige low-permeability gas field in China, method and procedure of old well sidetracking selection standards are established, which provides a theoretical basis for quan-

Fig. 11 Production curve of well Su 36-6-9CH



titative determination of sidetracking selection standards in actual gas field.

2. Based on corresponding technical economical indexes and reservoir geologic parameters in Sulige gas field, well selection standards of old well sidetracking are obtained. Daily production rate of the old well is lower than $0.2 \times 10^4 \text{ m}^3/\text{d}$, and cumulative production rate is lower than $1570 \times 10^4 \text{ m}^3$. Remaining geological reserve of sidetracking well should be higher than $4425 \times 10^4 \text{ m}^3$, whose lower limit of remaining reserve abundance should be higher than $0.54 \times 10^8 \text{ m}^3/\text{km}^2$. Cumulative thickness of gas pay should be higher than 5.0 m. Remaining recoverable reserve of sidetracking well should be higher than $1770 \times 10^4 \text{ m}^3$.
3. According to the old well sidetracking selection standards, well Su 36-6-9CH is selected to be sidetracked as a horizontal well. Production dynamics indicate that development effect of sidetracking well Su 36-6-9CH is good. Although the example study on Sulige gas field is case by case, the universal method is still applicable in other fields. Once corresponding economical parameters and reservoir geologic parameters are known, old well sidetracking selection standards can be determined in similar low-permeability gas reservoir.

Funding The authors thank National Natural Science Foundation of China (51574052), Chongqing Basic Science and Advanced Technology Research Project (cstc2019jcyj-msxm1762, cstc2018jcyjAX0700), National Science and Technology Major Projects (2016ZX05017-001-HZ02, 2016ZX05047-004-004), Internal research fund of Chongqing University of Science & Technology (ck2017zkyb004, ck2017zkyb006) for supporting this work.

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