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Research Article

Research on Rapid Identification and Evaluation Technology for Gas Formation during Underbalanced Drilling

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The underbalanced drilling (UBD) technology has been widely implemented due to its advantages in drilling efficiency improvement and cost reduction. However, this advanced technology requires very special equipment and operational mechanism, which raises multiple challenges to traditional well logging techniques. In this study, a real-time logging system (MWD/LWD and mud logging) was developed and utilized during underbalanced drilling, to quickly identify and evaluate gas formation. This advanced system enables fast detection of gas formation and determining the formation type while drilling, by monitoring the changes in gas production. This real-time logging system provides a powerful technical support to the gas reservoir drilling and development. A case study has clearly shown that the interpretation and evaluation results based on the real-time logging data agree well with the results of conventional well logging. Therefore, this advanced real-time logging technique can be utilized as an effective guidance for field operation.

1. Introduction

Underbalanced drilling (UBD) is a process by which the bottom pressure of the well is maintained below the formation pressure and causes the formation fluid to flow into the wellbore and then to the surface under control [1]. With the increasing complexity of oil and gas reservoirs, the proportion of reservoirs with low porosity, permeability, pressure, and abundance increases annually. It is difficult to achieve expected targets with conventional drilling technology, but the use of UBD technology has been able to multiply production in this type of reservoir. However, there are also certain risks in UBD. When drilling into hydrocarbon reservoirs, especially gas reservoirs, kicks or blowout accidents may be caused if well control is handled poorly [2, 3]. Therefore, timely monitoring and control of the fluid production and appraising the hydrocarbon reservoir while drilling become particularly important.

The real-time evaluation of gas formation during UBD is very critical to gas reservoir exploration and development [4–6]. Currently, the most common approach is to monitor the changes of total hydrocarbon value and gas production in the real-time logging [7]. However, during UBD, formation gas constantly enters into the wellbore, which severely disturbs the background gas value. As a result, the conventional well logging approaches are not able to interpret gas formation accurately [8]. Bao and Chen (2005) discussed the method of identifying and evaluating the gas formation by analyzing the gas bearing condition of drilling cuttings with UBD. Xu et al. (2007) put forward the comprehensive discriminating and evaluating method of recognizing the gas formation by monitoring the drilling time, gas logging values, and the gas flow rate, observing the variation of drilling parameters, the change of the mud ditch surface, and the state of the torch combustion with UBD. This study has analyzed the real-time well logging measurements (MWD/LWD, mud logging) and

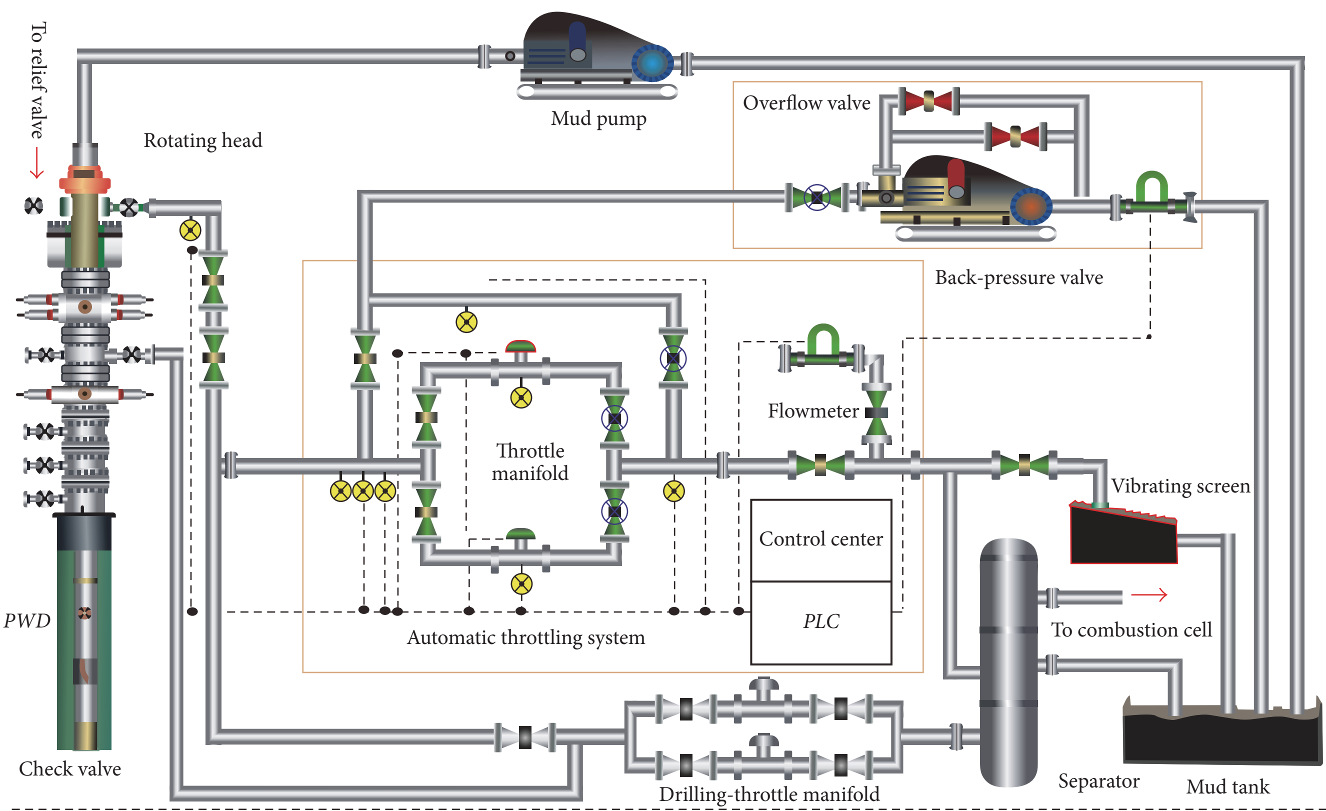

Figure 1: Flow chart of underbalanced drilling.

established a novel approach to identify and evaluate gas formation with underbalanced drilling. This new approach has provided significant improvement to the conventional well logging techniques. Meanwhile, it is also critical to a robust drilling program by rapidly evaluating gas formation and effectively guiding the site operation.

2. Measurement While Drilling in Underbalanced Drilling

To evaluate gas formation timely during UBD, a real-time surface monitoring system is necessary to monitor multiple variables during drilling process. In conventional drilling, this task is achieved by well logging system. However, the equipment and operation process of UBD is significantly different from that of conventional drilling (Figures 1 and 2). Thus, the well logging system is unable to monitor multiple parameters in UBD. To address these challenges, multiple instruments have been added to the original equipment, such as drilling mud performance sensor at the outlet, degasser, and gas sample collector [9].

The real-time well logging system is composed of data acquisition, signal processing, data transferring, monitoring, and data evaluation [10, 11] (Figure 3). The data acquisition sensors conduct multiple measurements of the mud system before the mud is injected and after the mud is returned. The preinjection measurements typically include determination of temperature, pressure, volume, and rheological parameters of the mud. The return mud measurements (mud logging) include the total returned volume, gas flux, and rheological parameters at the outlet. The original analog signals are converted to digital signals using composite A/D signal adapter. Finally, the data signals are transferred to computer terminal wirelessly, and the interpretation results in the form of charts and diagrams can be visualized in real-time manner. This data processing and control system provides to field personnel capability of real-time monitoring and preventing the fluid loose/kick situation during UBD [12, 13].

When logging while drilling, there is a time difference (lag time) between the real data on the bit and the data on the wellhead sampled by log equipment. The lag time depends on the mud circling time and could be impacted by the circling speed and formation temperature. The theoretical lag time is expressed as

$$T = \frac{V}{Q_0} = \frac{\pi\left(D^2 - d^2\right)H}{4Q_0}, \tag{1}$$

where T is the lag time, min; Q_0 is mud flow rate, L/min; D is wellbore diameter, m; d is outer diameter of drill string, m; V is borehole annulus volume, m^3; H is well depth, m.

The drilling tool assembly uses English unit; for the convenience of field application, taking π value as 3.14 and

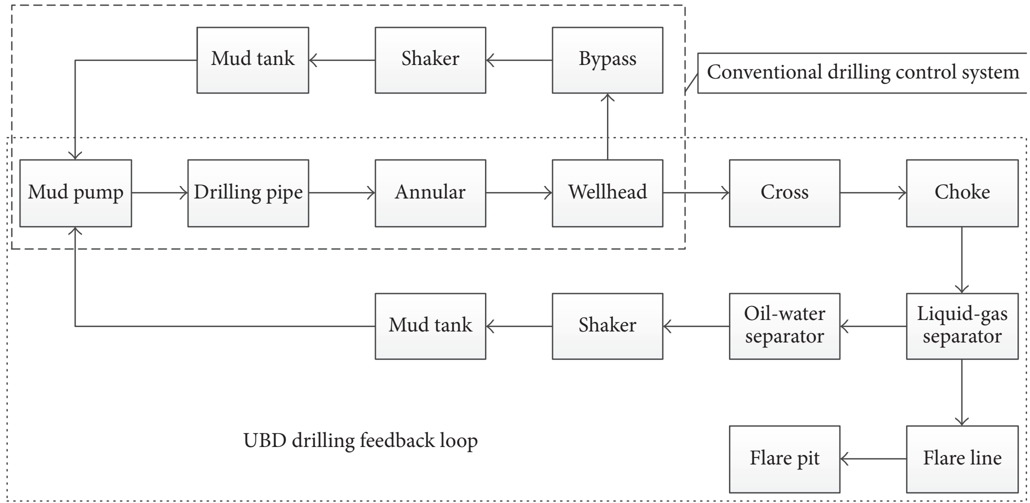

Figure 2: Control and feedback loop of underbalanced drilling.

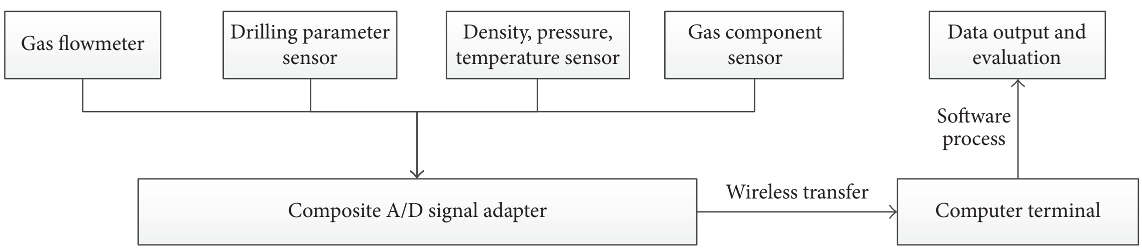

Figure 3: Organization chart of monitoring system.

converting from metric to English units, formula (1) can be written as

$$T = \frac{\left(D^2 - d^2\right) H}{118.5 Q_0}, \quad (2)$$

where T, Q_0, and H are the same as above, while D is wellbore diameter, inch; d is outer diameter of drill string, inch.

Due to the effect of gas effusion, the actual lag time is typically less than the theoretical value. The time difference can be further modified by humidity correction method [14].

3. Gas Zone Identification and Evaluation While Drilling

3.1. Quick Identification of Gas Zone. During UBD, the wellbore is at lower pressure compared with the formation. Hence, the higher pressure formation gas tends to flow into wellbore during and after drilling. This usually creates a significant noise and causes the measurement inaccuracy. The conventional well logging method is not able to evaluate gas zones accurately in this case. Thus, additional measurements and techniques are needed to quickly recognize gas zones [15, 16].

3.1.1. Monitoring Hydrocarbon Concentration in Return Mud. During UBD, since the hydrocarbon content in the gas formation is much higher than that in the drilling mud, the hydrocarbon content in mud increases significantly after formation gas enters the wellbore and solubilizes (partially) in the drilling mud. Generally, when the hydrocarbon concentration in the return mud is increased by more than 3%, it indicates a gas zone is drilled.

3.1.2. Monitoring Drilling Time/Rate of Penetration (ROP). During UBD, the formation pressure is higher than the downhole pressure; thus the formation is easier to be drilled. When encountering porous or fracture-intensive formation, the drilling speed increases and the drilling time decreases noticeably. This becomes more obvious during liquid phase UBD; the ROP changes drastically when gas zone is encountered. However, when air drilling is applied in UBD, such change in ROP will not be so obvious. Hence, additional observations need to be made to detect gas zone.

3.1.3. Comprehensive Analysis of Drilling Parameters. When drilling into a new gas zone is determined by increased ROP and higher hydrocarbon content in the return mud, it is good practice to increase wellhead back pressure accordingly to prevent a kick. When exiting out of a gas zone, the wellhead back pressure is lowered again to create underbalance condition in wellbore, and thus ROP is increased. The adjustment of wellhead back pressure inevitably causes the changes in stand pipe pressure, casing pressure, gas flux, and so on.

When formation gas flows into annulus and goes up to wellhead, the stand pipe pressure drops significantly. If a significantly large volume of formation gas flows into the wellbore annulus, choke valves should be turned off. This operation controls the influx volume of formation gas and thus increases stand pipe pressure and casing pressure.

If stand pipe pressure decreases as the casing pressure increases, or both pressures fluctuate evidently, it suggests a gas zone is encountered in drilling. Additionally, since wellhead pressure drops significantly compared with bottom-hole pressure, formation gas expands quickly as it travels up to the wellhead, causing the volume of drilling mud increases. As a result, the density of the return mud drops. By monitoring the changes in the return mud density, the encountering of a gas zone can be determined.

In summary, a number of indicators have been found to be able to determine whether a gas zone is encountered while drilling, such as

(i) the increase of ROP,

(ii) the increase of total hydrocarbon content in return mud,

(iii) the increase of casing pressure coupled with decreasing stand pipe pressure,

(iv) the significant fluctuation of these pressures,

(v) the reduced density of return mud,

(vi) the increase of viscosity of the outlet drilling fluid,

(vii) the increase of drilling fluid temperature,

(viii) the decrease of the outlet electrical conductivity,

(ix) the increase of gas flux volume.

Although some indicators mentioned above are not explicitly discussed in this study, those can provide additional evidence in the identification of the gas formation.

3.2. Detection of Gas Zone Medium. There is quite obvious difference in gas production while drilling the homogeneous gas layer and the fractured gas layer. The formation property of the gas layer could be identified in a real-time manner by interpreting the variation of gas production volume. In addition, the gas production rate from the gas zone drilled can also be estimated roughly. The gas production rates while drilling are expressed as

$$\text{Mud drilling: } Q = \frac{L_1}{\eta L_2} T_g \cdot q$$
$$\text{Air drilling: } Q = \frac{\left(\left(L_1/\eta L_2\right) T_g\right)}{\left(1 - T_g\right)}, \tag{3}$$

where Q is the gas production rate while drilling, L/min; q is the inlet volume flux, L/min; T_g is the total hydrocarbon value, %; L_1 is the gas extraction volume of the pump, mL/min; L_2 is the electrical degasser volume, mL/min; η is the electrical degasser efficiency, %.

Under stable operation environment, using the same instruments in the same operation, the pumping capacity and the electric degassing efficiency of sample pumps remain constant; thus, $L_1/\eta L_2$ is considered as a constant.

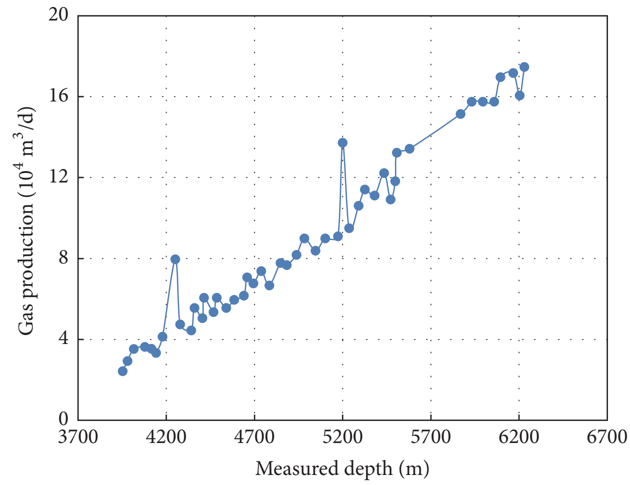

Figure 4: Gas production from a homogeneous sandstone while drilling.

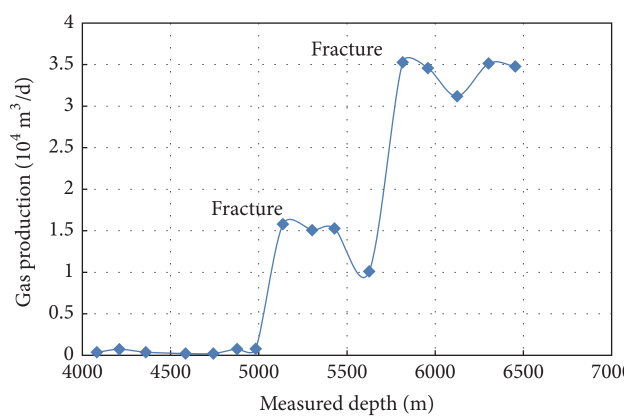

Figure 5: Gas production from a fractured reservoir while drilling.

We are able to interpret formation type (homogeneous or fractured reservoirs) when gas production rate data is obtained while drilling. As seen in Figure 4, the gas production from a homogeneous sandstone formation changes linearly along the drilling depth. Figure 5 shows that the gas production is at various drilling depths in a fractured reservoir, where the gas production rate exhibits sudden change caused by the large permeability contrast between neighboring strata.

3.3. Evaluation and Interpretation Method of Gas Zone. During UBD, the flow of formation gas into wellbore causes the reduction of the density of drilling mud at outlet. Meanwhile, the release of formation gas from the drilling mud takes away the heat, causing the reduction of outlet temperature of drilling mud. Therefore, changes in the drilling fluid outlet density and temperature can be utilized as an indirect indicator to interpret the encountering of gas production zone. In addition, the responses of porosity logs to a gas

Table 1: Evaluation criteria for gas zone.

Effective porosity (%)	Density decrease (%)	Temperature decrease (%)	Result
>8	>15	>10	Gas zone
5–8	8–15	5–10	Poor gas zone
<5	3–8	3–5	Gas-water zone

formation are obvious; thus the drilling fluid outlet density and the temperature can be combined with logging porosity data to generate a better evaluation tool. Through the in-depth study of the characteristic parameters of the gas zone in the Peng Lai area (Shandong, China), based on mathematical statistics, a set of criteria for the evaluation of quality of the gas zone in Peng Lai area is summarized in Table 1.

In field practice, MWD/LWD data is usually used to identify the entrance of a gas zone. Then, this new set of evaluation criteria can be applied to interpret the type of gas zone. Finally, these interpretation results need to be studied, combining with the effective porosity log, to further verify the preliminary evaluation result.

4. Case Study

The PL133 well was designed to have a measured depth of 2769 m, and the main target layer was the Xujiahe Formation (T_3X_2). The low-density drilling fluid and underbalanced drilling technology were deployed in the well section between 1733 m and 2769 m MD. Through the analysis of the hydrocarbon in the adjacent wells, it was expected that the formation encountered in this well drilling would mainly be composed of gas, with some water saturation. According to the core analysis results, the average porosity of the Xujiahe Formation is 6.6% and the average permeability is 0.09 mD. The results have revealed that the formation in Penglai area has the extremely low porosity and low permeability characteristics. Underbalanced drilling technology was utilized in this well in order to detect and protect gas zone in a timely manner.

4.1. Rapid Identification of Gas Zone While Drilling. A comprehensive well logging interpretation result for the interval of PL113, 2520–2620 m MD, is shown in Figure 6. In the section above, 2532 m, the total hydrocarbon concentration stays at about 9.5% and no obvious increase is noticed. Meanwhile, the drilling time-curve shows the average drilling rate is larger than 13 min/m. Thus, the formation above 2532 m MD is considered as a nonreservoir formation. The total hydrocarbon value monitored is from the previously opened reservoir. In the 2532 m–2556 m interval, the total hydrocarbon value increases linearly from 10.04% to 16.22%. Meanwhile, the drilling time decreases from the average of 13 min/m to 7.5 min/m. The change of drilling parameters suggests the presence of a section of homogeneous gas formation. Below 2556 m MD, the total hydrocarbon value appears to drop significantly to 13.11%, while drilling rate gradually rises to about 10 min/m, which suggests an exit of the gas zone. By applying the same method to the entire section, one can determine that gas bearing sections are present at 2564 m–2569 m, 2581 m–2584 m, 2593 m–2595 m, and 2613–2618 m MD.

As seen from Figure 6, the interpretation results from the traditional logging tools (borehole indication, porosity indication, and resistivity curve) and the newly added indicators (drilling indication, outlet indication, and gas logging indication) stay very consistent along each other. The results from traditional logging tools were obtained from well logging after drilling completion and the results from newly added indicators were obtained from logging while drilling. Therefore, it can be concluded that the real-time logging and monitoring data can be used to identify and evaluate the gas zones fast and accurately.

4.2. Interpretation of the Types of Gas Formation. From the drilling depth of 2532 m to 2556 m MD, the gas production rate increases from 0.59 m^3/min to 1.03 m^3/min, as seen in Figure 6. The relatively slow and also steady change of gas production rate indicates a homogeneous gas zone was encountered while drilling. At around 2564 m MD, the gas production increases sharply from 0.84 m^3/min to 1.54 m^3/min, which implies that a fractured gas zone might be drilled. From the gas production chart, the rapid surges at 2581 m–2584 m, 2593 m–2595 m, and 2613 m–2618 m are also indications of fractured gas zones, as shown in Figure 7. The conventional well logging results for PL 113 well reconfirm these assessments in Figure 7. In summary, a reasonably accurate interpretation of formation type of gas zone can be made by analyzing the changes in gas production rate while drilling.

4.3. Evaluation of Reservoir Property of a Gas Zone. The drilling fluid density, temperature, and gas zone's effective porosity of the PL113 well are presented in Figure 8. A significant decrease of density and temperature in the interval 2564–2569 m MD is observed. The percentages of these changes were calculated and showed in Table 2. This formation was initially identified as the gas zone during UBD. Using the proposed evaluation criteria (Table 1), we have interpreted this formation as a poor quality gas zone (Table 1). Similarly, the section 2581–2584 m MD is also classified as a poor quality gas zone. This interpretation agrees with the extremely low porosity and low permeability characteristics in this region. The mud density and temperature for 2613–2618 m MD interval indicate the presence of both gas and water, suggesting the possibility of water invasion in this zone. The conventional well log interpretation in Table 3 matches exactly the interpretation from Table 2, which further validates our interpretation.

Based on the analysis on the adjacent wells of the same formation and their well test results, it was found that the primary pay zone in this formation is gas zone and the pay is continuously distributed in the upper part of Xujiahe Formation (T_3X_2). Through comprehensive analysis in PL113 well, it was discovered that the favorable production zones are mainly located in the upper part of the Xujiahe Formation,

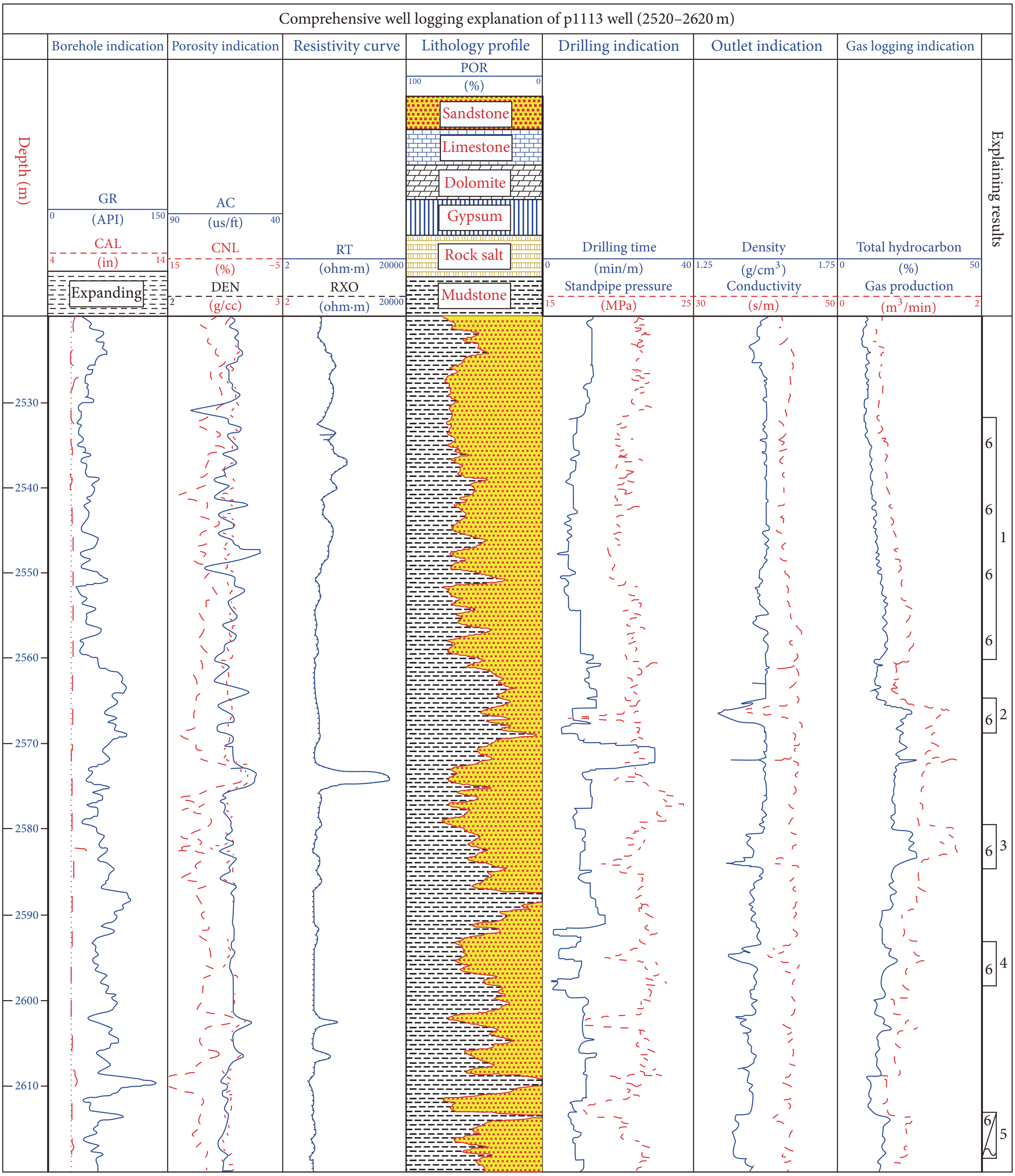

Figure 6: Comprehensive well logging of PL113 well (2520–2620 m).

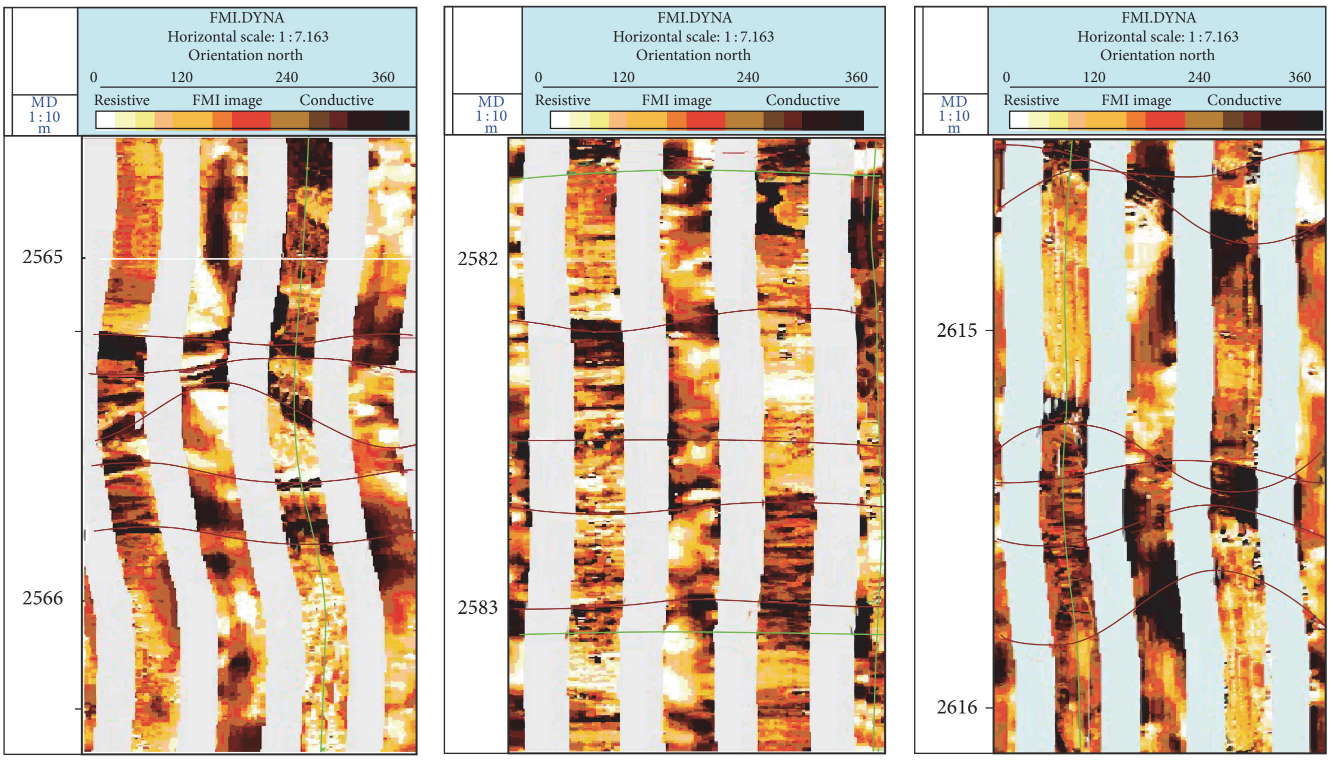

Figure 7: Depth imaging log in PL 113 well.

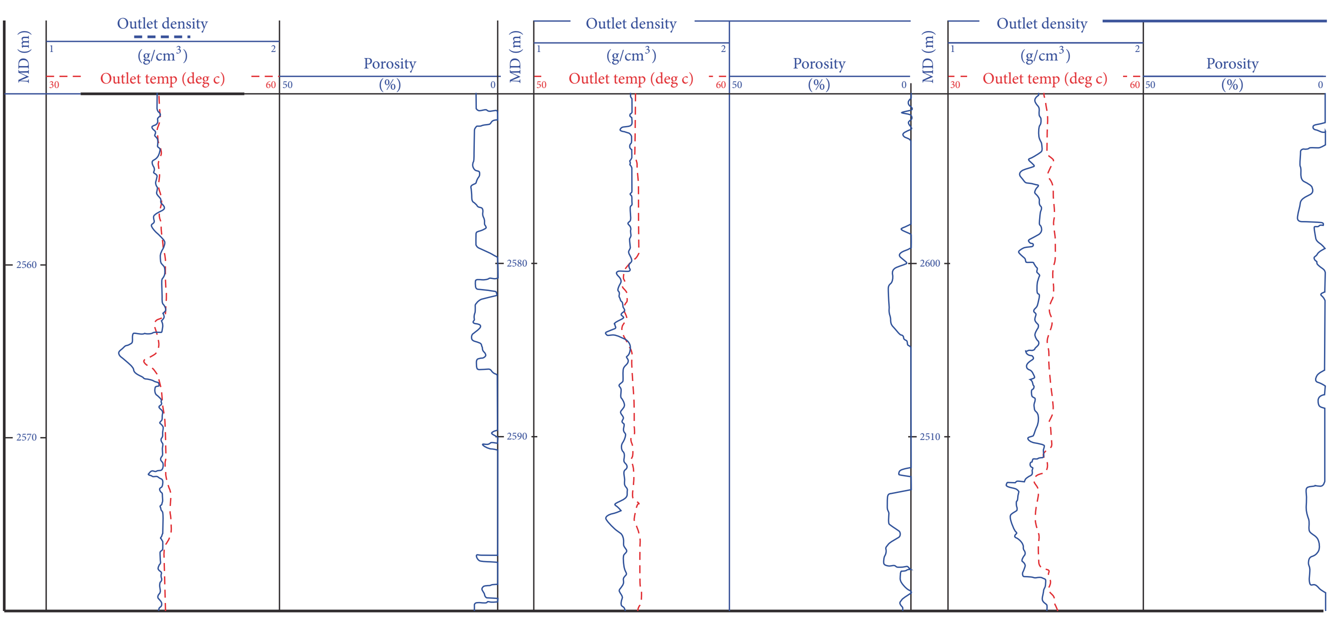

Figure 8: Changes in well log curves in gas zones, PL 113.

which should be considered during the later horizontal drilling design as well as reservoir development plan.

5. Conclusions

(1) By utilizing of real-time logging data (MWD/LWD, mud logging), an accurate and timely identification of gas zone in underbalance drilling becomes possible. In addition, the formation type and quality of gas zone could be determined using the change of gas production rate data along the depth. This new approach enables us to stay informed of the existence and quality of underground gas layers.

Table 2: Real-time logging interpretation results for PL113 well intervals.

MD (m)	Average effective porosity (%)	Outlet drilling fluid density		Outlet drilling fluid temperature		Interpreted result
		Variation (g/cm^3)	Drop (%)	Variation (°C)	Drop (%)	
2564–2569	6.07	1.50 to 1.31	12.67	45.47 to 42.71	6.07	Poor gas zone
2581–2584	6.36	1.49 to 1.37	8.05	46.33 to 43.57	5.96	Poor gas zone
2613–2618	5.18	1.46 to 1.36	6.84	46.05 to 44.51	3.34	Gas-water zone

Table 3: Conventional well logs interpretation results for PL113 well intervals.

MD (m)	Natural gamma ray (API)	Sonic log (us/ft)	Neutron log (P.U)	Density log (g/cm^3)	Deep lateral log (ohm·m)	Shallow lateral log (ohm·m)	Water saturation (%)	Interpreted result
2564.3–2568.6	45–114	59.1–67.9	7.6–10.1	2.52–2.66	23–38	23–38	31–49	Poor gas zone
2580.6–2584.5	43–83	59.5–67.5	7.2–13.7	2.37–2.58	18–37	16–35	31–47	Poor gas zone
2612.7–2618.1	44–86	59.0–66.5	9.2–12.8	2.47–2.62	16–22	15–23	59–88	Gas-water zone

(2) With a deep understanding of real-time logging data from different types of gas formation, we have established a methodology to quickly identify and classify gas zones during the UBD. Applying the evaluation criteria to the logging data enables us to have a real-time evaluation of the gas zones in the field.

(3) As the formation evaluation technique by monitoring and utilization of MWD data in the gas zone is still in its exploratory stage, hence, the proposed formation evaluation criteria in this study should be used cautiously and will be further refined.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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