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Realtime Monitoring, Using All Available Data, Plays A Vital Role In Successful Drilling Operations

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Abstract

In order to mitigate predrill uncertainties and provide the well team with the best information to drill proactively, monitoring of borehole operations in realtime is vital on wells drilled today. Realtime monitoring (Pore Pressure while Drilling ï PPwD) gives the team the best chance to drill the well safely and efficiently to planned targets. Recent proposals by the United Sates Bureau of Safety and Environmental Enforcement indicate realtime monitoring might soon be mandatory on many offshore US wells. One particularly important aspect of realtime monitoring is pore pressure and fracture gradient estimation and prediction.

Most analysis of drilling data, such as petrophysical, drilling parameters, gas and geology, relies solely on depth-based data, which of course are only available while drilling ahead, i.e. wellbore depth is increasing. The depth-based analysis model is relatively low resolution with data points at 0.5 foot or 0.2 meter intervals. If calibrated correctly the models are valuable and accurate, providing the well team with useful insight about present and possible future events.

However, there are many operations during the drilling of a well that do not generate depth-based data, such as pipe connections, circulating off-bottom, wiper trips, flow-checks etc., that instead, generate time-based data. When analyzed, such data provide invaluable information to permit further calibration of the models. Realtime pore pressure models that only contain depth-based information are potentially flawed because the many calibration points that occur while the bit is off bottom are not captured/recorded in the model. Building a time-based model in parallel to the depth-based model allows for a far more robust picture of downhole conditions.

This paper will use real examples from the Gulf of Mexico to explain the importance and benefits of constructing a time-based model that will be used alongside the depth-based model. It will also demonstrate how discrepancies between depth-based models and time-based models can arise.

The result of using all available data, in both depth and time domain, is a more robust, integrated model on which to base the pore pressure estimation and prediction and ensure the well team gets the best

possible information.

Introduction

Offshore operations can be very complex and time consuming. Often the actual drilling of strata only occupies a fraction of the whole well. Complications due to improper pore pressure and/or fracture pressure estimation and management can lead to rapidly increasing costs as non-productive time accumulates. Not only during the drilling process, but for the entire time the hole is open to the surface, when a continuous stream of information is being provided about the pore pressures and fracture strength of the exposed wellbore.

Typical realtime pore pressure monitoring requires numerous drilling, LWD/logging, gas and lithology data which may be then displayed and analyzed both in depth and time domain. For instance; drilling parameters such as rate of penetration (ROP), weight on bit (WOB), Torque (TRQ), stand pipe-pressure (SPP), mud flow in and out (MFI/MFO), mud density in/out (MWI/MWO), effective static and circulation densities (ESD/ECD), mud temperature in/out (MTI/MTO) can all be used to recognize any abnormal drilling trends (e.g. drilling breaks, high torque) and also for calculation of drilling exponent (DXC). For lithological discrimination and empirical PP modeling and calibration, MWD/LWD (and wireline) data such as gamma ray (GR, SGR), shallow/medium/deep resistivity (RESS/RESM/RESD), compressional and shear sonic (DT co and DT shr) and downhole temperature (TEMP lwd) is used. The third set of important information is gas data which typically consist of total, or background, gas (TG or BG), gas chromatograph breakdown (C1-C5n or higher), gas peaks, gas ratios. Additionally, the pore pressure (PP) analyst should also pay special attention to cuttings description and their character (e.g. recognition of PP-related cavings). In practice all data can be equally important for PP estimation.

Time-based data supplies a high resolution dataset of this information which, when correctly analyzed, increases the accuracy and confidence of the shale pore pressure and fracture strength (PPFG) estimation. The addition of the time-based data to the realtime depth-based disequilibrium compaction model increases its reliability and value to the drilling team. Conversely, a realtime depth-based pore pressure model made without fully analyzing time-based data can do more harm than good by not fully accounting for events that happened while off bottom.

The primary calibration factor for an empirically derived realtime depth-based disequilibrium compaction model is the reaction of mud gas levels to the hydrostatic head of the mud column. Time-based gas analysis can help us to create a narrower window of uncertainty for the pore pressure estimation. There are other calibration points for the depth-based model that are equally as important but they occur less frequently.

This paper will demonstrate discrepancies between depth-based and time-based data and how calibration points will not be available for the depth-based realtime PP model because the bit is not on bottom and drilling, thus not generating any depth-based data.

Where, why and how do we use PPwD?

Realtime pore pressure monitoring aids the drilling team in optimization of the mud gradient and casing setting depths (Doyle, 1999). A depth-based disequilibrium compaction model is the primary instrument used for making realtime pore pressure estimates and is calculated through the utilization of empirical methods, such as Eaton (1975), Bowers (1995) and Equivalent Depth Method (EDM; Foster and Whalen (1965)). These methods use depth-based porosity-dependent logging while drilling (LWD) and wireline data such as resistivity and sonic along with user-defined normal compaction trends to generate pore pressure estimates in shales. The models are then calibrated to pressure-related events such as gas peaks, gas trends, hole conditions and cuttings and cavings morphology.

The pre-drill pore pressure and fracture pressure profiles are used to define the planned mud weights and casing points for the well at the planning stage. However, a large degree of uncertainty accompanies these pre-drill models, such as seismic data quality, geological complexity, pre-drill data resolution, and scarcity/relevance of offset wells (Madatov & Doyle, 2014). Often the Pore Pressure/Fracture Gradient (PPFG) profile actually seen when drilling the well is quite different from pre-drill estimates, necessitating changes to the casing and mud programs, and 24/7 realtime pore pressure monitoring is a critical part of this process, saving time and money on wells with narrow drilling windows (OôConnor et al. 2014).

Discrepancies in Depth-Based Data vs. Time-Based Data and the crucial information missed

Depth-based data is constructed from time-stamped data that is then correlated back to a known datum and presented as depth. Depth-based models are then constructed with applicable data. However, when analyzing a well for pore pressure, a depth-based model will not tell the whole story, as a large component of what actually occurred while drilling is missing from the PPFG model. There is no information about what happened while the bit was off bottom; therefore, gas events that were lagged back to a time when drilling was not taking place will not be displayed on a depth-based plot. The consequence being that connection gas peaks and other important calibration information for realtime pore pressure prediction will be omitted from depth-based plots. Also, while drilling deviated or horizontal wells some data will not be displayed properly on depth plots, as all the PP analysis should be done in true vertical depth (TVD).

When constructing a pore pressure estimate, use of time-based data is essential as it presents a continuous log of all interactions while the bit is drilling, off bottom or out of the hole, and is much more suitable for analysis.

The following example demonstrates some discrepancies between depth-based and time-based data and pertinent information relative to the realtime pore pressure service that is lost in the depth-based plot. Figures 1 and 2 display depth-based and time-based plots of drilling parameters respectively, over an interval of 270 ft. It is clear that Figure 2, the time-based plot, provides a much more detailed picture of events and covers what transpired during connections, back reaming, directional surveys, mud conditioning, pump maintenance, etc. The drilling data displayed on the depth-based plot is somewhat muted; this is perhaps due to smoothing filters applied to the depth-based data, or time-to-depth conversions. Figure 3 shows the same information as Figure 2, but with additional datasets such as minimum ESD, block movement, bit depth, lag depth, tank volume and operational notes. Figure 3 is more suitable for time-based data analysis and is a typical representation of what is, or should be, used.

[Figure 1 item 1] (numbered arrow) shows a swab gas marker (purple square), a pumps-off gas marker (orange triangle) and a connection gas marker (black dot) that were all produced within 60 minutes of each other when the bit was pulled off bottom at the end of a stand [Figure 3 item 4]. These quantative gas markers are not on the actual depth-based gas log (red line) because none of these gas peak events were produced while the bit was on bottom. Therefore time-based data analysis is the only way to properly deduce if a gas peak event was produced while the bit was off bottom. Once the gas peak is identified in time-based data, proper analysis about the production of the gas peak event can be performed which can help to calibrate the realtime pore pressure estimation. Examples of this time-based data analysis will be given later in the paper.

Gas: What it means and how we use it

Gas analysis is typically undertaken by wellsite personnel, primarily mudloggers or wellsite geologists.

Usually communication between the rig and shore-based operations is seamless which allows for a high quality service. However, in our experience, small gas peaks which are indicative of pore pressure changes and transition zones are sometimes overlooked or mislabeled by wellsite personnel. At times an uncertainty in lag depth calculations due to the use of booster pumps in a long riser section will mask the depth of a connection gas peak and causing it to be disregarded; some examples of this are described here. A connection gas peak was not deemed to be a true connection gas because the lithology at the bottom hole was a coarse grained permeable sand package, or the gas peak was only a few units over background. For the purposes of realtime pore pressure prediction, it is crucial that we analyze the slightest gas peak to clarify whether it is due to operational procedures or an underbalance situation.

With long lag times the LWD petrophysical tools might log a stratigraphic interval before the cuttings are circulated out of the hole. Thus it is possible, and often occurs, that there are depth-based model predictions for the pore pressure before the gas response of the relevant interval is known. The depth-based model predictions might carry a large degree of uncertainty or variability, and it is possible to constrain these predictions to a higher degree of accuracy with time-based gas analysis.

The following, from Alberty and Fink, 2013, shows six principles used to quantitatively interpret mud gases relative to formation pore pressure:

- normal background and no reported connection gases, then PP < Swab < ESD < ECD.
- normal background and sporadic connection gases, then Swab < PP < ESD < ECD.
- normal background and consistent connection gases, then Swab < ESD < PP < ECD.
- elevated background and either sporadic or consistent connection gases, then Swab < ESD <ECD < PP.
- greatly elevated background and difficult to recognize connection gases, then Swab < ESD < ECD < < PP.
- and if total gas drops in response to an ECD increase, then PP > ECD.

Table 1. shows six principles used to quantitatively interpret mud gases relative to formation pore pressure.

By applying this specific information to time-based data we can analyze rig activities that resulted in the gas event and better deduce the pore pressure regime. In our experience, by applying quantitative interpretation of mud gases through time-based data analysis it is possible to provide calibration points for the pore pressure estimation that are only hundredths of a ppg from the post-drill, wireline direct pressure measurements.

When evaluating gas peaks in time-based data produced from off bottom periods it is important to first consider the timing of the gas event with respect to the lag interval being examined; did the gas peak come from the beginning, middle, or end of the lagged off bottom period. The second and third consideration once the lag timing is established are the block movement and mud flow rate during gas peak production. Once these three items are known, application of the principals in Table 1 can help improve pore pressure estimation.

Example: A gas peak is produced from the beginning of an off-bottom period. Upon further examination of block movement and flow rate it is noted that at the beginning of the off-bottom period the drill string was reciprocated without the pumps on. Furthermore the gas response during the latter part of the off-bottom period is steady and muted implying sufficient overbalance of the mud relative to the pore pressure. From these observations it would be safe to assume that the gas peak was produced from swabbing action when the drill string was reamed without the pumps on. Applying the principles in Table 1, we can now narrow the estimated pore pressure between the swab pressures and the ESD.

How does time-based data calibrate the depth-based model?

Figure 4 is a plot from a realtime depth-based disequilibrium compaction-based model and covers an entire hole section. The following section will demonstrate how an accurate estimated pore pressure was generated using calibration points derived from time-based analysis. Even though the resulting estimated pore pressure was hundreds of psi different from those generated using the depth-based model, it was in fact correct.

In the upper half of the hole section [Figure 4 item 1], the depth-based models predicted overbalance, which was believable due to a lack of connection gas, good hole conditions and low background gas. Towards the bottom of the hole section, thin-bedded sands in pressure equilibrium with the surrounding shales were drilled and produced distinct gas peak events only visible on the time-based log. Furthermore, the depth-based disequilibrium compaction model was predicting pore pressures far too low to be responsible for these gas events. The under-prediction of the depth-based model was perhaps due to an increase in calcareous rocks with depth, which are stiffer and may contain overpressures without any associated influence on porosity, causing the depth-based model to underestimate disequilibrium compaction-derived overpressure. Alternatively, this could also be the effect of hydrocarbon-charged, coarser grained rocks in this section. The following is an example of how using the depth- and time-based data together can give a clearer understanding of what is actually happening with the pore pressure. This example will cover Figures 3 and 4. To briefly recap what happened in Figure 3, the time-based data plot; a swab gas from the first connection was followed on the next connection by a swab gas and two pump-off gases. During drilling the next stand the mud pumps required servicing, during which time an underbalance-related wellbore instability event occurred. Drilling resumed once the mud pumps were fixed and shortly after this an influx occurred. We will now briefly summarize the depth-based pore pressure estimation plot, Figure 4, which corresponded with the section drilled in Figure 3. The shallowest parts of the pore pressure plot predict sufficient overbalance, and the estimated pore pressure agrees with this prediction. Towards the middle of the section the pore pressure model begins to under-predict known pore pressures as analyzed in time-based data and the estimated pore pressure begins to diverge from the models predictions. In the deepest part of the model the predicted pore pressures are significantly lower than the estimated pore pressure. The estimated pore pressure was correct as confirmed by SIDPP (shut in drill pipe pressures); furthermore the pore pressure estimation was completely calibrated with time-based data.

We can now look at the third connection from bottom [Figure 4 item 2], which was the connection noted [Figure 3 item 1]. The depth-based models estimated overbalance conditions at this connection, [Figure 4 item 2], but the time-based data indicated otherwise; in [Figure 3 item 2] we can see a small gas peak which was produced from this connection and deemed to be a swab gas. Note that this gas peak is not seen on the depth-based model because the bit was off bottom. This small swab gas peak implies that pore pressure is still under ESD. Thus, the pore pressure was estimated to be near mud weight and increasing.

Shortly after the third connection from the bottom, [Figure 4 item 2], drill gas increased sharply reinforcing the previous estimation of the pore pressure being near balance. The mud weight was then raised 0.1ppg in response to the sudden increase in total gas, which lowered background gas levels. This made the analyst question the validity of the estimation, but at next connection, [Figure 4 item 3], and [Figure 3 item 3], three gas peaks are produced; the first a swab gas peak from the back reaming of the stand, the second a pumps-off gas from a directional survey, and the third a connection gas. The pressure was estimated to be on balance in relation to ESD, and 0.35ppg underbalanced in relation to surface-measured mudweight. In [Figure 3 item 6], nearly at the bottom of the stand, drilling ceased as work on the mud pumps took place. During this short downtime, wellbore instability due to the underbalance occurred. The instability can be seen in the time-based data through an erratic torque profile. When this event was circulated to surface, [Figure 3 item 8], an excess of sand from the collapsed wellbore clogged the shakers and stopped drilling operations. A pumps-off gas peak is also produced from this event, [Figure 3 item 7].

Drilling resumed after the shakers were cleared of the excess sand from the wellbore instability event.

However, within minutes the wellbore began to kick and the well was shut in, [Figure 3 item 9]. The pore pressure, despite adverse conditions for the disequilibrium compaction model, was correctly estimated by the application of time-based data analysis.

Pack-off tendencies for calibration

This next section illustrates how a time-based data plot, Figure 5, was used to confirm the estimations made in the depth-based disequilibrium compaction model (Figure 6).

A brief summary of the depth-based plot: the depth-based model was predicting a rising pore pressure trend that exceeded surface mudweight and was equal to ESD values by section TD. Though the section was drilled without complications despite the predicted pore pressure, confidence in the pore pressure model was high, and the estimated pore pressure followed the predicted pore pressure.

A brief summary of the time-based plot: the hole section was stopped short due to a drilling break. The hole was then circulated clear of cuttings without raising the mudweight. As the cuttings were circulated out of the hole the ECD began to decrease. This action lowered the hole into an underbalanced state relative to the ECD (effective circulating density). Shortly after this circulation began wellbore instability started to develop because of the underbalance in the hole. and. Unfortunately the cavings werenɑ̂t circulated to surface before a static flowcheck resulted in a packed off BHA.

The following will now go further into detail about the pore pressure estimations of the events just described. The time-based plot (Figure 5) begins in the last full stand of the hole section. For a casing rat hole, a single joint of drill pipe was then picked and almost drilled in its entirety [Figure 5 item 1], but because of a drilling break shortly into the joint of drillpipe the hole section TD was called. The hole was then circulated clean without raising the mud weight [Figure 5 item 2], which removed the cuttings load from the annulus and consequently reduced ECD and ESD values. During the circulation at section TD the first connection gas of the section was produced when the single joint of drill pipe was picked up to finish the hole section [Figure 5 item 3 and Figure 6 item 1]. The connection gas was misdiagnosed by wellsite personnel because it was broad and not the usual shape of a connection gas peak. [Figure 5 item 4 and Figure 6 item 2], a pump-off gas was produced when the pumps were shut down at section TD. After 3hrs of circulation, a 15 minute flowcheck showed the hole to be static [Figure 5 item 5]. However, when the pumps were brought back up, the standpipe pressure spiked, and it was soon evident that part of the wellbore had collapsed during the flowcheck and the BHA packed off [Figure 5 item 6]. The BHA was worked free and within 30 minutes circulation was regained at which point the mud weight was raised 0.1ppg to 12.1ppg. Shortly after commencing circulation of the elevated mud weight, pressure/splintery cavings came to surface from halfway between the period between section TD and the hole packing off after the flowcheck.

Circulation continued and a pump off gas from the flow check was circulated out [Figure 5 item 7 and Figure 6 item 2]. After the mud weight was raised, hole fill was encountered when returning to bottom which required reaming [Figure 5 item 8]. When the first stand was racked back to come out of the hole, the hole was still producing adverse conditions as 90klbs of overpull was applied to the drillpipe [Figure 5 item 9].

Examining the time-based data further, there were two calibration points within 90 minutes of each other, of the same value, an ESD and an ECD, from which the estimated realtime pore pressure was accurately confirmed. The first set of calibration points were the ESD values that produced the connection gas and pump off gas in the last 33ft of the hole section. The second set of calibration points were the lowered ECD values after section TD which initiated the wellbore instability. At section TD, as the wellbore was circulated clean of the cuttings load, the ECD dropped. From known lag calculations, we were able to deduce when the wellbore instability pressure cavings first occurred. It turns out that the pressure cavings were first produced when the ECD dropped below the ESD levels seen at section TD.

Conclusions

We have shown that there can be discrepancies in depth-based data analysis that need to be mitigated by looking also at time-based data. This greatly improves the whole picture of the drilling operation and will often provide a very different view of the operations. Depth-based data will not produce any information while the bit is off bottom. Time-based data provides an uninterrupted data set including additional information that depth-based data does not. Events such as gas peaks, pack off tendencies, or other pore pressure calibration points can be further analyzed and applied to the depth-based disequilibrium compaction model making the realtime pore pressure estimation more reliable and resilient. In the case that a key calibrator is missed, the pore pressure service relying only on depth-based data could actually do more harm than good to the drilling operation, as the depth-based model may not be correct all the time.

Drilling operations are complex and multi-faceted. Drilling may often proceed so fast that waiting for other external sources of information is too little too late. By combining both time- and depth-based data a fuller understanding of the pore pressure can be gained without the need to wait for external information sources. With the potential to save extensive nonproductive time, alert the rig personnel of impending underbalance drilling and aid the drilling team in determining the deepest that a hole section can be drilled without exiting the drilling window, realtime pore pressure estimation provides significant benefits and is increasingly becoming an integral part of drilling operations.

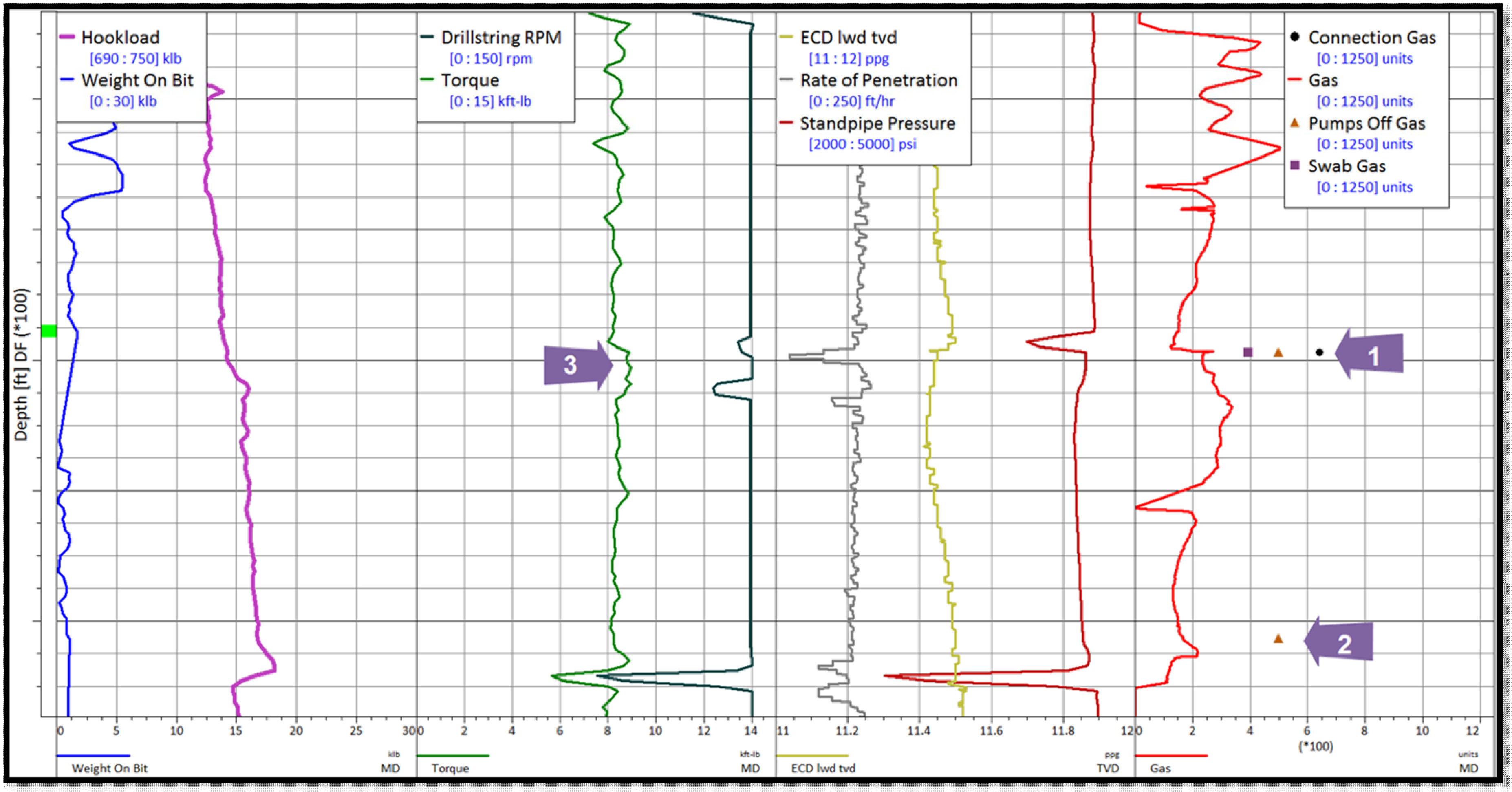

Figure 1. Depth-based plot: Drilling parameters for a 270ft section displayed on a depth-based plot.

Item 1: Three separate gas peak events - a swab gas, pumps off gas and connection gas - were produced from this depth; however they are not represented correctly on this plot because the bit was off bottom during their production.

Item 2: A pump-off gas peak produced while the bit was off bottom.

Item 3: High torque from a wellbore instability event that happened while the bit was off bottom.

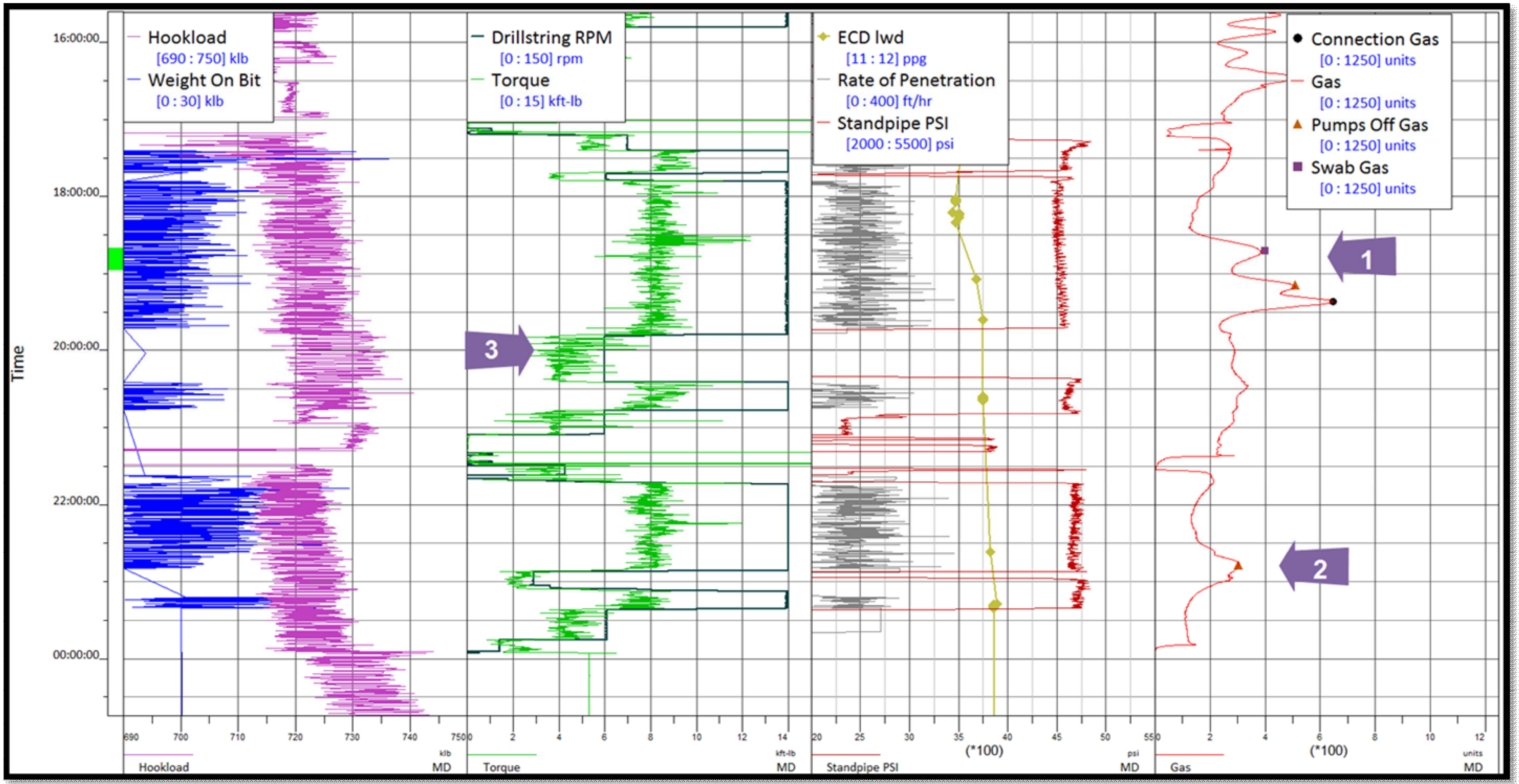

Figure 2. Time-based plot: The same drilling parameters for the 270ft of drilled hole section seen as depth data in Figure 1. Note, scaling for the parameters is the same as Figure 1.

Item 1: Three gas peak events - a swab gas, pumps-off gas and connection gas.
Item 2: A pump off gas peak.
Item 3: A wellbore instability event causes erratic and high torque.

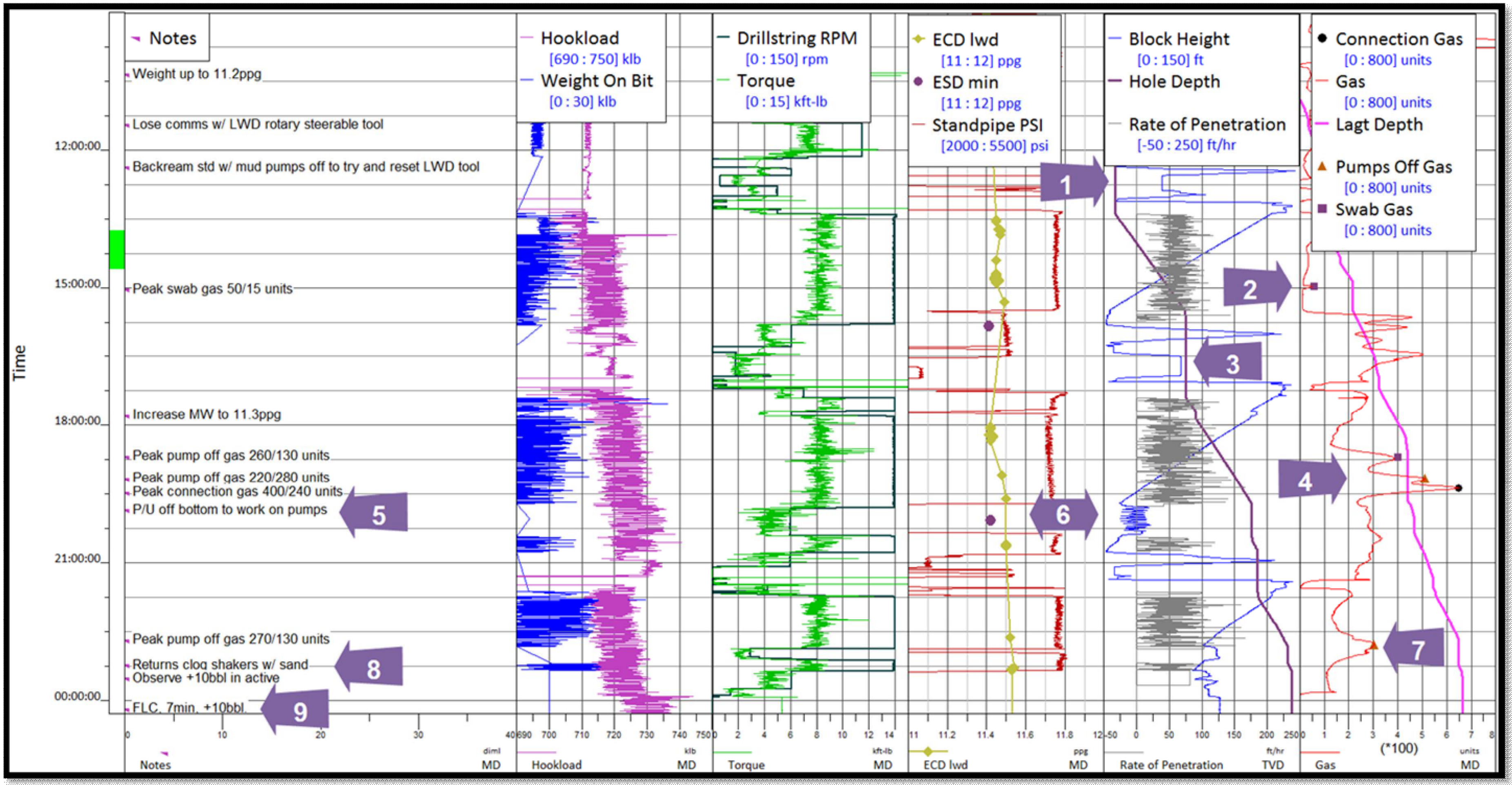

Figure 3. Annotated and expanded version of Figure 2. A time-based plot used for realtime pore pressure analysis

Item 1: A pipe connection

Item 2: A swab gas peak from the pipe connection noted in item 1.

Item 3: A pipe connection

Item 4: Three separate gas peaks, a swab gas, pumps off gas and connection gas, were produced from the pipe connection noted in item 3.

Item 5: Operational note about pulling off bottom to work on mud pumps.

Item 6: While the pumps were serviced, as noted in item 5, the block was reciprocated and rotated without flow, causing high torque.

Item 7: A pumps-off gas was produced from the mud pump service as noted in item 5 and 6.
Item 8: Operational note about the shakers clogging with sand from wellbore instability created while mud pumps were serviced in item 5 and 6.
Item 9: Operational note about the well kicking.

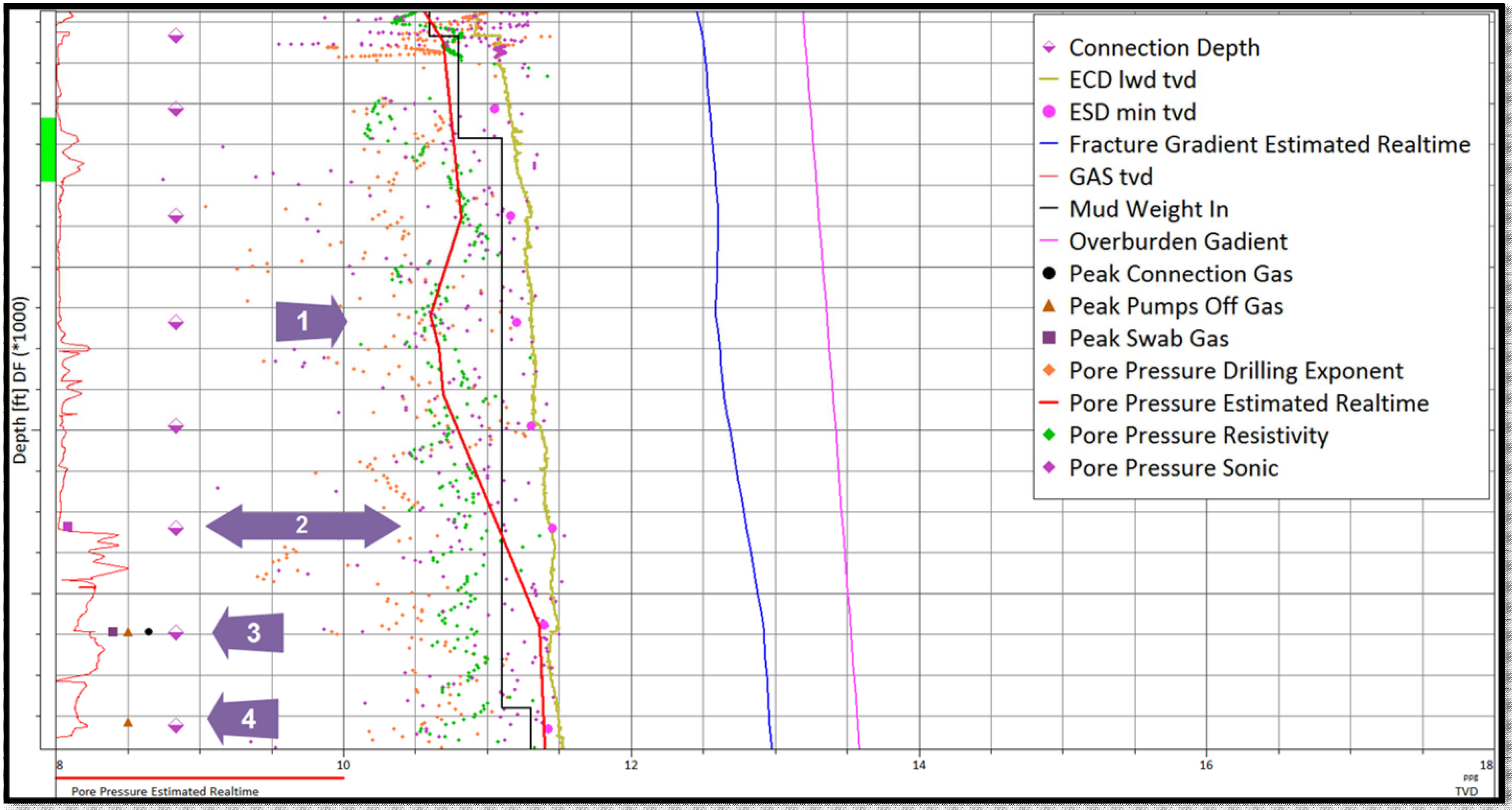

Figure 4. Realtime pore pressure depth-based disequilibrium compaction model. Estimated realtime PP calibrated with Figure 3.

Item 1: The Estimated Realtime pore pressure is predicting sufficient overbalance and is in agreement with predicted gradients produced by the depth-based disequilibrium compaction model.

Item 2: A swab gas, analyzed in time-based data [Figure 3 item 2] was used to calibrate the Estimated Realtime pore pressure which began to diverge from the predicted gradients produced by the depth-based disequilibrium compaction model.

Item 3: A swab gas, pumps-off gas and connection gas, analyzed in time-based data [Figure 3 item 4] were used to calibrate the Estimated Realtime pore pressure which is now significantly diverging from the depth-based disequilibrium compaction model.
Item 4: A pump off gas analyzed in time-based data [Figure 3 item 7] confirmed the Estimated Realtime pore pressure.

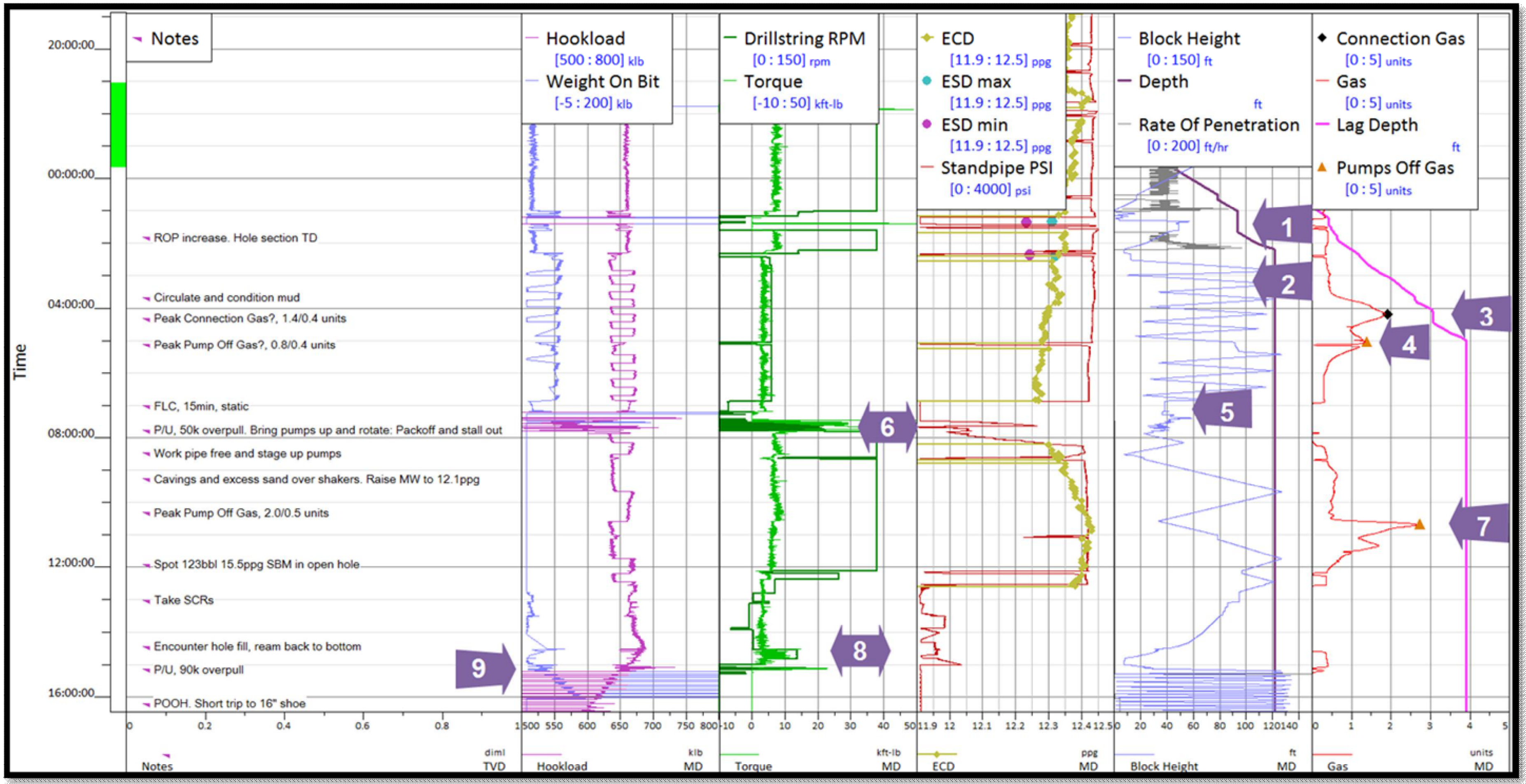

Figure 5. Time-based data plot of a pack-off event

Item 1: A single joint of drill pipe was picked up to drill to section TD.
Item 2: At section TD the hole was circulated clean without raising the mud weight.
Item 3: While circulating at section TD a connection gas from the last connection (item 1) is seen.
Item 4: While circulating at section TD a pumps-off gas is circulated out from when the pumps were brought down after drilling ceased.
Item 5: A 15 minute flowcheck after the hole is circulated clear of all cuttings shows the well is static
Item 6: The hole packs off and the pipe is stuck when the mud pumps are brought back up after the flowcheck (Item 5).
Item 7: A pumps-off gas from the flowcheck (item 5)
Item 8: Hole fill is encountered when returning to bottom, which requires reaming.

Item 9: Overpull is seen when racking back the first stand of drillpipe.

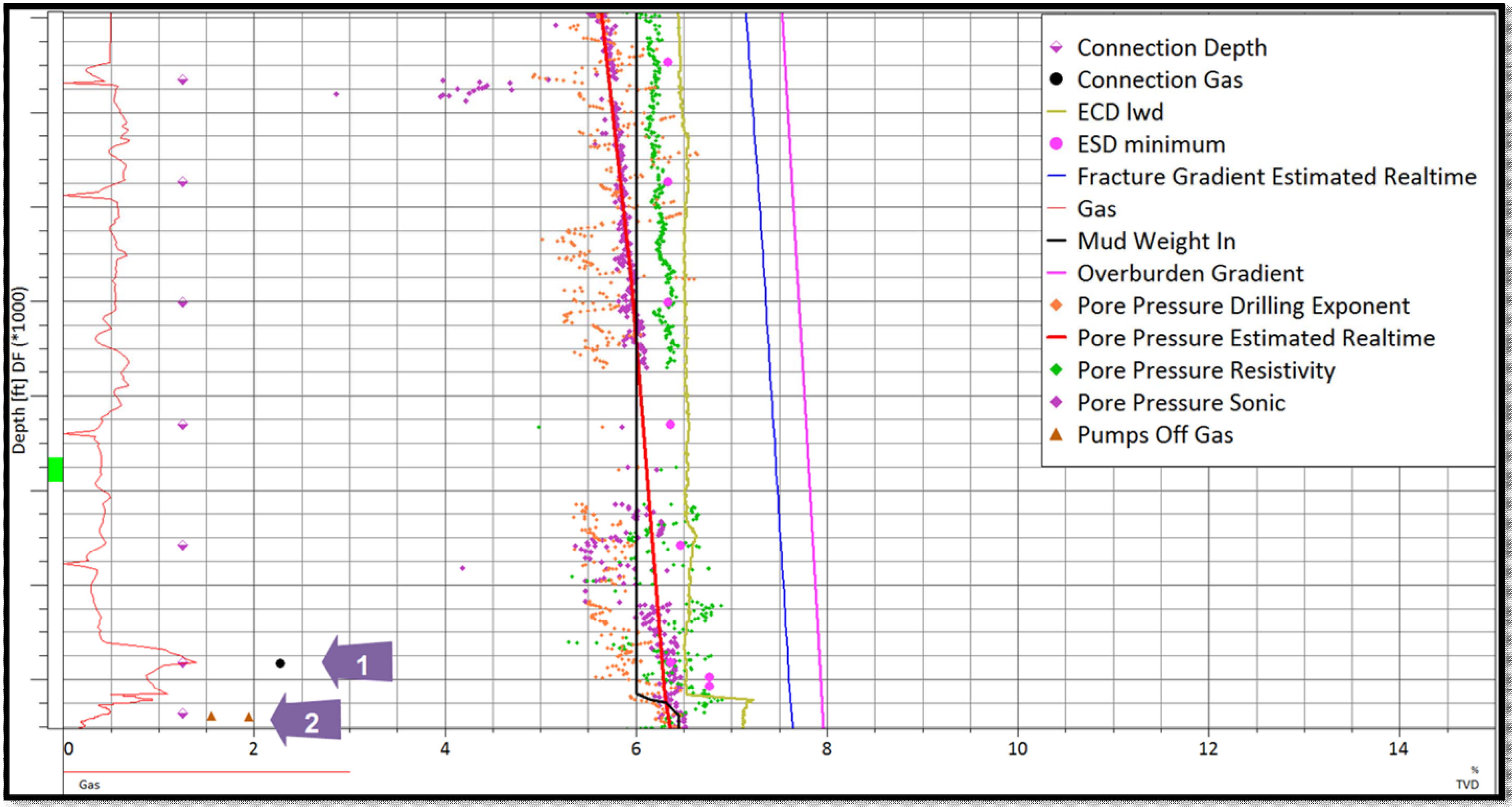

Figure 6. Realtime pore pressure depth-based disequilibrium compaction model. Estimated Realtime PP is confirmed with Figure 5.

Item 1: A connection gas, analyzed in time-based data [Figure 5 item 3] was used to confirm the Estimated Realtime pore pressure to be equal to ESD.

Item 2: Two pump-off gases from section TD [Figure 5 item 4 and 7] further confirmed the Estimated Realtime pore pressure to be equal to ESD.

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