INITIAL ASSESSMENT OF GAS HYDRATE PRESENCE IN THE UK NORTH ATLANTIC MARGIN

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By

Henry Westfall Tennant
The Ohio State University
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The purpose of this thesis is to provide an initial assessment of gas hydrate presence in the UK North Atlantic margin by examining petrophysical industry well logs. This was accomplished by combining datasets from the National Oceanic and Atmospheric Administration (NOAA) and the Oil and Gas Authorities’ (OGA) National Data Repository (NDR). The NOAA dataset contained seafloor temperature measurements that were vital for pre-analysis calculations, while the NDR dataset was used to identify wells of interest.

While dozens of wells were identified in the NDR as being potentially viable candidates for analysis, only thirteen were fully examined due to the scope of this thesis. Of these thirteen wells, eight were determined to have gas hydrate. Two wells displayed interesting resistivity measurements, but did so in segments where gas hydrate couldn’t form due to the temperature profile of the well. The remaining wells displayed no signs of gas hydrate presence.

The analysis presented in this thesis will contribute to a growing body of research trying to quantify the abundance of gas hydrates globally. With a more refined understanding of worldwide gas hydrate reserves, better predictions can be made regarding the potential of gas hydrate as both an energy source and a geohazard. Moreover, the interplay between gas hydrates and the carbon cycle becomes less opaque with more precise abundance estimates.
ACKNOWLEDGEMENTS

I would like to begin by thanking the National Science Foundation (NSF), Division of Ocean Sciences, for providing funding for this thesis through the Award #1752882 grant. I would also like to thank the incredible faculty and staff at the Ohio State University’s School of Earth Sciences for creating an exceptional learning environment. Specifically, I would like to thank Dr. Ann Cook for being an outstanding professional mentor and teacher. In addition, I want to thank Fawz Naim for providing me with guidance at every stage of the research process.

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1 Introduction

The purpose of this thesis is to determine the extent to which gas hydrates are present in the UK North Atlantic margin. Gas hydrates are crystalline minerals that form when frozen water encapsulates gas molecules such as carbon dioxide, methane, or ethane (Sloan et al., 2007). The subsurface of continental margins, such as the UK North Atlantic margin, are prime locations for hydrate formation due to the combination of low temperatures and high pressures (Kvenvolden, 1995).

The research presented below will provide meaningful insights concerning gas hydrate accumulations in the UK North Atlantic margin. These insights are important for several reasons. First, gas hydrates have the potential to be a rather substantial energy source. By containing gaseous hydrocarbons, hydrates could supplement traditional oil and natural gas production (Pierce et al., 2004). Second, hydrates could also be a geohazard if the trapped gases are released from the subsurface in an uncontrolled manner (Englezos, 1993). This is especially worrisome if the gas is methane, an extremely potent greenhouse gas and a hydrocarbon commonly found in hydrate. Lastly, and most importantly, gas hydrates may play an important role in the carbon cycle (Dickens, 2003). By researching regional gas hydrate accumulations, the link between the carbon cycle and gas hydrates will become less opaque.
The UK North Atlantic Margin is a passive margin connecting the European Continental Shelf with the seafloor of the North Atlantic Ocean. Consisting primarily of half graben rift sequences, the area is geologically complex (Parnell et al., 2005). The formation history of the broader North Atlantic region can help explain the complexity observed at smaller scales. Beginning around the Paleocene epoch, the North Atlantic Ocean experienced major rifting events (Doré et al., 2002). These rifting episodes were interrupted by periods of uplift (Ebdon et al., 1995). The uplift was caused by the presence of a massive mantle plume estimated to be over 2000 km in diameter and currently centered underneath Iceland (White, 1988).

The intensive rifting and uplift episodes were followed by tectonic changes during the Eocene epoch (Knott et al. 1993). The area now considered the UK North Atlantic Margin experienced tectonic compression during this epoch. The North Atlantic Ocean began a rapid period of seafloor spreading, and counterforces were provided by an expansive piece of land that would eventually become continental Europe (Knott et al. 1993). This period of compression led to the creation of important inversion structures. These inversions were paramount in allowing hydrocarbons to migrate and accumulate in the area (Lamers et al., 1999). Increasing amounts of marine sedimentation also occurred around this epoch, with copious amounts of shale, sandstone, and other types of sedimentary rock being deposited on the shelf and slope (Parnell et al., 2004). The material deposited during this time would eventually morph into the present-day subsurface of the UK Atlantic North Margin. Rifting events would continue to occur periodically throughout the North Atlantic Ocean during the Cenozoic Era (Parnell et al., 2005).

Figure 2.1: Topographic map of the UK North Atlantic Margin and surrounding areas. Image also contains the location of 165 industry wells.
3 Methods

The base of the hydrate stability zone (BHSZ) is the depth at which the subsurface becomes too warm for gas hydrates to form. The BHSZ was crucial in determining whether a given well log had data in the hydrate stability zone (HSZ). If high quality well log data exists above the BHSZ, then further analysis can be performed to determine whether gas hydrates are present. Before the BHSZ can be calculated, however, the seafloor temperature and geothermal gradient at the well must be acquired.

3.1 Seafloor Temperature

For this analysis, the World Ocean Atlas 2018 (WOA18) dataset was used to estimate seafloor temperature for the UK North Atlantic Margin and its neighboring areas (Locarnini et al., 2018). Released by NOAA, WOA18 contains mean ocean temperature measurements taken at a variety of depths starting at the sea surface and terminating at either the seafloor or a maximum depth of 5500 meters. The temperature data within WOA18 can be filtered both by time and grid resolution. The most recent period, which is from 2005-2017, was selected for this analysis. At a grid resolution of 0.25°, which is the highest resolution possible and the one used in this analysis, a temperature measurement is made at each standard depth every 0.25° in both the longitudinal and latitudinal directions. After applying these filters, temperature recordings at or near the seafloor of the UK North Atlantic Margin and surrounding regions were pulled from the dataset. Once graphed, seafloor temperature shows three distinct zones, as seen in Figure 3.1.1.

![Figure 3.1.1: Seafloor temperatures (°C) of the UK North Atlantic Margin and the North Sea.](image)

The area can be divided into three main seafloor temperature zones. The hottest zone, Zone 1, corresponds with the European continental shelf, where temperatures range from 8°C to 16°C at the seafloor. To the north of this zone is the much colder Zone 2, where water from the Atlantic
Ocean and the Artic Circle intermingle and seafloor temperatures hover narrowly between -1°C to 0°C. Lastly, to the east of the European continental shelf is Zone 3, an intermediate temperature zone. In this zone, seafloor temperatures vary from 3°C to 10°C.

Figure 3.1.2 shows the location of 165 industry wells from the UK National Data Repository (NDR) drilled in water depths exceeding 500 meters. The wells in this area can be grouped into two main clusters, as indicated by the red boxes seen in Figure 3.1.2. The larger of the two clusters resides primarily on the continental slope that connects Zone 1 with Zone 2, while the smaller cluster resides on the part of the slope connecting Zone 1 and Zone 3.

Figure 3.1.2: Seafloor temperatures (°C) of the UK North Atlantic Margin and the North Sea with well log locations marked.

Due to the location of wells relative to the three zones, two different seafloor temperature models were produced. The seafloor temperature data in the larger rectangle between Zone 1 and Zone 2, which is referred to as the Eastern Cluster, was used for one model. The second model used the temperature data found in the smaller rectangle between Zone 1 and Zone 3, known as the Western Cluster. To improve accuracy, both models only used seafloor temperatures recorded at depths exceeding 400 meters. Figure 3.1.3 represents the change in temperature as a function of depth for the two clusters.
Both models seen in Figure 3.1.3 were generated using a polynomial best-fit line. A 5th degree polynomial was used for both the Western and Eastern Cluster. These functions allowed the seafloor temperature at a given well location to be determined using water depth. If the longitude value of the well was less than -6°, the Western Cluster trendline was used. Otherwise, the well existed in the Eastern Cluster and its trendline was used.

3.2 Geothermal Gradient

The geothermal gradient, the other parameter needed to calculate the BHSZ along with seafloor temperature and water depth, is not constant throughout the subsurface. Moreover, geothermal data for this area is rather limited. To account for these facts, the lower and upper bounds of a geothermal gradient range were used to calculate two separate BHSZs: one BHSZ was calculated at 25°C/km and another at 35°C/km. This range allowed well logging data to be parsed and filtered more efficiently, since the exact value of the geothermal gradient at each well did not need to be calculated (and wells with non-existent or suboptimal temperature data could still be considered).

The range bounds of 25°C/km and 35°C/km were decided based on geothermal gradients derived from four high-quality temperature logs found in the NDR, as well as four geothermal gradient measurements from Green et al. (1999). These eight wells and their respective geothermal gradients are summarized in Table 3.2.1.
3.3 Well Log Analysis

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### Table 3.2.1: Summary of geothermal gradient data (yellow: well logs from NDR, blue: P.F. Green et al., 1999).

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Geothermal Gradient (°C/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>204/19-1</td>
<td>30.0</td>
</tr>
<tr>
<td>202/19-1</td>
<td>25.3</td>
</tr>
<tr>
<td>205/30-1</td>
<td>33.4</td>
</tr>
<tr>
<td>206/10-1</td>
<td>26.9</td>
</tr>
<tr>
<td>204/19-8</td>
<td>28.5</td>
</tr>
<tr>
<td>204/20-L10</td>
<td>26.0</td>
</tr>
<tr>
<td>206/01-1A</td>
<td>27.0</td>
</tr>
<tr>
<td>213/25C-1V</td>
<td>41.3</td>
</tr>
<tr>
<td><strong>Mean:</strong></td>
<td><strong>29.8</strong></td>
</tr>
</tbody>
</table>
Figure 3.3.1: Comparison of background resistivities between 204/10-1 (left) and 214/21a-1 (right). Well 204/10-1 has three unique background resistivities: 1.0 Ωm from 1605-1660 meters below rotary table (mbrt), 0.9 Ωm from 1660-1790 mbrt, and 0.8 Ωm from 1790-1852 mbrt. Meanwhile, well 214/21a-1 has a mostly constant lithology of alternating sandstone and claystone segments within the HSZ. This results in well 214/21a-1 having a constant background resistivity of 0.85 Ωm.

After a single or multiple background resistivity were selected, the quality and abundance of gas hydrate within the wells was classified. The classification system found in Table 3.3.1 is a slightly modified version of the system used in Majumdar et al. (2017).

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
</table>
| A     | Increase above Background: ≥ 5 Ωm  
Duration of Increase: ≥ 10 m |
| B     | Increase above Background: 2-5 Ωm  
Duration of Increase: ≥ 10 m  
OR  
Increase above Background: ≥ 5 Ωm  
Duration of Increase: < 10 m |
| C     | Increase above Background: 0.5-2 Ωm  
Duration of Increase: ≥ 10 m  
OR  
Increase above Background: 2-5 Ωm  
Duration of Increase: < 10 m |
| D     | Increase above Background: 0.5-2 Ωm  
Duration of Increase: < 10 m |

Table 3.3.1: Summary of the modified well log classification system from Majumdar et al. (2017).
The UK Oil & Gas Authority database contains information for over 10,000 wells. Of these more than 10,000 wells, only 165 were drilled at water depths at or exceeding 500 meters. Dozens of the 165 deep interval wells contained high-quality gamma ray and resistivity readings within the HSZ, but only thirteen were assessed. Eight of the thirteen wells were classified using the system outlined in Table 3.3.1. Three wells had no significant resistivity spikes above background, indicating sediments were water saturated. The remaining two wells, 204/10-1 and 204/10-2, did not receive a grade but are given greater attention in the following subsections due to their interesting measurements. In total, three wells were classified as Grade C and five as Grade D.

![Figure 4.1](image)

**Figure 4.1:** (Left) Binary representation of gas hydrate presence, black means the well did not have gas hydrate while white means it did. (Right) Gradient color scheme used to represent the grade of the wells

4.1 Well 204/10-1

Drilled in 2002, Well 204/10-1 resides in the UK 204/10 block to the west of the Shetlands. The seafloor is 1124 meters below the rotary table (mbrt), and at that depth the seafloor temperature for the Eastern Cluster (Figure 3.1.3) is estimated to be -0.91°C. Temperature measurements from RCI pressure tests indicate a high geothermal gradient of 43.3°C/km, as see in in Figure 4.1.1 (Gorrara, et al., 2007). This geothermal gradient results in a BHSZ of 1500 mbrt.
Figure 4.1.1: The geothermal gradient of Well 204/10-1 represented as the slope of the red best-fit line. Four temperature measurements were taken at the Rothbury formation (the green cluster) and the Upper Cambo Formation (the yellow cluster).

Sidewall core samples revealed changes in lithology throughout the HSZ. From approximately 1615 mbft (the depth at which resistivity recordings begin) through to 1660 mbft, the primary rock is siltstone. For the next roughly 130 m (1660-1790 mbft) loose sands and sandstone are the dominate rock type, with thin siltstone layers appearing occasionally. The loose sands are observed primarily in the upper half of this section (1660-1710 mbft). For the remaining ~60m (1790-1850 mbft), the lithology reverts to being predominately siltstone (with thin limestone layers making sporadic appearances) (Green, et al., 2007).
The most prominent feature of Well 204/10-1 is the massive spike in deep resistivity occurring just shy of 1700 mbtr. The maximum peak of this spike is recorded to be 83 Ωm. A smaller peak occurs at 1668 mbtr with a maximum recorded value of 3 Ωm. Both spikes would fall outside of the HSZ if the geothermal gradient is greater than 30°C/km, which temperature data for this well indicates is the case. Meanwhile, gamma ray measurements remain mostly constant.

4.2 Well 204/10-2

The sister well of 204/10-1, 204/10-2 was drilled two years later in 2004. The distance between the two wellheads is approximately 85 km. The purpose of 204/10-2 was to continue exploring the northern section of the Judd Basin for potential hydrocarbon reserves. Being geographically close to one another, these two wells have strikingly similar physical characteristics. The wellhead of 204/10-2 resides 1116 mbtr, with a near identical seafloor temperature to that of 204/10-1: -0.92°C.
Figure 4.2.1: Well log data for 204/10-2 from 1540-1860 mbft. Track 1: Gamma ray measurements (gAPI). Red and blue lines indicate the BHSZ for a geothermal gradient of 35°C/km and 25°C/km, respectively. Track 2: All resistivity measurements (Ωm) except Deep Resistivity. Background resistivity of 1.2 Ωm.

Side core sampling was utilized again to observe trends in lithology. The predominate rock type throughout the HSZ of well 204/10-2 is also siltstone. Like its sister well, 204/10-2 does transition from siltstone to a loose sand/sandstone hybrid in the Lower-Middle Eocene. The key difference between these two wells is the extent to which the loose sand/sandstone interval is present in the rock column. In Well 204/10-2, this interval only extends for around 25m (from 1670-1695 mbft) compared to the 130m seen in 204/10-1 (Bridle et al., 2004).

The wells begin to diverge somewhat in their similarities when examining log trends. Well 204/10-2 does see a slight decrease in gAPI at depths associated with the aforementioned sandstone member. As for resistivity, 204/10-2 has multiple, large spikes in deep resistivity. These spikes occur at 1586, 1694, and 1747 mbft with values of 12 Ωm, 11 Ωm, and 12 Ωm, respectively. Due to the proximity of Well 204/10-2 to 204/10-1, the geothermal gradient of 204/10-2 is most likely similar to that of its sister well. This would result in a BHSZ of approximately 1495 mbft, making these observed spikes very unlikely to be caused by gas hydrates.
5 Suggestions for Future Research

Wells 204/10-1 and 204/10-2 highlight the fact that the UK North Atlantic Margin may contain high-grade gas hydrate reserves. This claim can be further substantiated by analyzing the remaining wells that met the aforementioned data requirements. The thirteen wells discussed in this thesis provide a glimpse into the potential gas hydrate reserves locked beneath the UK North Atlantic Margin; but more wells will need to be examined to accurately quantify the amount of accumulated gas hydrate.

Another issue limiting the utility of the results is the rather large variability exhibited by the geothermal gradient, and the subsequently large variability in the BHSZ values. Table 3.2.1 shows that the geothermal gradient is volatile in the UK North Atlantic Margin. This volatility is difficult to track from one well to the next given limited availability of high-quality temperature measurements. Many measurements were inaccurate or non-existent in some cases. As Figure 4.1.1 and 4.2.1 clearly demonstrate, the exact value of the geothermal gradient at a given wellhead—and by extension the exact value of the BHSZ—is crucial in determining whether an observed spike in deep resistivity can be attributed to gas hydrates. Future analyses would benefit from having a higher resolution profile of the region’s geothermal gradient.
6 Conclusion

The purpose of this analysis was to determine whether gas hydrate was present in the UK North Atlantic Margin. Ultimately, eight out of thirteen wells with quality log data were found to have some amount of gas hydrate present. Three wells were considered Grade C and five wells were categorized as Grade D. Further data analysis will allow for a better estimate of total gas accumulation within the subsurface of the margin.
REFERENCES CITED


APPENDIX

Below are plots of the eight wells that received a grade but were not explicitly mentioned.

204/10a-5Z, Grade: D
204/18b-2, Grade: C

![Graphs showing Gamma Ray (gAPI), Resistivity (Ωm), and Gas Hydrate Saturation (%) for various depths in meters.](image)

- [35°C/Km]
- [25°C/Km]