The Barents Sea of the Norwegian Continental Shelf: drilling through carbonates, modelling, risk management and well planning

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Abstract. There are a number of geological and hydrogeochemical modelling techniques used in order to ascertain formation of the hydrogen sulphide (H2S) in the formation fluid within a geological setting in several blocks of the Norwegian Barents Sea. Careful consideration of the regional and chemical factors causing H2S generation can also be used in the drilling context. Thermochemical sulphate reduction (TSR) is the most likely process of H2S formation in this setting. Risk picture becomes different when presence of H2S is closely coupled with occurrence of Permian and Carboniferous carbonate plays prone to causing severe drilling fluid losses and increasing exposure time of the downhole equipment to the H2S. Using appropriate analogues and adequate well offset analysis tend to demonstrate that most of the risk factors can be well mitigated.

1. Introduction
The Norwegian Continental Shelf (NCS) is generally known for producing sweet, low-sulphur, petroleum. With first wells drilled mainly in the North Sea, exploration gradually moved further north in the Norwegian Sea with deeper target depths and high reservoir temperatures. Areas of the Barents Sea which have been opened for petroleum operations since the 1980’s are frequently designated Barents Sea South, delineated by latitude 74°30’N.

As of 2019, a total of 185 wells have been drilled in Norway’s Barents Sea sector, including 147 for exploration purpose only. Forty-nine discoveries were made in these waters from 1980 to 2016. With more discoveries potentially being evaluated for development and further production, e.g. Johan Castberg, Alta/Gohta and Wisting. Snøhvit and Goliat fields are currently the only two on stream.

2. Permian carbonates in the Norwegian Barents
Permian and Carboniferous carbonate plays started to gather a strong interest in the Norwegian part of the Barents Sea after the Gohta and Alta discoveries in 2013 and 2014. Drilling through carbonates can be challenging due to potential severe mud losses and hole instability. In case Hydrogen Sulphide (H2S) is present in high concentrations in these geological conditions, this could lead to hazards that are difficult to cope with.

H2S is a toxic gas and during drilling can be found and transported to surface in drilling fluids, recovered core samples or core barrels, and on downhole equipment. It is necessary to remove H2S and
soluble sulphites from drilling fluids as quickly as possible because of the destructive and corrosive effects of H₂S on personnel and materials.

Early well tests in the Norwegian Sea showed concentrations of hydrogen sulphide as high as 35-40 ppm, and the recent studies in the well planning phase in the Fedynsky High area of the Barents Sea East revealed a risk of possible H₂S presence in the Permian formation fluid.

Several wells with Palaeozoic carbonate reservoir targets either had minor shows (7128/6-1, 7130/4-1) or were dry (ex. 7229/11-1). The potential for high amounts of H₂S gas was recognized by the operators of well 7229/11-1, but this was not further quantified. A post drilling report on carbonate diagenesis in this well describes the initial plugging of primary porosity by anhydrite which is turned into calcite during Thermochemical Sulphate Reduction (TSR). A fluid inclusion stratigraphy report mentions the presence of pyrobitumen, sulfur species of thermal origin and fluid inclusion homogenization temperatures of ~ 140° C, all of which can form during the TSR process and may lead to substantial concentrations of hydrogen sulphide. The 3D regional basing modelling study allowed to estimate the reservoir paleo temperatures in the Barents Sea. Figure 1 shows the distribution of the maximum temperatures in the central region’s geological history.

![Temperature Distribution](image)

**Figure 1.** Distribution of paleo temperature in the central area of the Barents Sea.

The Palaeozoic sedimentary succession on the Finnmark Platform and in the Fedynsky High area consists of Caledonian basement overlain by Devonian and non-marine Early Carboniferous siliciclastics. A regional late Carboniferous transgression led to the development of an extensive carbonate platform that persisted throughout the Permian [1]. The Carboniferous–Permian ice age resulted in high-frequency, high-amplitude eustatic sea-level changes and in turn in intermittent flooding and subaerial exposure of the region. Siliciclastic shoreline progradation alternated with carbonate
deposition with phylloid algal thickets. The transition to the overlying warm shallow-marine calcareous to evaporitic facies of the Lower Permian carbonates was diachronous in response to palaeo-relief. Carboniferous-Permian carbonate build-up/reef growth has been reported from across the entire Arctic [1, 2]. Evaporites were deposited in sabkhas and salinas during sea-level lowstands in areas surrounding the then emerged build-ups. During the late Permian the carbonate depositional environment changed to a deep-water setting and the formation of cold-water carbonate build-ups. Based on analogue outcrop studies on Svalbard, well reports and data published in [3], the Carboniferous and Permian successions can contain source rocks of varying quality with terrigenous and/or marine organic matter.

During the middle to late Triassic the Fedynsky High area underwent rapid burial which initiated petroleum generation and migration from the Palaeozoic source rocks into the Permian aged carbonate reservoirs. Maximum burial likely occurred during the late Cretaceous, followed by tectonic uplift and several episodes of Cenozoic erosion and glacial tilting. The early charge, long residence time at temperatures above 120° C and the presence of anhydrite in or near the carbonate reservoir create a significant petroleum preservation and hydrogen sulphide risk for this Palaeozoic carbonate play type.

3. **Bacterial sulphate reduction and thermochemical sulphate reduction**

Sulphate can be reduced by hydrocarbons with concomitant oxidation of the organic compounds, either bacterially (BSR) or inorganically (TSR). BSR has been known for more than 50 years as a common and widespread process in near-surface and shallow burial diagenetic. Petrographic and geochemical data on BSR are widely scattered in the geologic literature and are derived from dozens of geologic settings that include lakes, marine sediments, salt domes, and shallow burial diagenetic environments with base metal sulphide deposit. BSR is known from a multitude of geologic settings that range in temperature from 0 to about 80 deg. C [4].

TSR has been recognized much more recently as a process of geologic significance, and most literature on TSR has been published only during the last decade. A number of case studies and theoretical reviews have shown that TSR is common and widespread in deep burial diagenetic settings (also called high-temperature environments/settings). Based on empirical evidence, BSR and TSR occur in two mutually exclusive thermal regimes, i.e. low-temperature and high-temperature diagenetic environments [4].

Temperature is a critical but not the only element in the regional and chemical factor analysis. This paper addresses a number of other regional and chemical factors to further create a de-risking workflow.

4. **TSR in the Permian play in the Norwegian Barents Sea**

TSR is the most likely process of H₂S formation in the setting presented in this paper, i.e. Permian play in the Norwegian Barents. TSR comprises a complex web of hydro-geochemical reactions between the rock minerals and the aqueous and hydrocarbon species in the reservoir [5]. Data from well tests and from the literature indicate a correlation between H₂S concentration in the reservoir fluids and reservoir temperature.

Numerical modelling provides a first-pass estimate for assessing H₂S formation risk by TSR during the exploration phase in the absence of any calibration wells for the Fedynsky High area.

5. **Modelling techniques as a proof of TSR**

A combination of 3D petroleum system and 1D hydrogeochemical modelling allow to investigate the sensitivity of the TSR process regarding reaction kinetics, migration dynamics, as well as the role of reservoir mineralogy and formation water as an H₂S sink.

The 3D migration modelling lacks spatial and chemical reaction resolution, but handles 3-phase fluid flow and a simplified TSR reaction scheme [6]. The 1D hydrogeochemical modelling following the [5] approach, on the other hand, handles the very complex chemical interactions but does not simulate 3-phase fluid flow. This approach, however, still results in a large uncertainty range. One important modelling outcome for this geologic setting is that iron-bearing minerals that act as H₂S sinks exert a
strong control on the H₂S gas content. Thus, the quantification of iron-bearing minerals in the Permian carbonates of analogue wells can provide a valuable tool for improving H₂S risk assessment.

6. Geological de-risking in the frontier region

The geologic de-risking went through 3 main phases going from regional to prospect specific scale.

The regional model first highlighted the H₂S risk due to the combination of the aforementioned factors. It constrained the thermal model, the petroleum migration dynamics and the overall timing of relevant events. The study was conducted together by LUKOIL Engineering and AkerBP. Unfortunately, the simplified TSR reaction scheme implemented in the modeling software could not help us de-risk the prospect, partially due to the absence of calibration data. One significant outcome was, that almost all of the formed H₂S can be dissolved in the formation water and thus be removed from the accumulation due to the long residence time.

But how much do we know about water flow in an undrilled carbonate reservoir in a frontier setting?

After the H₂S risk was flagged, an offset well analysis was conducted focusing on the products of TSR. For example, the 7229/11-1 well drilled in 1993, targeted the Paleozoic carbonates but was dry and the carbonates were not a reservoir facies in this location. The H₂S risk for this well was recognized at the time and drilling was prepared.

- Elevated H₂S was only encountered in the immature Jurassic Hekkingen Fm source rock. (probably related to bacterial sulfate reduction).
- The thin sections and diagenesis studies of the warm-water carbonate facies in the Ørn Fm mention pyrobitumen, dead oil staining and blocky pore filling calcite.
- Fluid inclusion studies mention the occurrence of several sulfur species that could be related to TSR and entrapment temperatures (aqueous inclusion homogenization temperatures) of 140°C or higher.
- There is an evidence that TSR has occurred in the area, and that H₂S might be a play risk.

In order to get a better understanding of the chemical process and main parameters that impact the present-day H₂S content, a 1D hydrogeochemical modelling study was conducted following the approach of [5]. It takes into account the complex web of (40+) chemical reactions between minerals, petroleum and various gaseous and aqueous species that make up TSR in a carbonate reservoir. Based on the modeling and evaluation techniques, a matrix for probability estimation on the H₂S formation was developed (Figure 2).

**Figure 2.** H₂S formation probability risk matrix. Regional and chemical risk factors.
7. Barents Sea regional overview
In order to study the frontier region in this area, experiences not only from the NCS were gathered, but also relevant analogues on the United Kingdom Continental Shelf (UKCS), on Karachaganak and Tengiz fields, Caspian region as well as in Timan-Pechora oil and gas province. The intention was to apply critical analysis on assumption around H₂S concentration vs. reservoir temperature. Real field examples were reviewed in order to assess the possibility for H₂S prediction, quantification and qualification prior to drilling a well. Among other critical elements in a well delivery process, factual drilling fluid design with H₂S scavenger, design of drilling tubulars and production casings with emphasis on prevention of sulfide cracking and brittleness have been analyzed in order to perform prudent risk assessment and develop a safe, robust and a cost-effective solution.

8. Experience from the Russian Barents and the Caspian regions
The Russian Barents Sea is yet to be explored however significant discoveries have been made in the Permian carbonates in the recent past with a profound effect on the entire region. These are Prirazlomnoye and Dolginskoe fields. Timan-Pechora oil province has been a source of hydrocarbons produced from the Permian and Devonian carbonate reservoirs for several decades. Exploration drilling in the Permian play on the Russian Continental Shelf in the Barents Sea that took place in the mid-80s, encountered at least 4 wells (Admiralteyskaya, Severo-Zapadnaya 202, Pomorskaya, Severo-Gulyaevskaya) with a very small amount of acid gas (H₂S) in a range of 1-3 ppm (Figure 3).

![Figure 3](image-url)

**Figure 3.** Barents Sea regional overview with exploration wells drilled through carbonates and H₂S traces encountered.

Recent exploration and production success in the Northern Caspian Sea revealed significant commercial potential for the hydrocarbon production from the terrigenous and carbonated reservoirs of Jurassic-Cretaceous age, e.g. Khazri offshore project. Exploration drilling within this area is taking place in the very challenging geological conditions in a fairly frontier region, high pressure (up to 1070 bar) and high temperature (up to 165 deg C) reservoir, carbon dioxide (CO₂) up to 4%, hydrogen sulphide...
up to 22% and a tight drilling window in the deeper sections of the well. There are also a number of world renowned production fields in this region in a similar geological setting, e.g., Karachaganak, Tengiz, Astrakhanskoe. Amount of H$_2$S on these fields normally reach 25% and sometimes higher whereas CO$_2$ level can be as high 22% [7].

9. Conclusions
The main objective of this paper is to demonstrate that modern modelling techniques allow comprehensive analysis of H$_2$S formation process in the reservoir fluid in the Norwegian Barents Sea.

Various modelling approaches have their strengths and weakness and are used to complement each other. The value of success in frontier exploration projects might determine the future of the entire region. Presence of H$_2$S in the reservoir fluid cannot be considered as a risk on its own but rather as a combination of risk factors caused by presence of anhydrite and carbonates in the geological cross-section, high CO$_2$, chemically balanced low pH, high level of inorganic and organic chloride's content, extremely high level of total dissolved solids, to name a few. Exploration and production drilling examples in the Caspian and Timan-Pechora regions demonstrate that these risk factors can be mitigated, when planned and managed appropriately.

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