Petroleum and Coal

Article **Open Access**

Experiences of Drilling Fluids in Shale Gas Fields

Chang Hong Gao

School of Mining and Geoscience, Nazarbayev University, Astana, Kazakhstan

Received January 10, 2023; Accepted June 19, 2023

Abstract

Shale gas is the fastest-growing energy source in the world. In USA, shale gas now contributes to more than 60% of natural gas supply. In China, annual shale gas production climbed to 800 Bcf (billion cubic feet) in 2021. However, since the dawn of petroleum industry, drilling in shale has been a challenge due to the reactive clay minerals. This paper surveys the field experiences of widely used drilling fluids in major shale plays. OBM (oil based mud) is usually made of diesel and low fraction of water phase. The oil phase in OBM provides effective shale stability, high rate of penetration (ROP), and excellent lubricity. Therefore, more than 70% of shale gas wells have been drilled with OBM, and very few wells reported wellbore instability. WBM (water-based mud) is made of water and necessary chemical additives. WBM is less costly and more environment-friendly than OBM, but some shale wells drilled with WBM reported severe instability issues. Nevertheless, recent innovations in WBM lead to successes in drilling major shale plays. WBM has great potential in shale drilling and deserves more research and improvements.

Keywords: *Drilling fluid; Oil-based mud; Water-based mud; Shale gas; Shale stability.*

1. Introduction

Energy Information Agency (EIA) estimated the proved U.S. shale gas reserves at 307.9 Tcf (trillion cubic feet). Large-scale natural gas production from shale began around 2000, when shale gas production became a commercial success in the Barnett Shale located in north-central Texas [1]. In 2010, the production at Barnett Shale exceeded 4 Bcf (billion cubic feet) of natural gas per day. So far, more than 16,000 wells have been drilled in this formation.

As natural gas producers gained confidence in their abilities to profitably produce natural gas in Barnett Shale and Fayetteville Shale, producers started developing other shale formations. These new formations included the Haynesville shale in eastern Texas and northern Louisiana, the Woodford shale in Oklahoma, the Eagle Ford shale in southern Texas, and the Marcellus and Utica shales in northern Appalachia [2]. In 2020, about 733 Bcm of dry natural gaswas produced from shale resources in the United States, which weighs 72% of total U.S. dry natural gas production. Shale gas industry has revolutionized the domestic energy landscape of United States.

EIA estimates that China holds the world's largest technically recoverable shale gas reserves. Inspired by the U.S. shale gas boom, China is turning to natural gas as a way to reduce air pollution created by the consumption of coal. China has made breakthroughs in shale gas exploration both in capacity and drilling techniques, making it one of the top shale gas suppliers in the world. In 2021, the shale gas production in China jumped to 24 Bcm (billion cubic meter), contributing about 10% of the total gas output in the nation [3-4].

Significant shale potential and surging gas demand in China motivate the Chinese companies to speed up the development of the shale gas plays. Reaching for this potential, the Chinese government has set a goal of 80 Bcm of shale gas production by 2030, which will account for 50% of domestic gas consumption [5].

Despite many years of research and practices, wellbore instability remains the major challenge for drilling. Wellbore stability is controlled by the complex mechanical and chemical factors such as earth stresses, rock strength, pore pressure, mud pressure, and mud chemistry. Wellbore instability may result in well pack-off, stuck pipe, lost borehole, and costly side-tracking [6]. Drilling related issues have been well documented in literature [7].

Shales are mainly composed of mud, silts, and clays. Clay minerals are flaky, mica-type crystalline in nature. Among the clay minerals, smectite has a high cation exchange capacity (CEC), therefore it is prone to swelling and dispersion when in contact with water [8]. Illite, chlorite and kaolinite have low CEC and low tendency to swell. However, another type of illite is produced by the transformation of smectite under high pressure and high temperature, which has more tendency to swell than its original form. This paper is focused on the field experiences of different mud systems in drilling shale reservoirs. Detailed analysis of shale instability and wellbore failure mechanisms can be found elsewhere [9-10].

2. Drilling with oil-based mud in shale fields

For Oil-based mud (OBM), water is the dispersed phase and oil is the continuous phase. Shales are no longer exposed to water, thus can be partially or completely stabilized. This is why OBM is used for drilling 70% of all reactive shale formations [11]. Diesel is the most commonly-used oil for OBM. Sometimes, refined white oil is used for better stability under high temperature. This section presents typical field cases of OBM in shale reservoirs.

2.1. Yanchang Field

The field is located in the Ordos basin in western China, covering an area of 250,000 km^2. The tectonic structure is quite simple, characterized by a single western-dipping monocline. The shale gas production started in 2010. Three critical horizontal wells were drilled with diesel based mud at Yanchang field. The well trajectory data is presented in Table 1 [12]. The wells were drilled to relative shallow TVD with maximum departures ranging from 1000 to 1925 m.

The mud formula contained diesel, 3-7% clay, 3-7% calcium oxide, 2-4% fluid loss additive, 1-5% emulsifier, 1.5-4% wetting agent, 2-4% bridging materials, plus weighting materials. Mud properties during drilling are shown in Table 2. The OBM system maintained stable viscosity and gel strength of 3-15 Pa, leading to excellent cutting transport. Electric stability above 1500V indicated good emulsion stability. Excellent lubricity produced low friction and torque. The friction factor in Table 2 was obtained with an industry-standard device that measures the sliding angle on a mud cake. High ROP of 5-13 m/h was achieved while drilling the horizontal laterals. With the implementation of OBM, the drilling days at Yanchang field reduced from 65 to 54 days. Till September 2014, more than 50 shale gas wells have been successfully drilled with oil-based mud, while four of them were horizontal wells.

Table 1. Well trajectory for horizontal wells at Yanchang field

Well No.	MD (m)	TVD (m)	Maximum departure (m)	Average ROP (m/h)
YYP-1	2344	1531	1000	4.26
YYP-2	2756	1514	1433	6.02
YYP-3	3275	1520	1925	9.98

Table 2. Properties of OBM for horizontal wells at Yanchang field

Well No.	Density (g/mL)	PV (cP)	YP (Pa)	ES (V)	Friction factor
YYP-1	1.18-1.25	21-39	8.5-16	1,551-1,615	0.05-0.07
YYP-2	1.18-1.29	20-38	8.5-18.5	1,551-1,629	0.05-0.07
YYP-3	1.18-1.25	20-40	8.5-19.6	1,551-1,631	0.05-0.06

2.2. Fuling Field

Fuling, located in the southwest municipality of Chongqing, came on stream in late 2012 and produced more than 6 Bcm (or 212 Bcf) of shale gas in 2018. The field's gas sales reached nearly 5.8 Bcm (or 205 Bcf), earning the first place in both production and sales in China. By the end of 2018, the Fuling shale gas field had produced more than 21.5 Bcm (or 759 Bcf), making it the largest shale gas field outside North America. Totally 438 wells had been drilled in Fuling till late 2018, while 321 wells were in production. Among them, more than 200 wells were drilled with diesel-based mud [13]. The mud system contained diesel, $CaCl_2$ solution, emulsifier, fluid loss additive, wetting agent, thickener, bridging material, and weight material [14]. The typical mud formula is presented in Table 3. Laboratory aging tests were conducted with roller oven. Test results in Table 4 revealed that mud maintained stable viscosity and low filtrate loss at high temperature of 160°C.

Table 3. Typical OBM formula at Fuling field

Material	Concentration	Function
Diesel	80%	Oil phase
35% $CaCl_2$ solution	20%	Water phase
Emulsifier	4.0%	Emulsify oil phase and water phase
Lime	1.5%	Adjust pH
Organic clay	1.0%	Provide initial viscosity and emulsion stability
Thickener	1.0%	Increase mud viscosity
Filtrate loss additive	3.0%	Reduce filtrate loss
Wetting agent	1.0%	Modify wettability of cuttings
Liquid asphalt	3.0%	Reduce filtrate loss
Oxidized asphalt	3.0%	Reduce filtrate loss
Plugging/sealing agent	3.0%	Reduce risk of lost circulation

Table 4. Aging test results for OBM at Fuling field

Aging temperature (°C)	Density (g/mL)	AV (cP)	PV (cP)	YP (Pa)	Gel 10s/10min (Pa)	HTHP filtrate (mL)
60	1.4	48	37	11	9/18	1.0
90	1.6	55	45	10	8/18	1.2
120	1.7	60	56	14	9/20	1.6
160	1.8	51	40	11	9/18	2.0

While drilling the wells, mud YP (yield point) maintained at 10-20 Pa, marsh funnel viscosity was around 50-80 s, HTHP filtrate loss was below 3 mL, and mud ES (electrical stability) was above 400V to avoid segregation of water phase and oil phase. Excellent ROP and wellbore integrity were observed, as shown in Table 5. For well JY65-3HF, lost circulation occurred at 4,080 m (or 13,386 ft) and again at 4,096 m (or 13,438 ft). Fine carbonate particles and Nano-sized bridging materials were added into circulation to successfully battle lost circulation [15]. The bridging material was made of SiO_2 with average size of 20 nm. The particles was transported into the macro fractures in shale, effectively blocking the tiny fractures that could not be sealed by traditional bridging materials. The wells drilled with OBM reported low skin factors, indicating low formation damage from the bridging materials.

Table 5. Typical drilling performance with OBM at Fuling field

Well No.	Length of horizontal lateral, (m)	Average ROP (m/h)	Average washout (%)
JY2-4HF	1530	14.87	2.03
JY11-3HF	1540	11.26	2.56
JY17-2HF	1398	11.25	1.58
JY28-2HF	1490	14.06	0.88
JY30-4HF	1730	13.85	1.82
JY31-2HF	1530	10.44	1.04

2.3. Shengli Field

Located in east China, Shengli field began production in 1961 and annual oil production peaked at 33.55 million tons (about 250 million barrels) in 1991. The company is actively exploring shale oil to battle production decline. The shale oil drilling started in Luojia block. The reservoir mineralogy was made of illite, smectite, quartz, calcite and dolomite. OBM was chosen because of the reactive clay minerals and natural fractures in the shale formation.

In November 2011, the first shale oil well BYP-1was drilled with diesel-based mud at Luojia block. The well was designed with a horizontal lateral of 1,225 m in length. Diesel-based mud was used in drilling MD from 2984 to 4335 m (or 4019 to 14222 ft). The properties of OBM were stable during drilling with PV of 34-51 cP, YP of 7-13 Pa, ES of 947-1447 V, and HTHP fluid loss less than 5 mL ROP for the horizontal lateral reached 4.81 m/h (or 15.8 ft/h). Drilling was successful without incidents [16-17].

For well BYP-2, a low-aromatic OBM was used in drilling the horizontal lateral of 881.88 m (or 2,893 ft) in length. The mud was formulated with refined white oil, $CaCl_2$ solution, 4% emulsifier, 2% wetting agent, 3% clay, 3% fluid loss additive, 2% CaO, 2% bridging agent, and 0.5% yield point booster [18]. Refined white oil contained much less aromatics, thus being less toxic to environment. White oil is also more stable under high temperature. The average ROP reached 8.22 m/h (or 27 ft/h), much higher than that for well BYP-1, and the washout for BYP-2 was only 2.3%. Till late 2014, totally 38 wells were producing commercial shale oil at Shengli field [19]. In 2019, Shell signed an agreement with Sinopec to further develop the shale oil at Shengli field.

2.4. Jianghan Field

At Jianghan field, a horizontal well HF-1 was drilled with Invermul OBM developed by Halliburton [20]. Reservoir rock contained 22.5% clay minerals including illite, kaolinite, and illite/smectite mixed layers. The Well was designed with a TVD of 600 m (or 1969 ft), MD of 1800 m (or 5905 ft), and a horizontal lateral of 1,003 m (or 3,290 ft) in length. Mud properties versus depths are presented in Table 6. The mud delivered excellent rheology and very low fluid loss without any complication during drilling.

Table 6. Properties of Invermul mud at various depths during drilling

MD (m)	Specific gravity	PV (cP)	YP (Pa)	HTHP fluid loss (mL)	ES (V)
372	1.40	26	13.5	0	642
413	1.41	28	8.0	1.0	854
657	1.49	27	5.5	1.8	935
1306	1.47	34	16.0	0.5	1500
1481	1.44	28	18.0	1.5	1600
1777	1.47	39	22.0	1.5	1470

3. Drilling with Water-Based Mud in Shale Fields

It is well known that certain chemicals, such as KCl, glycerol, and methyl glucoside, are able to inhibit shale hydration and swelling to certain extent [21]. Even though OBM has dominated the shale drilling market, innovations in WBM lead to a few successful field applications at major shale plays [22]. Unlike the similar formulas of OBM for shale reservoirs, WBM must be carefully customized and tested to satisfy the inhibition and lubrication requirements of specific shale formation [23].

3.1. Haynesville Shale

Located in northwestern Louisiana and eastern Texas, Haynesville is one of the largest shale plays in North America with estimated 251 Tcf of technically recoverable gas. As of 2011, totally 883 wells were producing, while 128 wells were being drilled in the field. The Haynesville reservoir is located at 10500-14000 ft TVD, where the bottom-hole temperatures exceeded 380°F (or 193°C). Moreover, CO_2 influx was another common issue.

According to X-ray diffraction (XRD) analysis, the mineralogy of Haynesville shale contained mainly illite (67%) and quartz (19%). The customized WBM was formulated with clay, thinner, shale stabilizer, deflocculant, surfactant, fluid loss additive, buffer agent, and caustic soda. Mud samples were aged at 400°F and 10000 psig, under the influence of CO_2 and low-gravity solids. No progressive gelation was observed in any mud sample, while mud fluid loss, mud PV and shear strength remained low.

The mud system was used in Red River parish in Louisiana. Drilling was challenged by high bottom-hole temperature and Constant CO_2 influx. Besides, mud was in open hole for 45 days due to complex well design. The drilling fluid handled these challenges very well with limited changes in rheology. Mud PV stabilized around 41-49 cP, while mud YP below 20 lb/100ft^2, and API fluid loss was lower than 5 mL.

3.2. Fayetteville Shale

The Fayetteville shale in north Arkansas is buried at 4,000-8,000 ft with an estimated reserve of 42 Tcf. The shale is primarily made of quartz (31%), mixed smectite and chlorite (35%), and illite (21%). Even though the bottom-hole temperature is not very high (120-220°F), troublesome delamination of smectite and chlorite presents challenge for mud design. The mud was formulated with modified silicate, lignite, sulphonated asphaltene, polyanionic cellulose, starch, xanthan gum, barite, bridging agent, and glycol.

After being soaked in the customized mud for 24 hours, the shale sample did not show delamination under microscope. The mud was very effective at inhibiting shale, as tested by linear swell meter. The WBM was tested at Van Buren County in Arkansas. The mud was introduced into the well at 3500 ft, and drilled to the total depth of 10000 ft. No incident was encountered during drilling. ROP reached 3-15 m/h (or 30-50 ft/h) while sliding, and 30-75 m/h (or 100-250 ft/h) while rotating. Mud PV stabilized around 21 cP, mud YP was 35-38 lb/100ft^2, and API fluid loss was less than 5 mL.

3.3. Barnett Shale

Spanning 21 counties in North Texas, the Barnett shale play contains 44 Tcf of technically recoverable resources. The reservoir is buried at 7000-10000 ft with bottom hole temperature at 125-225°F. Barnett shale at Denton County contains quartz (29%), illite (33%), and illite/smectite mixed layers (28%) that are much more reactive than illite alone. Traditionally, OBM has been widely used for drilling at Barnett due to the reactive clays, fully developed micro-fractures, and low gravity solid content.

A WBM was formulated and tried at Denton County in Texas. The mud contained silicate, sulfonated asphaltenes, lignite, polyanionic cellulose, starch, xanthan gum, barite, bridging material, glycol, and lubricant. Even though the shale was highly reactive, the linear swell test showed swelling by less than 15% in 48 hours of testing. The WBM was introduced into the well at 1000 ft, and drilled to the total depth of 9000 ft. No incident was encountered with trips and casing runs. ROP reached 7-24 m/h (or 24-80 ft/h) while sliding, and 30-75 m/h (or 100-250 ft/h) while rotating. Mud PV stabilized around 20 cP, while mud YP was 21-24 lb/100ft^2, and API fluid loss was below 6 mL.

3.4. Zhaotong Shale

Zhaotong shale play is one of the major shale plays in Sichuan basin. Outcrop and scanning electron microscope revealed developed micro-fractures in shale. Fluid may easily penetrate into fractures and weak bedding planes, causing wellbore instability. XRD analysis showed the shale was mainly made of quartz, illite and illte-smectite mixed layers. Illite is prone to dispersion, while illite-smectite mixed layers are much more reactive than illite.

A WBM was formulated with fluid loss additive, shale inhibitor, inorganic salt, liquid membrane agent, Nano sealing agent, liquid lubricant, lubricant, dispersant, and barite [24]. Linear swell meter test showed the WBM is very effective at inhibiting shale with a low swelling rate less than 1%. Mud properties on site were comparable to the properties of OBM used in the field, as seen in Table 7.

Table 7. Comparison of WBM and OBM properties

Mud sample	AV (cP)	PV (cP)	YP (Pa)	API Fluid loss (mL)	HTHP Fluid loss (mL)
WBM after aging	83	68	15	0.2	4
Field OBM	85	69	16	0	0.4

The mud was tried in well YS108H4 at Zhaotong field. The new WBM demonstrated stable and favorable properties at different intervals, as presented in Table 8. Drilling was smooth without complications. Caliper log indicated that washout was less than 6%. The horizontal lateral reached 1,460 m (or 4790 ft), while drilling time was reduced to 37 days.

Table 8. Mud properties at different depths

Well depth (m)	PV (cP)	YP (Pa)	HTHP Fluid loss (mL)	Specific gravity
2,560-3,180	60-64	15-20	5-7	1.81-1.82
3,180-3,596	58-65	16-22	5-6	1.80-1.81
3,596-3,833	61-66	15-22	4-6	1.79-1.80
3,833-4,020	59-65	17-21	4-6	1.79

4. Performance of OBM and WBM in the same field

According to the field cases presented in the previous section, both OBM and WBM reported successes in shale fields, even though most of shale wells were drilled with OBM. However, the wells surveyed in previous sections were drilled in different fields. At Eagle Ford, Marcellus, Changning and Weiyuan fields, both OBM and WBM were applied in the same shale field. These field cases present interesting comparison between the two mud systems.

4.1. Eagle Ford Shale

A comparison study was conducted at Eagle Ford shale [25]. The Eagle Ford shale play is located in the Maverick basin in southwestern Texas with 40-50 miles in width and 400 miles in length at depth of 6,000-15,000 ft. The mineralogy of Eagle Ford shale includes calcite (55%), quartz (29%), smectite (6%), and kaolinite (2%). Delamination along bedding planes and enlargement of natural fractures were recognized as the major concerns for wellbore instability.

Between 2008 and 2011, about 203 horizontal wells were drilled at Eagle Ford with lateral lengths varying from 5,000 to 15,000 ft. Among the wells drilled, OBM was used in drilling 155 wells (76%), while only 38 wells (19%) were drilled with WBM. With WBM, on average 36 days of drilling were required to reach a total depth of 16,000 ft. On contrast, only 27 days were required to reach the same depth with OBM. Obviously, drilling with OBM achieved shorter drilling time, but the cost of OBM was 10-15% higher than WBM.

Drilling with WBM encountered multiple hole-instability problems. Tight spots, well pack-off, and stuck pipe were the main issues for drilling through shale and buildup sections. These incidents led to excessive time spent on reaming, wellbore enlargement, fishing, and side-tracking operations, which resulted in longer drilling days compared with OBM. Four wells drilled with WBM experienced severe well instability and had to be sidetracked (see Table 9). In addition, another 12 wells drilled with WBM had to go through excessive reaming and hole enlargement which resulted in additional 3.6 days of drilling time per well.

Table 9. Drilling with WBM experienced well instability issues at Eagle Ford

Well location	Burleson County	Brazos County	Dewitt County	Leon County
Well MD (m/ft)	3773/12,453	4693/15,488	5098/16,823	4921/16,240
Well TVD (m/ft)	2666/8,800	4036/13,320	4386/14,475	4120/13,597
Well Size (in)	8-1/2	6-3/4	6	6-1/8
Mud Type	WBM	WBM	WBM	WBM
Mud Weight (ppg)	10.2	13	14.7	13.8
Depth of issue (m/ft)	3773/12,453	3976/13,120	4225/13,941	4348/14,350
Problems	Tight spots and stuck pipe	Tight spots and stuck pipe	Hole packoff; BHA parted	Tight spots and stuck pipe
Remedy	Plug well and sidetrack	Fishing and side-track	Fishing and side-track	Fishing and sidetrack
Non productive time (days)	13	15	22	12

It is obvious that OBM performed better than WBM at Eagle Ford. But 12 wells drilled with WBM showed impressive results. Those wells were drilled with saturated salt mud, and the drilling days were comparable to those drilled with OBM. Considering the high costs and environmental issues of OBM, saturated salt mud may be a good alternative for drilling shale reservoirs.

4.2 Marcellus Shale

Another example is Marcellus shale. Since the first wells was drilled in 2004, more than 1050 wells have been drilled in Marcellus shale play. In recent years, the average horizontal lateral length increased to 9450 ft. Until 2015, salt-water polymer mud was widely used at Marcellus shale play, but pack-off issues ensued and BHA was lost on several wells [26].

The drilling team compared WBM versus OBM on a four-well pad by running the same rotary steerable directional tools and changing only the mud systems. The drilling data was compared for laterals between 10042 ft and 10150 ft with similar wellbore trajectories. It was discovered that the torque was reduced by 9000 ft-lb with the diesel mud over WBM, while the wellbore stability drastically improved. Rotary steerable system coupled with OBM led to significant improvement in ROP.

4.3 Changning and Weiyuan Shales

The Changning and Weiyuan fields (also known as Chang-Wei fields) are adjacent shales located in south Sichuan basin, west to the city of Chongqing with 10 Bcm gas reserve. The primary producing zone is the Longmaxi (LMX) formation about 300-400 m in thickness. XRD analysis showed the mineralogy was mainly clay, quartz, and dolomite. Discovered in 2010, Chang-Wei field in the basin is currently the most productive shale gas field in China. The field’s daily gas production has exceeded 700 million cubic feet.

At Weiyuan shale field, two horizontal wells were drilled with clay OBM. The mud was formulated with diesel, clay, $CaCl_2$ solution, emulsifier, fluid loss additive, sealing material, wetting agent, fine carbonate particles, CaO, and barite [27]. The formation pressure was very high, therefore high mud specific gravity of 1.8 to 2.2 was required to balance formation pressure [28]. Well 201-H1 encountered severe wellbore instability while the horizontal lateral was being drilled, possibly due to inappropriate mud density. Excessive time (89 hours) was spent on reaming, while the average ROP was only 1.51 m/h (or 4.95 ft/h) for the 1,918 m (or 6,293 ft) horizontal lateral. Well 201-H3 was drilled with a similar trajectory, but mud weight was reduced while drilling the horizontal lateral. No wellbore instability issue was encountered. Reaming time reduced to 16 hours, while average ROP rose to 2.15 m/h (or 7 ft/h).

At Changning shale field, two horizontal wells were drilled with clay OBM, but experienced severe lost circulation issues. Well C1 encountered lost circulation at four depths, losing 220 m^3 (or 7,769 ft^3) of mud, and 19 days of drilling time. Well C6 experienced lost circulation at eight depths, sacrificing 640 m^3 (22,601 ft^3) of mud, and 25 days of drilling time. These incidents were possibly due to high mud density and unfavorable mud rheology. For those two wells, average ROP was 4.24 m/h (or 13.9 ft/h), and average drilling time was 56 days.

Afterwards, drilling company turned to a clay-free OBM to battle lost circulation. Since clay greatly contributes to the emulsion stability of OBM, thus the key was to find a suitable emulsifier for the clay-free OBM. The new clay-free OBM was formulated with white oil, $CaCl_2$ solution, emulsifier, $Ca(OH)_2$, mud thickener, fluid loss additive, and barite [29]. For the wells drilled with clay-free OBM, mud ES ranged from 800 to 2000 V, AV from 15 to 55 cP, PV from 11 to 37 cP, YP from 4 to18 Pa, and HTHP fluid loss was below 6 mL. The four wells drilled with clay-free OBM achieved good results with average ROP of 6.82 m/h (or 22.4 ft/h), and average drilling time of 30 days. The excellent performance led to another 26 wells drilled successfully with clay-free OBM [30]. It worth mentioning that for well Tan202-H2, the average ROP reached 14 m/h (or 46 ft/h), and the drilling time was 29 days [31].

WBM was also tried at the field. The WBM was formulated with fine carbonate, emulsified asphalt, PEG, KCl and lubricant. Linear swell test shows a swell rate less than 3%, comparable to that for OBM. Mud properties during drilling are presented in Table 10. Mud performance was comparable to OBM under bottom-hole temperature of 130°C, and no complication was encountered [32].

Table 10. Properties of WBM for Changning and Weiyuan field

Block	Specific gravity	PV (cP)	YP (Pa)	HTHP fluid loss (mL)	Friction factor
Changning	2.04-2.10	8-10	8-10	2.2-4.0	0.0437
Weiyuan	2.05-2.31	8-10	8-9	2.5-3.8	0.0412

5. Summary and discussions

The OBM field cases are summarized in Table 11. In this survey, more than 400 wells were drilled with OBM, and most wells reported excellent wellbore stability, high ROP, and stable mud rheology under high temperature. Only one well at Weiyuan reported wellbore instability issue due to unsuitable mud density. After mud density was adjusted, drilling of other wells in the same field was free of incidents. Besides, few wells at Fuling and Changning reported lost circulation, due to the natural fractures in shale. The well at Fuling received bridging materials to battle lost circulation. At Changning, the drilling company sought after a clay-free OBM to conquer lost circulation.

Table 11. Summary of field cases with OBM

Field name	Mud type	Problems reported	ROP reported
Yanchang	Diesel based mud	None	5-13 m/h
Fuling	Diesel based mud	Lost circulation (1 well)	10-15 m/h
Weiyuan	Diesel based mud	Wellbore instability (1 well)	1.51-2.15 m/h
Changning	Diesel based mud	Lost circulation (2 wells)	4.24 m/h average
Changning	Clay-free OBM	None	6.82 m/h average
Shengli	Diesel based mud	None	4.81 m/h average
Shengli	Low aromatic OBM	None	8.22 m/h average
Jianghan	Diesel based mud	None	Not reported
Eagle Ford	Diesel based mud	None	9 m/h average
Marcellus	OBM	None	Not reported

Table 12. Summary of field cases with WBM

Field name	Mud type	Problems reported	ROP reported
Haynesville	WBM	None	Not reported
Fayetteville	WBM with glycol	None	9-15 m/h sliding 30-75 m/h rotating
Barnett	WBM with glycol	None	7-24 m/h sliding 30-75 m/h rotating
Chang-Wei	WBM	None	Comparable to OBM
Zhaotong	WBM	None	Comparable to OBM
Eagle Ford	WBM	Well instability (16 wells)	Not reported
Eagle Ford	Saturated salt WBM	None	Comparable to OBM
Marcellus	Salt-Polymer WBM	Well instability (multiple wells)	Not reported

The WBM field cases are summarized in Table 12. Compare with OBM cases, low number of wells were drilled with WBM in shale plays. At Eagle Ford and Marcellus shales, a few wells encountered severe wellbore instability. Some of the wells had to be sidetracked. But at other shale fields, carefully engineered WBM achieved good drilling performance. The customized WBM must go through extensive lab testing to ensure successful field implementation. Even though it is much more challenging to drill with WBM in shale, mud design with appropriate inhibitors and lubricators can still lead to good wellbore stability and good drilling performance. At Eagle Ford, drilling with saturated salt mud achieved good wellbore stability, high ROP and short drilling time comparable to OBM. This agrees with a previous study that reported WBM with appropriate salt concentration proved effective in preventing penetration of water into shale [33].

At Barnett shale and Fayetteville shale, WBM with glycol/polyglycol lead to good wellbore stability and high ROP [34]. A glycol is soluble at low temperatures, but starts to form micelles (molecular agglomerates) as the temperature is raised, thus becoming cloudy [35]. The temperature at which this phenomenon occurs is named the cloud point temperature (CPT). Glycols, usually polyethylene glycol (PEG), are often used as shale inhibitors [36]. The purported mechanism is that the glycol clouds out at higher downhole temperatures, coating the surface of clays and preventing shale hydration [37]. Research also revealed that glycol effectively improved the thermal stability of certain polymers, thus reducing fluid loss and enhancing wellbore stability under high temperatures [38]. Glycol mud has been implemented since 1990s [39], and recent reports showed good drilling results in China as well [40-41].

6. Conclusions

Shale gas has become one of the major sources of energy in USA and China. However, wellbore instability has been a major challenge in shale drilling due to the reactive clay minerals. This paper surveys the drilling fluid technology in major shale reservoirs in USA and China. According to the field cases, majority of shale gas wells were drilled with OBM, because OBM provides excellent wellbore stability, high ROP, and great lubricity. Among the field cases, very few wells drilled with OBM reported wellbore issues. On the other hand, a few wells drilled with WBM reported wellbore instability. Some of the wells had to be repeatedly reamed or sidetracked. Nevertheless, field experiences show customized WBM, such as glycol mud and saturated salt mud delivered good drilling results in shale fields. WBM is less expensive and more environment-friendly than OBM. More research should be carried out to enhance the performance of WBM in drilling shale reservoirs.

References

[1] Jenkins C, Boyer C. Coalbed and shale gas reservoirs. Journal of Petroleum Technology, 2008; 2: 92-99.
[2] Mustafa K, Berk B. Effects of silica Nano particles on the performance of water-based drilling fluids. Journal of Petroleum Science and Engineering, 2019,180: 605-614
[3] Xie J. Practices and achievements of Changning-Weiyuan shale gas project. Natural Gas Industry, 2018, 38(2): 1-7.
[4] Guo X, Li Y, Li J, Feng M. Discovery of Fuling shale gas field and its prospects. Frontiers in Energy. 2018, 13: 354-366
[5] Gao CH. Petroleum Production Technology. 2018, Science Press, Beijing, pp121-135.
[6] Li S, George J, Purdy C. Pore pressure and wellbore stability prediction to increase drilling efficiency. Journal of Petroleum Technology, 2012, 2: 98-101.
[7] Emmanuel A, Godpower E, Ghasem N. Water-based drilling fluids for high-temperature applications and water-sensitive and dispersible shale formations. Journal of Petroleum Science and Engineering, 2019, 175: 1028-1038.
[8] Gao CH. Petroleum Drilling Technology. 2017, Science Press, Beijing, pp92-97.
[9] Cheatham J. Wellbore stability. Journal of Petroleum Technology, 1984, 6: 889-896.
[10] Gazaniol D, Forsans T, Boisson M, Piau J. Wellbore failure mechanisms in shales prediction and prevention. Journal of Petroleum Technology, 1995, 7: 589-595.
[11] Gholami R, Elochukwu H, Fakhari N. A review on borehole instability in active shale formations: interactions, mechanisms and inhibitors. Earth Science Reviews, 2018, 177: 2-13.
[12] Wu B, Wang J, Shu F, Nie M. Research of application of oil based mud in shale drilling. Journal of Oil and Gas Technology, 2014, 36(2): 101-104.
[13] Liang W. Application of diesel based drilling fluid in development of Fuling shale gas field. Journal of Jianghan Petroleum University, 2016, 29(4): 34-37.
[14] Tan X. Application of domestic OBM in Fuling shale gas horizontal wells. Journal of Jianghan Petroleum University, 2015, 28 (1): 26-29.
[15] Liang W. Application of diesel based drilling fluid at Jiaoshiba shale gas play of Fuling field. Natural Gas Exploration and Development, 2014, 37(3): 66-69.
[16] Wan X. Oil Based mud applied in drilling shale oil reservoirs in Bonan block. Petroleum Drilling Techniques, 2013, 41(6): 44-50.
[17] Sun M, Qiao J, Liu B. Research and application of biodiesel based mud. Drilling Fluid and Completion Fluid, 2013, 30(4): 15-18.
[18] Hou Y. Application of low-aromatic oil based mud in horizontal shale drilling. Drilling Fluid and Completion Fluid. 2013, 30(4): 21-24.

[19] Ning F. Accumulation of shale oil at Jiyang basin. Unconventional Oil and Gas Reservoirs, 2015, 22(3): 27-30.
[20] Yang S, Zheng S, Wu B, Wang J. Application of oil based drilling fluid Invermul at HF-1 horizontal well. Chemistry and Bioengineering, 2013, 30(8): 74-76.
[21] Simpson J, Walker T, Jian G. Environmentally acceptable water-based mud can prevent shale hydration and maintain borehole stability. SPE Drilling and Completion, 1995, 12: 242-249.
[22] Deville J, Fritz B, Jarrett M. Development of water based drilling fluids customized for shale reservoirs. SPE 140868 presented at SPE International Symposium on Oilfield Chemistry, Woodlands Texas. 11-13 April 2011
[23] Ewy R, Morton E. 2009. Wellbore stability performance of water based mud additives. SPE Drilling and Completion, 2009, 9:390-397.
[24] Yan L, Li C, Zhang Z, Wang J, Xu X, Sun J. Successful application of unique high-density water based drilling fluid used in Zhaotong shale gas horizontal wells. SPE 176428 presented at Asia Pacific Oil Gas Conference, Bali Indonesia, 20-22 October 2015
[25] Guo Q, Ji L, Rajabov V, Friedheim J. Shale gas drilling experience and lessons learned from Eagle Ford. SPE 155542 presented at Americas Unconventional Resources Conference, Pittsburg Pennsylvania, 5-7 June 2012.
[26] Doak J, Kravits M, Spartz M. Drilling extended laterals in the Marcellus shale. SPE 191783 presented at SPE Eastern Regional Meeting, Pittsburg Pennsylvania, 7-11 October 2018
[27] He T, Li M, Yang L, He J. 2012. Application of oil based mud in drilling horizontal wells at Weiyuan shale play. Drilling Fluid and Completion Fluid, 2012, 29(3): 1-5.
[28] Chen Z. 2015. Application of high-density clay-free oil based mud in drilling horizontal wells at Sichuan shale field. Drilling and Production Technology, 2015, 38(5): 70-72.
[29] Fan F, Wang J, Li W. Clay-free oil based drilling fluid technology for shale gas horizontal wells in the Changning block. Petroleum Drilling Techniques, 2016, 44(5): 34-39.
[30] Zhou F, Zhang H, Li M, Luo T. Application of clay-free OBM in drilling horizontal wells at Sichuan shale field. Drilling and Production Technology, 2016:106-109.
[31] Chen Z, Moh T, Phan V, Li W, Liu D, Wang R, Lin J. Drilling evolution in Changning shale gas block. SPE 176141 presented at Asia Pacific Oil Gas Conference, Bali Indonesia, 20-22 October 2015
[32] Peng B, Zhou F, Li M, Zhang J. Optimization and evaluation of water based drilling fluids for shale gas horizontal wells: a case study of Changning shale field. Drilling Engineering, 2017, 37(3): 81-86.
[33] Bol G, Wong S, Davidson C. Borehole stability in shales. SPE Drilling and Completion. 1994, 6: 87-94.
[34] Wang L, Wu Z, Zeng J, Wang W. Study of cloud point of glycol in drilling fluid, Drilling and Production Technology, 2009, 32 (6): 85-87
[35] Hu S, Bai J, Liu B, Li G. Study of thermal stability of glycol drilling fluid. Journal of Qingdao University of Science and Technology, 2003, 24(4): 366-368
[36] Bland R, Smith G, Eagart P, Van Oort E. Low salinity polyglycol water-based drilling fluids as alternatives to oil-based muds. IADC/SPE 36400, Asia Pacific Drilling Technology Conference, Kuala Lumpur, 9-11 September 1996
[37] Liao X, Yu M, Zhang Z, Liu Y. KCl-Glycol mud for drilling Yuedong block at Bohai Bay. Drilling Fluid and Completion Fluid, 2014, 31(2): 89-91
[38] Gao C.H. Glycol mud improves drilling performance in Chinese fields. J Petrol Explor Prod Technol, 2020, 10: 2447–2452. https://doi.org/10.1007/s13202-020-00907-3
[39] Gao CH. Potential applications of welan gum in upstream petroleum industry, International Journal of Oil Gas and Coal Engineering, 2016, 4(2): 16-23. doi:10.11648/j.ogce.20160402.12
[40] Gao C.H. Preliminary evaluation of gellan gum as mud thickener. J Petrol Explor Prod Technol, 2016, 6: 857–861. https://doi.org/10.1007/s13202-015-0223-5
[41] Gao C.H. Drilling fluids for high temperature wells. Petroleum and Coal, 2019, 61(6): 1479-1486

To whom correspondence should be addressed: Chang Hong Gao, School of Mining and Geoscience, Nazarbayev University, Astana, Kazakhstan, E-mail: mohamed.mongy@bue.edu.eg