Mechanism of wellbore collapse for Carboniferous, Ordovician and Cambrian strata in Southwestern Tarim of China

Yong Sheng, Jinzhi Zhu, Haiying Lu
Tarim Oil Field Company, Petro China, Korla, China

Bing Bai, Zexv Zhang, Mian Chen, Yunhu Lu
State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum, Beijing, China

ABSTRACT: Samples corresponding to severe wellbore collapse in Carboniferous, Ordovician and Cambrian strata were collected from oil field company according to drilling and logging data. In this study, X-ray diffraction, hydration inhibition (linear swelling, dispersion and cation exchange capacity) tests and SEM experiments were conducted on representative samples. With the combination of caving analysis, the mechanisms of wellbore collapse were investigated for specific strata in Southwestern Tarim. The results showed that in Carboniferous strata, wellbore collapse was the comprehensive results of mudstone hydration and the existence of weak planes. In Ordovician strata, it could be concluded that the existed natural fractures providing drilling fluid flow path was the dominant factor inducing the wellbore instability. In Cambrian strata, the results showed the salt dissolution was the main reason of borehole collapse.

Keywords: Hydration inhibition, Microstructure, Caving analysis, Wellbore stability, Southwestern Tarim.

1 INTRODUCTION

The Southwestern Tarim Basin of China is an important region for achieving high oil recovery in the future. Currently, the borehole instability phenomenon is frequently encountered in Carboniferous, Ordovician and Cambrian strata when exploratory wells are drilled. In these strata, the lithology and stress conditions are complex, drilling fluid could not effectively maintain wellbore stability due to the lack of knowledge about collapse mechanism. Thus, it is necessary to investigate the mechanism of wellbore collapse in these strata to achieve effective and economic further drilling in Southwestern Tarim of China.

During the process of qualitative analysis for wellbore collapse, mineral composition, hydration ability and microstructure characteristics are indicators of the reason for wellbore collapse (e.g. DeNinno et al. 2016, Mohammed et al. 2019 and Sandra et al. 2012). Meanwhile, the analysis of cavings shape is also an important indicator to illustrate the mechanism of wellbore collapse (e.g. Anjanava et al. 2020 and Jose et al. 2019).

In this research, X-ray diffraction, hydration tests and scanning electron microscope experiments were performed to investigate the hydration ability and microstructure of representative lithology in Carboniferous, Ordovician and Cambrian strata. With the combination of cavings shape, the mechanisms of wellbore collapse were studied.

2 EXPERIMENTAL PROCEDURES AND RESULTS

2.1 Sample preparation

The representative cuttings and debris corresponding to severe wellbore collapse in Carboniferous, Ordovician and Cambrian strata were selected based on drilling and logging data, meanwhile, the corresponding cavings were also collected from Tarim oil field company.

In Carboniferous strata, the main lithology contained mudstone (M), argillaceous limestone (A-L) and sandstone (SS). In Ordovician strata, the samples were mainly dolomite (D), calcareous dolomite (C-D), chert nodule dolomite (CN-D) and dolomitic limestone (D-L). And in Cambrian strata, the selected samples were mostly salt (S), gypsum (G), muddy dolomite (M-D), gypsum mudstone (G-M) and dolomitic mudstone (D-M).

2.2 Mineral composition

X-ray diffraction was utilized to determine the mineral composition of all samples. In this study, an X-ray diffractometer was used with instrument settings of 45 kV and 40 mA. The power samples were prepared using a mortar and pestle, then samples were tested in X-ray diffractometer for 2θ range from 5° to 75° with a step size of 1°/min. The mineral composition would be analyzed according to 2θ value and the intensity of the XRD diffraction pattern.

The results of mineral composition for representative lithology in Carboniferous, Ordovician and Cambrian strata were listed in Table 1. According to experimental results, in Carboniferous strata, the content of quartz and clay accounted for 50-80%, clay content of mudstone ranged from 25-30%, while the clay content of argillaceous limestone was 15-20%. Comparing to argillaceous limestone, mudstone was more sensitive to water. In Ordovician, dolomite was main mineral, accounting for 70-80%, the content of clay was 3-9%. In Cambrian, salt, gypsum, muddy dolomite and gypsum mudstone were main lithology, the content of gypsum was 40-70% and clay was about 10%. The content of salt was low due to dissolution in water.

Table 1. Mineral composition of representative lithology in Carboniferous, Ordovician and Cambrian strata.

Strata		Carboniferous			Ordovician		Cambrian			
Well		HT2	HT2	MD3	HT2	YL6	CT1	CT1	YL6	CT1
Depth/m		3326	3388	4756	4653	5151	7280	7250	6369	7240
Lithology		M	A-L	SS	D	C-D	S	G	M-D	G-M
XRD Bulk Mineral/ %	Quartz	48.5	10.9	63.4	5.7	17.5	2.6	3.1	13.7	34.7
	Feldspar	7.8	14.1	10.3	2.8	3.3	3.5	2.4	3.3	2.6
	Calcite	11.2	44.7	8.6	5.8	1.2	2.1	0.5	1.1	6
	Dolomite	2.4	12	3.7	74.8	69.8	4.3	15.7	64.5	9.6
	Hematite	1.2	0.9	0.9	1.3	3.5	1.5	1	2.1	1.7
	Gypsum	/	/	/	/	/	64	62	/	30
	Barite	2.4	2.9	6.8	0.7	0.7	2.3	4.7	1	2.6
	Halite	/	/	/	/	/	9.6	7.8	/	/
	Total Clay	26.5	14.5	6.3	8.9	4	10.1	2.8	14.3	12.8
XRD Clay fraction/ %	I-M	36	28	22	6	6	2.4	/	7.8	7.6
	Illite	17	34	29	82	75	46	67	16	64
	Kaolinite	28	/	33	5	4	33	/	45	18
	Chlorite	19	38	16	7	15	18.6	33	31.2	10.4

2.3 Hydration inhibition tests

2.3.1 Linear swelling test

Linear swelling ratio is an indication of clay hydration. In general, swelling percentage will increase with the increment of content of smectite and mixed layer. This test was carried out using the linear swell meter. The samples were first crushed into power with grinder, then power sample was placed into the cylindrical box to compact under pressure of 8000 psi using hydraulic compactor for 1 hour. Finally, the compacted power was tested in the linear swell meter using deionized water.

2.3.2 Dispersion test

Dispersion test was performed to evaluate the integrity of samples. In this study, 10 g of sample cuttings and 500 ml water were added into hot roll cell, then the cell was placed on the roller of the hot roll oven and it was rolled at 35 rpm for 24 hours. After 24 hours, the cell was removed from the hot roll oven and samples in the cell were poured into a 500 micron sieve. Finally, the cuttings bigger than 500 micron were dried at 105°C for 24 hours and weighed and recorded the dry weight.

2.3.3 Cation exchange test

Cation exchange capacity (CEC) is a measurement of exchangeable cations which evaluate samples reactivity and swelling tendency. Samples with high CEC are more reactive than those with low CEC. In this study, 1-3 g cuttings were prepared to crush into 0.25 mm, then the samples were mixed with 10 ml of de-ionized water with 15 ml Hydrogen Peroxide and 1 ml sulfuric acid in an Erlenmeyer flask. After that, the flask was placed on a hot plate to boil for 10 minutes, then the sample was cooled to room temperature and water was added to 50 ml to dilute the contents. Finally, the sample was titrated by adding methylene blue solution with the increment of 0.5 ml and the titration process was finished when the dye appeared as a faint blue ring.

2.3.4 Results of hydration inhibition tests

Table 2 showed the results of linear expansion, recovery and CEC for representative samples. In Carboniferous strata, linear expansion was 15-20%, recovery percentage was less than 50% and CEC ranged from 130 mmol/kg to 170 mmol/kg for mudstone. For argillaceous limestone, linear expansion was 7-15%, recovery percentage was greater than 70% and CEC was located at 30-50 mmol/kg. Mudstone was more prone to hydration comparing with argillaceous limestone. Thus, mudstone hydration might induce wellbore instability in Carboniferous strata. In Ordovician, for the lithology of dolomite, calcareous dolomite, chert nodule dolomite and dolomitic limestone, linear swelling was less than 5%, recovery percentage was usually greater than 60% and CEC was about 10 mmol/kg, carbonate rocks were not sensitive to water according to results of all hydration inhibition tests, thus, hydration was not the reason for wellbore collapse in Ordovician strata. In Cambrian, salt, gypsum, muddy dolomite, gypsum mudstone and dolomitic mudstone were also not easily hydrated according to hydration inhibition tests, however, salt and gypsum were easy to dissolve into water-based drilling fluid, which would lead wellbore collapse in Cambrian strata.

Table 2. Results of hydration inhibition test for representative samples.

Strata	Well	Depth/m	Lithology	Linear expansion/%	Recovery/ %	CEC/ mmol • kg^{-1}
Carboniferous	HT2	3326	M	20.9	2.18	160
	HT2	3388	A-L	14	75.3	50
	MD3	4756	SS	5.0	86.56	20
Ordovician	HT2	4653	D	1.7	36.88	10
	YL6	5151	C-D	2.3	67.9	10
	HT2	4683	CN-D	2.5	95.82	10

	MD2	4270	D-L	4.9	76.4	20
Cambrian	CT1	7280	S	1.6	16.78	10
	CT1	7250	G	7.7	16.4	10
	YL6	6369	M-D	2.4	79.5	15
	CT1	7240	G-M	3.9	50.28	10

2.4 Microstructure

Scan electron microscope (SEM) experiments were conducted on the cores in the well to observe the microstructure. In Fig.1, the outcrop samples of mudstone in Carboniferous strata was shown in the left image, it could be found that mudstone was easy to fracture into pieces along weak plane. The middle image represented the dolomite core located in the depth of 4291 m in Ordovician strata, and the right image was the photo of dolomite core in the depth of 7412 m in Cambrian strata. It could be observed that there were lots of natural fractures in the cores, especially, parallel natural fractures are developed in the core of Ordovician strata. Fig.2 exhibited the SEM photos of dolomite core in Ordovician strata, it was obvious that many fractures existed in the dolomite cores. The fractures provided the paths allowing drilling fluid to flow into reservoirs in Ordovician strata, which might induce wellbore collapse.

Figure 1. Outcrop samples of mudstone and dolomite core images.

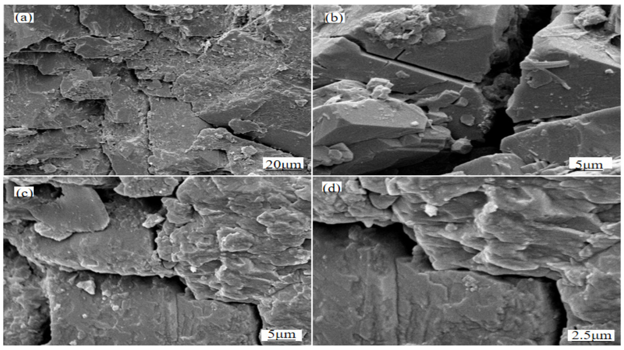

Figure 2. SEM photos of dolomite core in Ordovician strata.

3 CAVING MORPHOLOGY ANALYSIS

3.1 Theory of wellbore collapse by caving analysis

The main cavings morphologies encountered while drilling usually are splintery, platy/tabular, blocky and angular cavings. Each caving shape represents one failure mechanism (Anjanava et al. 2020).

Splintery caving is long and concave shape, major causes of splintery cavings are the negative differential between drilling fluid pressure and pore pressure, also called underbalanced drilling.

Platy/tabular cavings has flat and parallel surfaces, they are generated during failure due to slippage along weak planes, platy cavings are result of chemical instability inside a borehole rather than borehole wall failure induced by a mechanical instability. Blocky cavings have rough surfaces, they are caused by the invasion of drilling fluids into the natural fractures, these are typically expected in fractured rocks, around salt, and along faults. Angular cavings can be described by an arrowhead or triangular shape with faces and a rough surface structure, it is generated due to shear failure of the wellbore.

3.2 Caving characteristics in target strata

Fig.3 showed mudstone cavings in the depth of 4012 m in carboniferous strata, and the middle and right images are distinguished shape based on computer procedure. It could be found that mudstone cavings in carboniferous strata are mainly platy cavings and splintery cavings, thus, it was concluded that in carboniferous strata, the existence of weak planes which are confirmed by outcrop samples, clay hydration and negative pressure differential are the factors influencing wellbore collapse. Fig.4 illustrated that in Ordovician strata, dolomite cavings are mainly platy and blocky cavings, it was concluded that the existence of weak planes and natural fractures in dolomite are the main reasons that affect wellbore stability.

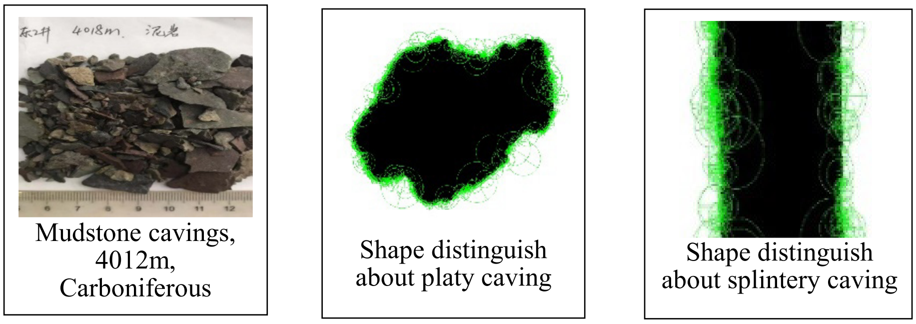

Figure 3. Mudstone cavings in Carboniferous strata.

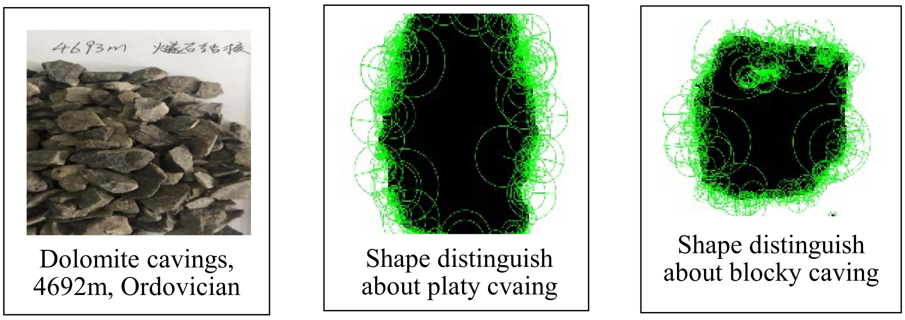

Figure 4. Dolomite cavings in Ordovician strata.

4 MECHANISM OF WELLBORE COLLAPSE

Based on all experimental results, it could be found that in Carboniferous strata, mudstone was sensitive to water according to clay content and hydration inhibition, meanwhile, the mudstone outcrop samples were found to contain lots of weak planes when mudstone samples were collected. Thus, mudstone hydration and weak planes were the causes of wellbore collapse, with the confirmation of platy and splintery cavings, it could be concluded that the comprehensive of mudstone hydration, the existence of weak planes and negative differential pressure were the main reasons of wellbore collapse.

In Ordovician strata, carbonate rocks were not prone to hydration swelling, however, there were lots of weak planes and natural fractures existed in dolomite according to microstructure observation of cores, these natural fractures provided the path for drilling fluid to flow, which caused wellbore instability. Also, the platy and blocky dolomite cavings confirmed that the existence of weak planes and natural fractures were the main causes of wellbore collapse.

In Cambrian strata, salt and gypsum were main lithology. In mineral composition, it could be found halite was low in salt rock, this was because that salt was dissolved into water-based drilling fluid, logging data analysis also showed that wellbore expansion rate could reach up to 60%. It could be concluded that salt dissolution was the main reason of wellbore collapse.

5 CONCLUSIONS

The mineral composition, hydration inhibition, microstructure experiments and caving analysis were conducted on samples in Carboniferous, Ordovician and Cambrian strata to investigated mechanism of wellbore collapse in Southwestern Tarim of China. The main findings were summarized as follows:

(1) In Carboniferous strata, the comprehensive results of mudstone hydration, weak planes and negative differential pressure were the reasons of wellbore collapse; In Ordovician strata, lots of weak planes and natural fractures in carbonate rocks which provided path for drilling fluid to flow were the main cause of wellbore collapse. In Cambrian strata, salt dissolution was the factors affecting wellbore stability.

(2) In Southwestern Tarim of China, lithology and stress conditions were complex, mechanism of wellbore collapse showed huge difference. It was necessary to investigate the mechanism of wellbore collapse by lots of research theories and methods.

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