GEO PROVIDER

Challenges and Opportunities for Shallow Hazard Risk Reduction

Study for the Norwegian Ocean Industry Authority | 21st of November, 2024

Version 1

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Contents

ABSTRACT

Despite considerable prevention efforts, shallow hazards related well control incidents remain a challenge for the oil and gas industry on the Norwegian Continental Shelf (NCS). Shallow hazard challenges persist in exploration and production wells, geotechnical boreholes, plugging and abandonment (P&A) operations. Further improvements in industry practices are sought.

This report intends to provide deeper insight into how data can be gathered and analyzed to help avoid shallow hazards during top-hole/pilot hole drilling on the NCS. The main focus is the avoidance of shallow gas (SG) and shallow water flow (SWF), which are the primary causes of well control incidents during riserless drilling. It was also noted that wells drilled through shallow gas have an increased likelihood of leaking following completion or P&A. Other shallow hazards, like faults and wellbore hole stability, are often an aggravating factor in well control incidents and are discussed in that context.

Avoidance of shallow seismic anomalies through pre-drill reflection seismic investigations is considered the primary means to reduce shallow hazard risk, including:

- Maximizing the resolution of sub-bottom profiler (SBP), 2D and 3D seismic datasets using appropriate seismic processing techniques like broadband designature and deghosting.
- Integration of 2D high and ultra-high resolution (UHR) site survey data with 3D data.
- High resolution velocity from seismic data as input to depth conversion.
- Integration of well data with site survey data using high-resolution tie-lines.
- Mapping and analysis of direct hydrocarbon and shallow fluid flow indicators.

The following best available techniques (BAT) are increasingly being applied and recommended:

- Acquisition of borehole data starting from or near the seafloor to allow seismic calibration.
- High resolution seismic inversion to identify shallow aquifers and constrain soil parameters.
- Drilling and log-based pore pressure analysis using high resolution seismic velocities to reduce the risk of shallow water flow.
- 3D UHR acquisition for enhanced seismic imaging of the shallow section.

Common shallow hazard detection pitfalls include:

- Limited investigation and geohazard analysis of site data due to insufficient lead time.
- Low resolution UHR data due to poor weather acquisition and/or limited seismic processing.
- Lack of integration between site survey, subsurface and well planning teams.
- Lack of experience and/or shallow hazard expertise.

When drilling riserless, ROV bubble monitoring and MWD sonic are effective at providing an early warning of possible shallow gas influx. In addition, kill mud, gas detectors and gas diverters can provide further mitigation. However, these measures do not replace well-controlled barriers and should be considered mitigation measures of last resort. Underwater video surveillance is also recommended for geotechnical drilling.

Riserless pilot holes are commonly drilled with seawater to ascertain the absences of shallow gas. While the reduction in hole size reduces the flow potential of the well, the risk and likelihood of well-control events are greater due to the chance of swabbing in smaller diameter holes. A high number of well-control events are seen in pilot holes and greater awareness is needed.

When avoidance can't be achieved, a single fluid barrier via a Riserless Mud Recovery (RMR) system or dual barrier casing with blowout preventer (BOP) and riser is required. Sufficient detection and analysis capability needs to be present to detect and handle well control during top hole drilling. Aggravating geological factors like wellbore stability are to be carefully considered in combination with elevated risks of shallow gas or SWF.

KEY WORDS

Shallow hazard, shallow gas, shallow water flow

ABBREVIATIONS

AUV	Autonomous Underwater Vehicles
BAT	Best available techniques
BHA	Bottom Hole Assembly
CPT	Cone Penetration Test
CSEM	Control Source Electromagnetic
GT	Geotechnical
HAVTIL	Havindustritilsynet
HR	High Resolution
IF	Instantaneous Frequency
NCS	Norwegian Continental Shelf
NOD	Norwegian Offshore Directorate (Sokkeldirektoratet or SODIR)
MBES	Multibeam echousounder
MWD	Measurement While Drilling
LWD	Logging While Drilling
ROV	Remotely Operated Vehicles
RMR	Riserless Mud Recovery
RMS	Root Mean Square
RTK	Real-Time Kinematic positioning
SBP	Sub-bottom Profiler
SD	Spectral Decomposition
SG	Shallow Gas
SSS	Sidescan sonar
SWF	Shallow Water Flow
UHR	Ultra-high resolution
UXO	Unexploded Ordnance

1. BACKGROUND

1.1. General

The Norwegian Ocean Industry Authority (HAVTIL) aims to contribute to a reduction in well control incidents on the Norwegian shelf. Well control incidents are a breach of barrier(s) in the well and have major accident potential. The number of incidents varies from year to year and has not shown a significant reduction over many years. Many of the incidents are related to the drilling of the upper sections of a well, before a BOP is installed on the wellhead.

This study was initiated to identify guidelines, best practices and methodologies that can contribute to a reduction of risks and uncertainties to be able to avoid some of these incidents. Part of this ambition is to develop recommendations around best practices for communicating shallow hazard risks and uncertainty through the data qualification, well planning and execution phases.

1.2. Scope of Work

The scope of this work focuses on practical clarifications and recommendations for the Activity Regulations §86 on well control, with a specific emphasis on mitigating risks from shallow hazards.

The key objectives are:

- Shallow Hazard Identification and Characterization: Evaluate techniques to accurately identify and map the distribution of shallow gas, shallow water flows, and seafloor instability hazards, integrating various data sources to develop comprehensive geological models.
- Shallow Hazard Risk Assessment and Mitigation: Develop quantitative risk assessment methodologies to evaluate the probability and consequences of encountering shallow hazards and identify effective technical and operational mitigation strategies to incorporate into well design, drilling programs, and emergency response plans.
- Regulatory Alignment and Compliance: Review the current regulations, propose clarifications and updates to ensure clear guidance on shallow hazard identification, assessment, and mitigation requirements, and recommend standardized reporting practices to demonstrate compliance if relevant.

The outcome will be a set of practical recommendations and best practices to enhance the industry's ability to identify, assess and mitigate shallow hazard risks during offshore drilling and well operations on the Norwegian Continental Shelf (NCS), in alignment with regulatory requirements.

1.3. Methodology

The work on shallow gas geohazards is based on the analysis of existing research and data, interviews with industry insiders and experience captured in reports and projects. Effective mitigation strategies are reviewed based on industry best practices and regulatory guidelines, including appropriate drilling and well control techniques, as well as monitoring and detection methods. The regulatory review examines relevant regulations and industry standards, ensuring the proposed strategies align with requirements and identifying any gaps. Finally, the study aims to incorporate relevant experiences and lessons learned from previous encounters with shallow gas geohazards, analysing successes, challenges and best practices.

1.4. Limitations & Further Work

The body of literature and information available for this study only provides a limited part of the total experience with shallow geohazards within the industry and on the NCS. To get a deeper understanding of the root causes of shallow hazards leading to well control events, an in-depth systematic study would be required focusing on shallow well control event including detailed re-evaluation of the geological and geophysical conditions that led to the events asking the questions “Why wasn’t this detected pre-drill?” and “What could have been done to detect the hazard pre-drill”.

In-depth analysis of shallow gas events and pilot holes of the last 5 years or more should provide a deeper updated understanding of the challenges, quantification of the risk and possible improvements. This work can both done in collaboration with industry using a similar model of the "Sharing to be better" meetings organised by the Well incident task force of the Offshore Norge Drilling Manager Forum with an integrated geoscience and well engineering focus. With the expected increase of geotechnical drilling related to offshore wind and P&A activities a wider audience would benefit to achieve a mutual understanding of the challenges and include both the operators and service companies doing the drilling.

2. SHALLOW HAZARDS

2.1. General

Shallow Hazards are natural or human-induced geological conditions encountered at shallow depths that pose significant risks to the people involved in the drilling operations, well integrity, and the environment. Shallow hazards can be encountered during geotechnical drilling, exploration drilling, development drilling, and plug and abandonment (P&A) operations.

<u>Shallow hazards must be identified and ranked with all associated risks determined, at the earliest opportunity in the planning process. Insufficient consideration of shallow hazards can result in severe consequences ranging from avoidable non-productive time to catastrophic events.</u>

The main relevant shallow hazards on the NCS include:

1. **Shallow Gas**: The presence of gas at shallow depths can lead to uncontrolled gas influxes, blowouts, and loss of well control, especially during exploration drilling or P&A operations when the blowout preventer (BOP) or barriers are in place. Shallow gas can originate from biogenic activity in the shallow sediments , migration from deeper sourced thermogenic gas, or communication with an adjacent producing well. Shallow gas can also occur in association with de-pressurisation of shallow aquifers and shallow water flow.
2. **Shallow Water Flows (SWF)**: Overpressured, unconsolidated water-bearing sands encountered at shallow depths can flow uncontrollably into the wellbore, eroding the foundation and potentially causing loss of well control. SWF can be caused by artesian flow or injection in nearby producing or abandoned fields.
3. **Seafloor Instability**: Unstable seafloor conditions, such as fault scarps, fluid expulsion sites, and slumps, can compromise the stability and integrity of drilling platforms, subsea installations or wellheads and BOPs. In extreme cases submarine slides can destroy underwater infrastructure and/or trigger tsunamis.
4. **Shallow Faults**: Faults encountered at shallow depths can cause drilling issues such as losses, stuck pipe, and pressure communication between zones.
5. **Boulders:** Boulders or large rocks are commonly encountered in formerly glaciated areas and leading to problems with drilling and casing of wells, so called "early refusal".
6. **Gas Hydrates**: The presence of gas hydrates at shallow depths can cause drilling difficulties. Hazard arises from two possible events: the release of over-pressured gas (or fluids) trapped below the zone of hydrate stability, or destabilisation of in-situ hydrates.

It is important to note that there is no clear definition of "shallow" in the industry and in extreme cases wellbores have been drilled barrierless deeper than 1500 m below the seabed.

In this study the following definitions are used:

- **Shallow Hazard** = Shallow hazards are adverse subsurface conditions that may be encountered prior to the setting of the first pressure containment string ("tophole or riserless section") and the emplacement of the BOP upon the well, generally down to 1,000 meters or 200 meters below potential surface casing depth, whichever is greater (IADC, 2024; BOEM, 2022, ISO 19901-10:2023).

- **Near Seafloor Shallow Hazard** = shallow hazards in the upper layer shallower than 25 m below the seafloor which is the depth limit for registration of a borehole as outlined in Ressursforskriften Kap 3 § 13 (https://lovdata.no/dokument/SF/forskrift/2017-12-13-2004/KAPITTEL_3#KAPITTEL_3)

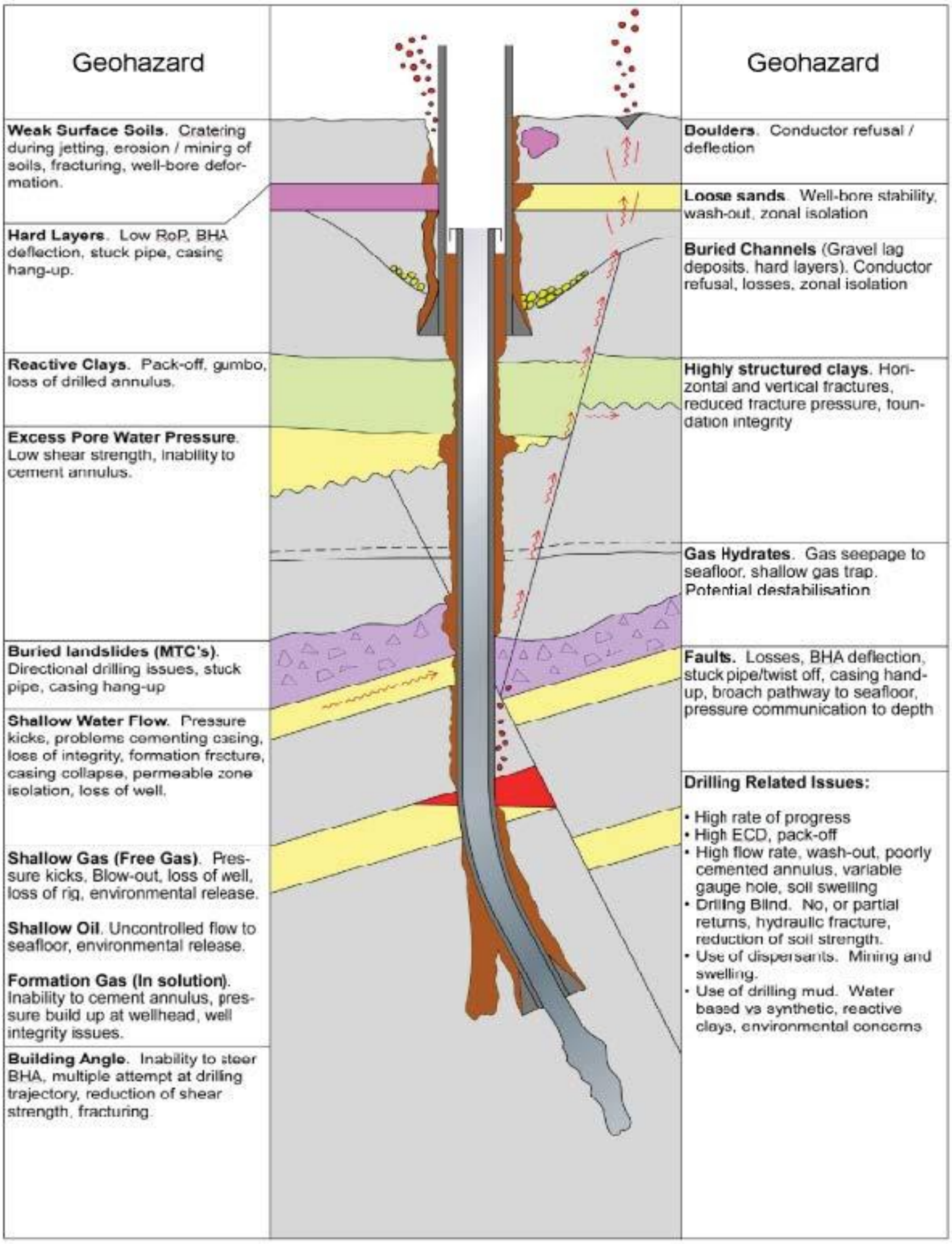

Figure 1: Overview Potential geohazards when drilling the top-hole section (SUT OSIG, 2017)

Shallow hazards include, but are not limited to (Fig 1):

Challenging Seafloor

- Slope angle (e.g. related to iceberg ploughmarks)
- Fault escarpments
- Diapiric structures
- Mud volcanoes
- Gas vents & pockmarks
- Unstable slopes
- Mud-flow gullies and slides
- Slumps
- Collapse features
- Sand waves
- Fluid expulsion features
- Rock outcrops
- Pinnacles
- Reefs
- Scouring and seabed mobility

Man-made Hazards

- Pipelines
- Umbilicals
- Power lines
- Communication cables
- Debris like anchors, nets or containers
- Unexploded Ordinance (UXO)
- Wrecks and archeological features

Shallow geohazards

- Shallow gas / shallow oil
- Shallow water flow / over pressured zones
- Boulders
- Soft / weak seabed conditions
- Weak formation / unstable subsurface / Reactive clays
- Faulting and glide planes
- Gas hydrates
- Hard grounds
- Seismicity

Geohazard	Potential impact(s) on drilling operations
Shallow gas (free gas) & Gassy soils (gas in solution)	Gas kick / Pressure build-up at wellhead / Well Control Incident / Blowout / Loss of well / Loss of rig buoyancy / Uncontrolled environmental emission / Inability to cement annulus / Well integrity issues / Formation fracture and flows to surface outside conductor / Shallow Casing Plan / Choice of location / Hydrate formation on wellhead (water depths > 600 m)
Shallow water flow	Pressure kicks / Loss of well / Uncontrolled flows to seafloor / Problems cementing surface casing / Loss of integrity of surface casing / Formation fracture and flows to surface outside conductor / Loss of foundation support-subsidence / Permeable zone isolation / Hole expansion / wash out
Shallow oil/ hydrocarbons	Uncontrolled flow of fluids to seafloor / Instability to cement annulus / Uncontrolled environmental release
Gas hydrates	Disassociated gas seepage to seafloor and consequent geotechnical uncertainty / Possible link to chemosynthetic communities / Shallow gas / Loss of Well
Buried landslide (mass transport complex)	Directional drilling issues / Stuck pipe/BHA / Casing hang-up /Jetted conductor problem
Faults	Losses / Stuck pipe / Casing hang-up / Uncontrolled flow of fluids to seafloor in underground blowout & seabed cratering / Directional drilling difficulties / Pressure communication with deeper strata / Drilling Fluid loss
Soft soils	Wellhead stability and verticality /Erosion of soils / Fracturing / Wellbore deformation / Excessive jack-up rig leg penetration / Insufficient rig anchor capacity / Cratering during jetting operations
Hardgrounds	Low Rates of Penetration (ROP) / Jetting resistance / Directional drilling issues /Stuck pipe /Casing hang-up / Challenging anchoring operations
Swelling clays (gumbo)	Pack-off / Loss of drilled annulus Plugging and fouling of tools and pipe
Boulders and gravels	Conductor drivability problems Conductor deflection/verticality issues Reduced rates of penetration / Stuck pipe Heavy drilling vibrations and bit damage
Unconsolidated Sands	Wellbore stability / Wash-out Inability to cement annulus Permeable zone isolation
Excess pore water pressure	Lower shear strength-reduced conductor axial and lateral capacity / Inability to cement annulus / Drilling-induced instability
Seafloor – e.g. steep gradients, channels, bedforms, plougmarks	BOP angle / Conductor instabilities Difficult anchoring conditions
Seepage features – e.g. pockmarks, fluid chimneys, craters	BOP angle / Conductor instabilities Soft soil / high gas content / hard soils

Table 1: Common geohazards and their potential impact on operations

2.2. Shallow Gas

2.2.1. Definition

Shallow gas refers to the presence of natural gas deposits located at shallow depths, typically within the first few hundred meters below the seafloor and can be up to 1500 m deep. Also shallow gas anomalies in the upper 100 m below the seafloor have been identified. In the context of the Norwegian Continental Shelf, shallow gas is a well-documented phenomenon that poses significant challenges and risks during offshore drilling operations and occurs often in combination with other geohazards or/and challenging drilling conditions.

The geological conditions in the Norwegian Continental Shelf, characterized by complex sedimentary environments, active tectonic processes, recent glacial history and active petroleum system, all contribute to the formation and trapping of shallow gas accumulations. These gas deposits can occur in a variety of geological settings, including abandoned channels, fault zones, and areas with high sedimentation rates.

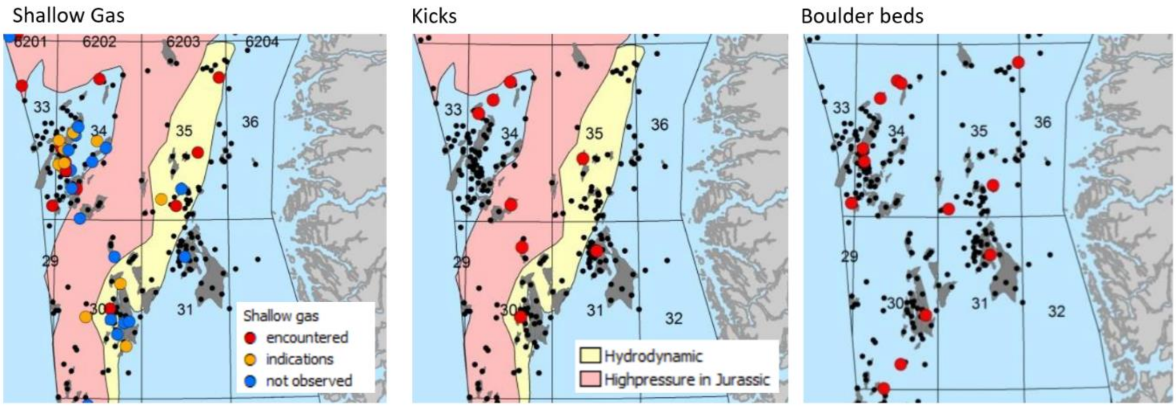

Figure 2: Overview of common identified Geohazards in the Norwegian Northern North Sea based on NOD factpages and published sources (after Riis & Wolf, 2019).

2.2.2. Drilling Hazards

The presence of shallow gas can lead to several geohazards that pose serious threats to drilling operations and personnel safety including:

- Blowouts: Shallow gas can create overpressured zones that can lead to uncontrolled influxes of gas into the wellbore, potentially resulting in blowouts and explosions.
- Gas Kicks: The sudden release of gas from the formation into the wellbore can cause rapid changes in downhole pressure, leading to gas entering the wellbore and loss of well control.
- Formation Instability: Shallow gas-bearing formations are often unconsolidated and can become unstable, leading to borehole collapse, stuck pipe, and other drilling complications.
- Shallow Water Flows: Permeable, gas-charged sediments can create zones of high-pressure formation fluids, resulting in uncontrolled influxes of water and sand into the wellbore.
- Seafloor Instability: Shallow gas accumulations can destabilize the seafloor, increasing the risk of seafloor failures, slumps, and other geohazards that can affect the drilling platform and associated infrastructure.
- Fire and Explosion: If the released gas above the sea surface finds an ignition source, it can result in fires or explosions, posing severe risks to the rig, personnel, and the environment. This is a particularly acute hazard on offshore rigs where gas can accumulate in confined spaces.
- Buoyancy Loss: A loss of buoyancy can occur for a floating vessel within a plume of expanding gas.

- Environmental Contamination: Uncontrolled releases of gas can lead to the contamination of surrounding water or the atmosphere. Methane, the primary component of natural gas, is a potent greenhouse gas and poses significant environmental concerns. If the source of the gas is thermogenic it can also be associated with liquid hydrocarbons and/or CO_2.

2.2.3. Detection Methods and Mitigation Strategies

Effective detection and characterization of shallow gas deposits are crucial for mitigating the associated drilling risks.

The primary methods used in the Norwegian Continental Shelf include:

1. Seismic Surveys: High-resolution 2D and 3D seismic data are used to identify the presence, depth, and distribution of shallow gas accumulations. Seismic attributes, such as amplitude, frequency, phase and velocity, can be analysed to detect gas-charged sediments.
2. Monitoring and detection systems during drilling operations can help identify the presence of shallow gas and trigger appropriate well control measures. Measurement while drilling (MWD) includes real-time measurement of drilling parameter, mud properties, pressure and gas detection systems
3. Geophysical Logging: Borehole data, including well logs and geophysical measurements, can provide valuable information about the subsurface lithology, pore pressure, and the presence of gas.
4. Seafloor Mapping: Techniques such as multibeam bathymetry, side-scan sonar, and sub-bottom profiling can help identify seafloor features indicative of shallow gas or fluid migration, such as pockmarks, gas chimneys, and mud volcanoes.

Controlled Source Electromagnetic (CSEM) is at present not used in the detection of shallow gas due to spatial uncertainty associated with the method. For areas with high uncertainty the method has the potential to help derisk or high grade the presence of shallow gas in combination with other methods.

To mitigate the risks associated with shallow gas, operators in the Norwegian Continental Shelf employ a range of strategies, including:

- Careful site selection and avoidance of high-risk areas
- Detailed well planning and well design to handle shallow gas encounters
- Implementation of robust well control procedures and blowout prevention systems
- Continuous monitoring and early detection of shallow gas during drilling
- Contingency planning and emergency response protocols

By combining advanced detection methods, rigorous risk assessment, and effective mitigation strategies, the oil and gas industry in the Norwegian Continental Shelf aims to safely navigate the challenges posed by shallow gas and ensure the successful and sustainable development of offshore resources.

In Table 2 is an example of summarized risk management strategies for shallow gas occurrences.

Mitigation Strategy	Description	Application	Benefits
Pre-Drilling Planning	Thorough assessment and planning based on survey data to anticipate and avoid shallow gas zones.	Using seismic and other survey results to design the well path and casing programs to minimize the risk of encountering shallow gas.	Reduces the likelihood of unexpected gas encounters, enhancing safety and operational efficiency.
Blowout Preventers (BOPs)	Mechanical devices installed on the wellhead to control well pressure and prevent blowouts.	BOPs can seal the wellbore in case of a gas influx, maintaining well control.	Provides a critical safety barrier, protecting personnel, equipment, and the environment.
Appropriate Mud Weight	Using drilling mud with sufficient density to counteract formation pressures.	Adjusting mud weight to balance formation pressure, preventing gas from entering the wellbore.	Maintains well control and minimizes the risk of gas kicks and blowouts.
Casing and Cementing	Installing steel casing and cement to isolate formations and stabilize the wellbore.	Proper casing and cementing prevent gas migration into the wellbore and to the surface.	Enhances well integrity and reduces the risk of gas-related incidents.
Gas Detection Systems	Installing sensors to monitor gas levels continuously.	Real-time detection of gas leaks or influxes allows for immediate response.	Early warning systems enhance safety by allowing prompt action to control gas.
Well Control Drills and Training	Regular training and emergency drills for drilling personnel.	Ensuring that the crew is prepared to respond effectively to gas-related emergencies.	Improves readiness and response time, reducing the potential impact of incidents.
Emergency Response Plans	Developing and regularly updating comprehensive response plans for gas-related emergencies.	Detailed procedures for handling blowouts, fires, and other incidents involving shallow gas.	Ensures a coordinated and effective response, minimizing risks to personnel, equipment, and the environment.

Table 2: Example of mitigation strategies for shallow gas occurrences

Seismic technology for detecting shallow gas hazards

Improved 2D / 3D Seismic Data

Conventional 2D and 3D exploration seismic data is inadequate for identifying shallow gas due to limited vertical resolution. In shallow water, UHR/HR2D and HR3D seismic data is required to properly characterize the shallow subsurface and detect potential gas hazards.

Seismic Attribute Analysis

A combination of seismic and well data analysis are used to identify the location and distribution of shallow gas. Key seismic features are:

- High amplitudes
- Push-down effects (low seismic velocity, e.g. a gas chimney or salt diapir)
- Low frequency shadows
- Bright spots
- Flat spots indicating gas-water contacts
- Attenuation and gas chimneys

Quantitative Seismic Characterization

Seismic data can be used to semi-quantitatively assess and de-risk shallow gas. Techniques include:

- Amplitude versus offset (AVO) analysis
- Mapping flat spots to estimate gas column heights
- Velocity push-down to estimate total gas column
- Attenuation to estimate gas saturation

2.3. Shallow Water Flow

2.3.1. Definition

Shallow Water Flow (SWF) refers to the uncontrolled flow of water and sediments from overpressured zones in the shallow sections of a well. These flows cause large volumes of water and sand to flow along the wellbore and can lead to severe consequences such as erosion of the well's foundation, buckling of the casing, and compromise wellbore integrity.

SWF sands are often considered a secondary concern since they are not an immediate safety risk, however due to the depressurisation of the aquifer gas bubbling has often been reported in relation to SWF together with severe for the wellbore environment and should be mapped and assessed. Attention should be paid to the seafloor in the immediate vicinity (within a 1000 m radius) of wellsites for signs of instability and for sensitive biota.

SWF is considered one of the most critical shallow drilling hazards in deep-water basins. These sandy sediments are typically unconsolidated and lack proper drainage conditions, leading to the rapid expulsion of overpressured sands into the wellbore upon drilling. This can result in significant damage to drilling platforms, facilities, and rigs, causing substantial financial losses. The phenomenon of SWF was first identified in 1985 (Lu et al., 2005), and since then, various studies have focused on understanding its mechanisms, geological settings, and predictive methods.

Table 3. Sedimentary features associated with the SWF as described in literature (after Noorbakhsh Razmi, 2023).

Stratigraphic Feature	Authors
Canyon	Ostermeier et al., 2002; Zhang et al., 2018
Channel	Ostermerier et al.; Lu et al., 2005; Dutta et al., 2010; Wu et al., 2018; Zhang et al., 2018
Slump, Debris flow	McConnell, 2000, Lu et al., 2005; Zhang et al., 2018
Turbidite sands	Dutta et al., 2010, 2021
Other: submarine fans, sheet sands,..	Huffman and Castagna, 2001; Lu et al., 2005; Dutta et al., 2010, Shaker, 2016

Drilling Hazards Created by Shallow Water Flow

Well Control Issues

1. Uncontrolled Flow to Seafloor: problems killing the well, followed closing and sealing off the flow zone.
2. Bubbling out of solution gas: increasing severity of well control incident.

Structural Issues

1. Uncontrolled Flow to Seafloor: This can cause significant erosion around the wellhead, compromising structural stability and potentially causing subsidence and the formation of large fissures.
2. Erosion Around the Casing Shoe: This can lead to dilation of sands, flow into the hole, and sedimentation within the ocean floor.
3. Sand Washout: Leading to instability and potential damage to the drilling operation.
4. Buckling and Destruction of the Casing: Continuous flow can lead to the collapse of the surface casing and potential loss of the well.
5. Sinking Wellhead and Conductor: Continuous erosion and subsidence can lead to a sinking wellhead.

Compaction and Formation Damage

1. Significant Compaction: The release of formation fluid can lead to subsidence and the creation of large cracks within the wellhead and crater.

2. Formation Fracture and Surface Flow: Over pressured fluids can fracture the formation, leading to flow along unintended paths and causing structural damage to nearby wells.

Cementing and Well Integrity Issues

1. Cementing Problems: SWF can cause difficulties in cementing the surface casing string, resulting in poor zonal isolation and potential transmission of overpressure through cement channels.
2. Cement Failure and Cracking: This occurs due to low differences in fracture gradient and pore pressure, affecting the surrounding wellbore.
3. Loss of Well Integrity: SWF can cause a loss of control over the well, leading to its abandonment.

Financial Risks: Significant costs may be incurred due to well control issues and the need for remedial actions. The costs of preventing and repairing SWF incidents are substantial, often constituting a major part of deep-water exploration expenses.

Detection Methods

The detection of SWF involves several geoscience techniques including:

1. Seismic Surveys: Use of high-resolution (HR) 2D and 3D seismic data to identify potential overpressured sands and map the seafloor's geological features (Noorbakhsh Razmi et al., 2023 and Kulkarni et al., 2022).

- Prestack Inversion: This technique uses prestack seismic data to estimate rock properties such as P-wave velocity (Vp), S-wave velocity (Vs), and density. It accounts for interference from various wave modes, allowing for reliable estimates of Vp/Vs and Poisson's ratio, which are critical for identifying SWF zones. Prestack waveform inversion can handle large incidence angles, providing detailed information on the elastic properties of the sediments.
- Post-Stack Inversion: This method involves converting seismic reflection data into P-impedance (acoustic impedance) to identify low impedance zones indicative of SWF. The process uses seismic data and impedance models derived from well logs.
- Amplitude Variation with Offset (AVO): AVO analysis involves studying the changes in seismic reflection amplitudes with varying angles of incidence. It helps in identifying zones with high Vp/Vs and Poisson's ratios indicative of SWF. However, site survey data is often limited to smaller incidence angles and might not fully capture the characteristics of SWF zones, which require analysis at larger angles.
- Seismic Stratigraphy and Attributes: This method involves analysing 3D seismic data to interpret sedimentary systems and stratigraphic features. Specific seismic attributes such as sweetness, which highlights sandy channels and slumps, are used to identify SWF-prone areas.
- Pore Pressure Prediction: Predicting pore pressure is essential for identifying over pressured SWF zones. This involves analysing well logs (sonic, gamma ray, resistivity, density) and seismic data to estimate the pore pressure and effective stress using classic.
- Rock Property Trends: Rock properties of SWF sediments, such as low bulk densities and low P- and S-wave velocities, are key indicators. These properties lead to high Vp/Vs ratios and Poisson's ratios, typical of over pressured SWF sediments. Elastic property trends of regular sands and shales are used to infer the properties of SWF sands due to the difficulty of direct measurement under SWF conditions.
- Geological Model Building: Developing geological models that incorporate stratigraphic and structural controls helps in understanding the conditions leading to SWF. These models guide the application of seismic inversion and other detection techniques.

2. Geotechnical Data: Integration of geotechnical soil data and sub bottom profiler data to assess the presence of permeable units and overpressured zones.

3. Offset Well Data: Analysis of data from nearby wells to understand local geological conditions and predict potential SWF zones.

4. Real-Time Monitoring: Utilization of Remotely Operated Vehicles (ROVs) for real-time monitoring of the wellhead and surrounding seafloor during drilling operations.

Data Types for SWF Detection	
Pre-stack	2D / 3D seismic data
Post Stack	
Multicomponent	
Sonic	Log Types
Gamma Ray	
Resistivity	
Density	
Pressure measurement	
Geotechnical data (e.g. CPTu) & laboratory measurement	In situ Measurements

Table 4: Data required for SWF evaluation after Noorbakhsh Razmi et al., 2023

2.4. Other shallow geohazards

A number of shallow hazards exist which can severely impact drilling and are know from the NCS.

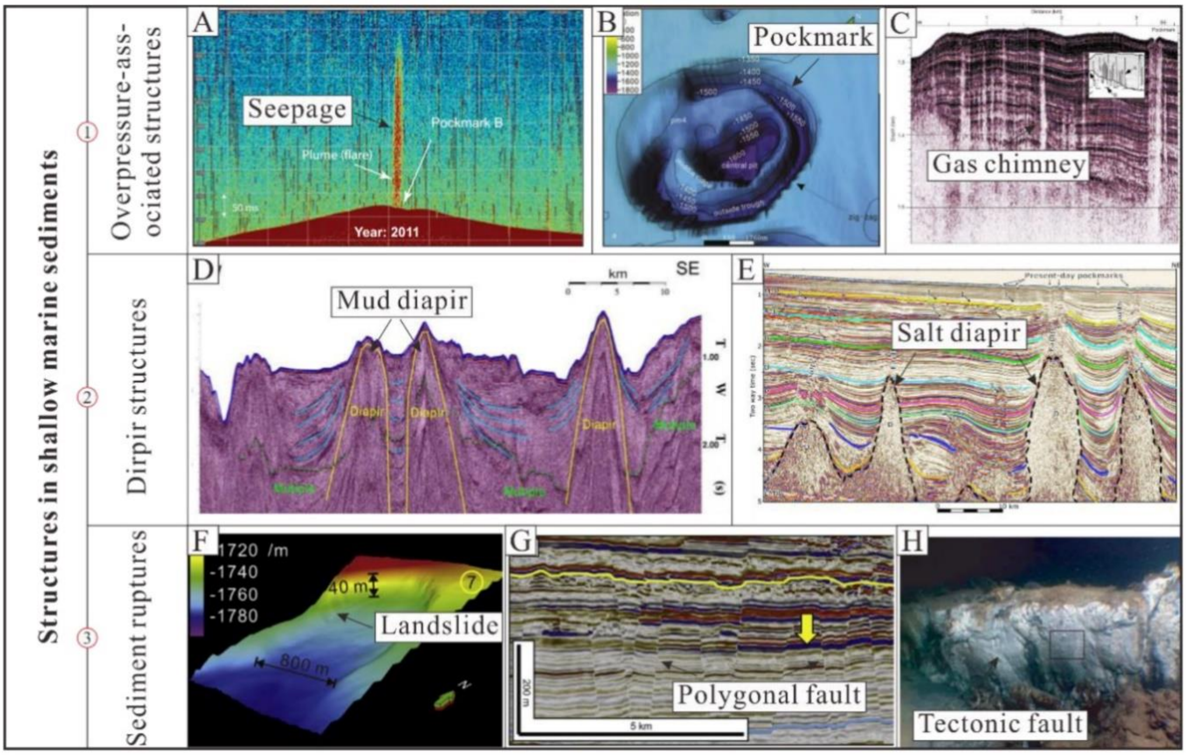

Figure 3: Examples of shallow geohazard structures in shallow marine sediments (Ma et al., 2021).

2.4.1. Pockmarks

Pockmarks are crater-like depressions found on the seafloor. They vary widely in size, from less than ten meters to over one kilometer in diameter and can reach several tens of meters. Pockmarks are commonly associated with gas and fluid leakage from sedimentary rocks or sediments below. They are significant in petroleum exploration as indicators of subsurface hydrocarbon systems and potential geohazards to offshore installations and pipelines. Pockmarks occur not only on continental shelves but also in fjords and nearshore areas and are commonly related to dewatering of sub glacially deposited water rich tills. Pockmarks are commonly associated with chemosynthetic and/or protected benthic communities including cold water corals and sea feathers.

On the Norwegian Continental Shelf, extensive patches of shallow gas-charged sediments have been documented in areas like the Skagerrak strait and the Barents Sea. The presence of these shallow gas accumulations poses both risks and opportunities for the offshore industry (Hovland, 1981 & 2002).

Detection methods

- High-resolution bathymetric surveys and parametric sub-bottom profiling are used to map and characterize pockmarks.
- Side-scan sonar has been employed to create detailed mosaics of pockmark distributions over large seafloor areas.
- Visual inspection and water column data are used to determine if the pockmarks are actively venting fluids or bubbling gas.
- 2D and 3D high resolution seismic provides insights into the subsurface geology and potential geological controls on pockmark formation.

Mitigation Strategies

- Geological Investigation: Detailed studies of pockmarks, including their dimensions, shapes, and relief, help in understanding the geological context and potential hazards associated with these features, allowing for more effective mitigation strategies. Active pockmarks systems are generally avoided.
- Monitoring and Mapping: Advanced technologies, such as observation remote operated vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs) and landers with various sensors (temperature, pressure, current, video camera and hydrophone), are used to map gas-related features and provide long-term monitoring of the site.
- Site Conservation Objectives: In case of presence of sensitive benthic communities mitigation strategies are put in place to ensure that marine discharge effects do not undermine site conservation objectives. This includes measures to prevent physical damage, smothering by drilling discharges, or the interruption or alteration of gas supply to the pockmarks.

2.4.2. Boulders

Boulders are large, isolated rock fragments that are typically greater than 256 mm (10 inches) in diameter. In offshore environments, boulders can be found embedded in marine sediments or resting on the seafloor. These boulders can vary in size from small rocks to massive formations and can consist of several types of rock, such as granite, basalt or limestone. They often originate from a variety of sources, such as glacial deposits, mass wasting events, or erosion of bedrock, and can also be remnants of underwater landslides or sediment transport processes (Kvalstad, 2007 and Bui et al., 2023).

Impact and Effect on Offshore Drilling

1. *Structural Damage*
   - Boulders can pose significant risk to offshore drilling equipment and infrastructure. During drilling operations, encountering boulders can lead to damage to drill bits, casings, and other drilling tools, increasing maintenance and replacement costs.
   - The presence of boulders can complicate the installation of subsea structures, such as platforms, pipelines, and cables, potentially leading to misalignment or structural instability. Encountering boulders during drilling can cause the borehole to become unstable or collapse, requiring remedial actions or redrill.

2. *Operational Delays*
    - The need to remove or navigate around boulders can cause delays in drilling operations, leading to increased operational costs.
    - Specialized equipment and techniques may be required to drill through or around boulders, further complicating the drilling process, so called "Boulder Busters".

3. *Foundation Stability*
    - Large boulders can affect the stability and load-bearing capacity of foundations for offshore structures.
    - Uneven seabed conditions caused by boulders can lead to uneven settling and potential tilting of structures.

Detection Methods

1. *Seismic Surveys*
    - Seismic reflection and refraction surveys are used to map subsurface structures and identify the presence of boulders on or beneath the seabed.
    - These surveys provide detailed images of the subsurface, helping to locate and assess the size and distribution of boulders.

2. *Multibeam Echosounder Surveys*
    - Multibeam echosounders create detailed bathymetric maps of the seafloor, revealing the presence of boulders and other irregularities.
    - These surveys can provide high-resolution data on the size, shape, and location of boulders.

3. *Side-scan Sonar*
    - Side-scan sonar provides high-resolution images of the seafloor, allowing for the identification of boulders and their distribution.
    - This method is effective for mapping large areas and detecting boulders that may pose hazards to drilling operations.

4. *Visual inspections & Sector Scan*
    - Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) are used for visual inspection and detailed mapping of boulders on the seabed.
    - These vehicles can capture high-resolution images and videos, providing valuable information for assessing the impact of boulders on drilling operations.

5. *Geotechnical Investigations*
    - Geotechnical methods, such as cone penetration tests (CPTs), coring and boreholes, are used to assess the mechanical properties of sediments, identify the presence or confirm the absence of boulders.
    - These investigations provide key geotechnical data for designing foundations and top hole drilling.

2.4.3. Seabed and subsurface stability

Soft seabed conditions refer to seafloor environments characterized by very soft, unconsolidated sediments that are prone to instability and can pose significant challenges for offshore operations. These conditions are typically found in areas with high sedimentation rates, such as river deltas, submarine fans, and continental slopes. In Norway also fjords and the Norwegian Channel contain soft to very soft sediments.

Soft seabed are often composed of fine-grained materials like clay, silt, and organic matter, which have low shear strength and high-water content. These sediments can easily be disturbed by drilling activities, leading to potential hazards like seafloor instability, equipment sinking, and drilling problems.

Impact and Effect on Offshore Drilling

- Increased risk of seafloor instability: Soft sediments are prone to slope failures, which can cause damage to drilling equipment and pipelines.
- Difficulty in securing drilling platforms: Soft seabed may not provide adequate support for drilling platforms, leading to stability issues and potential accidents.
- Increased risk of equipment sinking: Subsea equipment and pipelines can sink into soft sediments, causing operational delays and potential environmental damage.
- Difficulty in predicting drilling conditions: Soft seabed can be highly variable and unpredictable, making it challenging to plan and execute drilling operations effectively.

Detection Methods

- Seismic surveys: Sub-bottom profiler and high-resolution seismic data can help identify soft sediments and potential associated hazards like gas pockets and shallow faults.
- Sediment coring and CPTs: Physical sampling or testing of seafloor sediments can provide detailed information about their composition, strength, and water content.
- Remotely Operated Vehicles (ROVs): ROVs equipped with cameras and sensors can be used to visually inspect the seafloor and collect data on sediment characteristics and potential hazards.
- Geotechnical testing: Laboratory tests on sediment samples, such as shear strength measurements and consolidation tests, can help determine the engineering properties of soft seabed and inform drilling design.

2.4.4. Scouring and seabed mobility

Scouring is the process of sediment transport and erosion around offshore structures, such as wellheads, spud cans or foundations, due to the action of waves and currents. It can lead to the erosion of sediment, creating depressions or scour holes around the structure.

Impact and Effect on Offshore Drilling

- Reducing the stability and load-bearing capacity of foundations, potentially leading to structural failure.
- Scour can expose buried pipelines or cables, making them vulnerable to damage.
- Changes in seabed morphology due to scour can affect the thermal design and management of power cables.

Methods of Detection

- Bathymetric surveys using multibeam echo sounders to map the seabed topography and identify scour holes.
- Side-scan sonar surveys to detect changes in seabed sediment characteristics and the presence of bedforms.
- Remotely operated vehicles (ROV), camara, AUVs or divers to visually inspect the seabed around the structure.
- Geotechnical investigations of grab samples or cores including particle size analysis.

2.4.5. Irregular sub surface and seabed conditions

Irregular sub-surface and seabed conditions refer to the non-uniform and unpredictable features found beneath the seabed that can significantly affect offshore drilling operations. These conditions include variations in soil types, the presence of boulders, sand waves, pockmarks, fault lines, and other geological irregularities not previously mentioned like injectites, salt or mud diapirism.

Impact and Effect on Offshore Drilling

- Drilling Challenges: Irregular sub-surface conditions can make it difficult to predict the behaviour of drilling equipment and the stability of the borehole. This can lead to equipment failure, loss of drilling fluid, or even blowouts.
- Foundation Stability: Offshore structures like oil rigs and wind turbines require stable foundations. Irregular seabed conditions can compromise the stability and safety of these structures, leading to costly design modifications or even structural failure.
- Increased Costs: Unanticipated irregularities can lead to delays, additional surveys, and increased operational costs. Remediation measures to stabilize the seabed or adapt the drilling plan can be expensive.
- Environmental Risks: Disturbing certain subsurface features can release trapped gases or contaminants, leading to environmental pollution and safety hazards.
- Equipment Wear and Tear: Drilling through heterogeneous materials can accelerate wear and tear on drilling equipment, leading to increased maintenance costs and downtime.

Detection Methods

- Seismic Reflection Surveys: These surveys use sound waves to create detailed images of sub-surface structures. They are essential for identifying irregularities such as fault lines, gas pockets, and sediment layers.
- Side-Scan Sonar: This technique provides detailed images of the seabed by emitting sound waves and measuring their return. It is useful for detecting surface irregularities and objects on the seabed.
- Sub-Bottom Profiling: Like seismic reflection, sub-bottom profiling uses lower frequency sound waves to penetrate the seabed and reveal sub-surface structures. It is effective for identifying sediment layers and buried objects.
- Magnetometer Surveys: These surveys detect variations in the Earth's magnetic field caused by different types of subsurface materials. They are useful for identifying ferrous objects and certain geological formations.
- Geotechnical Sampling: Core samples and other geotechnical tests provide direct information about the composition and properties of seabed materials. These samples help to validate data from remote sensing techniques.
- Multibeam Echo Sounding: This technique uses multiple sound beams to map the seabed in high detail, providing 3D images of seabed topography and identifying potential hazards.

2.4.6. Unstable soils and low fracture pressures

Unstable soils and low fracture pressures includes heterogeneous, unstable, or weak soil and rock formations, such as soft sediments, fractured bedrock, buried channels, and zones of high pore pressure or low fracture gradients. Unstable or weak soils and low fracture pressures refer to geotechnical conditions where soil lacks the strength to support structures, and the subsurface pressure needed to fracture rock is low (Alberty & McLean (2004) and Morita et al., 1990).

Impact and Effect on Offshore Drilling

- Structural Stability: Weak soils can cause borehole collapse or foundation failure.
- Well Integrity: Low fracture pressures can lead to blowouts and well control issues.
- Operational Challenges: Difficulties in achieving secure casing and cementing operations, risking gas leaks or well collapse.
- Platform and Pipeline Stability: Irregular seabed topography affects the stability and installation of offshore infrastructure.

Detection Methods

- Geophysical Surveys: Use multibeam echosounders, side-scan sonar, and sub-bottom profilers.
- Seismic Surveys: Map subsurface structures and identify weak soil layers.
- Geotechnical Investigations: Conduct cone penetration tests (CPT) and boreholes.
- Borehole Logging: Determine rock properties and fracture pressures.
- Visual Inspections: Employ remotely operated vehicles (ROVs) and divers.
- Pore Pressure Monitoring: Identify high-pressure zones during drilling.

2.4.7. Faulting and glide planes at shallow depths

Shallow faults are fractures or zones of fractures between two blocks of rock that are located near the surface of the Earth's crust. They allow the blocks to move relative to each other, often resulting in earthquakes and other geological events. Shallow faults can have significant impacts on drilling operations, potentially causing lost circulation, underground blowouts, seabed cratering, stuck pipe, twist-offs, casing hang-ups, and casing collapse. The presence and geometry of shallow faults can be assessed through an integrated use of profiler data, multi-channel HR seismic data, side scan sonar data, and in some cases, exploration 3D seismic data (Almansoori, 2019 and SUT Guidance)

Impact and Effect on Offshore Drilling

Shallow faults can have the following impacts on operations for several types of rigs (Dynamical and Anchored):

- Lost circulation
- Flow to surface in event of underground blowout, leading to seabed cratering, and resultant loss of rig
- BHA deflection
- Stuck pipe and/or twist-offs
- Casing hang-ups
- Requirement for additional casing strings
- Casing collapse

Detection methods

The presence and geometry of shallow faulting can be assessed through an integrated use of the following data:

- Profiler data
- Multi-Channel HR seismic data
- Side-scan sonar data

In shelf waters, but more normally in deep waters exceeding 750 m, integrated or standalone use of exploration 3D seismic data can also be used, depending on the quality of the data.

2.4.8. Mud diapirism & Mud volcanoes

Mud or shale diapirims from mud volcanoes are geological structures formed by the of mud, water, and gases from the subsurface. They are not true igneous volcanoes, as they do not produce lava. Mud volcanoes are typically caused by the upward movement of pressurized, water-saturated sediments and gases through faults or fractures in the Earth's crust. These eruptions can form large, cone-shaped structures on the seabed or on land and are often driven by overpressure in subsurface layers related to tectonic activity, hydrocarbon deposits, or geothermal systems. From the NCS these know from the mid Norwegian margin

Impact and Effects on Offshore Drilling

1. **Structural Damage**

- Mud volcano eruptions can cause severe damage to offshore infrastructure, including drilling platforms, pipelines, and subsea installations, due to the force of the expelled material and the resulting instability.
- The shifting and upheaval of the seabed can lead to the collapse or tilting of structures, posing serious operational hazards.
- The eruption of mud, water, and gases can trigger seafloor instability, leading to the failure of well casings and blowouts.
- Large mud volcanoes can generate destructive tsunamis that threaten coastal communities and offshore facilities.

2. **Well Control Issues**

- The pressure changes associated with mud volcanic activity can lead to well control problems, such as blowouts or uncontrolled hydrocarbon releases.
- High-pressure zones created by mud volcanoes can complicate drilling operations and increase the risk of wellbore instability.

3. **Environmental Impact**

- Mud volcanoes can release significant quantities of methane and other hydrocarbons, contributing to greenhouse gas emissions and potentially contaminating marine ecosystems.
- The mudflows can bury seabed habitats, affecting benthic organisms and altering local ecosystems.

4. **Operational Disruptions**

- The presence of mud volcanoes can disrupt drilling operations and cause delays due to the need for damage assessment and repairs.

Detection Methods

1. **Seismic Surveys**

- Seismic reflection and refraction techniques are used to map subsurface structures and identify areas of overpressure and potential mud volcanic activity.
- These surveys can detect gas chimneys and other anomalies indicative of mud volcanoes.

2. **Multibeam Echosounder Surveys**
- These surveys provide detailed bathymetric maps of the seafloor, revealing the characteristic mounds or craters formed by mud volcanoes.
- They can also detect pockmarks and other seabed features associated with gas seeps and mud eruptions.

3. **Remote Sensing**
- Satellite imagery and aerial photography can be used to monitor large areas for signs of mud volcanic activity, such as surface domes or discoloration of water due to sediment plumes.
- These methods are particularly useful for identifying and monitoring mud volcanoes in remote or inaccessible regions.

4. **Geochemical Analysis**
- Sampling and analysis of seabed sediments and water can detect hydrocarbons and other chemicals associated with mud volcanic activity.
- Geochemical markers help in identifying active or recent mud volcanic events.

5. **Seafloor Monitoring**
- Pressure sensors or tilt meters are used to detect precursory movements or deformation, indicating potential mud volcanic activity.

6. **ROVs and AUVs**
- Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) are deployed for close-up inspection and sampling of mud volcanoes.
- These vehicles provide high-resolution images and data from the seafloor, enabling detailed analysis of mud volcanic structures and activity.

2.4.9. Gas hydrates

Gas hydrates or methane hydrates are ice-like crystalline structure, that contain natural gas usually methane surrounded by water molecules. Gas hydrate deposits are found wherever methane occurs in the presence of water under elevated pressures and at relatively low temperatures, such as beneath permafrost or in shallow sediments along deepwater continental margins. relatively high. On the NCS gas hydrates have often been detected in deep water.

Impact and Effects on Offshore Drilling
- Formation of hydrate can lead to lost circulation and underground blowouts.
- In deep water, gas hydrates can cause difficulty with emergency disconnect, temporary and final well abandonment.
- Destabilization of hydrated soils in deep water could lead to wellhead sinking, loss of wells, and seabed slope failure.

Detection Methods

- Water temperature probe data
- Gross water depths
- Heat flow data
- Gas hydrate stability modeling
- Side scan sonar data
- Sub-bottom profile data
- Multi-channel HR seismic data
- Offset well data and reports

In deep water exceeding 750 meters, integrated or standalone use of exploration 3D seismic data can also be used to assess indirect evidence for the presence of a hydrated shallow section, depending on the quality of the data.

2.4.10. Slope Failure

Slope failure, also known as submarine landslides, mudslides or mudflows, are rapid downslope movements of water-saturated sediments in offshore environments, triggered by earthquakes, storms, or human activities. They can vary from small, localized events to massive regional failures like the Storegga Slide offshore the Norwegian Møre coast. On the NCS slope failure events are not a common phenomenon but the geological record shows these can occur.

Impact and effects on Offshore Drilling

- Structural Damage: Can damage or destroy platforms, pipelines, and other infrastructure.
- Well Integrity: Can cause seafloor instability, leading to well casing failures and blowouts.
- Tsunami Risk: Large mudslides can generate tsunamis, threatening coastal and offshore facilities.
- Operational Disruption: Can cause delays due to damage assessment and repairs.

Detection Methods

- Bathymetric Surveys: Map seafloor topography using multibeam echo sounders.
- Seismic Reflection Surveys: Image subsurface stratigraphy to identify weak layers.
- Seafloor Monitoring: Use pressure sensors or tilt meters to detect movements.
- Visual Inspections: Employ ROVs or AUVs for seafloor inspection and sampling.

2.4.11. Seismicity

Seismicity can be an additional factor to consider when assessing shallow hazards in offshore drilling. Here are the main points regarding seismicity:

- Small-magnitude ($M_L \leq 3.5$), shallow (depth<4 km) seismic events can be induced by gas exploitation and cause light damage. These induced earthquakes can raise concern for people working offshore on platforms.
- Seismic hazard analysis can be required for large projects. Probabilistic Seismic Hazard Analysis (PSHA) can provide quantitative hazard estimates, predicting the Peak Ground Accelerations (PGA). Relevant hazard estimates in terms of Peak Ground Velocity (PGV) or maximum 50% damped response spectra at 10 Hz can be obtained using PSHA.
- Liquefaction can be triggered in loose sands and silts by multiple cyclic loading processes. When structures are dependent on the bearing capacity of loose sediments, liquefaction analysis is considered mandatory.

Seismic events related to fault movement can lead to release of fluids including case in some cases. No such events have ever been reported from the NCS and the geology is not considered conducive to such events.

3. GOVERNING STANDARDS, REGULATIONS AND GUIDELINES

3.1 General

Regulations regarding preparedness and contingency planning in case of a blowout vary across the globe. The main standards referenced globally are from Norway, USA, Canada, Australia, New Zealand and the UK. Even if there are variations between the legislations, the industry (both regulators and operators) will benefit from a harmonized and consistent approach towards the planning of operations internationally. This chapter references some of the governing regulations for the mentioned locations. Even if the scope of work for this study relates to Norwegian water, it will be worth-while throwing a glance of what other regulators are requiring.

In addition to governmental regulations, some industry standards and some operator's internal guidelines are referenced.

3.2 Regulations

3.2.1 Norway

The Activity Regulations relates to conducting petroleum activities in Norwegian Waters. In Chapter XV and § 83 "Shallow gas and shallow formation fluids", the following is presented:

"The responsible party shall ensure that necessary measures are planned and can be implemented to handle situations with ***shallow gas or other formation fluids****, cf. also Section 82.*

When drilling in shallow formations, the selection of well structure and drilling parameters ***shall prevent gas or formation fluid from the well posing a threat to personnel, environment and facility****."*

Furthermore, the Guideline to this paragraph provides the following info:

Formation fluids as mentioned in the first subsection, also means hydrates and water under pressure.

To fulfil the requirement, the NORSOK D-010 standard, Chapter 6.7.2, should be used in health, working environment and safety, cf. Section 17 of the Management Regulations.

Additional relevant regulations are specified in Activity Regulations § 77 "Handling hazard and accident situations" and Management Regulation § 29 "Notification and reporting of hazard and accident situations to the supervisory authorities" with reference to Offshore Norge guideline 135 – "Offshore Norge Recommended guidelines for Classification and categorization of well control incidents and well integrity incidents."

3.2.2 European Union

In June 2013, the European Union (EU) Parliament introduced a new Directive (2013/30/EU) with the intention of creating the frame to standardize some of the requirements in terms of contingency planning for the oil and gas industry across the EU area and, to some extent, outside the EU area as well. As part of the Directive considerations, the following comprise some of the most important instructions: a) in respect of installations, to give independent assurance that the safety and environmental critical elements identified in the risk assessment for the installation, as described in the report on major hazards, are suitable and that the schedule of examination and testing of the safety and environmental critical elements is suitable, up-to-date and operating as intended; b) in respect of notifications of well operations, to give independent assurance that the well design and well control measures are suitable for the anticipated well conditions at all times. 5. Member States shall ensure that operators and owners respond to and take appropriate action based on the advice of the independent verifier. 6. Member States shall require operators and owners to ensure that advice received from the independent verifier pursuant to point (a) of paragraph 4 and records of action taken on the basis of such advice are made available to the competent authority and retained by the operator or the owner for a period of six months after completion of the offshore oil and gas operations to which they relate.

3.2.3 UK

Regulations in the UK are focused on the responsibility as operator as specified in The offshore installations and wells (design and construction etc) regulations 1996 – Chapter Well control (regulation 17):

The regulations incorporate parts of the Extractive Industries (Borehole) Directive regarding the supply and use of blow-out preventers. There is a duty to provide suitable well control equipment for all operations on a well, and to deploy it where conditions require. The duty to ensure the equipment is provided is on the well operator, and includes specifying pressure, temperature and other service requirements of the equipment.

The duty to deploy it is on the installation dutyholder. Deployment means both installation of the equipment and its use to control an influx from the well. For well operations from a well intervention vessel, which is not an offshore installation, the well operator is responsible for both provision and deployment.

Additionally the Health and Safety Executive regulates the industry using "Offshore Installations (Offshore Safety Directive) (Safety Case etc) Regulations 2015 (SI 2015/398)".

Based on the general framework Oil and Gas operators in the UK have developed industry guidelines called "CONDUCT OF MOBILE DRILLING RIG SITE SURVEYS Volumes 1 and 2" which were issued as final in 1997. These guidelines were updated and superseded by IOGP guidelines:

- IOGP Report 373-18-1, IOGP Guidelines for the Conduct of Offshore Drilling Hazard Site Surveys
- IOGP Report 373-18-2 Conduct of offshore drilling hazard Site Surveys – Technical Notes

3.2.4 US

While no formal detailed requirements exists on site survey and shallow hazards, the BOEM in it's "Instruction to licenses" states that *"You must acquire data to provide information on seafloor conditions that may present hazards to rig set-down, rig anchoring, platform construction, or drilling operations. Your survey must also provide information on sub-seafloor conditions to be taken into consideration during design, construction, and operation to mitigate any potential hazards to drilling operations, production activities, and platform integrity. The depth of investigation of the shallow hazards survey must be sufficient to reliably cover any portion of a borehole that will be drilled without a Blowout Preventer (BOP) stack, generally down to 1,000 meters (3,280 feet) or 200 meters below potential surface casing depth, whichever is greater. You may meet shallow hazards survey requirements by using a survey strategy that combines different systems. If you propose to use new technologies or a different type of survey strategy to meet the shallow hazards survey requirements, BOEM will consider the new technologies and survey strategies you propose to determine if they meet the minimum data requirements*."

3.2.5 Canada

The Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) has guidelines for Contingency Plans: The operator is expected to have a contingency plan for the identification and sourcing of an alternate drilling installation(s) that is capable of drilling a relief well. The plan should provide a description of the installation's required operating capability, ancillary equipment, availability, and the schedule for mobilization to the wellsite. The source of supply for a backup wellhead system and all consumables required to set conductor and surface casing for the relief well should also be identified. C-NLOPB also references the NORSOK standard and expects operators to follow section 5.8 in NORSOK D-010. The National Energy Board (NEB) reviewed the offshore drilling safety and environmental requirements for Canada's Arctic ("The Arctic Review") soon after the Deepwater Horizon incident. The Board reaffirmed its policy that says any applicant requesting authorization to drill must demonstrate, in its contingency plan, the capability to drill a relief well to kill an out-of-control well during the same drilling season. The flowing applies to demonstrate Same Season Relief Well (SSRW) capability: a) Identification of the drilling unit that will be used, including mobilization details; b) Identification of a minimum of two suitable locations for drilling a same season relief well, including shallow seismic interpretation of the top-hole section; c) A hazard assessment for positioning the relief well close to the out-of-control well; d) Confirmation that the relief well drilling unit, support craft, and supplies are available and can drill the relief well and kill the out-of-control well in the same drilling season; and e) Confirmation of the availability of well equipment and specialized equipment, personnel, services, and consumables to kill the out-of-control well during the same drilling season. (National Energy Board 2015)

3.3 Standards and Guidelines

3.3.1 NORSOK D-010:2023

NORSOK D-010, which sets standards for well integrity, requires two well barriers to be available during all well activities and operations. This two-barrier principle applies to situations where a pressure differential exists that could cause uncontrolled outflow from the borehole or well to the external environment. This requirement is particularly relevant when dealing with potential shallow gas zones.

The overall goal of NORSOK standards, including those related to shallow gas, is to ensure adequate safety, value addition, and cost-effectiveness for petroleum industry developments and operations. In the context of shallow gas, this means implementing measures to reduce the risk of uncontrolled release of gas during drilling operations.

Operating companies are responsible for ensuring compliance with NORSOK standards, including those related to shallow gas handling. This includes selecting appropriate technical solutions and equipment that meet or exceed the minimum requirements set by the standards.

4 SHALLOW HAZARD EXPERIENCE

4.1 General

Shallow gas accumulations have historically caused severe accidents to happen in all areas where drilling for oil and gas has taken place, including Norway. Depending on the areas numbers as high as 90 % of all blowouts are due to shallow gas accumulations in some areas. The world average is 33 %. Research has been done to find the best ways to prevent shallow gas blowouts from occurring, and the common practice is to drill a pilot hole. Pilot holes are smaller, causing a greater chance of swabbing. Holand (1997) noted that swabbing caused 20% of shallow gas blowouts in exploration wells and 40% of shallow gas blowouts in development wells.

Based on older blowout statistics 80% of all shallow gas blowouts with known origin occurred during the following activities:

- actual drilling
- tripping out
- waiting on cement to harden

Experience shows that the shallow gas blowout frequency is approximately 2.3 times higher during exploration drilling than during development drilling. Modern NCS experience seems to fit in this pattern, however no systematic recent analysis has been done.

Swabbing

Swabbing is one of the dominant causes of losing the hydrostatic barrier and can hence lead directly to shallow gas blowouts. Swabbing creates a suction in the wellbore which may induce well fluids out of the formation, creating a kick. Swabbing is usually caused by pulling the drill string too quickly out of the well. Based on Holand (1997) approximately 40% of the shallow gas blowouts in development wells and 20% of shallow gas blowouts in exploration wells were caused by swabbing. In many cases, other factors help create the swabbing effect. Sticky swelling clay (gumbo) balling up the drill bit and/or the stabilizer or unstable borehole reducing the wellbore diameter, all can reduce the annular space for mud passage.

Swabbing can never be eliminated, but the probability of a blowout may be reduced by taking precautions. The most obvious precautions are:

- Circulate mud while pulling out of the hole
- Pull out carefully and pay special attention to narrow holes and sticky clay problems.

Generally, it is more likely to experience the swabbing effect in narrow holes. The use of small diameter pilot holes has become normal procedure in the North Sea when drilling the shallow section of a well and extra care should be taken during riser less pilot hole drilling.

NOD also recommends this practice when drilling in areas where shallow gas might be expected (Cox et al., 2020b). This will thereby increase the swab probability. The pilot holes are used partly to reduce the shallow gas flow, and partly to be able to dynamically kill a well. The technique is based on increasing the annular friction by high-rate mud pumping. according to Adams, dynamic killing is not possible due to inherent hole washouts in soft, shallow sediments (Lafuerza et al., 2006). Hellstrand also realizes this problem (Morita et al., 1990), although Equinor has controlled a few shallow gas incidents by using this method, but the company was reported to not be entirely sure whether the well was killed by the annulus friction or by the weight of the kill mud.

Unexpected high well pressure and too low mud weight

Unexpected high well pressure and too low mud weight are described together because it is likely that an unexpected high well pressure was the reason for reporting too low mud weight, not because the mud weight as mixed to a lower density than specified. As expected, this blowout cause is far more frequent during exploration drilling than during development drilling, primarily because knowledge about the shallow formation is far better during development drilling.

4.2 Norway

Shallow gas exists and represents a problem over large areas on the Norwegian Continental Shelf, and it does vary regionally as well as locally. Biogenic as well as petrogenic shallow gas has been encountered on the Norwegian Continental Shelf. So far shallow gas has been reported in 150 of the 558 wildcat and appraisal wells drilled on the Norwegian Continental Shelf. 7 blowouts and several smaller kicks caused by shallow gas have been recorded. Experience, however, proves that the probability of failing to predict shallow gas pockets has been very high.

0stebø et al. investigated 60 exploration wells drilled in four different areas on the Norwegian Continental Shelf from 1978-1986 (NOROG, 2015). They predicted no shallow gas for 31% of these wells, and shallow gas for 69%. For 47% of the wells where shallow gas was not predicted, shallow gas was experienced. Further, for 45% of the wells where shallow gas was predicted, shallow gas was not experienced. Predicting shallow gas during those years had little or no value.

According to Hellstrand (1990), shallow gas prediction improved significantly after the 1985 West Vanguard accident (Morita et al., 1990 and Wilpshaar et al., 2020). All the shallow gas zones drilled from 1986 until 1990 in five Haltenbanken wells (west of mid Norway) were predicted. Shallow gas was, however, also predicted in some other wells, but not encountered. This improvement in shallow gas prediction is claimed to be the result of using 2D and 3D seismic. However, the use of 2D and 3D seismic does not guarantee that all shallow gas accumulations will be predicted (IMCA S 003 Rev. 2, 2015). The risk of drilling unexpectedly into shallow gas pockets will, however, be reduced.

As part of the RNNP in 2011 Causes and measures related to well control incidents in Norwegian petroleum activities were investigated. For the period 2003-2010, a total of 146 well control incidents were registered of which 17 in Category 4 (“Shallow Gas”) and one incident in Category 5 (“High Risk Shallow Gas”). Typical measures described for handling gas were weighing and pumping kill mud to stabilise/kill the well or plugging and abandoning the location. An alternative is to first plug the well with cement, whereupon drilling out and cementing a casing over the gas zone followed by install a “marine riser” and BOP. Better routines with pre-studies of new areas and greater consideration to shallow gas in planning were marked as a possible improvement.

4.3 The Netherlands

Shallow gas is a relative common feature of the Dutch offshore and has been the target for exploration. There are 8 proven shallow gas fields in the Netherlands of which 3 are currently producing, accounting for ~8.5 BCM recoverable. In a study by TNO (Wilpshaar et al., 2020). A total of 216 out of a total of 2027 Dutch offshore wells (including side-tracks) penetrates bright spots. Of those 37 out 58 with sufficient well data had gas shows. Also 14 well with strong gas shows occurred outside bright spots.

In a study investigating 57 wells in the Dutch Norse Sea it was found that all wells drilled through shallow gas were found to be leaking and one-third of all abandoned wells was found to be drilled through shallow gas. Nine locations showed bubble plumes (acoustic flares). A distinct difference between gas leakage of abandoned wells and locations with natural gas seepage was noted. It was found that 18% of wells drilled through shallow gas were leaking, with 11% of all abandoned wells being drilled through shallow gas. When compensating for over-representation of shallow gas wells in the study it was estimated that less than 2% of all abandoned wells in the Dutch North Sea is likely leaking. Well leakage seems to occur when large quantities of shallow gas are present and the abandoned well apparently suffers from an integrity issue (de Bruin et al., 2025).

5 SHALLOW HAZARD SURVEY

5.1 General

Table 3 presents typical geohazard that can be encountered in the shallow section, and some of the potential impacts their presence may have on drilling operations in the tophole section. The table also offers some guidance on the data and investigations that may be suitable for identifying and charactering geohazards so that they can be assessed and managed effectively according to the risk they pose.

It is the aim of a successful well site investigation to produce a ground model that contains the information required for a thorough understanding of the seafloor and seabed conditions relevant to drilling the tophole section. This may be an iterative process, whereby insight into the relative significance of seismic horizons is gained by comparing geophysical with geotechnical and geological data, which thereby leads to re-interpretation and refinement of the seismic analysis for specific areas. The available data needs to be analysed for all geohazards contained in Table 3, and the potential for hazardous conditions evaluated and assessed.

The first step is to gather and review available information from previous studies and boreholes with identified shallow hazard occurrences. This data is used to characterize the subsurface and geohazards. Next, the potential geohazards associated with the planed well location is evaluated, and the impact on drilling operations, well integrity, and personnel safety is analysed. The critical factors contributing to the severity and likelihood of these geohazards are identified.

5.2 Shallow Hazard Survey Requirements

The operator must acquire data to provide information on seafloor conditions that may present hazards to rig set-down, rig anchoring, platform construction, or drilling operations. The survey must also provide information on sub-seafloor conditions to be taken into consideration during design, construction, and operation to mitigate any potential hazards to drilling operations, production activities, and platform integrity.

The depth of investigation of the shallow hazards survey must be sufficient to reliably cover any portion of a borehole that will be drilled without a Blowout Preventer (BOP) stack, generally down to 1,000 meters or 200 meters below potential surface casing depth, whichever is greater.

5.2.1 Survey Design

Survey designs are determined by several factors and will vary depending on whether one is drilling from a subsea structure, a floating platform, or a jack-up rig. These designs also depend on the surveying systems used: high-frequency or low-frequency profiling systems, magnetometer, side-scan sonar, or multi-beam sonar. The optimum survey area and grid-spacing are also affected by the water depth, degree of certainty on where the well will be located and on how many and where the wells will be drilled.

Reference is made to ISO 19901-10:2021 providing a clear overview of the scoping, planning and data quality of geophysical site surveys.

The recommended 2D UHR line spacing for each type of survey as proposed by IOGP 373-18-1 is 50 meters for water depths between 25 and 150 m. While IOGP indicates that the lines spacing can be increased with water depth, shallow gas mapping requires a sufficiently dense grid and in most cases 50 m line spacing or better is needed to determine distance from the borehole to potential anomaly.

Additional cross lines should be acquired normal to the main line direction at an increased spacing to provide ties for interpretation and processing. If the final drilling location is known at the time of the survey, thought should be given to acquiring extended location lines and closer line spacing either side of the location in both line directions both for the main planned well location (PWL) and possible relief well locations (RWL). All lines should be extended with a sufficient distance beyond intersections to ensure full fold, grid closure, and subsurface ties. Wherever possible, to support interpretation, tie line(s) should be acquired to relevant offset wells, geotechnical boreholes, or other data calibration points.

It is encouraged to discuss the survey grid strategy during the planning stage using available preexisting 3D, well and site survey data.

5.2.2 Navigation & Positioning

A state-of-the-art navigational positioning system, with an accuracy of ±2 meters or better is needed and the latest real-time kinematics (RTK) positioning techniques are recommended. Augmented surface positioning using RTK can achieve positioning accuracy to below 0,2 m. Vessel track should not vary more than ±15 meters from the pre-plot line, except to avoid obstructions. All geophysical systems should be integrated with ships navigation, including any relevant offset, resulting in accurate posting of data points on survey lines and records. Fix marks should be easily identifiable on post-plot maps. For marine deep-tow systems, an ultra-short baseline system may be required to track the towfish within ±1% error and should be integrated with the ship's navigation. Navigation systems should be calibrated, and both relative and absolute position accuracy verified before the start of the survey and immediately after completion of the survey.

The following industry guidelines relate to the installation, calibration, verification and operation of surface and sub-sea positioning systems:

- ISO 19901-10:2021
- IOGP Report 373-19
- IOGP Report 373-18-2
- IMCA Report S-017 Rev.1

Common pitfalls include differences in coordinate reference system and vertical reference system, both in between surveys and between surveys and planned well or borehole locations. It is imperative that the correct systems are used, communicated and used correctly.

5.2.3 Recommended Sensors

A detailed description of all sensors and requirements are beyond the scope of this report. A short description of each sensor will be provided here with focus on how the data can be applied to improve the detection of shallow hazards.

- Multibeam Echosounder (MBES) Bathymetry - Data may be acquired using a multi-beam echo-sounder bathymetry system that provides high quality 150% coverage over the survey area. Single-beam echo-sounder data may be used to verify the results.
- MBES Backscatter – Backscatter data acquisition and processing can provide additional information of seepage structures and is therefore of interest in the assessment of shallow hazards.
- MBES Water Column Data
- Side-Scan Sonar (SSS)
- Sub bottom Profiler (SBP)
- 2D Multi-Channel High Resolution (2D HR)
- 3D Seismic Reflection - For areas in water depths greater than 200 meters (655 feet), BOEM recommends to consult a 3D seismic reflection survey for subsurface hazards over 100 percent of the area. These data should be processed in a manner to preserve a frequency of 60 hertz or more for the shallow interval. The minimum expected coverage area for 3D data is the same as that for high-resolution surveys.

More detailed relevant information on sensor specifications, data acquisition methods and data formats can be found in ISO 19901-10:2021.

Geohazard	**Identification and characterisation techniques**						
	HR	**OFF**	**SBP**	**3D**	**GT**	**SSS**	**MBE**
Shallow gas (free gas)	x	X	x	x			
Gassy soils (gas in solution)		X			x		
Shallow water flow	x	x		x			
Shallow oil	x	x	x	x	x		
Gas hydrates	x	x	x	x	x	x	
Buried relict landslide (mass transport complex)	x	x	x	x	x		
Faults	x	x	x	x	x	x	X
Soft soils	x	x	x		x		
Hard soils	x	x	x		x		
Swelling clays (gumbo)		x			x		
Boulders and gravels	x	x	x		x		
Unconsolidated Sands	x	x	x		x		
High salinity		x			x		
Excess pore water pressure		x			x		
High structured clays		x			x		
Seafloor – e.g. steep gradients, channels, bedforms, **plougmarks**				x		x	x
Seepage features – e.g. pockmarks, fluid chimneys, craters	x		x	x		x	x

Table 5. Summary of geohazards, identification and characterization techniques. Relevant geohazards for the NCS are marked in bold.

5.2.4 Seismic Processing

To optimize marine seismic reflection data for shallow gas detection and velocity analysis, carefully designed seismic processing workflows are essential. Most site surveys delivered for oil and gas only use basic processing sequences and velocity models leading to suboptimal imaging.

By integrating the different processing steps, interpreters can maximize the resolution and reliability of shallow seismic images for gas detection and velocity model building. Significant improvements in shallow hazard imaging can be achieved using the latest processing techniques in a cost-effective manner. This approach enables more accurate geohazard assessments, characterization of shallow gas pockets, and planning of boreholes, wells and seafloor infrastructure.

The following steps, presented in order of application, outline an effective approach. Additional detailed requirements on the recommended processing parameters for seismic reflection methods can be found in ISO 19901-10:2021.

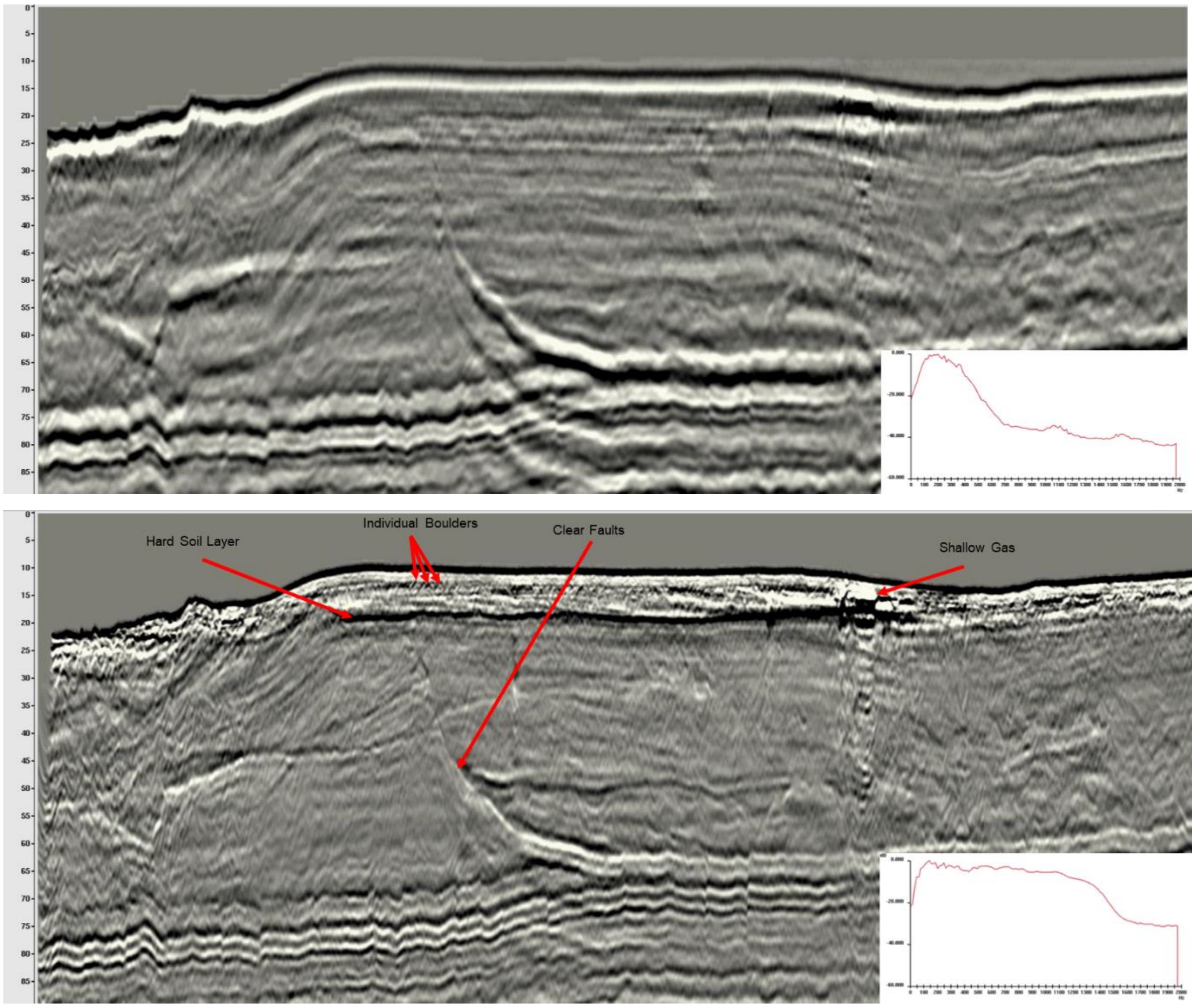

Figure 4: Examples of standard 2D UHR site survey data (top) and high resolution processing of data (bottom). Source: Geoprovider.

1. Designature, Zero Phasing and Ghost Notch Inversion

Ghost reflections of the sea surface for both the source and receiver can significantly degrade data quality and obscure parts of the data. Especially for near seafloor imaging, ghost removal is key including:

- Source designature using operators derived from seabed reflections including zerophasing to improve temporal resolution
- Adaptive deghosting filters based on source and receiver depths. Towing the source and receivers at different depths will achieve the best results.

2. Noise Attenuation and Demultiple

Multi-domain denoising techniques are crucial for improving the signal-to-noise ratio including:

- Application of swell noise attenuation in several domains as required
- Multi-channel filtering to remove coherent noise
- Simultaneous, multi-model, adaptive subtraction using an optimum combination of surface-related multiple elimination (SRME), wave equation demultiple, Tau-p deconvolution and deterministic, shallow water demultiple.
- Radon demultiple
- Interbed demultiple

- Targeted horizon demultiple

3. Spectral Broadening

Increasing the spectral bandwidth enhances the seismic resolution by collapsing the wavelet and the following techniques can be use including spectral balancing techniques to extend the frequency content.

4. Seabed Corrections

Accurate seabed corrections are essential for proper imaging of shallow features and using MBES bathymetry as an input is recommended. Tying the recorded data to the measured water depth will correct for gun and cable statics, tides and heave. The derived sea water velocity and smoothed interval velocities can then be used to convert two-way travel time to depth if so required.

5. Velocity Analysis and Migration

Accurate velocity analysis should be performed as part of the seismic processing of the site survey data for use as input to migration and NMO correction of the data. Typically, this would include high-density automatic picking of every CMP. Depth migration can be considered for areas with complex geology but is considered unusual for site survey data. Full waveform inversion (FWI) for high-resolution near-surface velocity models can also be considered for 3D data but depends on the maximum offset recorded. For a typical site survey acquisition configuration, the recorded offsets are too short for this type of analysis. (Provenzano et al., 2018).

5.3 Shallow Gas Analysis

A rigorous integrated approach is required for the identification of geohazards and as described in Hill et al., 2013, the most significant of which will often be shallow gas. However careful consideration must be given to all potential geohazards to get a complete assessment of the site and avoid aggravating factors. Geophysical data rarely enables an unambiguous interpretation, and conclusions should be arrived at following the systematic assessment of all the seismic properties and attributes associated with each geohazard, considered in the context of geological understanding, preferably integrated with available seabed sample, core and/or borehole data.

A key improvement step in the detection and verification of shallow hazards is the use of 2D UHR data in relation with available 3D data as recommended by IOGP. It is considered best practise to integrate as much as possible of pre-existing seismic data for shallow assessment in relation to well planning, since possible structural and stratigraphic trapping of shallow gas are difficult to assess on 2D site survey data alone. In addition, the offset stacks of the 3D data allow for AVO (amplitude versus offset) observations as direct indicators of hydrocarbons if present. High resolution short offset processing will in many cases provide valuable additional information allowing de-risking of anomalies and position wells and boreholes in the lowest risk locations.

Anomalously strong amplitudes, geophysical anomalies, mud volcanoes and zones of weak amplitudes (’gas chimneys’) are to be identified. Interval attributes can help to successfully map these features. Different color pallets can enhance different features of the seismic and aid in the detection and mapping of anomalies.

To evaluate the shallow gas risk the following attributes are preferred

- Amplitude of 3D and HR2D
- RMS amplitude
- Sweetness attribute (instantaneous amplitude divided by the square-root of instantaneous frequency)
- Envelope
- Instantaneous frequency
- Frequency decomposition at multiple frequencies

The sweetness seismic attribute is used to highlight thick, clean reservoir (sands and sandstones), and/or hydrocarbons filled reservoir. In the case of hydrocarbons, the effects are that amplitude increases due to higher reflectivity and frequency of the reflection is lower due to the combined effect of hydrocarbons on the frequency content assuming an AVO Class 3 anomaly.

The envelope seismic attribute is a physical attribute and can be used as an effective discriminator for the following characteristics: The magnitude of the trace envelope is proportional to the acoustic impedance contrast, hence is related to reflectivity, bright spots, possible gas accumulation, sequence boundaries, thin-bed tuning effects, unconformities, major changes in lithology, major changes in depositional environment, lateral changes indicating faulting and spatial correlation to porosity and other lithologic variations

Frequency attributes involve separating and classifying seismic events within each trace based on their frequency content. The application of these attributes is commonly called spectral decomposition. When a spectral decomposition algorithm is applied to seismic reflection data, it breaks down the seismic signal into its frequency components and this allows visualization of the data at specific frequencies, and identification of stratigraphic and structural features that would otherwise be overlooked in full bandwidth displays. Total reflection" spectral decomposition showing "white colours" at top of the soft anomaly on RGB blending

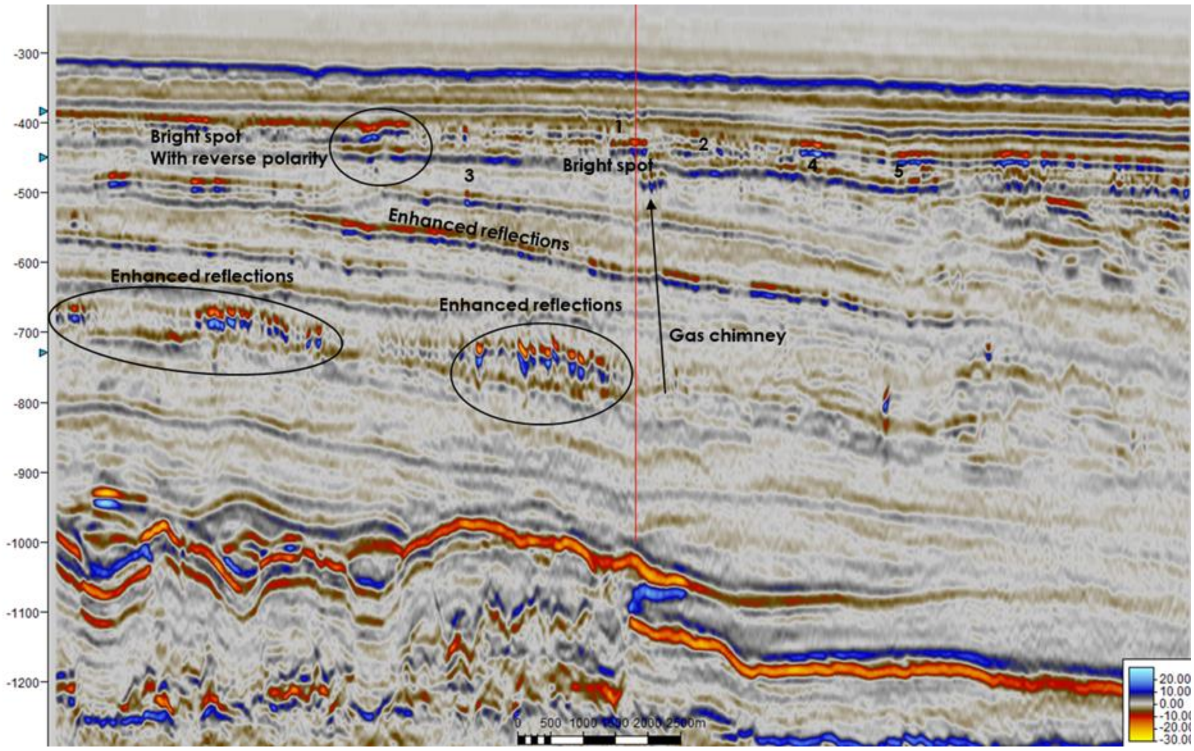

Figure 5: Examples of high risk anomalies around a proposed well location likely to be associated with shallow gas.

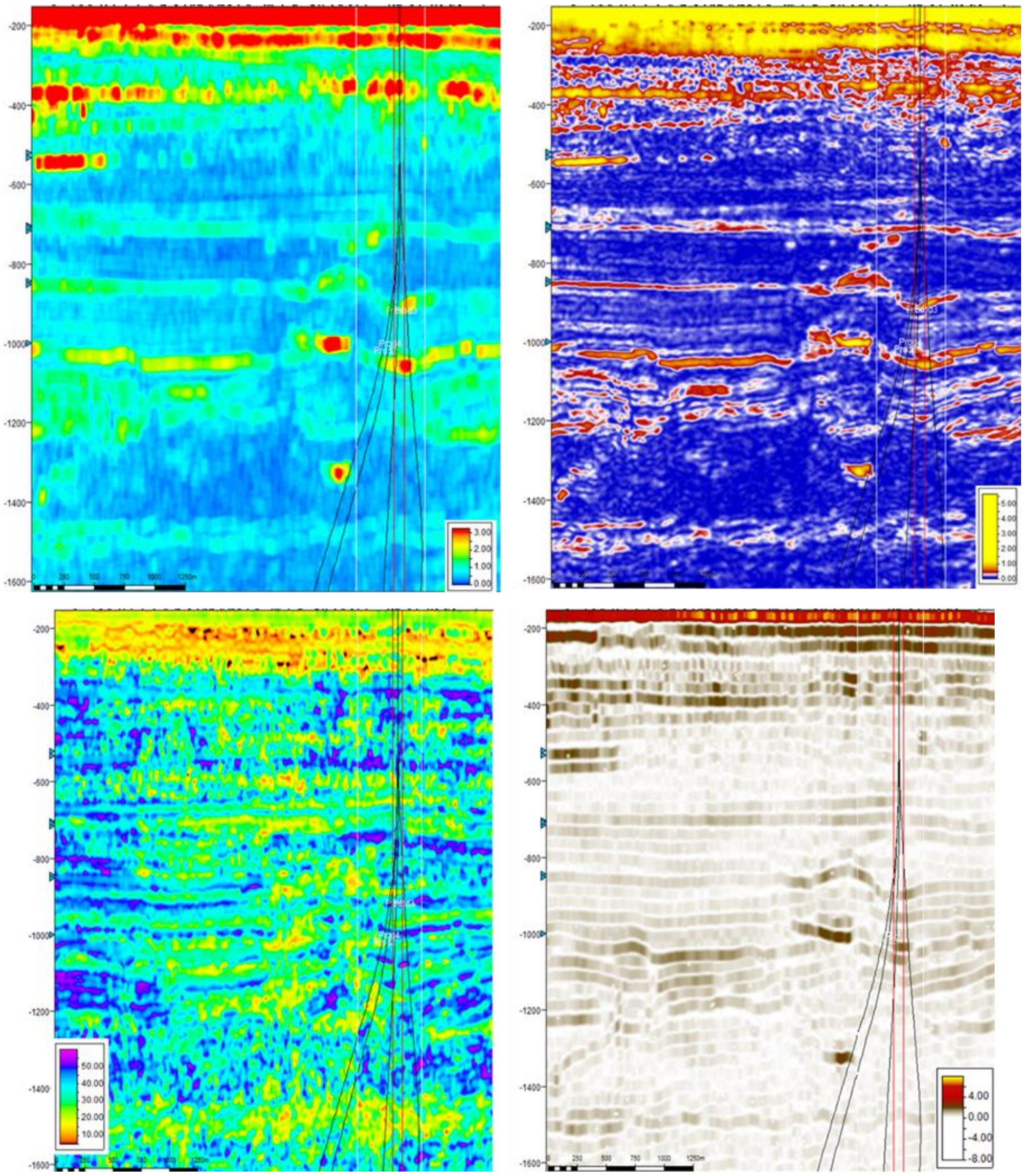

Figure 6: seismic displayed using different attributes aiding in the detection of shallow gas. Upper left: Root mean square (RMS), upper right: Sweetness; Lower left: instantaneous frequency (IF); Lower right: Spectral Decomposition (SD).

For consistent mapping and assessing a table summarizing the seismic observation can provide insight into the risk. Note that structural conformance of anomalies includes any conformance of anomalies to trapping. Different companies and organizations use different wording and naming. Based on the semi-quantitative observations the anomalies can be categorized as no indicators, low, medium or high risk.

Table 6: Geophysical semi-quantitative scoring table of shallow gas anomalies

#	Depth		Distance to PWL (m)	Amp.	AVO	Structural conformance	Frequency	Seismic facies	Risk	Comments
	(ms)	(m)								
1				0/+1	-1/0/+1	0/+1	0/+1	0/+1	4-5	High
2				0/+1	-1/0/+1	0/+1	0/+1	0/+1	2-3	Medium
3				0/+1	-1/0/+1	0/+1	0/+1	0/+1	1	Low
4				0/+1	-1/0/+1	0/+1	0/+1	0/+1	0	No Indicators

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