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Research article

Safe and efficient drilling and completion technology for deep shale gas in Sichuan and Chongqing

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ABSTRACT

The world is rich in coalbed methane (CBM) resources and has broad exploration and development prospects. In this paper, first, the technical difficulties of drilling and completion in deep shale formations in the Sichuan and Chongqing region is systematically summarized. Second, a systematic evaluation was conducted on the optimization of temperature resistance performance and trajectory control technology of the rotary guidance system. Third, evaluation and economic analysis were conducted on the experimental effects of different technologies. Results show that: (a) the optimization technology for temperature resistance performance of integrated high-temperature resistant guide head and surface cooling equipment has been formed, which can effectively reduce the circulation cooling time and improve drilling efficiency. (b) Real time measurement of underground engineering parameters and monitoring and evaluation of wellbore cleanliness can reduce drilling risks, while achieving quantitative evaluation of drilling fluid gas content. (c) Assisted by real-time optimization technology of mechanical drilling speed based on underground surface engineering parameters, the acceleration effect has been significantly improved.

1. Introduction

Shale gas is a kind of unconventional natural gas that occurs in the reservoir rock series mainly rich in organic shale in free and adsorbed states [1–3]. Shale gas has the advantages of large reserves, long production cycle and low environmental pollution [4–6]. The rapid progress of horizontal well drilling and large-scale fracturing technology has laid the foundation for the commercial development of shale gas [7–9]. The successful development of shale gas in Indiana, Michigan and other basins has promoted the upsurge of shale gas exploitation in the world [10–12]. After the United States, Canada has become another important country to vigorously explore and develop shale gas [13–15]. China's shale gas reserves are about 1.5–2.5 times of conventional natural gas reserves, mainly distributed in Sichuan Basin, Tuha Basin, Songliao Basin, Junggar Basin and other regions [16–18]. Compared with the United States, the formation and enrichment conditions of shale gas in China are special [19–21]. Different types of organic shale developed in different regions and periods have significant differences in gas production capacity [22–25].

At present, there are more than 60 oil companies involved in shale gas development, such as PetroChina, Sinopec, BP, Shell and other oil companies are conducting shale gas exploration and development [26]. In 2002, Devon Company achieved great success in horizontal well drilling and development test in Barnett shale gas reservoir [27]. At present, the main technologies used in the drilling and completion of shale gas horizontal wells include [28]: (a) rotary steering technology [29]. It is mainly used for formation guidance

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and evaluation to ensure drilling in the target area [30]. It has the advantages of low frictional and torsional resistance, high drilling speed, low cost, short well construction period, smooth and easy adjustment of wellbore trajectory [31,32]. (b) Pressure control or underbalanced drilling technology [33]. Low density fluids such as aerosol, air and foam are used as circulating media for drilling [34]. It is beneficial for improving drilling speed, shortening drilling cycles, protecting reservoirs, and reducing the occurrence of drilling accidents [35,36]. (c) Logging while drilling and measurement while drilling technology [37,38]. It can be used for precise positioning of horizontal wells, guiding targeted geological targets, making drilling operations faster, safer, and more effective, thereby reducing drilling time and costs [39,40]. (d) Foam cementing technology [41,42]. It can be used to solve the problem of poor cementing quality in low pressure and easy to leak long sealing horizontal sections [43–45] After casing cementing and perforation completion, high-speed fluid is sprayed through the casing and reservoir through the nozzle after casing perforation, thus achieving the purpose of perforation [46,47]. Although open-hole perforation completion can effectively avoid damage to the reservoir caused by cement slurry, it is also cost-effective [48,49]. Leonard [50] evaluated the effectiveness of Barnett shale completion by using completion analysis techniques such as radioactive tracer, logging and chemical tracer on synchronous fracturing horizontal wells in Shale gas reservoir. Waters [51] analyzed the completion design process of Woodford shale gas well from the perspective of optimal fracture spacing. Pope [52] summarized the parameter selection during the completion process of the Haynesville shale based on on-site experience. Soliman [53] studied the influence of fracture spacing and net pressure in fractures on the formation of complex fractures. Roussel [54] studied the effect of fracture spacing on the formation of multiple transverse fractures in horizontal wells, taking into account the influence of interlayer. Thompson [55] used self-organizing graph method to conduct principal component analysis on 11 completion factors of high and low production wells in the Haynesville shale formation, and obtained the variation patterns of the main completion parameter values that affect productivity. Cipolla [56,57] discussed how to select the optimal fracturing stages and perforation clusters in tight gas and shale gas well completion, and proposed a set of algorithms and processes. Roussel [58] studied how to minimize the fracture spacing under the condition of ensuring that the fractures between fracture sections do not interfere with each other. Wutherich [59] summarized the perforation completion optimization method of Marcellus shale gas horizontal well. Durst [60] compared the advantages and disadvantages of two completion methods, open hole and cement cementing. Yu et al. [61,62] established a set of optimization systems with the goal of maximizing production capacity and net present value by using CMG software and design of experiments method. Falola et al. [63] conducted research on potential high-yield wells drilled in shale and elucidated the geophysical characteristics of water sources during shale drilling. Basfaret al. [64] studied the effect of Qusaiba shale kaolin from Saudi Arabia on the properties of WBDF. Sichuan and Chongqing deep shale gas is mainly located in Weiyuan, Luzhou, Yuxi and Changning [65,66]. Therefore, based on the drilling example of Great Wall Drilling Company in deep shale gas, this paper systematically combs the technical difficulties of Sichuan and Chongqing deep shale gas drilling and completion, summarizes the main key technologies and application effects, and provides reference for subsequent drilling and completion construction.

In summary, at present, systematic research has been conducted on the mechanical characteristics of shale drilling and completion both domestically and internationally, and a relatively systematic technical system has been formed. However, there is a lack of systematic summary of the technical difficulties in drilling and completing deep shale in the Sichuan and Chongqing region, and there is a lack of systematic experiments and practical research on the key technologies for drilling and completing deep shale. Therefore, this article takes deep shale drilling and completion in the Sichuan and Chongqing region as the research object, and systematically carries out the following three parts of research work: (a) Systematically summarizes the technical difficulties of drilling and completion in deep shale formations in the Sichuan and Chongqing region; (b) A systematic evaluation was conducted on the optimization of temperature resistance performance and trajectory control technology of the rotary guidance system, the technology of increasing drilling speed in large-sized well sections, the integrated technology of underground safety in engineering logging, and the prevention technology of gas well annular pressure; (c) Evaluation and economic analysis were conducted on the experimental effects of different technologies.

2. Difficulties in drilling and completion of deep shale gas in Sichuan and Chongqing

2.1. The failure rate of the rotary guide system in the deep high-temperature well section is high, and effective construction is difficult

The buried depth of deep shale gas exceeds 3500 m. Taking Luzhou Block as an example, the Geothermal gradient is as high as 2.85–3.5 °C/100 m [67], and the formation temperature of some wells is as high as 150 °C. General rotary guidance tools are insufficient to overcome long-term high-temperature underground environments. At the same time, it will accelerate the aging of electronic components, greatly affecting drilling efficiency. During the drilling of well L202 in the 4524–5400 m section, high

Table 1
Statistics on the number of failures of rotary guidance instruments in some deep blocks of Great Wall Drilling.

Construction area	Number of completed wells	Average well depth (m)	Average vertical depth (m)	Average well temperature (°C)	failure frequency	Fault time (h)	Mean well failure time (days/well)
Weiyuan Ziying	27	5902	3674.26	139.2	29	60.83	2.25
Jilin Liuzhuan	2	6213	3972.83	151.5	10	837	6.19
Luzhou Deep Layer	15	6145	3991.3	145.9	45	2802	7.78
Amount to					84	5099	4.83

temperatures caused instrument failures such as tool blockage, communication abnormalities, gamma abnormalities, and MWD signal failure [68]. Frequent tripping in and out of the hole is necessary, which seriously affects the drilling speed. Table 1 shows the failure of rotary steering instrument caused by high temperature during drilling in some deep shale gas blocks of Great Wall Drilling Company. It can be seen from Table 1 that high temperature environment is one of the key difficulties restricting the safe and efficient development of deep shale gas.

2.2. Complicated and frequent occurrences of well leakage and instability, resulting in long drilling loss cycles

Deep shale often has stronger brittleness, more developed fractures, and a higher risk of downhole complications such as lost circulation and instability. Table 2 summarizes the leakage situation of drilling at different layers in some deep blocks by Great Wall Drilling. It can be seen from Table 2 that the increase in drilling cycle and cost caused by lost circulation is a problem that cannot be ignored in safe and efficient drilling of deep shale gas. At the same time, due to the influence of rock properties and geological environment such as hard and brittle texture, developed bedding and complex in-situ stress, wellbore instability accidents often occur, which seriously hampers the efficient development of deep shale gas.

2.3. The actual efficiency of downhole tools is unclear, and the acceleration measures are difficult to be precise

Table 3 shows the difference between the average completion indicators of some deep blocks of Great Wall Drilling and the regional indicators of wells. It is a common phenomenon that using the same construction template and acceleration tools, it is still difficult to meet the standards. From Tables 3 and it can be seen that the actual efficiency of downhole tools is not clear enough. The acceleration measures are difficult to be precise. The technical template still needs to be upgraded. Especially as the drilling depth advances deeper. The geological conditions have changed, and the existing template content such as drill screw selection and drilling parameters cannot meet the needs of on-site construction well. There are differences in the selection of drilling and completion tools, drilling parameters, and cyclic drilling time among different construction teams. The efficiency of drilling and completion also shows differentiation.

2.4. The problem of pressure in the technical casing annulus is prominent, and the cementing technology urgently needs to be upgraded

In the process of deep shale gas drilling, due to mud cake attached to the well wall, it is difficult for cement paste to be directly cemented with the well wall, which is easy to form micro annulus, thus affecting the cementing quality. During the production process, there is pressure in the annulus, which poses a risk of well control [69]. For example, multiple wells completed in 2021, such as Wei 204H19-2 and Wei 204H14-1, have experienced casing head pressure or square well gas leakage. Therefore, full attention should be paid to the bonding quality of the second interface in cementing, and the cementing technology urgently needs to be upgraded.

3. Main key technologies and application effects

3.1. Optimization of temperature resistance performance and trajectory control technology for rotary guidance systems

The temperature in the horizontal section of deep shale gas horizontal wells is high, and the circulating temperature can reach 140–150 °C. At present, most directional tools on the market must stop drilling when the temperature exceeds 125 °C and use cooling technology to circulate and cool down. This makes it difficult to achieve continuous drilling and hinders the smoothness of construction. Therefore, there is an urgent need to improve the temperature resistance performance of the existing spin guide system.

3.1.1. High temperature resistant guide head and ground cooling equipment

The secondary circuit communication board, main control board, motor control board, and motor power supply board were renovated and replaced with high-temperature resistant circuit boards. After indoor testing, the high-temperature resistance has been

Table 2
Statistics of drilling losses at different layers in some deep blocks of the Great Wall Drilling Company.

Construction area	Horizon	Number of lost wells	Lost time (h)	Loss of drilling fluid (m^3)
Jilin Liuzhan	Maokou Formation	14	740.63	2847.3
	Qixia Formation	11	370.05	1267.8
	Hanjiadian Group	4	264.9	719
	Longmaxi Formation	1	126.6	137.3
	Baota Formation	1	45.43	14.4
Weiyuan Ziying	Maokou Formation	2	83.62	128.3
	Shiniulan Formation	5	126.12	811.7
	Longmaxi Formation	2	9.58	15.3
Luzhou Deep Layer	Changxing Formation	1	135	210.6
	Maokou Formation	1	35.75	52.2
	Qixia Formation	3	315.33	443.8
	Hanjiadian Group	2	282.33	180.41
Amount to		47	2535.34	6828.11

Table 3
Statistics of the gap between the average indicators of completed wells and regional indicators in some deep blocks of Great Wall Drilling.

Block		Pure drilling	Circular eyeliner	Underground fault	Instrument has no signal	Amount to
Zigong liuzhuan	Average index	34.16	15.6	3.91	4.27	
	Zi215H1-2 well	29.29	11.86	0	0.21	
	Gap	4.87	3.74	3.91	4.06	16.58
Luzhou deep layer	average index	31.7	13.96	3.81	4.46	
	Yang 101H11-4 Well	19.69	8.93	0	0	
	Gap	12.01	5.03	3.81	4.46	25.30
Weiyuan ziying	Average index	32.24	12.27	5.77	4.91	
	Wei 202H85-1 well	28.27	6.71	0	2.48	
	Gap	3.97	5.56	5.77	2.43	17.73

increased from 135 °C to 145 °C. In 2021, the failure rate of Great Wall Drilling Company in deep shale gas drilling will be 2.41 times/thousand hours after the independent transformation of high-temperature resistant guide head. A decrease of 55.5% compared to 2020. At the same time, upgrade the surface cooling equipment to reduce the circulating temperature at the bottom of the well by 5 °C. Effectively reducing circulation cooling time and improving drilling efficiency. Through on-site tests on two wells, Wei 204H14-2 and Wei 204H14-5, it was found that the temperature at the completion of drilling was higher than 130 °C, while the temperature at the actual drilling was higher than 140 °C. However, the rotary guidance system did not malfunction, achieving the high-temperature resistance upgrade of the instrument equipment.

3.1.2. Fine control technology for rotary guidance trajectory

On the basis of ensuring the high temperature resistance and reliability of the instrument, two measures are taken to achieve precise trajectory control in the four opening inclined section on the Wei 204H14 platform. One is to analyze element logging data and azimuth gamma changes in real time, proactively predict formation trends, and achieve precise landing. The second is the formation of “bedding drilling technology”. After finding the geological dessert, actively reduce the rib force of the rotary instrument by 16%. By allowing the trajectory to increase or decrease naturally along the changes in the strata, frequent trajectory adjustments are avoided and the number of command transmissions is reduced. Improve the mechanical drilling speed while achieving a drilling rate of up to 98.3%.

3.2. Speed up technology for large-scale well drilling

3.2.1. Efficient PDC drill bit + high torque equal wall thickness screw “three pass drilling” technology

For φ311.1 mm large-sized well sections, targeted drill bit selection and optimization design have been adopted based on the rock characteristics of different formations, forming an efficient PDC drill bit + high torque equal wall thickness screw “three pass drilling” technology. At the top of Xujiahe Formation-Jialing River Formation, the limestone formation of Leikoupo Formation is highly abrasive, which is a difficult formation for speed increase in this well section. Optimize and improve the model DS664H-KY drill bit, using 16 mm main cutting teeth and a 6-blade double row tooth design. Select high resistance grinding flat teeth to enhance the anti-grinding ability of the drill bit. The mechanical drilling speed of the test well is 10.1 m/h, which is an average increase of 9.3% compared to the block.

From the top of Jialing River Formation to the middle of Maokou Formation, the bauxite mudstone of Longtan Formation has strong plasticity and low penetration rate, which is the difficult stratum for speed increase in this well section. By optimizing and improving

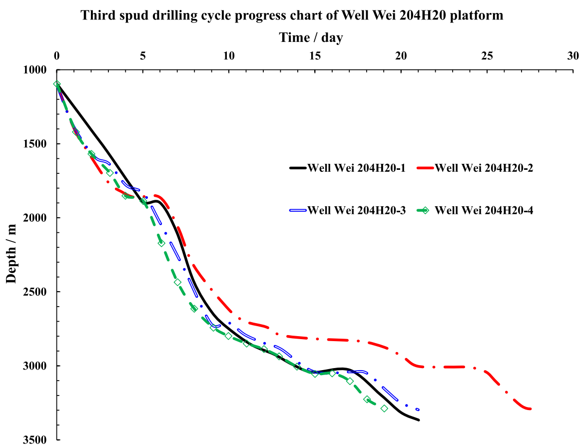

Fig. 1. Progress chart of the third drilling cycle of Wei 204H20 platform.

the model DS653H-KY drill bit, it adopts a 16 mm main cutting tooth and a 5-blade double row tooth drill bit design. The cutting teeth use imported teeth with high impact resistance to enhance the drill bit's impact resistance. The mechanical drilling speed of the test well below the Longtan Formation is 4.57 m/h, especially when the mechanical drilling speed of the Longtan Formation reaches 3.13 m/h, which is 52.15% higher than the average (2.04 m/h) of the block.

In the middle of the Maokou Formation to the top of the Shiniulan Formation, the hard interlayer of flint nodules is the main factor affecting the mechanical drilling speed. Select the improved model DS664H-KY drill bit, which adopts a 16 mm main cutting tooth and a 6-blade double row tooth drill bit design to enhance the drill bit's crushing ability to the formation and reduce the impact damage of the front teeth, thereby improving the mechanical drilling speed of the drill bit. The mechanical drilling speed of the test well this time was 5.21 m/h, which is an average increase of 14.5% compared to the block. Meanwhile, the 7LZ244 × 7.0-DW (1.25°) model high torque equal wall thickness screw is preferred, with a maximum torque of 31500 N·m. Compared to the original ordinary screw, the torque is increased by 30%, ensuring the transmission effect of drilling pressure and rotation speed.

The above technology has achieved three rounds of drilling completion for the 311.1 mm section of Well Wei 204H20-4: footage of 2198 m, pure drilling time of 302.4 h, and mechanical drilling speed of 7.27 m/h. The drilling cycle is 18.87 days, which is 24.52% shorter than the assessment indicators. The fastest drilling cycle is recorded in the 311.1 mm well section of the Chuangwei 204 deep block, as shown in Fig. 1.

3.2.2. Real time optimization technology for mechanical drilling speed based on underground surface engineering parameters

A real-time optimization system for mechanical drilling rate was developed using the engineering parameters measured underground and ground engineering parameters modeling, and the Changepoint Intelligent Algorithm. Adjust construction parameters in real-time through software analysis and optimization. The average drilling time in the 2904–2915 m well section decreased to 15.84 min/m, which increased the speed by 43.43% compared to before optimization. Compared to the adjacent well H20-3 on the same platform, the average length of the same well section (21.91 min/m) has increased by 27.7%. It can be see from Fig. 2 that the acceleration effect is significant [70].

3.3. Integrated underground safety technology for engineering logging

3.3.1. Quantitative evaluation technology for gas content of drilling fluid

We have designed and developed a pneumatic quantitative degasser for drilling fluid. A new design has been made for drilling fluid filtration, drilling fluid extraction, flow detection, multi-layer stirring degassing, start stop control unit, and signal acquisition unit, as shown in Fig. 3. Based on this device and combined with gas logging and total hydrocarbon analysis parameters, a calculation method for drilling fluid gas content and a calculation method for formation rock gas content have been established. First, calculate the degassing rate of the drilling fluid, as shown in Eq. (1):

$$q_{df} = q_{sc} - q_a \tag{1}$$

Where, q_{df} is the degassing rate, q_{sc} is the gas flow rate in the sample, q_a is the compensation air flow rate.

Second, calculate the gas content per unit volume of drilling fluid again, as shown in Eq. (2):

$$R_i = \frac{q_{df}}{(F_d \times E_f)} \tag{2}$$

Where, R_i is the gas content per unit volume of drilling fluid, F_d is the volume of mud sampled quantitatively, E_f is the degassing efficiency.

Gas content per unit volume of rock, as shown in Eq. (3):

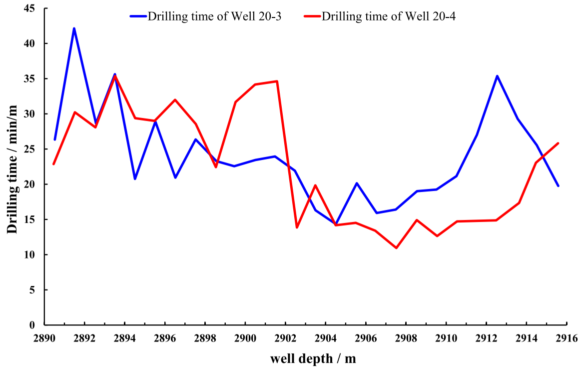

Fig. 2. Comparison of drilling time between two wells before and after using real-time optimization technology for mechanical drilling speed.

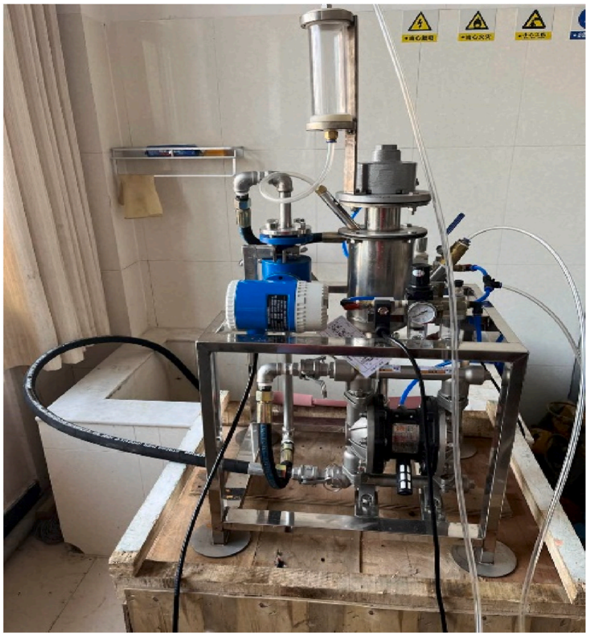

Fig. 3. Pneumatic quantitative degasser for drilling fluid.

$$R_{rock} = \frac{4000 \times R_i \times Vol \times ROP}{\pi \times D^2} \tag{3}$$

Where, R_{rock} is the gas content per unit volume of rock, ROP is the mechanical drilling rate, D is the wellbore diameter.

3.3.2. *Well cleaning monitoring and evaluation technology*

We have developed a tipping bucket type rock debris flow measurement device, which has improved issues such as slurry leakage in scraper type measurement. Applied in wells 4/5/6 of Wei 202H35 platform and Ning 209H67-3. At the same time, in order to enhance the durability, lightweight, modularization, and convenient installation of equipment on-site applications, the second generation prototype design optimization has been carried out to improve equipment capabilities. Based on this device, a change in rock debris return rate was formed. A monitoring and evaluation method for drilling hole cleaning in conjunction with auxiliary methods such as friction sensitivity analysis, hydraulic parameters, and block removal. Implemented a semi quantitative, theoretical and practical data analysis mode. Improved the application process of supporting technologies. With the application of the drilling hole cleaning monitoring system in Weiyuan shale gas for 11 wells, 19 abnormal cuttings returns were successfully predicted, effectively preventing the occurrence of downhole complications.

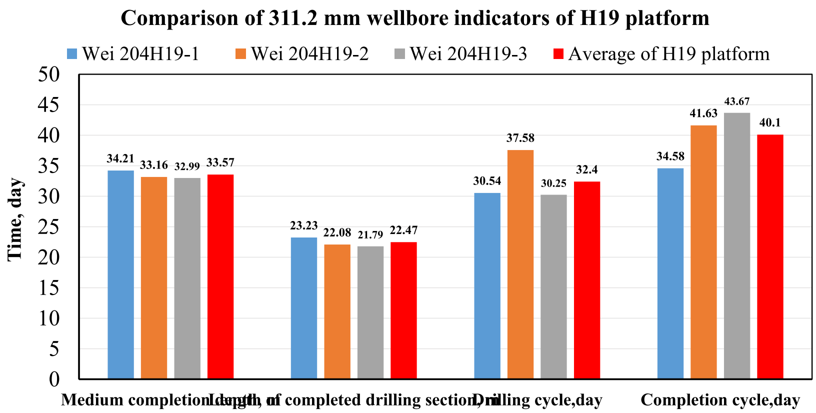

Fig. 4. Test results of parameter measurement technology for downhole drilling engineering (Comparison of 311.2 mm wellbore indicators of H19 platform).

3.3.3. Real time measurement technology for underground engineering parameters

We have conquered the design and manufacturing technology of underground engineering parameter measuring instruments. Innovative technologies such as decoupling of engineering parameters, multi factor calibration of drilling pressure and torque, and intelligent master control communication have been developed. Accurate measurement and real-time uploading of 12 parameters including downhole drilling pressure, internal and external pressure, torque, rotational speed, and vibration have been achieved. Real time evaluation of underground conditions and precise prevention of engineering risks. Subsequently, 9 trips of drilling were conducted in Wei 204H19-2 and Wei 202H84-2 wells, with an application time of 1458 h and a safe footage of 3653 m. Through parameter monitoring and analysis, the complexity of underground operations is avoided, drilling parameters are optimized, and precise pressure control is assisted, effectively improving construction efficiency. Among them, the third spud completion cycle of H19-2 well constructed later was shortened by 4.8% compared to H19-3 well constructed earlier, and the gas invasion loss time was saved by 2.95 days compared to 19–3 well, laying a foundation for the smooth construction of H19-1 well. The completion cycle of the third spud of Well H84-2 is 36.33 days, which is 26.7% shorter on average compared to the platform, as shown in Figs. 4 and 5.

This technology has achieved real-time parameter analysis and process adjustment in specific applications. For example, in the H19-2 well, through the monitoring of measurement system data, the vibration values of the early strata (1130–1145 m) of Xujiahe are relatively high. The average radial vibration is 4.09 g, and the average axial vibration is 0.97 g. The tool surface is noticeably unstable, which affects the initial inclination. When vibration data fluctuates, it is recommended to adopt pulling, idling, or small drilling pressure sliding drilling methods to improve the deflection effect. During the sliding drilling of 1967–1972 m in this well, it was found through monitoring that while the surface drilling pressure remained unchanged, the bottom drilling pressure continued to decrease, and the tool surface rose, resulting in the discovery of support pressure. It is suggested that this layer should be quickly drilled into the formation, with a combination of inclination reduction and azimuth increase, in order to optimize the drilling parameters (high drilling pressure and low rotation speed to ensure trajectory effect) and avoid sliding.

In addition, this technology is also beneficial for storing data, verifying and optimizing drilling parameter templates. By comparing and analyzing the underground surface parameters of each layer, it is believed that the underground surface parameters of the Xujiahe Formation to Feixianguan Formation have a consistent trend. The torque and vibration values of each layer increase with the increase of well depth. In the Changxing Formation to Qixia Formation, the drilling pressure and rotational speed effectively act on the bottom of the well, but the torque difference is significant, and the vibration value is smaller than that of the upper formation. Based on this, the construction parameter template has been refined, as shown in Table 4.

In application, this technology also achieves complex well control risk warning such as overflow and leakage. The H19-2 well was drilled to 2823.56 m (Changxing Formation), and the outer annulus pressure decreased from 54.3 MPa to 54.01 MPa (pressure decreased by 0.29 MPa). A gas invasion warning was issued to the drilling team, and then the logging monitoring showed an increase in outlet flow and an increase in total hydrocarbons. The well was immediately shut in. This well has successfully achieved three gas invasion warnings (2824 m, 2866 m, 3007 m), 3–5 min ahead of ground monitoring.

3.4. Prevention technology for annular pressure in gas well

3.4.1. Optimize the mud cake curing agent

By selecting mud cake curing agents suitable for cementing, including GJE-I and GJE-II, the detailed components are shown in

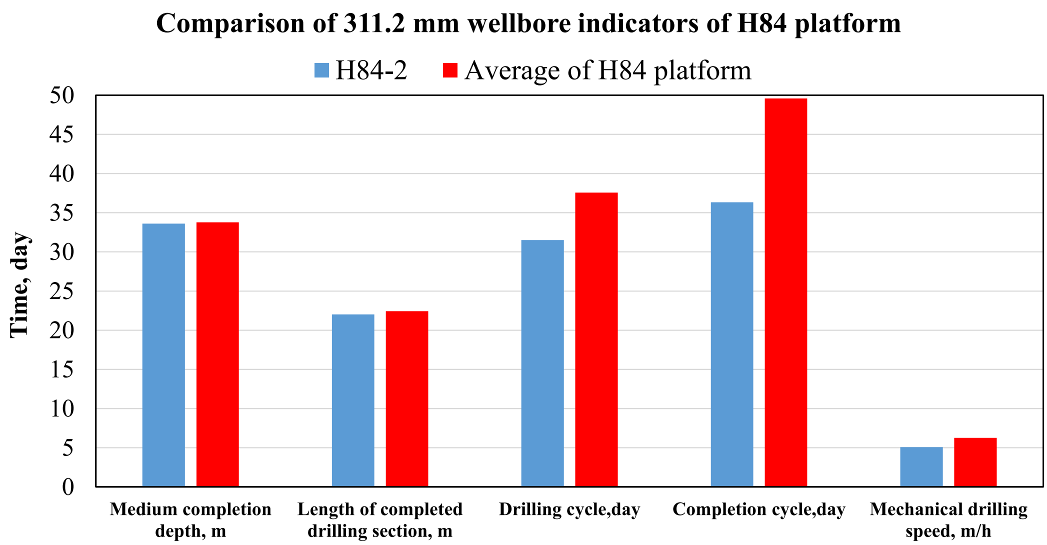

Fig. 5. Test results of parameter measurement technology for downhole drilling engineering (Comparison of 311.2 mm wellbore indicators of H84 platform).

Table 4
Construction parameter refinement template based on real-time measurement technology of underground engineering parameters.

Formation	Construction template refinement
Xujiahe	Upper limit of drilling pressure during rotation (drilling pressure: 160 KN) Adjust parameters according to the sliding state during sliding (drilling pressure: 100-180 KN)
Leikoupo	Reference upper limit (drilling pressure: 150-160 KN)
Jialing River	Reference medium and upper limits before 2220 m (drilling pressure: 120-160 KN) Reference middle limit after 2220 m (drilling pressure: 120 KN)
Feixiangaun	Reference upper limit before 2500 m (WOB: 170-180 KN, RPM: 80+) Reference middle limit after 2500 m (WOB: 140 KN, RPM: 70+)
Changxing	Reference upper limit (WOB: 170-180 KN, RPM: 80+)
Longtan	Reference upper limit (WOB: 170-180 KN, RPM: 80+)
Maokou	Reference middle limit before 3100 m (WOB: 100, RPM: 65+) Reference upper limit after 3100 m (WOB: 120, RPM: 70+)
Qixia	Reference upper limit (WOB: 120, RPM: 70+)

Table 5 [71]. This forms a filter cake solidification flushing solution and eliminates annular pressure operation method. A supporting process technology has been established to improve the bonding quality of the secondary interface, namely the application of mud cake solidification and anti-channeling cementing technology. Field tests have shown that the isolation fluid added with mud cake solidification agent has good compatibility with cement slurry and on-site drilling fluids in different blocks.

3.4.2. High temperature and high density anti channeling micro expansion cement slurry system

Based on the theory of tight packing, 10 fillers such as CEA-1 with small particle size and high strength were added to a cement slurry system with a density of 2.30–2.60 g/cm^3 to improve the strength and bonding quality of cement paste. Finally, the elastic modulus of cement is reduced by 62.5%, the Poisson's ratio is increased by 27.8%, the channeling prevention index SPN $\leq$3, and the expansion rate is adjustable at 0–1.0%. The qualification rate of shale gas horizontal section cementing quality is 96.3%, and the high quality rate is 92.1%.

3.4.3. Horizontal well rotary casing cementing process

As it is difficult to remove the cuttings bed of shale gas horizontal wells, affecting the uniform distribution of cement sheath and affecting the cementing quality, we independently designed and manufactured the first rotary casing cementing cement head in China, with a rotary sealing pressure of 87.5 MPa, a torsional resistance of 30,000 N m, and a tensile capacity of 300 t, which realized the continuous rotation of the casing during the high pressure cementing construction, disturbed the cuttings around the casing and recycled them out of the wellbore, improving the annulus displacement efficiency.

4. Overall technical test results and economic benefits

The optimization of thermal resistance performance and trajectory control technology of rotary conductivity have been successfully tested in Well Wei 204H21-5. The maximum temperature at which the instrument enters the well is 136.1 °C. The normal circulation time of a single drilling instrument entering the well is 343 h. The drilling cycle is 16.2 days. The success rate of one-time landing is 100%. The trajectory compliance rate is 100%, and the penetration rate of Longyi small layer is 100%.

The technology of increasing drilling speed in large-scale well sections has been successfully tested in Well Wei 204H20-4. Three rounds of drilling were completed for the 311.1 mm borehole. The drilling cycle is 18.87 day, with the fastest drilling cycle recorded in the deep 311.1 mm section of Chuangwei 204. The actual drilling cycle of the Xujiahe Formation and Changxing Formation well section is 10.46 days. The actual mechanical drilling speed of Longtan Formation is 4.57 m/h, and the actual drilling cycle is 8.41 day.

The integrated underground safety technology of engineering logging has been successfully tested in wells such as Wei 204H19-2 and Wei 202H84-2. It has played an important role in real-time parameter analysis of drilling, well control risk warning, and updating drilling speed increase parameter templates.

The prevention technology for annular pressure in gas wells has been successfully tested in 4 wells. During the entire process of cementing construction and subsequent four spud drilling, there was no occurrence of annular pressure. The average qualification rate of the second cementing interface in the entire well sealing section is 95.6%.

The above technical systems have been promoted and applied. In the past five years, 25 ″science and technology demonstration wells" have been integrated and demonstrated in Changning Weiyuan and Zhaotong national shale gas demonstration areas. The mechanical drilling speed of demonstration wells increased by an average of 18.9 % year-on-year in the block. The fault complexity rate has been reduced to 4.45%. Reduce drilling cycle by 37.5%. The penetration rate of desserts is 98.7%. It provides reliable technical support for further expanding the scale benefit development achievements of Sichuan Chongqing shale gas. Since 2016, the project has been applied to a total of 264 wells on a large scale. The output value was 1.554 billion yuan, the gas increase revenue was 6.616 billion yuan, and the comprehensive efficiency was 6.849 billion yuan.

5. Conclusions

In this paper, first, the technical difficulties of drilling and completion in deep shale formations in the Sichuan and Chongqing

Table 5
Comparison of GJE-I and GJE-II components for mud cake curing agent.

	GJE-I	GJE-II
Colloid type	Colloidal solution	Hydrophilic glue
Component	Sodium silicate, organic polymer	Sodium silicate, sulfate
Phase type	Multi-phase heterogeneous dispersion system	Single phase uniform dispersion system

region is systematically summarized. Second, a systematic evaluation was conducted on the optimization of temperature resistance performance and trajectory control technology of the rotary guidance system. Third, evaluation and economic analysis were conducted on the experimental effects of different technologies. Key findings are shown below:

(1) In view of the technical difficulties in deep shale gas drilling in the middle and high temperature well section, which is easy to lead to high fault rate of the rotary conductivity system and difficult to effectively construct, the optimization technology for temperature resistance performance of integrated high-temperature resistant guide head and surface cooling equipment has been formed. It can effectively reduce the circulation cooling time and improve drilling efficiency. Field tests have shown that the fault rate of the rotary guide system has been reduced by 55.5% before and after optimizing its temperature resistance performance.
(2) In response to the technical difficulties such as stronger brittleness of formation rock, more developed fractures, and higher risks of wellbore leakage and instability in deep shale sections, an integrated safety technology for engineering logging has been formed. Real time measurement of underground engineering parameters and monitoring and evaluation of wellbore cleanliness can reduce drilling risks, while achieving quantitative evaluation of drilling fluid gas content.
(3) In response to the technical difficulties of successful promotion of existing acceleration templates and difficulty in precise acceleration measures, a precise control technology for rotary steering trajectory with the core of “active prediction of formation direction + drilling along layers” has been formed in deep well sections. For φ 311.1 mm large-sized well section, a high-temperature PDC drill bit + high torque equal wall thickness screw “three pass drilling” technology was formed. Assisted by real-time optimization technology of mechanical drilling speed based on underground surface engineering parameters, the acceleration effect has been significantly improved.
(4) In response to the technical difficulties of poor cementing quality caused by mud cake adhesion, which leads to pressure in the gas well annulus, the mud cake curing agent was optimized, and a high-temperature and high-density anti channeling micro expansion cement slurry system and horizontal well rotary casing cementing process were formed, effectively preventing the problem of pressure in the annulus.

Data availability statement

Data is available on request.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Liwei Sun: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] B. Liu, M. Mohammadi, Z. Ma, L. Bai, L. Wang, Y. Xu, M. Ostadhassan, A. Hemmati-Sarapardeh, Evolution of porosity in kerogen type I during hydrous and anhydrous pyrolysis: experimental study, mechanistic understanding, and model development, Fuel 338 (2023) 127149.
[2] B. Liu, Y. Yang, J. Li, Y. Chi, J. Li, X. Fu, Stress sensitivity of tight reservoirs and its effect on oil saturation: a case study of Lower Cretaceous tight clastic reservoirs in the Hailar Basin, Northeast China, J. Petrol. Sci. Eng. 184 (2020) 106484.
[3] H. Li, Z. Tan, Y. Hu, et al., Reservoir fluid type identification while drilling for Archaeozoic buried hill reservoir of M structure at southwest margin of Bozhong Sag,Bohai Sea,East China, Petroleum Geology and Recovery Efficiency 28 (5) (2021) 22–31.
[4] B. Liu, J. Sun, Y. Zhang, J. He, X. Fu, L. Yang, J. Xing, X. Zhao, Reservoir space and enrichment model of shale oil in the first member of Cretaceous Qingshankou Formation in the Changling sag, southern Songliao Basin, NE China, Petrol. Explor. Dev. 48 (3) (2021) 608–624, https://doi.org/10.1016/S1876-3804(21)60049-6.

[5] X. Zhou, L. Li, Y. Su, et al., Experimental study on enhancing shale oil recovery by supercritical CO_2/H_2O mixture huff and puff, Petroleum Geology and Recovery Efficiency 30 (2) (2023) 77–85.
[6] B. Liu, Y. Song, K. Zhu, P. Su, X. Ye, W. Zhao, Mineralogy and element geochemistry of salinized lacustrine organic-rich shale in the Middle Permian Santanghu Basin: implications for paleoenvironment, provenance, tectonic setting and shale oil potential, Mar. Petrol. Geol. 120 (2020) 104569, https://doi.org/10.1016/j.marpetgeo.2020.104569.
[7] B. Liu, H. Wang, X. Fu, Y. Bai, L. Bai, M. Jia, B. He, Lithofacies and depositional setting of a highly prospective lacustrine shale oil succession from the upper cretaceous qingshankou formation in the gulong sag, northern Songliao Basin, northeast China, AAPG (Am. Assoc. Pet. Geol.) Bull. 103 (2019) 405–432, https://doi.org/10.1306/08031817416.
[8] S.W. Meng, D.X. Li, X. Liu, et al., Study on dynamic fracture growth mechanism of continental shale under compression failure, Gas Science and Engineering 114 (2023) 2949–9089.
[9] J.P. Tao, S.W. Meng, D.X. Li, et al., Analysis of CO_2 effects on porosity and permeability of shale reservoirs under different water content conditions, Geoenergy Science and Engineering 226 (2023) 2949–8910.
[10] H. Yu, W.L. Xu, B. Li, et al., Hydraulic fracturing and enhanced recovery in shale reservoirs: theoretical analysis to engineering applications, Energy Fuel. 37 (14) (2023) 9956–9997.
[11] S.W. Meng, Z.H. Zhang, J.P. Tao, et al., A novel upscaling method for evaluating mechanical properties of the shale oil reservoir based on cluster analysis and nanoindentation, J. Energy Resour. Technol. 145 (11) (2023) 112901.
[12] B. Yuan, Z.M. Zhao, S.W. Meng, et al., Intelligent identification and real-time warning method of diverse complex events in horizontal well fracturing, Petrol. Explor. Dev. 50 (5) (2023) 1–9.
[13] H. Liu, S.W. Meng, S.L. Wang, et al., Mechanical characteristics and fracture propagation mechanism of the Gulong shale, Oil Gas Geol. 44 (4) (2023) 820–828.
[14] X. Liu, S.W. Meng, Z.Z. Liang, et al., Microscale crack propagation in shale samples using focused ion beam scanning electron microscopy and three-dimensional numerical modeling, Petrol. Sci. 20 (3) (2022) 1488–1512.
[15] H. Liu, L.C. Kuang, G.X. Li, et al., Considerations and suggestions on optimizing completion methods of continental shale oil in China, Acta Pet. Sin. 41 (4) (2020) 489–496.
[16] F. Sun, Y. Yao, M. Chen, X. Li, L. Zhao, Y. Meng, Z. Sun, T. Zhang, D. Feng, Performance analysis of superheated steam injection for heavy oil recovery and modeling of wellbore heat efficiency, Energy 125 (2017) 795–804, https://doi.org/10.1016/j.energy.2017.02.114.
[17] F. Sun, Y. Yao, X. Li, The heat and mass transfer characteristics of superheated steam coupled with non-condensing gases in horizontal wells with multi-point injection technique, Energy 143 (2018) 995–1005, https://doi.org/10.1016/j.energy.2017.11.028.
[18] R. Wu, Y. Liu, H. Yu, X. Lan, X. AI, X. Guo, P. Gao, F. Deng, Three-low" drilling fluid technology for ultra-shallow horizontal well with extended reach, Unconventional Oil & Gas,11(01) (2024) 119–127.
[19] F. Sun, Y. Yao, G. Li, X. Li, Numerical simulation of supercritical-water flow in concentric-dual-tubing wells, SPE J. 23 (6) (2018) 2188–2201, https://doi.org/10.2118/191363-PA.
[20] J. Cai, C. Li, K. Song, S. Zou, Z. Yang, Y. Shen, Q. Meng, Y. Liu, The influence of salinity and mineral components on spontaneous imbibition in tight sandstone, Fuel 269 (2020) 117087, https://doi.org/10.1016/j.fuel.2020.117087.
[21] J. Cai, Y. Xia, C. Lu, H. Bian, S. Zou, Creeping microstructure and fractal permeability model of natural gas hydrate reservoir, Mar. Petrol. Geol. 115 (2020) 104282, https://doi.org/10.1016/j.marpetgeo.2020.104282.
[22] F. Sun, Y. Yao, G. Li, X. Li, Geothermal energy extraction in CO_2 rich basin using abandoned horizontal wells, Energy 158 (2018) 760–773, https://doi.org/10.1016/j.energy.2018.06.084.
[23] J. Li, X. Zhang, Li, Y. Han, Z. Zhuo, G. Mu, Experimental evaluation study of reservoir plugging in Guantao Formation of Bohai C oilfield, Unconventional Oil & Gas 11 (1) (2024) 103–109.
[24] J.Z. Zhang, Y.J. Tang, D.X. He, et al., Full-scale nanopore system and fractal characteristics of clay-rich lacustrine shale combining FE-SEM, nano-CT, gas adsorption and mercury intrusion porosimetry, Appl. Clay Sci. 196 (2020) 105758, https://doi.org/10.1016/j.clay.2020.105758.
[25] H. Yu, H.Y. Xu, J.C. Fan, Y.B. Zhu, F.C. Wang, H.A. Wu, Transport of shale gas in microporous/nanoporous media: molecular to pore-scale simulations, Energy Fuel. 35 (2) (2021) 911–943, https://doi.org/10.1021/acs.energyfuels.0c03276.
[26] L.D. Geng, A Production Forecasting Model and Optimization of Completion Parameters for Shale Gas Reservoirs Based on the Micro/Nano-Scale Flow, China University of Petroleum, Beijing, 2017.
[27] M. Fry, Urban gas drilling and distance ordinances in the Texas Barnett Shale, Energy Pol. 62 (2013) 79–89, https://doi.org/10.1016/j.enpol.2013.07.107.
[28] S.S. Janwadkars, S. Morris, M. Thomas, et al., Barnett Shale Drilling and Geological Complexities—Advanced Technologies Provide the Solution, IADC/SPE Drilling Conference, 2008.
[29] Y.Y. Li, Y.P. Yu, Y.H. Sun, et al., Dynamics and fatigue life investigation of push-the-bit rotary steerable bottom hole assembly with whirling finite element model, Eng. Fail. Anal. 150 (2023) 107300, https://doi.org/10.1016/j.engfailanal.2023.107300.
[30] H. Zafarian, M. Ameri, Y.A. Vaghasloo, et al., Error reduction of tracking planned trajectory in a thin oil layer drilling using smart rotary steerable system, J. Petrol. Sci. Eng. 196 (2021) 107668, https://doi.org/10.1016/j.petrol.2020.107668.
[31] W.J. Huang, G. Wang, D.L. Gao, A method for predicting the build-up rate of 'push-the-bit' rotary steering system, Nat. Gas. Ind. B 8 (6) (2021) 622–627, https://doi.org/10.1016/j.ngib.2021.11.010.
[32] F. Sun, Y. Yao, G. Li, X. Li, Performance of geothermal energy extraction in a horizontal well by using CO_2 as the working fluid, Energy Convers. Manag. 171 (2018) 1529–1539, https://doi.org/10.1016/j.enconman.2018.06.092.
[33] J.G. Tsiagadigui, B. Ndiwe, M.N. Yamben, N. Fotio, F.E. Belinga, E. Njeugna, The effects of multiple drilling of a bone with the same drill bit: thermal and force analysis, Heliyon 8 (2) (2022) E08927, https://doi.org/10.1016/j.heliyon.2022.e08927.
[34] P. Jagadeesh, S.M. Rangappa, I. Suyambulingam, et al., Drilling characteristics and properties analysis of fiber reinforced polymer composites: a comprehensive review, Heliyon 9 (3) (2023) E14428, https://doi.org/10.1016/j.heliyon.2023.e14428.
[35] P.V. Vaidya, A. Dutta, S. Rooj, et al., Design modification of surgical drill bit for final osteotomy site preparation towards improved bone-implant contact, Heliyon 9 (6) (2023) E16451, https://doi.org/10.1016/j.heliyon.2023.e16451.
[36] J.H. Choi, Y.S. Lee, K.T. Hwang, et al., Usefulness of a drill stopper to prevent iatrogenic soft tissue injury in orthopedic surgery, Heliyon 9 (10) (2023) E20772, https://doi.org/10.1016/j.heliyon.2023.e20772.
[37] Z.G. Wu, H. Li, X.Z. Yue, 2.5-Dimensional modeling of EM logging-while-drilling tool in anisotropic medium on a Lebedev grid, Petrol. Sci. 20 (1) (2023) 249–260, https://doi.org/10.1016/j.petsci.2022.09.010.
[38] F. Sun, Y. Yao, G. Li, X. Li, Geothermal energy development by circulating CO_2 in a U-shaped closed loop geothermal system, Energy Convers. Manag. 174 (2018) 971–982, https://doi.org/10.1016/j.enconman.2018.08.094.
[39] L. Zhao, Elements that associate with participants' psychological discomfort during simplified fire drills, Heliyon 9 (6) (2023) E16635, https://doi.org/10.1016/j.heliyon.2023.e16635.
[40] L. Deng, X. Li, W. Xu, et al., Measurement while core drilling based on a small-scale drilling platform: mechanical and energy analysis, Measurement 204 (2022) 112082, https://doi.org/10.1016/j.measurement.2022.112082.
[41] V.L. Poliakov, S.Y. Martynov, Technological modeling of physicochemical removal of iron from deep groundwater, Heliyon 9 (9) (2023) E20202, https://doi.org/10.1016/j.heliyon.2023.e20202.
[42] H.S. Ashrith, M. Doddamani, Point angle effect in drilling of syntactic foams, Composites Part C: Open Access 6 (2021) 100179, https://doi.org/10.1016/j.jcomc.2021.100179.
[43] X. Xi, S. Yang, Z. Shipton, et al., Modelling the near-wellbore rock fracture tortuosity: role of casing-cement-rock well system, perforation and in-situ stress, Int. J. Rock Mech. Min. Sci. 157 (2022) 105182, https://doi.org/10.1016/j.ijrmms.2022.105182.

[44] S. Ahmed, H. Patel, S. Salehi, Effects of wait on cement, setting depth, pipe material, and pressure on performance of liner cement, J. Petrol. Sci. Eng. 196 (2021) 108008, https://doi.org/10.1016/j.petrol.2020.108008.
[45] Y. Yan, Z. Guan, Y. Xu, et al., Numerical investigation of perforation to cementing interface damage area, J. Petrol. Sci. Eng. 179 (2019) 257–265, https://doi.org/10.1016/j.petrol.2019.04.031.
[46] X. Liu, J. Li, H. Yang, et al., A new investigation on optimization of perforation key parameters based on physical experiment and numerical simulation, Energy Rep. 8 (2022) 13997–14008, https://doi.org/10.1016/j.egyr.2022.10.051.
[47] Y. Yan, Z. Guan, W. Yan, et al., Mechanical response and damage mechanism of cement sheath during perforation in oil and gas well, J. Petrol. Sci. Eng. 188 (2020) 106924, https://doi.org/10.1016/j.petrol.2020.106924.
[48] H.A. Ramis, C. Teodoriu, O. Bello, et al., High definition optical method for evaluation of casing - cement microannulus (CCMA), J. Petrol. Sci. Eng. 195 (2020) 107719, https://doi.org/10.1016/j.petrol.2020.107719.
[49] J. Jiang, J. Li, G. Liu, et al., Numerical simulation investigation on fracture debonding failure of cement plug/casing interface in abandoned wells, J. Petrol. Sci. Eng. 192 (2020) 107226, https://doi.org/10.1016/j.petrol.2020.107226.
[50] R. Leonard, K. Bullard, M. Middlebrook, et al., Barnett Shale Completions: a Method for Assessing New Completion Strategies, SPE Annual Technical Conference and Exhibition, 2007.
[51] Waters G., Dean B., Downie R., et al. Simultaneous hydraulic fracturing of adjacent horizontal wells in the Woodford Shale. SPE Hydraulic Fracturing Technology Conference.
[52] C. Pope, B. Peters, T. Benton, et al., Haynesville shale-one operator's approach to well completions in this evolving play, SPE Annual Technical Conference and Exhibition (2009).
[53] M.Y. Soliman, J. Augustine, Fracturing Design Aimed at Enhancing Fracture Complexity, SPE EUROPEC/EAGE Annual Conference and Exhibition, 2010.
[54] N.P. Roussel, M.M. Sharma, Optimizing fracture spacing and sequencing in horizontal well fracturing, SPE International Symposium and Exhibition on Formation Damage Control (2010).
[55] J.W. Thompson, L. Fan, D. Grant, et al., An Overview of Horizontal Well Completions in the Haynesville Shale, Canadian Unconventional Resources & International Petroleum Conference, 2010.
[56] C. Cipolla, X. Weng, H. Onda, et al., New algorithms and integrated workflow for tight gas and shale completions, SPE Annual Technical Conference and Exhibition (2011).
[57] C. Cipolla, T. Fitzpatrick, M.J. Williams, et al., Seismic-to-simulation for unconventional reservoir development, SPE Reservoir Characterisation and Simulation Conference and Exhibition (2011).
[58] N.P. Roussel, M.M. Sharma, Strategies to minimize frac spacing and stimulate natural fractures in horizontal completions, SPE Annual Technical Conference and Exhibition (2011).
[59] K.D. Wutherich, W.K. Jon, Designing completions in horizontal shale gas wells-perforation strategies, Americans Unconventional Resources Conferenc (2012).
[60] D.G. Durst, M. Vento, G. Tucker, et al., Long-term comparison of production results from open hole and cemented multi-stage completions in the Barnett shale, SPE Asia Pacific Drilling Technology Conference and Exhibition (2010).
[61] W. Yu, K. Sepehrnoori, An efficient reservoir-simulation approach to design and optimize unconventional gas production, J. Can. Petrol. Technol. 53 (2) (2014) 109–121.
[62] W. Yu, K. Sepehrnoori, Simulation of Gas Desorption and Geomechanics Effects for Gas Reservoir Systems, SPE Annual Technical Conference and Exhibition, 2009.
[63] Y. Falola, S. Misra, J. Foster, et al., Data-driven workflow for the preemptive detection of excess water producing wells drilled in unconventional shales, J. Nat. Gas Sci. Eng. 103 (2022) 104609, https://doi.org/10.1016/j.jngse.2022.104609.
[64] S. Basfar, B. Bageri, S. Elkatatny, Effect of Qusaiba shale formation on high-pressure high-temperature drilling fluids properties, Geoenergy Science and Engineering 224 (2023) 211608, https://doi.org/10.1016/j.geoen.2023.211608.
[65] H. Fan, Y. Zang, J. Zhang, Difficulties and countermeasures of deep Shale gas drilling technology, Drill. Prod. Technol. 42 (3) (2019) 20–23+7.
[66] X. He, G. He, Y. Gao, Progress in key technologies for exploration and development of atmospheric Shale gas and the direction of tackling key problems, Nat. Gas. Ind. (2023). http://kns.cnki.net/kcms/detail/51.1179.TE.20230313.1415.002.html.
[67] J. Yan, X. Ye, Y. Fu, Breakthrough of bottleneck in rotary steering drilling technology for deep Shale gas in southern Sichuan, Logging Engineering 32 (3) (2021) 6–10.
[68] G. Wang, S. Gao, Y. Zhang, Key technologies for optimal and fast drilling of deep shale gas in Luzhou, China Petroleum and Chemical Standards and Quality 42 (24) (2022) 154–156+159.
[69] Y. Xi, F. Li, S. Wang, et al., Study on the prevention of cement ring micro annular gaps using prestressed cementing method, Special Oil Gas Reservoirs 28 (6) (2021) 144–150.
[70] J. Zhong, Research and test on drilling speed increase technology of Weiyuan deep Shale gas 311.1 mm well section, China Petroleum and Chemical Standards and Quality 43 (5) (2023) 46–48+5.
[71] H. Chen, Application of mud cake solidification anti channeling cementing technology in high shale gas wells, Journal of Petroleum and Petrochemical 364 (5) (2017) 101–102.