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DRILLING IN KARSTIFIED CARBONATES: EARLY RISK DETECTION TECHNIQUE

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ABSTRACT

Heterogeneous nature and complex rock properties of carbonate reservoirs makes the drilling process challenging. One of these challenges is uncontrolled mud loss. Caves or a system of cavities could be a high-risk zone for drilling as the mud losses cannot always be controlled by conventional methods, such as mud weight (MW) / equivalent mud weight (ECD) *optimization, or by increasing concentration of lost circulation material (LCM) in the drilling mud. Seismic-based detection of such karstification objects is inefficient due to relatively small size, various shapes and low contrast environment. In this paper we, based on drilling data from the Barents sea, analyzed possible patterns in real-time drilling data corresponding to drilling through karstification objects. These patterns can serve as real-time indicators of zones with higher risk of karsts and can be used as an online tool for decision support while drilling in karstified carbonates.*

Keywords: karstification, cave, sinkhole, karsts, vugs, fractured rocks, carbonate, drilling, mud losses, drilling brakes, subsea pump module.

NOMENCLATURE

MW	Mud weight
ECD	Equivalent Circulation Density
LCM	Lost Circulation Material
BHA	Bottom Hole Assembly
MPD	Managed Pressure Drilling
PMCD	Pressurized Mud Cap Drilling
RCD	Rotational Control Device
TST	True Stratigraphic Thickness
WL	Wireline
LWD	Logging While Drilling
S&V	Shocks and Vibrations
ROP	Rate of Penetration
WOB	Weight on Bit
UCS	Uniaxial Compressive Strength
SPM	Subsea Pump Module
DIF	Drilling Induced Fractures

1. INTRODUCTION

Karstified carbonates pose significant challenges in drilling, which can be associated with both the drilling process and unique geological properties. In subsequent sections, we will refer to common in karstology definition of the karst, introduced to describe the landscape, which contains caves, underground channels, and other associated with soluble rocks features [1]. Sudden encountering of some karst-forms during drilling in carbonates may lead to potentially dangerous scenarios. Serious heterogeneity of carbonate reservoirs, cause a high probability of dealing with challenges, unforeseen in offset wells. For some challenges, there is a solution. High shock levels when drilling in carbonates can be mitigated by drilling parameters optimization or by adjusting BHA configuration. The volume of mud loss in some conductive fractures can be successfully controlled by varying concentration of Lost Circulation Material (LCM) or by changing mud chemical composition. Thus, on the one side, some difficulties related to drilling in carbonates can be effectively mitigated by modern technologies. However, some carbonate challenges still pose high drilling risks. Aforementioned common solutions for mud loss mitigation in carbonates may be inefficient in case of severe mud loss zones such as highly permeable channels or cavities. Total mud loss situations may lead to well control incidents.

One solution to overcome this challenge is to use MPD technology and its modifications, such as Pressurized Mud Cap Drilling (PMCD). In this technology, the well, converted from a

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conventional drilling to PMCD, requires injection of fluid into the annulus to maintain the mud cap. During bull-heading cycles, sacrificial fluid and cuttings are pumped into formation to fill any conductive fractures or channels. Many companies currently use PMCD for drilling in fractured carbonates. Nonetheless, there is an operational necessity of additional equipment installation on the rig site such as Rotational Control Device (RCD). Besides that, in some cases, a significant volume of sacrificial fluid is required for PMCD, which makes this technique inapplicable in some regions. In case of exploration drilling, the rig may not be equipped for PMCD due to underestimation of the risks based on the offset wells drilling experience. This eventually can lead to well control situations as prediction of karsts zones is challenging with the limited information about the field.

In addition, even if mud losses can be controlled in certain cases, it still leaves the challenge of BHA drops into open channels or cavities. This may lead to core sampling problems, increased drilling risks due to possible damage of BHA components and other serious consequences. Drawing of the example of Loppa High region of the Barents Sea, the size of such channels can vary from decimeter up to several meters of true stratigraphic thickness (TST).

Foresaid is a significant contributory factor to the development of methodology to identify/detect zones with high risk of karsts. This, in turn, allows for decision making on rigging up MPD equipment, LCM chemicals rig-logistics, optimization of well path and well geological targets.

It is now well established from a variety of studies that carbonates are prone to development of very complex karst structures of different shapes and sizes. However, geometric diversity of karst structures makes their detection challenging even at shallow depths. Detection complexity increases significantly with burial depth of karsts. In case of high contrast environment and significant sizes of the karst structures, some of them can be detected by seismic. However, many karstification objects are not visible from seismic due to limitations of vertical resolution. These not-detectable objects pose serious challenges for drilling. This motivates our study of the possibility to detect such karstification zones in real time from drilling measurements.

It is very difficult to predict an individual karst ahead of the bit. Instead of this, we try to identify objects that indicate that we are drilling through a zone with a high probability of karstification objects. Geological conditions, which are favorable for development of a single-karst object, may also be favorable for development of many other karst-forms within the same region. Some of them may pose challenges for drilling, others not. Still all of them can serve as indicators of subsurface conditions favorable to karstification. Detection of different signs of karst-forms while drilling may provide a vital information about possible regional drilling risks. Early detection of intervals with high drilling risk, such as cavities or vugs, might be an important component of a decision support tool.

The main focus of this paper is to identify karst-objects from real-time drilling data. This will serve as a decision support tool while drilling in karstified carbonates. In Section 2, we make a review of different types of karsts and conditions for their genesis. This gives us enhanced understanding of types of objects, which can be encountered while drilling and interpreted as indicators of zones with high risks of karstification. In Section 3, we review drilling experience in karstified carbonates in the Barents Sea and identify karstification from the logged borehole image data. Although borehole imaging may not be appropriate due to relatively large offset between the drill bit and the corresponding sensor (and, thus, delay in the sensor data that is too large for a real-time decison support tool), localization of the karstification objects along the wellbore allows us analyze other real-time drilling data around these objects and identify specific patterns that may serve as real-time indicators for karstificton zones. Such analysis based on drilling mechanics measurement and flow data are done in Section 4 and Section 5, respectively. Conclusions, discussion and future work are presented in Section 6.

2. KARST PHENOMENA

This chapter gives an overview of main types of karst-forms, with specific focus on the karst-forms that can be encountered in carbonate reservoirs. There are a number of processes contributing to karstification. Dissolution of soluble rocks by meteoric waters along pathways specified by geological structure is considered as one of the main mechanisms of karstification [2]. However, solubility of the rock alone is not sufficient to form a karst. Favorable geology, formation lithology, rock mechanical properties, burial depth of carbonates, rock fracturing and other characteristics are important factors for karsts development.

Karsts and signs of karstification can be found at different depths. To investigate subsurface geological indicators of karsts formation surroundings, it is essential to review common features of karstified landscapes. Karstification of a landscape may be seen by different large and small-scale surface or subsurface objects as shown in Fig. 1 Karst-classification, presented in this section, will be divided into surface (micro- and macro-forms) and subsurface (sinkhole and caves) categories. Some of the karst-forms like sinkhole may fall into both categories.

Surface micro-forms objects can generally be developed in the limestone or other soluble rocks such as carbonate or gypsum. As shown in the Fig. 1, typical result of this process is development of some salient features such as division of limestone into blocks (clints) bordered by vertical fractures (gricks) [1]. This is a widespread sign of landscape karstification presented by variety of shapes and sizes, spanning up to tens of meters. Larger scale surface signs of karstification fall under the surface macro-forms objects category, which are the results of karsts/collapse features. As illustrated in Fig. 1, round depressions of different scales are the common results of this process. This process underlies genesis of Doline or Uvala (set of Doline) surface signs of karstification. The largest macroform phenomena is Polje. Typically, it has landforms of a kilometer scale, and is often seen in tectonically active karsts areas. Poljes landscape can be defined as karst basin, with steep peripheral slopes and karstic drainage.

Sinkhole form stands out in a separate class of objects and refers to a phenomenon of preceding cavity collapse with a subsequent development of surface sinks as the cavity becomes filled with soil or coarse-grained material. Depending on the mechanisms of the ground failure and rock type involved in subsidence, different types of sinkholes can be defined. Fig. 1 provides an overview of the sinkhole form.

It should be noted that besides the aforementioned landscape phenomena, there are many other signs of surface karstification, which cannot fit into provided definitions as they consist of complex forms and cannot be described with a few criteria [3, 4]. Furthermore, in certain cases even surface signs of karstification can be challenging to reveal. For instance, various subsequent processes such as immersion of a landscape caused by tectonics can be accompanied to karstification, which makes detection process complicated.

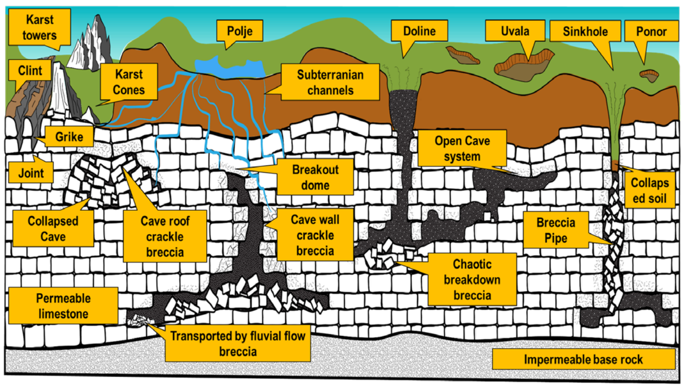

FIGURE 1: KARSTIC LANDSAPE

Having discussed the surface signs of karstification, let us now turn to next significant aspect of karst-forms - subsurface karst systems at large burial depths. Cave form is a conventional subsurface karst feature of soluble rocks. Based on Bella's [5] classification, the following mechanisms of caves development can be distinguished: chemical erosion (corrosion caves) and turbulent streams erosion (fluvial caves). Corrosion caves are more numerous unlike the turbulent caves and in general are smaller (diameter and length). Frequently, some caves can be a combination of these types of erosion.

Highly permeable channels, formed by a soluble action of water, create a primary network of channels, called anastomotic caves. The channels are typically spread along certain geological features such as fractures or system of faults, and can penetrate the system of fluvial caves. Besides that, there are isolated caves types, which are not connected to any network. This type of caves is defined as voids. Many objects fall under this definition. Such voids can range from the vugs-size small scale, up to the full caves scale. They pose a significant risk in case of sudden revealing by well path crossing.

Regardless of the processes, that cause enlargement of the caves, dimensions of the caves cannot infinitely expand. Resulted cave size have certain limits [6]. One of the main factors restricting the growth of the cave is elastic limit of the rock masses surrounding the cave. As soon as certain limit is reached, the cave starts to collapse. Cave collapse initiates events, that have a serious impact on reservoir properties and are actively used as part of reservoir characterization study. Products of collapse, called cave-collapse breccia are composed of different angular fragments with interspace filled by finer sediments or matrix particles. There are several cave-related breccias types depending on their texture and foregoing processes as shown in Fig. 1. Progressive roof collapse with subsequent upward migration of the cave creates a breccia pipe [7]. Ceilings and walls collapse resulted chaotic breakdown in a breccia. Cave-roof crackle breccia is formed by stress-contrast fractures of cave-roof rocks. However, brecciated rocks do not necessarily belong to the places of their development. For example, transported by fluvial flow, roof-collapse breccia rocks might be moved to a significant distance from original places of their development.

Study of the products of cave collapse is important for different purposes, such as quantifying geological processes or reservoir modeling for flow simulators. For the sake of early karsts detection, breccia plays a crucial role. Cave-collapse breccia is a direct sign of zones with open or partially filled caves. Drilling through open or filled caves can cause serious well control scenarios due to possible lost circulation of drilling fluid or damage of drill string components due to BHA drops. Distinguishing different types of breccia while drilling can be an essential information about type of karst object approaching by the well path.

It should be emphasized that karstification does not always create potentially dangerous objects for drilling. In the oil and gas industry, karstification plays an important role. It is considered as the key process for the development of the permeability and porosity of carbonate reservoirs. In some cases, highly karstified intervals are the pay zones of the well. However, as stated previously, karstification is a complex process and the results of this process can be everything from the small-scale porosity until the development of a large cave system. For the industry, on the one hand, porosity plays an important role for the reservoir development purposes. On the other hand, there is the high risk associated with crossing the system of caves or vugs while drilling.

Cave form is the most complex structure among of all the other landforms discussed in this section. For instance, dissolution caves are characterized by numerous three-dimensional patterns developed within different rock types with variety of shapes and lengths. Mechanism of cave development can be explained by influence of any of the following factors or by a combination of the factors such as tectonic, climatic, hydrological, chemical and many others. Different theories exist nowadays in karstology that have been proposed to classify the caves based on development mechanism. However, many of researches argue that there is no single theory of genesis which can encompass all the caves, except for some trivial level of explanation.

Sometimes it is mistakenly assumed that large cave systems typically occur only at shallow depths, as the rock strength is sufficient to support overlaying sediments. Deeply buried open caves in general are not frequently occurring objects as the increasing buried depth is directly related to the increased probability of a cave collapse. Nevertheless, there are many evidences of deeply buried caves, that are not collapsed and can exist during many centuries in an equilibrium with the surrounding rocks.

In this section, we have identified main objects of karstification, which can be encountered both on surface and subsurface. The discussed mechanisms of karstification strengthens the idea that geological conditions for a single karst-form development might be also suitable for development of other karsts within the same region. Thus, detection of a single karstification object can be an important indicator of increased drilling risks, as there is an increased probability to discover other karsts objects. Identification of one or several karst forms like breccias, vugs, or filled with sediments caves can serve as an indication that more karst-forms can be encountered in this zone, including forms that may pose significant challenges for drilling (e.g. large open caves or an interconnected system of channels which may result in total mud-losses). This can further be used in decision-making process for mitigating the risks and consequences related to drilling into a karst.

In the following sections, we will consider the different types of the real-time drilling data and will correlate them with the discussed karsts forms.

3. KARSTS MAPPING – BOREHOLE IMAGES AND DRILLING EVENTS STUDY

In the previous section, we have discussed main karst forms and their signs, which can be encountered in surroundings the karsts rocks. To be able to study real-time responses of drilling measurements to karstification objects, the section below will demonstrate localization of karasts based on borehole image data from the wells drilled in the studied region. Once the mapping of the karsts is performed, we will utilize the defined intervals of karsts in Section 4 and Section 5 to identify corresponding signatures or patterns of in the corresponding real-time measuremsnts.

In the following sections of the paper, we consider the real case of a discussed above karstified stratum. The studied area is located in the Barents Sea and is the largest of the three defined offshore petroleum provinces in Norway: the North Sea, the Norwegian Sea and the Barents Sea. It covers the area around 2/3 of the entire Norway offshore. The study will focus on the recent discoveries in the Loppa High region. They are located ~160km (100miles) off the coastline with the water depth ~300-400m (980-1300ft).

The seafloor of the studied region consists of complex patterns, formed as a result of considerable uplift and Cenozoic era erosion. Uplift has brought high density rocks close to the seafloor. This creates additional difficulties for seismic studies of the region [8]. This tectonic event led to the development of a complex underlying structure with an extensive faulting and significant altitude change of more than 1000m (~3281ft) (Kobbe formation).

Deeper layers of naturally fractured carbonates were weathered and buried. This caused karstification with a subsequent development of voids. As will be discussed later in the paper, some of the larger karsts and voids are collapsed and filled with sediments, others remain «open». These regional features become a significant challenge for drilling.

Borehole imaging is commonly used in the oil and gas industry. Interpretation of images data is intended to determine the magnitudes, azimuths and geometrical properties of numerous geological features along the wellbore. Image tools can provide images of vugs, breccias, caves and other karst-forms. Image of the wellbore is the "unrolling" of a wellbore picture along the well path. Physical principles underlying borehole imaging tools are the propagation of ultrasonic waves and electrical conductivity of the formation.

Let us now consider previously discussed geological signs of subsurface karstification. Collapse breccia example is presented in Fig. 2 by two intervals of the well. Patchy patterns of the low resistive black in surrounding of the light brown resistive pattern might be interpreted as breccia. The breccias in this example are considered to be formed due to cavities collapse that were possibly created by evaporate dissolution. This collapsed cavity was successfully drilled through without any drilling challenges. However, detection of this type of karst form may serve as indicator of increased risks of encountering other karst forms that can pose significant risks to drilling.

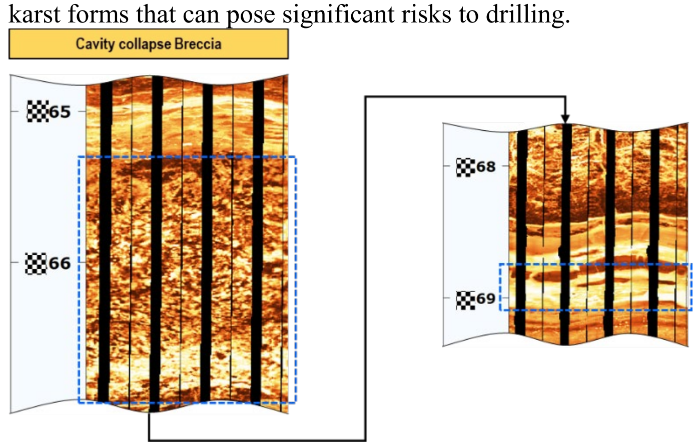

FIGURE 2: *EXAMPLE OF* BRECCIAS DEVELOPED DUE TO CAVITY COLLAPSE

Below is another example of the discussed earlier karst-forms. Well path crossed two intervals of conductive vugs up to dm scale size and then intersected a cavern located above the wellbore, which is open for the fluid flow. This case is shown in Fig. 3. Geometrical properties of the cavern are not defined. However, the part, which can be seen in they borehole image is more than 50cm (19.7") in length with circumference of 21.6cm (8.5" section of the well). This case demonstrates the geological signs preceding to the cave encountering: as can be noted from the image data the first signs of karstification appeared more than

10m ahead of the cave. Potential detection of these signs, based on drilling data, can contribute to decision support while drilling.

Borehole imaging is a very powerful tool in terms of identification of a variety of geological attributes. However, it is unsuitable for online-detection of karst forms. Typical sources of borehole images are WL logging, recorded after a certain interval or section of the well has been drilled, and LWD tools, which have significant sensors-bit offset and a data-transmission/processing delay. This demonstrates the necessity to determine a set of real-time measurements that can reveal the signs of karstification while drilling.

Comprehensive study of the borehole images was performed for the wells in the Loppa-High region in order to identify breccia, vugs, caves, and other signs of karstification. For convenience, all specified intervals with identified geological attributes for each of the wells are displayed in the intersection window as shown in Fig. 4.

Once the borehole image data have been analyzed, detailed study of drilling events and end of well reports have been performed. Consequently, we obtained rig-site drilling events overview for all wells within the region of study. These events are displayed in Fig. 4. Joint analysis of the borehole images and drilling events is quite revealing in the several ways.

First, analysis of these data has shown that in some cases drilling breaks and tight spots encountered in the intervals, which are close to cave or breccia intervals. This determines the need for a detailed study of drill string dynamics. The results of this analysis will be discussed in Section 4. Secondly, drilling in breccia intervals is often accompanied by mud losses of varying volumes. In Section 5 we will examine whether the profile of mud losses changes while drilling can be linked with karsts.

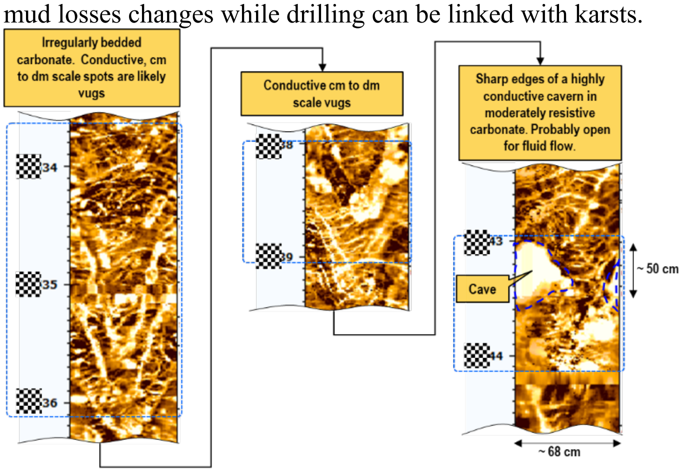

FIGURE 3: EXAMPLE OF VUGS KARST-FORMS PRECEEDING THE CAVERN

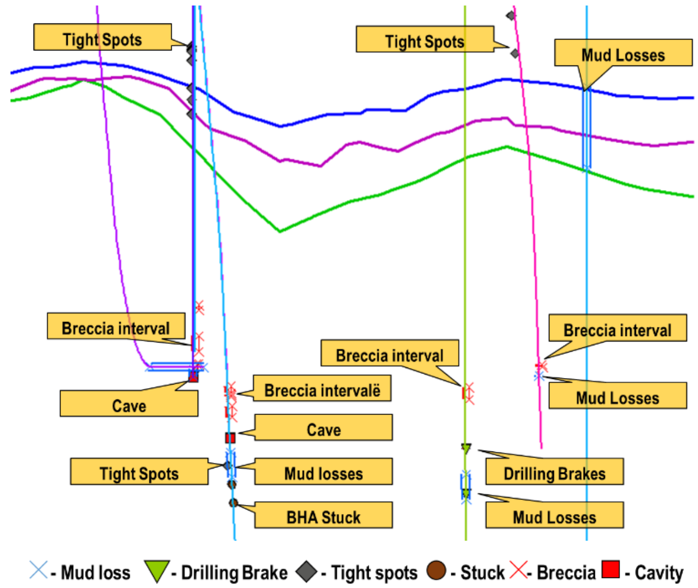

FIGURE 4: DRILLING EVENTS IN THE KARSTIFICATION INTERVALS

In this section, we have identified objects of karstification in the studied area of the Barents Sea based on borehole images from offset wells the images were obtained after drilling had been completed. These results indicate that vugs and breccia might be interpreted as indicators of caves or overall karstification of the interval. Joint analysis of the rig-site events, performed for all wells within the region of study confirmed occurrences of specific BHA behavior in the intervals surrounding the caves, such as drill-brakes, reported high level of shocks and tight spots.

This demonstrates the necessity to determine a set of real-time measurements that can reveal the signs of karstification while drilling as will be considered in Section 4.

4. DETECTION OF KARSTS BASED ON DRILLING MECHANICS

Having discussed the process of mapping karst-forms based on borehole images, joint analysis of drilling events indicated a need to investigate drilling mechanics data in the intervals of karstification. In this section, we will consider a set of real-time drilling measurements, which can demonstrate unique responses in the intervals of karsts. The set of drill string measurements provided in this section may be used as the first set of proposed indicators for real-time detection of zones with high risk of encountering karsts. It should be emphasized that in the current section we will focus primarily on the dynamics of the drill string. However, hydraulic data will be also considered as an auxiliary factor for better understanding of drilling events.

Principal source of information for evaluation drilling dynamics in the intervals of karstification are downhole measurements as they can be more accurate for detecting drill-string behavior in contrast to rig surface measurements. Three-axis accelerometer is typically incorporated into the downhole acquisition sub, aimed to measure changes of the acceleration magnitudes in axial, tangential and radial directions of BHA. Whirling, lateral shocks, stick-slip and bit bouncing can be detected based on acceleration analysis.

There are two main factors affecting the level and type of shocks and vibrations (S&V) registered by accelerometer: rock properties and drilling parameters. Operational parameters play an important role in shocks gain or attenuation. To establish S&V unique responses in karsts, we located intervals with constant operational parameters. This could help to eliminate the factors, which are not related to geological signs of karstification. Drilling in carbonate reservoirs is frequently accompanied by high level of S&V. This is a complicating factor for distinguishing shock types based on the nature of their causes.

Another aspect, which needs to be considered, is ROP in the intervals of karstification. Typically, there are a number of drilling parameters, which have considerable influence on the ROP. The influence of these parameters is far from simple and lies outside the scope of this paper. However, ROP is an essential parameter for the aim of karst detection as it is directly linked to rock properties. This principle underlies many studies devoted to drillability. Drillability was first defined by Teale [9] as the ability of a rock to be drilled. Overall, these studies highlight that the rock properties such as UCS, brittleness, abrasiveness, texture, mineralization and many other, are influence factors on ROP apart from drilling parameters [10]. An implication of the facts mentioned above is that, for constant drilling parameters, fluctuations of the ROP while drilling might be related to rock properties. For the sake of early karst detection, as will be illustrated later, ROP variations might be an indicator of drilling through different karst objects such as breccias, vugs or caves.

However, it should be emphasized that ROP or S&V measurements alone cannot be considered as one and only indicator of karst objects by straightforward analysis of their trends while drilling. In this study, the authors were guided by analysis of real-time drilling data in the intervals of karsts, which were defined by borehole images.

A notable example of drilling mechanics study will be demonstrated by time-drilling data analysis of Ørn Formation, which is dominated by marine, shelf / platform carbonates with bryozoan bioherm build ups and shallow marine, supra-tidal carbonates.

Initial analysis of drilling events revealed the following cases. During core-sampling run, BHA was dropped 2m without WOB. Initial loss rate was 40 m^3/h (176.1 gal (US)/min) and increased to total mud loss situation. Full well control incident came into effect. This sequence of events demonstrates the result of drilling into an open cave. However, the most important research information here are the signs of karstification in the interval above of the discovered cave.

Figure 5 schematically depicts the timeline of precursory to the cave events occurrences. It can be noticed that a number of small mud losses were observed in the interval of more than 10 m (32.8 ft) above the cave. This allows us to assume the possible presence of a conductive system of vugs and/or the presence of a breccia zone, as mentioned earlier. This is also confirmed by the core-sample photos, which were acquired after Core Run 1. As shown in Fig. 6, the interval of 20m (65.6 ft) above the cave is presented by brecciated dolomites, which contains cemented clasts of different size and shape. In the interval 15m (49.2 ft) above the cave, it can be noticed cm-scale round to oval conductive spots, which may be interpreted as vugs, which likely formed due to dissolution of the massive facies by corrosive fluids. The closest to the cave core sample is 10m (32.8 ft) above the cave is presented by a weekly cemented carbonate.

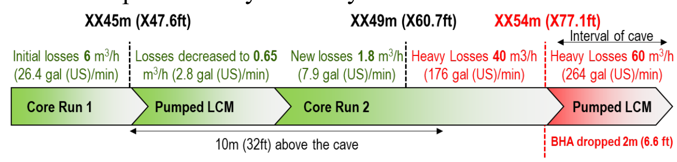

FIGURE 5: EVENTS AUDIT IN THE INTERVAL ABOVE OF THE DISCOVERED CAVE

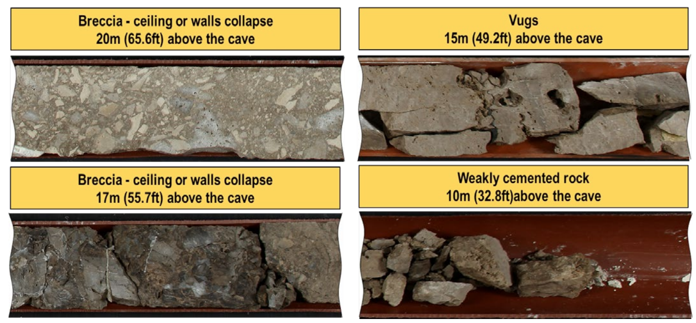

FIGURE 6: CORE-SAMPLES PHOTOS OF THE INTERVAL PRECEDING THE CAVE

As this cave was discovered during coring runs, there is rather limited information for drilling mechanics analysis, for example, there is no information about S&V and there is no borehole images data available for this interval. However, this cave is one of the largest in the region of study and we can still recover some information about drilling close to the cave zone as shown on the Fig. 7. According to these data, we can infer that based on the drilling mechanics data in the time domain, certain features are visible in the BHA behavior. In particular, we can notice recurring mud loss events at a distance of 6 and 5 meters from the cave. These intervals correlate with the decrease of WOB, which might be a sign of drilling through intervals with different mechanical properties. In addition, before the cave interval, there are a number of sharp ROP increases, with simultaneous growing of the hook load and WOB decrease, which can be interpreted as drill breaks.

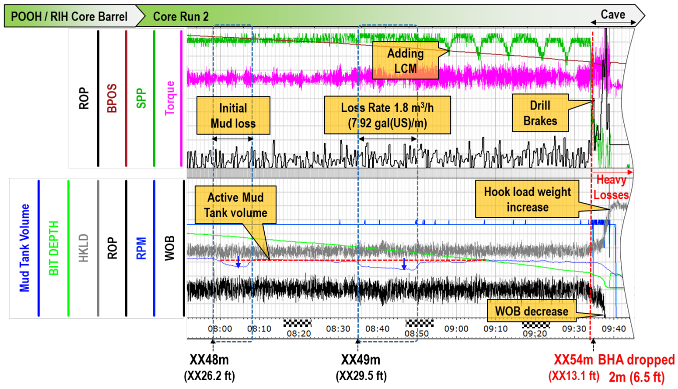

FIGURE 7: DRILLING MECHANICS DATA IN THE INTERVAL CLOSE TO THE CAVE

This observation may support the hypothesis that it is possible to detect signs of karstification in the intervals surrounding the cave based on real-time drilling measurements. In order to assess discussed earlier S&V response to different karst objects, the following examples will be considered.

The first example demonstrates an interval of drilling through conductive patches, which are interpreted as large vugs, probably formed due to post-depositional (e.g. karstic) carbonate dissolution. The interval is identified based on borehole imaging, dark areas of the acoustic image represent low-amplitude response, light areas in the resistivity image corresponds to the resistive facies (Fig. 8). Defined interval is interpreted as carbonate with large vugs facies, dm-scale, conductive, irregular features. As can be seen in Fig. 8, there is a step increase of the S&V in the interval of vugs. Drilling regime remains constant within this interval, which allows us to conclude that these changes of S&V might be related to the vugs facies. As can be noted, this case also demonstrates similar to the previous case increase of ROP, which might be explained by faster drilling through small cavities inside the rock (vugs).

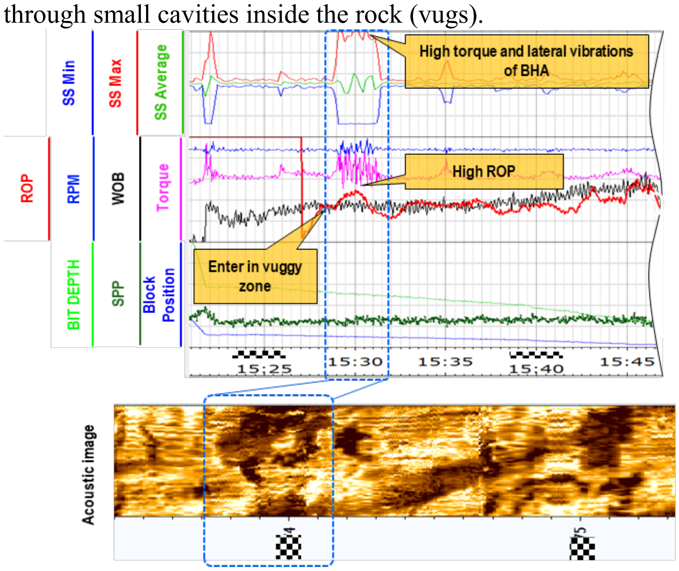

FIGURE 1: DRILLING MECHANICS DATA IN THE INTERVAL OF FRACTURE AND VUGS

The second example illustrates drilling through a 6m vuggy interval of cm scale vugs framed by two erosive surfaces as shown in Fig. 9. Thickness of the interval helps us to assess drill string dynamics in the extended vugs zone, without any other geological features crossed by the well path as can be seen in the borehole image. These conductive patches are interpreted as large vugs, which are probably formed due to post-depositional (e.g. karstic) carbonate dissolution. Beginning of drilling in this interval is characterized by a drill-brake. Drilling within the vuggy interval is accompanied by a constantly high level of shocks in comparison with the outer intervals. This case study confirms that high level of S&V may be associated with interval of karstification.

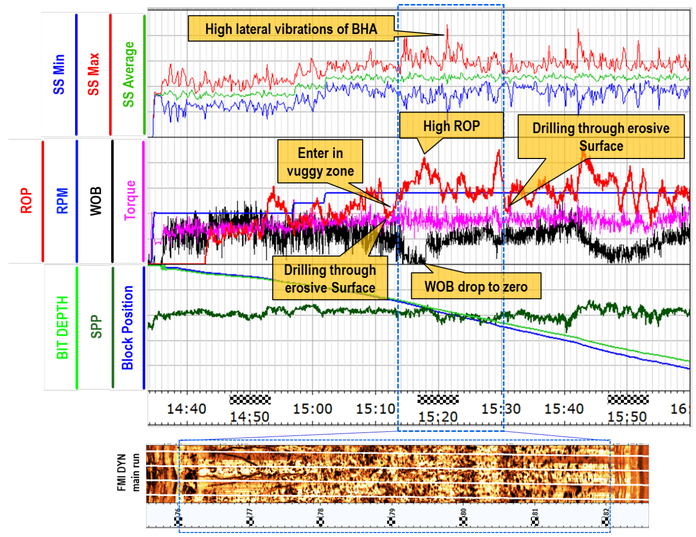

FIGURE 9: DRILLING MECHANICS DATA IN THE 6M (19.7FT) INTERVAL OF VUGS 6M THICKNESS

This section has reviewed the key aspects of drill string behavior in the zones of karstification. High level of shocks, ROP increase, drill brakes within carbonate intervals can often indicate that the well path is going through a karstification object and may be close to other karsts. However, these indicators have drawbacks. They cannot be considered as a standalone instrument for predicting karsts ahead of the bit. As will be shown in the next section, drill string dynamics is often not sensitive enough to detect some small-scale features or filled caves, which are also important signs of karsts and indicators of high risk intervals. In the section that follows, we will consider a set of additional indicators, which can significantly improve detection of karsts and small-scale geological features that can be missed by drill string dynamics measured by surface and downhole sensors.

5. DETECTION OF KARSTS BASED ON FLOW-DATA

So far, this paper has focused on the dynamics drilling data. In this section, we will consider a set of flow-based indicators of karsts. This will enable us to consider the problem of karsts detection based on a fundamentally different set of measurements, which might significantly increase the accuracy of detection signs of karstification. In this section, we will identify corresponding to karsts patterns based on flow-measurements and pump performance characteristics.

Drilling mud is essential for many drilling tasks, from cuttings transfer to transmitting hydraulic energy to the downhole tools. Drilling mud is pumped through main rig pumps to the Kelly hose, enter into the drilling collars, sprays out of the drilling nozzles and is pushed up in the annulus to the surface mud cleaning system and then pumped back again. Analysis of the difference between inflow and outflow rates (delta-flow) underlies kick/loss monitoring and reservoir characterization methods. The range of applications of this methodology is attributed to the accuracy of delta-flow measurements.

The benefit of this approach for advance karsts detection is based on a different type of measurements. In contrast to drill-string dynamics analysis, flow-based approach allows one to determine open caves (e.g. by specific BHA behavior in the intervals of karstification: drill-brake etc.), but also caves filled with clastic material. For instance, in case of filled cave, depending on the mechanism of cave genesis and the clastic material property, it is challenging to detect an increase of ROP and link it to the event of drilling through collapsed roof of the cave.

Before proceeding to examining the delta flow approach for karsts detection, it is important to consider pump performance data as part of mud circulation system. Generally, pump performance monitoring is an important component of different control and monitoring systems across many industries. Below, we will examine real-time Subsea Pump Module (SPM) performance driven by an automatic control system, integrated in controlled Mud Level (CML) system. Figure 10 shows a schematic placement of different components of the CML system. As can be seen, the level of the fluid in the riser is measured by pressure sensors, which serves for tracking changes of the hydrostatic column during drilling. Mud outflow from the wellbore, gets into the SPM. Based on the difference between the desired level of the liquid in riser (specified by the driller) and the actual fluid level, the control system defines required SPM performance. While the drilling mud is pumped through the SPM module, pressure and flow rate are measured by sensors, which are installed in the Mud Return Line. Having discussed previously, the importance of the information obtained from the delta-flow data, CML system provides an extensive set of measurements:

- SPM real-time performance measurements: voltage, current, electric mechanical power and shaft RPM
- Riser fluid level
- Precise measurements of the inflow and outflow using the flowmeters

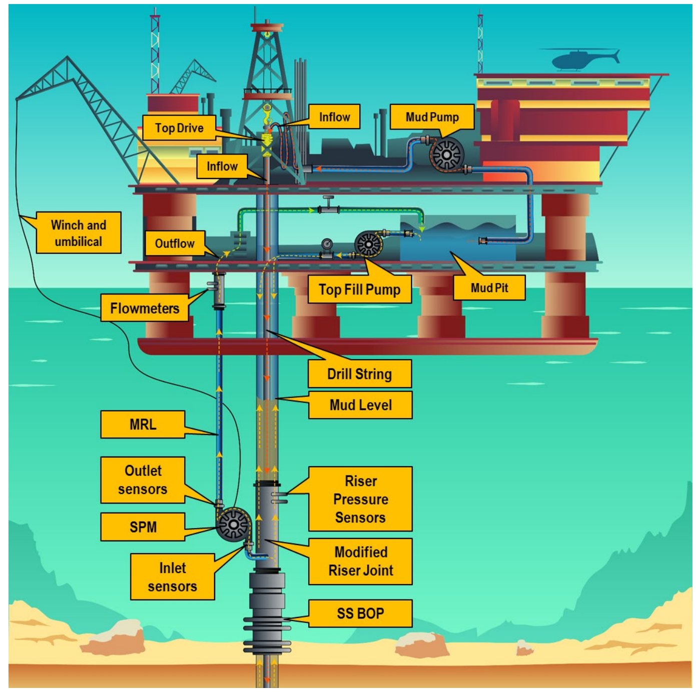

FIGURE 10: CML COMPONENTS

Having defined the type of measurements for the study, we can now consider the following examples of drilling in karsts intervals. Figure 11 represents a combination of two different types of measurements. The first type are the standard measurements, which are typically available while drilling. The second set of measurements represents additional data, available with a CML implementation. Interval #1 in the figure represents the response of drilling-based and flow-based measurements in the cm to dm scale interval of vugs. The interval of drilling begins from a drill brake, represented by a drop of WOB with simultaneous increase of ROP. After that, ROP profile, the level of the shocks as well as other drilling parameters remain constant in this interval. It proves the limitation of the drilling dynamic approach, as it is not accurate enough to detect small changes of the rock properties.

However, analysis of the CML data can reveal some additional information. When the bit passes through a zone with vugs or fractures, drilling mud invades into some of the open channels, which results in a consequent drop in the riser level. As has been mentioned, the system in this example is automated. The level of the fluid drops, which is recognized by pressure sensors, and optimization of SPM performance (reduction of the pumping rate) is done automatically by the automatic control unit. Thus, as we can notice in the interval #1, the subsea pump voltage (or pump power) increases when the riser level drops. Initial point, when the first difference between the inflow and outflow is noticed correlates with the interval of the vugs facies defined by the borehole image.

Interval #2 illustrates an example of drilling through a cave. Initial depth of the cave boundary is defined by borehole image and represents the beginning of interval #2. As can be noted, at the depth defined by the borehole image there are no visible changes in any measurements. However, in the close proximity to the cave there are spiky changes of the SPM voltage with consequent decrease of the SPM torque and voltage in the cave zone. Mud losses in the interval of the cave reached 2000 l/min (528.3 gal (US)/min). The clear response can be noticed by a step change of many logged parameters, such as ROP, S&V, WOB, torque and SPM related measurements.

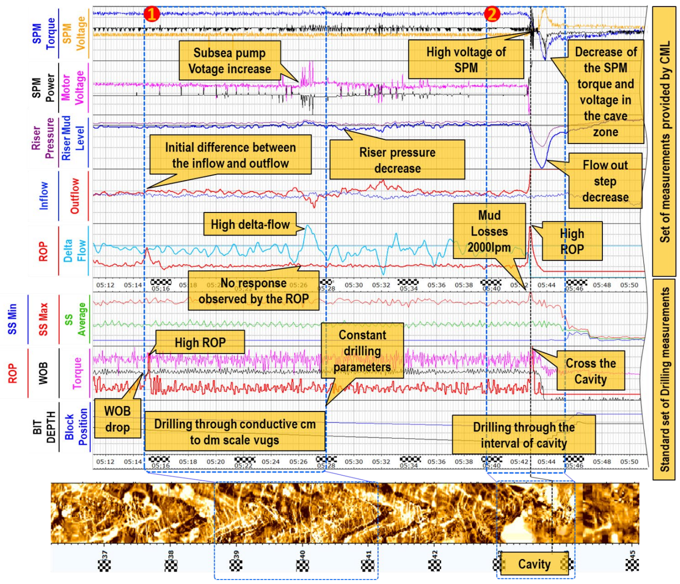

FIGURE 11: DRILLING THROUGH THE INTERVALS OF VUGS AND CAVE (STANDARD AND FLOW DATA)

The next example demonstrates the response of the drill string dynamics and SPM performance during drilling through bedding planes and drilling induced fractures. The logged response in this case differs from the karsts-related response. Interval #1 in Fig. 12 represents drilling through bedding planes. As can be seen, ROP profile at the beginning of the interval #1 shows similar behavior to the ROP in the karstified interval from the previous example. In contrast, other logs behave differently. For instance, there is no significant increase of the shocks level as was discussed in section 4. Similar behavior can be noticed in the interval of DIF (#2). Drilling mechanics data in this interval shows comparable behavior to the interval #1. However, profile of the mud losses is different and characterized by an immediate recover of the outflow, which indicates initiation of DIF and subsequent filling with the drilling mud.

Interval #3 demonstrates the transient zone from DIF to the bedding planes interval. It represents the combination of two discussed earlier responses in the zones #1 and #2.

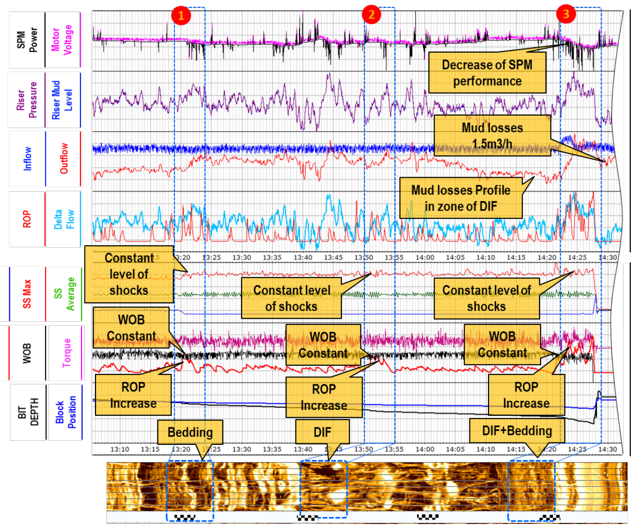

FIGURE 12: DRILLING IN THE INTERVALS OF BEDDING AND DRILLING INDUCED FRACTURES (STANDARD AND FLOW DATA)

In this section, it has been discussed applicability of flow-based measurements for karsts detection. Provided examples allowed us to demonstrate that the responses of drilling dynamic and flow-based indicators can complement each other. Delta flow profile might reveal additional signs of karstification in the intervals that are undetectable for drilling measurements, such as filled caves or small vugs. Detection of even small forms of karstification can be an important part of early cave detection methodology, as they can indicate drilling in a karstified zone. Revealed intervals of vugs, based on flow-measurements, are characterized by moderate values of delta flow, without significant fluctuations in contrast to the caves intervals encountered by a step change of the delta-flow profile. In addition to the delta-flow profile analysis, subsea pump performance monitoring can be utilized as a confirmation factor of karsts. The flow-based indicators, proposed in this section, can further be used in decision making process for drilling related risks minimization of drilling in carbonates.

6. CONCLUSIONS

In this paper, we considered the problem of karsts detection based on real-time drilling data. First, we presented an overview of the main signs of surface and subsurface karstification, including discussion of main mechanisms of karst genesis. Second, based on borehole image data from already drilled wells we performed localization of defined karst forms along the well paths. This study provided insight into karst types and their geometrical properties within the region of the study in the Barents Sea. Joint analysis of the borehole images and rig-site events demonstrated high probability of encountering deeply buried caves and other karst forms, which pose significant challenges for drilling. This analysis, performed for the entire area of the study, revealed sequences of drilling events, which preceded hitting dangerous for drilling karst forms. Based on this analysis, we reached the conclusion that encountering of karstification objects is not always unpredictable during drilling and that zones with high risk of karsts can be detected from real-time drilling measurements. Third, based on analysis of identified intervals of karstification, we confirmed applicability of the two proposed approaches for detection of karstification: based on drilling mechanics data and based on flow data. We demonstrated that combined, these two approaches can reveal additional signs of karstification, such as filled caves or small vugs, that might be undetectable by these methods applied alone. This combination of drilling dynamics and flow-based sets of measurements can be further implemented for karst detection based on real-time drilling data. The identified patterns of real-time measurements in the karsts intervals can be utilized for karsts detection either by engineers, or, after further development, by automatic data processing.

This study is limited in terms of the number of wells available for the analysis. Even in the well-studied fields, percentage of the wells, which encountered caves and at the same time contained full set of necessary well-logs data (e.g. images, or delta-flow data) is rather small. Being limited to the area of research, the study did not include other karsts regions. Future work on this subject should go towards additional analysis of well data from other fields with different geology. This will allow collecting a complete picture of unique real-time indicators of karsts, regardless to the geography of the research region. Further research might be also undertaken to investigate different techniques of early cave detection based on acoustic wave propagation and automatic detection of karsts from real-time drilling data based on the methods proposed in this paper.

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