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Drilling in karst carbonate formations.

1. Introduction

Karst cavities and depressions are collectors of various minerals, such as oil and gas, drinking and industrial waters, bauxite, various ores, phosphates, diamonds, gold and tin stone, refractory clay and many others. Of these, oil and gas are of paramount importance. To carbonate 40% of oil is associated with karst reservoirs and a significant percentage of gas. 40% of oil and a significant percentage of gas are confined in carbonate karst reservoirs.

High interest of the oil and gas industry in carbonate sediments is the fact that carbonate rocks serve as reservoirs of at least 40% of the world's oil, gas and condensate reserves. It is considered that more than 60% of the world's oil and 40% of the world's gas reserves are accumulated in these reservoirs. Drilling of such rocks implies many challenges and one of them is a karst in the carbonate formations. Karst identification, mapping, drilling have caused challenges worldwide. The main concerns are lost circulation while drilling through the formation which causes non-productive time, severe mud losses that can lead to abandoning of the well. Karstification process mainly occur in zones of cracks, faults where fresh water can flow and slowly expand cavities. The speed of this process is conditional on the mineralogy and solubility of the rock. Regardless of methodology, it is hard to avoid drilling into caves, large cavities or faults. The MPD (managed pressure drilling) technique is relatively new drilling method that can significantly reduce drilling related risks. [1] In this thesis some of the known offshore fields in the Norwegian continental shelf are taken into consideration.

The first chapter contains a brief background on carbonate karst's description. The next chapter includes general information on basics of drilling technology and drilling methods to mitigate karst related risks. The following chapter contains information about carbonates and karst phenomena following by description of techniques of karst identification by seismic and petrophysical logs. In the end there is a discussion on drilling methods with some of the solutions are included.

Figure 1.1 Carbonate deposits in Pyefjellet layers, Ultuna Mountain, Spitsbergen. Photo: T.A. Svånå [1].

2. Basics of drilling

This chapter will cover the basic principles of drilling operations and their methods.

2.1 There are pressure regimes that is important to comprehend in order to perform successful drilling operations. While drilling there is a lower and upper limit pressures and the window between these two limits are is known as the drilling window. Lower limit is pore pressure line compliance of which helps to avoid kicks or any undesired influxes, while upper limit is fracture line surplus of which can cause lost circulation.

Drilling operations can be roughly divided into three categories there are: conventional drilling, underbalanced drilling (UBD), managed pressure drilling(MPD).

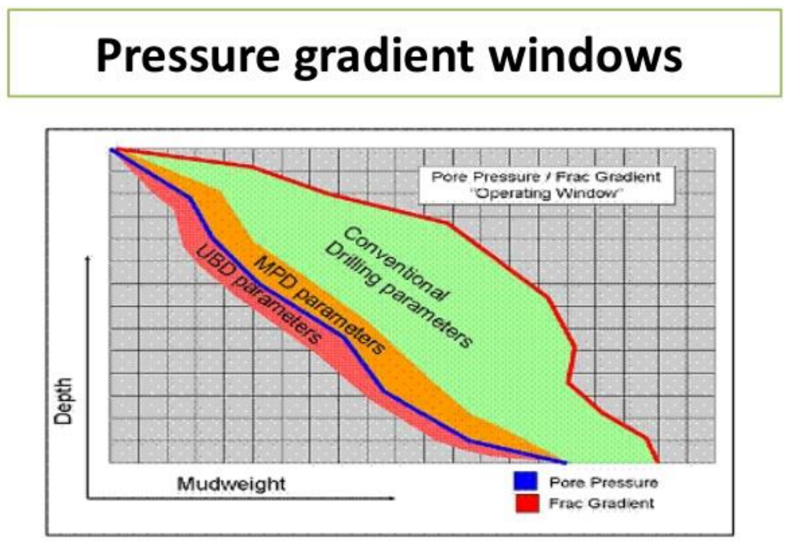


Figure 2.1 - Drilling windows for conventional drilling, underbalanced drilling and MPD

2.1 Conventional drilling

In conventional drilling the bottom hole pressure is kept higher than the pore pressure gradient but the lower than fracture pressure gradient.

Circulation process starts by pumping mud from the pit through the lines to the drill string down to the borehole. The mud flows through bit nozzles and transport cuttings upwards to the surface while whole string rotates around its axis. Then mixture of liquids and cuttings flows toward shakers or mud cleaners, where after being processed will be pumped back to the mud pit.

This is an open vessel system which means pressure readings in the surface will be equal to atmospheric [2].

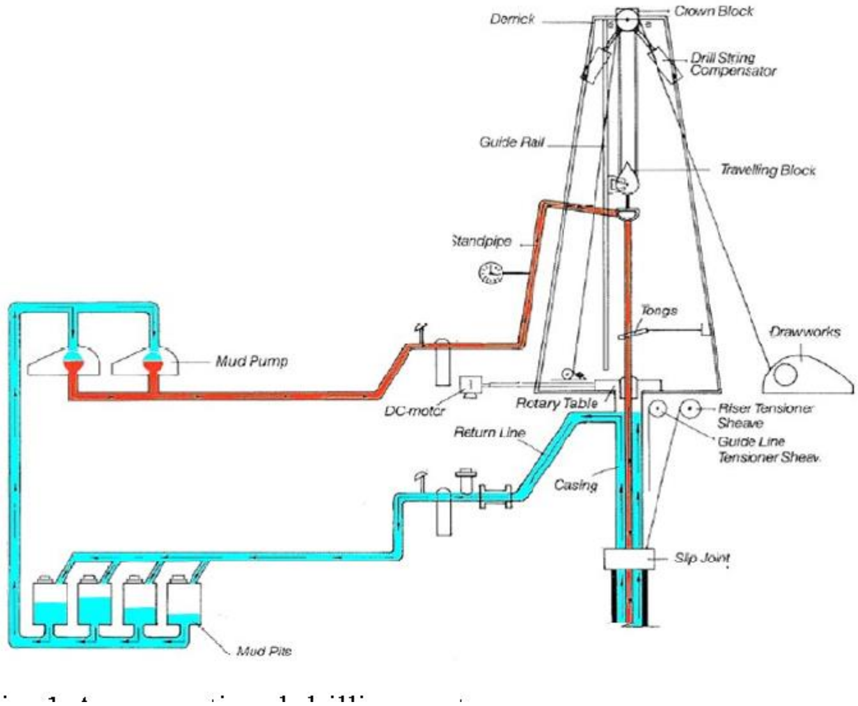


Figure 2.2 - Conventional drilling system [3]

2.2 Underbalanced drilling

Underbalanced drilling (UBD) is a technology of drilling with negative differential pressure in the well-formation system, when the formation pressure exceeds the pressure of the liquid column in the well. In this method formation properties remain undamaged, this achieved by using a very light well liquid. When an underbalanced condition is created, a formation fluid (gas, oil, water) will flow into the well at a different flow rate. Which mainly depends on a pressure difference and reservoir properties.

UBD advantages:

- Formation(reservoir) contamination is minimized
- Ensure a simultaneous increase in oil recovery factor and inflow, due to minimization of damage to reservoirs;
- Increase in the rate of penetration due to of the inhibitory pressure at the bottom of the well

Underbalanced drilling allows to effectively maintain (regulate) the specified differential pressure in the well-reservoir system, which reduces the chances of well liquid absorption, fluid, debris, collapses and other wellbore complications. In this method different types of agents are used: - low density solution, for example, water or oil; aerated solutions gasified with air, nitrogen, natural gas, or even exhaust gases of internal combustion engines.

Effectiveness of this technology is reduced by its high cost.

2.3 MPD – Managed pressure drilling

The Underbalanced Operations & Managed Pressure Drilling Committee of the IADC defines MPD as [3]:

"Managed Pressure Drilling is an adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly. It is the intention of MPD to avoid continuous influx of formation fluids to the surface. Any influx incidental to the operation will be safely contained using an appropriate process."

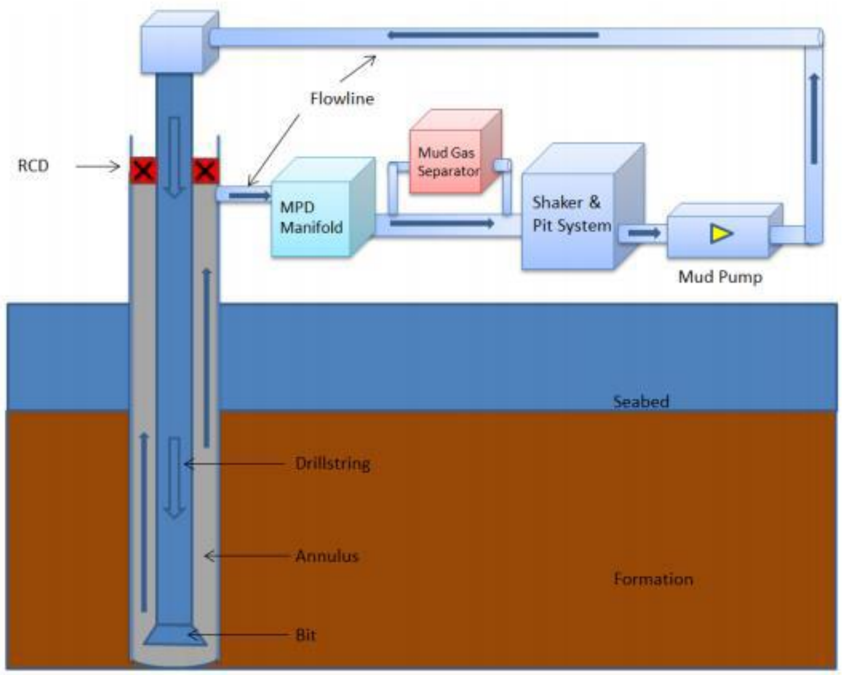


Figure – 2.3 The principle of the MPD system [3]

The MPD system differs from the conventional system by presence of rotating control device and pressure manifold. The wellbore pressures in this system are controlled by closed system and applying backpressure through chokes and the pump in the MPD manifold as it is shown on the Figure -2.3. [4]

2.3.1 Categories of MPD

The Underbalanced Operations & Managed Pressure Drilling Committee of the International Association of Drilling Contractors (IADC) [3] separates MPD into two categories, *reactive and proactive*, defined as:

"Reactive MPD - Using MPD methods and/or equipment as a contingency to mitigate drilling problems as they arise.

"Proactive MPD - Using MPD methods and/or equipment to actively control the pressure profile throughout the exposed wellbore." [3]

Managed Pressure Drilling (MPD) drilling allows to reduce the risks involved in drilling, increase its efficiency

MPD allows:

- prevent the inflow of well fluid into the well and safely eliminate the influx without stopping drilling with the help of specialized equipment;

- manage the pressure profile in the well at any given depth,

- to determine the actual gradients of reservoir pressure and pressure gradient of fracturing pressure in the dynamics,

- perform drilling while maintaining constant pressure at the bottom in wells with a narrow drilling window (including drilling for longer intervals)

- promptly increase the pressure at the bottom, without the need to replace the drilling fluid in the well while an influx occurs and instability of the well,

- control the main parameters of the system: back pressure, fluid density, its rheological properties and level in the annulus, loss of circulating pressure on friction in the annulus. [4]

2.4 Drilling fluids

Drilling fluids or drilling mud is complex multicomponent disperse system of suspension, emulsion and aerated fluids used for transport cuttings from the wellbore to the surface in the drilling process. Drilling mud also used to create mud cake around the wellbore as well as to lubricate the drill bit and helps to prevent wellbore collapse while drilling.

When circulating in the well drilling mud:

- Compensates reservoir pressure;
- forms a filter cake on the walls of the well, thus strengthening unstable deposits. Reduces the effect of mud filtrate on rocks by separating the drilled formations and the open hole
- transports the cuttings from the well and keeps them in suspension after the termination of circulation
- transfers hydraulic energy to a downhole motor and chisel

- warns of debris, landslides
- provides high-quality opening of productive layers
- provides a lubricating and anti-corrosion effect on the drilling tool
- cools and lubricates the bit
- prevents the occurrence of drilling complications (differential sticking, absorption, hydrocarbon influx)
- provides information about the geological cross-section.

There are two main types of drilling fluids, classified by which fluid is used as a base:

- Water-based mud (WBM)
- Oil-based mud (OBM)

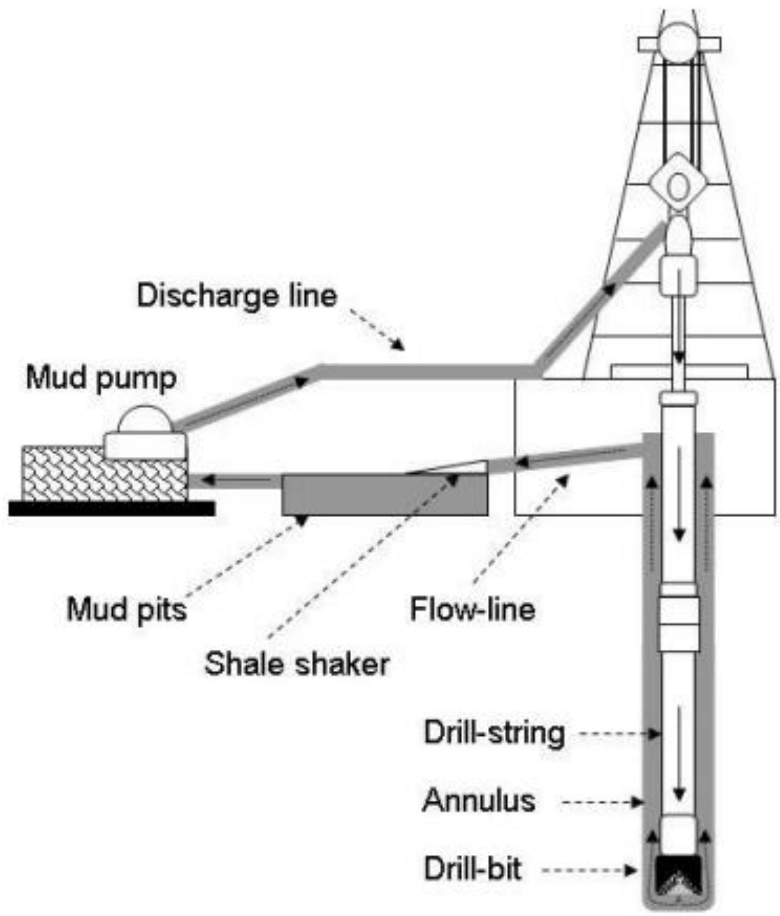


Figure – 2.4. Drilling fluids cycle [5]

Chapter 3

3.1. Carbonates

Carbonates are one of the sedimentary rock types which is a product of different geological processes on the Earth's surface. Carbonate rocks are sedimentary formations composed of 50% or more carbonate minerals. The latter include calcite (and aragonite) —$CaCO_3$, dolomite — $CaMg(CO_3)_2$, and much more rarely encountered magnesite — $MgCO_3$, ankerite — Fe, Ca $(CO_3)_2$, Siderite— $FeCO_3$, strontianite - $SrCO_3$ and other types. Among these carbonate minerals, only calcite and dolomite are widespread in nature, the rest are found in the form of scattered secretions, individual lenses, nests, rarely forming significant solid clusters. In these cases, they are of practical importance as mineral raw materials used in many areas of the industry. Calcite and dolomite, being the main rock-forming carbonate minerals, compose limestone, dolomite and rocks of a mixed lime-dolomite composition. These rocks are found in sediments of various tectonic structures (platform and geosynclinals) and of the most diverse ages, from Precambrian to this day. Their share in the total mass of sedimentary formations of the earth's crust is estimated differently. In all probability, values around 20% are the most realistic.[7]

In response to gravity sedimentation process is considered as a downhill process as transportation of sediments follows downhill trend and the process of sedimentation starts where moving of the rocks end. Formation of sediments occurs on land surface, in rivers, lakes, seas, oceans, partly due to terrigenous (allogenic) material brought from the outside in ready form, partly due to biogenic and chemogenic shedding of some (usually the most insoluble) compounds from the bottom water (reservoirs) and the current (in rivers, streams flowing down from the slopes). [6]

Figure-3.1. The rare igneous rock known as carbonatite.[8]

Limestone is the most common carbonate rock formed by the lithification of carbonate sediments and formed from carbonate mud and sand or is some cases from ancient reefs [9].

3.2 Karst phenomena

Karst is a system of processes and phenomenon, emerging and developing underground or on its surface as a result of the interaction (dissolution, transport and deposition of a substance) of natural waters with the rocks soluble in this condition. [10] This topography can be located in many places around the world where acidic groundwater substantially has formed the landscape. These areas will often have a disproportionate land with depressions called sinkholes and in addition there will be a lack of surface streams. The streams mostly located underground [11]. In figure 3.2. an image of a common development of a karst development. The process can be divided into three stages. In early stages of the development groundwater will make a hole in through limestone to dissolve the limestone rocks resulting into the formation and expanding of cavities at and below the water table [11]. In the next stage in the figure illustrates more developed sinkholes and surface streams is now channeled below ground. The last stage in the figure shows, as time passes, the cavities became larger, as well as an increase in sinkholes size and amount [11].

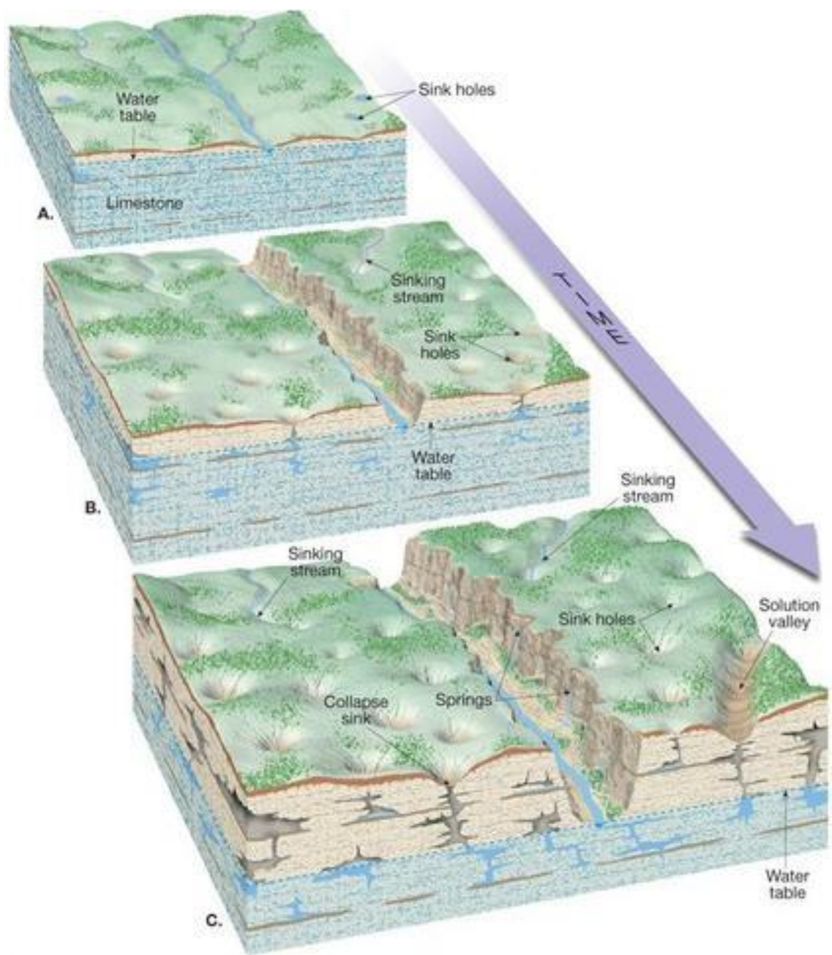


Figure – 3.2. Karst development [11]

In general Karst will not develop in dry areas since there is not enough groundwater, however, if Karst essential qualities is seen in dry areas, they are possibly to be remains of a more humid time. Thus, carbon dioxide and humidity presence with heavy rainfalls, rapids Karst development [11].

As the geology of the earth is in continuous alteration, some of these cavities that occurred millions of years ago in a humid area near surface may have been exposed to burial processes and could now be located in a subsurface environment[4].

Figure 3.3-Tower karst—Fengcong along Li Yiang River (*left*) and in Xiangqiao geopark (Guanxi province, south China) [12].

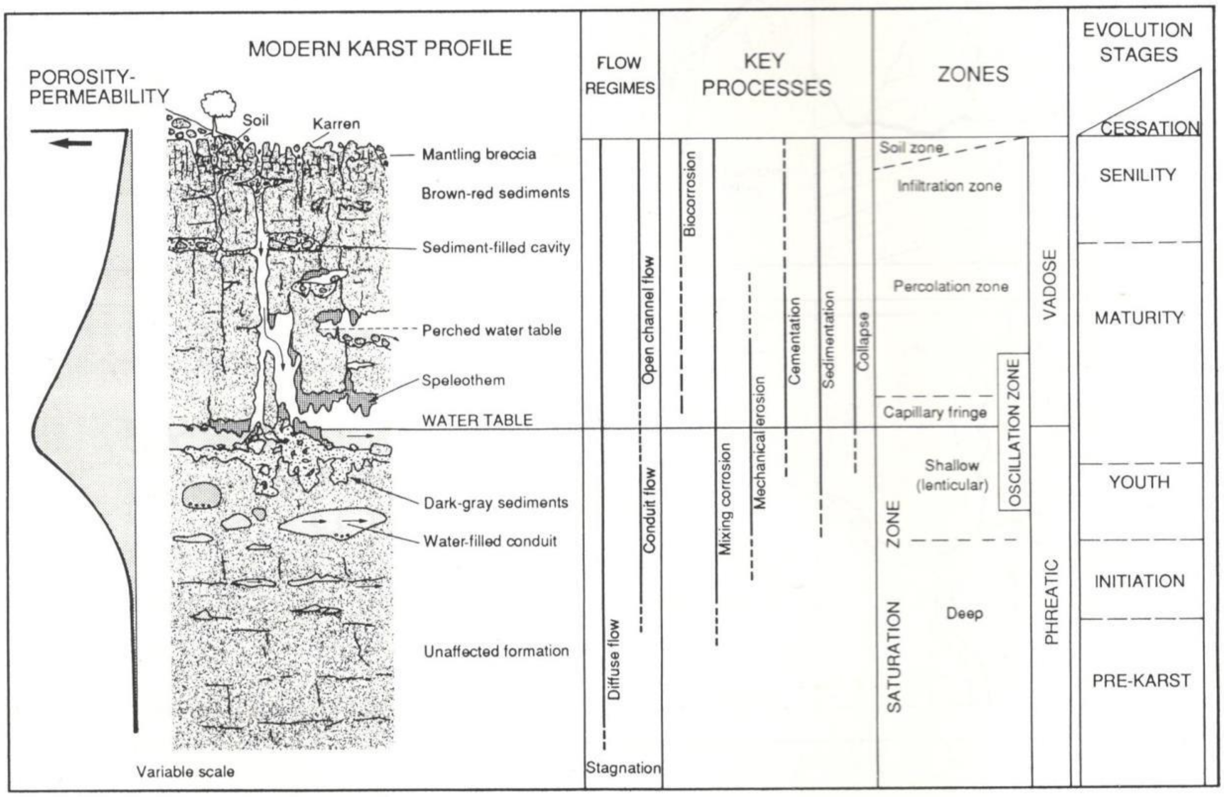


Figure -3.4. Profile illustrating stages in karst development and the relationship to development of
porosity and permeability [16]

3.3 Karst classification

There are different types of classifications and regionalization of karst depending on the author. The classification principle contains factors that affected karstification, driving mechanisms as well as lithology types, morphological forms and climate conditions [12].

Gvozdeckiy (1981) arranges several morphogenetical variety of karst. Among them are buried karst, covered karst, relict tropical karst, permafrost karst, and seashore karst [12]. Also based on lithology, Gvozdeckiy makes the further divisions:

- Limestone karst,
- Dolomite karst,
- Marble karst,
- Chalky karst,
- Gypsum–anhydrite karst
- Salty rocks karst [12].

In accordance with the main genetic factors of the creation of caves, i.e., speleogenesis, Klimchouk distinguish the two principal groups which can be identified as karst typology[12]:
1. *Hypergene* or (*meteoric*, *unconfined*, *phreatic*) *karst*.
2. *Hypogene* (*deep*, *confined*) *karst* [12].

The main dissolution agents of hypogene karst are juvenile waters and gases, while hypergene properties are created by infiltrated meteoric waters. In addition to the two main groups, there are younger coastal caves developed in rocks which have newly emerged. [12]

There are other classifications distinguish the karst types in accordance with some particular developments or forms created by karstic or other mainly tectonic and erosional synergetic processes, as well as those established under specific climate circumstances. Further down are clarifications of some of these types [12].

Exokarst is a surficial type of karst, while endokarst considers internally developed forms inside unbounded karstic rocks. Cryptokarst refers to confined karst and forms developed subsufrace, till, residual clays, or similar sediments.[13]

Buried karst, paleokarst, and fossil karts are all represent covered karst. Exception is exhumed karst, which is covered, but its actual status and exposure to the surface is different than in the creation phase [12].

Bare karst is commonly representing karst which exists, but without presence of vegetation. This name is frequently applied to the karst which consists of big blocks with fast vertical karstification but without epikarst [12] The term is used for the net of small fissures and a destroyed subsurficial part of karst. Depending on either lack of vegetation or epikarst, term naked karst is often used instead of bare karst making them synonyms [12]

Barrier karst is an isolated karst bordered by commonly impermeable rocks or karst where the process has been interrupted due to the transgression of sea or lake waters. It can cause secondary plunging and dislocation of primary discharge outlets. [14].

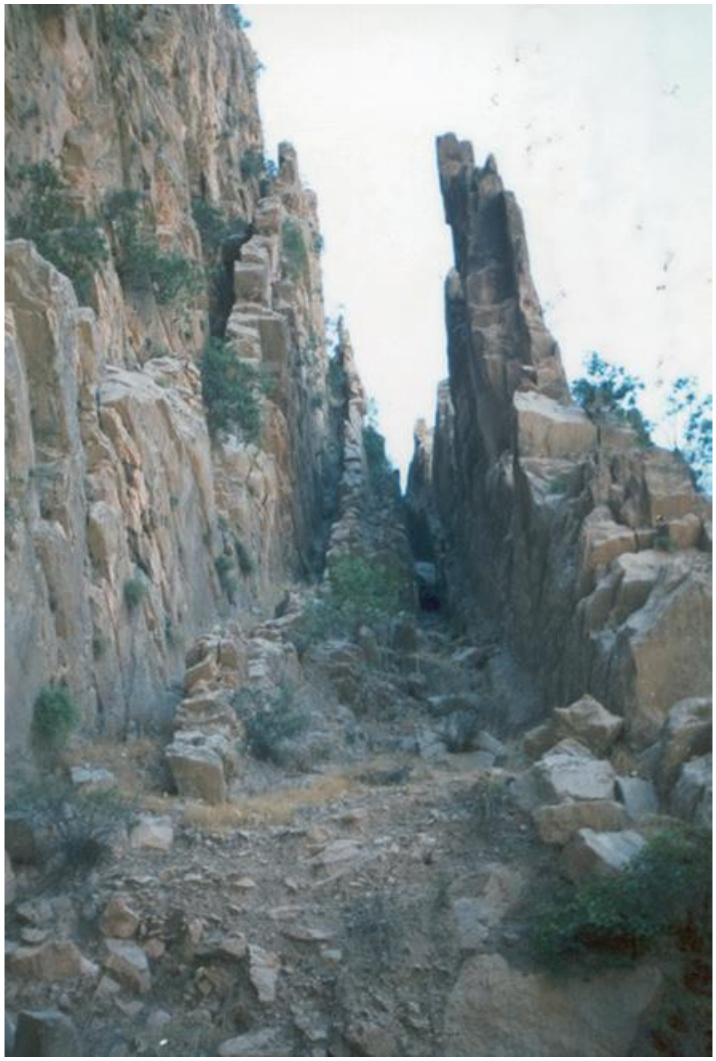


Figure – 3.5. Karst: Tectonically disturbed limestones and subvertical residual strata of Pila Spi Fm. (Darbandikhan area, northern Iraq)[12].

3.4 Karst distribution

Surface and subsurface outcrops of potentially soluble karstic rocks occupy close to 20 % of the planet's ice-free land, but not more than 10–15 % is widely karstified [13]. Nearly more than 90 % of the evaporitic rocks anhydrite and gypsum do not crop out, while this percentage in the case of salty rocks is close to 99 %: Salt is significantly soluble (360 g/l at 20 °C) and highly ductile, and the salt deposits quickly erode after precipitation.[15]

Figure – 3.6. Salt spring and deposits in the foothill of Konarsiah diapir (Iran)[15].

Excluding Antarctica, Greenland and Iceland, the overall surface area of carbonate outcrops on the soil is about 17.7 million km2 or 13.2 %. The biggest part is in Central and North America, with estimated 4 million km2, but the largest presence of carbonate rocks in the overall surface coverage is in the Middle East and Central Asia, where they occupy around 23 % of the total land. [12]

3.5 Examples of carbonate formations with karst and cavities.

Figure 3.7. The gypsum formation. Spitsbergen [17].

Example of partial dissolution of anhydrite and subsequent deposition of layered material lime sludge and gypsum / anhydrite in the recesses. The gypsum formation, Gipsdalen, Spitsbergen. [1]

Figure – 3.8. High energy carbonate deposits in Pyefjellet layers, Ultuna Mountain, Spitsbergen [17].

The top of the layers shows signs of exposure or erosion in several places. There is a big difference in this type of exposure surfaces in geological sense is very brief compared to surfaces formed by prolonged exposure and deep erosion. Arrows indicate two large dissolved cavities that are both attached to a bedding plane. During drilling, such cavities can be recorded as "bit drop", with possible loss of circulation. [1]

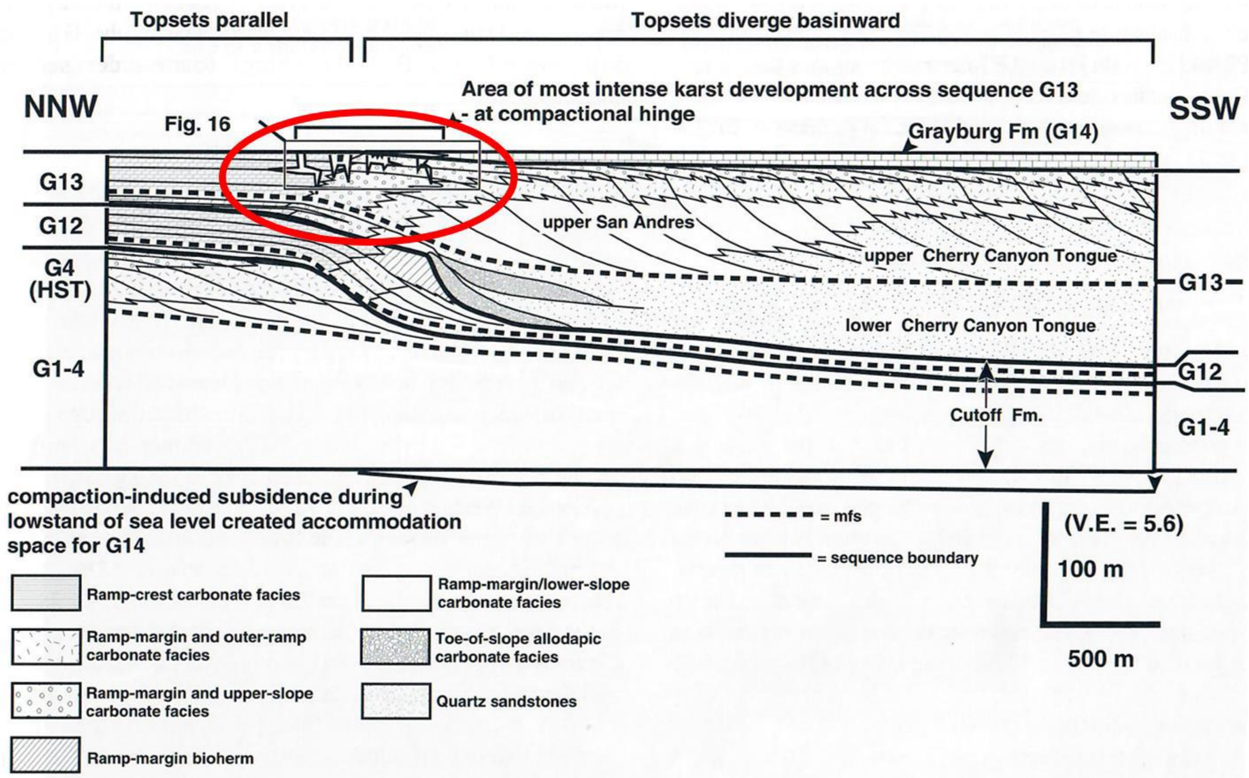


Figure - 3.9. San Andres formation in New Mexico and West Texas [18].

Example from the San Andres formation in New Mexico and West Texas taken from Hunt & Finch (1999). The zone with the most intense fracture with subsequent karstification occurs in an area along the margin of the carbonate platform and is caused by differential subsidence [18].

3.6 Offhosre karst distribution

Karst environments over a period of geological time could get covered by other rocks becoming inactive. They are called paleokarsts – an ancient rock that lie discordantly under cover rocks often becoming victim to tectonic subsidence [19],[20].

The Loppa high where karstification process has been passed to the reservoir rocks. As an outcome of the rifting between Norway and Greenland during the late Paleozoic and from the late Jurassic-Early Cretaceous rifting Loppa high has been emerged [21,22]. The Karst processes at the High Loppa are represented by three major reasons:

- Subaerial exposures due to glacioeustatic sea level changes
- Subaerial exposure and karstification associated with third- and second order sequence boundaries

• Extended exposure and the formation of a major unconformity between the late Permian and the Anisian, for 25 million years. [4]

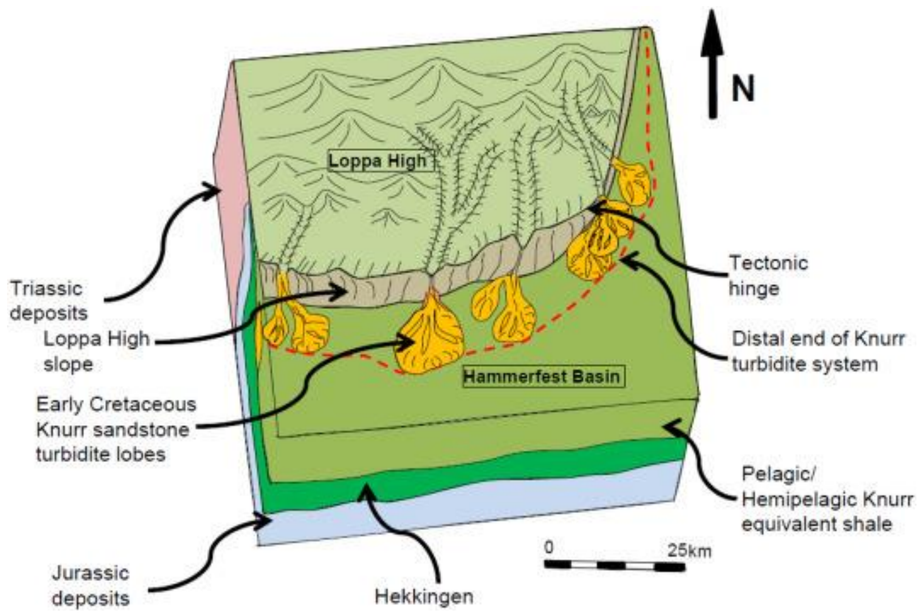


Figure – 3.10 Loppa High, Barents Sea

In subsurface environment different types of structures such as large cracks or cavities of different scales are created over the period of karstification period. When the system is buried, the overlying layers increase stress as it gets heavier and eventually the ceiling will collapse [20]. After the ceiling collapse chaotic breakdown breccia is produced, while due to stress exposure around the cavity that collapsed, walls will create crackle and mosaic breccia on the floor [20].

Breccias are rocks which has been created by cave collapse. The classification with cave sediment fill is shown on figure – 3.13. They are divided into three main types which is crackle breccia, mosaic breccia and chaotic breccia.[4] Crackle breccia is a fractured rock where clasts are not displaced far from each other, whilst the same rocks but with more displaced clasts are called mosaic breccias, in both cases it is feasible to gather clasts together [23]. The chaotic breccias are the rocks that falls to the floor with no obvious connection in the clasts [22]. As the burial process continue further smaller cavities will collapse creating more brecciation of already existing rocks [21]. Figure 3.13 shows a picture from a cave where the chaotic breccias forms the cave floor and large crackle breccias occur in the cave ceiling, the person for scale representation [4].

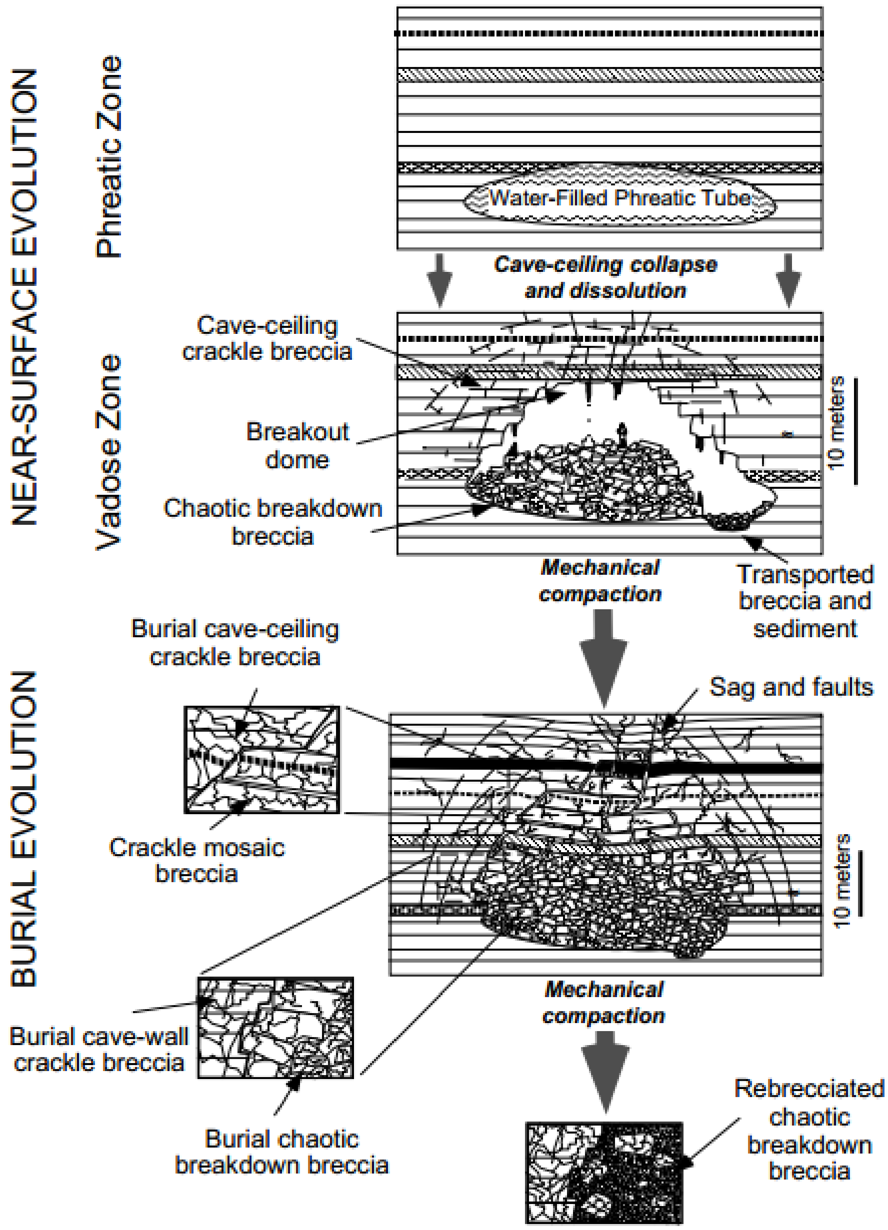


Figure 3.11 - Evolution of a single cave passage from formation in near surface Karst environment to burial in the subsurface where collapse and brecciation occurs [20]

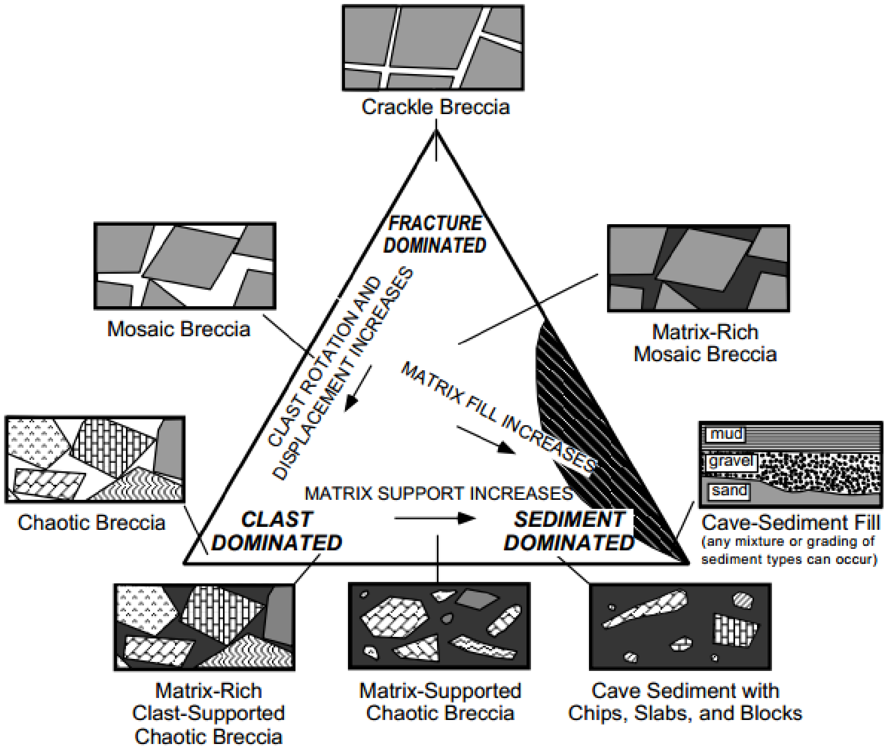


Figure 3.12 Breccia classification[20]

Figure 3.13 Example of cave breccias [20]

In the same areas over a long period of time different phases of collapse may occur. However, open cavities can be found at deep depths, there are reports of bit drop up to 3000m. [20]. This fact shows that it is possible confront open cave systems or filled and collapsed ones at great depths in karstified subsurface reservoirs which accents the importance of understanding the properties and distribution of karst and paleokarst.

Karst processes can lead to increased porosity and permeability in rocks by erosion which will remove parts of the rock volume. Karstification could enhance reservoir quality since karstification process of rocks will cause secondary porosity in carbonate rocks [23]. It is considered that more than 40% of recoverable hydrocarbons in carbonate deposits have karst origin [21].Some researches have assumption that most karst related reservoirs due to their great scale, they could cover thousands of meters across, are the result of numerous collapsed cave systems [20,21]. It is known that reservoir created by both karstification and burial processes often have complex structure with great dimensional heterogeneity [21]. All these facts underline importance of capabilities to identify and predict karst features in subsurface environment [4].

4 Karst identification

Developing value methods in the subsurface to recognize karst properties and features is important part. It's needed in order to interpret reservoir properties and anticipate potential thief zones avoiding drilling issues [4]. However, due to several reasons it is not always a simple task to recognize karst, these are:

- Karst distributed not evenly but shows an extreme spatial variability
- It is difficult to map since mainly karst features are close to seismic resolution
- Karsts have different type of shapes and characteristics which affect the formation rocks in different ways
- Cementation and diagenesis can overprint properties of rock that has been a result of karst process changing its petrophysical properties [51].

Seismic three-dimensional mapping shows how important and useful it is to have access to a good performed 3D seismic in areas where karstification processes has been widely exposed. While getting in connection with drilling the opportunity to calibrate seismic observations against petrophysical logs and most preferably also cores from previous wells in the area, one is much better equipped for further successful and safe drilling operations [4].

It's generally not adequate enough to differentiate karst areas from their surrounding environment by conventional seismic methods that exists, therefore is useful to compare with data of paleokarst with studies of different areas with the same continuous karst processes [4].

4.1 Karst identification by history matching and neutral networking

History matching is complex and time consuming since multiple parameters affects the match and inter-dependency causes effects that are hard to anticipate [24].

The methodology is well designed to confront the challenge of history matching, following these key steps [24]:

- Selecting of key parameters with variance analysis,
- Reduction of dimensionality by creating hybrid parameters, using techniques related to principle component analysis,
- Predicting matching domains [24].

The resulting models are then tested against operational data to confirm presence of karst features where wells have experienced mud losses [25].

At the Loppa high another mapping of karst features has been carried out. An integrated approach including core analysis and 3D seismic mapping combination and multi-attribute seismic facies (SF) classification was used to perform this mapping [21]. Observations of Loppa high seismic, both 2D and 3D made prior to this study showed the presence of karst plains in the form of sinkholes, caves and other phenomena associated with a paleokarst terrain [22][4].

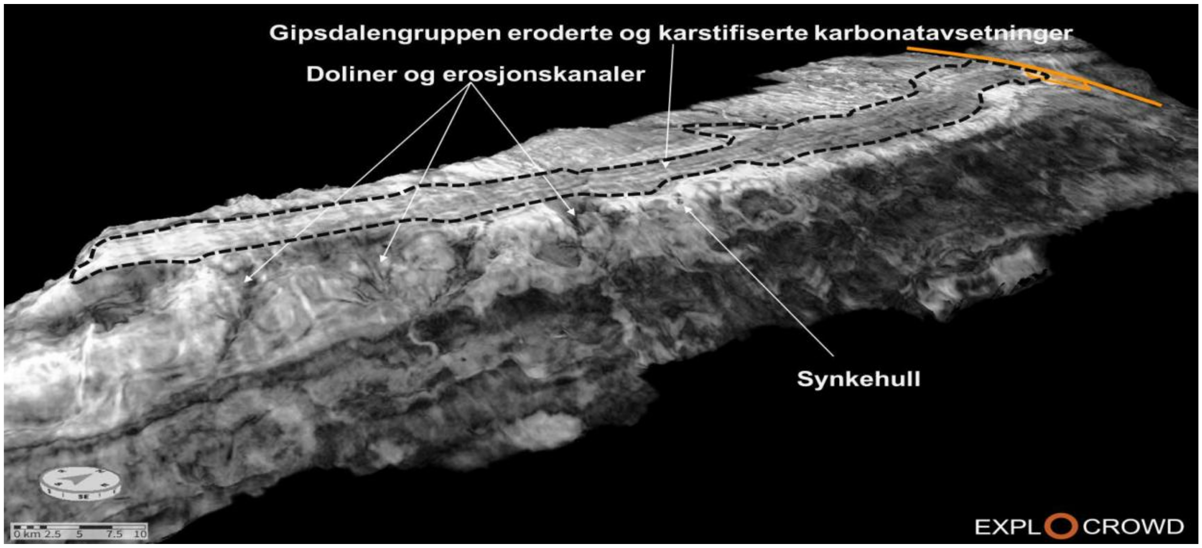


Figure 4.1. 3D over the Loppa High. The wells that until now have been drilled are in the zone between the two dotted yellow lines, in the area where the gypsum group is deeply eroded and karstified. Further down flanks there are also many signs of karstification near it mapped the top of the gypsum group [1].

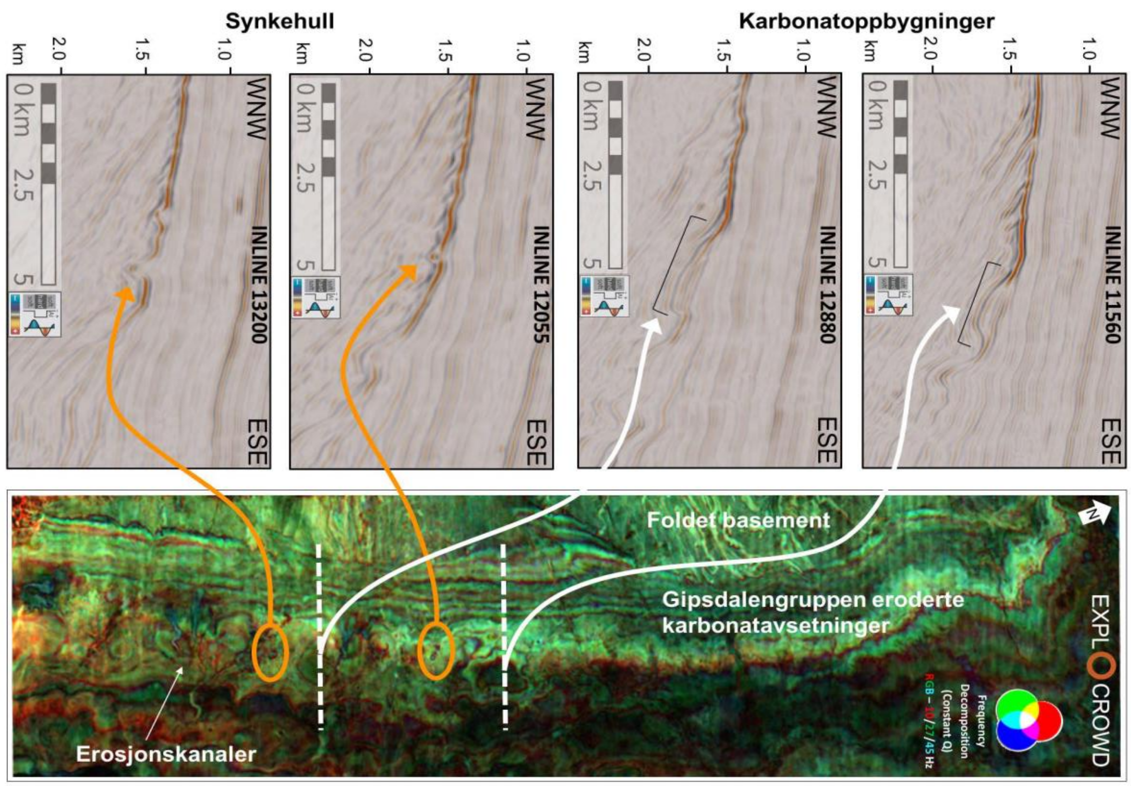


Figure 4.2. Seismic examples of both carbonate structures and sinkholes near the top of the gypsum group of carbonates, SG9810 3D [1].

From the Statoil drilled 7220/6-1 well and the Esso Exploration and Production Norway drilled 7121/1-1R, core samples were logged and described, and the data was used for calibrating stratigraphic markers along with the 3D survey SG9810 [21].

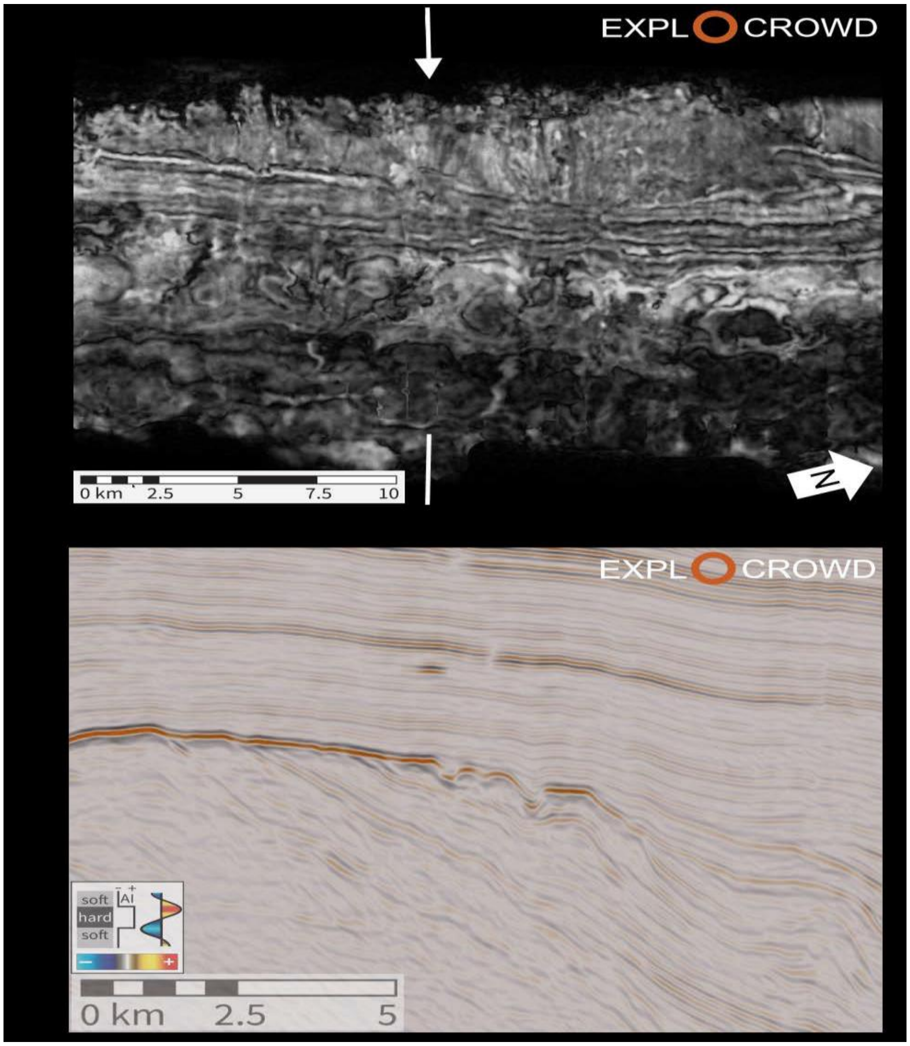


Figure 4.3. Seismic example of both large carbonate structures and sinkholes near the top of the gypsum group of carbonates, SG9810 3D [1].

To perform the seismic well calibration data from the available wells and from the 3D survey was combined, resulting in the construction of a 3D seismic stratigraphic model of reference [21]. The model showed the lateral magnitude as well as the main stratigraphic units within the 3D survey.[4]

The next step was the 3D SF classification and first the number of seismic attributes where decided. In this case 18 seismic attributes where calculated and they were all visually evaluated and studied against the reference model to find corresponding geologic correlations and trends

[21]. The attributes chosen to have geologic or geophysical significance rather than mathematical meaning [21][4].

Seismic Attribute	Basic Seismic Information	Event Continuity	Lithology	Structures	Fluid Content	Sequence Boundaries	Rock Properties	Stratigraphic Features
Apparent polarity	Sign of seismic trace	✓✓				✓✓		
Gradient magnitude	Amplitude	✓✓		✓✓		✓		
Reflection intensity	Amplitude	✓✓	✓✓			✓✓		
RMS** amplitude	Amplitude			✓	✓✓			
First derivative	Amplitude							✓
Instantaneous quality	Amplitude				✓			
Envelope	Total energy of the seismic trace		✓			✓✓		
Cosine of instantaneous phase	Phase	✓✓		✓✓		✓✓		✓✓
Instantaneous bandwidth	Frequency						✓✓	✓
Instantaneous frequency	Frequency		✓✓				✓✓	
Dominant frequency	Frequency						✓✓	
Instantaneous phase	Phase	✓✓		✓✓		✓✓		
Chaos	Chaoticness of seismic signal	✓✓		✓✓				
Variance	Structural information	✓✓		✓✓		✓✓		
Relative acoustic impedance	Apparent acoustic contrast		✓		✓✓	✓✓		
Local structural dip	Dip of seismic events	✓		✓✓				
Local structural azimuth	Azimuth of seismic events			✓✓				
Attenuation	Frequency	✓		✓	✓✓		✓✓	

*The table shows the geophysical and geologic significance of each seismic attribute.
**RMS = root mean square.
†✓✓ = good indicator; ✓ = medium indicator.

Table 1 - 18 computed attributes chosen for the study of Loppa High [21]

Excess of data is not desired in this matching method, so further assessment of the attributes are carried out by a cross-plot method to analyze the sufficiency of each attribute [21]. In figure 4.4 parts of such a cross plot can be seen, images A and B shows spread correlation whilst images C and D shows linear correlation. As it seen in the plot A and B show different seismic properties and can be considered for the classification process, while C and D plots are show identical pattern and cannot be taken into consideration for further classification.[21][4].

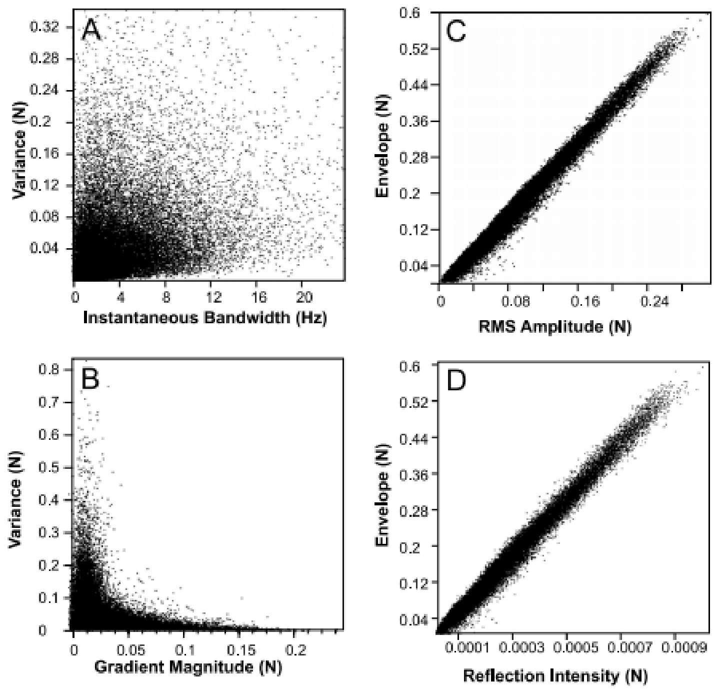


Figure 4.4. Cross plots of seismic attributes performed in the study [21]

This technique gave six attributes which were dominant frequency, chaos, gradient magnitude, instantaneous bandwidth, variance and envelope, they are listed with their seismic information and function for this study in the table [21].[4]

Seismic Attribute	Basic Seismic Information	Type of Seismic Attribute	Application in This Study
Envelope	Energy of the seismic trace	Complex trace attribute	Acoustic impedance contrast and detection of major lithologic changes and sequence boundaries
Dominant frequency	Frequency	Complex trace attribute	Time-varying spectral properties of seismic data
Chaos	Chaoticness of seismic signal	Stratigraphic attribute	Recognition of chaotic texture in seismic data
Gradient magnitude	Amplitude sensitive	Structural attribute	Determination regions of weak coherent signal from the ones with significant reflectivity and signal strength
Instantaneous bandwidth	Frequency	Complex trace attribute	Time-varying spectral properties of seismic data; good indicator of lower frequency areas
Variance	Structural information	Structural and/or stratigraphic attribute	Isolation of edges from the input data set

Table 2 - Chosen attributes from the cross-plot analysis, showing basic seismic information, type of seismic attribute, application of attribute[21][4].

The next step is to classify the seismic facies, which can be done in supervised- or unsupervised mode [21][4] In an unsupervised mode a natural selection of the data is acquired by different combinations of the seismic attributes into an artificial neural network [21][4]. An artificial neural network (ANN) is a computational model which is able to recognize patterns. In the supervised mode on the other hand, sets of various SF were selected from the 3D survey and used to develop the ANN as seen in the table 3 [21]. Both the unsupervised mode and the supervised mode resulted in similar patterns. A schematic workflow is shown step by step in figure 5.23, this is repeated until a satisfying result is obtained [21][4].

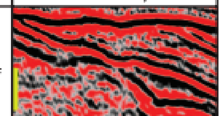
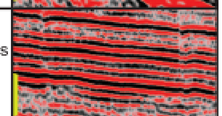
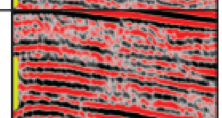
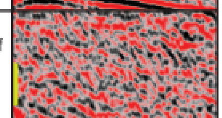
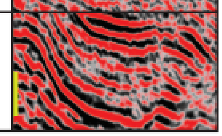
Seismic Facies	Reflection geometry	Amplitude characteristic	Spatial distribution	Example (Vertical bars represent 100 ms)
SF1	Parallel continuous	High amplitude	Occurs mainly at the crest of the structural high and at the top of basement	
SF2	Parallel continuous	Medium to low amplitude	Occurs mostly towards the flanks of the Loppa High	
SF3	Parallel discontinuous	Medium to low amplitude	In overlying Triassic clastics and some areas of the carbonate intervals	
SF4	Chaotic	Low amplitude	Present at the core of the buildups and in the basement	
SF5	Semiparallel dipping discontinuous	Medium amplitude	Occurs mostly in the slopes of buildups	

Table 3 - Seismic Facies (training data) to train the Artificial Neural Network [21]

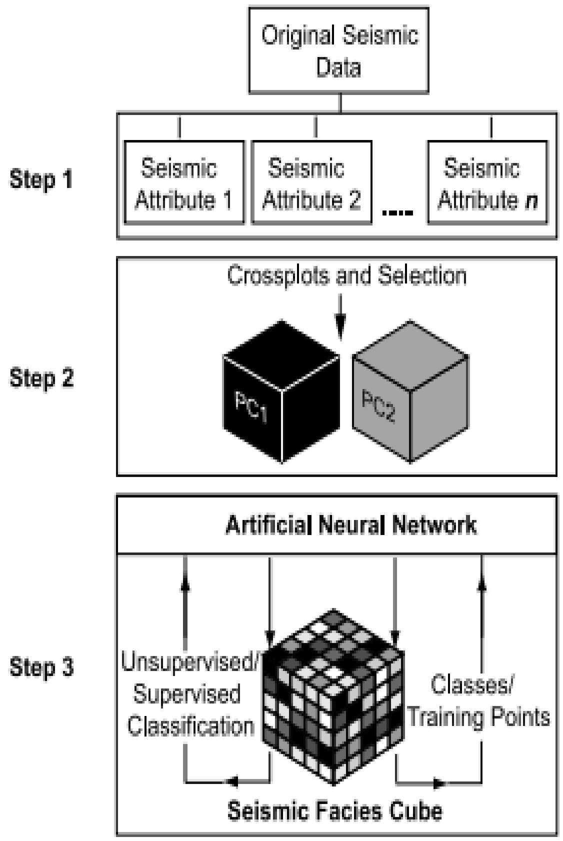


Figure 5.23- Schematic workflow of a seismic classification process using an artificial neural network [21]

This integrated approach of various techniques combined helped to map and characterize a buried paleokarst terrain[21,4]. The core analysis indicates that 50 m thick breccia deposits cover large parts of Loppa High and facies analysis show that these deposits formed during times of cave development and the subsequent cave collapse associated with karst networks [21][4].Approximately an area of 50km long and to 10-12 km wide with the thickness of 10-150m of breccia occupation was estimated together with the 3D SF classification.[21]. Application of this mapping and karst identification method is possible in other areas where 3D seismic as well as core data is available [21].

5. Drilling issues in karst

The most common problems while drilling in karst carbonate formations are loss circulation due to mud loss into the karst formation and drop of drill bit while penetrating karst zone. When planning drilling in areas where sign of karstified rock are present it is vital that one should deepen the risk involved in the process at early stage [1]. Loss of drilling fluid into formation is a risk one takes into account when drilling all types of wells and lost circulation material (LCM) should be available all the time as well as an updated plan on when and how to pump this material into the well to mitigate the consequences [1]. In case of large immediate loss of circulation, one should take into consideration to posses extra volume drilling fluid on rig [1].

When drilling into karstified formations, this risk must be upgraded, where an even larger range of LCMs of different types and particle sizes are planned for both drilling fluid and cementation processes. This in combination with storage of even larger volumes of drilling fluid on the rig or on a nearby boat [1]. Managing large quantities of LCM and drilling fluid place greater demands on logistics handling and capacity on board rig and vessels, and in operations for example in the Barents Sea, this is an even greater challenge since available material is not necessarily present on a platform and must be transported from the south [1]

In conventional drilling mud density gradient is kept higher than pore pressure gradient but lower than fracture gradient. During drilling processes some of drilling fluid can absorbed into formation until filter cake is formed around the wellbore which seals the pores and mitigates further losses.[1] It is also important to take into account that while drilling so called ECD(equivalent circulating density) is higher than static mud density due to centrifugal forces. Thus, one should adjust mud density in order avoid fluid loss [1].

When drilling into karstified rocks with underground cavities, collapsed or partially collapsed, the open cracks can be so large that it is impossible for drilling fluids to form filter cake on the wellbore[1].These cavities can be so large that it can swallow huge amount of drilling fluids. The first thing that one should do is add LCM with large particles and high concentrations to try to clog the cracks [1].

If one has not stopped or reduced the loss of drilling fluid with LCM, the next step is to pump cement down the string, then adding a special type of LCM which is added fiber or other particles designed to clog large cracks. The drill sting then usually shot off and the well drilled from a sidetrack above the karstified zone [1].

5.1 Managed pressure drilling (MPD) in karst.

Use of MPD method is required where there is little margin window between pore pressure and fracture gradient. In the market service companies offer different types of solutions but the philosophy in this is similar [1]. Controlled mud level (CML) is an example of MPD technology that adjusts the height of drilling fluid in the riser [1]. One can then drill with higher mud weight but still adjust the bottom hole pressure by adjusting the level in the riser. This means that it is possible to drill a section with one mud density just by adjusting the riser level even though it is required different type of mud density [1].

In this method it is possible to adjust the bottom hole pressure as low as possible to make it slightly higher than pore pressure while entering the formation where risk of cracking or loss are present.

There are two other concepts that come under MPD: CBHP (constant bottomhole pressure) and PMCD (pressurized mud cap drilling) [1]. Application of these techniques has made it possible to drill demanding prospects which have been considered non-drillable by conventional drilling techniques [1]. But with drilling into karstified formations with large cracks and cavities, there will probably still be a great risk of large losses, it is seen from events where drilling fluid and seawater simply disappear into the formation even though the total hydrostatic pressure is lower than the pore pressure [1].

It is important to assemble data collection program that allows future wells in the area to be drilled as safe as possible [1]. Core analysis can give information on rocks properties that lie underground. It helps to understand better and interpret the seismic signals and imaging. Obtaining cores early in the exploration can potentially provide savings and more secure drilling at later stage [1].

Collection of petrophysical logs such as well-known microresistivity measurements where cracks and cavities have distinct resistivity from formation resistivity. The advantage of such logs are having very good resolution [1]. Details such as cracks, small cavities can be depicted.

Companies have different names on these lists, and it is important to have a good dialogue between the operator and the company that will perform the petrophysical data collection in order to identify the best and most relevant tools [1].

When drilling production wells and production planning from fractured reservoirs, it is important to have the best possible knowledge of the direction and extent of the fractures [1]. Then it may be appropriate to collect and process seismic data with a specific configuration that enables such mapping [1].

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